Cosmology and Black Holes with the Ghost Condensate

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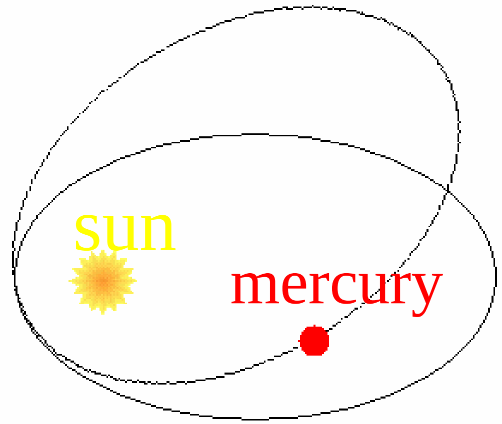
Motivation

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

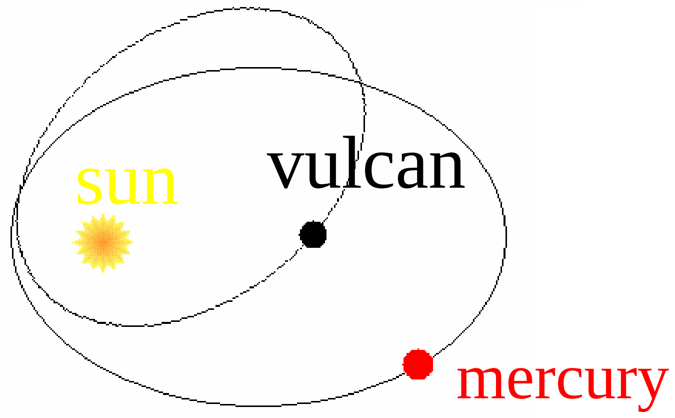
- Usual explanation: new forms of matter (DARK MATTER) and energy (DARK ENERGY).

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?

- Very first step: is it even possible to modify gravity in IR in a theoretically consistent way?

Previous proposals

- Massive gravity

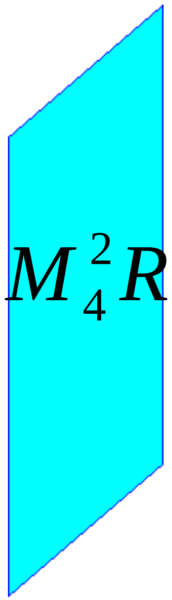
$$S = M_{Pl}^2 \int d^4x \sqrt{-g}\, R + f^4 \int d^4x \left(h_{\mu\nu}^2 - h^2\right)$$

