Higgs Phase of Gravity

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Arkani-Hamed, Cheng, Luty and Mukohyama, hep-th/0312099
Arkani-Hamed, Creminelli, Mukohyama and Zaldarriaga, hep-th/0312100
Arkani-Hamed, Cheng, Luty and Mukohyama and Wiseman, hep-ph/0507120
Cheng, Luty, Mukohyama and Thaler, hep-th/0603010
Mukohyama, hep-th/0502189, hep-th/0607181, hep-th/0610254

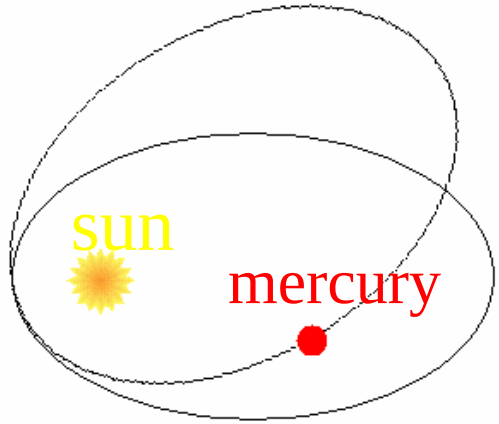
Motivation

- Gravity at long distances
  Flattening galaxy rotation curves
  Dimming supernovae
  accelerating universe

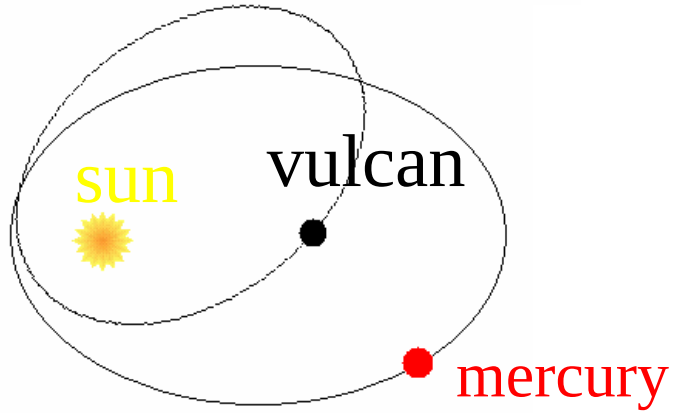
- Usual explanation: new forms of matter (DARK MATTER) and energy (DARK ENERGY).

Historical remark:

Precession of perihelion observed in 1800's…



which people tried to explain with a "dark planet", Vulcan,



But the right answer wasn't "dark planet", it was "change gravity" from Newton to GR.

Can we change gravity in IR to address these mysteries?

- Change theory?

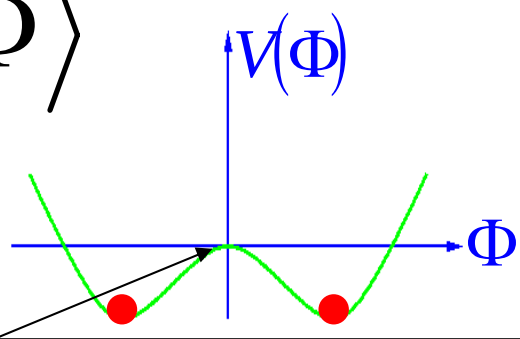
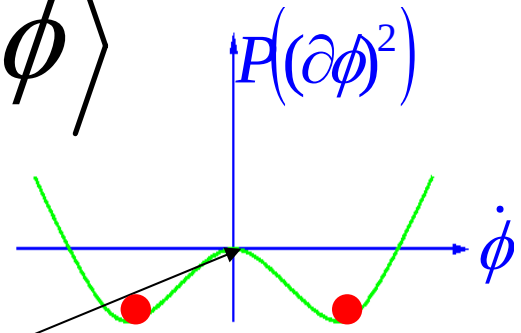
  Macroscopic UV scale…

- Change state (phase)?

  Higgs phase of gravity

  The simplest: Ghost Condensation

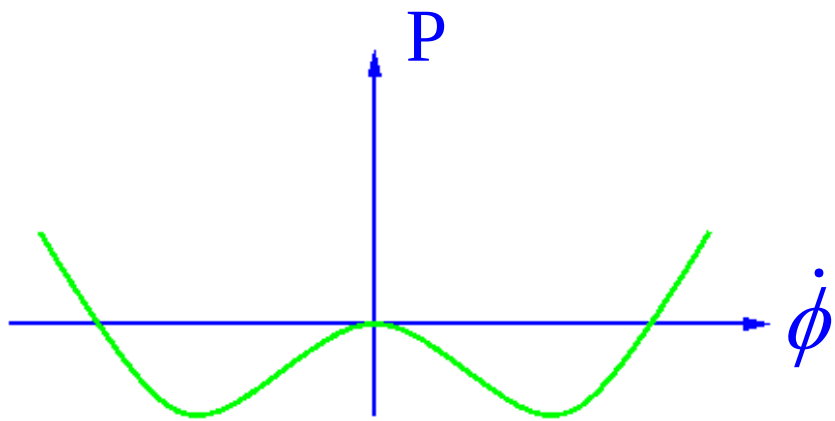
  Arkani-Hamed, Cheng, Luty and Mukohyama, hep-th/0312099

	Higgs Mechanism	***Ghost Condensation***
Order Parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
Instability	Tachyon $-m^2\Phi^2$	Ghost $-\dot{\phi}^2$
Condensate	V'=0, V''>0	P'=0, P''>0
Spontaneous breaking	Gauge symmetry	Lorents symmetry (Time translation)
Modifying	Gauge force	Gravitational force
New potential	Yukawa-type	Oscillating in space Growing in time

For simplicity

$$L_\phi = P\left((\partial\phi)^2\right)$$

in FRW background.



