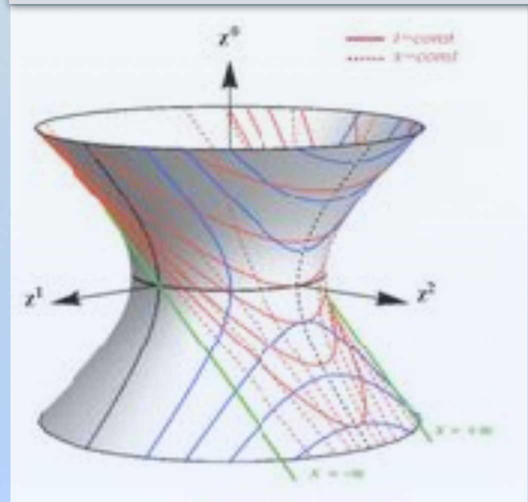
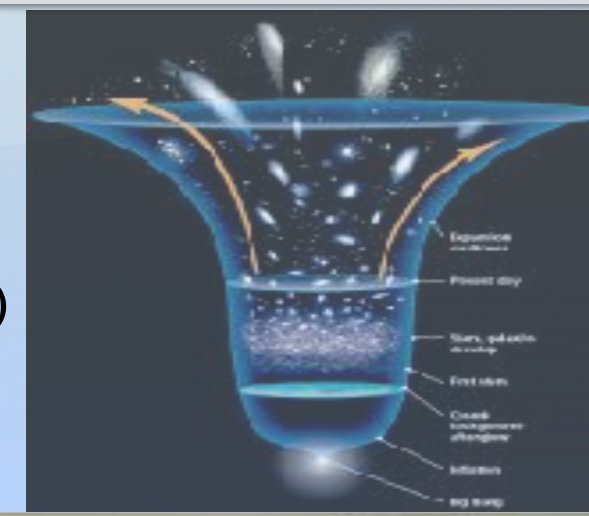
Holographic Dark Matter Fluid in Late Time Universe



by **Yun-Long Zhang** (张云龙)

Asia Pacific Center for Theoretical Physics(APCTP)
@Pohang, Korea (韩国浦项)



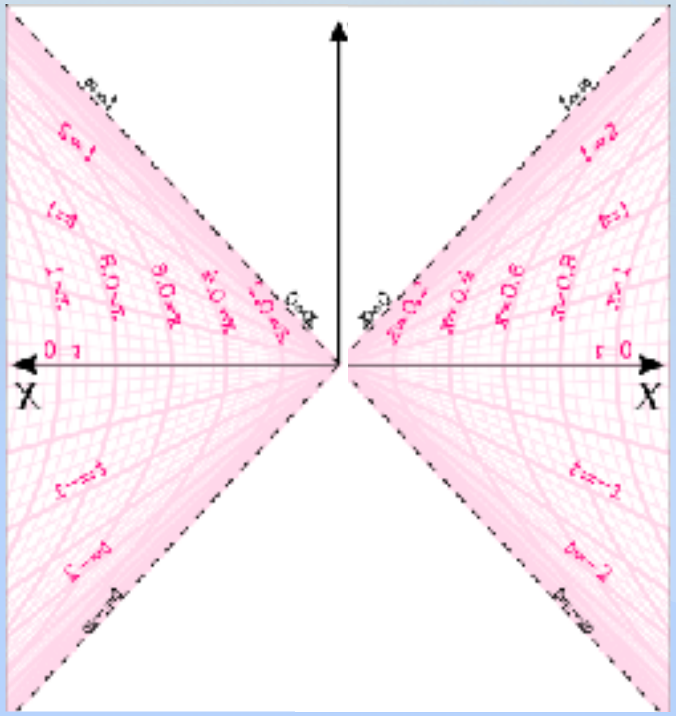
Emergent Dark Matter in Late Universe on Holographic Screen

Rong-Gen Cai (ITP) & Sichun Sun(NTU) & **Yun-Long Zhang**(APCTP)
[arXiv: 1712.09326]

Aug 30, 2018 @ Daejeon

Outline

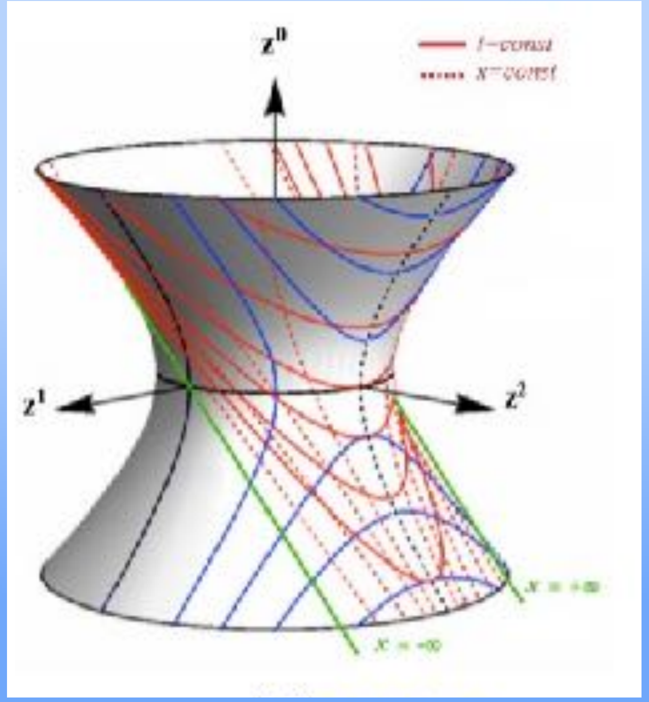
Holographic Screens in Flat Spacetime



I. Holographic Rindler Fluid

Accelerating Screen in Flat Spacetime

From Conformal Fluid to Rindler Fluid

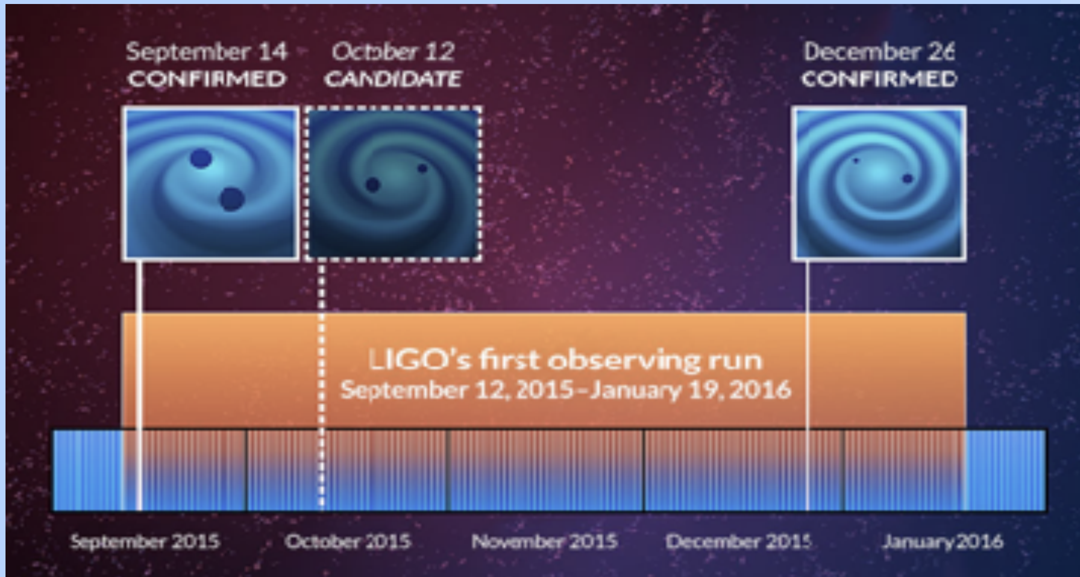


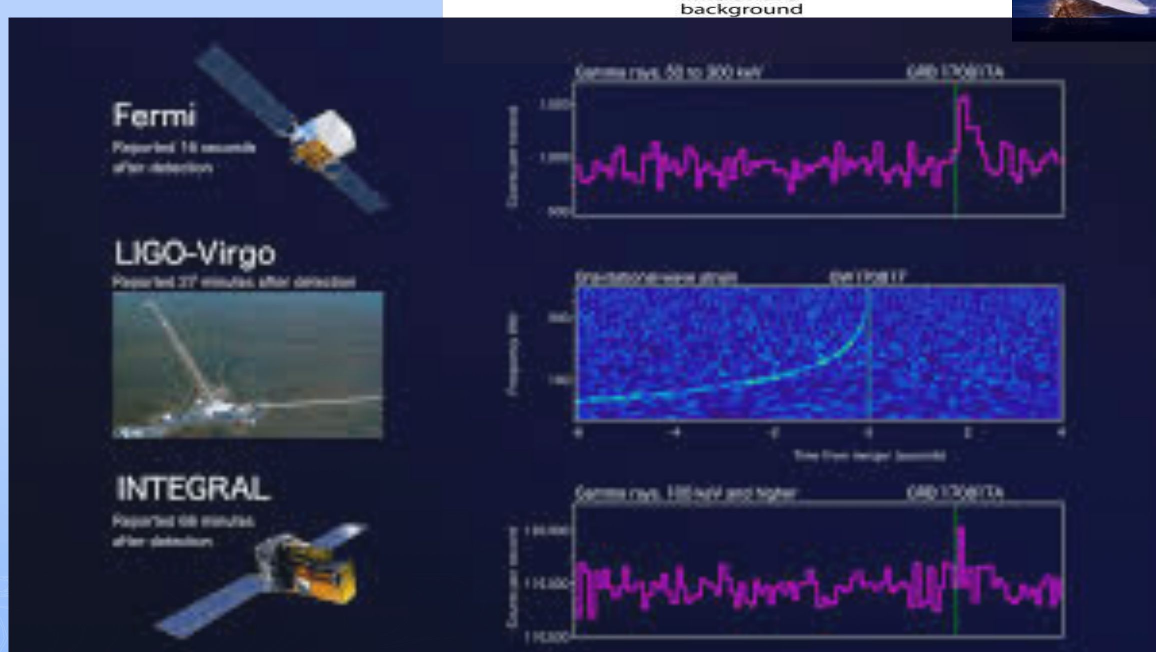
II. Holographic de-Sitter Fluid

de-Sitter & FRW Screen

Compare with DGP brane world

New Era in Black Holes & Gravitational Waves (2016-)

