Title: Thermal Friction in Early Cosmology

Speakers: Kim Berghaus

Series: Particle Physics

Date: November 17, 2020 - 1:00 PM

URL: http://pirsa.org/20110058

Abstract: Rolling scalar fields play an important role in understanding cosmology within a particle physics framework. Coupling a rolling scalar field to light degrees of freedom gives rise to a thermal friction which, if large enough, induces a thermal bath. In the context of inflation the presence of such a thermal bath has compelling consequences as it significantly alters the usual observables, leading to a suppression of the tensor-to-scalar ratio r and a unique prediction for non-gaussianities. In my talk, I will illuminate why the axion of a non-Abelian gauge group is the ideal candidate for generating the thermal friction and how it sets the stage for a minimal setup of warm inflation, as well as a potential solution to the Hubble tension.

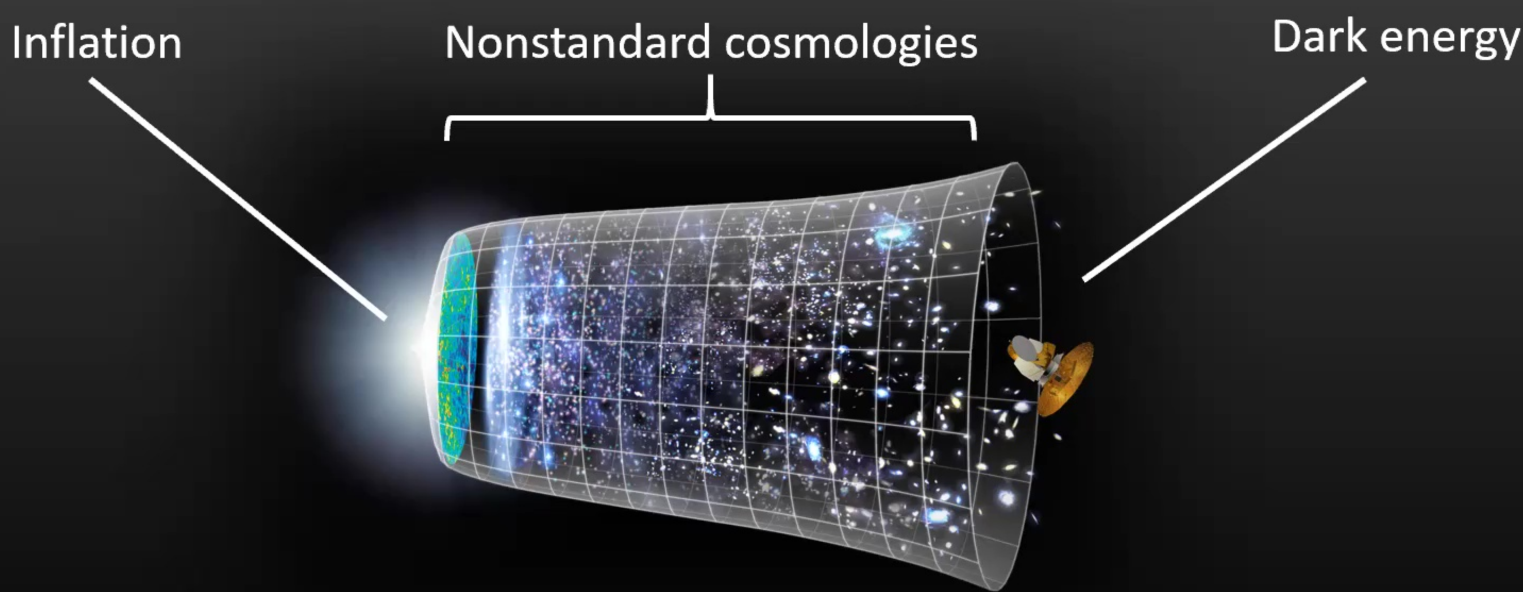
Thermal Friction in Early Cosmology

Kim V. Berghaus, YITP Stony Brook

Content

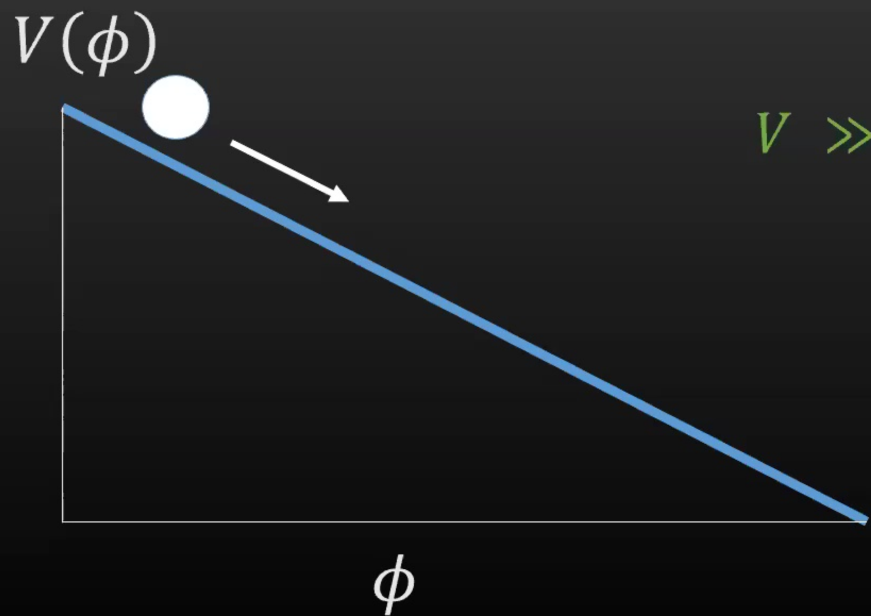
1. The Dissipative Axion
2. Minimal Warm Inflation
3. A Particle Solution of the Hubble Tension

Rolling Scalar Fields in Cosmology



Rolling Scalar Fields in Cosmology

Condition for accelerated expansion: $\frac{P}{\rho} \approx -1$ negative pressure



$$V \gg \frac{1}{2}\dot{\phi}^{2}$$

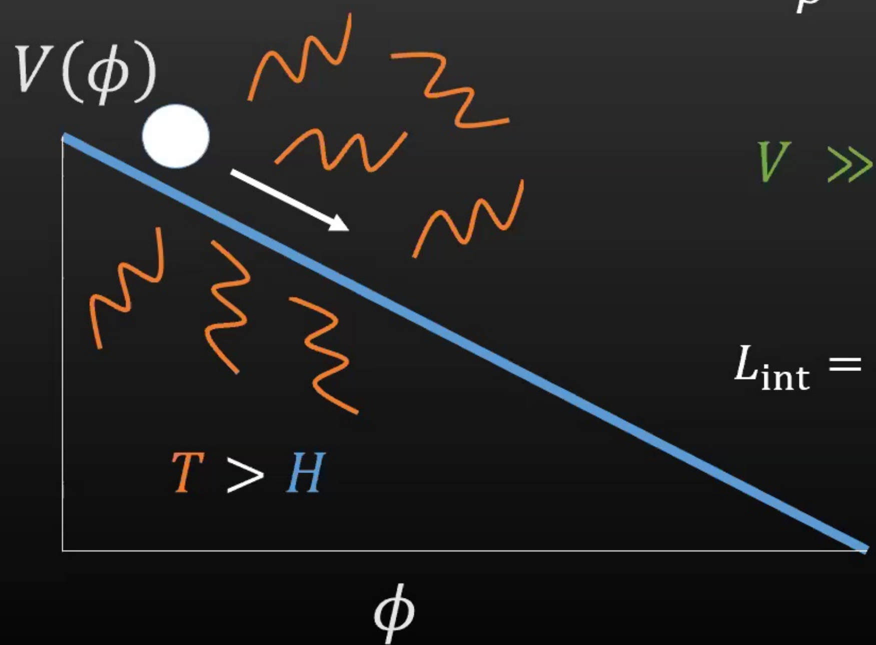
$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Hubble friction

Rolling Scalar Fields in Cosmology

Condition for accelerated expansion: $\frac{P}{\rho} \approx -1$

negative pressure



$$V \gg \frac{1}{2}\dot{\phi}^{\,2}$$

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

thermal friction

$$L_{\text{int}} = -\phi\, J_{\text{int}}$$

Thermal Friction

$$\frac{\partial L}{\partial \phi} - \frac{d}{dt}\frac{\partial L}{\partial \dot{\phi}} = 0$$

- Couple scalar fields to light degrees of freedom $L_{\text{int}} = -\phi\, J_{\text{int}}$

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\langle J_{int} \rangle_{\text{non-eq}}(\phi)$$

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$$\langle J_{int} \rangle_{\text{non-eq}}(\phi) \approx m_{th}^2 \phi + \Upsilon \dot{\phi} + O(\ddot{\phi})$$

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$$f(\langle J_{\mathrm{int}}\rangle_{\mathrm{eq}}) \qquad f(\langle J_{\mathrm{int}} J_{\mathrm{int}}\rangle_{\mathrm{eq}})$$