E.O.M.

$$\partial_t[a^3 P' \cdot \dot{\phi}] = 0 \Rightarrow P'\dot{\phi} \to 0 \text{ as } a \to \infty$$

$$\Rightarrow \dot{\phi} = 0$$

(unstable ghosty background)

or

$$\boxed{P'(\dot{\phi}^2) = 0}$$

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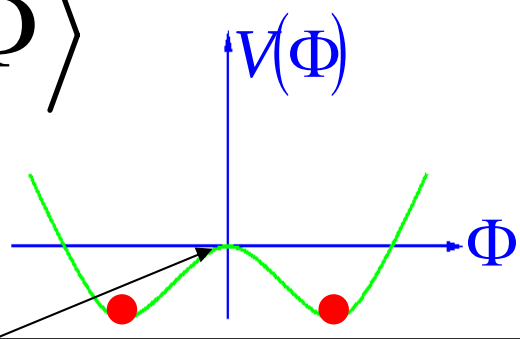
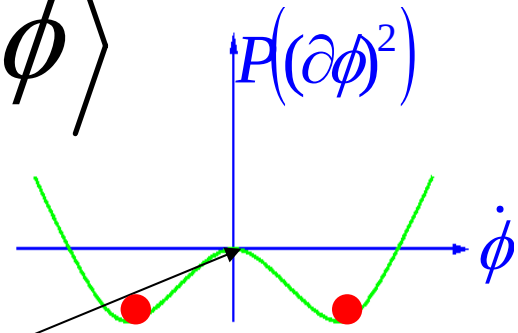
Order Parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
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Systematic construction of Low-energy effective theory

Backgrounds characterized by

- $\left\langle \partial_\mu \phi \right\rangle \neq 0$ and timelike

- Background metric is maximally symmetric, either Minkowski or dS.

Gauge choice: $\phi(t,\vec{x}) = t. \quad \pi \equiv \delta\phi = 0$

(Unitary gauge)

Residual symmetry: $\vec{x} \to \vec{x}'(t,\vec{x})$

⟹ Write down most general action invariant under this residual symmetry.

(⟹ Action for π: undo unitary gauge!)

Start with flat background $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$\delta h_{\mu\nu} = \partial_\mu \xi_\nu + \partial_\nu \xi_\mu$$

Under residual ξ^i

$$\delta h_{00} = 0, \delta h_{0i} = \partial_0 \xi_i, \delta h_{ij} = \partial_i \xi_j + \partial_j \xi_i$$

Action invariant under ξ^i

$$\begin{cases} (h_{00})^2 & \text{OK} \\ \cancel{(h_{0i})^2} & \\ K^2, K^{ij}K_{ij} & \text{OK} \end{cases}$$

$$K_{ij} = \frac{1}{2}\left(\partial_0 h_{ij} - \partial_j h_{0i} - \partial_i h_{0j}\right)$$

$$\Rightarrow \quad L_{eff} = L_{EH} + M^4\left\{(h_{00})^2 - \frac{\alpha_1}{M^2}K^2 - \frac{\alpha_2}{M^2}K^{ij}K_{ij} + \cdots\right\}$$

Action for π

$$\xi^0 = \pi \qquad \begin{cases} h_{00} \to h_{00} - 2\partial_0\pi \\ K_{ij} \to K_{ij} + \partial_i\partial_j\pi \end{cases}$$

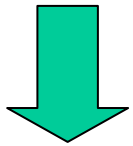
$$\Rightarrow \quad L_{eff} = L_{EH} + M^4\left\{(h_{00} - 2\dot{\pi})^2 - \frac{\alpha_1}{M^2}\left(K + \vec{\nabla}^2\pi\right)^2 - \frac{\alpha_2}{M^2}\left(K^{ij} + \vec{\nabla}^i\vec{\nabla}^j\pi\right)\left(K_{ij} + \vec{\nabla}_i\vec{\nabla}_j\pi\right) + \cdots\right\}$$

$$L_{eff} = L_{EH} + M^4 \left\{ \left(h_{00} - 2\dot{\pi}\right)^2 - \frac{\alpha_1}{M^2}\left(K + \vec{\nabla}^2\pi\right)^2 - \frac{\alpha_2}{M^2}\left(K^{ij} + \vec{\nabla}^i\vec{\nabla}^j\pi\right)\left(K_{ij} + \vec{\nabla}_i\vec{\nabla}_j\pi\right) + \cdots \right\}$$

