Relaxing Λ

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1608.05715

The CC problem

$$\langle T_{\mu\nu} \rangle = -\rho_{\text{vacuum}} g_{\mu\nu}$$

$$\rho_{\text{vacuum}} = \Lambda + \rho_{\text{vacuum}}^{SM} \qquad \simeq (10^{-3}\text{eV})^4$$

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$$\int d^4x \sqrt{-g}\Big(M^2_{\rm Pl} R - \Lambda\Big)$$

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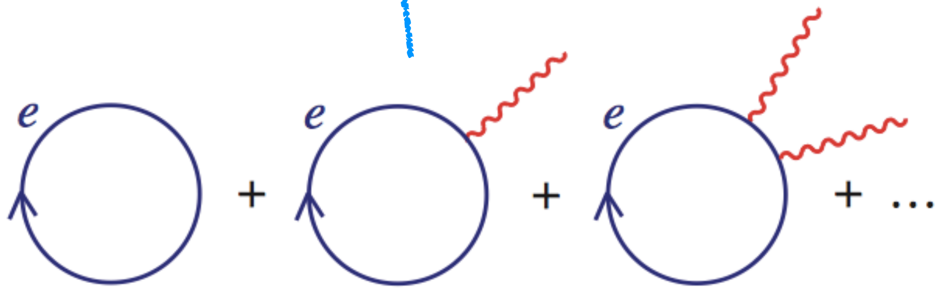


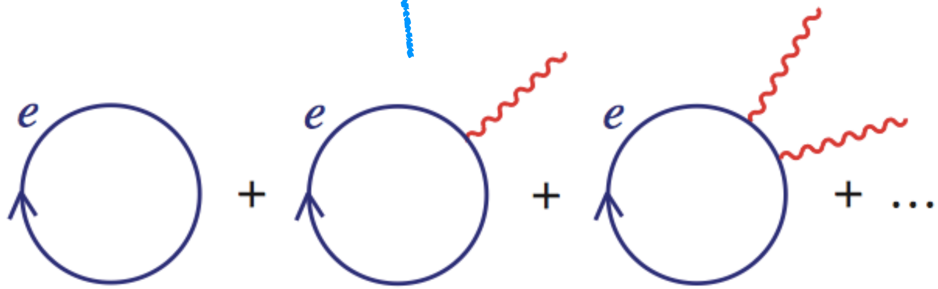
$$\rho_{\rm vacuum} = \mathcal{O}(M_*^4) + \mathcal{O}(M_*^2 m_{\rm e}^2) + \mathcal{O}(m_{\rm e}^4 \log M_*/m_{\rm e})$$

The CC problem

$$\langle T_{\mu\nu} \rangle = -\rho_{\text{vacuum}} g_{\mu\nu}$$

$$\rho_{\text{vacuum}} = \Lambda + \rho^{SM}_{\text{vacuum}} + \rho^{NP}_{\text{vacuum}} \simeq (10^{-3}\text{eV})^4$$

$$\int d^4x \sqrt{-g}\Big(M^2_{\text{Pl}} R - \Lambda\Big)$$



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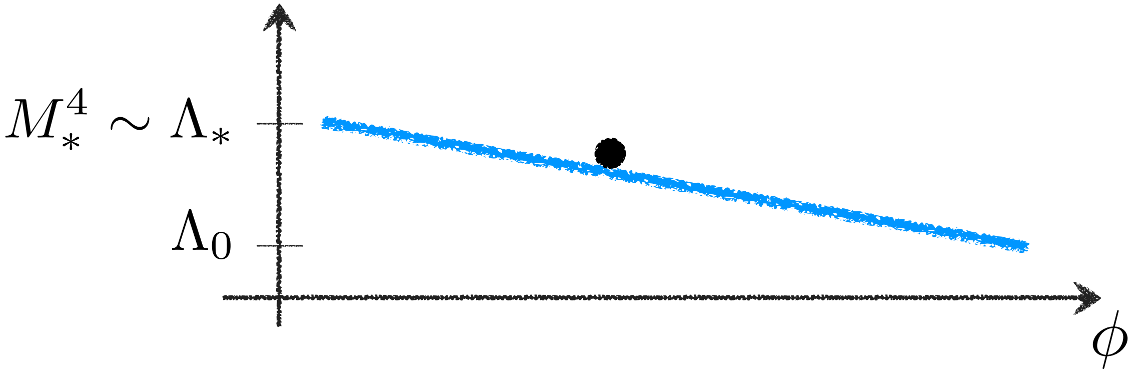
A simple idea…

Abbott '85

Add a compensating field whose vacuum energy dynamically adjusts itself to cancel the large contribution to the CC



Explain why this dynamics produces the observed value of the CC

Involve very small mass scales: they must be radiatively stable

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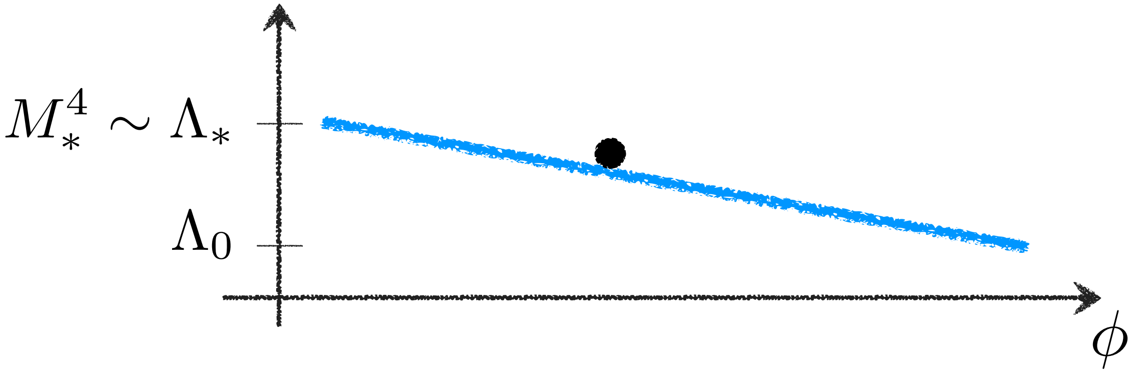
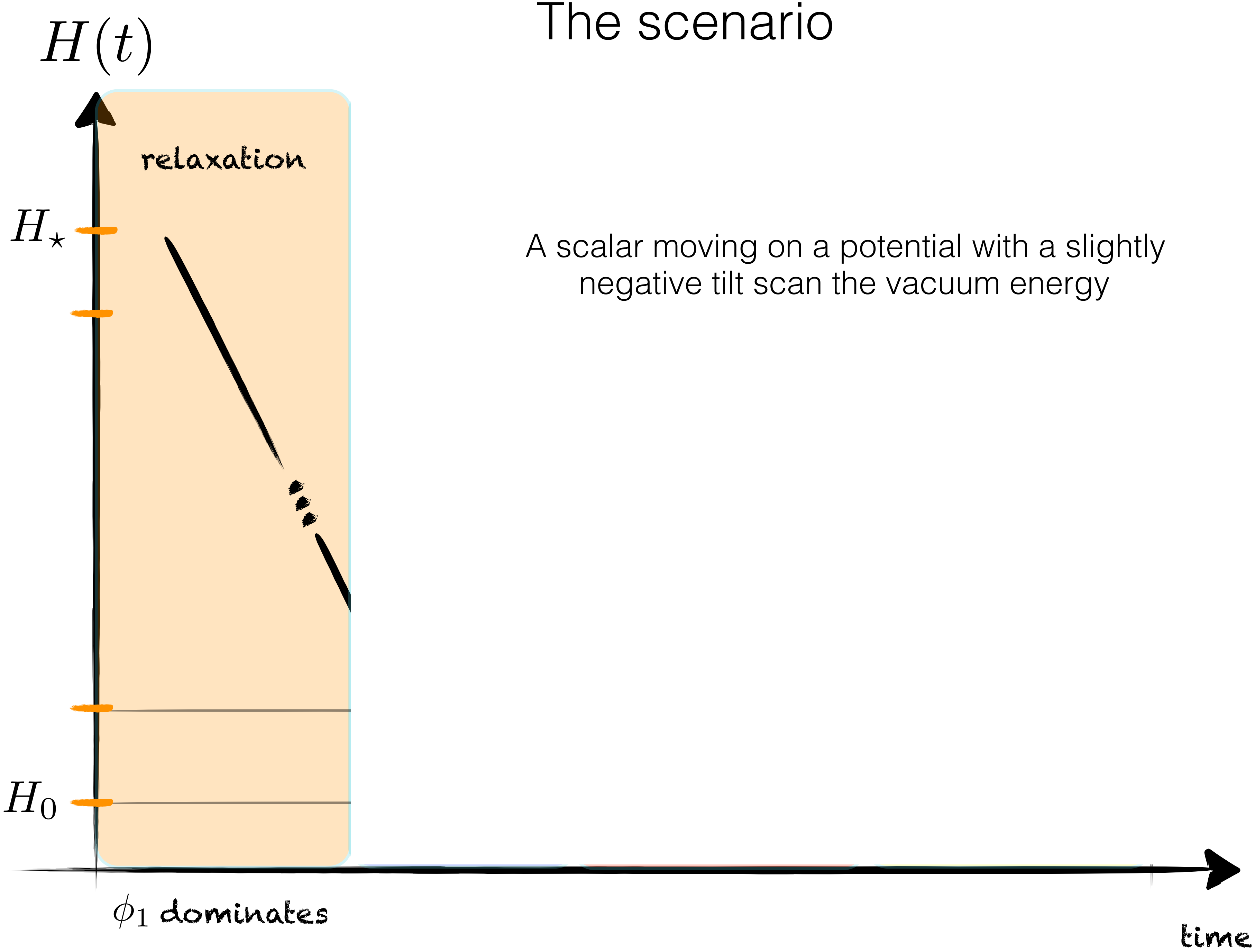


…that doesn't work

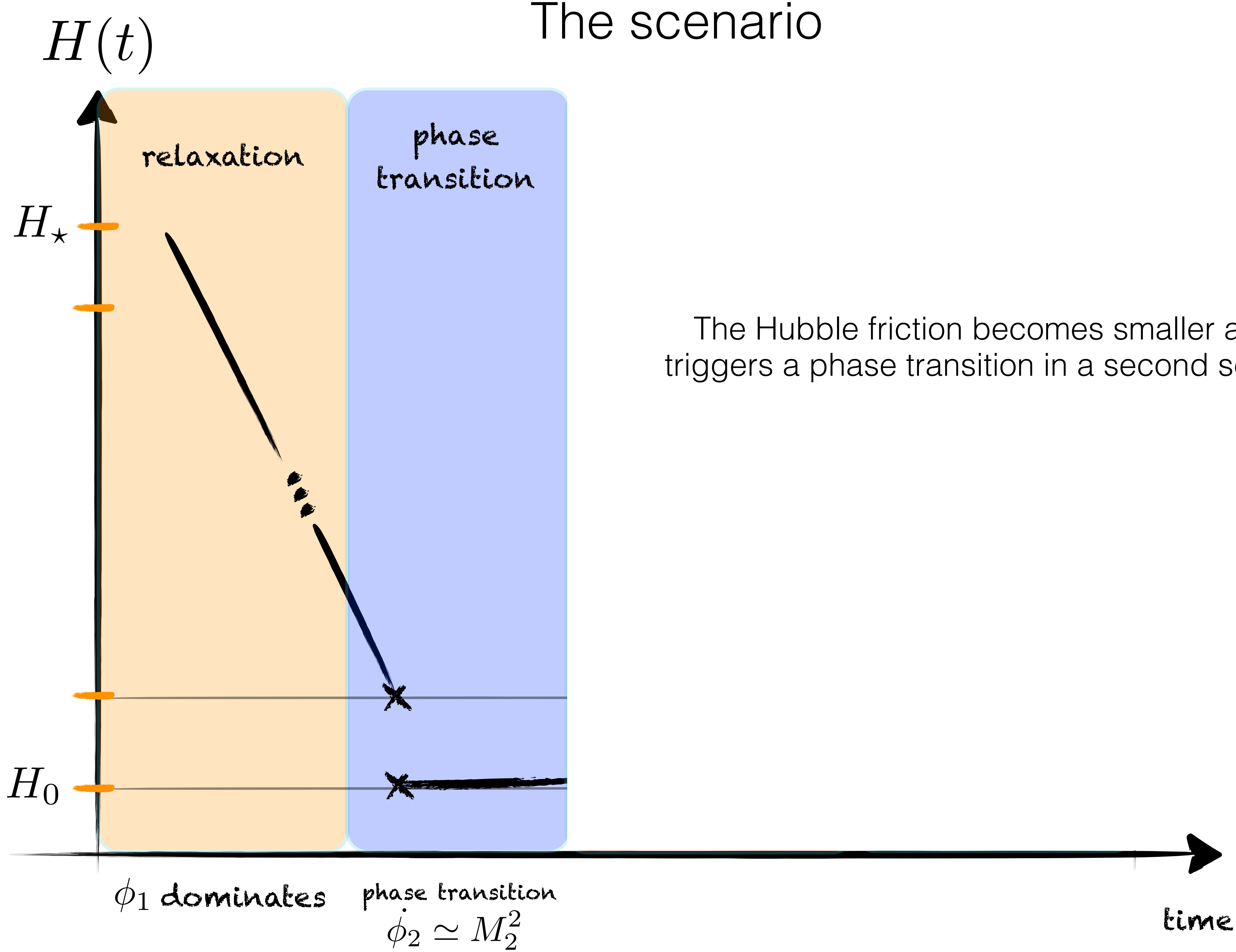
Empty Universe	Sensitive to small Λ only when the Universe is empty
Eternal inflation	In which minimum do we live? Measure problem

