Thermal Friction in Early Cosmology

Kim Berghaus, Johns Hopkins University

Content

1. The Dissipative Axion
2. Minimal Warm Inflation
3. A Particle Solution of the Hubble Tension

Content

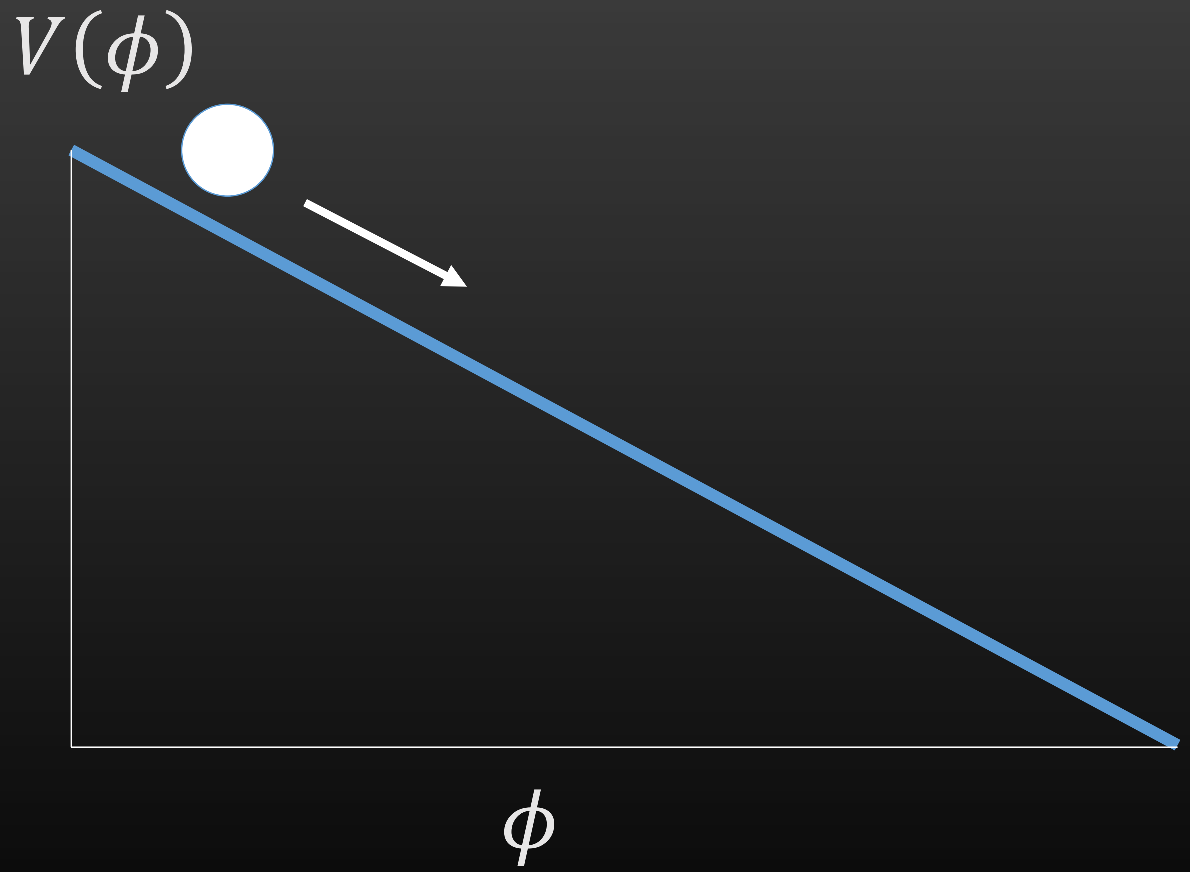
1. The Dissipative Axion
    - Rolling Scalar Fields in Cosmology
    - Thermal Friction
2. Minimal Warm Inflation
3. A Particle Solution of the Hubble Tension

Rolling Scalar Fields in Cosmology

Energy content of universe determines cosmological evolution

	Matter	Radiation	Dark energy
Redshift:	a^{-3}	a^{-4}	$\sim a^{0}$
$a(t) \propto$:	$t^{\frac{2}{3}}$	$t^{\frac{1}{2}}$	e^{Ht}

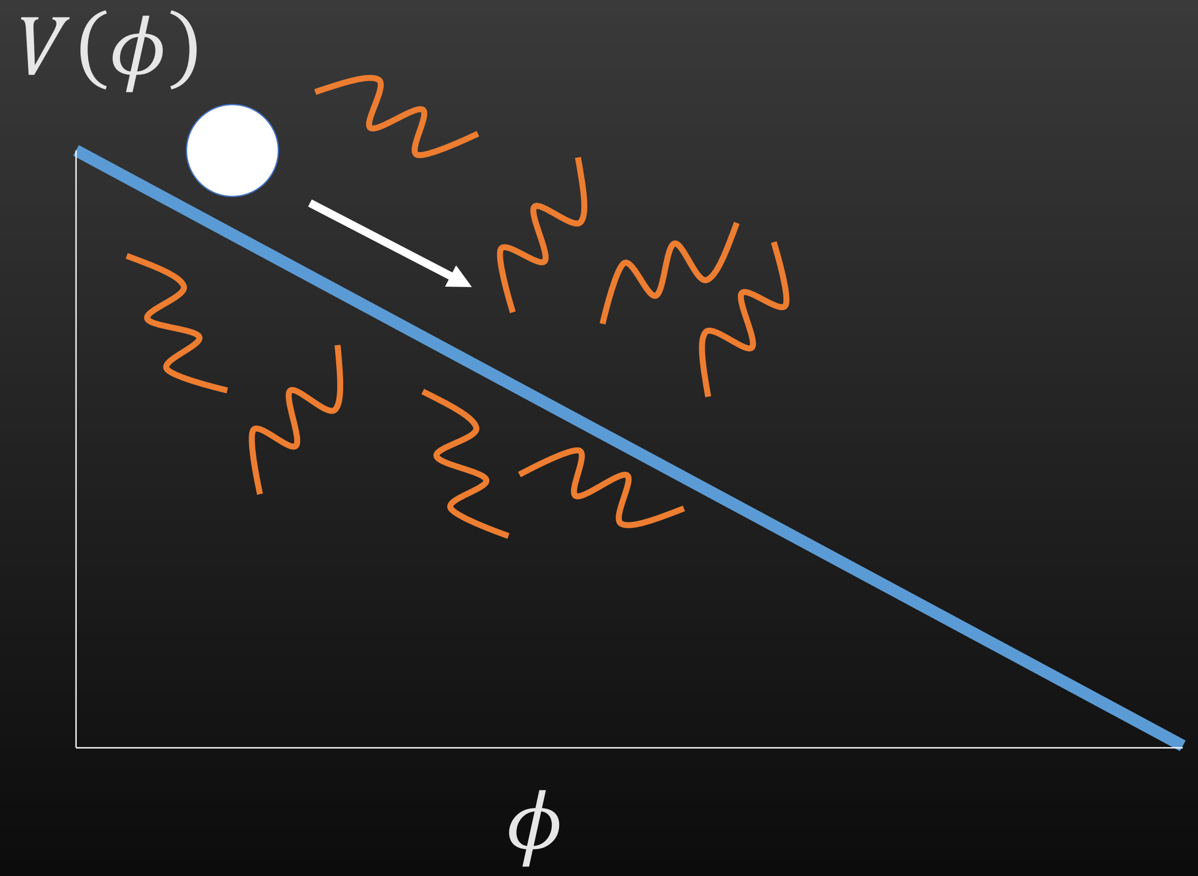
Rolling Scalar Fields in Cosmology



- Model dark energy component using particle physics
- Slow-rolling scalar field mimics Λ

$$\ddot{\phi} + 3\underbrace{H}_{\text{Hubble friction}}\dot{\phi} + V' = 0$$

Thermal Friction

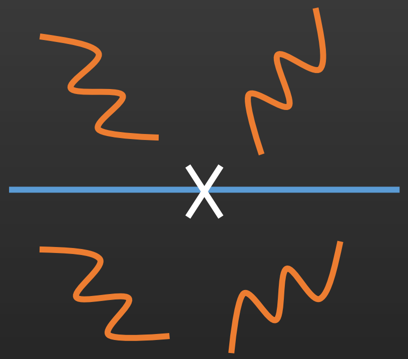


- Couple ϕ to light fields

- Coupling gives rise to additional friction

$$\ddot{\phi} + (3H + \underbrace{\Upsilon}_{\text{thermal friction}})\dot{\phi} + V' = 0$$

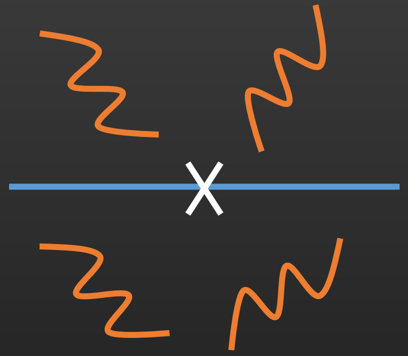
The Thermal back-reaction



Thermal bath gives finite thermal contribution to mass

$$\delta m_\phi^2 \propto T^2$$

The Thermal back-reaction



$$\Upsilon\,\dot{\phi} \ll V'_{eff}$$

Thermal bath gives finite thermal contribution to mass

$$\delta m_\phi^2 \propto T^2$$

Thermal Friction is due to temperature fluctuations

$$\Upsilon \propto \Delta T$$

How can we only have friction and avoid the thermal back-reaction?

The Dissipative Axion

How can we only have friction and avoid the thermal back-reaction?

Make the scalar field the axion of a pure Yang-Mills gauge group:

- $L_{int} = \frac{\alpha}{16\pi}\frac{\phi}{f}\tilde{G}G$ $\qquad T \gg T_c$

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- Axion does not get perturbative mass corrections due to shift symmetry
- But axion has large friction due to non-perturbative effects $\Upsilon \propto \alpha^5 \frac{T^3}{f^2}$

Content

1. The Dissipative Axion
2. Minimal Warm Inflation
3. A Particle Solution of the Hubble Tension

Dissipative Axion produces large friction without unwanted side effects

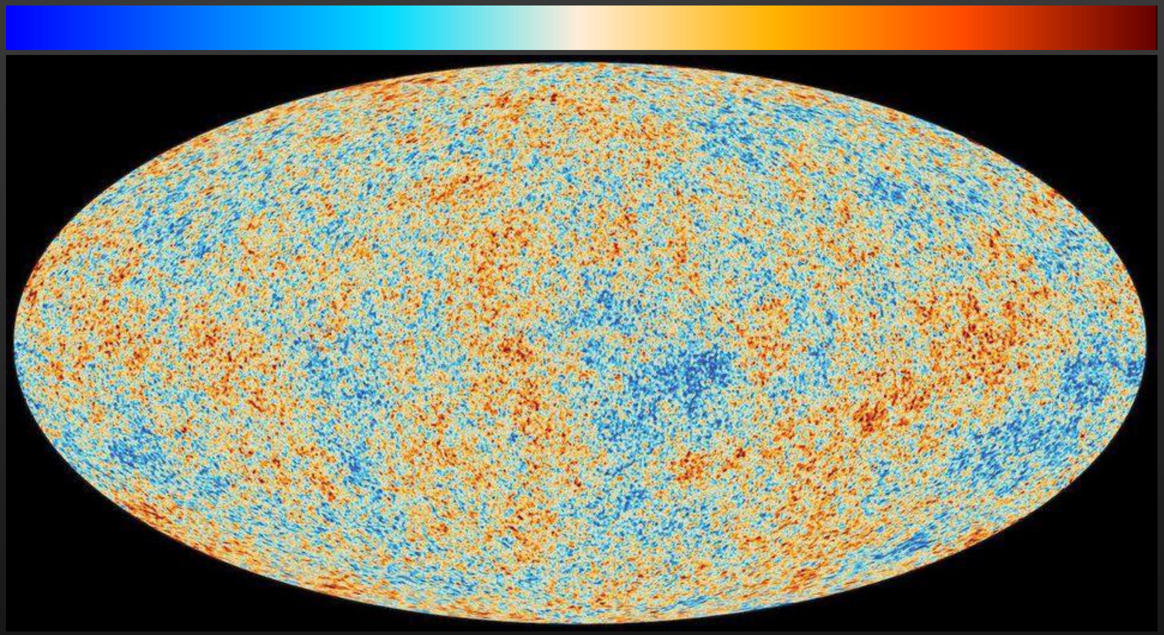
Content

1. The Dissipative Axion
2. Minimal Warm Inflation
    - Inflation
    - Warm Inflation
3. A Particle Solution of the Hubble Tension

Why Inflation?