Dispersion relation

$$\omega^2 = \frac{\alpha}{M^2}k^4$$

k^2 term is forbidden by symmetry



Coupling to gravity

$$\omega^2 = \frac{\alpha}{M^2}k^4 - \frac{\alpha M^2}{2M_{Pl}^2}k^2$$

$O(M^2/M_{Pl}^2)$ correction

Jeans-like (IR) instability

$\omega^2 < 0$ for $k < k_c = M^2/2M_{pl}$

$r_J \sim M_{pl}/M^2$, $t_J \sim M_{pl}^2/M^3$

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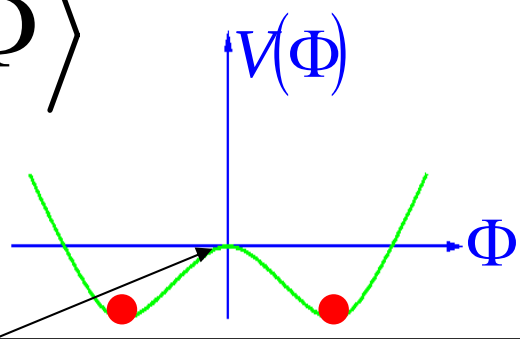
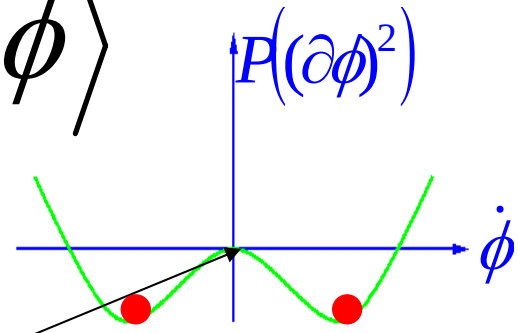
Order Parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
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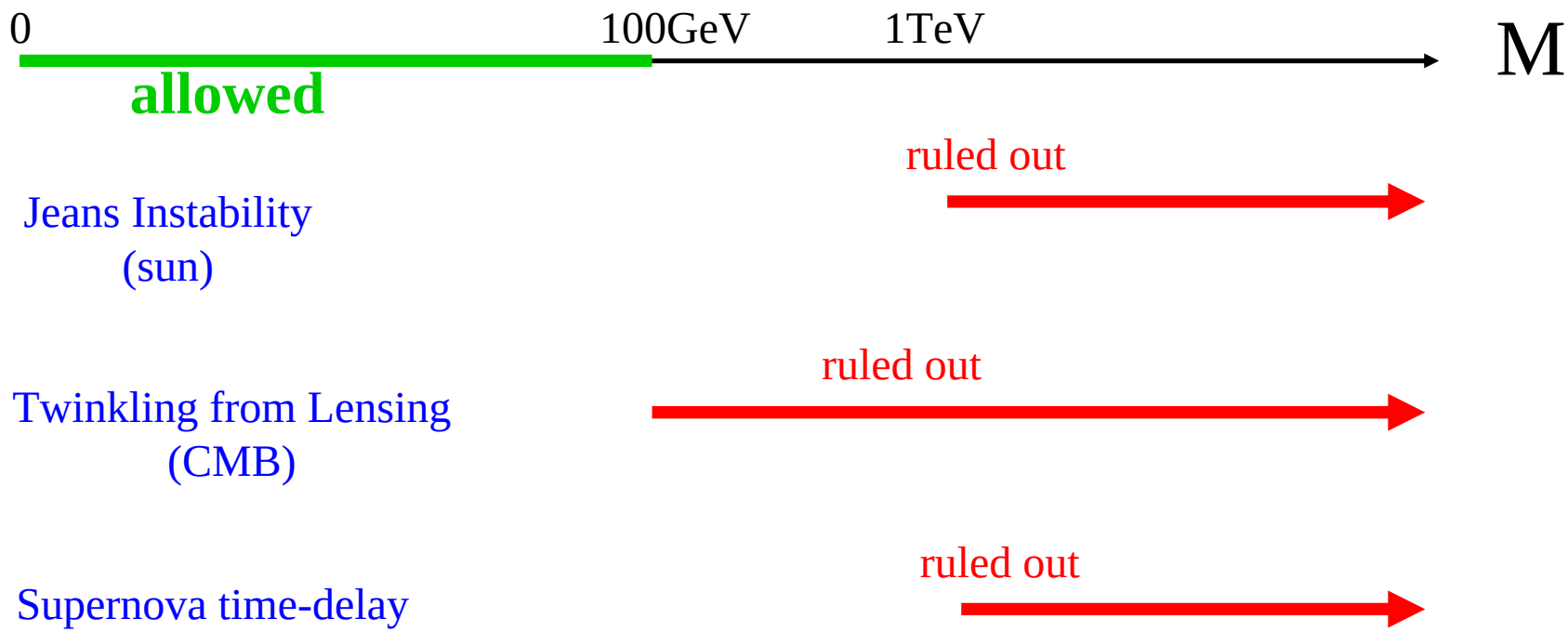
Bounds on symmetry breaking scale M

Arkani-Hamed, Cheng, Luty and Mukohyama and Wiseman, hep-ph/0507120

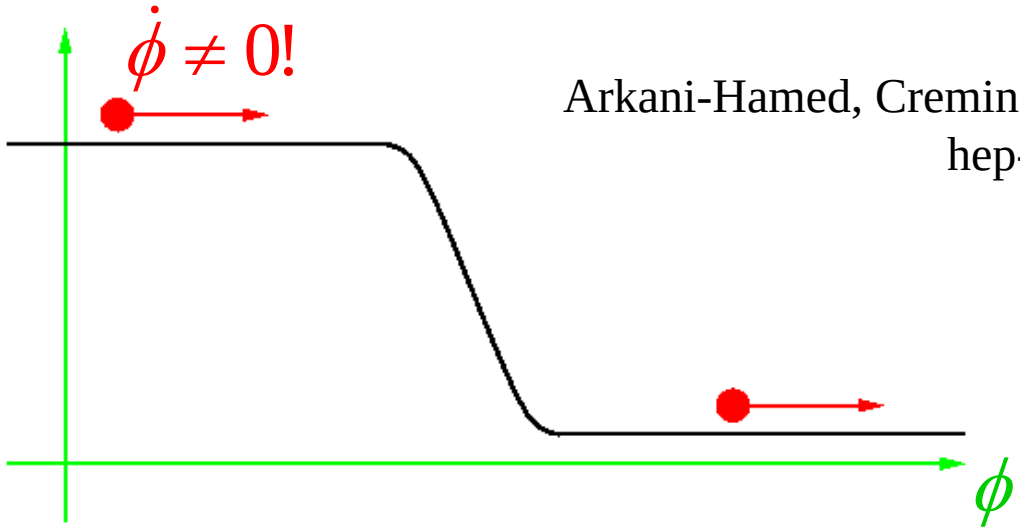


c.f. Gauged ghost condensation allows much higher M (M < 10^{12} GeV)

Cheng, Luty, Mukohyama and Thaler, hep-th/0603010

Applications to Cosmology (I)

Ghost Inflation



Arkani-Hamed, Creminelli, Mukohyama and Zaldarriaga
hep-th/0312100

eg. hybrid type

NOT SLOW ROLL

Scale-invariant perturbations

scaling dim of π

$$\frac{\delta\rho}{\rho} \sim \frac{H\delta\pi}{\dot{\phi}} \sim \left(\frac{H}{M}\right)^{5/4}$$

$$\delta\pi \sim M\cdot(H/M)^{1/4} \qquad \dot{\phi} \sim M^2$$

[compare $\dfrac{H}{M_{Pl}\sqrt{\varepsilon}}$]

$$E \to rE$$

$$dt \to r^{-1} dt$$

$$dx \to r^{-1/2} dx$$

$$\pi \to r^{1/4} \pi$$

Make invariant

$$\int dt d^3x \left[\frac{1}{2}\dot{\pi}^2 - \frac{\alpha(\nabla^2\pi)^2}{M^2} + \cdots \right]$$

$$- P'(M^4)(\nabla\pi)^2$$

Scaling dim of π is 1/4!

not the same as the mass dim 1!

cf. This is the reason why higher terms such as

$$\int dt d^3x \frac{\dot{\pi}(\nabla\pi)^2}{\tilde{M}^2}$$

are irrelevant at low E.

Prediction of Large (visible) non-Gauss.