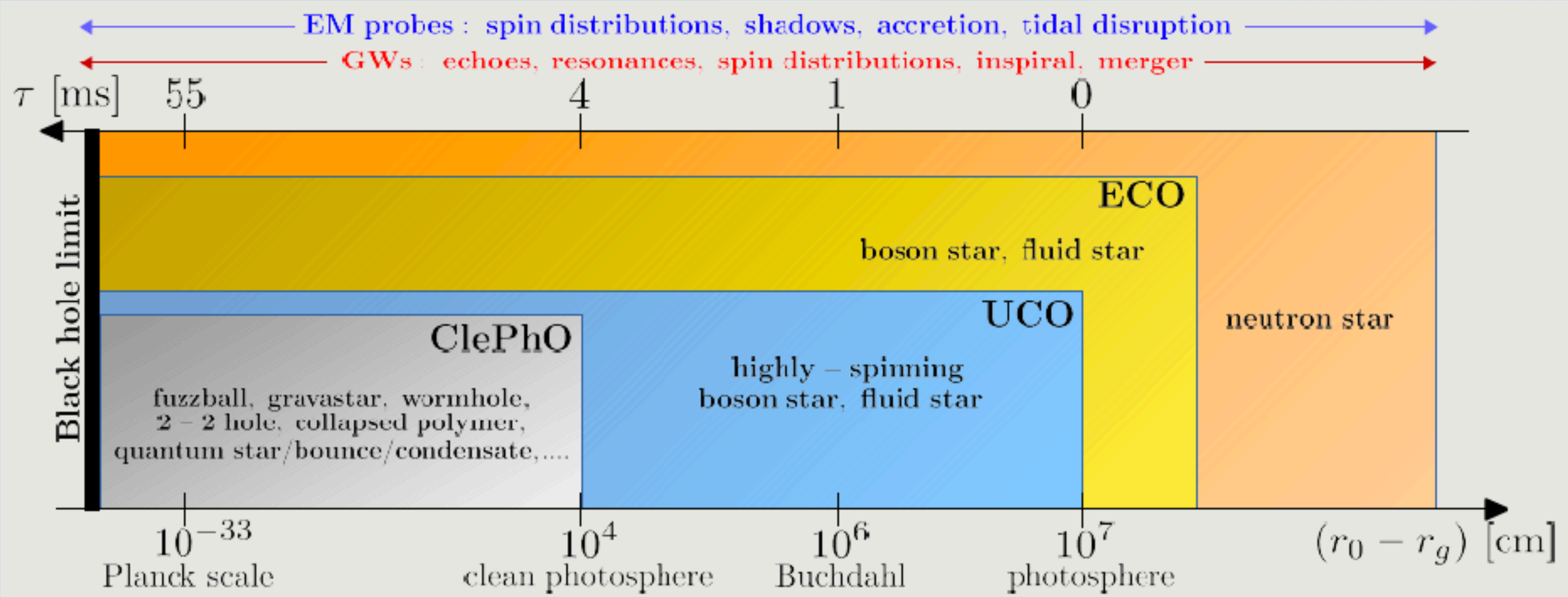


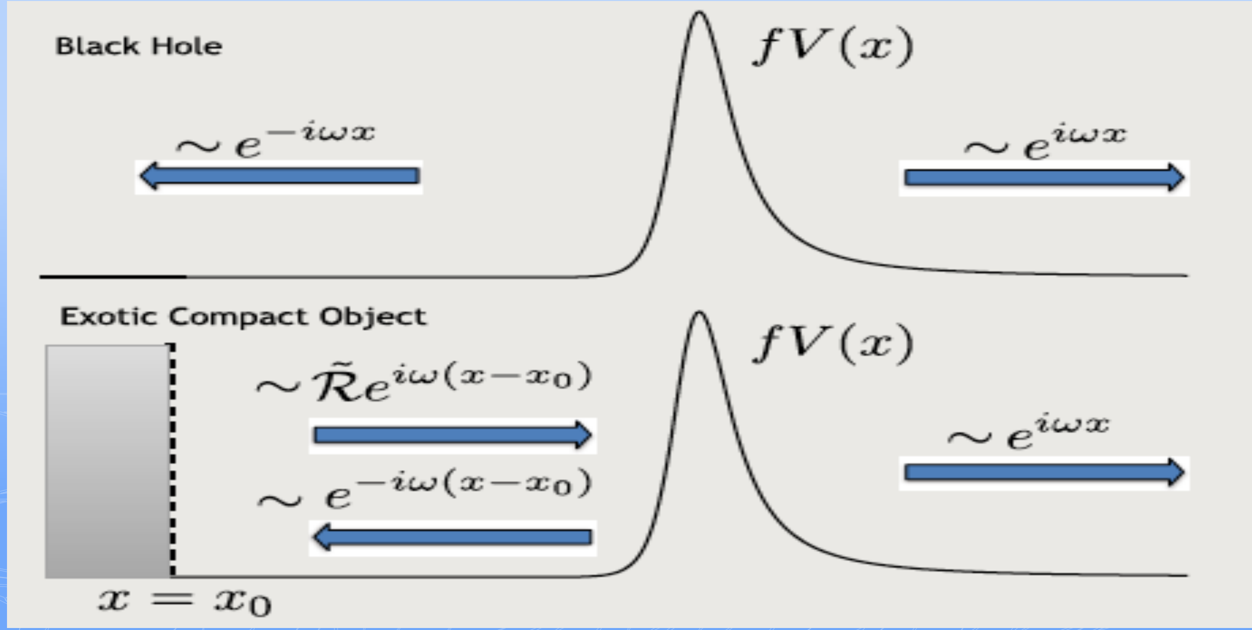


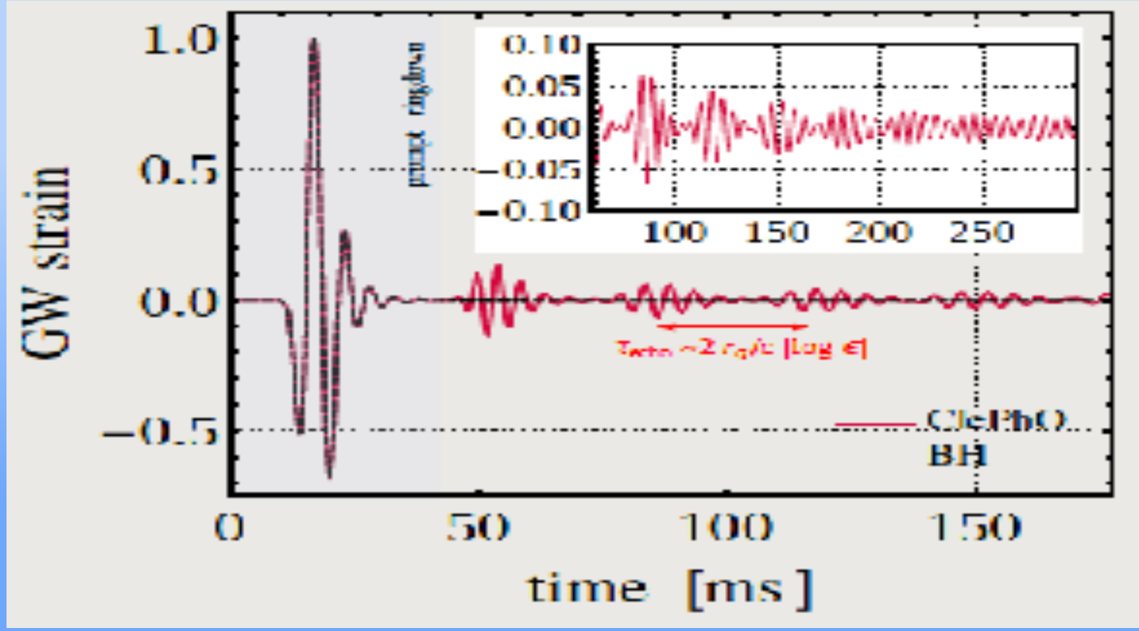
Gamma Ray Burst: NS-NS
Fermi-GBM 2017

High Energy Neutrino: Blazar!
IceCube 2018

New Physics Between Neutron Star and Black Holes?





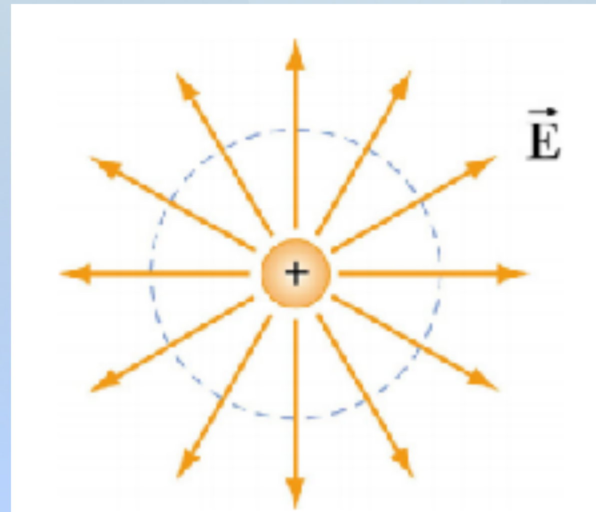


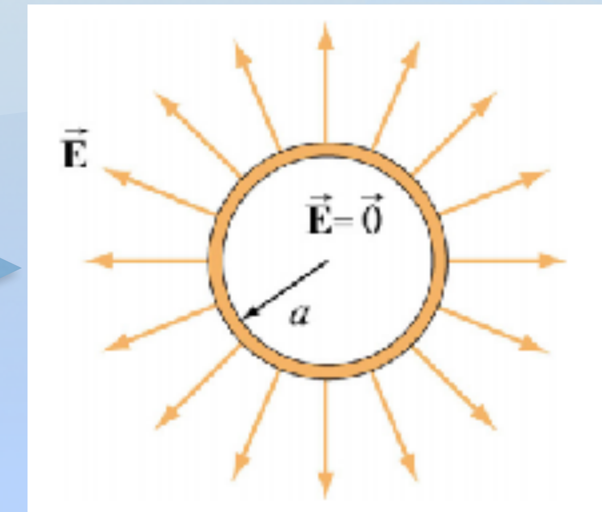
Holographic Duality in Classical Mechanics

I. Electromagnetism

Surface Charge

Electric Field

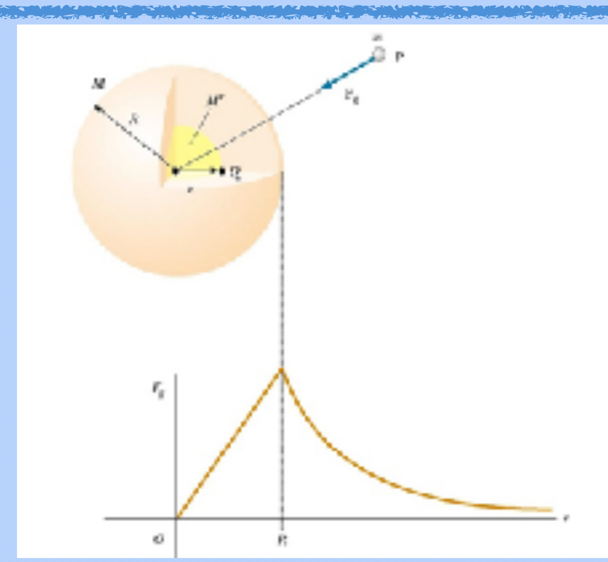


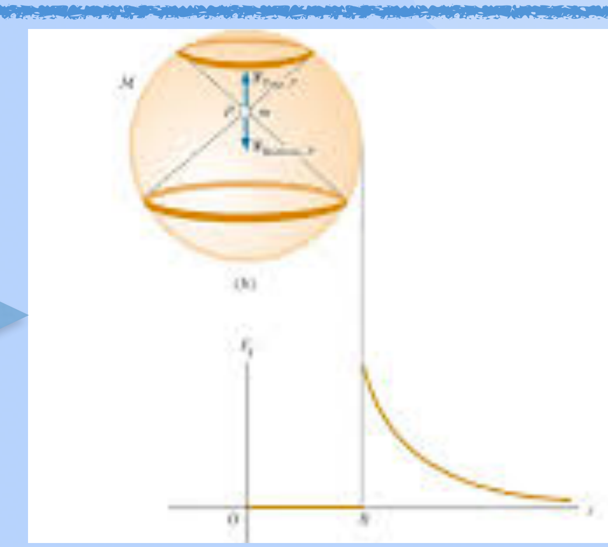


II. Newton Gravity

Mass Sphere Shell

Gravitational Field

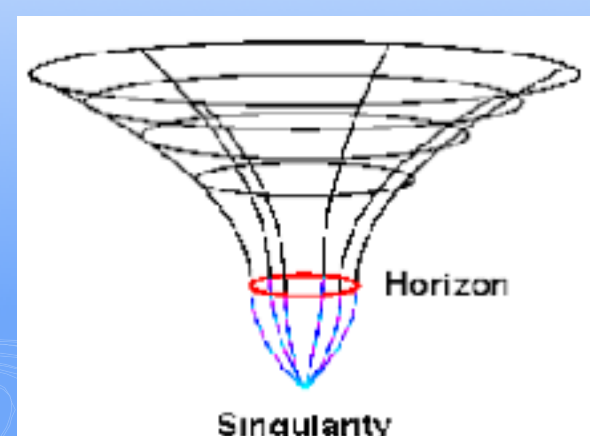


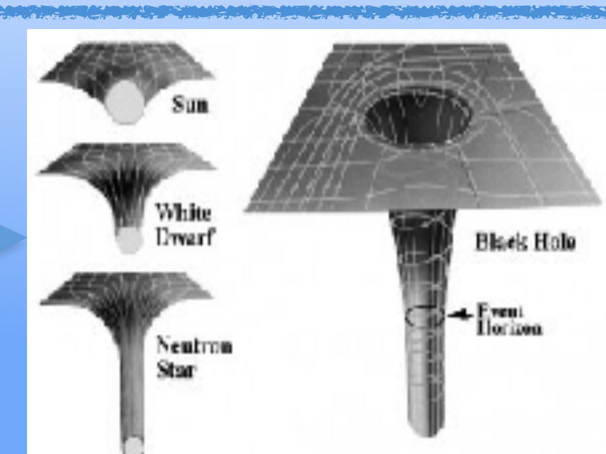


III. Einstein Gravity

Surface Stress Tensor

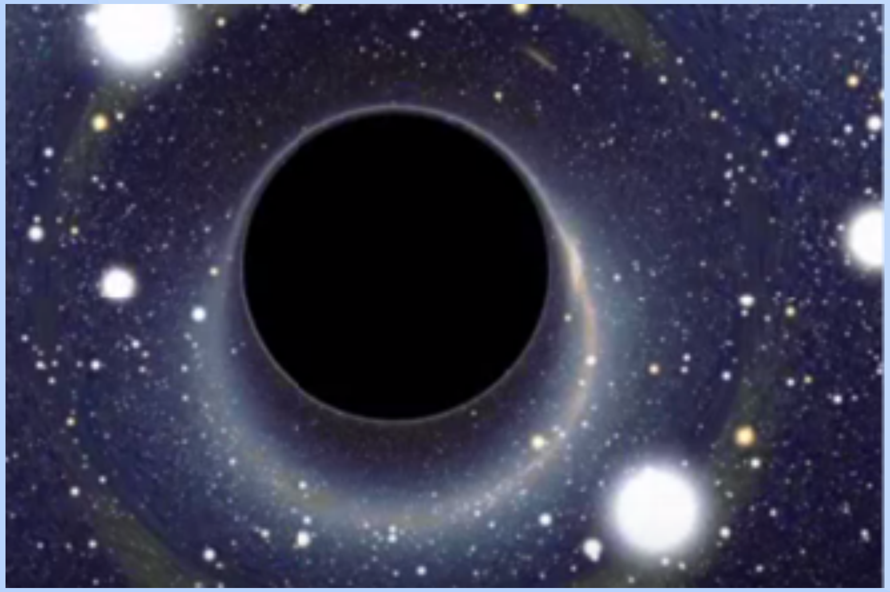
Extrinsic Curvature





Black Hole Thermodynamics (1970s): Hawking Radiation

Bekenstein & Hawking, …



Hawking Temperature $T_H = \frac{\hbar c^3}{8\pi G M k_B} = \frac{\kappa}{2\pi},$

Bekenstein-Hawking Entropy $S_{\rm BH} = \frac{kA}{4\ell_{\rm P}^2}$

0th Law: constant surface gravity

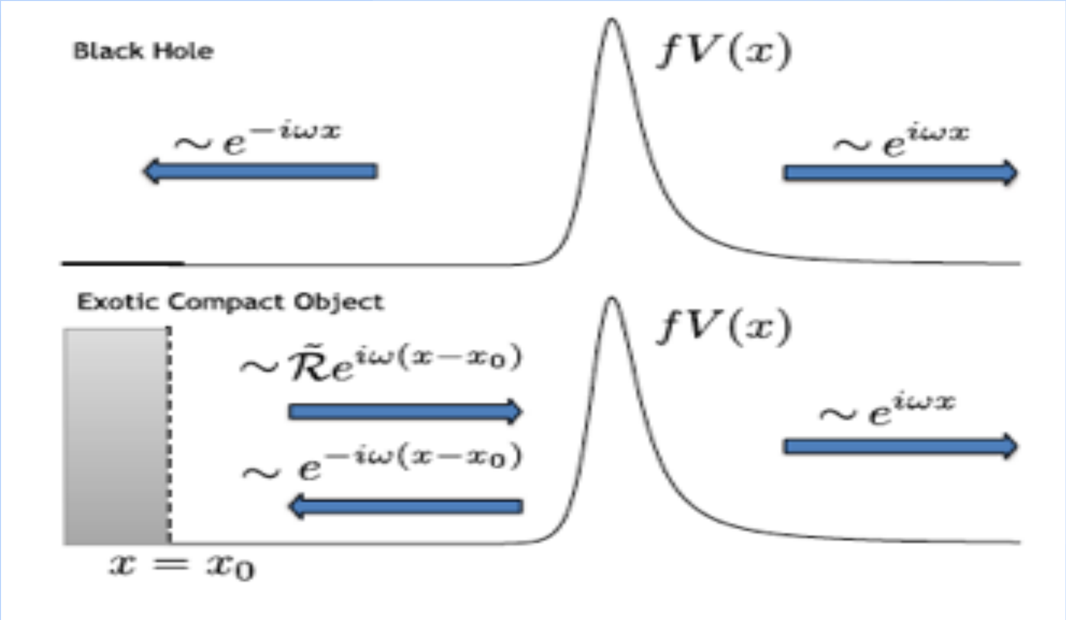
1st Law: $dE = \frac{\kappa}{8\pi} dA + \Omega\, dJ + \Phi\, dQ,$

2nd Law: non-decreasing of entropy

3rd Law: extremal black hole is not possible

Membrane paradigm (1980s): Effective Fluid

T. Doumer & K. Thorne, ···

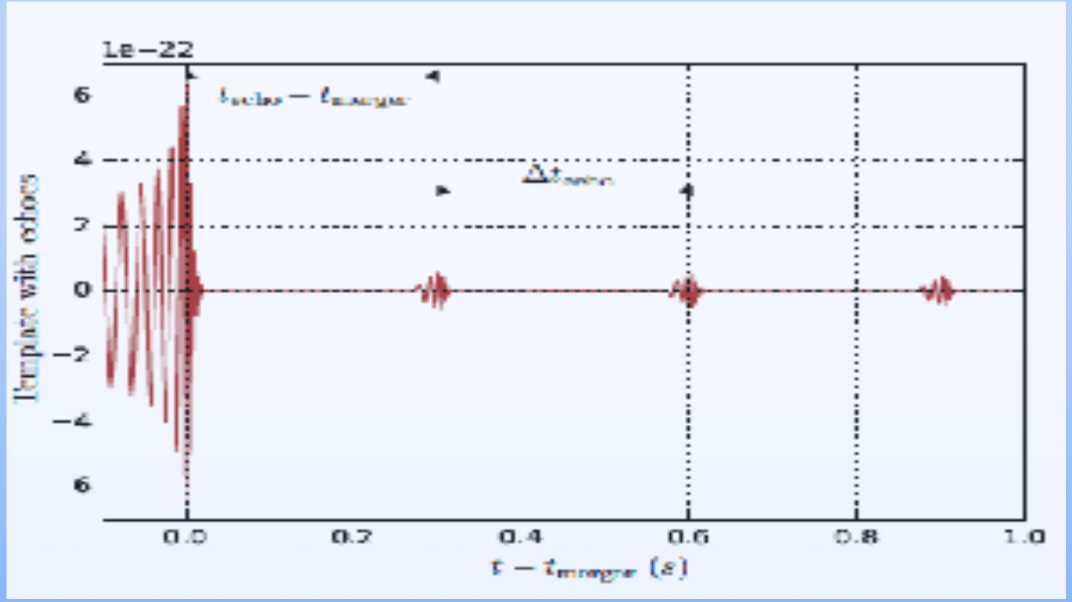


Effective Description

$$\mathcal{T}_{ab} = -2(K_{ab} - K\gamma_{ab})$$

Membrane on Stretched horizon

Viscosity & Conductivity



Echoes from the Abyss [1612.00266 PRD'17]

