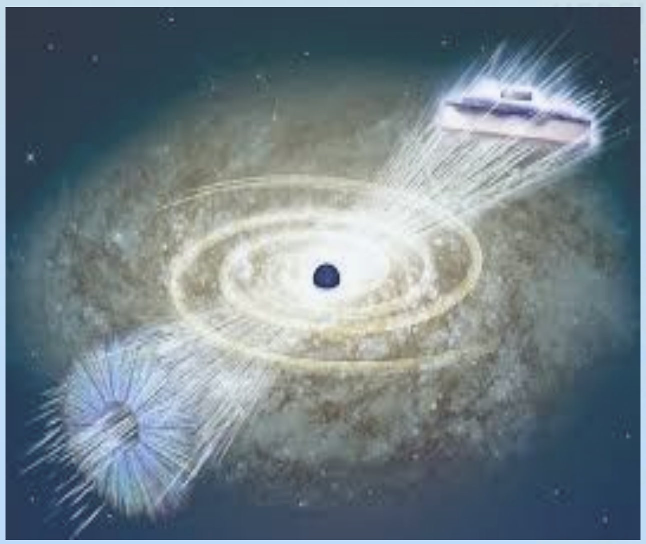
Holographic Model of the Dark Universe & the Late Time Evolution



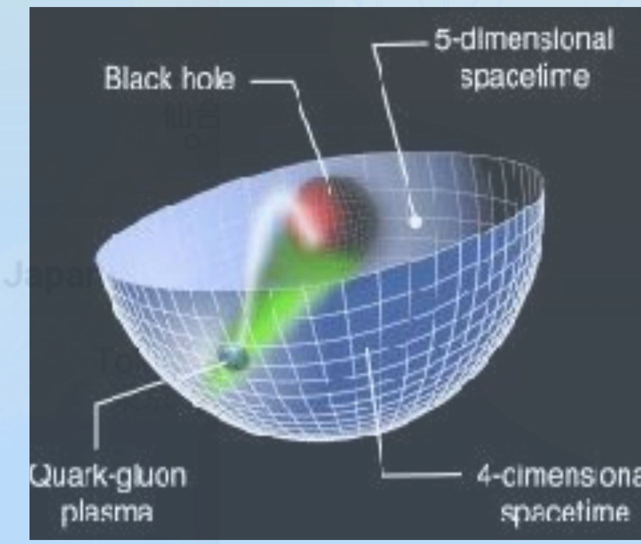
by **Yun-Long Zhang** (張, 雲龍)

Yukawa Institute for Theoretical Physics

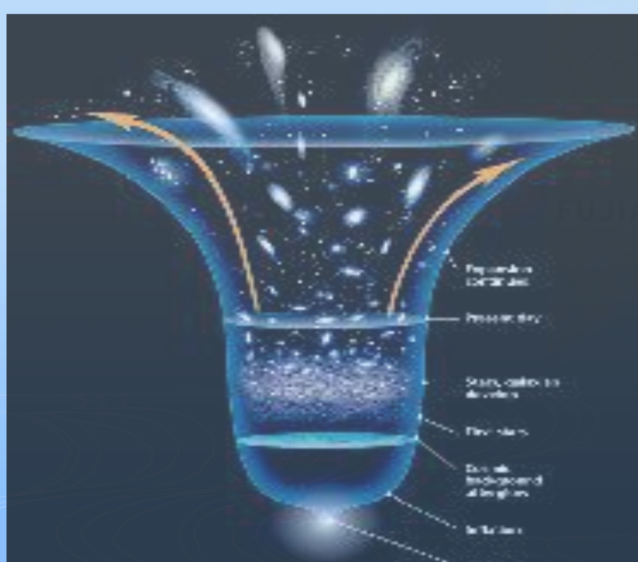
Nov. 2018 – @ YITP, Kyoto, Japan

Asia Pacific Center for Theoretical Physics

(2016-2018 @APCTP, Pohang, Korea)



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



Ref: JHEP 1810 (2018) 009 [arXiv: 1712.09326]

by: Rong-Gen **Cai** (ITP/ Beijing)

Sichun **Sun** (NTU/ Taipei)

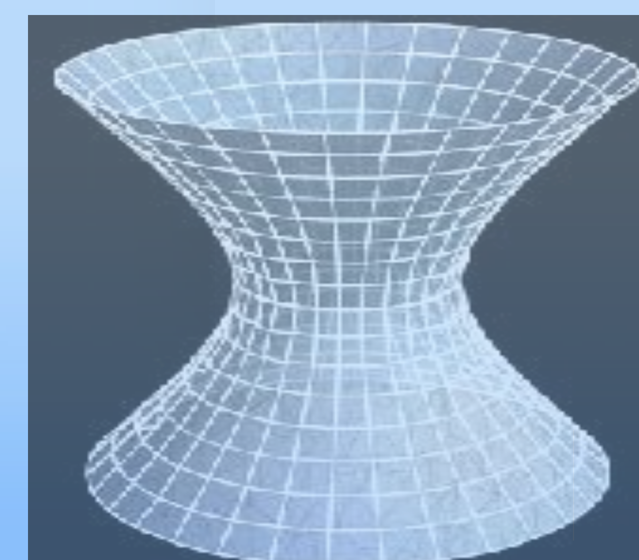
Yun-Long **Zhang** (APCTP/ Pohang)

& Fitting with SNIa [arXiv: 1812.11105]

with Bum-Hoon **Lee** (Sogang U./ Seoul)

Sunly **Khimphun** (Phnom Penh)

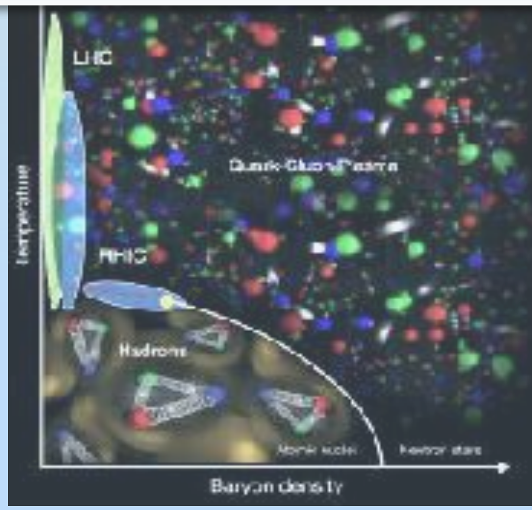
Gansukh **Tumurtushaa** (IBS/Daejeon)



Motivations — Holographic Hydrodynamics

Quark Gluon Plasma

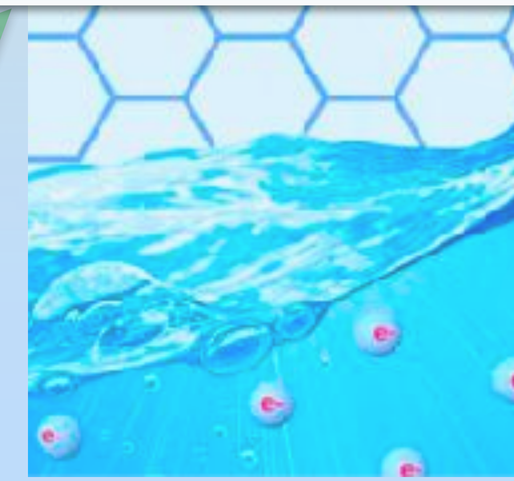
RHIC ['08] & LHC ['16]



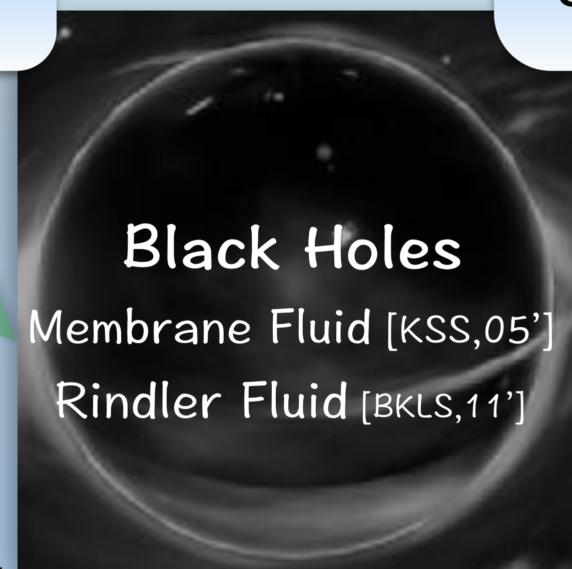
$$\frac{\eta}{s} \simeq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

Quantum Critical Liquid

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

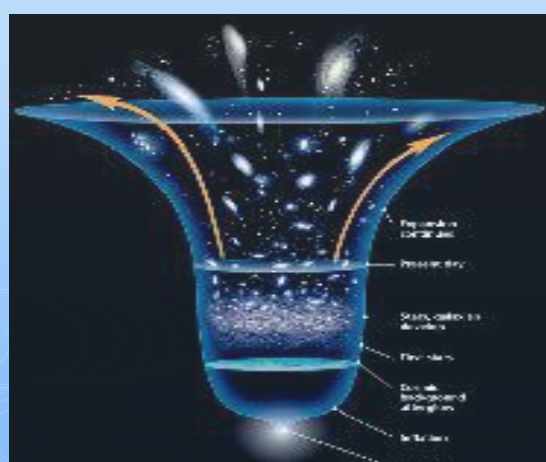


$$\tau_c^{-1} \simeq \frac{k^2}{4\pi T_c}$$



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

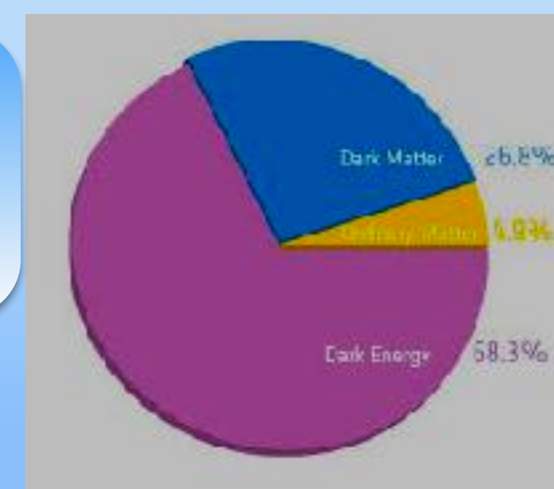
$$\Omega_D^2 \simeq \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B)$$



Cosmological Fluid ['00,'17]