The scenario



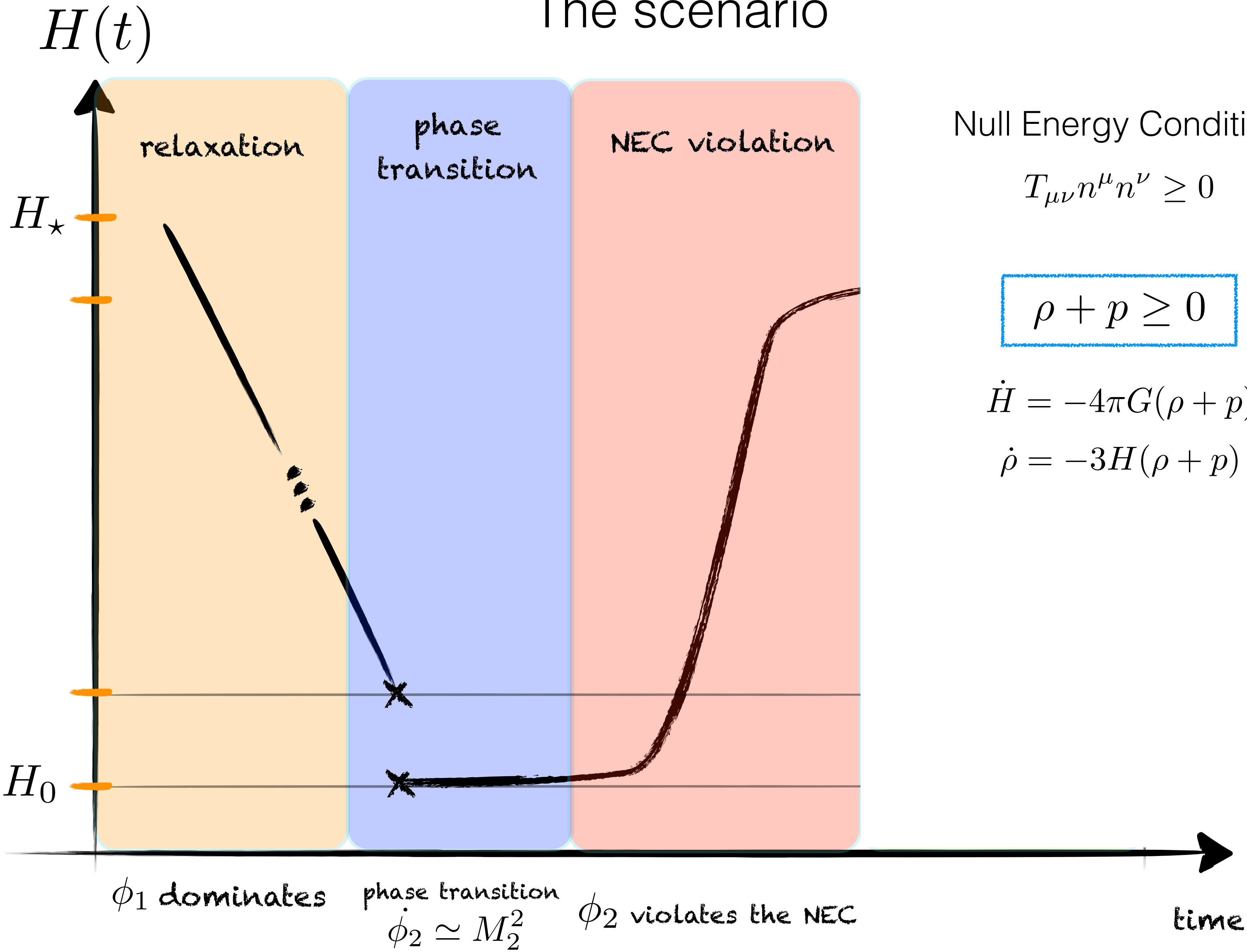
A scalar moving on a potential with a slightly negative tilt scan the vacuum energy

The scenario



The Hubble friction becomes smaller and triggers a phase transition in a second sector

The scenario



Null Energy Condition

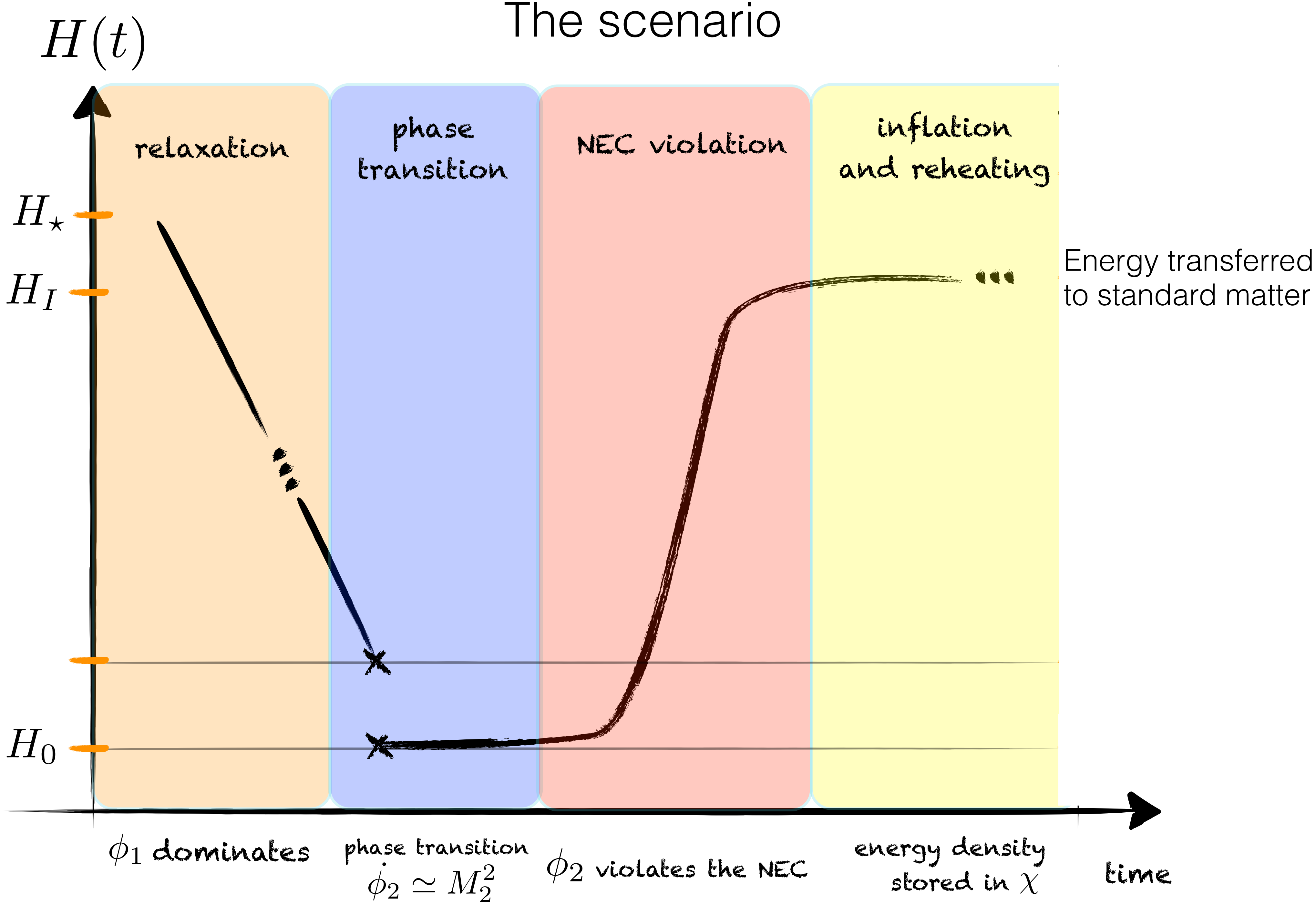
$$T_{\mu\nu} n^\mu n^\nu \geq 0$$

$$\rho + p \geq 0$$

$$\dot{H} = -4\pi G(\rho + p)$$

$$\dot{\rho} = -3H(\rho + p)$$

The scenario



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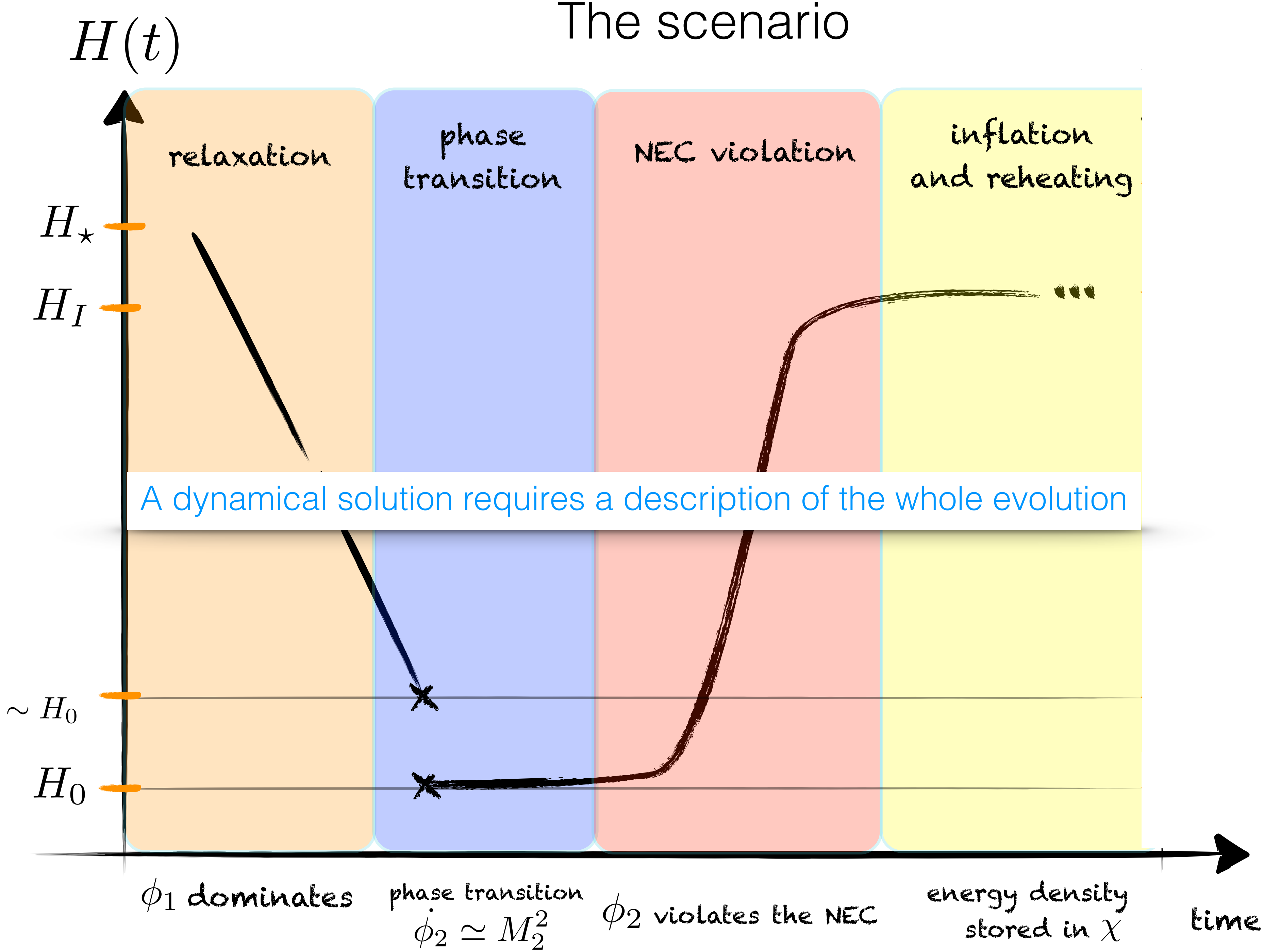