- Universe is isotropic
- Universe is flat

$\delta T \approx 10^{-4.5}$



Planck 2018

Period of accelerated expansion ($\approx$ 60 e-folds) can explain both

Slow-roll Inflation

- Inflaton field fluctuations $\delta\phi$ source anisotropies
- Predicts an almost scale invariant CMB power spectrum:
- $$\Delta_R^2(k) = \underbrace{A_s}_{\sim 10^{-9}} \left(\frac{k}{k_*}\right)^{\overbrace{n_s - 1}^{\approx -0.035}}$$

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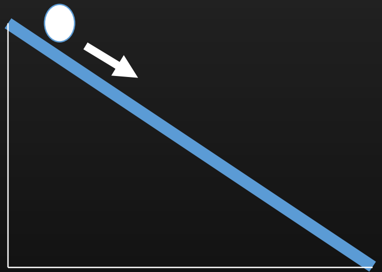
- $\Delta_R^2(k) \propto \delta\phi^2 \propto H^2$

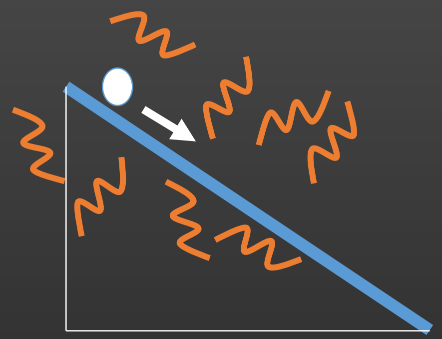


$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\eta_V = M_{Pl}^2 \frac{V''}{V} \ll 1$$

$$H^2 \approx \frac{V}{3M_{pl}^2}$$

Warm Inflation

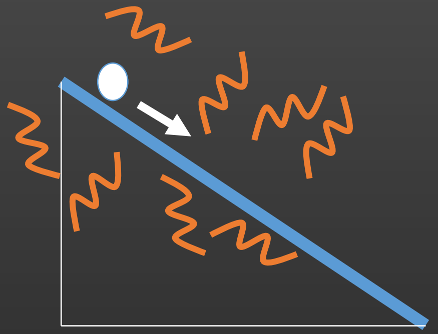


- $\delta\phi_{thermal} > \delta\phi_{quantum}$ $T_{eq} > H$
- Friction continuously extracts energy from rolling field to maintain an equilibrium temperature

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

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^{\,2}$$

Warm Inflation



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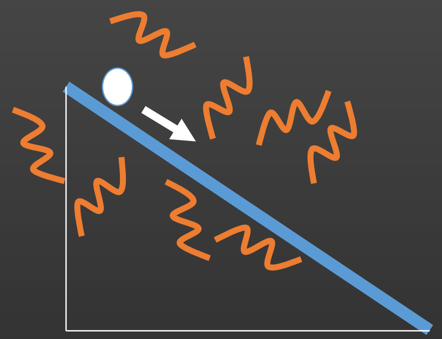
Steady state:

$$(3H + \Upsilon)\dot{\phi} + V' \approx 0$$

$$4H\rho_R \approx \Upsilon\dot{\phi}^{\,2}$$

$$4Hg_*T_{eq}^4 \approx \alpha^5 \frac{T_{eq}^3}{f^2}\dot{\phi}^{\,2}$$

Warm Inflation



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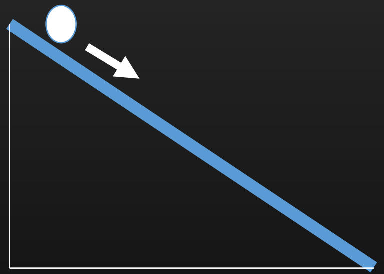
Cold Inflation vs. Warm Inflation

- $\Delta_R^2(k) \propto \delta\phi^2 \ \propto H^2$
- Tensor to scalar ratio $\mathrm{r} \approx 16\varepsilon_V$



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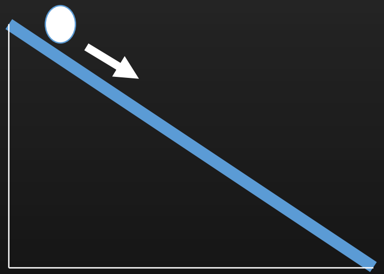

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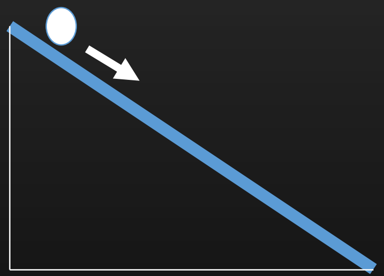

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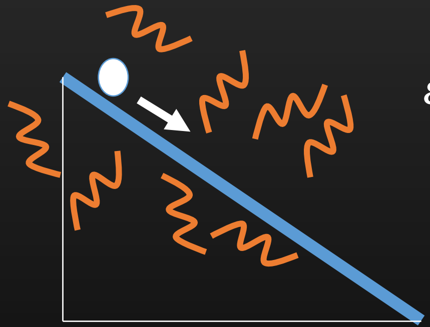
- $\Delta_R^2(k) \propto \delta\phi^2 \propto H\, T \left(\frac{\Upsilon}{3H}\right)^{\frac{19}{2}}$
- Tensor to scalar ratio r ≈ 0



$$\varepsilon_V = \frac{M_{Pl}^2}{2}\frac{3H}{\Upsilon}\left(\frac{V'}{V}\right)^2 \ll 1$$

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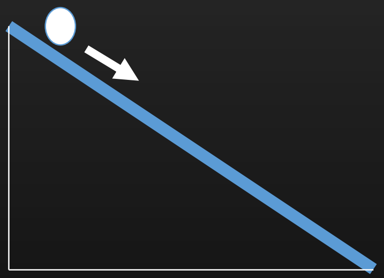

$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

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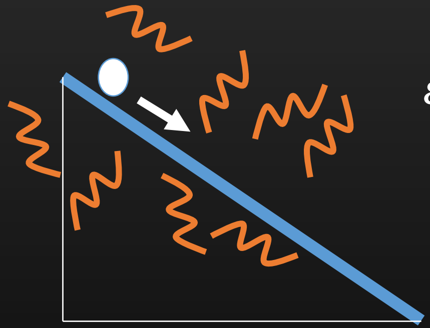
- Small non-gaussianities

- $\Delta_R^2(k) \propto \delta\phi^2 \propto H\,T\left(\frac{\Upsilon}{3H}\right)^{\frac{19}{2}}$
- Tensor to scalar ratio $\mathrm{r} \approx 0$



$$\varepsilon_V = \frac{M_{Pl}^2}{2}\frac{3H}{\Upsilon}\left(\frac{V'}{V}\right)^2 \ll 1$$

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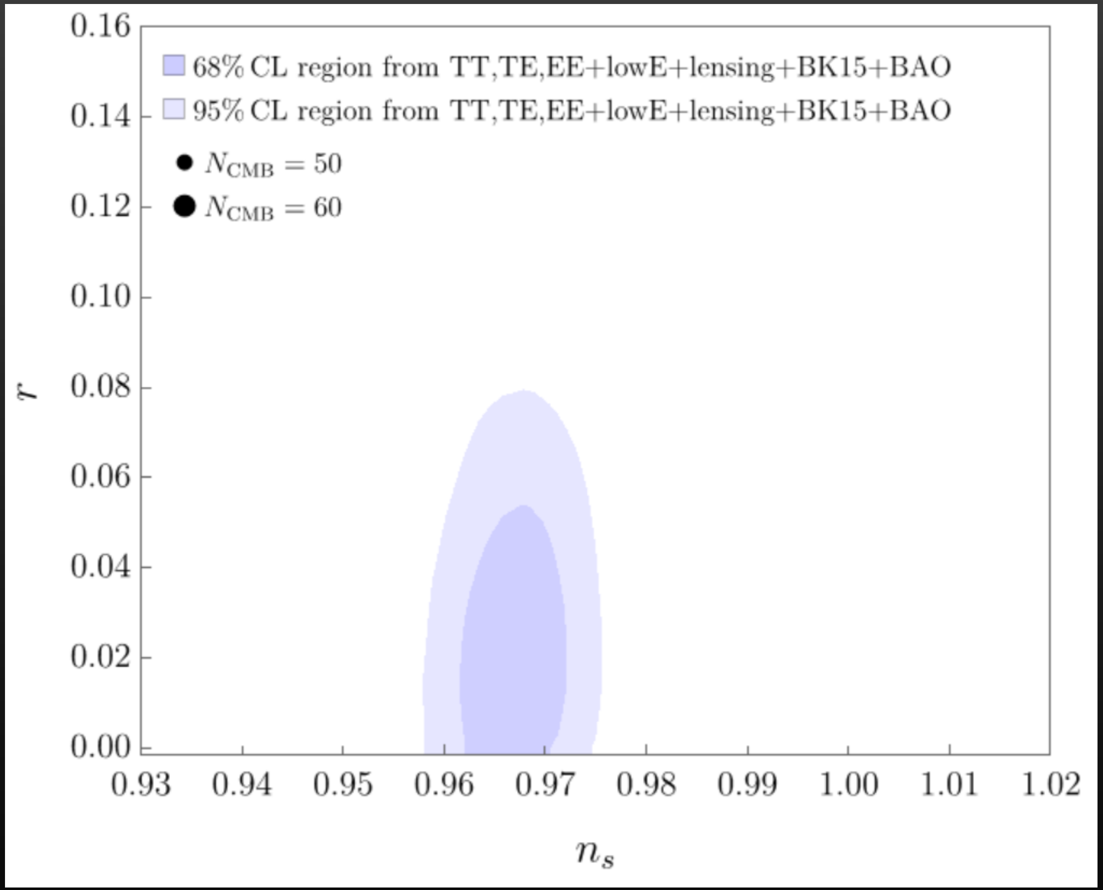
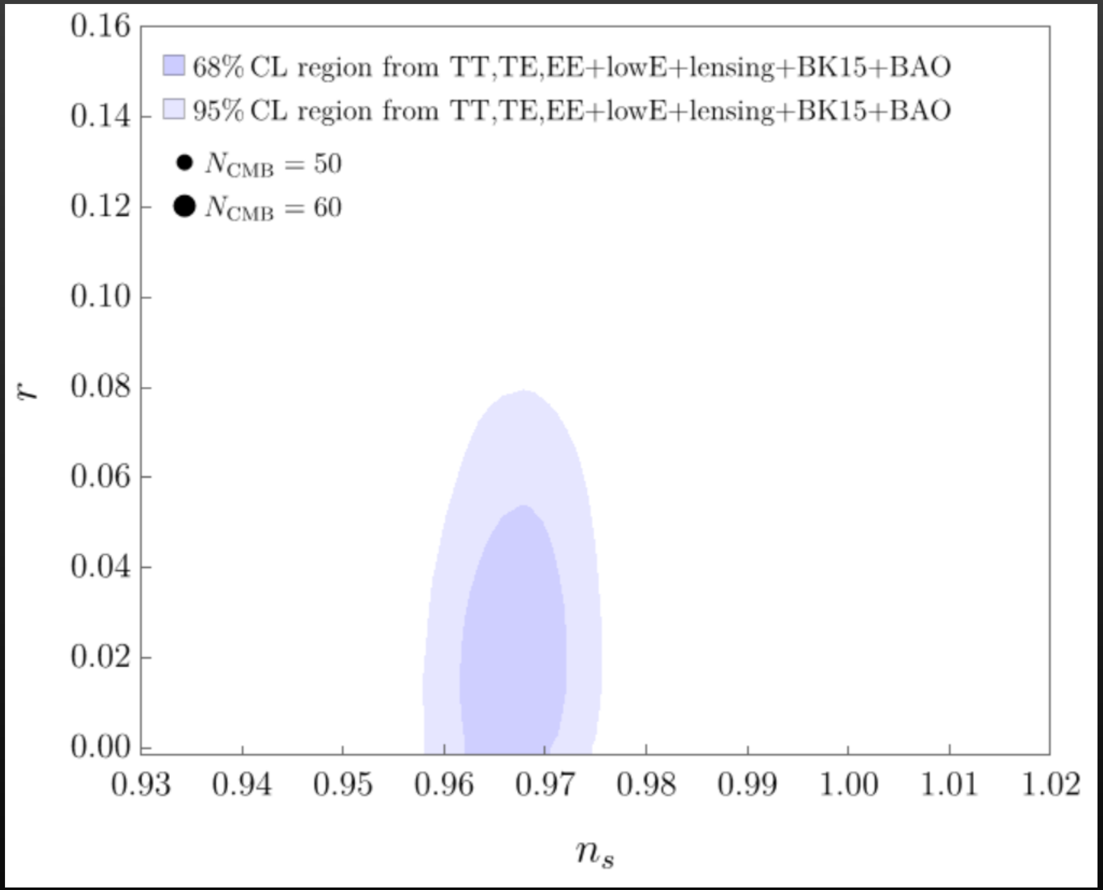
- Sizeable non-gaussianities $f_{NL} \approx 1.5$
- Unique bispectral shape