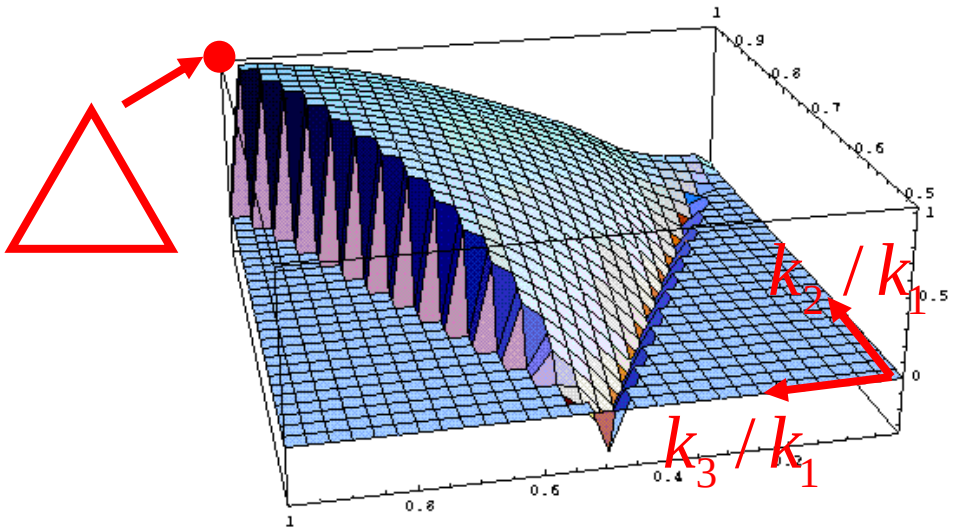
Leading non-linear interaction $\dfrac{\dot{\pi}(\nabla\pi)^2}{M^2}$

non-G of $\sim \left(\dfrac{H}{M}\right)^{1/4}$ ← scaling dim of op.

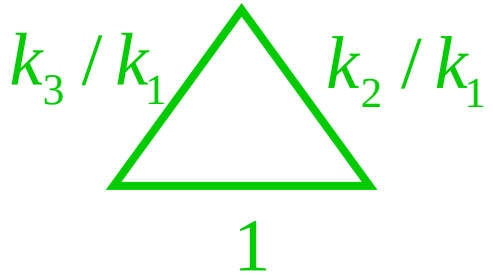
$\sim \left(\dfrac{\delta\rho}{\rho}\right)^{1/5}$

[Really "0.1"$\times\left(\delta\rho/\rho\right)^{1/5} \sim 10^{-2}$. VISIBLE.
Compare with usual inflation where
non-G $\sim\left(\delta\rho/\rho\right) \sim 10^{-5}$ too small.]

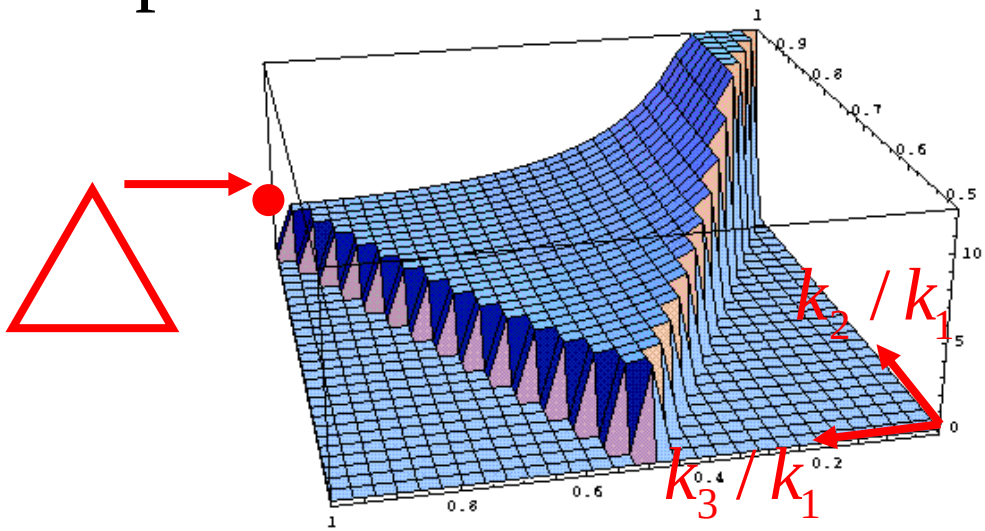
3-point function for ghost inflation



$$F(k_1,k_2,k_3)=\frac{1}{k_1^6}F\left(\frac{k_2}{k_1},\frac{k_3}{k_1}\right)$$



3-point function for “local” non-G

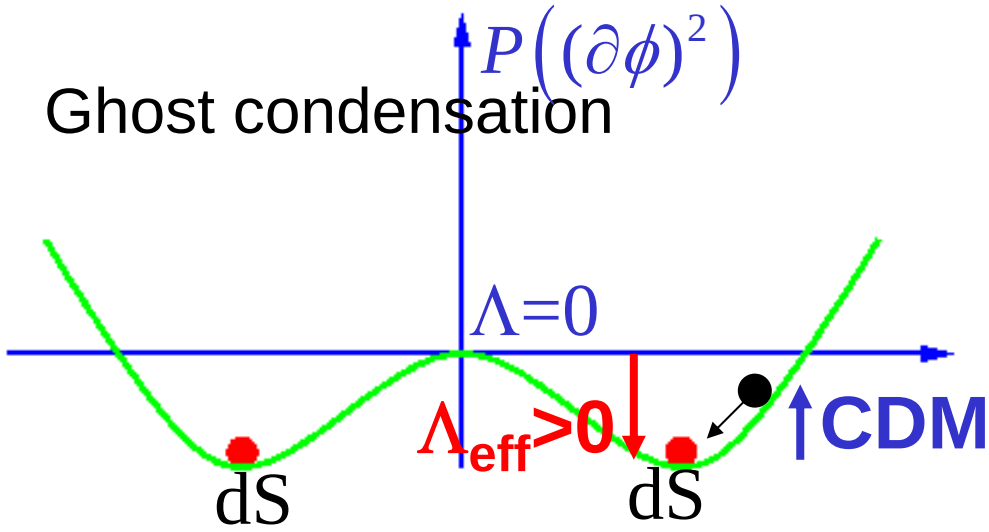


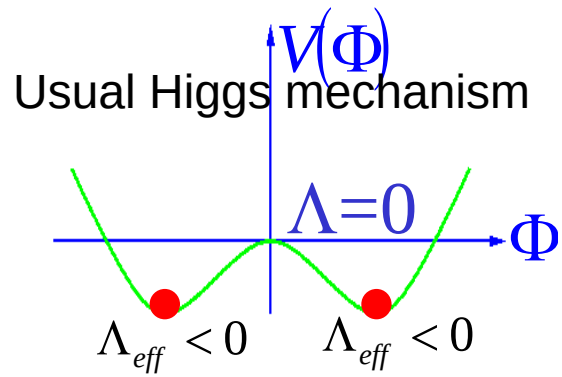
$$\varsigma=\varsigma_G-\frac{3}{5}f_{NL}\cdot\left(\varsigma_G^2-\left\langle\varsigma_G^2\right\rangle\right)$$