AdS/CFT Duality (2000s): Black Hole in a Box

Maldacena & Gubser & Witten,et al

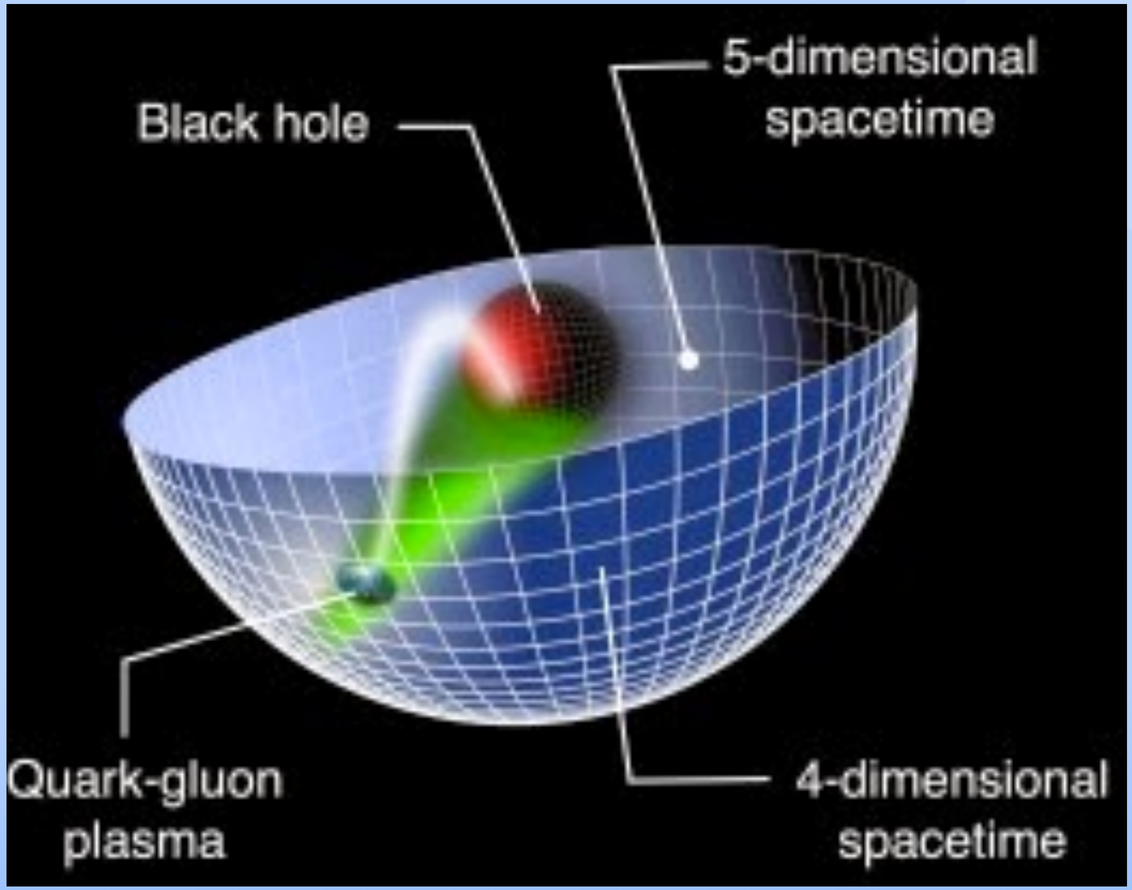
AdS/CMT Correspondence $$Z_{CFT} = \langle e^{S_{CFT}} \rangle \overset{AdS/CFT}{\simeq} e^{S_{AdS}}$$

Shear Viscosity $\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$

Conductivity $\sigma \simeq \pi T$

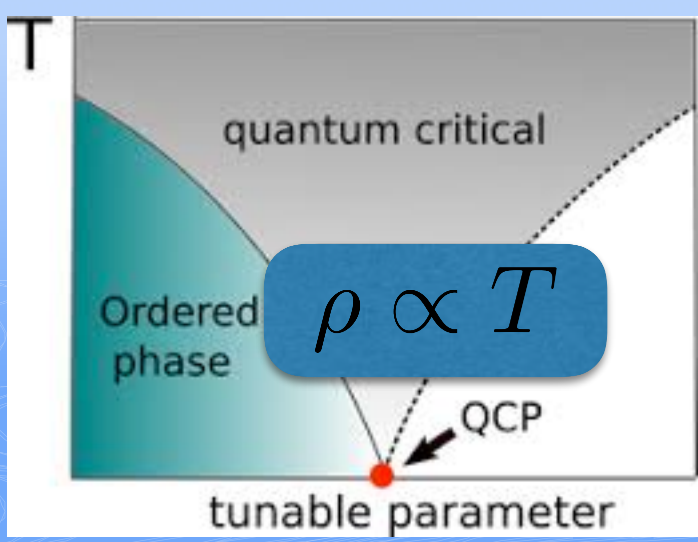
Holographic Superconductor

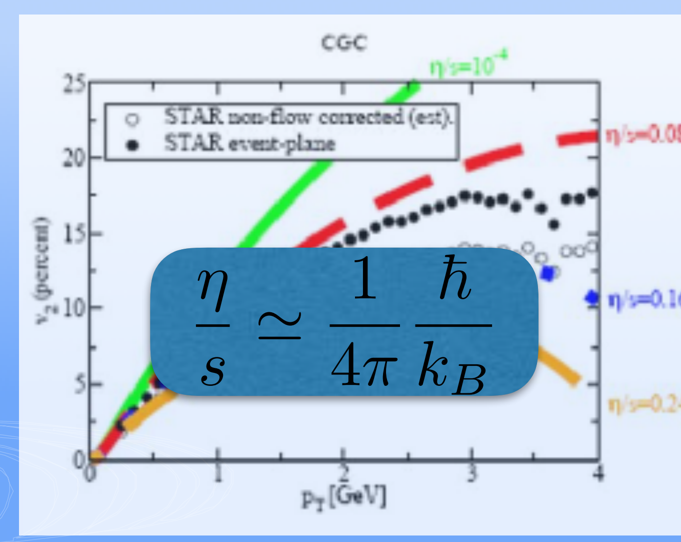
Holographic Non-Fermi Liquid

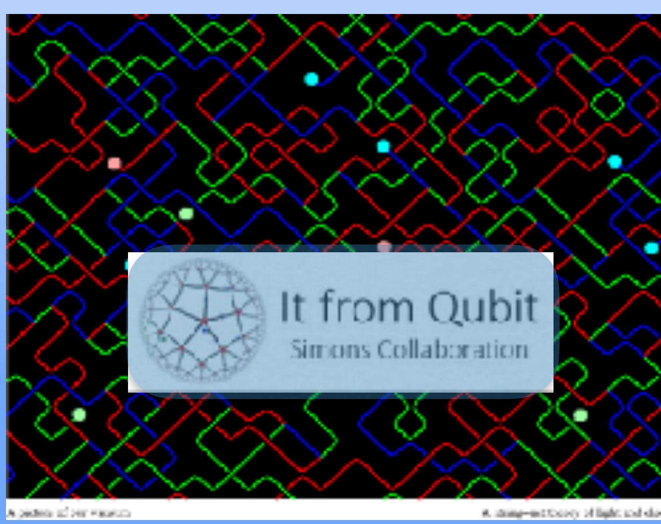


Succesful Holographic Models — ICTP Dirac Medal 2018

		
S. Sachdev (Harvard)	Dom T. Son (Chicago)	Xiao-Gang Wen(MIT)
Holographic Strange Metal	Holographic Quark-Gluon Plasma	Order Parameters Emergent & Entanglement







Motivations for Holography at the Cutoff Screen

Extremal Charged BH

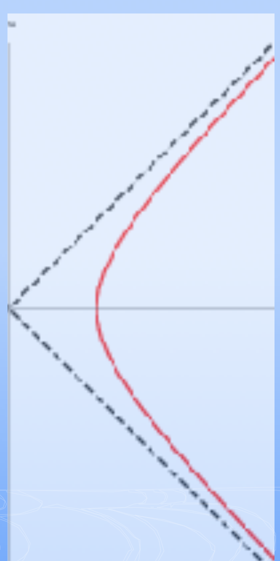
$AdS_2/CFT_1 \times R_p$ & Non-Fermi Liquid ← Near Horizon — **Cutoff AdS / Effective CMT?** — Near Boundary → **AdS /CFT&CMT**

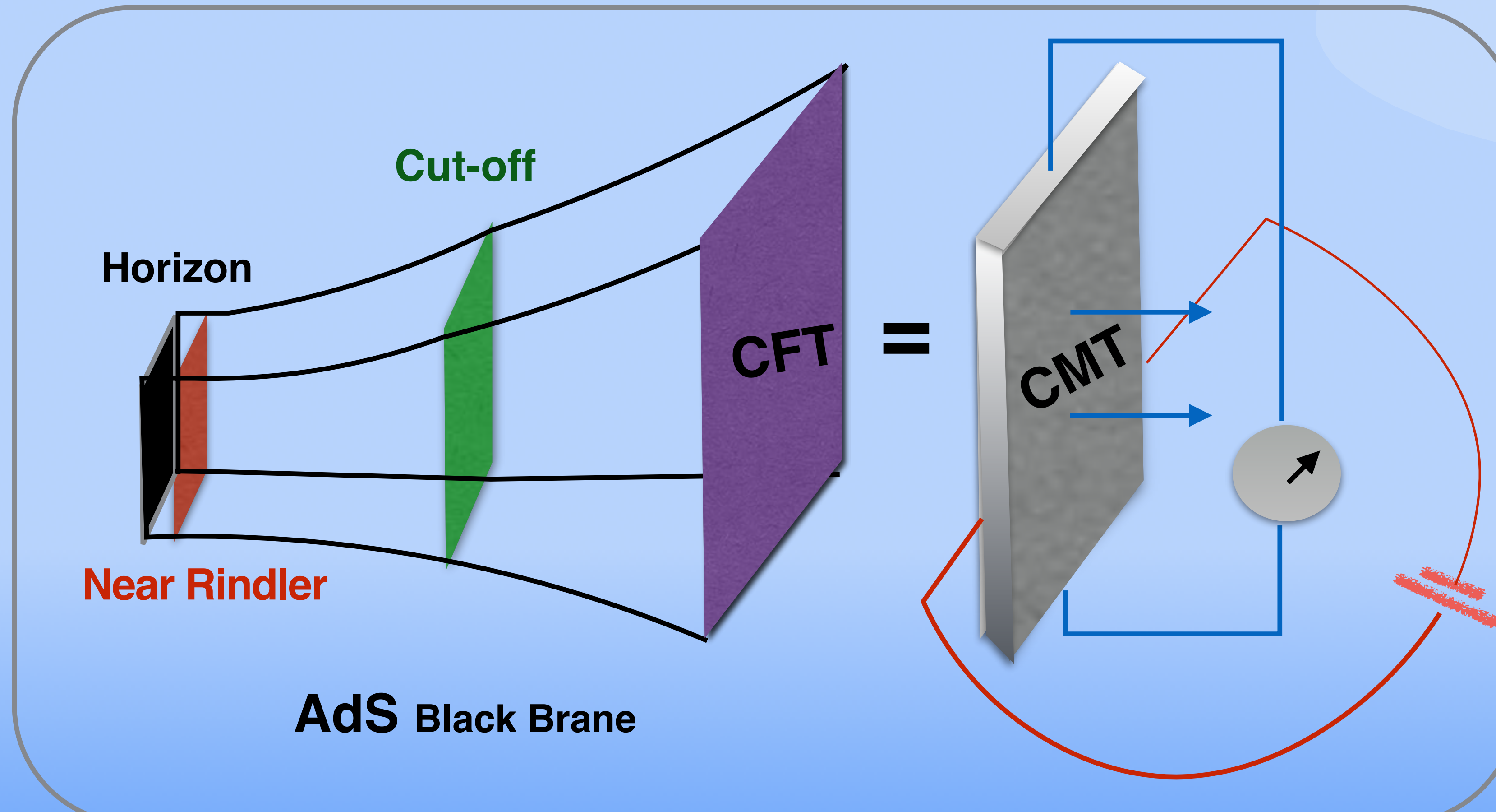
Finite Temperature ↓

Rindler Space/ Special CMT

⋮ ↓

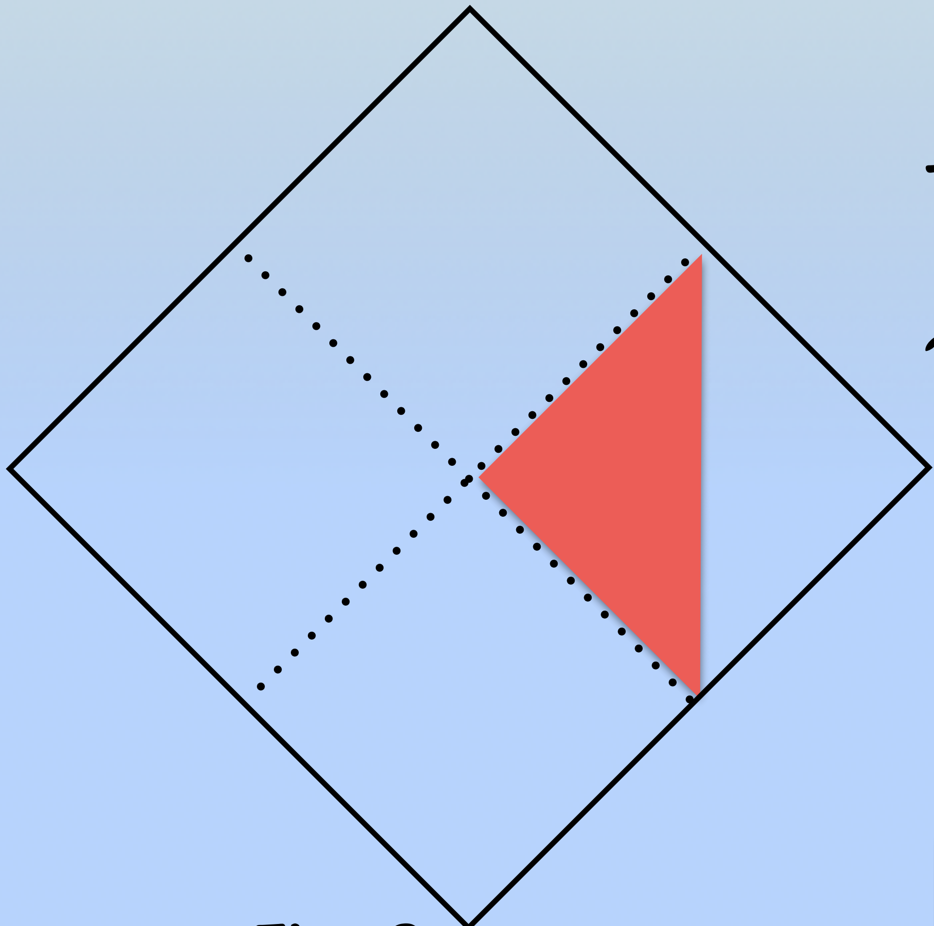
Membrane Black Holes





Wilsonian Approach to Fluid/Gravity Duality [Bredberg, Keeler, Lysov, Strominger, '11]

