Quantum Tunneling in the Early Universe: Inflation and the Hubble Tension

Martin W. Winkler

in collaboration with K. Freese

based on Phys. Rev. D103 (2021) and arXiv:2102.13655

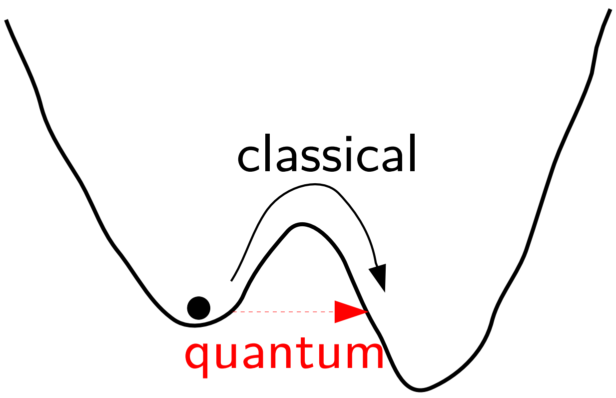
MPIK Heidelberg
June 28, 2021

Outline

- Quantum Tunneling
- Old and New Inflation
- Chain Inflation
- Hubble Tension
- Chain Early Dark Energy

Quantum Tunneling

Voloshin, Kobzarev, Okun 1974, Coleman 1977



probability of vacuum decay per volume and time: $\Gamma = Ae^{-S/\hbar}$

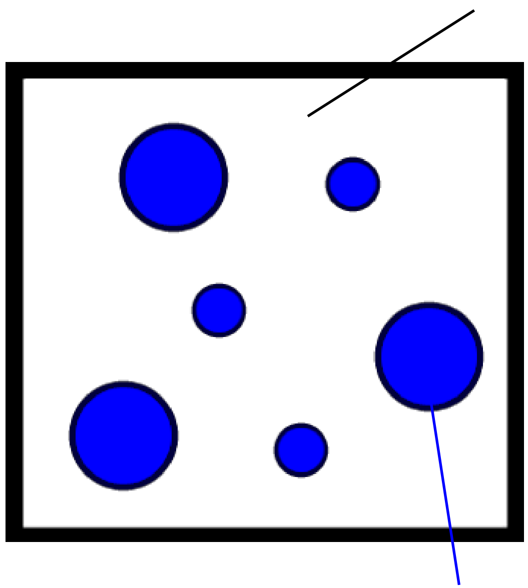
"tunneling rate"

S: action of the bounce

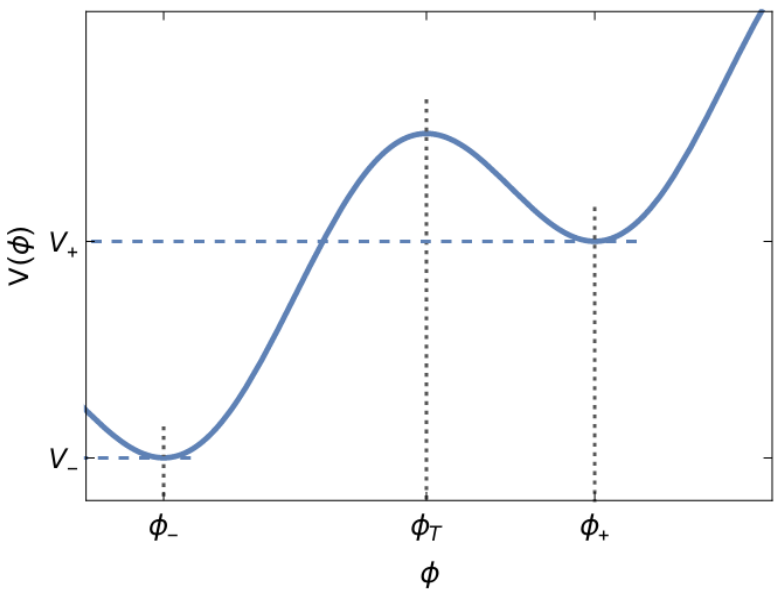
(path of least residence)

$$\frac{d^2\phi}{d\rho^2} + \frac{3}{\rho}\frac{d\phi}{d\rho} = V'(\phi)$$

$$S \propto \int_0^\infty d\rho \rho^3 \left[\frac{1}{2}\left(\frac{d\phi}{d\rho}\right)^2 + V\right]$$



Bounce Action



example potential:

$$V = \mu^3\phi + \Lambda^4 \cos\frac{\phi}{f}$$

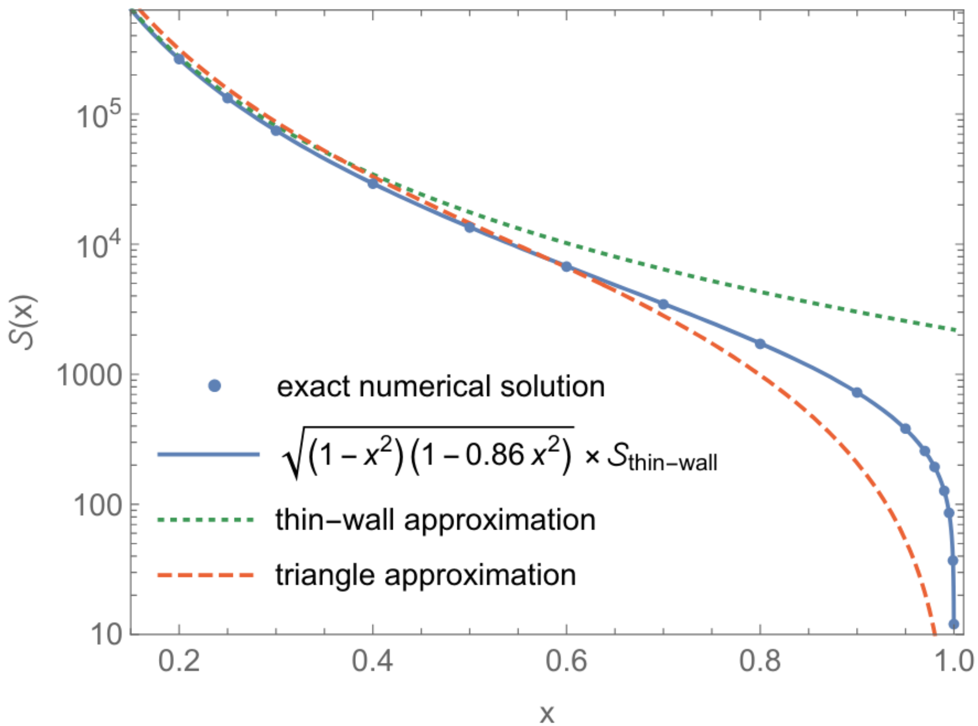
we define: $x = \dfrac{f\mu^3}{\Lambda^4}$

thin-wall approximation:

$$S_{\text{thin-wall}} = \frac{4}{\pi}\frac{f^4}{\Lambda^4}\left(\frac{12}{x}\right)^3$$

improved approximation:

$$S_{\text{improved}} = S_{\text{thin-wall}} \times \sqrt{(1-x^2)(1-0.86x^2)}$$



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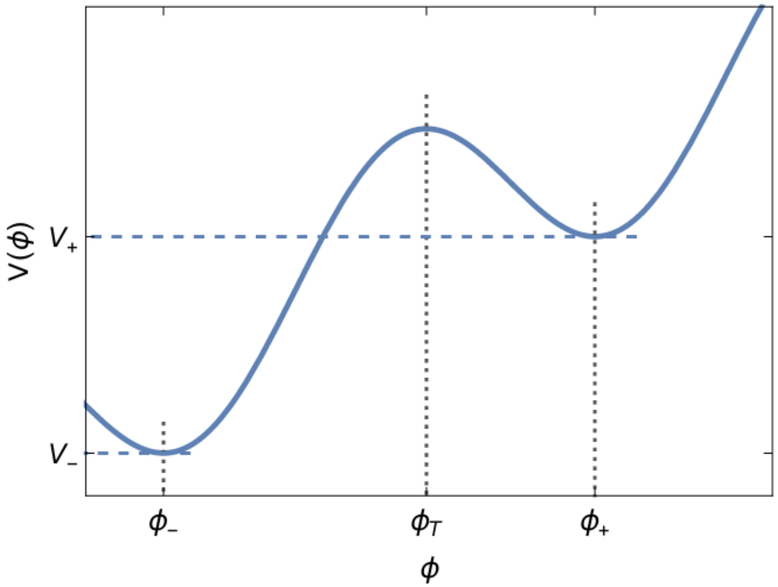

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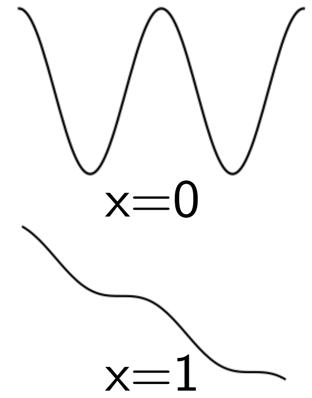

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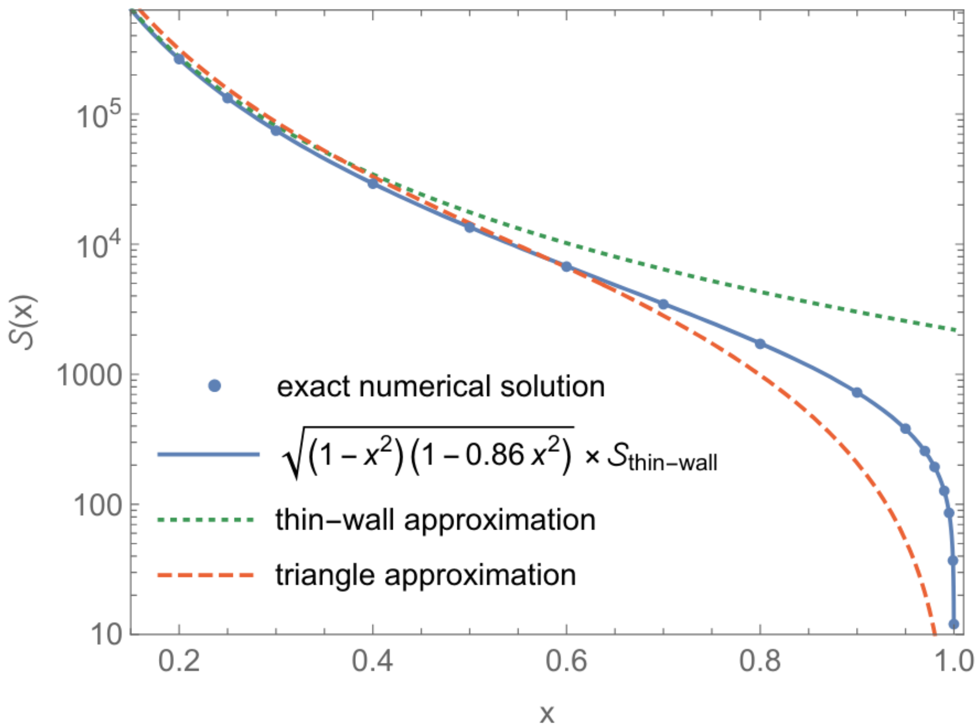
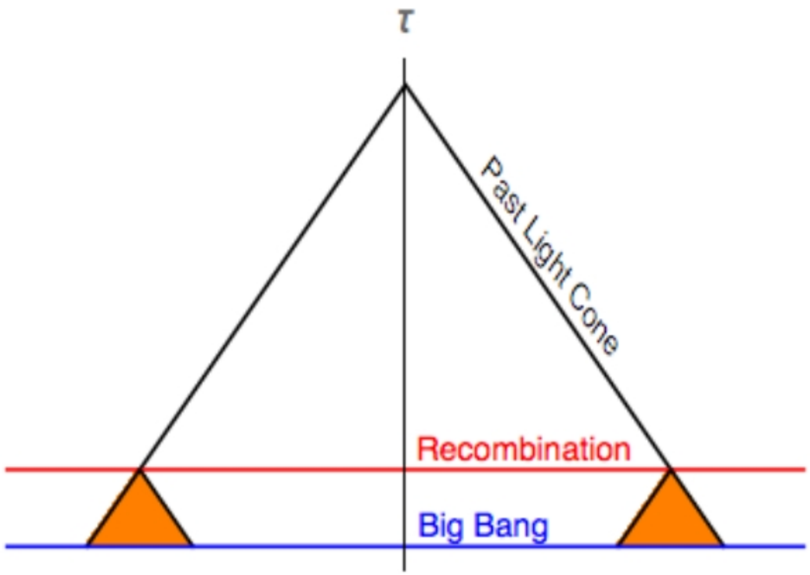