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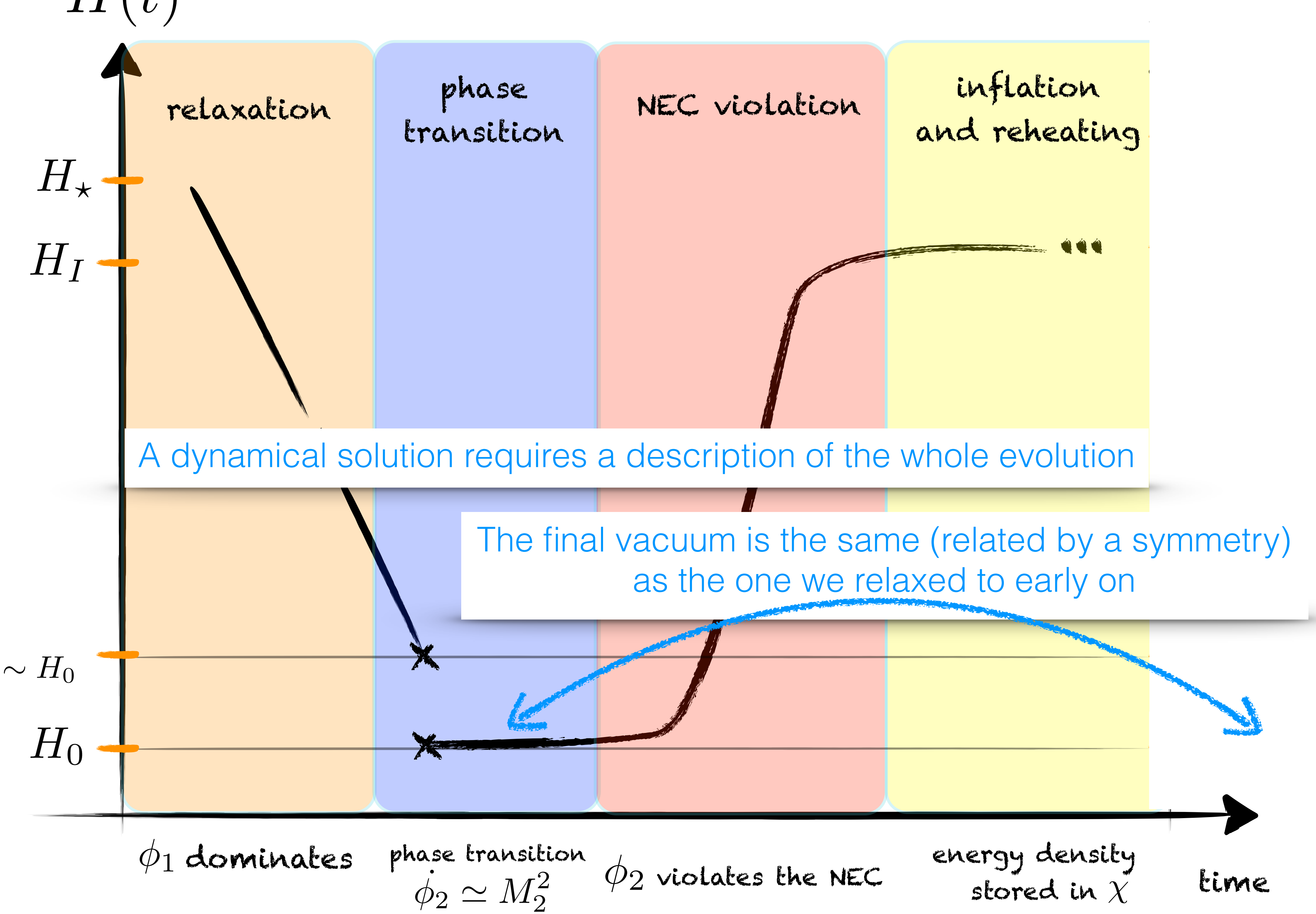
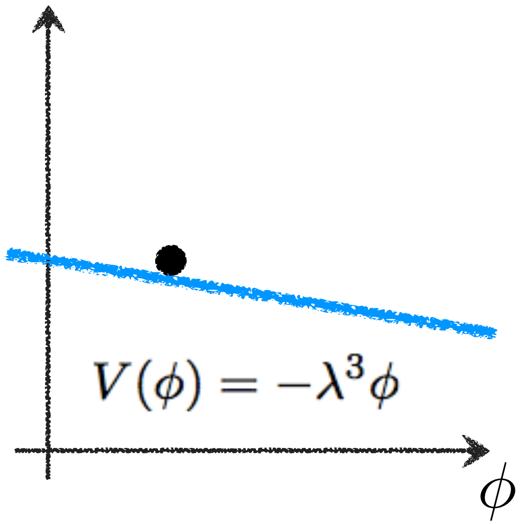


Additional motivations

The only motivation for dark energy is the CC problem
but no DE model addresses it

In this scenario two DE component related to the CC problem!

Is NEC violation theoretically consistent? Possible UV obstruction



The relaxing sector

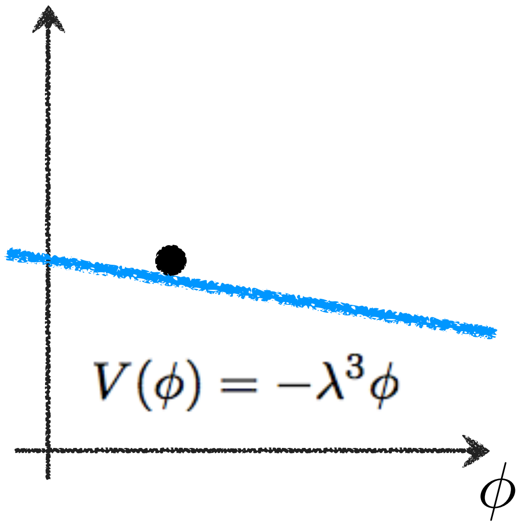
Stable under *O*(1) variation of Λ_*

Avoid eternal inflation and all the measure related issues

Slow roll $\lambda_1^3 \ll M_{\rm Pl} H^2$

Classical evolution $\dot{\phi}_1 \frac{1}{H} \gg H \quad \Rightarrow \quad \lambda_1^3 \gg H^3$

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



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Keep a classical motion even if $\lambda_1^3 \to 0$

A scalar field in the “Ghost condensate” regime

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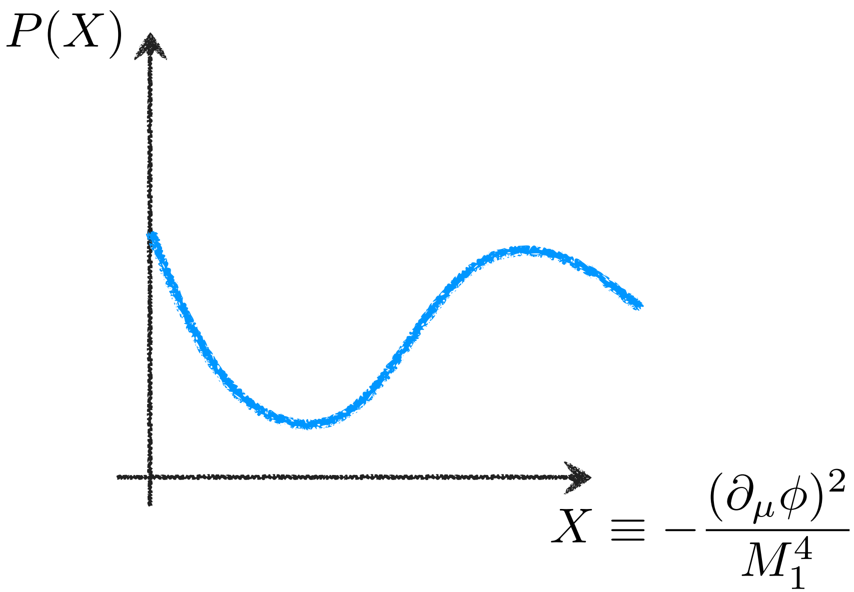

The ghost condensate

Arkani-Hamed, Cheng, Luty, Mukohyama ‘03

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

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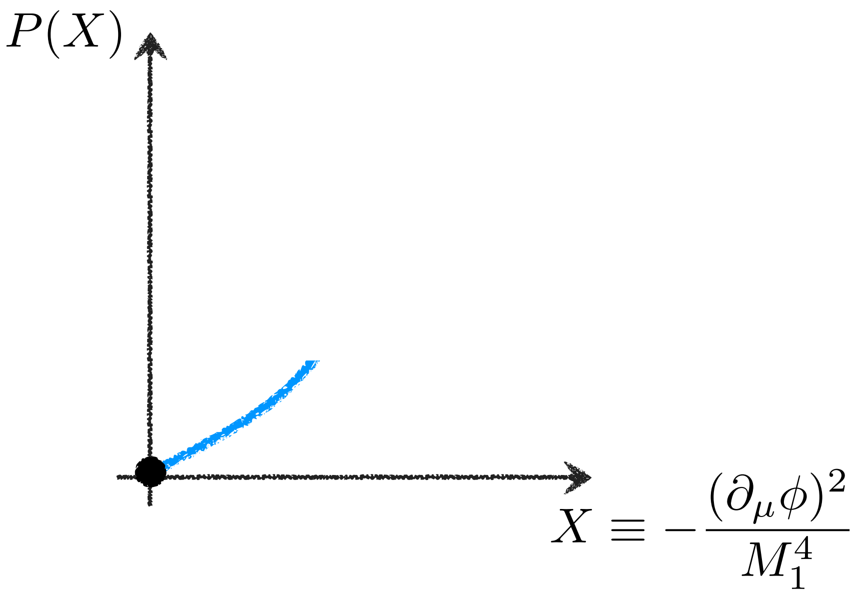

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$$S = \int d^4x \sqrt{-g}\left[M_1^4 P_1\left(X_1\right) + \cancel{\lambda_1^3 \phi_1} - \Lambda_\star + \ldots\right]$$

$$-(\partial_\mu \phi_1)^2 + \ldots$$

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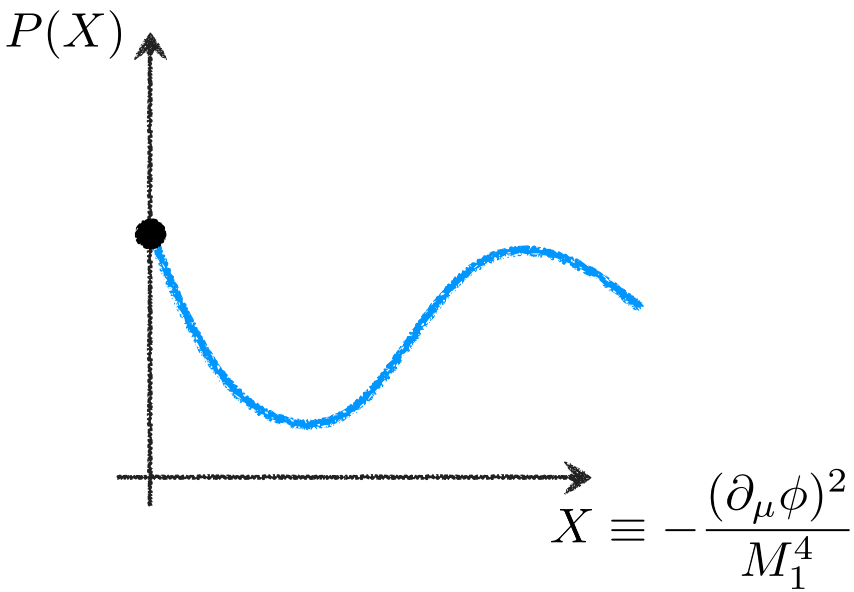

