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Relaxing Λ

with L. Alberte, A. Khmelnitsky, D. Pirtskhalava and E. Trincherini 1608.05715, JHEP

(with D. Pirtskhalava, L. Santoni and E. Trincherini 1610.04207, JCAP)

DESY, 27th September 2017

Motivations

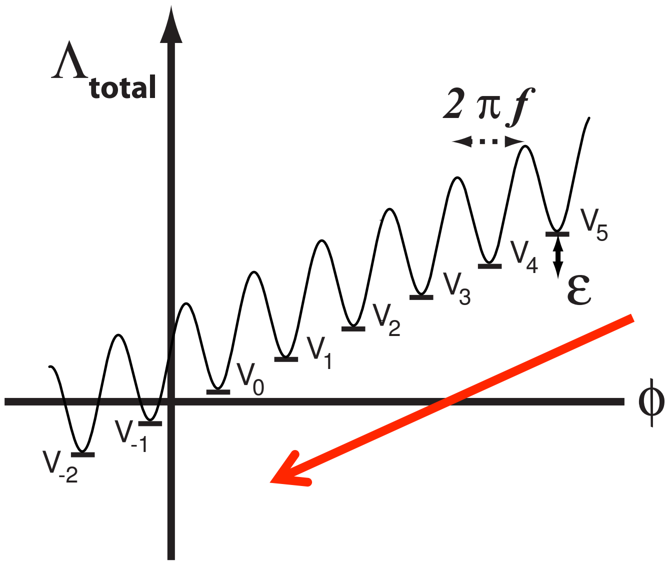
Can we build a model that dynamically relaxes Λ ?

- Danger of "premature application" of anthropic principle
- The only reason for dark energy is the c.c. problem,
  but concrete models have nothing to do with its solution
- Predicts existence of light states
- It requires NEC violation: could be theoretically ruled out

(Motivation for motivations: the actual implementation sucks)

Abbott's model

Abbott 85



$$V(\phi) = -M^4 \cos\left(\frac{\phi}{f}\right) + \epsilon \frac{\phi}{2\pi f} + V_{other}$$

Quickly goes down because of dS fluctuations and tunneling

Two main problems:

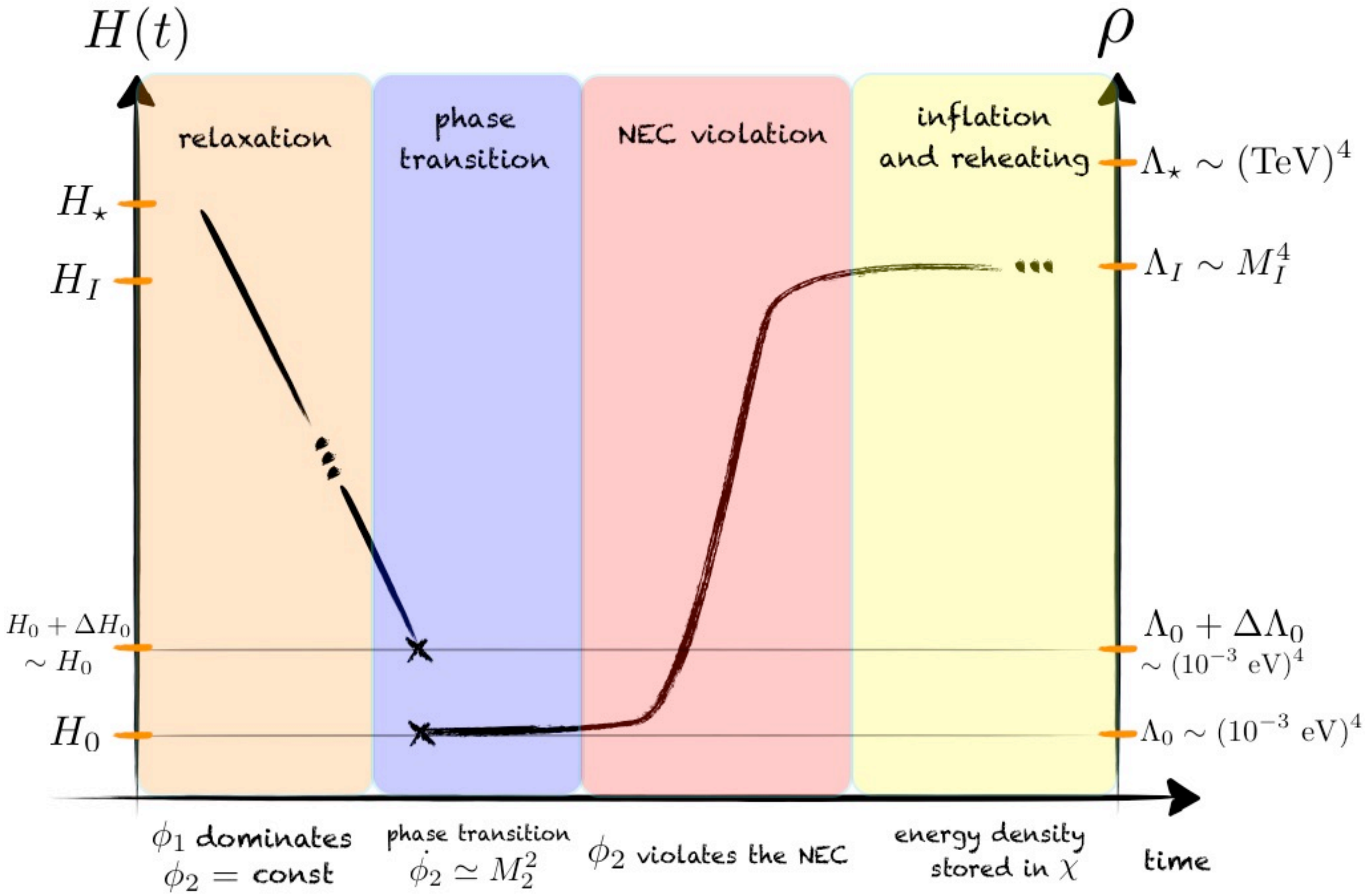
- Empty Universe. Generic: sensitive to small Λ when universe is empty