Inflation

- rapid expansion of space
  Guth 1981



- solves horizon problem
- solves flatness problem
- dilutes dangerous relics

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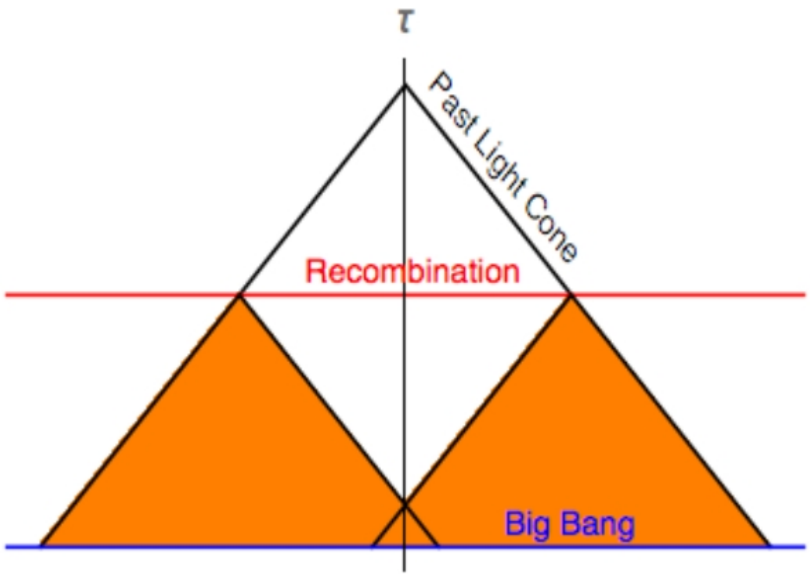

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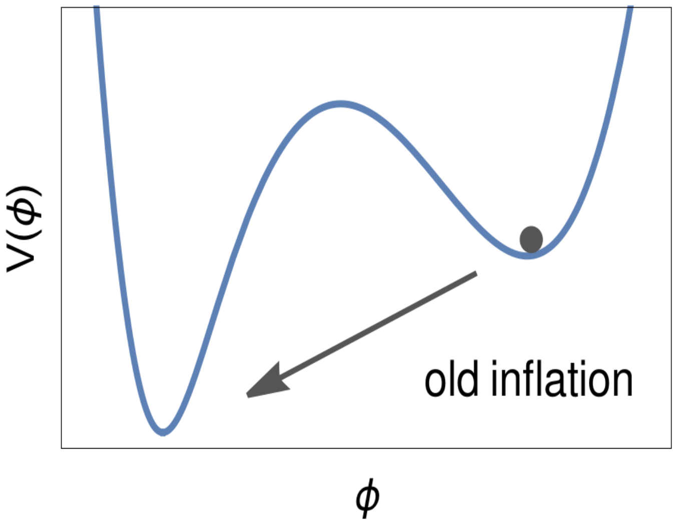
Old Inflation

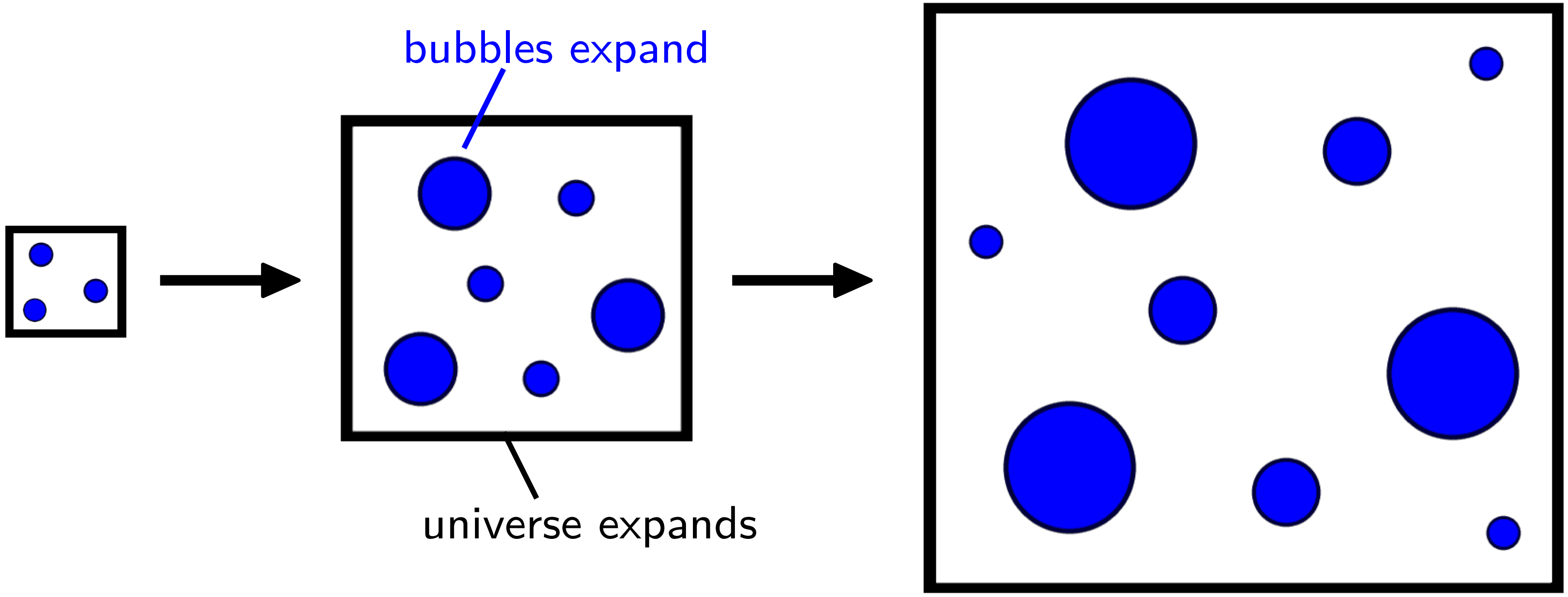
- inflation driven by potential energy of the inflaton field
- inflation models



Guth 1981

The Empty Universe Problem

- bubble formation rate = tunneling rate must be low enough to get 60 e-folds of inflation



bubbles don't percolate, no reheating, no particles

Guth-Weinberg Argument

Guth, Weinberg 1983

- volume of a single bubble created at time t_0

$$V_b \simeq \frac{4\pi}{9} e^{H(t-t_0)} \qquad (\text{for } t \gg t_0)$$

- volume of all bubbles vs. volume of the universe

$$\frac{\sum V_b}{V_{tot}} = \frac{4\pi}{9} \frac{\Gamma}{H^4}$$

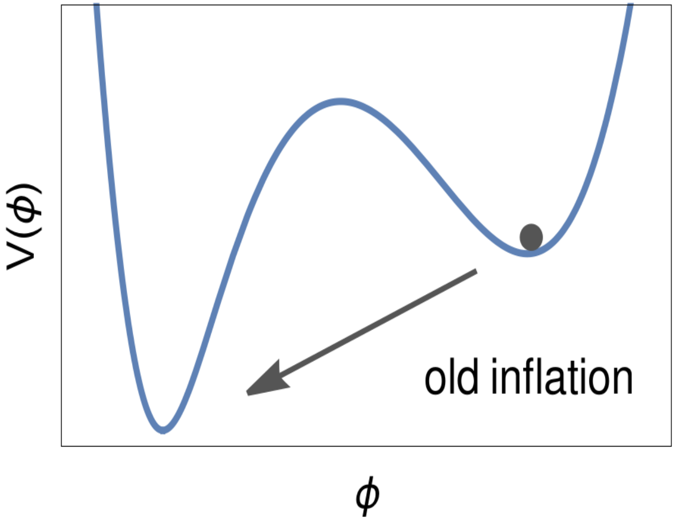
- bubble percolation hence requires $\Gamma/H^4 \gtrsim 1$

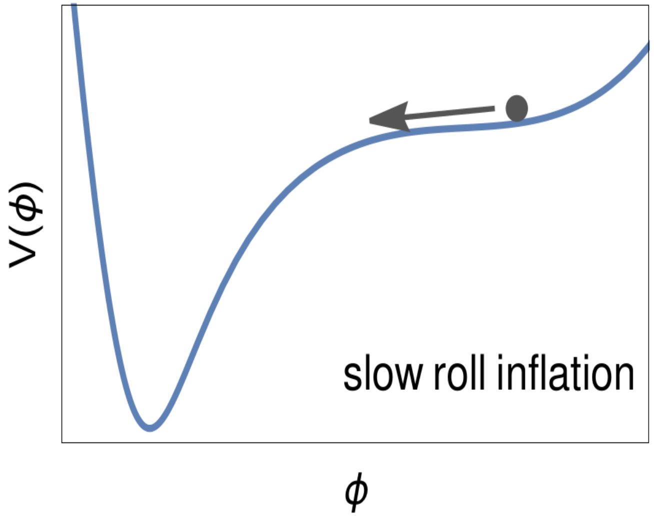
- inflation can only last for ~1 e-fold, but need 60 e-folds

Slow Roll Inflation

- inflation driven by potential energy of the inflaton field

- inflation models





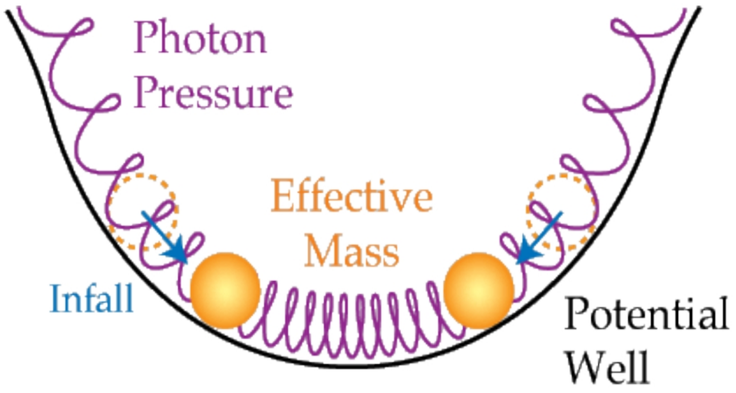
Guth 1981

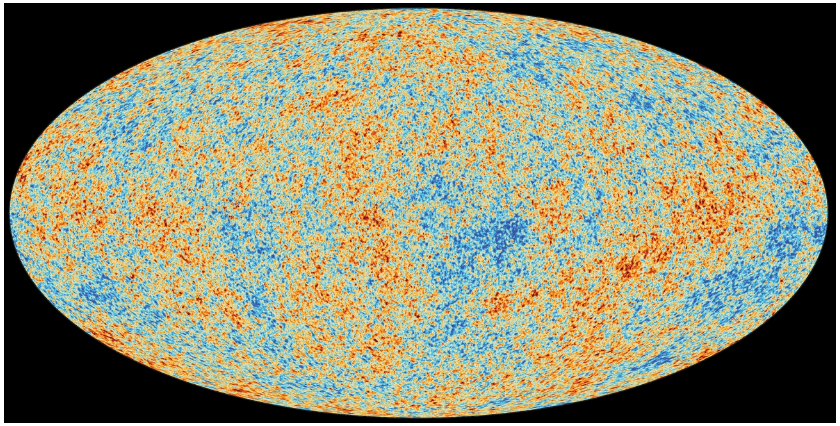
Linde 1982

Albrecht, Steinhardt 1982

Slow Roll Inflation

- quantum fluctuations of the inflaton are stretched, reheating converts them into density fluctuations