Dark Radiation & Energy & Matter

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

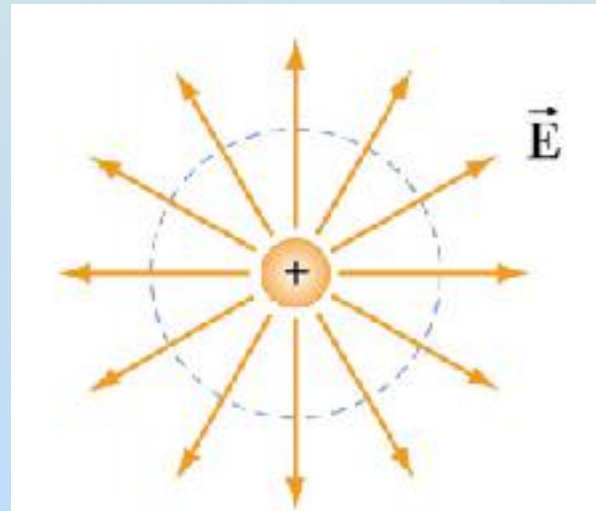


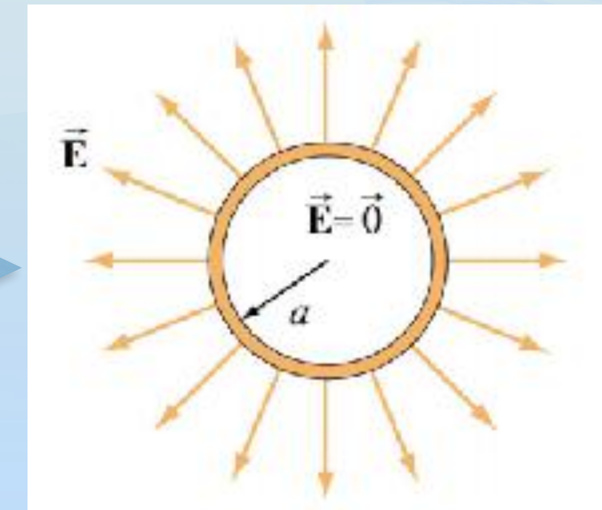
Toy Duality: Field & Surface Matter

I. Electromagnetism

Electric Field &

Surface Charge

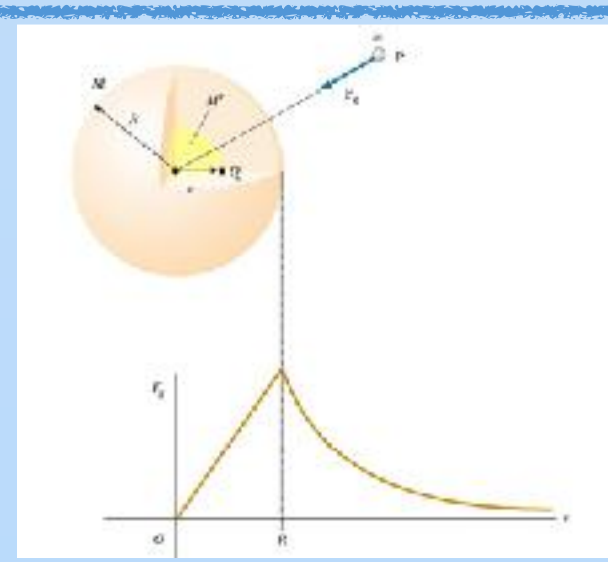


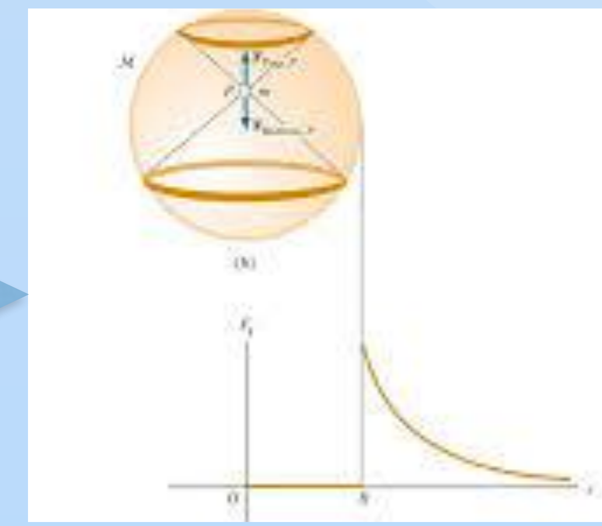


II. Newton Gravity

Massive Star &

Surface Shell

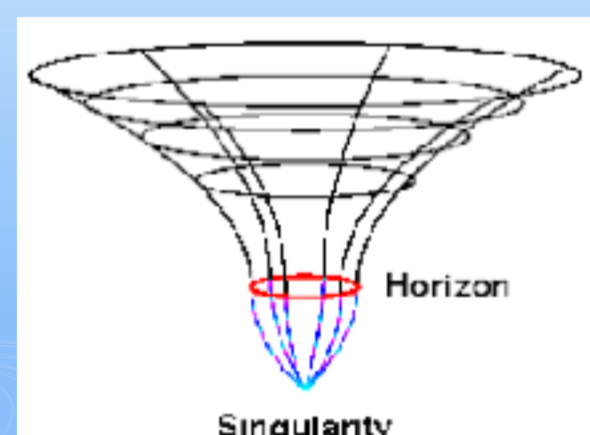


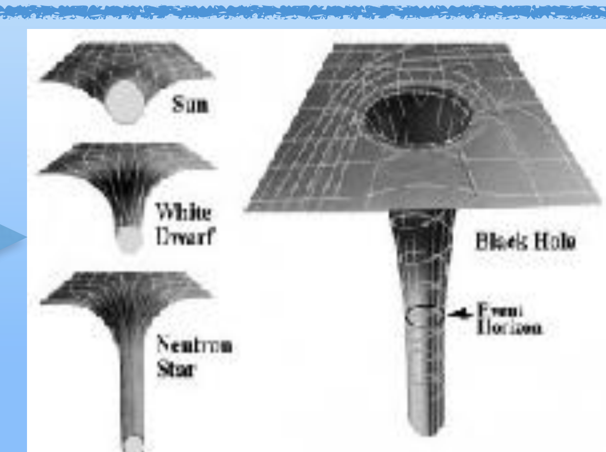


III. Einstein Gravity

Black Hole &

Surface Fluid

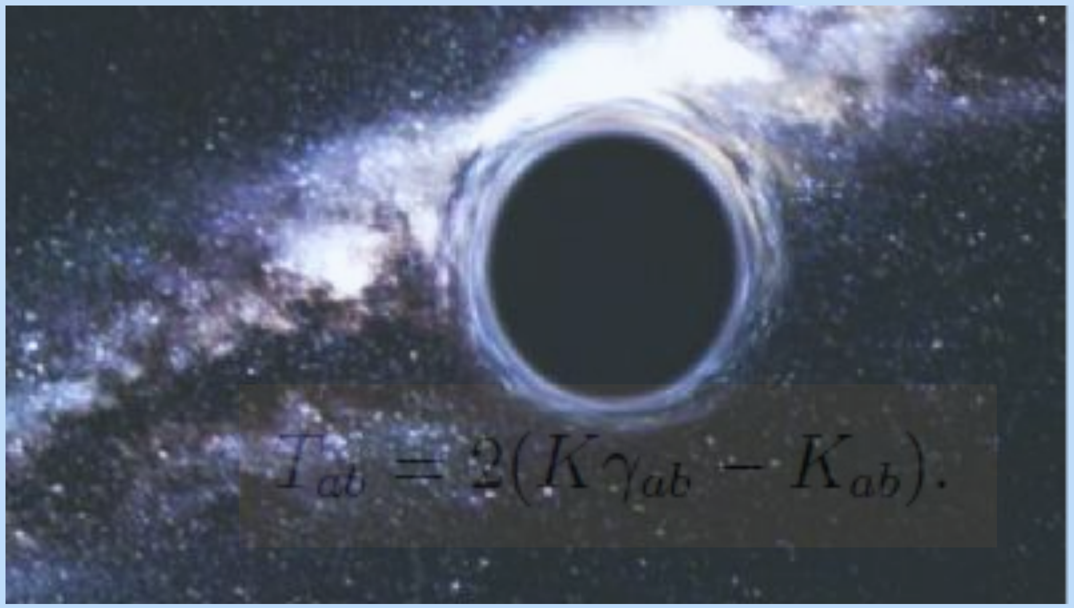


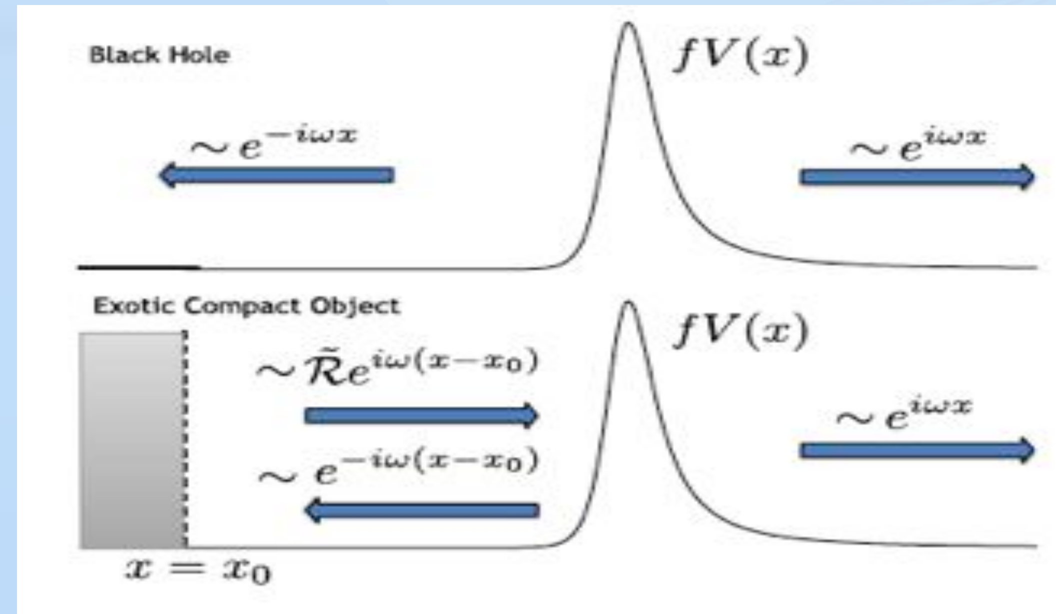


Figures Credit: searched from Google

Membrane Duality: Black Hole & Surface Fluid

T. Doumer & K. Thorne, (1980s-)





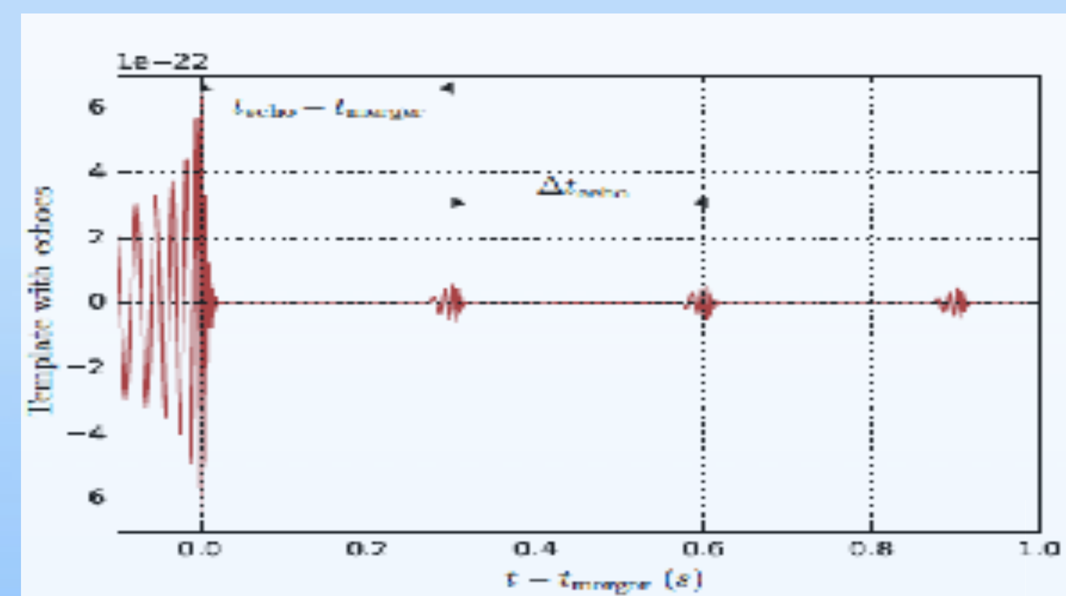
Echoes from Compact Objects [1706.06155 PRD'17]

Effective Description

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

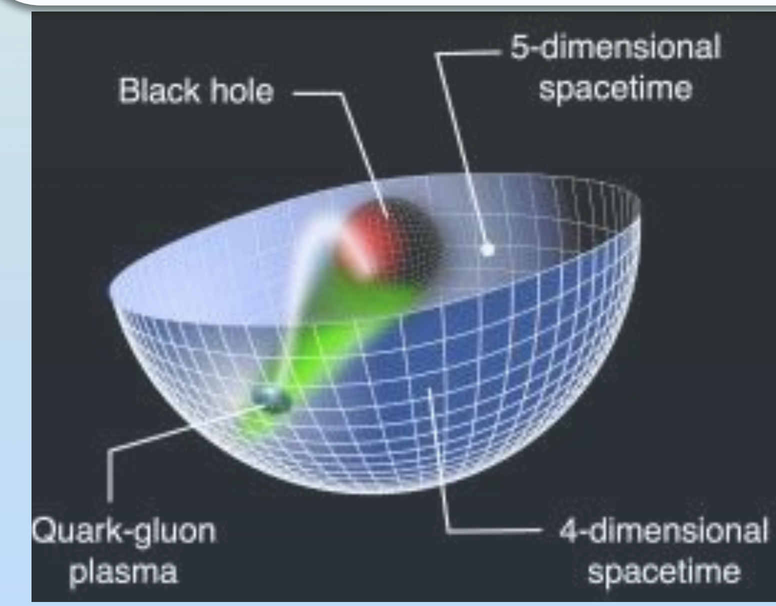
Membrane on Stretched horizon

Viscosity & Conductivity



Echoes from the Abyss [1612.00266 PRD'17]

