December 2, 2024

Pre-reception

(1 min. per each person, very informal)

Motivation

- **There are many interesting research from participants, but we cannot hear all of them.**
- **Let's introduce own research briefly.**

1. **Miok Park (IBS-CTPU)**
2. **Gungwon Kang (Chung-Ang University)**
3. **Dong-Han Yeom (Pusan National University)**
4. **Hyeong-Chan Kim (Korea National University of Transportation)**
5. **Wontae Kim (Sogang University)**
6. **O-Kab Kwon (Sungkyunkwan University)**
7. **Jeongwon Ho (CQUEST)**
8. **Yoonbai Kim (Sungkyunkwan University)**
9. **Shinji Mukohyama (YITP)**
10.
11. **Sungwook E. Hong (KASI)**
12. **Madhu Mishra (APCTP)**
13. **Bum-Hoon Lee (Sogang University)**
14. **Kyung Kiu Kim (Kookmin University)**
15. **Inyong Cho (SeoulTech)**
16. **Sojeong Cheong (Sogang University)**
17. **Mu-In Park (Sogang University)**
18. **Hideki Maeda (Hokkai-Gakuen University)**
19. **Matti Jarvinen (APCTP)**
20. **Rinku Maji (IBS-CTPU-CGA)**
21. **David Kubiznak (Charles University)**
22. **Pavan Dharanipragada (IIT Madras)**
23. **Young-Hwan Hyun (Chung-Ang University)**
24. **Stefano Scopel (Sogang University)**
25. **Changhyun Ahn (Kyungpook National University)**
26. **Theodoros Nakas (IBS-CTPU-CGA)**
27. **Mohammad Ali Gorji (IBS-CTPU-CGA)**
28. **Qianhang Ding (IBS-CTPU-CGA)**
29. **Jai-chan Hwang (IBS-CTPU)**

30. Hyeonmo Koo (University of Seoul)

31. Toshali Mitra (APCTP)

32. Temple He (California Institute of Technology)

33. Shuang-Yong Zhou (University of Science and Technology of China)

34. Krzysztof Jodlowski (IBS-CTPU)

35. Stephen Angus (CQUeST, Sogang University)

01. Miok Park

Hairy black holes by spontaneous symmetry breaking

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We study hairy black hole solutions in Einstein(-Maxwell)-scalar-Gauss-Bonnet theory. The complex scalar coupling function includes quadratic and quartic terms, so the gravitational action has a U(1) symmetry. We argued that when the effective mass of the scalar field is at the critical value, the black holes without hairs transform into hairy black holes in a symmetry-broken vacuum via spontaneous symmetry breaking. These hairy black holes are stable under scalar perturbations, and the Goldstone bosons are trivial. Moreover, we found that the spontaneous symmetry breaking associated with local U(1) is unlikely to occur in this theory.

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I. INTRODUCTION

The detection of gravitational waves from the merger of binary black holes by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [1] was a major breakthrough in recent decades. One of the missions of gravitational waves is to test general relativity since it alone struggles to explain the presence of dark matter, dark energy, and inflationary expansion [2–4]. As an alternative to general relativity [5–9], we consider the Einstein(-Maxwell)-scalar-Gauss-Bonnet theory which has a nonminimal coupling of the scalar field with the Gauss-Bonnet(GB) term. The theory belongs to Horndeski gravity and has second-order field equations, so it is free of the ghost problem. Additionally, the evasion of the no-hair theorem was first studied in [10] and later in [11] based on Bekenstein's argument [12,13]. The complete derivation for the evasion of the no-hair theorem was done in [14]. At the same time as the discovery of hairy black holes in [10], spontaneous scalarization was proposed to explain how black holes without hair can acquire scalar hair [15]. This mechanism relies on a tachyonic instability that triggers the spontaneous growth of a scalar hair on a black hole background [15]. However, the produced hairy black holes are unstable under the perturbation of scalar fields [16,17]. Later studies showed that the coupling function with quadratic and quartic terms can generate stable hairy black holes in some parameter regimes [18–20]. Recently stable spontaneous scalarization for a quadratic coupling is suggested in [21,22].

We here consider Einstein-scalar-Gauss-Bonnet theory in (2). We employ the scalar field coupling function f which enjoys U(1) symmetry with a single complex scalar field and a nonminimal coupling to the GB term:

$$f(\varphi^*,\varphi) = \alpha\varphi^*(r)\varphi(r) - \lambda\big(\varphi^*(r)\varphi(r)\big)^2. \qquad (1)$$

This allows us to study hairy black holes in symmetric and symmetry-broken phases. We define the *symmetric phase* as the phase in which the scalar fields near the horizon are at either the "global" minimum ($\alpha < 0$) or the "local" maximum ($\alpha > 0$) of the interacting potential ($V = -f(\varphi^*,\varphi)\mathcal{G}$). The *symmetry-broken phase* is the phase in which the scalar field near the horizon is at the "global" minimum ($\alpha > 0$). In contrast to spontaneous scalarization, which requires a negative effective mass squared to generate hairy black holes, we show that stable hairy black holes are generated in the symmetry-broken phase when the effective mass squared is positive. Thus we provides a mechanism for generating stable hairy black holes rooted from the symmetry of the theory.

This paper is organized as follows. Section II discusses the global U(1) symmetric theory and shows that the Schwarzschild black hole becomes unstable beyond $\alpha_{\rm Sch}$. against the scalar field perturbation. In Sec. III, we find hairy black holes in symmetric and symmetry-broken phases and investigate their instability. We also calculate the mass and scalar charge of those hairy black holes. In Sec. IV, we study electrically charged hairy black holes by spontaneous symmetry breaking in the theory with local U(1) symmetry. Section V summarizes our results.

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Scalar field perturbation of hairy black holes in EsGB theory

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Abstract: We investigate scalar field perturbations of the hairy black holes involved with spontaneous symmetry breaking of the global U(1) symmetry in Einstein-scalar-Gauss-Bonnet theory for asymptotically flat spacetimes. We consider the mechanism that black holes without hairs become unstable at the critical point of the coupling constant and undergo a phase transition to hairy black holes in the symmetry-broken phase driven by spontaneous symmetry breaking. This transition occurs near the black hole horizon due to the diminishing influence of the Gauss-Bonnet term at infinity. To examine such process, we introduce a scalar field perturbation on the newly formed background spacetime. We solve the linearized perturbation equation using Green's function method. We begin by solving the Green's function, incorporating the branch cut contribution. This allows us to analytically investigate the late-time behavior of the perturbation at both spatial and null infinity. We found that the late-time behavior only differs from the Schwarzschild black hole by a mass term. We then proceed to calculate the quasinormal modes (QNMs) numerically, which arise from the presence of poles in the Green's function. Our primary interest lies in utilizing QNMs to investigate the stability of the black hole solutions both the symmetric and symmetry-broken phases. Consistent with the prior study, our analysis shows that hairy black holes in the symmetric phase become unstable when the quadratic coupling constant exceeds a critical value for a fixed value of the quartic coupling constant. In contrast, hairy black holes in the symmetry-broken phase are always stable at the critical value. These numerical results provide strong evidence for a dynamical process that unstable black holes without hairs transition into stable hairy black holes in the symmetry-broken phase through the spontaneous symmetry breaking.

Keywords: Black Holes, Classical Theories of Gravity, Spontaneous Symmetry Breaking

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Black holes in Einstein-scalar-Gauss-Bonnet model probed with scattering amplitudes

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We examined the quantum properties of scalar-tensor gravity with a coupling to the Gauss-Bonnet term in the low-energy limit, exploring both linear and quadratic couplings. We calculated the leading-order corrections to the nonrelativistic one-body gravitational potential and the metric by studying the gravitational field of a pointlike scalar particle. We studied lightlike scattering and compared it with the classical theory. We found that the nonminimal coupling does not contribute to the small-angle scattering for the quadratic coupling but does in the case of linear coupling. The results provide an opportunity to constrain the linear nonminimal coupling to the Gauss-Bonnet term with forthcoming observational data.

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I. INTRODUCTION

Creating an ultraviolet complete quantum theory of gravity is one of the most challenging problems of contemporary physics. One of the major obstacles is the nonrenormalizability of general relativity [1–3]. In contrast with renormalizable theories, general relativity generates new operators at each level of perturbation theory. One can subtract ultraviolet divergences in any amplitude at any order of the perturbation theory. However, the subtraction requires initial data to normalize the finite part of the expression. Since the theory generates new operators at every order of perturbation theory, it also needs a new set of initial data at every new order, and the theory loses predictability.

Perturbative quantum gravity aligns with the effective field theory paradigm, which does not aim to provide a complete ultraviolet theory but instead focuses on applicability in low-energy regimes [4–6]. Perturbative quantum gravity is a quantum theory describing small metric perturbations propagating around flat spacetime. The theory remains applicable if metric perturbations are small, which constrain the theory to the sub-Planck region. The theory remains nonrenormalizable and requires new initial data at each new perturbation theory level. The lack of renormalizability within the effective field theory is due to the need for more information on its ultraviolet extension since each new perturbative correction extends the theory in the ultraviolet region and requires additional data.

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The perturbative approach to quantum gravity offers a powerful tool to calculate scattering amplitudes involving gravitons using the standard tools of quantum field theory. Recent advancements in scattering amplitude calculations have further validated the applicability of perturbative quantum gravity [7–12]. These methods use causality and unitarity relations to recover amplitudes without direct reliance on Feynman rules. The corresponding results exist within the effective theory paradigm, confirming perturbative quantum gravity calculations. Despite the active development of methods for scattering amplitude calculations, this paper uses the widely adopted standard methods based on Feynman rules.

The low-energy limit is a valuable tool for studying perturbative quantum gravity. Its key feature is the decoupling of scales, which allows one to study the low-energy behavior independently from possible ultraviolet extensions. The low-energy limit takes place when the spatial momenta of all particles approach zero. Consequently, the particle interaction energy also approaches zero. The Bogoliubov-Parasyuk-Hepp-Zimmermann (BPHZ) theorem [13–16] governs the theory behavior in this limit. According to the theorem, ultraviolet divergences are always multiplied by operators, which are analytic functions of external momenta. Consequently, all terms with ultraviolet divergences remain bounded in the low-energy limit and do not grow. The ultraviolet finite terms, in contrast, are not constrained by the theorem and can contain nonlocal operators, which are nonanalytic functions of external momenta. Such nonanalytic operators are not bounded and grow uncontrollably in the low-energy limit. Consequently, in the low-energy limit, the leading-order contribution is entirely free from ultraviolet

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Thermodynamics with conformal Killing vector in the charged Vaidya metric

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Abstract: We investigate the charged Vaidya spacetime with conformal symmetry by classifying the horizons and finding its connection to Hawking temperature. We find a conformal Killing vector whose existence requires the mass and electric charge functions to be proportional, as well as linear in time. Solving the Killing equations for the conformally transformed metric from the linear charged Vaidya metric yields the required form of the conformal factor. From the vanishing of the norm of the conformal Killing vector, we find three conformal Killing horizons which, under the transformation, are mapped to the Killing horizons of the associated static spacetime, if the spherical symmetry is maintained. We find that the conformal factor is not uniquely determined, but can take any function of the ratio of the radial coordinate to the dynamical mass. As an example, we illustrate a static spacetime with our choice of the conformal factor and explicitly show that the surface gravity of the conformal Killing horizons, which is conformally invariant, yield the expected Hawking temperature in the static spacetime. This static black hole spacetime contains a cosmological horizon, but it is not asymptotically de Sitter. We also investigate the case when the mass parameter is equal to the constant electric charge. While in this case the standard pair of horizons, the loci of the time component of the metric, degenerate, the conformal Killing horizons do not degenerate. This therefore leads to a non-zero Hawking temperature in the associated static spacetime.

Keywords: Black Holes, Classical Theories of Gravity, Scale and Conformal Symmetries

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02. Gungwon Kang

Ringdown Gravitational Waves from Close Scattering of Two Black Holes

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We have numerically investigated close scattering processes of two black holes (BHs). Our careful analysis shows for the first time a nonmerging ringdown gravitational wave induced by dynamical tidal deformations of individual BHs during their close encounter. The ringdown wave frequencies turn out to agree well with the quasinormal ones of a single BH in perturbation theory, despite its distinctive physical context from the merging case. Our study shows a new type of gravitational waveform and opens up a new exploration of strong gravitational interactions using BH encounters.

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Introduction.—Lots of numerical studies on binary black hole (BH) coalescence have primarily focused on quasicircular cases, presumably because they are the main sources of gravitational wave (GW) observations [1–3]. As the sensitivity of GW detectors increases and various future observation plans are proposed [4–6], however, a broader range of GW sources becomes of interest, resulting in active studies on eccentric binary black hole (BBH) systems in both numerical and approximation methods. In particular, highly eccentric BBHs and scattering BHs on hyperbolic orbits have been investigated [7–24]. However, studies on strong interactions in these systems remain limited. Investigating dynamical behaviors of BH horizons and radiated waveforms through varying initial parameters can broaden our knowledge beyond quasicircular scenarios.

In the perturbation regime, the system of a BH and an orbiting particle showed oscillatory imprints in GWs linked to the BH's quasi-normal mode (QNM) excitations [25–28]. The tidal Love number for stationary BH horizons was also examined [29–31]. In the nonlinear regime, eccentric binary neutron star mergers between head-on and circular have been studied, revealing tidal oscillations induced by the companion stars [32]. In the case of BBHs, ringdown GWs are well known as imprints of deformations in the merged BH. In scattering BHs, each BH's spin-up effects were found [23,24], indicating tidal interactions between BHs. In quasicircular BBH inspirals, BH source moments were explored, showing nonvanishing tidal Love numbers for constituent BH horizons [33]. However, tidally excited gravitational radiations of individual BH horizons without merging remain unexplored.

This work presents the first full general relativistic simulation of scattering BHs, showing ringdown GWs from tidal deformations of nonmerging constituent BHs. Remarkably, these GWs' leading frequencies agree with individual BH's QNM frequencies in perturbation theory. One may explore much more various features of strong interactions and BH tidal deformations by adjusting impact parameters and speeds. Finally, observational implications of this new class of GWs are discussed.

Numerical simulation of scattering black holes.—For the numerical relativity (NR) simulations, we use EinsteinToolkit [34,35]. McLachlan [36] is used for time evolution with an eighth-order spatial finite difference method and CARPET [37] for the adaptive mesh refinement. The computational domain extends to $770M$ in geometrized units with radiative boundary conditions for an outer boundary, and seven mesh refinement levels are used with the finest grid spacings for different resolutions, $h \simeq 0.0137M$ and $h \simeq 0.0156M$, around the BHs. These resolutions are higher than those used in previous convergent tests [9,10], ensuring they fall within the convergent regime.

Using TwoPuncture [38], initial conditions are set for two equal-mass and nonspinning BHs to be in hyperbolic motion during the whole scattering process. To avoid overlap between physical and junk radiations, the initial positions of the two BHs are set at $(\pm X, Y, Z) = (\pm 200, 0, 0)M$. Components of the initial momenta are given by $\vec{p} = \pm|\vec{p}|(-\sqrt{1-[b/(2X)]^2}, b/(2X), 0)$. We have set $|\vec{p}| = 0.2886751M$, which corresponds to $v \approx 0.5$, and considered two different impact parameters $b = 8M$ and $b = 10M$. In all cases, the Arnowitt-Deser-Misner (ADM) energies are nearly identical to $M_{\rm ADM} \approx 1.1563547M$, with only a very small difference on the order of 10^{-8}. Consequently, we conducted a total of four simulation models, using two different impact parameters and two different grid resolutions for each.

The Weyl scalar Ψ_4 has been extracted up to $l = 16$ mode in spin-weighted spherical harmonics, and we set the several extraction surfaces up to $r_{\rm ext} = 400M$, which is far

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A Superconducting Tensor Detector for Mid-Frequency Gravitational Waves: Its Multichannel Nature and Main Astrophysical Targets

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Mid-frequency band gravitational-wave detectors will be complementary to the existing Earth-based detectors (sensitive above 10 Hz or so) and the future space-based detectors such as the Laser Interferometer Space Antenna (LISA), which will be sensitive below around 10 mHz. A ground-based superconducting omnidirectional gravitational radiation observatory (SOGRO) has recently been proposed along with several design variations for the frequency band of 0.1–10 Hz. For two conceptual designs of SOGRO (i.e. SOGRO and advanced SOGRO [aSOGRO]), we examine their multichannel natures, sensitivities, and science cases. One of the key characteristics of the SOGRO concept is its six detection channels. The response functions of each channel are calculated for all possible gravitational wave (GW) polarizations including scalar and vector modes. Combining these response functions, we also confirm the omnidirectional nature of SOGRO. Hence, even a single SOGRO detector will be able to determine the position of a source and polarizations of GWs, if detected. Taking into account SOGRO's sensitivity and technical requirements, two main targets are most plausible: GWs from compact binaries and stochastic backgrounds. Based on assumptions we consider in this work, detection rates for intermediate-mass binary black holes (in the mass range of hundreds up to $10^5\ M_\odot$) are expected to be 0.0065–8.1 yr^{-1}. In order to detect the stochastic GW background, multiple detectors

03. Dong-Han Yeom

Yang-Mills instantons as the endpoint of black hole evaporation

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Nonperturbative contributions of the Euclidean path integral are important to understand the information loss paradox. In this paper, we revisit the Yang-Mills instantons in the Einstein-Yang-Mills theory. There exists a globally regular solution that is known as the Bartnik-McKinnon solution and a black hole solution. The regular and the black hole solutions are smoothly connected in the small horizon limit. Their Euclidean action is solely characterized by the ADM mass, and the transition probability follows the usual Bekenstein-Hawking entropy formula. Therefore, the Yang-Mills instantons provide a nonperturbative channel to the black hole evaporation, which competes effectively with perturbative processes, and becomes dominant toward the end of evaporation. We show that these instantons provide a smooth transition mechanism from a black hole to regular spacetime.

DOI: 10.1103/PhysRevD.110.044043

I. INTRODUCTION

The evaporation of black holes is a consequence of general relativity and quantum mechanics [1]. It poses, however, a serious challenge about the consistency between these two fundamental theories since it appears to imply the violation of unitarity. In other words, a consistent description of an evaporating black hole demands the reconciliation of the tension between general relativity and unitary quantum mechanics [2]. Recently, many important and interesting solutions are reported in the literature [3]. The common features of them indicate that the following two conditions are required to explain the unitarity of black hole evaporation [4]:

(1) *Multihistory condition*: One must take account of the contribution of different semi-classical histories to the wave function of the system, which include information-preserving histories, i.e., geometries without event horizons.

(2) *Late-time dominance condition*: The contribution of information-preserving histories should dominate the wave function at the late time of the black hole evaporation.

If these two conditions are realized, the unitary evolution of the black hole system is automatically guaranteed, and one can consistently derive the Page curve [5] for the entanglement entropy [4].

Although the above two conditions look conceptually simple, they are practically highly nontrivial to realize. First, one needs a formulation that is naturally endowed with the multihistory condition, which includes information-preserving histories. One possibility is to take account of replica wormholes [3]. In this case, the two conditions seem realizable by including replica wormhole configurations in the path integral. However, since the computations of replica wormholes are based on the density matrix instead of the wave function, it is unclear whether they can be embedded in the canonical path integral formalism. An alternative is to develop a method to compute the contribution of trivial geometries, i.e., those with neither

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Hairy Reissner-Nordström black holes with asymmetric vacua

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We minimally coupled a scalar potential $V(\phi)$ with asymmetric vacua to the Einstein gravity to numerically construct the hairy Reissner-Nordström black hole (RNBH) as a direct generalization of RNBHs to possess scalar hair. By fixing the electric charge to mass ratio q, a branch of hairy RNBHs bifurcates from the RNBH when the scalar field ϕ_H is nontrivial at the horizon. The values of q are bounded for $0 \leq q \leq 1$, which contrast to a class of hairy black holes with $q > 1$ in the Einstein-Maxwell-scalar theory. We find that the profiles of solutions affected by the competition between the strength of ϕ_H and q, for instance, the gradient of scalar field at the horizon can increase very sharply when $q \to 1$ and ϕ_H is small, but its gradient can be very small which is independent of q when ϕ_H is large. Furthermore, the weak energy condition of hairy RNBHs, particularly at the horizon can be satisfied when $q > 0$.

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I. INTRODUCTION

According to the no-hair theorem [1–3], the state of black holes in general relativity (GR) can only be described by the three global charges which are the mass, electrical charge, and angular momentum. The Reissner-Nordström black hole (RNBH) [4,5] is the solution to the Einstein-Maxwell theory and satisfies the no-hair theorem. Nevertheless, a black hole is known as a hairy black hole when it is supported by a matter field outside the event horizon and may possess additional global charge (refers to "hair") which is associated with the matter field. Hairy black holes can exhibit a deviation of their properties from the electrovacuum black holes in the strong gravity regime but are indistinguishable in the weak gravity regime. A mechanism which is known as the spontaneous scalarization (SS) to allow black holes can evade the no-hair theorem to possess a nontrivial scalar field ϕ outside the horizon; hence the RN black hole can be extended to a broader class of charged hairy black holes; for instance, a various form of scalar function $f(\phi)$ nonminimally couples with the Maxwell field [6–32] in the Einstein-Maxwell-scalar theory can give rise to the tachyonic instabilities so that charged hairy black holes can be spontaneously scalarized from the RNBH. A few decades ago T. Damour and G. Esposito-Farèse [33] proposed the concept of SS to predict the deviation of properties for the neutron stars from GR in the strong gravity regime, but it becomes indistinguishable in the weak gravity regime within the framework of the scalar-tensor theory, which nonminimally couples a scalar function with the Ricci scalar.

However, one may overlook that an RNBH can also be extended to another class of charged hairy black holes in the simplest and direct manner, i.e., one can minimally couple the Einstein gravity and Maxwell field with a scalar potential $V(\phi)$. By properly introducing the form of $V(\phi)$ which is associated with the profile of $V(\phi)$ to evade the no-hair theorem, the solutions of hairy black holes can be bifurcated from the electrovacuum black holes, and they are regular everywhere in the spacetime. Recently, the authors have employed two different profiles of $V(\phi)$ to construct the neutral hairy black holes without the anticipation of other extended objects, for instance the Gauss-Bonnet term or matter fields and study their properties in detail [34–36]. The first profile of $V(\phi)$ with the shape of two asymmetric vacua which contain a local maximum, a local minimum, and a global minimum to describe the phase transition of vacuum bubbles from the false vacuum (local minimum) to the true vacuum (global minimum) [37]. The second profile of $V(\phi)$ with the shape of the inverted Mexican hat contains two degenerate maxima and a local minimum [36]. Therefore, we generalize those neutral hairy black holes in [35] to possess an electric charge and study their

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A possible origin of the α-vacuum as the initial state of the Universe

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We investigate the cosmological observables using the Euclidean path integral approach. Specifically, we study both the no-boundary compact instantons scenario and the Euclidean wormholes scenario that can induce the creation of two universes from nothing. It is known that perturbations associated with the no-boundary scenario can only be consistent with the Bunch-Davies vacuum. Here we demonstrate that the Euclidean wormholes can allow for a de Sitter invariant vacuum, the so-called α-vacuum state, where the Bunch-Davies vacuum is a special case. This therefore provides the α-vacuum a geometrical origin. As an aside, we discuss a subtle phase issue when considering the power spectrum related to α-vacuum in the closed universe framework.