Thermal Friction

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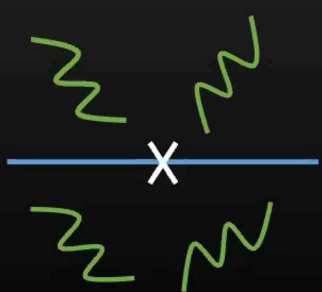
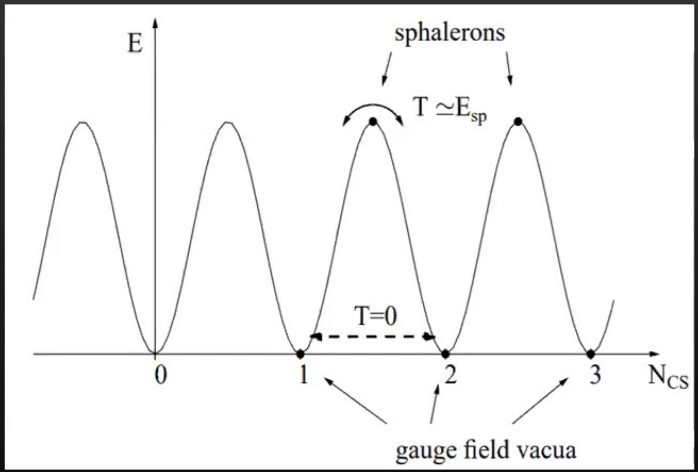


$f(\langle J_{\text{int}} \rangle_{\text{eq}})$ $\propto T^n$

$f(\langle J_{\text{int}} J_{\text{int}} \rangle_{\text{eq}})$ $\propto (\Delta T)^{n-1}$

The Dissipative Axion

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



Herranen, arXiv:0906.3136

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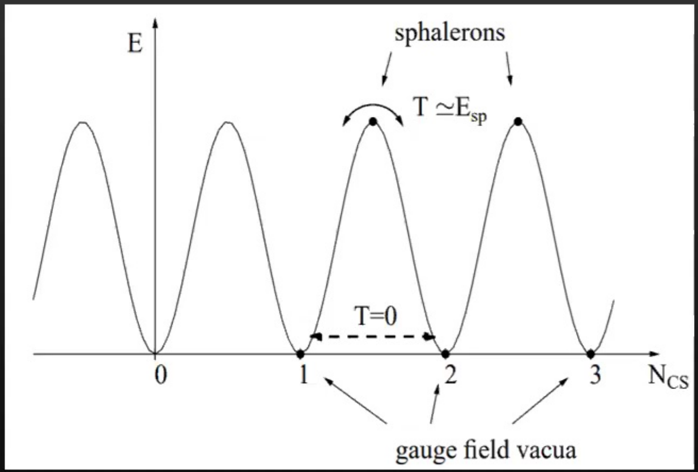

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$$\Upsilon \propto \langle \Delta N_{CS}{}^2 \rangle$$

- Large friction due to non-perturbative effect

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

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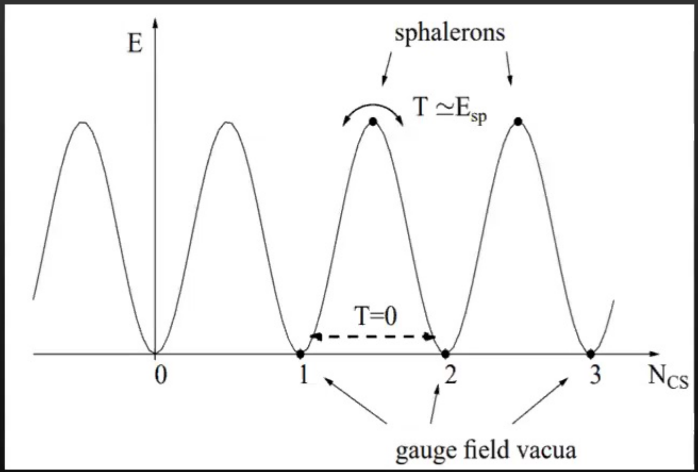

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$$\Upsilon \propto \langle \Delta N_{CS}{}^2 \rangle$$

- Large friction due to non-perturbative effect

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

- No mass correction due to symmetry

Content

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

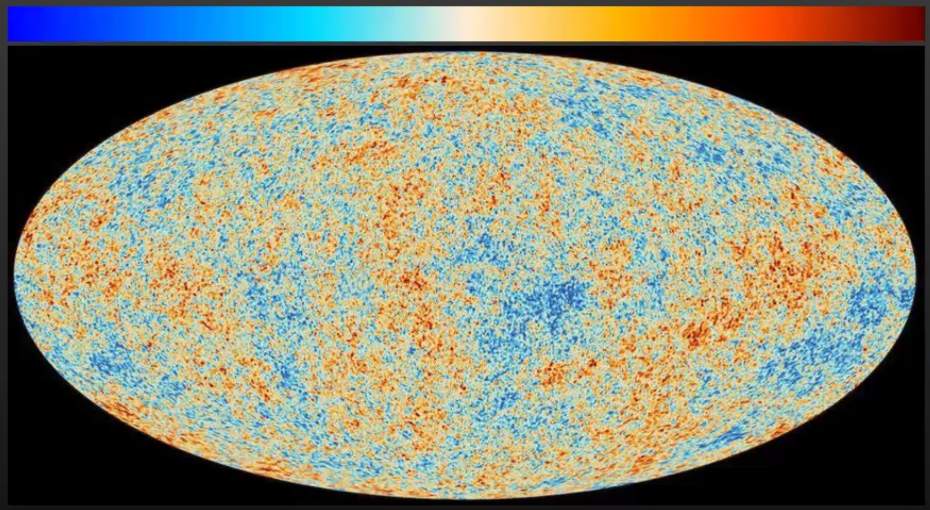
Dissipative Axion produces large friction without unwanted side effects

Content

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

Why Inflation?

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



Planck 2018

- Universe is isotropic
- Universe is flat

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:
- $$\Delta_R^2(k) = \underbrace{A_s}_{\sim 10^{-9}} \left(\frac{k}{k_*}\right)^{n_s - 1}$$ $n_s - 1 \approx -0.035$

Slow-roll Inflation

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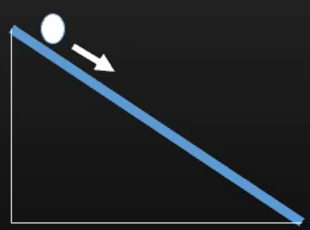
- $$\Delta_R^2(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

  $A_s \sim 10^{-9}$, $\quad n_s - 1 \approx -0.035$

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

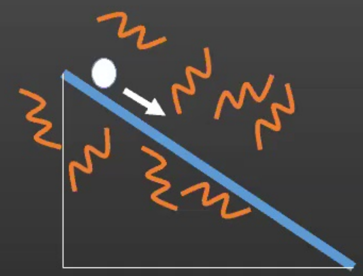


$$\varepsilon_V = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

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

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

Warm Inflation

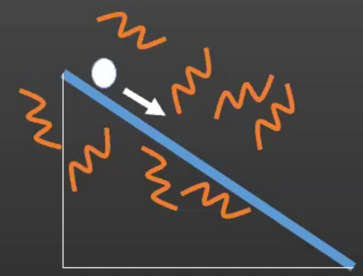


- $\delta\phi_{thermal} > \delta\phi_{quantum}$ $\qquad T_{eq} > H$
- Friction continuously extracts energy from rolling field to maintain an equilibrium temperature

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

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

Warm Inflation



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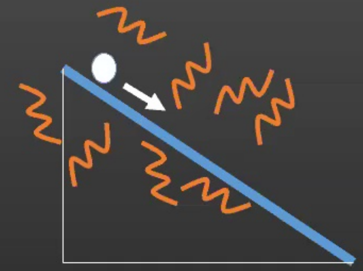
Steady state:

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

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

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

Warm Inflation



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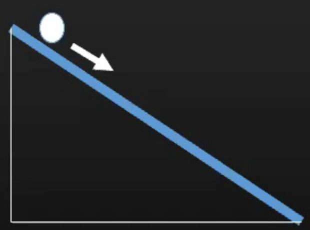
} Attractor solution

Cold Inflation vs. Warm Inflation

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



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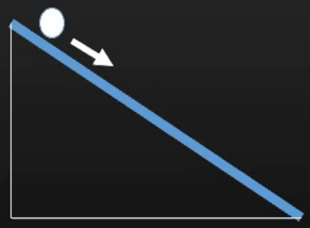

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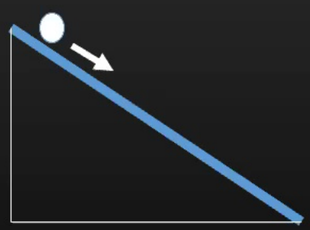

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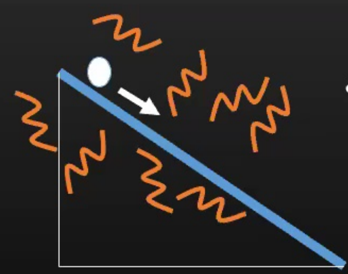
- $\Delta_R^2(k) \propto \delta\phi^2 \propto H\, T \left(\frac{\Upsilon}{3H}\right)^{\frac{19}{2}}$
- Tensor to scalar ratio $\mathrm{r} \approx 0$



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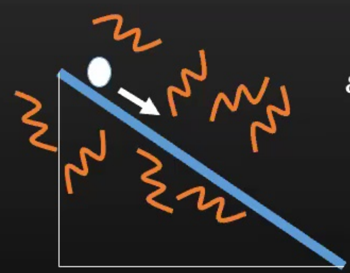
- Small non-gaussianities

