Emergent Dark Matter and the Evolution of the Late Universe

by **Yun-Long Zhang** (张云龙)

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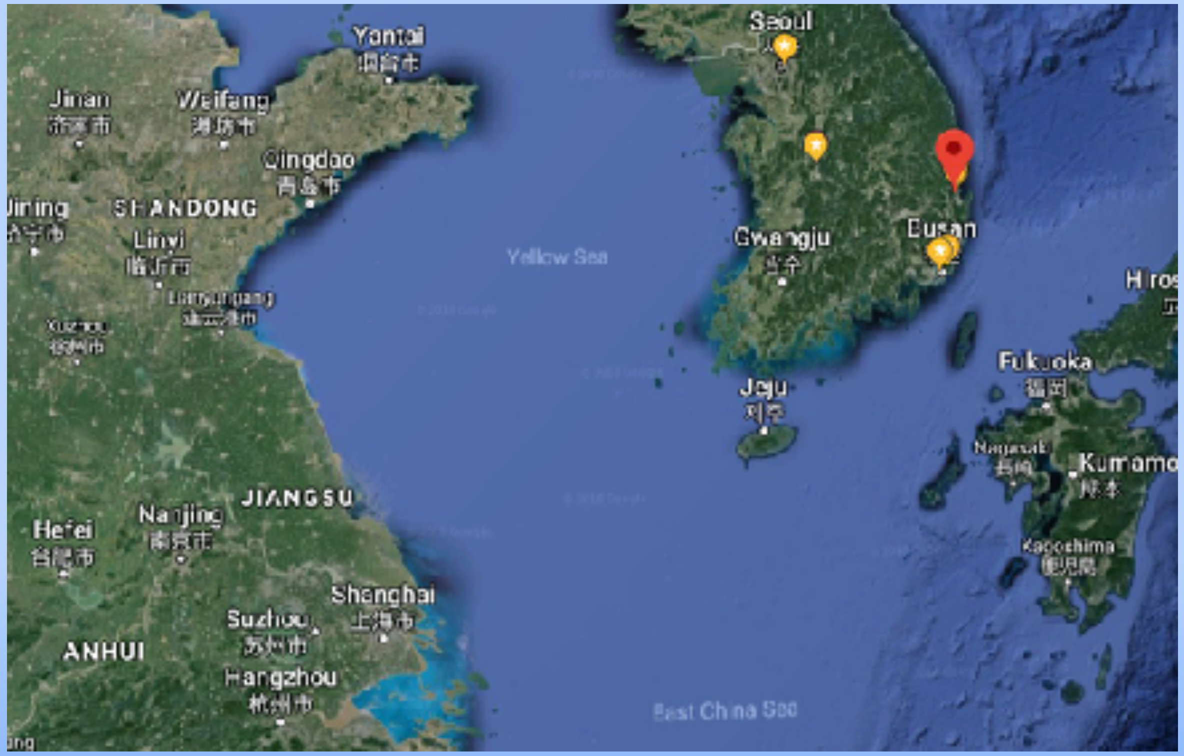
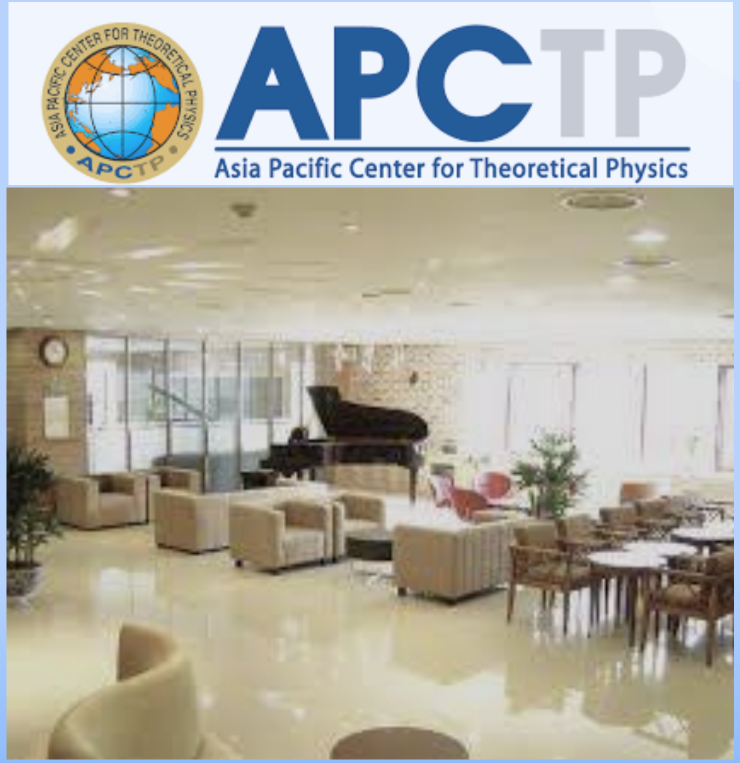




Emergent Dark Matter in Late Universe on Holographic Screen

by R.-G. Cai, S.-C. Sun, **Yun-Long Zhang** [arXiv: 1712.09326]

Research Background of Y.L.Zhang

Gravity and Hydrodynamics

Einstein Equations & Navier-Stokes Equations

2009-2014 Ph.D at ITP/CAS (中科院理论物理所)

with Prof. R. G. Cai @Beijing

Holography and Effective Theory

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

2014-2016 Postdoc at NTU（台湾大学）

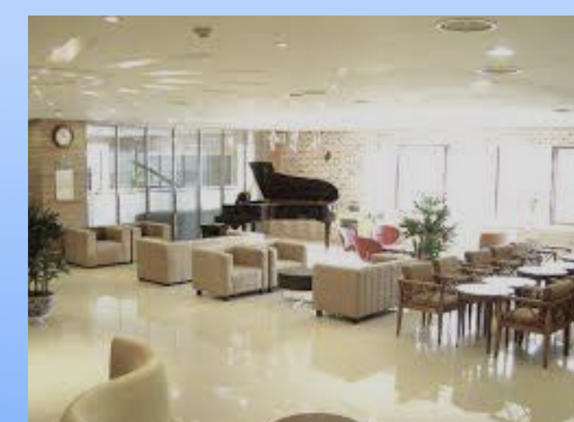
with Prof. J. W. Chen @Taipei

Black Holes and Quantum Matters

Diffusions & Emergent Theory & SYK Model

2016-now Postdoc at APCTP (亚太理论物理中心)

YST Program @Pohang



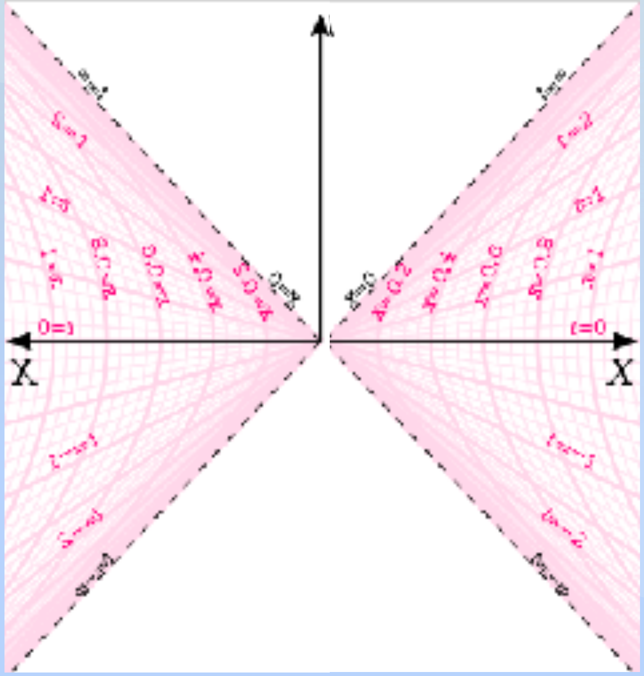
Holographic Screens in Flat Spacetime

— Rindler Screen & de-Sitter Screen

I. Black Holes & Rindler Fluid

— Accelerating Screen

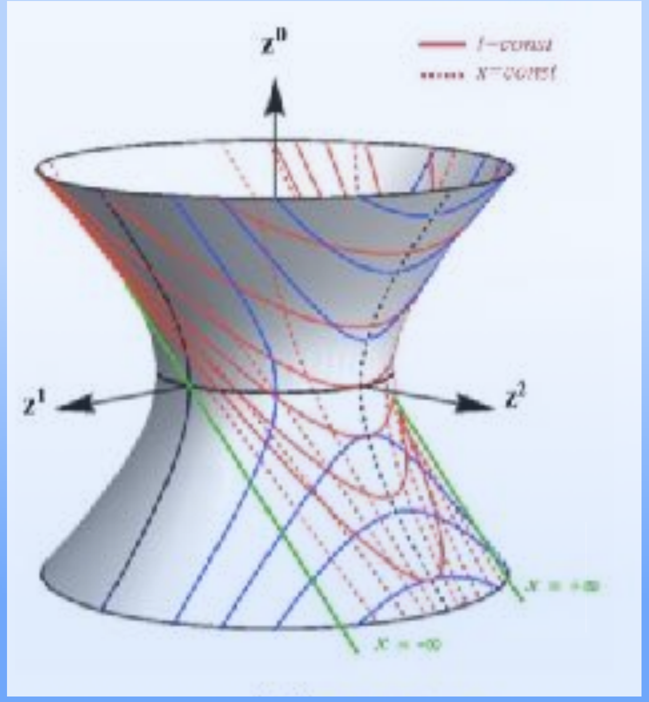
— Relation to AdS/CFT



II. Dark Matter Fluid & dS Membrane

— de-Sitter & FRW Screens

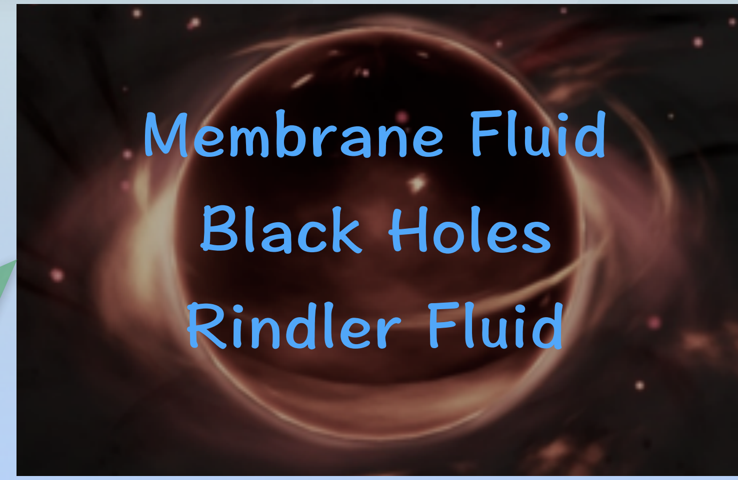
— Relation to DGP Brane-world



Universal Holographic Properties of Horizon

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

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

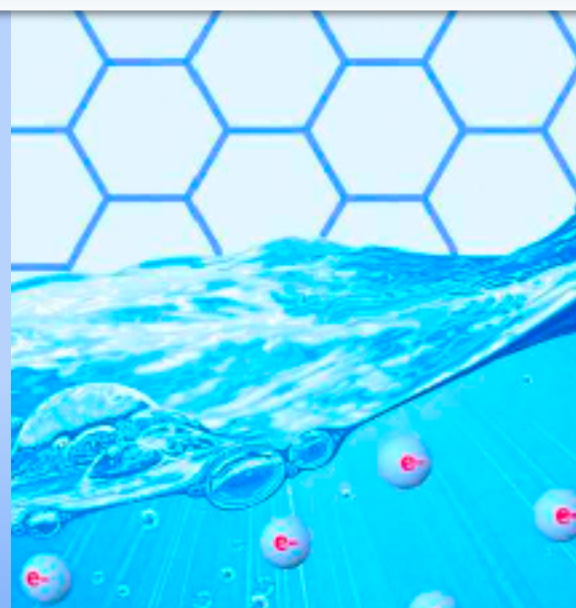


$$\Omega_D^2 \simeq \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B)$$

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

Quantum Critical Liquid

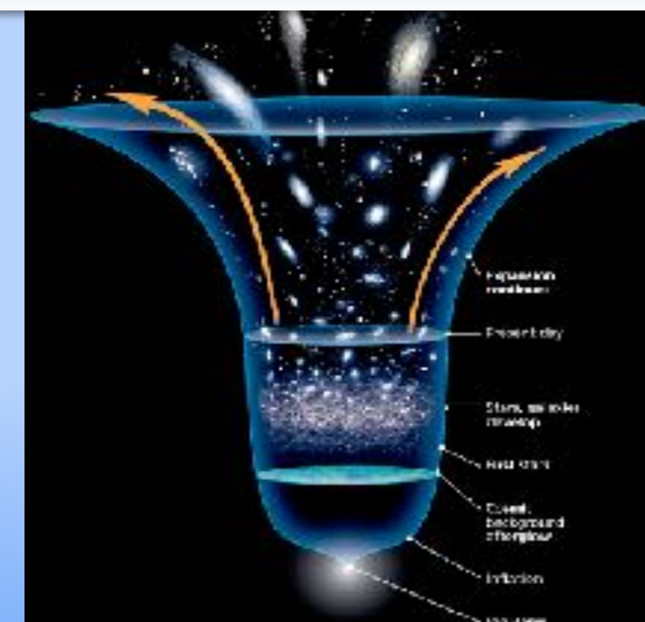
Graphene & Semi-Metal & QGP



Rindler Fluid [1705.05078]