→ NEC violation

Steinhardt, Turok 06

- Eternal Inflation. In which minimum do we live? It is a landscape...

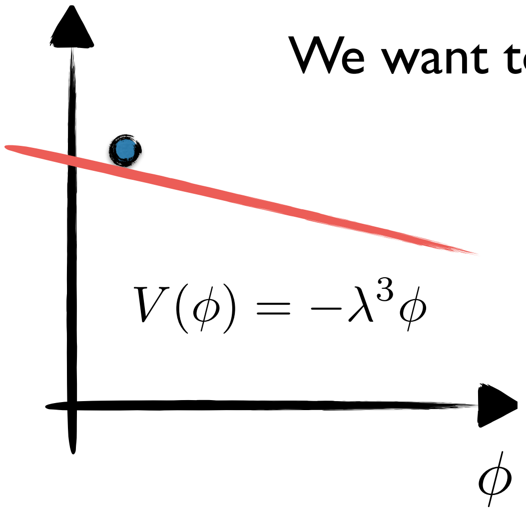
Sketch



$H(t)$
ρ
relaxation
phase transition
NEC violation
inflation and reheating
$H_\star$
H_I
$H_0 + \Delta H_0$
$\sim H_0$
H_0
$\Lambda_\star \sim (\mathrm{TeV})^4$
$\Lambda_I \sim M_I^4$
$\Lambda_0 + \Delta\Lambda_0$
$\sim (10^{-3}\ \mathrm{eV})^4$
$\Lambda_0 \sim (10^{-3}\ \mathrm{eV})^4$
ϕ_1 dominates
$\phi_2 =$ const
phase transition
$\dot{\phi}_2 \simeq M_2^2$
ϕ_2 violates the NEC
energy density stored in χ
time

Relaxing sector

We want to avoid Eternal Inflation and all measure-related issues

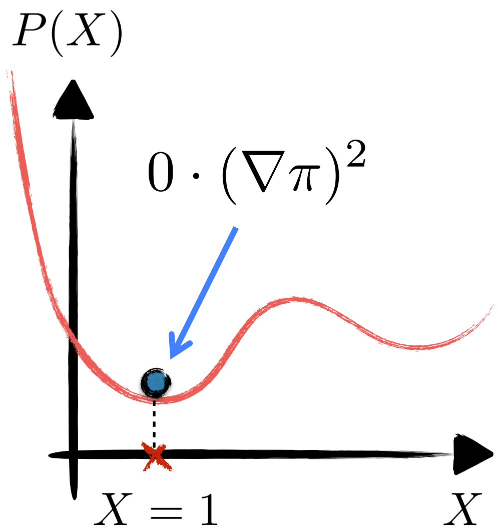


$$\lambda_1^3 \ll M_{\rm Pl} H^2 \qquad \text{(slow roll)}$$

$$\frac{\dot{\phi}_1}{H} \gg H \quad \Rightarrow \quad \lambda_1^3 \gg H^3 \qquad \text{(classical evolution)}$$