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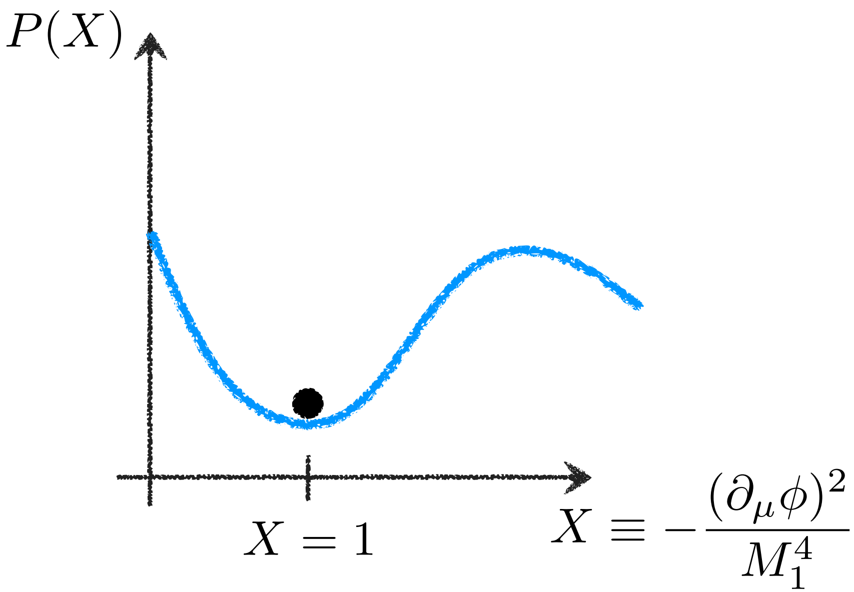

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Once minimally coupled to gravity
it sources dS

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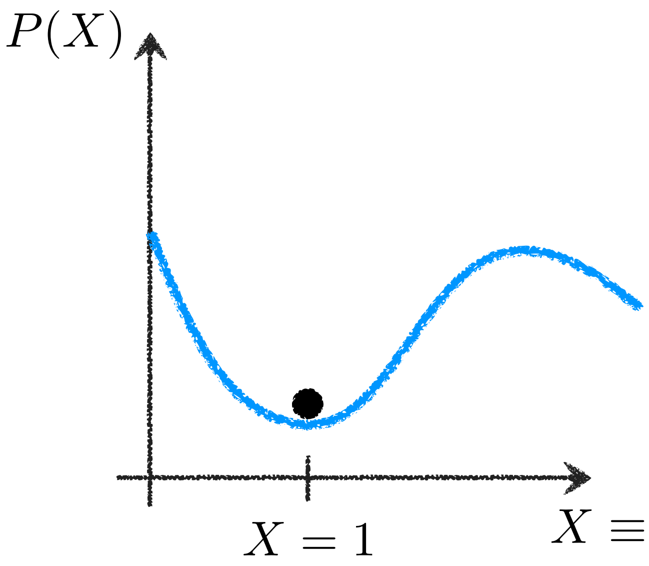

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With a tilted potential, the solution is perturbed by a homogeneous $\pi_1(t)$ with $\boxed{\dot{\pi}_1 \simeq \frac{\lambda_1^3}{3H}}$

It is a small perturbation if $\lambda_1^3 \ll 3HM_1^2$

$$\frac{(\delta\phi_1)_{\text{quant}}}{(\delta\phi_1)_{\text{class}}} \sim \left(\frac{H}{M_1}\right)^{5/4}$$ The amplitude of fluctuations is independent of the tilt of the potential

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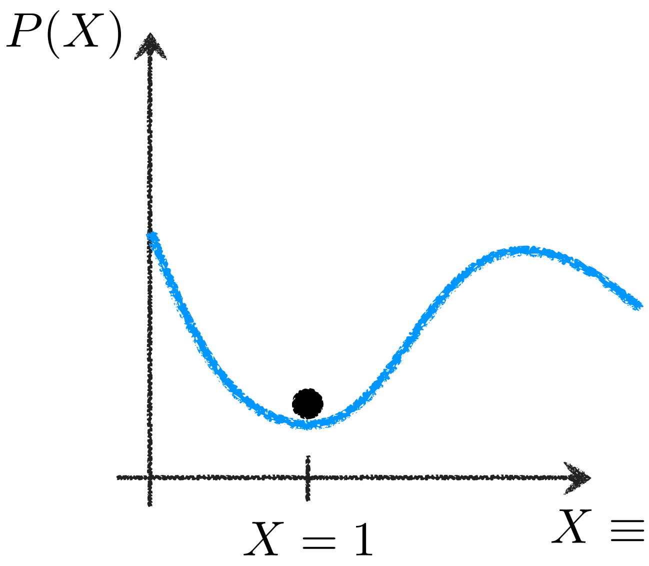

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Mixing with gravity introduces a Jeans-like instability for long modes $\omega^2 \sim \frac{k^4}{M_1^2} - \frac{M_1^2}{M_{\rm Pl}^2} k^2$

Characteristic time of instab longer than H_0 constrains the cutoff $M_1^3 < M_{\rm Pl}^2 H_0 \sim (10\,{\rm MeV})^3$

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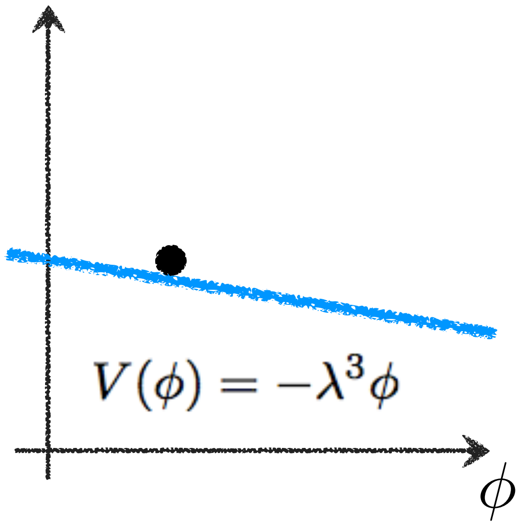

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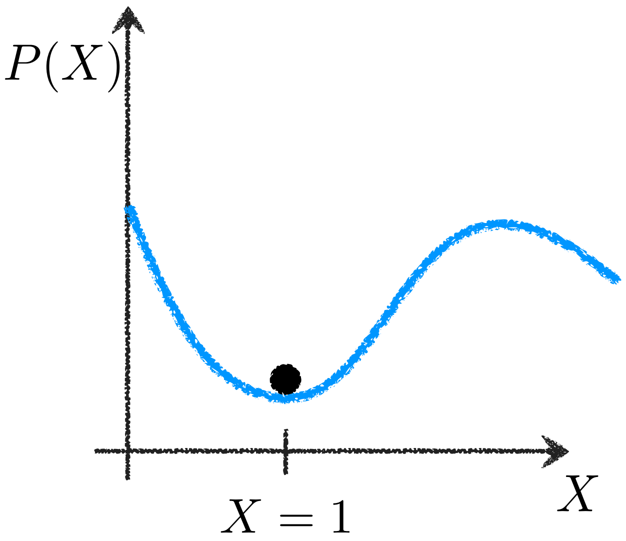

Classical evolution $\quad$ No constraints

But relaxation within EFT $H_\star < M_1$

$$\Lambda_* \sim M_{\rm Pl}^{10/3} H_0^{2/3} \sim (10^5\ {\rm TeV})^4$$

Slow roll $\quad \epsilon_0 \equiv \left(-\frac{\dot H}{H^2}\right)_{H=H_0} \sim \frac{\lambda_1^3 m_1^2}{6 M_{\rm Pl}^2 H_0^3} \ll 1$

The trigger

The ~~NEC~~ given by a second sector ϕ_2 with UV cutoff M_2

A phase transition $\phi_2 = \mathrm{const} \;\rightarrow\; \phi_2 \sim \phi_{\mathrm{NEC}}$ is triggered by ϕ_1 when vacuum energy $\sim \Lambda_0$

The PT will change the vacuum energy $\sim M_2^4$

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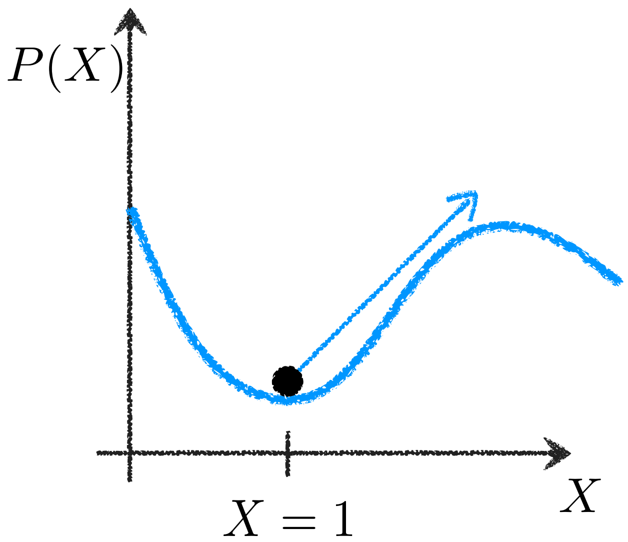

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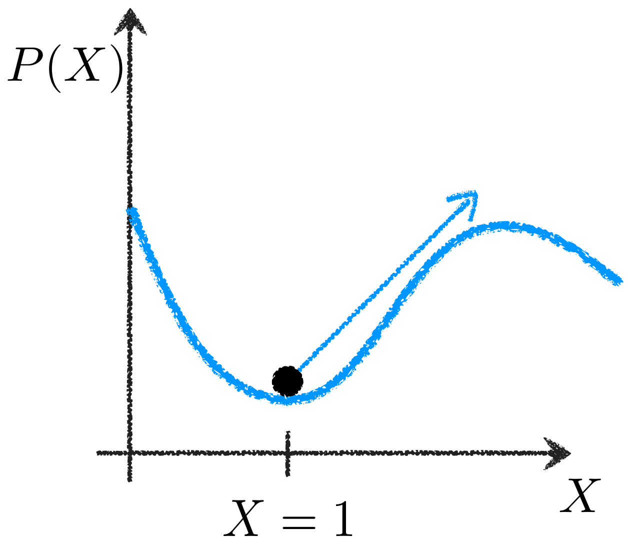


π_1 grows with the relaxation of the CC as a result of the reduced Hubble friction $\dot{\pi}_1 \simeq \frac{\lambda_1^3}{3H}$

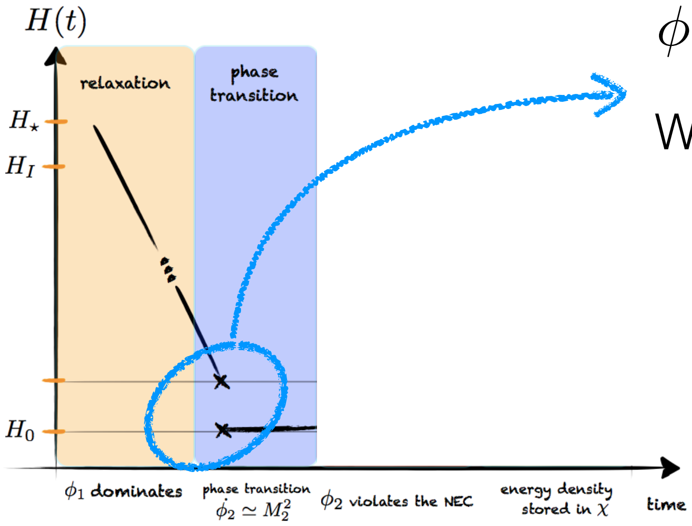
Suppose $\int d^4x \sqrt{-g} M_2^4 P(X_1, X_2)$

This interaction affects significantly the dynamics of the second field when $\dot{\pi}_1 \sim M_1^2$

The observed value of the vacuum energy is fixed in terms of the parameters

$$\Lambda_0 \sim \frac{\lambda_1^6 M_{\mathrm{Pl}}^2}{M_1^4}$$

The trigger



$$\phi_2 = \text{const} \;\rightarrow\; \phi_2 \sim \phi_{\text{NEC}}$$

When $\dfrac{\dot\pi_1}{M_1^2} \equiv x \sim 1$

What happens to ϕ_1?