Cosmological Application (II)

Alternative to DE/DM

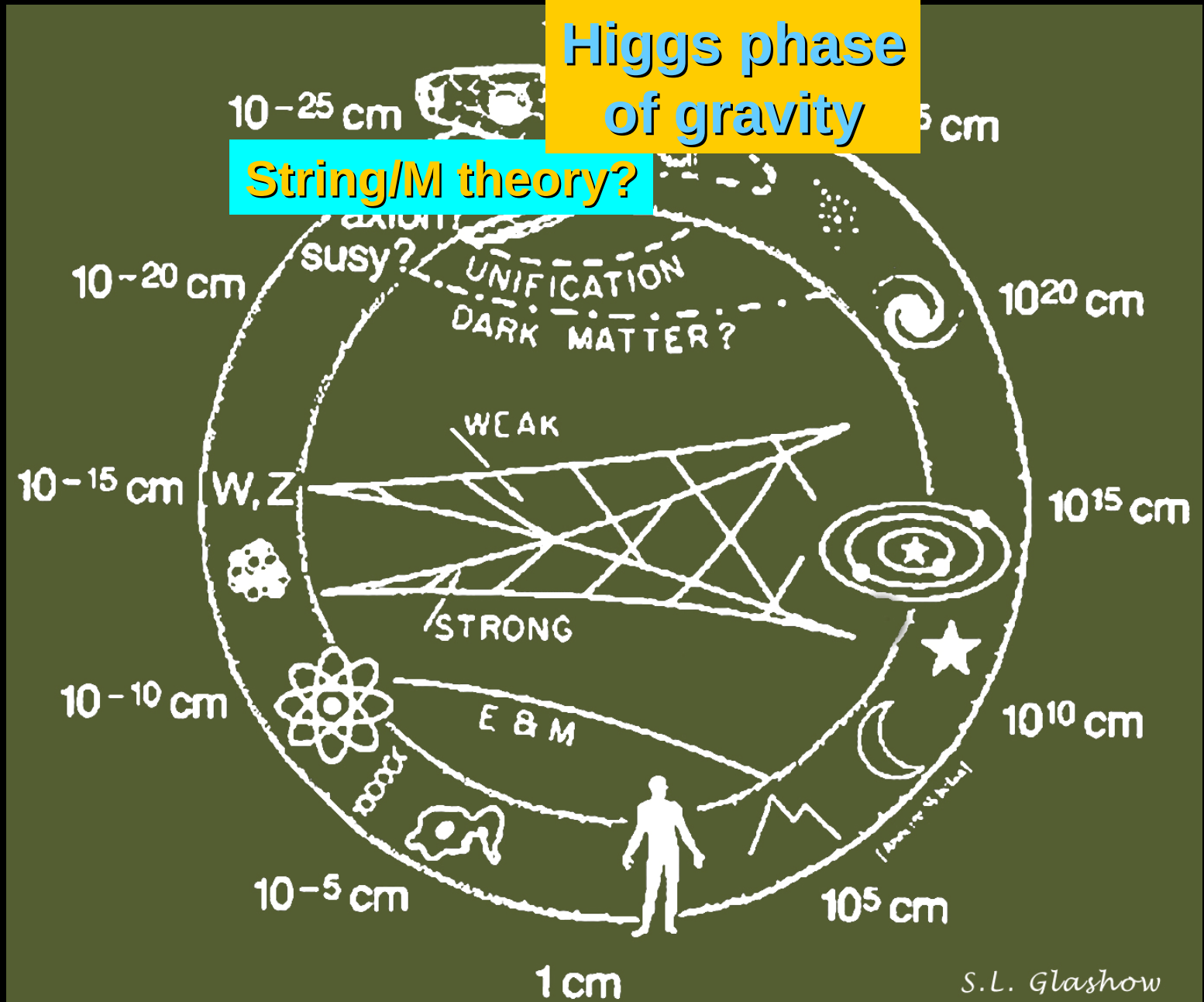
- For FRW universe, it **behaves like c.c. + CDM**.





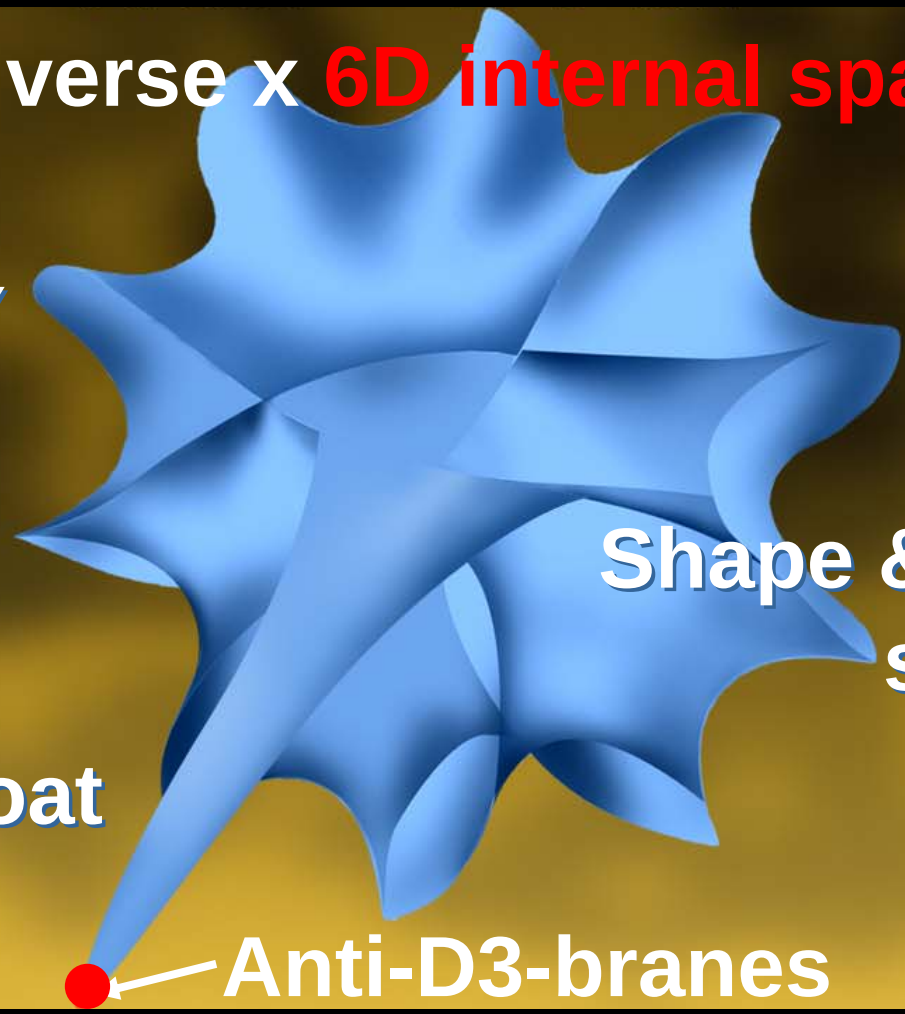
- **Clustering properties** remain unexplored and may be different from c.c. + CDM.