Cosmological Fluid

Dark Matter & Energy



Cosmic Fluid [1712.09326]

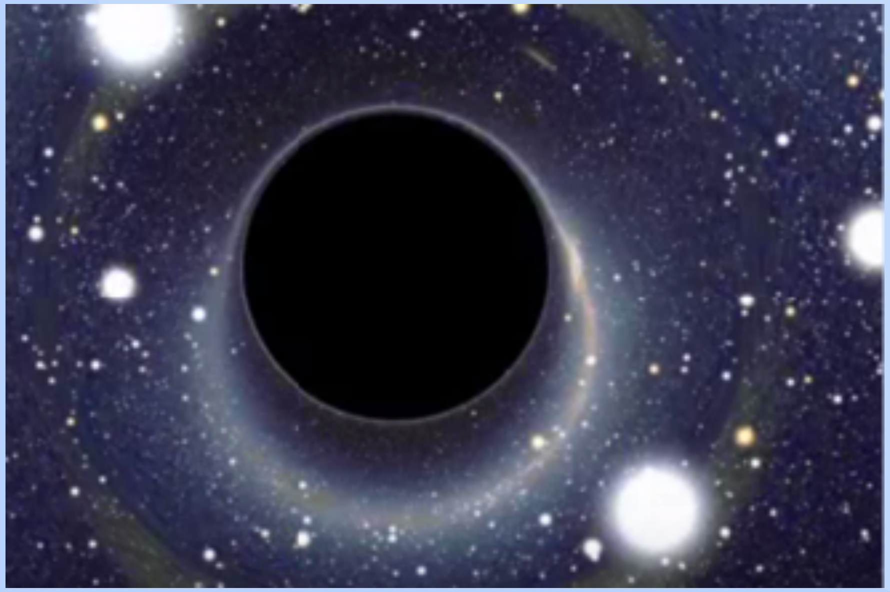
Figures Credit: Nature & Wiki

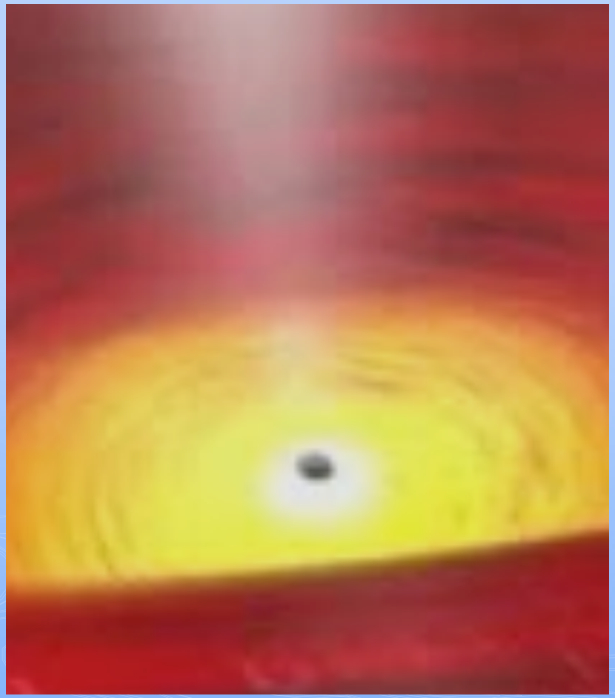
Thermodynamics (1970s): Hawking Radiation

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

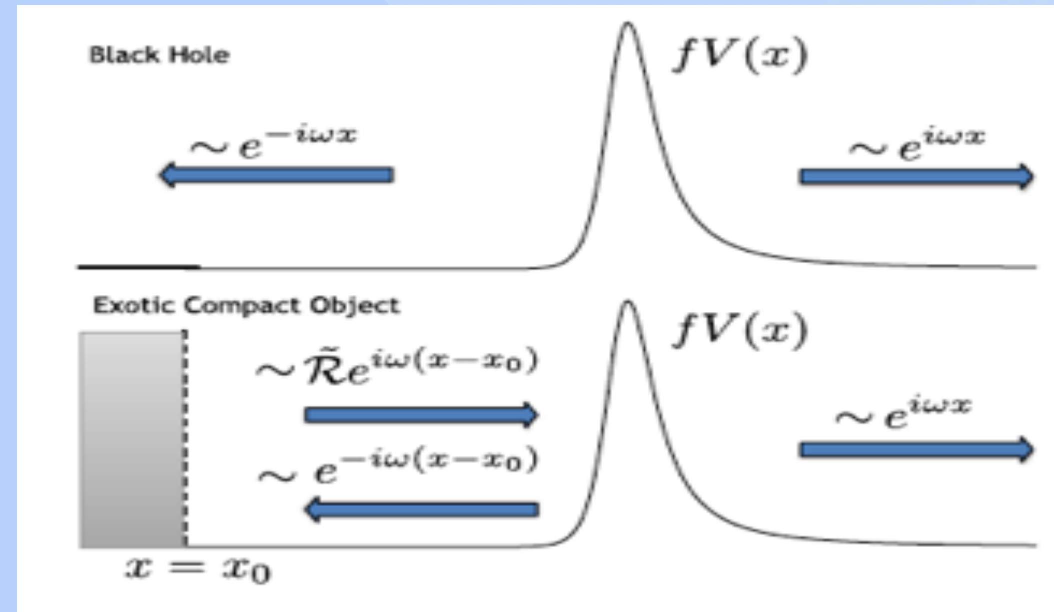
1st Law: $dE = \frac{\kappa}{8\pi} dA + \Omega\, dJ + \Phi\, dQ,$

2nd Law: non-decreasing of entropy

3rd Law: extremal black hole is not possible

Membrane paradigm(1980s): Effective Fluid

T. Doumer & K. Thorne, ···

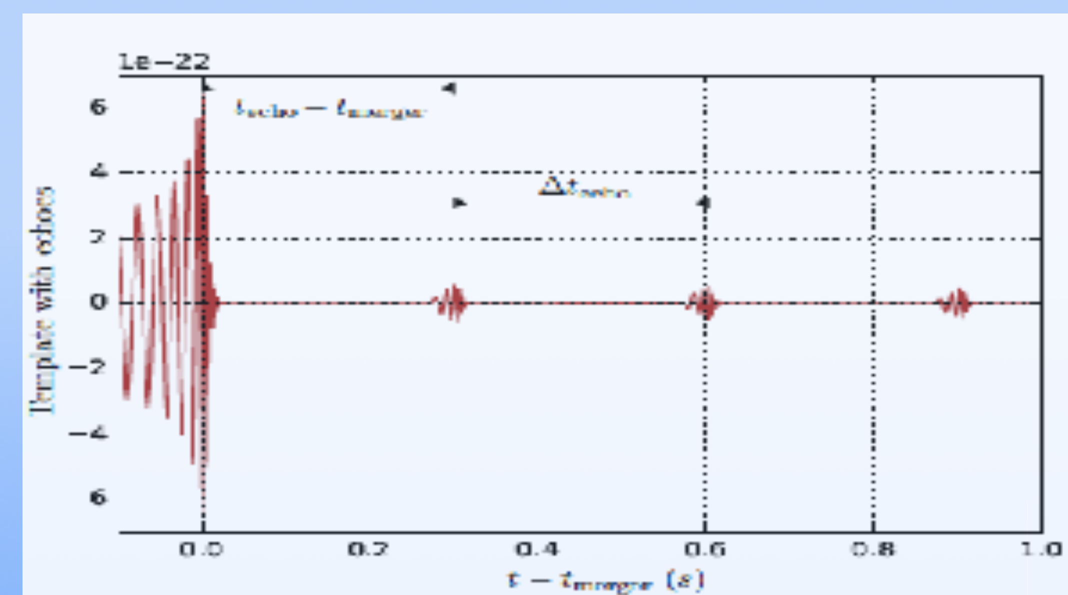


Effective Description

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

Membrane on Stretched horizon

Viscosity & Conductivity



Echoes from the Abyss [1612.00266 PRD'17]

AdS/CFT Duality (2000s):

Maldacena & Gubser & Witten,et al

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

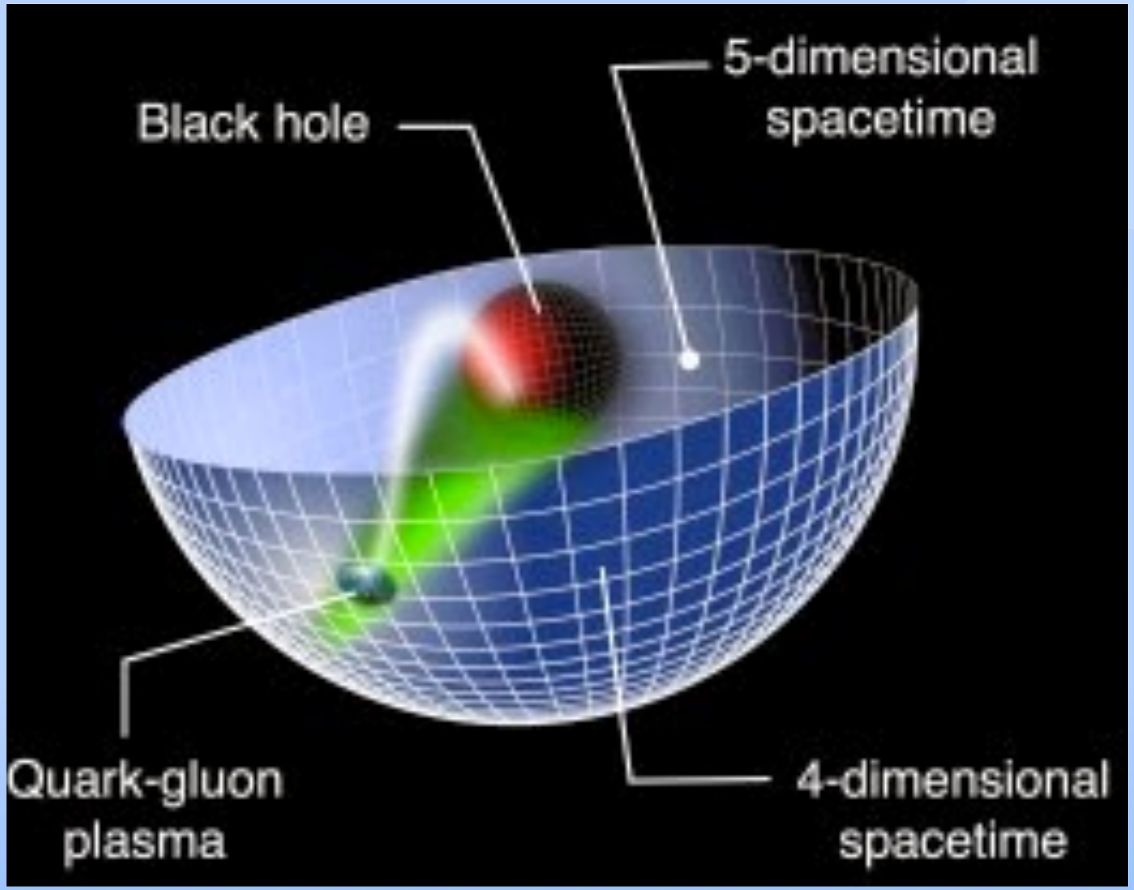
AdS/CMT Correspondence Black Hole in a natural Cavity