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



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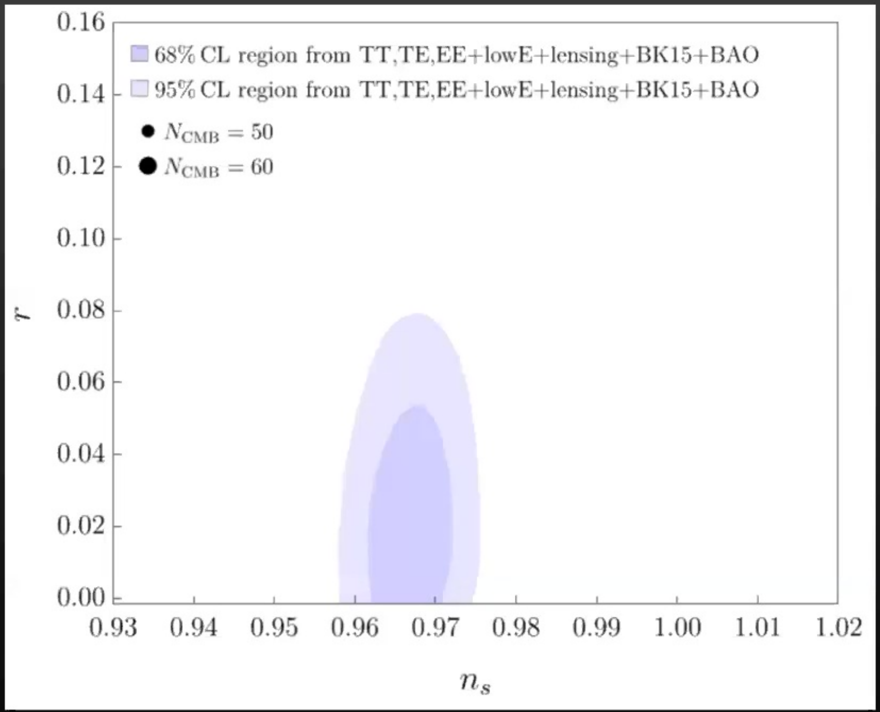
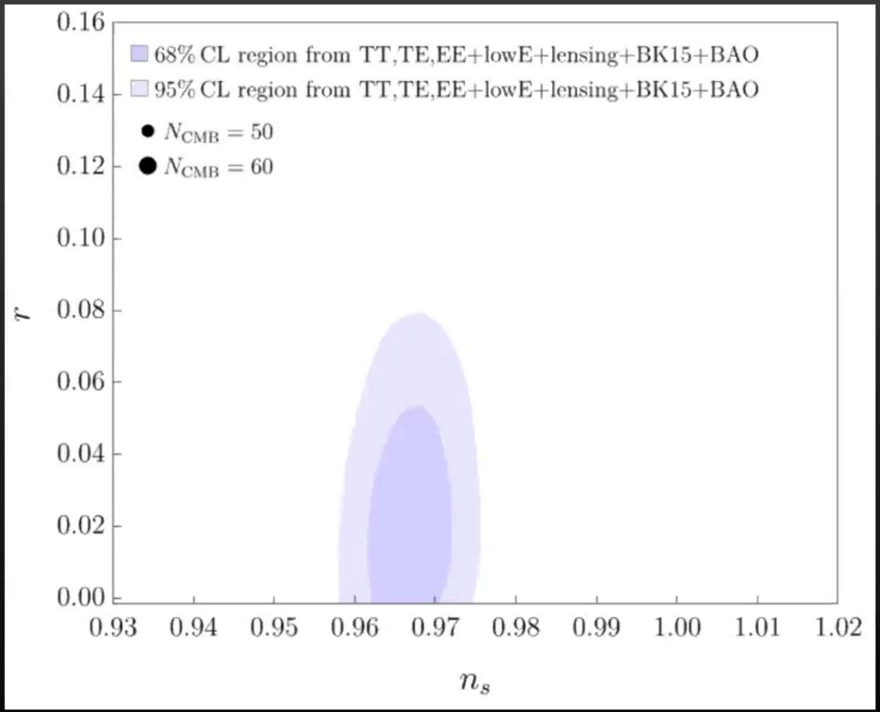
- Sizeable non-gaussianities $f_{NL} \approx 1.5$
- Unique bispectral shape