From AdS/CFT to Holographic Rindler Fluid



Flat Spacetime

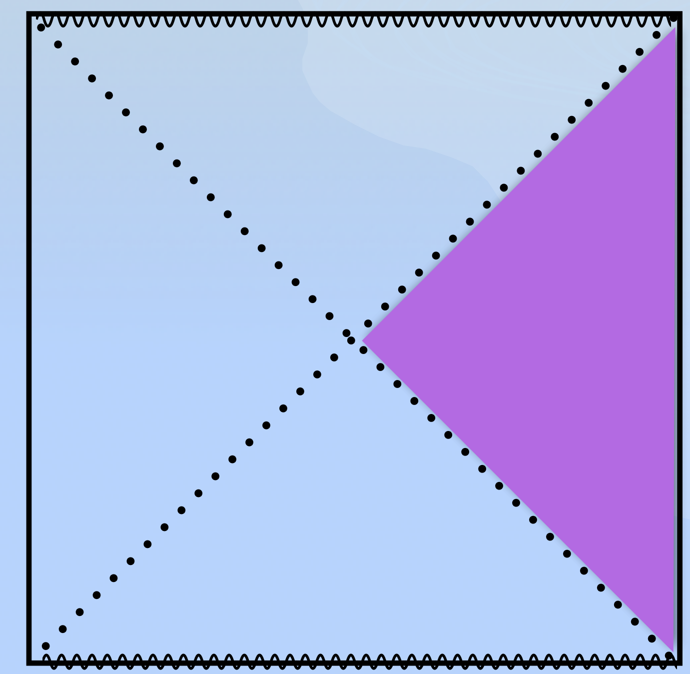
Holographic Screen

the Time-like boundary

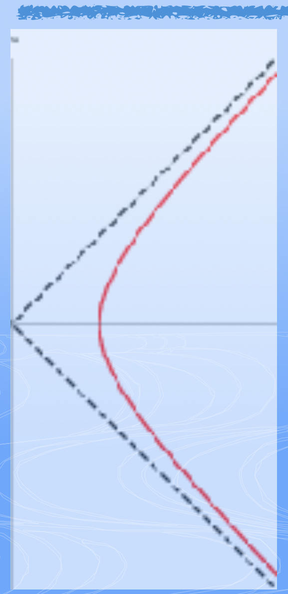
$$\mathcal{T}_{ab} = -2(K_{ab} - K\gamma_{ab})$$

What is Rindler Fluid?

Fluid dual to Rindler spacetime



AdS Spacetime



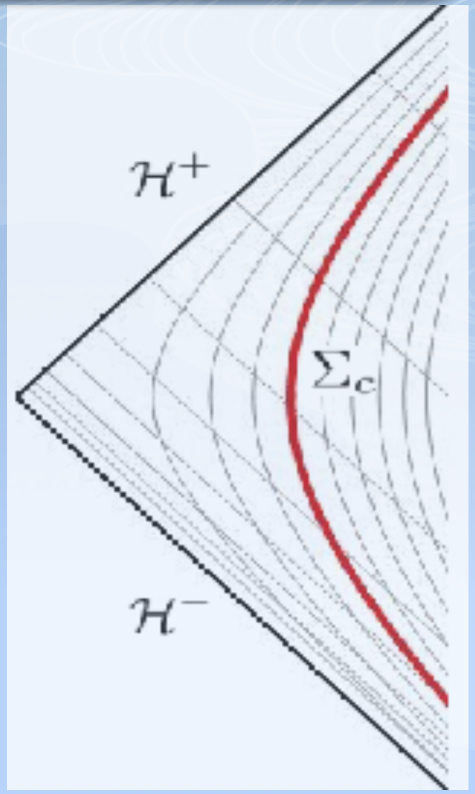
Navier-Stokes Equations:	Bredberg, Keeler, Lysov, Strominger ['10,'11]
Fluid/Gravity Expansion:	Compere, McFadden, Skenderis, Taylor ['11,'12]
Entropy Current and Constraint:	Chirco, Eling, Liberati, Meyer, Oz ['12,'13]
Comparison with AdS/Fluid:	Matsuo, Natsuume, Ohta, Okamura ['12,13]
Rindler Fluid and Recurrence Relation	Cai, Li, Yang, Zhang ['13,'14]
Rindler Fluid with Momentum Relaxation	Khimphun, Lee, Park, Zhang ['17]

Hydrodynamics of the Rindler Fluid

Rindler Metric $$ds^2 = -r d\tau^2 + \frac{1}{r} dr^2 + dx_i dx^i$$

Induced Metric $$ds^2 = -r_c d\tau^2 + dx_i dx^i$$

Dual Tensor $$\mathcal{T}_{ab} = -2(K_{ab} - K\gamma_{ab})$$



Constraint equations

$$2G_{\mu b} n^\mu |_{r_c} = 2\partial^a (K_{ab} - \gamma_{ab} K) = 0 \;\Rightarrow\; \partial^a T_{ab} = 0$$

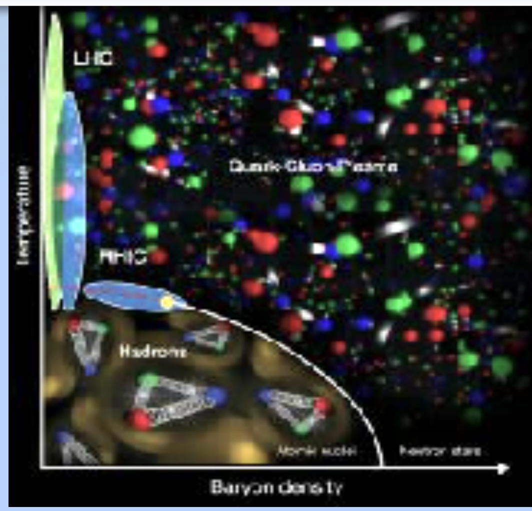
$$2G_{\mu\nu} n^\mu n^\nu |_{r_c} = (K^2 - K_{ab} K^{ab}) = 0 \;\Rightarrow\; T^2 - p T_{ab} T^{ab} = 0$$

Bredberg, Keeler, Lysov, Strominger (JHEP 07 (2012) 146)

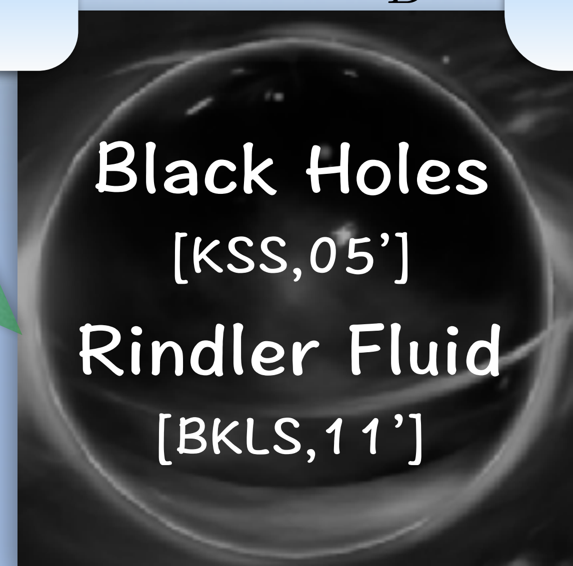
Holographic Fluid on the Screen

Quark Gluon Plasma

in RHIC [08'] & LHC [16']



$$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$



Black Holes

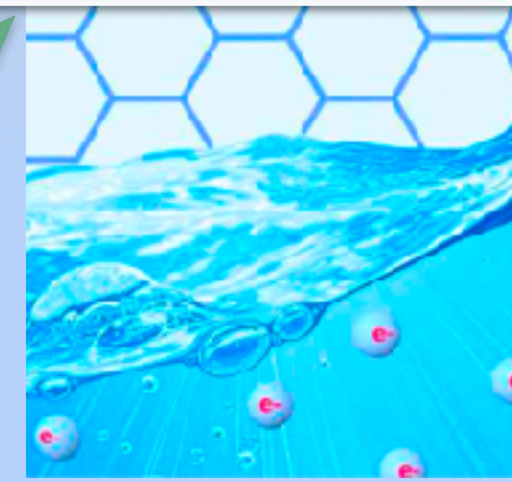
[KSS,05']

Rindler Fluid

[BKLS,11']

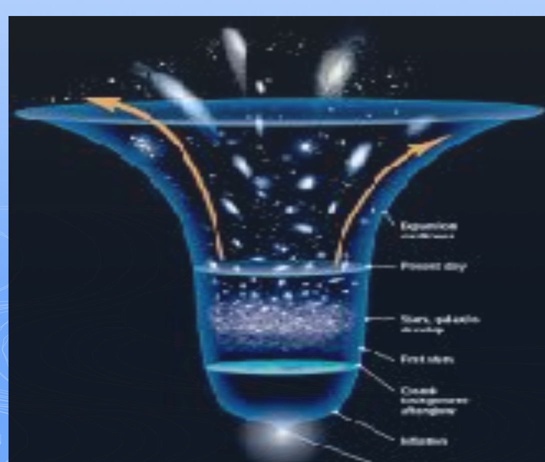
Quantum Critical Liquid

Graphene [09'] & Semi-Metal[16']



$$\frac{H^2}{H_0^2} \simeq \frac{\Omega_B}{a^3} + \sqrt{\Omega_\Lambda\Big(\frac{H^2}{H_0^2} + \frac{\Omega_I}{a^4}\Big)}$$

$$\Omega_D^2 \simeq \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B)$$

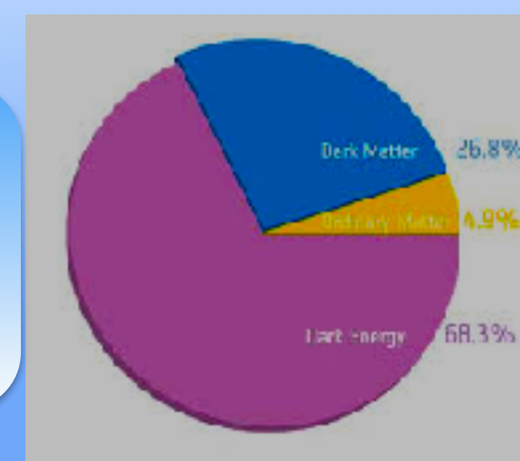


Dark Fluid in the Universe?

Cosmological Fluid [CSZ,17']

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{1}{L}\left(\mathcal{K}_{\mu\nu} - \mathcal{K}g_{\mu\nu}\right) = \kappa_4 T_{\mu\nu}$$

[1712.09326, Cai, Sun, Zhang]

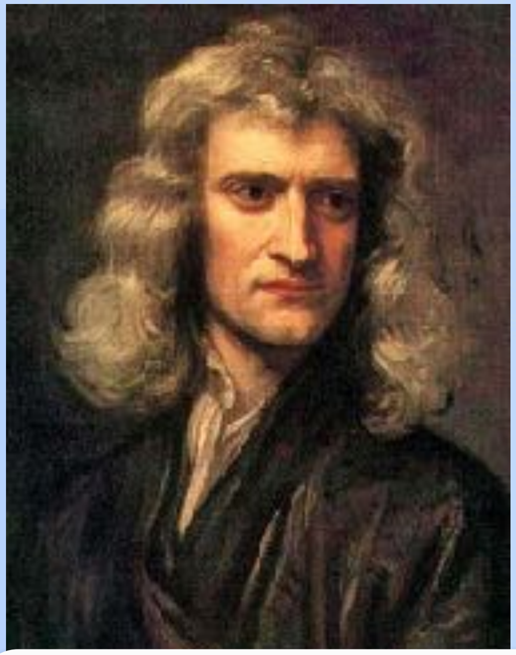


Figures Credit: RHIC & Google

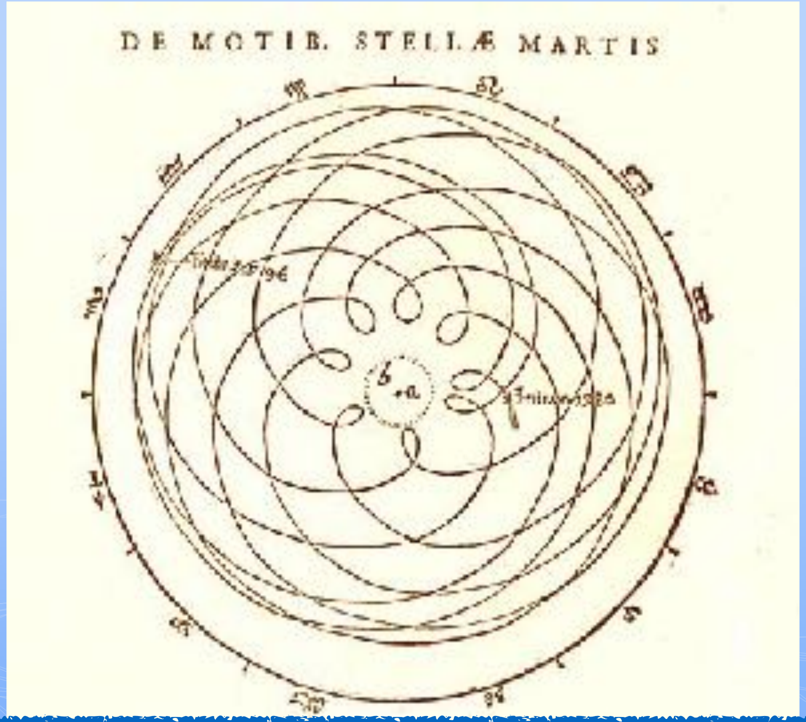
From Observation to Newton's Gravity

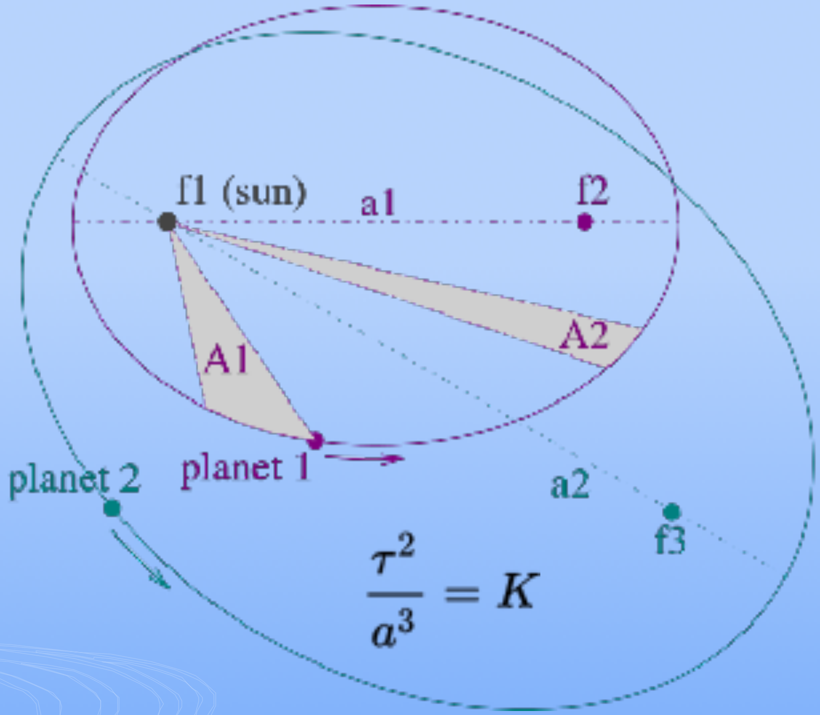
Tycho's Data (1590s)

