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
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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

<table>
<thead>
<tr>
<th>Energy Content</th>
<th>Matter</th>
<th>Radiation</th>
<th>Dark Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift:</td>
<td>$a^{-3}$</td>
<td>$a^{-4}$</td>
<td>$\sim a^0$</td>
</tr>
<tr>
<td>$a(t) \propto$:</td>
<td>$\frac{2}{t^3}$</td>
<td>$\frac{1}{t^2}$</td>
<td>$e^{Ht}$</td>
</tr>
</tbody>
</table>
Rolling Scalar Fields in Cosmology

- Model dark energy component using particle physics
- Slow-rolling scalar field mimics $\Lambda$

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

Hubble friction
Thermal Friction

- Couple $\phi$ to light fields
- Coupling gives rise to additional friction

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

thermal friction
The Thermal back-reaction

Thermal bath gives finite thermal contribution to mass

\[ \delta m_\phi^2 \propto T^2 \]
The Thermal back-reaction

Thermal bath gives finite thermal contribution to mass

$$\delta m^2_\phi \propto T^2$$

Thermal Friction is due to temperature fluctuations

$$\gamma \propto \Delta T$$

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:

\[ L_{\text{int}} = \frac{\alpha}{16\pi} \frac{\Phi}{f} \tilde{G} G \]

\[ T \gg T_c \]
The Dissipative Axion

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The Dissipative Axion

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

- \( L_{\text{int}} = \frac{\alpha}{16\pi f} \tilde{G} G \)
  - \( T \gg T_c \)

- Axion does not get perturbative mass corrections due to shift symmetry

- But axion has large friction due to non-perturbative effects \( \Upsilon \propto \alpha^5 \frac{T^3}{f^2} \)
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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

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:

  \[
  \Delta_R^2(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \approx -0.035
  \]

  \[
  \sim 10^{-9}
  \]
Slow-roll Inflation

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  \[
  \Delta_R^2(k) \propto \delta \phi^2 \propto H^2
  \]

  \[
  \epsilon_V = \frac{M_{Pl}^2}{2} \left( \frac{V'}{V} \right)^2 \ll 1
  \]

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

  \[
  H^2 \approx \frac{V}{3M_{Pl}^2}
  \]
Warm Inflation

- $\delta \phi_{\text{thermal}} > \delta \phi_{\text{quantum}}$
- $T_{eq} > H$

Friction continuously extracts energy from rolling field to maintain an equilibrium temperature

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

$$\dot{\rho}_R + 4H\rho_R = \gamma \dot{\phi}^2$$
Warm Inflation

- $\delta\phi_{\text{thermal}} > \delta\phi_{\text{quantum}}$ \hspace{2cm} $T_{\text{eq}} > H$

- Friction continuously extracts energy from rolling field to maintain an equilibrium temperature

Steady state: $$(3H + \gamma)\dot{\phi} + V' \approx 0$$

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

$$4H g_s T_{eq}^4 \approx \alpha^5 \frac{T_{eq}^3}{f^2} \dot{\phi}^2$$
Warm Inflation

- $\delta\phi_{thermal} > \delta\phi_{quantum}$

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Steady state:

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

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

Attractor solution
Cold Inflation vs. Warm Inflation

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

- Tensor to scalar ratio $r \approx 16 \varepsilon_V$

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

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- $\Delta_R^2(k) \propto \delta \phi^2 \propto H T \left( \frac{\Upsilon}{3H} \right)^{19/2}$

- Tensor to scalar ratio $r \approx 0$

  \[
  \varepsilon_V = \frac{M_{Pl}^2}{2} \frac{3H V'}{\Upsilon V} \ll 1
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Cold Inflation vs. Warm Inflation

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• Small non-gaussianities

• Sizeable non-gaussianities $f_{NL} \approx 1.5$

• Unique bispectral shape

\[ H \ll \gamma \propto \alpha^5 \frac{T^3}{f^2} \]

\[ \Delta_R^2(k) \propto \delta \phi^2 \propto H T \left( \frac{\gamma}{3H} \right) \frac{19}{2} \]