Cold Inflation vs. Warm Inflation

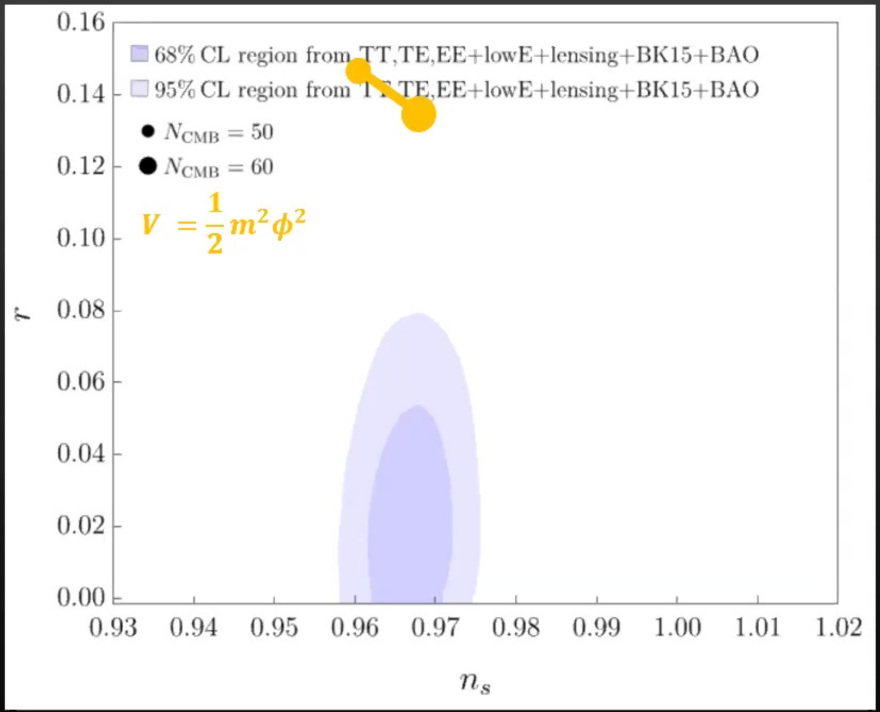


Cold

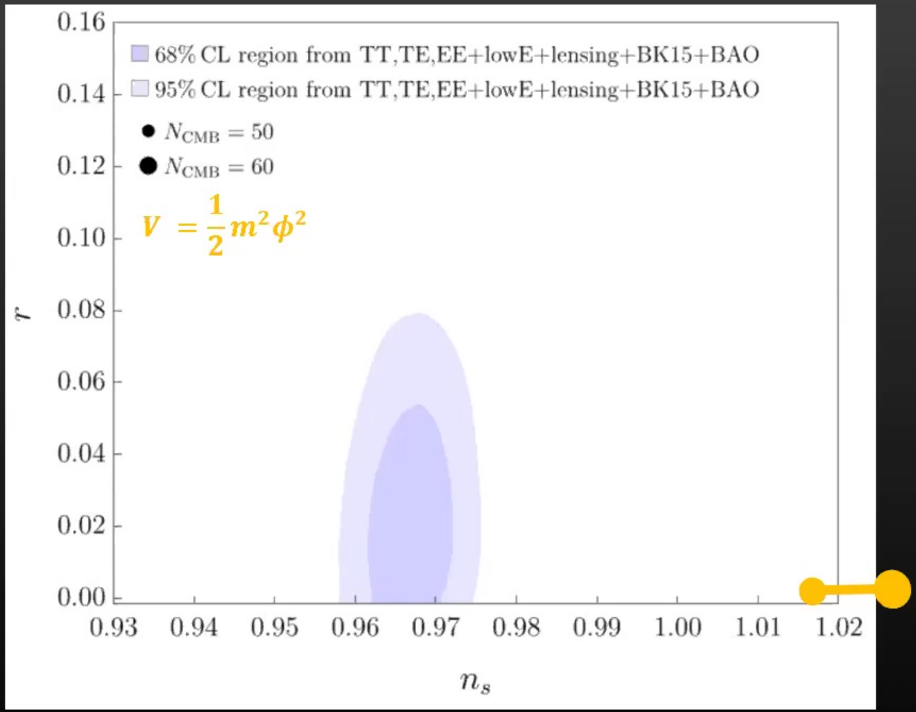


Warm

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

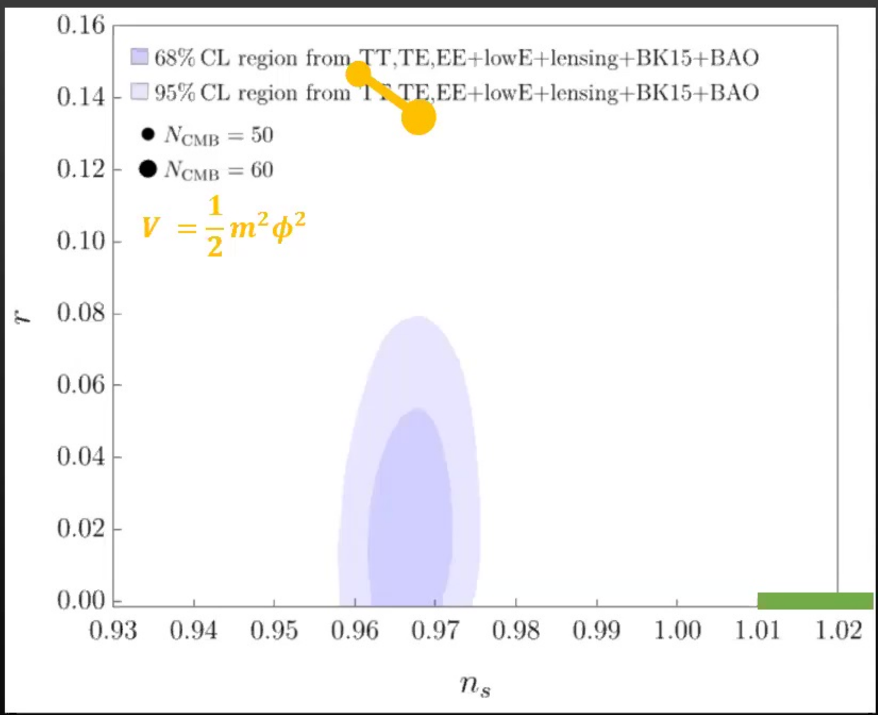


Cold

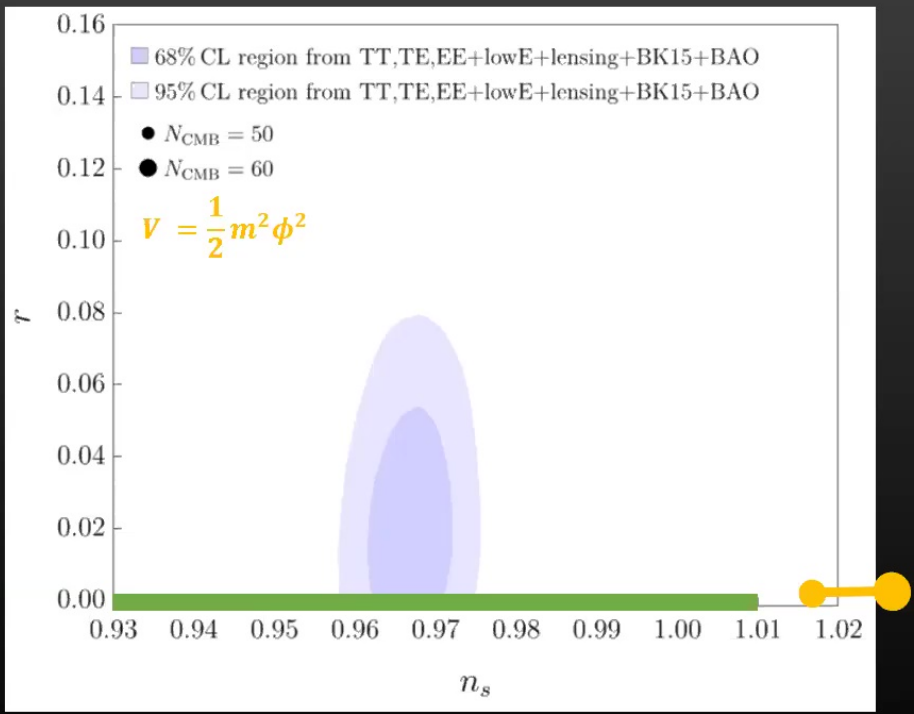


Warm

Cold Inflation vs. Warm Inflation : Hybrid

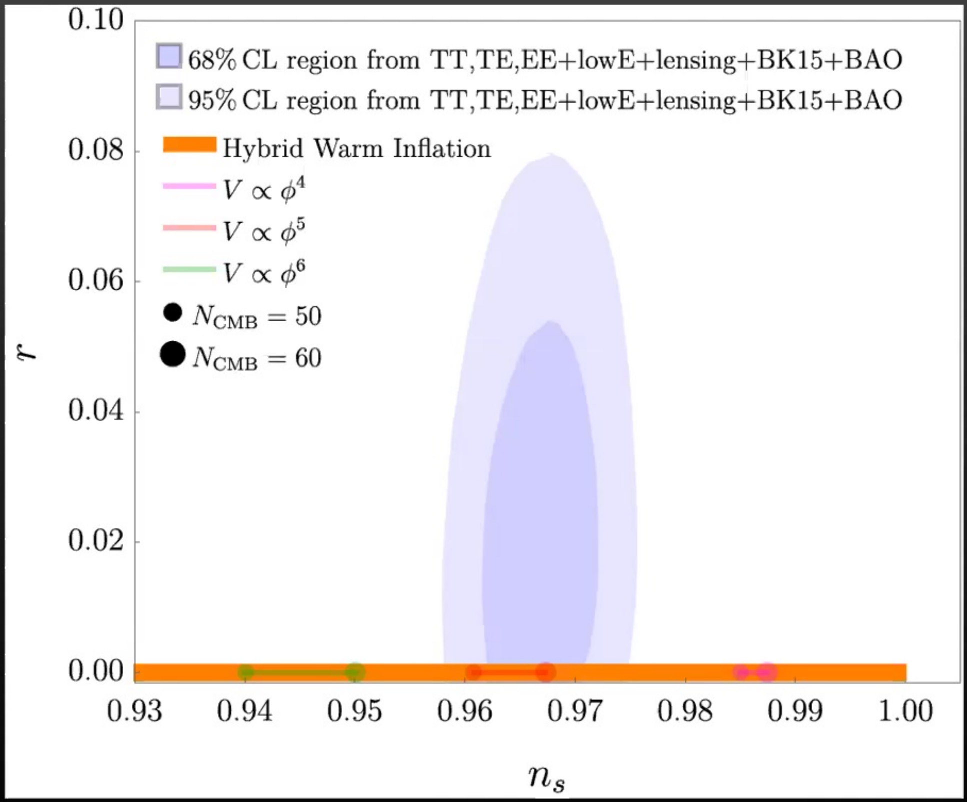


Cold



Warm

Warm Inflation

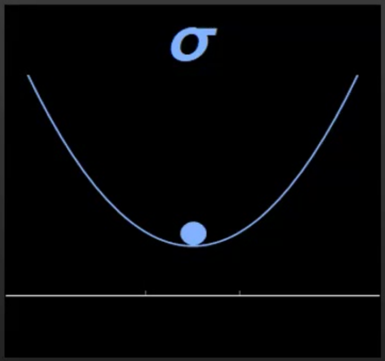


Berghaus et al. (JCAP 03 (2020) 034)

Hybrid Inflation

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

σ drives inflation



Hybrid Inflation

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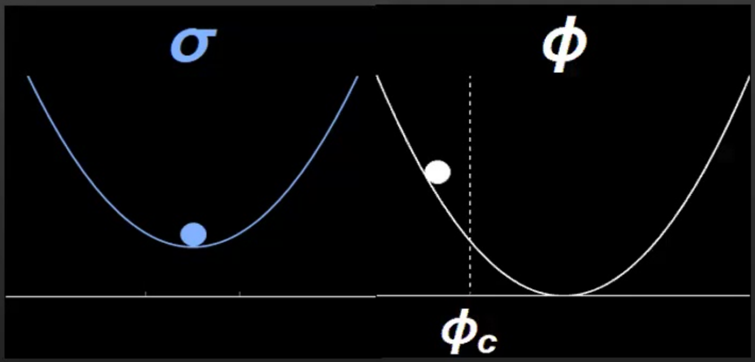
ϕ rolls towards ϕ_c