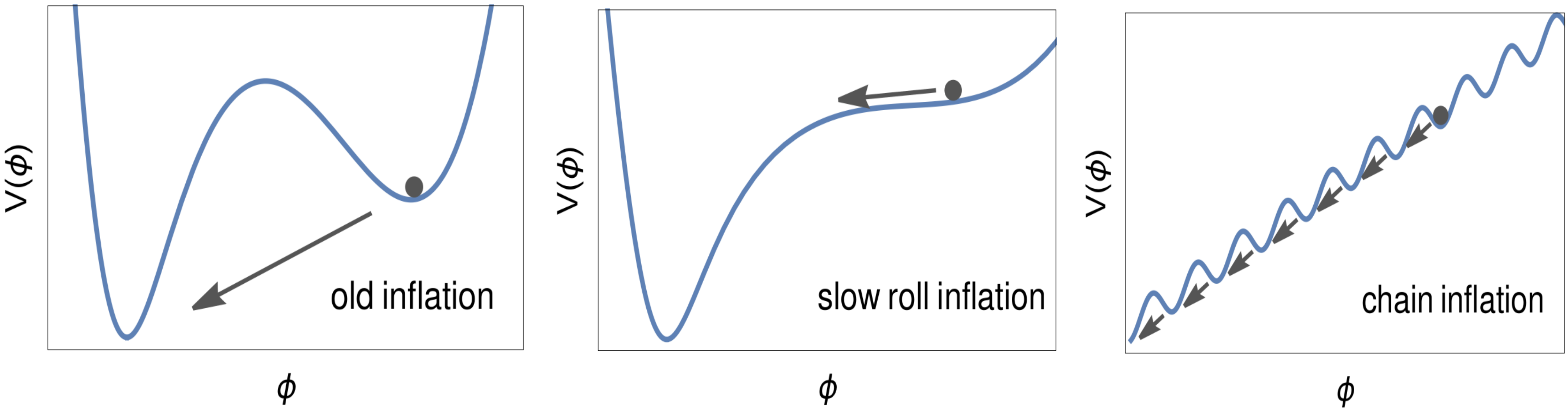




- create potential wells for baryon photon plasma
- acoustic oscillations due to radiation pressure
- CMB provides snaphot at last scattering

Chain Inflation

- inflation driven by potential energy of the inflaton field
- inflation models

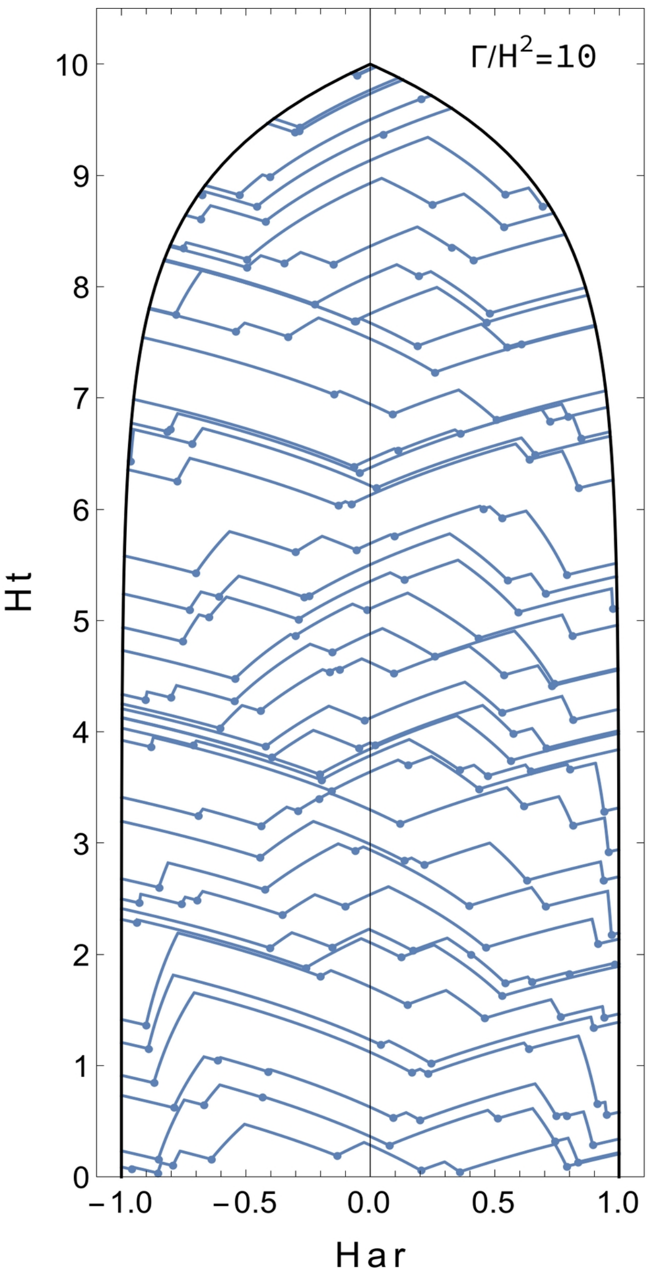


Guth 1981

Linde 1982
Albrecht, Steinhardt 1982

Freese, Spolyar 2005

Chain Inflation



- inflaton tunnels along a series of false vacua of ever lower energy
- large Γ, bubbles are formed close to each other and percolate quickly
- bubble collisions create radiation which is quickly redshifted away
- what about the CMB?

CMB Anisotropies in Chain Inflation

origin of fluctuations:

- quantum fluctuations of the inflaton

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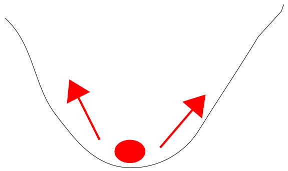
suppressed by inflaton mass



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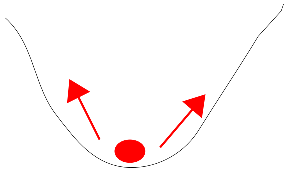

- bubble wall collisions

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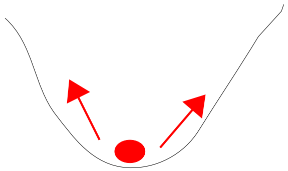

- (bubble wall collisions)

  maybe, but complicated

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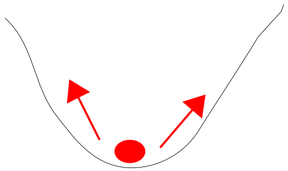

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- probabilistic nature of tunneling

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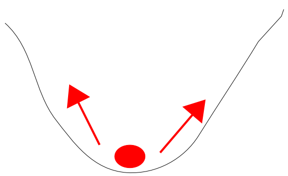

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- probabilistic nature of tunneling

scalar power spectrum:

$$\Delta_{\mathcal{R}}^2 = \frac{H^2}{4\pi^2 c_s \epsilon}(-k c_s \eta)^{-2\epsilon}$$

$$\Delta_{\mathcal{R}}^2 = (0.04 \pm 0.02)\left(\frac{\Gamma}{H^4}\right)^{-0.42\pm 0.03}$$

$$\Delta_{\mathcal{R}}^2 = \frac{H^2}{8\pi^2 \epsilon}$$

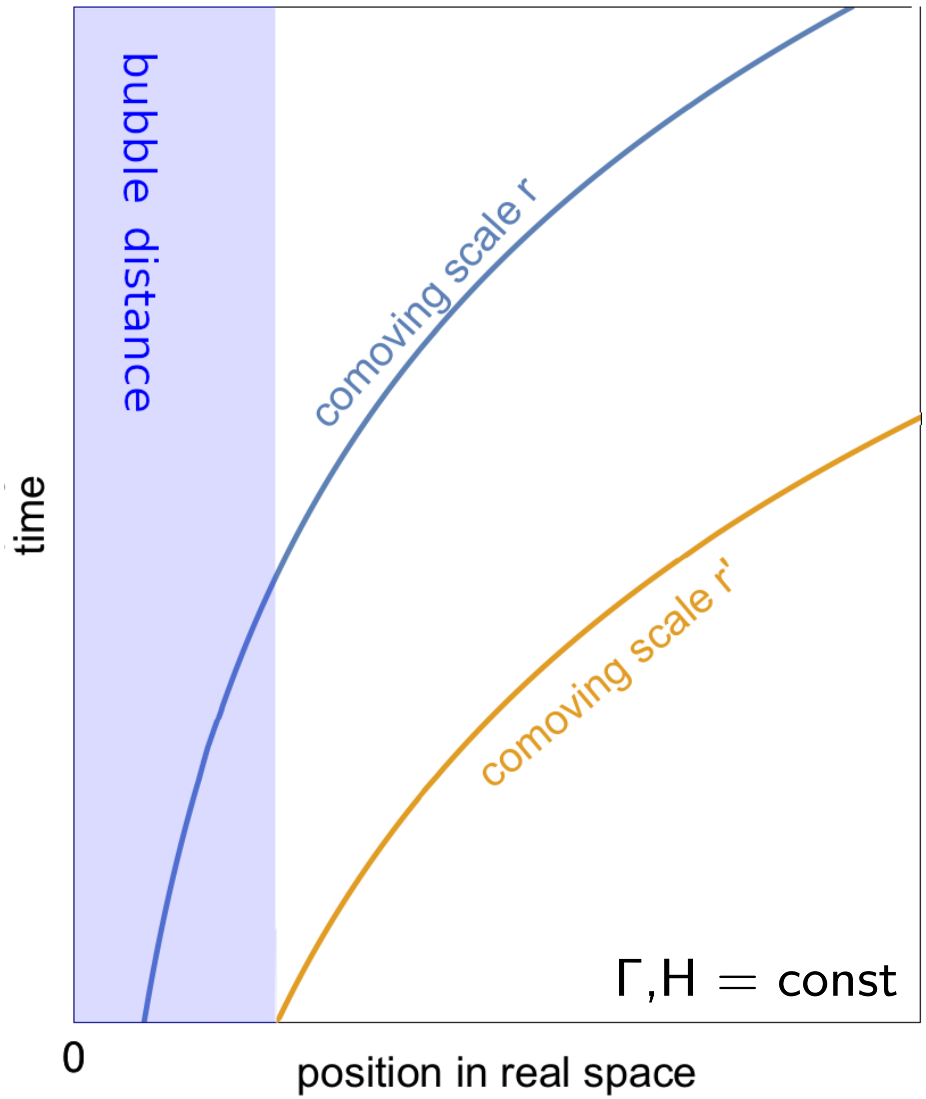
$$\Delta_{\mathcal{R}}^2 = \frac{H^2}{8\pi^2 \epsilon/\sqrt{3}}$$

$$\Delta_{\mathcal{R}}^2 = \frac{3}{4\pi}\frac{H^4}{\Gamma}$$

Watson et al. 2007, Feldstein, Tweedie 2007, Huang 2007, Chialva, Danielsson 2008 & 2009, Cline, Moore, Wang 2011

literature in vast disagreement

Scalar Power Spectrum



two-point correlation:

$$\langle \delta\phi(\mathrm{r})\delta\phi(0)\rangle = \mathrm{var}\phi(\Delta \mathrm{t}) + \mathrm{const}$$

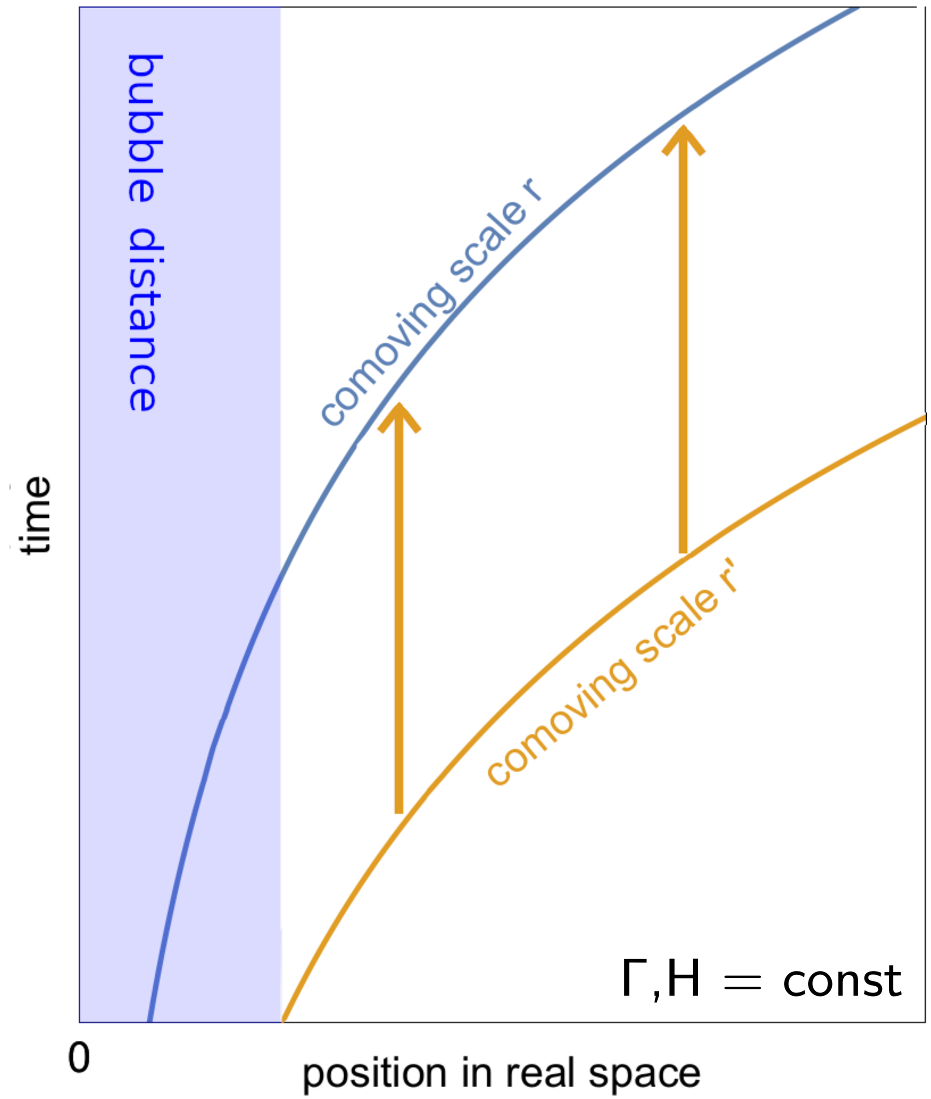
curvature perturbation

$$\mathcal{R} = \mathrm{H}\left(\frac{\mathrm{d}\langle\phi\rangle}{\mathrm{dt}}\right)^{-1}\delta\phi$$

scalar power spectrum

$$\Delta^2_{\mathcal{R}} = \left(\frac{\mathrm{d}\langle\phi\rangle}{\mathrm{Hdt}}\right)^{-2}\frac{\mathrm{dvar}\phi}{\mathrm{Hdt}}$$