Fierz-Pauli mass term

graviton mass $m_g^2 \approx f^4 / M_{Pl}^2$

- Dvali-Gabadadze-Porrati model

3+1 brane



$M_4^2 R^{(4)}$

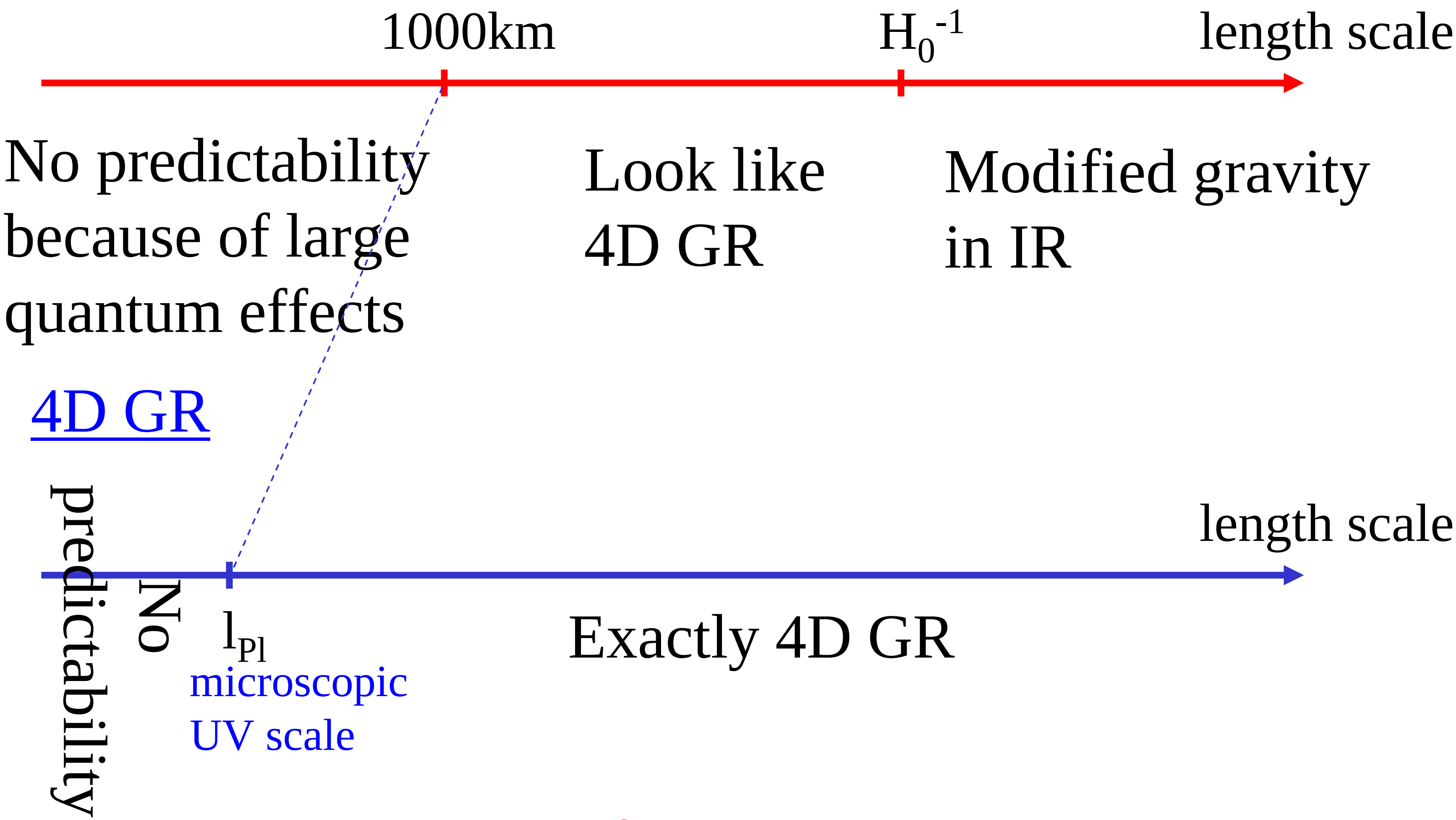
Infinite volume 5th dim.

$M_5^3 R^{(5)}$

$V(r)$ ~ 4D for $r < r_c$, $\quad r_c \sim M_4^2 / M_5^3$

5D for $r > r_c$

Massive gravity & DGP brane model



Is it possible to modify gravity in the IR in a way that avoids the problem of macroscopic UV scale?

Ghost condensation

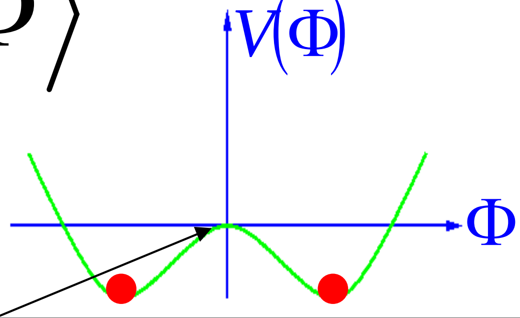
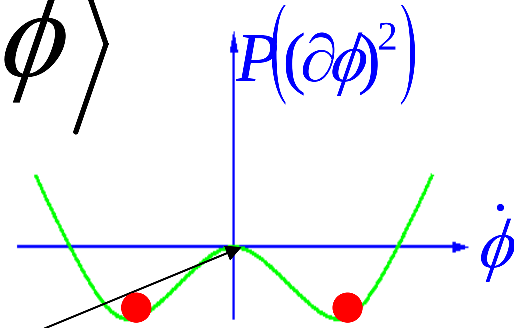
	Potentially dominated	***Kinematically dominated***
Cosmology	Inflation	K-inflation
Symmetry breaking & Modifying force law	Higgs mechanism	Ghost condensation = Gravity in Higgs phase