Hybrid Inflation

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

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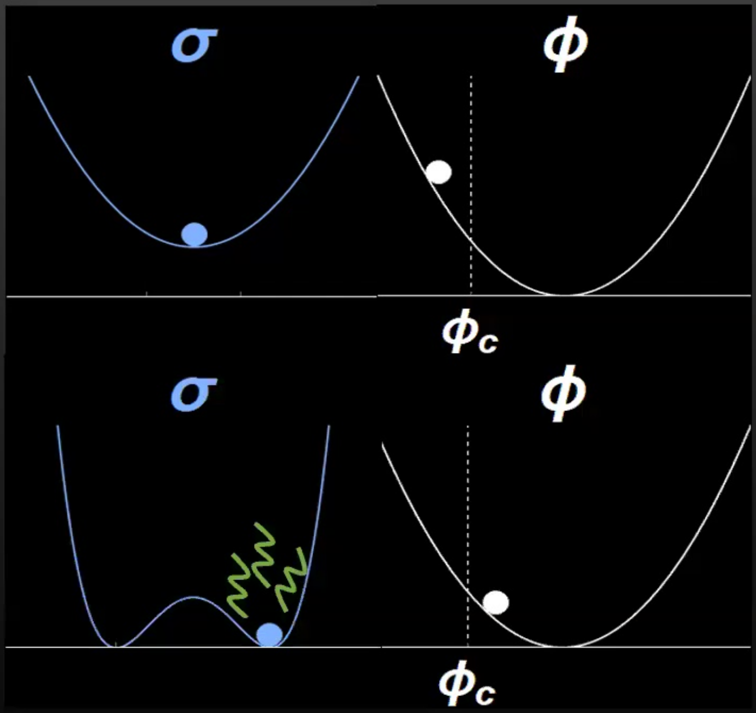
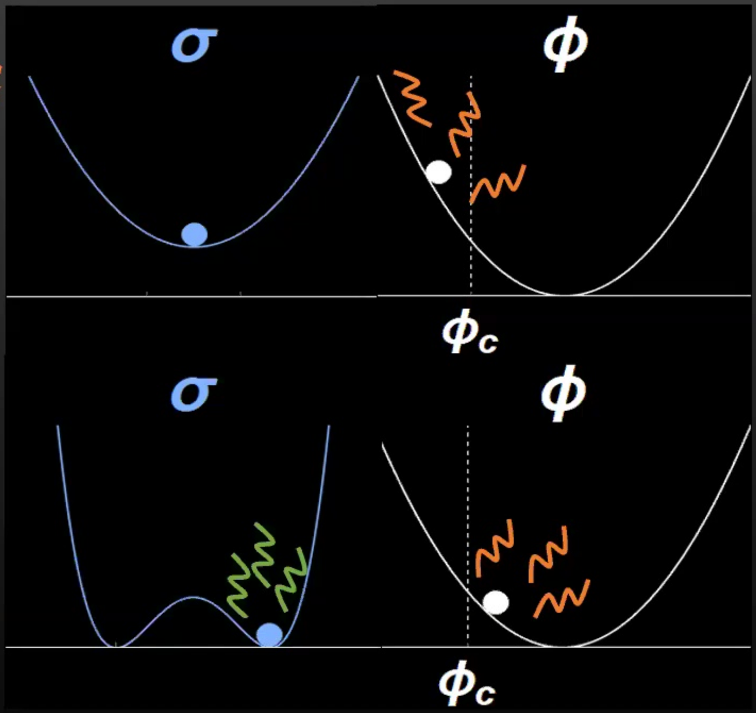
ϕ rolls towards ϕ_c

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

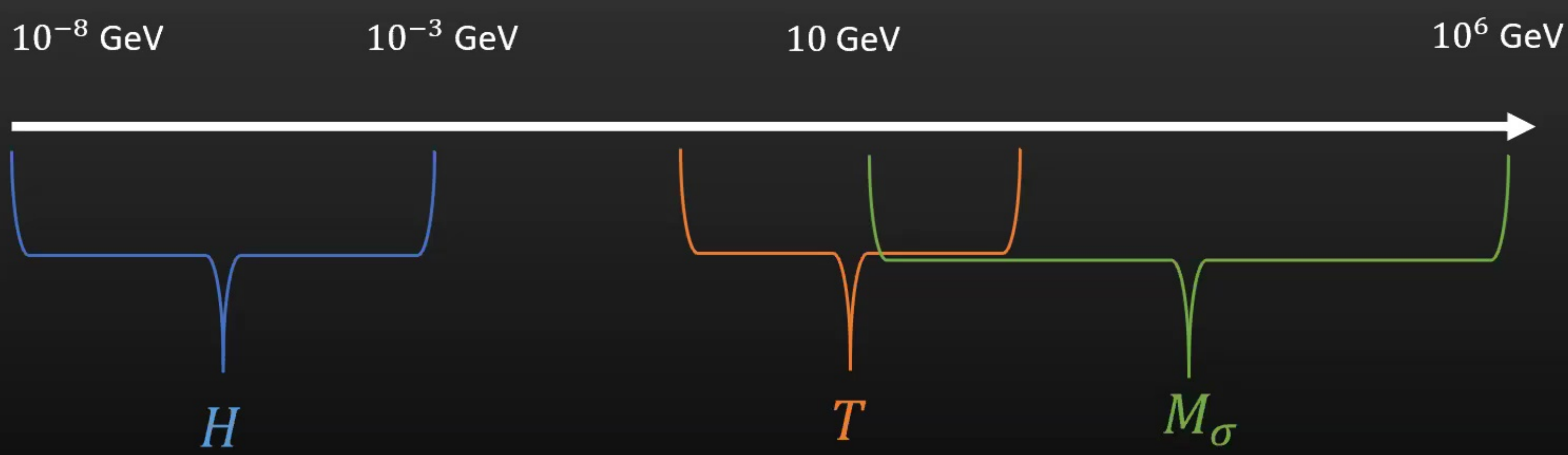
Reheating

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

10^{-8} GeV 10^{-3} GeV 10 GeV 10^{6} GeV

Reheating

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



Content

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Hybrid warm inflation appealing theoretical candidate

testable on 10 year time scale

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1. The Dissipative Axion
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3. A Particle Solution of the Hubble Tension
   - The Hubble Tension
   - Solving the Hubble with the Dissipative Axion

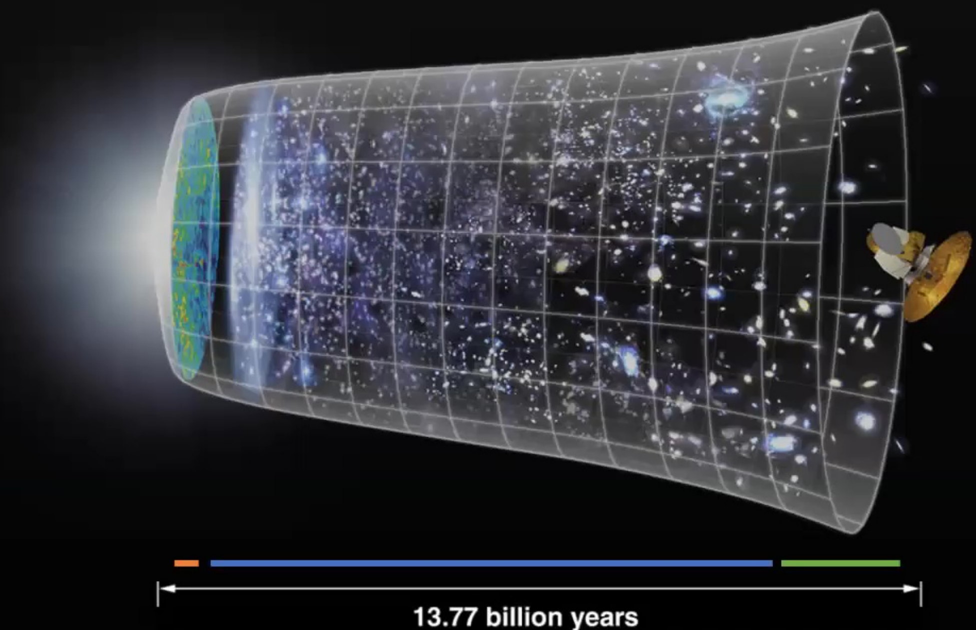
The ΛCDM model of Cosmology

Energy content

Matter $\propto a^{-3}$

Radiation $\propto a^{-4}$

$\Lambda \propto a^{0}$



Resolving the Hubble Tension

Energy content

ΛCDM + EDE +
CMB measurement

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

~ 4.4 σ

Direct
measurement

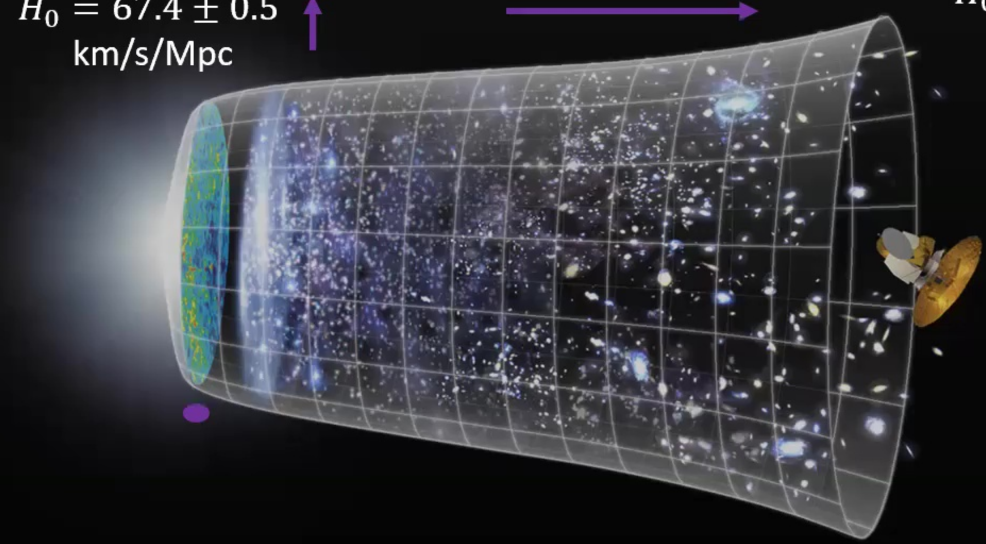
$H_0 = 74.03 \pm 1.42$
km/s/Mpc

Matter $\propto a^{-3}$

Radiation $\propto a^{-4}$

$\Lambda \propto a^0$

Early Dark Energy



13.77 billion years

Resolving the Hubble Tension

ΛCDM + EDE +
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$H_0 = 67.4 \pm 0.5$
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~ 4.4 σ

