December 2, 2025

Pre-reception

(1 min. per each person, very informal)

Motivation

- **Although the participants have brought many interesting research topics, it is not possible for us to include all of them in the program.**
- **Let's introduce own research briefly.**

1. Miok Park (IBS-CTPU-PTC)
2. Hong Guo (IBS-CTPU-PTC)
3. Chanyong Park (GIST)
4. Yun Soo Myung (CQUeST and Sogang U.)
5. Sojeong Cheong (CQUeST and Sogang U.)
6. Yoonbai Kim (Sungkyunkwan U.)
7. Sangmin Choi (U. of Amsterdam)
8. Hideki Maeda (Hokkai-Gakuen U.)
9. Robert Saskowski (Tianjin University)
10. O-Kab Kwon (Sungkyunkwan U.)
11. Wontae Kim (CQUeST and Sogang U.)
12. Mu-In Park (CQUeST and Sogang U.)
13. Hocheol Lee (Dongguk University)
14. Stephen Angus (CQUeST and Sogang U.)
15. SeungJun Jeon (Sungkyunkwan U.)
16. Kuan-Nan Lin (APCTP)
17. Bum-Hoon Lee (CQUeST and Sogang U.)
18. Gitae Kim (Hanyang U.)
19. Debangshu Mukherjee (POSTECH)
20. Theodoros Nakas (IBS-CTPU-CGA)
21. Kunal Pal (APCTP)
22. Masroor Pookkillath (CQUeST and Sogang U.)
23. Robert B. Mann (U. of Waterloo)
24. Sang-Jin Sin (Hanyang U.)

01. Miok Park (IBS-CTPU-PTC)

Rectifying no-hair theorems in Gauss-Bonnet theory

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We revisit the no-hair theorems in Einstein-Scalar-Gauss-Bonnet theory with a general coupling function between the scalar and the Gauss-Bonnet term in four dimensional spacetime. We first resolve the conflict caused from the incomplete derivation of the old no-hair theorem by taking into account the surface term and restore its reliability. We also clarify that the novel no-hair theorem is always evaded for regular black hole solutions without any restrictions as long as the regularity conditions are satisfied.

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I. INTRODUCTION

The uniqueness theorems [1,2] made us believe that black holes might have no hair except for the mass, electromagnetic charge or angular momentum. This motivated the assertion of the no-hair theorem [3–5] which proved the nonexistence of black hole solutions with nontrivial scalar field for asymptotically flat spacetime. The cases for the massive vector or spinor field were also discussed respectively in [6,7]. However the desire to find new black hole solutions led to the discovery of several kinds of nontrivial field such as colored black holes [8] or Skyrmion hair black holes [9]. More recently, the evasion of the no-hair theorem has been shown for Einstein theory with a Gauss-Bonnet (GB) term which couples to massless scalar fields [10–17]. These results were subsequently extended to consider self-interactions [18,19] or a cosmological constant [20].

The theory of general relativity with higher derivatives is well motivated. The early study arose in quantum field theory by finding that higher derivative terms stabilize the divergent structure of gravity and helps to establish a renormalizable theory of gravity in the absence of matter fields [21,22]. Inspired by this result, application to cosmology was initially investigated in [23] and later more broad construction of modifying Einstein gravity has been widely studied in many works (see [24] and references therein) which have increasing interest due the emergence of novel ways to test the high curvature limit of GR via gravitational waves [25,26] and black hole shadows [27,28]. Furthermore, from the perspective of string theory, taking the low energy limit, gravity theory is reduced to Einstein theory with higher derivative terms whose coefficient is α', the inverse string tension, and associated with the dilaton coupling. Therefore the α' correction is considered as the stringy effect beyond Einstein gravity. Moreover, the swampland conjecture asserts the "no global symmetry" in quantum gravity regimes and this is supported by the no-hair theorem [29,30]. These circumstances draw attention to the existence of black hole solutions in higher derivative theories.

In particular, the Gauss-Bonnet theory has a special interest since it is topological in four dimensions. The no-hair theorems for Einstein-Scalar-Gauss-Bonnet theory (ESGB) are argued in [13] but their analysis was not complete both for the old no-hair theorem as well as the novel version of the theorem as follows.

First, the old no-hair theorem for ESGB theory in [10,13] showed the positive definite coupling $f(\varphi) > 0$ as a necessary requirement for the evasion of the old no-hair theorem. However the evasion of the old no-hair theorem was also found for $f(\varphi) < 0$ in [31], which is contrary to the previous studies. One might think that there is a privileged manner to validate the evasion of the old no-hair theorem, but then the theorem loses its universal power. This situation has caused suspicion on the reliability of the old no-hair theorem. Here we resolve this issue by giving a correct treatment of a surface term and restore the reliability of the old no-hair theorem. Indeed, this situation differs from the original work of Bekenstein [4], where the surface term vanishes because either the field is massive and therefore enjoys a Yukawa-like, exponential decay, or the field is massless and the theory is shift symmetric. In the latter case, the surface term is unphysical since it can always be canceled by a field shift which leaves the Lagrangian invariant. On the other hand, in ESGB theory with a massless scalar field, the surface term survives in

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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.

02. Hong Guo (IBS-CTPU-PTC)

Novel black holes with scalar hair in the Einstein-Maxwell-scalar theory with positive coupling

PDF

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Hong Guo[1,*], Wei-Liang Qian[1,2,3,†], and Bean Wang[4]

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Abstract

In this work, we find a new branch of hairy black hole solutions in the Einstein-Maxwell-scalar theory in four-dimensional asymptotically flat spacetimes. Different from spontaneous scalarization induced by tachyonic instabilities in Reissner-Nordström (RN) black holes with a negative coupling parameter, these scalar-hairy black hole solutions arise when the coupling parameter is positive, where nonlinear coupling plays the dominant role, meaning that the coupling is positively correlated with the degree of deviation from the trivial state. Our numerical analysis reveals that the scalar field grows monotonically with the radial coordinate and asymptotically approaches a finite constant, exhibiting behavior that is qualitatively similar to that of the Maxwell potential. In these solutions, an increase in the charge q causes the scalar-hairy solutions to deviate further from the RN state, while excessive charging drives the system back toward hairless solutions. Strengthening the coupling parameter compresses the existence domain of the scalar-hairy state, which lies entirely within the parameter region of RN black holes. Moreover, by evaluating the quasinormal modes, we show that the obtained scalar-hairy solutions are stable against linearized scalar perturbations.

Parameter constraints on Horndeski rotating black hole through quasiperiodic oscillations

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In this paper, we perform small perturbations around the circular timelike orbit in the equatorial plane of the Horndeski rotating black hole, and analyze the effects of Horndeski hair on the three fundamental frequencies of the epicyclic oscillations. Since this operation can model the quasiperiodic oscillations (QPOs) phenomena of the surrounding accretion disc, we then employ the MCMC simulation to fit the theoretical results with three QPO events, including GRO J1655-40, XTE J1859+226 and H1743-322, and constrain the characteristic radius r, black hole mass M and spinning parameter a, and the Horndeski hair parameter h. Our constraint on the Horndeski hair parameter is much tighter than QPOs simulation from the existed accretion models, suggesting slight deviation from classical Kerr black hole.

Contents

CTPU-PTC-25-34

Negative potential-induced scalarization in the Einstein-Euler-Heisenberg black hole

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Abstract

We investigate a negative potential-induced scalarization of the Einstein-Euler-Heisenberg (EEH) black hole in the EEH-scalar (EEHS) theory, characterized by mass M, Euler–Heisenberg parameter μ, and magnetic charge q. Within this framework, the charge q can exceed the extremal bound $q/M > 1$, and a single event horizon is maintained provided the parameter μ exceeds the $\mu_{\max} = 0.019$, with the ADM mass fixed at $M = 1/2$. We obtain a single branch of scalarized EEH (sEEH) black holes for $q > 0$ which is considered as the simplest model for scalarization of EEH black holes. We found that this class of hairy black holes is not thermodynamically favored, and their quasinormal modes indicate they are dynamically unstable. An interesting feature is that when $q < 1/2$, the scalar charge varies only slightly with q for a fixed mass. In contrast, for $q > 1/2$, the scalar charge increases more rapidly as q increases. This distinct behavior suggests that the scalar charge exhibits the characteristics of a primary charge for $q < 1/2$, and of a secondary charge for $q > 1/2$. This finding reveals notable features of hairy black holes in EEH theory, specifically in the overcharging regime.

A Critical Point on the Hairy Black Hole Phase Boundary in the Improved Holographic Einstein-Maxwell-Dilaton Theory

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Abstract

In this work, we investigate the hairy black hole solutions and their dual phase diagram in the improved holographic Einstein–Maxwell–Dilaton (EMD) model. From the gravitational perspective, the rich phase structures observed in the dual boundary field theory originate from the intricate interplay between the scalar field formalism and the Maxwell field coupling mechanism. Two distinct types of hairy black hole solutions are found in this framework. Type-I hairy black holes are predominantly governed by scalar potential dynamics, whereas Type-II solutions emerge through nonminimal coupling to the $U(1)$ gauge field. We map out the phase distribution in the (μ_B, T) parameter plane and delineate the boundary separating these two hairy phases. The phase diagram exhibits a first-order phase transition line consistent with previous findings, accompanied by a subtle third-order phase transition line that terminates at a critical point positioned at the turning point of the entire phase boundary curve. Our results complement existing research on holographic EMD theory by offering a comprehensive characterization of phase distributions, transition boundaries, and their gravitational sector interpretations. These insights will enable more effective engineering of specific phase structures for simulating strongly coupled systems through targeted modifications to the EMD model.

Using precession and Lense-Thirring effect to constrain a rotating regular black hole

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In this paper, we investigate the frame-dragging effect on an accretion disk and test gyroscope orbiting around a rotating regular black hole with a Minkowski core. Firstly, we perturb a bound time-like circular orbit around the black hole, and analyze the periastron precession and Lense-Thirring (LT) precession frequencies of the orbit's epicyclic oscillations. Since these epicyclic oscillations can be used to explain the quasiperiodic oscillations (QPOs) phenomena of the accretion disc around this rotating regular black hole, we then employ the Markov Chain Monte Carlo (MCMC) simulation to fit our theoretical results with five QPOs events (GRO J1655-40, GRS 1915+105, XTE J1859+226, H1743-322 and XTE J1550-564). The simulations give the relevant physical parameter space of the black hole, including the characteristic radius r, the mass related parameter M, the spinning parameter a and the quantum gravity effect α. The results give the constraint on the quantum effect parameter, with an upper limit $\alpha/M^{3/2} < 0.60$ at the 95% C.L., which is tighter than < 0.7014 in our pervious study within static case. Then, we theoretically explore the LT precession frequency, geodetic precession frequency, and the general spin precession frequency of a test gyro attached to a stationary observer in this black hole background. We find that the quantum gravity effect suppresses the precession frequencies comparing against those in Kerr black hole, further providing a theoretical diagnostic of the potential quantum gravity effect.

03. Chanyong Park (GIST)

April 15, 2025

Asymmetric RG flow to lower-dimensional effective theories

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ABSTRACT

We investigate an asymmetric RG flow from a d-dimensional UV CFT to a lower-dimensional IR CFT. The asymptotic geometry of a $(d+1)$-dimensional AdS charged black hole is given by a $(d+1)$-dimensional AdS space while its near horizon geometry is reduced to $\text{AdS}_2 \times \Sigma_{d-1}$. According to the AdS/CFT correspondence, the dual field theory describes an RG flow from a d-dimensional CFT to IR QFT defined in $R_t \times \Sigma_{d-1}$. We show that one-dimensional conformal quantum mechanics can effectively describe the IR QFT due to the rapid suppression of the correlation in the Σ_{d-1} sector. In this case, the IR conformal dimension crucially relies on the blackening factor, which on the dual QFT side is associated with the matter's density. We further study an asymmetric RG flow from a four-dimensional UV CFT to a two-dimensional IR CFT by turning on an external magnetic field, which leads to a localization in the directions perpendicular to the magnetic field.

04. Yun Soo Myung (CQUeST and Sogang U.)

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Thermodynamic analysis and shadow bound of black holes surrounded by a dark matter halo

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Abstract We perform the thermodynamic analysis of a black hole (BH) immersed in a dark matter halo (DMH). It is shown that the BH could not be in thermal equilibrium with the DMH in any regions outside the event horizon. This means that the thermodynamic influence of the environment (DMH) is relatively small on the BH. Importantly, it does not alter the nature of the negative heat capacity for the BH. We stress that the Newtonian ($1/a_0$) approximation gives us a correct thermodynamic description for the BH surrounded by DMH because the first law of thermodynamics and Smarr formula are satisfied. Hence, the Newtonian Helmholtz free energy is employed to reveal that there is the absence of phase transition to other BH with a positive heat capacity. Finally, we investigate the shadow bound of favored region for the BH immersed in the DMH by comparing EHT observations.

1 Introduction

It is known that supermassive black holes founded at the center of galaxies have played an important role in galaxy formation and galaxy evolution. The ground breaking results of the Event horizon Telescope (EHT) collaboration have shed bright light on a new era of black hole (BH) observations.

Shadows and strong gravitational lensing was discussed in [1] and analytic study on the shadow including Ref. [2] was reviewed in [3]. In addition, the shadows of magnetically charged black holes from non-linear electrodynamics [4], rotating regular black holes [5], non-rotating Kerr black hole [6], BHs in the presence of plasma [7,8], BH surrounded by dark matter [9], and BHs and naked singularities [10] were studied.

Especially, the images of the M87* BH [11–13] have inspired many studies on the BH shadow to test modified gravity theories. Recently, the EHT results have focussed on the center of our galaxy and revealed interesting images of the SgrA* BH [14–16]. In this direction, the shadow of BH with scalar hair was used to test the EHT results [17], while the shadows of other BHs, worm holes, and naked singularities found from modified gravity theories have been employed to constrain their parameters [18].