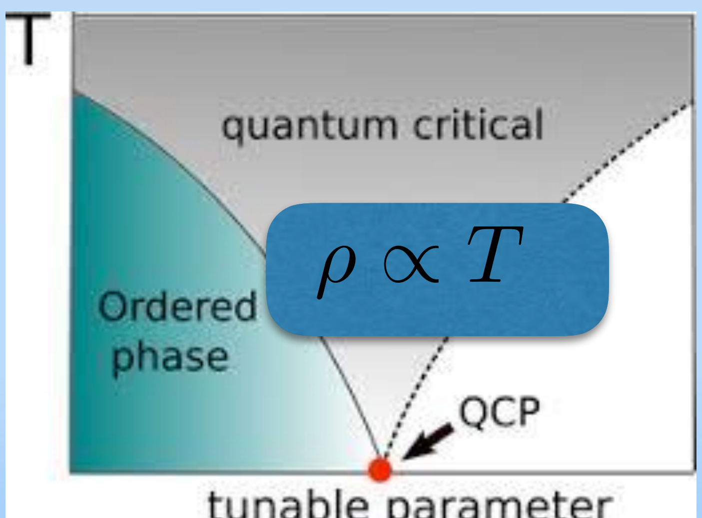
AdS/CMT Duality: Geometry & Quantum Matters



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

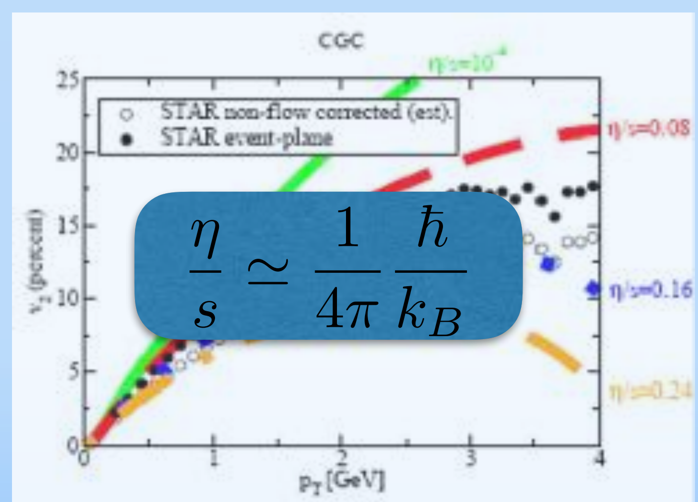
Holographic Condensed Matters

Holographic Strange Metal (2008-)



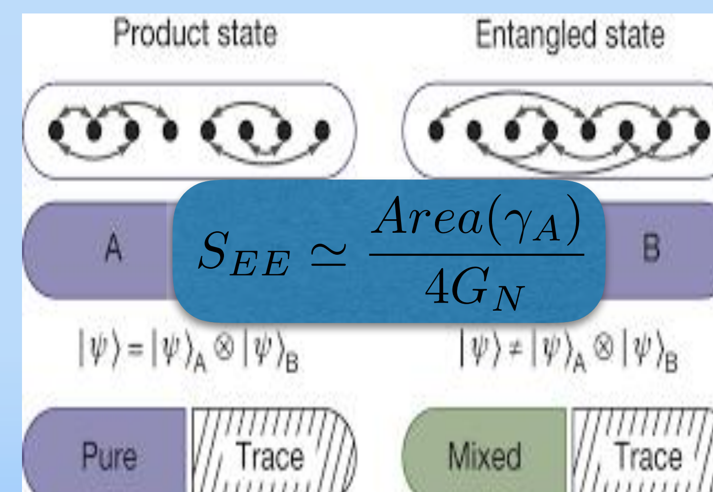
$$\rho \propto T$$

Holographic Hydrodynamics (2003-)



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

Holographic Entanglement (2006-)



$$S_{EE} \simeq \frac{Area(\gamma_A)}{4G_N}$$

ICTP Dirac Medal 2018

Subir Sachdev (Quantum & Phase)

Dam Thanh Son (Nuclear & Fluid)

Xiao-Gang Wen (Entanglement & Order)

Figures Credit: searched from Google

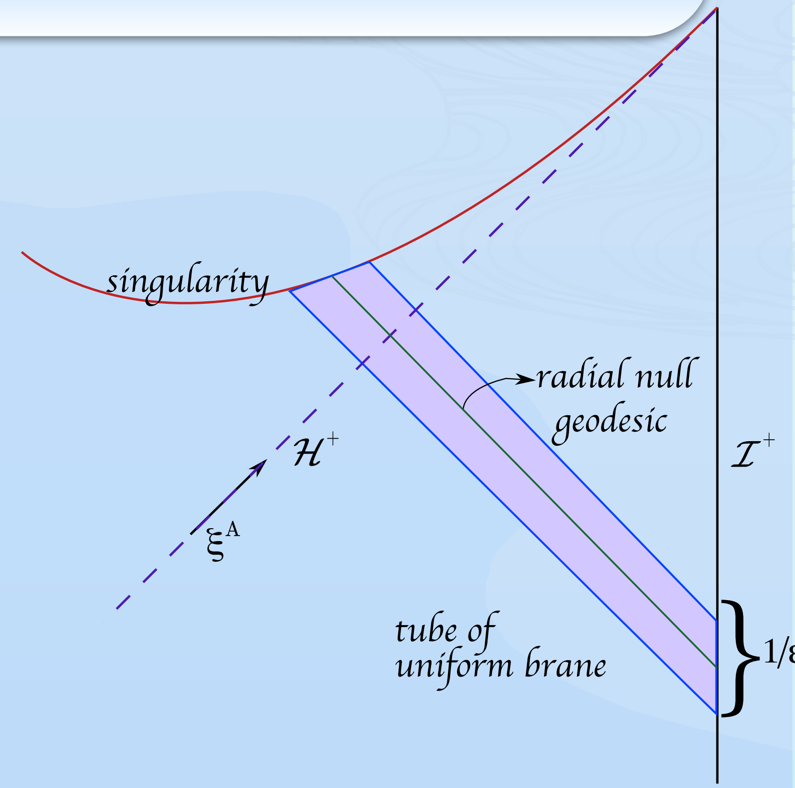
Fluid/Gravity Duality (2008-)

AdS Black Brane

$$ds^2 = -2\,u_\mu\,dx^\mu dr + r^2\,\left(\eta_{\mu\nu} + [1 - f(r/\pi T)]\,u_\mu\,u_\nu\right)\,dx^\mu dx^\nu$$
$$+\;2r\left[\frac{r}{\pi T}\,F(r/\pi T)\,\sigma_{\mu\nu} + \frac{1}{3}\,u_\mu u_\nu\,\partial_\lambda u^\lambda - \frac{1}{2}\,u^\lambda\partial_\lambda\,(u_\nu u_\mu)\right]\,dx^\mu dx^\nu,$$

$$g_{ab} = \sum_{k=0}^{\infty}\epsilon^k\,g_{ab}^{(k)}\,,\qquad T = \sum_{k=0}^{\infty}\epsilon^k\,T^{(k)}\,,\qquad u_\mu = \sum_{k=0}^{\infty}\epsilon^k\,u_\mu^{(k)}\,.$$

$$T^{\mu\nu} = \lim_{r_c\to\infty}\frac{r_c^{d-2}}{16\pi\,G_N}\left[K^{\mu\nu} - K\,\gamma^{\mu\nu} - (d-1)\,\gamma^{\mu\nu} - \frac{1}{d-2}\left(R^{\mu\nu} - \frac{1}{2}\,R\,\gamma^{\mu\nu}\right)\right]$$



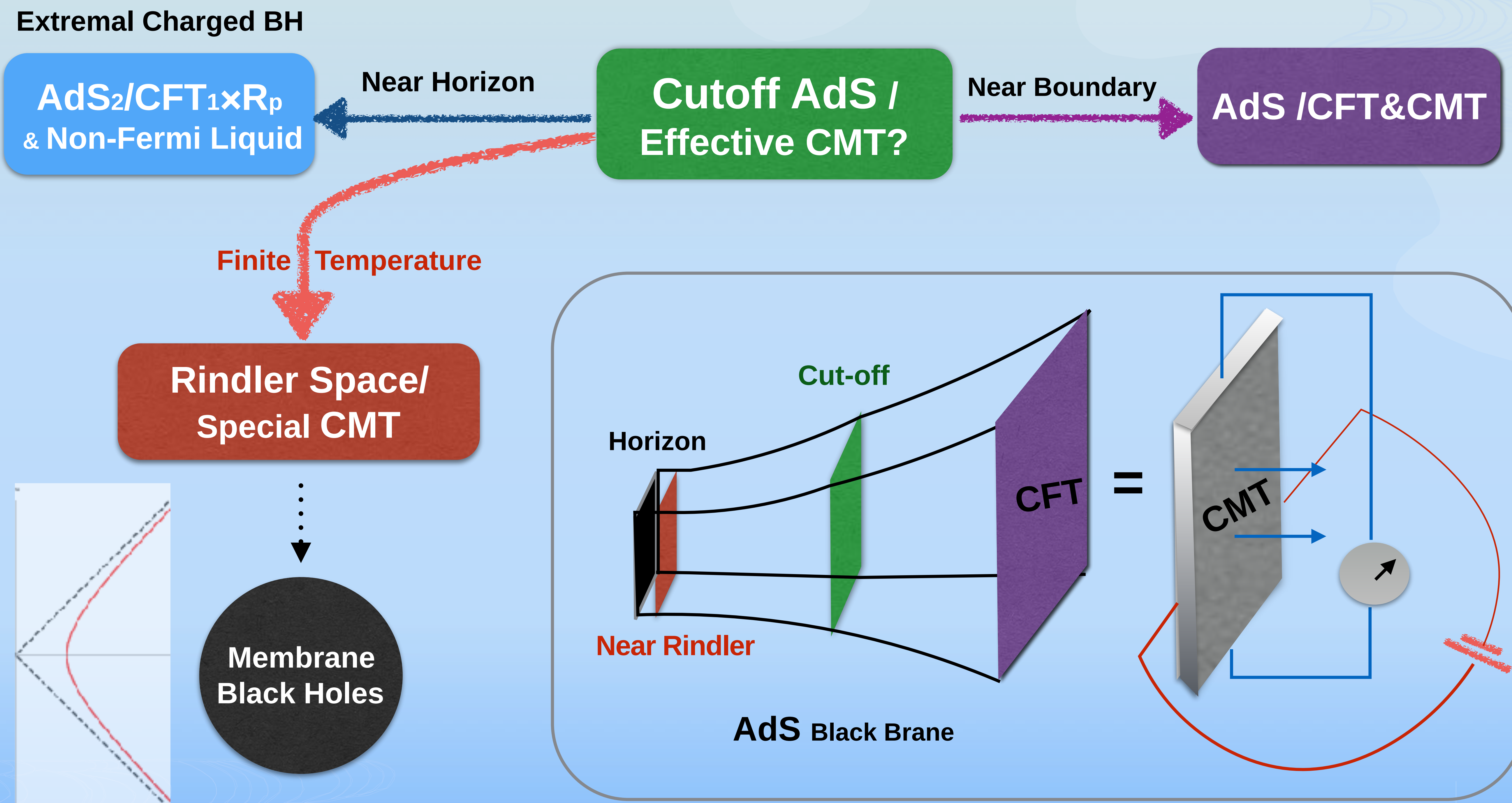
Conformal Fluid

$$T^{\mu\nu} = P\,(\gamma^{\mu\nu} + d\,u^\mu\,u^\nu) - 2\,\eta\,\sigma^{\mu\nu}$$
$$+\,2\,\eta\,\left[\tau_1\,u^\lambda\,\mathcal{D}_\lambda\sigma^{\mu\nu} - \tau_\epsilon\,(\omega^\mu{}_\lambda\,\sigma^{\lambda\nu} + \omega^\nu{}_\lambda\,\sigma^{\lambda\mu})\right] + \xi_C\,C^{\mu\alpha\nu\beta}\,u_\alpha\,u_\beta$$
$$+\,\xi_\sigma\left[\sigma^\mu{}_\lambda\,\sigma^{\lambda\nu} - \frac{P^{\mu\nu}}{d-1}\sigma_{\alpha\beta}\,\sigma^{\alpha\beta}\right] + \xi_\omega\left[\omega^\mu{}_\lambda\,\omega^{\lambda\nu} + \frac{P^{\mu\nu}}{d-1}\omega_{\alpha\beta}\,\omega^{\alpha\beta}\right],$$

$$P = \frac{1}{16\pi G_N}\left(\frac{4\pi\,T}{d}\right)^d$$
$$\eta = \frac{s}{4\pi} = \frac{1}{16\pi G_N}\left(\frac{4\pi\,T}{d}\right)^{d-1}$$
$$\tau_1 = \frac{d}{4\pi\,T}\left(1 - \int_1^\infty dy\,\frac{y^{d-2}-1}{y\,(y^d-1)}\right)$$
$$\tau_\epsilon = \frac{d}{4\pi\,T}\int_1^\infty dy\,\frac{y^{d-2}-1}{y\,(y^d-1)}$$
$$\xi_\sigma = \xi_C = \frac{d}{4\pi\,T}\,2\,\eta$$
$$\xi_\omega = 0\;.$$

