Balancing the medium response in Minimal Warm Inflation

ICCUB School Primordial Black Holes - Barcelona

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Motivation

- Standard Cosmological Model, Standard Model & General Relativity
  - Homogeneity and isotropy, FLRW space-time metric
  - Radiation, non-relativistic matter, curvature and vacuum energy
  - Cosmological evolution from BBN onwards
- Still several problems to be answered...
  - Flatness, Horizon...
  - Anisotropies in CMB, origin of Large-Scale Structure in the Universe...
  - Dark Matter
- Inflation *A. Guth, A. Linde, A. Starobinsky A.Albrecht and P. Steinhartdt*
  - Early phase of accelerated expansion, around 50-60 efolds
  - Unknown particle physics description
  - Connection with Standard Cosmology through reheating

$$S_\phi = \int d^4x\sqrt{-g}(-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi))$$

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

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$p_\phi = \omega\rho_\phi$$

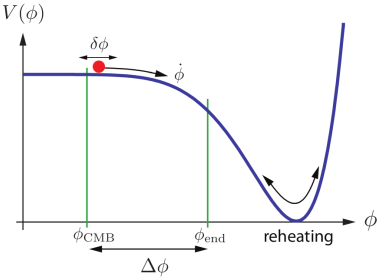
- With dominant potential $p_\phi = -\rho_\phi \Rightarrow \omega = -1 \rightarrow$ Accelerated Expansion

D. Baumann 0907.5424

$$\frac{1}{2}\dot{\phi} \ll V(\phi) \qquad \epsilon_V = \frac{m_P^2}{16\pi}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 \ll 1$$

$$\ddot{\phi} \ll 3H\dot{\phi} \qquad \eta_V = \frac{m_P^2}{8\pi}\frac{V''(\phi)}{V(\phi)}^2 \ll 1$$

$$N_e = \log\left(\frac{a_0}{a_i}\right) = \int_{a_0}^{a_e}\frac{da}{a} \simeq -\frac{1}{m_P^2}\int_{\phi_i}^{\phi_e}\frac{V(\phi)}{V'(\phi)}d\phi$$



Inflation: Contact with Observations

$$A_S = \frac{H^4}{(2\pi)^2\dot{\phi}^2} \simeq 2.2 \times 10^{-9}$$

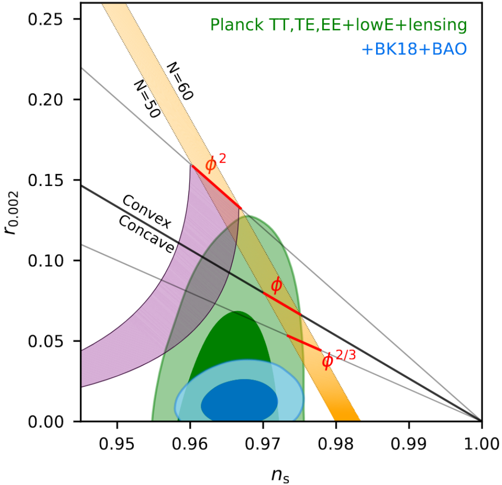
$$r = \frac{\Delta_h^2(k)}{\Delta_{\mathcal{R}}^2(k)}$$

$$n_s - 1 = \frac{d\log\Delta_{\mathcal{R}}^2(k)}{d\log k}$$

$$\Delta_{\mathcal{R}}^2(k) = \frac{H^4}{(2\pi)^2\dot{\phi}^2}\left(\frac{k}{aH}\right)^{n_s-1}$$

$$\Delta_h^2(k) = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2\left(\frac{k}{aH}\right)^{n_t}$$

Planck+ BICEP/Keck 2110.00483



Warm Inflation

- Typically interactions negligible during ”cold” Inflation $\Longrightarrow$ Particle interactions at Reheating

- However if $\Gamma > H$, particle interactions are relevant during inflation.

- Moreover if $T > H$, thermal fluctuations of the inflaton field will become important $(m_\phi \sim H)$

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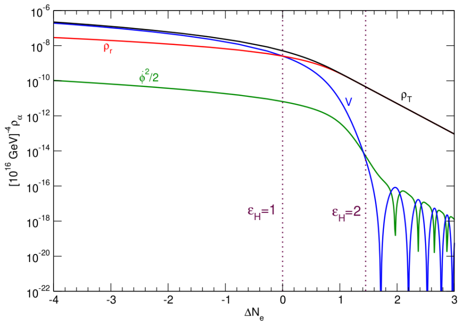
New Dynamics!