$$\Lambda_{\rm max} \sim M_{\rm Pl}^{8/3} H_0^{4/3} \sim (10\ \text{MeV})^4$$

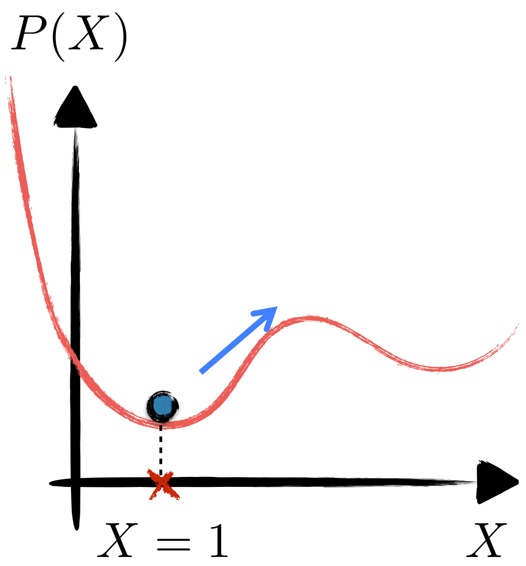
Models of inflation (e.g. Ghost Inflation, Galileon Inflation...) with a smooth λ → 0 limit



$$S = \int d^4x \sqrt{-g} \left[M_1^4 P_1(X_1) + \lambda_1^3 \phi_1 - \Lambda_\star + \ldots \right]$$

$$X_1 \equiv -\frac{(\partial\phi_1)^2}{M_1^4} \qquad\qquad \frac{(\delta\phi_1)_{\rm quant}}{(\delta\phi_1)_{\rm class}} \sim \left(\frac{H}{M_1}\right)^{5/4}$$

Dynamically Λ = 0 is special



System destabilized when H (Hubble friction) small enough

$$\dot{\pi}_1 \simeq \frac{\lambda_1^3}{3H}$$

Phase transition when $\dot{\pi}_1 / M_1^2 \sim 1$

This fixes observed value of cc: $$\Lambda_0 \sim \frac{\lambda_1^6 M_{\rm Pl}^2}{M_1^4}$$

Small λ_1 is technically natural, breaks shift symmetry

$$M_{\rm Pl}^2 \dot{H}_0 \sim M_1^4$$

$$\Lambda_\star \lesssim 3 M_{\rm Pl}^2 M_1^2 \sim M_{\rm Pl}^2 \Lambda_0^{1/2} \epsilon_0^{1/2} \sim (1\ {\rm TeV})^4 \epsilon_0^{1/2}$$

The model can relax up to TeVish cc after HUGE excursion $\Delta\phi_1 / M_{\rm Pl} \simeq M_{\rm Pl} / H_0$

NEC violators

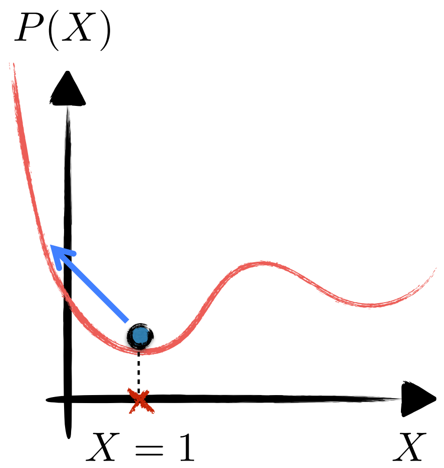
$$T_{\mu\nu}k^\mu k^\nu \geq 0 \quad \Rightarrow \quad \rho + p \geq 0 \qquad \dot{\rho} = -3H(\rho + p)$$

Usually associated with instabilities, but stable examples exist

(recent 4d NEC violation via extra dimension)