The trigger

$$\phi_1 = M_1^2 t + \pi_1 \to \phi_1 = \text{const}$$

Jump in vacuum energy $\sim M_1^4$

$$\phi_2 = \text{const} \;\to\; \phi_2 \sim \phi_{\rm NEC}$$

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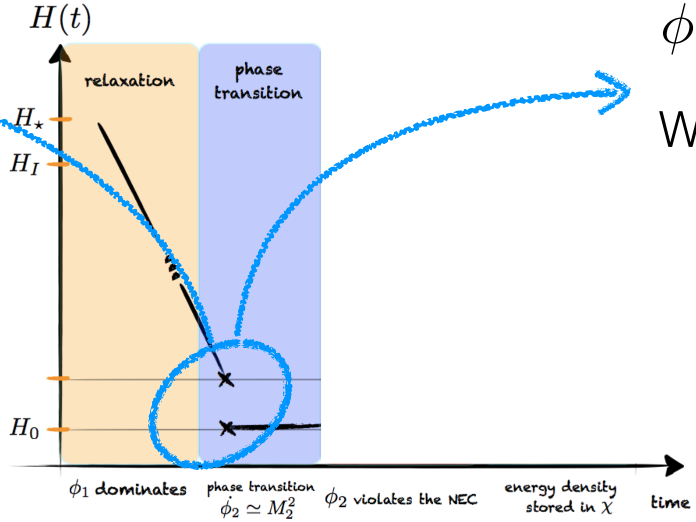

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Scenario 1: Slow ~~NEC~~

Phase transition when $x \sim 1$

The EFT for the scanning field breaks down:

Gets stabilized in a trivial vacuum $\phi_1 = \text{const}$

Scanning of the CC stops at Λ_0

Unlimited time for ~~NEC~~

$$M_1 \simeq M_2 \simeq \Lambda_0^{1/4} \sim 10^{-3}\ \text{eV}$$

$$\boxed{\Lambda_* \sim M_{\rm Pl}^2 H_*^2 \lesssim M_{\rm Pl}^3 H_0 \sim (1\ \text{TeV})^4}$$

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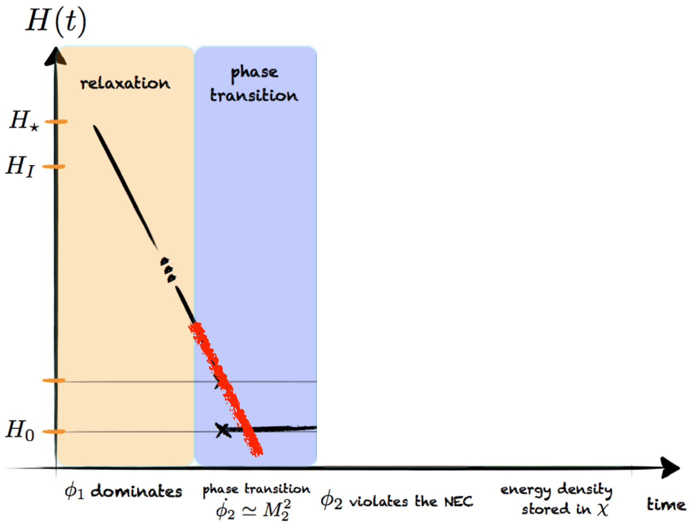

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Scenario 2: Fast ~~NEC~~

Phase transition when $x \lesssim 1$

Scanning of the CC goes on with $\epsilon_0 \sim x \dfrac{M_1^4}{\Lambda_0}$

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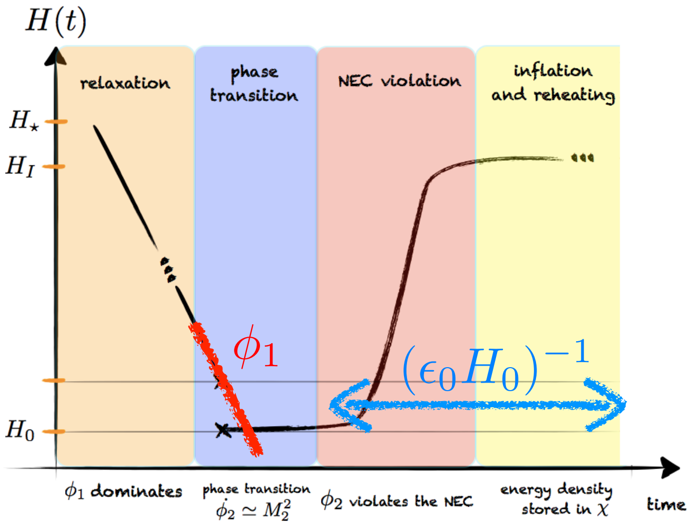

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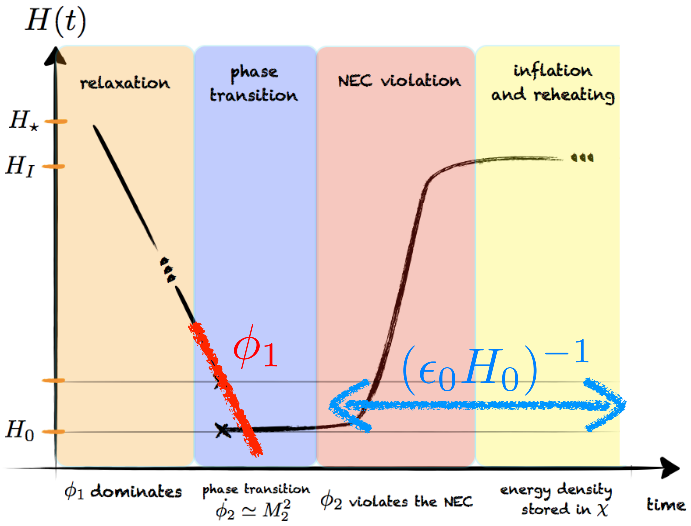

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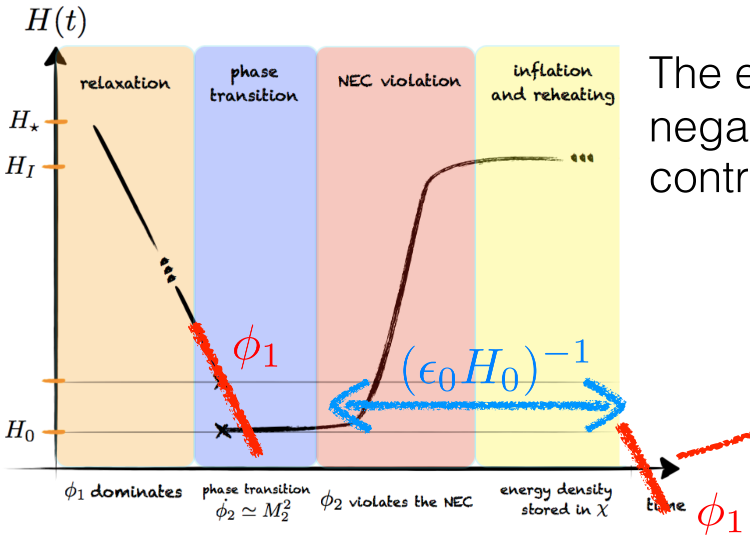
$$\Lambda_* \lesssim M_{\text{Pl}}^2 M_1^2 \sim (1\ \text{TeV})^4 \left(\frac{\epsilon_0}{x}\right)^{1/2}$$

Constrained by current dark energy eq of state

$$\epsilon_0 \lesssim 0.05$$

The trigger



The evolution drives the energy to negative values:
contraction and collapse within

$\epsilon_0^{-1/3} H_0^{-1}$

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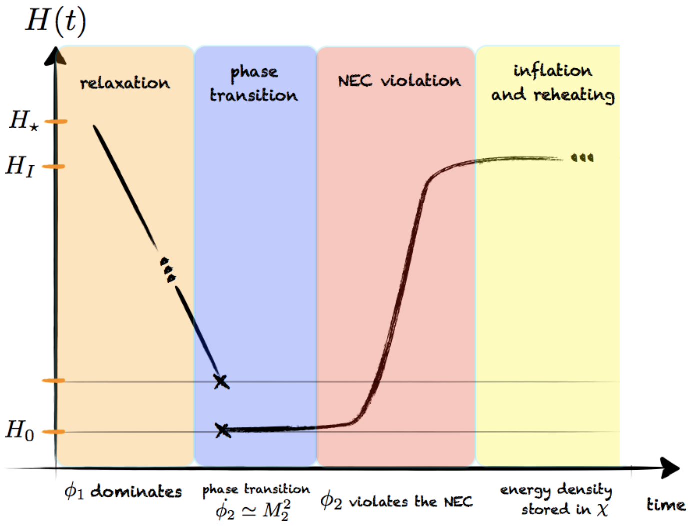

The model can relax up to O(TeV) CC after huge field excursion $\Delta\phi_1 \sim M_{\rm Pl}\dfrac{M_{\rm Pl}}{H_0}$

NEC violators

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Usually associated to instabilities

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But…

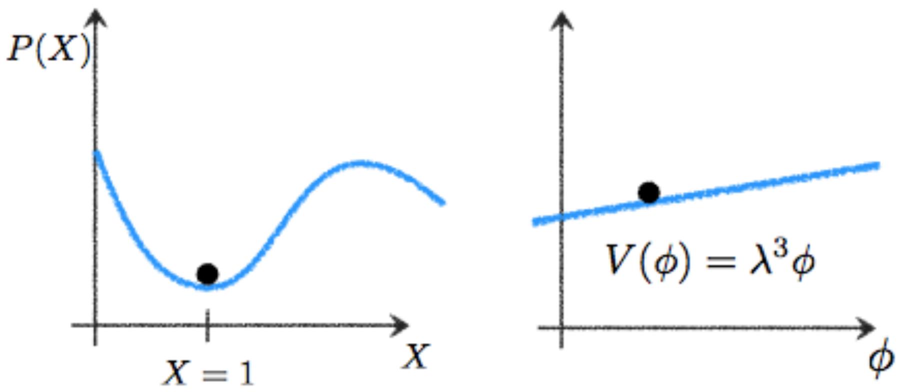
1) The Galileon

Nicolis, Rattazzi, ET '09

2) The ghost condensate

Deform the theory with a rising potential

Creminelli, Luty, Nicolis, Senatore '06



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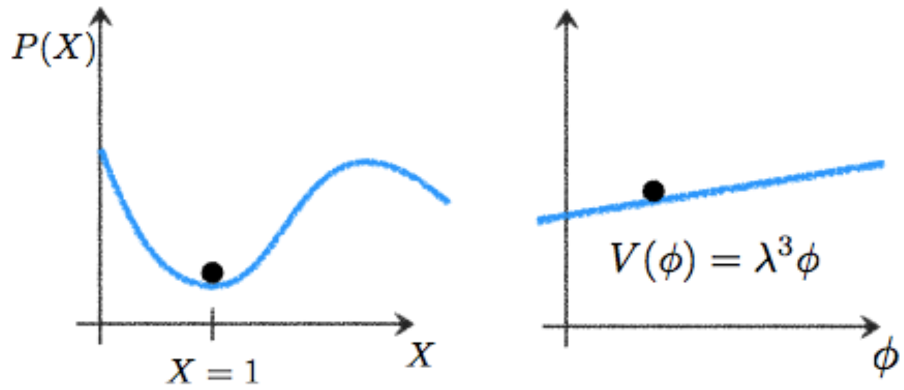