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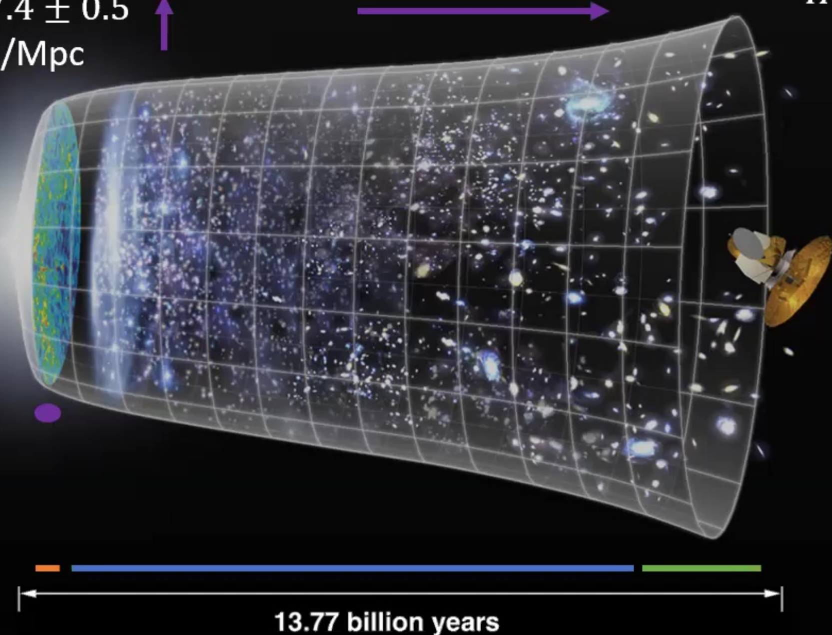
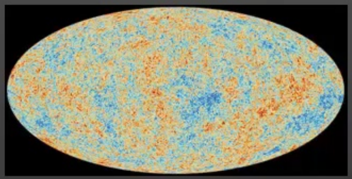
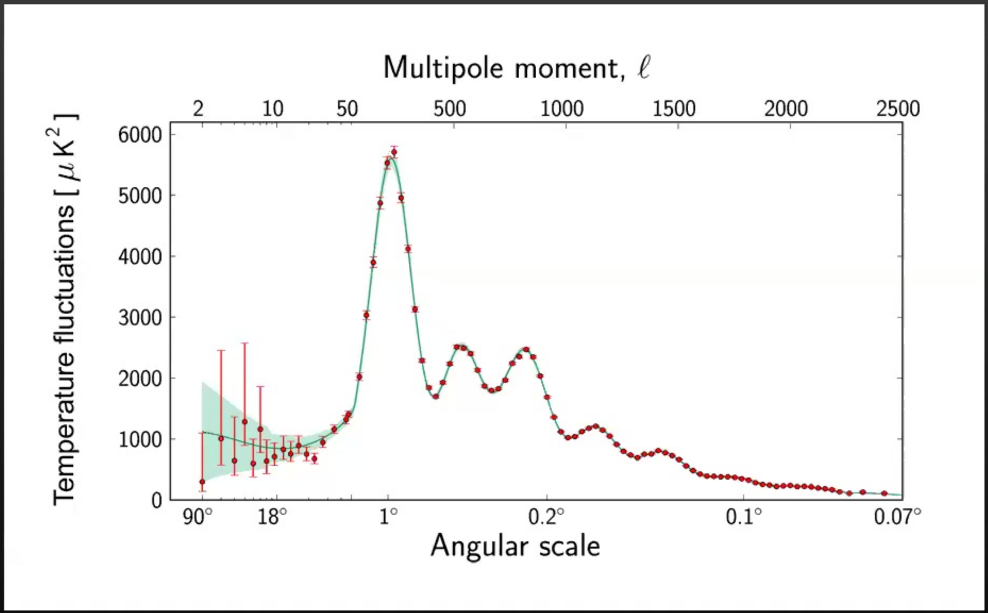