Graham, Kaplan, Rajendran 17

Starting from theories with exact dS solution with dynamical field



1. Ghost Condensate
   Deform theory with a rising potential

   Control instabilities if $\dot{H} \lesssim H^2$

2. Galileon theories

$$\mathcal{S}_\pi = \int d^4x\,\sqrt{-g}\left[f^2 e^{2\pi}(\partial\pi)^2 + \frac{f^3}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{f^3}{2\Lambda^3}(\partial\pi)^4\right]$$

$$S \supset \int d^4x\sqrt{-g}M_2^4 P(X_1, X_2)$$

$M_2 \lesssim \Lambda_0^{1/4} \sim 10^{-3}\ \mathrm{eV}$

Small cc jump

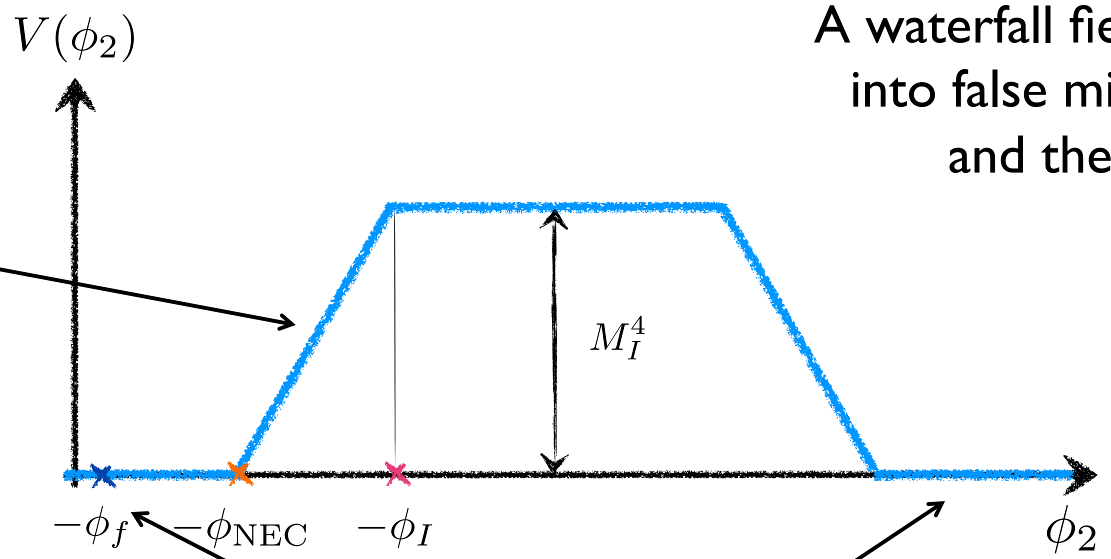
Slow NEC violation

If ϕ_1 stops, one has plenty of time to make the Universe
(but eternal inflation in the future)

Very slow NEC violation:

