INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Higgs phase of gravity and ghost condensate

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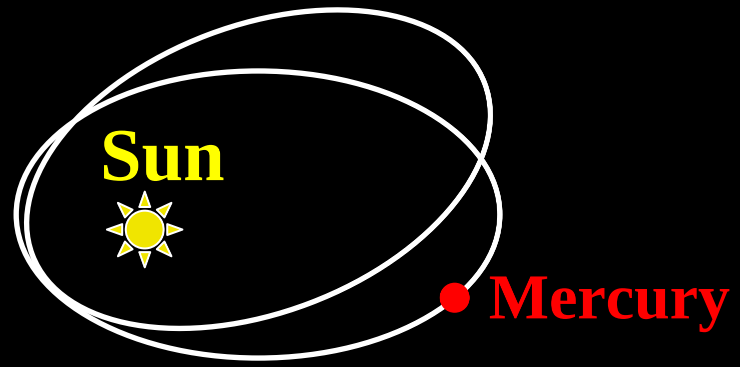
Introduction

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

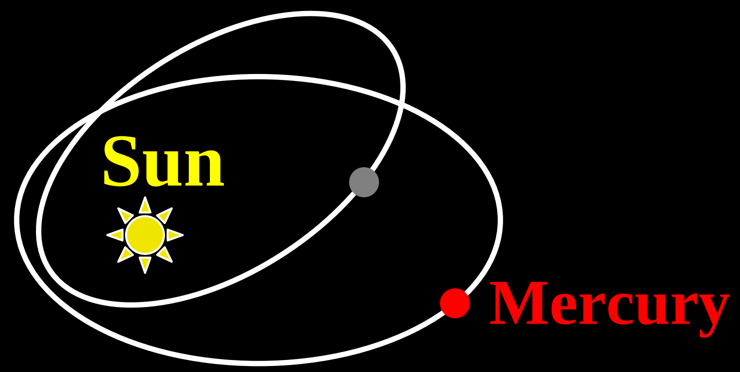
- Usual explanation: new forms of matter (DARK MATTER) and energy (DARK ENERGY).

Dark component in the solar system?