Shear Viscosity $\frac{\eta}{s} \approx \frac{\hbar}{4\pi k}$

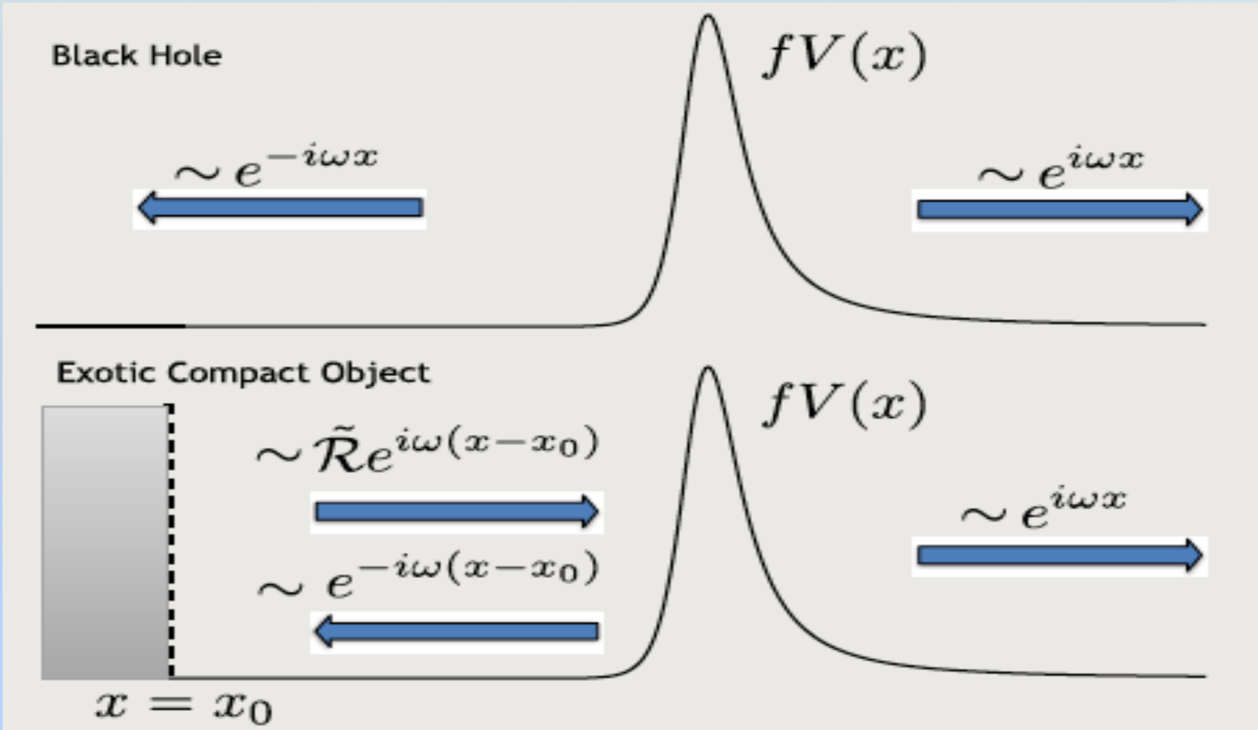
Conductivity

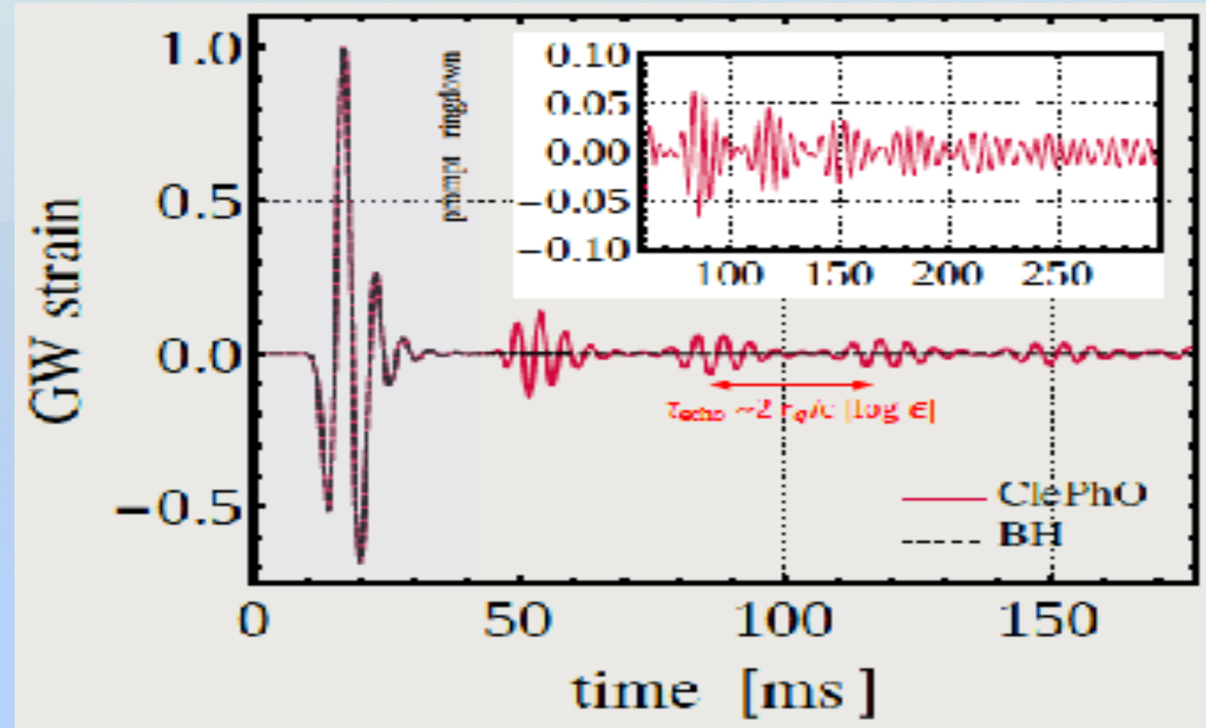
Holographic Superconductor

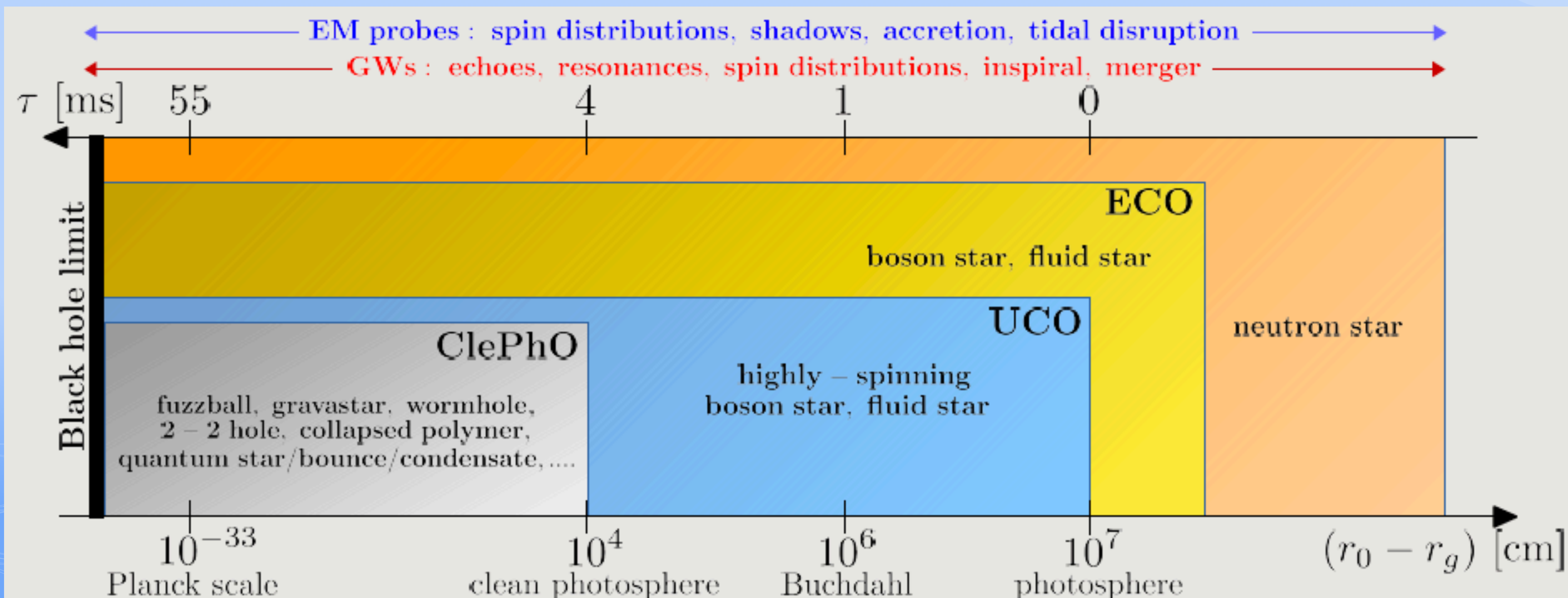
Holographic Non-Fermi Liquid



New Physics Between Neutron Star and Black Holes?







1709.01525[Nat.Astron.]

Traversable Wormholes or Black Holes?

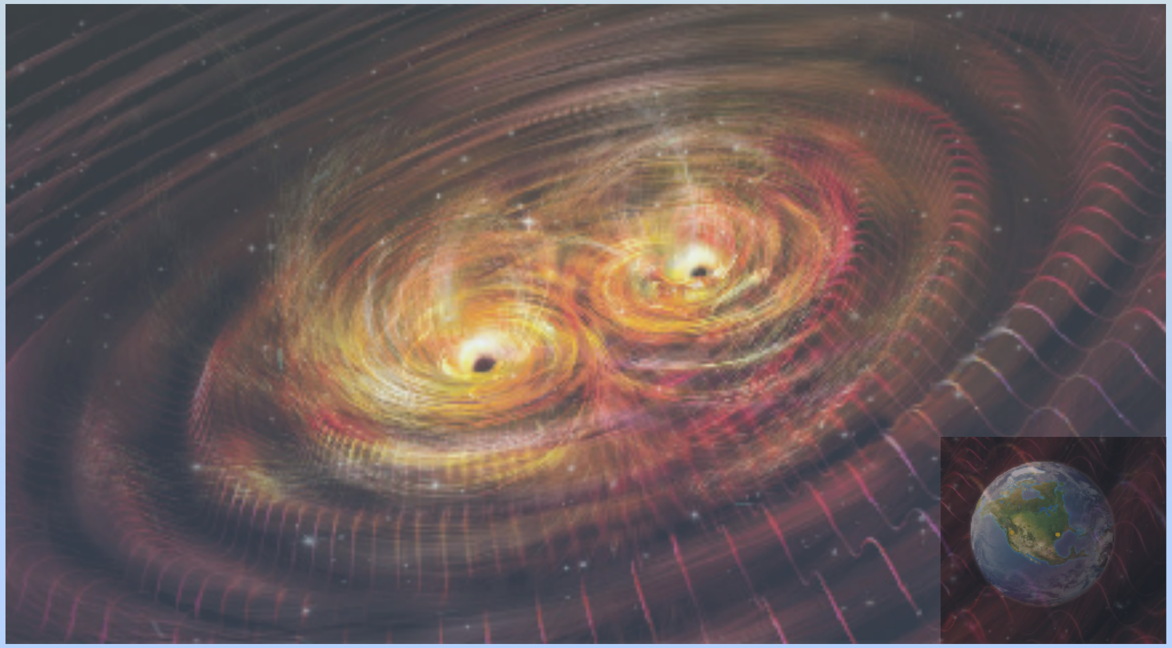
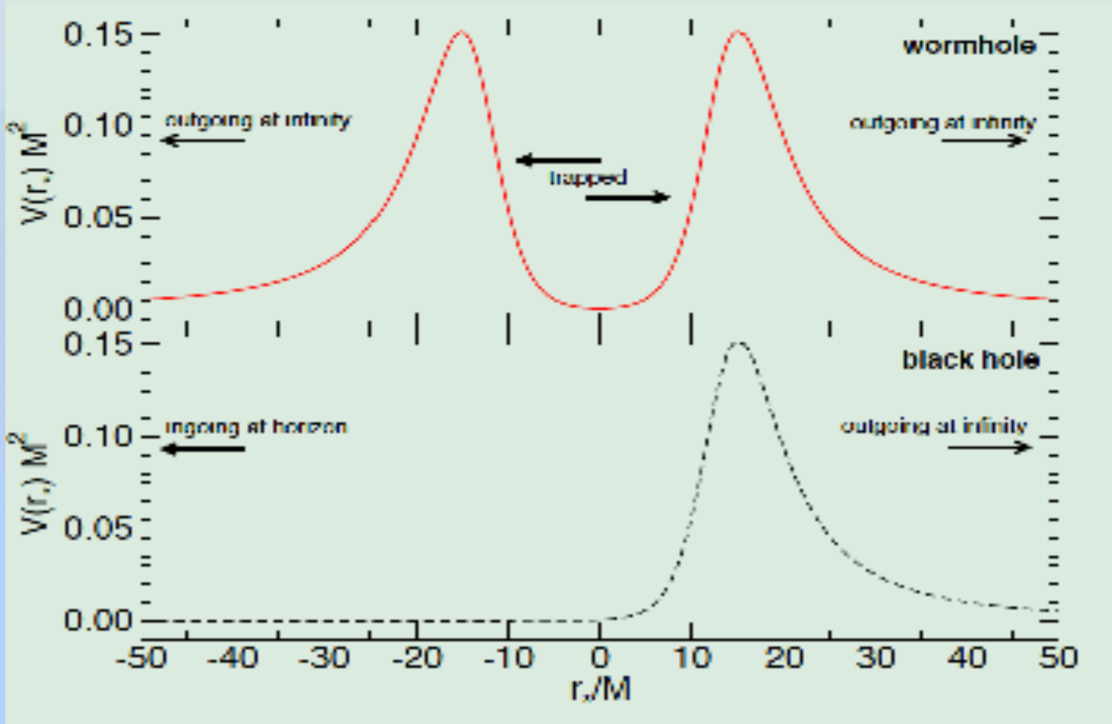
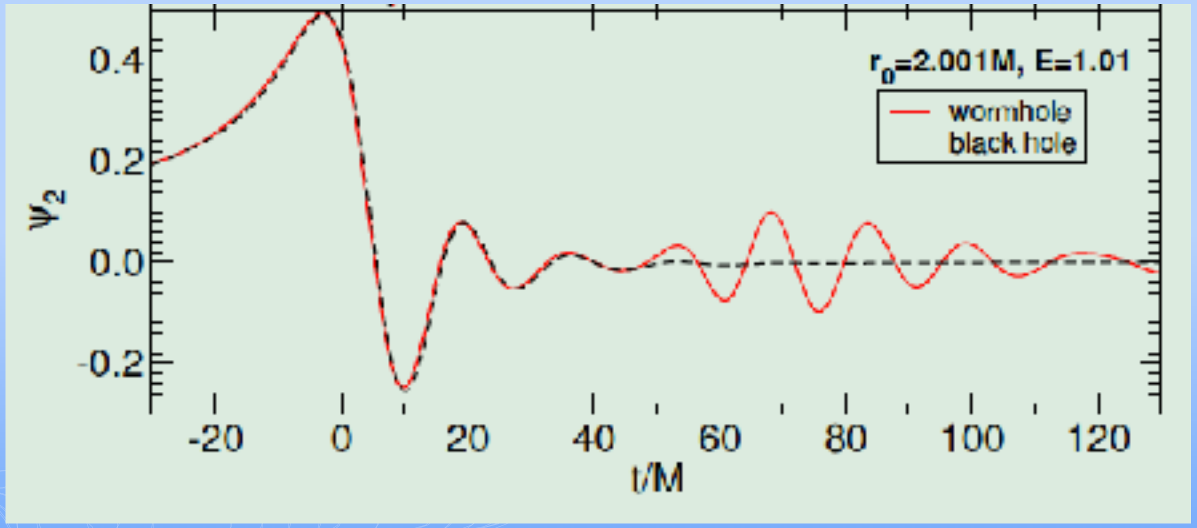
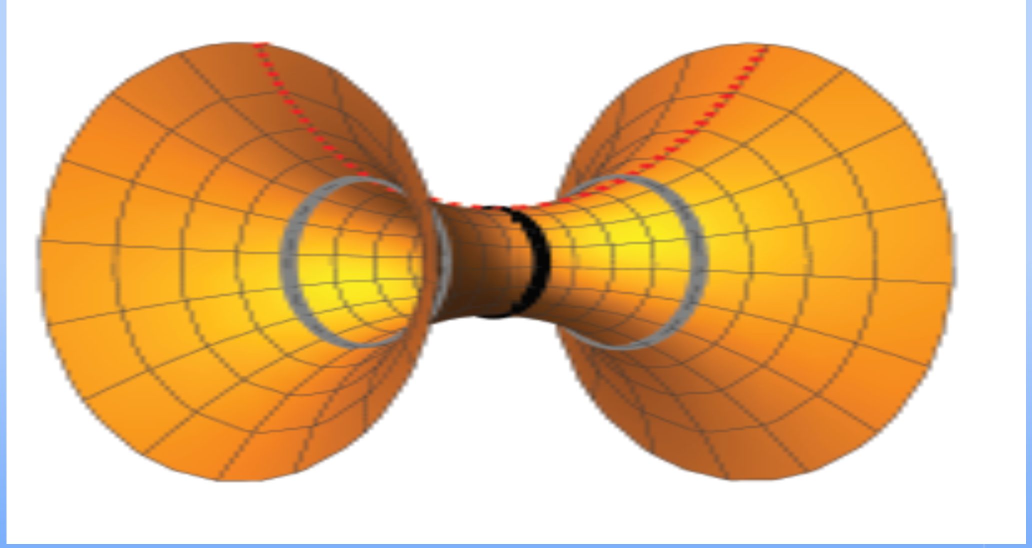