[Bhattacharyya, Hubeny, Minwalla, Rangamani et al]

Moving the Holographic Screen to the Finite Cutoff



Wilsonian Approach to Fluid/Gravity Duality [Bredberg, Keeler, Lysov, Strominger, JHEP 1103(2011)141]

Non-Relativistic Fluid Dual to Asymptotically AdS Gravity at Finite Cutoff Surface [Cai, Li, Zhang, JHEP 1107(2011)027]

Hydrodynamics of the Cutoff AdS Fluid

AdS Metric $$ds^2_{p+2} = -r^2 f(r) d\tau^2 + \frac{1}{r^2 f(r)} dr^2 + r^2 dx_i dx^i$$

Induced Metric $$ds^2_{p+1} = -r_c^2 f(r_c) d\tau^2 + r_c^2 dx_i dx^i$$

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

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

Our contributions in the Holographic Cutoff AdS Fluid

Holographic Cutoff AdS Fluid in Non-relativistic limit
[Cai, Li, **Zhang**, JHEP 1107(2011)027]

$$\partial_r \sim \epsilon^0, \quad \partial_i \sim v_i \sim \partial_i \phi \sim \epsilon^1, \quad \partial_\tau \sim P \sim \epsilon^2$$

Holographic Forced Fluid Dynamics on finite Cutoff
[Cai, Li, Nie, **Zhang**, NPB 864 (2012) 260]

$$\partial_i v^i = 0, \quad \partial_\tau v_i + v^j \partial_j v_i + \partial_i P - \nu \partial^2 v_i = f_i^\phi + f_i^q$$

Incompressible Navier-Stokes from Chern-Simons Modified Gravity
Cai, Li, Qi, **Zhang**, PRD 86 (2012) 086008]

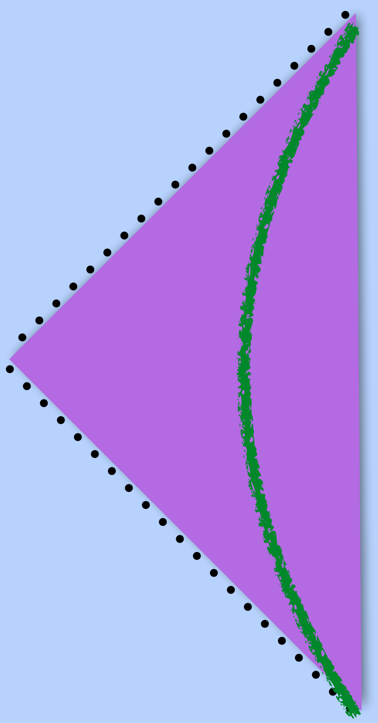
$$\partial_\tau v_i + v^j \partial_j v_i + \partial_i P - \nu \partial^2 v_i - (\tilde{\nu} \epsilon_{ij} \partial^2 v_j + \tilde{\zeta} \epsilon^{jk} \partial_i \partial_j v_k) = f_i$$

Holographic Charged Fluid with Anomalous Current at Finite Cutoff
[Bai, Hu, Lee, **Zhang**, JHEP 1211 (2012) 054]

$$\xi_B = c\left(\mu - \frac{1}{2}\frac{n\mu^2}{\rho + p}\right), \quad \xi_V = c\left(\mu^2 - \frac{2}{3}\frac{n\mu^3}{\rho + p}\right)$$

Cutoff AdS Fluid with Momentum Relaxation

Rindler Fluid ← Near Horizon — **Cutoff AdS/Fluid** — Near Boundary → **AdS/CFT Fluid**



Ward Identity

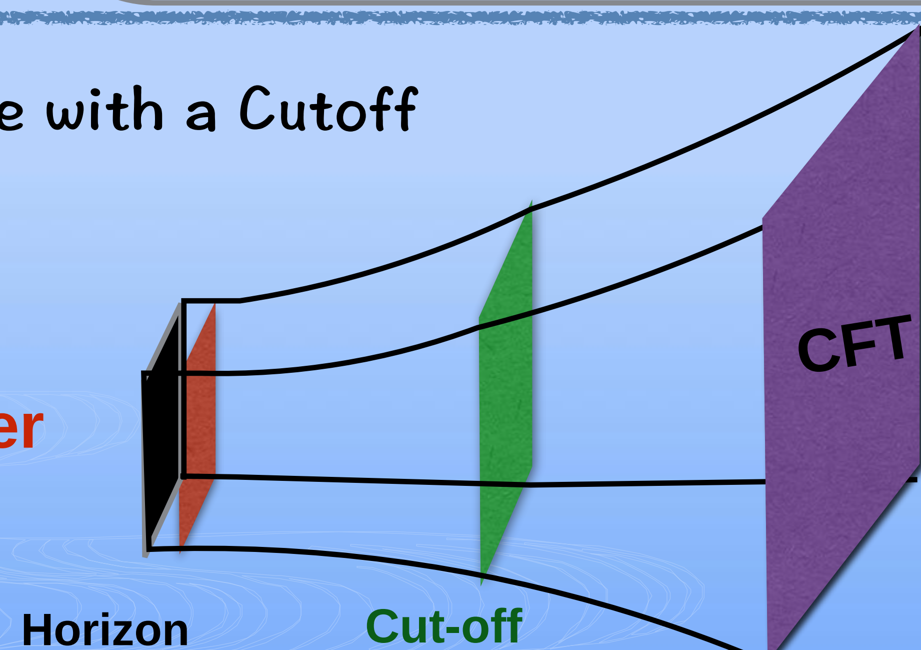
$$\partial_t \langle \mathcal{T}^t{}_i \rangle + \partial_i \tilde{\mathcal{P}} = -\bar{\tau}_c^{-1} \langle \mathcal{T}^t{}_i \rangle - \ell_c k^2 \partial_t v_i + \cdots \,, \qquad \bar{\tau}_c^{-1} = \frac{k^2 \tilde{s}_c}{4\pi(\tilde{\mathcal{E}} + \tilde{\mathcal{P}})}.$$

Thermal Conductivity & Relaxation Rate

$$\tilde{\kappa}_\omega = \frac{1}{1 - \mathbb{i}\omega\tau_c} \frac{4\pi \tilde{s}_c \tilde{T}_c}{k^2}, \qquad \tau_c^{-1} = \frac{k^2}{4\pi \tilde{T}_c}\left[1 - \frac{\ell_c T_c}{s_c}\frac{k^2}{T_c^2}\right] + O(k^6).$$

AdS Black Brane with a Cutoff

Near Rindler



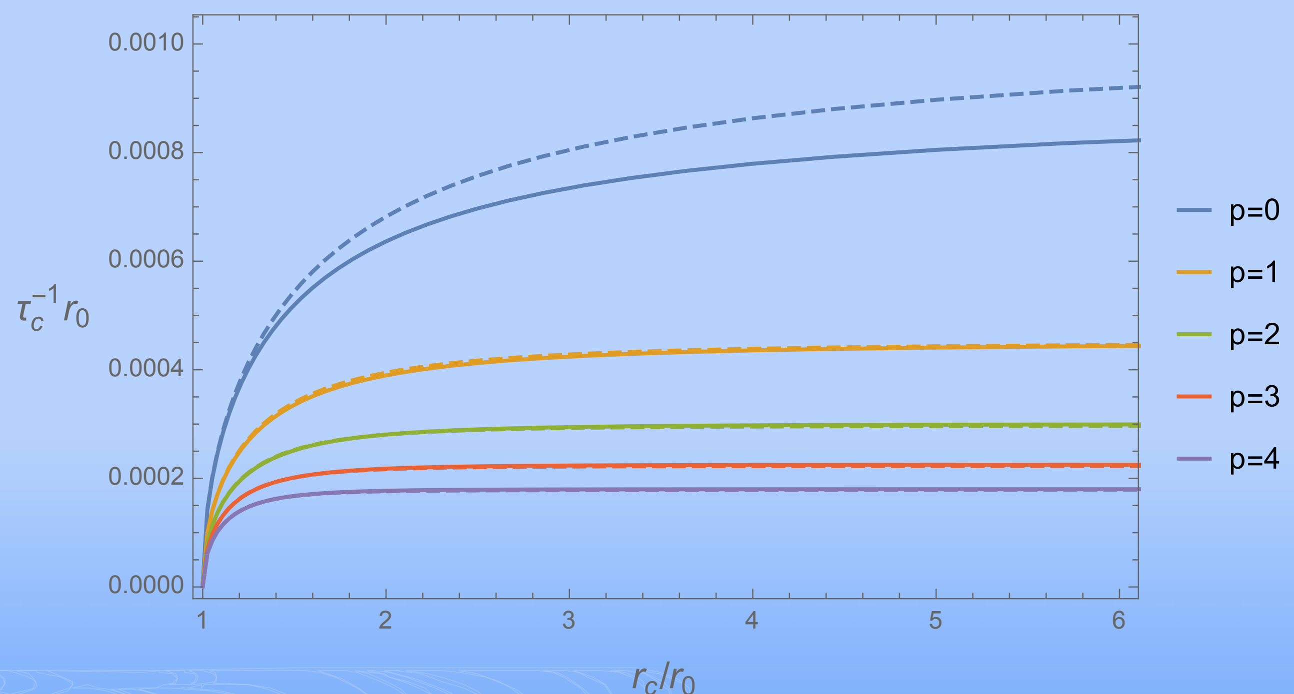
Sub-Leading Correction

$$\xi_c \equiv \frac{\ell_c T_c}{s_c} = (p+1)\left[\tilde{\xi}_p(r_c) - \frac{r_c \tilde{\xi}'_p(r_c)}{(p-1)}\right],$$