Cold Inflation vs. Warm Inflation

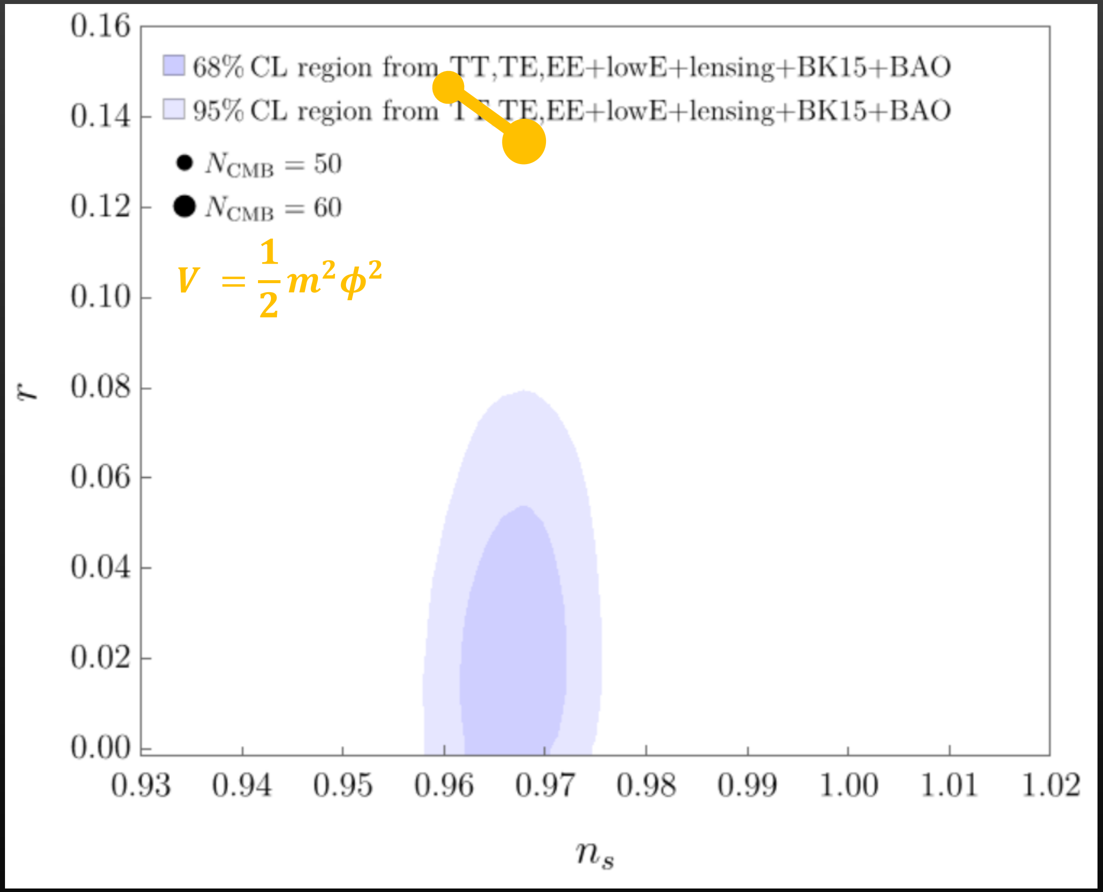


Cold

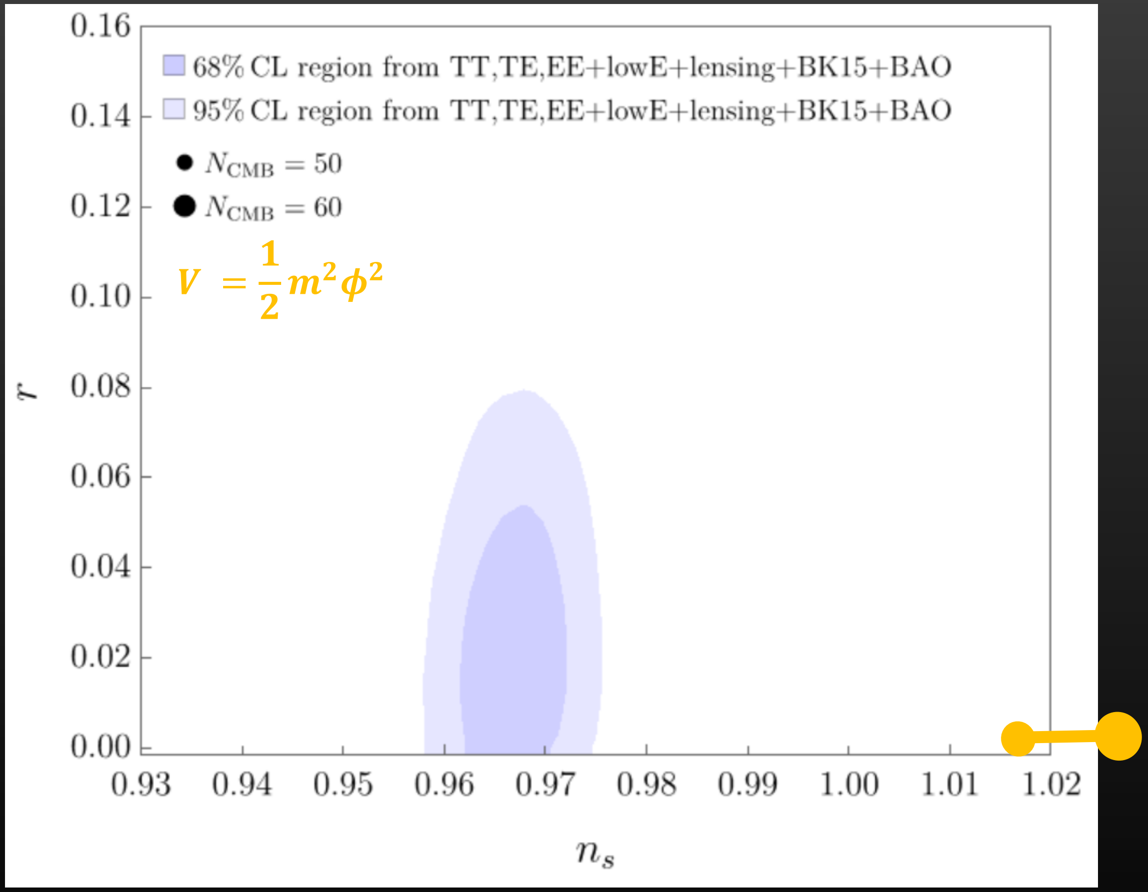


Warm

Cold Inflation vs. Warm Inflation : $V = \frac{1}{2}m^2\phi^2$

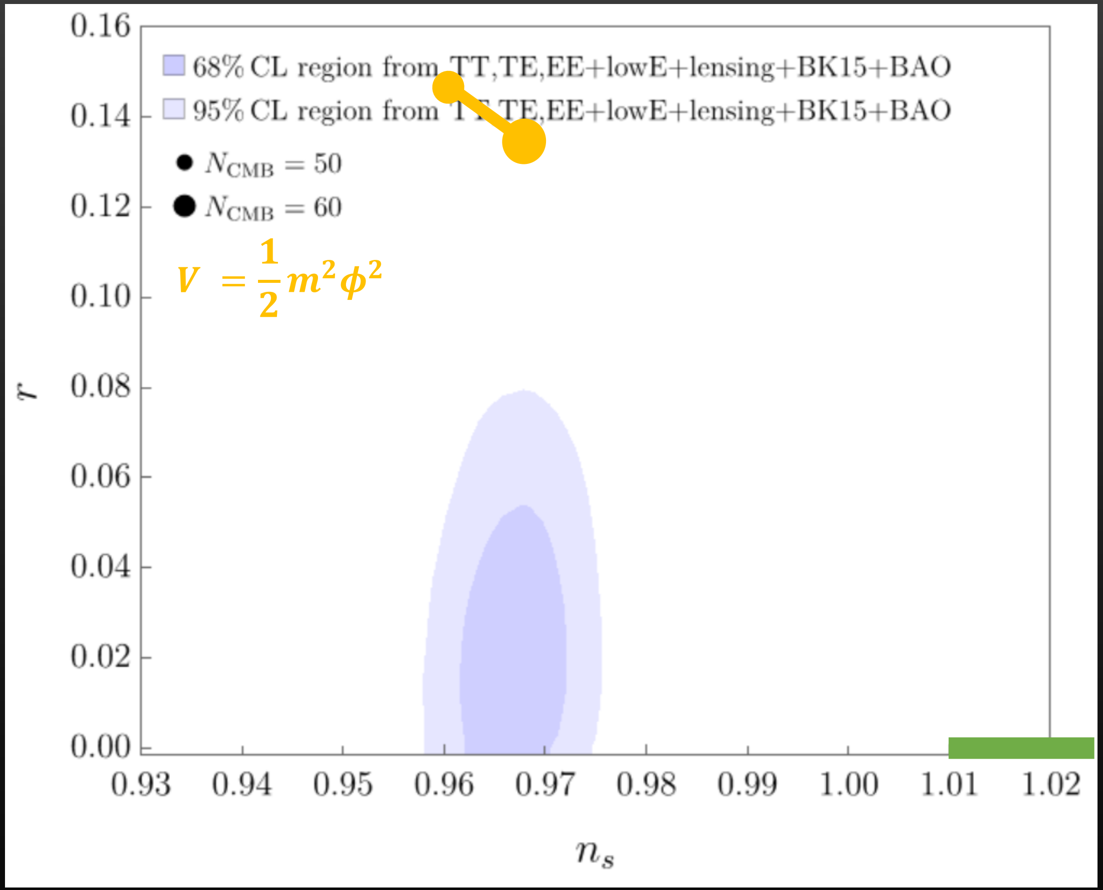


Cold

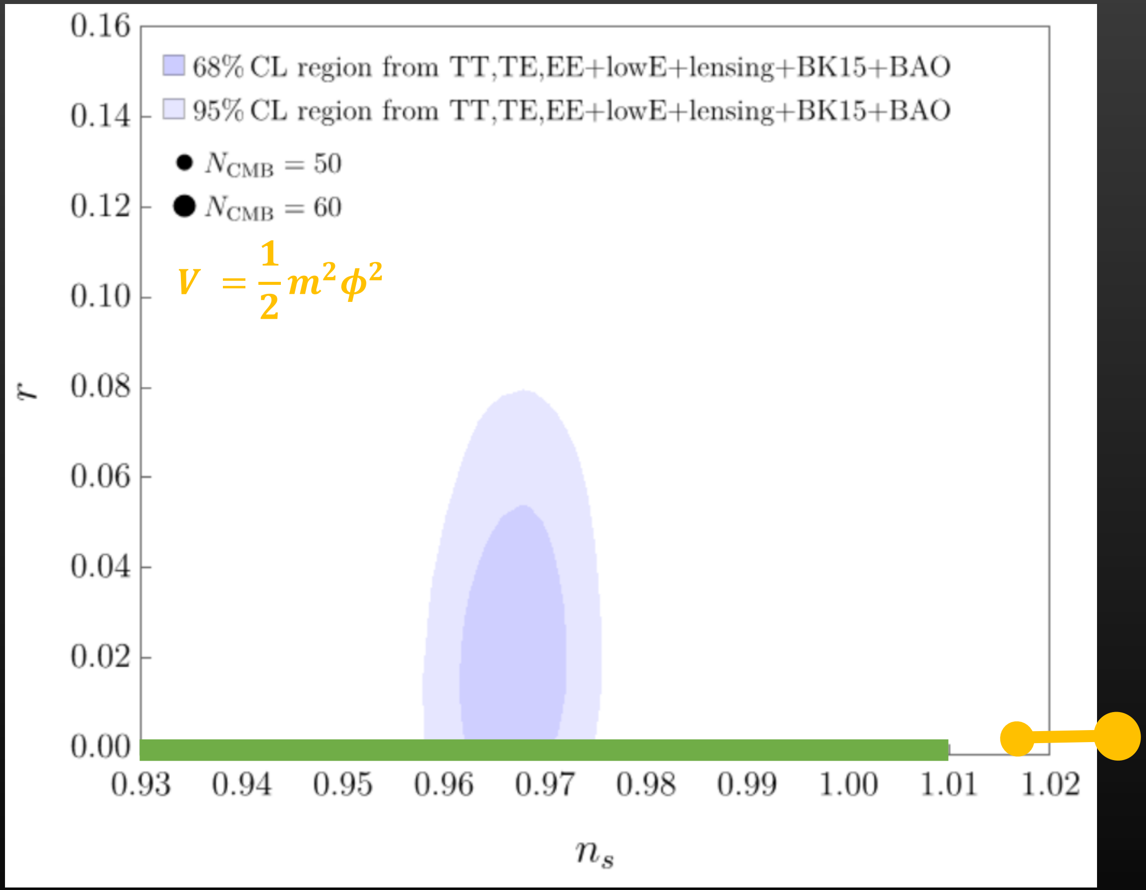


Warm

Cold Inflation vs. Warm Inflation : **Hybrid**

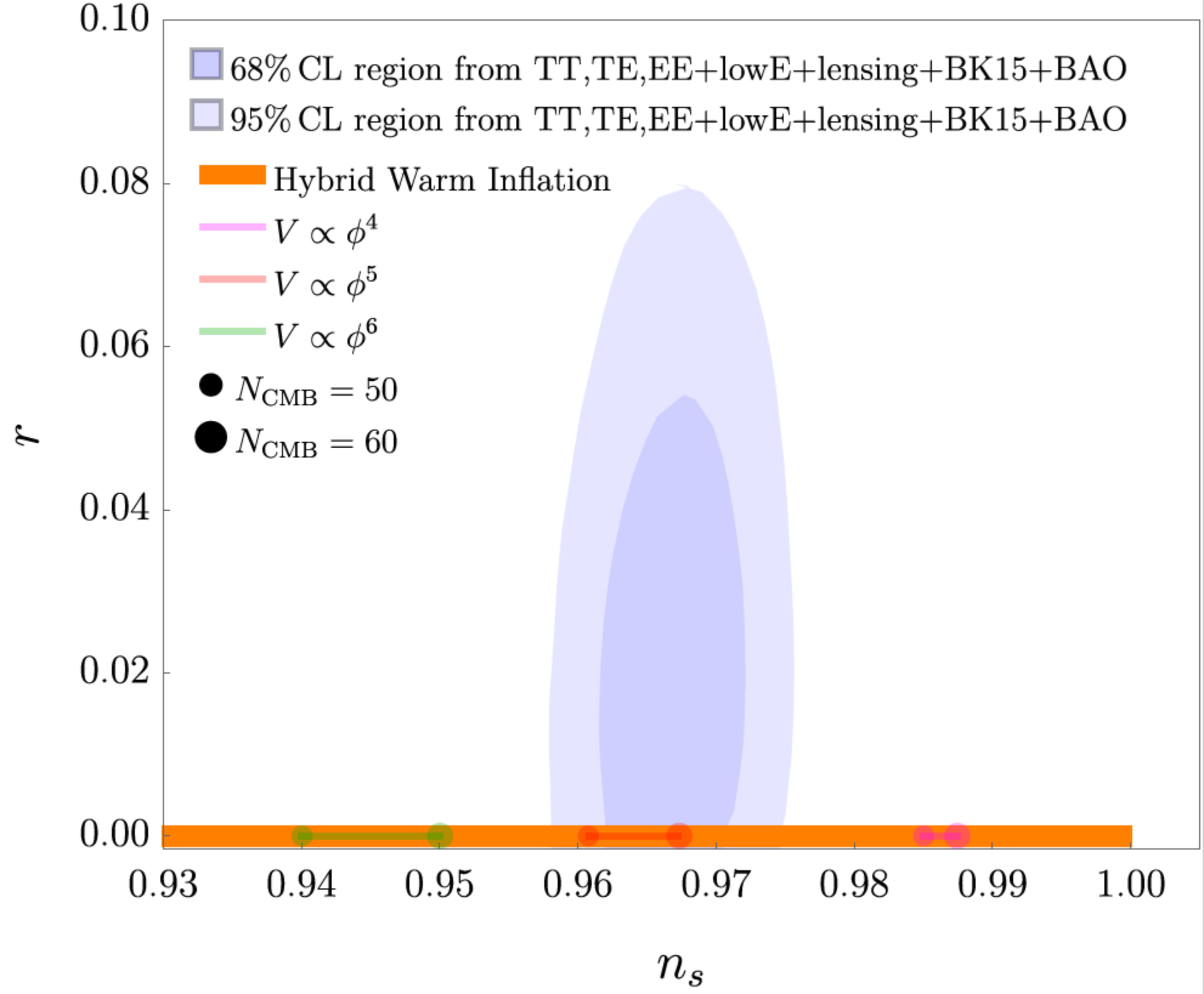


Cold



Warm

Warm Inflation