Figure Credit: ScienceNews



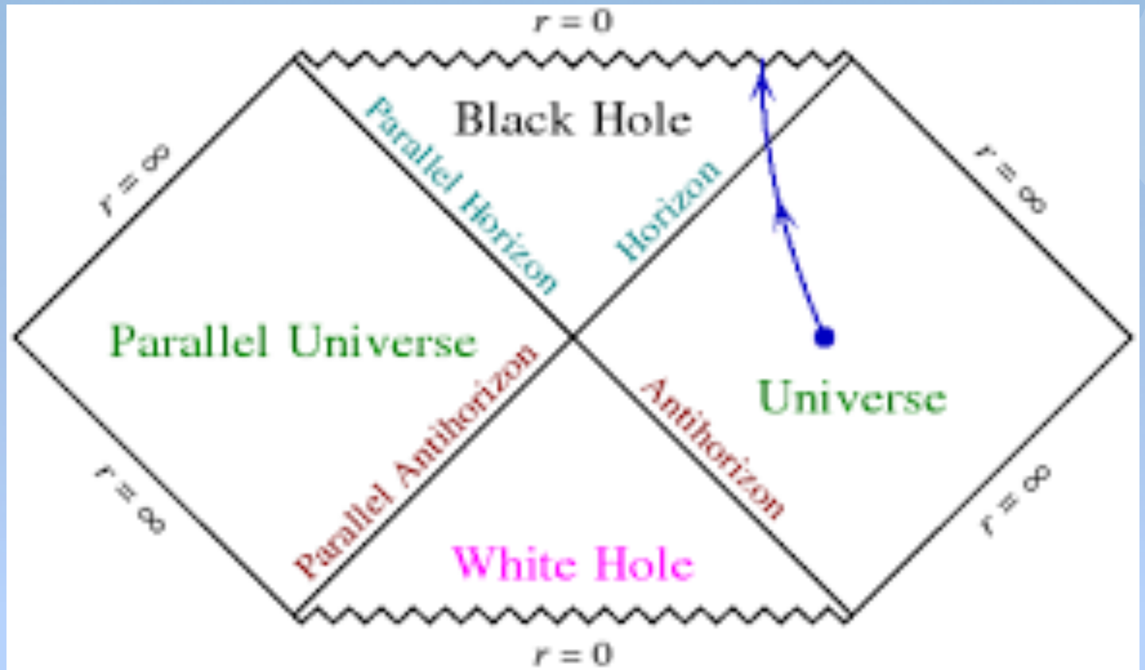


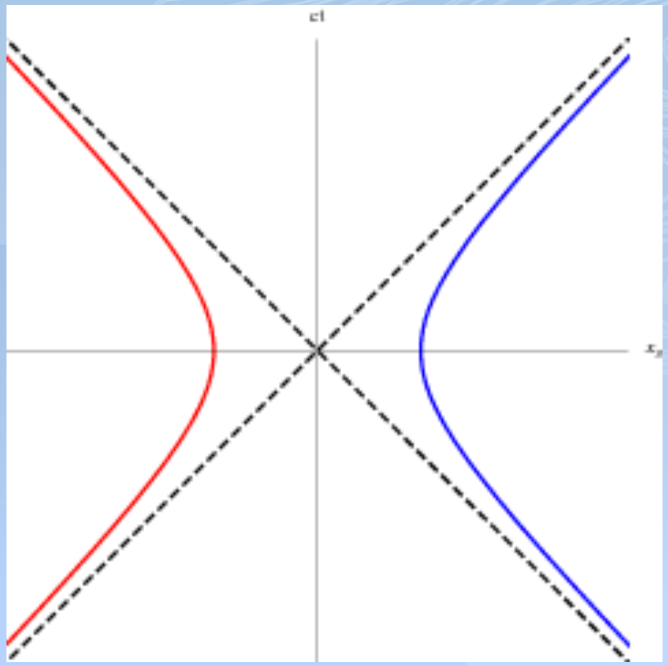


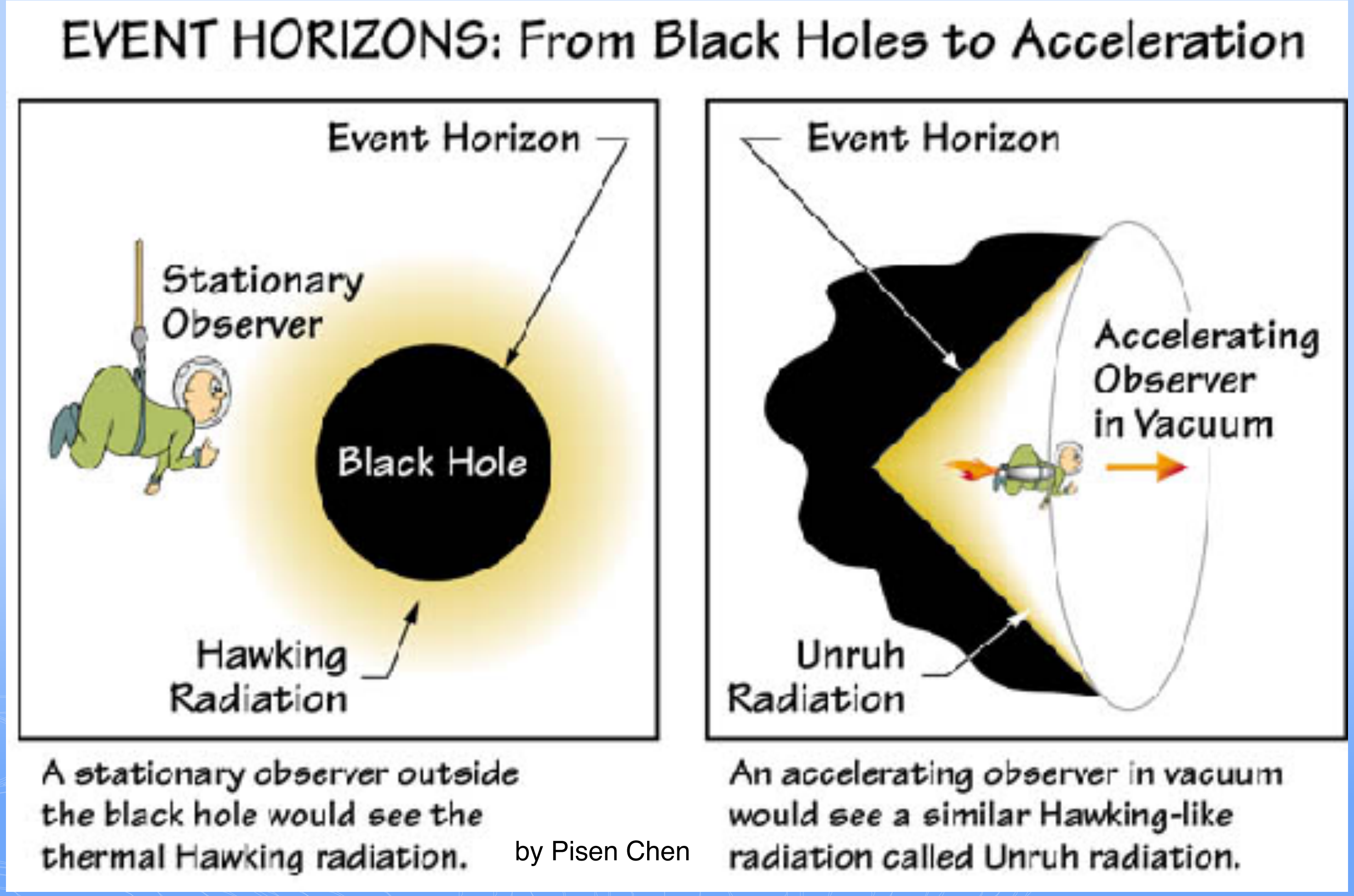
Is the Gravitational-Wave Ringdown a Probe of the Event Horizon?

V. Cardoso, E. Franzin, P. Pani [PRL. 116, 171101 (2016)]

Why in Rindler Frame

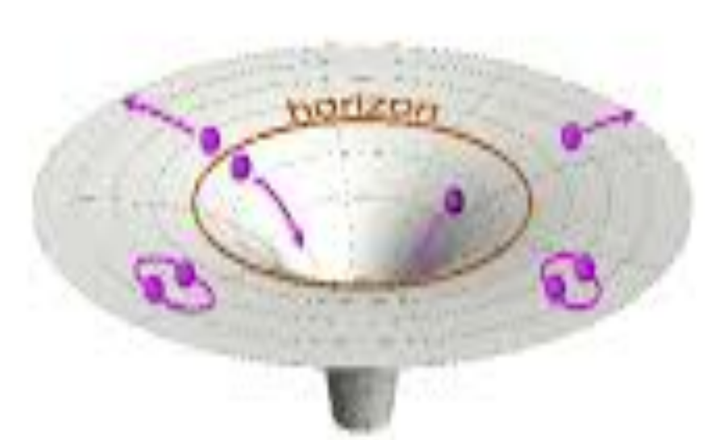






$$\mathcal{T}_{ab} = -2(K_{ab} - K\gamma_{ab})$$

Credit: Physics Napkins

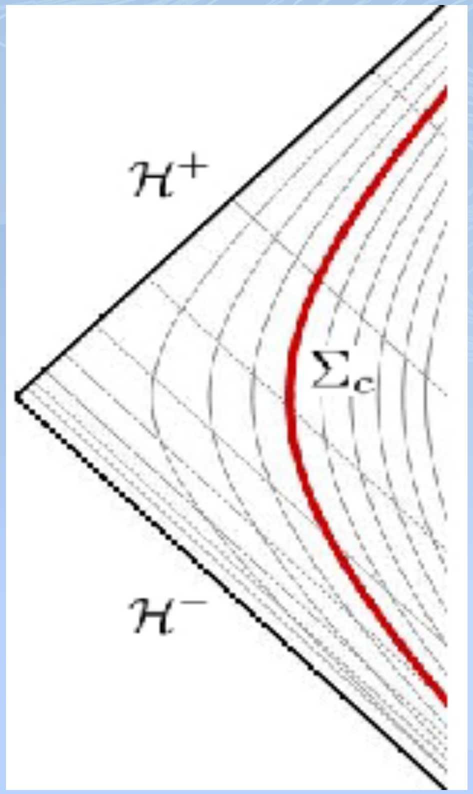


Rindler Hydrodynamics

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

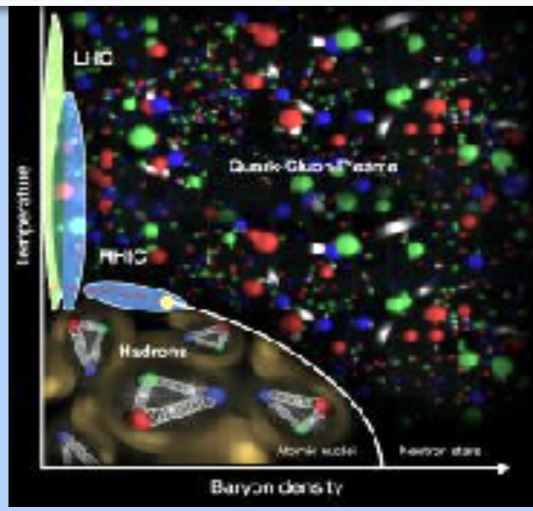
$$2G_{\mu b} n^\mu |_{r_c} = 2\partial^a (K_{ab} - \gamma_{ab} K) = 0 \;\Rightarrow\; \partial^a T_{ab} = 0$$