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Can a naked singularity be formed during the gravitational collapse of a Janis-Newman-Winicour solution?

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The Janis-Newman-Winicour (JNW) spacetime possesses a naked singularity, although it represents an exact particle-like solution to the Einstein-Klein-Gordon theory with a massless scalar field. Here, we investigate the possible formation of a naked singularity in the JNW spacetime, using the thin-shell approximation to describe the gravitational collapse. By introducing different matter contents to construct thin-shells, we demonstrate the impossibility of naked singularity formation during the gravitational collapse unless the *causality* or *null energy condition* of the thin-shell is violated. Therefore, the weak cosmic censorship is satisfied even with the naked singularity of the JNW spacetime.

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Chapter 1
Information retrieval from Euclidean path integral

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Abstract In this article, we review the information loss paradox in the spirit of the Euclidean path integral approach. First, we argue that there is a long debate about the information loss paradox, and the non-perturbative quantum gravitational wave function must include the clue to the paradox. The Euclidean path integral approach provides the best way to describe the wave function. From this wave function, we can notice that there are not only semi-classical but also non-perturbative contributions, which are highly suppressed but preserved information. Information retrieval will be sufficiently explained if such non-perturbative contributions must be dominated by the late time. We will show that there is sufficient evidence that this scenario can be realized in generic circumstances. Finally, we compare this scenario with alternative approaches. Also, we comment on some unresolved issues that need to be clarified.

1.1 Introduction

The information loss paradox [34] is one of the fundamental questions that must be resolved by the quantum theory of gravity, or the Theory of Everything. Black holes will evaporate due to Hawking radiation in a finite time [33]. However, Hawking radiation seems to depend only on the information of its horizon, e.g., the mass M, the charge Q, and the angular momentum J. After the evaporation, can Hawking radiation carry quantum mechanical information? If not, we will eventually lose the unitarity of quantum mechanics and the fundamental predictability. On the other hand, if information must be preserved, how can Hawking radiation carry information without causing further inconsistency? This paradox drastically reveals the ten-

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04. Hyeong-Chan Kim

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Research article

Temperature upper bound of an ideal gas

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ABSTRACT

We study thermodynamics of a heat-conducting ideal gas system. The study is based on i) the first law of thermodynamics from action formulation which expects heat-dependence of energy density and ii) the existence condition of a (local) Lorentz boost between an Eckart observer and a Landau-Lifshitz observer–a condition that extends the stability criterion of thermal equilibrium. The implications of these conditions include: i) Heat contributes to the energy density through the combination $q/n\Theta^2$ where q, n, and Θ represent heat, the number density, and the temperature, respectively. ii) The energy density has a unique minimum at $q = 0$. iii) The temperature upper bound suppresses the heat dependence of the energy density inverse quadratically. This result explains why the expected heat dependence is difficult to observe in ordinary situation thermodynamics.

The lower bound of temperature, referred to as the absolute zero in Kelvin, is determined by the behavior of the ideal gas volume (or pressure) in thermal equilibrium, contingent upon the temperature changes. On the other hand, a precise upper bound of temperature lacks a unique definition. In the theory of particle physics, the 'Hagedorn temperature' [1] for hadrons serves as an upper bound. Beyond this temperature ordinary matter is no longer stable, and must either "evaporate" or convert into other (quark-gluon) phase. Similarly, the string Hagedorn temperature [2] plays a comparable role for strings. Given that temperature is a thermodynamic quantity, it is natural to inquire about the implications of the existence of the temperature upper bound on thermodynamics. In this work, we show that it affects the nature of heat conduction.

In the kinetic theory picture, an ideal gas is a theoretical gas consisting of numerous randomly moving, non-interacting point particles. The model is useful as it adheres a simplified equation of state known as the ideal gas law, effectively approximating the states of most physical gases under non-extreme conditions. The thermodynamic properties of an ideal gas can be described by two equations. The first is the ideal gas law, $\Psi V = N k_B \Theta$, where Ψ, V, N, k_B and Θ denote the pressure, the volume, the total number of particles, the Boltzmann constant, and the temperature, respectively. Dividing both sides of the equation by the volume V and adopting the natural units with $k_B = 1$, the law presents a simple relation between pressure and temperature:

$$\Psi = n\Theta, \tag{1}$$

where $n (\equiv N/V)$ denotes the number density. Because we are interested in the relativistic thermodynamics based on local description of the theory, we write physical quantities in terms of densities such as n. The other equation expresses the energy density $\rho (\equiv E/V)$ of the gas consisting of particles with mass m as:

$$\rho(n, s) = nm + c_v n\Theta, \tag{2}$$

where c_v is a constant denoting the dimensionless specific heat capacity at constant volume, approximately $3/2$ or $5/3$ for monoatomic or diatomic gases, respectively. Other quantities can be obtained from these two laws. For example, one can calculate the entropy

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Temperature of a steady system around a black hole

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Abstract

We study the issue of temperature in a steady system around a black hole event horizon, contrasting it with the appearance of divergence in a thermal equilibrium system. We focus on a spherically symmetric system governed by general relativity, particularly examining the steady state with radial heat conduction. Employing an appropriate approximation, we derive exact solutions that illuminate the behaviors of number density, local temperature, and heat in the proximity of a black hole. We demonstrate that a carefully regulated heat inflow can maintain finite local temperatures at the black hole event horizon, even without considering the back-reaction of matter. This discovery challenges conventional expectations that the local temperature near the event horizon diverges in scenarios of thermal equilibrium. This implications shows that there's an intricate connection between heat and gravity in the realm of black hole thermodynamics.

Keywords: temperature, blackhole, steady state, relativistic thermodynamics

1. Introduction

Consider an observer who watches a thermodynamic system interacting with a static black hole described by spatially varying metric components, g_{ab}, in Einstein gravity. If he/she measures the temperature of the system in thermal equilibrium, it ticks the local Tolman temperature [1, 2],

$$\Theta\left(x^i\right) = \frac{T_\infty}{\sqrt{-g_{00}\left(x^i\right)}}, \tag{1}$$

where g_{00} and T_∞ represent the time-time component of the metric on the static geometry and the physical temperature at the zero gravitational potential hypersurface usually located at spatial infinity, respectively. The temperature is regarded as a physical one in the sense that

Charged rotating wormholes: charge without charge

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Abstract

We present a family of charged rotating wormhole solutions to the Einstein-Maxwell equations, supported by anisotropic matter fields. We first revisit the charged static cases and analyze the conditions for the solution to represent a wormhole geometry. The rotating geometry is obtained by applying the Newman-Janis algorithm to the static geometry. We show the solutions to Maxwell equations in detail. We believe that our wormhole geometry offers a geometric realization corresponding to the concept of 'charge without charge'.

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Investigation of black hole complementarity in AdS_2 black holes

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Abstract: Black hole complementarity plays a pivotal role in resolving the information loss paradox by treating Hawking radiation as carriers of information, apart from the complicated mechanisms involved in decoding information from this radiation. The thought experiment proposed by Susskind and Thorlacius, as well as the criteria set forth by Hayden and Preskill, provide deep insights into the intricate relationship of black hole complementarity between fiducial and infalling observers. We execute the Alice-Bob thought experiment in the context of two-dimensional anti-de Sitter black holes. It turns out that information cloning can be avoided in the case of a large black hole. According to the Hayden-Preskill criteria, if the scale parameter associated with the explicit breaking of the one-dimensional group of reparametrizations is significantly exceed the squared mass of the black hole, then information cloning can be effectively evaded.

Keywords: 2D Gravity, Black Holes, Models of Quantum Gravity

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Quantum geodesics reflecting the internal structure of stars composed of shells

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Abstract: In general relativity, an external observer cannot distinguish distinct internal structures between two spherically symmetric stars that have the same total mass M. However, when quantum corrections are taken into account, the external metrics of the stars will receive quantum corrections depending on their internal structures. In this paper, we obtain the quantum-corrected metrics at linear order in curvature for two spherically symmetric shells characterized by different internal structures: one with an empty interior and the other with N internal shells. The dependence on the internal structures in the corrected metrics tells us that geodesics on these backgrounds would be deformed according to the internal structures. We conduct numerical computations to find out the angle of geodesic precession and show that the presence of internal structures amplifies the precession angle reflecting the discrepancy between the radial and orbital periods within the geodesic orbit. The amount of the precession angle increases monotonically as the number of internal shells increases and it eventually converges to a certain value for $N \to \infty$.

Keywords: modified gravity, quantum field theory on curved space

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Letter

The quasilocal energy and thermodynamic first law in accelerating AdS black holes

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ABSTRACT

We scrutinize the conserved energy of an accelerating AdS black hole by employing the off-shell quasilocal formalism, which amalgamates the ADT formalism with the covariant phase space approach. In the presence of conical singularities in the accelerating black hole, the energy expression is articulated through the surface term derived from our formalism. The essence of our analysis of the quasilocal energy resides in the surface contributions coming from the conical singularities as well as the conventional radial boundary. Consequently, the resultant conserved quasilocal energy naturally conforms the thermodynamic first law for the black hole without necessitating any augmentation of thermodynamic variables.

1. Introduction

The thermodynamics of black holes provides deep insights into the quantum theory of gravity. In the seminal works of Bekenstein [1,2] and Hawking [3], it was revealed that the area of a black hole and its surface gravity are correlated with the black hole's entropy and temperature. Given that thermal properties of a physical system are closely intertwined with the statistical description of its microstates, black hole thermodynamics would elucidate the underlying microscopic degrees of freedom, potentially illuminating certain quantum aspects of gravity [4]. Consequently, black hole thermodynamics has been investigated across numerous gravity models over the past decades. In particular, recent studies have explored the thermodynamics of accelerating black holes [5–23], which are described by the C-metric as an exact solution to the Einstein field equations [24–28]. A notable feature of these black holes is the presence of at least one irremovable conical deficit angle along the azimuthal axis. This conical singularity is responsible for the acceleration of the black hole, which may be understood by replacing it with an energy-momentum tensor corresponding to finite-width topological defects [29] or magnetic flux tubes [30].

Exploring the thermodynamics of accelerating black holes in the presence of conical singularities remains challenging. One main difficulty arises in defining the conserved energy of these black holes, which is complicated by their nontrivial asymptotic structure. In particular, the conical singularities reach the conformal infinity of the black hole [31,32], rendering the asymptotic structure topologically different from $\mathbb{R} \times S^2$ due to the deficit angle. Thus, this topological disparity disturbs the use of conformal regularization methods, developed initially by Ashtekar, Magnon, and Das (AMD) [33–36], for determining the conserved energy of accelerating black holes. Regarding the conserved energy of the black holes, recent studies [7,10–12] also suggest that string tensions associated with the conical singularities are required to be constant in order to satisfy the conventional form of the thermodynamic first law.

To effectively evade the complexities associated with the exotic asymptotic structure, one can adopt a quasilocal formalism for the conserved energy. The quasilocal approach, unlike global asymptotic methods, provides a robust framework for defining a conserved charge within a finite region of spacetime, thereby avoiding the difficulties associated with the asymptotic region. For a comprehensive review of this approach, see Ref. [37] and references therein. In particular, the quasilocal method developed in Ref. [38] derives the conserved charges in a covariant manner by correlating the Abbott-Deser-Tekin (ADT) current [39–43] with the linearized Noether current. Remarkably, the correspondence between these formalisms is established at the off-shell level, rendering it independent of the asymptotic behavior, in contrast to the original ADT method, which relies on asymptotic conditions.

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Validity of black hole complementarity in an accelerating Schwarzschild black hole

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Abstract

Black hole complementarity has been well understood in spherically symmetric black holes. To study its validity for an accelerating Schwarzschild black hole, which has a preferred direction, we perform the thought experiment proposed by Susskind and Thorlacius and further investigate the criteria set by Hayden and Preskill. First, we derive thermodynamic quantities that satisfy the first law of thermodynamics. Using these quantities, we conduct thought experiments based on the Page time and the scrambling time, which show that black hole complementarity remains valid, although the energy required for the duplication of information depends on the angle due to the axisymmetric metric.

Keywords: Black Holes, Models of Quantum Gravity, Black Hole Complementarity

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07. Jeongwon Ho

Quantum Inhomogeneous Field Theory: Unruh-Like Effects and Bubble Wall Friction

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Abstract

In this paper, we study a free scalar field in a specific (1+1)-dimensional curved spacetime. By introducing an algebraic state that is locally Hadamard, we derive the renormalized Wightman function and explicitly calculate the covariantly conserved quantum energy-momentum tensor up to a relevant order. From this result, we show that the Hadamard renormalization scheme, which has been effective in traditional quantum field theory in curved spacetime, is also applicable in the quantum inhomogeneous field theory. As applications of this framework, we show the existence of an Unruh-like effect for an observer slightly out of the right asymptotic region, as well as a quantum frictional effect on the bubble wall expansion during the electroweak phase transition in the early universe. Consequently, this study validates the consistency of our method for constructing meaningful physical quantities in quantum inhomogeneous field theory.

All authors contributed equally.

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Inhomogeneous Abelian Chern-Simons Higgs Model with New Inhomogeneous BPS Vacuum and Solitons

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Abstract

We study an inhomogeneous U(1) Chern-Simons Higgs model with a magnetic impurity in the BPS limit. The potential is sextic with both broken and unbroken phases, but its minimum varies spatially depending on the strength of the impurity. While the system lacks translation symmetry, it admits a supersymmetric extension. Depending on the sign of the impurity term, it has either a BPS sector or an anti-BPS sector (but not both), which satisfies the Bogomolny equations. The vacuum configuration of the broken phase is not simply determined by the the minimum of the potential since it is no longer constant, but it becomes a nontrivial function satisfying the Bogomolny equations. Thus, the energy and angular momentum densities of the vacuum locally have nonzero distributions, although the total energy and angular momentum remain zero. As in the homogeneous case, the theory supports various BPS soliton solutions, including topological and nontopological vortices and Q-balls. The vorticities as well as the U(1) charges are exclusively positive or negative. For a Gaussian type impurity as a specific example, we obtain rotationally symmetric numerical solutions and analyze their detailed properties.

Vacuum and Vortices in Inhomogeneous Abelian Higgs Model

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Abstract

The inhomogeneous abelian Higgs model with a magnetic impurity in the BPS limit is studied for both relativistic and nonrelativistic regimes. Though the symmetry of spatial translation is broken by inhomogeneity, extension to an $\mathcal{N}=1$ supersymmetric theory is admitted. The quartic scalar potential has minimum value depending on strength of the impurity but possesses broken phase at spatial asymptote. The vacuum configuration of broken phase can be neither a constant nor the minimum of the scalar potential, but is found as a nontrivial solution of the Bogomolny equations. While its energy density and magnetic field are given by the function of spatial coordinates, the energy and magnetic flux remain zero. The sign of the magnetic impurity term allows either a BPS sector or anti-BPS sector but not both. Thus the obtained solution is identified as the new inhomogeneous broken vacuum of minimum zero energy. In the presence of rotationally symmetric Gaussian type inhomogeneity, topological vortex solutions are also obtained and the effects of the impurity to the vortex are numerically analyzed.

Existence and Uniqueness of BPS Vacuum and Multi-vortices in Inhomogeneous Abelian Higgs Model

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Abstract

The BPS limit of the inhomogeneous abelian Higgs model is considered in $(1+2)$-dimensions. The second order Bogomolny equation is examined in the presence of an inhomogeneity expressed as a function of spatial coordinates. Assuming a physically reasonable upper bound on the $L^2(\mathbb{R}^2)$ norm of the inhomogeneity function, we prove the existence and the uniqueness of nontrivial BPS vacuum solution of zero energy and topological BPS multi-vortex solutions of quantized positive energies.

09. Shinji Mukohyama

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Effective field theory of black hole perturbations in vector-tensor gravity

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Abstract: We formulate the effective field theory (EFT) of vector-tensor gravity for perturbations around an arbitrary background with a *timelike* vector profile, which can be applied to study black hole perturbations. The vector profile spontaneously breaks both the time diffeomorphism and the U(1) symmetry, leaving their combination and the spatial diffeomorphism as the residual symmetries in the unitary gauge. We derive two sets of consistency relations which guarantee the residual symmetries of the EFT. Also, we provide the dictionary between our EFT coefficients and those of generalized Proca (GP) theories, which enables us to identify a simple subclass of the EFT that includes the GP theories as a special case. For this subclass, we consider the stealth Schwarzschild(-de Sitter) background solution with a constant temporal component of the vector field and study the decoupling limit of the longitudinal mode of the vector field, explicitly showing that the strong coupling problem arises due to vanishing sound speeds. This is in sharp contrast to the case of gauged ghost condensate, in which perturbations are weakly coupled thanks to certain higher-derivative terms, i.e., the scordatura terms. This implies that, in order to consistently describe this type of stealth solutions within the EFT, the scordatura terms must necessarily be taken into account in addition to those already included in the simple subclass.

Keywords: gravity, modified gravity

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CMB spectrum in unified EFT of dark energy: scalar-tensor and vector-tensor theories

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Abstract: We study the cosmic microwave background (CMB) radiation in the unified description of the effective field theory (EFT) of dark energy that accommodates both scalar-tensor and vector-tensor theories. The boundaries of different classes of theories are universally parameterised by a new EFT parameter α_V characterising the vectorial nature of dark energy and a set of consistency relations associated with the global/local shift symmetry. After implementing the equations of motion in a Boltzmann code, as a demonstration, we compute the CMB power spectrum based on the wCDM background with the EFT parameterisation of perturbations and a concrete Horndeski/generalised Proca theory. We show that the vectorial nature generically prevents modifications of gravity in the CMB spectrum. On the other hand, while the shift symmetry is less significant in the perturbation equations unless the background is close to the ΛCDM, it requires that the effective equation of state of dark energy is in the phantom region $w_{\rm DE} < -1$. The latter is particularly interesting in light of the latest result of the DESI+CMB combination as the observational verification of $w_{\rm DE} > -1$ can rule out shift-symmetric theories including vector-tensor theories in one shot.

Keywords: modified gravity, Cosmological perturbation theory in GR and beyond, CMBR theory

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Tidal Love numbers from EFT of black hole perturbations with timelike scalar profile

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Abstract: We study static tidal Love numbers (TLNs) of a static and spherically symmetric black hole for odd-parity metric perturbations. We describe black hole perturbations using the effective field theory (EFT), formulated on an arbitrary background with a timelike scalar profile in the context of scalar-tensor theories. In particular, we obtain a static solution for the generalized Regge-Wheeler equation order by order in a modified-gravity parameter and extract the TLNs uniquely by analytic continuation of the multipole index ℓ to non-integer values. For a stealth Schwarzschild black hole, the TLNs are vanishing as in the case of Schwarzschild solution in general relativity. We also study the case of Hayward black hole as an example of non-stealth background, where we find that the TLNs are non-zero (or there is a logarithmic running). This result suggests that our EFT allows for non-vanishing TLNs and can in principle leave a detectable imprint on gravitational waves from inspiralling binary systems, which opens a new window for testing gravity in the strong-field regime.

Keywords: modified gravity, Gravitational waves in GR and beyond: theory

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Bridging Dark Energy and Black Holes with EFT: Frame Transformation and Gravitational Wave Speed

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Abstract

Typically, constraints on parameters of the effective field theory (EFT) of dark energy have been obtained in the Jordan frame, where matter fields are minimally coupled to gravity. To connect these constraints with those of the EFT of black hole perturbations with a timelike scalar profile, it is necessary to perform a frame transformation on the EFT in general. In this paper, we study the conformal/disformal transformation of EFT parameters on an arbitrary background. Furthermore, we explore the effect of an EFT operator $M_6(r)\bar{\sigma}^\mu_\nu \delta K^\nu_\alpha \delta K^\alpha_\mu$, which is elusive to the LIGO/Virgo bound on gravitational-wave speed, on the dynamics of odd-parity black hole perturbations. Intriguingly, a deviation from luminal propagation shows up only in the vicinity of the black hole, and the speeds of perturbations in the radial and angular directions are different in general due to the traceless part $\bar{\sigma}^\mu_\nu$ of the background extrinsic curvature. This study establishes an important link between cosmological constraints and those obtained in the black hole regime.

11. Sungwook E. Hong

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The effects of non-linearity on the growth rate constraint from velocity correlation functions

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ABSTRACT

The two-point statistics of the cosmic velocity field, measured from galaxy peculiar velocity (PV) surveys, can be used as a dynamical probe to constrain the growth rate of large-scale structures in the Universe. Most works use the statistics on scales down to a few tens of Megaparsecs, while using a theoretical template based on the linear theory. In addition, while the cosmic velocity is volume-weighted, the observable line-of-sight velocity two-point correlation is density-weighted, as sampled by galaxies, and therefore the density–velocity correlation term also contributes, which has often been neglected. These effects are fourth order in powers of the linear density fluctuation $\delta_{\rm L}^4$, compared to $\delta_{\rm L}^2$ of the linear velocity correlation function, and have the opposite sign. We present these terms up to $\delta_{\rm L}^4$ in real space based on the standard perturbation theory, and investigate the effect of non-linearity and the density–velocity contribution on the inferred growth rate $f\sigma_8$, using *N*-body simulations. We find that for a next-generation PV survey of volume $\sim \mathcal{O}(500\,h^{-1}\,{\rm Mpc})^3$, these effects amount to a shift of $f\sigma_8$ by ∼10 per cent and is comparable to the forecasted statistical error when the minimum scale used for parameter estimation is $r_{\rm min} = 20\,h^{-1}$ Mpc.

Key words: cosmological parameters – cosmology: observations – large-scale structure of Universe.

1 INTRODUCTION

The cosmic velocity field is an important cosmological probe, due to its capability of constraining the dynamical evolution of the Universe (Ferreira et al. 1999). It can be used to discriminate between cosmological models and gravity theories that otherwise may have indistinguishable observables related to the background geometry, such as BAO, CMB, and type Ia supernovae (Eisenstein et al. 2005; Dunkley et al. 2009; Bautista et al. 2018; Abbott et al. 2019; Aghanim et al. 2020). Therefore, many upcoming cosmological surveys include measuring the cosmic velocity field as one of their key science objectives (DESI: DESI Collaboration 2016; Euclid: Amendola et al. 2018).