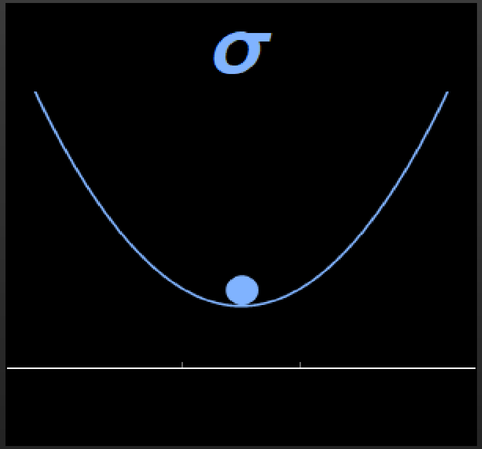


Berghaus et al. (arXiv: 1910.07525)

Hybrid Inflation

$$V = M_\sigma{}^4 + \frac{1}{2} m_\phi{}^2 \phi^2;$$

σ drives inflation



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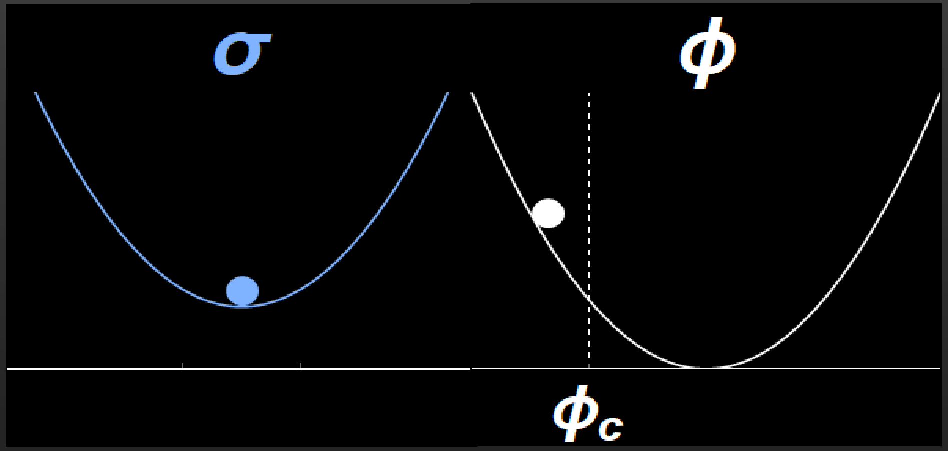

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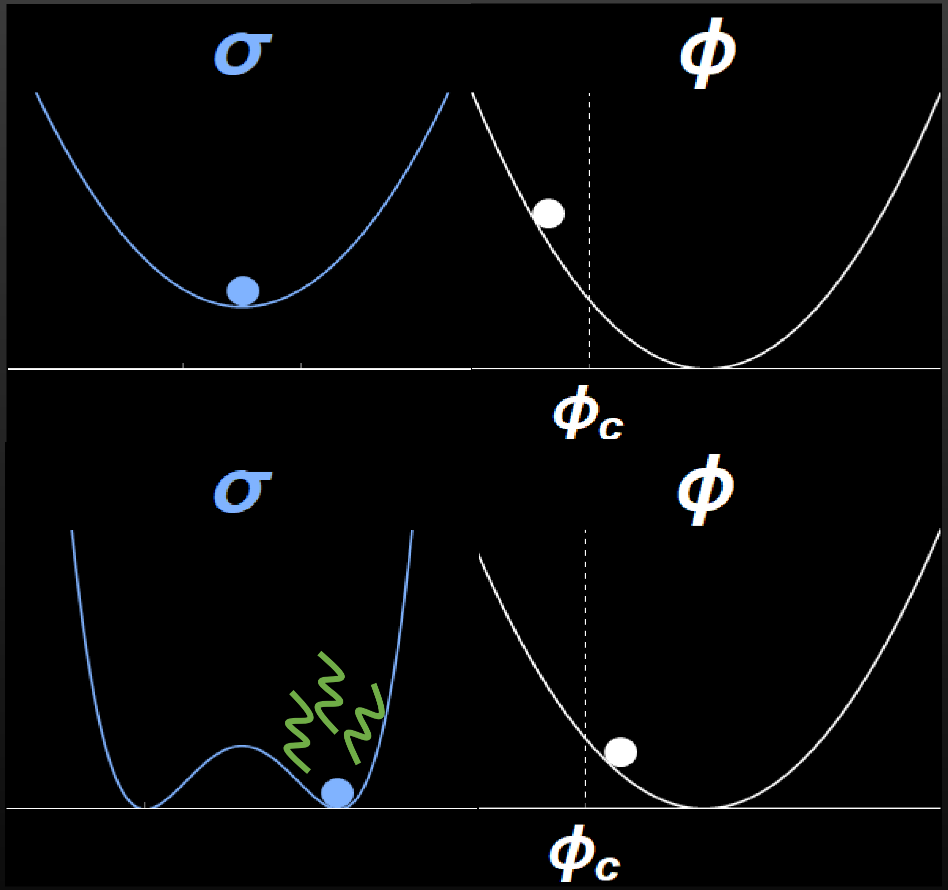
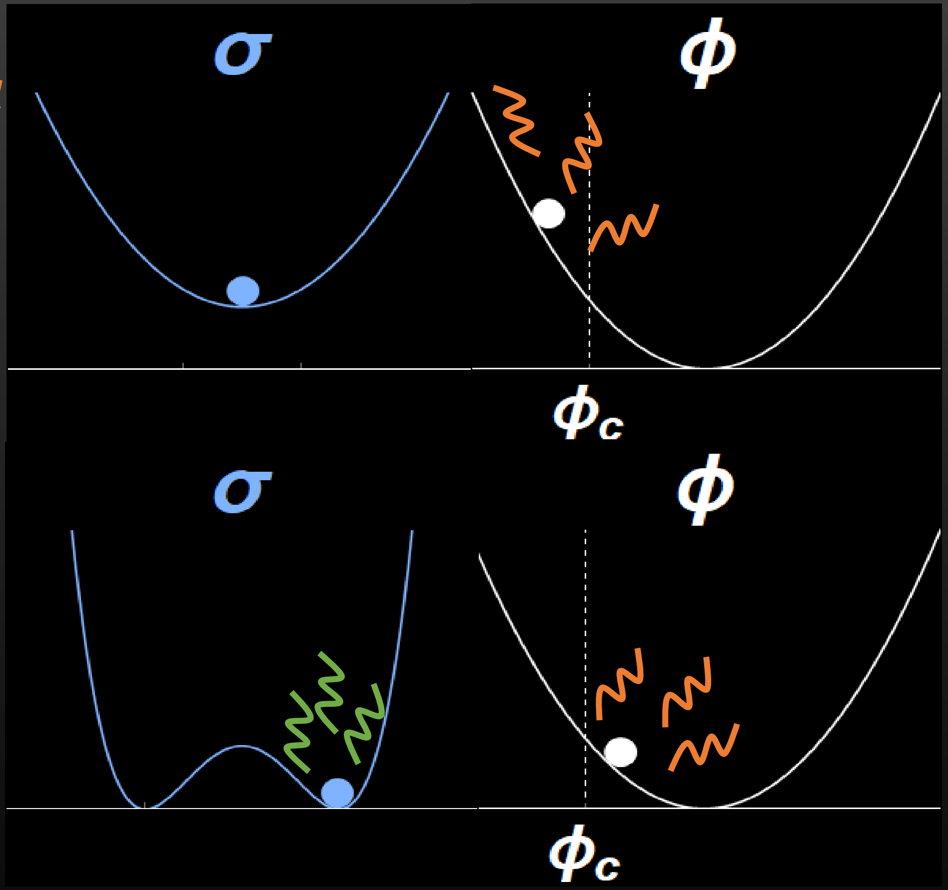
ϕ rolls towards ϕ_c