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

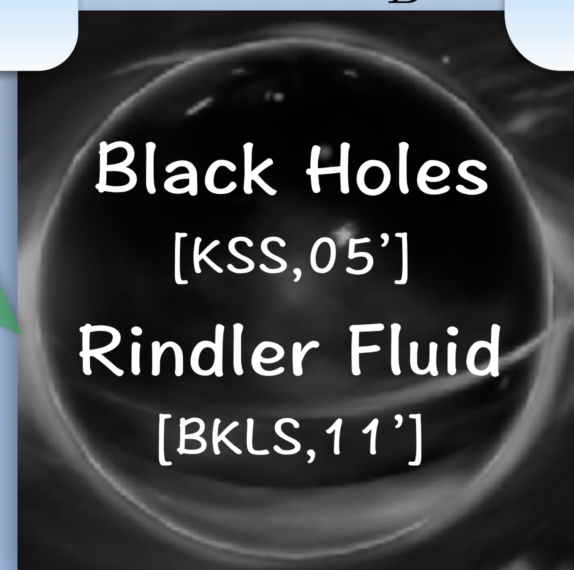
Bredberg, Keeler, Lysov, Strominger (JHEP 07 (2012) 146)

What is the Most Perfect Fluid in the World?

Quark Gluon Plasma
in RHIC [08'] & LHC [16']



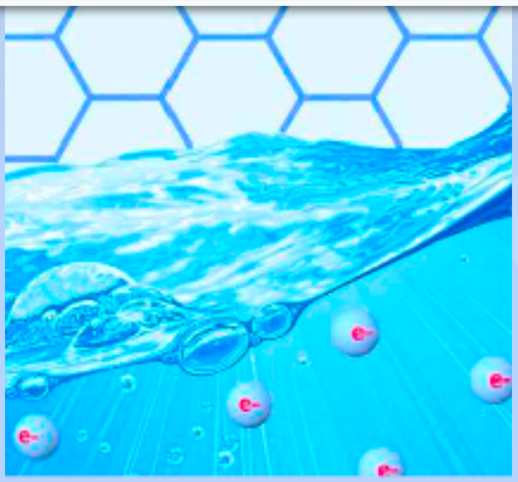
$$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$



Black Holes
[KSS,05']

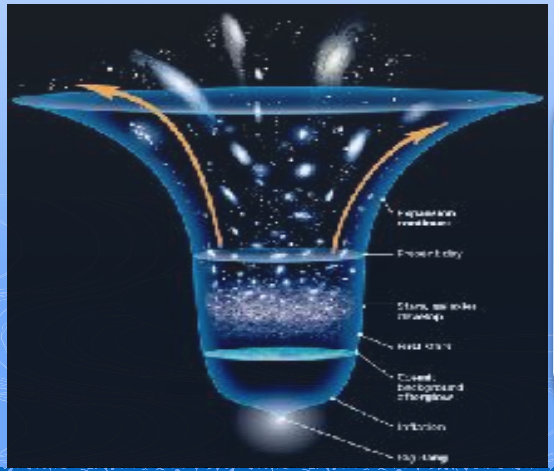
Rindler Fluid
[BKLS,11']

Quantum Critical Liquid
Graphene [09'] & Semi-Metal[16']

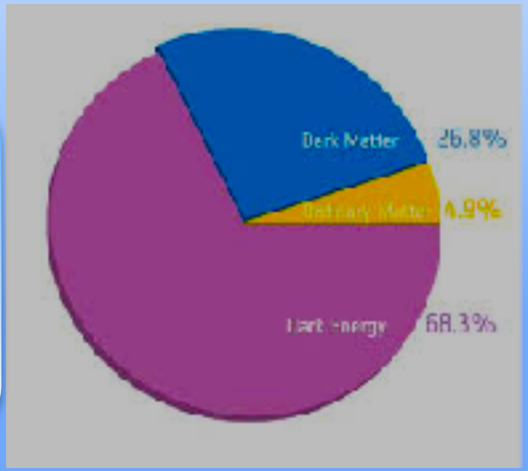


$$\frac{H^2}{H_0^2} \simeq \frac{\Omega_B}{a^3} + \sqrt{\Omega_\Lambda\left(\frac{H^2}{H_0^2} + \frac{\Omega_I}{a^4}\right)}$$

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



Dark Fluid in the Universe?
Cosmological Fluid [CSZ,17']
[1712.09326, Cai, Sun, Zhang]

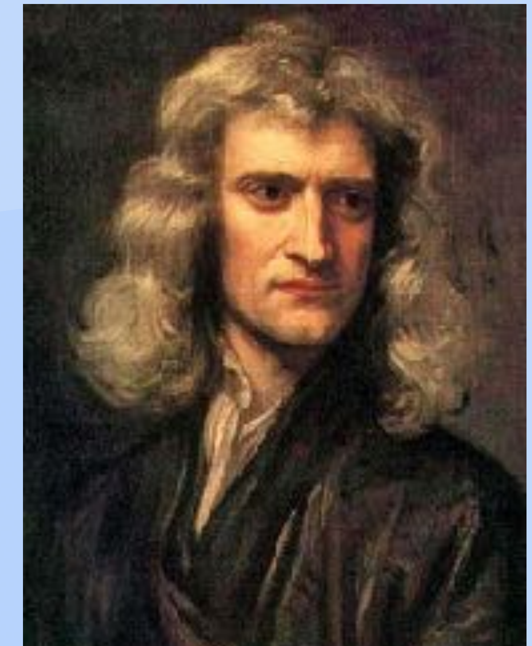


Figures Credit: RHIC & Google

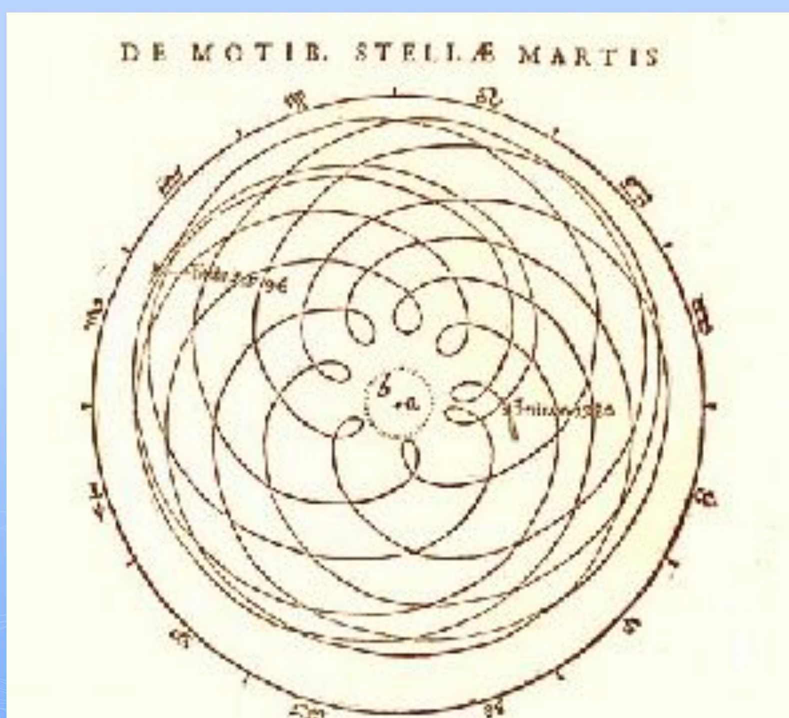
From Observation to Newton's Gravity

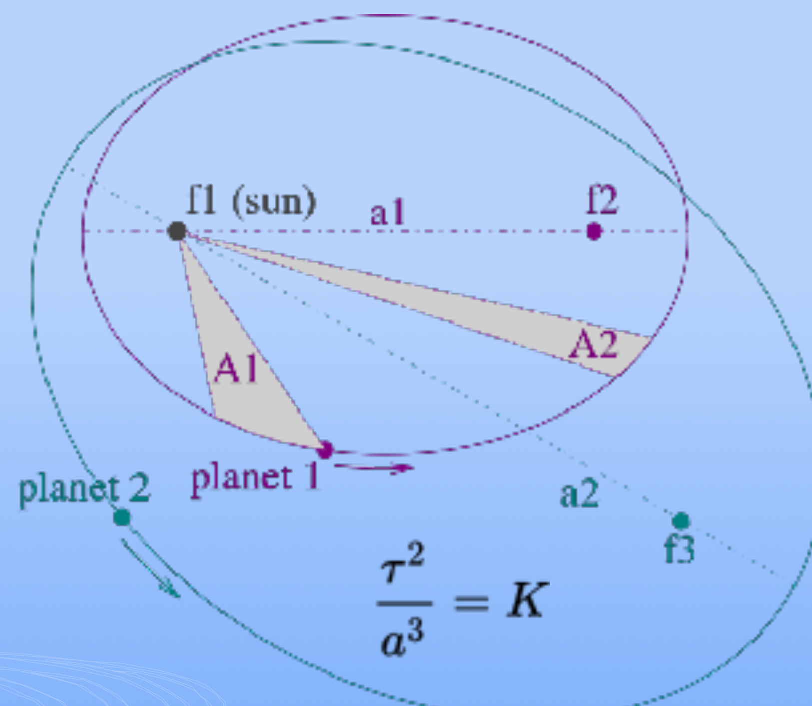
Tycho's Data (1590s)

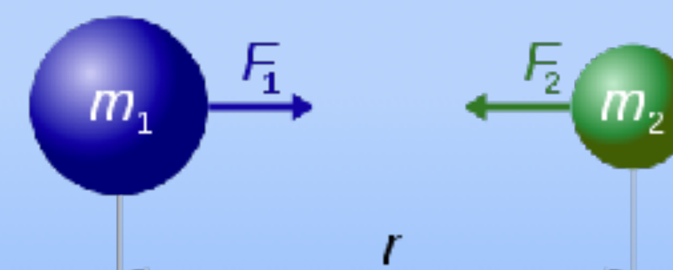
Kapler's Law (1618)



Newton's Gravity (1687)







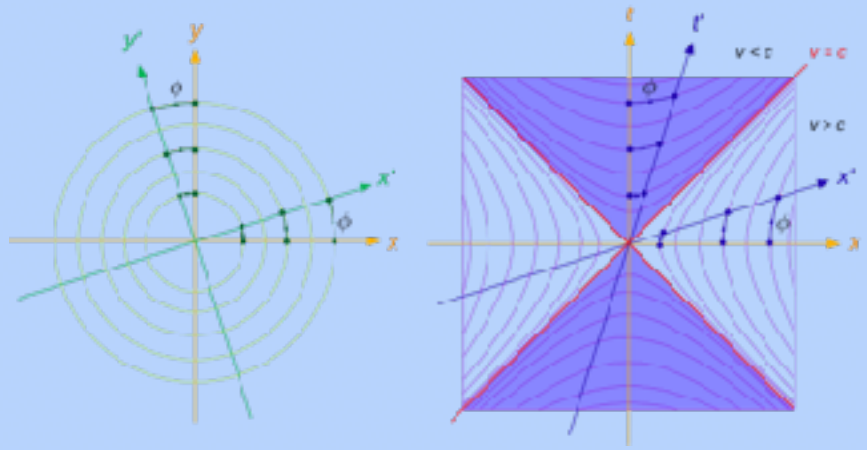
$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

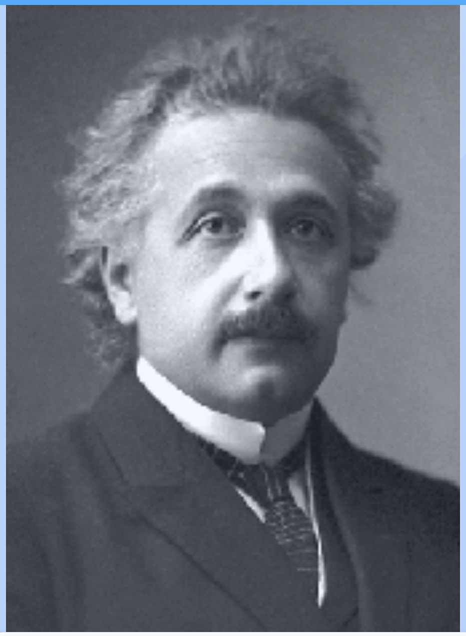
NATURE and Nature's Laws lay hid in Night: God said, "Let Newton be!" and all was light.