Precession of perihelion
observed in 1800's…



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

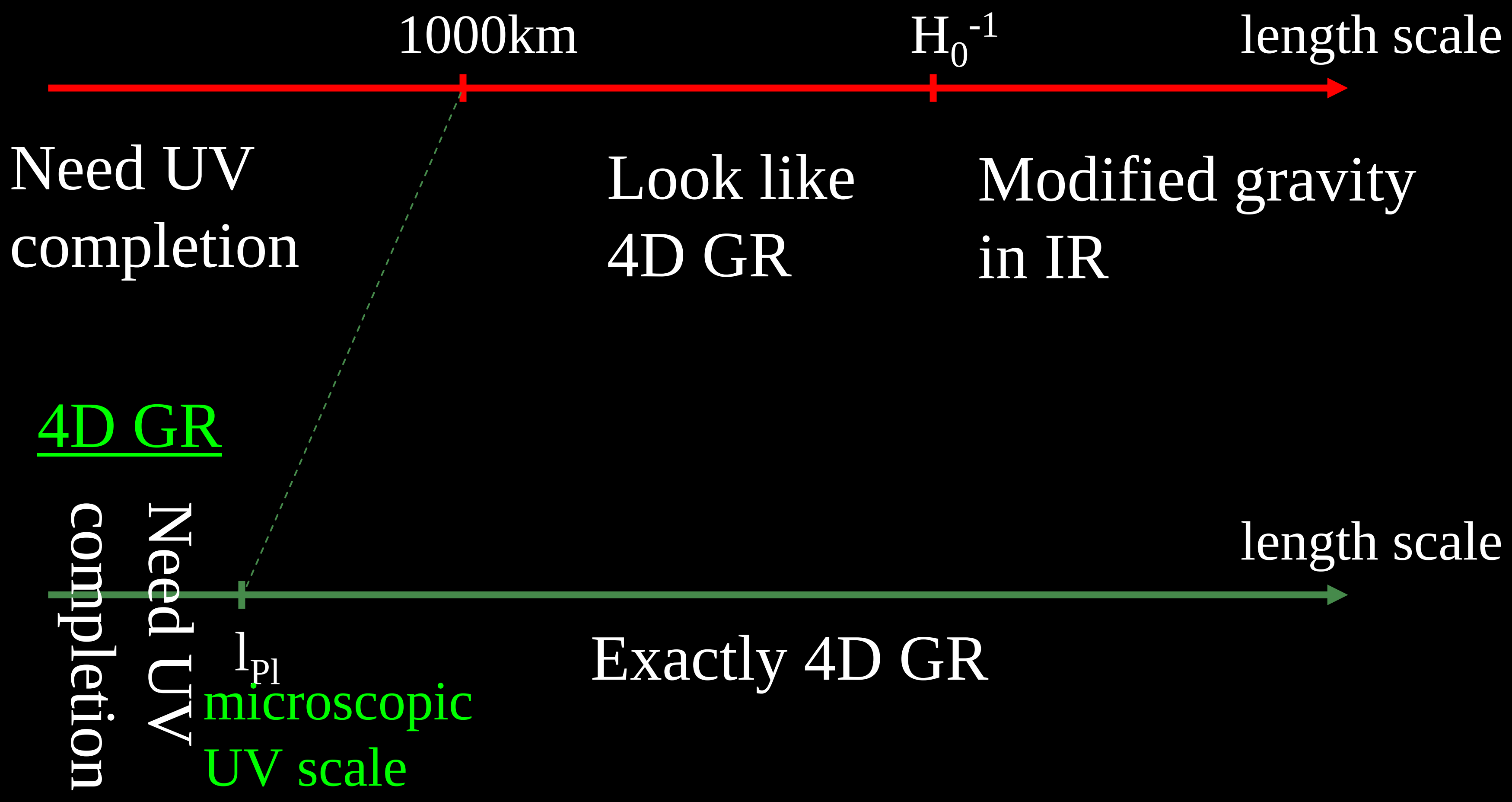


But the right answer wasn't "dark planet", it was "change gravity" from Newton to GR.

Can we change gravity in IR?

- **Change Theory?**
  (eg. Massive gravity, DGP model)

Massive gravity & DGP model



Can we change gravity in IR?

- **Change Theory?**
  (eg. Massive gravity, DGP model)
  Macroscopic UV scales
  Cannot be decoupled

- **Change State?**
  Higgs phase of gravity
  The simplest: Ghost condensation

  Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004.

Higgs mechanism

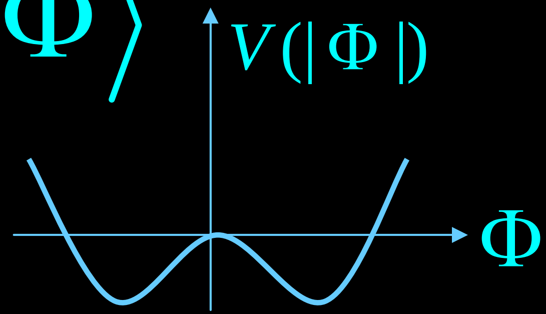
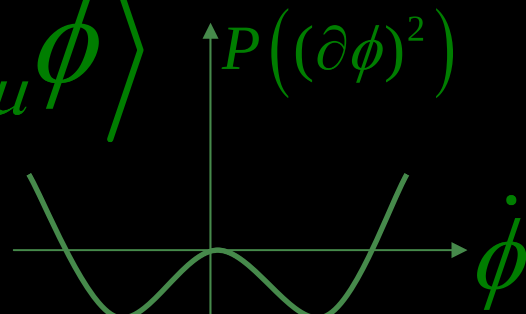
- Spontaneously breaks gauge symmetry.
  (Theory itself has gauge symmetry.)
- Gives mass to gauge boson.
- Changes Gauss law to Yukawa law!
- Can describe weak interaction!