σ reheats into standard model



Hybrid **Warm** Inflation

$$V = M_\sigma{}^4 + \frac{1}{2} m_\phi{}^2 \phi^2 ; L_{int} = \frac{\alpha}{16\pi} \frac{\phi}{f} \tilde{G} G$$



σ drives inflation

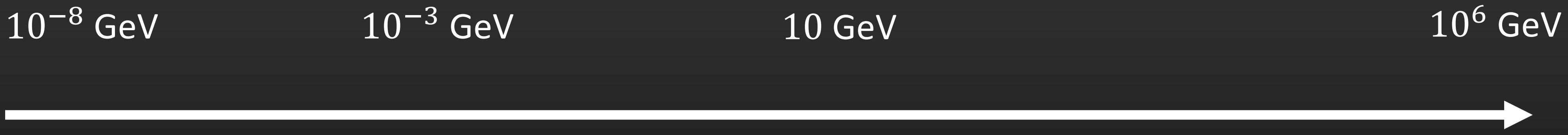
ϕ rolls towards ϕ_c

σ reheats into standard model

ϕ sources radiation bath

Reheating

Couple waterfall field to Standard Model: $\frac{\alpha_B \ \sigma}{16\pi f_B}\tilde{B}B$



Reheating

Couple waterfall field to Standard Model: $\frac{\alpha_B}{16\pi}\frac{\sigma}{f_B}\tilde{B}B$

10^{-8} GeV

10^{-3} GeV

10 GeV

10^{6} GeV

H

T

M_σ

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Hybrid warm inflation appealing theoretical candidate

testable on 10 year time scale

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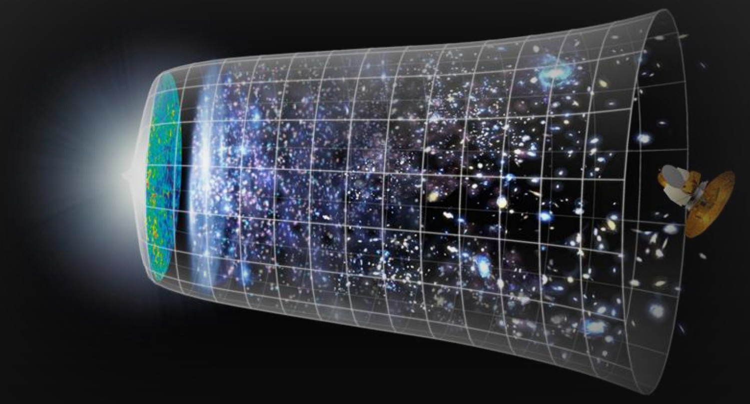
   - The Hubble Tension
   - Early Dark Energy

The Hubble Tension

H_0 is a measure of expansion rate of universe

Directly parameterizes amount of dark energy

$$\underbrace{\Lambda}_{\text{assumed to be a constant}}\text{CDM}$$



The Hubble Tension

H_0 is a measure of expansion rate of universe

Directly parameterizes amount of dark energy

$$\underbrace{\Lambda}_{\text{assumed to be a constant}}\text{CDM}$$

...but...