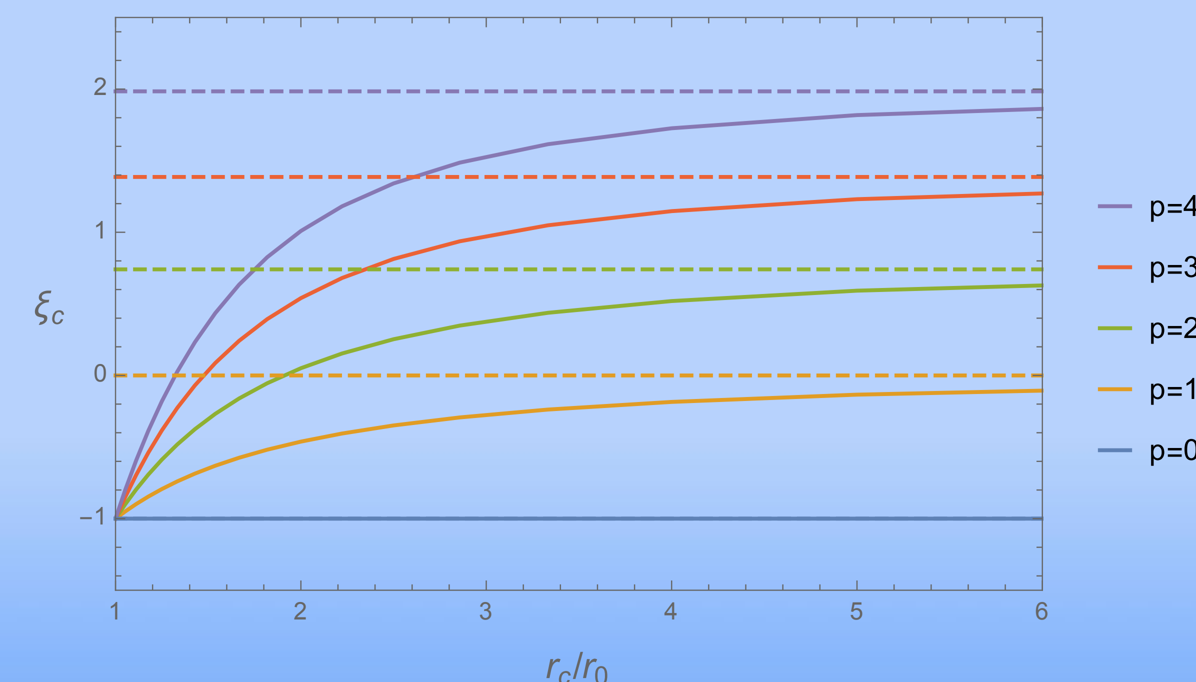
Running From Conformal Fluid to Rindler Fluid

$$S_{\text{Rindler}} = S_{\text{CFT}} - S_{\text{AdS}}\big|_{r_0+\epsilon}^{\infty} \qquad S_{\text{Cutoff}} = S_{\text{CFT}} - S_{\text{AdS}}\big|_{r_c}^{\infty} \qquad S_{\text{AdS}} = S_{\text{CFT}}$$

Momentum Relaxation Rate



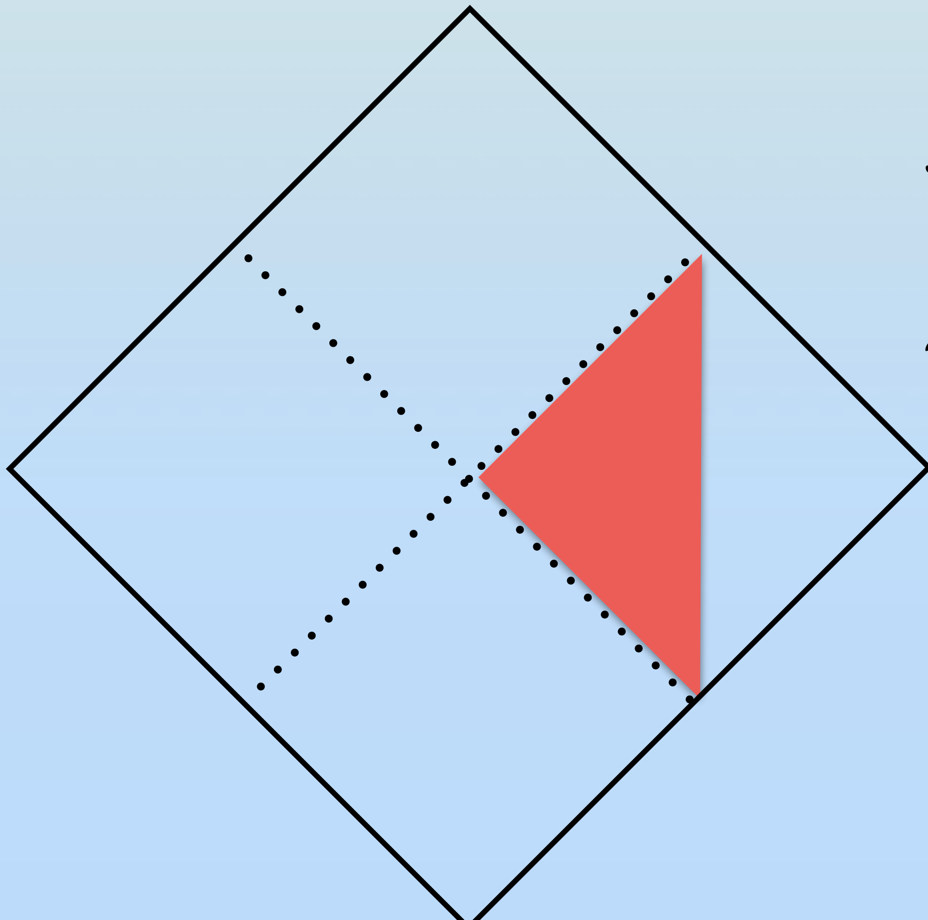
Sub-leading Corrections



$$\tau_c^{-1} = \frac{k^2}{4\pi \tilde{T}_c}\left(1 - \xi_c \frac{k^2}{\tilde{T}_c^2}\right), \qquad \xi_c = \frac{\ell_c T_c}{s_c}.$$

$$\tilde{\xi}_p(r) \equiv \int_{r_0}^{r} \frac{d\tilde{r}\, r_0^2}{\tilde{r}^3 f(\tilde{r})}\left(1 - \frac{r_0^{p-1}}{\tilde{r}^{p-1}}\right).$$

From AdS/CFT to Holographic Rindler Fluid



Flat Spacetime

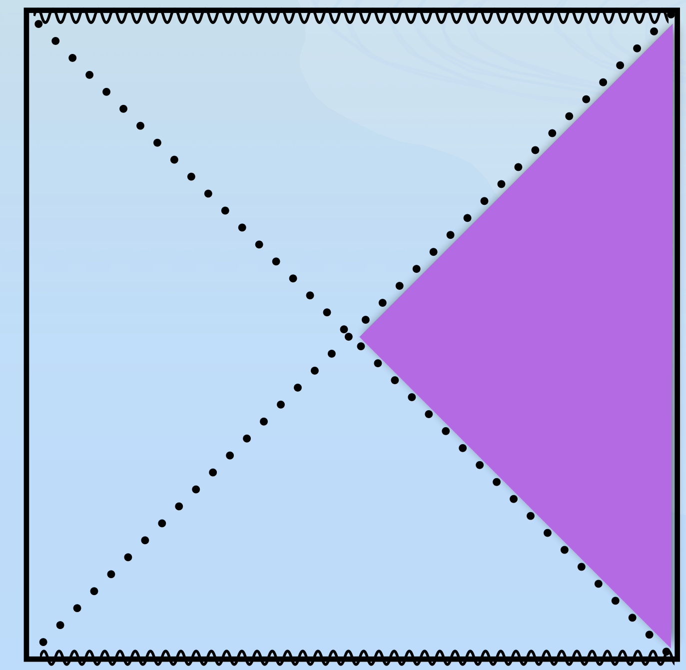
Holographic Screen

the Time-like boundary

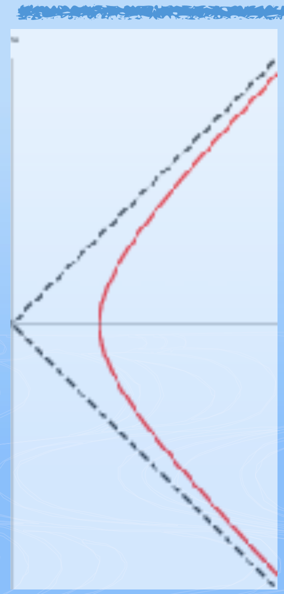
$$\mathcal{T}_{ab} = -2(K_{ab} - K\gamma_{ab})$$

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]

Rindler Fluid in Relativistic Derivative Expansion

Rindler Metric with Perturbations

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -2\mathrm{p}u_a dx^a dr + g_{ab}dx^a dx^b,$$

where $g_{ab} = g_{ab}^{(0)} + g_{ab}^{(1)} + g_{ab}^{(2)}$,

$$g_{ab}^{(0)} = -\mathrm{p}^2(r-r_c)u_a u_b + \gamma_{ab},$$

$$g_{ab}^{(1)} = 2\mathrm{p}(r-r_c)\left(u^c\partial_c \ln\mathrm{p}\, u_a u_b + 2a_{(a}u_{b)}\right),$$

$$\begin{aligned} g_{ab}^{(2)} =& 2(r-r_c)\Big[(\mathcal{K}_{cd}\mathcal{K}^{cd})u_a u_b - 2u_{(a}h_{b)}^c\partial_d\mathcal{K}^d{}_c \\ &- \mathcal{K}_a{}^c\mathcal{K}_{cb} + 2\mathcal{K}_{c(a}\Omega^c{}_{b)} - 2h_a^c h_b^d u^e\partial_e\mathcal{K}_{cd}\Big] \\ &+ \mathrm{p}^2(r-r_c)^2\Big\{\big(\frac{1}{2}\mathcal{K}_{cd}\mathcal{K}^{cd} + a_c a^c\big)u_a u_b \\ &+ 2u_{(a}h_{b)}^c\left[\partial_d\mathcal{K}^d{}_c - (\mathcal{K}_{cd}+\Omega_{cd})a^d\right] - \Omega_{ac}\Omega^c{}_b\Big\} \\ &+ \mathrm{p}^4(r-r_c)^3\big(\frac{1}{2}\Omega_{cd}\Omega^{cd}\big)u_a u_b. \end{aligned}$$

Holographic Fluid

$$T_{ab} = T_{ab}^{(0)} + T_{ab}^{(1)} + T_{ab}^{(2)} + O(\partial^3),$$

$$\begin{aligned} T_{ab}^{(0)} =& \mathrm{p}h_{ab}, \\ T_{ab}^{(1)} =& \zeta'(u^c\partial_c\ln\mathrm{p})u_a u_b - 2\eta\mathcal{K}_{ab}, \\ T_{ab}^{(2)} =& \mathrm{p}^{-1}\Big\{\big[d_1\mathcal{K}_{ab}\mathcal{K}^{ab} + d_2\Omega_{ab}\Omega^{ab} + d_3(u^c\partial_c\ln\mathrm{p})^2 \\ &+ d_4 u^c\partial_c(u^d\partial_d\ln\mathrm{p}) + d_5 h^{cd}(\partial_c\ln\mathrm{p})(\partial_d\ln\mathrm{p})\big]u_a u_b \\ &+ \big[c_1\mathcal{K}_{ac}\mathcal{K}^c{}_b + c_2\mathcal{K}_{c(a}\Omega^c{}_{b)} + c_3\Omega_{ac}\Omega^c{}_b + c_4 h_a^c h_b^d\partial_c\partial_d\ln\mathrm{p} \\ &+ c_5\mathcal{K}_{ab}(u^c\partial_c\ln\mathrm{p}) + c_6(h_a^c\partial_c\ln\mathrm{p})(h_b^d\partial_d\ln\mathrm{p})\big]\Big\}. \end{aligned}$$

Constraint Equations

$$\partial_a u^a = 2\mathrm{p}^{-1}\mathcal{K}_{ab}\mathcal{K}^{ab} + O(\partial^3),$$

$$a_a + h_a^b\partial_b\ln\mathrm{p} = 2\mathrm{p}^{-1}h_a^c\partial_b\mathcal{K}_c^b + O(\partial^3).$$

Ref: Eling, Meyer, Oz , JHEP 1205 (2012) 116

Compère, McFadden, Skenderis ,Taylor, JHEP 1203 (2012) 076

Transport coefficients

$$\begin{aligned} \zeta' &= 0, & \eta &= 1, \\ d_1 &= -2, & d_2 &= d_3 = d_4 = d_5 = 0, \\ c_1 &= -2, & c_2 &= c_3 = c_4 = c_5 = -c_6 = -4. \end{aligned}$$