Ghost condensation

Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

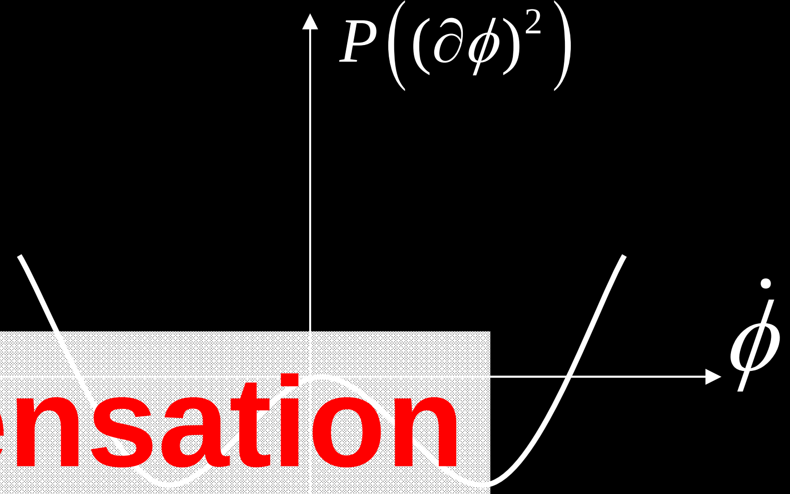
- Spontaneously breaks diffeo invariance. (Theory itself has diffeo invariance.)
- Gives "mass" to graviton.
- Adds oscillating time-dependent potential to Newton potential! (But the time scale is very long.)

= Higgs phase of gravity

	Higgs mechanism	***Ghost condensate***
Order parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
Instability	Tachyon $-\mu^2\Phi^2$	Ghost $-\dot{\phi}^2$
Condensate	V’=0, V’’>0	P’=0, P’’>0
Broken symmetry	Gauge symmetry	Time translational symmetry
Force to be modified	Gauge force	Gravity
New force law	Yukawa type	Newton+Oscillation

For simplicity

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



in FRW background

Ghost condensation is an attractor!

E.O.M.

$$\partial_t[a^3 P' \cdot \dot\phi] = 0 \Longrightarrow P'\dot\phi \propto a^{-3} \to 0$$

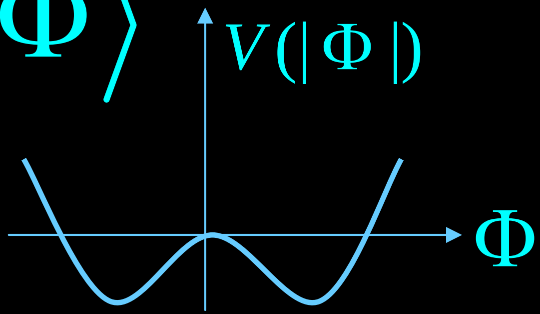
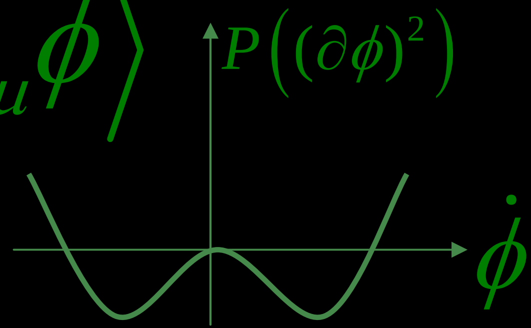
$$(a \to \infty)$$

$\Longrightarrow$ $\dot\phi = 0$

(unstable ghosty background)

or

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

	Higgs mechanism	*Ghost condensate*
Order parameter	$\left\langle \Phi \right\rangle$ 	$\left\langle \partial_\mu \phi \right\rangle$ 
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Systematic construction of Low-energy effective theory

Backgrounds characterized by

✧ $\langle \partial_\mu \phi \rangle \neq 0$ and timelike

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

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

(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

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

Beginning at quadratic order, since we are assuming flat space is good background.