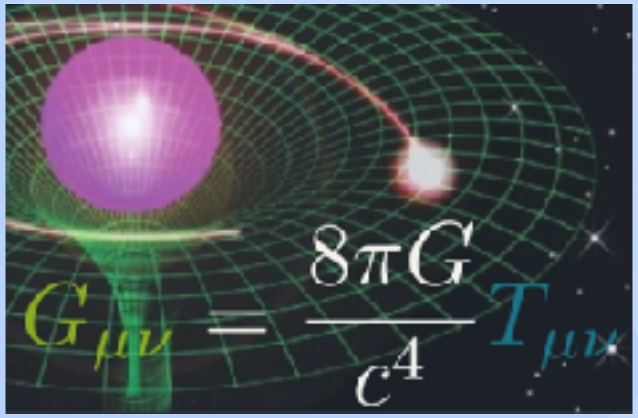
— Alexander Pope

Figures credit: Wiki

From Einstein's Gravity to Dark Universe







Newton's Gravity

Special Relativity(1905)

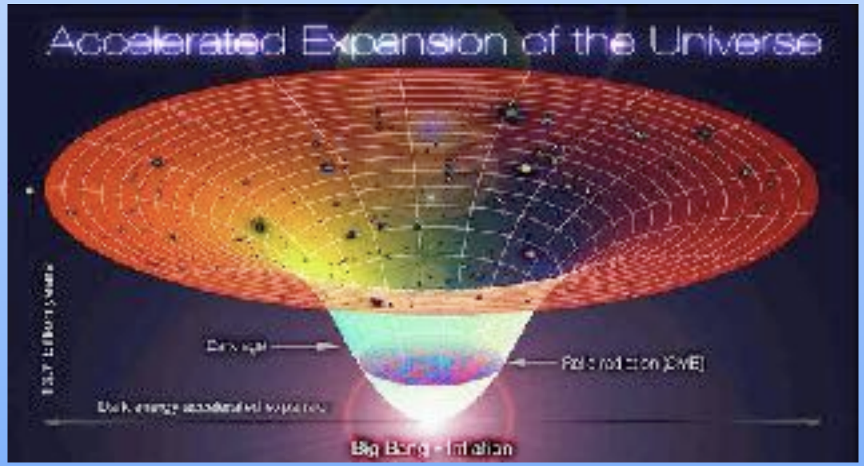
Einstein's Gravity (1915)

Dark Matters

Gravitational Waves (2016)

Black Holes

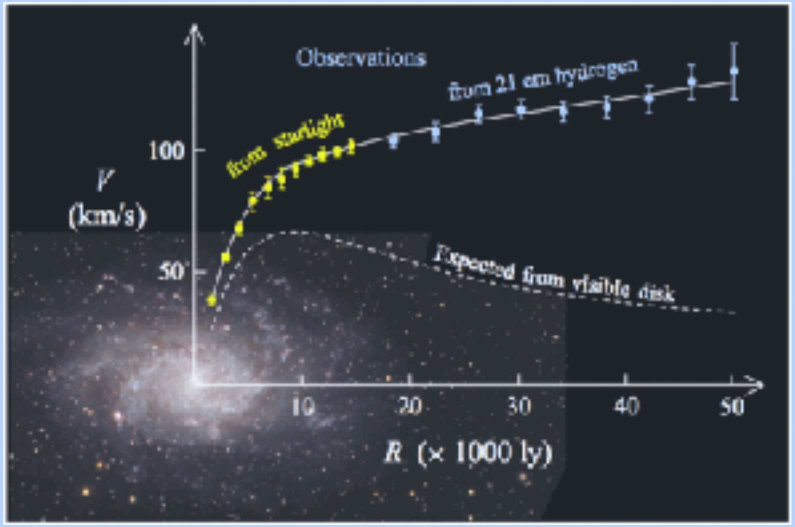
Dark Energy

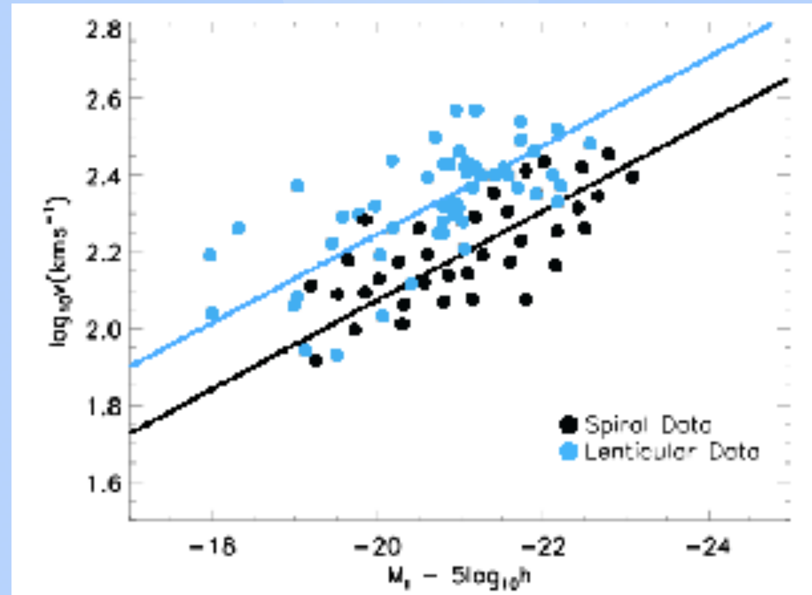


It did not last: the Devil howling: "Ho! Let Einstein be!" restored the status quo. — J. C. Squire

Figures credit: Wiki

From Observation to Milgrom's MOND
(Modified Newton Dynamics)





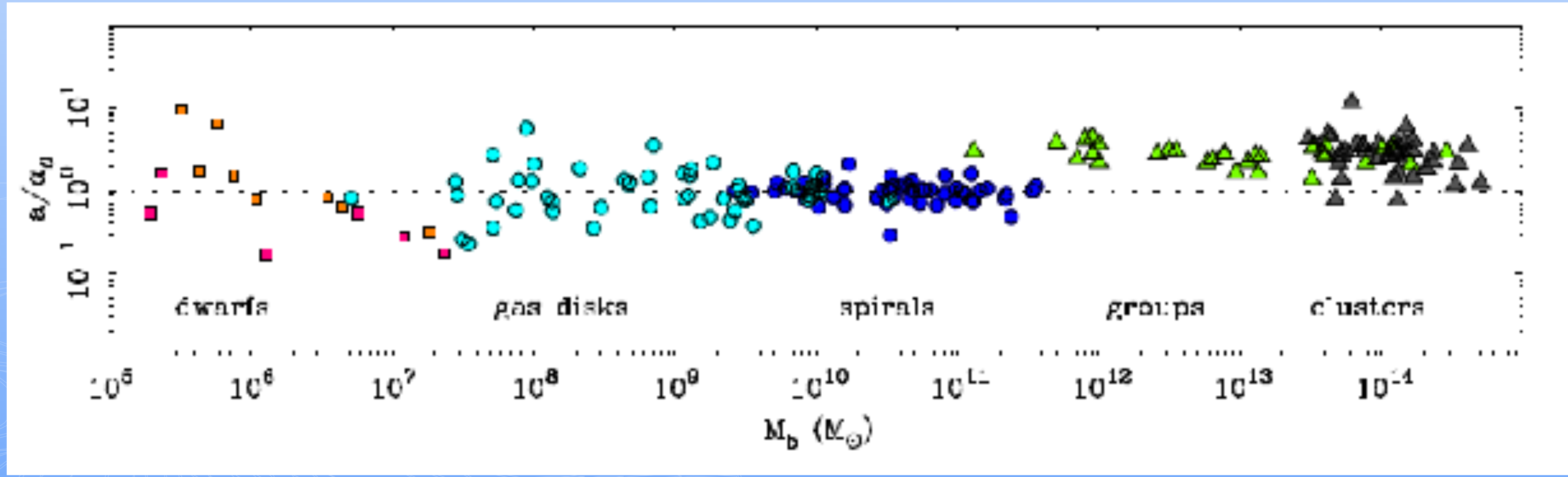
Galaxy Rotation Curve (1970s) → **Tully–Fisher Relation (1977)** → **Milgrom's MOND (1983)**

Tully–Fisher Relation (1977) ⇢ **Dark Matter**

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

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

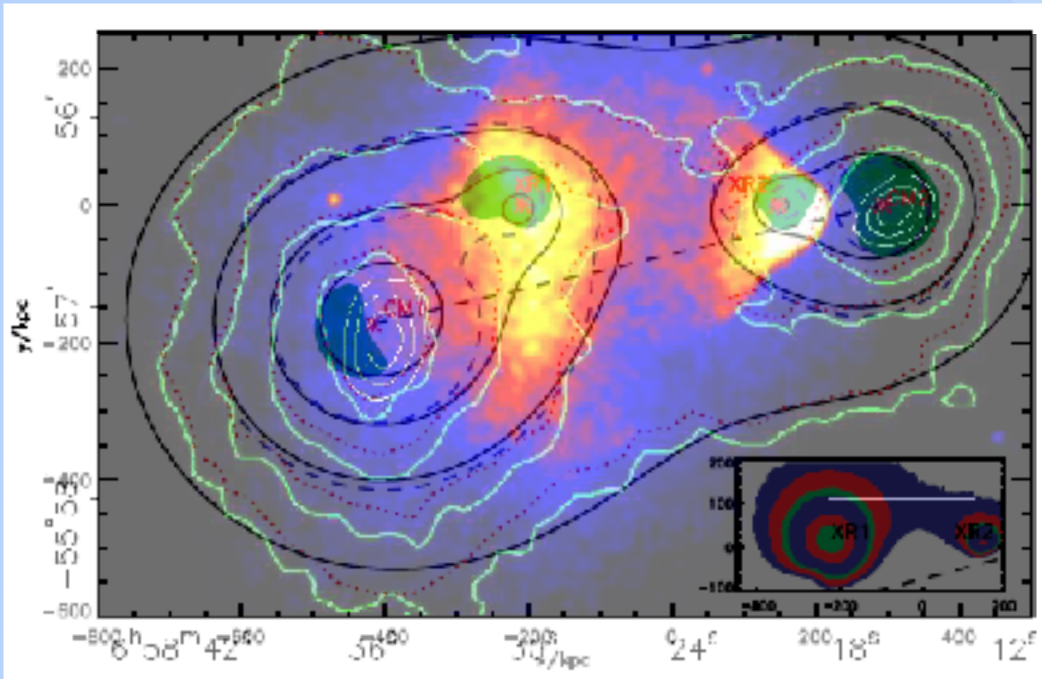
$$a_0 \simeq \sqrt{\Lambda}$$



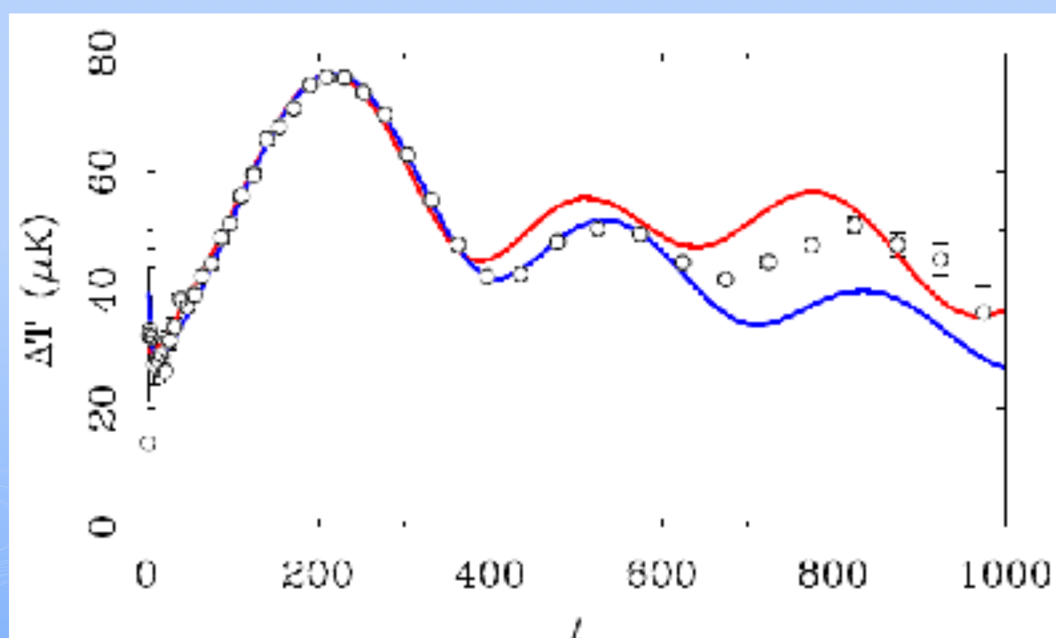
20 years after MOND

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

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



Bullet Clusters

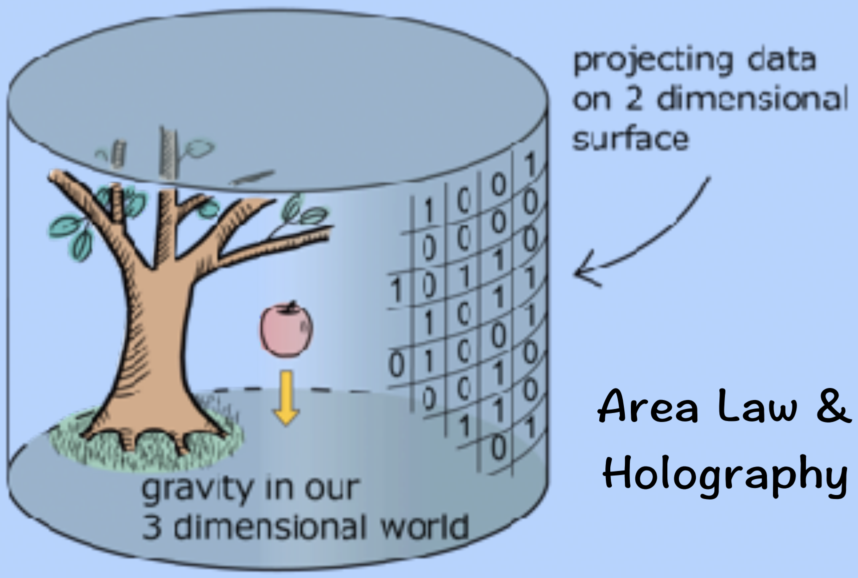


Acoustic Power Spectrum of CMB

Table 2: Observational tests of MOND.