Rindler Fluid and Recurrence Relation

Petrov Type I Condition $\qquad \mathbb{P}_{ab} \equiv \boldsymbol{n}^r h_a^c \boldsymbol{n}^r h_b^d C_{rcrd}$

$$T_{ab}^{(0)} = \mathcal{E} u_a u_b + \mathcal{P} h_{ab} \overset{\mathbb{P}_{ab}=0}{\Longrightarrow} T_{ab}^{(1)} = -2\eta\sigma_{ab} + \ldots \overset{\mathbb{P}_{ab}=0}{\Longrightarrow} T_{ab}^{(2)} = \ldots$$

$$\begin{aligned} 4\mathbb{P}_{ab} = h_a^m h_b^n \big[& (T_{mc}T_{nd} - T_{mn}T_{cd})\, u^c u^d - T_{mc}T^c{}_n \\ & - 4u^c \partial_c T_{mn} + 4u^c \partial_{(m} T_{n)c} \big] \\ & + p^{-2} \big[T(T + p\, T_{cd} u^c u^d) + 4p\, u^c \partial_c T \big] h_{ab}. \end{aligned}$$

Petrov type I Spacetime and Dual Relativistic Fluids
[Cai, Yang, **Zhang**, PRD90 (2014) 041901(R)]

Rindler-Fluid		AdS Cutoff-Fluid		AdS-CFT Fluid
Up to 2nd order **How about Higher orders?** [Cai, Yang, Zhang 1401.7792]	→	**Up to to 0th order** **Modified Condition?** [1306.5633]	→	**Up to to 0th order** **AdS/Rindler correspondence?**

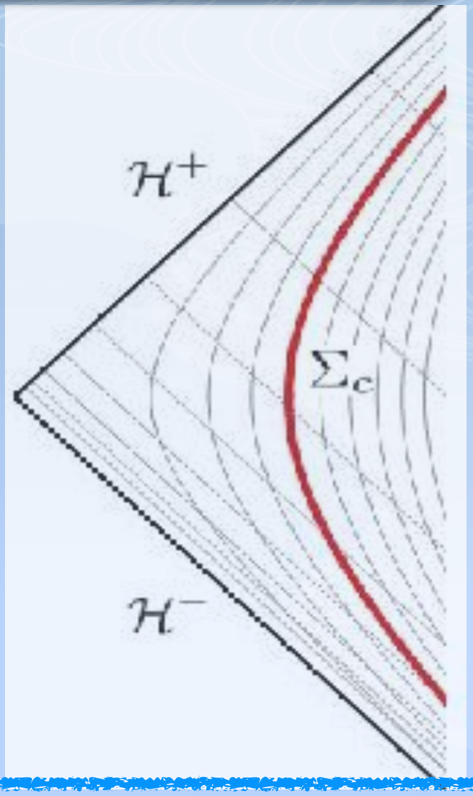
Petrov type I Condition and Rindler Fluid in Vacuum Einstein-Gauss-Bonnet Gravity
[Cai, Yang, **Zhang**, JHEP 1412 (2014) 147]

I. Flat Bulk/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

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

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

Non-relativistic limit -> Incompressible Navier-Stokes Equations

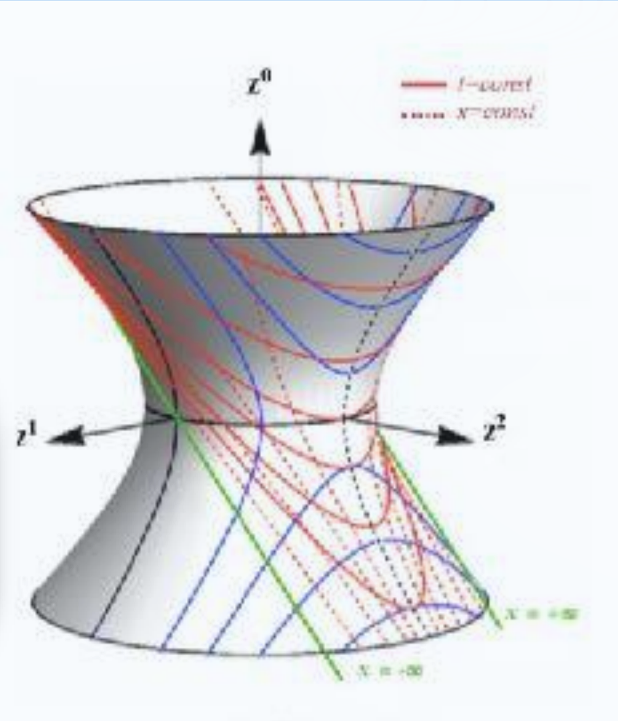
$$\partial_i v^i = 0 \qquad \partial_i P + \partial_\tau v_i + v^j \partial_j v_i - \eta \partial^2 v_i = 0$$

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

II. Flat Bulk/de-Siter Fluid

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

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

$$\langle T_{\mu\nu} \rangle = -\frac{\Lambda}{\kappa_4} g_{\mu\nu}$$

$$L = \frac{\kappa_5}{\kappa_4}$$

Hamiltonian constraints

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

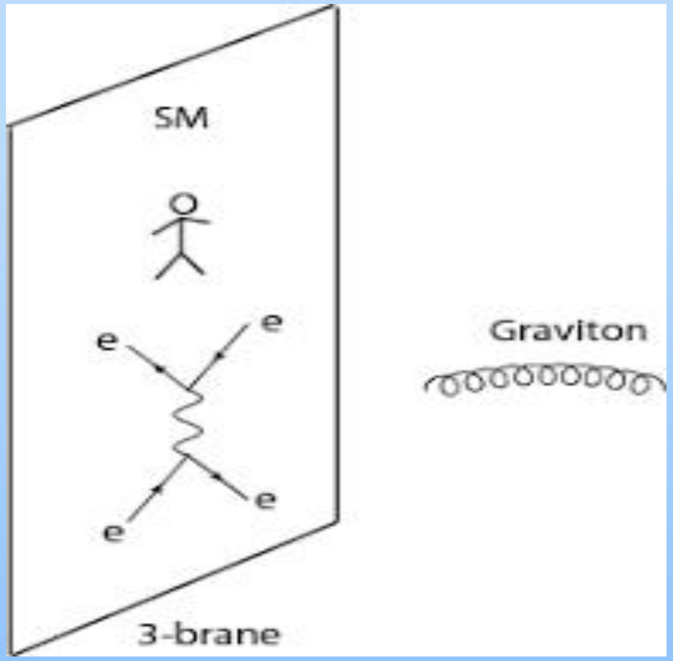
2) Embedding in higher dimensions — Brane World Models

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

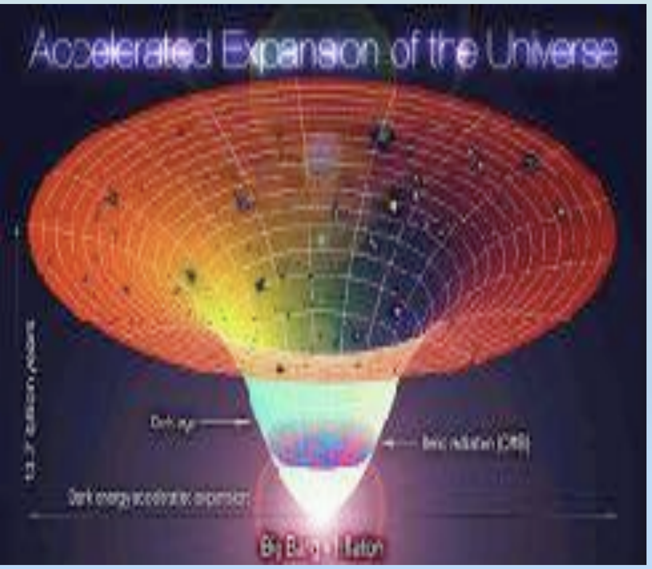
$$\mathcal{T}^{\mathcal{M}}_{\mu\nu} \equiv (\mathcal{K} g_{\mu\sigma} - \mathcal{K}_{\mu\sigma})\mathcal{K}^{\sigma}{}_{\nu} + \mathcal{M}_{\mu\nu} - \frac{1}{2}\left(\mathcal{K}^2 - \mathcal{K}_{\rho\sigma}\mathcal{K}^{\rho\sigma}\right) g_{\mu\nu},$$

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

[Maeda, Mukohyama, Sasaki, Shiromizu, …, ['99, '10]



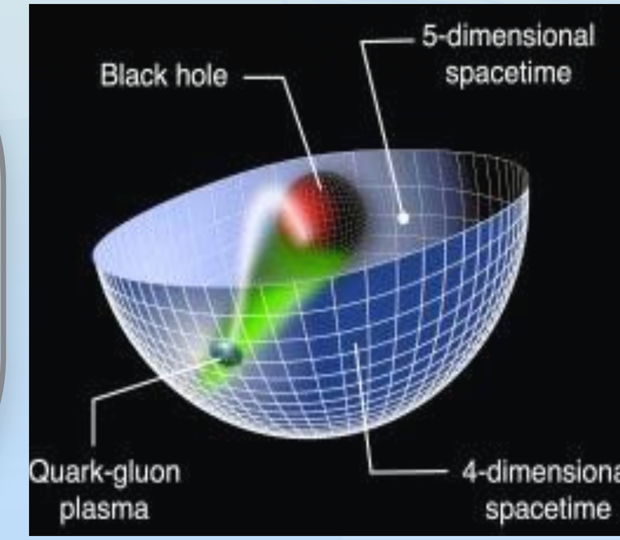
III. Flat Bulk/FRW Fluid



The Total Action

$$\mathcal{S}_{tot} = \int_{\mathcal{H}} \mathrm{d}^4x\sqrt{-g}\left(\frac{1}{2\kappa_4}R + \mathcal{L}_m\right) + \mathcal{S}_5\,,$$

$$\mathcal{S}_5 \equiv \int_{\mathcal{M}} \mathrm{d}^5x\sqrt{-\tilde{g}}\left(\frac{1}{2\kappa_5}\mathcal{R}\right) + \int_{\mathcal{H}} \mathrm{d}^4x\sqrt{-g}\,\frac{1}{\kappa_5}\mathcal{K},$$



Einstein Field Equations

$$\frac{1}{\kappa_4}G_{\mu\nu} = T^m_{\mu\nu} + \langle\mathcal{T}\rangle^d_{\mu\nu},$$

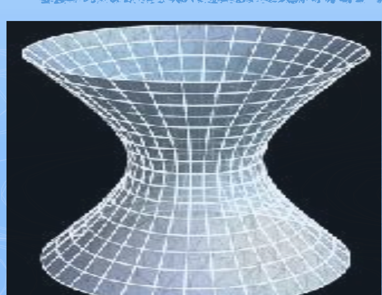
Holographic Dark Fluid?