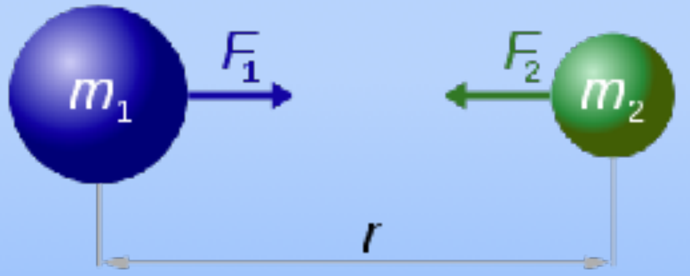
Kapler's Law (1618)



Newton's Gravity (1687)







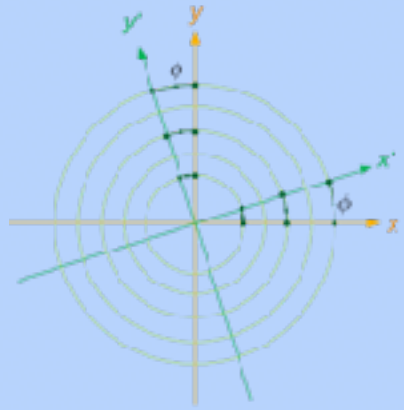
$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

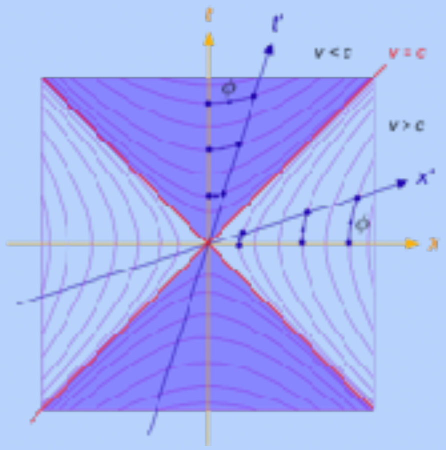
NATURE and Nature's Laws lay hid in Night: God said, "Let Newton be!" and all was light.

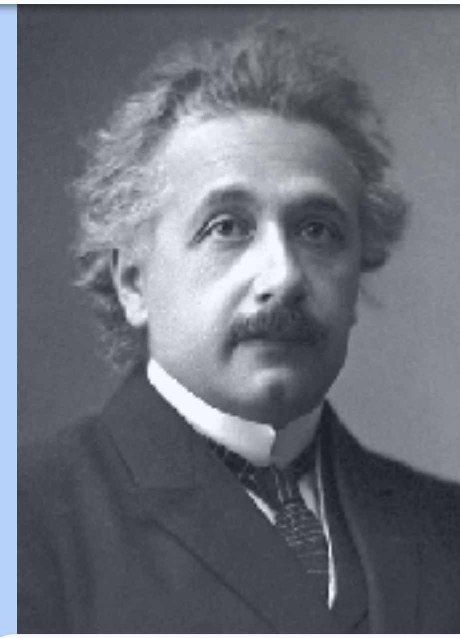
— Alexander Pope

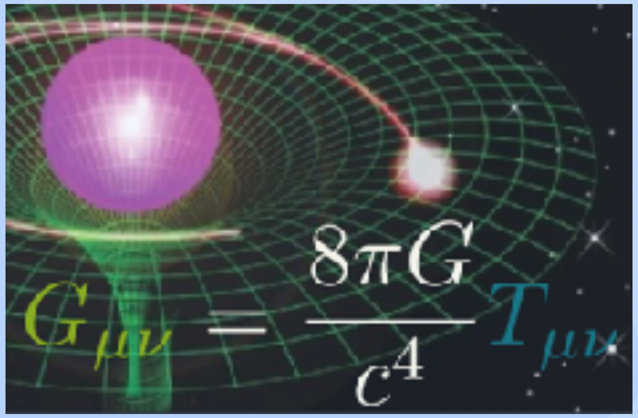
Figures credit: Wiki

From Einstein's Gravity to Dark Universe









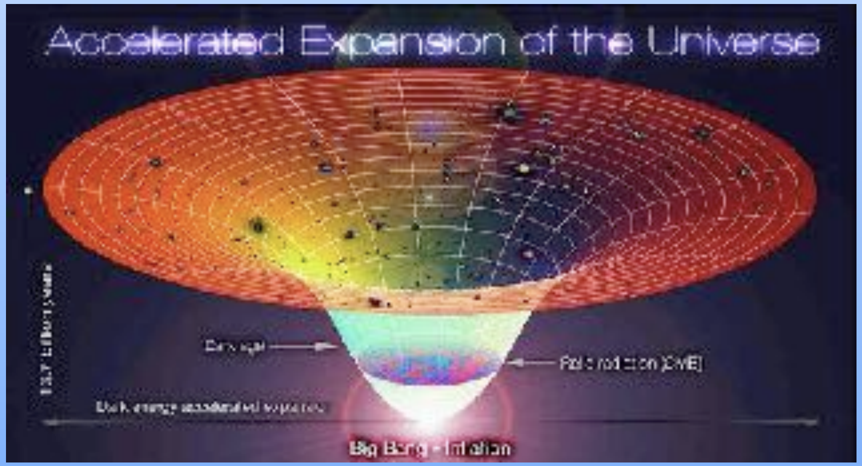
Newton's Gravity → Special Relativity(1905) → **Einstein's Gravity (1915)**

Einstein's Gravity (1915) ⇢ **Dark Matters**

Einstein's Gravity (1915) ⇢ **Dark Energy**

Einstein's Gravity (1915) → **Gravitational Waves (2016)**

Einstein's Gravity (1915) → **Black Holes**

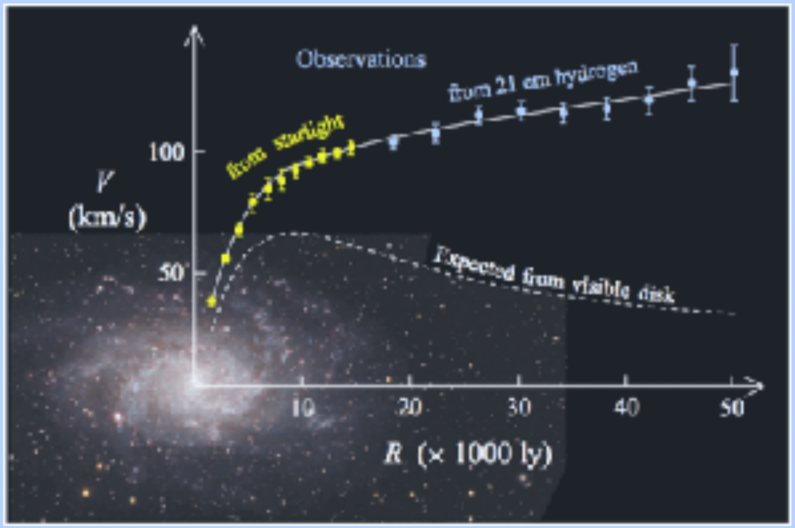


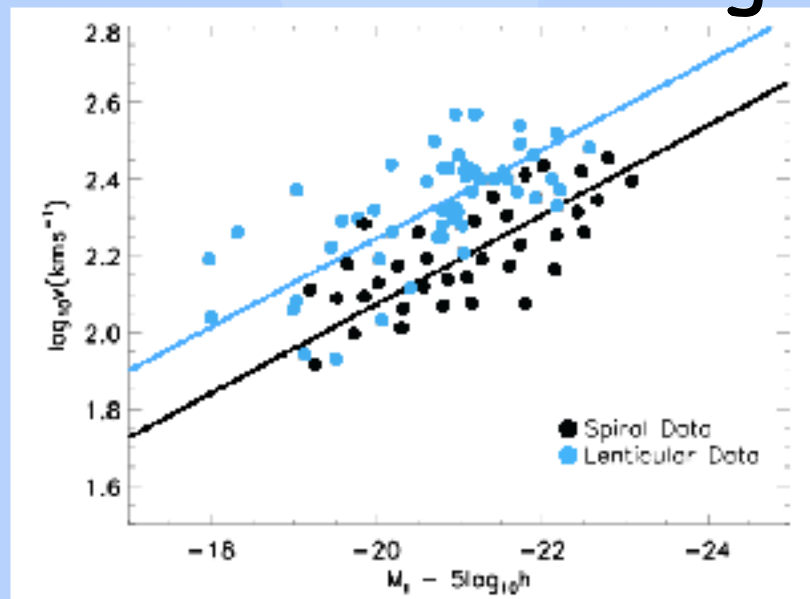
It did not last: the Devil howling: "Ho! Let Einstein be!" restored the status quo. — J. C. Squire

Figures credit: Wiki

I. From Observation to Milgrom's MOND

— Modified Newton Dynamics





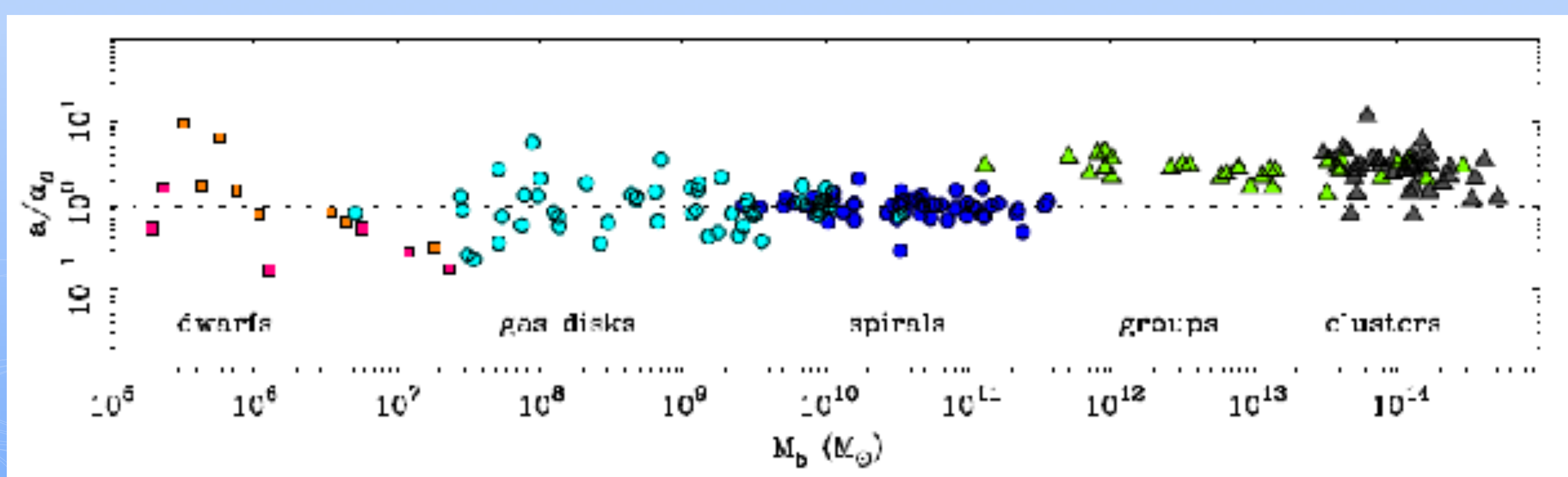
Galaxy Rotation Curve (1970s) → **Tully–Fisher Relation (1977)** → **Milgrom's MOND (1983)**