Tachyons and Ghosts

	Particle mechanics	Field theory
Tachyon	Causality violation ⇒ Sick	Instability ⇒ condense to a stable background

⇓ Expectation

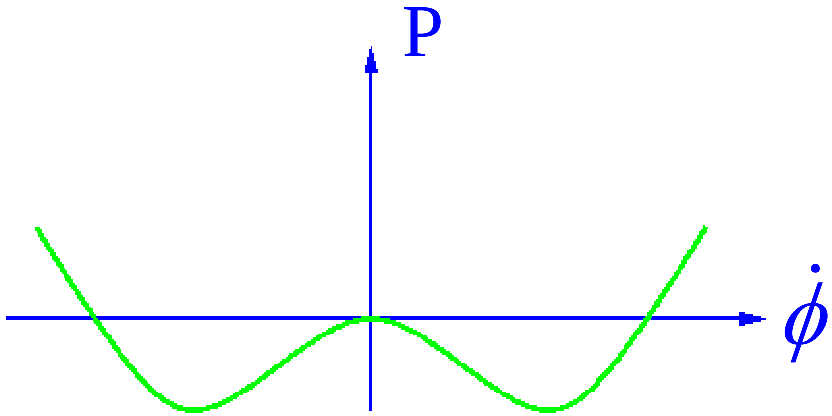
Ghost	Negative norm ⇒ Sick	Instability ⇒ condense to a stable background
	Field theory	More general framework

	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

For simplicity

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

in FRW background.

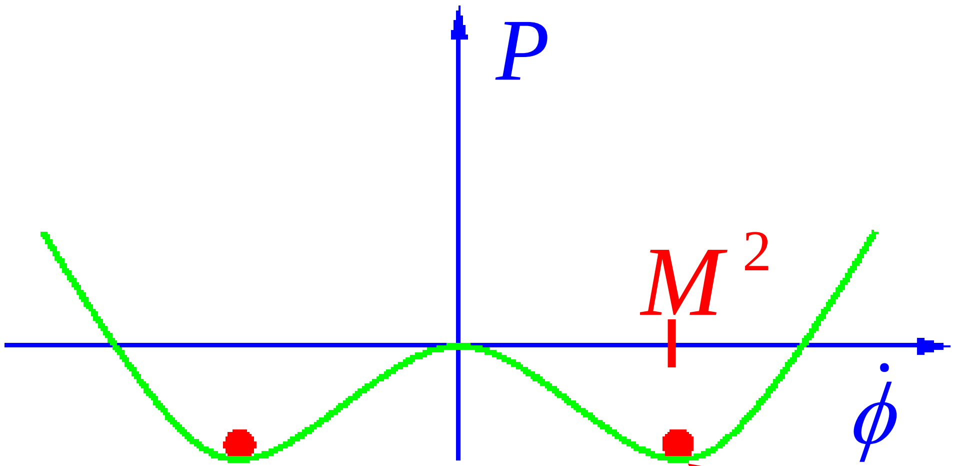


E.O.M.

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

$$\Longrightarrow \quad \dot{\phi} = 0 \qquad \text{or} \qquad \boxed{P'(\dot{\phi}^2) = 0}$$

(unstable ghosty background)



Attractor

Gravity (Hubble friction) drives you here!

$$T_{\mu\nu} = P(M^4)g_{\mu\nu} + P'(M^4)\partial_\mu\phi\partial_\nu\phi$$

Exactly that of c.c. $-P(M^4)$!