There are two kinds of observations to probe the cosmic velocity field. One is redshift space distortions (RSD; Kaiser 1987; Hamilton 1998), as probed by spectroscopic data. Redshifts measured using spectral features of galaxies are shifted by the Doppler effect caused by the peculiar velocity (PV) of galaxies. This velocity field is sourced by the gravitational potential of the matter distribution and coherent on large scales, causing a compression of the two-point statistics along the line of sight on large scales. The degree of anisotropy is sensitive to the growth rate parameter $f\sigma_8$. There have been many successful detections of RSD (Guzzo et al. 2008; Blake et al. 2011; Samushia, Percival & Raccanelli 2012; Reid et al. 2014; Okumura et al. 2016), placing a constraint on the growth rate of the large-scale structure. The second is inference of the velocity field from distance measurements. Certain classes of galaxies are known to have a tight correlation between stellar kinematics and luminosity (Faber & Jackson 1976; Tully & Fisher 1977). These relations allow us to deduce the luminosity of galaxies, which in turn can be translated into true distances. Combined with spectroscopic redshifts, one can extract PVs, because the observed redshift comprises a combination of the Hubble flow and PV. Numerous theoretical studies relating to PV statistics have been carried out (Park 2000; Koda et al. 2014; Saito et al. 2014; Okumura et al. 2016; Castorina & White 2020), and measurements with existing data have been undertaken (Davis & Peebles 1982; Park & Park 2006; Johnson et al. 2014; Adams & Blake 2017; Howlett et al. 2017b). With increasingly large catalogues becoming available, PV draws attention as a promising way to constrain cosmological models (Howlett, Staveley-Smith & Blake 2017a; Dupuy, Courtois & Kubik 2019; Turner, Blake & Ruggeri 2021; Tully et al. 2023).

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Letter

Final parsec problem of black hole mergers and ultralight dark matter

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ABSTRACT

When two galaxies merge, they often produce a supermassive black hole binary (SMBHB) at their center. Numerical simulations with stars and cold dark matter show that SMBHBs typically stall out at a distance of a few parsecs apart and take billions of years to coalesce. This is known as the final parsec problem. We suggest that ultralight dark matter (ULDM) halos around SMBHBs can generate dark matter waves due to dynamical friction. These waves can effectively carry away orbital energy from the black holes, rapidly driving them together. To test this hypothesis, we performed numerical simulations of black hole binaries inside ULDM halos. Due to gravitational cooling and quasi-normal modes, the loss-cone problem can be avoided. The decay time scale gives lower bounds on masses of the ULDM particles and SMBHBs comparable to observational data. Our results imply that ULDM waves can lead to the rapid orbital decay of black hole binaries.

1. Introduction

The mystery of supermassive black hole (SMBH) growth is one of the unsolved problems in astronomy. When two galaxies merge, they can form a supermassive black hole binary (SMBHB) at their center. However, numerical simulations show that SMBHBs typically become stuck at a distance of a few parsecs apart, and can take billions of years to merge. At this distance the density of the stars and gas near the SMBHB is too low for dynamical friction to be efficient, while the loss of orbital energy of the SMBHB due to gravitational waves is only efficient for distances less than $\mathcal{O}(10^{-2})$ pc [1,2]. Furthermore, the loss cone is depleted as the black holes (BHs) approach each other. This difficulty is known as the final parsec problem. The gravitational wave background recently observed by NANOGrav [3] is usually attributed to efficient SMBH mergers. This fact deepens the mystery. Proposed solutions to the final parsec problem often involve bringing in extra matter, such as additional stars or another BH interacting with the black hole binaries (BHBs) to help them merge.

Ultralight (fuzzy) dark matter (ULDM) [4–9] is a promising alternative to cold dark matter (CDM), as it has the potential to solve some of the small-scale issues of CDM such as the missing satellite problem, the plane of satellite galaxies problem, and the core-cusp problem [10–13]. In this model, the ULDM is in a Bose-Einstein condensate state of ultralight scalar particles with a typical mass $m \gtrsim 10^{-22}$eV. ULDM can be described with a macroscopic wave function ψ and the uncertainty principle suppresses too many small-scale structure formations. Beyond the galactic scale, the ULDM behaves like CDM and hence naturally solves the problems of CDM. This model has also been shown to be able to explain a wide range of astrophysical observations, including the rotation curves of galaxies [8,14,15], and the large-scale structures of the universe [16]. Recently, there has been a growing interest in the interactions between BHs and ULDM halos surrounding them [17], as these interactions could change the patterns of gravitational waves generated by BHBs.

In this letter, we suggest that, inside ULDM halos (for a review, see [18–23]), BHBs can generate dark matter (DM) waves due to dynamical friction (DF) and gravitational cooling (GC). The dynamical friction of ULDM [24] refers to the frictional force that arises from the gravitational interaction between a moving celestial object and ULDM wakes generated by the object. On the other hand, gravitational cooling [25] is a mechanism for relaxation by ejecting ULDM waves carrying out excessive kinetic energy and momentum. These waves can effectively carry away orbital energy

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12. Madhu Mishra

Stability and topological nature of charged Gauss–Bonnet AdS black holes in five dimensions

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Abstract

We examine the thermodynamic characteristics and phase structures of a black hole, where the black hole horizon could be a hypersurface with positive, zero, or negative constant curvature, within the framework of Einstein-Maxwell theory, incorporating a negative cosmological constant and a Gauss-Bonnet (GB) correction. Our research follows the topological approach to black hole thermodynamics where we treat anti-de Sitter (AdS) black holes as topological defects in thermodynamic space. We study the nature of the black hole's critical points and local stability by computing the winding numbers/topological charge associated with the zero point of the vector field, derived from the temperature of extremal points and the generalized off-shell Gibbs free energy, respectively. Black holes are classified into different topological classes based on their topological number. In this study, we found unlike the charged AdS black hole, the charged GB AdS black hole exhibits a critical point. Our findings reveal the occurrence of a liquid/gas-like first-order phase transition between small-large black hole phases of the spherical charged GB AdS black hole. We conclude that the charged GB AdS and charged AdS black holes belong to different topological classes in the grand canonical ensemble. Furthermore, connecting with the previous studies, we conclude that the charged AdS and charged GB AdS black holes in canonical and charged GB in the grand canonical ensemble belong to the same topological classes.

13. Bum-Hoon Lee

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Full length article

Induced cosmological anisotropies and CMB anomalies by a non-abelian gauge-gravity interaction

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ABSTRACT

We present a non-abelian cousin of the model presented in Lee et al. (2024) which induces cosmological anisotropies on top of standard FLRW geometry. This is in some sense doing a cosmological mean field approximation, where the mean field cosmological model under consideration would be the standard FLRW, and the induced anisotropies are small perturbative corrections on top of it. Here we mostly focus on the non-abelian $SU(2)$ gauge fields coupled to the gravity to generate the anisotropies, which can be a viable model for the axion-like particle (ALP) dark sector. The induced anisotropies are consequences of the non-trivial back-reaction of the gauge fields on the gravity sector, and by a clever choice of the parametrization, one can generate the Bianchi model we have studied in this note. We also show that the anisotropies influence the Sachs–Wolfe effect and we discuss the implications.

1. Introduction

One the most successful and still a de-facto standard model of cosmology has been the Λ Cold Dark Matter (LCDM) model. The basic building blocks of the model is the spatially flat, homogeneous and isotropic Friedmann–Lemaitre–Robertson–Walker (FLRW) geometry, which along with General Relativity and a positive cosmological constant is in excellent agreement with current cosmological observations. In this model, the only inhomogeneities are those of small perturbations in the early Universe, which together with the inflationary mechanism seeds formation of large-scale structure. Despite all this success, there are a number of issues currently being brought to light by new observations and the careful reanalysis of current data. The most glaring of these issues may be the *Hubble tension*, i.e. the 5σ discrepancy between the local (determined from the distance ladder) and cosmological (determined from the Cosmic Microwave Background (CMB)) value of the Hubble constant H_0 [2]. In light of this, a number of theoretical mechanisms have been explored in order to alleviate this tension, for example early dark energy [3,4]. The QCD axion is a compelling contender for beyond the Standard Model physics, since it is a natural candidate for Cold Dark Matter (CDM) and solves the strong CP problem [5,6]. Its pseudoscalar analogue in string theory is the axion-like particle (ALP), which is also interesting, as it introduces several important cosmological effects [7][1]; this is particularly relevant for cosmological tensions, as the axion field can introduce thermal friction in the early Universe.

Recently, signals of *cosmic birefringence*, the parity-odd rotation of the polarization plane of E and B modes in the CMB, were reported, examined, and discussed in a series of papers [8–17], where the constraint on the polarization angle has now reached $\beta = 0.342^{\circ}{}^{+0.094^{\circ}}_{-0.091^{\circ}}$ (1σ) which is a non-zero signal at 3.6σ. Such a signal can arise through several mechanisms, and it has been determined [9,10] that the signal is consistent with being produced through an axion–photon coupling of the Chern–Simons $F_{\rm em}\widetilde{F}_{\rm em}$ type,[2] and such terms arise naturally in supergravity models (see for example [18] for an introduction and review.). Apart from cosmic birefringence and the established Hubble parameter tension, the geometry of spacetime itself has recently come into question, with a number of observational probes reporting departures from the homogeneous and isotropic nature of FLRW. Hints of a

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[1] See also our previous work on cosmology and ALP's [1].

[2] Here, $F_{\rm em}$ is the electromagnetic field strength, with the subscript added to distinguish it from the F used in Eq. (1) and onwards.

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Charged rotating wormholes: charge without charge

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Abstract

We present a family of charged rotating wormhole solutions to the Einstein-Maxwell equations, supported by anisotropic matter fields. We first revisit the charged static cases and analyze the conditions for the solution to represent a wormhole geometry. The rotating geometry is obtained by applying the Newman-Janis algorithm to the static geometry. We show the solutions to Maxwell equations in detail. We believe that our wormhole geometry offers a geometric realization corresponding to the concept of 'charge without charge'.

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Gauss-Bonnet Cosmology: large-temperature behaviour and bounds from Gravitational Waves

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Abstract: We provide a transparent discussion of the high temperature asymptotic behaviour of Cosmology in a dilaton-Einstein-Gauss-Bonnet (dEGB) scenario of modified gravity with vanishing scalar potential. In particular, we show that it has a clear interpretation in terms of only three attractors (stable critical points) of a set of autonomous differential equations: $w = -\frac{1}{3}$, $w = 1$ and $1 < w < \frac{7}{3}$, where $w \equiv p/\rho$ is the equation of state, defined as the ratio of the total pressure and the total energy density. All the possible different high-temperature evolution histories of the model are exhausted by only eight paths in the flow of the set of the autonomous differential equations. Our discussion clearly explains why five out of them are characterized by a swift transition of the system toward the attractor, while the remaining three show a more convoluted evolution, where the system follows a meta-stable equation of state at intermediate temperatures before eventually jumping to the real attractor at higher temperatures. Compared to standard Cosmology, the regions of the dEGB parameter space with $w = -\frac{1}{3}$ show a strong enhancement of the expected Gravitational Wave stochastic background produced by the primordial plasma of relativistic particles of the Standard Model. This is due to the very peculiar fact that dEGB allows to have an epoch when the energy density $\rho_{\rm rad}$ of the relativistic plasma dominates the energy of the Universe while at the same time the rate of dilution with T of the total energy density is slower than what usually expected during radiation dominance. This allows to use the bound from Big Bang Nucleosynthesis (BBN) to put in dEGB a constraint $T_{\rm RH} \lesssim (10^8$–$10^9)$ GeV on the reheating temperature of the Universe $T_{\rm RH}$. Such BBN bound is complementary to late-time constraints from compact binary mergers.

Keywords: cosmology of theories beyond the SM, Gauss-Bonnet-Lovelock-Horndeski-Palatini etc gravity theories

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Stability and topological nature of charged Gauss–Bonnet AdS black holes in five dimensions

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Abstract

We examine the thermodynamic characteristics and phase structures of a black hole, where the black hole horizon could be a hypersurface with positive, zero, or negative constant curvature, within the framework of Einstein-Maxwell theory, incorporating a negative cosmological constant and a Gauss-Bonnet (GB) correction. Our research follows the topological approach to black hole thermodynamics where we treat anti-de Sitter (AdS) black holes as topological defects in thermodynamic space. We study the nature of the black hole's critical points and local stability by computing the winding numbers/topological charge associated with the zero point of the vector field, derived from the temperature of extremal points and the generalized off-shell Gibbs free energy, respectively. Black holes are classified into different topological classes based on their topological number. In this study, we found unlike the charged AdS black hole, the charged GB AdS black hole exhibits a critical point. Our findings reveal the occurrence of a liquid/gas-like first-order phase transition between small-large black hole phases of the spherical charged GB AdS black hole. We conclude that the charged GB AdS and charged AdS black holes belong to different topological classes in the grand canonical ensemble. Furthermore, connecting with the previous studies, we conclude that the charged AdS and charged GB AdS black holes in canonical and charged GB in the grand canonical ensemble belong to the same topological classes.

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Observational evidence for Early Dark Energy as a unified explanation for Cosmic Birefringence and the Hubble tension

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Abstract. We test the n=3 Ultralight Axion-like model of Early Dark Energy (EDE) with the observations of the EB mode of the cosmic microwave background (CMB) radiation, and local expansion rate measurements. We find that the shape of the CMB EB angular power spectrum is sensitive to the background cosmological parameters. Unlike previous articles which fix the background cosmology and fit the coupling constant and rotation angles, we run Markov chain Monte Carlo (MCMC) simulations to fit the ΛCDM + EDE parameters simultaneously. We find that the EDE model with n=3 can provide a good fit to the observed CMB EB spectra, consistent with a Hubble constant value that is in good agreement with the locally measured value. Our result is the first to show that axion-like EDE can provide a unified explanation for the observed cosmic birefringence and the Hubble tension.

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14. Kyung Kiu Kim

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Regular Article - Theoretical Physics

End of the world perspective to BCFT

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Abstract In this work, we study the end-of-the-world (EOW) branes anchored to the boundaries of $BCFT_2$ dual to the BTZ black hole. First, we explore the thermodynamics of the boundary system consisting of the conformal boundary and two EOW branes. This thermodynamics is extended by the tension appearing as the effective cosmological constant of JT black holes on the EOW branes. The tension contribution is identified with the shadow entropy equivalent to the boundary entropy of the $BCFT_2$. The thermodynamics of the JT black holes and the bulk of $BCFT_2$ can be combined into a novel grafted thermodynamics based on the first law. Second, we focus on the observer's view of the EOW branes by lowering the temperature. We show that the EOW branes generate a scale called "reefs" inside the horizon. This scale also appears in the grafted thermodynamics. At high temperatures, observers on the EOW branes see their respective event horizons. The reef starts to grow relatively to the horizon size at the temperature, T_{grow}. As the temperature cools down the reef area fills the entire interior of the JT black holes at the temperature T_{out}. Then, the observers recognize their horizons disappear and see the large density of the energy flux. At this temperature, the two JT regions become causally connected. This connected spacetime has two asymptotic AdS_2 boundaries with a conformal matter. Also, we comment on the grafted thermodynamics to higher dimensions in Appendix B.

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1 Introduction

The information problem based on Hawking radiation [1,2] is essential to understanding quantum gravity. The unitarity of the system requires a sudden change of the entropy curve at a horizon scale [3,4]. Recently, there has been a prominent development in this problem [5–8]. Thanks to this development, we can see how the entropy curve can be obtained, and the origin of the dramatic change of the entropy is coming from a quantum wormhole in a replica space [6] and the entanglement between radiation outside of the horizon and interior region [5]. The next step of this success would be the physical implication of the sudden change of the black hole's interior. This work is an endeavor to find the physical aspect of this change inside the horizon.

The modern approach to obtain the entropy curve, the so-called "Page curve", is inspired by a holographic consideration of the entanglement [5,9,10]. A construction of the model is made of the EOW branes and AdS_3 bulk for a pure system. This EOW brane or the Planck brane is also used to construct a holographic setup of the boundary conformal field theory (BCFT) [11–13]. Therefore, one may say that the holographic BCFT is also important to understand quantum gravity. See, e.g., [13–25]. Also, there are recent applications of BCFT or EOW brane for the early universe or swampland criteria. See, e.g., [26–34].

Although the boundary is ignored usually for simplicity, it is of great importance in physics. Physicists usually allude to its existence to consider realistic situations. The reason why such an important concept is ignored is that this breaks some symmetries such as translation. Due to this symmetry reduction, one may have some trouble dealing with physical problems under consideration. One way to alleviate the difficulty is imposing a suitable boundary condition that does not spoil all the bulk symmetry. Even in a d-dimensional conformal field theory (CFT), it is an intriguing problem to introduce boundaries. Since CFTs have a huge symmetry, there is hope-

Construction of superconducting dome and emergence of quantum critical region in holography

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In this work, we investigate an extended model of holographic superconductor by a nonlinear electrodynamic interaction coupled to a complex scalar field. This nonlinear interaction term can make a quantum phase transition at zero temperature with finite charge carrier density. By solving full equations of motion, we can construct various shapes of the superconducting phase in the phase diagram. With a specific choice of interaction coefficients, we can construct a phase diagram with a superconducting dome. Also, we find a new geometric solution inside the superconducting dome, which turns out to be a Lifshitz-type geometry. This geometry is characterized by a dynamical critical exponent, which plays a crucial role near the quantum critical point. We refer to this region of the phase diagram as a quantum critical region.

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I. INTRODUCTION

The high T_C superconductor is one of the most fascinating materials due to its potential applications in the industry and theoretical perspectives. For the conventional superconductor, BCS [1] theory can explain superconducting phase transition by using a pairing mechanism. However, this theory can not be applied to understanding the high T_C superconductor. Therefore, constructing the theoretical framework of the high T_C superconductor is still challenging in condensed matter physics.

The high T_C superconducting materials have various phases. For example, the cuprate shows several phases in doping parameters and temperature [2]. Together with the superconducting dome, the phase diagram contains the antiferromagnetic insulating phase, strange metal phase, and Landau-Fermi liquid phase. These various phases, except for the Fermi liquid, are believed to be raised by the strongly correlated nature of the electron system. Therefore, we need a theoretical tool beyond perturbative calculations to understand these phases and their transition phenomena.

Like other materials with several phases, there is a quantum critical point at zero temperature. In the cuprate case, this quantum critical point is claimed to be hidden behind the superconducting dome. Due to the absence of thermal fluctuation, the transition at the quantum critical point is believed to be fully quantum.

A condensed matter study says that there are new scaling symmetries near the quantum critical point, and these symmetries are classified by two critical exponents [3–8]. One exponent is called a "dynamical critical exponent" z. This exponent indicates the different scaling of time and space, $x \to \lambda x$, $t \to \lambda^z t$. The other exponent is the "hyperscaling violation exponent" θ, which means that the effective theory can be described in $(d-\theta)$ spatial dimensions.

Due to the strongly interacting nature of the high T_C superconducting materials, it is extremely hard to understand the phase transition mechanism and properties near the quantum critical point by traditional approaches. Fortunately, gauge/gravity duality based on AdS/CFT correspondence [9–11] has been widely studied for understanding strongly interacting systems, i.e., [12–21]. A gravity model describing superconductors was first introduced by Hartnoll, Herzog, and Horowitz (HHH) [22,23]. After HHH's work, enormous studies and developments have been achieved by many researchers. We refer [24–26] for reviews and references.

The original model of the holographic superconductor has a translation symmetry, and hence, there is a delta function peak at $\omega = 0$ in the electrical conductivity. This delta function exists even in the normal phase. Therefore, whether this delta function peak comes from a superconducting nature or the translation symmetry must be clarified. This issue can be resolved by introducing a linear axion field proposed for momentum relaxation in the boundary theory [27,28]. In the work of [29,30], the authors confirmed that the delta function peak in the electric conductivity appears only in the superconducting phase, while the Drude-like peak is in the normal phase.

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Phase Diagram from Nonlinear Interaction between Superconducting Order and Density: Toward Data-Based Holographic Superconductor

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Abstract

We address an inverse problem in modeling holographic superconductors. We focus our research on the critical temperature behavior depicted by experiments. We use a physics-informed neural network method to find a mass function $M(F^2)$, which is necessary to understand phase transition behavior. This mass function describes a nonlinear interaction between superconducting order and charge carrier density. We introduce positional embedding layers to improve the learning process in our algorithm, and the Adam optimization is used to predict the critical temperature data via holographic calculation with appropriate accuracy. Consideration of the positional embedding layers is motivated by the transformer model of natural-language processing in the artificial intelligence (AI) field. We obtain holographic models that reproduce borderlines of the normal and superconducting phases provided by actual data. Our work is the first holographic attempt to match phase transition data quantitatively obtained from experiments. Also, the present work offers a new methodology for data-based holographic models.

Keywords: Gauge/gravity duality, Machine Learning, Phase diagram, Holographic superconductor

15. Inyong Cho

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Perfect fluid with shear viscosity and spacetime evolution

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ABSTRACT

We investigate the anisotropic evolution of spacetime driven by perfect fluid with off-diagonal shear-viscosity components. We consider the simplest form of the equation of state for fluid, for which the pressure and the shear stress are proportional to the energy density individually. At late times, compared with the usual Friedmann universe, we find that the spacetime expands less rapidly as the energy density drops faster due to the transfer to the shear stress. Very interestingly, for some ranges of the equation-of-state parameters, we find that the initial big-bang singularity can be removed.

1. Introduction

It is well known how the Friedmann universe evolves with perfect fluid, in particular, barotropic fluid. With the energy–momentum tensor,

$$T^{\mu}_{\nu} = \mathrm{diag}[-\rho, p, p, p], \tag{1}$$

of which the equation of state is given by $p = w\rho$, and with the metric ansatz,

$$ds^2 = -dt^2 + a^2(t)\left(dx^2 + dy^2 + dz^2\right), \tag{2}$$

the solutions to the Einstein's equation provides the scale factor, the energy density, and the three-volume density as (for $w > -1$)

$$a = a_0 t^{2/[3(1+w)]}, \tag{3}$$

$$\rho = \rho_0 a^{-3(1+w)} \propto \frac{1}{t^2}, \tag{4}$$

$$\mathcal{V}_3 \equiv \sqrt{g^{(3)}} = a^3 = a_0^3 t^{2/(1+w)}. \tag{5}$$

However, the Friedmann universe with the off-diagonal stress components (T^i_j) of fluid has not been studied well. There are a few trials considering these components in fluid dynamics [1–3], but not in the scope of spacetime structure. In this paper, we consider the fluid of which the energy–momentum tensor contains the off-diagonal stress terms in addition to the diagonal terms.

The physical meaning of T^{ij} is the flux of the i-component of momentum across the surface of x^j = constant [3]. Hence, it represents a stress in the i direction on the surface of x^j = constant. This type of stress component may arise in the cosmological perturbations when both the scalar and the tensor modes are introduced. In particular, it appears in the effective energy–momentum tensor composed of the quadratic terms of the coupled linear scalar and tensor modes. The ×-polarization tensor mode induces such off-diagonal components in the energy–momentum tensor, while the + -polarization mode induces diagonal components. Although

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Homogeneous spacetime with shear viscosity

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Abstract: We study the homogeneous and anisotropic evolution of Bianchi type-I spacetime driven by perfect fluid with shear viscosity. We obtain exact solutions by considering the simplest form of the equation of state wherein the pressure and the shear stress are proportional to the energy density individually. A special case of our general solutions represent Bianchi type-VII cosmology. We analyse the singularity structure of the solutions and its connection with various energy conditions. We find that the initial singularity can be removed only for the Bianchi type-VII. We also analyse the late-time behaviour of the solutions and find that, compared to the usual Friedmann universe, the spacetime expands less rapidly and the energy density drops faster.