Jeans-like instability

$$\omega_{\rm Jeans} \sim M_2^3/M_{\rm Pl}^2$$

$$M_2 \lesssim (M_{\rm Pl}^2 H_0)^{1/3} \sim 10\ \mathrm{MeV}$$

Harmless if $\omega < H$

Gradient instability

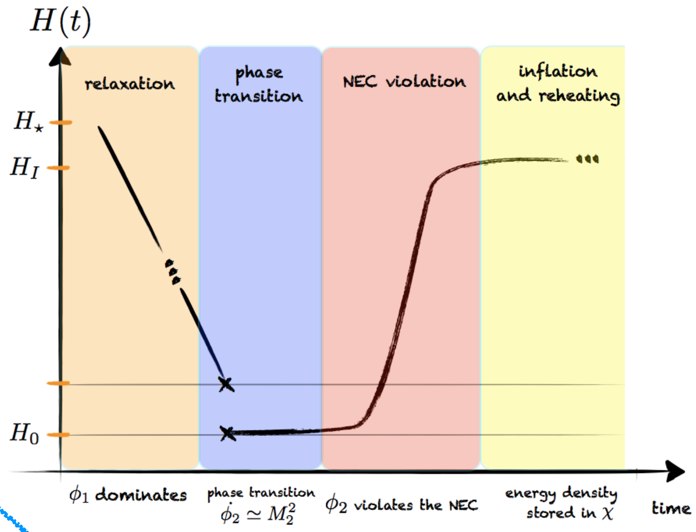
$$\omega_{\rm grad} \sim \dot{H} M_{\rm Pl}^2/M_2^3$$

$$\omega^2 \sim \frac{k^4}{M_2^2} - \frac{\dot{H} M_{\rm Pl}^2 k^2}{M_2^4}$$

$$\lambda_2^3 \lesssim M_2 H_0^2$$

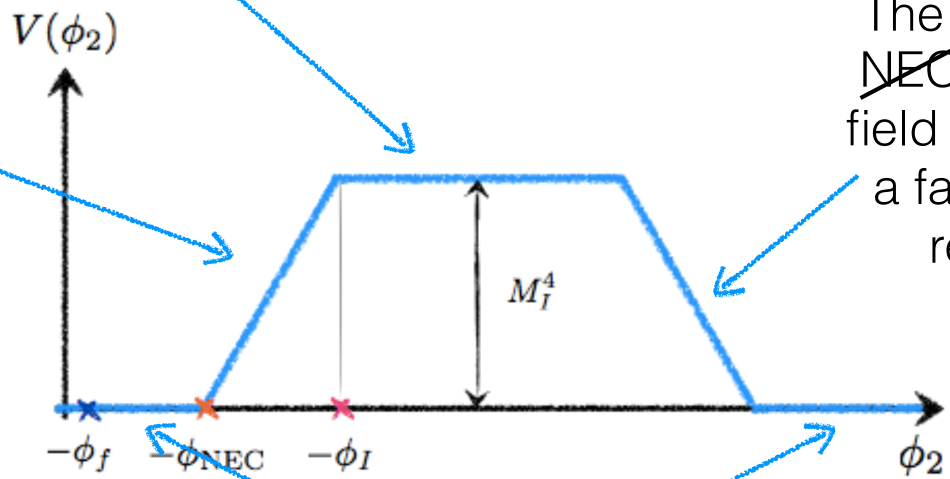
$$\frac{\lambda_2}{M_{\rm I}} \sim 10^{-35}$$ for maximal M_I

Slow NEC violation



Inflation takes place

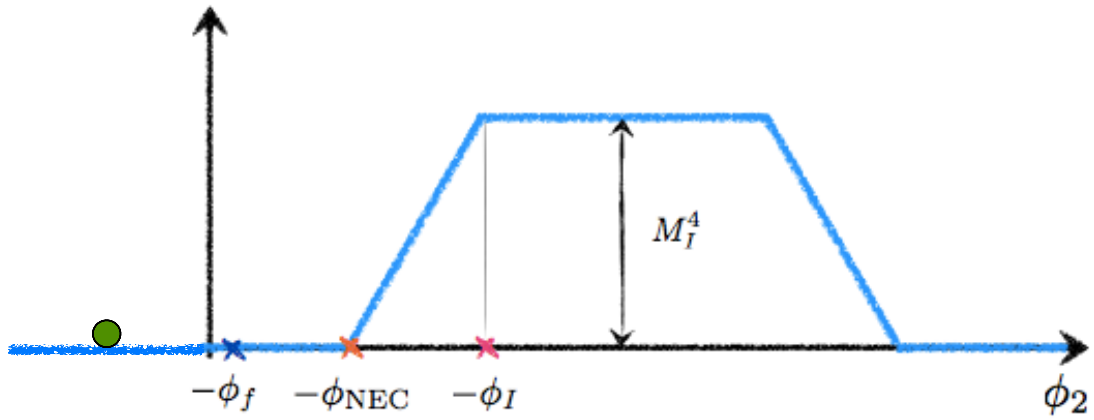
Very slow NEC violation

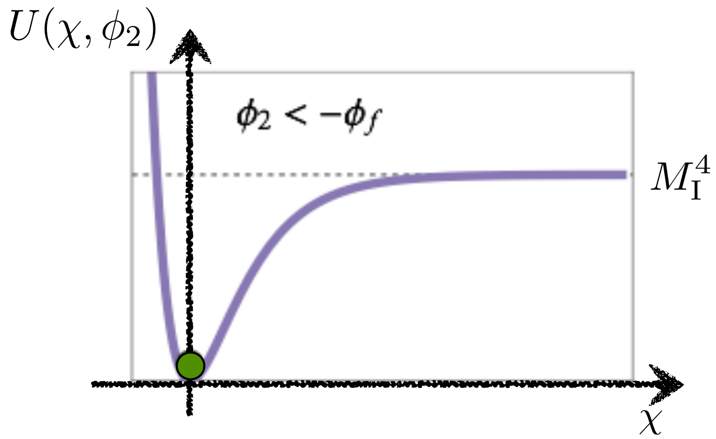


The energy created during ~~NEC~~ is stored in a waterfall field χ that gets trapped into a false minimum and then reheats the Universe

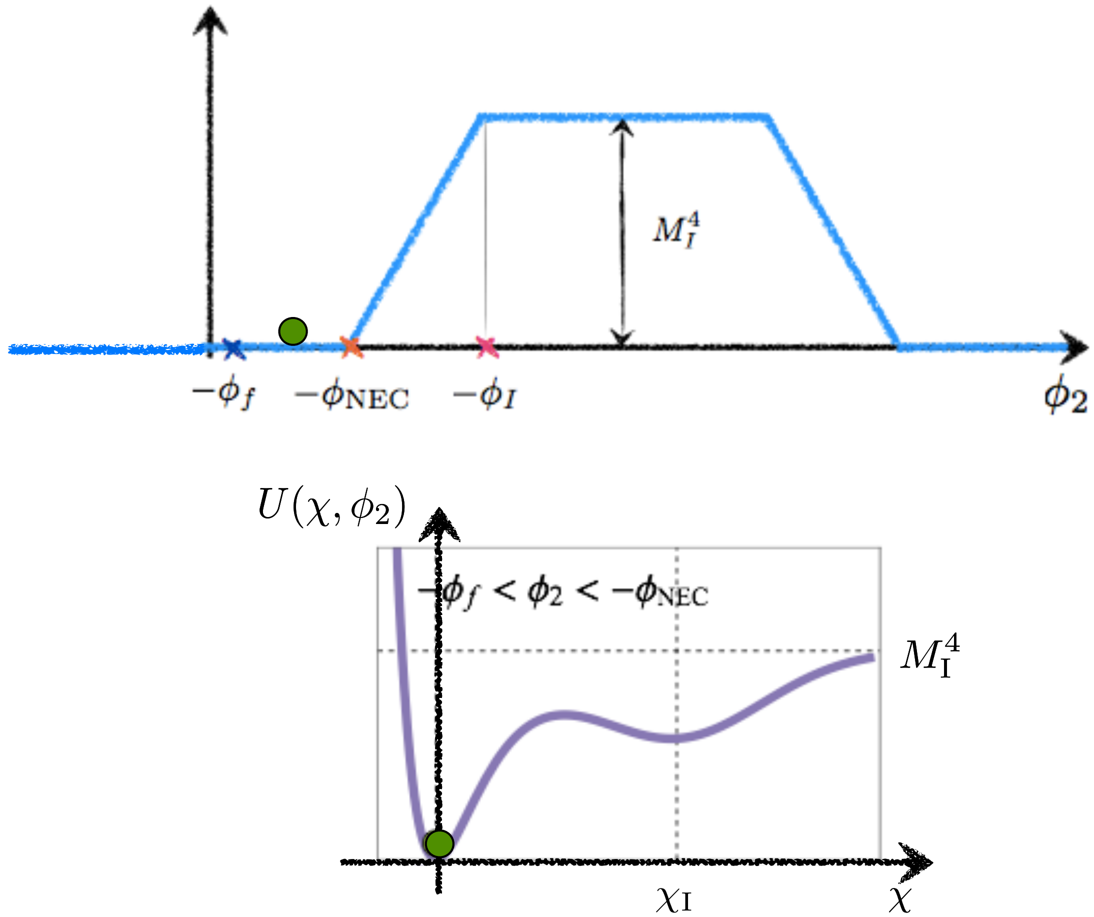
Same CC before and after NEC violation due to a Z_2 symmetry of the action