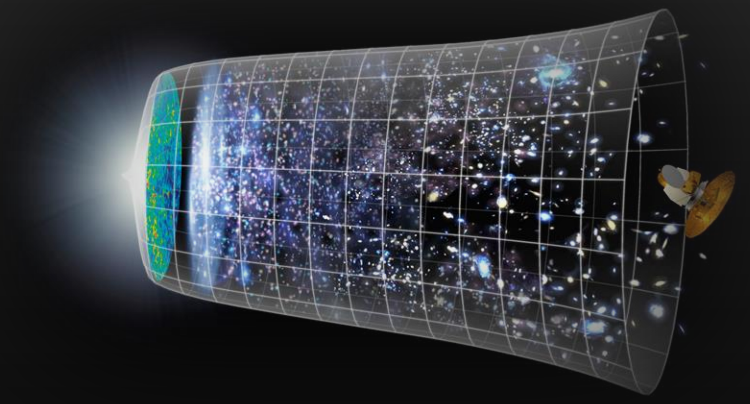
ΛCDM +
CMB measurement

$H_0 = 67.4 \pm 0.5$ km/s/Mpc

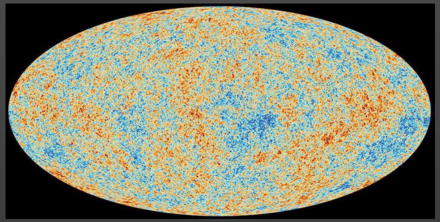
~ $4.4\,\sigma$ ⟷

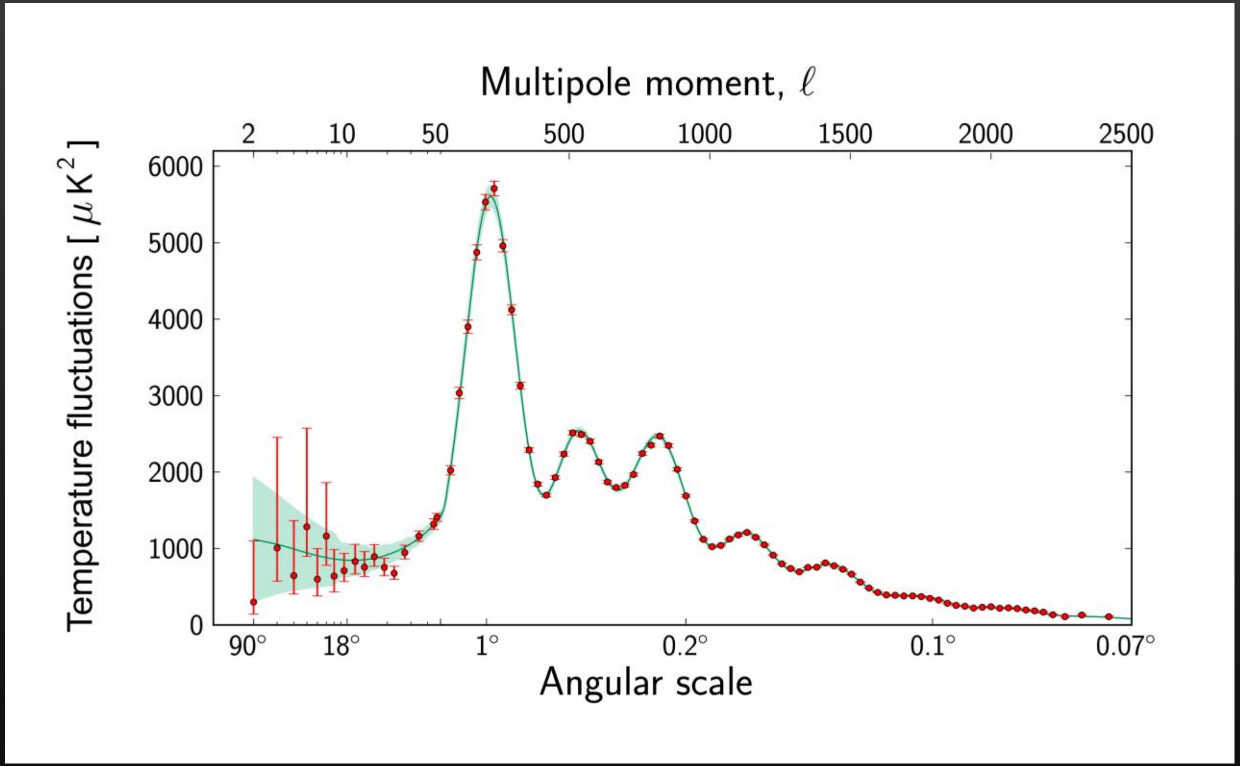
Direct
measurement

$H_0 = 74.03 \pm 1.42$ km/s/Mpc



The Hubble Measurement with the CMB





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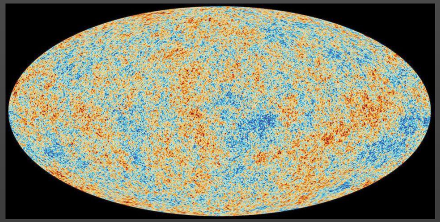
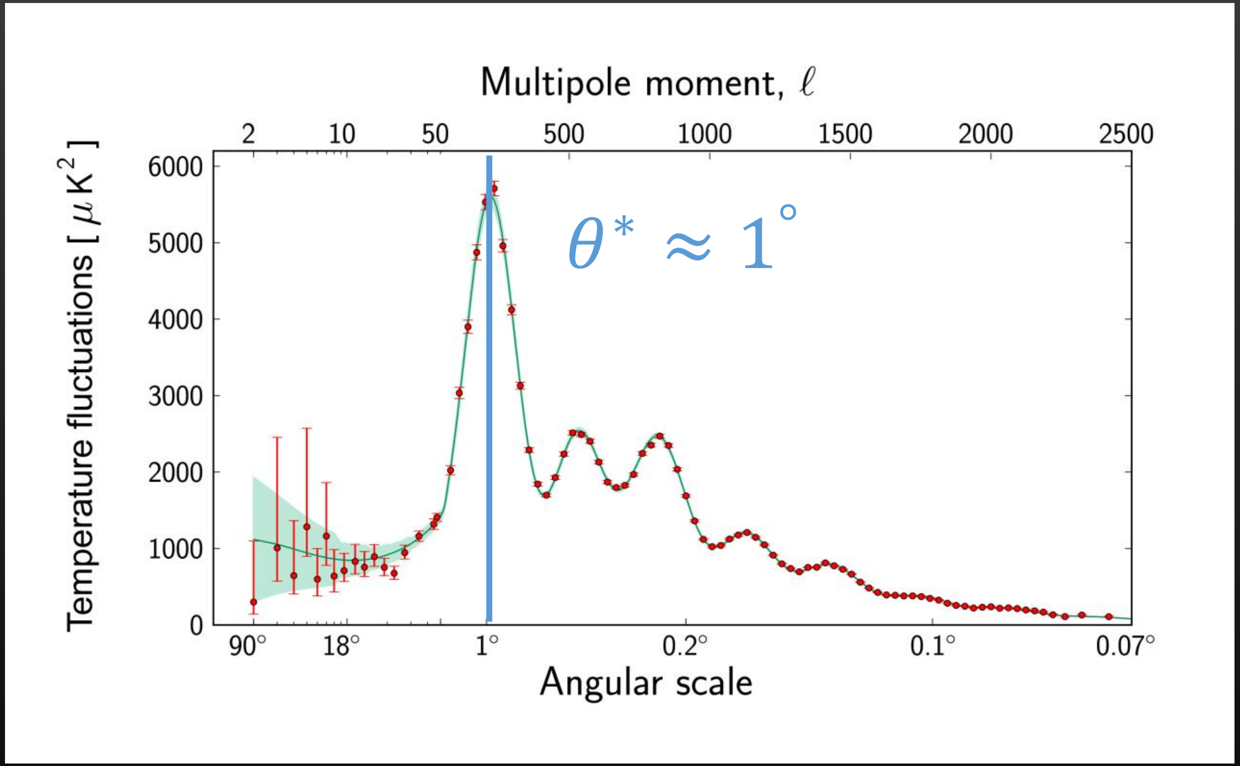
The Hubble Measurement with the CMB



$$\theta^* \propto r_s H_0$$



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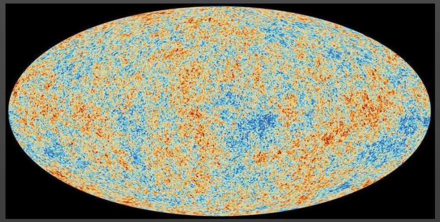
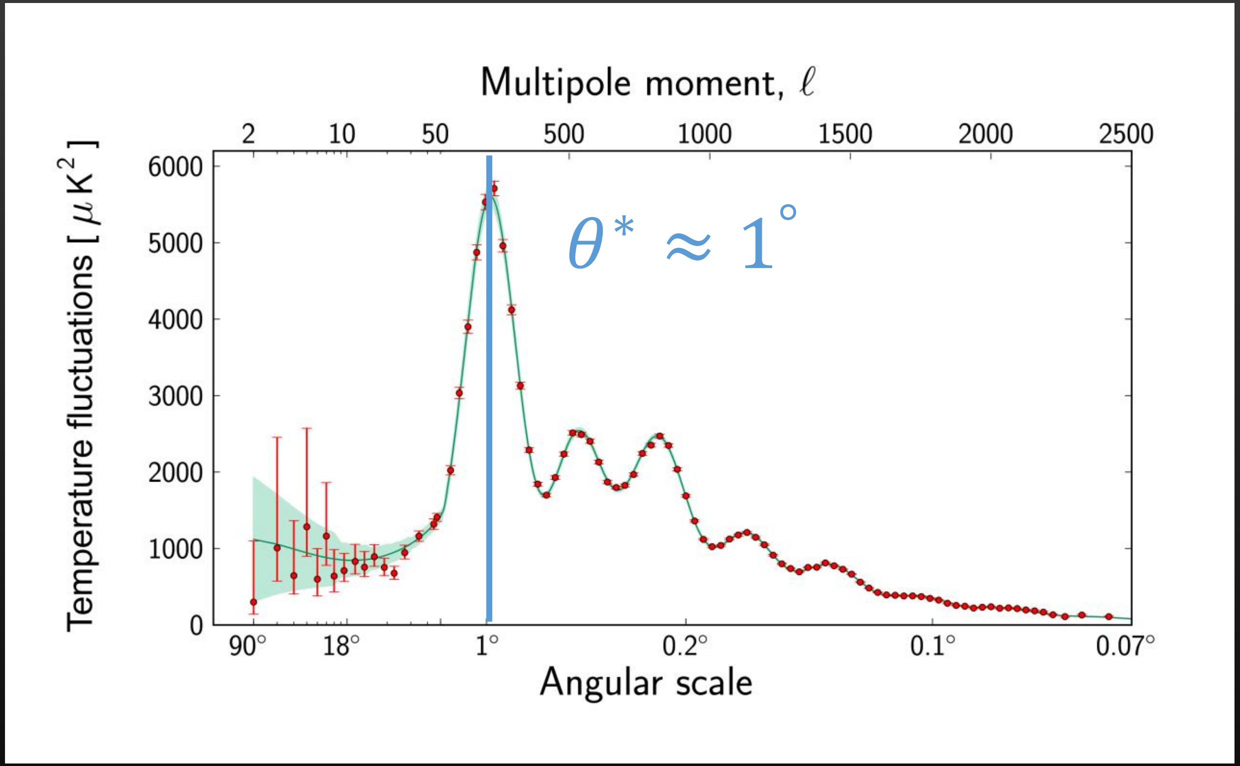


$$\theta^* \propto r_s H_0$$

- r_s depends only on physics before formation of CMB



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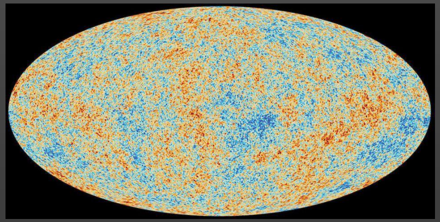
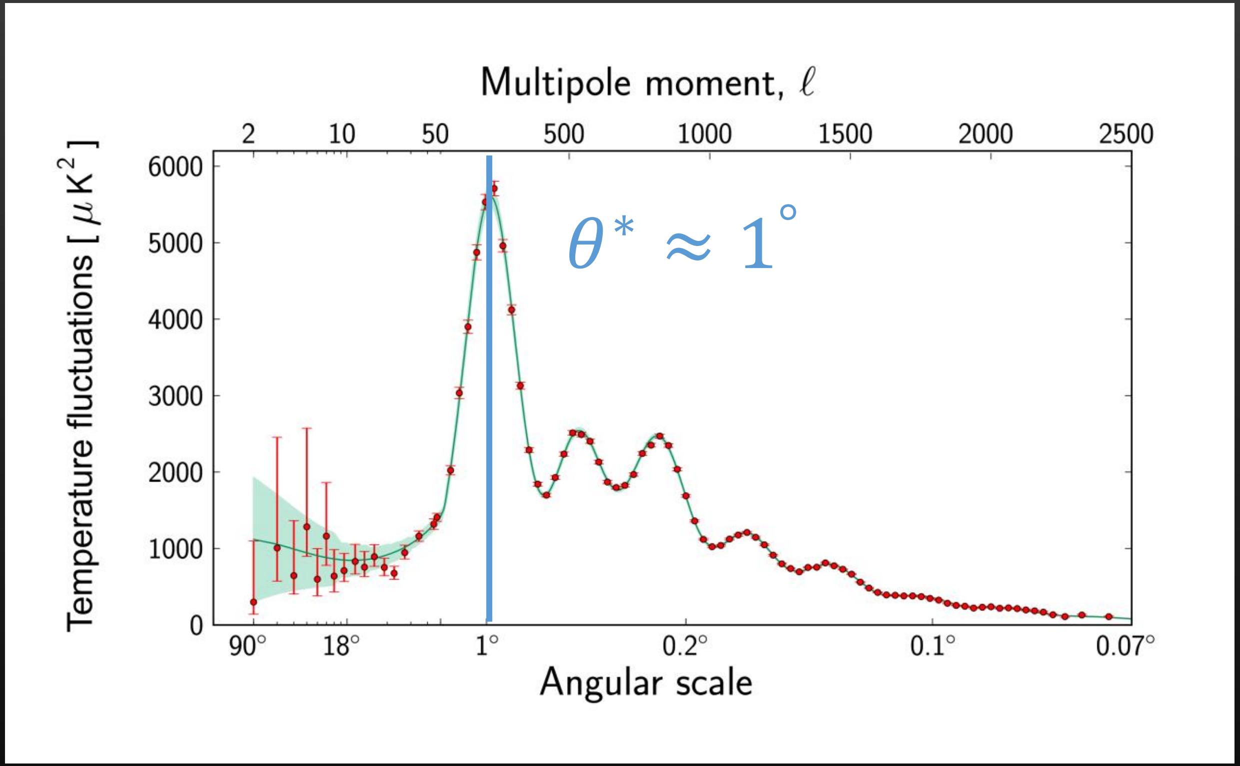
The Hubble Measurement with the CMB



$$\theta^* \propto r_s H_0$$

- r_s depends only on physics before formation of CMB
- Lowering r_s increases H_0



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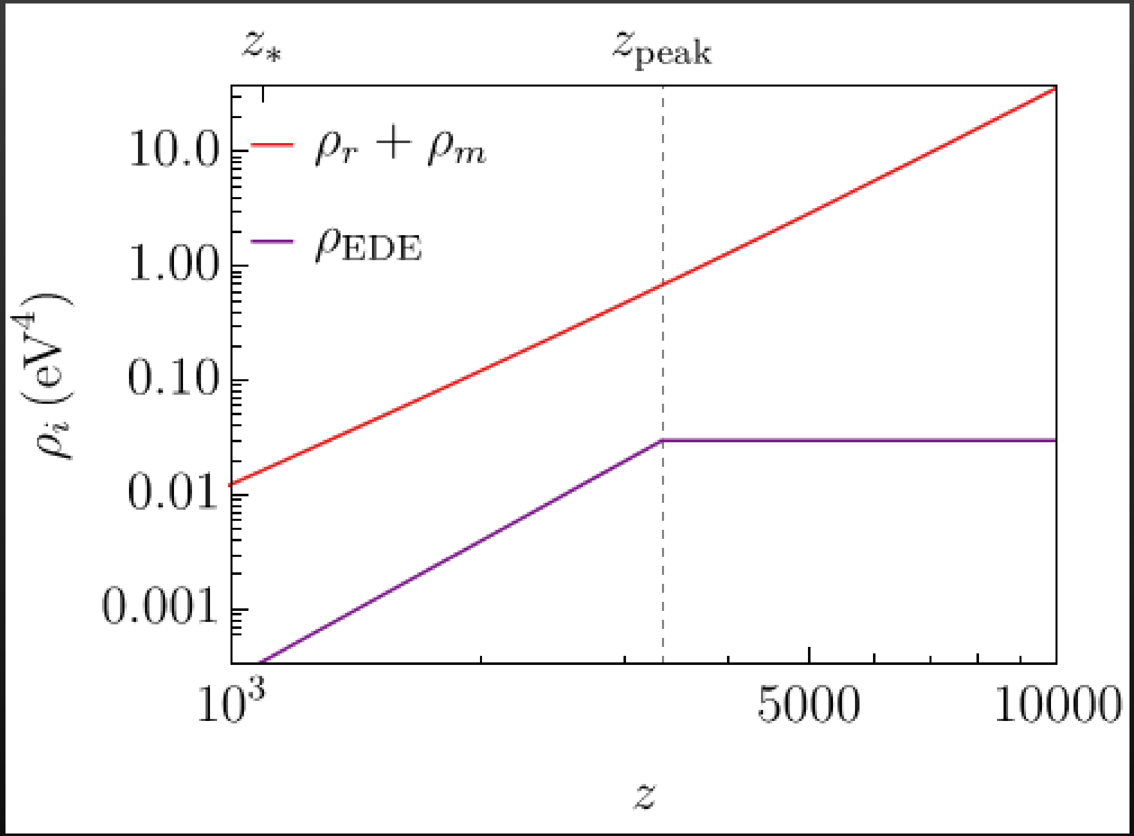
Early Dark Energy (EDE)