Keywords: cosmic singularity, Exact solutions, black holes and black hole thermodynamics in GR and beyond

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Cosmological scalar and tensor perturbations with a scalar field: quadratic-order effective energy-momentum tensor

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We introduce the scalar and tensor modes of the gravitational perturbation in the presence of a scalar field which describes inflation. We investigate the back-reaction of the perturbations to the background by studying the effective energy-momentum tensor (2EMT) which is the second order constructed by the quadratic terms of the linear perturbations. 2EMT is gauge dependent due to the scalar mode. We obtain 2EMT in the slow-roll stage of inflation, and get its cosmological expressions in three (longitudinal, spatially flat, and comoving) gauge conditions. We find that the pure scalar-mode part in 2EMT is stronger in the short-wavelength limit, while the parts involved with the tensor mode (the pure tensor-mode part and the scalar-tensor coupled part) are stronger in the long-wavelength limit.

I. INTRODUCTION

For the last decades, the cosmological perturbation theory has been well established, and applied to cosmological situations. In particular, the density perturbation during inflationary period could explain the data of the cosmic microwave background radiation successfully. As the observational precision is improved, people starts to pay more attention to the higher-order phenomena than linear.

Recently the effective energy-momentum tensor (2EMT) produced by a fluid [1] and by a scalar field [2] has been investigated individually. 2EMT was constructed by the quadratic terms of the linear perturbations of the matter and the gravitational fields. The gauge issue of 2EMT was studied in those works. 2EMT was found to be gauge dependent in both works. The gauge dependence of 2EMT of a scalar field had been issued in Refs. [3, 4] and in Refs. [5–7]. More work have been done in Refs. [8–11]. In all of these works, only the scalar perturbation of the gravitational field had been considered.

In this work, we investigate 2EMT of a scalar field in the inflationary period. We consider both of the scalar and the tensor perturbations together. In the linear order, they are decoupled and the solutions are the same with those obtained separately. In the second order, however, the quadratic-order terms contain the coupled terms of the scalar and the tensor modes.

In scalar-vector-tensor (SVT) decomposition of the gravitational perturbations, the scalar or tensor mode of perturbations can be considered solely with the other modes turned off in *vacuum*. However, when a "matter field" is introduced, the tensor mode cannot be considered solely while the scalar mode can. It is because the tensor mode represents only *two* degrees of freedom which are responsible for the gravity wave while the matter-field degree of freedom is implied by the scalar mode. Therefore, if there is a matter field, we need to consider the tensor mode together with the scalar mode, which inevitably induces the coupled scalar-tensor terms in the quadratic order.

In this work, we shall consider the cosmological perturbations during inflation. We introduce the matter-field perturbation of the inflaton (scalar field) and the scalar and the tensor modes of the gravitational perturbations. We shall obtained 2EMT constructed by the quadratic terms of the linear-order perturbations. It contains the scalar-only terms that were obtained in Refs. [2–4], and the tensor-only terms obtained in Refs. [3, 4]. In addition there are the coupled terms of scalar and tensor modes.

2EMT is constructed as following. We expand the Einstein's equation by order, then the second-order equation consists in two parts; the linear-order terms of the second-order perturbations, and the quadratic-order terms of the first-order perturbations as

$$G^{(1)}_{\mu\nu}[g^{(2)}] + G^{(2)}_{\mu\nu}[g^{(1)}] = 8\pi G T^{(1)}_{\mu\nu}[g^{(2)}, \delta\phi^{(2)}] + 8\pi G T^{(2)}_{\mu\nu}[g^{(1)}, \delta\phi^{(1)}]. \tag{1}$$

2EMT is made of the quadratic terms,

$$T^{(2,\text{eff})}_{\mu\nu} \equiv T^{(2)}_{\mu\nu}[g^{(1)}, \delta\phi^{(1)}] - \frac{G^{(2)}_{\mu\nu}[g^{(1)}]}{8\pi G}. \tag{2}$$

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Quantum geodesics reflecting the internal structure of stars composed of shells

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Abstract: In general relativity, an external observer cannot distinguish distinct internal structures between two spherically symmetric stars that have the same total mass M. However, when quantum corrections are taken into account, the external metrics of the stars will receive quantum corrections depending on their internal structures. In this paper, we obtain the quantum-corrected metrics at linear order in curvature for two spherically symmetric shells characterized by different internal structures: one with an empty interior and the other with N internal shells. The dependence on the internal structures in the corrected metrics tells us that geodesics on these backgrounds would be deformed according to the internal structures. We conduct numerical computations to find out the angle of geodesic precession and show that the presence of internal structures amplifies the precession angle reflecting the discrepancy between the radial and orbital periods within the geodesic orbit. The amount of the precession angle increases monotonically as the number of internal shells increases and it eventually converges to a certain value for $N \to \infty$.

Keywords: modified gravity, quantum field theory on curved space

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17. Mu-In Park

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

No scalar-haired Cauchy horizon theorem in charged Gauss–Bonnet black holes

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Abstract Recently, a "no inner (Cauchy) horizon theorem" for static black holes with *non-trivial scalar hairs* has been proved in Einstein–Maxwell–scalar theories and also in Einstein–Maxwell–Horndeski theories with the non-minimal coupling of a charged (complex) scalar field to Einstein tensor. In this paper, we study an extension of the theorem to the static black holes in Einstein–Maxwell–Gauss–Bonnet-scalar theories, or simply, charged Gauss–Bonnet (GB) black holes. We find that *no inner horizon with charged scalar hairs* is allowed for the planar ($k = 0$) black holes, as in the case without GB term. On the other hand, for the non-planar ($k = \pm 1$) black holes, we find that the haired inner horizon can not be excluded due to GB effect generally, though we can not find a simple condition for its existence. As some explicit examples of the theorem, we study numerical GB black hole solutions with charged scalar hairs and Cauchy horizons in asymptotically anti-de Sitter space, and find good agreements with the theorem. Additionally, in an Appendix, we prove a "no-go theorem" for charged de Sitter black holes (with or without GB terms) with charged scalar hairs in arbitrary dimensions.

1 Introduction

It is an important question in general relativity (GR) whether the predictability is lost due to an inner (Cauchy) horizon or not. Recently, Cai et al. established [1–4] a "no inner (Cauchy) horizon theorem" for both planar and spherical static black holes with *charged* (complex) scalar hairs in Einstein–Maxwell–scalar (EMS) theories that suggests unstable Cauchy horizons in the presence of charged scalar hairs. A remarkable thing in the proof is its simplicity and quite generic results which do not depend on the details of the scalar potentials and so it's applicability would be quite far-reaching.

As the first step towards the classification of all possible extensions of the theorem, we extended the theorem to black holes in Einstein–Maxwell–Horndeski (EMH) theories, with the non-minimal coupling of a charged scalar field to Einstein tensor as well as the usual minimal gauge coupling [5]. Actually, since the Horndeski term is a four-derivative term via the Einstein coupling, it generalizes the recent set-up in [1–4] into *higher-derivative* theories. There have been also several other generalizations of the theorem [6–8].

In this paper, we will consider an extension of the theorem in another important higher-derivative gravity, Einstein–Maxwell–Gauss–Bonnet-scalar (EMGBS) theories with the coupling of a charged scalar hair and the Gauss–Bonnet (GB) term [9], whose equations of motion remain second order as in the Horndeski case. The organization of this paper is as follows. In Sect. 2, we consider the set-up for EMGBS theories in arbitrary dimensions and obtain the equations of motion for a static and spherically symmetric ansatz. In Sect. 3, we consider the radially conserved scaling charge and "no scalar-haired Cauchy horizon theorem" for charged GB black holes. In Sect. 4, we consider the near horizon relations for the fields and the condition of scalar field at the horizons. In Sect. 5, we consider numerical black hole solutions with a Cauchy horizon in asymptotically anti-de Sitter (AdS) space and find good agreements with the theorem. In Sect. 6, we conclude with several remarks. In Appendix D, in addition, we prove a no-go theorem for charged de Sitter black holes (with or without GB terms) with charged scalar hairs in arbitrary dimensions.

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Regular Article - Theoretical Physics

Rotating black holes in a viable Lorentz-violating gravity: finding exact solutions without tears

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Abstract We introduce a two-step procedure for finding Kerr-type rotating black hole solutions without tears. Considering the low-energy sector of Hořava gravity as a *viable* Lorentz-violating gravity in four dimensions which admits a different speed of gravity, we find the exact rotating black hole solutions (with or without cosmological constant). We find that the singular region extends to $r < 0$ region from the ring singularity at $r = 0$ in Boyer–Lindquist coordinates. There are two Killing horizons where $g^{rr} = 0$ and the black hole thermodynamics laws are still valid. We find the rotating black hole solutions with electromagnetic charges only when we consider the *noble* electromagnetic couplings, in such a way that the speed of light is the same as the speed of gravity. With the noble choice of couplings, our Lorentz-violating gravity can be consistent with the recently-observed time delay of the coincident GW and GRB signals. Furthermore, in Appendices, we show that (a) the uniqueness of the invariant line element ds^2 under *the foliation-preserving* diffeomorphism $Diff_{\mathcal{F}}$, contrary to Lorentz-violating action, (b) the solutions are the Petrov type I with four distinct principal null vectors, and (c) the Hamilton-Jacobi equation for the geodesic particles are *not* separable.

1 Introduction

The rotating black hole solution which was discovered by Kerr [1] in general relativity (GR) has occupied an immovable position: The solution structure is quite rigid and it is extremely difficult to find another *exact* solution with nontrivial deformations by cracking the rigid solution structure. Moreover, even deriving the known Kerr solution is not quite easy task and requires some sophisticated methods whose generic validities in other gravity theories are not clear [2]. In particular, from the separability of Hamilton–Jacobi equation for the geodesic particles in a quite general context, Carter obtained the Carter constant as well as the Kerr solution [3]. Later, it was proved that the Petrov type-D solutions, like Kerr metric, guarantee the existence of a Killing tensor and its concrete form was derived in GR [4].

In this paper, we introduce a two-step procedure to find Kerr-type exact solutions without much tears. We apply the procedure to the low-energy sector of Hořava gravity as a Lorentz-violating (LV) gravity in four dimensions which admits a different speed of gravity, and we find the exact rotating black hole solutions (with or without cosmological constant). In addition, if we consider charged rotating black holes, the *noble* electromagnetic couplings are needed for consistency, in such a way that the speed of light is the same as the speed of gravity. In Sect. 2, we introduce our two-step procedure to find Kerr-type exact solutions. In Sect. 3, we apply the procedure to the low-energy sector of Hořava gravity in four dimensions and find the exact rotating black hole solution without cosmological constant. In Sect. 4, we study the singularity structure which is richer than Kerr solution. In Sect. 5, we study the horizon structure and new barriers for geodesic particles which are genuine to our LV gravity. In Sect. 6, we consider the generalizations with cosmological constant and electromagnetic charges, and show that the first law of black hole thermodynamics is satisfied. In Sect. 7, we consider some observational constraints and in Sect. 8, we conclude with some discussions. In Appendix C, we prove the uniqueness of the invariant line element ds^2 under *the foliation-preserving* diffeomorphism $Diff_{\mathcal{F}}$, contrary to widespread belief based on LV action. In Appendix D, we study the Petrov classification, the Killing tensor, and the Hamilton–Jacobi equation.

Dedicated to the memory of Roman Jackiw (8 November 1939–14 June 2023).

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18. Hideki Maeda

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Charged rotating BTZ solution revisited: new coordinates and algebraic classifications

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Abstract

We revisit the charged rotating Bañados–Teitelboim–Zanelli (BTZ) solution in the three-dimensional Einstein–Maxwell-Λ system. After the erroneous announcement of its discovery at the end of the original BTZ paper in 1992, the solution was first obtained by Clément in the paper published in 1996 by coordinate transformations from the charged non-rotating BTZ solution. While Clément's form of the solution is valid only for $\Lambda < 0$, we present a new form for a wider range of Λ by uniform scaling transformations and a reparametrization. We also introduce new coordinates corresponding to the Doran coordinates in the Kerr spacetime, in which the metric and also its inverse are regular at the Killing horizon, and described by elementary functions. Lastly, we show that (i) the algebraic Cotton type of the spacetime is type III on the Killing horizon and type I away from the horizon, and (ii) the energy-momentum tensor for the Maxwell field is of the Hawking–Ellis type I everywhere.

Keywords: charged rotating BTZ solution,
algebraic classifications (Cotton and Hawking–Ellis types),
horizon-penetrating coordinates,
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Existence and absence of Killing horizons in static solutions with symmetries

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Abstract

Without specifying a matter field nor imposing energy conditions, we study Killing horizons in $n(\geqslant 3)$-dimensional static solutions in general relativity with an $(n-2)$-dimensional Einstein base manifold. Assuming linear relations $p_{\rm r} \simeq \chi_{\rm r}\rho$ and $p_2 \simeq \chi_{\rm t}\rho$ near a Killing horizon between the energy density ρ, radial pressure $p_{\rm r}$, and tangential pressure p_2 of the matter field, we prove that any non-vacuum solution satisfying $\chi_{\rm r} < -1/3$ ($\chi_{\rm r} \neq -1$) or $\chi_{\rm r} > 0$ does not admit a horizon as it becomes a curvature singularity. For $\chi_{\rm r} = -1$ and $\chi_{\rm r} \in [-1/3, 0)$, non-vacuum solutions admit Killing horizons, on which there exists a matter field only for $\chi_{\rm r} = -1$ and $-1/3$, which are of the Hawking–Ellis type I and type II, respectively. Differentiability of the metric on the horizon depends on the value of $\chi_{\rm r}$, and non-analytic extensions beyond the horizon are allowed for $\chi_{\rm r} \in [-1/3, 0)$. In particular, solutions can be attached to the Schwarzschild–Tangherlini-type vacuum solution at the Killing horizon in at least a $C^{1,1}$ regular manner without a lightlike thin shell. We generalize some of those results in Lovelock gravity with a maximally symmetric base manifold.

Keywords: killing horizon, black hole, exact solutions, static solutions, regularity of spacetime

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PTEP

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Extremal Rotating BTZ Black Holes Cannot Be Dressed in (anti-)Self-Dual Maxwell Field

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Under the (anti-)self-dual condition for orthonormal components of the Faraday tensor, the 3D Einstein–Maxwell system with a negative cosmological constant Λ admits a solution obtained by Kamata and Koikawa and later by Cataldo and Salgado in the most general form. Actually, Clément first obtained this solution and interpreted it as a regular particle-like solution without horizon. Nevertheless, it has been erroneously stated in some literature that this Clément–Cataldo–Salgado (CCS) solution, locally characterized by a single parameter, describes a black hole even in the charged case as it reduces to the extremal rotating Bañados–Teitelboim–Zanelli (BTZ) solution in the vacuum limit and its curvature invariants are constant. In this paper, we supplement Clément's interpretation by showing that there appears a parallelly propagated curvature singularity corresponding to an infinite affine parameter along spacelike geodesics at the location of the Killing horizon in the extremal rotating BTZ solution when the (anti-)self-dual Maxwell field is added. If the spatial coordinate θ is periodic, closed timelike curves exist near the singularity. It is also shown that the CCS solution is of Cotton type N (in contrast to charged rotating BTZ black holes which are of type I away from the horizon), and the energy-momentum tensor of the Maxwell field is of Hawking–Ellis type II. The metric solves the Einstein-Λ equations also with a massless scalar field or a null dust fluid. We explicitly demonstrate that it belongs to the Kundt shear-free, nontwisting, and nonexpanding class of geometries, whereas extremal rotating BTZ black holes have expanding principal null directions. It means that the CCS metric represents the specific null (i.e. "radiative") Maxwell field generated by a singular source, rather than an extremal rotating BTZ black hole dressed in an (anti-)self-dual Maxwell field.

Subject Index E00, E01

1. Introduction

Three-dimensional (3D) gravity has been studied very intensively so far as a testing ground for quantum gravity due to its simplicity [1]. In particular, the Bañados–Teitelboim–Zanelli (BTZ) vacuum black-hole solution [2] in the presence of a negative cosmological constant Λ is expected to provide clues to the description of black holes in quantum gravity. Since the numbers of independent components of the Riemann tensor and Ricci tensor are the same in three dimensions, the BTZ spacetime is locally identical to the maximally symmetric anti-de Sitter (AdS) spacetime. Nevertheless, their global structures are different as the BTZ spacetime is obtained by identifications in the AdS spacetime [3].

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Fake Schwarzschild and Kerr black holes

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Abstract

We present exact solutions describing a *fake Schwarzschild* black hole that cannot be distinguished from the Schwarzschild black hole by observations. They are constructed by attaching a spherically symmetric dynamical interior solution with a matter field to the Schwarzschild exterior solution at the event horizon without a lightlike thin shell. The dynamical region inside a Killing horizon of a static spherically symmetric perfect-fluid solution obeying an equation of state $p = \chi\rho$ for $\chi \in [-1/3, 0)$ can be the interior of a fake Schwarzschild black hole. The matter field inside such a black hole is an anisotropic fluid that violates at least the weak energy condition and can be interpreted as a spacelike (tachyonic) perfect fluid. While the author constructed the first model of fake Schwarzschild black holes using Semiz's solution for $\chi = -1/5$, we present another one using Whittaker's solution for $\chi = -1/3$ in this paper. We also present a model of *fake Kerr* black holes whose interior is filled with a different matter field violating only the dominant energy condition near the event horizon. Whether a fake Schwarzschild or Kerr black hole can be realized under the dominant energy condition is an open question.

19. Matti Jarvinen

Estimate for the Bulk Viscosity of Strongly Coupled Quark Matter Using Perturbative QCD and Holography

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Modern hydrodynamic simulations of core-collapse supernovae and neutron-star mergers require knowledge not only of the equilibrium properties of strongly interacting matter, but also of the system's response to perturbations, encoded in various transport coefficients. Using perturbative and holographic tools, we derive here an improved weak-coupling and a new strong-coupling result for the most important transport coefficient of unpaired quark matter, its bulk viscosity. These results are combined in a simple analytic pocket formula for the quantity that is rooted in perturbative quantum chromodynamics at high densities but takes into account nonperturbative holographic input at neutron-star densities, where the system is strongly coupled. This expression can be used in the modeling of unpaired quark matter at astrophysically relevant temperatures and densities.

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Introduction—During the last ten years, neutron stars (NSs) and their binary mergers—observable through both electromagnetic and gravitational waves (GW) [1,2]—have established themselves as the leading laboratory for dense quantum chromodynamics (QCD) matter. While the observable properties of single quiescent NSs and even the inspiral parts of NS mergers are mostly determined by the equation of state (EoS) of the constituent matter, the ringdown phase of a NS merger constitutes a considerably more complicated out-of-equilibrium system. In preparation for the eventual observation of a ringdown GW signal, extensive hydrodynamic simulations of NS mergers are currently being carried out, with one crucial challenge being to correctly account for energy dissipation and transport in NS matter [3].

Among the different transport coefficients, the bulk viscosity ζ, which quantifies energy dissipation during a rapid compression or expansion of matter, stands out as particularly important [4–12]. For isolated NSs, it affects the emission of continuous GWs [13], expected to be detectable in next-generation GW observatories such as the Einstein Telescope [14] and Cosmic Explorer [15], and determines the maximal rotation frequencies of pulsars in a temperature-dependent fashion, giving rise to the so-called r-mode stability window in the 1–100 keV range [16–18] (for a review of NS oscillatory modes, see [19]). In NS

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Prompt Black Hole Formation in Binary Neutron Star Mergers

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We carry out an in-depth analysis of the prompt-collapse behaviour of binary neutron star (BNS) mergers. To this end, we perform more than 80 general relativistic BNS merger simulations using a family of realistic Equations of State (EOS) with different stiffness, which feature a first order deconfinement phase transition between hadronic and quark matter. From these simulations we infer the critical binary mass $M_{\rm crit}$ that separates the prompt from the non-prompt collapse regime. We show that the critical mass increases with the stiffness of the EOS and obeys a tight quasi-universal relation, $M_{\rm crit}/M_{\rm TOV} \approx 1.41 \pm 0.06$, which links it to the maximum mass $M_{\rm TOV}$ of static neutron stars, and therefore provides a straightforward estimate for the total binary mass beyond which prompt collapse becomes inevitable. In addition, we introduce a novel gauge independent definition for a one-parameter family of threshold masses in terms of curvature invariants of the Riemann tensor which characterizes the development toward a more rapid collapse with increasing binary mass. Using these diagnostics, we find that the amount of matter remaining outside the black hole sharply drops in supercritical mass mergers compared to subcritical ones and is further reduced in mergers where the black hole collapse is induced by the formation of a quark matter core. This implies that $M_{\rm crit}$, particularly for merger remnants featuring quark matter cores, imposes a strict upper limit on the emission of any detectable electromagnetic counterpart in BNS mergers.

Keywords: neutron stars, equation of state, binary neutron star mergers, black holes

I. INTRODUCTION

Neutron stars have become leading laboratories to study dense matter in the course of the past decade. As a key component in this development, multi-messenger signals from binary neutron star (BNS) mergers include information about the properties of strongly interacting matter at densities not accessible to terrestrial experiments. The detection of gravitational waves (GW) from the GW170817 event [1] already provided constraints on the neutron star Equation of State (EOS) [2] that complement those from direct mass [3–6] and radius measurements [7–11] as well as from microphysics calculations in nuclear theory [12–15] and perturbative Quantum Chromodynamics (QCD) [16–19]. Neutron stars with masses close to the maximal limiting value set by collapse into a black hole are particularly interesting for EOS inference, since their cores reach densities multiple times larger than the nuclear saturation density $n_s = 0.16/\mathrm{fm}^3$. Our theoretical understanding of QCD, the fundamental theory for matter, at these densities is very limited, which makes observations of highly massive neutron stars and their mergers currently the only reliable source of information about their material properties.

There exists a simple and well defined notion for the limiting mass of isolated static ($M_{\rm TOV}$) and rotating stars ($M_{\rm max}$), beyond which they become unstable against gravitational attraction and collapse into a black hole, in terms of the so-called turning-point criterion [20]. While the values of $M_{\rm TOV}$ and $M_{\rm max}$ individually depend strongly on the EOS, in case of uniformly rotating stars they were shown to satisfy the quasi-universal (EOS independent) relation $M_{\rm max} \approx 1.2\ M_{\rm TOV}$ [21–23]. In contrast to isolated neutron stars, which are well approximated by a stationary and axially symmetric spacetime, the notion of a limiting mass is more intricate for dynamic systems like BNS mergers, because they evolve non-linearly in time and possess essentially no symmetries. Crucially, the time-dependent differential angular velocity profile of the merger remnant influences the stability and changes the simplified picture observed for isolated, uniformly rotating stars, so that simple recipes like the turning-point criterion do not apply. Depending on the total mass and its division into its binary constituents, a BNS merger can either result in the prompt formation of a black hole or a (meta-)stable neutron star merger remnant, which may collapse into a black hole at later times. These two scenarios feature different patterns of GW emission and electromagnetic (EM) radiation [24].

