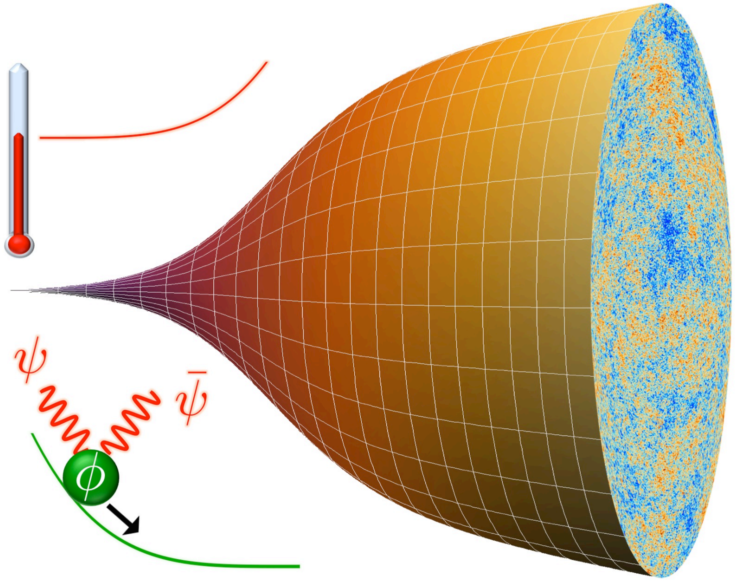
Warm Little Inflaton



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Inflation: a window into high energies

CMB anisotropies require inflation to occur at high energies:

$$V^{1/4} \sim 10^{16} \left(\frac{r}{0.1}\right)^{1/4} \ \mathrm{GeV}$$

Can the inflaton be embedded into a fundamental theory?

We need to know how it interacts with other fields!

Warm inflation

[Berera 1995]

Interactions with cosmic plasma induce dissipation:

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

This damps inflaton's motion and sources radiation:

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

In slow-roll regime:

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

for $Q = \Upsilon/3H$ and $\epsilon_\phi, |\eta_\phi| \ll 1 + Q$.

Warm inflation

Dissipative effects can sustain a warm thermal bath:

$$\frac{T}{H} \sim Q^{1/4}\left(\frac{\dot{\phi}}{H^2}\right)^{1/2} \gtrsim 1 \quad \Rightarrow \quad H^2 \ll \dot{\phi} \ll \sqrt{V(\phi)} \sim H M_P$$

The inflationary Universe need not be empty and cold!

Why should inflation be warm?

- Extra friction prolongs inflation
- Radiation sub-dominant but can smoothly take over

$$\frac{\rho_R}{V(\phi)} \simeq \frac{1}{2}\frac{\epsilon_\phi}{1+Q}\frac{Q}{1+Q}$$

- Dissipation induces thermal inflaton fluctuations and changes observational predictions
- Stable Higgs vacuum during inflation [Fairbairn & Hogan, 2014]
- Baryogenesis during inflation (testable with CMB)

[Bastero-Gil, Berera, Ramos & JGR, 2012]

(...)

Warm inflation

Challenges: [Berera, Gleiser & Ramos; Yokoyama & Linde (1998)]

- Coupling the inflaton to light particles is hard:

$$\mathcal{L} = -g\phi\bar{\psi}\psi \qquad \Rightarrow \qquad m_\psi = g\phi \gtrsim T$$

- Light particles induce large thermal mass corrections:

$$\Delta m_\phi^2 \sim g^2 T^2 \gg H^2$$

- Small couplings yield little dissipation…

Can couple indirectly through heavy mediators, but one needs a large number of mediators to sustain the thermal bath!

[Berera & Ramos (2003); Moss & Xiong (2006);Bastero-Gil, Berera, Ramos + JGR (2011-15)]

Warm Little Inflaton

Consider a U(1) gauge theory spontaneously broken by two complex Higgs fields:

$$\langle\phi_1\rangle = \langle\phi_2\rangle \equiv M/\sqrt{2}$$

One Nambu-Goldstone boson is "eaten" by the gauge field, while the other becomes the physical singlet scalar inflaton:

$$\phi_1 = \frac{M}{\sqrt{2}}e^{i\phi/M} \quad , \qquad \phi_2 = \frac{M}{\sqrt{2}}e^{-i\phi/M}$$

"Little Higgs"

[Arkani-Hamed, Cohen & Georgi (2001)]