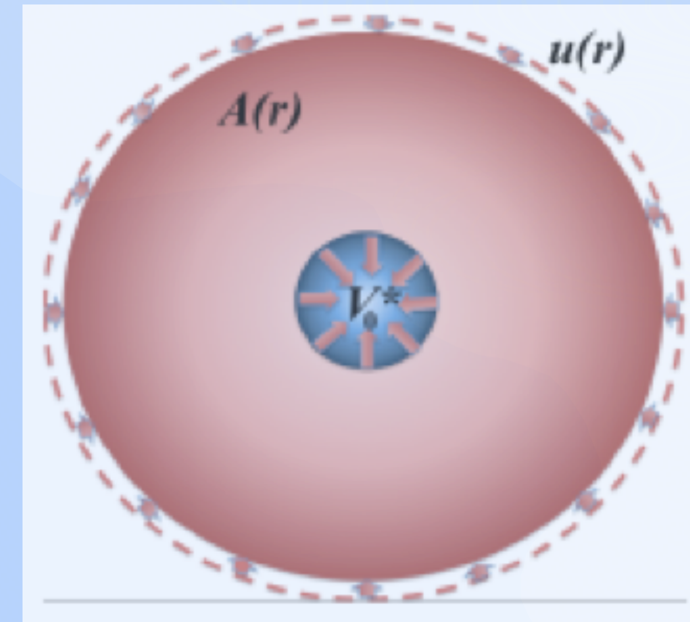
Observational Test	Successful	Promising	Unclear	Problematic
Rotating Systems				
solar system			X	
galaxy rotation curve shapes	X			
surface brightness $\propto \Sigma \propto a^2$	X			
galaxy rotation curve fits	X			
fitted M_*/L	X			
Tully–Fisher Relation				
baryon based	X			
slope	X			
normalization	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			

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!

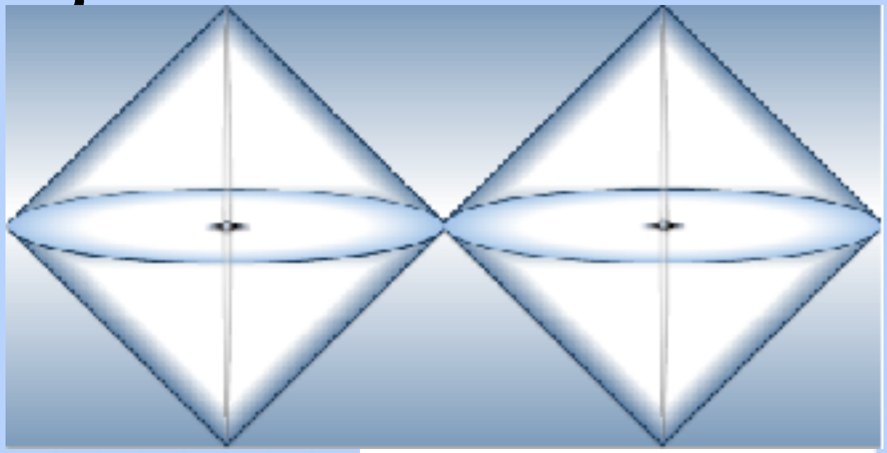
Figures credit: Wiki

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?

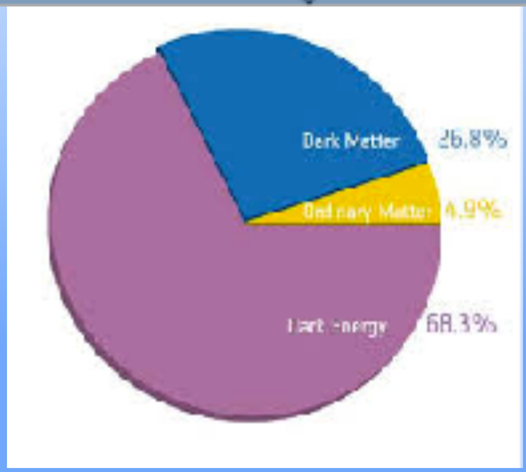
$$\frac{\mathcal{T}^2}{d-1} - \mathcal{T}_{\mu\nu}\mathcal{T}^{\mu\nu} = -\frac{\rho_\Lambda c^2}{d-1}(T + \mathcal{T}).$$



Constrain Equations

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

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



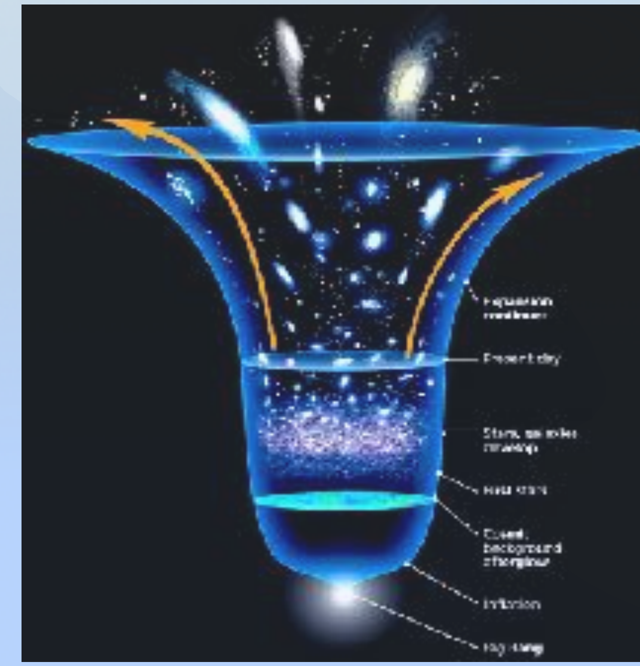
R.G. Cai, S. Sun, Y.L. Zhang, 1712.09326

LCDM Universe?

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

FRW Screen in a Flat Bulk

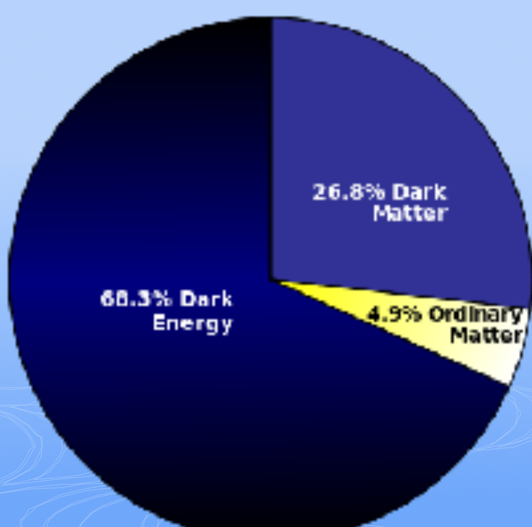
$$\mathcal{S}_5 = \frac{1}{2\kappa_5}\int_{\mathcal{M}} \mathrm{d}^5x\sqrt{-\tilde{g}}\,\mathcal{R} + \frac{1}{\kappa_5}\int_{\partial\mathcal{M}} \mathrm{d}^4x\sqrt{-g}\,\mathcal{K},$$
$$\mathcal{S}_4 = \frac{1}{2\kappa_4}\int_{\partial\mathcal{M}} \mathrm{d}^4x\sqrt{-g}\,R + \int_{\partial\mathcal{M}} \mathrm{d}^4x\sqrt{-g}\mathcal{L}_M.$$



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

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

Ref: 1712.09326 [Cai, Sun, Zhang]



DGP BraneWorld

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

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

Ref: 1106.2476 [Living Rev. '10]

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

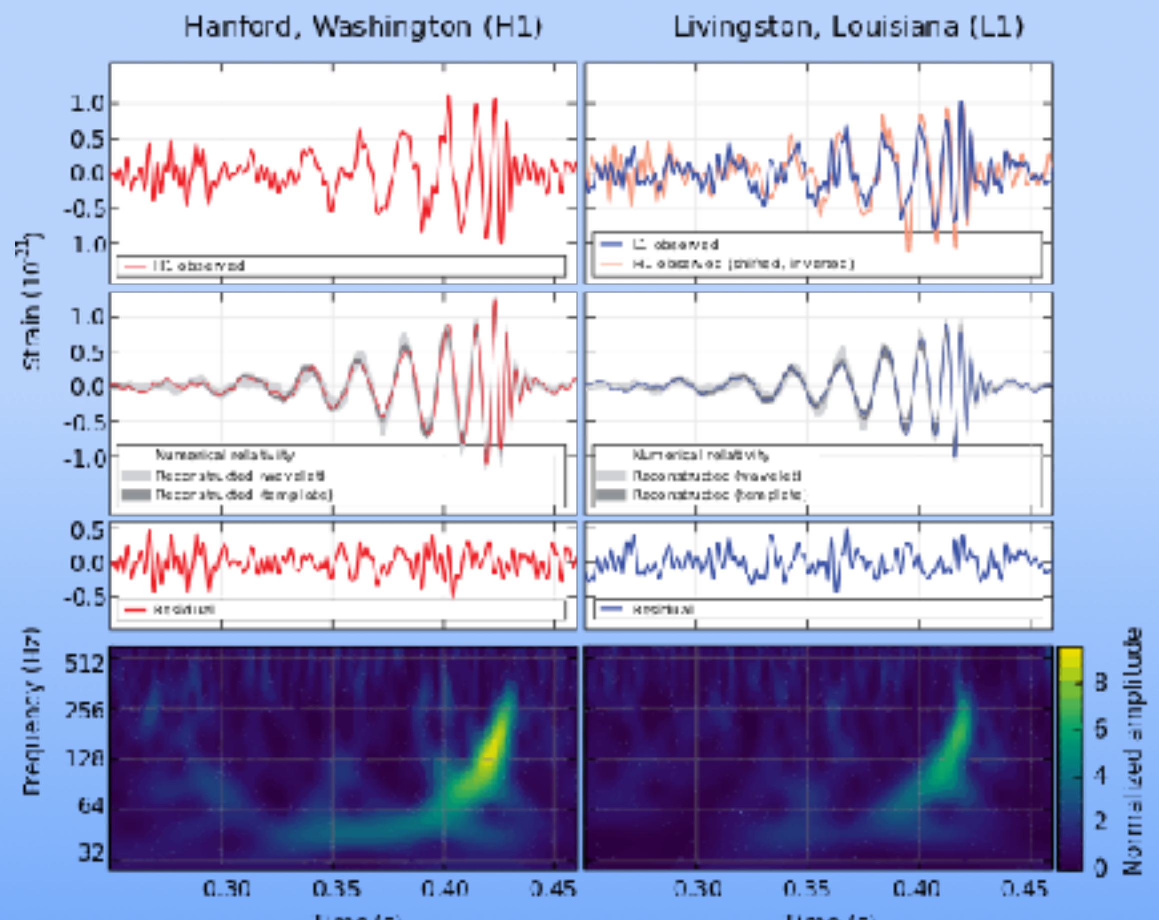
The observed gravitational waveforms from LIGO, which are consistent with Einstein's gravity

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

Einstein-Aether theory (2004, Bekenstein)

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

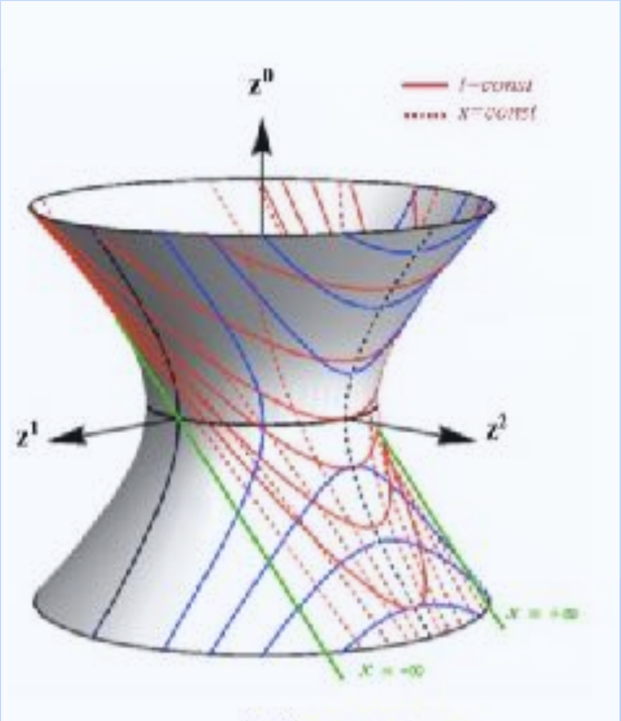
$$\begin{aligned} \mathcal{T}_{\alpha\beta} &= \tfrac{1}{2}\nabla_\sigma\{\mathcal{F}'[J_{(\alpha}{}^\sigma A_{\beta)} - J^\sigma{}_{(\alpha}A_{\beta)} - J_{(\alpha\beta)}A^\sigma]\} \\ &- \mathcal{F}'Y_{\alpha\beta} + \tfrac{1}{2}g_{\alpha\beta}\mathcal{M}^2\mathcal{F} + \lambda A_\alpha A_\beta, \end{aligned}$$