- Interactions with the cosmic plasma induce Dissipation
- New friction term $Q = \frac{\Upsilon}{3H}$ with $\Upsilon(T, \phi)$

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + \partial_\phi V(\phi, T) = 0$$
$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2$$

- Q varies during inflation
  - Weak Dissipative Regime WDR $Q < 1$
  - Strong Dissipative Regime SDR $Q > 1$

Bastero Gil & Subías 2105.08045



Warm Inflation

- New Slow roll equations

$$3H(1+Q)\dot{\phi} \simeq -\partial_\phi V(\phi, T)$$
$$\rho_R \simeq \frac{3}{4} Q \dot{\phi}^2$$

- New Slow roll conditions

$$\epsilon_V < 1 + Q \qquad |\eta_V| < 1 + Q$$

Thermal corrections under control $\quad \delta_T V = T \frac{\partial_T \partial_\phi V}{\partial_\phi V} < 1$

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- Dissipation induces thermal inflaton fluctuations, different primordial spectrum

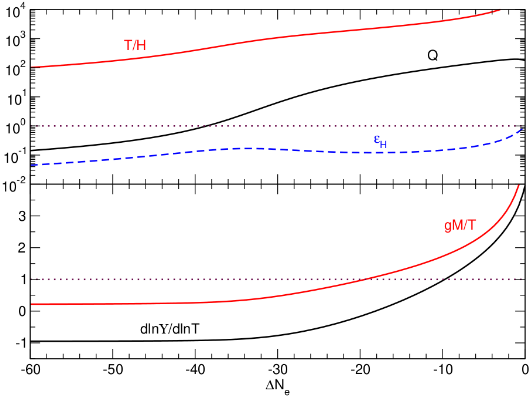
$$\Delta^2_{\mathcal{R}} = \left(\frac{H_*}{2\pi}\right)^2 \left(\frac{H_*}{\dot{\phi}_*}\right)^2 \left(1 + 2n_* + \frac{2\sqrt{3}\pi Q_*}{\sqrt{3+4\pi Q_*}} \frac{T_*}{H_*}\right) G(Q_*)$$

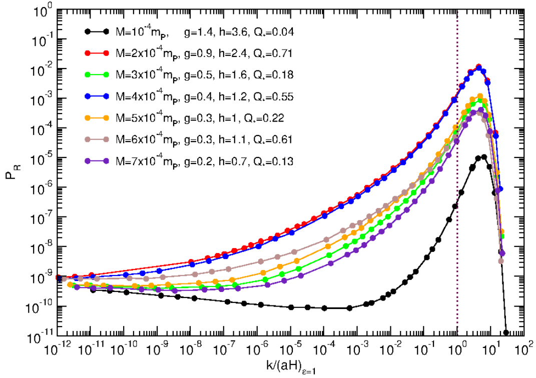
- Inflation lasts longer due to extra friction $H_{60}^{warm} < H_{60}^{cold} \longrightarrow r < 0.1$

Example: Scalar Warm Little Inflaton in quartic chaotic potential

$$\Upsilon = 4\frac{g^2}{h^2}\frac{g^2 M^2}{T}F[m_\chi/T] \qquad \text{s.t.} \qquad \Upsilon = \begin{cases} \frac{M^2}{T} & \text{at CMB scales} \\ \frac{T^3}{M^2} & \text{end of inflation} \end{cases}$$

Bastero Gil & Subías 2105.08045





Light & evaporating PBHs: $M_{PBH} \sim O(10^3 - 10^6)g$

Minimal Warm Inflation

- Axion-like inflation (PNGB of a broken gauge symmetry) with gauge production $SU(N)$

Berghaus, Graham, Kaplan 1910.07525

$$\mathcal{L}_{int} = \frac{\alpha_g}{8\pi}\frac{\phi}{f_a}\tilde{F}^{a\,\mu\nu}F^a_{\mu\nu}$$

- Dissipation from Gauge production !