Inflation and Reheating

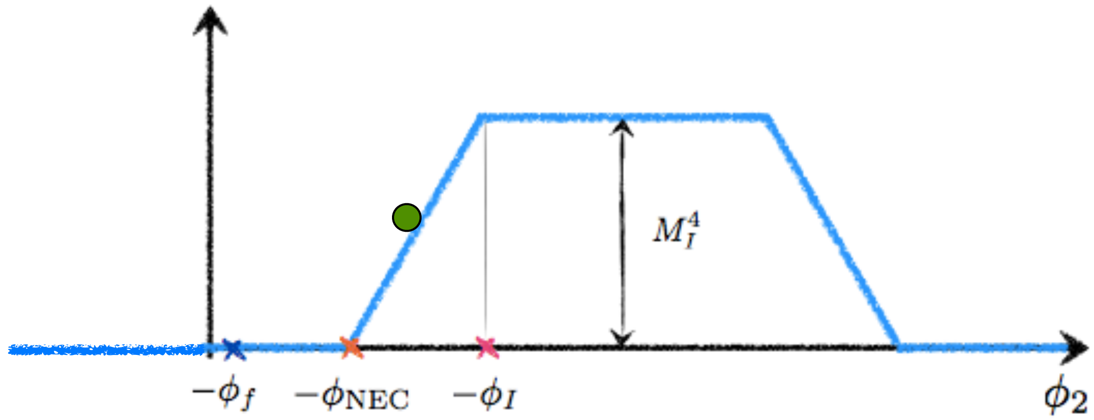


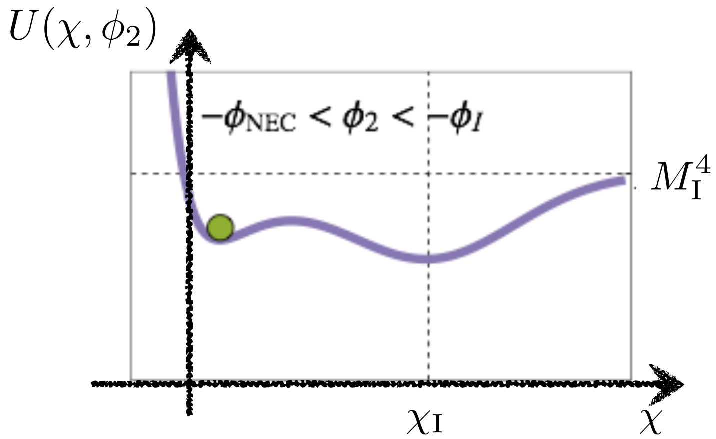


Inflation and Reheating

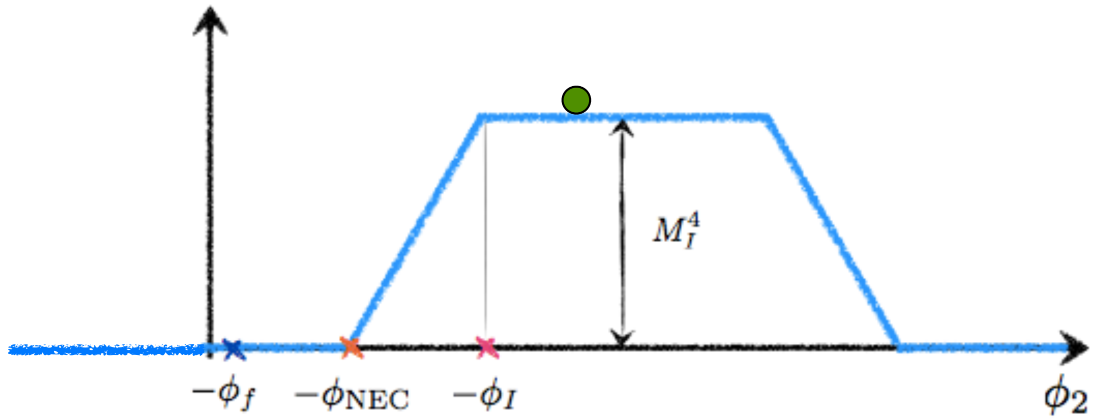


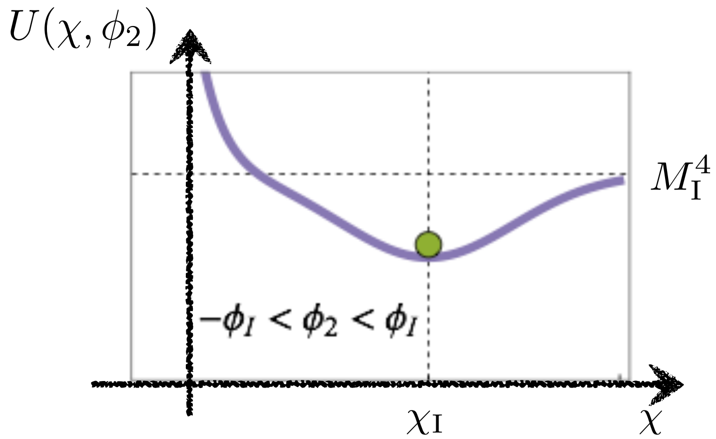
Inflation and Reheating





Inflation and Reheating

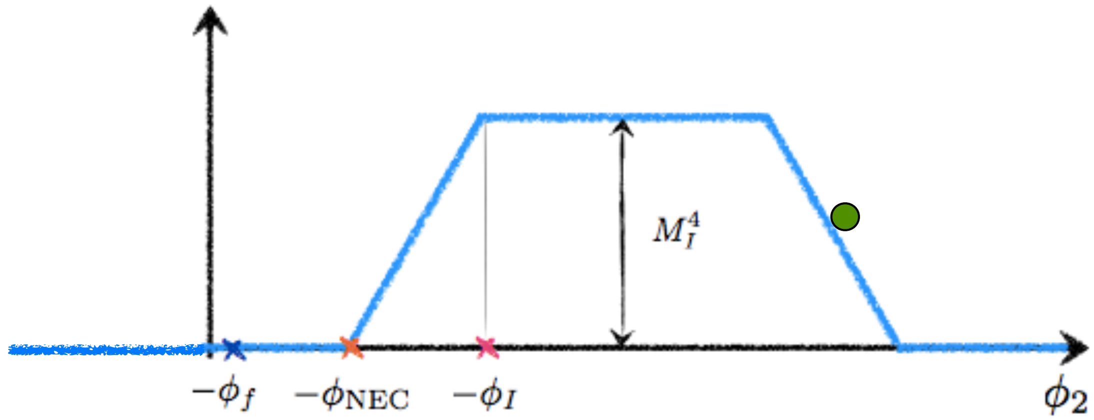


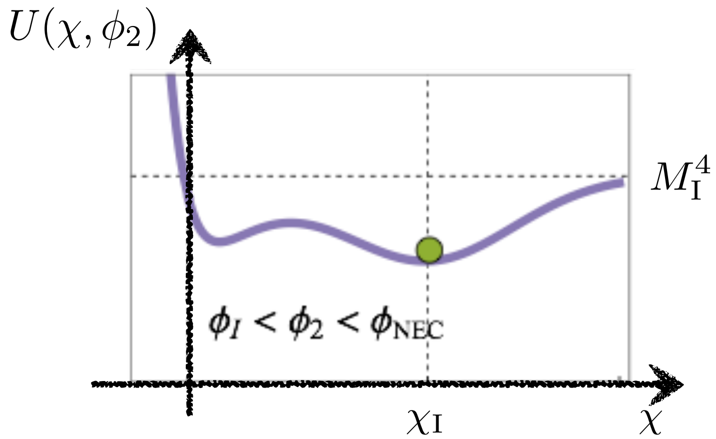


While χ is sitting in the false vacuum, the common potential $U(\chi, \phi_2)$ is nearly flat and the Universe inflates

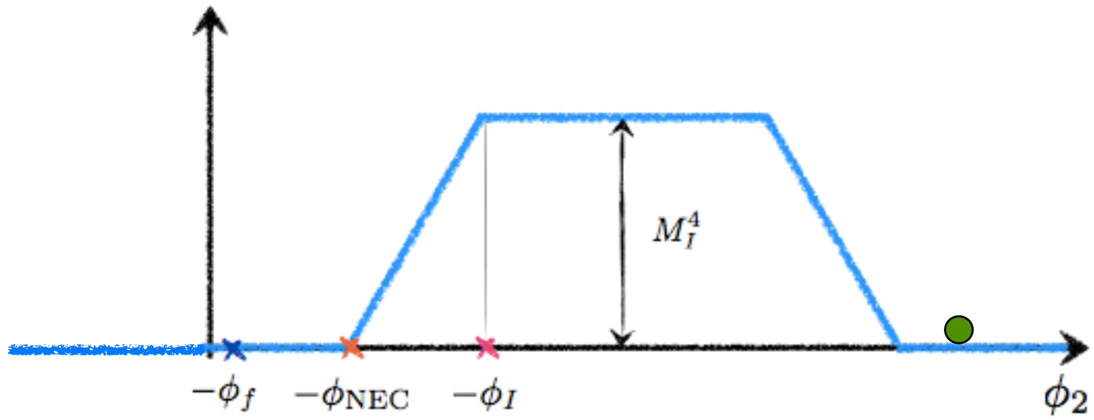
Ghost inflation ⟶ peculiar phenomenology $\quad (H_{\rm I} M_{\rm Pl})^2 \sim (10\ {\rm GeV})^4$

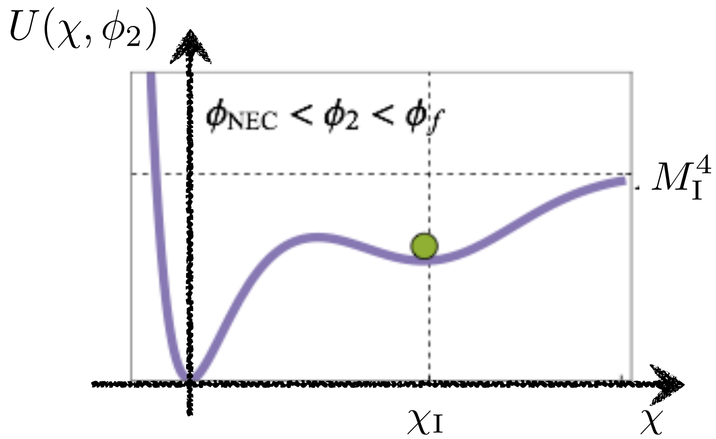
Inflation and Reheating



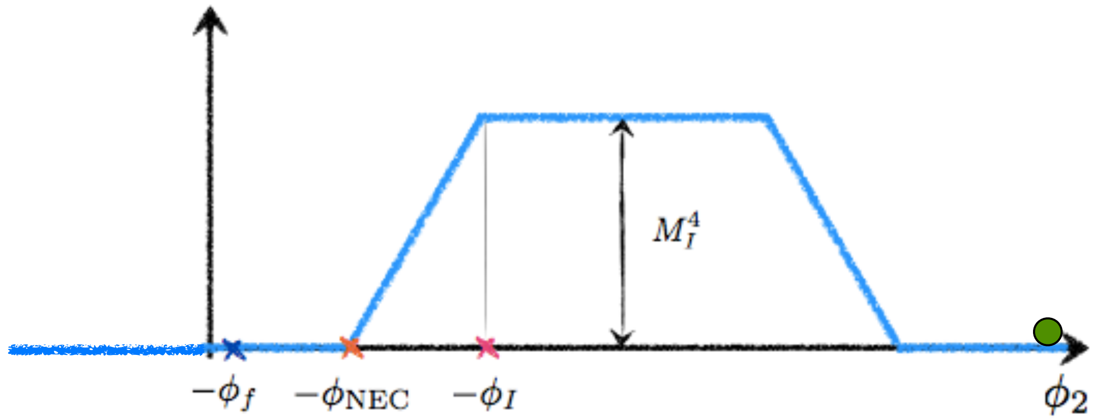


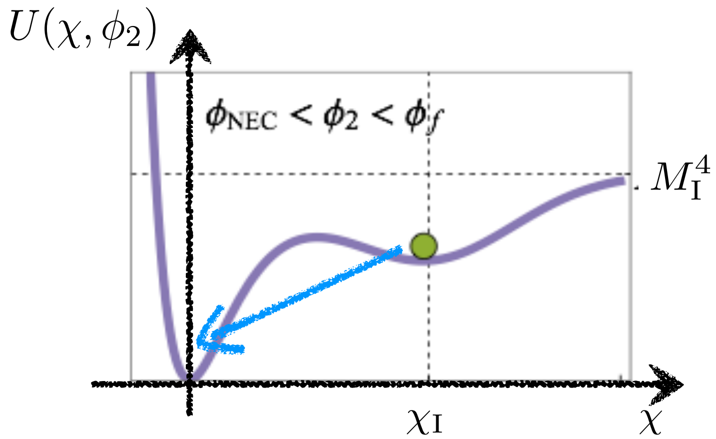
Inflation and Reheating





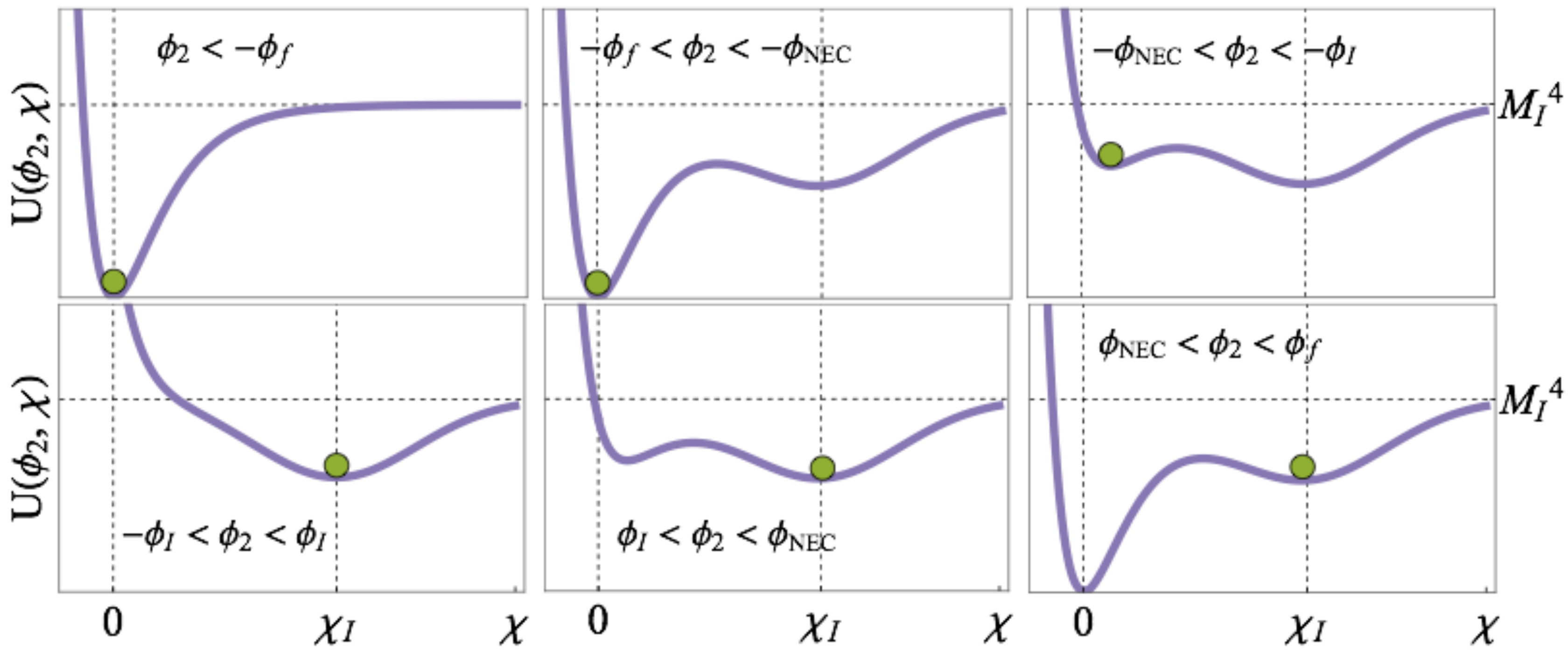
Inflation and Reheating





χ starts rolling back towards the true minimum and oscillates around it, eventually transferring energy to the SM d.o.f.