It is believed that astrophysical BHs are not isolated objects in the universe. In addition to their accretion disks, they are immersed in the dark matter halo (DMH) which engulfs the whole galaxy [19]. The authors of [20] have suggested an interesting model of how to embed a BH into a DMH by introducing a Hernquist-type density distribution that are observed in bulges and elliptical galaxies [21]. That is, a combined geometry of the BH with the DMH came as a solution to the Einstein theory coupled to an anisotropic fluid with $T_\mu{}^\nu = \text{diag}(-\rho, 0, p_t, p_t)$ where the mass (energy) density ρ includes the Hernquist-type distribution. A lot of recent studies on this and related models are found in [22–32]. Most of related works have included the computation of quasinormal modes for BHs surrounded by DMH, whereas the effects of dark matter on the shadow of BHs were discussed recently in [33–35]. Further, it is necessary to understand how this combined geometry differs from others including a BH. It is suggested that the effect of dark matter on the shadow of a BH is similar to the effect of a constant scalar hair existing outside the event horizon on the shadow of a BH [17,36], even though their equations of state are different.

In this work, we will study a key feature, thermodynamics, and shadow bound of a BH with mass M_b immersed in the DMH with mass M and galaxy length-scale a_0. Here, we may consider an astrophysically relevant regime of $M_b \ll M \ll a_0$ [37]. A key feature of the solution appeared in [20] is the presence of the redshift factor $e^{\Upsilon(r)}$ in the lapse function $f(r)$ when comparing with other black hole solutions. We clarify that it has arisen from the mass

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Shadow radius and classical scattering analysis of two secondary hair Horndeski black holes

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Received: 11 April 2025 / Accepted: 27 August 2025

Abstract We perform the shadow radius analysis of a charged Horndeski black hole (CHB) and the naked singularity (NS) with secondary scalar hair obtained from the Einstein-Horndeski-Maxwell theory. For this analysis, we include the beyond Horndeski black hole (bH) with secondary scalar hair and the magnetically charged black hole (MC) found from the Einstein-Euler-Heisenberg theory. It is worth noting that the NS versions of CHB and bH arise from the charge extension of their photon spheres, while there is no NS version for MC. One branch (i) from the CHB is a point in the horizon realization but it shows up on the photon sphere and shadow radius. The shadow radius for the CHB is the nearly same as that for the MC with a single horizon and the charge of the NS is constrained by the EHT observation. From classical scattering analysis, it turns out that i-NS and NS play different roles from CHB, bH, and MC.

1 Introduction

It is strongly suggested that supermassive black holes founded at the center of galaxies have played the important role in galaxy formation and galaxy evolution. The images of the M87* BH [1–3] have inspired enormous studies on the BH. The recent EHT observation has concentrated on the center of our galaxy and delivered promising images of the SgrA* BH [4–6]. The BH images showed that a dark central region is surrounded by a bright ring called shadow cast and photon ring of the BH, respectively. The size of the shadow corresponds to the photon sphere size additionally increased by bending of light rays, amounting to the size of the photon ring. The shadow of BH with scalar hair was used to test the EHT results [7], while the shadows of other BHs, wormholes, and naked singularities obtained from modified gravity theories have been selected to constrain their hair parameters [8].

Horndeski gravity [9] was regarded as the most general scalar-tensor theory of gravitation in four dimensional spacetime, yielding second-order field equations without ghosts. Among many kinds of Horndeski gravity, an important thing is to include the nonminimal derivative coupling between scalar and Einstein tensor. Various black hole solutions were found from this gravity [10–13]. An interesting black hole obtained from the Einstein–Horndeski–Maxwell (EHM) theory is the charged Horndeski black hole (CHB) with electric charge q ∈[0,1.06] [14,15], which implies the presence of the secondary scalar hair $\phi(r)$ and the existence of the naked singularity (NS) for $q \in (1.06, \infty)$ [16].

At this stage, we wish to distinguish between primary and secondary scalar hairs. A primary scalar hair contains an independent scalar charge, but a secondary scalar hair does not involve any independent scalar charge. Furthermore, recent achievements have allowed for the beyond Horndeski gravities [17–21]. The BH solutions with primary scalar hair have derived from the shift and parity-symmetric subclass of beyond Horndeski gravities [22–24]. On later, the regular (Bardeen) BH solution was found from the this theory [25]. We wish to call it the beyond Horndeski black hole (bH) with secondary scalar hair.

In this work, we wish to perform the shadow radius analysis of CHB, NS, and bH. The shadow radius analysis for CHB was recently done in [26], but this analysis is incomplete in the sense that it includes the single horizon $r_+(M = 1, Q)$ and single photon sphere radius $r_{ph}(1, Q)$ for $Q < 1$. Here, the electric charge $q \in [0, 1.06)$-range is allowed for the CHB, the i-NS appears at $q = 1.06$, and the $q \in (1.06, \infty)$-range is allocated for the NS by considering three horizons $r_1(m = 1, q)$, $r_2(1, q)$, $r_i(1, q)$ and three photon sphere radii $L_1(1, q)$, $L_2(1, q)$, $L_i(1, q)$.

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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Scalarizations of qOS-extremal black hole and Aretakis instability

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Received: 1 October 2025 / Accepted: 10 November 2025

Abstract We study scalarization of quantum Oppenheimer–Snyder (qOS)-extremal black hole in the Einstein–Gauss–Bonnet-scalar theory. This black hole is described by mass ($M = 4\sqrt{\alpha}/3\sqrt{3}$) with α quantum parameter. Investigating the onset of scalarization, we find the appearance of the single branch of scalarized qOS-extremal black holes. To obtain the tachyonic scalar cloud being a seed to generate the single branch of scalarized qOS-extremal black holes, we consider the near-horizon geometry of the Bertotti–Bobinson (BR) spacetime. In this case, it is shown that the appearance of a large scalar cloud at the horizon ($\rho = 0$) is a new feature to represent onset scalarization of extremal black holes for tachyon with negative mass. However, it is not related to the Aretakis instability of a propagating scalar with standard mass around the BR spacetime, showing polynomial instability of the ingoing time v. The Aretakis instability is connected to the scalar cloud with standard mass, indicating the blow-up at the horizon.

1 Introduction

The quantum Oppenheimer–Snyder (qOS)-black hole was recently found from investigating the qOS gravitational collapse within the loop quantum cosmology [1]. However, one does not know its action $\mathcal{L}_{\rm qOS}$ to give the qOS-black hole described by mass (M) and quantum parameter (α) as a direct solution. Various studies of this black hole included quasinormal mode analysis for tensor and scalar perturbations [2], thermodynamics [3–5], shadow radius [6,7], and scalarization within the Einstein–Gauss–Bonnet-scalar (EGBS) theory [8,9].

On the other hand, extremal black holes have played an important role in various aspects. They possess zero Hawking temperature and zero heat capacity and thus, are expected to bring us valuable insights into black hole thermodynamics [10] and Hawking radiation [11]. In the astrophysics, it was proposed that many astrophysical black holes are nearly extremal [12,13]. To understand the nature of extremal black holes, it is valuable to study the dynamical properties of test fields and particles propagating around them. In this direction, Aretakis [14] has discussed late-time behaviors of massless scalars in the extremal Reissner–Nordström (RN) black holes, leading to that higher-order transverse derivatives of the scalar fields blow up polynomially in the ingoing time v on the event horizon. This blow-up on the horizon is called the Aretakis instability. In the near-horizon approximation, the leading behavior of a massive scalar was described by power-law tails, showing the Aretakis instability too [15,16].

The no-hair theorem implies that a black hole can be completely described by three observable parameters: mass (M), electric charge (Q), and rotation parameter (a) in Einstein-Maxwell gravity [17,18]. If a scalar field is minimally coupled to gravitational and electromagnetic fields, there is no scalar hair [19]. However, its evasion occurred in the context of scalar-tensor theories with the nonminimal scalar coupling either to Gauss-Bonnet (GB) term [20–22] or to Maxwell term [23,24], where the former is called GB$^+$ scalarization with a positive coupling parameter triggered by tachyonic instability. For review on spontaneous scalarization, see Ref. [25].

The spin-induced (GB$^-$) scalarization of Kerr black holes with rotation parameter a was demonstrated for $a_c(= 0.5) < a \leq 1$ in the EGBS theory with a negative coupling parameter [26–30]. In this direction, we would like to mention that GB$^-$ scalarization was realized for a very narrow region of $q_c(= 0.9571) < q \leq 1$ with $q = Q/M$ in the Einstein–Gauss–Bonnet–Maxwell-scalar (EGBMS) theory [31,35,36]. Here, the charge Q played a role of the rotation parameter a. Also, we note that the quantum parameter (α)-mass (M) induced scalarization (GB$^-$) was studied

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05. Sojeong Cheong (CQUeST and Sogang U.)

Einstein ring of dust shells with quantum hair

Sojeong Cheong, Wontae Kim and Mungon Nam

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Authors

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Abstract

The information about the internal structure of a compact object is classically inaccessible to external observers. In this paper, we investigate how quantum corrections to gravitational fields can reveal the internal structure of compact objects composed of dust shells. Using an effective field theory approach to incorporate quantum corrections up to second order in curvature, we derive a quantum-corrected metric for N uniformly spaced shells with equal surface mass density and then examine how these corrections manifest in the deflection angle for gravitational lensing. In particular, we mainly investigate quantum-corrected astrophysical observables such as the Einstein ring and image magnification. Compared to the classical scenario, the deflection angle and the corresponding Einstein angle differ by a term that depends explicitly on the number of dust shells, which play the role of quantum hair. Specifically, the quantum correction to them diminishes as N increases, yet a finite deviation from the classical result remains even in the continuum limit $N \longrightarrow \infty$. Consequently, our results show that the internal structures of compact objects with identical iPhone I and radius can be distinguished by quantum hair through their lensing observables.

Strong gravitational lensing effects of black holes with quantum hair

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(Dated: August 12, 2025)

Abstract

According to the no-hair theorem, stationary black holes are uniquely characterized by their mass, charge, and angular momentum. In this paper, we explore quantum hair by deriving the quantum-corrected black hole metric within the Barvinsky-Vilkovisky formalism. The quantum-corrected metric is obtained perturbatively around flat spacetime without assuming either the commutativity between the nonlocal operator and covariant derivatives or the nonlocal Gauss-Bonnet theorem, both of which are adopted in previous studies. Using this metric, we evaluate the deflection angle in the strong-field limit and compute the associated strong gravitational lensing observables, such as the angular separation and the relative magnification. Our results show that as the quantum hair, determined by the number of virtual massless quantum fields in the nonlocal effective action, increases, the photon sphere radius, the strong deflection angle, and the relative magnification all increase, whereas the angular separation decreases. In addition, the role of quantum hair is discussed in the weak and strong naked singularities. As a result, we demonstrate that the quantum hair affects not only the black hole geometry but also its strong gravitational lensing effects.

Keywords: Models of quantum gravity, effective field theory, quantum hair, black holes, gravitational lensing

06. Yoonbai Kim (Sungkyunkwan U.)

Effect of Impurity on Inhomogeneous Vacuum and Interacting Vortices

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Abstract

We study the inhomogeneous abelian Higgs model with a magnetic impurity. The vacuum configuration of the symmetry-broken phase is not simply the constant Higgs vacuum but is a nontrivial function of spatial coordinates, satisfying the Euler-Lagrange equations. The vacuum of zero winding number has zero magnetic flux but its non-zero magnetic field depends on spatial coordinates. The corresponding vacuum energy is negative for weak coupling ($\lambda < 1$), zero for critical BPS coupling ($\lambda = 1$), and positive for strong coupling ($\lambda > 1$) by an over-, exact-, and under-cancellation of the huge positive impurity energy. This distinct vacuum energies are consistent with classification of the type I and Ⅱ superconductivity in dirty conventional superconductors. Non-BPS vortex configurations are also obtained in the presence of inhomogeneity. Their rest energies favor energetically vortex-impurity composite in conventional type Ⅱ superconductivity, consistent with imperfect diamagnetism. The delta function limit of Gaussian type impurity suggests the formation of vortex-lattice composite which elucidates flux-pinning in the context of inhomogeneous field theory.

Field Theory of Superconductor and Charged Vortex

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Abstract

A Lagrangian of a Schrödinger type complex scalar field of Cooper pair, a U(1) gauge field of electromagnetism, and a neutral scalar field of acoustic phonon with constant background charge density is proposed for an effective field theory of conventional superconductivity. We find static charged vortex solutions of finite energy and, for the critical couplings of the quartic self-interaction coupling of complex scalar field and the cubic Yukawa type coupling between neutral and complex scalar field, these charged vortices saturate the BPS (Bogomolny-Prasad-Sommerfield) bound, that guarantees the nonperturbative classification of type I and II superconductors.

07. Sangmin Choi (U. of Amsterdam)

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The classical super-rotation infrared triangle. Classical logarithmic soft theorem as conservation law in gravity

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Abstract: The universality of gravitational scattering at low energies and large distances encoded in soft theorems and memory effects can be understood from symmetries. In four-dimensional asymptotically flat spacetimes the infinite enhancement of translations, extending the Poincaré group to the BMS group, is the symmetry underlying Weinberg's soft graviton theorem and the gravitational displacement memory effect. Beyond this leading infrared triangle, loop corrections alter their nature by introducing logarithms in the soft expansion and late time tails to the memory, and this persists in the classical limit. In this work we give the first complete description of an 'infrared triangle' where the long-range nature of gravitational interactions is accounted for. Building on earlier results [1] where we derived a novel conservation law associated to the infinite dimensional enhancement of Lorentz transformations to superrotations, we prove here its validity to all orders in the gravitational coupling and show that it implies the classical logarithmic soft graviton theorem of Saha-Sahoo-Sen [2]. We furthermore extend the formula for the displacement memory and its tail from particles to fields, thus completing the classical superrotation infrared triangle.

Keywords: Gauge Symmetry, Scattering Amplitudes, Space-Time Symmetries

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The classical super-phaserotation infrared triangle. Classical logarithmic soft theorem as conservation law in (scalar) QED

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Abstract: The universality of the logarithmic soft photon theorem in four dimensions can be traced to an infinite-dimensional asymptotic symmetry which acts as a local phase rotation on matter as we have shown in [1]. Here we extend our earlier results for the charges associated to these superphaserotations to all orders in the coupling and prove that their conservation is exactly the classical logarithmic soft photon theorem discovered by Saha, Sahoo and Sen [2]. We furthermore generalize the formulae for the associated electromagnetic displacement memory and its tail from particles to scalar matter fields. This completes the classical superphaserotation infrared triangle.