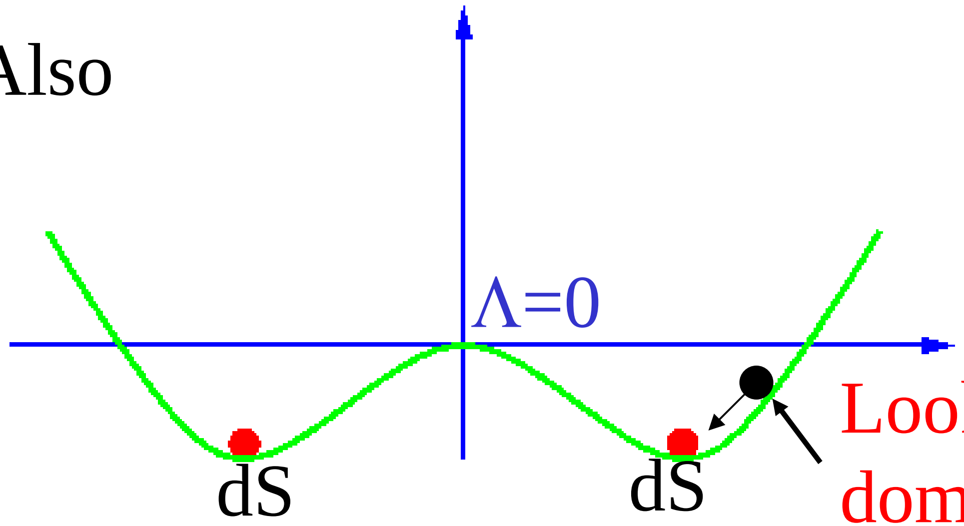
Possible Applications:

(I) Alternate origin for de Sitter phases in universe.

* Acceleration today, with $\Lambda=0$.

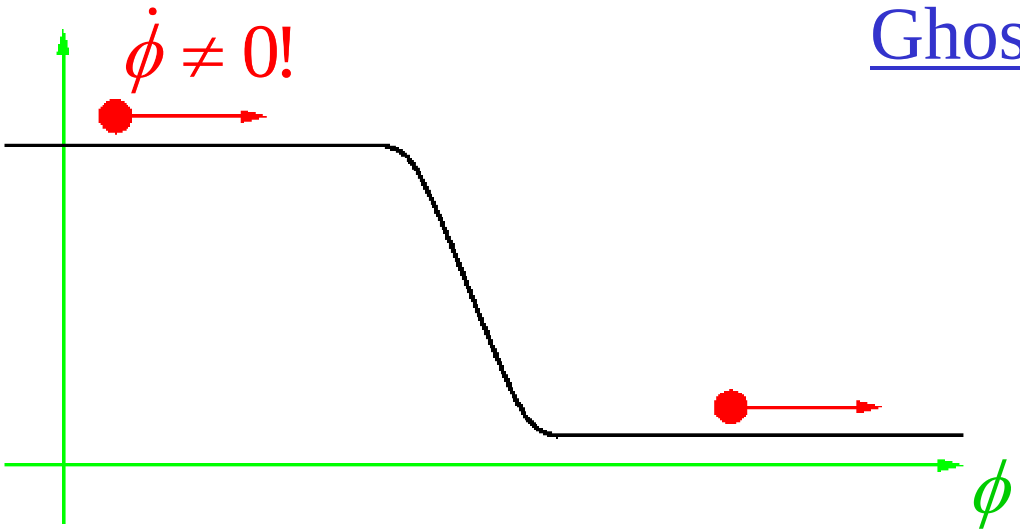
Cosmological observations alone can't distinguish from C.C.! However, tiny Lorentz violation, spin-dependent long-range forces…

