Warming up Cold Inflation

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based on arXiv:2107.07517

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Warming Up Cold Inflation

- Punchline: Generic inflaton couplings can turn cold axion inflation models warm!
- Dissipative effects will source a thermal bath (at some $T_{\rm eq}$)
- This equilibrium will be reached regardless of initial conditions
- The bath can alter the predictions and dynamics of inflation for large parts of parameter space

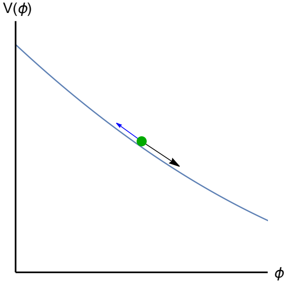
Warm Inflation Dynamics

- Scalar equation of motion:

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

- Friedmann equation:

$$H^2 - \frac{1}{3M_{\rm pl}}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right) = 0$$



Warm Inflation Dynamics

- Scalar equation of motion:

$$\ddot{\phi} + 3H\dot{\phi} + \Upsilon(T)\dot{\phi} + V'(\phi) = 0$$

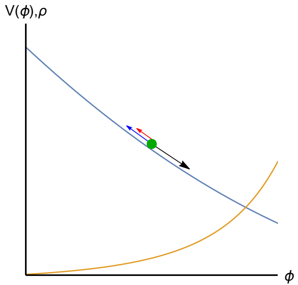
- Friedmann equation:

$$H^2 - \frac{1}{3M_{\rm pl}}\left(\rho_R + \frac{\dot{\phi}^2}{2} + V(\phi)\right) = 0$$

- Dissipation $\Upsilon(T)$ sources bath:

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

where $\rho_R = \frac{\pi^2 g_*}{30} T^4$



Axion in a Thermal Bath

- Axion coupled to $SU(N_c)$ gauge sector:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2g^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{\phi}{16\pi^2 f}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} - V(\phi)$$

- No thermal correction to V because of ϕ shift symmetry

- Thermal friction

$$\Upsilon(T) \sim \frac{T^3}{f^2}$$

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$$-\bar{\psi}(\not{D} - m_f)\psi$$

- No thermal correction to V because of ϕ shift symmetry

- Thermal friction

$$\Upsilon(T) \sim \frac{m_f^2 T}{f^2}$$

- Light fermions ($m_f \ll T$) lead to suppression of friction

Warm Inflation is an Attractor Solution

- If inflation begins in a thermal bath, it will quickly reach T_{eq}
  - If $T_0 > T_{\text{eq}}$, it will redshift in $\ln(T_0/T_{\text{eq}})$ e-folds
  - If $H < T_0 < T_{\text{eq}}$, thermal friction will heat bath within Hubble time [1910.07525 Berghaus, Graham, Kaplan]

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  - If $H < T_0 < T_{\text{eq}}$, thermal friction will heat bath within Hubble time [1910.07525 Berghaus, Graham, Kaplan]
- If inflation begins in vacuum, can still source thermal bath!
  - Rolling inflaton causes exponential production of gauge bosons [0908.4089 Anber & Sorbo]
  - Can generate $\rho_R \gg H^4$ before self-interactions take over
  - If self-interactions thermalize, then $T_0 > H$ so above case applies!

Inflationary Regimes

- Quantities of interest:
  - $Q \equiv \Upsilon/3H$: dynamics dominated by Hubble or bath
  - T vs. H: predictions dominated by Hubble or bath
  - If H or $T > f$, then EFT breaks down!

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- Inflationary regimes:
  - Strong warm inflation: $Q > 1$ and $T > H$
  - Weak warm inflation: $Q < 1$ and $T > H$
  - Cold inflation: $T < H$
  - Broken: $H > f$
  - Thermally Broken: $T > f > H$

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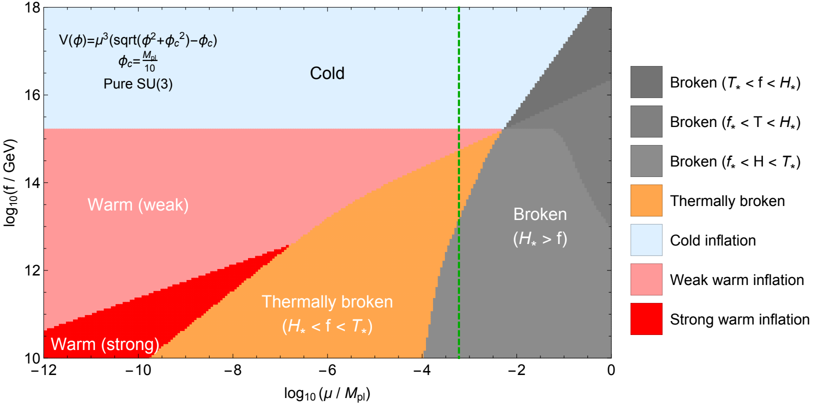
- All quantities evaluated at $N_* = 60$ e-folds before inflation ends

Parameter Space – Pure $SU(3)$ Case

$$V(\phi) = \mu^3(\sqrt{\phi^2+\phi_c^2}-\phi_c), \quad \phi_c = M_{pl}/10$$

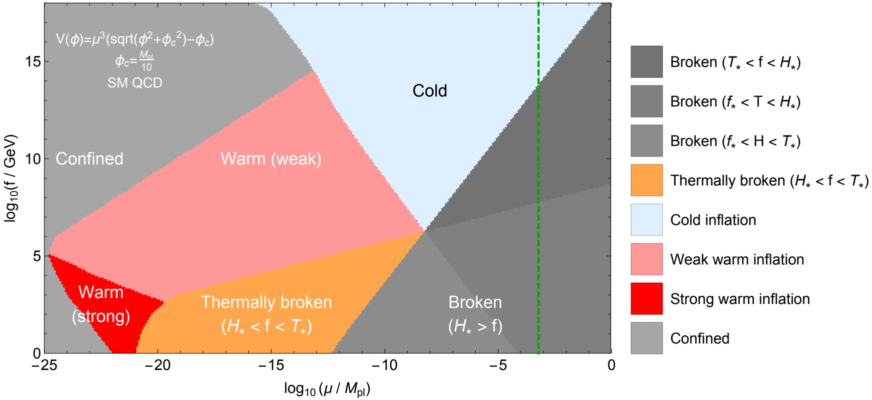


$$N_c = 3, \alpha = 0.1, g_* = 17, N_* = 60$$

Green line indicates normalization which matches observed CMB amplitude in cold inflation

Parameter Space – Standard Model Case

$$V(\phi) = \mu^3(\sqrt{\phi^2 + \phi_c^2} - \phi_c), \quad \phi_c = M_{\rm pl}/10$$



$N_c = 3$, T-dependent α and g_*, $m_f = 1$ MeV, $N_* = 60$

Green line indicates normalization which matches observed CMB amplitude in cold inflation
Light gray region indicates that QCD has confined ($T \lesssim 0.1$ GeV)

Summary

- Dissipative effects generate thermal bath during inflation

- Bath is an attractor solution, which is insensitive to initial conditions

- Thermal effects can ruin cold inflation even for small couplings!

- Public Service Anouncement: Thermal effects must be accounted for when building inflation models