Holographic dS Universe? — de-Sitter Screen

1) Holographic Stress Tensor — Dark Sectors

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



Modified Einstein equations

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

Hamiltonian constraints

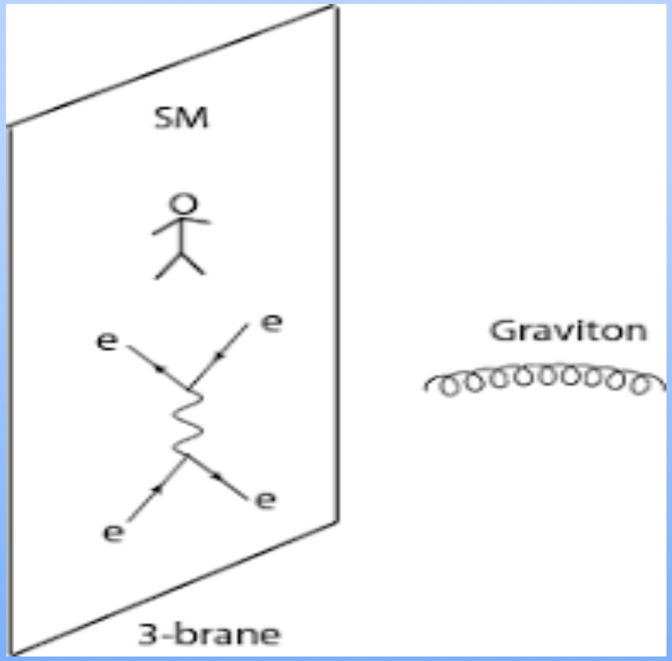
$$\mathcal{K}^2 - \mathcal{K}_{\mu\nu}\mathcal{K}^{\mu\nu} = R + 2\, G^{(d+1)}_{MN} \mathcal{N}^M \mathcal{N}^N,$$

2) Embedding in higher dimensions — Brane Worlds

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

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

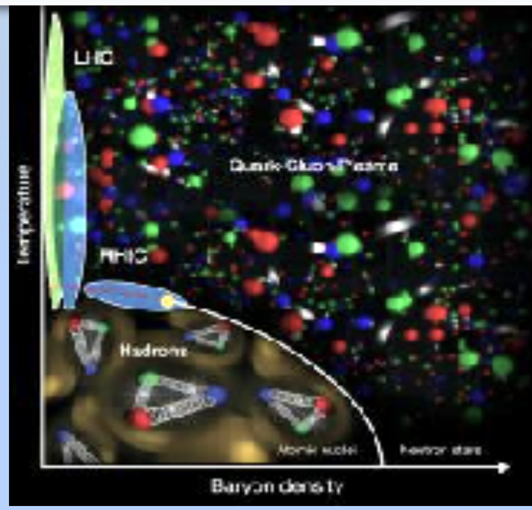
$$\mathcal{M}_{\mu\nu} \equiv g_{\mu}{}^{M} g_{\nu}{}^{N} R^{(d+1)}_{MN} - g_{\mu}{}^{M} \mathcal{N}^P g_{\nu}{}^{N} \mathcal{N}^Q R^{(d+1)}_{MPNQ}.$$



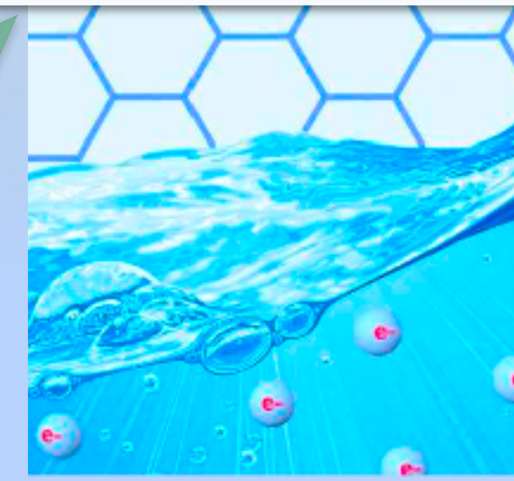
Ref: 1106.2476 [Living Rev. '10]

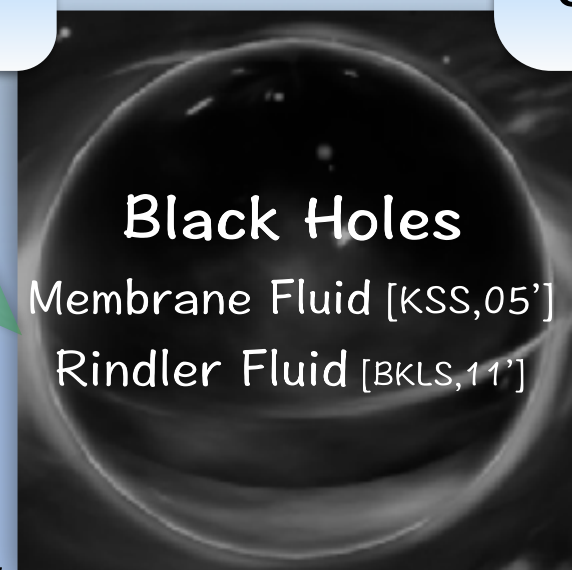
Summary of the Membrane Fluid

Quark Gluon Plasma
RHIC ['08] & LHC ['16]



Quantum Critical Liquid
Graphene ['09] & Semi-Metal['16]





Black Holes

Membrane Fluid [KSS,05']

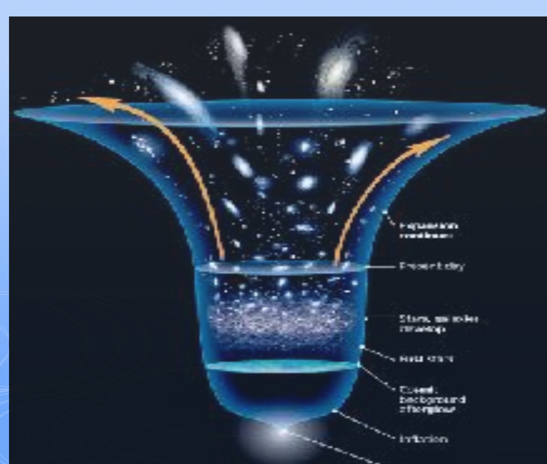
Rindler Fluid [BKLS,11']

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

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

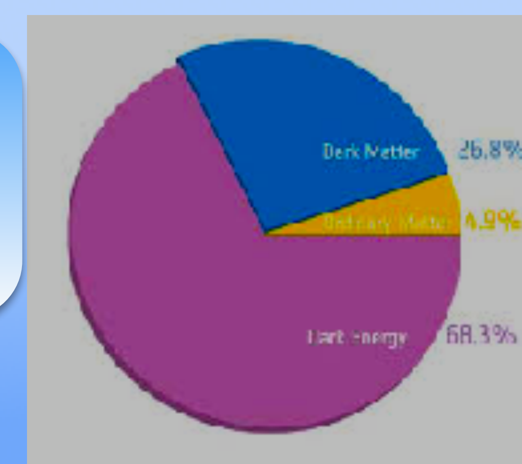
$$\frac{H^2}{H_0^2} \simeq \frac{\Omega_B}{a^3} + \sqrt{\Omega_\Lambda\Big(\frac{H^2}{H_0^2} + \frac{\Omega_I}{a^4}\Big)}$$

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



Cosmological Fluid [CSZ,'17]
Dark Matter & Dark Energy

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

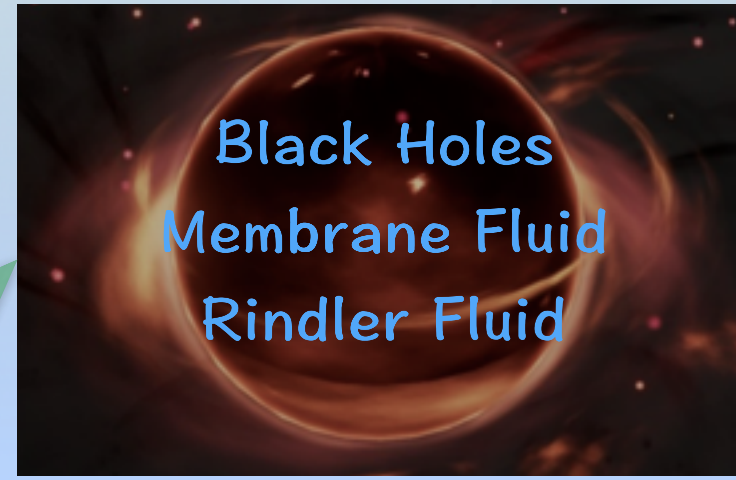


Figures Credit: RHIC & Google

Summary & Outlook

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

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



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

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

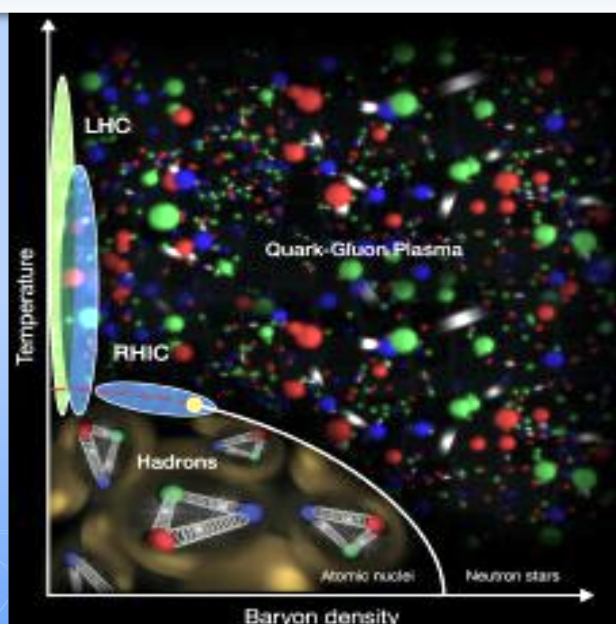
Quark Critical Liquid

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

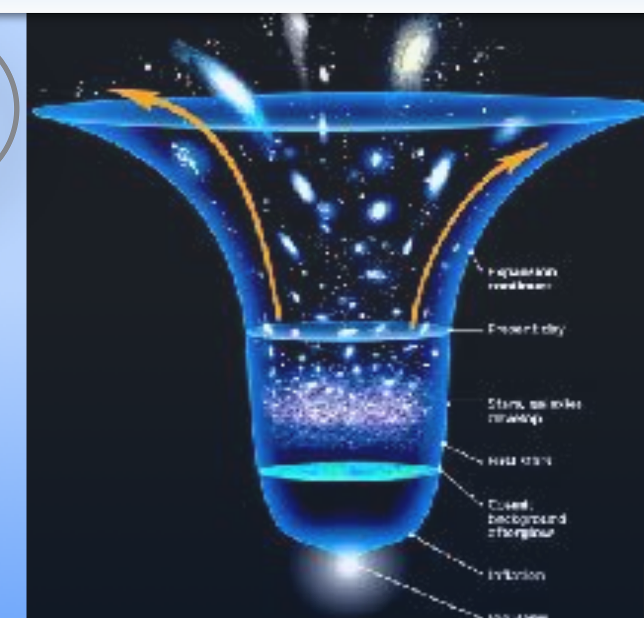
?

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.

OutLine for Holographic Hydrodynamics

I. Gravity, Black Holes and Holography
II. Hydrodynamics and Membrane Fluid
III. Rindler Horizon and Relevant topics

Rindler Fluid with Weak Momentum Relaxation

JHEP 1801 (2018) 058 [arXiv: 1705.05078]

by S. Khimphun, B.-H. Lee, C. Park, **Yun-Long Zhang**



S. Khimphun(Hangyang), **B.-H. Lee** (Sogang), **C.-Y. Park** (GIST)

Emergent Dark Matter in Late Universe on Holographic Screen

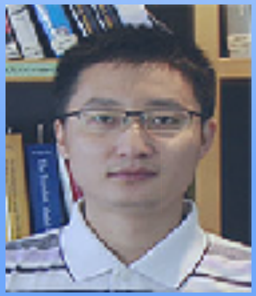
by R.-G. Cai, S.-C. Sun, **Yun-Long Zhang** [arXiv: 1712.09326]

R.-G. Cai
(ITP-CAS)

Holographic Bell Inequality [arXiv: 1612.09513]

by J.-W. Chen, S.-C. Sun, **Yun-Long Zhang** [to appear in PRD]





J. -W. Chen(NTU) **S. -C. Sun**(NTU) **Y. -L. Zhang**(APCTP)