$$\frac{\dot{H}}{H} \lesssim \frac{M_2^3}{M_{\rm Pl}^2} \lesssim H$$

A waterfall field gets trapped into false minimum until ϕ_f and then reheats

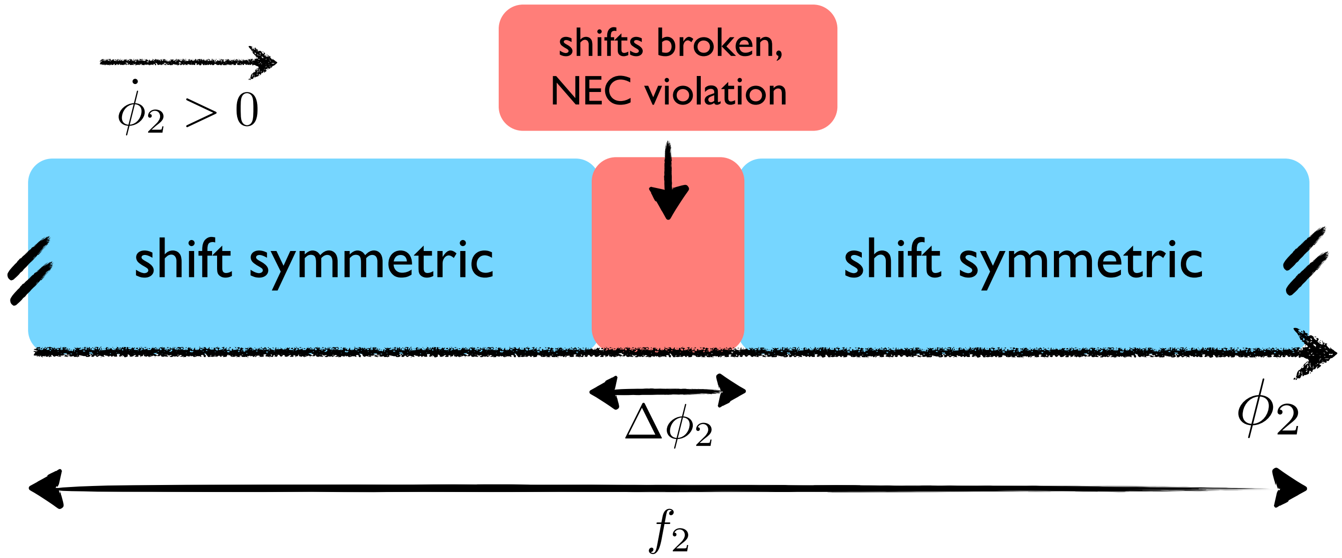


Same cc before and after NEC violation due to Z_2

We relaxed the low-temperature c.c. of today

Fast NEC violation

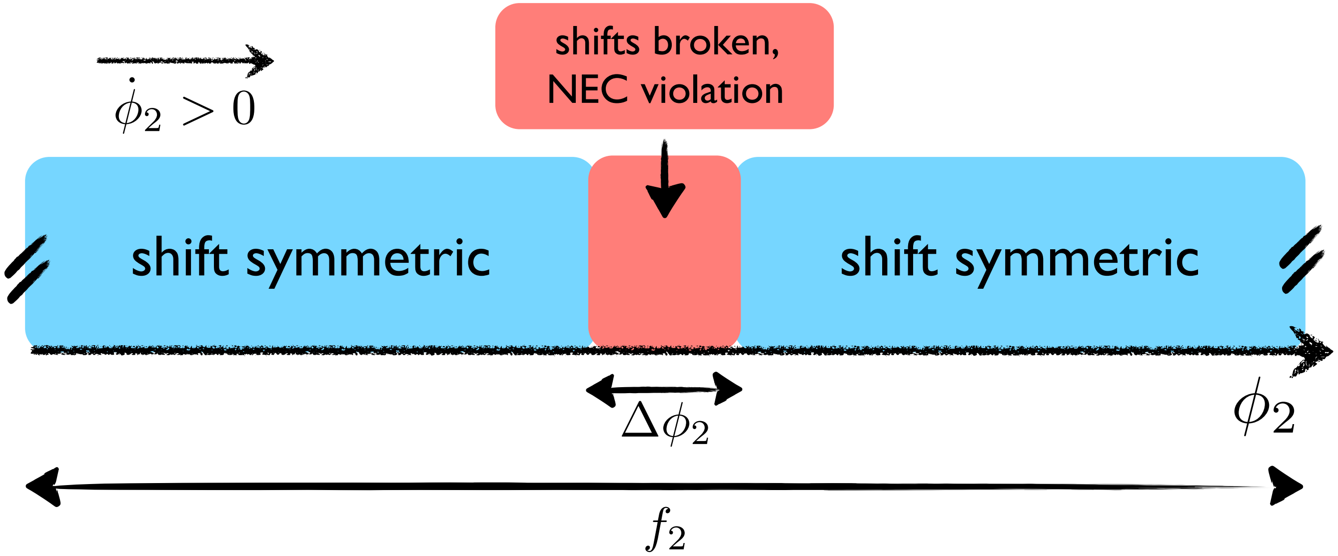
When scanning field proceeds one needs to create universe in $(\epsilon_0 H_0)^{-1}$



Same cc before and after NEC violation due to periodicity

Fast NEC violation

When scanning field proceeds one needs to create universe in $(\epsilon_0 H_0)^{-1}$



$$S_\theta = \int d^4x\, \sqrt{-g}\, \left[f_2^2 \mathcal{F}_1(\theta)(\partial\theta)^2 + \frac{f_2^3}{M_\theta^3}\mathcal{F}(\theta)(\partial\theta)^2\Box\theta + \frac{f_2^3}{2M_\theta^3}\mathcal{F}_2(\theta)(\partial\theta)^4 - V(\theta) \right]$$

Different asymptotic V followed by reheating to relaxed cc

Reverse engineering

Elder, Joyce, Khoury 13
Pirstkhalava, Santoni, Trincherini, Uttarayat 16

$$S_\theta = \int d^4x\,\sqrt{-g}\,\left[f_2^2\boxed{\mathcal{F}_1(\theta)}(\partial\theta)^2 + \frac{f_2^3}{M_\theta^3}\boxed{\mathcal{F}(\theta)}(\partial\theta)^2\Box\theta + \frac{f_2^3}{2M_\theta^3}\boxed{\mathcal{F}_2(\theta)}(\partial\theta)^4 - \boxed{V(\theta)}\right]$$