Also



Looks like matter-domination before it gets to dS phase! Dark matter? Need to see if it clumps properly

(II) Qualitatively different picture of inflationary dS phase:



Ghost Inflation

eg. hybrid type

NOT SLOW ROLL

Scale-invariant perturbations

scaling dim of π

$$\frac{\delta\rho}{\rho} \sim \frac{H\delta\pi}{\dot{\phi}} \sim \left(\frac{H}{M}\right)^{5/4} \qquad \delta\pi \sim M \cdot (H/M)^{1/4} \qquad \dot{\phi} \sim M^2$$

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

$$\left.\begin{aligned} E &\to rE \\ dt &\to r^{-1}dt \\ dx &\to r^{-1/2}dx \\ \pi &\to r^{1/4}\pi \end{aligned}\right\} \text{Make invariant} \Rightarrow \int dt d^3x \left[\frac{1}{2}\dot{\pi}^2 - \frac{\alpha(\nabla^2\pi)^2}{M^2} + \cdots\right]$$

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

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.

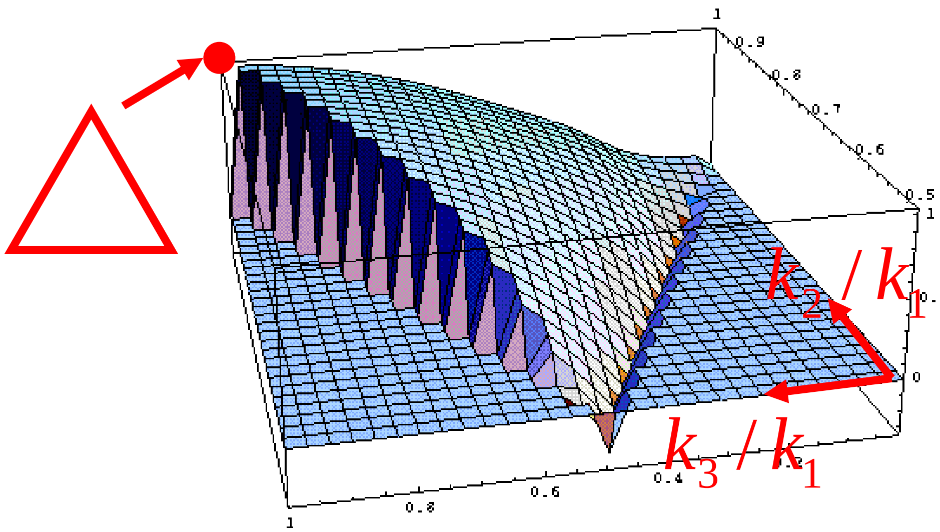
Leading non-linear interaction $\dfrac{\dot{\pi}(\nabla\pi)^2}{M^2}$

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

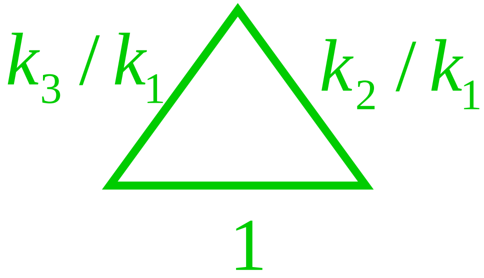
$\sim \left(\dfrac{\delta\rho}{\rho}\right)^{1/5}$