Significant effort has been put in the field towards investigating the collapse of isolated neutron stars [25–27] and black hole formation in neutron star head-on collisions [28, 29]. More recently the mass-threshold to prompt black hole formation has also been investigated in numerical simulations of BNS mergers starting from more realistic inspiral initial conditions [30–35] rather than head-on conditions. Such threshold mass analysis, in combination with observational data from the GW170817 event, lead to estimated lower bounds of neutron star radii [31, 36] that agree surprisingly well with those from entirely different theoretical approaches [37]. The aforementioned studies provided important insights about the collapse behaviour of BNS mergers, but also rely on various simplifying assumptions to estimate the threshold mass. These assumptions include for example an approximate description for the gravitational field [36], simple gauge dependent criteria based on a Newtonian notion of free-fall [31] or

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Holographic transport in anisotropic plasmas

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We study energy-momentum and charge transport in strongly interacting holographic quantum field theories in an anisotropic thermal state by contrasting three different holographic methods to compute transport coefficients: standard holographic calculation of retarded Green's functions, a method based on the null-focusing equation near horizon and the novel method based on background variations. Employing these methods we compute anisotropic shear and bulk viscosities and conductivities with anisotropy induced externally, for example by an external magnetic field. We show that all three methods yield consistent results. The novel method allows us to read off the transport coefficients from the horizon data and express them in analytic form from which we derive universal relations among them. Furthermore we extend the method based on the null-focusing equation to Gauss-Bonnet theory to compute higher derivative corrections to the aforementioned transport coefficients.

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I. INTRODUCTION

Quark-gluon plasma produced in heavy-ion collisions is well described as a strongly interacting relativistic fluid, see Refs. [1–4] for reviews. Anisotropies in pressure gradients in directions transverse to the beam, that are present in off-central collisions, played an important role in establishing this hydrodynamic description early on, through matching the experimentally observed flow parameters to hydrodynamic simulations, see Refs. [5–7] for recent updates. There is a second source of anisotropy that arises from expansion of the plasma along the beam direction which is faster than its transverse expansion. Finally, intense magnetic fields[1] are produced in off-central collisions, leading to yet another source of anisotropy in the plasma. Indeed, a back-of-the-envelope estimate based on the Biot-Savart law leads to a maximal magnetic field of $B \approx 10^{15}$–10^{19} G at Relativistic Heavy Ion Collider and $B \approx 10^{16}$–10^{21} G at LHC [9–16].

Another important physical system subject to extremely high magnetic fields is a neutron star. The strength of the magnetic field can reach 10^{15} G on the surface of a magnetar [17] and 10^{16} G inside it [18,19]. Moreover, the strength can be amplified during a binary merger and can exceed 10^{16-17} G [20–23], overlapping with the values of the magnetic field produced in heavy-ion collisions [24] in the later times of the plasma evolution before freeze-out. Although it is still an open question whether neutron stars with quark matter cores exist, the characteristics of neutron star matter have been demonstrated to agree better with the anticipated features of nearly conformal quark matter than with those of nuclear matter [25,26]. Even if quark matter does not exist inside isolated neutron stars, it can be created in neutron star binary mergers [27–29]. When the anticipated extremely large magnetic fields during a merger event are taken into account, the deconfined quark matter accommodates magnetic-field-induced anisotropy. As suggested in [30], neutron star matter during a merger event is

[1]Large vorticities are produced in off-central collisions which break the rotational invariance in the plasma [8] also leading to anisotropic transport. We will however not discuss vortical effects in this paper.

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Modulated instabilities and the AdS_2 point in dense holographic matter

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Abstract: We investigate fluctuations of hot and dense QCD plasma by using the gauge/gravity duality. To this end, we carry out a comprehensive classification and analysis of quasinormal modes of charged black holes in the holographic V-QCD model. It turns out that the Chern-Simons term determined by the flavor anomalies of QCD is strong enough to drive a modulated instability. While such an instability is expected at high densities, we find that the unstable phase extends to surprisingly low densities and high temperatures, close to the region where data from lattice simulations is available. We also analyze the limit of small temperature which is controlled by a quantum critical AdS_2 point. We study in detail the signatures of the critical point in the quasinormal mode spectrum, focusing on the interplay between the hydrodynamic modes and other modes.

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Refining holographic models of the quark-gluon plasma

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Abstract

We investigate quark-gluon plasma at nonzero density by using two holographic models for QCD based on either brane or Einstein–Maxwell–dilaton actions. We determine the parameters of these models through a systematic statistical fitting procedure to lattice QCD data, which encompasses the equation of state (through the entropy density) and the two lowest baryon number susceptibilities. The predictions from the two models for the higher-order susceptibilities and the equation of state at nonzero density are strikingly similar. In particular, both models suggest the presence of a critical point on the (μ_{B}, T)-phase diagram near $\mu_{\mathrm{B}}/T \approx 6$. The results for the equation of state are in agreement with lattice data for higher-order susceptibilities and experimental data for the cumulants of the net-proton number from the Beam Energy Scan program at the Relativistic Heavy-Ion Collider.

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21. David Kubiznak

Homogeneous symmetry operators in Kerr-NUT-AdS spacetimes

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It is well known that the Kerr-Newmann-Unti-Tamburino-anti–de Sitter spacetimes possess hidden symmetries encoded in the so-called principal Killing-Yano tensor. In this paper, focusing on the four-dimensional case, we obtain a number of symmetry operators for scalar, vector, and tensor perturbations, that are of degree 2 (to be defined below) and homogeneous in the principal tensor. In particular, by considering homogeneous operators that are linear, quadratic, and cubic in the principal tensor, we recover a complete set of four mutually commuting operators for scalar perturbations, underlying the separability of (massive) scalar wave equation. Proceeding to vector and tensor perturbations of the Kerr-Newmann-Unti-Tamburino-anti–de Sitter spacetimes, we find a set of seven and eight commuting operators, respectively. It remains to be seen whether such operators can be used to separate the corresponding spin 1 and spin 2 test field equations in these spacetimes.

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I. INTRODUCTION

Hidden symmetries play an important role in black hole physics. As opposed to explicit symmetries, that are "visible" in the spacetime and are encoded in Killing vector fields, hidden symmetries correspond to genuine symmetries of the phase space, e.g. [1,2], and are described by higher rank tensors that obey a natural generalization of the Killing vector equation. Among these, perhaps the most remarkable is the hidden symmetry of the *principal Killing-Yano (PKY) tensor*, see Ref. [3] for a review.

The PKY tensor is a nondegenerate closed conformal Killing-Yano 2-form k_{ab}. This is an object whose covariant derivative is completely encoded in its divergence

$$\xi_a = \frac{1}{d-1}\nabla^b k_{ba}, \tag{1}$$

where d stands for the number of spacetime dimensions. This divergence is a Killing vector by construction and explicitly the PKY tensor satisfies the following defining equation:

$$\nabla_c k_{ab} = g_{ca}\xi_b - g_{cb}\xi_a. \tag{2}$$

The principal tensor exists in the Kerr spacetime and its "square" gives rise to Carter's famous constant for geodesics [4]. More generally, the PKY tensor can be found in a large class of the (off-shell) Kerr-Newmann-Unti-Tamburino (NUT)-anti–de Sitter (AdS) spacetimes in any number of dimensions [5–7], and underlies many of its remarkable properties, such as complete integrability of the geodesic equations [8], separability of the Hamilton-Jacobi and Klein-Gordon equations [9], separability of the Dirac equation [10], or the special algebraic type of these metrics [11].

More recently [12,13], it was also shown how, using the PKY tensor, one can construct a "polarization tensor" $B_{ab} = (g_{ab} + \lambda k_{ab})^{-1}$, which gives rise to a separable ansatz for the (massive) vector perturbations:

$$A^a = B^{ab}\partial_b Z, \tag{3}$$

where Z is the scalar function that takes a standard separable form, and λ is the additional separation constant, see Ref. [13] for details.

Interestingly, in the scalar [14,15], conformal scalar [16,17], and the Dirac [18,19] cases, the separation can be linked to the existence of a *compete set* of the mutually *commuting operators* (called symmetry operators) whose common eigenfunction is the separable solution. Remarkably, such operators take a simple form that is homogeneous (linear, quadratic, cubic, and so on) in the principal tensor and contains a fixed number of derivatives (some of which may act on the principal tensor while others are free act on the field). We call this number the *degree* of the corresponding operator. In this work, we study such *homogeneous operators* and restrict ourselves to degree 2. Such operators can be of the first order or

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Optical properties of black holes in regularized Maxwell theory

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Regularized Maxwell electrodynamics is a recently discovered theory of nonlinear electrodynamics, with a minimally regularized field strength of a point charge, that is very close to the Maxwell theory in many aspects. In this paper we investigate some of the optical properties of its black holes. Namely, we study geodesics, gravitational redshift, black hole shadow, as well as investigate the relationship between the behavior of (null geodesic) Lyapunov exponents and the existence of thermodynamic critical points in both canonical and grand-canonical ensembles.

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I. INTRODUCTION

The first (fully covariant) theories of nonlinear electrodynamics (NLE) were formulated in the 1930s as a classical attempt at regularizing the field of a point charge in Maxwell's theory [1–4]. The key idea was to modify the corresponding electromagnetic Lagrangian, making it sufficiently nonlinear, so that the point charge could be characterized by a finite field strength and finite self-energy. Since then, many other theories with various characteristics were constructed—nowadays NLE provides a general framework for studying classical electrodynamics with improved properties—while maintaining the second-order equations of motion and covariant action, see [5] for a recent review.

Among many NLEs, perhaps the most prolific to date is the Born-Infeld theory, developed by M. Born and L. Infeld in [2,3]. This theory yields a finite point charge self-energy, possesses an electromagnetic duality [6], and approaches Maxwell's electrodynamics in the weak-field limit. It finds applications in string theory [7], D-brane physics [8,9], or cosmology [10]. Moreover, as found by Plebańsky [11] (see also [12,13]), it is the unique NLE (apart from Maxwell), in which light rays propagate without birefringence, that is, the two electromagnetic modes in vacuum have equal phase velocities. Other NLEs thus suffer from birefringence, which can in some cases lead to pathologies, such as superluminal photons, providing a basis for excluding the corresponding NLE. As we shall review in this paper, a common approach to deal with the birefringence is to formulate an effective geometry, which governs the propagation of the corresponding mode in the geometric optics approximation, e.g., [14].

The current interest in NLEs, however, goes well beyond the original Born-Infeld theory. For example, it was shown, that the framework of NLEs can naturally provide physical sources for regular black hole spacetimes. In this spirit, the famous regular Bardeen black hole [15] has been identified with a magnetically charged black hole in due NLE [16], see also [17–19] for other regular black hole models interpreted as solutions of nonlinear electrodynamics. Another example of a very interesting NLE is the so called ModMax theory [20,21], which is the most general NLE that admits the same symmetries as Maxwell's theory, namely, the conformal invariance and the electromagnetic duality (see [22] for a recent discussion of causal NLEs with electromagnetic duality).

In this paper, we focus on yet another recently formulated theory of NLE, called the regularized Maxwell (RegMax) theory [23]. This theory is in many aspects very close to the linear Maxwell electrodynamics. It gives rise to a minimally regularized field strength of a point charge, replacing the r^{-2} behavior with $(r+r_0)^{-2}$, for some positive constant r_0. At the same time, many of its self-gravitating solutions are remarkably Maxwell-like. Namely, it is the unique NLE theory, whose radiative solutions can be (similar to Maxwell) found in the Robinson-Trautman class [23] and are (contrary to Maxwell) well-posed [24]. Moreover, it is the unique NLE apart from Maxwell whose slowly rotating charged solutions are fully characterized by the electrostatic potential [25]. A general overview of the basic properties of RegMax theory, including black hole thermodynamics, phase transitions, and a novel C-metric solution, were shown in [26].

The aim of the present paper is to study optical properties of RegMax black holes, such as photon spheres, gravitational redshift, or the black hole shadow (see, e.g., [27–30]

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Inner-extremal regular black holes from pure gravity

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Abstract

Recently it was shown that essentially all regular black hole models constructed so far can be obtained as solutions of vacuum gravity equations, upon considering an infinite series of quasi-topological higher curvature corrections. Here we show that such a construction can be upgraded to yield regular black holes with vanishing inner horizon surface gravity. In four dimensions, such a condition is necessary for the absence of classical instabilities associated with mass inflation on the inner horizon.

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Regularized conformal electrodynamics: Novel C metric in $2+1$ dimensions

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Conformal electrodynamics is a particularly interesting example of power Maxwell nonlinear electrodynamics, designed to possess conformal symmetry in all dimensions. In this paper, we propose a regularized version of conformal electrodynamics, minimally regularizing the field of a point charge at the origin by breaking the conformal invariance of the theory with a dimensionful "Born-Infeld-like" parameter. In four dimensions the new theory reduces to the recently studied regularized Maxwell electrodynamics, distinguished by its "Maxwell-like" solutions for accelerated and slowly rotating black hole spacetimes. Focusing on three dimensions, we show that the new theory shares many of the properties of its four-dimensional cousin, including the existence of the charged C-metric solution (currently unknown in the Maxwell theory).

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I. INTRODUCTION

Nonlinear electrodynamics (NLE) arose out of attempts to deal with the singular nature of the classical Maxwell's (linear) theory of electrodynamics when applied to point charges. One of the first and certainly the most famous nonlinear model was proposed by Born and Infeld almost a hundred years ago [1]—it is distinguished by the absence of birefringence and other unique properties [2]. Subsequently, other models were proposed to achieve better regularization [3], to embody quantum corrections to Maxwell's theory coming from QED [4], and (much later) string theory [5], or to offer a maximally symmetric alternative to Maxwell's theory [6] (see also [7] for the "democratic formulation" of this theory).

NLE was also used as a "physical" source of regular black holes, increasing its significance for physics of spacetime, see [8,9] for original references and [10–12] for more recent works employing double copy. In this regard, one may formulate new criterion for the importance of a given NLE model by demanding its compatibility with essential spacetime geometries (going beyond spherical symmetry) [13–16], thus mimicking the success of Maxwell's linear theory in this regard.

While predominantly studied in four dimensions, theories of nonlinear electrodynamics are also interesting in lower-/higher-dimensional settings. Among these, conformal electrodynamics [17] is of particular interest. It is a special example of power Maxwell electrodynamics [18], designed in a way to preserve Weyl symmetry in any number of dimensions, such that in four dimensions it reduces to the Maxwell theory and yields dimension-independent (four-dimensional) Coulomb law for a point charge.

In this paper, we propose a "regularized" version of conformal electrodynamics. Namely, we design a one-parametric generalization of conformal electrodynamics characterized by a dimensionful Born-Infeld-like parameter α, which yields a finite (minimally regularized) field of a point charge in the origin. While the new regularized conformal electrodynamics naturally breaks the Weyl symmetry of the original theory, it possesses a number of interesting properties. Namely, in four dimensions it reduces to the recently studied regularized Maxwell (RegMax) electrodynamics, which is a unique NLE (constructed from a single field invariant $F_{\mu\nu}F^{\mu\nu}$ that admits Maxwell-like Robinson-Trautman [13,16], C metric [15], and slowly rotating [14] spacetimes; see also [19] for a recent discussion of optical properties of the corresponding RegMax black holes). As we shall show in this paper, in three dimensions the regularized theory admits a well-behaved generalized charged Bañados-Teitelboim-Zanelli (BTZ) black hole with improved thermodynamic charges that are not plagued by at infinity logarithmically divergent vector potential. Perhaps most importantly, it also admits a novel charged C-metric solution (at the moment unknown to exist in three-dimensional Einstein-Maxwell theory). We shall argue that the last property is very exceptional among all three-dimensional theories of NLE.

Our paper is organized as follows. The basic properties of NLE theories are reviewed in the next section. Conformal electrodynamics together with an overview of its spherical solutions are gathered in Sec. III. The novel regularized

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Love symmetry in higher-dimensional rotating black hole spacetimes

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Abstract: We develop a method for constructing a 1-parameter family of globally-defined Love symmetry generators in rotating black hole spacetimes of general dimension. The key ingredient is to focus on the vicinity of the (physical) outer horizon, matching only the radial derivative and the outer horizon pole pieces of the Klein–Gordon operator in the black hole spacetime to the $SL(2,\mathbb{R})$ Casimir operator. After revisiting the 4D Kerr and 5D Myers–Perry cases, the procedure is illustrated on generalized Lense–Thirring spacetimes which describe a wide variety of slowly rotating black hole metrics in any number of dimensions. Such spacetimes are known to admit an extended tower of Killing tensor and Killing vector symmetries and, as demonstrated in this paper, allow for separability of the massive scalar wave equation in Myers–Perry-like coordinates. Interestingly, separability also occurs in the horizon-penetrating Painlevé–Gullstrand coordinates associated with the freely infalling observer who registers flat space around her all the way to singularity.

20. Rinku Maji

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Inflation, superheavy metastable strings and gravitational waves in non-supersymmetric flipped SU(5)

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Abstract: Motivated by the NANOGrav 15 year data and other recent investigations of stochastic gravitational background radiation based on pulsar timing arrays, we show how superheavy strings survive inflation but the slightly heavier monopoles do not in a non-supersymmetric hybrid inflation model based on flipped SU(5). With the dimensionless string tension parameter $G\mu \sim 10^{-6}$, the gravitational wave spectrum emitted by the strings, which are metastable due to breaking caused by monopole-antimonopole quantum mechanical tunneling, is compatible with the latest NANOGrav measurement as well as the advanced LIGO-VIRGO third run data. The string network undergoes about 30 e-foldings of inflation which suppresses the spectrum in the LIGO-VIRGO frequency range. With the symmetry breaking chain $SU(5)\times U(1)_X \to SU(3)_c\times SU(2)_L\times U(1)_Z\times U(1)_X \to SU(3)_c\times SU(2)_L\times U(1)_Y$, the estimated proton lifetime is of order $10^{36} - 10^{37}$ yrs.

Keywords: Cosmic strings, domain walls, monopoles, inflation, particle physics - cosmology connection, physics of the early universe

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Supersymmetric $\mathrm{U}(1)_{B-L}$ flat direction and NANOGrav 15 year data

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Abstract: We show that, when connected with monopoles, the *flat* D-flat direction breaking the local $\mathrm{U}(1)_{B-L}$ symmetry as an extension of the minimal supersymmetric standard model can be responsible for the signal of a stochastic gravitational wave background recently reported by NANOGrav collaborations, while naturally satisfying constraints at high frequency band. Thanks to the flatness of the direction, a phase of thermal inflation arises naturally. The reheating temperature is quite low, and suppresses signals at frequencies higher than the characteristic frequency set by the reheating temperature. Notably, forthcoming spaced based experiments such as LISA can probe the cutoff frequency, providing an indirect clue of the scale of soft SUSY-breaking mass parameter.

Keywords: Cosmic strings, domain walls, monopoles, cosmological phase transitions, cosmology of theories beyond the SM, gravitational waves / sources

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Quantum tunneling in the early universe: stable magnetic monopoles from metastable cosmic strings

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Abstract: We present a novel mechanism for producing topologically stable monopoles (TSMs) from the quantum mechanical decay of metastable cosmic strings in the early universe. In an SO(10) model this mechanism yields TSMs that carry two units $(4\pi/e)$ of Dirac magnetic charge as well as some color magnetic charge which is screened. For a dimensionless string tension parameter $G\mu \approx 10^{-9}$–10^{-5}, the monopoles are superheavy with masses of order 10^{15}–10^{17} GeV. Monopoles with masses of order 10^{8}–10^{14} GeV arise from metastable strings for $G\mu$ values from $\sim 10^{-22}$ to 10^{-10}. We identify the parameter space for producing these monopoles at an observable level with detectors such as IceCube and KM3NeT. For lower $G\mu$ values the ultra-relativistic monopoles should be detectable at Pierre Auger and ANITA. The stochastic gravitational wave emission arise from metastable strings with $G\mu \sim 10^{-9}$–10^{-5} and should be accessible at HLVK and future detectors including the Einstein Telescope and Cosmic Explorer. An E_6 extension based on this framework would yield TSMs from the quantum mechanical decay of metastable strings that carry three units $(6\pi/e)$ of Dirac magnetic charge.

Keywords: Cosmic strings, domain walls, monopoles, cosmology of theories beyond the SM, gravitational waves / sources, physics of the early universe

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Topological structures, dark matter and gravitational waves in E_6

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Abstract: We discuss the appearance of topological structures from the spontaneous breaking of E_6 to the Standard Model via its maximal subgroup $\mathrm{SO}(10) \times \mathrm{U}(1)_\psi$. They include dumbbells, metastable strings, as well as domain walls bounded by necklaces. We provide a novel scenario for producing metastable strings based on the symmetry breaking $\mathrm{U}(1)_\psi \longrightarrow \mathbb{Z}_8 \longrightarrow \mathbb{Z}_4$. The metastable string arises from the merger of $\mathbb{Z}_8$ strings that bound a domain wall. An unbroken gauge $\mathbb{Z}_2$ symmetry from SO(10) breaking yields viable stable dark matter candidates as well as topologically stable strings. We discuss the gravitational wave emission from two varieties of cosmic strings, namely the superheavy metastable ones and the intermediate scale topologically stable cosmic strings.

Keywords: Cosmology of Theories BSM, Early Universe Particle Physics, Grand Unification, Phase Transitions in the Early Universe

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Kinetic mixing, proton decay and gravitational waves in SO(10)

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Abstract: We present an SO(10) model in which a dimension five operator induces kinetic mixing at the GUT scale between the abelian subgroups $\mathrm{U}(1)_{B-L}$ and $\mathrm{U}(1)_R$. We discuss in this framework gauge coupling unification and proton decay, as well as the appearance of superheavy quasistable strings with $G\mu \sim 10^{-8} - 10^{-5}$, where μ denotes the dimensionless string tension parameter. We use Bayesian analysis to show that for $G\mu$ values $\sim 4 \times 10^{-7} - 10^{-5}$, the gravitational wave spectrum emitted from the quasistable strings is in good agreement with the recent pulsar timing array data. Corresponding to $G\mu$ values $\sim 10^{-8} - 2 \times 10^{-7}$, proton decay is expected to occur at a rate accessible in the Hyper-Kamiokande experiment. Finally, we present the gravitational wave spectrum emitted by effectively stable strings with $G\mu \approx 10^{-8}$ that have experienced a certain amount of inflation. This can be tested with future detectors in the μHz frequency range.