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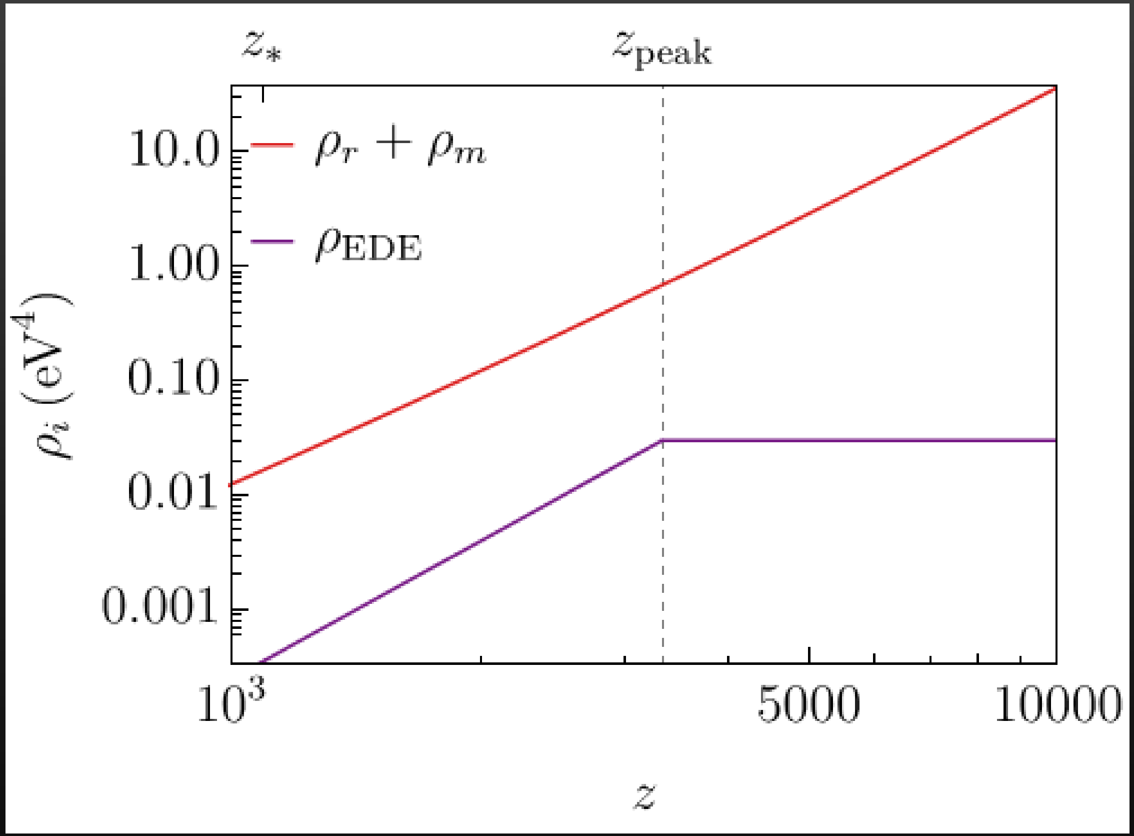
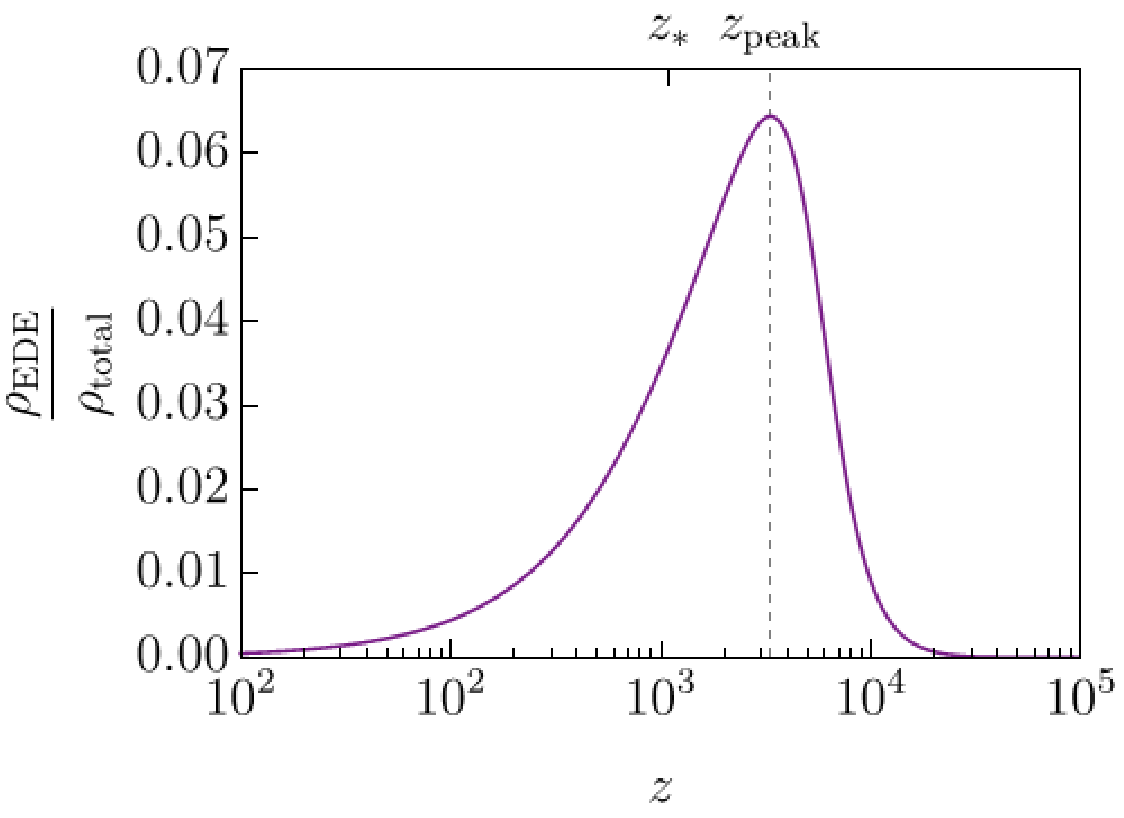
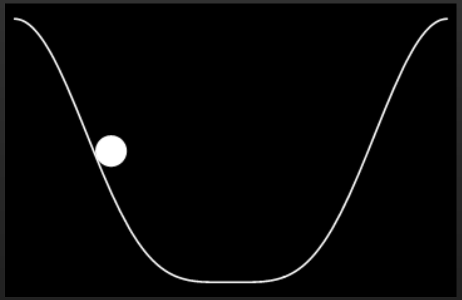




EDE Scalar Field Models

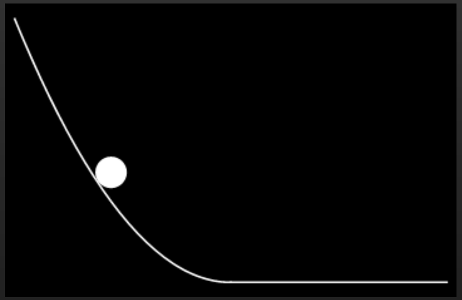
Requirement: Dilute as radiation or faster



Oscillatory

$$V \propto \left(1 - \cos\frac{\phi}{f}\right)^n$$

$n \geq 2$



Non-oscillatory

$$\underbrace{\hspace{10em}}_{\text{Phenomenological Solutions}}$$

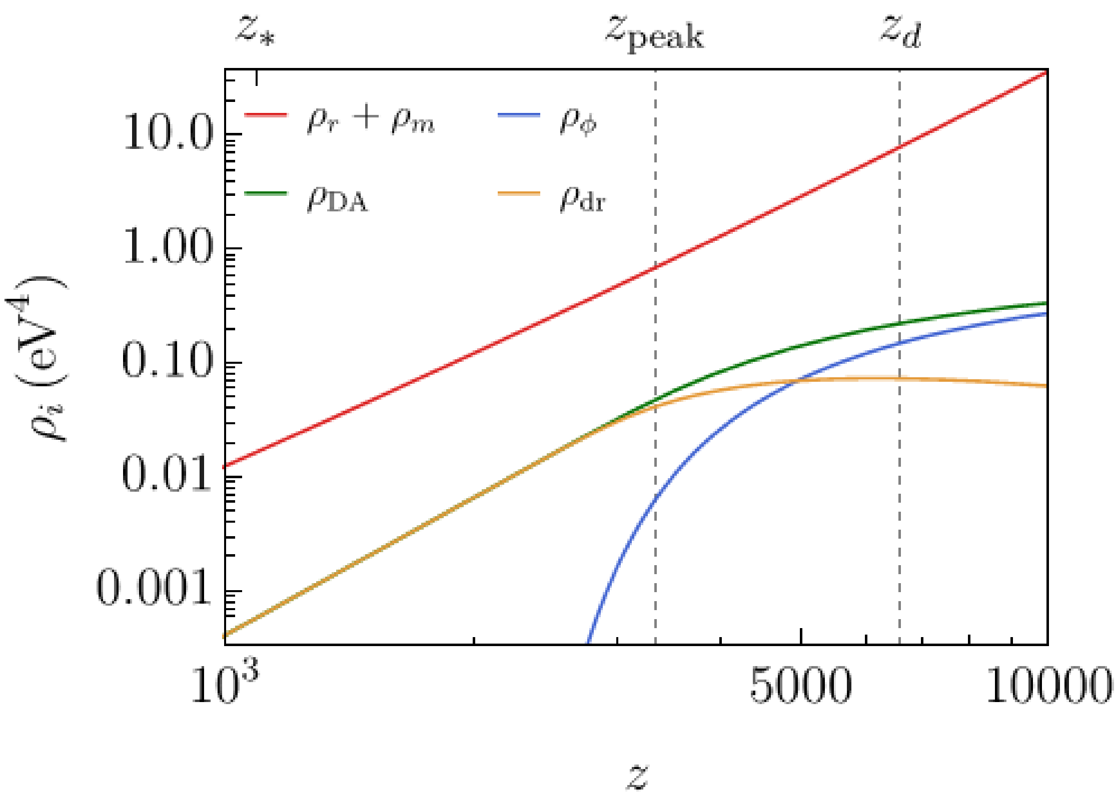
The Dissipative Axion as Early Dark Energy

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

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^{\,2}$$

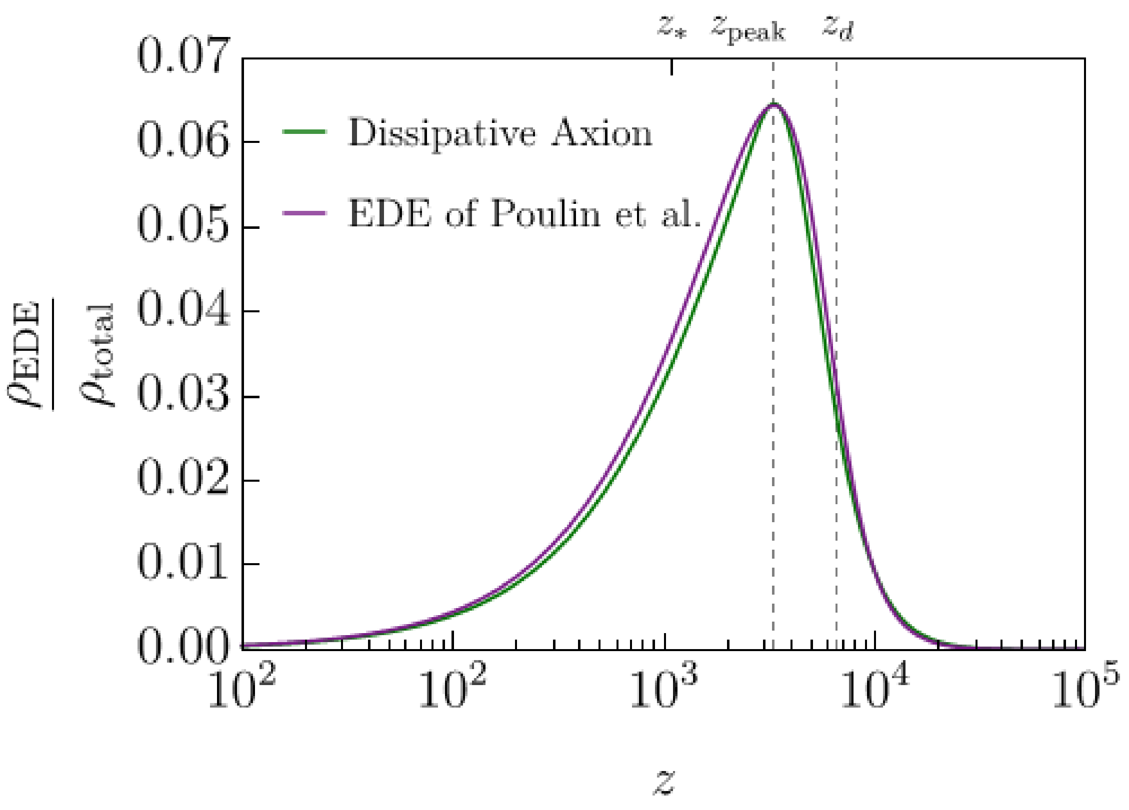
Add Axion and dark SU(N)