Scalar Power Spectrum



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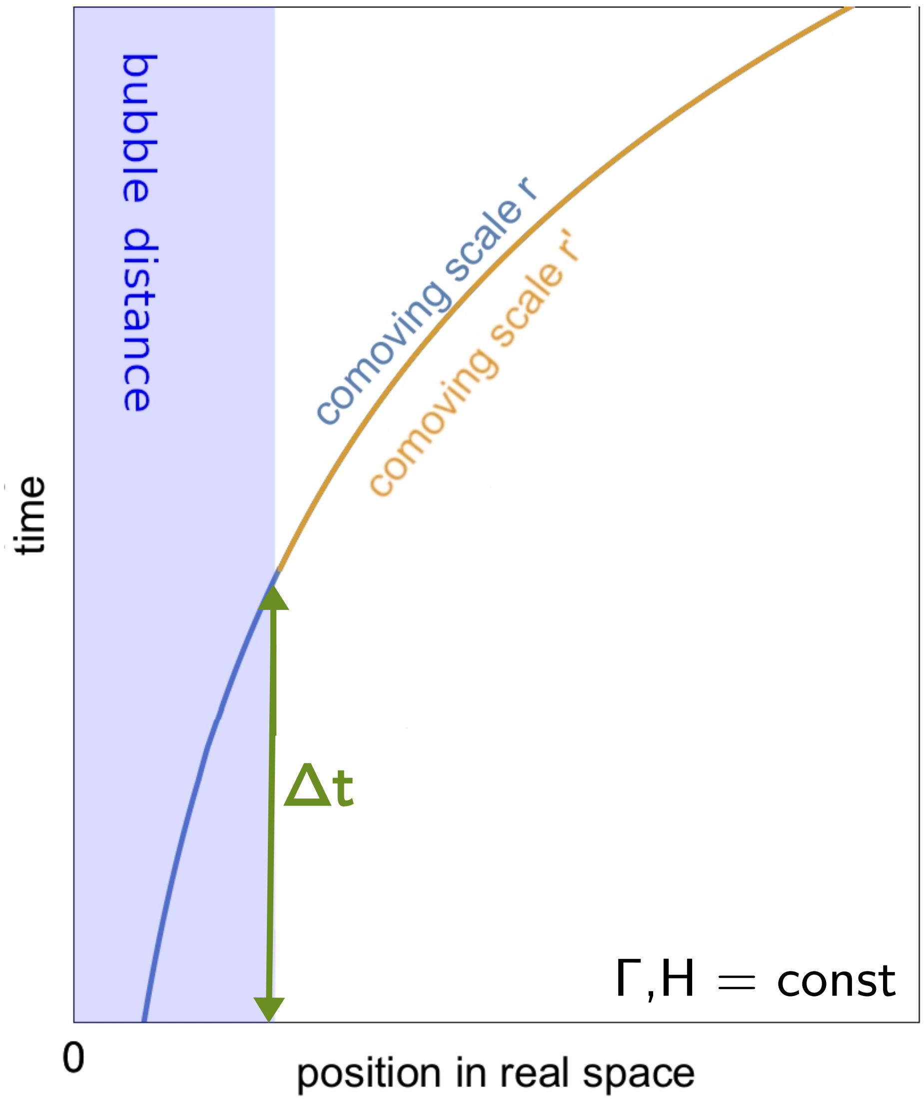
Scalar Power Spectrum



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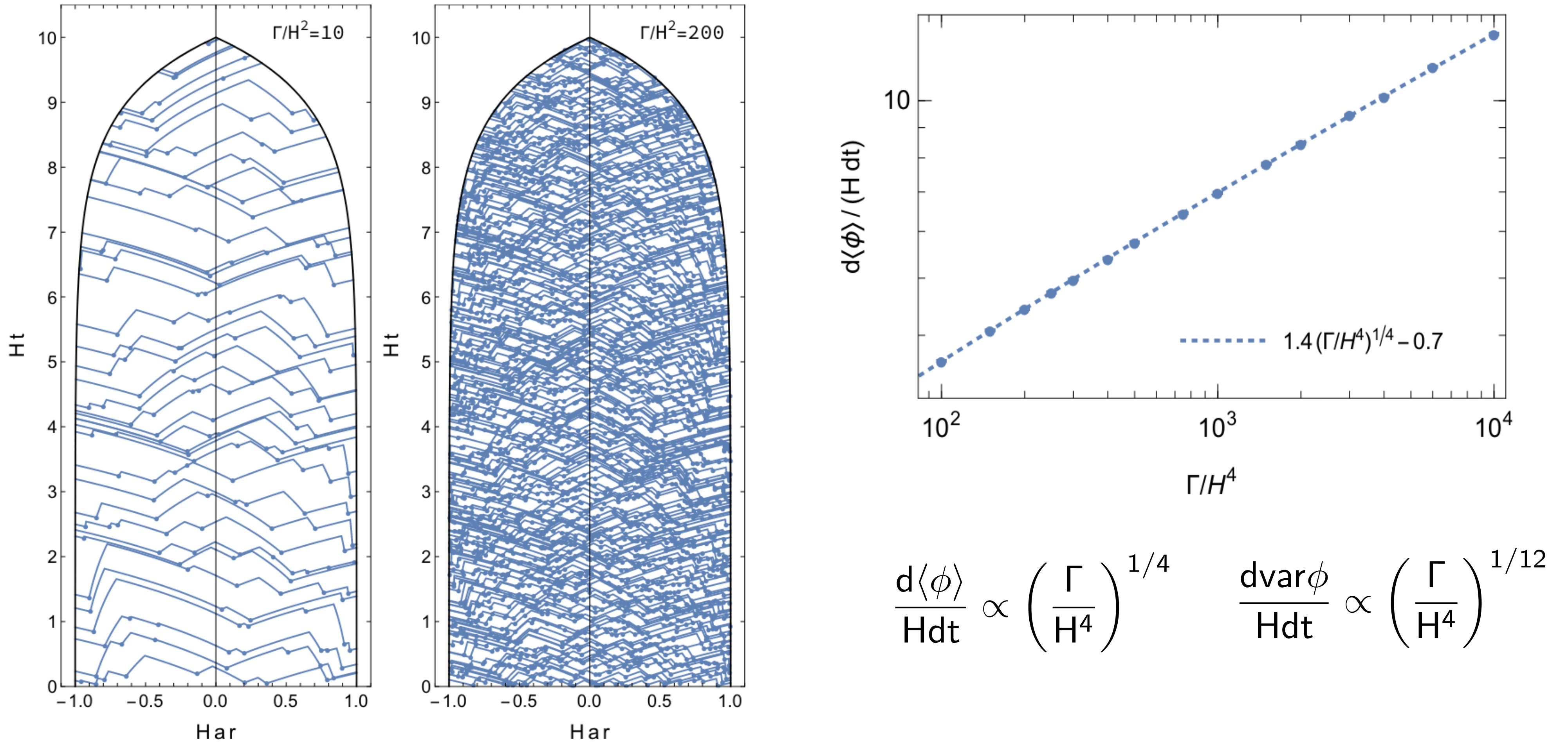
Simulations



$$\frac{d\langle\phi\rangle}{Hdt} \propto \left(\frac{\Gamma}{H^4}\right)^{1/4} \qquad \frac{d\mathrm{var}\phi}{Hdt} \propto \left(\frac{\Gamma}{H^4}\right)^{1/12}$$

$$\Delta^2_{\mathcal{R}} \simeq 0.06 \left(\frac{\Gamma}{H^4}\right)^{-5/12}$$

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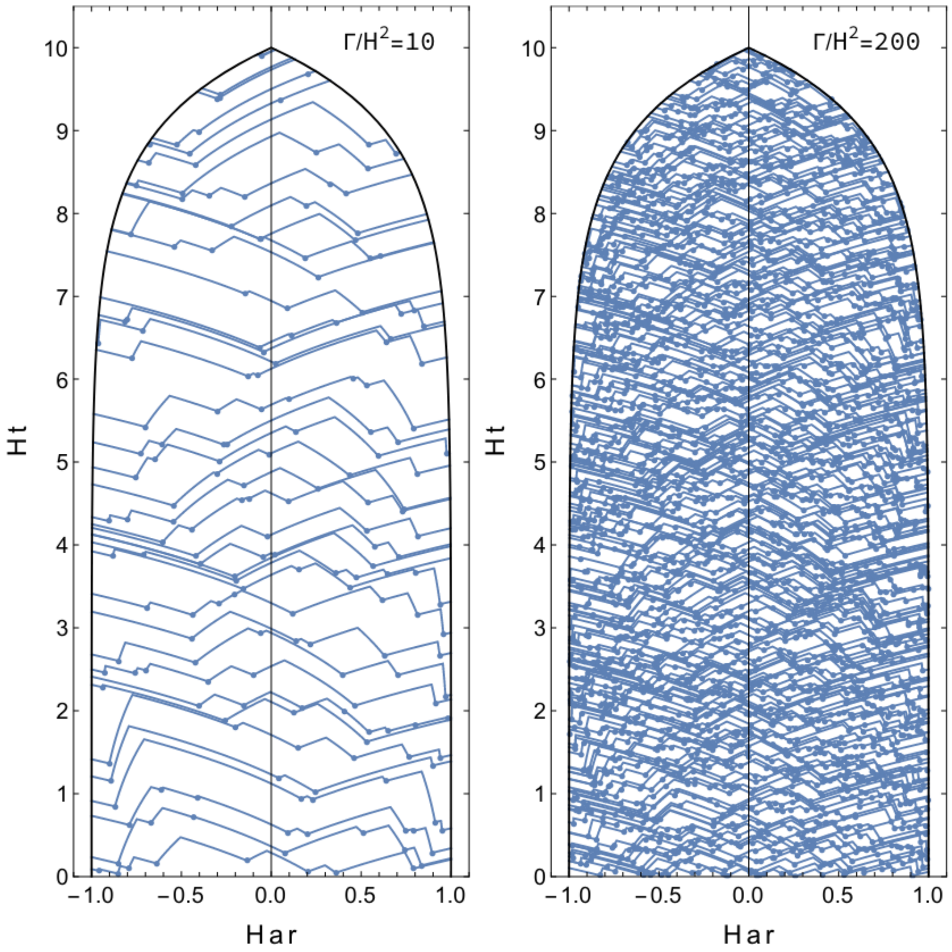

