

# Warming up Cold Inflation

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based on arXiv:2107.XXXXX

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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  $T_{\text{eq}}$ )
- 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

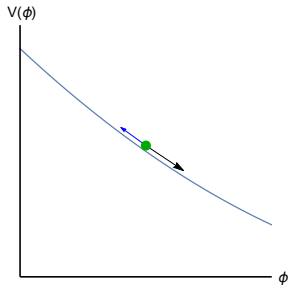
# Warm Inflation Dynamics

- Scalar equation of motion:

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

- Friedmann equation:

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



# Warm Inflation Dynamics

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

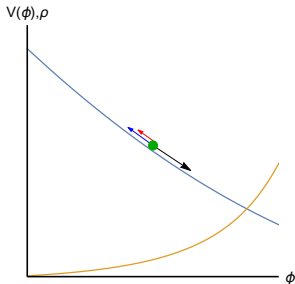
- Friedmann equation:

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

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

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

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



## Axion in a Thermal Bath

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

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

- No thermal correction to  $V$  because of  $\phi$  shift symmetry
- Thermal friction

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- No thermal correction to  $V$  because of  $\phi$  shift symmetry
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$$\Upsilon(T) \sim \frac{m_f^2 T}{f^2}$$

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

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  - If  $T_0 < T_{\text{eq}}$ , thermal friction will heat up 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]
  - Once there are enough,  $3 \rightarrow 2$  scattering allows sector to thermalize
  - Leads to thermal case, as long as this happens within Hubble time and before inflaton slows down



# 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!

# Inflationary Regimes

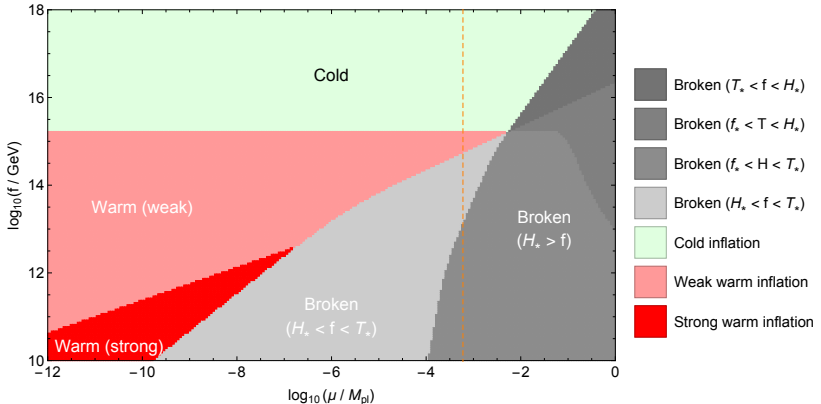
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- Inflationary regimes:
  - Strong warm inflation:  $Q > 1$  and  $T > H$
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  - Cold inflation:  $T < H$
  - Broken:  $H$  or  $T > f$

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  - Cold inflation:  $T < H$
  - Broken:  $H$  or  $T > f$
- All quantities evaluated at  $N_* = 60$  e-folds before inflation ends

# Parameter Space – Pure $SU(3)$ Case

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

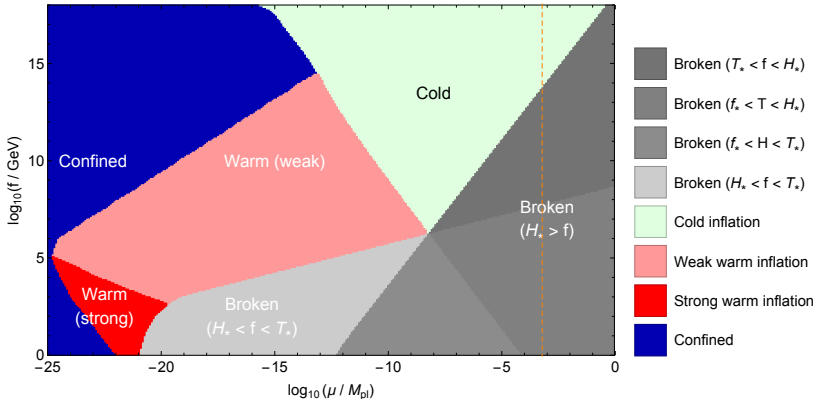


$$N_c = 3, \alpha = 0.1, g_* = 17, N_* = 60$$

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

# Parameter Space – Standard Model Case

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



$$N_c = 3, T\text{-dependent } \alpha \text{ and } g_*, m_f = 1 \text{ MeV}, N_* = 60$$

Orange line indicates normalization which matches observed CMB amplitude in cold inflation  
 Blue region indicates that QCD has confined ( $T \lesssim 0.1 \text{ GeV}$ )

## 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 Announcement:** Thermal effects must be accounted for when building inflation models

Thank You!

## Slow Roll Approximation

- Slow roll parameters:

$$\epsilon_W = \frac{1}{1+Q} \frac{1}{2} \left( \frac{V'}{V} \right)^2 M_{\text{pl}}^2 \ll 1$$

$$\eta_W = \frac{1}{1+Q} \left( \frac{V''}{V} \right) M_{\text{pl}} \ll 1$$

- Slow roll steady state

$$\dot{\phi} \approx -\frac{V'(\phi)}{3H(1+Q)}$$

$$H^2 \approx \frac{V(\phi)}{3M_{\text{pl}}^2}$$

$$\rho_R \approx \frac{3Q\dot{\phi}^2}{4}$$



## Beginning from Low Temperature

- Can show that bath is generated within a Hubble time, using only:

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

$$\rho_R \sim T^4, \quad \Upsilon \sim T^3$$

- If  $T$  begins small, we can neglect  $4H\rho_R$

$$\dot{\rho}_R \sim \Upsilon\dot{\phi}^2 \implies \dot{T} \sim \dot{\phi}^2 > \dot{\phi}_{\text{eq}}^2$$

- Therefore the time to equilibrium  $t_{\text{eq}}$  is at most

$$T_{\text{eq}} \gtrsim \dot{\phi}_{\text{eq}}^2 t_{\text{eq}}$$

- At equilibrium, we can neglect  $\dot{\rho}_R$

$$HT_{\text{eq}}^4 \sim T_{\text{eq}}^3 \dot{\phi}_{\text{eq}}^2 \implies t_{\text{eq}} \lesssim H^{-1}$$

- If  $T$  begins large, bath will dilute to equilibrium in  $\ln(T_0/T_{\text{eq}})$  e-folds
- Caveat: assumes thermalization rate  $\Delta \sim T$  greater than  $H$

## Beginning from Vacuum

- Three conditions for exponentially-produced bosons to thermalize:
  - Does scattering become efficient within a Hubble time?

$$\frac{f}{M_{\text{pl}}} \ll \mathcal{O}(10^{-1})\alpha\sqrt{\epsilon_V}$$

- Does EOM remain perturbative until scattering becomes efficient?

$$\frac{f}{M_{\text{pl}}} \ll \mathcal{O}(10^{-2})N_c\alpha^2\sqrt{\epsilon_V}$$

- Does scattering become efficient before inflaton slows down?

$$f \gg 2 \times 10^{10} \text{ GeV} \left(\frac{\alpha}{0.1}\right)^{4/7} \left(\frac{N_c}{3}\right)^{-1/7} \left(\frac{\epsilon_V}{10^{-3}}\right)^{3/14} \left(\frac{H}{10^{-10} M_{\text{pl}}}\right)^{4/7}$$