Keywords: Gauge Symmetry, Scattering Amplitudes

ArXiv ePrint: 2412.16149

Gravitational Entropy

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Abstract: We formulate the classical gravitational entropy of a horizon as a Noether charge that does not require the notion of a temperature, and which is applicable to horizons that are not necessarily associated with black holes. This introduces a correction to the covariant phase space formalism that accounts for the configuration-dependence of the generating vector field conjugate to the charge. The vector field is related to the proposal of Bousso that the gravitational entropy of a region is determined by the lightsheet at its boundary. We test the formula on various black hole and cosmological horizons.

08. Hideki Maeda (Hokkai-Gakuen U.)

Fake Schwarzschild and Kerr black holes

Hideki Maeda

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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. Because it contradicts the conservation theorem, this configuration of black holes is, in fact, precluded by the dominant energy condition.

Planar black holes and wormholes with a flat exterior

PDF

Hideki Maeda [1,*] and Cristián Martínez [2,3,†]

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Phys. Rev. D **112**, 084035 – **Published 15 October, 2025**

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Abstract

We present $n(\geq 4)$-dimensional planar black holes and wormholes with a *flat* exterior, which are originated by an exact solution in general relativity. The nonvacuum regions of these objects are described by the extended dynamical region inside a nondegenerate Killing horizon of Gamboa's static plane symmetric solution with a perfect fluid obeying a linear equation of state $p = \chi\rho$ for $\chi \in [-1/3, 0)$. The matter field inside the horizon is not a perfect fluid but an anisotropic fluid that may be interpreted as a *spacelike* (tachyonic) perfect fluid. While it satisfies the null and strong energy conditions in the black hole case, it violates all the standard energy conditions in the wormhole case. The metric on the horizon is not analytic but at least $C^{1,1}$ in the single-null coordinates in both cases, so it is regular and there is no lightlike massive thin shell on the horizon.

Exact plane symmetric black bounce with a perfect-fluid exterior obeying a linear equation of state

Hideki Maeda [1,*] and Cristián Martínez [2,3,†]

Show more

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Abstract

We investigate an exact two-parameter family of plane symmetric solutions admitting a hypersurface-orthogonal Killing vector in general relativity with a perfect fluid obeying a linear equation of state $p = \chi\rho$ in $n(\geq 4)$ dimensions obtained by Gamboa in 2012. The Gamboa solution is identical to the topological Schwarzschild–Tangherlini–(anti–)de Sitter Λ-vacuum solution for $\chi = -1$ and admits a nondegenerate Killing horizon only for $\chi = -1$ and $\chi \in [-1/3, 0)$. We identify all possible regular attachments of two Gamboa solutions for $\chi \in [-1/3, 0)$ at the Killing horizon without a lightlike thin shell, where χ may have different values on each side of the horizon. We also present the maximal extension of the static and asymptotically topological Schwarzschild-Tangherlini Gamboa solution, realized only for $\chi \in (-(n-3)/(3n-5), 0)$, under the assumption that the value of χ is unchanged in the extended dynamical region beyond the horizon. The maximally extended spacetime describes either (i) a globally regular black bounce whose Killing horizon coincides with a bounce null hypersurface or (ii) a black hole with a spacelike curvature singularity inside the horizon. The matter field inside the horizon is not a perfect fluid but rather an anisotropic fluid that can be interpreted as a spacelike (tachyonic perfect fluid. A fine-tuning of the parameters is unnecessary for the black bounce, but the null energy condition

09. Robert Saskowski (Tianjin University)

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Multicenter higher-derivative BPS black holes

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Abstract: We consider the reduction of four-derivative heterotic supergravity on a torus and construct two-charge multicenter BPS black hole solutions. In $d = 5$, the three-form field can be dualized to a gauge field and we correspondingly construct three-charge multicenter BPS black hole solutions to the dualized Bergshoeff-de Roo action. This makes precise the embedding of known solutions into five-dimensional α'-corrected STU supergravity.

Keywords: Black Holes in String Theory, Supergravity Models

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Remarks on nonperturbative perturbations

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Abstract: We consider the linearized perturbations of near-horizon extremal Reissner-Nordström black holes in d-dimensional Einstein-Maxwell-Gauss-Bonnet gravity and seven-dimensional third-order Lovelock gravity. We find the solutions for the gravitational perturbations as a function of the higher-derivative coupling coefficients, which we treat nonperturbatively. Consequently, we observe a breakdown in perturbation theory for large harmonics for the six-derivative corrections.

Keywords: Black Holes, Classical Theories of Gravity

ArXiv ePrint: 2503.06005

USTC-ICTS/PCFT-25-23

Higher-derivative Heterotic Kerr-Sen Black Holes

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(Dated: October 28, 2025)

Abstract

We obtain the four-derivative corrections to the Kerr-Sen solution in heterotic supergravity, which includes the Gibbons-Maeda-Garfinkle-Horowitz-Strominger solution as a limiting case. In particular, we first embed the Kerr solution into heterotic supergravity and compute the higher-derivative corrections. We then obtain the corrections to the Kerr-Sen solution by performing an $O(2,1)$ boost of the Kerr solution, which, in contrast to the two-derivative case, requires field redefinitions to make the $O(2,1)$ invariance of the action manifest. Finally, we compute the multipole moments and find that they are distinct from those of the Kerr solution at the four-derivative level. We also find that the multipole moments are distinct from those of the Kerr-Newman solution in Einstein-Maxwell theory at the four-derivative level, even for the most general choice of four-derivative corrections. This gives a way to experimentally distinguish traces of string theory in gravitational wave data.

USTC-ICTS/PCFT-25-34

Consistent Four-derivative Heterotic Truncations and the Kerr-Sen Solution

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(Dated: September 10, 2025)

Abstract

Four-derivative heterotic supergravity (without gauge fields) reduced on a p-dimensional torus leads to half-maximal supergravity coupled to p vector multiplets, and it is known that removing the vector multiplets is a consistent truncation of the theory. We find a new consistent truncation of four-derivative heterotic supergravity on a torus that keeps the vector multiplets and precisely reproduces the bosonic action of heterotic supergravity (with heterotic gauge fields). We show that both truncations have an $O(d+p,d)$ symmetry when reduced on a d-dimensional torus and demonstrate how this embeds in the $O(d+p,d+p)$ symmetry that one gets from reducing on a $(d+p)$-dimensional torus without truncation. We then use our new truncation to obtain four-derivative corrections to the Kerr-Sen solution and compute thermodynamic quantities and multipole moments. Finally, we compare the Kerr-Sen solutions of the actions corresponding to the two different choices of truncation with the Kerr solution, the Kerr-Newman solution, and each other, and show that they have distinct four-derivative multipole structures.

10. O-Kab Kwon (Sungkyunkwan U.)

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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 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. We also discuss the case of a delta-function impurity as the infinitely thin limit of the Gaussian impurity which shows some nontrivial feature of BPS Chern-Simons Higgs theory.

Keywords: Chern-Simons Theories, Field Theories in Lower Dimensions, Solitons Monopoles and Instantons

ArXiv ePrint: 2409.11978

Vacuum and vortices in the inhomogeneous Abelian Higgs model

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The inhomogeneous Abelian Higgs model with a magnetic impurity in the Bogomolny-Prasad-Sommerfield (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 a minimum value depending on strength of the impurity but possesses a broken phase at a spatial asymptote. The vacuum configuration of a 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.

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I. INTRODUCTION

Field theories have been regarded as a most suitable tool for describing the fundamental forces in the microscopic level. On the other hand, samples in real experiments involve diversified impurities, defects, disorders, etc., by doping, imperfect growth of samples, junctions of heterogeneous materials, etc. Hence, a field theoretic description of these samples immediately encounters difficulty in analytic treatment, and an adequate guideline is necessary. Since the majority of field theories consists of the fields and constant parameters such as masses and couplings at least at the textbook level, an available and simple window is to allow inhomogeneity or spatial dependence, in one or a few parameters. Then the field theories with these additional ingredients become complicated as usual, and another controllable guideline is indispensable for tractability. A familiar option in field theories is supersymmetry. Even if a part of spacetime symmetries, the Poincaré symmetry or the Galilean symmetry, is explicitly broken by the presence of inhomogeneity, a reduced number of supersymmetries are known to survive. These so-called inhomogeneous field theories have begun with the name of Janus in supersymmetric and nonsupersymmetric field theories under the supervision of holography [1–6]. Then, the mass-deformed Aharony-Bergman-Jefferis-Maldacena (ABJM) theory in three dimensions and super Yang-Mills theory in three and four dimensions can allow inhomogeneous mass deformations in relation to the irregular form fields on the branes, preserving the same amount of supersymmetries [7–10]. Solitonic excitations, kinks, are explored in two-dimensional supersymmetric theories, including impurities [11–17], and then general form of the superpotential with spatial dependence for a single scalar field is identified, and the corresponding general solutions of the Bogomolny equation is obtained [18]. It has also been reported that, at the classical level, there is a one-to-one correspondence between supersymmetric inhomogeneous field theories in $(1+1)$ dimensions and supersymmetric field theories on a specific curved background metric [19]. In relation with electromagnetism, inhomogeneous supersymmetric Abelian gauge theories, including electric and magnetic impurities, have been considered in three and four dimensions, and the effect of impurities on point charges and vortices are studied, including vortex dynamics [20–22].

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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.

Keywords: Effective Field Theories, 2D Gravity, Supersymmetric Effective Theories, Phase Transitions in the Early Universe

ArXiv ePrint: 2410.24011

11. Wontae Kim (CQUeST and Sogang U.)

Gravitational constant as a conserved charge in black hole thermodynamics

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(Dated: September 11, 2025)

Abstract

Recent work has demonstrated that coupling constants in a given action can be promoted to the role of conserved charges. This is achieved by introducing pairs of field variables constructed from combinations of scalar and gauge fields. This framework naturally suggests that the gravitational constant itself can be interpreted as a conserved charge, arising from an associated gauge symmetry. In a modified four-dimensional Einstein-Hilbert action, we explicitly show that the gravitational constant, in addition to the mass and the cosmological constant, emerges as a conserved charge. Our derivation, which employs the quasi-local off-shell ADT formalism, yields a result that is fully consistent with the extended thermodynamic first law and the Smarr formula.

Keywords: Black Holes, Models of Quantum Gravity, Conserved Charges, Symmetries

12. Mu-In Park (CQUeST and Sogang U.)

Chronology Protection of Rotating Black Holes in a Viable Lorentz-Violating Gravity

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(Dated: November 26, 2025)

Abstract

We study causal properties of the recently found rotating black-hole solution in the low-energy sector of Hořava gravity as a viable Lorentz-violating (LV) gravity in four dimensions with the LV Maxwell field and a cosmological constant $\Lambda(> -3/a^2)$ for an arbitrary rotation parameter a. The region of non-trivial causality violation containing closed timelike curves is exactly the same as in the Kerr-Newman or the Kerr-Newman-(Anti-)de Sitter solution. Nevertheless, chronology is protected in the new rotating black hole because the causality violating region becomes physically inaccessible by exterior observers due to the new *three*-curvature singularity at its boundary that is topologically two-torus including the usual ring singularity at $(r, \theta) = (0, \pi/2)$. As a consequence, the physically accessible region outside the torus singularity is causal everywhere.

Keywords: Chronology protection, Rotating black-hole solutions, Lorentz violations, Horava gravity

13. Hocheol Lee (Dongguk University)

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Letter

Traversable wormhole for string, but not for particle

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ABSTRACT

We propose a Lorentzian wormhole geometry characterized by a closed string massless sector with nontrivial H-flux and a scalar dilaton. In the string frame, the dilaton exhibits a negative kinetic term, enabling the existence of the wormhole. The geometry consists of three distinct regions. The middle region contains the throat, and its boundaries with the other two regions form non-Riemannian two-spheres, where a fundamental string becomes chiral, akin to a non-relativistic string. While point-particle geodesics are complete within each region and non-traversable across regions, strings perceive the geometry differently, allowing a chiral string to traverse freely.

Chiral strings are fundamental constituents of string theory. In flat spacetime, an ordinary string arises as a superposition of chiral (worldsheet-wise left-moving) and anti-chiral (right-moving) modes. However, in highly curved spacetimes or in certain infinite limits of the spacetime metric, this pairing often breaks down, causing the string to become chiral [1]. For example, chiral strings appear at black hole horizons, illuminating the microscopic origin of black hole entropy [2]; at cosmological orbifold singularities, where they prevent divergences in scattering amplitudes [3]; in worldsheet scattering theory, where they correspond to the fundamental asymptotic states [4] or ambitwistor strings [5]; and in the non-relativistic limit of flat spacetime [6–8], which generalizes to the recently explored Newton–Cartan strings [9–18]. Furthermore, in the geometric framework of double field theory, the entanglement of left- and right-moving modes can condense to produce a Riemannian spacetime from non-Riemannian pregeometry [19], identifying the metric as a Nambu-Goldstone boson [20], in line with earlier insights [21]. Chiral closed strings remain localized in spacetime, whereas chiral open strings attach to null branes [22]. In this Letter, we introduce a wormhole as another example of a background that admits freely traversing chiral strings.

A Lorentzian wormhole is among the earliest solutions in General Relativity (GR), connecting distinct flat regions of spacetime [23,24]. Its realization, stability, observability, and traversability—as well as its relationship to quantum entanglement—have been longstanding and active areas of research [25–38]. In particular, traversability depends on specific wormhole criteria [26], including the flare-out conditions [32] which necessitate violations of a null energy condition.