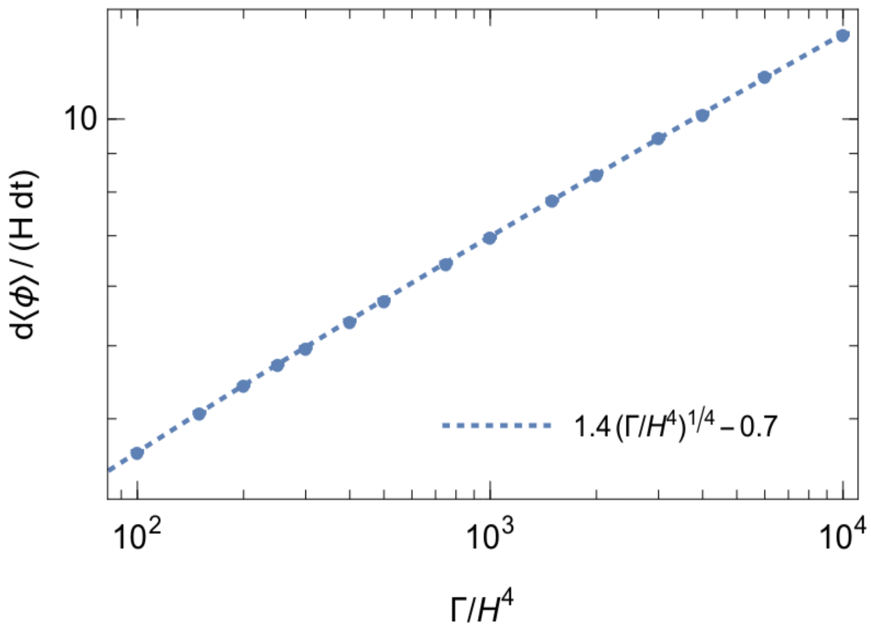

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$$\Delta^2_{\mathcal{R}} \simeq 0.06 \left(\frac{\Gamma}{H^4}\right)^{-5/12} \qquad \Delta^2_{\mathcal{R}} = (0.04 \pm 0.02) \left(\frac{\Gamma}{H^4}\right)^{-0.42\pm0.03}$$

Feldstein, Tweedie 2007

Comparison with CMB

- COBE normalization $\Delta^2_{\mathcal{R}} = 2 \times 10^{-9}$ implies

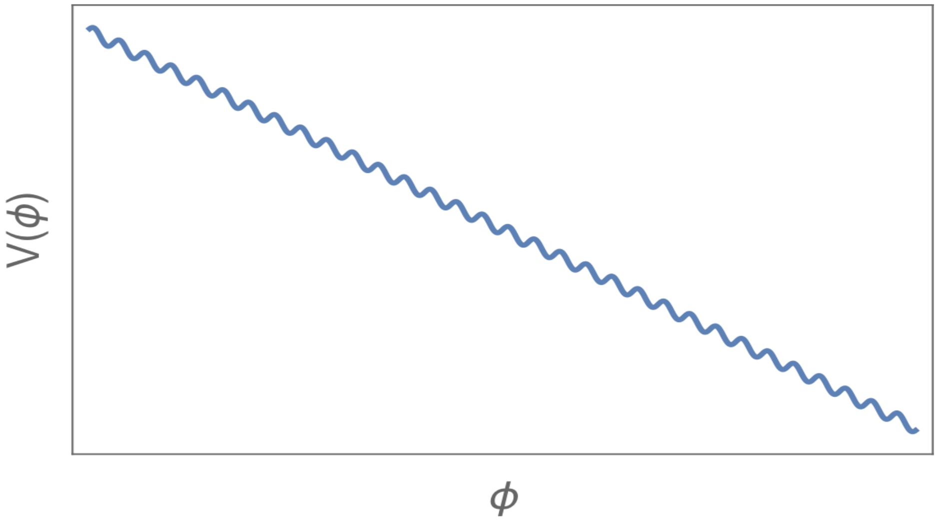
$$\frac{\Gamma}{H^4} = 10^{18} \implies \frac{\text{vacuum transitions}}{\text{e-fold of inflation}} \simeq \left(\frac{\Gamma}{H^4}\right)^{1/4} \simeq 4 \times 10^4$$

- scale-invariance of power spectrum broken by $\dot{H}$, $\dot{\Gamma}$

$$n_s = 1 + \frac{5}{12}\left(\frac{4\dot{H}}{H^2} - \frac{\dot{\Gamma}}{H\Gamma}\right)$$

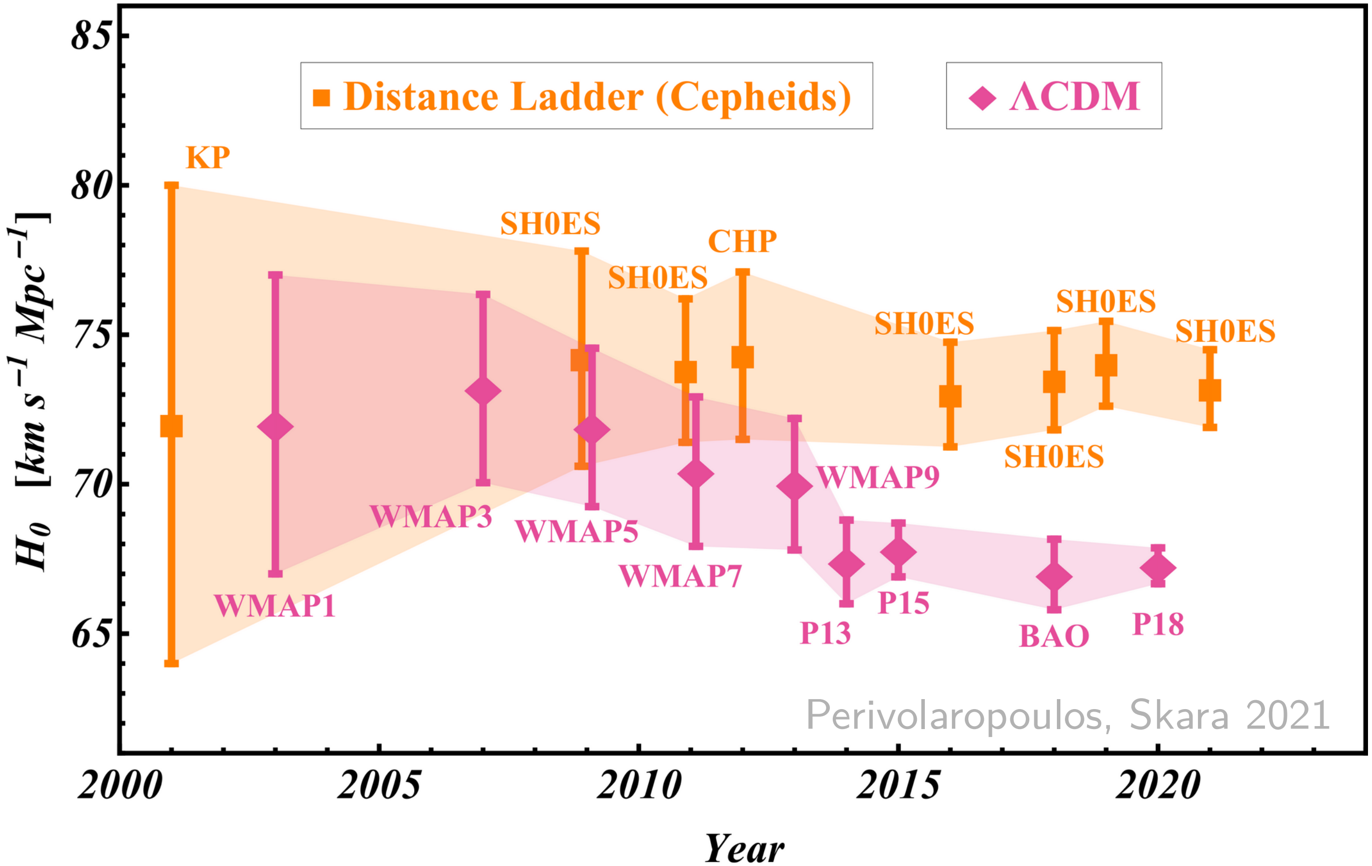
- simplest scenario with pure tilted cosine potential

$$n_s \simeq 1 - 0.03\left(\frac{\Delta V}{10^{-6}\,V}\right)$$



Hubble Crisis

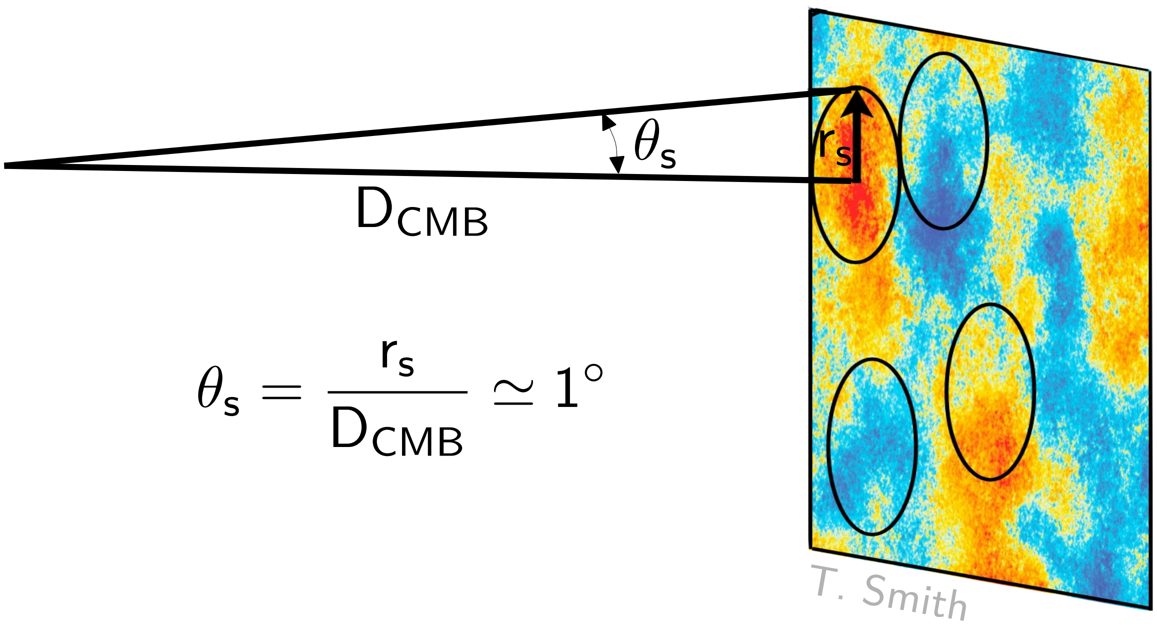
- H_0 disagrees between CMB and local measurements



$H_0[\frac{\text{km}}{\text{s Mpc}}] = 73.2 \pm 1.3$ (SH0ES) $\quad$ $H_0[\frac{\text{km}}{\text{s Mpc}}] = 67.3 \pm 0.6$ (Planck 2018)