Visinelli 1107.3523; Ferreira Notari 1711.07483; Kamali 1901.01897

- Axion mass protected by shift symmetry
$\longrightarrow$ Radiative and Thermal corrections to the axion potential are naturally suppressed

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- Warm inflation is an attractor solution

DeRocco, Graham, Kalia 2107.07517

- "Cold" initial conditions $\rightarrow$ "Warm" evolution!

- Even with T=0 , sphaleron diffusion rate induces $\sim$ constant dissipation

Laine & Procacci 2102.09913

$$\Upsilon_{UV} = \frac{\alpha_g^2\,\omega^3}{f_a^2} \qquad (\omega \gg \pi T)$$

- At large temperatures the Medium has different response

$$\Upsilon_{IR} = \frac{\alpha_g^5\,T^3}{f_a^2} \qquad (\omega < \alpha N_c T)$$

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- Complete medium response requires combining vacuum dynamics & non-perturbative YM input

Klose, Laine, Procacci 2210.11710

$$\Upsilon \simeq \frac{d_A\,\alpha_g^2}{f_a^2}\left(\kappa(\alpha_g N_c T)^3\,\frac{1+\frac{\omega^2}{(c_{IR}\alpha_g^2 N_c^2 T)^2}}{1+\frac{\omega^2}{(c_M\alpha_g N_c T)^2}} + \left[1+2n_B\left(\frac{\omega}{2}\right)\right]\frac{\pi\omega^3}{(4\pi)^4}\right)$$

$d_a = N_c^2 - 1,\ \kappa = 1.5,\ c_{IR} = 106,\ c_M = 5.1$

Balancing the Medium response

"Two"-stage dissipation rate

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- α_g will dictate the hierarchy in the medium response
- α_g/f_a sets the scale for $Q = \Upsilon/(3H)$

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Phenomenologically interesting scenario

- Υ_{UV} **at CMB scales &** Υ_{IR} **afterwards**

Balancing the Medium response

- Final ingredient $\Rightarrow$ ω defined by $V(\phi)$

  $\rightarrow$ Chaotic models

$$V(\phi) = \lambda m_p^4 \left(\frac{\phi}{m_p}\right)^{\alpha}, \qquad \omega^2 = \lambda\alpha(\alpha-1)m_p^2\left(\frac{\phi}{m_p}\right)^{\alpha-2}$$

- Simplifying $\Upsilon \simeq C_0 + C_T T^3$

$$\frac{d\ln T}{dN} = \frac{\varepsilon_V \frac{3+Q}{1+Q} - 2\eta_V}{4-q+(4-q)Q} \quad \text{with} \quad q = \frac{d\ln\Upsilon}{d\ln T}$$

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- Quartic potential $\omega^2 = 12\lambda\phi^2$
  - $Q \ll 1 \quad \rightarrow \frac{d\ln T}{dN} \sim 0$; Cannot go from $\Upsilon_{UV} \Rightarrow \Upsilon_{IR}$
  - If Υ_{IR} dominant at CMB scales need to ensure $Q < 10^{-2}$ (WDR)
- Quadratic potential $\omega^2 = 2\lambda m_p^2$
  - Transition is possible; $Q_{CMB} \sim 10^{-5}$
  - At transition $Q \sim 10^{-2}$, with tendency to grow

Balancing the Medium response

$\rightarrow$ α-attractor

$$V(\phi) = \lambda m_p^4 \tanh^{2n}\left(\frac{\phi}{m_p\sqrt{6\alpha}}\right), \qquad \omega^2 = \partial_{\phi\phi} V(\phi)$$

- ω^2 is negative for most of the evolution.

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- With this definition
  - $\alpha = 1$; no transition $\Upsilon_{UV} \Rightarrow \Upsilon_{IR}$
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- Different definitions ?
  - $\omega^2 = |\partial_{\phi\phi} V(\phi)|$
  - $\omega^2 = H^2$

  In these cases α-attractors can also lead to interesting signals

Conclusion & Future Work

- Warm inflation can appear naturally if $\Gamma > H$ and $T > H$

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- Proving an example of warm inflation evolution, even from cold initial conditions

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Outlook

- Need to figure out observational compatible parameter spaces for the different inflationary models
- We will test chaotic, α-attractors & hilltop potentials

- Calculate the scalar & tensor amplifications at the later stages of inflation for the realizable models