Cosmic Uroboros



KKLT setup

10D = 4D universe x 6D internal space



CY

Shape & Volume stabilized

Warped Throat

Anti-D3-branes

→ Non-SUSY NS5-brane

Kachru, Pearson & Verlinde (2002)

Correspondence principle

Horowitz & Polchinski (1997)

Stringy Object ⟺ **Black-Brane**

Size > R_{grav}

Size < R_{grav}

Non-SUSY NS5-brane ⟹ **Black-Brane**

$$\left(M_{RR}/\bar{N}_3\right)^2 \gtrsim g_s \bar{N}_3 \gg 1$$

Mukohyama, hep-th/0610254

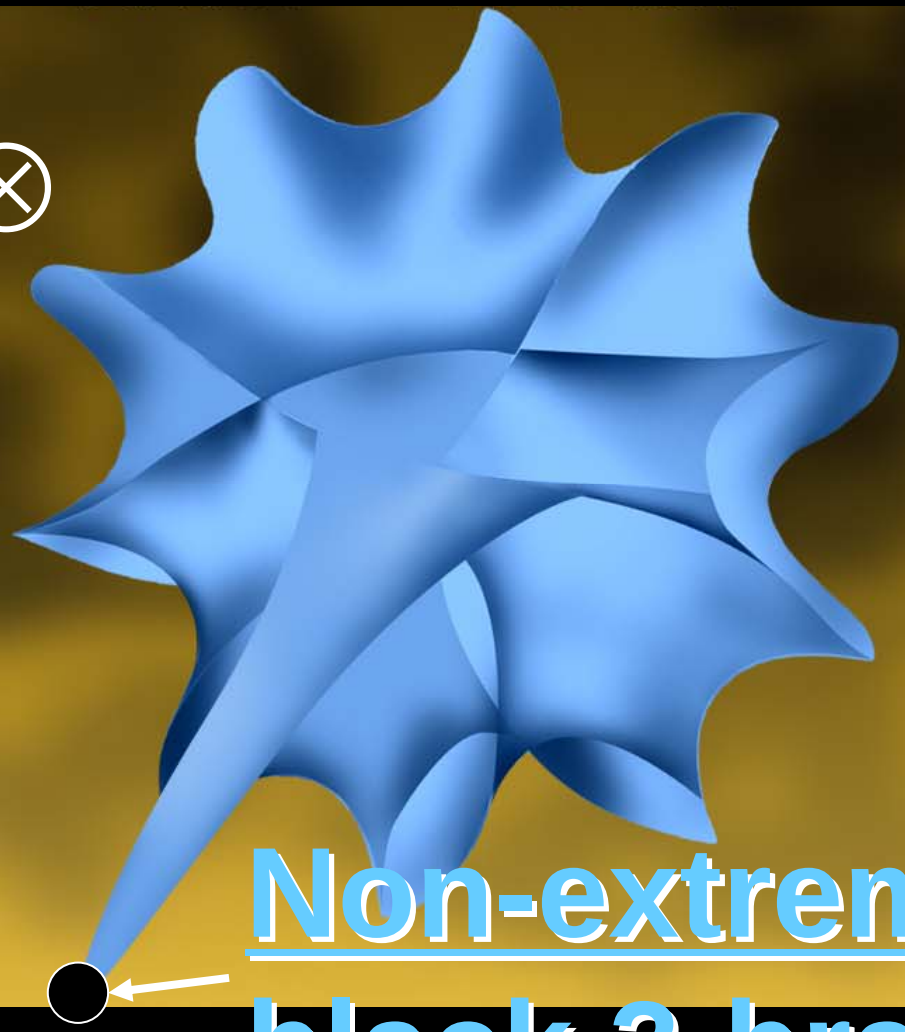
M_{RR}: # of R-R flux

$\bar{N}_3$: # of $\overline{D3}$'s

g_s : string coupling

Black brane at the tip

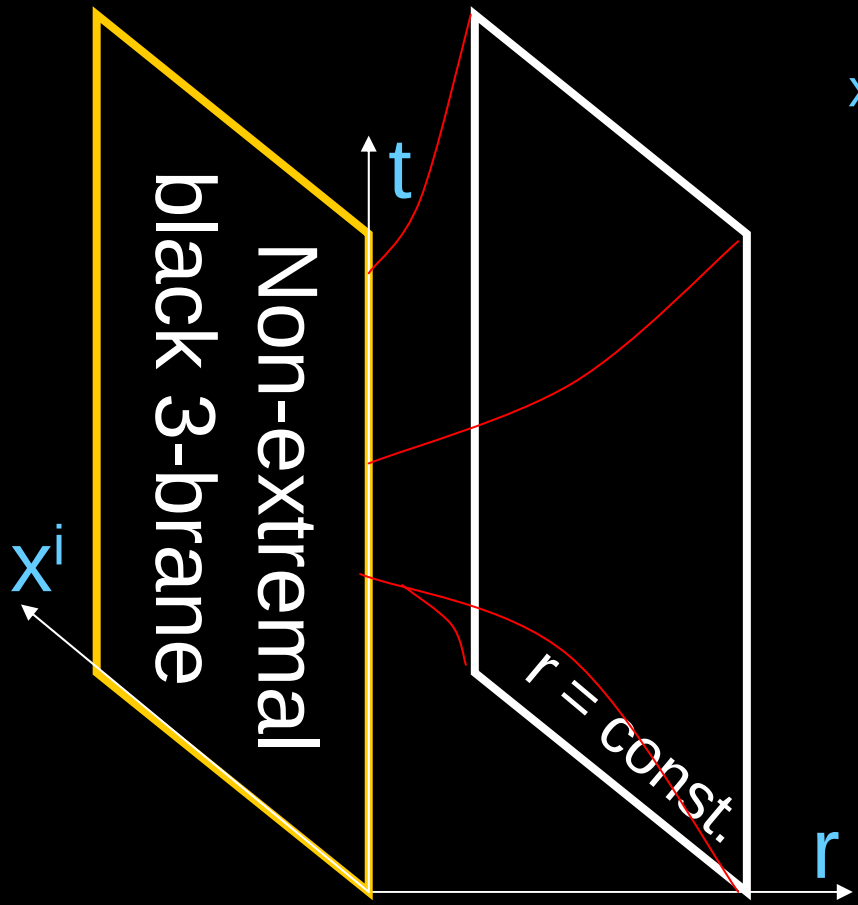