Riess et al. 2021

- CMB fixes angular size of sound horizon



$$\theta_s = \frac{r_s}{D_{CMB}} \simeq 1^\circ$$

dominated by H_0

$$r_s = \int_{z_{CMB}}^{\infty} \frac{c_s\, dz}{H(z)}$$

$$D_{CMB} = \int_{0}^{z_{CMB}} \frac{dz}{H(z)}$$

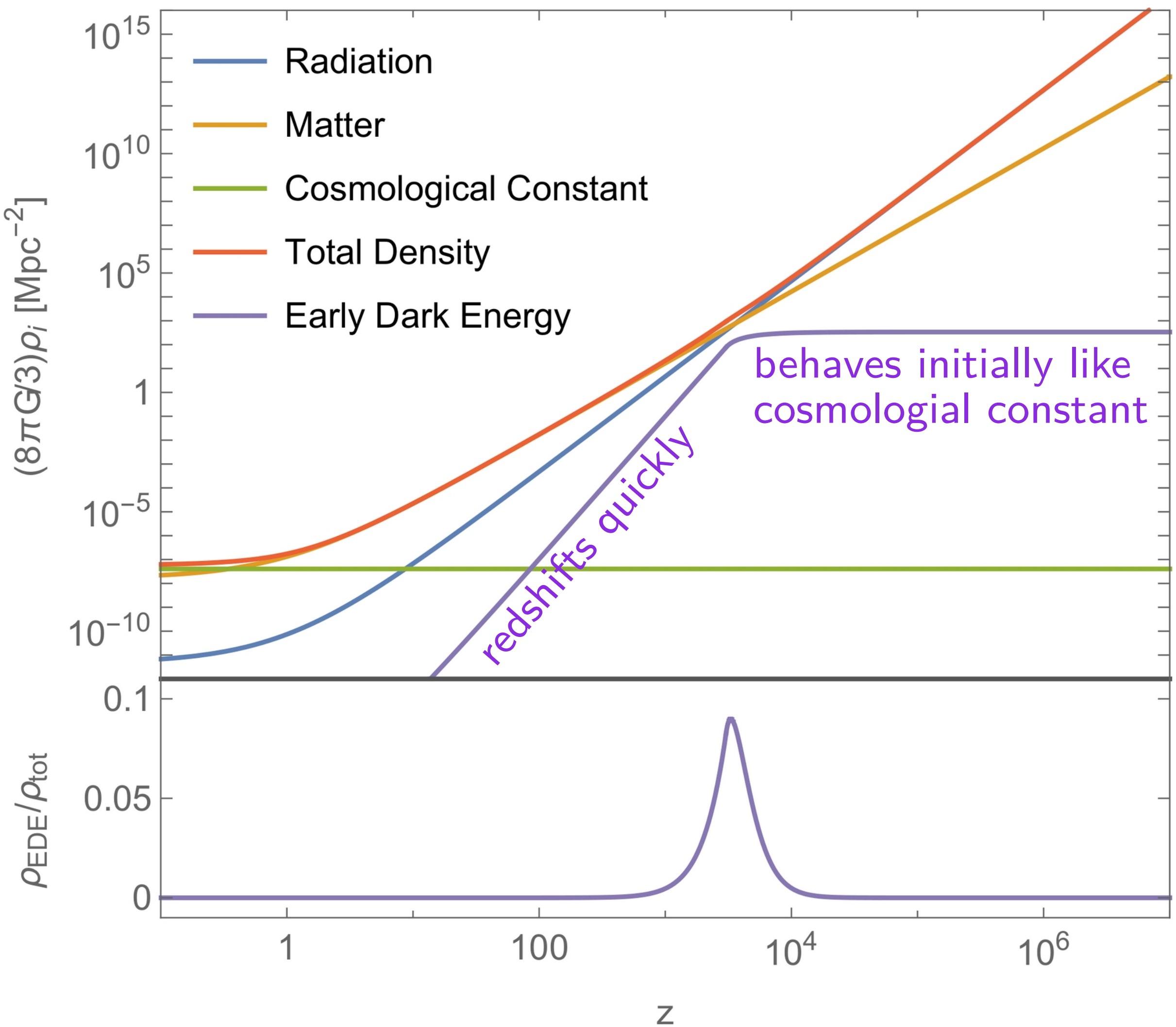
dominated by $H(z)$ around z_{CMB}

- additional energy density before recombination reduces sound horizon

- fixed θ_s then requires larger D_{CMB} $\longrightarrow$ H_0 increases

Early Dark Energy

Karwal, Kamionkowski 2016, Poulin et al. 2018 & 2019



- cosmological data favor peaked energy injection around z~4000

Smith et al. 2020

Datasets	ΛCDM	EDE
Planck high-ℓ	2446.66	2444
Planck low-ℓ	10496.65	10493.25
Planck lensing	10.37	10.24
BAO-low z	1.86	2.53
BAO-high z	1.84	2.1
Pantheon	1027.04	1027.11
SH0ES	16.80	1.68
Total $\chi^2_{\rm min}$	14001.23	13980.94
$\Delta\chi^2_{\rm min}$	0	-20.29

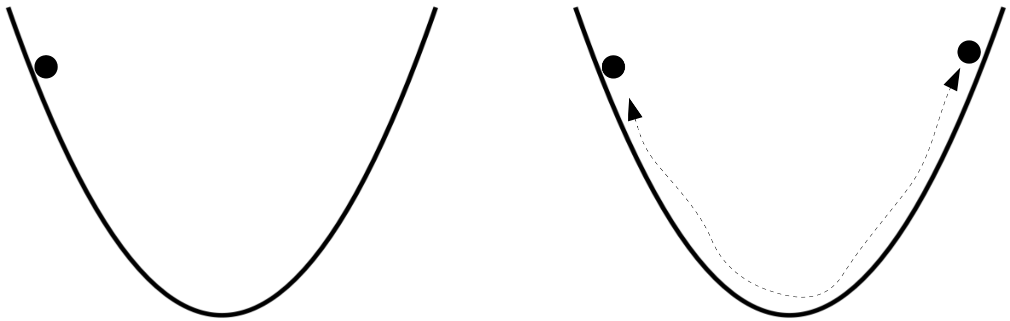
dark radiation only yields $\Delta\chi^2_{\rm min} \simeq -4$

Agrawal et al. 2019

Oscillating Scalar Field Models

- scalar field in the dark sector displaced from its minimum

Smith et al. 2020



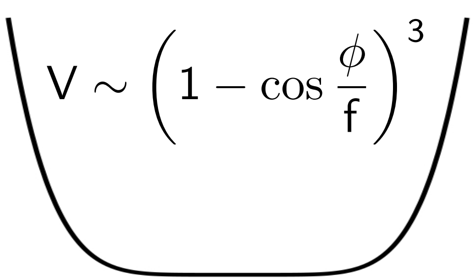
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

initially trapped
by Hubble friction
$\rho_\phi = \text{const}$

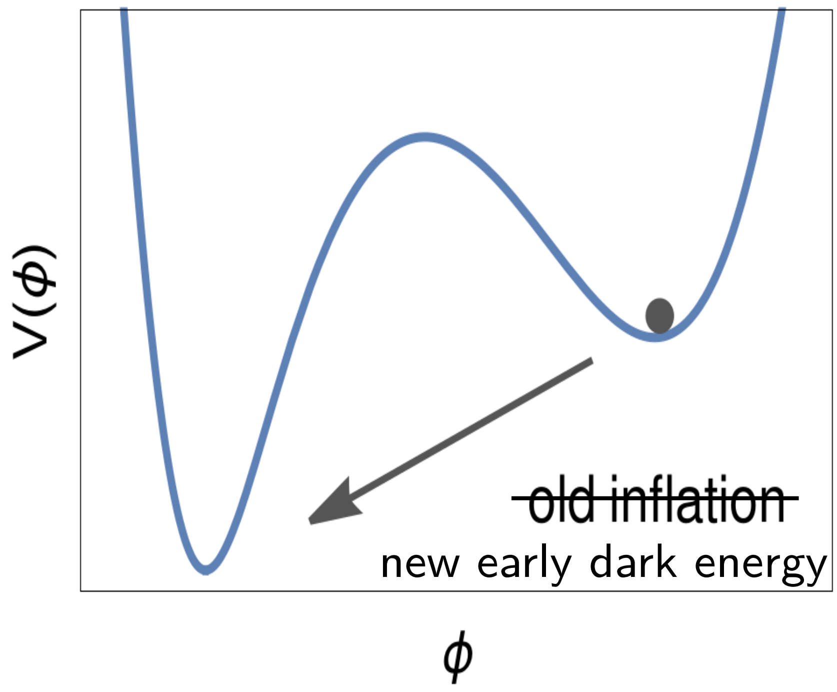
oscillations once
$H < m_\phi$
$\rho_\phi \propto a^{-n}$

- problem: standard potentials yield
  too slow redshift ($n{\sim}3$),
  'weird' potential required

like non-relativistic matter



Early Dark Energy via Phase Transition



- dark sector scalar field trapped in false vacuum

  $\rho = \text{const}$

- bubbles of true vacuum, energy stored in bubble walls

- upon collision wall energy is transferred to

  (1) anisotropic stress $\rho \propto a^{-6}$ (?)

  (2) gravity waves $\rho \propto a^{-4}$

  (3) dark radiation $\rho \propto a^{-4}$

  } consistent with EDE

Niedermann, Sloth 2020 & 2021

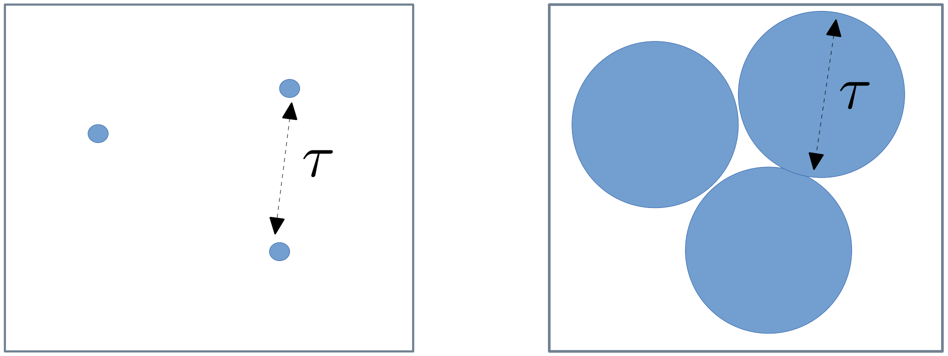
The Anisotropy Problem

- required lifetime of the universe in the false vacuum

$$\tau \sim 2.5 \times 10^4\,\text{yr} \times \left(\frac{5000}{z_*}\right)^2$$

EDE solution $z_* \lesssim 5000$

- anisotropies of size $\Gamma^{-1/4} \sim \tau$ are formed



- angular size of fluctuations at last scattering

$$\theta \simeq 0.1^\circ \times \frac{5000}{z_*}$$

CMB observations: $\theta \gtrsim 0.05$

Large Scale Structure: $\theta \simeq 0.002 - 0.2$

► CMB, LSS spoiled

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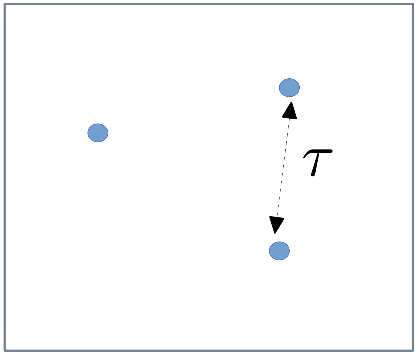

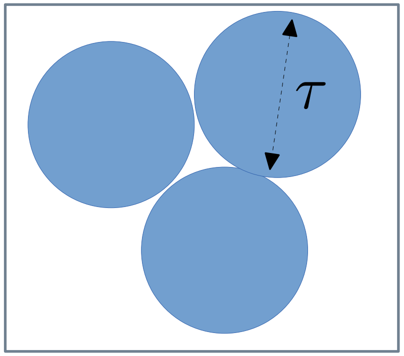

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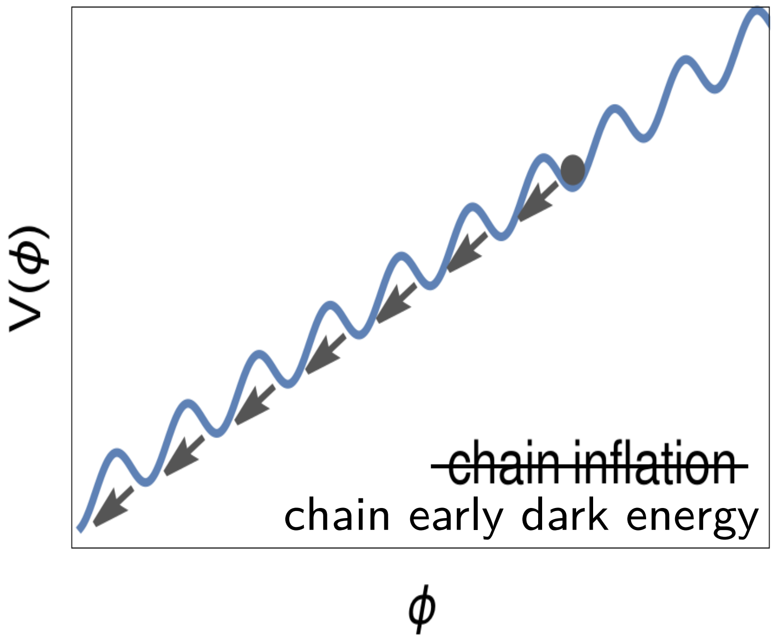
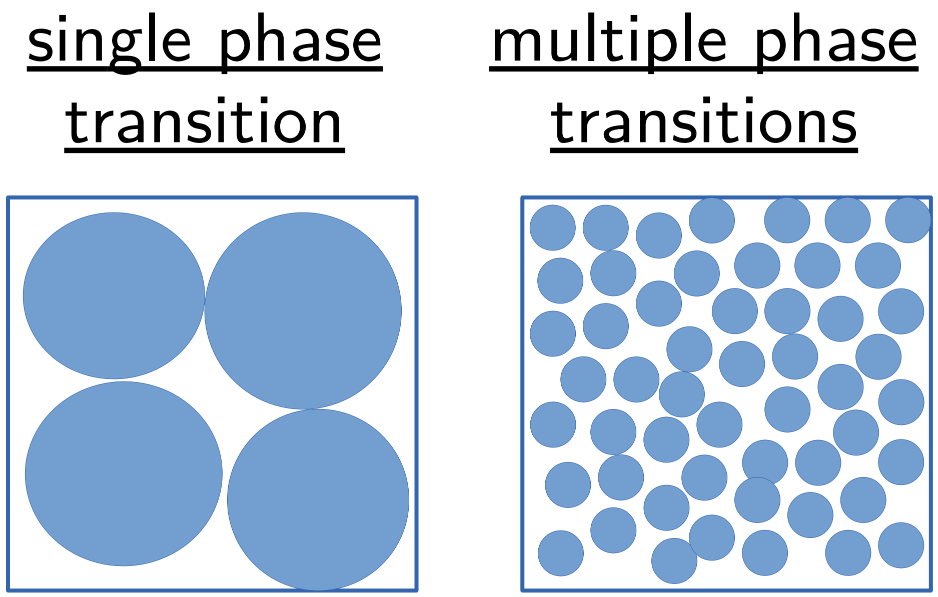
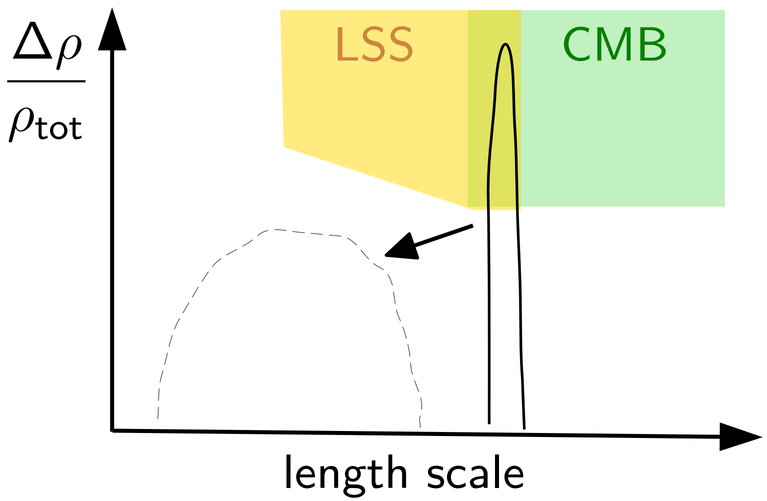
<u>caveat:</u> make Γ time-dependent in two-field system