Stress Energy Tensors

$$T^m_{\mu\nu} \equiv -\frac{2}{\sqrt{-g}}\frac{\delta(S_m)}{\delta g^{\mu\nu}},\qquad \langle\mathcal{T}\rangle^d_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta(\mathcal{S}_5)}{\delta g^{\mu\nu}} = \frac{1}{\kappa_5}\left(\mathcal{K}_{\mu\nu} - \mathcal{K}g_{\mu\nu}\right)$$

In the Bulk => Modified GR

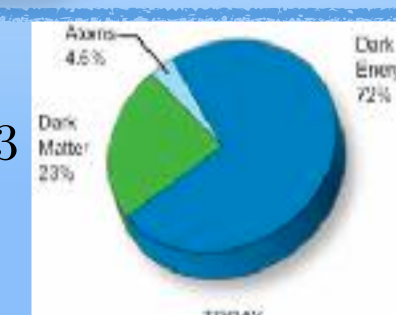
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{\kappa_4}{\kappa_5}\left(\mathcal{K}_{\mu\nu} - \mathcal{K}g_{\mu\nu}\right) = \kappa_4 T^m_{\mu\nu}$$



Hamilton Constraint Equation
& Emergent de-Sitter Universe

$$\delta_{CSZ} \equiv \Omega_D^2 - \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B) \simeq -0.003$$

$$\delta_V \equiv \Omega_D^2 - \frac{4}{3}\Omega_B \simeq 0.004\,.$$



holographic Emergent Dark Universe (hEDU) & SNIa Data

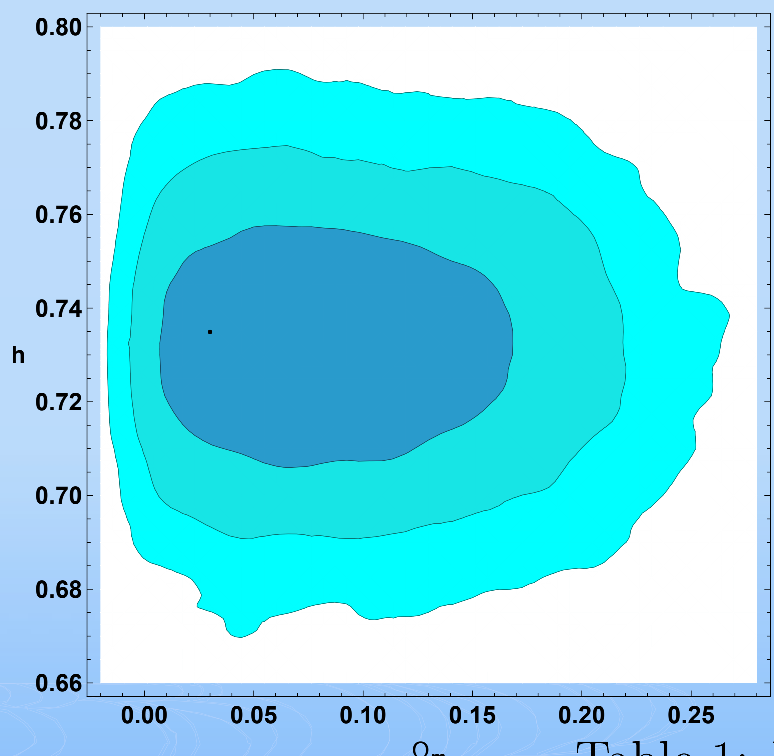
Friedmann Equations

$$\text{LCDM}: \quad \frac{H(z)^2}{H_0^2} = \Omega_\Lambda + \Omega_m (1+z)^3$$

$$\text{sDGP}: \quad \frac{H(z)^2}{H_0^2} = \frac{\Omega_\Lambda}{2} + \Omega_m (1+z)^3 + \frac{\Omega_\Lambda}{2}\sqrt{1 + \frac{4\Omega_m}{\Omega_\Lambda}(1+z)^3}$$

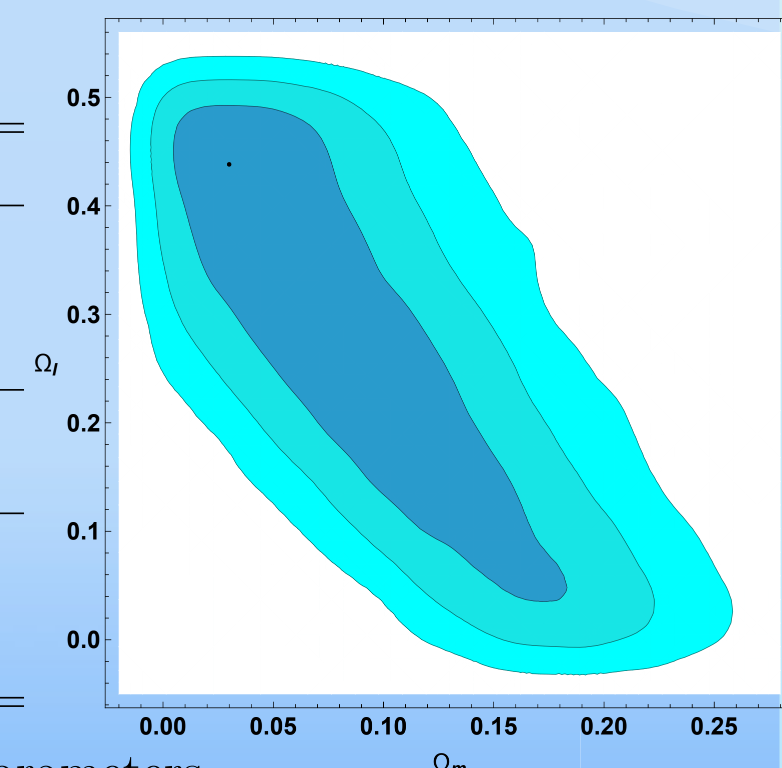
$$\text{hEDU}: \quad \frac{H(z)^2}{H_0^2} = \frac{\Omega_\Lambda}{2} + \Omega_m (1+z)^3 + \frac{\Omega_\Lambda}{2}\sqrt{1 + \frac{4\Omega_m}{\Omega_\Lambda}(1+z)^3 + \frac{4\Omega_I}{\Omega_\Lambda}(1+z)^4}$$

$$\langle \mathcal{T} \rangle^d_{\mu\nu} = -\frac{2}{\sqrt{-g}} \frac{\delta(\mathcal{S}_5)}{\delta g^{\mu\nu}} = \frac{1}{\kappa_5}\left(\mathcal{K}_{\mu\nu} - \mathcal{K} g_{\mu\nu}\right)$$



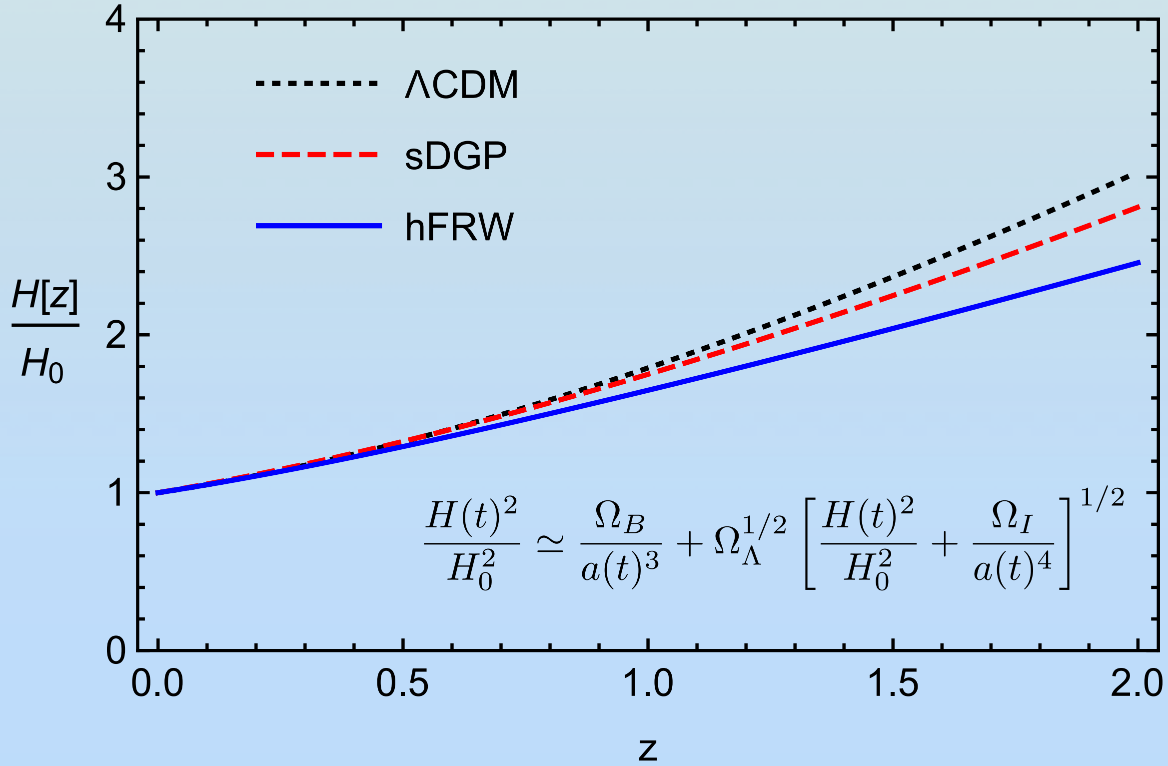
Parameters	LCDM	hEDU
h	0.7330 ± 0.0180	0.7349 ± 0.0179
Ω_m	0.2969 ± 0.0352	0.0299 ± 0.0515
Ω_I	—	0.4382 ± 0.1317
α	0.1403 ± 0.0068	0.1409 ± 0.0068
β	3.1081 ± 0.0892	3.1144 ± 0.0896
$\chi^2_{\min}$	695.063	694.321
ΔAIC	0	1.258
ΔBIC	0	5.866

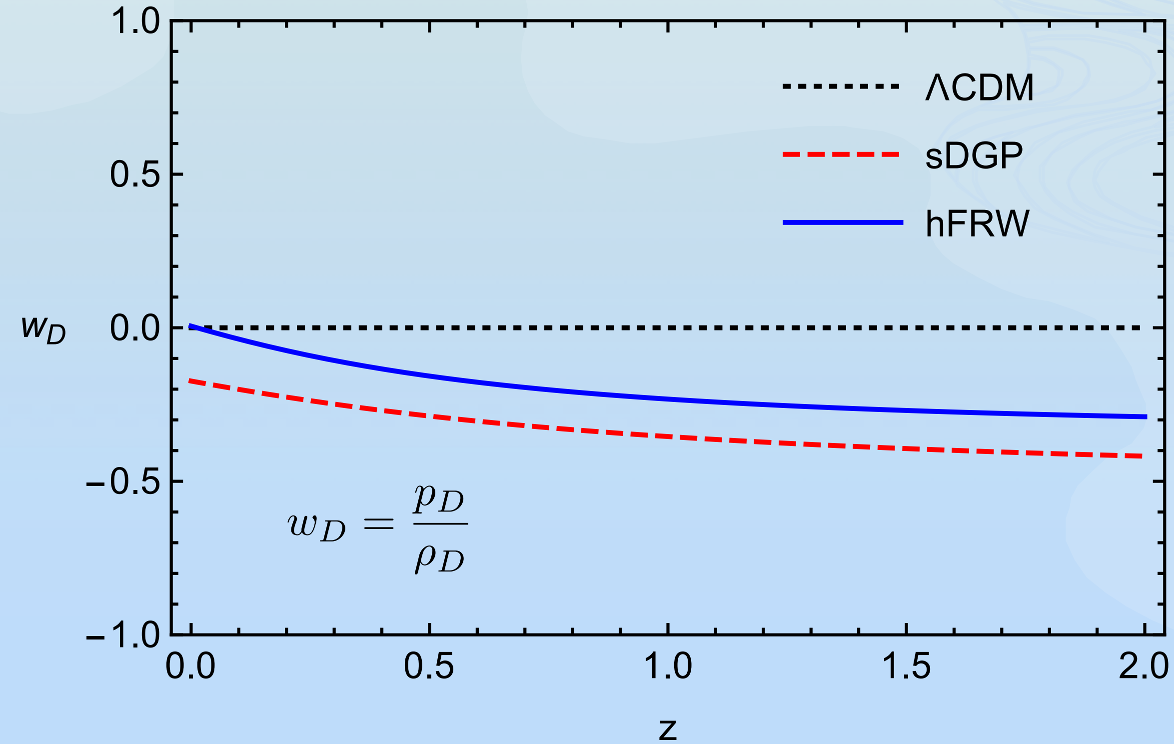
Table 1: Fitting values and uncertainties of the cosmological parameters.