Keywords: Cosmology of Theories BSM, Grand Unification, Early Universe Particle Physics, Phase Transitions in the Early Universe

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22. Pavan Dharanipragada

Holographic RG from an exact RG: Locality and general coordinate invariance in the bulk

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In earlier papers it was shown that the correct kinetic term for scalar, vector gauge field and the spin two field in AdS_{D+1} space is obtained starting from the exact renormalization group (ERG) equation for a CFT_D perturbed by scalar composite, conserved vector current, and conserved traceless energy momentum tensor respectively. In this paper interactions are studied, and it is shown that a flipped version of the Polchinski ERG equation that evolves toward the UV can be written down and is useful for making contact with the usual AdS/CFT prescriptions for correlation function calculations. The scalar-scalar-spin-2 interaction in the bulk is derived from the ERG equation in the large N semiclassical approximation. It is also shown that after mapping to AdS the interaction is local on a scale of the bare cutoff rather than the moving cutoff (which would have corresponded to the anti–de Sitter scale). The map to AdS_{D+1} plays a crucial role in this locality. The local nature of the coupling ensures that this interaction term in the bulk action is obtained by gauge fixing a general coordinate invariant scalar kinetic term in the bulk action. A wave function renormalization of the scalar field is found to be required for a mutually consistent map of the two fields to AdS_{D+1}.

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I. INTRODUCTION AND OUTLINE

A precise realization of holography [1,2] is the AdS/CFT correspondence [3–7]. One of the most interesting ideas that have come out of the AdS/CFT correspondence is that of holographic RG [8–22]. It has been shown in a series of papers by one of the authors of this paper [23–26] that the bulk anti–de Sitter (AdS) dual can be derived from first principles starting from a Polchinski exact renormalization group (ERG) equation [27–36] of the boundary conformal field theory (CFT).[1]

In this paper we build on the work done in [23–26]. Our goal is to construct, from "first principles" the bulk AdS dual of the O(N) vector model in $D = 3$. The O(N) vector model has two fixed points—the Gaussian point and the Wilson-Fisher fixed point. Both these fixed point theories are conjectured to have as bulk AdS dual some variant of the higher spin theory [37] of the type studied by Vasiliev [38].

By the phrase "from first principles" we mean the following:

We start with the boundary field theory with $D = 3$. We then write down an ERG for the evolution of single trace perturbations. These are functional differential equations. We then write down an evolution operator for this ERG equation in the form of a functional integral over a field theory in one higher dimension, i.e., $D + 1$ dimensions. This field theory is *nonlocal* and has nonlocal kinetic and interaction terms. Because this bulk action implements an RG evolution they are guaranteed to reproduce the correct correlators of the boundary theory. We map this nonlocal action by a field redefinition to an action in AdS space where the kinetic term has the standard *local* form. This bulk action is by construction the AdS dual one is looking for.

We also get a well-defined mathematical expression for the interaction terms. This was done for the three scalar interactions in [25]. In this paper we obtain the graviton-scalar-scalar interaction. There is no guesswork involved in this procedure: One does not have to start with a general ansatz and fix the coefficients so that the boundary correlators are reproduced using the standard AdS/CFT

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[1]To avoid confusion, one should emphasize that a CFT is a field theory at a fixed point of the RG and as such has no RG flow. The RG flow is for the CFT perturbed by the addition of some terms, for instance of the form $\int \lambda O$ where O is some operator in the CFT.

Attractor saddle for 5D black hole index

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Abstract

In a recent paper, Anupam, Chowdhury, and Sen [arXiv:2308.00038] constructed the non-extremal saddle that reproduces the supersymmetric index of the BMPV black hole with three independent charges in the classical limit. This saddle solution is a finite temperature complex solution saturating the BPS bound. In this paper, we write this solution in a canonical form in terms of harmonic functions on three-dimensional flat base space, thereby showing that it is supersymmetric. We also show that it exhibits the new form of attraction.

23. Young-Hwan Hyun

Ringdown Gravitational Waves from Close Scattering of Two Black Holes

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We have numerically investigated close scattering processes of two black holes (BHs). Our careful analysis shows for the first time a nonmerging ringdown gravitational wave induced by dynamical tidal deformations of individual BHs during their close encounter. The ringdown wave frequencies turn out to agree well with the quasinormal ones of a single BH in perturbation theory, despite its distinctive physical context from the merging case. Our study shows a new type of gravitational waveform and opens up a new exploration of strong gravitational interactions using BH encounters.

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Introduction.—Lots of numerical studies on binary black hole (BH) coalescence have primarily focused on quasicircular cases, presumably because they are the main sources of gravitational wave (GW) observations [1–3]. As the sensitivity of GW detectors increases and various future observation plans are proposed [4–6], however, a broader range of GW sources becomes of interest, resulting in active studies on eccentric binary black hole (BBH) systems in both numerical and approximation methods. In particular, highly eccentric BBHs and scattering BHs on hyperbolic orbits have been investigated [7–24]. However, studies on strong interactions in these systems remain limited. Investigating dynamical behaviors of BH horizons and radiated waveforms through varying initial parameters can broaden our knowledge beyond quasicircular scenarios.

In the perturbation regime, the system of a BH and an orbiting particle showed oscillatory imprints in GWs linked to the BH's quasi-normal mode (QNM) excitations [25–28]. The tidal Love number for stationary BH horizons was also examined [29–31]. In the nonlinear regime, eccentric binary neutron star mergers between head-on and circular have been studied, revealing tidal oscillations induced by the companion stars [32]. In the case of BBHs, ringdown GWs are well known as imprints of deformations in the merged BH. In scattering BHs, each BH's spin-up effects were found [23,24], indicating tidal interactions between BHs. In quasicircular BBH inspirals, BH source moments were explored, showing nonvanishing tidal Love numbers for constituent BH horizons [33]. However, tidally excited gravitational radiations of individual BH horizons without merging remain unexplored.

This work presents the first full general relativistic simulation of scattering BHs, showing ringdown GWs from tidal deformations of nonmerging constituent BHs. Remarkably, these GWs' leading frequencies agree with individual BH's QNM frequencies in perturbation theory. One may explore much more various features of strong interactions and BH tidal deformations by adjusting impact parameters and speeds. Finally, observational implications of this new class of GWs are discussed.

Numerical simulation of scattering black holes.—For the numerical relativity (NR) simulations, we use EinsteinToolkit [34,35]. McLachlan [36] is used for time evolution with an eighth-order spatial finite difference method and CARPET [37] for the adaptive mesh refinement. The computational domain extends to $770M$ in geometrized units with radiative boundary conditions for an outer boundary, and seven mesh refinement levels are used with the finest grid spacings for different resolutions, $h \simeq 0.0137M$ and $h \simeq 0.0156M$, around the BHs. These resolutions are higher than those used in previous convergent tests [9,10], ensuring they fall within the convergent regime.

Using TwoPuncture [38], initial conditions are set for two equal-mass and nonspinning BHs to be in hyperbolic motion during the whole scattering process. To avoid overlap between physical and junk radiations, the initial positions of the two BHs are set at $(\pm X, Y, Z) = (\pm 200, 0, 0)M$. Components of the initial momenta are given by $\vec{p} = \pm|\vec{p}|(-\sqrt{1-[b/(2X)]^2}, b/(2X), 0)$. We have set $|\vec{p}| = 0.2886751M$, which corresponds to $v \approx 0.5$, and considered two different impact parameters $b = 8M$ and $b = 10M$. In all cases, the Arnowitt-Deser-Misner (ADM) energies are nearly identical to $M_{\rm ADM} \approx 1.1563547M$, with only a very small difference on the order of 10^{-8}. Consequently, we conducted a total of four simulation models, using two different impact parameters and two different grid resolutions for each.

The Weyl scalar Ψ_4 has been extracted up to $l = 16$ mode in spin-weighted spherical harmonics, and we set the several extraction surfaces up to $r_{\rm ext} = 400M$, which is far

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Scalar field perturbation of hairy black holes in EsGB theory

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Abstract: We investigate scalar field perturbations of the hairy black holes involved with spontaneous symmetry breaking of the global U(1) symmetry in Einstein-scalar-Gauss-Bonnet theory for asymptotically flat spacetimes. We consider the mechanism that black holes without hairs become unstable at the critical point of the coupling constant and undergo a phase transition to hairy black holes in the symmetry-broken phase driven by spontaneous symmetry breaking. This transition occurs near the black hole horizon due to the diminishing influence of the Gauss-Bonnet term at infinity. To examine such process, we introduce a scalar field perturbation on the newly formed background spacetime. We solve the linearized perturbation equation using Green's function method. We begin by solving the Green's function, incorporating the branch cut contribution. This allows us to analytically investigate the late-time behavior of the perturbation at both spatial and null infinity. We found that the late-time behavior only differs from the Schwarzschild black hole by a mass term. We then proceed to calculate the quasinormal modes (QNMs) numerically, which arise from the presence of poles in the Green's function. Our primary interest lies in utilizing QNMs to investigate the stability of the black hole solutions both the symmetric and symmetry-broken phases. Consistent with the prior study, our analysis shows that hairy black holes in the symmetric phase become unstable when the quadratic coupling constant exceeds a critical value for a fixed value of the quartic coupling constant. In contrast, hairy black holes in the symmetry-broken phase are always stable at the critical value. These numerical results provide strong evidence for a dynamical process that unstable black holes without hairs transition into stable hairy black holes in the symmetry-broken phase through the spontaneous symmetry breaking.

Keywords: Black Holes, Classical Theories of Gravity, Spontaneous Symmetry Breaking

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24. Stefano Scopel

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WIMP constraints from black hole low-mass X-ray binaries

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Abstract: The abnormally fast orbital decay observed in the black hole (BH) Low-Mass X-ray binaries (BH-LMXB) A0620-00 and XTE J1118+480 can be explained by the dynamical friction between Dark Matter (DM) and the companion star orbiting around the low-mass BH ($\simeq$ a few $M_\odot$) of the system. In this case the value of the index $\gamma_{\rm sp}$ of the DM spike surrounding the BH can be pinned down with an accuracy of $\simeq$ a few percent, way better than that for much bigger systems such as the super massive BHs (SMBHs) in the Galactic Center or in M87. We have used data from XTE J1118+480 to put bounds on the WIMP annihilation cross section times velocity $\langle \sigma v \rangle$, assuming that DM annihilation is driven by the $\chi\chi \to b\bar{b}$ annihilation channel and that it proceeds in s-wave. The bounds are driven by the radio synchrotron signal produced by $e^\pm$ final states propagating in the magnetic field in the vicinity of the BH. We find that for DM masses m_χ up to the TeV scale XTE J1118+480 allows to constrain $\langle \sigma v \rangle$ well below the standard value $\langle \sigma v \rangle_{\rm thermal}$, corresponding to the observed DM relic density in the Universe for a thermal WIMP. On the other hand, for $m_\chi \gtrsim 15\,\text{GeV}$, the bounds from the SMBHs in the GC or in M87 do not reach $\langle \sigma v \rangle_{\rm thermal}$ when the very large uncertainties on the corresponding spike indices are taken into account, in spite of potentially producing much larger DM densities compared to XTE J1118+480. Our bounds for XTE J1118+480 have a mild sensitivity on the effect of spatial diffusion (which implies at most a weakening of the bounds of a factor $\lesssim 6$ at large m_χ). However, diffusion is instrumental in enhancing the sensitivity of the results upon the intensity of the magnetic field. In particular, our bounds rest on the assumption that the magnetic field B reaches the equipartition value $B^{\rm eq}$. We find that a reduction factor of the magnetic field $B^{\rm eq}/B$ larger than about 14 at low m_χ, becoming progressively smaller at higher WIMP masses, would be

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Gauss-Bonnet Cosmology: large-temperature behaviour and bounds from Gravitational Waves

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Abstract: We provide a transparent discussion of the high temperature asymptotic behaviour of Cosmology in a dilaton-Einstein-Gauss-Bonnet (dEGB) scenario of modified gravity with vanishing scalar potential. In particular, we show that it has a clear interpretation in terms of only three attractors (stable critical points) of a set of autonomous differential equations: $w = -\frac{1}{3}$, $w = 1$ and $1 < w < \frac{7}{3}$, where $w \equiv p/\rho$ is the equation of state, defined as the ratio of the total pressure and the total energy density. All the possible different high-temperature evolution histories of the model are exhausted by only eight paths in the flow of the set of the autonomous differential equations. Our discussion clearly explains why five out of them are characterized by a swift transition of the system toward the attractor, while the remaining three show a more convoluted evolution, where the system follows a meta-stable equation of state at intermediate temperatures before eventually jumping to the real attractor at higher temperatures. Compared to standard Cosmology, the regions of the dEGB parameter space with $w = -\frac{1}{3}$ show a strong enhancement of the expected Gravitational Wave stochastic background produced by the primordial plasma of relativistic particles of the Standard Model. This is due to the very peculiar fact that dEGB allows to have an epoch when the energy density $\rho_{\rm rad}$ of the relativistic plasma dominates the energy of the Universe while at the same time the rate of dilution with T of the total energy density is slower than what usually expected during radiation dominance. This allows to use the bound from Big Bang Nucleosynthesis (BBN) to put in dEGB a constraint $T_{\rm RH} \lesssim (10^8\text{–}10^9)$ GeV on the reheating temperature of the Universe $T_{\rm RH}$. Such BBN bound is complementary to late-time constraints from compact binary mergers.

Keywords: cosmology of theories beyond the SM, Gauss-Bonnet-Lovelock-Horndeski-Palatini etc gravity theories

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Low-mass constraints on WIMP effective models of inelastic scattering using the Migdal effect

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Abstract. We use the Migdal effect to extend to low masses the bounds on each of the effective couplings of the non-relativistic effective field theory of a WIMP of mass m_χ and spin 1/2 that interacts inelastically with nuclei by either upscattering to a heavier state with mass splitting $\delta > 0$ or by downscattering to a lighter state with $\delta < 0$. In order to do so we perform a systematic analysis of the Migdal bounds in the $m_\chi - \delta$ parameter space comparing them to those from nuclear recoil searches. The Migdal effect allows to significantly extend to low WIMP masses the nuclear recoil bounds for $\delta < 0$. In this case the bounds are driven by XENON1T, except when δ is vanishing or very small, when, depending on the WIMP–nucleus interaction, in the lower end of the m_χ range either DS50 or SuperCDMS are more constraining. On the other hand, when $\delta > 0$ and the WIMP particle upscatters to a heavier state nuclear recoil bounds are stronger than those from the Migdal effect.

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Sensitivity of WIMP bounds on the velocity distribution in the limit of a massless mediator

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Abstract: We discuss the sensitivity of the bounds on the spin–independent (SI) and spin–dependent (SD) WIMP–proton and WIMP–neutron interaction couplings $\alpha^{p,n}_{SI,SD}$ on the WIMP velocity distribution for a massless mediator in the propagator by combining direct detection and the neutrino signal from WIMP annihilation in the Sun (fixing the annihilation channel to $b\bar{b}$). We update the bounds in the Standard Halo Model (SHM) and using the halo–independent single–stream method. In the case of a massless mediator the SHM capture rate in the Sun diverges and is regularized by removing the contribution of WIMPs locked into orbits that extend beyond the Sun–Jupiter distance. We discuss the dependence of the SHM bounds on the Jupiter cut showing that it can be sizeable for $\alpha^p_{\rm SD}$ and a WIMP mass m_χ exceeding 1 TeV. Our updated SHM bounds show an improvement between about two and three orders of magnitude compared to the previous ones in the literature. Our halo–independent analysis shows that, with the exception of $\alpha^p_{\rm SD}$ at large m_χ, the relaxation of the bounds compared to the SHM is of the same order of that for contact interactions, i.e. relatively moderate in the low and high WIMP mass regimes and as large as a few $\times \sim 10^2$ for $m_\chi \simeq 30$ GeV. On the other hand, the exact determination of the relaxation of the bound becomes not reliable for $\alpha^p_{\rm SD}$ and $m_\chi \gtrsim 1$ TeV due to the sensitivity of the SHM capture rate in the Sun to the details of the Maxwellian velocity distribution at low incoming WIMP speeds. The halo–independent bounds do not depend on the Jupiter cut needed to regularize the calculation of the capture rate.

Keywords: WIMP direct detection, WIMP capture in the Sun, massless mediator, velocity-independent limit

25. Changhyun Ahn

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The $\mathcal{N} = 2, 4$ supersymmetric linear $W_\infty[\lambda]$ algebras for generic λ parameter

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Abstract: The four different kinds of currents are given by the multiple (β, γ) and (b, c) ghost systems with a multiple product of derivatives. We determine their complete algebra where the structure constants depend on the deformation parameter λ appearing in the conformal weights of above fields nontrivially and depend on the generic spins h_1 and h_2 appearing on the left hand sides in the (anti)commutators. By taking the linear combinations of these currents, the $\mathcal{N} = 4$ supersymmetric linear $W_\infty[\lambda]$ algebra (and its $\mathcal{N} = 4$ superspace description) for generic λ is obtained explicitly. Moreover, we determine the $\mathcal{N} = 2$ supersymmetric linear $W_\infty[\lambda]$ algebra for arbitrary λ. As a by product, the λ deformed bosonic $W_{1+\infty}[\lambda] \times W_{1+\infty}[\lambda + \frac{1}{2}]$ subalgebra (a generalization of Pope, Romans and Shen's work in 1990) is obtained. The first factor is realized by (b, c) fermionic fields while the second factor is realized by (β, γ) bosonic fields. The degrees of the polynomials in λ for the structure constants are given by $(h_1 + h_2 - 2)$. Each $w_{1+\infty}$ algebra from the celestial holography is reproduced by taking the vanishing limit of other deformation prameter q at $\lambda = 0$ with the contractions of the currents.

Keywords: Conformal and W Symmetry, Extended Supersymmetry, Superspaces

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A supersymmetric extension of $w_{1+\infty}$ algebra in the celestial holography

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Abstract: We determine the $\mathcal{N}=1$ supersymmetric topological W_∞ algebra by using the λ deformed bosons (β,γ) and fermions (b,c) ghost system. By considering the real bosons and the real fermions at $\lambda=0$ (or $\lambda=\frac{1}{2}$), the $\mathcal{N}=1$ supersymmetric $W_{\frac{\infty}{2}}$ algebra is obtained. At $\lambda=\frac{1}{4}$, other $\mathcal{N}=1$ supersymmetric $W_{1+\infty}[\lambda=\frac{1}{4}]$ algebra is determined. We also obtain the extension of Lie superalgebra $\mathrm{PSU}(2,2|\mathcal{N}=4)$ appearing in the worldsheet theory by using the symplectic bosons and the fermions. We identify the soft current algebra between the graviton, the gravitino, the photon (the gluon), the photino (the gluino) or the scalars, equivalent to $\mathcal{N}=1$ supersymmetric $W_{1+\infty}[\lambda]$ algebra, in two dimensions with the $\mathcal{N}=1$ supergravity theory in four dimensions discovered by Freedman, van Nieuwenhuizen and Ferrara in 1976 and its matter coupled theories, via celestial holography.

Keywords: Conformal and W Symmetry, Supergravity Models

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26. Theodoros Nakas

Exact black holes in string-inspired Euler-Heisenberg theory

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We consider higher-order derivative gauge field corrections that arise in the fundamental context of dimensional reduction of string theory and Lovelock-inspired gravities and obtain an exact and asymptotically flat black hole solution, in the presence of nontrivial dilaton configurations. Specifically, by considering the gravitational theory of Euler-Heisenberg nonlinear electrodynamics coupled to a dilaton field with specific coupling functions, we perform an extensive analysis of the characteristics of the black hole, including its geodesics for massive particles, the energy conditions, thermodynamical and stability analysis. The inclusion of a dilaton scalar potential in the action can also give rise to asymptotically (anti) de Sitter spacetimes and an effective cosmological constant. Moreover, we find that the black hole can be thermodynamically favored when compared to the Gibbons-Maeda-Garfinkle-Horowitz-Strominger black hole for those parameters of the model that lead to a larger black hole horizon for the same mass. Finally, it is observed that the energy conditions of the obtained black hole are indeed satisfied, further validating the robustness of the solution within the theoretical framework, but also implying that this self-gravitating dilaton-nonlinear-electrodynamics system constitutes another explicit example of bypassing modern versions of the no-hair theorem without any violation of the energy conditions.

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I. INTRODUCTION

In the pursuit of a comprehensive understanding of gravitational phenomena in the cosmos as well as gravity itself, the theoretical examination of black holes stands as an essential frontier. The general theory of relativity (GR), while highly successful in describing the macroscopic behavior of these celestial entities, becomes subject to scrutiny under extreme conditions. This investigation prompts the exploration of modified gravitational theories and theories with extra dimensions. Among the theories attempting to unify fundamental interactions, string theory stands as the leading contender. In particular, the heterotic-string theory stands as an essential branch within the broader scope of string theory, distinguished by its capability to unify gravitational interactions with other fundamental forces. Notably, it excels in synthesizing these interactions into a cohesive framework. A focal point of interest lies in the derivation of an effective four-dimensional theory, offering insights into quantum corrections that modify Einstein's theory of gravity. These corrections can potentially incorporate terms ranging from the Gauss-Bonnet, quadratic-curvature term [1–4] to nonlinear electromagnetic corrections (see, e.g., [5–8] and references within).

Drawing therefore inspiration only from the aforementioned corrections introduced by string/brane theory, in this article, we aim to elucidate the implications of departing from the conventional electromagnetic framework and embracing the intricacies of nonlinear electrodynamics (NED) and scalar fields within the context of black hole solutions. In addition to the above, it is important to mention that four-dimensional scalar-vector-tensor theories can be also obtained via an appropriate reduction from a higher-dimensional Lovelock theory [9]. Under this perspective, scalar-tensor-vector theories can be understood as natural extensions of the scalar-tensor theories that have been extensively studied in the last decades [4,10–51]. Such scalar-vector-tensor theories offer a very fruitful framework for finding novel compact-object solutions,

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27. Mohammad Ali Gorji

Cosmological perturbation theory in metric-affine gravity

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We formulate cosmological perturbation theory around the spatially curved FLRW background in the context of metric-affine gauge theory of gravity which includes torsion and nonmetricity. Performing scalar-vector-tensor decomposition of the spatial perturbations, we find that the theory displays a rich perturbation spectrum with helicities 0, 1, 2, and 3, on top of the usual scalar, vector, and tensor metric perturbations arising from Riemannian geometry. Accordingly, the theory provides a diverse phenomenology, e.g. the helicity-2 modes of the torsion and/or nonmetricity tensors source helicity-2 metric tensor perturbation at the linear level leading to the production of gravitational waves. As an immediate application, we study linear perturbation of the nonmetricity helicity-3 modes for a general parity-preserving action of metric-affine gravity which includes quadratic terms in curvature, torsion, and nonmetricity. We then find the conditions to avoid possible instabilities in the helicity-3 modes of the spin-3 field.

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I. INTRODUCTION

Over the past few decades, numerous cosmological observations have provided compelling evidence that the universe is undergoing accelerated expansion. Additionally, data from sources like the cosmic microwave background (CMB) and galactic rotation curves indicate the presence of no ordinary matter, which does not interact with light, may exist at cosmological scales. These observations have led to the introduction of two mysterious components in cosmology, known as dark energy and dark matter [1–4]. The simplest model capable of explaining these phenomena relies on general relativity (GR) and a cosmological constant, which together constitute the ΛCDM model that incorporates both dark constituents.