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

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

Action for π

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

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

$$\left.\begin{aligned} &E \to rE \\ &dt \to r^{-1} dt \\ &dx \to r^{-1/2} dx \\ &\pi \to r^{1/4} \pi \end{aligned}\right\}$$

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

Leading nonlinear operator in infrared $\int dt d^3x \frac{\dot{\pi}(\nabla\pi)^2}{\tilde{M}^2}$

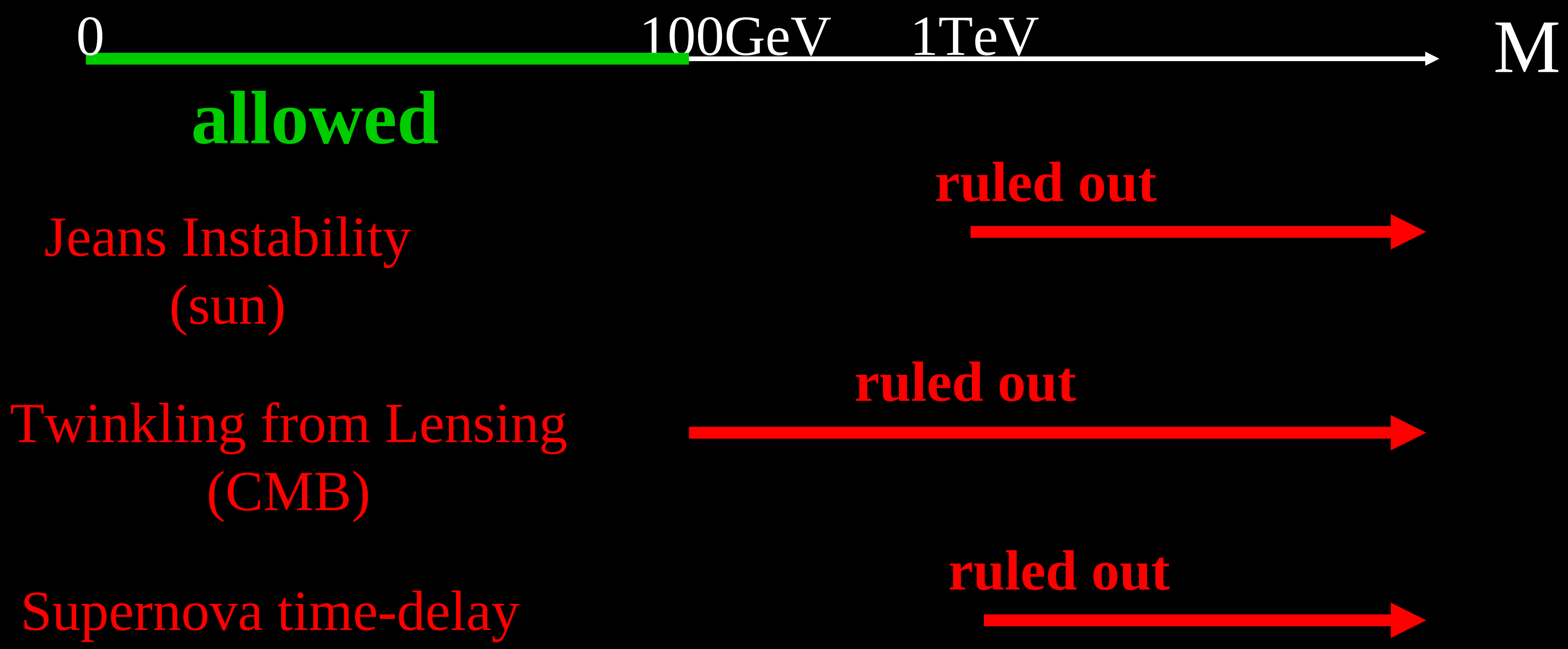
has scaling dimension 1/4. **(Barely) irrelevant**

⇨ Good low-E effective theory

Robust prediction

Bounds on symmetry breaking scale M

Arkani-Hamed, Cheng, Luty and Mukohyama and Wiseman, JHEP 0701:036,2007



So far, there is no conflict with experiments and observations if M < 100GeV.