$$\rho = \frac{f_2^2}{H_0^2}\,\dot\theta^2\left[\mathcal{F}_2(\theta)\dot\theta^2 + 4\mathcal{F}(\theta)H\dot\theta - H_0^2\mathcal{F}_1(\theta)\right] - \frac{2}{3}\frac{f_2^2}{H_0^2}\mathcal{F}'(\theta)\dot\theta^4 + V(\theta)$$

$$p = \frac{f_2^2}{3H_0^2}\,\dot\theta^2\left[\mathcal{F}_2(\theta)\dot\theta^2 - 4\mathcal{F}(\theta)\ddot\theta - 3H_0^2\mathcal{F}_1(\theta)\right] - \frac{2}{3}\frac{f_2^2}{H_0^2}\mathcal{F}'(\theta)\dot\theta^4 - V(\theta)$$

$$3M_{\rm Pl}^2H^2 = \rho \qquad\qquad M_{\rm Pl}^2(3H^2 + 2\dot H) = -p$$

$$\mathcal{F}_1 = \frac{18M_{\rm Pl}^2H_0^2H^2 + 9M_{\rm Pl}^2H_0^2\dot H - 6f_2^2\mathcal{F}H\dot\theta^3 - 6f_2^2\mathcal{F}\dot\theta^2\ddot\theta - 2f_2^2\dot{\mathcal{F}}\dot\theta^3 - 6H_0^2V}{3f_2^2H_0^2\dot\theta^2}$$

$$\mathcal{F}_2 = \frac{9M_{\rm Pl}^2H_0^2H^2 + 3M_{\rm Pl}^2H_0^2\dot H - 6f_2^2\mathcal{F}H\dot\theta^3 - 2f_2^2\mathcal{F}\dot\theta^2\ddot\theta - 3H_0^2V}{f_2^2\dot\theta^4}\,.$$

$$\theta, \mathcal{F}, H, V \quad\rightarrow\quad \mathcal{F}_1, \mathcal{F}_2$$

Stability checks

$$S_\zeta = \int d^4x \; a^3 \left[A(t)\; \dot{\zeta}^2 - B(t)\; \frac{1}{a^2} \,(\partial\zeta)^2 \right]$$

$$A(t) = \frac{M_{\rm Pl}^2(-4M_{\rm Pl}^4\dot{H} - 12M_{\rm Pl}^2 H\hat{M}^3 + 3\hat{M}^6 + 2M_{\rm Pl}^2 M^4)}{(2M_{\rm Pl}^2 H - \hat{M}^3)^2}$$

$$B(t) = \frac{M_{\rm Pl}^2\left(-4M_{\rm Pl}^4\dot{H} + 2M_{\rm Pl}^2 H\hat{M}^3 - \hat{M}^6 + 2M_{\rm Pl}^2\partial_t\hat{M}^3\right)}{(2M_{\rm Pl}^2 H - \hat{M}^3)^2}$$

$$M^4(t) = \frac{4}{3}\frac{f_2^2}{H_0^2}\left(2\mathcal{F}_2(\theta)\dot{\theta}^4 + \mathcal{F}\dot{\theta}^2\ddot{\theta} + 9\mathcal{F}H\dot{\theta}^3\right) - \frac{4}{3}\frac{f_2^2}{H_0^2}\dot{\mathcal{F}}\dot{\theta}^3, \quad \hat{M}_3^3(t) = \frac{4}{3}\frac{f_2^2}{H_0^2}\mathcal{F}\dot{\theta}^3$$