Nonetheless, recent cosmological observations have raised concerns about the viability of the standard cosmological model, primarily due to various tensions [5–8]. For instance, there is a growing tension, currently at a significance level of approximately 4.4σ, in the measurement of the Hubble constant H_0 as determined by model-dependent observations on early-time cosmology (such as Planck) [9–11] and direct measurements in the late universe (for example, using ladder measurements) [12–14]. Additionally, there are other, albeit less severe, tensions, such as the σ_8 tension—a parameter related to the clustering of matter, which also implies discrepancies between local and early-time observations [15,16]. The scientific community is engaged in a lively debate regarding whether these tensions stem from new physics or systematic errors [17–20]. One potential approach to addressing or mitigating these tensions is to modify the ΛCDM model, and one avenue for doing so is indeed to modify GR. Furthermore, there are other theoretical motivations for modifying GR, including the cosmological constant problem, the issue of singularities, and the quest for a consistent framework of quantum gravity [21–23].

There exist various strategies to formulate alternative theories of gravity beyond GR (for comprehensive reviews, see [24–31]). In this work, our focus is on a geometrical extension of GR, which introduces the torsion and nonmetricity tensors as post-Riemannian degrees of freedom (d.o.f.) into the geometrical structure of the space-time. From a theoretical point of view, the resulting geometry can be related to the existence of a new fundamental symmetry

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Effective field theory of black hole perturbations in vector-tensor gravity

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Abstract: We formulate the effective field theory (EFT) of vector-tensor gravity for perturbations around an arbitrary background with a *timelike* vector profile, which can be applied to study black hole perturbations. The vector profile spontaneously breaks both the time diffeomorphism and the U(1) symmetry, leaving their combination and the spatial diffeomorphism as the residual symmetries in the unitary gauge. We derive two sets of consistency relations which guarantee the residual symmetries of the EFT. Also, we provide the dictionary between our EFT coefficients and those of generalized Proca (GP) theories, which enables us to identify a simple subclass of the EFT that includes the GP theories as a special case. For this subclass, we consider the stealth Schwarzschild(-de Sitter) background solution with a constant temporal component of the vector field and study the decoupling limit of the longitudinal mode of the vector field, explicitly showing that the strong coupling problem arises due to vanishing sound speeds. This is in sharp contrast to the case of gauged ghost condensate, in which perturbations are weakly coupled thanks to certain higher-derivative terms, i.e., the scordatura terms. This implies that, in order to consistently describe this type of stealth solutions within the EFT, the scordatura terms must necessarily be taken into account in addition to those already included in the simple subclass.

Keywords: gravity, modified gravity

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Nonlinear gravitational waves in Horndeski gravity: scalar pulse and memories

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Abstract: We present and analyze a new *non-perturbative radiative* solution of Horndeski gravity. This exact solution is constructed by a disformal mapping of a seed solution of the shift-symmetric Einstein-Scalar system belonging to the Robinson-Trautman geometry describing the gravitational radiation emitted by a time-dependent scalar monopole. After analyzing in detail the properties of the seed, we show that while the general relativity solution allows for shear-free parallel transported null frames, the disformed solution can only admit parallel transported null frames with a non-vanishing shear. This result shows that, at the nonlinear level, the scalar-tensor mixing descending from the higher-order terms in Horndeski dynamics can generate shear out of a pure scalar monopole. We further confirm this analysis by identifying the spin-0 and spin-2 polarizations in the disformed solution using the Penrose limit of our radiative solution. Finally, we compute the geodesic motion and the memory effects experienced by two null test particles with vanishing initial relative velocity after the passage of the pulse. This exact radiative solution offers a simple framework to witness nonlinear consequences of the scalar-tensor mixing in higher-order scalar-tensor theories.

Keywords: Exact solutions, black holes and black hole thermodynamics in GR and beyond, gravitational waves / theory, Gravitational waves in GR and beyond: theory , modified gravity

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Disformal gravitational waves

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Abstract

Contrary to conformal transformations, disformal transformations can change the principal null directions of a spacetime geometry. Thus, depending on the frame a gravitational wave (GW) detector minimally couples to, the properties of GWs may change under a disformal transformation. In this paper, we provide *necessary* and *sufficient* conditions which determine whether GWs change under disformal transformations or not. Our argument is coordinate-independent and can be applied to any spacetime geometry at the fully non-linear level. As an example, we show that an exact radiative solution of massless Einstein-scalar gravity which admits only shear-free parallel transported frame is mapped to a disformed geometry which does not possess any shear-free parallel transported frame. This radiative geometry and its disformed counterpart provide a concrete example of the possibility to generate tensorial GWs from a disformal transformation at the fully non-linear level. This type of non-linear effect can be completely overlooked in the usual linear perturbation theory.

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CMB spectrum in unified EFT of dark energy: scalar-tensor and vector-tensor theories

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Abstract: We study the cosmic microwave background (CMB) radiation in the unified description of the effective field theory (EFT) of dark energy that accommodates both scalar-tensor and vector-tensor theories. The boundaries of different classes of theories are universally parameterised by a new EFT parameter α_V characterising the vectorial nature of dark energy and a set of consistency relations associated with the global/local shift symmetry. After implementing the equations of motion in a Boltzmann code, as a demonstration, we compute the CMB power spectrum based on the wCDM background with the EFT parameterisation of perturbations and a concrete Horndeski/generalised Proca theory. We show that the vectorial nature generically prevents modifications of gravity in the CMB spectrum. On the other hand, while the shift symmetry is less significant in the perturbation equations unless the background is close to the ΛCDM, it requires that the effective equation of state of dark energy is in the phantom region $w_{\rm DE} < -1$. The latter is particularly interesting in light of the latest result of the DESI+CMB combination as the observational verification of $w_{\rm DE} > -1$ can rule out shift-symmetric theories including vector-tensor theories in one shot.

Keywords: modified gravity, Cosmological perturbation theory in GR and beyond, CMBR theory

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28. Qianhang Ding

Merger rate of primordial black hole binaries as a probe of the Hubble parameter

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We propose that the merger rate of primordial black hole (PBH) binaries can be a probe of Hubble parameter by constraining PBH mass function in the redshifted mass distribution of PBH binaries. In next-generation gravitational wave (GW) detectors, the GWs from PBH binaries would be detected at high redshifts, which gives their redshifted mass and luminosity distances. From a number of detected events, the redshifted mass distribution of PBH binaries can be statistically obtained, and it depends on PBH mass function and redshift distribution of detected PBH binaries. The PBH mass function can be inversely solved by applying the gradient descent method in the relation between redshifted mass distribution and redshift distribution. However, the construction of redshift distribution requires an assumed Hubble parameter in a background cosmology to extract redshift from luminosity distances, which causes solved PBH mass function also depends on assumed Hubble parameter. To determine the Hubble parameter, the merger rate of PBH binaries constrains on this Hubble parameter-dependent PBH mass function by comparing calculated merger rate distribution with observed one, and the best-fit result produces an approximate mass distribution of the physical PBH mass function and pins down the Hubble parameter.

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I. INTRODUCTION

The value of Hubble parameter is of central importance in modern cosmology. However, cosmological observations report an inconsistency in the measurement value of Hubble parameter. The local measurement of Hubble parameter gives a local value of $H_0 = 73.04 \pm 1.04\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [1] (also see [2] for a review), which is 5σ larger than the measurement value of Hubble parameter $H_0 = 67.4 \pm 0.5\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ from Planck 2018 result under lambda-cold dark matter (ΛCDM) model [3]. This is so-called Hubble tension and its 5σ inconsistency has become a cosmological crisis in ΛCDM cosmology [4–6].

To reveal Hubble tension and toward a concordance cosmological model, the dynamical evolution of Hubble parameter from the early universe to the late universe should be well measured. Currently, for early universe probes, cosmic microwave background (CMB) provides a Hubble parameter measurement at redshift $z \simeq 1100$ by fitting CMB power spectrum [3]. For late universe probes, type Ia supernovae (SNe) provide a Hubble parameter measurement at redshift $z < \mathcal{O}(1)$ by constraining redshift-luminosity distance relation [7,8], which works as standard candles. And baryon acoustic oscillation can measure Hubble parameter at redshift $z \sim \mathcal{O}(1)$ by calibrating redshift-angular diameter distance relation [9–11], which is so-called standard rulers. In the intermediate epoch between early universe and late universe, gravitational waves (GWs) from compact binaries and their electromagnetic counterparts can be a potential Hubble parameter probe up to redshift $z \sim \mathcal{O}(10)$ as a standard siren in next-generation GW detectors [12–15]. However, Hubble parameter measurement between redshift $z \sim \mathcal{O}(10)$ and $z \sim \mathcal{O}(1000)$ is still not promising, due to lack of enough cosmological signals in the dark age [16], which causes difficulty in constructing redshift-distance relation to extract Hubble parameter.

The possible existence of primordial black hole (PBH) binaries changes the story. PBHs are hypothetical astrophysical objects, which were born from primordial perturbations in highly overdense regions by gravitational collapse [17–20]. The formation of PBH binaries occurs in early universe epoch, like radiation-domination era or matter-radiation equality, depends on PBH mass and abundance [21,22]. The GWs emitted from PBH binaries could propagate cosmological distance from the early epoch to the present, where luminosity distance is encoded in their GW waveform. Although redshift information is still missing, due to no electromagnetic counterpart of PBH binaries in the dark age [16], and causes difficulty in breaking the mass-redshift degeneracy in GW waveform [12]. The unique statistic properties of PBH binaries open another window in cosmic probes, the statistic distribution of PBH binaries, such as PBH mass

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Primordial Black Hole Mergers as Probes of Dark Matter in Galactic Center

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Primordial black holes (PBHs) from the early Universe that can contribute to dark matter (DM) abundance have been linked to gravitational wave observations. Super-massive black holes (SMBHs) at the centers of galaxies are expected to modify distribution of DM in their vicinity, and can result in highly concentrated DM spikes. We revisit PBH merger rates in the presence of DM spikes, tracking their history. We find novel peaked structure in the redshift-evolution of PBH merger rates at low redshifts around $z \sim 5$. These effects are generic and are present for distinct PBH mass functions and spike profiles, and also can be linked to peaked structure in redshift evolution of star formation rate. Redshift evolution characteristics of PBH merger rates can be distinguished from astrophysical black hole contributions and observable with gravitational waves, enabling them to serve as probes of DM in galactic centers.

I. INTRODUCTION

Primordial black holes (PBHs) could have formed in the early Universe and contribute to abundance of dark matter (DM) (see e.g. [1–3] for review). Recent gravitational wave (GW) detections by LIGO-Virgo-KAGRA (LVK) have been linked to stellar-mass black holes of primordial origin (e.g. [4–8]). Such PBHs can contribute to a substantial fraction of DM mass density $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$ as suggested by various complementary constraints including gas heating in dwarf galaxies [9–11], cosmic microwave background radiation (e.g. [12–14]), dwarf galaxy star dynamics [15–17], radio and X-ray observations [18, 19] as well as gravitational lensing [20]. Current LVK observations imply $f_{\rm PBH} \lesssim \mathcal{O}(10^{-3})$ assuming that stellar-mass PBH mergers are responsible for the observed GW signals (e.g. [21]). However, the exact origin of these events remains uncertain.

Variety of GW signatures associated with PBHs can originate at different stages of cosmic history and connect to distinct phenomena. Among them, PBH mergers can carry information about cosmic expansion [22, 23], source stochastic GW background in different GW frequency bands [24–26], and also serve as probes of primordial perturbations [23, 27, 28]. PBHs can also source GWs not expected to originate from black holes of astrophysical origin, such as (sub-)solar mass black holes [29–39]. The potential role of PBH mergers in GW observations as well as associated rich physics call for detailed investigation of their merger rates and evolution.

Observations definitively suggest presence of supermassive black hole (SMBH) Sgr A* residing in the Galactic Center of Milky Way [40, 41]. More generally, SMBHs inhabit centers of galaxies [42]. Recently, observations by James Webb Space Telescope (JWST) of high-redshift active galactic nuclei (AGN) found prevalence of SMBHs (e.g. [43, 44]). The presence of SMBHs can significantly modify distribution of DM in their vicinity. It has been argued [45] that cold DM density around SMBHs can be dramatically enhanced forming a "DM spike" particularly when galactic halos follow a cuspy density profile as suggested by some N-body simulations (e.g. [46, 47]). Analyses based on general relativity [48, 49] further highlight significance of DM spike formation for observations. Recently, claims of DM spike detection based on SMBH binary orbital decay observations have been put forth [50], but require further scrutiny. Further, DM spikes have also been studied in the context of intermediate-mass black holes and related GW observations [51–55]. More so, related formation of DM halos surrounding PBHs have been linked to novel signatures, including GWs [56, 57] and gravitational lensing of fast radio bursts [58]. Recently, it was demonstrated that GW lensing observations of PBHs in DM halos enable definitively probing scenarios of DM composed of combination of PBHs and particles [59].

In this work, we establish novel and distinct features in PBH merger rate evolution driven by SMBH DM spikes.

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Full length article

On graviton–photon conversions in magnetic environments

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ABSTRACT

Graviton–photon conversions in a given external electric or magnetic field, known as the Gertsenshtein mechanism, are usually treated using the four-potential for photons. In terms of the electric and magnetic (EM) fields, however, proper identification of the fields in curved spacetime is important. By misidentifying the fields in Minkowski form, as is often practiced in the literature, we show that the final equation for photon conversion is correct in transverse-tracefree gauge *only* for planar gravitational waves in a uniform and constant external field. Even in the former method, to recover the EM fields from the four-potential in curved spacetime, one should properly take into account the metric involved in the relation. By including the metric perturbation in the graviton conversion equation, we show that a magnetic environment can cause tachyonic instability term in gravitational wave equation.

1. Introduction

The gravitational wave generation mechanism by photons in a uniform and constant external electric or magnetic field is studied by Gertsenshtein [1]. The opposite process, known as the inverse Gertsenshtein process is also possible and provides potential methods of detecting gravitational waves using electromagnetic means [2–5]; for recent applications in the high-frequency gravitational wave detection and cosmological constraints, see [6–10]. The original studies used the electric and magnetic (EM) fields for photons (electromagnetic waves), while a more popular formulation uses the four-potential for photons [11].

When we use the EM fields for photons, for the correct analysis, it is important to properly identify the EM fields from the field strength tensor based on the covariant decomposition using the observer's four-vector [12–15]. This may sound obvious, but in curved spacetime, this fundamental fact is often ignored by a widespread misconception that F_{ab}, with the two covariant indices, is independent of the metric. This is not true if F_{ab} is expressed in terms of the EM fields. Missing the metric in F_{ab} directly leads to the homogeneous Maxwell's equations, the same form known in Minkowski space. For a recent occurrence in the context of the Gertsenshtein process, see [16].

The confusion may arise as F_{ab} expressed in terms of the four-potential is independent of the metric, but *not* in terms of the EM fields, see [17,18] for recent cases. Consequently, while the homogeneous Maxwell's equation is identically valid in terms of the potential, it is affected by the metric in terms of the EM fields and becomes nontrivial. If the basic equations are incorrect, the result must be incorrect. Here, we will show that, using a transverse-tracefree gauge for gravitational waves, incorrect analysis happens to give the correct result for a uniform and constant (independent of the space and time coordinate) external magnetic field and a plane gravitational wave which is the case studied in the literature, but not in general, see Section 3.2.

The analysis is often made using the four-potential for photons [11]. The four-potential depends on the electrodynamic gauge choice, whereas the EM fields are gauge-invariant. Besides the gauge dependence, it is not well known that, in curved spacetime, the relation between the potential and EM fields involves the metric perturbation even to the linear order [19]; in this way, F_{ab} expressed using the EM fields involves metric. To recover the EM fields from the potential, we should take into account the metric (gravitational waves) involved in the relation. Without considering the metric, we recover the wrong result as the one using the EM variables naïvely defined in special relativistic form, see Section 3.3. Thus, previous works using the potential are incomplete in this sense.

Our main emphasis in this work is clarifying the above two points (metric dependence of F_{ab} in terms of the EM fields and of the relation between the potential and the EM fields) in the context of graviton–photon conversions. Recently, we have resolved similar issues appearing in the high-frequency gravitational wave detection proposals using electromagnetic means [15] and in the medium interpretation of gravity in electrodynamics [19].

In Sections 2 and 3 we derive equations for the photon-to-graviton conversion and its inverse process, respectively, using both the EM

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Pulsar Timing Array signature from oscillating metric perturbations due to ultra-light axion

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Abstract: A coherently oscillating ultra-light axion can behave as dark matter. In particular, its coherently oscillating pressure perturbations can source an oscillating scalar metric perturbation, with a characteristic oscillation frequency which is twice the axion Compton frequency. A candidate in the mass range $10^{(-24,-21)}$eV can provide a signal in the frequency range tested by current and future Pulsar Timing Array (PTA) programs. Involving the pressure perturbations in a highly nonlinear environment, such an analysis demands a relativistic and nonlinear treatment. Here, we provide a rigorous derivation of the effect assuming weak-gravity and slow-motion limit of Einstein's gravity in zero-shear gauge and show that dark matter's velocity potential determines the oscillation phase and frequency change. A monochromatic PTA signal correlated with the velocity field would confirm the prediction, for example, by cross-correlating the PTA results with the future local velocity flow measurements.

Keywords: axions, Gravitational waves in GR and beyond: theory

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RESEARCH

On gravity as a medium property in Maxwell equations

Jai-chan Hwang[1] · **Hyerim Noh**[2]

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Abstract

The effect of gravity in Maxwell's equations is often treated as a medium property. The commonly used formulation is based on managing Maxwell's equations in exactly the same form as in Minkowski spacetime and expressing the effect of gravity as a set of constitutive relations. We show that such a set of Maxwell's equations is, in fact, a combination of the electric and magnetic fields defined in two different non-covariant ways, both of which *fail* to identify the associated observer's four-vectors. The suggested constitutive relations are also *ad hoc* and unjustified. To an observer with a proper four-vector, the effect of gravity can be arranged as effective polarizations and magnetizations appearing in both the homogeneous and inhomogeneous parts. Modifying the homogeneous part by gravity is inevitable to any observer, and the result cannot be interpreted as the medium property. For optical properties one should directly handle Maxwell's equations in curved spacetime.

Contents

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Full length article

Graviton–photon conversions in Euler–Heisenberg nonlinear electrodynamics

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ABSTRACT

We study graviton–photon conversions in an environment of the uniform and constant magnetic field considering Euler–Köckel–Heisenberg-type nonlinear corrections in electrodynamics. We take the transverse-tracefree gauge for gravitons and employ both the field potential and the electric and magnetic (EM) fields for photons. The nonlinear correction causes parity violating (chiral) graviton propagation equations, which depend on the two treatments for photons. Thus, the medium becomes effectively birefringent for two polarizations of gravitational waves similar to the photon birefringence, a characteristic of the nonlinear correction. In the presence of gravity, due to the nontrivial relation between the potential and EM fields, it is important to present the result using the EM fields.

1. Introduction

The graviton–photon conversions mediated by external magnetic field, known as Gertsenshtein and its inverse mechanism, are processes naturally arising in classical Maxwell's equations in the curved spacetime of Einstein's gravity [1–6]. The mechanism can be used to detect gravitational waves by observing the converted photons in the presence of external magnetic field in celestial objects or in the Laboratory [7–11].

In the graviton–photon conversions, the presence of gravitons in the energy–momentum tensor, which works as a source of the graviton, is often ignored. The ignored term, however, is of the same order as the other terms. Recently, by including its effect, we show that the effect causes a negative effective mass-squared (tachyonic instability) term in the graviton propagation equation, and showed that the effect depends on whether we use the potential or EM fields [12].

The transverse-tracefree (TT) gauge is often adopted for gravitons and the external (or background) magnetic field is usually assumed to be uniform and constant with its gravity often ignored in the analysis. These are assumptions. We can relax these assumptions on the background magnetic field and take other gauges for gravitons. For example, in the case of gravitational wave detection using the electromagnetic method, only the graviton to photon conversion is considered with the Fermi normal coordinate preferred for the detector instead of the TT gauge [13–18].

In a strong magnetic field, the quantum correction can cause nonlinear corrections in electrodynamics, interpreted as the vacuum polarization. Euler–Köckel–Heisenberg correction is well known in quantum electrodynamics (QED) [19–21]. There are other similarly motivated nonlinear corrections [22–24]. The nonlinear correction is often included in the graviton–photon conversion [6,11,25–27] and axion-photon conversion [6]. Previous studies exclusively used the potential for photons.

In electrodynamics, we have two options of using the electric and magnetic (EM) fields or using the field potential. As a natural solution of the homogeneous Maxwell's equation $\nabla_{[a}F_{bc]} = 0$, the potential is introduced as $F_{ab} \equiv \nabla_a A_b - \nabla_b A_a$; the covariant derivatives become ordinary derivatives and these are valid in curved spacetime of gravity. In the absence of gravity the relation between the potential and EM fields is trivial and well known [28]: $\mathbf{E} = -\nabla\phi - \frac{1}{c}\dot{\mathbf{A}}$ and $\mathbf{B} = \nabla \times \mathbf{A}$ with $\phi = -A_0$. Thus, we can easily recover the EM fields from the potential.

In curved spacetime the relation becomes complicated. The EM fields, being measurable quantities by a given observer, are defined from the field-strength tensor in a sophisticated manner [29–31]. Even in the flat spacetime the EM fields are defined by decomposing the field-strength tensor using a four-vector associated with the observer. The above EM fields are the quantities measured by an Eulerian observer associated with the normal four-vector [32–34] which can be chosen as $n_a = (-1, 0, 0, 0)$ in flat spacetime.

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RESEARCH

Check for updates

On gravity as a medium property in Maxwell equations

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Abstract

The effect of gravity in Maxwell's equations is often treated as a medium property. The commonly used formulation is based on managing Maxwell's equations in exactly the same form as in Minkowski spacetime and expressing the effect of gravity as a set of constitutive relations. We show that such a set of Maxwell's equations is, in fact, a combination of the electric and magnetic fields defined in two different non-covariant ways, both of which *fail* to identify the associated observer's four-vectors. The suggested constitutive relations are also *ad hoc* and unjustified. To an observer with a proper four-vector, the effect of gravity can be arranged as effective polarizations and magnetizations appearing in both the homogeneous and inhomogeneous parts. Modifying the homogeneous part by gravity is inevitable to any observer, and the result cannot be interpreted as the medium property. For optical properties one should directly handle Maxwell's equations in curved spacetime.

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Letter

Final parsec problem of black hole mergers and ultralight dark matter

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ABSTRACT

When two galaxies merge, they often produce a supermassive black hole binary (SMBHB) at their center. Numerical simulations with stars and cold dark matter show that SMBHBs typically stall out at a distance of a few parsecs apart and take billions of years to coalesce. This is known as the final parsec problem. We suggest that ultralight dark matter (ULDM) halos around SMBHBs can generate dark matter waves due to dynamical friction. These waves can effectively carry away orbital energy from the black holes, rapidly driving them together. To test this hypothesis, we performed numerical simulations of black hole binaries inside ULDM halos. Due to gravitational cooling and quasi-normal modes, the loss-cone problem can be avoided. The decay time scale gives lower bounds on masses of the ULDM particles and SMBHBs comparable to observational data. Our results imply that ULDM waves can lead to the rapid orbital decay of black hole binaries.