Tully–Fisher Relation ⇢ **Dark Matter**

$$v_f^4 \simeq a_0 G_N M_B$$

$$F_N = ma\,\mu\left(\frac{a}{a_0}\right)$$

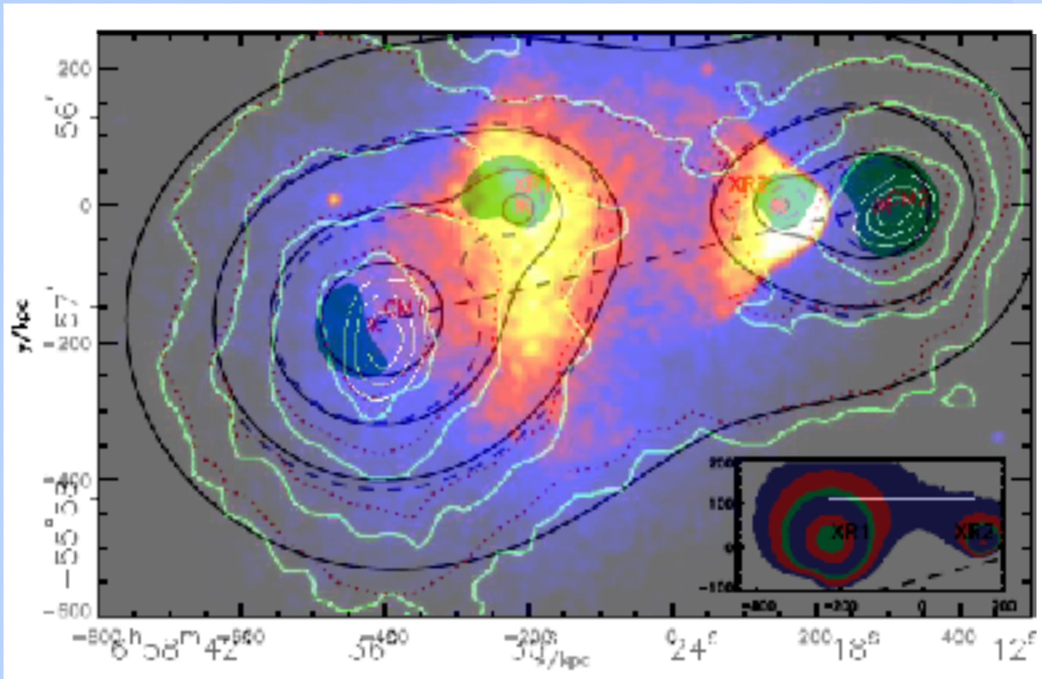
$$a_0 \simeq \sqrt{\Lambda}$$



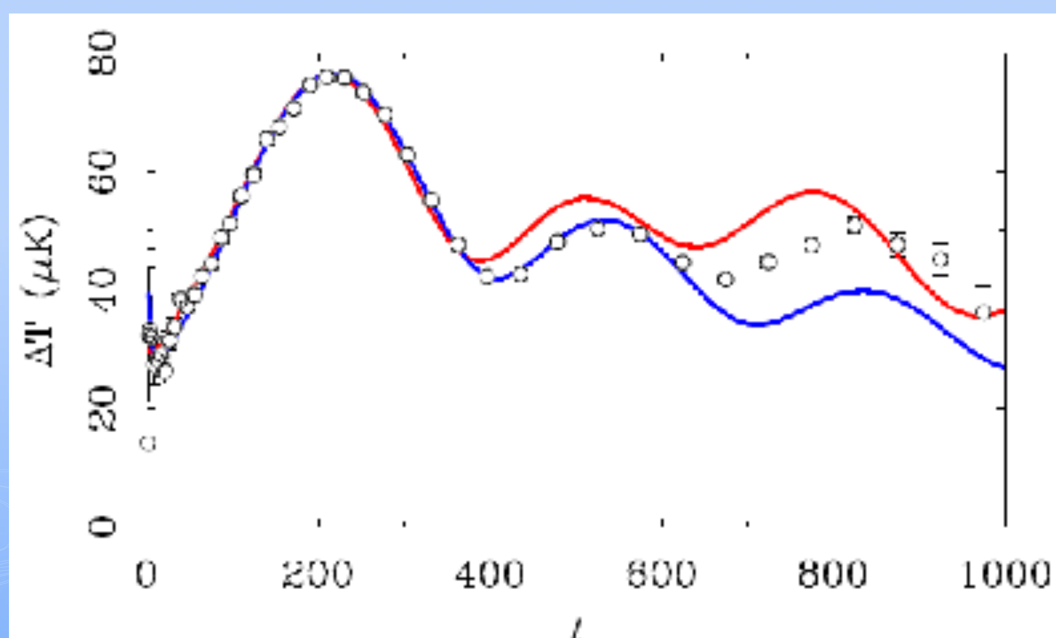
20 years after MOND

$$\nabla \cdot \left[\mu\left(\frac{|\nabla\Phi|}{a_0}\right)\nabla\Phi\right] = 4\pi G\rho$$

Famaey & McGaugh, Living Rev.Rel. 15 (2012) 10



Bullet Clusters

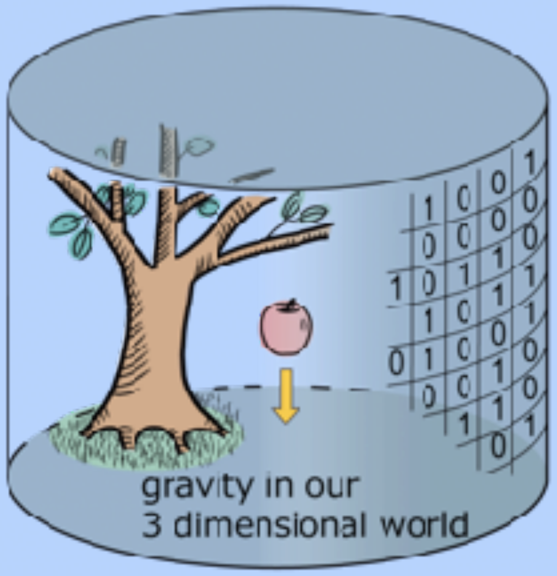


Acoustic Power Spectrum of CMB

Table 2: Observational tests of MOND.

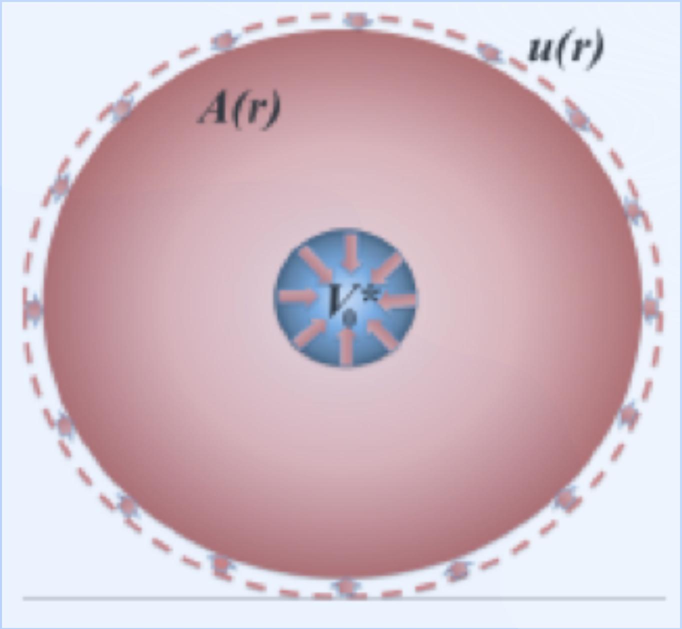
Observational Test	Successful	Promising	Unclear	Problematic
Rotating Systems				
solar system			X	
galaxy rotation curve shapes	X			
surface brightness $\propto \Sigma \propto a^2$	X			
galaxy rotation curve fits	X			
fitted M_*/L	X			
Tully–Fisher Relation				
baryon based	X			
slope	X			
normalization	X			
no size nor Σ dependence	X			
no intrinsic scatter	X			
Galaxy Disk Stability				
maximum surface density	X			
spiral structure in LSBGs	X			
thin & bulgeless disks		X		
Interacting Galaxies				
tidal tail morphology		X		
dynamical friction			X	
tidal dwarfs	X			
Spheroidal Systems				
star clusters			X	
ultrafaint dwarfs			X	
dwarf Spheroidals	X			
ellipticals	X			
Faber-Jackson relation	X			
Clusters of Galaxies				
dynamical mass				X
mass–temperature slope	X			
velocity (bulk & collisional)		X		
Gravitational Lensing				
strong lensing	X			
weak lensing (clusters & LSS)			X	
Cosmology				
expansion history			X	
geometry			X	
big bang nucleosynthesis	X			
Structure Formation				
galaxy power spectrum			X	
empty voids		X		
early structure		X		
Background Radiation				
first:second acoustic peak	X			
second:third acoustic peak				X
detailed fit				X
early re-ionization	X			

II. From Verlinde's Gravity to Dark Universe



Area Law &
Holography

Volume Law &
Entanglement



Entropy Gravity (2010) → **Velinde's Gravity (2016)**

$$\int_0^r \frac{GM_D^2(r')}{r'^2}dr' = \frac{M_B(r)a_0 r}{6}.$$

Tully–Fisher relation

$$g_D(r) = \sqrt{a_M g_B(r)}$$

$$a_M = \frac{a_0}{6}$$

Cluster of galaxies

$$\overline{\rho}_D^2(r) = \left(4 - \overline{\beta}_B(r)\right)\frac{a_0}{8\pi G}\frac{\overline{\rho}_B(r)}{r}$$

$$a_0 = cH_0$$

Parameters in **LCDM**

$$\Omega_D^2 = \frac{4}{3}\Omega_B$$

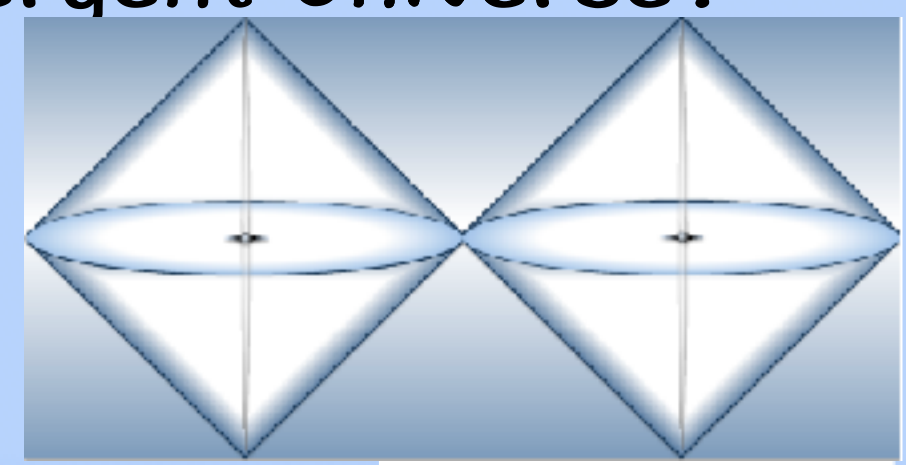
No Covariant Equations of Motion!

Figures credit: Wiki

Compare with Verlinde's Emergent Universe

Gravitational quantity		Elastic quantity		Correspondence
Newtonian potential	Φ	displacement field	u_i	$u_i = \Phi n_i / a_0$
gravitational acceleration	g_i	strain tensor	ε_{ij}	$\varepsilon_{ij} n_j = -g_i / a_0$
surface mass density	Σ_i	stress tensor	σ_{ij}	$\sigma_{ij} n_j = \Sigma_i a_0$
mass density	ρ	body force	b_i	$b_i = -\rho\, a_0 n_i$
point mass	m	point force	f_i	$f_i = -m\, a_0 n_i$

Holographic Universe vs. Emergent Universe?



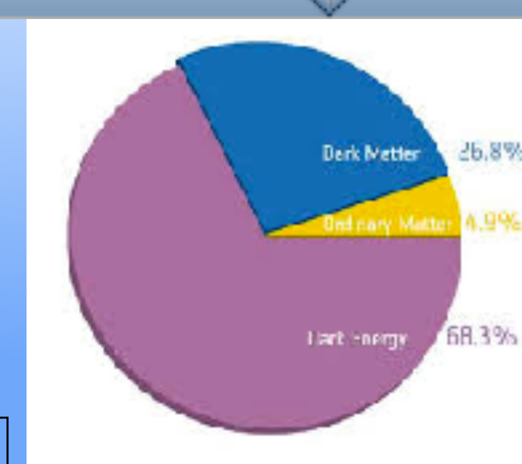
$$\frac{\mathcal{T}^2}{d-1} - \mathcal{T}_{\mu\nu}\mathcal{T}^{\mu\nu} = -\frac{\rho_\Lambda c^2}{d-1}(T + \mathcal{T}).$$

Constrain Equations

$$\Delta_V \equiv \Omega_D^2 - \frac{4}{3}\Omega_B \simeq 0.36\%\,,$$

$$\Delta_{CSZ} \equiv \Omega_D^2 - \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B) \simeq -0.34\%\,.$$

R.G. Cai, S. Sun, Y.L. Zhang, 1712.09326



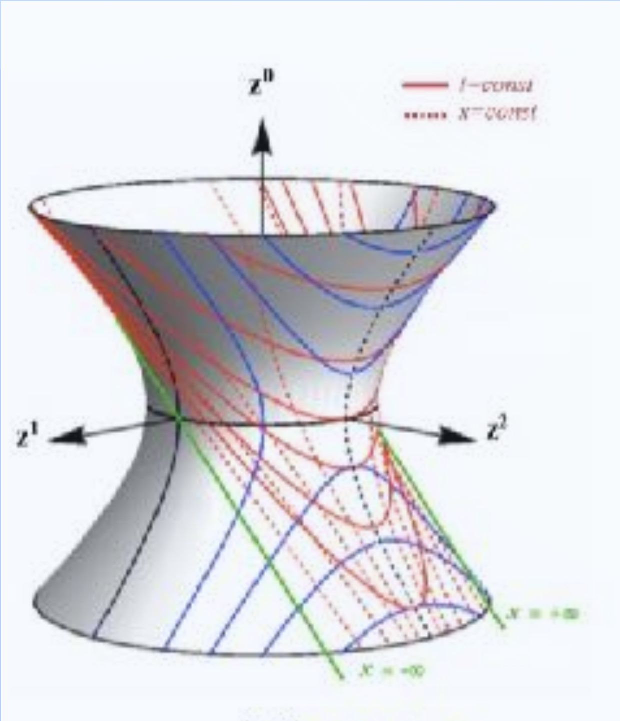
LCDM Universe?

$$H(a)^2 = H_0^2\left[\Omega_\Lambda + (\Omega_D + \Omega_B)a^{-3} + \Omega_R a^{-4}\right]$$

III. Holographic dS Universe? — dS Screen in a Flat Bulk

1) Holographic Stress Tensor — Dark Sectors

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \kappa_4 T_{\mu\nu} + \kappa_4 \langle \mathcal{T} \rangle_{\mu\nu}, \qquad \langle \mathcal{T} \rangle_{\mu\nu} \equiv \frac{1}{\kappa_4 L} \left(\mathcal{K}_{\mu\nu} - \mathcal{K} g_{\mu\nu} \right)$$



Modified Einstein equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} - \frac{1}{L} \left(\mathcal{K}_{\mu\nu} - \mathcal{K} g_{\mu\nu} \right) = \kappa_4 T_{\mu\nu}$$

Hamiltonian constraints

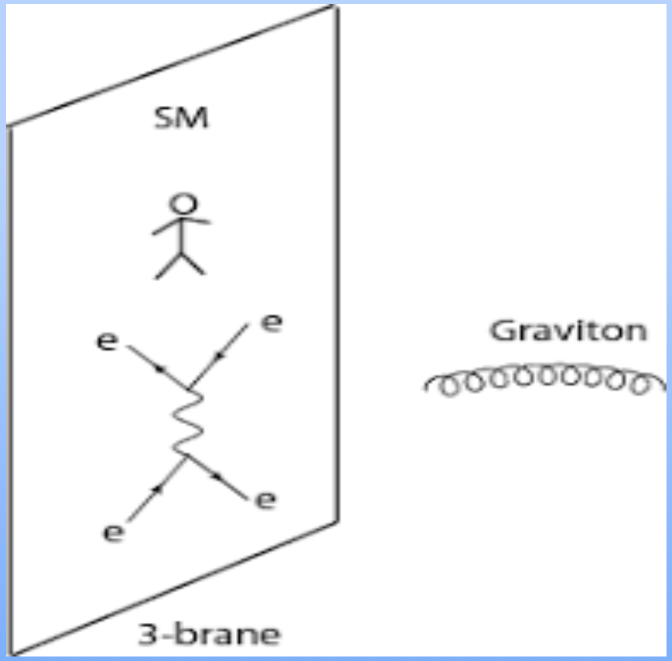
$$\mathcal{K}^2 - \mathcal{K}_{\mu\nu} \mathcal{K}^{\mu\nu} = R + 2\, G^{(d+1)}_{MN} \mathcal{N}^M \mathcal{N}^N,$$