4D Universe ⊗

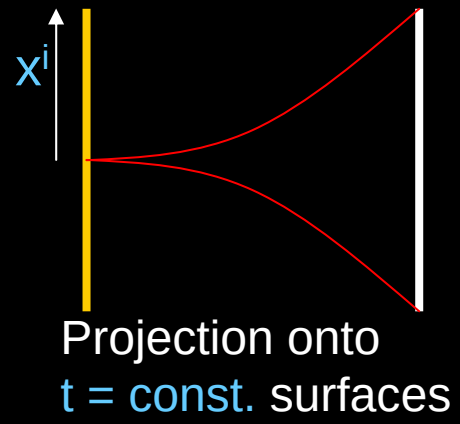


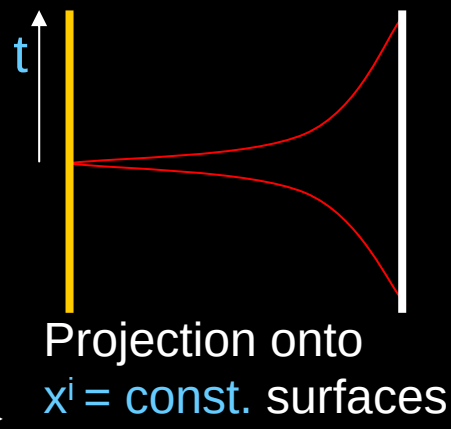
Non-extremal black 3-brane

Spontaneous Lorentz breaking

- The (3+1)-dim spacetime is spanned by (t , x^i).







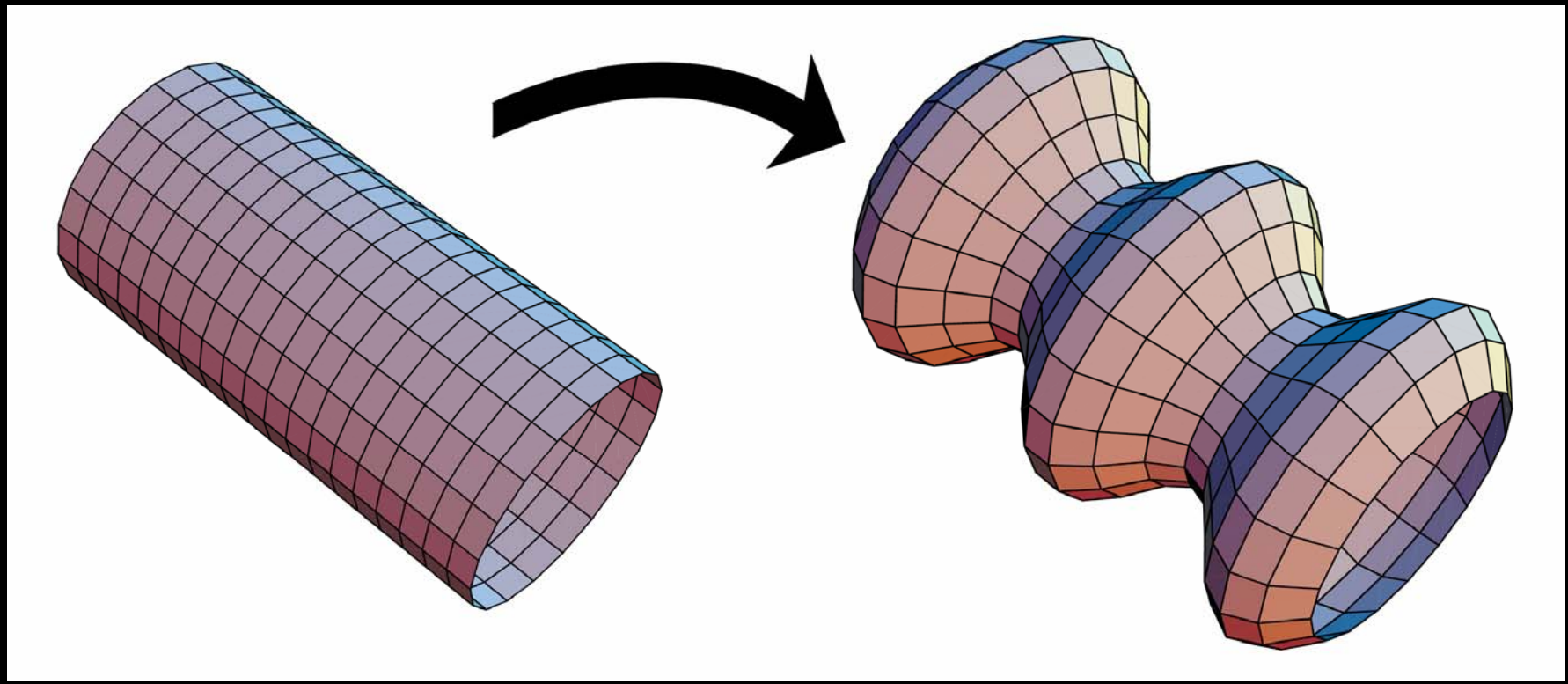
Warp factors for the tt-component and the ij-components are different.

Spontaneous Lorentz breaking!

Gauged Ghost Condensation

GL instability

- Non-extremal Black branes are gravitationally unstable. [Gregory-Laflamme, PRL70, 2837 (1993); NPB428, 399 (1994)]



- The dispersion relation is similar to that for the NG boson in our setup with $g_{GCC}^2 < g_c^2$.