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

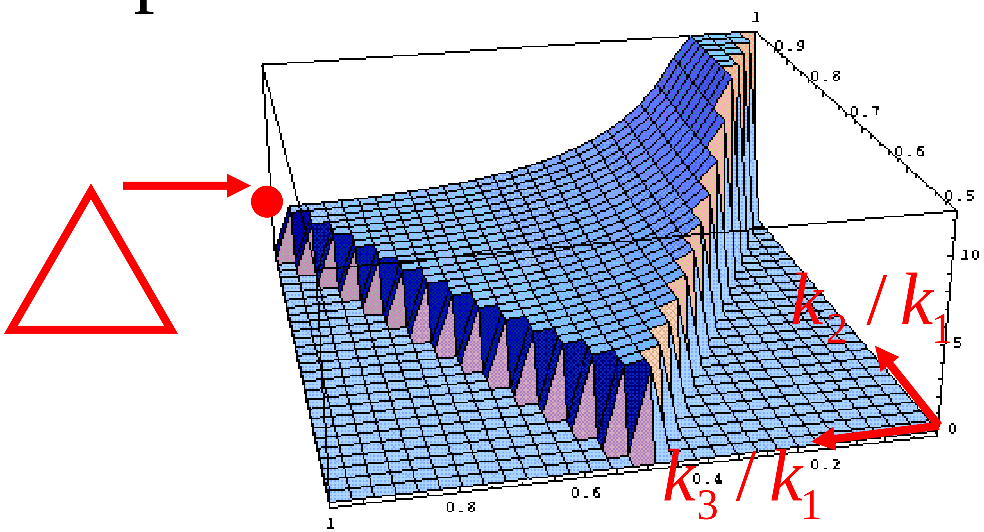
3-point function for ghost inflation



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



3-point function for “local” non-G



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

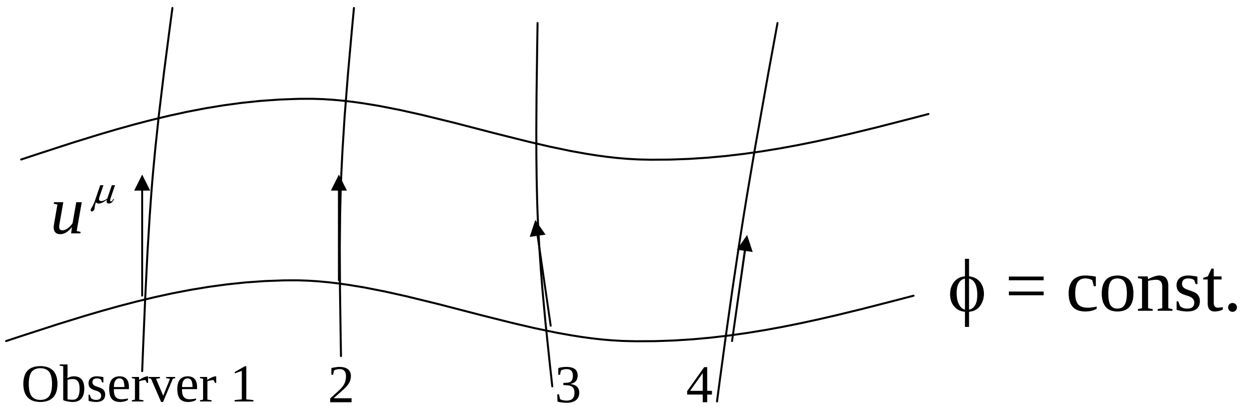
What happens near a black hole?

Mukohyama (in preparation)

$$L = P(X) - \frac{\alpha(\nabla^2\phi)^2}{2M^2} \qquad X = -\partial^\mu\phi\partial_\mu\phi$$

cf. $P' \to 0$ in early universe

- Ghost condensate $\Rightarrow$ $\partial_\mu\phi \neq 0$
- $u^\mu = -\partial^\mu\phi$ defines a hypersurface orthogonal congruence of timelike curves ~ observers



Two different calculations by myself and A.Frolov

Objects	Force
Freely-falling pointlike objects	Zero
Freely falling extended objects	Small tidal force

Myself

Accretion rate	Ghost condensate
Zero for $\alpha = 0$	P'=0 solution for $\alpha = 0$
Small corrections (for a large BH)	with $\dfrac{\alpha(\nabla^2\phi)^2}{2M^2}$