2) Embedding in higher dimensions — Brane World Models

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \mathcal{T}^{\mathcal{M}}_{\mu\nu} + T^{B}_{\mu\nu},$$

$$\mathcal{T}^{\mathcal{M}}_{\mu\nu} \equiv (\mathcal{K} g_{\mu\sigma} - \mathcal{K}_{\mu\sigma}) \mathcal{K}^{\sigma}{}_{\nu} + \mathcal{M}_{\mu\nu} - \frac{1}{2} \left(\mathcal{K}^2 - \mathcal{K}_{\rho\sigma} \mathcal{K}^{\rho\sigma} \right) g_{\mu\nu},$$

$$\mathcal{M}_{\mu\nu} \equiv g_{\mu}{}^{M} g_{\nu}{}^{N} R^{(d+1)}_{MN} - g_{\mu}{}^{M} \mathcal{N}^{P} g_{\nu}{}^{N} \mathcal{N}^{Q} R^{(d+1)}_{MPNQ}.$$

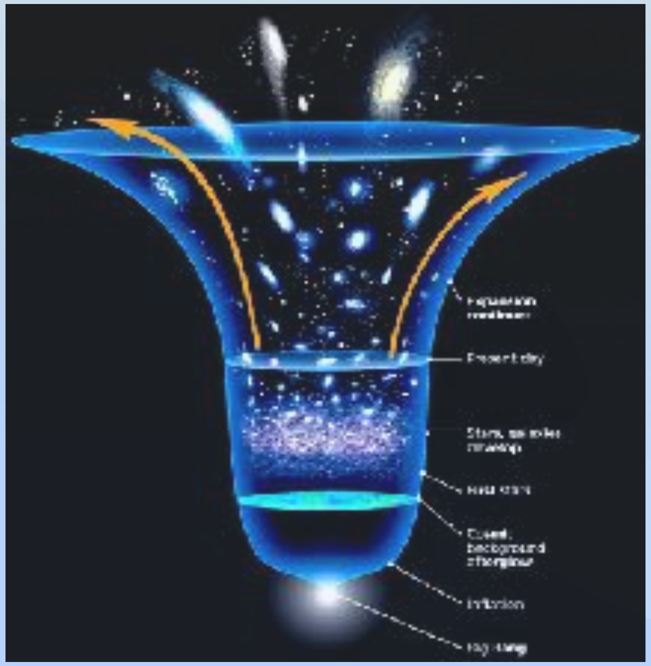


Ref: 1106.2476 [Living Rev. '10]

Holographic FRW Universe? — FRW Screen in a Flat Bulk

$$\mathcal{S}_5 = \frac{1}{2\kappa_5}\int_{\mathcal{M}} \mathrm{d}^5x\sqrt{-\tilde{g}}\,\mathcal{R} + \frac{1}{\kappa_5}\int_{\partial\mathcal{M}} \mathrm{d}^4x\sqrt{-g}\,\mathcal{K},$$

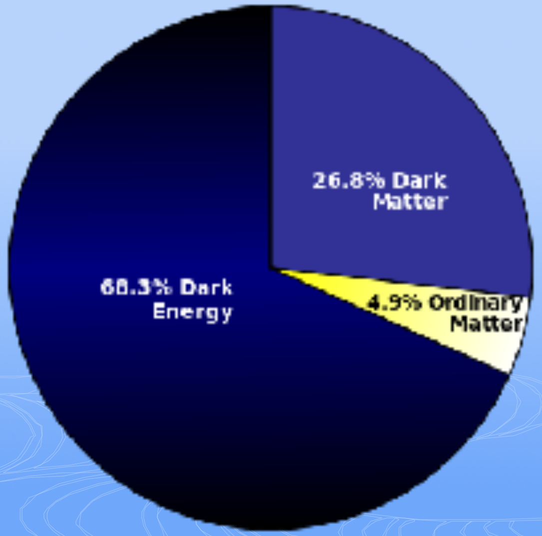
$$\mathcal{S}_4 = \frac{1}{2\kappa_4}\int_{\partial\mathcal{M}} \mathrm{d}^4x\sqrt{-g}\,R + \int_{\partial\mathcal{M}} \mathrm{d}^4x\sqrt{-g}\mathcal{L}_M.$$



FRW Screen $$\mathrm{d}s_4^2 = -\,c^2\mathrm{d}t^2 + a(t)^2\left[\mathrm{d}r^2 + r^2\mathrm{d}\Omega_2\right]$$

Friedmann eq. $$\frac{H(t)^2}{H_0^2} \simeq \frac{\Omega_B}{a(t)^3} + \Omega_\Lambda^{1/2}\left[\frac{H(t)^2}{H_0^2} + \frac{\Omega_I}{a(t)^4}\right]^{1/2}$$

Ref: 1712.09326 [Cai, Sun, Zhang]

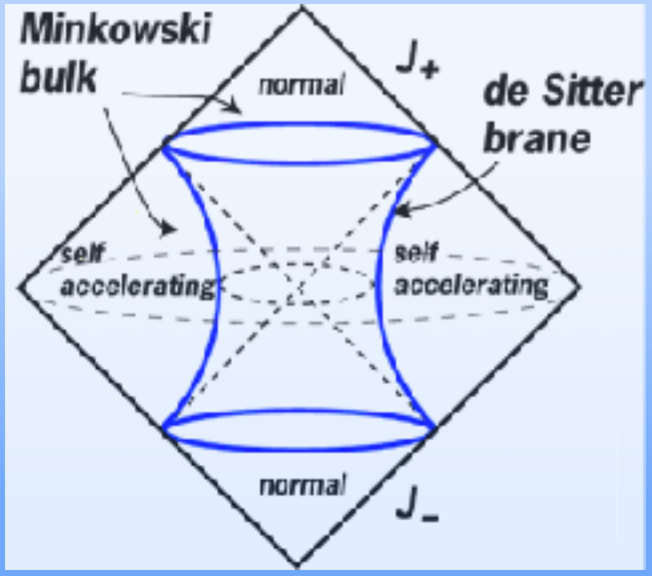


DGP BraneWorld

$$\frac{H(t)^2}{H_0^2} = \frac{\Omega_M}{a(t)^3} + \Omega_\ell^{1/2}\frac{H(t)}{H_0},$$

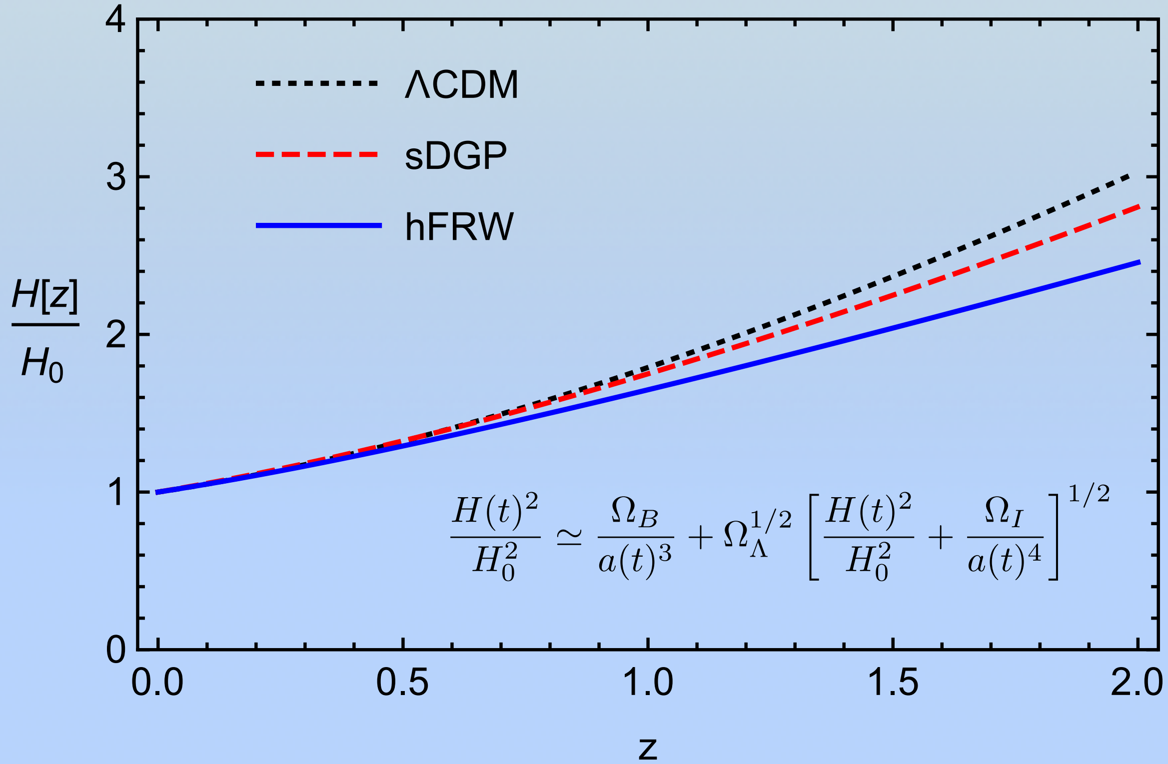
$$\dot{\rho}_\imath(t) = -3H(t)\left[\rho_\imath(t) + p_\imath(t)/c^2\right],$$

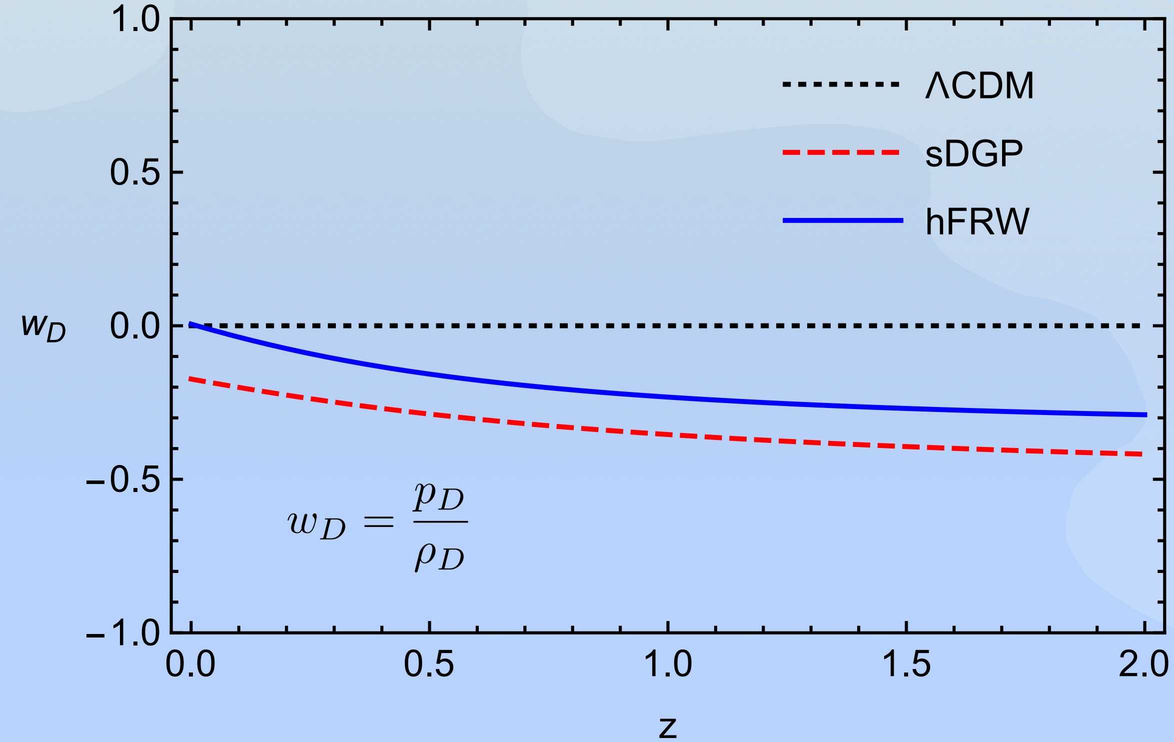
Self accelerating Branch



Ref: 1106.2476 [Living Rev. '10]

Late-Time Evolution of Holographic FRW Model





Holographic dark matter Fluid: Equation of State

$$\Delta_B = \frac{\Omega_M}{a(t)^3} = \frac{H(t)^2}{H_0^2} - \Delta_{\mathcal{H}}, \quad \Delta_{\mathcal{H}} \equiv \frac{\rho_{\mathcal{H}}}{\rho_c} = \Omega_\Lambda^{1/2}\left[\frac{H(t)^2}{H_0^2} + \frac{\Omega_I}{a(t)^4}\right]^{1/2},$$

$$\Delta_\Lambda = \Omega_\Lambda, \qquad \Delta_D = \Delta_{\mathcal{H}} - \Omega_\Lambda, \qquad w_D = -1 - \frac{1}{3H(t)}\frac{\dot{\Delta}_{\mathcal{H}}}{\Delta_{\mathcal{H}}}.$$

Embedding Function

$$\mathrm{d}s_5^2 = \tilde{g}_{AB}\mathrm{d}x^A\mathrm{d}x^B = \mathrm{d}y^2 - \mathbf{n}(y,t)^2\ c^2\mathrm{d}t^2 + \mathbf{a}(y,t)^2\left[\mathrm{d}r^2 + r^2\mathrm{d}\Omega_2\right].$$

$$\mathbf{a}(y,t)^2 = a(t)^2 + y^2\frac{\dot{a}(t)^2}{c^2} \pm 2y\sqrt{a(t)^2\frac{\dot{a}(t)^2}{c^2} + I},$$

$$\mathbf{n}(y,t) = \frac{\partial_t \mathbf{a}(y,t)}{\dot{a}(t)}. \qquad (\kappa_5 c^2)\rho_{\mathcal{H}} = -\frac{3\partial_y \mathbf{a}(y,t)}{\mathbf{a}(y,t)}\Big|_{y=0} = 3\left[\frac{H(t)^2}{c^2} + \frac{I}{a(t)^4}\right]^{1/2},$$

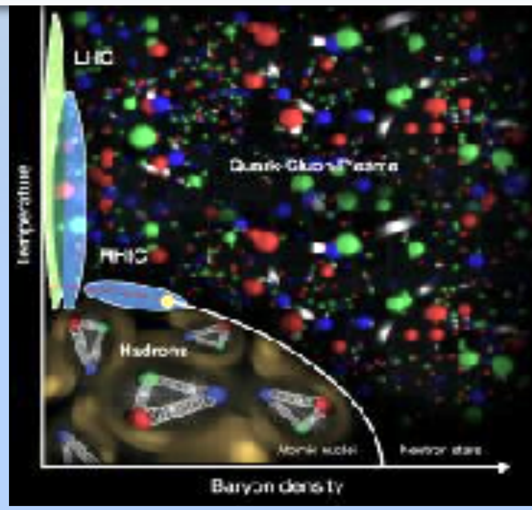
Summary of the Holographic Fluid

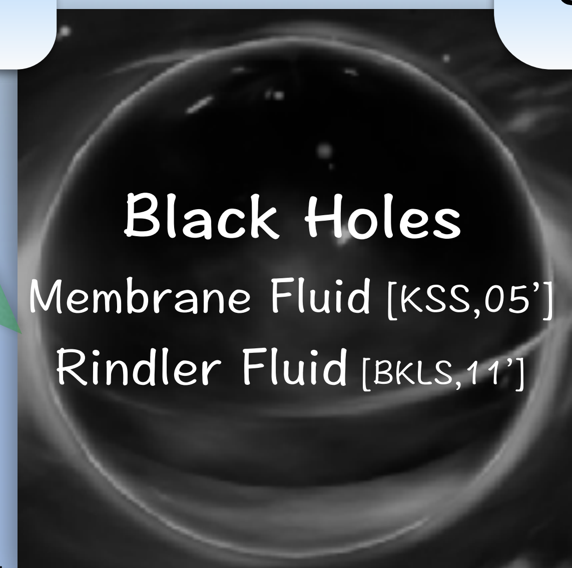
Quark Gluon Plasma

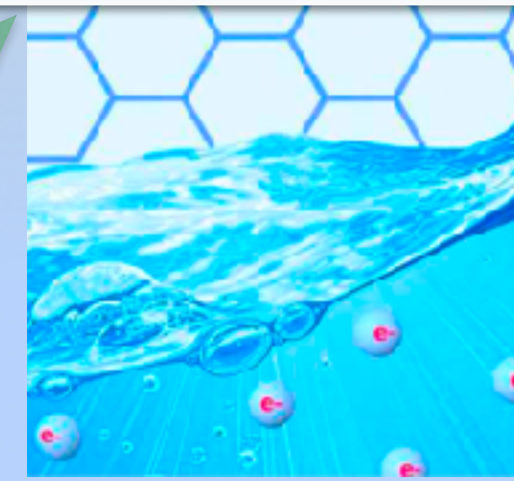
RHIC ['08] & LHC ['16]