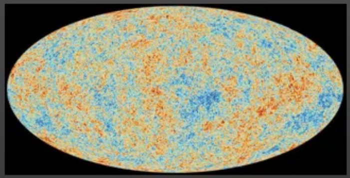
The Hubble Measurement with the CMB



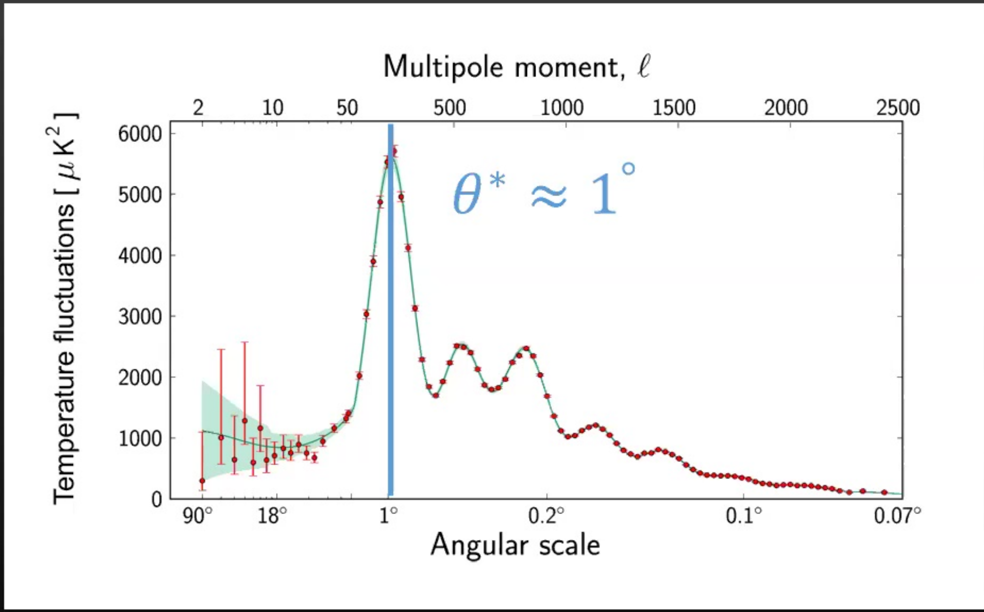


Planck 2018

The Hubble Measurement with the CMB

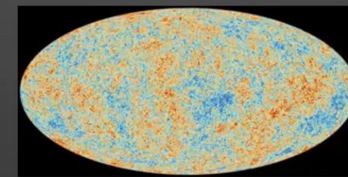


$\theta^* \propto r_s H_0$



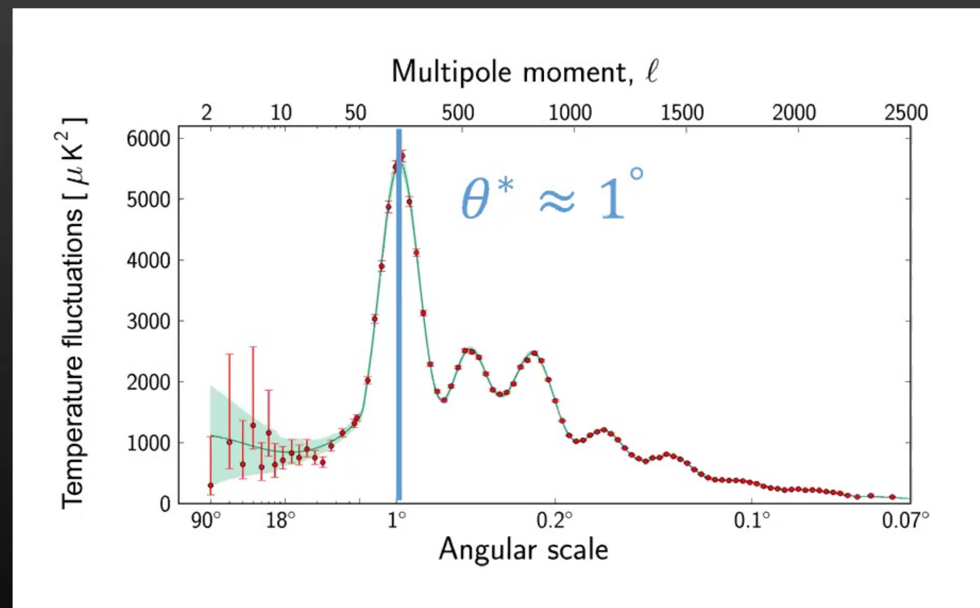
Planck 2018

The Hubble Measurement with the CMB



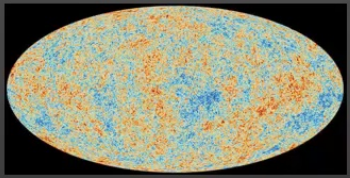
$$\theta^* \propto r_s H_0$$

- r_s depends only on physics before formation of CMB



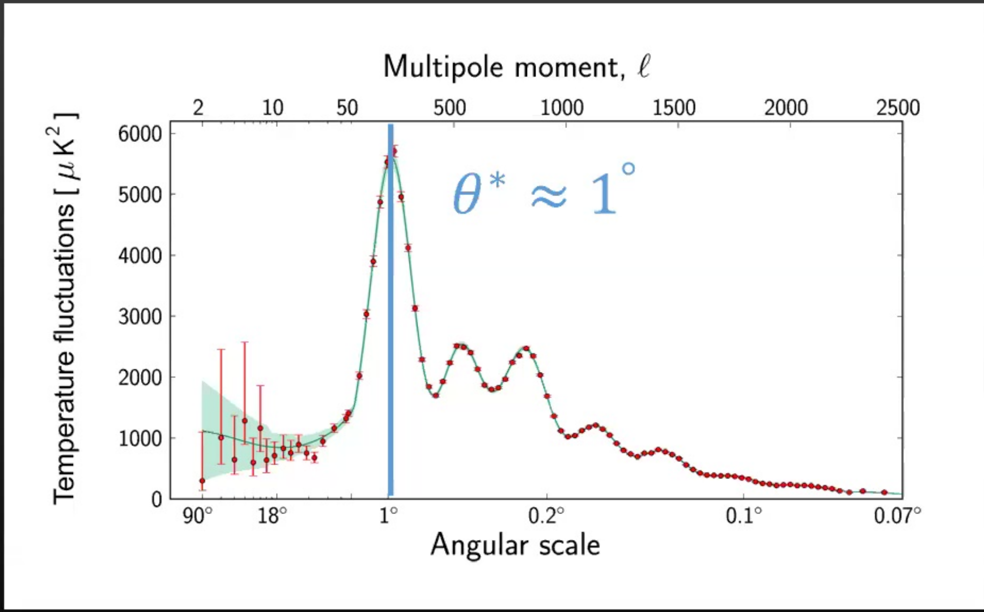
Planck 2018

The Hubble Measurement with the CMB



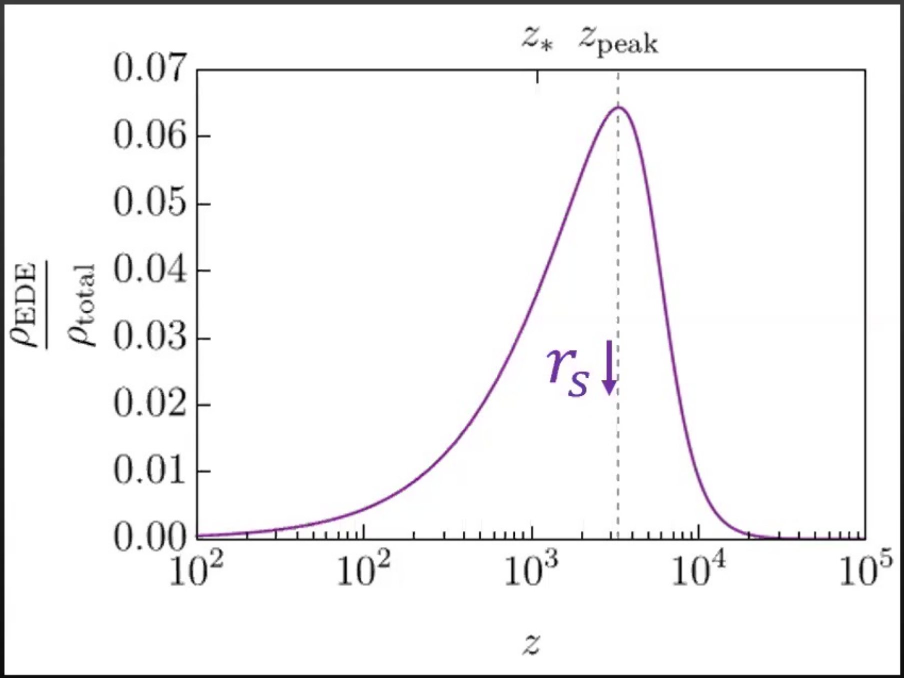
$$\theta^* \propto r_s H_0$$

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



Planck 2018

Resolving the Hubble Tension



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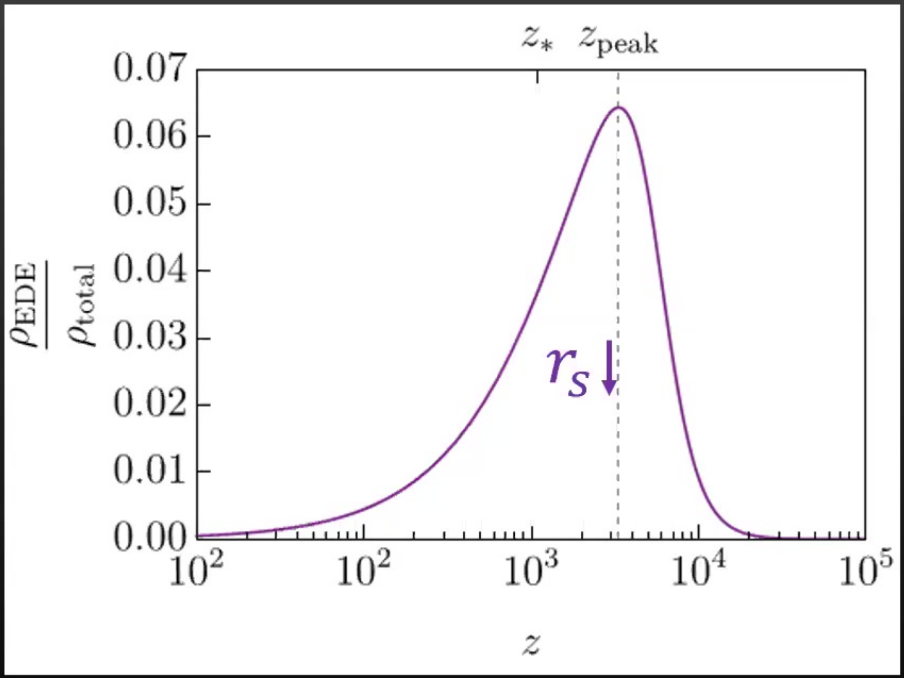
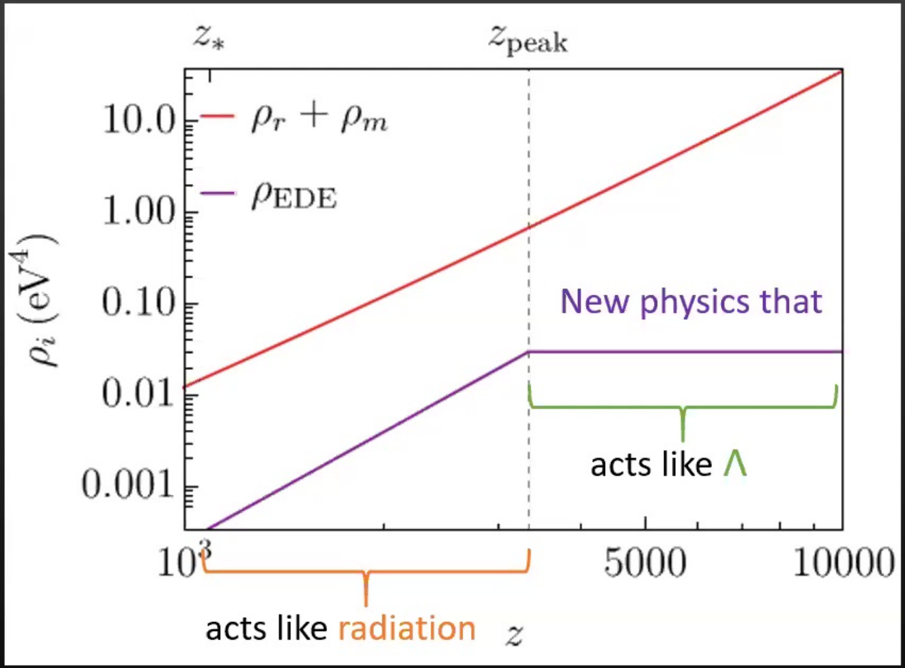
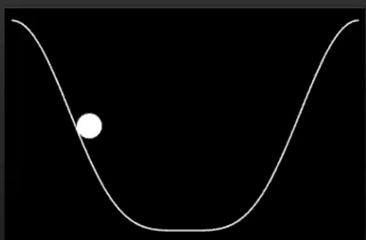




Phenomenological early dark energy solution to Hubble tension by Poulin et. al. (2019)

EDE Scalar Field Models

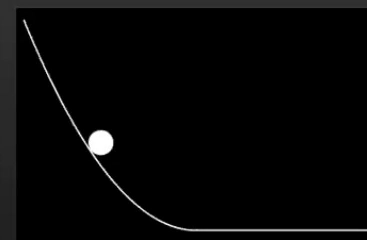
Requirement: Dilute as radiation or faster