No restrictions on potential

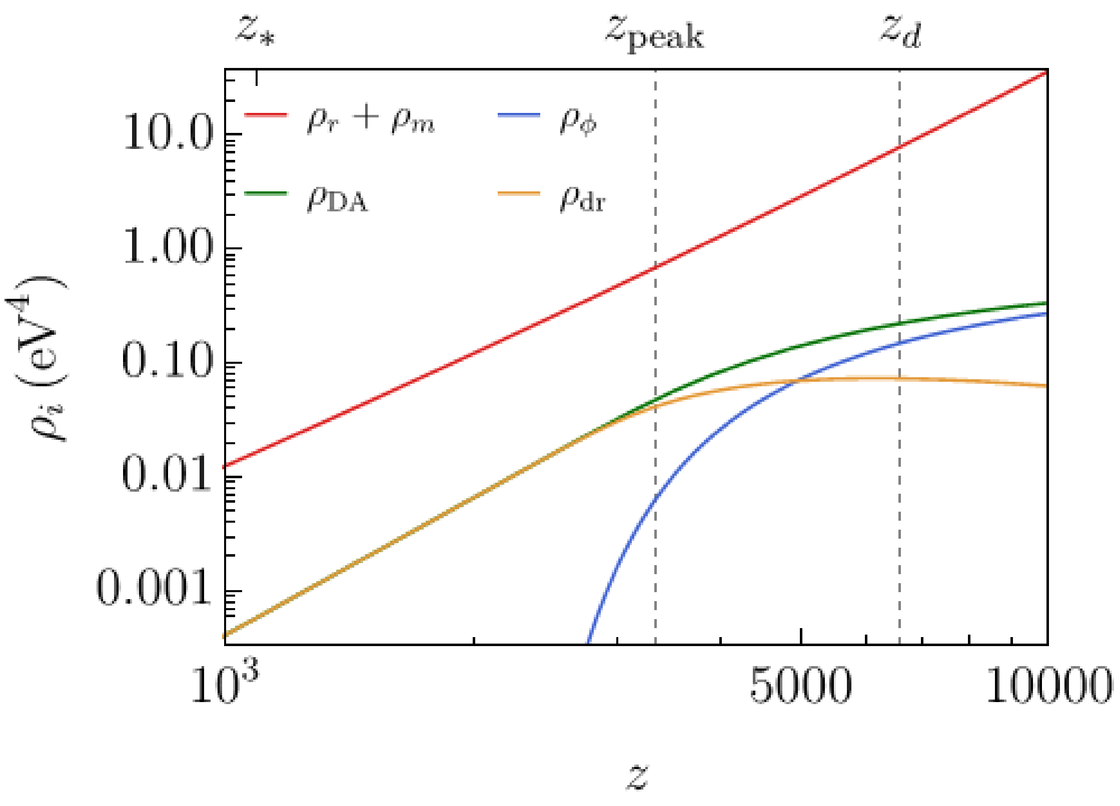


Berghaus et al. 1911:06281

The Dissipative Axion as Early Dark Energy

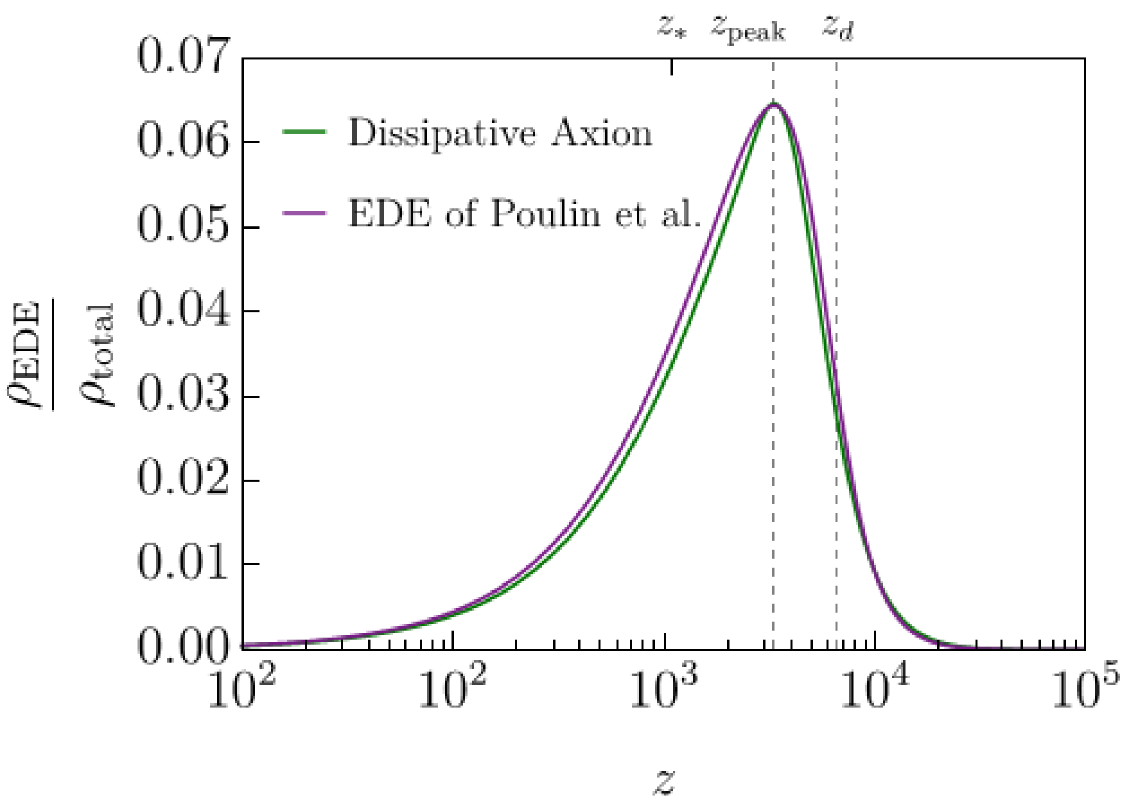


Berghaus et al. 1911:06281



Berghaus et al. 1911:06281

The Dissipative Axion as Early Dark Energy



Berghaus et al. 1911:06281

$$\theta^* \propto r_s H_0$$

r_s = 145 Mpc

H_0 = 67.4 km/s/Mpc

ΛCDM

r_s = 140 Mpc

H_0 = 71.1 km/s/Mpc

EDE

Poulin et al. 1811.04083v2

The Dissipative Axion as Early Dark Energy

Mimics EDE at background level

$$\theta^* \propto r_s H_0$$

$r_s = 145$ Mpc

$H_0 = 67.4$ km/s/Mpc

ΛCDM

Future Work:

- Full implementation of perturbations in CLASS
- Model building to address injection time of EDE

$r_s = 140$ Mpc

$H_0 = 71.1$ km/s/Mpc

EDE

Poulin et al. 1811.04083v2

Content

1. The Dissipative Axion
2. A Simple Model of Warm Inflation
3. A Particle Solution of the Hubble Tension

The Dissipative Axion can act like Early Dark Energy

Including dynamics in the dark sector avoids fine-tuned potentials

Summary

1. The Dissipative Axion
2. A Simple Model of Warm Inflation
3. A Particle Solution of the Hubble Tension

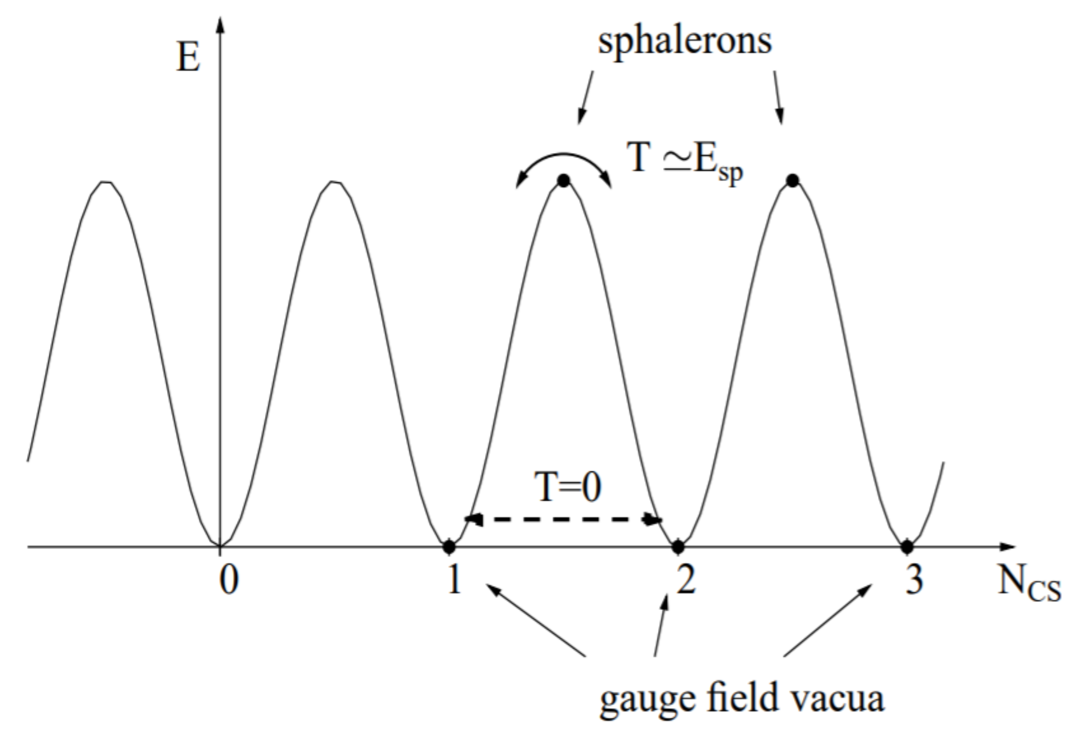
Mechanism to produce radiation sourcing friction for rolling Axion field

Leads to a minimal model of warm inflation with unique observables

Is a well motivated particle candidate for solving the Hubble tension

Back-up

The Axion Friction



Herranen, arXiv:0906.3136

Sphaleron transitions give rise to a large friction Υ :

$$\Upsilon \propto \alpha^5 \frac{T^3}{f^2}$$

Topological back-reaction

This quantity is well known in the literature because it determines the axion mass

χ(T)=$m_a^2(T) f_a^2$

Rapidly falls off at temperatures above the confinement scale as $\sim T^{-7}$

$$m_a^2(T) = \frac{T_c^4}{f_a^2}\left(\frac{T}{T_c}\right)^7$$

Axion has large friction with negligible back-reaction