Warm Little Inflaton

Couple the inflaton to charged and singlet Weyl fermions:

$$\begin{aligned} -\mathcal{L}_{\phi\psi} &= \frac{g}{\sqrt{2}}(\phi_1+\phi_2)\bar{\psi}_{1L}\psi_{1R} - i\frac{g}{\sqrt{2}}(\phi_1-\phi_2)\bar{\psi}_{2L}\psi_{2R} + \mathrm{h.c.} \\ &= gM\cos(\phi/M)\bar{\psi}_1\psi_1 + gM\sin(\phi/M)\bar{\psi}_2\psi_2\ . \end{aligned}$$

with interchange symmetry:

$$\phi_1 \leftrightarrow i\phi_2, \qquad \psi_{1L,R} \leftrightarrow \psi_{2L,R}$$

Fermion masses are bounded and can be light!

$$gM \lesssim T \lesssim M$$

Warm Little Inflaton

Effective potential at high temperature:

$$V_T \simeq \sum_{i=1,2} \left[-\frac{7\pi^2}{180} T^4 + \frac{m_i^2 T^2}{12} + \frac{m_i^4}{16\pi^2} \left(\log\left(\frac{\mu^2}{T^2}\right) - c_f \right) \right]$$

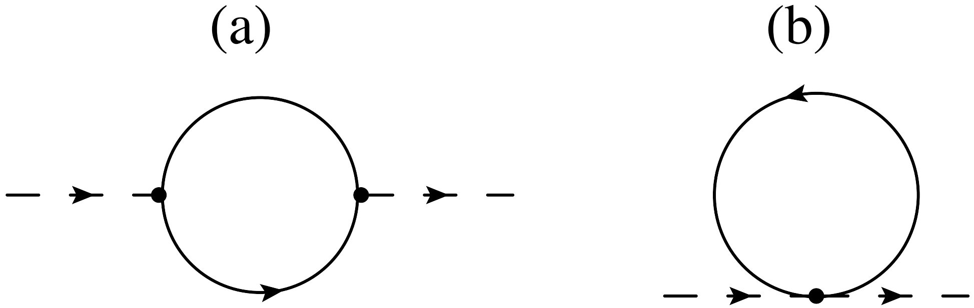
No thermal inflaton masses!

Alternatively, expand Lagrangian to quadratic order:

$$\mathcal{L}_{\phi\psi} = -\sum_i \left[m_i + g_i \delta\phi + \frac{f_i}{2} \delta\phi^2 + \ldots \right] \bar{\psi}_i \psi_i$$

Warm Little Inflaton

Inflaton self-energy:



$$\begin{aligned}\Sigma_\phi(0) &= \left[\left(g_1^2+m_1f_1\right)+\left(g_2^2+m_2f_2\right)\right] I_T \\ &= g^2\left[-\cos(2\phi/M)+\cos(2\phi/M)\right] I_T = 0\ ,\end{aligned}$$

where $I_T \simeq -(\Lambda^2/2\pi^2)+(T^2/6)$.

Cancellation of quadratic divergences and thermal masses!

Warm Little Inflation

Dissipation comes from non-local terms in the effective action, which come only from diagram (a):

No cancellation of dissipative terms!

$$\begin{aligned}\Upsilon &= \int d^4x'\Sigma_R(x,x')\,(t'-t)\\ &= \sum_i 4\frac{g_i^2}{T}\int\frac{d^3p}{(2\pi)^3}\frac{m_i^2}{\Gamma_{\psi_i}\omega_p^2}n_F(\omega_p)\,[1-n_F(\omega_p)]\end{aligned}$$

where $\omega_p = \sqrt{|\mathbf{p}|^2+m_i^2}\,.$ [Bastero-Gil, Berera & Ramos (2001)]

Little Warm inflation

Fermion decay from additional Yukawa interactions:

$$\mathcal{L}_{\psi\sigma} = -h\sigma \sum_{i=1,2} \left(\bar{\psi}_{iL}\psi_{\sigma R} + \bar{\psi}_{\sigma L}\psi_{iR}\right)$$

Dissipation coefficient proportional to the temperature:

$$\Upsilon \simeq \alpha(h)\frac{g^2}{h^2}T \ , \qquad \alpha(h) \simeq \frac{3}{1 - 0.34\log(h)}$$

with $m_i^2 \simeq \Delta m_T^2 \simeq h^2T^2/8$. [c.f. Yokoyama & Linde (1998)]

Warm inflation dynamics

Dynamics in the slow-roll regime: $Q = \Upsilon/(3H) \propto T/H$

$$\frac{Q'}{Q} = \frac{6\epsilon_\phi - 2\eta_\phi}{3+5Q}\ , \qquad \frac{\phi'}{M_P} = -\frac{\sqrt{2\epsilon_\phi}}{1+Q}$$

Field fluctuations satisfy Langevin equation:

$$\delta\ddot{\phi}_k + 3H\delta\dot{\phi}_k + \Upsilon\delta\dot{\phi}_k + \frac{k^2}{a^2}\delta\phi_k = \sqrt{2\Upsilon T}a^{-3/2}\xi_k$$

Which follows from the Fluctuation-Dissipation theorem.