⇨ Application to Cosmology!

Can be an alternative to DE and DM?

Maybe yes, for FRW background!

w<-1 is also possible!

Creminelli, Luty, Nicolis and Senatore, JHEP0612:080, 2006

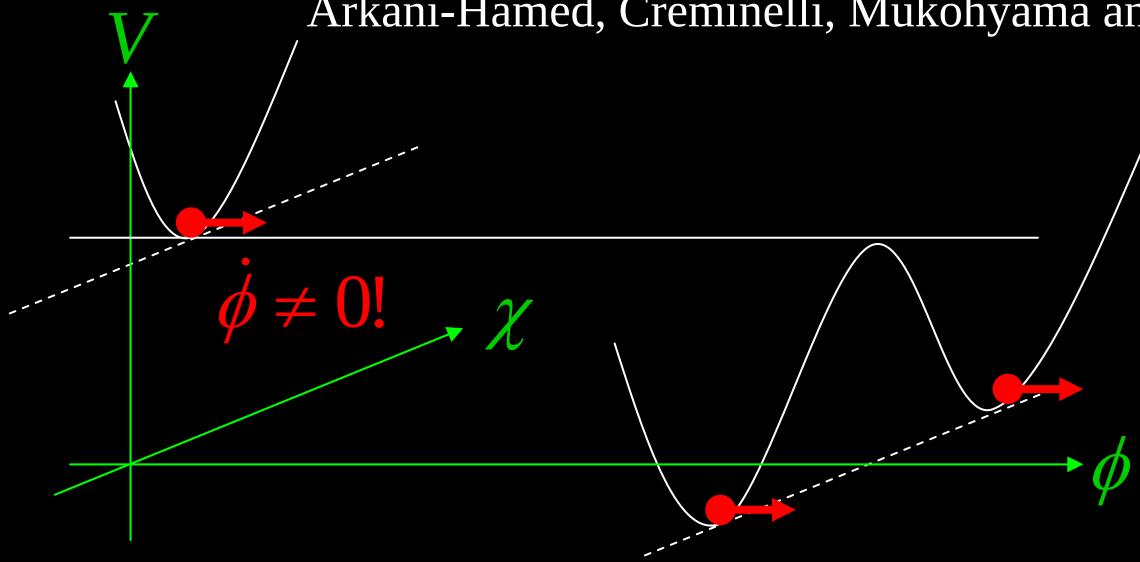
Also for linear perturbation!

Non-linear dynamics?

Can drive inflation?

Ghost inflation:

Arkani-Hamed, Creminelli, Mukohyama and Zaldarriaga, JHEP 0404:001,2004



Similar to
hybrid inflation but
<u>NOT SLOW ROLL</u>

Scale-invariant perturbations

cf. tilted ghost inflation, Senatore (2004)

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

Prediction of Large (visible) non-Gauss.