As a leading candidate for quantum gravity, string theory naturally raises the question: *Can traversable Lorentzian wormholes exist within string theory without invoking exotic matter?* It is the purpose of the present Letter to propose a Lorentzian wormhole within the context of string theory at leading order in α' and to show its traversability by chiral strings but not by particles nor ordinary strings. Our wormhole solution corresponds to a pure Neveu–Schwarz Neveu–Schwarz (NS-NS) geometry that does not require any (exotic) extra matter. The gravitational action we assume is the renowned low-energy effective action of the NS-NS string massless sector comprising a metric, B-field, and scalar dilaton, *i.e.* $\{g_{\mu\nu}, B_{\mu\nu}, \phi\}$:

$$\int \mathrm{d}^D x\, \sqrt{-g}\, e^{-2\phi}\big(R + 4\partial_\mu\phi\partial^\mu\phi - \tfrac{1}{12}H_{\lambda\mu\nu}H^{\lambda\mu\nu}\big), \tag{1}$$

of which the Euler–Lagrange equations lead to

$$\begin{aligned} R_{\mu\nu} + 2\nabla_\mu(\partial_\nu\phi) - \tfrac{1}{4}H_{\mu\rho\sigma}H_\nu{}^{\rho\sigma} &= 0,\\ \tfrac{1}{2}e^{2\phi}\nabla^\rho\big(e^{-2\phi}H_{\rho\mu\nu}\big) &= 0,\\ R + 4\nabla_\mu(\partial^\mu\phi) - 4\partial_\mu\phi\partial^\mu\phi - \tfrac{1}{12}H_{\lambda\mu\nu}H^{\lambda\mu\nu} &= 0\,. \end{aligned} \tag{2}$$

Here $H_{\lambda\mu\nu}$ is the field strength of the B-field, or H-flux. Although superstring theory is formulated in ten dimensions, we focus on a four-dimensional external spacetime (with $D = 4$), implicitly leaving the detailed treatment of compactified (Ricci flat) internal dimensions aside.

Double Field Theory (DFT), initiated in [39,40] and [41–44], provides a framework in which the entire Lagrangian (1) transforms into an $\mathbf{O}(D, D)$-symmetric generalized scalar curvature [45,46].

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Bound on Lyapunov exponent for a charged particle in Kerr-Sen-AdS black hole

PDF

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Hocheol Lee [*] and Bogeun Gwak [†]

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Abstract

We investigate the upper bound of the Lyapunov exponent for a charged particle in the Gibbons-Maeda-Garfinkle-Horowitz-Strominger-AdS (GMGHS-AdS) and Kerr-Sen-AdS black hole backgrounds, which originate from the low-energy effective actions of heterotic string theory and gauged supergravity. We analyze the Lyapunov exponent near the unstable orbit to examine possible violations of the bound. Our results indicate that the bound is sensitive to the signs and magnitudes of the charges, angular momentum of the particle, black hole spin, and negative cosmological constant. The violations are pronounced in the extremal or near-extremal regime. Numerical analysis supports the analytical predictions and highlights the interplay between the string-inspired black hole and the charged particle.

Frame Dependence of Bound on Lyapunov Exponent in Dilatonic Reissner–Nordström–AdS and Kerr–Sen–AdS Black Holes

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Abstract

We investigate the frame dependence of the Lyapunov exponent bound for charged particles in dilatonic Reissner–Nordström–AdS and Kerr–Sen–AdS black hole backgrounds, derived from Einstein–Maxwell–dilaton theory and the low-energy effective action of heterotic string theory, respectively. The analysis is performed in both the Einstein and string (Jordan) frames to examine the influence of conformal transformations on chaotic behavior. For massless particles, the Lyapunov exponent remains invariant under frame transformations, whereas for massive particles, it exhibits frame dependence owing to coupling to the dilaton field. Our results indicate sensitivity of the bound on chaos to the choice of frame. Depending on various parameters, the bound can be satisfied in the Einstein frame and violated in the string frame, while the opposite situation may occur for different parameter values. Numerical computations corroborate the findings of our analysis and demonstrate modifications in the chaotic behavior of string-inspired black holes induced by the dilaton field and the choice of frame.

Unbounded Radius of Innermost Stable Circular Orbit in Higher-Dimensional Black Holes

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Abstract

The innermost stable circular orbit (ISCO) offers a fundamental test of spacetime structure. However, its behavior in higher-dimensional black holes influenced by anisotropic energy-momentum tensors remains insufficiently explored. In this work, we investigate the upper bound of the ISCO in higher-dimensional, static, spherically symmetric, and asymptotically flat black hole spacetimes in the presence of an anisotropic energy-momentum tensor. The energy-momentum tensor is assumed to satisfy the weak energy condition, possess a non-positive trace, and obey constraints on radial and tangential pressures, collectively equivalent to the dominant energy condition with additional constraints. By analyzing the effective potential for timelike geodesics and imposing ISCO conditions, we demonstrate the general absence of an upper bound on the ISCO radius in higher-dimensional spacetimes. For dimensions greater than or equal to eight, an ISCO may not exist, depending on the radial and tangential components of the energy-momentum tensor. If an ISCO exists, its radius remains unbounded. These findings advance our understanding of orbital stability in higher-dimensional gravitational systems and highlight fundamental differences from four-dimensional black hole dynamics.

14. Stephen Angus (CQUeST and Sogang U.)

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Regular Article - Theoretical Physics

Perturbations in 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.

Contents

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15. SeungJun Jeon (Sungkyunkwan U.)

Effective Field Theory of Superconductivity

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Abstract

A field theory of a Schrödinger type complex scalar field of Cooper pair, a U(1) gauge field of electromagnetism, and a neutral scalar field of gapless acoustic phonon is proposed for superconductivity of s-waves. Presence of the gapless neutral scalar field is justified as low energy residual acoustic phonon degrees in the context of effective field theory. The critical coupling of quartic self-interaction of complex scalar field is computed from a 1-loop level interaction balance between the repulsion mediated by massive degree of the U(1) gauge field and the attraction mediated by massive Higgs degree, in the static limit. The obtained net attraction or repulsion in perturbative regime matches the type I or II superconductivity, respectively. We find the new critical coupling of cubic Yukawa type interaction between the neutral and complex scalar fields from another tree level interaction balance between the Coulomb repulsion mediated by massless degree of the U(1) gauge field and the attraction mediated by the gapless neutral scalar field, in the static limit. Superconducting phase is realized at or in the vicinity of this critical coupling. A huge discrepancy between the propagation speeds of photon and phonon gives a plausible explanation on low critical temperatures in conventional superconductors.

Charged Vortex in Superconductor

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Abstract

We find the charged spinless vortices in the effective field theory of a Schrödinger type complex scalar field of Cooper pair, a U(1) gauge field of electromagnetism, and a gapless neutral scalar field of acoustic phonon. We show that regular static vortex solutions are obtained only for the nonzero critical cubic Yukawa type coupling between neutral and complex scalar fields. Since the Coulombic electric field is exactly cancelled by the phonon, the obtained charged vortices have finite energy. When the quartic self-interaction coupling of complex scalar field has the critical value, the BPS (Bogomolny-Prasad-Sommerfield) bound is saturated for multiple charged vortices of arbitrary separations and hence the borderline of type I and Ⅱ superconductors is achieved in nonperturbative regime.

16. Kuan-Nan Lin (APCTP)

Possible origin of α-vacua as the initial state of the Universe

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Pisin Chen[1,2,3,4,*], Kuan-Nan Lin[1,2,†], Wei-Chen Lin[5,6,‡], and Dong-han Yeom[1,5,7,8,§]

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Abstract

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 conjecture that the Euclidean wormholes can allow for a class of de Sitter invariant vacua, the so-called α-vacua, where the Bunch-Davies vacuum is a special case. This therefore provides the α-vacua a geometrical origin. As an aside, we discuss a subtle phase issue when considering the power spectrum related to α-vacua in the closed universe framework.

Entanglement between pair-created twin universes with opposite time arrows should leave a birthmark on CMB spectrum

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Why (and how) the Universe was born is one of the ultimate questions in physics. Another big puzzle is about the arrow of time: why is there only one direction of time? Are these two issues related? One way to solve both puzzles at one stroke is to posit that our universe was pair-created with a twin, whose time arrow is opposite to ours. If so, then the twins must naturally be quantum entangled. In Euclidean quantum gravity, this implies the existence of a Euclidean wormhole bridging the twin universes. Each universe is then in a mixed-state and the mutual entanglement shall leave signatures in the cosmic microwave background (CMB) power spectrum. Invoking the Klebanov-Susskind-Banks wormhole as a toy model for the sake of tractability, we show that the entanglement selects a novel and unique global vacuum for the total inflaton perturbations in both universes. This is equivalent to imposing a simple harmonic oscillator boundary condition on the Euclidean wavefunction of the total perturbations, and it turns out that the entanglement enhances the CMB power spectrum for long-wavelength modes. Such a birthmark renders our notion refutable.

Introduction—Why and how was the universe born? The standard Big Bang theory suggested the birth of the universe from a hot, dense spacetime singularity [1]. But why and how did that happen? There have been a plethora of solutions proposed, where physical entities beyond the big bang singularity, either by classical or quantum means, are invoked. To name just a few, the ekpyrotic model suggested to replace the hot Big Bang by a big bounce due to periodic brane collisions in higher dimensional spacetime [2] (See also the counter argument by Linde [3]). Loop quantum cosmology also supports the big bounce scenario via quantum geometry effects [4]. Conformal cyclic cosmology suggests that the big bang of each aeon (cosmic cycle) can be viewed as the future boundary of the previous aeon [5]. What is the evidence for any of these proposals?

Another big puzzle about the universe is the *arrow of time*. The thermodynamic arrow of time can be addressed by thermodynamic entropy and the second law of thermodynamics [6, 7]. However, if time had already emerged before the hot big bang, then the argument for the arrow of time based on thermodynamics becomes unclear. On the other hand, entanglement entropy seems to provide a fundamental quantum origin for the arrow of time [8–10]. But what did the baby universe entangle with in the first place?

In this Letter, we attempt to address these puzzles via the scenario of pair-created twin universes with opposite time arrows. Euclidean quantum gravity allows twin universes to be created from nothing due to quantum fluctuations, and the twins are endowed with opposite signs of the time arrow, where the global time symmetry is preserved. We point out that quantum entanglement between the twin universes at birth would leave a birthmark on the cosmic microwave background (CMB) power spectrum.

It is well known that Euclidean gravity can facilitate the initial quantum state of a Lorentzian system, through which the cosmic microwave background (CMB) power spectrum is affected [11–15]. In Hartle-Hawking's *no-boundary proposal* (NBP) [16], a de Sitter universe is nucleated from a Euclidean hemisphere, which imposes strict boundary conditions at the pole such that the *Bunch-Davies vacuum* is uniquely selected for the inflaton perturbations [17–19].

While not yet at the 5σ-level precision, the current

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17. Bum-Hoon Lee (CQUeST and Sogang U.)

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

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We investigate the thermodynamics of Reissner-Nordström Gauss-Bonnet (RN-GB) black holes in anti–de Sitter (AdS) space with three horizon geometries ($k = +1, 0, -1$) within the grand canonical ensemble. Using the recently developed topological approach to black hole thermodynamics, inspired by Duan's ϕ-mapping theory, we analyze the black holes by treating both critical points in the phase diagram and black hole solutions as defects in the thermodynamic parameter space. Our results show that the Gauss-Bonnet coupling significantly alters the topological classification of RN-GB AdS black holes, distinguishing them from their RN AdS counterparts in the grand canonical ensemble while aligning with their canonical ensemble counterparts. Complementary analyses of local stability using specific heat validate the implication of topological analysis. Furthermore, an evaluation of global stability via Gibbs free energy provides a comprehensive understanding on system phase structure. Notably, for $k = +1$, topological analysis suggests liquid-gas-type phase transitions, whereas global analysis favors Hawking-Page transitions. For $k = -1$, topology indicates a single stable black hole branch, yet the global analysis reveals the presence of Hawking-Page transitions.

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I. INTRODUCTION

Black hole thermodynamics is one of the most fascinating subjects in theoretical physics. The thermal nature of black holes, characterized by their temperature and thermal entropy [1,2], provides important theoretical guidance for exploring the quantum aspects of gravitational interactions. As thermal objects, understanding their stability and phase structures has been an area of active research for several decades.

The static and spherically symmetric Schwarzschild black hole is unstable due to its negative specific heat. This negativity means that as the black hole loses energy (e.g., through Hawking radiation), its temperature increases, causing it to lose energy even faster. This self-reinforcing cycle leads to a runaway process, making the black hole unstable. To address this issue, researchers have employed mathematical treatments, such as placing the black hole in a large box [3]. A modern approach involves placing black holes in anti–de Sitter (AdS) spacetime, which ensures thermal stability for sufficiently large black holes. This setup features a transition between large black holes and thermal gas in AdS space at low temperature, known as the Hawking-Page transition [4].

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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 axionlike 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. Our results show that the shape of the CMB EB angular power spectrum is sensitive to the background cosmological parameters. We run Markov chain Monte Carlo simulations to fit the $\Lambda\mathrm{CDM} + \mathrm{EDE}$ parameters simultaneously and find that the EDE model with $n = 3$ can provide a good fit to the observed CMB EB spectra, consistent with the locally measured value of the Hubble constant. To the best of our knowledge, these results are the first to show that axionlike EDE can provide a unified explanation for the observed cosmic birefringence and the Hubble tension.

Wolf

Constraints on Cosmic Birefringence from SPIDER, Planck, and ACT observations

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(Dated: November 17, 2025)

The Early Dark Energy (EDE) model has been proposed as a candidate mechanism to generate cosmic birefringence through a Chern–Simons coupling between a dynamical scalar field and the cosmic microwave background (CMB) photon. Such birefringence induces a nonzero cross-correlation between the CMB E- and B-modes, providing a direct observational signature of parity violation. Recent measurements of the EB and TB power spectra, however, cannot yet unambiguously separate instrumental miscalibration (α) from a true cosmic-rotation angle (β). For this reason, we perform a model-independent analysis in terms of the total effective rotation angle $\alpha+\beta$. We analyze the latest EB and TB measurements from the SPIDER, *Planck*, and ACT experiments and derive constraints on the Chern–Simons coupling constant gM_{Pl} and on the polarization rotation angle $\alpha+\beta$. We find that the coupling gM_{Pl} provides reasonable fits to the SPIDER, *Planck* and ACT measurements. The fits for $\alpha+\beta$ prefer a value larger than zero: when combined, *Planck*+ACT yield a detection significance of approximately 7σ. We also find that ACT data alone do not provide sufficiently tight constraints on either gM_{Pl} or $\alpha+\beta$, whereas the combination *Planck*+ACT improves the statistical significance of ACT's high-ℓ results and leads to a better PTE for those measurements.