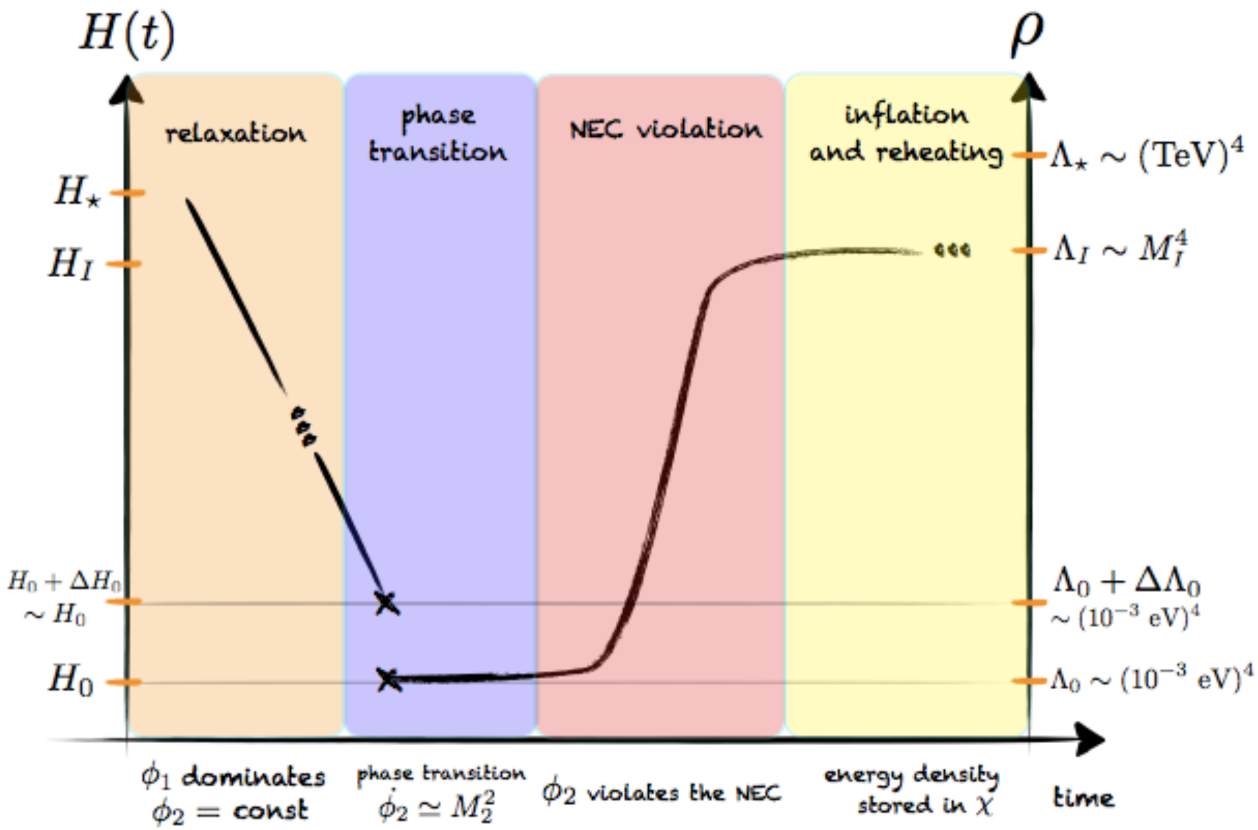
Inflation and Reheating



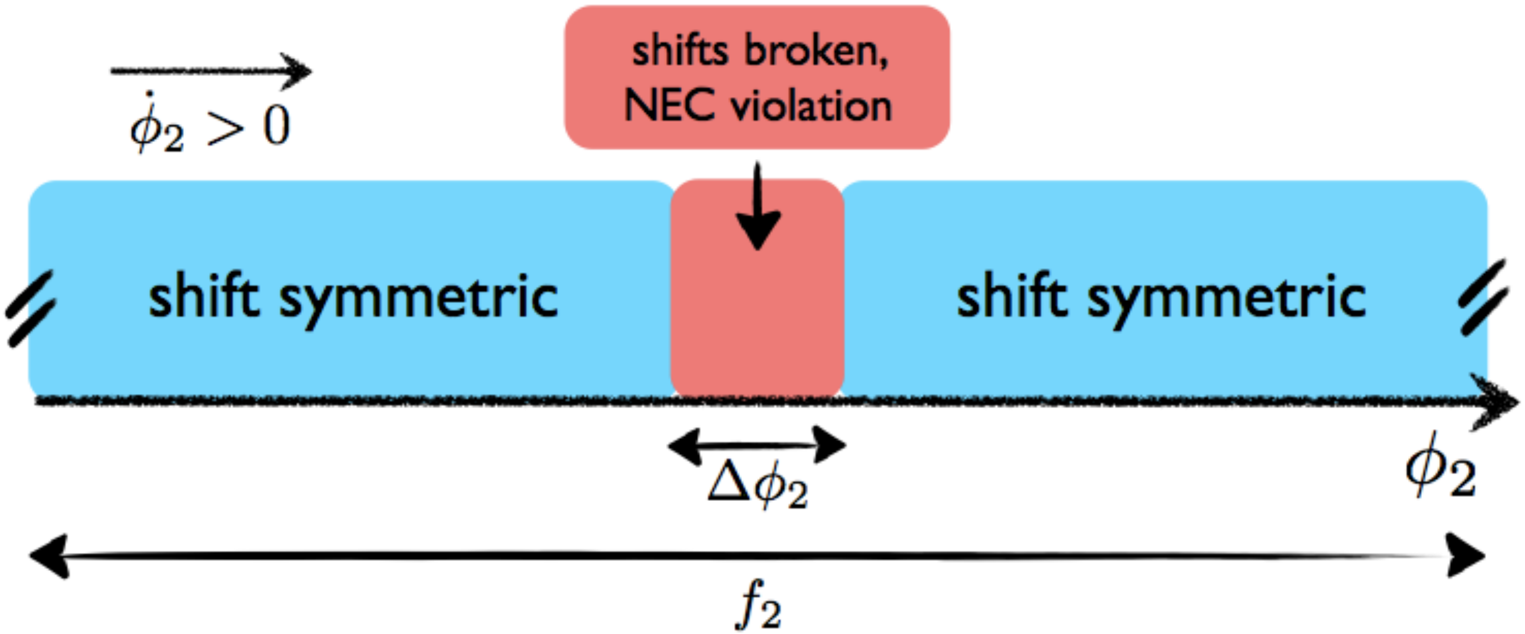
- Back reaction of χ on the dynamics of ϕ_2 should be negligible
- No fluctuations in χ $\quad m_\chi^2 > H_{\rm I}^2$

Conclusions

- It is possible to relax the CC (the whole evolution of the Universe must be described)
- only IF NEC is violated
- Connection with present dark energy. However it is model dependent



Fast NEC violation



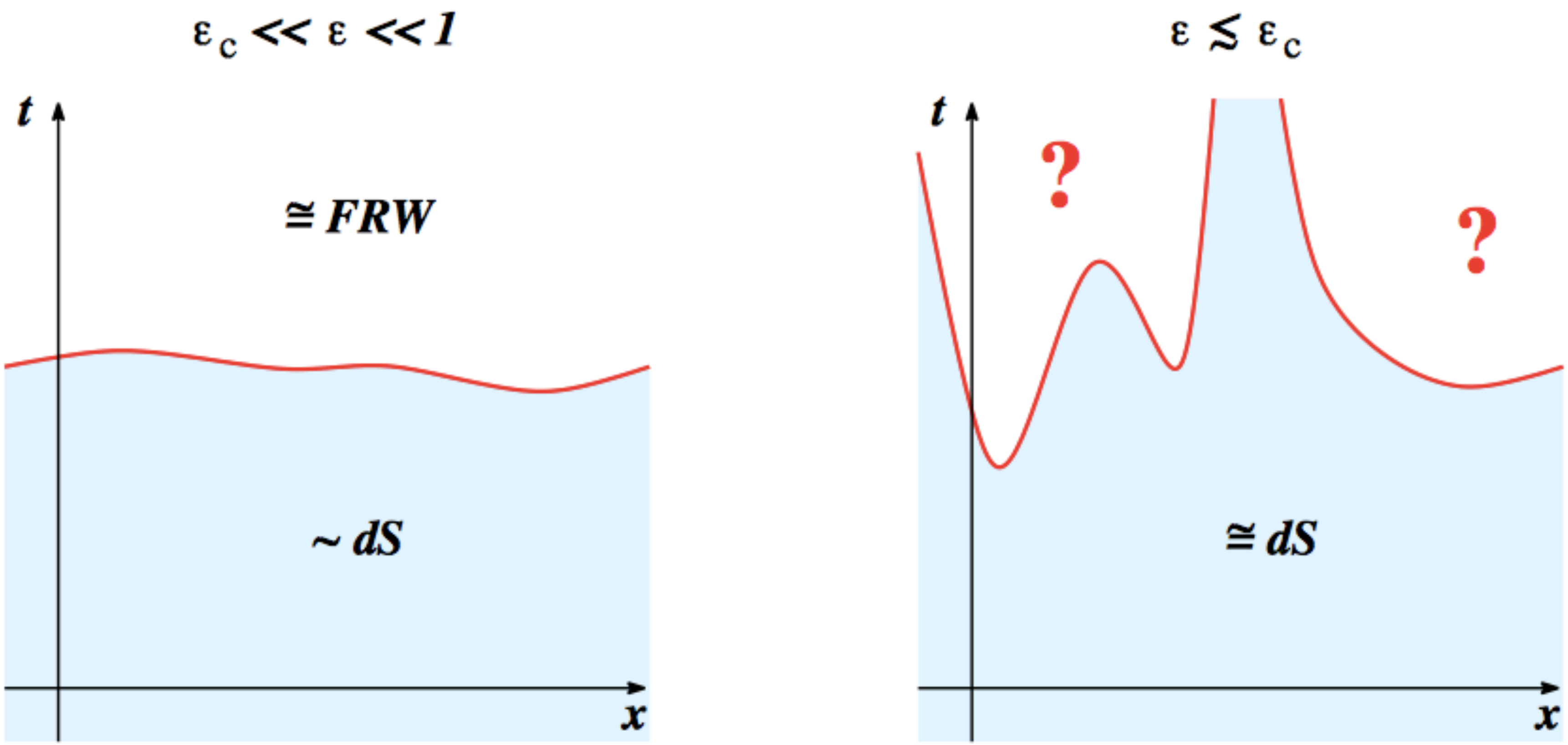
Same CC before and after NEC violation due to periodicity $\phi_2 \to \phi_2 + f_2$

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

It is possible to create the Universe in H_0^{-1}

i) Stability
ii) Cutoff $\gg H_0$
iii) Subluminality

Slow roll eternal inflation



$$\Delta\phi_{\rm cl} \sim \dot{\phi}_0 H^{-1} \sim \frac{(-\dot{H} M_{\rm Pl}^2)^{1/2}}{H}$$

$$\Delta\phi_{\rm quantum} \sim H$$