Possible to create universe in a time ~ H_0^{-1} with

- stability
- subluminality
- cutoff >> H

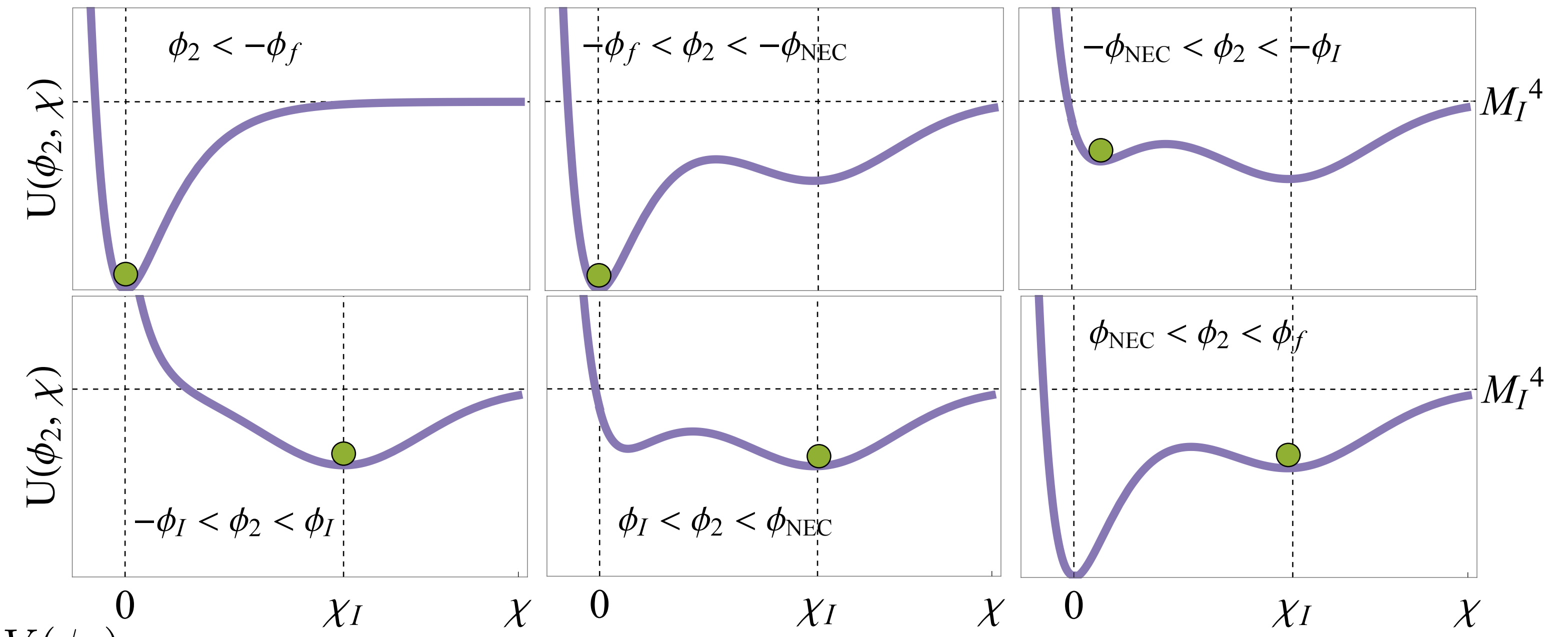
Tuning functions? Unrelated to c.c.

Well it is possible... but it is disgusting... it cannot happen...

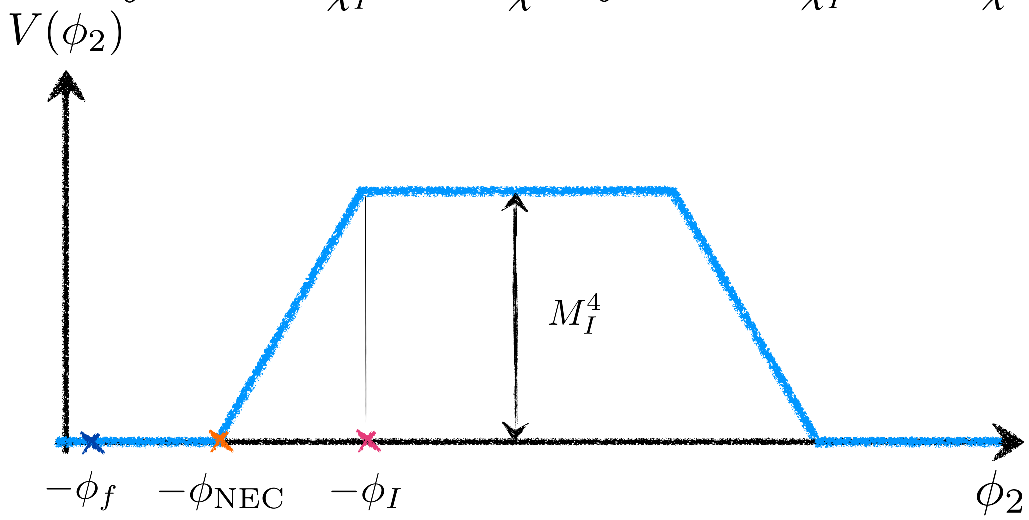
Well it is possible... but it is disgusting... it cannot happen...

Reheating

Store the energy in a (canonical) waterfall field χ which then reheats



...and then reheating



- No backreaction on ϕ_2
- No χ perturbations

UV extension of Ghost Condensate

Ivanov, Sibyriakov 14

Can one trigger the NEC violating phase? Can one turn on the GC?