I. INTRODUCTION

The discovery of the Cosmic Microwave Background (CMB) was a turning point in twentieth-century physics, providing decisive evidence for the hot Big Bang picture and establishing the ΛCDM model as the standard cosmological framework [1–5]. Although this model matches most observations with remarkable accuracy, recent advances in precision cosmological observation have begun to expose possible cracks in the paradigm [6]. Two anomalies in particular motivate the present work: the hints of cosmic birefringence [7, 8] and the Hubble constant discrepancy [9].

Cosmic birefringence refers to a rotation in the linear polarization of CMB photons as they travel across cosmic distances [10–12]. Analyses of Planck data suggest a non-zero rotation angle β with a significance of about 3.6σ, corresponding to $\beta = 0.342^{\circ}{}^{+0.094^{\circ}}_{-0.091^{\circ}}$ (68% C.L.) [13, 14]. The phenomenon reveals itself through correlations between the E and B polarization modes [15]. In standard parity-conserving physics, $E_{\ell m}$ and $B_{\ell m}$ have well-defined transformation rules under inversion, which guarantee that their auto-spectra remain unchanged while their cross-spectrum C_ℓ^{EB} flips sign. A non-zero EB signal therefore points directly to parity violation[16–28], even for CPT violation [29–35] and the anisotropic effect [36–39]. One compelling possibility is the existence of axion-like fields that couple to the electromagnetic tensor via an interaction $g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ [40–42]. Such term would rotate polarization directions and generate EB correlations, while simultaneously leaking power from E into B modes. At present, there are already many detectors that have published their observation for EB correlation. For example, such as POLARBEAR [43], ACT [44], SPT [3], and SPIDER [5]. Upcoming polarization experiments, including the Simons Observatory [45], AliCPT [46, 47], and LiteBIRD [48], are expected to probe these effects with much higher sensitivity. In particular, LiteBIRD is forecast to detect not only a potential EB signal but also the secondary BB component sourced by birefringence.

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Extreme-Mass-Ratio Inspirals Embedded in Dark Matter Halo I: Existence of Homoclinic Orbit and Near-Horizon Chaos

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Abstract. We study the existence of homoclinic orbit and the onset of chaotic motion for a massive particle moving around a Schwarzschild-like black hole embedded in a Dehnen-$(1, 4, 5/2)$ type dark matter halo, within the extreme-mass-ratio limit $q = m/M << 1$, where m and M are the masses of the particle and the central black hole, respectively. The presence of the halo modifies the spacetime curvature and consequently deforms the effective potential governing the particle's motion. Using the Hamiltonian formulation, we derive the conditions under which unstable circular orbit and the associated homoclinic trajectory arise, marking the separatrix between bound and plunging motion. By analyzing the effective potential and the corresponding phase-space structure, we identify the transition from regular to chaotic dynamics in the near-horizon region. Numerical analyses through Poincaré sections and Lyapunov exponents calculations demonstrate that increasing the halo density, scale radius along with energy amplifies nonlinear effects which leads to chaos eventually. We demonstrate that within a dark matter halo environment, the dynamical stability of particle motion can be significantly altered without violating the universal surface gravity bound on chaos. This work provides a deeper understanding of horizon-induced chaos in astrophysically realistic environments and serves as a theoretical basis for exploring its possible imprints on gravitational wave signals in extreme-mass-ratio inspirals system.

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18. Gitae Kim (Hanyang U.)

Analytic approaches to anisotropic holographic superfluids in asymptotically hyperscaling violation geometry

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Abstract

We explore anisotropic holographic superfluidity and find analytic solutions near critical point where superfluid/normalfluid phase transition appears in a holographic dual fluid system. In arXiv:hep-th/1109.4592, the authors obtained such an analytic solution in 5-dimensional Einstein-SU(2)Yang-Mills system, and it is asymptotically AdS_5. What is more in this note is that we get analytic solutions near the critical point in 3- and 4- dimensional Einstein-Scalar-U(1)$\times$SU(2)Yang-Mills systems, which become asymptotically hyperscaling violation geometry. We also get leading order back reactions to the background geometry, which clearly shows spatial anisotropy of the bulk geometry. To explore the properties of the spacetime, we compute holographic entanglement entropy and confirm that the superfluid/normalfluid phase transition must occur at the critical point.

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19. Debangshu Mukherjee (POSTECH)

Emergent factorization of the Hilbert space at large N and the black hole information paradox

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We investigate the emergent factorization of Hilbert space in the low-energy description of matrix models, addressing key aspects of the black hole information paradox. We examine the collective description for the low-energy sector of $SU(N)$ matrix model, characterized by a factorized Hilbert space composed of a finite number of boxes and anti-boxes. This factorization leads us to examine the emergence of thermofield dynamics state in the low energy sector from a fine-tuned state. Our investigation of these matrix models elucidates a concrete mechanism for constructing the truncated algebra of accessible observables, thereby facilitating an understanding of black hole complementarity. In the context of the black hole information paradox, we discuss the origin of the island appearing inside the black hole and provide a reinterpretation of the recent proposal—the holography of information.

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I. INTRODUCTION

The study of emergent collective phenomenon in physics has unveiled profound insights into complex systems, where individual components interact to manifest new and often unexpected collective behaviors, including superconductivity, magnetism, and solitons. From the perspective of the AdS/CFT correspondence [1], semiclassical gravity can also be viewed as an emergent collective phenomenon in the large N Conformal Field Theory (CFT) [2–10], emphasizing the emergence of the holographic coordinate from the boundary CFT.

Black holes stand as another quintessential example of complex systems in physics, epitomizing the intricacies of emergent collective phenomena in gravity. The study of black holes, particularly in the context of the black hole information paradox [11,12], poses one of the most challenging puzzles in theoretical physics. The essence of the paradox lies in the entanglement between Hawking radiation and the inside of the black hole. Consequently, understanding the nature of operators inside black holes, known as *mirror operators* [13,14], is essential for the black hole information paradox.

Recently, black hole microstates have been investigated through cohomology for Bogomol'nyi–Prasad–Sommerfeld (BPS) operators in the $\mathcal{N} = 4$ supersymmetric Yang-Mills theory (SYM) [15–18], where the BPS black hole operator, defined by nongraviton cohomologies, has been explicitly identified for small values of $N = 2, 3, 4$. This explicit construction of the black hole operators raises a question regarding the black hole information paradox: What is the microscopic origin of the mirror operators in the framework of constructing the BPS black hole operator? If black hole operators are formulated within a single $\mathcal{N} = 4$ SYM theory in large N limit, the origin of operators inside the black hole could also be traced back to that SYM theory. This aligns with black hole complementarity [13,14,19–25],

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PHYSICAL REVIEW D **111,** 086021 (2025)

Monotonicity of the RG flow in an emergent dual holography of a worldsheet nonlinear σ model

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Based on the renormalization group (RG) flow of worldsheet bosonic string theory, we construct an effective holographic dual description of the target space theory identifying the RG scale with the emergent extra dimension. This results in an effective dilaton-gravity-gauge theory, analogous to the low-energy description of bosonic M theory. We argue that this holographic dual effective field theory is nonperturbative in the α' expansion, where a class of string quantum fluctuations are resummed to all orders. To investigate the monotonicity of the RG flow of the target space metric in the emergent spacetime, we consider entropy production along the RG flow. We construct a microscopic entropy functional based on the probability distribution function of the holographic dual effective field theory, regarded as Gibbs- or Shannon-type entropy. Given that the Ricci flow represents the 1-loop RG flow equation of the target space metric for the 2D nonlinear sigma model, and motivated by Perelman's proof of the monotonicity of Ricci flow, we propose a Perelman's entropy functional for the holographic dual effective field theory. This entropy functional is also nonperturbative in the α' expansion, and thus, generalizes the 1-loop result to the all-loop order. Furthermore, utilizing the equivalence between the Hamilton-Jacobi equation and the local RG equation, we suggest that the RG flow of holographic Perelman's entropy functional is the Weyl anomaly. This eventually reaffirms the monotonicity of RG flow for the emergent target spacetime but in a nonperturbative way. Interestingly, we find that the microscopic entropy production rate can be determined by integrating the rate of change of the holographic Perelman's entropy functional over all possible metric configurations along the flow.

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I. INTRODUCTION

One of the fundamental challenges in quantum field theories (QFTs) is finding an effective low-energy description for strongly coupled theories. Strong-weak duality, which transforms "electric" degrees of freedom into "magnetic" ones essentially, serves as a promising way for addressing this problem [1,2]. Another type of strong-weak duality is the holographic dual description [3–6], where strong interactions are introduced by the renormalization group (RG) flows of collective dual fields [7–9]. These RG flow equations can be made manifest at the level of an effective action, where an emergent extra dimension is identified as an RG scale parameter [10–23]. As a result, such collective dual fields serve as semiclassical backgrounds for original degrees of freedom, i.e., UV quantum fields. Diagrammatically, not only self-energy corrections given by the RG flows of either scalar or electromagnetic fields but also vertex corrections described by the RG flows of gravitational fields are self-consistently introduced to form coupled differential equations in the semiclassical (strong coupling) regime of dual holography (QFTs).

In general, to verify this fascinating strong-weak duality conjecture, entropy has been investigated to count the number of all accessible quantum microstates and to show the correspondence between the microstates of QFTs and those of their holographic duals. In this regard, the black hole entropy problem has been studied extensively [24–30]. The Bekenstein-Hawking entropy formula, i.e., the area law of the black hole entropy [24–28] is modified by quantum gravity corrections [31,32]. Not only bulk gravitational path integrals in anti-de Sitter space (AdS) but also conformal field theory (CFT) calculations are shown to give the same entropy formula, that is, the leading area law

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Logarithmic corrections to near-extremal entropy of charged de Sitter black holes

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Abstract

We calculate the logarithmic temperature corrections to the thermodynamic entropy of four-dimensional near-extremal Reissner-Nordström de Sitter (dS) black hole by computing a one-loop contribution within the path integral framework in the near-horizon limit. Due to the presence of three horizons, the extremal limit of a charged dS black hole is fundamentally different from its flat and AdS counterparts. In the near-horizon limit, there are three distinct extremal limits known as cold, Nariai, and ultracold configurations. We compute the tensor zero modes of the Lichnerowicz operator acting on linearized metric perturbations for the cold and Nariai extremal limits which are associated with near-horizon AdS_2 and dS_2 asymptotic symmetries. In particular in the near-Nariai limit we compute the quantum corrections to the Hartle-Hawking wavefunction at late times. Our computation establishes the result that at leading order, the small temperature corrections to the extremal entropy is universal in the cold and Nariai limit, paving the way for similar such computations and tests in higher dimensional dS black hole spacetimes, including rotating dS black holes.

Dual holography as functional renormalization group

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Abstract: We investigate the relationship between the functional renormalization group (RG) and the dual holography framework in the path integral formulation, highlighting how each can be understood as a manifestation of the other. Rather than employing the conventional functional RG formalism, we consider a functional RG equation for the probability distribution function, where the RG flow is governed by a Fokker-Planck-type equation. The central idea is to reformulate the solution of Fokker-Planck type functional RG equation in a path integral representation. Within the semiclassical approximation, this leads to a Hamilton-Jacobi equation for an effective renormalized on-shell action. We then examine our framework for an Einstein-Hilbert action coupled to a scalar field. Applying standard techniques, we derive a corresponding functional RG equation for the distribution function, where the dual holographic path integral serves as its formal solution. By synthesizing these two perspectives, we propose a generalized dual holography framework in which the RG flow is explicitly incorporated into the bulk effective action. This generalization naturally introduces RG β-functions and reveals that the RG flow of the distribution function is essentially identical to that of the functional RG equation.

Three-dimensional non-relativistic chiral massive higher-spin gravity

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Abstract: We obtain a non-relativistic chiral massive higher-spin gravity in a deformed AdS_3 spacetime by applying a Lifshitz deformation and subsequent null reduction to chiral massless higher-spin gravity in AdS_4. Intriguingly, the vertices of this non-relativistic theory are less constrained than the ones of the original $4d$ chiral massless theory since we do not have enough dynamical generators to fix the couplings uniquely. Anticipating higher-spin interactions should be suppressed, we propose a simple approximate mass-spin relation which interpolates between the relativistic and non-relativistic regimes. With the proposed mass-spin relation, we observe that that higher-spin interactions indeed become suppressed at large spins, consistent with low-energy physics. We conjecture that the holographic dual of the non-relativistic chiral massive higher-spin gravity proposed in this work is a $2d$ non-relativistic Landau-Ginzburg theory in the light-cone gauge. This non-relativistic theory is expected to describe a two-fluid system with a λ-point constrained in one spatial dimension.

20. Theodoros Nakas (IBS-CTPU-CGA)

Smarr formula for black holes with primary and secondary scalar hair

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Yun Soo Myung [1,*] and Theodoros Nakas [2,†]

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Phys. Rev. D **112**, 064002 – **Published 2 September, 2025**

Export Citation

DOI: https://doi.org/10.1103/qv3n-r8q9

Abstract

In this article, we revisit the thermodynamics of black holes endowed with primary and secondary scalar hair in the shift and Z_2 symmetric subclass of beyond Horndeski gravity. Under a specific fine-tuning of the scalar parameter q in terms of the black hole mass, the singular black hole solution with primary scalar hair reduces to the regular Bardeen solution featuring secondary scalar hair. We first demonstrate that the traditional thermodynamic approach fails to yield a consistent Smarr formula for both solutions under consideration. To address this issue, we adopt the approach introduced in [Phys. Rev. Lett. **132**, 191401 (2024).], and we derive both the first law of black hole thermodynamics and the Smarr formula, offering a consistent thermodynamic description for scalar-hairy black holes. As an additional outcome, our analysis reveals a connection between singular and regular black hole solutions with primary and secondary scalar hair, respectively.