Quantum Critical Liquid

Graphene ['09] & Semi-Metal['16]





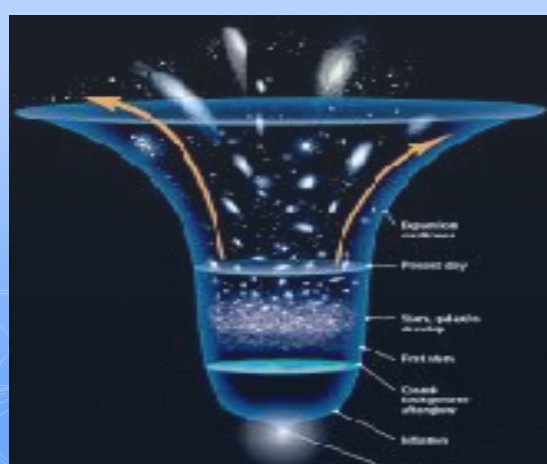


$$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

$$\tau_c^{-1} \simeq \frac{k^2}{4\pi T_c}$$

$$\frac{H^2}{H_0^2} \simeq \frac{\Omega_B}{a^3} + \sqrt{\Omega_\Lambda\left(\frac{H^2}{H_0^2} + \frac{\Omega_I}{a^4}\right)}$$

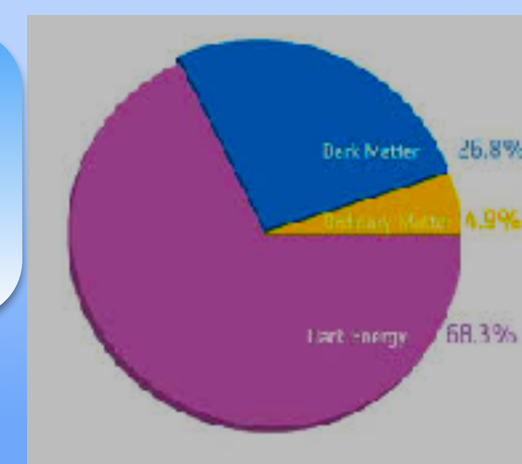
$$\Omega_D^2 \simeq \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B)$$



Cosmological Fluid [CSZ,'17]

Dark Matter & Dark Energy

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{1}{L}\left(\mathcal{K}_{\mu\nu} - \mathcal{K}g_{\mu\nu}\right) = \kappa_4 T_{\mu\nu}$$



Figures Credit: RHIC & Google

Constrains on MOND from Gravitational waves

Chesler & Loeb, arXiv:1704.05116 [PRL, '17]

1) The Speed of gravitational waves

Constraint of energy loss rate from ultra-high energy cosmic rays

2) Linear equations of motion in the weak-field limit

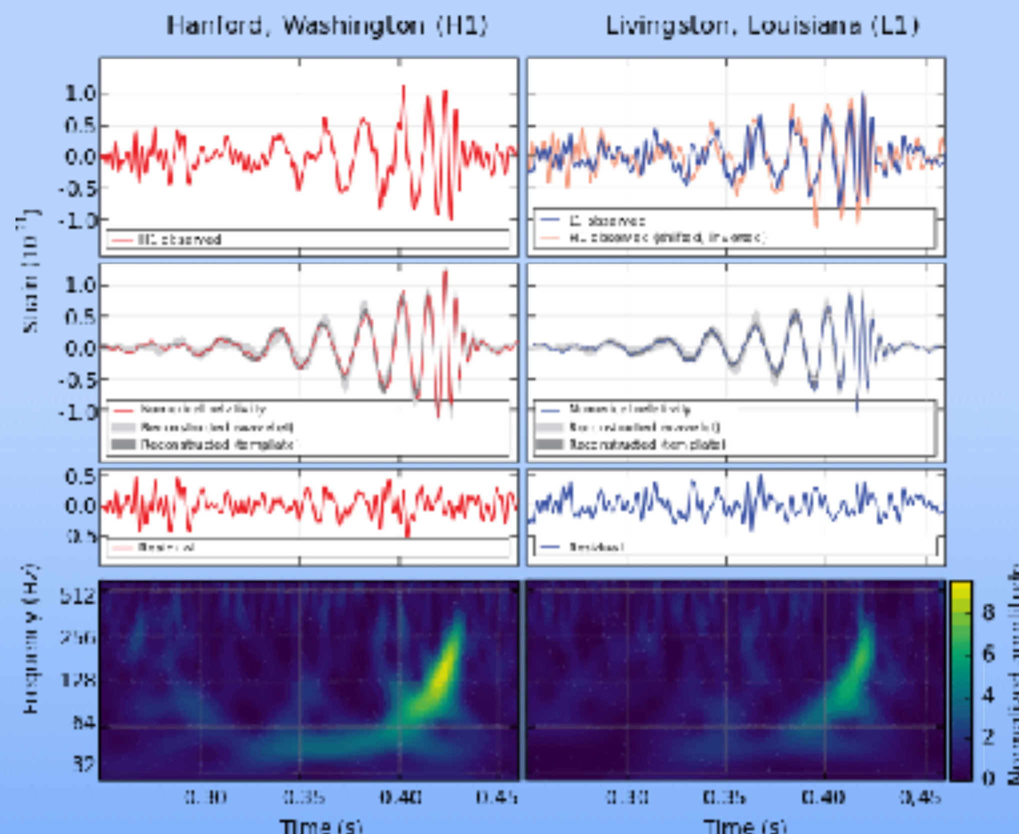
The observed gravitational waveforms from LIGO, which are consistent with Einstein's gravity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{g}\,\left[R + \mathcal{M}^2\mathcal{F}(\tfrac{\mathcal{K}}{\mathcal{M}^2}) + \lambda(A^2{+}1)\right] + S_{\rm mat}$$

Einstein-Aether theory (2004, Bekenstein)

$$\begin{aligned} R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} &= \mathcal{T}_{\mu\nu} + 8\pi G T^{\rm mat}_{\mu\nu}, \\ \nabla_\alpha[\mathcal{F}' J^\alpha_{\ \beta}] - \mathcal{F}' y_\beta &= 2\lambda A_\beta, \end{aligned}$$

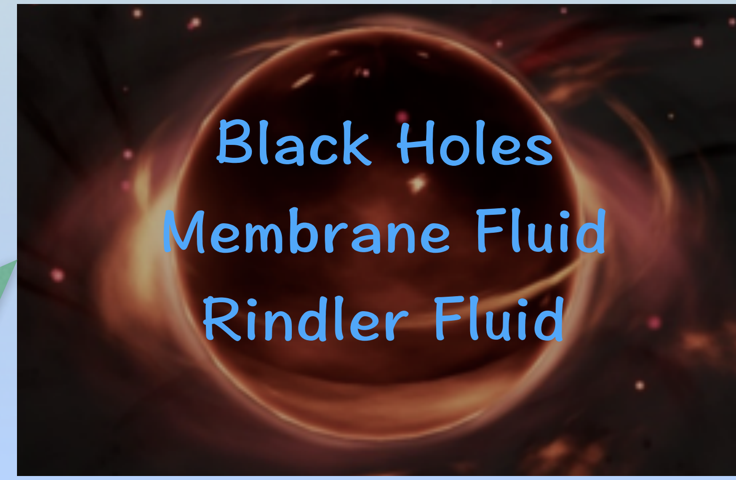
$$\begin{aligned} \mathcal{T}_{\alpha\beta} &= \tfrac{1}{2}\nabla_\sigma\{\mathcal{F}'[J_{(\alpha}{}^{\sigma}A_{\beta)} - J^{\sigma}{}_{(\alpha}A_{\beta)} - J_{(\alpha\beta)}A^\sigma]\} \\ &- \mathcal{F}'Y_{\alpha\beta} + \tfrac{1}{2}g_{\alpha\beta}\mathcal{M}^2\mathcal{F} + \lambda A_\alpha A_\beta, \end{aligned}$$



Summary & Outlook

$$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

$$\tau_c^{-1} \simeq \frac{k^2}{4\pi T_c}$$



$$\Omega_D^2 \simeq \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B)$$

$$\frac{H^2}{H_0^2} \simeq \frac{\Omega_B}{a^3} + \sqrt{\Omega_\Lambda\left(\frac{H^2}{H_0^2} + \frac{\Omega_I}{a^4}\right)}$$

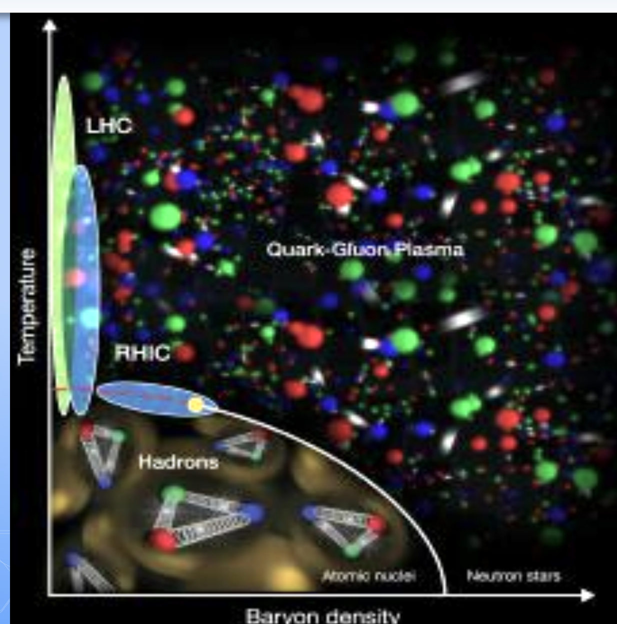
Quark Critical Liquid

QGP in RHIC ['08] & LHC ['16]

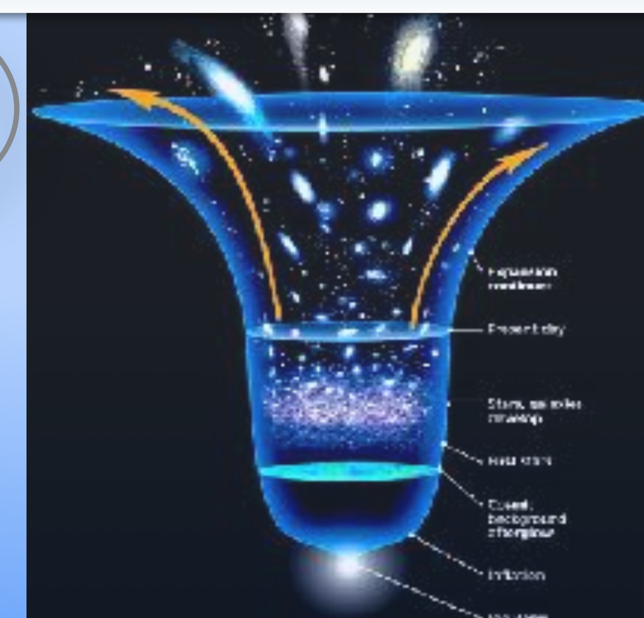
?

Cosmological Fluid

Dark Matter['70s] & Energy['90s]



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{1}{L}\left(\mathcal{K}_{\mu\nu} - \mathcal{K}g_{\mu\nu}\right) = \kappa_4 T_{\mu\nu}$$



Thanks for All Your Attention!

Ref: 1712.09326 [Cai, Sun, Zhang]

Figures Credit: Nature & Wiki

Report on JHEP_066P_0418

Date: June 6, 2018

Author(s): Rong-Gen Cai, Sichun Sun, Yun-Long Zhang

Title: Emergent Dark Matter in Late Universe on Holographic Screen

Received: 2018-04-09 14:35:06.0

This took quite a long while. Given the gravity of this affair, I approached two quite distinguished referee's. You may guess who is the second referee who let me wait quite long. Even he likes it! In principle your work has survived scrutiny of the most serious kind. But both referee's come up with the same recommendation: given that it is a very serious and potentially highly consequential contribution, please put in some extra effort to improve the quality of the text and the coherence of the line of arguments. Such an extra investment is just worthwhile.Surely you should exploit the suggestion of the first referee associated with the DM equation of state.

Report of referee 1

Dear Editor,

I recommend that the article "Emergent Dark Matter in Late Universe on Holographic Screen" by R.-G. Cai, S. Sun, and Y.-L. Zhang be published in

Report of referee 2

This paper proposes an holographic approach to explain the dark contributions to the cosmological energy density: dark energy as well as dark matter. The central idea is appealing: the universe is modeled as a brane embedded in a higher dimensional spacetime, in which only the ordinary (=baryonic) matter (and radiation) are described by a stress energy tensor on the brane. The dark components of the stress energy tensor are in this approach induced by the extrinsic curvature components associated with the brane embedding.

The paper logically consists of three parts. In the first part a relation between the energy densities associated with dark energy, dark matter and baryonic matter is derived in a simplified toy model. Despite the simplicity of the model, it is striking that this relation appears to hold in the current late universe to a very good degree. This part is well presented and logically coherent.

Research Background of Y.-L. Zhang

Nov. 2018 — JSPS Fellow at Kyoto U. with Prof. Shinji Mukohyama(YITP)

Black Holes and Quantum Matters

Diffusions & Emergent Gravity & SYK Model

2016-2018 Postdoc at APCTP (亚太理论物理中心)

Young Scientist Training(YST) Program @Pohang

Holography and Effective Theory

Phase Transition & mu2e &$0\nu\beta\beta$

2014-2016 Postdoc at NTU（台湾大学）

with Prof. Jiunn-Wei Chen @Taipei

Gravity and Hydrodynamics

Einstein Eqs & Navier-Stokes Eqs

2009-2014 Ph.D at ITP/CAS (中科院理论物理所)

with Prof. Rong-Gen Cai @Beijing

[2013-2014 visiting at U. of Southampton(UK)]

2005-2009 B.S. at Lanzhou U.(兰州大学) with Prof. Yu-Xiao Liu