Adams, Freese 1991, Niedermann, Sloth 2020 & 2021

Chain Early Dark Energy







- multiple phase transitions reduce size and amplitude of anisotropies
- constraints evaded for $N > 600$ transitions

Evolution of Energy Density

including energy from bubble collisions:

$$z\,\frac{d\rho_\phi}{dz} \simeq \frac{1.4\,\Delta V\,\Gamma^{1/4}}{H(z)}$$

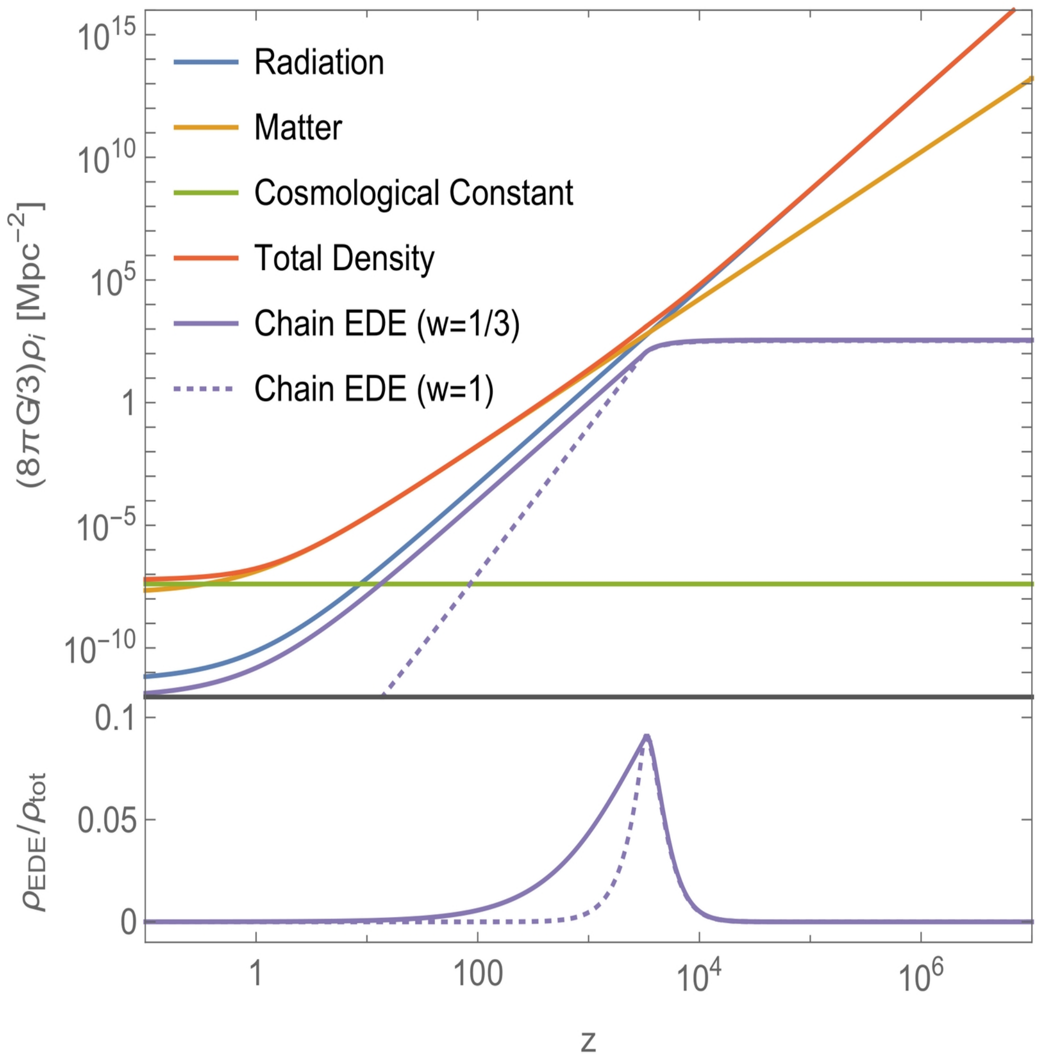
$$z\,\frac{d\rho_{DS}}{dz} \simeq -\frac{1.4\,\Delta V\,\Gamma^{1/4}}{H(z)} + 3(1+w)\,\rho_{DS}$$

$w = 1/3$ (dark radiation)

$w = 1$ (anisotropic stress)

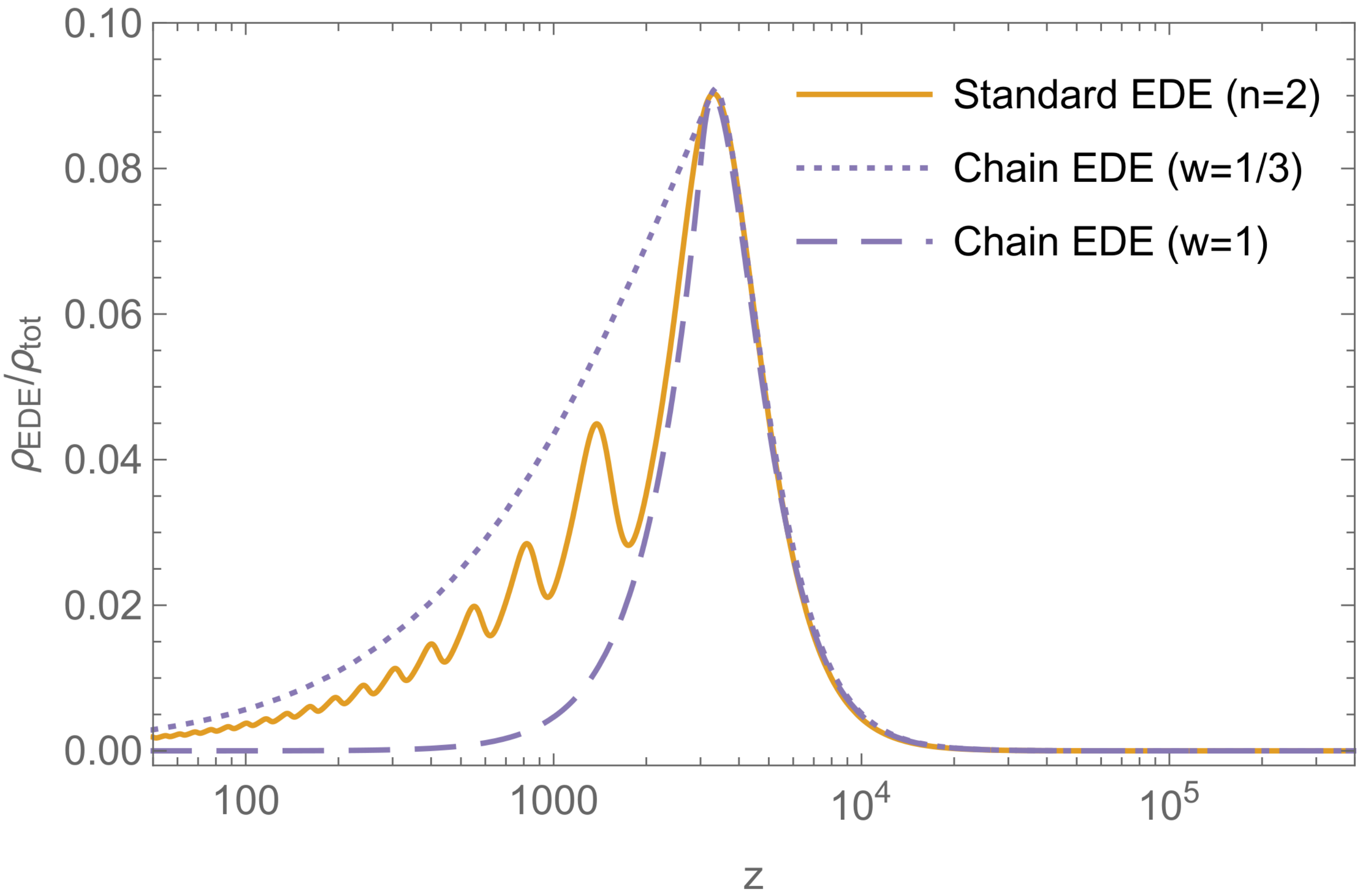
$\Gamma^{-1/4} \sim$ lifetime in single vacuum

$\Delta V =$ energy difference between vacua



$V_0 = 0.25\ \mathrm{eV}^4 \quad N\,\Gamma^{-1/4} = 8\times 10^4\ \mathrm{yr}$

Comparison with Standard EDE

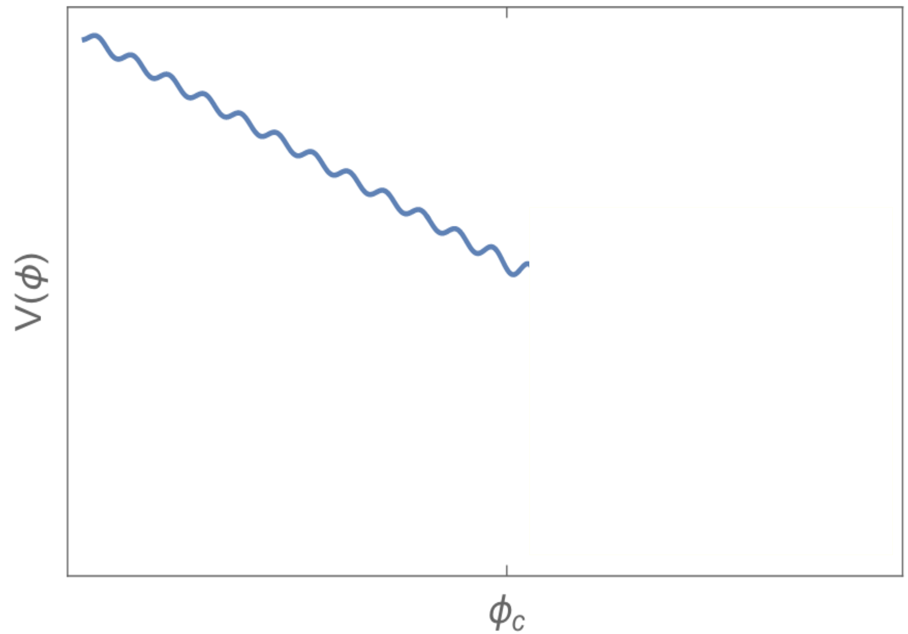


- evolution of ρ_{EDE} very similar to best-fit oscillating scalar field models ► solution to Hubble tension