Einstein-aether: $u_\mu u^\mu = 1$

$$S_{[EH]} + S_{[u]} = -\frac{M_0^2}{2}\int \mathrm{d}^4x\sqrt{-g}\left(R + K^{\mu\nu}{}_{\rho\sigma}\nabla_\mu u^\rho \nabla_\nu u^\sigma\right)$$

$$u_\mu \equiv \frac{\nabla_\mu \sigma}{\sqrt{\nabla^\nu\sigma\nabla_\nu\sigma}} \qquad \sigma \mapsto \tilde{\sigma}(\sigma)$$

$$K^{\mu\nu}{}_{\rho\sigma} = c_1 g^{\mu\nu}g_{\rho\sigma} + c_2\delta^\mu_\rho\delta^\nu_\sigma + c_3\delta^\mu_\sigma\delta^\nu_\rho + c_4 u^\mu u^\nu g_{\rho\sigma}$$

Cut-off almost at Planck scale

$$S_{[\Theta]} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\Theta\partial_\nu\Theta + \frac{\varkappa}{2}(u^\mu\partial_\mu\Theta)^2 - \boxed{\mu^2} u^\nu\partial_\nu\Theta - V\right]$$

$$\dot{\Theta} = \mu^2$$

- Can be turned on and off (by ϕ_1)
- Around it at low energy, one light ghost-condensate field

Conclusions

- It is possible to relax the cc. One needs to describe the whole evolution.
- Unless NEC violation is forbidden.
- Light states are present.
- Connection with present dark energy. Model dependent.

- (Or I convinced you it is anthropic?)

Stability of geodesically complete cosmologies

with Pirstkhalava, Santoni, Trincherini 16
Elder, Joyce, Khoury 13
Libanov, Mironov, Rubakov 16
Kobayashi 16 Ijjas, Steinhardt 16
Cai, Wan, Li, Qiu, Piao 16

No general pathology in violating NEC

Can we have a complete cosmology?
(e.g. Bouncing or a → const.)

$$\int_{-\infty}^{t} dt \; a(t) = \infty \qquad \frac{\mathrm{d}t}{\mathrm{d}\lambda} = \frac{1}{a}$$

$$S = \int \mathrm{d}^4x \, N\sqrt{h}\Big[\frac{1}{2}M_{\rm Pl}^2\left({}^{(3)}R + \frac{E_{ij}E^{ij} - E^2}{N^2}\right) - \frac{M_{\rm Pl}^2\dot{H}}{N^2} - M_{\rm Pl}^2(3H^2 + \dot{H}) \\ + \frac{1}{2}m_2^4\delta N^2 - \hat{m}_1^3\delta N\delta E - \frac{1}{2}\bar{m}_1^2\delta E^2 - \frac{1}{2}\bar{m}_2^2\delta E^i{}_j\delta E^j{}_i - \bar{m}_3^2\,{}^{(3)}R\delta N + \dots\Big] \, .$$

- Einstein frame
- $\bar{m}_1^2 = -\bar{m}_2^2 = 0$ to avoid higher spatial derivatives.
  Removable with disformal transf: c_T=1
- $-\bar{m}_3^2\,{}^{(3)}R\delta N$ has 3 derivatives, but does not propagate extra dof
  (beyond Horndenski)

Stability

$$S_\zeta = \int \mathrm{d}^4x \; a^3 \left[A\dot{\zeta}^2 - B\frac{1}{a^2}\left(\vec{\nabla}\zeta\right)^2 \right]$$

$$A = M_{\rm Pl}^2 \cdot \frac{3(2M_{\rm Pl}^2 H - \hat{m}_1^3)^2 + 2M_{\rm Pl}^2(m_2^4 - 2M_{\rm Pl}^2\dot{H} - 6M_{\rm Pl}^2 H^2)}{(2M_{\rm Pl}^2 H - \hat{m}_1^3)^2}$$

$$B = -M_{\rm Pl}^2 + \frac{1}{a}\cdot\partial_t Y \; , \qquad\qquad Y \equiv a \cdot \frac{2M_{\rm Pl}^2(M_{\rm Pl}^2 - 2\bar{m}_3^2)}{2M_{\rm Pl}^2 H - \hat{m}_1^3}$$

$$Y(t_f) - Y(t_i) > M_{\rm Pl}^2 \int_{t_i}^{t_f} \mathrm{d}t \; a(t)$$

- $-\,\bar{m}_3^2\,{}^{(3)}R\delta N$ must be there and change sign (not removable)
- Any action with explicit 2nd order EOM has gradient instability!
- Valid including any number of fields and fluids

Backup slides