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

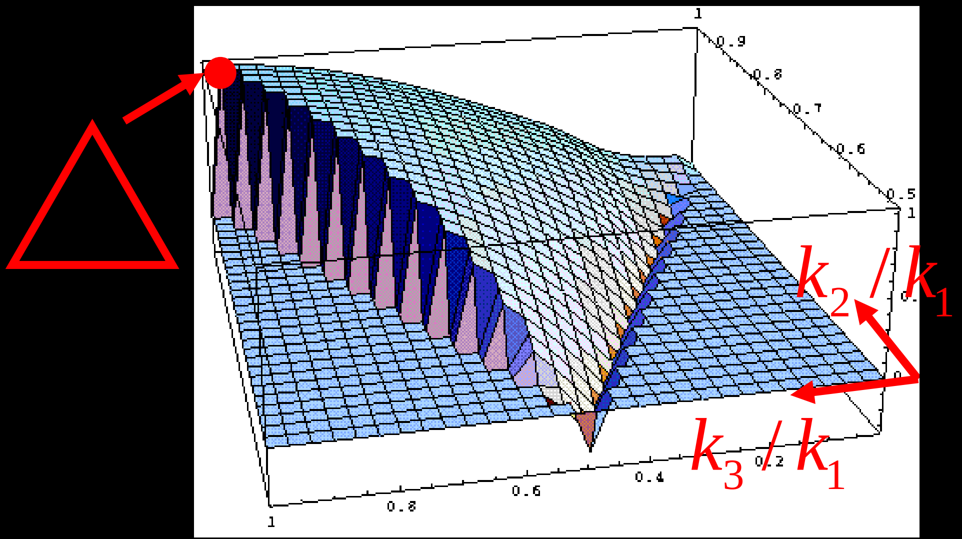
non-G of $\sim \left(\frac{H}{M}\right)^{1/4}$ ← scaling dim of op.

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

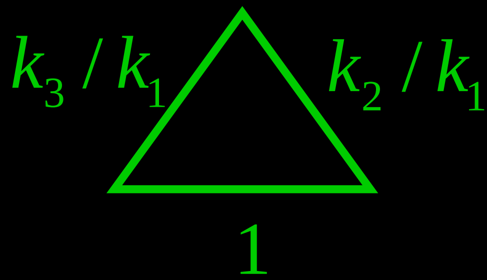
[Really "0.1" $\times \left(\delta\rho/\rho\right)^{1/5} \sim 10^{-2}$. VISIBLE.
Compare with usual inflation where
non-G $\sim \left(\delta\rho/\rho\right) \sim 10^{-5}$ too small.]