Theoretical filters for shift-symmetric Horndeski gravities

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Abstract. We investigate the structure of nontrivial maximally symmetric vacua and compact-object solutions in shift-symmetric scalar-tensor theories. Focusing on Horndeski gravity, we derive consistency conditions directly from the field equations to identify the subclasses that admit Minkowski and de Sitter vacua with a nontrivial scalar field. In doing so, we obtain a filtering mechanism that operates independently of observational data. In this context, we introduce the notion of stealth vacua, where the scalar field remains active without altering the vacuum. Following this, we examine the theoretical framework of Horndeski theories that admit homogeneous geometries and we extract the implicit form of the solution pertaining to the entire family of theories. Building upon these frameworks, we construct exact solutions in beyond-Horndeski gravity by applying a linear disformal transformation to the regularized Einstein-Gauss-Bonnet black hole. This procedure yields solitonic spacetimes with scalar hair as well as black holes carrying primary scalar hair, demonstrating how disformal maps can qualitatively modify solution properties. We delineate the parameter space in which the transformation is well-defined and analyze the solutions. Our results provide both a principled criterion for selecting viable Horndeski models and a framework for exploring rich solution spaces in beyond-Horndeski gravity.

CONTENTS

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21. Kunal Pal (APCTP)

Smarr formula for black holes with primary and secondary scalar hair

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21. Kunal Pal (APCTP)

PAPER

Dynamical interiors of black-bounce spacetimes

Kunal Pal, Kuntal Pal and Tapobrata Sarkar

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Authors

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Abstract

Using the Israel-Darmois junction conditions, we obtain a class of regular dynamical interiors to the recently proposed black-bounce spacetimes which regularises the Schwarzschild singularity by introducing a regularisation parameter. We show that a regularised Friedmann-Lemaitre-Robertson-Walker like interior geometry can not be matched smoothly with the exterior black-bounce spacetime through a timelike hypersurface, as there always exists a thin shell of non-zero energy-momentum tensor at the matching hypersurface. We obtain the expressions for the energy density and pressure corresponding to the thin-shell surface energy-momentum tensor in terms of the regularisation parameter and derive an evolution equation for the scale factor of the interior geometry by imposing physical conditions on these components. We also discuss the formation of the event horizon inside the interior in the case when the initial conditions are such that the situation describes a collapsing matter cloud. We elaborate upon the physical implications of these results.

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Statistics and complexity of wavefunction spreading in quantum dynamical systems

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Abstract: We consider the statistics of the results of a measurement of the spreading operator in the Krylov basis generated by the Hamiltonian of a quantum system starting from a specified initial pure state. We first obtain the probability distribution of the results of measurements of this spreading operator at a certain instant of time, and compute the characteristic function of this distribution. We show that the moments of this characteristic function are related to the so-called generalised spread complexities, and obtain expressions for them in several cases when the Hamiltonian is an element of a Lie algebra. Furthermore, by considering a continuum limit of the Krylov basis, we show that the generalised spread complexities of higher orders have a peak in the time evolution for a random matrix Hamiltonian belonging to the Gaussian unitary ensemble. We also obtain an upper bound in the change in generalised spread complexity at an arbitrary time in terms of the operator norm of the Hamiltonian and discuss the significance of these results.

Keywords: Gauge-Gravity Correspondence, Holography and Condensed Matter Physics (AdS/CMT)

Generalised state space geometry in Hermitian and non-Hermitian quantum systems

Kunal Pal[1,*]

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One of the key features of information geometry in the classical setting is the existence of a metric structure and a family of connections on the space of probability distributions. The uniqueness of the Fisher–Rao metric and the duality of these connections is at the heart of classical information geometry. However, these features do not carry over straightforwardly to quantum systems, where a Hermitian inner product structure on the Hilbert space induces a metric on the complex projective space of pure states—the Fubini-Study tensor, which is preserved under the unitary evolution. In this work, we explore how modifying the Hermitian tensor structure on the projective space may affect the geometry of pure quantum states, and whether such generalisations can be used to define dual connections with a direct correspondence to classical probability distribution functions, modified by the presence of a non-trivial phase. We show that it is indeed possible to construct a family of connections that are dual to each other in a generalised sense with respect to the real-valued sector of the Fubini–Study tensor. Using this biorthogonal formalism, we systematically classify the four types of tensors that can arise when the dynamics of a quantum system are governed by a non-Hermitian Hamiltonian, identifying both the complex-valued metric and the Berry curvature. Finally, we elucidate the role of the metric in a quantum natural gradient descent optimisation problem, generalised to the non-Hermitian case for a suitable choice of cost function.

I. INTRODUCTION

In classical information geometry, it is possible to ascribe a unique differential geometric structure on the space of probability distributions by means of the Fisher-Rao metric and the family of α-connections, which provide a notion of distance and parallel transport on these generally curved spaces [1]. A collection of probability distributions $P(x;\theta)$ for a random variable x, parametrised by a set of continuous parameters θ, can be most conveniently thought of as a differential manifold, which is equipped with the classical information metric that quantifies the notion of distance in terms of statistical distinguishability: two distributions are considered distant if they can be reliably differentiated with only a small number of observations of x. The classical Fisher-Rao metric can then be written for a well-defined and normalised probability distribution as

$$g_{ij}^{FR} = \mathcal{E}_p\Big[\partial_i \ln P(x;\theta)\partial_j \ln P(x;\theta)\Big] . \tag{1}$$

Here and in subsequent discussions, we use $\mathcal{E}_p[]$ to represent the statistical average of a quantity with respect to the probability distribution function under consideration, and the partial derivatives are with respect to the parameters θ_i. The classical information metric tensor and the α-family of connections can be obtained from a consistent expansion of the one-parameter family of the so-called divergence functionals. Importantly, defining the metric and the family of connections gives rise to a duality between the α and $-\alpha$ connections with respect to the metric [2, 3].

The classical formulation of information geometry has been widely applied to various fields, particularly in classical statistical systems, to understand phenomena ranging from phase transitions to the emergence of chaotic properties. The Fisher information metric defines a Riemannian structure on parameter spaces of probability distributions, enabling the study of phase transitions through curvature singularities [4]. In equilibrium thermodynamics, the information geometric formulation and the related Ruppeiner geometrical picture have been used to investigate the critical behaviour and thermodynamic stability of fluids, black holes, and spin systems [5–16]. The scalar curvature derived from the Fisher metric often encodes information about the interaction strength and the correlation length in many-body systems. This geometric perspective complements traditional approaches by linking thermodynamic fluctuations to an underlying statistical manifold structure [17]. [1]

For quantum systems, on the other hand, parametrised by a set of parameters, the notion of distance between quantum states can be defined in the space of quantum states or density matrices [18]. On the complex projective space of the pure quantum states, a Hermitian tensor structure can be written down, in accordance with the inner product on the Hilbert space. This is the natural Fubini-Study (FS) tensor structure for a quantum state Ψ, which we have assumed to be normalised to unity and is by construction invariant under $U(1)$ transformations [19]. Then the pull-back of the FS tensor of the complex projective space to the parameter manifold is essentially what is known as the quantum geometric tensor (QGT), which can be written in the real coordinates, parameterising the pure quantum state $\{\theta_i\}$ as [20–24] as

$$FS_{ij} = \langle \partial_i \Psi(\theta) | \partial_j \Psi(\theta)\rangle - \langle \partial_i \Psi(\theta) | \Psi(\theta)\rangle \langle \Psi(\theta) | \partial_j \Psi(\theta)\rangle \ . \tag{2}$$

Starting from this tensor on the complex projective space of pure states, it was shown in [25] that it is possible to write the real and symmetric part of the FS tensor in explicit coordinate notation as

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[1] The references cited above represent only a very selective section of works that have appeared over the years; for a complete history and references, we refer the reader to the excellent reviews [4, 8].

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[1] The references cited above represent only a very selective section of works that have appeared over the years; for a complete history and references, we refer the reader to the excellent reviews [4, 8].

22. Masroor Pookkillath (CQUeST and Sogang U.)

Effective field theory of coupled dark energy and dark matter

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Abstract: We formulate an effective field theory (EFT) of coupled dark energy (DE) and dark matter (DM) interacting through energy and momentum transfers. In the DE sector, we exploit the EFT of vector-tensor theories with the presence of a preferred time direction on the cosmological background. This prescription allows one to accommodate shift-symmetric and non-shift-symmetric scalar-tensor theories by taking a particular weak coupling limit, with and without consistency conditions respectively. We deal with the DM sector as a non-relativistic perfect fluid, which can be described by a system of three scalar fields. By choosing a unitary gauge in which the perturbations in the DE and DM sectors are eaten by the metric, we incorporate the leading-order operators that characterize the energy and momentum transfers besides those present in the conventional EFT of vector-tensor and scalar-tensor theories and the non-relativistic perfect fluid. We express the second-order action of scalar perturbations in real space in terms of time- and scale-dependent dimensionless EFT parameters and derive the linear perturbation equations of motion by taking into account additional matter (baryons, radiation). In the small-scale limit, we obtain conditions for the absence of both ghosts and Laplacian instabilities and discuss how they are affected by the DE-DM interactions. We also compute the effective DM gravitational coupling $G_{\rm eff}$ by using a quasi-static approximation for perturbations deep inside the DE sound horizon and show that the existence of momentum and energy transfers allow a possibility to realize $G_{\rm eff}$ smaller than in the uncoupled case at low redshift.

23. Robert B. Mann (U. of Waterloo)

LETTER

Universal topological classifications of black hole thermodynamics

PDF

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Shao-Wen Wei[1,2,*], Yu-Xiao Liu[1,2,†], and Robert B. Mann[3,‡]

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Abstract

In this Letter, we investigate the universal classifications of black hole states by considering them as topological defects within the thermodynamic parameter space. Through the asymptotic behaviors of the constructed vector, our results indicate the existence of four distinct topological classifications, denoted as W^{1-}, W^{0+}, W^{0-}, and W^{1+}. Within these classifications, the innermost small black hole states are characterized as unstable, stable, unstable, and stable, respectively, while the outermost large ones exhibit an unstable, unstable, stable, and stable behavior. These classifications also display contrasting thermodynamic properties in both low and high Hawking temperature limits. Furthermore, we establish a systematic ordering of the local thermodynamically stable and unstable black hole states as the horizon radius increases for a specific topological classification. These results reveal the universal topological classifications governing black hole thermodynamics, providing valuable insights into the fundamental nature of quantum gravity.

Letter

Novel topological classes in black hole thermodynamics

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By viewing black hole solutions as topological defects in thermodynamic parameter space, we unveil a novel topological class and two new topological subclasses, respectively, denoted as $W^{0-\leftrightarrow 1+}$, $\bar{W}^{1+}$, and $\hat{W}^{1+}$, that extend beyond the four established categories proposed by Wei *et al.* [Phys. Rev. D **110**, L081501 (2024)]. Within the newly identified class and these two novel subclasses, the innermost small black hole states exhibit a distinct sequence of unstable, stable, and stable behaviors, while the outermost large black hole states display a uniform pattern of stable behaviors. These classifications indicate thermodynamic properties both in the low and high Hawking temperature regimes that are strikingly different from the previously known four topological classes. In particular, we demonstrate that the static charged anti–de Sitter black holes in gauged supergravity exhibit an intricate thermodynamic evolution that is notably distinct from that of the Reissner-Nordström anti–de Sitter black hole. From a topological perspective, we emphasize the advantages and potential of investigating thermodynamic phase transitions in these black hole spacetimes, an area that has been rarely explored in the previous research. Our findings not only enrich and sharpen the framework of topological classifications in black hole thermodynamics but also represent a significant stride toward unraveling the fundamental nature of black holes and gravity.

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Introduction. Black holes serve as a crucial testing ground for quantum gravity theories, stemming from the discovery that they exhibit thermal properties, with entropy proportional to the area of their event horizons [1,2]. Over the past two decades, our understanding of black hole mechanics has expanded to include concepts of pressure and volume [3–7]. This area, commonly referred to as black hole chemistry [8], has provided new insights into gravitational phase transitions [9–12] and entropy bounds [13–15], with a holographic interpretation now becoming established that includes heat engines [16], complexity [17], the significance of the central charge [18–24], and its origins in higher dimensions [25].

Although there has been significant progress in recent years, exploring the universal properties of black hole thermodynamics continues to be a complex undertaking. Recent developments suggest that topology can sheds new light on addressing this issue [26–28] by considering black hole solutions as topological defects in the thermodynamic parameter space. Initially, such defects were classified into three categories based on their different topological numbers [26]. This approach was later refined in Ref. [27], categorizing black hole solutions into four more general classes based on their thermodynamic asymptotic behaviors. For more examples of the latest representative developments, see Refs. [29–38]. Furthermore, the topology of thermodynamics and phase transition for certain anti–de Sitter (AdS) black holes have been studied in Refs. [39–42] in the context of bulk, mixed bulk/boundary, and conformal field theory (CFT) thermodynamics by using different holographic dictionaries for the dual CFT. In particular, a residue method was adopted in [39] to study the topological properties of the phase transitions of charged AdS_4 black holes and showed that the bulk and boundary thermodynamics are topologically equivalent for both criticality and first-order phase transition in the canonical ensembles. On the other hand, Ref. [41] showed that a Born-Infeld-AdS black hole and its dual CFT share the identical topology, so there is a parallel transition in the

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Neutron stars in 4D Einstein-Gauss-Bonnet gravity

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Abstract

Since the derivation of a well-defined $D \to 4$ limit for 4D Einstein-Gauss-Bonnet (4DEGB) gravity coupled to a scalar field, there has been considerable interest in testing it as an alternative to Einstein's general theory of relativity. Past work has shown that this theory hosts interesting compact star solutions which are smaller in radius than a Schwarzschild black hole of the same mass in general relativity (GR), though the stability of such objects has been subject to question. In this paper we solve the equations for radial perturbations of neutron stars in the 4DEGB theory with Skyrme Lyon (SLy)/Brussels-Montreal Skyrme functionals (BSk) class equations of state (EOSs), along with the Müller-Serot (MS2) EOS, and show that the coincidence of stability and maximum mass points in GR is still present in this modified theory, with the interesting additional feature of solutions reapproaching stability near the black hole solution on the mass-radius diagram. Besides this, as expected from previous work, we find that larger values of the 4DEGB coupling α tend to increase the mass of neutron stars of the same radius (due to a larger α weakening gravity) and move the maximum mass points of the solution

Thermodynamics of charged and accelerating black holes

PDF

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Tomáš Hale*, David Kubizňák†, and Jana Menšíková‡

Robert B. Mann§ and Jiayue Yang‖

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Abstract

We reconsider various C-metric spacetimes describing charged and (slowly) accelerating AdS black holes in different theories of (nonlinear) electrodynamics and revisit their thermodynamic properties. Focusing first on the Maxwell theory, we find a parametrization of the metric where we can eliminate the nontrivial "normalization" of the boost Killing vector which was crucial for obtaining consistent thermodynamics in previous studies. We also calculate the Euclidean action using (i) the standard holographic renormalization and (ii) the topological renormalization, showing that in the presence of overall cosmic string tension the two do not agree. These results are also extended to accelerating black holes in ModMax and RegMax nonlinear electrodynamics. Interestingly, for the latter the electrostatic potential picks up a modification, that remains to be explained, but is consistent with the topological renormalization and the (generalized) Hawking-Ross prescription. Our study indicates that thermodynamics of charged accelerating black holes is far from being completely understood.