Model Realization via Axions

- tilted cosine

$$V = -gM^3\phi + \Lambda_0^4 \cos\frac{\phi}{f}$$



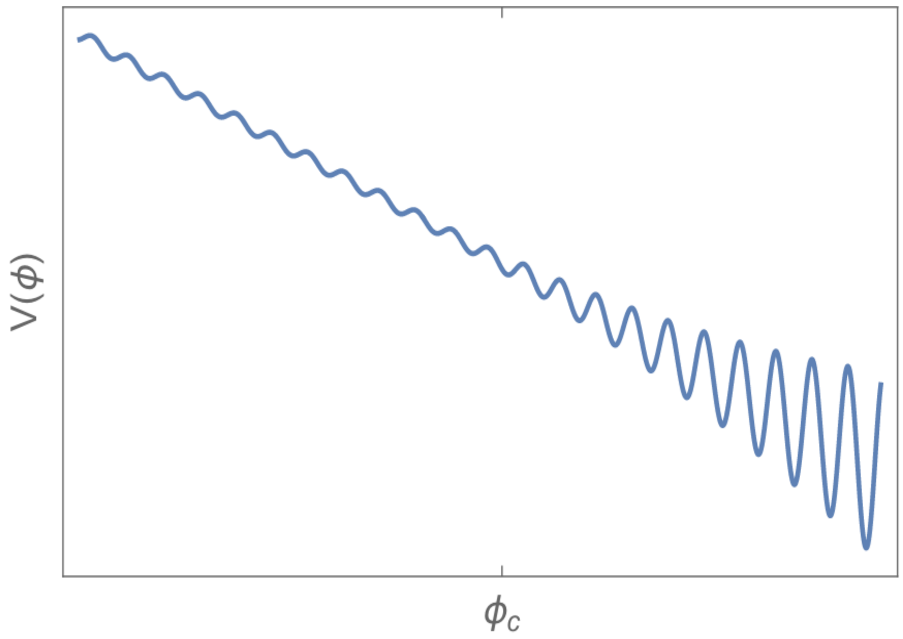
Model Realization via Axions

- tilted cosine + stopping

$$V = -gM^3\phi + (\Lambda_0^4 + \Lambda_1^2\chi^2)\cos\frac{\phi}{f}$$

$$+ (M^2 - gM\phi)\chi^2 + \lambda\chi^4$$

Graham, Kaplan, Rajendran 2015



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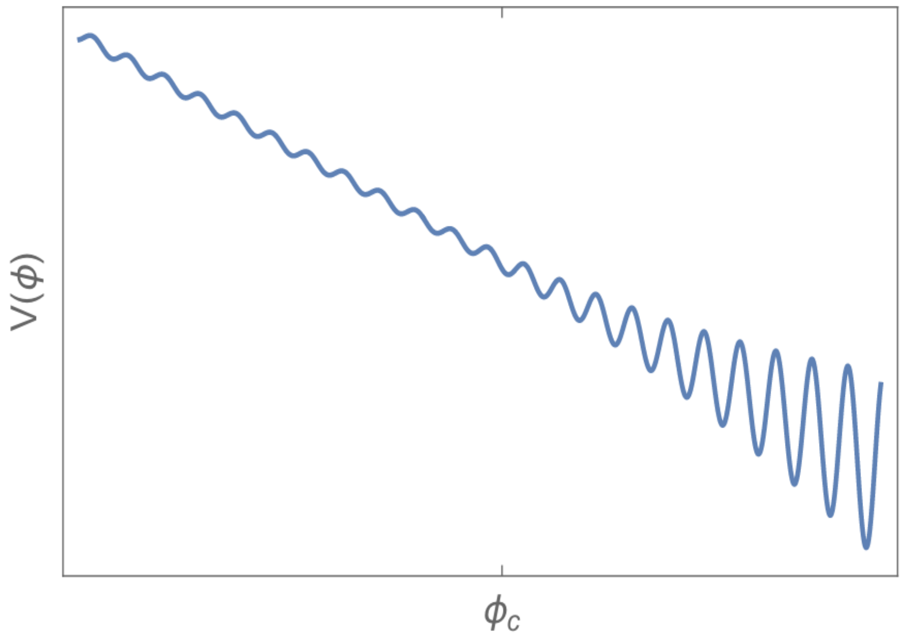
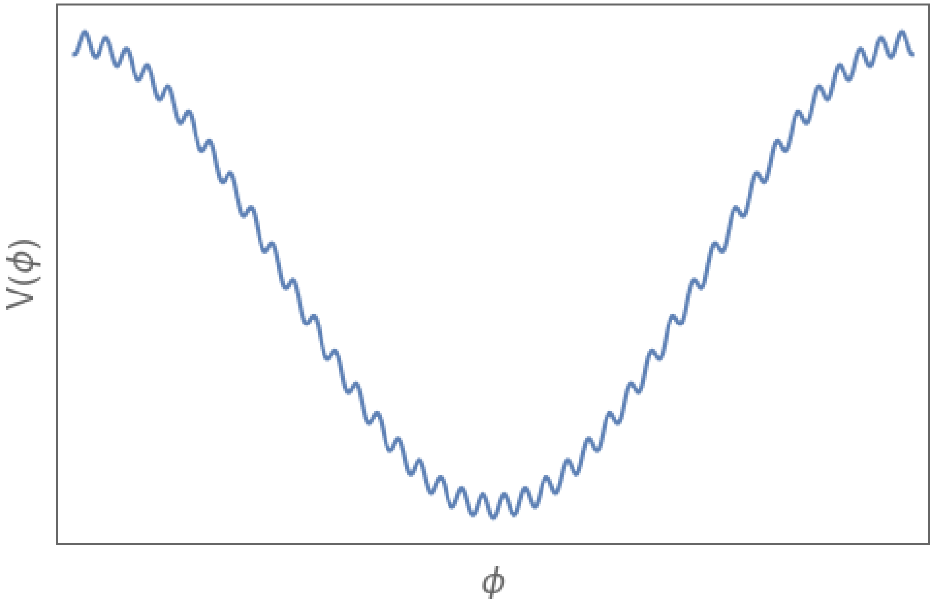




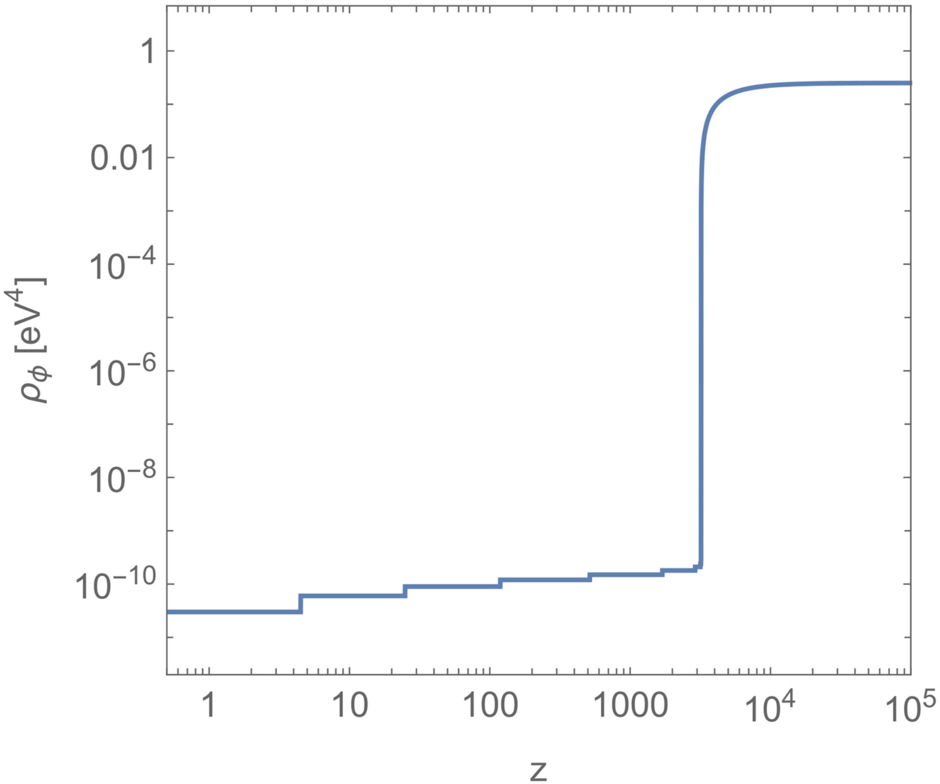
- double-periodic potentials, e.g. axion with leading and subleading instanton

Connection to Dark Energy

- energy difference between minima in chain EDE

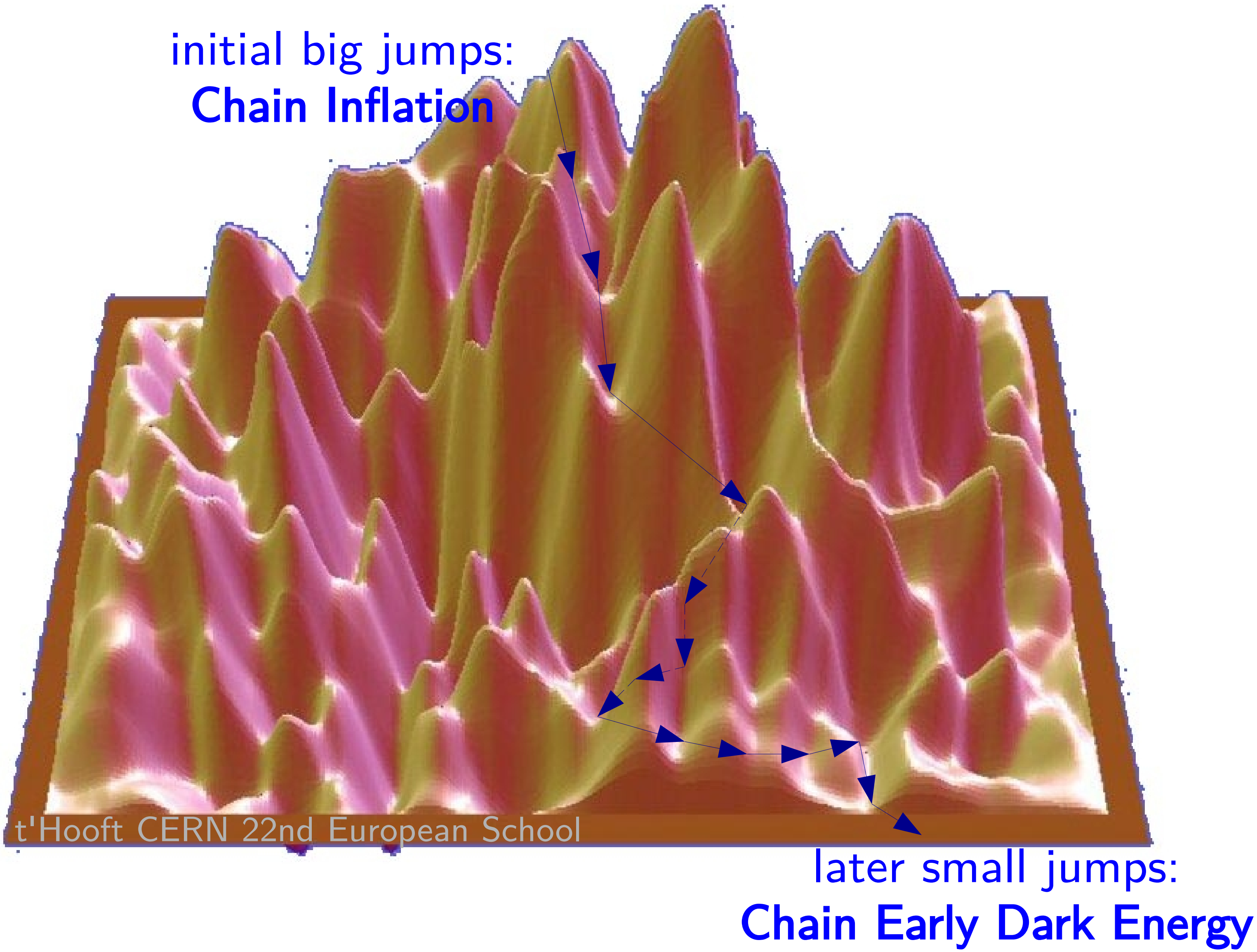
$$(\Delta V)^{1/4} \sim 2\,\text{meV} \times \frac{300}{N^{1/4}}$$

scale of today's Dark Energy



- EDE field may get trapped in the lowest minimum with positive energy and account for today's Dark Energy

Recurrent Chain Dark Energy



see also: Freese, Liu, Spolyar 2006

Summary

- vacuum transitions can have played a major role in the history of the universe
- chain inflation is a serious competitor for slow roll inflation
- chain early dark energy provides a solution to the H_0 tension