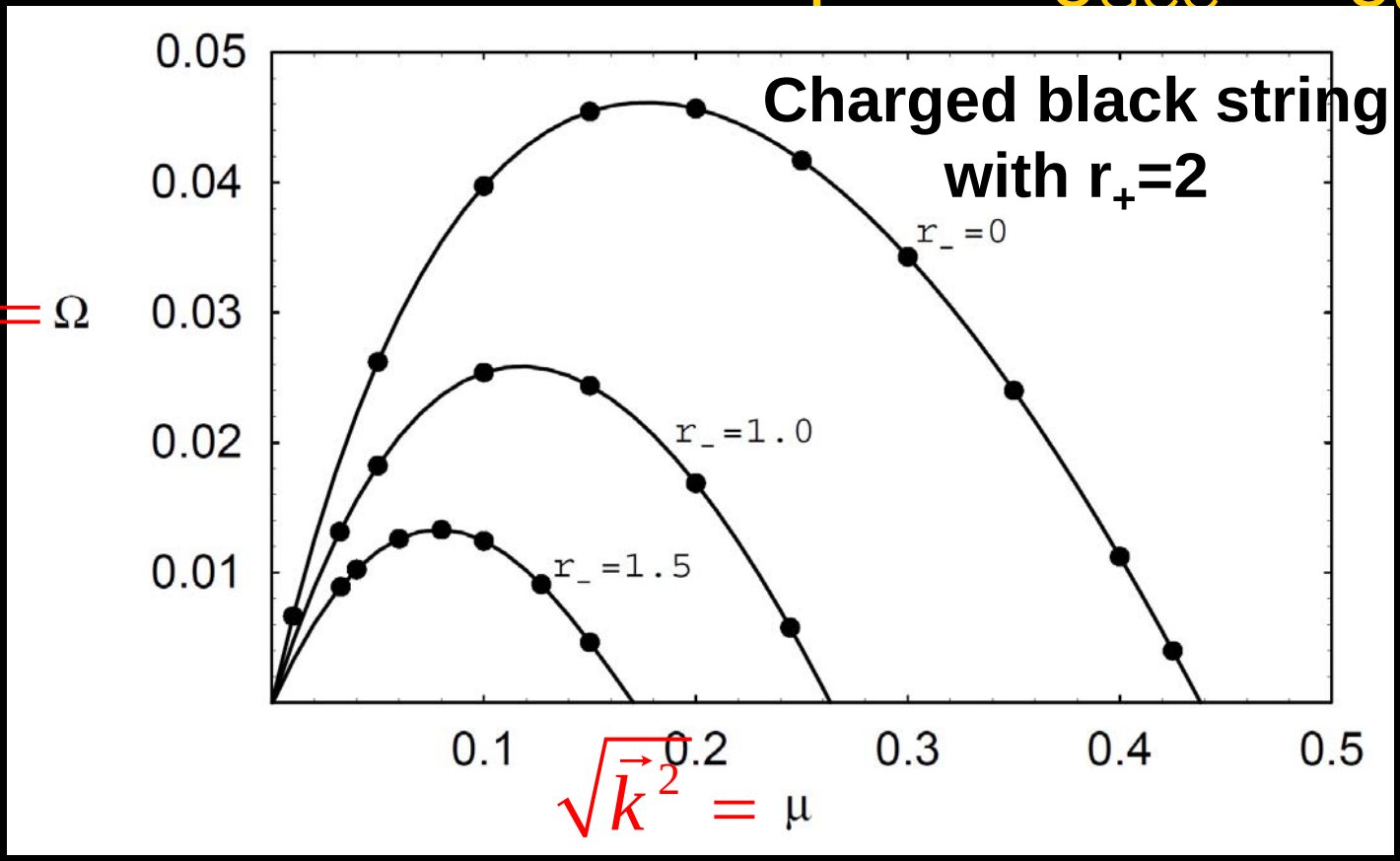


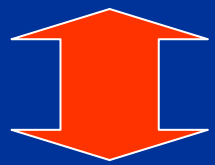
Figure 6. Plot of Ω as a function of μ for a charged 5d black string with charges corresponding to $r_- = 0, 1.0, 1.5$ and $r_+ = 2$ for which an instability has been found. The bold points correspond to value calculated numerically and the lines have been traced to guide the eye.

[Gregory-Laflamme, NPB428, 399 (1994)]

- In our geometrical setup there is a black brane at the bottom of the warped throat.
- The world-volume of the black brane is parallel to our world.

Conjecture Mukohyama, hep-th/0610254

Low-E EFT: Jeans-like instability



DUAL

Geometrical: GL instability

Summary

- Ghost condensation is **the simplest Higgs phase of gravity**, including only one Nambu-Goldstone boson. No ghost included.
- **Can drive inflation.**
- **Can be alternative to DE/DM.**
- The KKLT setup in the regime of parameters

$$\left(M_{RR} / \bar{N}_3 \right)^2 \gtrsim g_s \bar{N}_3 \gg 1$$

is a UV completion (string theory version) of the gauged ghost condensation.

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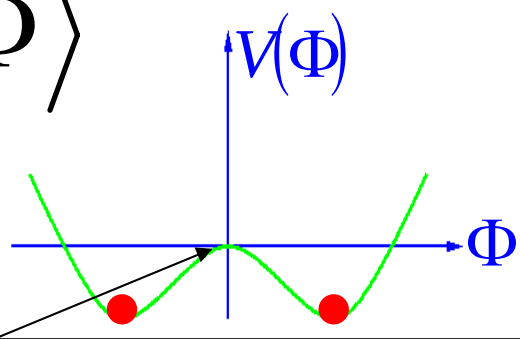
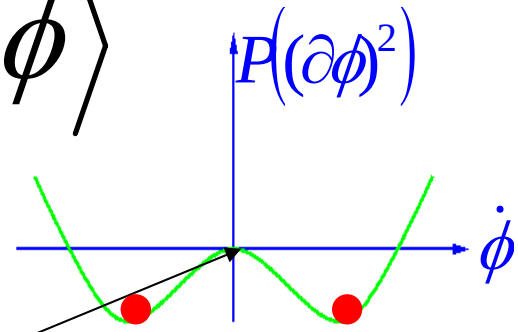
Order Parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
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