Oscillatory

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

$$n \geq 2$$



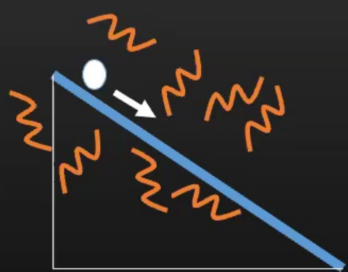
Non-oscillatory

Phenomenological Solutions

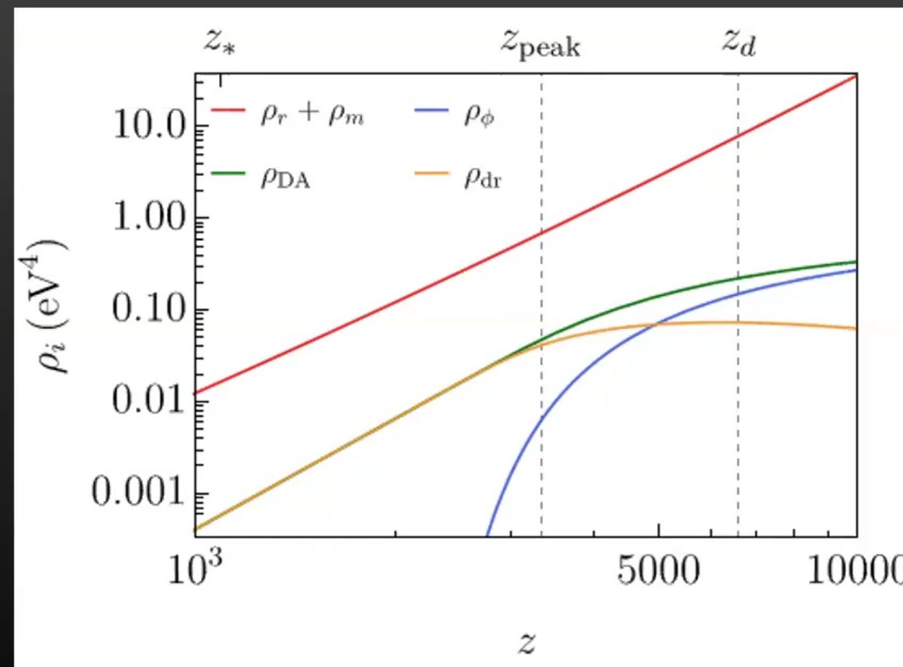
Resolving the Hubble Tension within a particle model…

…using the dissipative axion

$$L_{int} = \frac{\alpha}{16\pi}\frac{\phi}{f}\tilde{G}G$$



radiation dilutes away automatically



Berghaus et. al. PhysRevD.101.083537

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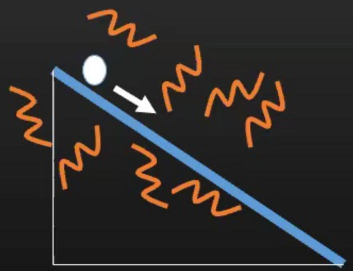

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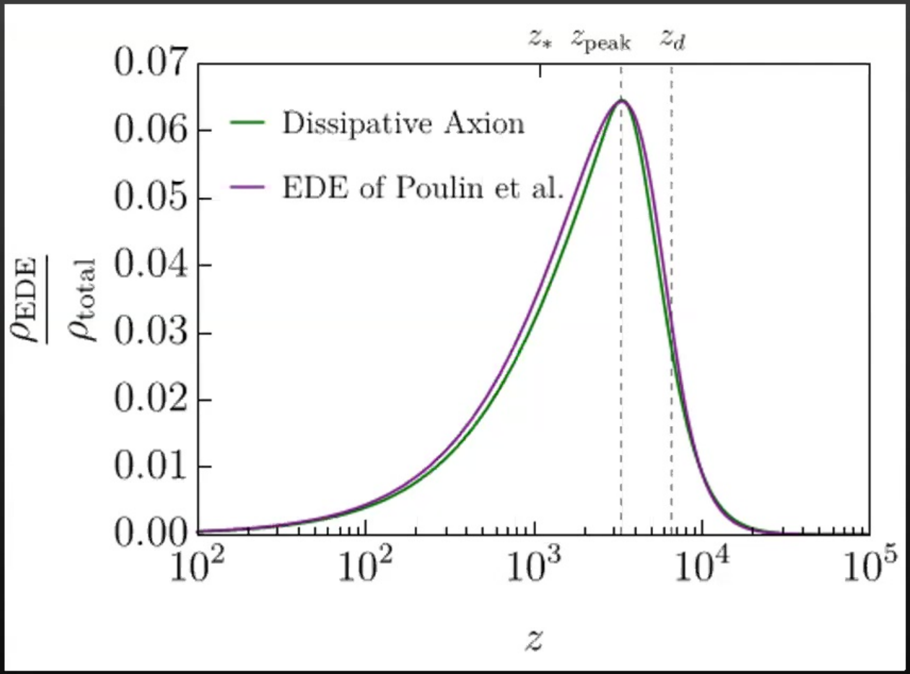

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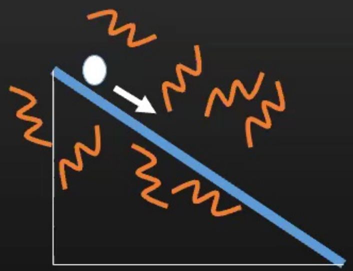

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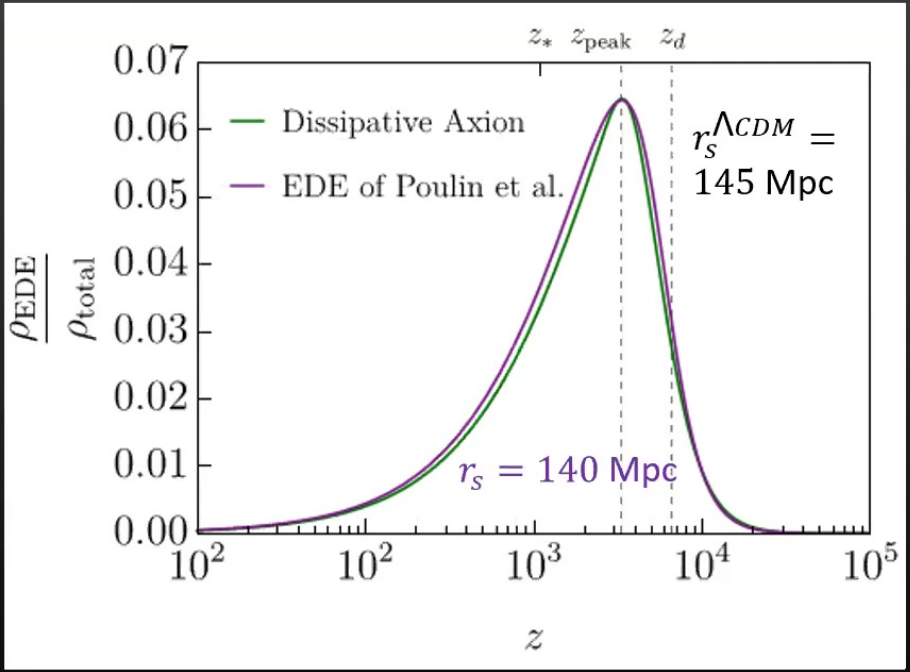

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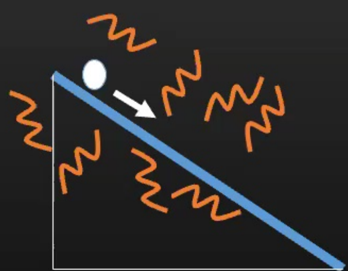

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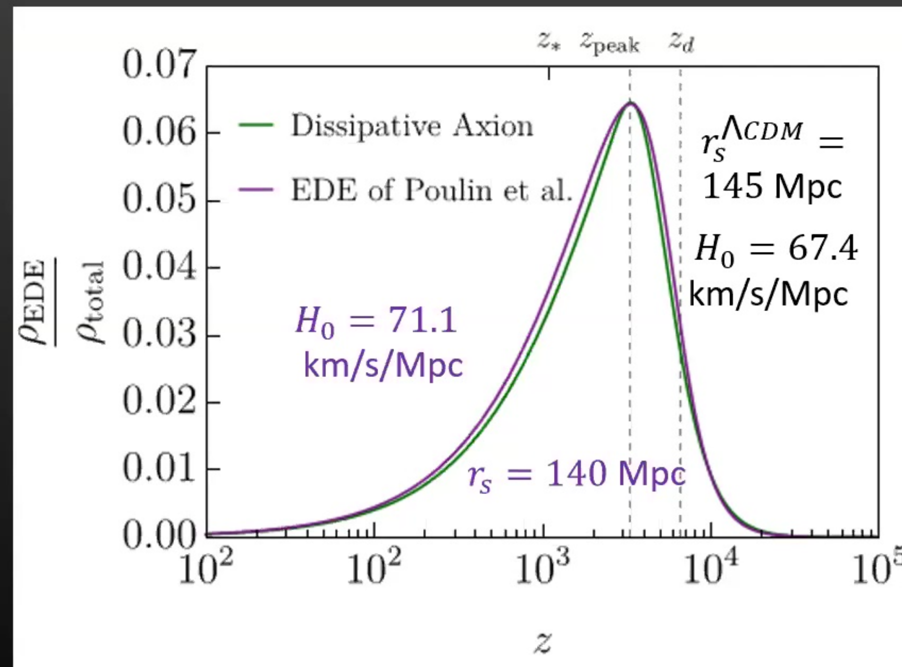

Content

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

Outlook

- Currently analyzing dissipative axion at perturbative level using CLASS
  - Potentially promising to address Hubble tension + Large-Scale-Structure Tension

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- Currently analyzing dissipative axion at perturbative level using CLASS
  - Potentially promising to address Hubble tension + Large-Scale-Structure Tension
- The dissipative axion as late time dark energy (coming soon to the arxiv)
  - Interesting signature in the dark energy equation of state
  - Potential to reheat the relic neutrino background

Thank you

Invitation to Open Office at 3 pm today. Am happy to chat more, answer questions and learn about your work!

Meeting ID: 928 5186 1865
Passcode: 628201