• Tensor to scalar ratio $r \approx 0$

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

\[ \eta_V = M_{Pl}^2 \frac{3H V''}{\gamma V} \ll 1 \]
Cold Inflation vs. Warm Inflation

6/23/2020, CERN

Kim Berghaus, JHU
Cold Inflation vs. Warm Inflation: \[ V = \frac{1}{2} m^2 \phi^2 \]
Cold Inflation vs. Warm Inflation: Hybrid

\[ V = \frac{1}{2} m^2 \phi^2 \]

Cold

Warm
Warm Inflation

Berghaus et al. (arXiv: 1910.07525)
Kim Berghaus, JHU
Hybrid Inflation

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

\( \sigma \) drives inflation
Hybrid Inflation

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\( \sigma \) drives inflation

\( \phi \) rolls towards \( \phi_c \)
Hybrid Inflation

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\( \sigma \) drives inflation

\( \phi \) rolls towards \( \phi_c \)

\( \sigma \) reheats into standard model
Hybrid Warm Inflation

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

\( \sigma \) drives inflation

\( \phi \) rolls towards \( \phi_c \)

\( \sigma \) reheats into standard model

\( \phi \) sources radiation bath
Reheating

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

- \(10^{-8} \text{ GeV}\)
- \(10^{-3} \text{ GeV}\)
- 10 GeV
- \(10^6 \text{ GeV}\)

6/23/2020, CERN
Couple waterfall field to Standard Model: \( \frac{\alpha_B \sigma}{16\pi f_B} \tilde{B} B \)
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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

$\Lambda$CDM

assumed to be a constant
**The Hubble Tension**

$H_0$ is a measure of expansion rate of universe

Directly parameterizes amount of dark energy

$\Lambda$CDM

assumed to be a constant ...but...

$\Lambda$CDM + CMB measurement

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

Direct measurement

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

~ 4.4 $\sigma$
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

\( \theta^* \approx 1^\circ \)
Early Dark Energy (EDE)

\[ \rho_{r} + \rho_{m} \]

\[ \rho_{\text{EDE}} \]
Early Dark Energy (EDE)
EDE Scalar Field Models

Requirement: Dilute as radiation or faster

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

\[ n \geq 2 \]

Phenomenological Solutions

Oscillatory

Non-oscillatory
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 \( \text{SU}(N) \)

No restrictions on potential

Berghaus et al. 1911:06281
No restrictions on potential

Add Axion and dark

SU(N)

Berghaus et al. 1911:06281

Berghaus et al. 1911:06281
The Dissipative Axion as Early Dark Energy

\[ \theta^* \propto r_s H_0 \]

\[ r_s = 145 \text{ Mpc} \]

\[ H_0 = 67.4 \text{ km/s/Mpc} \]

\[ r_s = 140 \text{ Mpc} \]

\[ H_0 = 71.1 \text{ km/s/Mpc} \]

Berghaus et al. 1911:06281

Poulin et al. 1811.04083v2

6/23/2020, CERN

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The Dissipative Axion as Early Dark Energy

Mimics EDE at background level

\[ \theta^* \propto r_s H_0 \]

Future Work:

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

\[ r_s = 145 \text{ Mpc} \]
\[ H_0 = 67.4 \text{ km/s/Mpc} \]

\[ r_s = 140 \text{ Mpc} \]
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Poulin et al. 1811.04083v2

\[ \Lambda \text{CDM} \]

\[ \text{EDE} \]
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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
Sphaleron transitions give rise to a large friction $\Upsilon$:

$$\Upsilon \propto \alpha^5 \frac{T^3}{f^2}$$
Topological back-reaction

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

\[ X(T) = m_a^2(T) f_a^2 \]

Rapidly falls off at temperatures above the confinement scale as \(~T^{-7}\)

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

Axion has large friction with negligible back-reaction