⇒ $f_{NL} \sim O(100)$, equilateral type

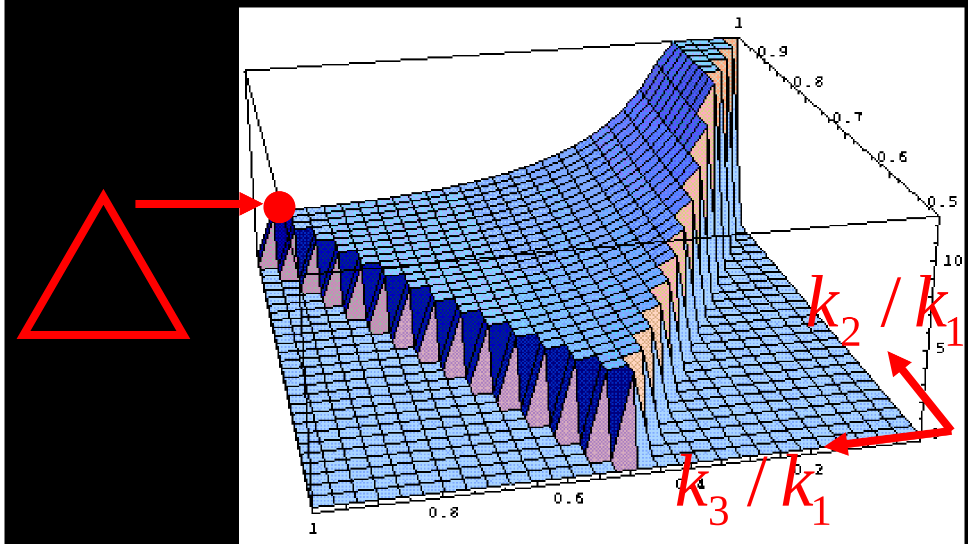
3-point function for ghost inflation



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



3-point function for “local” non-G



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

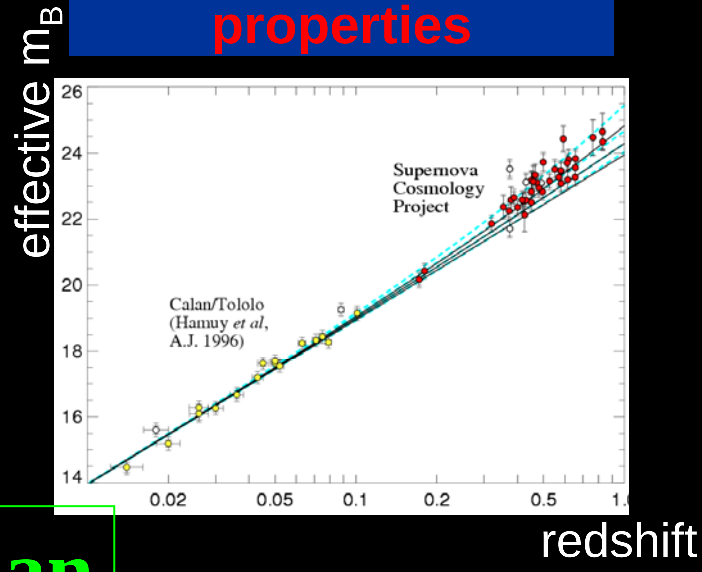
Can drive inflation?

- Ghost inflation
  Arkani-Hamed, Creminelli, Mukohyama and Zaldarriaga, JCAP 0404:001,2004
  Hybrid type
  not slow-roll
- Scale invariant perturbation
  COBE [illegible]: $H/M \sim 10^{-4}$
- Observationally distinguishable
  large non-Gaussianity
  Equilateral-type with
  $f_{NL} \sim O(100)$, $\tau_{NL} \sim O(10000)$

Yes, in the regime of validity of EFT!

Observationally distinguishable!

Linear Perturbation



Geometrical properties

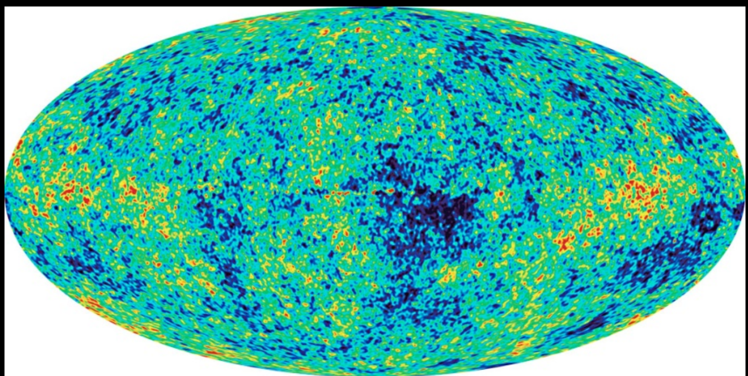
Input $H(z)$ & $\rho_{vis}(z)$

Mukohyama, JCAP 0610:011,2006.

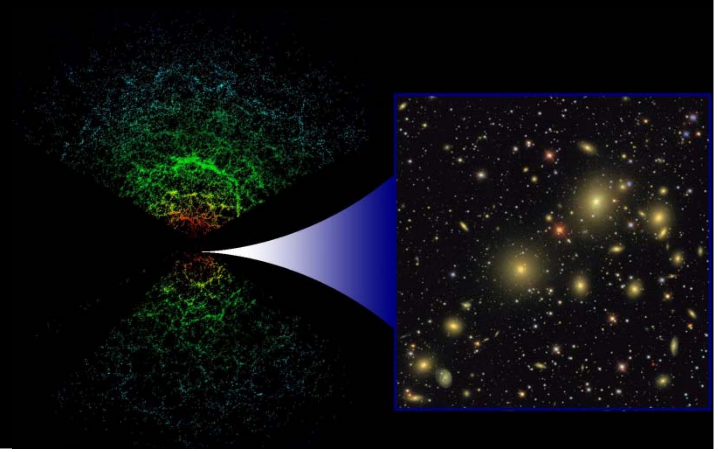
Output **Higgs sector Lagrangian**

Linear perturbation equation

Compare!