1. Introduction

The mystery of supermassive black hole (SMBH) growth is one of the unsolved problems in astronomy. When two galaxies merge, they can form a supermassive black hole binary (SMBHB) at their center. However, numerical simulations show that SMBHBs typically become stuck at a distance of a few parsecs apart, and can take billions of years to merge. At this distance the density of the stars and gas near the SMBHB is too low for dynamical friction to be efficient, while the loss of orbital energy of the SMBHB due to gravitational waves is only efficient for distances less than $\mathcal{O}(10^{-2})$ pc [1,2]. Furthermore, the loss cone is depleted as the black holes (BHs) approach each other. This difficulty is known as the final parsec problem. The gravitational wave background recently observed by NANOGrav [3] is usually attributed to efficient SMBH mergers. This fact deepens the mystery. Proposed solutions to the final parsec problem often involve bringing in extra matter, such as additional stars or another BH interacting with the black hole binaries (BHBs) to help them merge.

Ultralight (fuzzy) dark matter (ULDM) [4–9] is a promising alternative to cold dark matter (CDM), as it has the potential to solve some of the small-scale issues of CDM such as the missing satellite problem, the plane of satellite galaxies problem, and the core-cusp problem [10–13]. In this model, the ULDM is in a Bose-Einstein condensate state of ultralight scalar particles with a typical mass $m \gtrsim 10^{-22}$eV. ULDM can be described with a macroscopic wave function ψ and the uncertainty principle suppresses too many small-scale structure formations. Beyond the galactic scale, the ULDM behaves like CDM and hence naturally solves the problems of CDM. This model has also been shown to be able to explain a wide range of astrophysical observations, including the rotation curves of galaxies [8,14,15], and the large-scale structures of the universe [16]. Recently, there has been a growing interest in the interactions between BHs and ULDM halos surrounding them [17], as these interactions could change the patterns of gravitational waves generated by BHBs.

In this letter, we suggest that, inside ULDM halos (for a review, see [18–23]), BHBs can generate dark matter (DM) waves due to dynamical friction (DF) and gravitational cooling (GC). The dynamical friction of ULDM [24] refers to the frictional force that arises from the gravitational interaction between a moving celestial object and ULDM wakes generated by the object. On the other hand, gravitational cooling [25] is a mechanism for relaxation by ejecting ULDM waves carrying out excessive kinetic energy and momentum. These waves can effectively carry away orbital energy

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Holographic Gubser flow. A combined analytic and numerical study

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Abstract: Gubser flow is an evolution with cylindrical and boost symmetries, which can be best studied by mapping the future wedge of Minkowski space ($R^{3,1}$) to $dS_3 \times \mathbb{R}$ in a conformal relativistic theory. Here, we sharpen our previous analytic results and validate them via the first numerical exploration of the Gubser flow in a holographic conformal field theory.

Remarkably, the leading generic behavior at large de Sitter time is free-streaming in transverse directions and the sub-leading behavior is that of a color glass condensate. We also show that Gubser flow can be smoothly glued to the vacuum outside the future Minkowski wedge generically given that the energy density vanishes faster than any power when extrapolated to early proper time or to large distances from the central axis. We find that at intermediate times the ratio of both the transverse and longitudinal pressures to the energy density converge approximately to a fixed point which is hydrodynamic only for large initial energy densities. We argue that our results suggest that the Gubser flow is better applied to collective behavior in jets rather than the full medium in the phenomenology of heavy ion collisions and can reveal new clues to the mechanism of confinement.

Keywords: Gauge-Gravity Correspondence, Non-Equilibrium Field Theory, de Sitter space, Quark-Gluon Plasma

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Superfluids in expanding backgrounds and attractor times

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We determine the behavior of an out-of-equilibrium superfluid, composed of a $U(1)$ Goldstone mode coupled to hydrodynamic modes in a Müller-Israel-Stewart theory, in expanding backgrounds relevant to heavy ion collision experiments and cosmology. For suitable initial conditions, the evolution of the hydrodynamic variables leads to a change in the potential of the Goldstone mode, spontaneously breaking the symmetry. After some time, the condensate becomes small, leading the system evolution to be well described via hydrodynamic attractors for a timescale that we determine in Bjorken and Gubser flows. We define this new timescale as the *attractor time* and show its dependence on initial conditions. In the case of the Gubser flow, we provide for the first time a complete description of the nonlinear evolution of the system, including a novel nonlinear regime of constant anisotropy not found in the Bjorken evolution. Finally, we consider the superfluid in the dynamical FLRW (Friedmann-Lemaitre-Roberston-Walker) background, where we observe a similar attractor behavior, dependent on the initial conditions, that at late times approaches a regime dominated by the condensate.

I. INTRODUCTION

Superfluidity is a ubiquitous phenomenon found in diverse fields of physics, including high energy particle physics [1, 2], condensed matter systems such as cold atoms [3] and the description of astrophysical objects such as neutron stars [4]. Recently, there has been considerable interest in promoting the Goldstone mode to a state parameter to study the interplay between such modes and hydrodynamic modes, for example in the case of the chiral phase transition [5–8] as it may prove relevant in the search for the QCD critical point at the Beam Energy Scan experiment [9]. Moreover, in certain systems, such as in heavy ion collisions with approximately boost-invariant flows [10], small systems of strongly interacting fermions [11] or time dependent scattering length in cold atoms [12], it has been observed that although the system is far from equilibrium, hydrodynamics remains a remarkably good description of the system outside its naive range of validity, which can be explained in part due to the presence of hydrodynamic attractors (for reviews, see [13, 14]). Thus, the question naturally arises of how hydrodynamic attractors change in the vicinity of a superfluid phase transition.

In this work, we employ the formalism of [15], which builds on the Son-Nicolis approach [16, 17]. The central premise is that we dynamically couple a $U(1)$ scalar field to a fluid in an expanding background, whose dissipation is governed by the Müller-Israel-Stewart (MIS) framework [18, 19]. The potential of the scalar field is chosen such that the mass term is dependent on the energy density of the fluid, changing sign as the system passes a critical value. The expansion of the background metric cools the system, eventually leading to the symmetry of the scalar field to be spontaneously broken (see Fig 1).

More concretely, we study the boost-invariant Bjorken [20] and Gubser flow [21, 22] (see also the related exact solutions in boost-invariant superfluid flows [23]), both of which have seen successful phenomenological exploitation in heavy ion physics [24, 25], as well as the Friedmann–Lemaître–Robertson–Walker (FLRW) background [26], a cornerstone for describing the evolution of the early universe [27]. For a guide to the metrics used, see Fig. 2. In these backgrounds, depending on the initial conditions, we see that the evolution of the superfluid is dictated by the hydrodynamic attractor with unbroken symmetry at intermediate times, while at late times the system approaches one of the symmetry breaking fixed points.

A key result of this work is the novel notion of attractor time, the interval of time that the dynamics of a system is governed primarily by the attractor solution. Concretely, for the Bjorken flow, this occurs when the system is initially in the unbroken phase (for systems with sufficiently large initial temperatures compared to the critical temperature, $T_0 > T_c$) and the condensate is at the minimum of the potential, $\sigma = 0$. As the condensate dynamics essentially decouple, the system is governed by the hydrodynamic equations in an expanding background, which is denoted as the hydrodynamic attractor. Eventually, as the system cools and the temperature drops, the potential transits to the

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On Capped Higgs Positivity Cone

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Abstract: The Wilson coefficients of the Standard Model Effective Field Theory are subject to a series of positivity bounds. It has been shown that, while the positivity part of the UV partial wave unitarity leads to the Wilson coefficients living in a convex cone, further including the non-positivity part caps the cone from above. For the Higgs scattering, a capped positivity cone have been obtained using a simplified, linear unitarity conditions and without utilizing the full internal symmetries of the Higgs scattering. Here we further implement the stronger nonlinear unitarity conditions from the UV, which generically gives rise to better bounds. We show that, for the Higgs case in particular, while the nonlinear unitarity conditions per se do not enhance the bounds, the fuller use of the internal symmetries do shrink the capped positivity cone significantly.

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Post-Newtonian Dynamics of Spinning Black Hole Binaries in Einstein-Scalar-Gauss-Bonnet Gravity

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We explore the post-Newtonian dynamics of spinning black hole (BH) binaries in Einstein-Scalar-Gauss-Bonnet (ESGB) gravity, a theory that modifies general relativity by introducing a massless scalar field coupled nonminimally to gravity via the Gauss-Bonnet term. By employing an effective field theory (EFT) approach, we extend the Routhian formalism to incorporate spin effects in scalar interactions. In this formalism, we derive for the first time the effective two-body potential for spinning BHs up to the third post-Newtonian (3PN) order in generic ESGB gravity theories. This potential is expressed in terms of the sensitivities of the BHs, which are then obtained through a matching procedure using analytic BH solutions derived here within a slow-rotation approximation, accurate to seventh order in the Gauss-Bonnet coupling and fifth order in the BH spin. We also examine the thermodynamic properties of these rotating solutions, which, as shown in previous work, yield important insights into the inspiral phase evolution in ESGB gravity.

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I. INTRODUCTION

The detection of gravitational waves (GWs) from binary black hole (BH) mergers [1] by the LIGO-Virgo-KAGRA collaboration [2–4] has opened a new era in astrophysics, allowing us to probe the dynamics of these extreme systems with unprecedented precision [5]. These observations provide a unique opportunity to test the limit of general relativity (GR) in the strong-field regime, where deviations might appear.

Among the many alternative theories of gravity (see Ref. [6] for a comprehensive introduction), Einstein-Scalar-Gauss-Bonnet (ESGB) gravity, which modifies GR by introducing a scalar field φ coupled to the Gauss-Bonnet invariant $\mathcal{G} = R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$ in the form of $\alpha f(\varphi)\mathcal{G}$ has attracted considerable interest in recent years. This is mainly because, being some of the lowest order EFT corrections, it allows for BH solutions to present nontrivial scalar field profiles [7–10], thereby evading the no-hair theorems of GR [11–15] (see [16] for a review) and giving rise to BH spontaneous scalarization [17, 18] (see [19] for a review). Additionally, the coupling leads to second-order field equations [20, 21], making it a subclass of the Horndeski's theory [22], and is also well-motivated as it emerges from the low-energy limit of heterotic string theory [23, 24]. All this makes ESGB gravity a compelling theory for exploring deviations from GR, especially in the context of the strong-field phenomena in BH mergers.

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Scalar-Gauss-Bonnet gravity: Infrared causality and detectability of GW observations

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We investigate time delays of gravitational wave and scalar wave scatterings around black hole backgrounds in scalar-Gauss-Bonnet effective field theories of gravity. By requiring infrared causality, we impose a lower bound on the cutoff scale of the theories. With this bound, we further discuss the detectability of scalar-Gauss-Bonnet gravity in gravitational waves from binary black hole mergers. Comparing with the gravitational effective field theories that only contain the two tensor modes, adding a scalar degree of freedom opens up a detectable window in the planned observations.

I. INTRODUCTION

Scalar-Gauss-Bonnet (sGB) gravity has been extensively studied for its interesting phenomenological differences from general relativity (GR) in strong gravity regimes. In particular, the sGB couplings can induce hairy black holes (BHs) [1–8] and give rise to spontaneous scalarization [9–14]. The nature of such BHs, such as stability and quasi-normal modes, and gravitational waves (GWs) emissions from binary BHs in sGB gravity have also been studied [15–29]. With probes to the strong gravity regime offered by future observations, gravitational theories including sGB gravity can be tested with unprecedented precision [30–43].

While low-energy EFTs provide an efficient framework for searching for new physics in observations, their validity and consistency must be justified from theoretical considerations. For instance, it has been long known that many low-energy EFTs manifest superluminal propagations in curved spacetimes [44–63]. These superluminal propagations, however, are unresolvable within the EFT. Nevertheless, one can impose the so-called asymptotic causality [55, 62, 64–68], which argues that the speed of all species in an EFT cannot be secularly superluminal for the theory to be causal. In the case of wave scattering, asymptotic causality requires that the net time delay caused by the scattering, if resolvable, must be positive. However, it has recently been pointed out in Refs. [48–50, 57, 69–79] that asymptotic causality does not fully capture all causality conditions available within the EFT (see Ref. [80] for a review). Instead of the net time delay, one can require the EFT corrections on all resolvable time delays to be positive. This criterion is called infrared causality and is based on the following reasoning: Causality requires any support outside the light cone determined by the background geometry to be unresolvable, and the causal structure of the background geometry can be seen by high-frequency modes, which are only sensitive to local inertial frame. In the case of scattering, it is the EFT corrections on the time delay that reflect the differences between the low- and high-frequency modes. In particular, a negative EFT correction indicates support outside the light cone seen by the high-frequency modes, and hence should not be resolvable in a causal EFT. The infrared causality is very powerful such that it indicates the gravitational EFTs that only contain the two tensor modes cannot be tested with current GW observations [70].

sGB gravity has been tested with various astrophysical observations, such as low-mass X-ray binary orbital decay, binary compact object mergers, and neutron star measurements [32–41]. It has also been constrained by positivity/causality bounds based on the dispersion relations of Poincaré invariant scattering amplitudes that connect the EFT with (unspecified) UV completions that are unitary and causal [81, 82], which gives rise to bounds that are mostly independent of the EFT cutoff (See for example Refs. [83–104] for some recent developments along this direction and Ref. [80] for a review). In this work, we discuss the infrared causality constraints on sGB gravity by considering GWs and scalar waves scattering on BHs. We derive the master equations for the linear metric and scalar field perturbations, and manage to decouple them at the leading orders of EFT corrections. As we shall see, infrared causality can impose a lower bound on the EFT cutoff of sGB gravity, which strongly constrains the parameter space that is tested in the current and upcoming GW experiments. Yet, compared to the pure gravity case, we see that a detectable window opens up when the theory is endowed with an extra scalar degree of freedom. In this paper we shall work with natural units with $c = \hbar = 1$.

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Matrix moment approach to positivity bounds and UV reconstruction from IR

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Abstract: Positivity bounds in effective field theories (EFTs) can be extracted through the moment problem approach, utilizing well-established results from the mathematical literature. We generalize this formalism using the matrix moment approach to derive positivity bounds for theories with multiple field components. The sufficient conditions for obtaining optimal bounds are identified and applied to several example field theories, yielding results that match precisely the numerical bounds computed using other methods. The upper unitarity bounds can also be easily harnessed in the matrix case. Furthermore, the moment problem formulation also provides a means to reverse engineer the UV spectrum from the EFT coefficients, often uniquely, as explicitly demonstrated in examples such as string amplitudes and the *stu* kink theory.

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Non-topological solitons and quasi-solitons

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Solitons in relativistic field theories are not necessarily topologically charged. In particular, non-topological solitons—known as Q-balls—arise naturally in nonlinear field theories endowed with attractive interactions and internal symmetries. Even without stabilizing internal symmetries, quasi-solitons known as oscillons, which are long-lived, can also exist. Both Q-balls and oscillons have significant applications in cosmology and particle physics. This review is an updated account of the intriguing properties and dynamics of these non-topological solitons and quasi-solitons, as well as their important roles in early-universe scenarios and particle physics models.

CONTENTS

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I. INTRODUCTION AND SUMMARY

Following extensive and fruitful applications of the perturbative approach to quantum field theory, the quest for nonperturbative field-theoretical structures has gained significant traction since the 1960s. A multitude of solitons have been discovered in various relativistic field theories. These are typically localized, smooth solutions to the fully nonlinear field equations, exhibiting particle-like characteristics.

The study of solitons dates back at least to the investigations of solitary waves on shallow water surfaces by naval architect John Scott Russell in the early 1800s, who famously chased a solitary wave along a canal in Scotland. Despite being rebuked by the scientific establishment at the time, solitary waves were later shown by Korteweg and de Vries to be described by the celebrated KdV equation, building on earlier work by Boussinesq. General multi-solitary wave solutions were subsequently

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Exploring CP violation beyond the Standard Model and the PQ quality with electric dipole moments

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Abstract: In some models of physics beyond the Standard Model (SM), one of the leading low energy consequences of the model appears in the form of the chromo-electric dipole moments (CEDMs) of the gluons and light quarks. We examine if these CEDMs can be distinguished from the QCD θ-term through the experimentally measurable nuclear and atomic electric dipole moments (EDMs) in both cases with and without the Peccei-Quinn (PQ) mechanism solving the strong CP problem. We find that the nucleon EDMs show a distinctive pattern when the EDMs are dominantly induced by the light quark CEDMs without the PQ mechanism. In the presence of the PQ mechanism, the QCD θ-parameter corresponds to the vacuum value of the axion field, which might be induced either by CEDMs or by UV-originated PQ breaking other than the QCD anomaly, for instance the PQ breaking by quantum gravity effects. We find that in case with the PQ mechanism the nucleon EDMs have a similar pattern regardless of what is the dominant source of EDMs among the CEDMs and θ-term, unless there is a significant cancellation between the contributions from different sources. In contrast, some nuclei or atomic EDMs can have characteristic patterns significantly depending on the dominant source of EDMs, which may allow identifying the dominant source among the CEDMs and θ-term. Yet, discriminating the gluon CEDM from the QCD θ-parameter necessitates additional knowledge of low energy parameters induced by the gluon CEDM, which is not available at the moment. Our results imply that EDMs can reveal unambiguous sign of CEDMs while identifying the origin of the axion vacuum value, however it requires further knowledge of low energy parameters induced by the gluon CEDM.

Keywords: Axions and ALPs, CP Violation, Electric Dipole Moments, SMEFT

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Covariant quantum field theory of tachyons is unphysical

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Tachyons have fascinated generations of physicists due to their peculiar behavior, but they did not solve any real physical problem. This changed with the recent work of Dragan and Ekert, who have shown that superluminal observers may be related to the foundations of quantum mechanics (QM), since they require introducing non-determinism and wave-like behavior at the fundamental level. In fact, both classical and quantum field theory of tachyons have been constructed. Unfortunately, we will show that the latter theory contains several flaws, mostly caused by adapting incorrect results due to other authors, which puts the aforementioned program in question. In particular, unlike Feinberg, we show that tachyon microcausality violation spoils fundamental features of QFT such as statistical independence of distant measurements, and it negatively affects constructing Lorentz invariant scattering theory of tachyons. Moreover, the Feynman propagator, which was adapted from Dhar and Sudarshan, is shown to violate unitarity, the tachyonic vacuum is unstable due to radiatively generated tachyon self-interactions, and an interpolating tachyon field likely does not satisfy the LSZ asymptotic condition. Our analysis indicates that a covariant QFT of tachyons seems impossible, hence superluminal observers are unphysical and cannot be used to derive QM.

I. INTRODUCTION

Many works have investigated tachyons, superluminal particles characterized by a negative mass squared parameter, due to their peculiar behavior, *e.g.*, causality paradoxes or nondeterministic behavior; see the discussion and references given in Ref. [1]. The challenges facing consistent description of tachyons (*e.g.*, group theory precludes the democratic treatment of subluminal and superluminal observers [2]) have recently been overcome [3] at the cost of interpreting the 1+3 spacetime of a subluminal observer as a 3+1 spacetime of a superluminal observer (in particular, subluminal and superluminal observers are distinguishable). However, these two families of observers are still postulated to be equivalent in the sense of the "Quantum principle of relativity" (QPR).

A fascinating observation of Ref. [3] is that superluminal observers actually require the introduction of nondeterministic physics similar to QM, *e.g.*, a wave-like - instead of point-like - description of Nature using complex numbers. Moreover, it was shown that proper formulation of superluminal reference frames must invoke field theory, and both classical [4] and quantum [1] field theory (QFT) of tachyons have been developed. Since QFT is the most fundamental description of physical interactions, the *ultimate* test of such a program is to build a consistent covariant QFT of tachyons, which Ref. [1] has claimed to accomplish.

We note there are works that questioned the results of Ref. [3], *e.g.*, [5–7]. However, they used only classical relativity or non-relativistic QM, and each of them have obtained rather convincing replies [8–10], so the status of QPR is so far ambiguous. Therefore, it is worthwhile to explore both the relativistic and QM aspects of tachyons, which is the main goal of this paper.

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To achieve this, and to structure the discussion, we will answer the following questions. They are largely inspired, but, as we will discuss later, are not limited to the results of Ref. [1]. i) Is the formalism proposed in Ref. [1] consistent with the standard QFT framework based on relativistic covariance of fields, locality of interactions, and Lorentz invariance, unitarity and cluster decomposition property of the S matrix [11–13]? ii) Since tachyons satisfy the Bose statistics - a scalar field is the only finite irreducible unitary representation of the Poincare group for $m^2 < 0$ - which principle forbids its self-interactions, represented by cubic, quartic, etc. terms in its potential? Due to quantum fluctuations, such terms will modify the vacuum structure, *i.e.*, what protects the origin of the tachyon potential, corresponding to negative mass squared excitations, as the proper vacuum? iii) Is the reaction rate for the process of tachyon emission/absorption shown in Fig. 1 of Ref. [1] well-defined and consistent with the standard QFT?

These questions are particularly relevant because the celebrated Higgs mechanism of the electroweak symmetry breaking is based on the dynamics (condensation) of a scalar field with negative mass squared. In the conventional view, such state is an instability of the theory due to quantization around the origin of the scalar potential, which is a local maximum instead of the minimum. On the other hand, Ref. [1] has shown at tree level that by restricting the tachyon momentum to $|\vec{k}| > m$, and by extending the ordinary Fock space to the twin space, the tachyonic vacuum is in fact stable and Lorentz invariant (LI). Moreover, Ref. [14] proposed that emission of tachyons by massless particles may be relevant to the Higgs mechanism, which is otherwise an effective description whose deeper dynamics is currently unknown.

Therefore, the interest in QFT of tachyons is not only purely theoretical (QPR and foundations of QM), but also phenomenological. Unfortunately, we will show that the answers to the above questions are all negative. In

35. Stephen Angus

Perturbations in $\mathbf{O}(D,D)$ string cosmology from double field theory

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Abstract

The low-energy limit of string theory contains additional gravitational degrees of freedom, a skew-symmetric tensor B-field and a scalar dilaton, that are not present in general relativity. Together with the metric, these three fields are naturally embedded in the $\mathbf{O}(D,D)$-symmetric framework of double field theory. The $\mathbf{O}(D,D)$ symmetry uniquely prescribes the interactions between the extended gravitational sector and other matter, leading to novel features beyond conventional string cosmology. In this work we present the equations of motion for linear perturbations around $\mathbf{O}(D,D)$ string cosmological backgrounds in $D=4$ under a scalar-vector-tensor decomposition. We obtain analytic solutions in the superhorizon limit for scalar perturbations around various homogeneous and isotropic background solutions, including some candidate models for bouncing cosmologies. The generalized energy-momentum tensor includes source terms for the B-field and dilaton, and we show how the resulting generalized conservation laws modify the conditions for conservation of curvature perturbations.

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