Ref: [arXiv: 1812.11105] with Gansukh Tumurtushaa(IBS/Korea) et al

Late-Time Evolution of Holographic FRW Model





Hamiltonian Constraint from FRW Hypersurface

$$\tilde{\Omega}_D^2 = \frac{\tilde{\Omega}_\Lambda}{2(1+3\tilde{w}_D)}\left[\tilde{\Omega}_D(1-3\tilde{w}_D) - \tilde{\Omega}_B\right].$$

$$\tilde{\Omega}_\Lambda = \Omega_\Lambda, \qquad \tilde{\Omega}_D = \Omega_{\mathcal{H}}(t) - \Omega_\Lambda, \qquad \tilde{\Omega}_B \equiv \frac{\Omega_M}{a(t)^3} = \frac{H(t)^2}{H_0^2} - \Omega_{\mathcal{H}}(t),$$

$$\tilde{w}_D = -1 - \frac{1}{3H(t)}\frac{\dot{\Omega}_{\mathcal{H}}(t)}{\Omega_{\mathcal{H}}(t) - \Omega_\Lambda}, \qquad \Omega_{\mathcal{H}}(t) \equiv \frac{\rho_{\mathcal{H}}}{\rho_c} = \Omega_\Lambda^{1/2}\left[\frac{H(t)^2}{H_0^2} + \frac{\Omega_I}{a(t)^4}\right]^{1/2}.$$

Late Time Universe

$$\delta_{CSZ} \equiv \Omega_D^2 - \frac{1}{2}\Omega_\Lambda(\Omega_D - \Omega_B) \simeq -0.003\,,$$

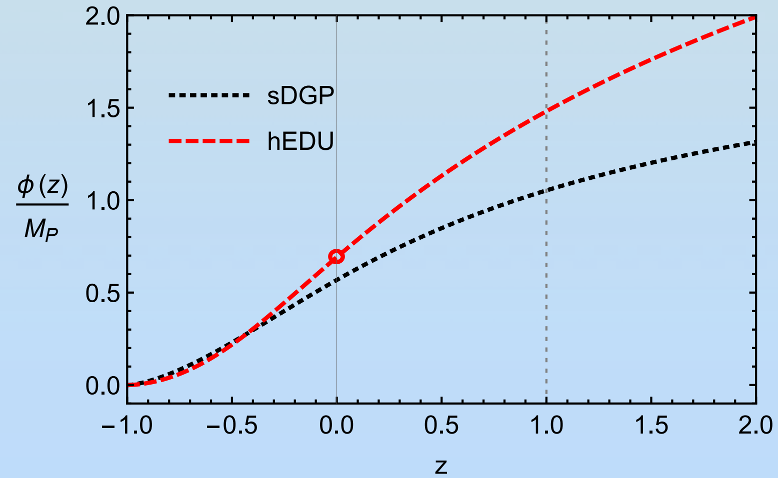
$$\delta_V \equiv \Omega_D^2 - \frac{4}{3}\Omega_B \simeq 0.004\,. \qquad \Omega_\Lambda \simeq 0.685, \quad \Omega_D \simeq 0.265, \quad \Omega_B \simeq 0.050,$$

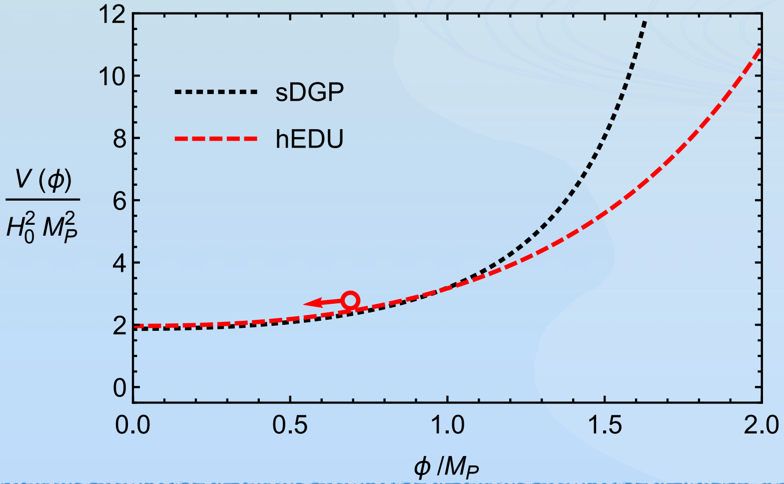
Effective Potential & Swampland Criteria

Effective Action

$$\mathcal{S}_{tot} = \int \mathrm{d}^4x\sqrt{-g}\Big[\frac{1}{2\kappa_4}R + \mathcal{L}_m - \frac{1}{2}(\partial\phi)^2 - V(\phi)\Big].$$

$$V[\phi(t)] = \frac{1}{2}\left[\rho_d(t) - p_d(t)\right],$$
$$\dot\phi(t) = -\sqrt{\rho_d(t) + p_d(t)}\,.$$



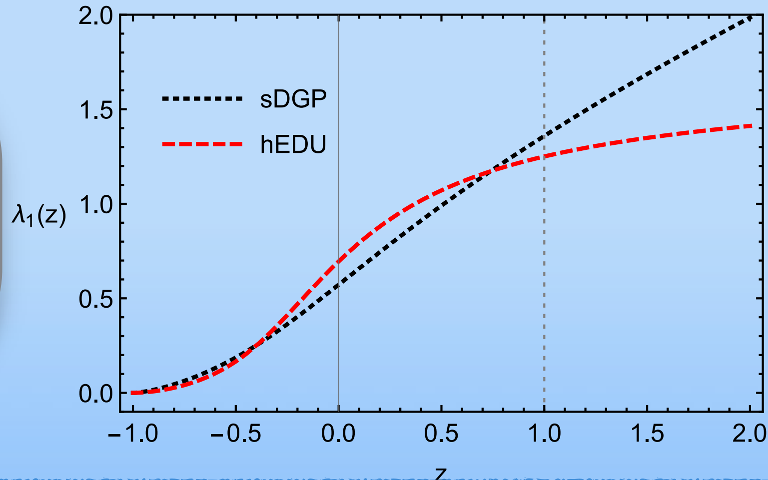


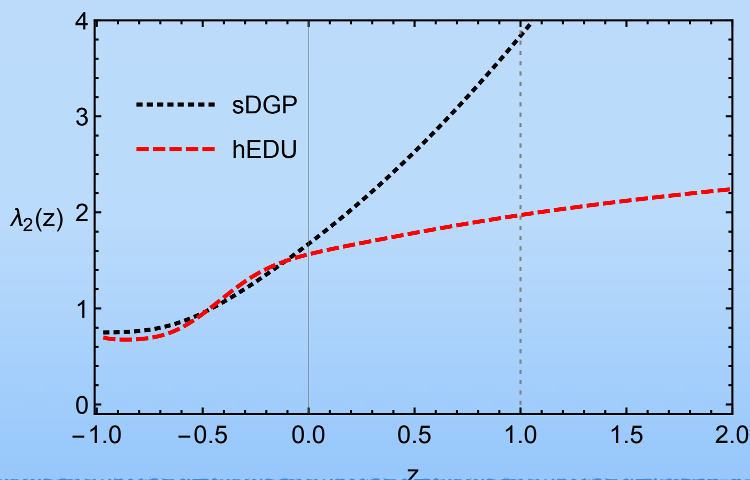
Swampland Criteria

$$\text{Criterion 1}: \quad \frac{|\Delta\phi|}{M_P} \le d_0, \qquad d_0, c_1, c_2 \sim \mathcal{O}(1)$$

$$\text{Criterion 2}: \quad M_P|\nabla V| \ge c_1 V \quad \text{or} \quad M_P^2 \min[\nabla_i\nabla_j V] \le -c_2 V,$$

$$\lambda_1 \equiv M_P\frac{V'}{V}, \qquad V' \equiv \frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} = \frac{\dot V(t)}{\dot\phi(t)},$$
$$\lambda_2 \equiv M_P^2\frac{V''}{V}, \qquad V'' \equiv \frac{\mathrm{d}}{\mathrm{d}\phi}\frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} = \frac{1}{\dot\phi(t)}\frac{\mathrm{d}}{\mathrm{dt}}\Big[\frac{\dot V(t)}{\dot\phi(t)}\Big].$$





$$\frac{H(z)^2}{H_0^2} = \frac{\Omega_\Lambda}{2}\sqrt{1 + \frac{4}{\Omega_\Lambda}\left[\Omega_m(1+z)^3 + \Omega_I(1+z)^4\right]} + \frac{\Omega_\Lambda}{2} + \Omega_m(1+z)^3. \qquad (\text{:}$$

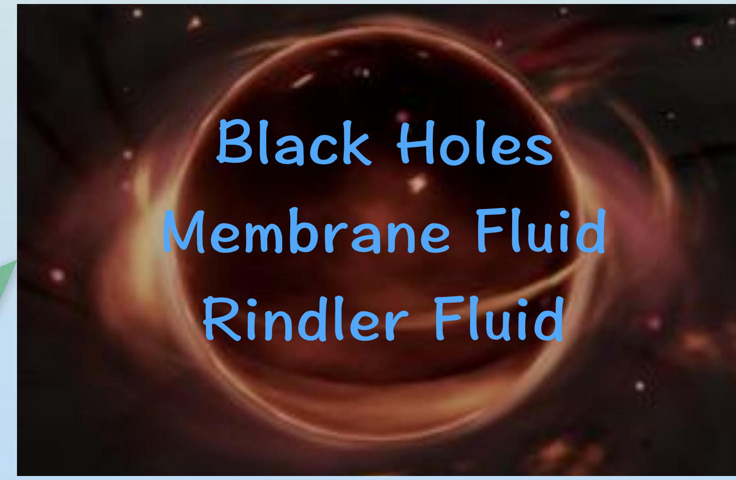
$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} - \frac{1}{L}\left(\mathcal{K}_{\mu\nu} - \mathcal{K}g_{\mu\nu}\right) = \kappa_4 T_{\mu\nu}$$

Ref: [arXiv: 1812.11105] Emergent Dark Universe and the Swampland Criteria

Summary & Outlook

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

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



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

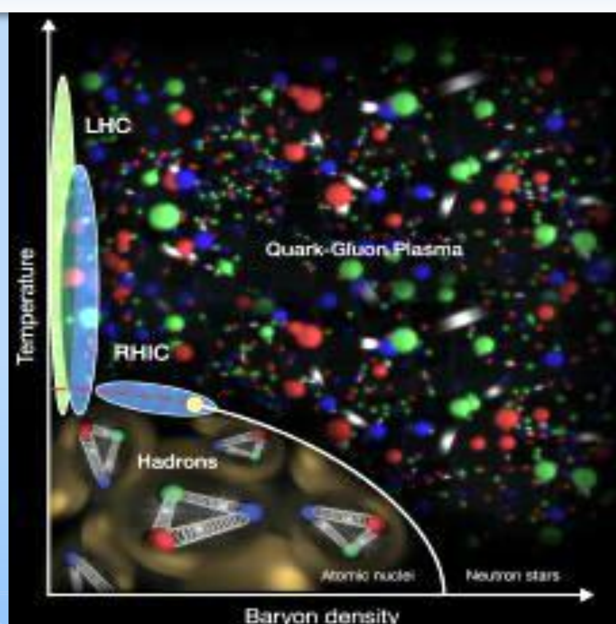
$$\frac{H^2}{H_0^2} \simeq \frac{\Omega_B}{a^3} + \sqrt{\Omega_\Lambda\left(\frac{H^2}{H_0^2} + \frac{\Omega_I}{a^4}\right)}$$

Quark Critical Liquid

QGP [00s] & strange metal ['10s]

Cosmological Fluid

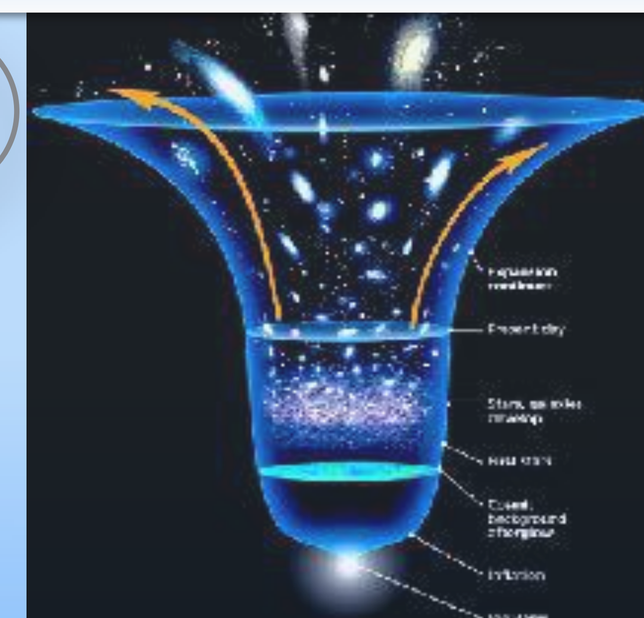
Dark Matter['70s] & Energy['90s]



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

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

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



AdS/FRW (Gansukh's poster No.37)

Holographic Big Bang [Pourhasan, Afshordi, Mann, '14]

Thanks for Your Attention!