Quenched entanglement harvesting

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Ultracold fermionic atoms in an optical lattice, with a sudden position-dependent change (a quench) in the effective dispersion relation, have been proposed by Rodríguez-Laguna *et al.* as an analog spacetime test of the Unruh effect. We provide new support for this analog by analyzing the entanglement of a scalar field in a $(1+1)$-dimensional continuum spacetime with a similar quench, and the harvesting of this entanglement by a pair of Unruh-DeWitt detectors. We present numerical evidence that the concurrence and mutual information harvested by the detectors are qualitatively similar to those in Rindler spacetime, but they exhibit a small yet noticeable variation when the energy pulse created by the quench crosses the detectors. These findings provide further motivation to implement the experimental proposal of Rodríguez-Laguna *et al.*

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I. INTRODUCTION

It has long been known that the vacuum state of a quantum field contains entanglement [1,2]. This has led to the expectation that such entanglement can be extracted, or harvested, by physical devices or objects such as atoms [3–5], and that this can take place even when these objects are spacelike separated.

The general paradigm for the entanglement harvesting protocol [6] considers two initially uncorrelated detectors that locally interact with a quantum field in some state (typically the vacuum state). The amount of harvested correlations is sensitive to both the composition and states of the detectors (for example, their motion) [7–15] as well as the spacetime background [16–31].

This effect is extraordinarily difficult to measure in vacuum, particularly given the length and timescales involved. This has motivated efforts to consider alternative settings in which entanglement harvesting can be observed, with recent experiments detecting correlations of the electromagnetic ground state in a ZnTe crystal [32–34] providing further impetus to this end. Indeed there has been a recent proposal to extract entanglement from the ZnTe crystal [35], as well as from quantum surface fluctuations of a Bose-Einstein condensate [36].

New analog settings that behave as relativistic quantum field theories, originally proposed in the context of testing the Unruh effect, provide a promising avenue in which to test entanglement harvesting. These have a causal structure that is bounded by the speed of sound of the medium and not the speed of light, allowing for entanglement harvesting properties to be within reach of measurement techniques.

Amongst the various analog settings, one of particular note is that proposed by Rodríguez-Laguna *et al.* [37] and Kosior *et al* [38], in which an optical lattice with ultracold fermionic atoms is used to model a Dirac field in a curved spacetime in a setup that permits control of the low energy effective Hamiltonian of the system. To model the Unruh effect, the Hamiltonian is first set to be that of a free Dirac fermion in Minkowski spacetime. Then there is a "quench" of the Hamiltonian, so that it effectively becomes the one associated with a free fermion in a spacetime whose $(1+1)$-dimensional part is

$$ds^2 = -\chi^2 d\eta^2 + d\chi^2, \tag{1}$$

known as the Rindler metric.

In this proposal, the field is initialized in its Minkowski vacuum state, after which it evolves through the quench [37]. Numerical simulations indicated that Unruh-like effects should be present, despite the analog nature of the proposed experiment. It was subsequently argued in a

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Finite-cutoff Holographic Thermodynamics

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We develop a framework for holographic thermodynamics in finite-cutoff holography, extending the anti-de Sitter/conformal field theory (AdS/CFT) correspondence to incorporate a finite radial cutoff in the bulk and a T^2-deformed CFT on the boundary. We formulate the first laws of thermodynamics for a Schwarzschild-AdS (SAdS) black hole with a Dirichlet cutoff on the quasilocal boundary and its dual deformed CFT, introducing the deformation parameter as a thermodynamic variable. The holographic Euler relation for the deformed CFT and its equation of state are derived, alongside the Smarr relation for the bulk. We show that the Rupert teardrop coexistence curve defines a phase space island where deformation flow alters states, with up to three deformed CFTs or cut-off SAdS sharing a same phase transition temperature, one matching the seed CFT or original SAdS. These results offer insights into gravitational thermodynamics with boundary constraints and quantum gravity in finite spacetime regions.

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Introduction—The equivalence principle and the relativistic paradigm introduce a fundamentally new geometric framework for understanding gravity at macroscopic and cosmological scales. Contradistinctively, the development of the Standard Model has demonstrated that the electromagnetic, weak, and strong nuclear forces are effectively described by gauge theories grounded in the principle of gauge symmetry [1, 2]. Another foundational concept—the holographic principle [2, 3], states that gravitational physics is dual to quantum physics. This principle is embodied by the anti-de Sitter/conformal field theory (AdS/CFT) correspondence [4–8], which proposes that a gravitational theory in a $(d+1)$-dimensional AdS spacetime (e.g., an AdS black hole) is equivalent to a strongly coupled gauge theory (at finite temperature in the case of a black hole) defined on its d-dimensional conformal boundary. In this duality, the generating functionals of gravitational and gauge theories coincide; bulk fields correspond directly to gauge-invariant operators on the boundary, and the source terms for these dual operators are determined by the leading boundary behavior of bulk fields near the boundary [9–12].

The thermodynamics of AdS black holes has been extensively studied following the discovery of the Hawking-Page phase transition in Schwarzschild-AdS black holes [13]. Phase structures analogous to the van der Waals liquid–gas system have been identified for charged Reissner-Nordström AdS black holes, exhibiting first-order phase transitions and critical phenomena [14–16]. Recently, significant advances have been achieved in AdS black hole thermodynamics by treating the cosmological constant as a variable, resulting in phenomena such as fluid/superfluid phase transitions [17], black hole microstructures [18], and more [19–24]. The study of thermodynamics within this extended phase space has developed into a subdiscipline known as black hole chemistry [25].

The Hawking-Page phase transition of the Schwarzschild-AdS black hole was holographically interpreted as the confinement-deconfinement phase transition of the quark-gluon plasma in the boundary CFT [10], and subsequently understood as a solid-liquid transition in the context of black hole chemistry [26]. The holographic interpretation of black hole chemistry (i.e., holographic thermodynamics) has recently garnered significantly more attention. Exploratory studies [27–31] indicate that the thermodynamic pressure P and its conjugate volume V in the bulk correspond to the central charge c and its conjugate chemical potential μ on the boundary. Given that the background metric for the CFT is obtained through conformal completion of the AdS bulk, there is flexibility in rescaling the spatial radius of the boundary CFT. Specifically, the boundary radius R may either match the AdS radius ℓ directly [32], or differ by a conformal factor $\omega = R/\ell$ [5, 6]. Rather than varying Newton's constant [33] or fixing the spatial volume of the boundary CFT [34], a recent study has treated the conformal rescaling factor as an independent thermodynamic parameter [35]. This approach established an exact duality between the first law of extended black hole thermodynamics in the bulk and the first law in the dual CFT, ensuring independent

Analytic Tools for Harvesting Magic Resource in Curved Spacetime

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The quantum vacuum is not really empty; it is a reservoir of operationally accessible non-classical resources. Understanding how to extract these resources to fuel information processing is a core objective in quantum technologies and lies at the heart of relativistic quantum information (RQI). While earlier studies of quantum resource harvesting protocols relied primarily on numerical methods, we present, for the first time, exact analytic results for the transition probability and coherence of a qutrit Unruh-DeWitt detector interacting with a scalar field in anti-de Sitter spacetime of arbitrary dimension. Leveraging these results, we analytically investigate the harvesting of non-stabilizerness and demonstrate that stronger spacetime curvature and higher dimensionality significantly suppress the amount of extractable magic resource from the vacuum. Our analytic framework is readily applicable to other scenarios, laying the groundwork for further analytic studies in RQI.

Introduction—Understanding the deep connections between quantum physics, information theory, and gravity is one of the most intriguing questions of modern physics, driving research in areas as diverse as holography [1–11], analogue gravity [12–19] and relativistic quantum information (RQI) [20–32]. The latter has matured into a vibrant cross-disciplinary field bridging quantum information and relativity, opening new avenues for quantum information processing [33–43], quantum teleportation [22, 44–49], entanglement degradation [21, 50–53], entanglement creation [23, 54–60], and relativistic implementations of quantum gates [28, 29, 61–65]. One key question of interest is the extraction of quantum resources from the vacuum of a quantum field [66–68]. Resource harvesting protocols transfer non-classical resources – initially hidden and confined within the field – to localized detectors, where they become operationally accessible. A remarkable example is entanglement harvesting [69–73], in which detectors can acquire entanglement through their interaction with a quantum field, even when they are causally disconnected.

Following these foundational studies, entanglement extraction has been extensively investigated in diverse gravitational settings, such as anti–de Sitter (AdS) spacetime [74, 75], expanding universes [76–79], black hole geometries [80–83], and cosmic string spacetime [84] (see also [85–100] for other circumstances). However, in curved spacetime all existing studies rely on numerical integration (or multiple sums over field modes), with analytic results for the detector's density matrix elements lacking. In this Letter, we break new ground by presenting analytic derivations and results of key quantities such as transition probability and coherence. We demonstrate our analytic methods by computing the extraction of non-stabilizerness (or magic resource) [101–105] for a qutrit detector [106] in $d+1$-dimensional AdS spacetime, a maximally symmetric manifold with constant negative curvature that serves as a cornerstone in quantum gravity and holography [107–111]. Note that our analytic tools also apply to entanglement and magic harvesting in various scenarios. To the best of our knowledge, this is the first instance in which exact analytic results of this kind have been obtained. An advantage of our analytic approach is the straightforward renormalization of divergences that would otherwise hinder reliable numerical evaluation. Furthermore, as the dimension gets larger ($d > 4$) numerical methods [74, 75] become less precise and eventually break down, whereas our method is applicable for arbitrary d, yielding deeper insight into the resource harvesting protocol and opening up a new set of analytic tools for RQI.

Non-stabilizerness, commonly referred to as magic resource, quantifies the non-Clifford component required to achieve universal fault-tolerant quantum computation and encapsulates the capability of a quantum system to perform tasks that are classically intractable [101–105]. Although entanglement characterizes non-classical correlations, entangled states can still be efficiently simulated classically, indicating that entanglement alone does not necessarily signify the quantum advantage [101–105]. Unlike entanglement, magic resource acts as a more fundamental indicator of quantum advantage and plays a central role in quantum computation. Recent advances have revealed that the magic resource is more than just computational power. It has been employed to diagnose criticality in many-body physics [112–116], quantify complexity in nuclear physics and particle physics [117–119], describe information scrambling and retrieval in black holes [120–125], and shed light on gravitational back-reaction [126] as well as the emergence of spacetime [127]. From the RQI perspective, a central issue is whether the vacuum can supply such quantum computational power. While entanglement harvesting probes the vacuum's entanglement structure, magic harvesting

24. Sang-Jin Sin (Hanyang U.)

Holographic fermions in the dyonic Gubser-Rocha black hole

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We investigate the fermionic properties of a dyonic Gubser-Rocha model in the context of gauge/gravity duality. This model incorporates both a magnetic field and momentum relaxation. We have derived this model's scaling exponent, revealing the influence of the magnetic field and momentum relaxation on low-energy physics. As the magnetic field strength and momentum relaxation increase, the spectral function of the dual field changes significantly. Specifically, we observe variations in the scaling exponent, Fermi momentum, and dispersion relations as the magnetic field increases, highlighting the system's transition from a Fermi liquid to a non-Fermi liquid, and eventually to an insulating state. Our analysis of the magneto-scattering rate reveals that it is nearly zero in the Fermi liquid region, increases significantly in the non-Fermi liquid region, and ultimately arrives at a maximum value in the insulating state.

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I. INTRODUCTION

The Landau Fermi liquid theory has been highly successful in describing quantum many-body fermionic systems, particularly at low temperatures, where strongly interacting Fermi liquids exhibit behavior that can be captured by quasiparticles with effective masses and spin interactions [1]. These quasiparticles obey Fermi-Dirac statistics and form the foundation of Fermi liquid theory. However, in the 1980s, the discovery of new materials, particularly high-temperature cuprate superconductors [2], revealed properties that extend beyond the quasiparticle framework. These materials display unusual thermodynamic and transport behaviors, such as T-linear resistance, which cannot be adequately explained by Fermi liquid theory, thus giving rise to what is now referred to as non-Fermi liquids.

In 1997, Juan Maldacena introduced the groundbreaking anti–de Sitter/conformal field theory (AdS/CFT) Correspondence, by analyzing the $\mathcal{N}=4$ Yang-Mills theory in an $\mathrm{AdS}_5 \times S^5$ spacetime [3]. This duality opened a novel approach to studying strongly coupled systems. While gravity remains weakly coupled, its dual counterpart can capture the dynamics of strongly coupled systems. In 2009, Liu *et al.* demonstrated the possibility of exploring fermionic systems by introducing a probe Fermi field into the dual bulk spacetime [4]. They extracted the Fermi response of a condensed matter system from a Reissner-Nordström (RN)-AdS black hole, corresponding to a non-Fermi liquid. Through this approach, the spectral function, a key observable in angle-resolved photoemission spectroscopy (ARPES) experiments, could be obtained.