Dynamical properties



Simplest case

- **Exact shift symmetry, i.e. no potential**
- **May be called ΛGDM.** $H^2 = H_0^2\left[\Omega_m(1+z)^3 + (1-\Omega_m)\right]$
  (FRW evolution is exactly like ΛCDM.)
- **Linear perturbation equation**
  (derived using the formalism in Mukohyama, JCAP 0610:011,2006)

$$(1+z)^2\frac{d^2g}{dz^2} + \left[A_{CDM}(z) + A_{mod}(z)\right](1+z)\frac{dg}{dz} + \left[B_{CDM}(z) + B_{mod}(z)\right]g = 0$$

$$\begin{aligned} A_{CDM}(z) &= -\frac{3[\Omega_m + 2(1-\Omega_m)(1+z)^{-3}]}{2[\Omega_m + (1-\Omega_m)(1+z)^{-3}]} \\ B_{CDM}(z) &= \frac{3(1-\Omega_m)(1+z)^{-3}}{\Omega_m + (1-\Omega_m)(1+z)^{-3}} \end{aligned}$$

$$g(z)a = \Delta = \frac{\vec{k}^2}{a^2}\frac{\Phi}{-dH/dt}$$

$$\begin{aligned} A_{mod}(z) &= \frac{y(z)}{3\Omega_m + y(z)} \\ B_{mod}(z) &= \frac{3\Omega_m x(z) + x(z)y(z) - y(z)\left[\frac{1}{2} + \frac{\Omega_m + (1-\Omega_m)(1+z)^{-3}}{3\Omega_m + y(z)}\right]}{\Omega_m + (1-\Omega_m)(1+z)^{-3}} \end{aligned}$$

$$\begin{aligned} x(z) &= \frac{H_0^2 M_{Pl}^2}{M^4}\frac{\vec{k}^2}{a_0^2 H_0^2}(1+z)^2 \\ y(z) &= \frac{\alpha M^2}{M_{Pl}^2}\frac{\vec{k}^2}{a_0^2 H_0^2}(1+z)^{-1} \end{aligned}$$

Summary

- Ghost condensation is the simplest Higgs phase of gravity.
- The low-E EFT is determined by the symmetry breaking pattern. No ghost in the EFT.
- Gravity is modified in IR.
- Consistent with experiments and observations if $M < 100$GeV.
- Ghost inflation predicts large non-Gaussianity.
- Behaves like DE+DM for FRW background and large-scale linear perturbation.
- Cosmological perturbation may distinguish ghost condensation from DE/DM.

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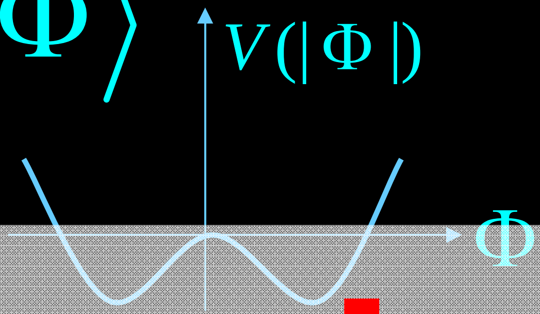
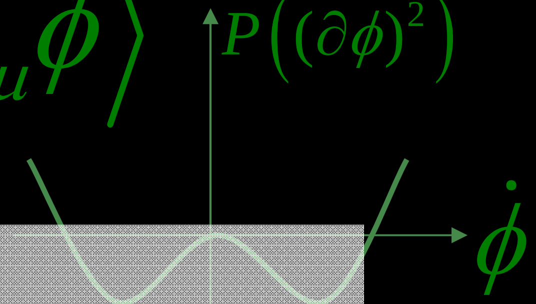
Order parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
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Thank you very much!