A.Frolov

Accelerated objects	Could be huge

Could be huge	$P' \neq 0$

Q&A for the two calculations

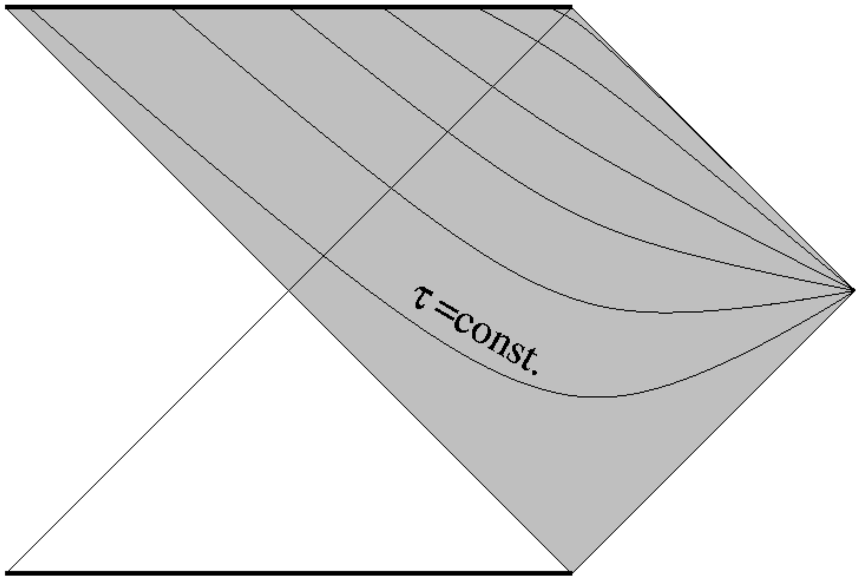
- Q1. Which is correct?
- A1. Both are correct in some sense since both should give upper bounds for the late time accretion rate. But, the smaller upper bound is more useful.
- Q2. Why do they give upper bounds, not lower bounds?
- A2. The system should settle to a configuration with less backreaction and less accretion rate.

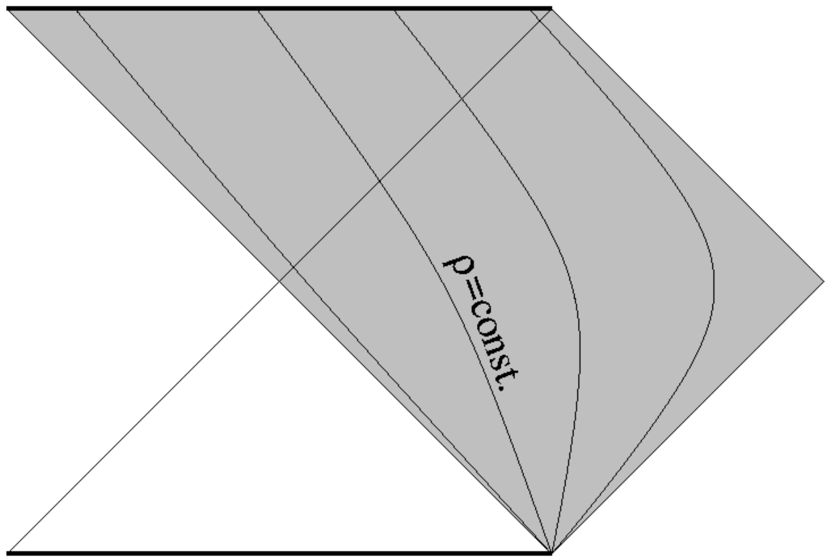
Black hole in the ghost condensate

Schwarzschild geometry in Gaussian coordinate

$$ds^2 = -d\tau^2 + \frac{d\rho^2}{a(\tau,\rho)} + \rho^2 a^2(\tau,\rho) d\Omega^2_{(2)}$$

$$a(\tau,\rho) = \left[1 - \frac{3\tau}{4m_0}\left(\frac{2m_0}{\rho}\right)^{3/2}\right]^{2/3}$$





An exact solution without α term: $\phi = M^2 \tau$

With α term, this is no longer a solution.