The gauge/gravity duality has since provided a powerful framework for studying strongly coupled fermionic systems, extending beyond the quasiparticle picture and encompassing Fermi liquids, non-Fermi liquids, and marginal Fermi liquids. Early studies focused on the Reissner-Nordström AdS background [4–6], revealing corrections to transport properties due to holographic fermions [7]. These studies also showed how holographic fermions could lead to Cooper pairing and superconducting instabilities [8]. Subsequent work expanded this framework to include magnetic field backgrounds [9–11], momentum relaxation [12,13], holographic superconductors [14–17], anisotropic backgrounds [18,19], holographic lattices [20–23], dipole couplings [24,25], the Weyl semimetal [26], and the Mott transition [27,28]. Despite its successes, the holographic Green's function does not satisfy the electronic sum rule, prompting the development of semiholography as a more effective theoretical framework [29,30]. Recently, holographic fermions have been applied in experimental contexts [31,32].

The Gubser-Rocha model, proposed in 2009 [33], offers a compelling description of linear resistivity in strange metals. Strange metals are classified as non-Fermi liquids and known to be the normal phase of high-temperature superconductors. Investigations into the Fermi response of

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Hall angle of a spatially random vector model

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Strange metals exhibit linear resistivity and anomalous Hall transport, yet a comprehensive theory that accounts for both phenomena is still lacking. Recent studies have shown Sachdev-Ye-Kitaev-like spatially random couplings between a Fermi surface and a bosonic field, either scalar or vector type, can yield linear-T resistivity. In this paper, we continue the investigation of vector coupling in the presence of a magnetic field. We compute the fermion and boson propagators, along with the self-energy and polarization functions, and determine their dependence on the magnetic field. Although the Hall angle does not exhibit the signature of a strange metal, the linear-in-temperature resistivity remains at low temperatures. Results indicate that random interactions can robustly support linear transport, although additional ingredients may be required to capture the full phenomenology of strange metals.

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I. INTRODUCTION

Strange metal, the normal state of high-temperature superconductivity, is one of the important subjects whose solution is most tantalizing in modern physics [1–7]. Much effort has been made to achieve a consistent theory of strange metals, but there was not a single model which produced its behavior until recently. A nontrivial step toward this goal was taken recently in Ref. [8], where a model giving linear-T resistivity at low temperatures was constructed using a spatially random coupling between a Fermi surface and a critical scalar field. The mechanism based on spatial randomness was claimed to be a "universal theory of strange metal" [8]. The essential idea of the model [8] is to consider Yukawa coupling between electrons ψ and critical scalar bosons ϕ, $g_{ijl}(\boldsymbol{r})\psi_i^\dagger(\tau,\boldsymbol{r})\psi_j(\tau,\boldsymbol{r})\phi_l(\tau,\boldsymbol{r})$, such that

$$\langle g_{ijl}(\boldsymbol{r})\rangle = 0, \quad \langle g^*_{ijl}(\boldsymbol{r})g_{i'j'l'}(\boldsymbol{r}')\rangle = g^2\delta(\boldsymbol{r}-\boldsymbol{r}')\delta_{ii',jj',ll'}.$$

Assigning each field a flavor where $i, j, l = 1, \dots, N$ and taking the large-N limit, this coupling is an analog of the Sachdev-Ye-Kitaev (SYK) model [9–11], so we can call it an "SYK-rised Yukawa model." Such a SYK-rised scalar interaction yields the linear resistivity at low temperatures [8].

Inspired by this scalar model, we [12] built a vector version and found linearity in T as well. In [12], a Fermi surface was coupled to a *vector field* a_μ, and the interaction reads

$$K_{ijl}(\boldsymbol{r})\psi_i^\dagger(\tau,\boldsymbol{r})\overset{\leftrightarrow}{\nabla}_\mu\psi_j(\tau,\boldsymbol{r})a_l^\mu(\tau,\boldsymbol{r}).$$

Strictly speaking, the scalar model and the vector model are supported by different mechanism, as the Feynman diagrams for the polarization bubble giving linear resistivity are different. Despite this difference, the common origin of the strange metallicity seems to be the spatially random coupling between electrons and boson.

Although linear-T resistivity, a hallmark of strange metals, has been achieved, further scrutiny is therefore required to establish the SYK-rised electron-boson coupling as a viable theory of the strange metal. According to Anderson, the theory of strange metals should also account for other anomalies [13,14], such as the Hall angle, among other things. It thus behooves us to compute the Hall conductivity. Suppose we have a $(2+1)$-dimensional system in the x-y plane and a magnetic field in the z direction; the *Hall angle* is defined as

$$\tan(\Theta_H) \equiv \frac{\sigma_{xy}}{\sigma_{xx}}. \tag{1.1}$$

It has been observed that many strange metals exhibit quadratic T dependence, $\cot(\Theta_H) \sim A + BT^2$ [15–17], first reported in 1991, where $A = 0$ in pure samples. Admittedly, the quadratic Hall angle is less universal than linear resistivity. In fact, there are observations showing the breakdown of the scaling law [16,18] or even of the polynomial fit [19–21]. Our major motivation in this article, however, is to test whether this random coupling mechanism could correspond to some realistic materials or, equivalently, whether it could reproduce other properties of at least a certain class of materials. To this end, this article continues investigating the vector model [12] in a magnetic field. In spite of the linear-T resistivity found in [8,12], the behavior of the Hall angle does not correspond to experimental observations.

This paper is organized as follows. In Sec. II, we offer a quick review of the SYK-rised vector model and Landau basis. Section III illustrates how to solve the Schwinger-Dyson equations numerically. After obtaining numerical solutions, we compute the conductivity as well as the Hall angle in Sec. IV and provide a discussion in Sec. V.

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Symmetric Tensor Coupling in Holographic Mean-Field Theory: Deformed Dirac Cones

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Abstract: We extend the holographic mean-field theory to rank-two symmetric tensor order parameter field coupled with fermion. We classify the roles of symmetric tensor order according to the effect on the spectral density: cone-angle change, squashing, and tilting of the spectral light cones. The over-tilted light cone is also achieved in a generalized prescription, which consistently preserves the causality condition. Our results provide agreements between the holographic spectra with those observed in real materials, such as type-II Dirac cones and strained graphene.

Keywords: Holography and Condensed Matter Physics (AdS/CMT), AdS-CFT Correspondence, Gauge-Gravity Correspondence

ER=EPR and Strange Metals from Quantum Entanglement: Disorder theory vs quantum gravity

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(Dated: August 8, 2025)

We give an understanding how strange metals arise from the spatially random Yukawa-SYK model based on the wormhole picture and find a parallelism between the disorder theory and quantum gravity. We start from the observation that the Gaussian average over the spatial random coupling gives a wormhole, defined as a mechanism for long range interaction without causal suppression outside the lightcone. We find that the large-N limit equivalence of the quenched and annealed averages provides a field theory version of the ER=EPR. Since the wormhole establises momentum exchanges over arbitrary distance without causal suppression, it provides a mechanism of the planckian dissipation. It also tells us why SYK-like models describe strongly interacting systems even in the small coupling case. We classify the disorder samples into two classes: I) spatially random coupling with wormholes and no information loss, II) spatially uniform coupling with decoherence.

Introduction The strange metal, characterised by a linear-T resistivity, has been one of the most profound puzzles in modern physics [1–7] due to the lack of theory, despite its universal appearance in strongly correlated metalic system. Recently, it was shown that a class of simple models [8–10] can produce the linear-T resistivity in $(2+1)$-dimension based on the disorder field theory. These models resemble the Sachedev-Ye-Kitaev (SYK) model [11–13] in the sense that interaction is all to all and randomised over the space dependent coupling. The simplest such model is the Yukawa-SYK model whose action consists of Yukawa interaction:

$$\mathcal{L}_{\text{int}} = g_{ijk}(\boldsymbol{r})\psi_i^\dagger\psi_j\phi_k/N \equiv g_{ijk}(\boldsymbol{r})H_{ijk}(\boldsymbol{r},t), \quad (1)$$

with spatially random coupling satisfying

$$\langle g_{ijk}(\boldsymbol{r})\rangle = 0, \quad (2)$$
$$\langle g^*_{ijk}(\boldsymbol{r})g_{i'j'k'}(\boldsymbol{r}')\rangle = g^2\delta(\boldsymbol{r}-\boldsymbol{r}')\delta_{ii'jj'kk'}. \quad (3)$$

The theory is defined by a quenched disorder with Gaußian distribution. Each field is labeled with a color index $i = 1, ..., N$, ensuring that the vertex correction of the theory is well controlled in IR limit [14]. The universality of this model was examined by replacing the Yukawa interaction by a vector interaction: $\phi\psi\psi \to A^\mu_{ext}\psi\partial_\mu\psi$ [9], which turns out to be the only alternative. It was also pointed out that the inverse Hall angle does not have T^2 behavior.

The origin of strange metals is widely believed to lie in many-body quantum entanglement [13]. However, it is unclear how SYK-rised models formulated in terms of the disorder can generate quantum critical point which is rooted in quantum coherence [8–10]. Entanglement alone does not account for the emergence of the strange-metal phase: while many interactions can generate entanglement, few lead to this behaviour. What, then, is the distinctive feature of the Yukawa–SYK model that produces it? Addressing this question is the central aim of this work.

The key observation of this work is that the spatially random correlation condition (3) effectively acts as a wormhole, enabling long-range momentum transfer and generating quantum entanglement. Thus, the role of spatially random couplings is not to induce decoherence, but rather to create entanglement that coherently links different regions of the sample into a single quantum state. This mechanism parallels phenomena in quantum gravity, where wormholes serve to connect disconnected regions of spacetime into a unified geometry [15].

Yukawa-SYK model We start with an action with disorder, $S_{\text{tot}} = S_\psi + S_\phi + S_{\text{int}}$, where

$$S_\psi = \int d\tau d^2\boldsymbol{r}\Big[\sum_{a=1}^N \psi_a^\dagger(\boldsymbol{r},\tau)\left(\partial_\tau - \frac{\nabla^2}{2m} - \mu\right)\psi_a(\boldsymbol{r},\tau) + \sum_{a,b=1}^N V_{ab}(\boldsymbol{r})\psi_a^\dagger(\boldsymbol{r})\psi_b(\boldsymbol{r})\Big], \quad (4)$$

$$S_\phi = \frac{1}{2}\int d\tau d^2\boldsymbol{r}\sum_{a=1}^N \phi_a\left(-\partial_\tau^2 - \nabla^2 + m_b^2\right)\phi_a(\boldsymbol{r},\tau), \quad (5)$$

and $S_{int} = \int d^2\mathbf{r}d\tau\mathcal{L}_{int}$ with $\mathcal{L}_{\text{int}}$ given by (1) together with condition (3). The potential $V_{ab}(\boldsymbol{r}) \equiv \sum_i V_{\text{imp}(ab)}(\boldsymbol{r}-\boldsymbol{r}_i)$ is due to imperfections at $\boldsymbol{r}_i$, which satisfies $\langle V_{ab}(\boldsymbol{r})\rangle = 0$ and

$$\langle V^*_{ab}(\boldsymbol{r})V_{a'b'}(\boldsymbol{r}')\rangle = v^2\delta(\boldsymbol{r}-\boldsymbol{r}')\delta_{aa',bb'}, \text{ with } v\in\mathbb{R}. \quad (6)$$

The path integral quantization of this system is given by $\mathcal{Z} \equiv \int D[\Psi]\exp(-S_{\text{tot}})$, with $D[\Psi] = D[\psi,\psi^\dagger]D[\phi]$. The free energy in the *quenched* average is defined by

$$\langle\ln\mathcal{Z}\rangle_{\text{dis}} = \int D[g]P[g]\left[\ln\left(\int D[\Psi]e^{-S_{\text{tot}}[g,\psi,\phi]}\right)\right], \quad (7)$$

Topology in Holographic Mean-Field Theory at Zero and Finite Temperature

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ABSTRACT: We investigate topological invariants in strongly interacting many-body systems within holographic mean-field theory (H-MFT) framework. Analytic expressions for retarded Green's functions are obtained for all possible fermionic bilinear interactions in the limit of probe background limit AdS_4, from which we construct topological Hamiltonians. Integrating Berry curvature over the momentum domain for the gapped spectra yields well-defined and quantized Chern numbers, enabling a systematic classification of them across interaction types. These topological invariants remain robust under deformation parameters like interaction and temperature, indicating that H-MFT encodes effective single-particle-state topology near a quantum critical point in strongly correlated systems. We point out why topological number is defined in the holographic theories while it is not in the perturbative field theory.

KEYWORDS: Holography, Condensed Matter Physics, AdS/CMT, Topology

Tilted Dirac cones and their topology in Holographic Materials

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Abstract: We explore strongly correlated materials with tilted Dirac cone by introducing a method to realize this spectral feature within a holographic setup. Following the work by Moradpouri et al., we construct an asymptotically AdS spacetime by uplifting the vielbein of Volovik et al to tilt the flat spacetime light cone. We then couple the resulting metric to holographic fermions and compute their spectral functions, confirming the presence of a tilted Dirac cone in momentum space. We also calculate the topological number using the holographic Green's function and find that the Chern number is independent of the tilting parameter. Additionally, we show that the optical conductivity exhibits a Drude peak even at zero chemical potential, revealing nontrivial strong-coupling effects absent in field-theoretic models.

Keywords: Tilted Dirac cone, Topological invariant, Weyl semimetal, AdS/CMT, Holography

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Lifshitz transition in a holographic finite density flavour brane Weyl semimetal

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Abstract: We extend a top-down holographic model of a Weyl semimetal to finite charge density and compute the fermionic spectral function by introducing two probe fermions of opposite chirality. The model is controlled by the boundary fermion mass M and the chemical potential μ. In the zero density, small-M limit, we recover four energy bands, two Weyl points, and linear dispersion in their vicinity, the hallmarks of a Weyl semimetal. As M increases, the bands between the Weyl points become progressively compressed and the spectral weight associated with those bands is smeared out. At finite charge density, we map the Fermi surface in momentum space and identify a Lifshitz transition: two distinct Fermi pockets, each enclosing a different Weyl point, merge into a single large Fermi surface that encloses both. This transition can be induced by either control parameter. Varying M alters the band structure and thus the band shape, which drives the Lifshitz transition, whereas changing μ shifts the bands relative to the Fermi level without qualitatively changing the band structure, producing the Lifshitz transition by moving the band positions.