Accretion of ghost condensate into black hole

Accretion rate suppressed by M^2/M_{pl}^2

Asymptotic formula:

$$\frac{m_1}{m_0} \approx \frac{9M^2}{4M_{pl}^2}\left(\frac{3t}{4m_0}\right)^{2/3}, m_{MS} = m_0 + \alpha m_1 + O(\alpha^2)$$

$$P(X) - \frac{\alpha}{2M^2}(\Box\phi)^2$$

I have set $P'(X)=0$ in the lowest order in α because the Hubble friction during, say, inflation makes P' vanish with extremely good accuracy ($P' \propto a^{-3}$).

If $P'(X)=O(1)$ then we would obtain much larger accretion rate [A.Frolov] because $\rho_\pi \approx M^4 P'(X)$.

Anyway, this non-zero ρ_π soon accretes to the black hole and P'(X) should relax to zero.

If we set $P'(X)=0$ in the lowest order, then we obtain a very small accretion rate suppressed by M^2/M_{pl}^2.

Summarizing:

Ghost condensate, new kind of fluid that does not dilute as universe expands. But not a C.C.! A real fluid with a real scalar excitation.

Modification of linear gravity in IR:

- Anti gravity
- Oscillating forces
- Change at different length & time scales

Ghost inflation:

- Scale-invariant (n=1) perturbations
- Low H with sufficient quantum fluctuations
- Large non-Gaussianity

Even richer dynamics:

Arkani-Hamed, Cheng, Luty, Mukohyama and Wiseman (in preparation)

- Finite size effect
- Moving source, friction, frame dragging effect
- Non-linear dynamics, would-be caustics, bounce
- Large-scale structure of ether frame
- Accretion into a black hole   Mukohyama (in preparation)

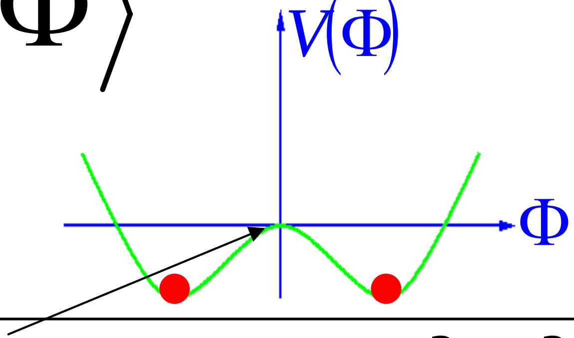
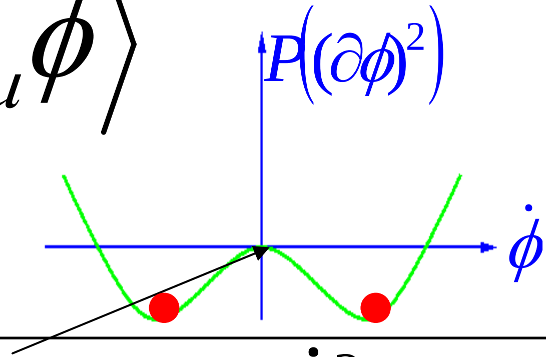
More new results will come out!

Gauged ghost condensation

Cheng, Luty, Mukohyama and Thaler (in preparation)

Final remark

- The most symmetric class of backgrounds for **gravity + field theory** has maximal symmetry: Minkowski, AdS, dS.
- dS in superstring theory was just recently constructed by KKLT.
- **GHOST CONDENSATION provides the second most symmetric class of backgrounds.**
- **Superstring construction wanted!**

	Higgs Mechanism	***Ghost Condensation***
Order Parameter	$\left\langle \Phi \right\rangle$ 	$\left\langle \partial_\mu \phi \right\rangle$ 
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Thank you very much for your listening!