Observational predictions

Curvature power spectrum:

$$\Delta^2_{\mathcal{R}} = \frac{V_*(1+Q_*)^2}{24\pi^2 M_P^4 \epsilon_{\phi_*}} \left(1+2n_* + \frac{2\sqrt{3}\pi Q_*}{\sqrt{3+4\pi Q_*}} \frac{T_*}{H_*} \right) G(Q_*)$$

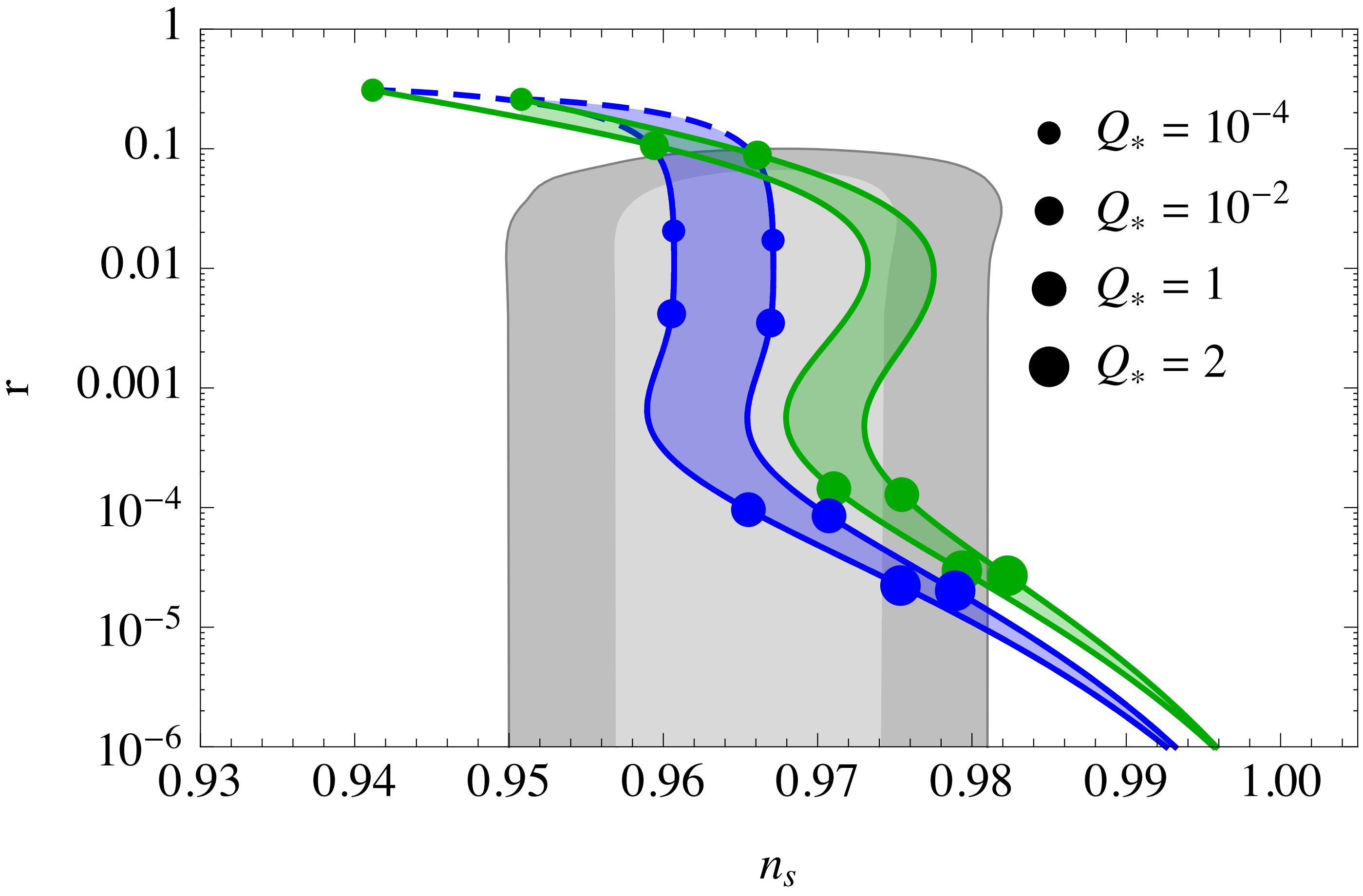
For weak dissipation and thermal pertb. at horizon crossing:

$$n_s \simeq 1 + (2/3)(2\eta_\phi - 6\epsilon_\phi)$$

Tensor pert. are not affected by dissipative/thermal effects

Generically lower tensor-to-scalar ratio

Observational predictions



$$V(\phi) = \lambda\phi^4$$

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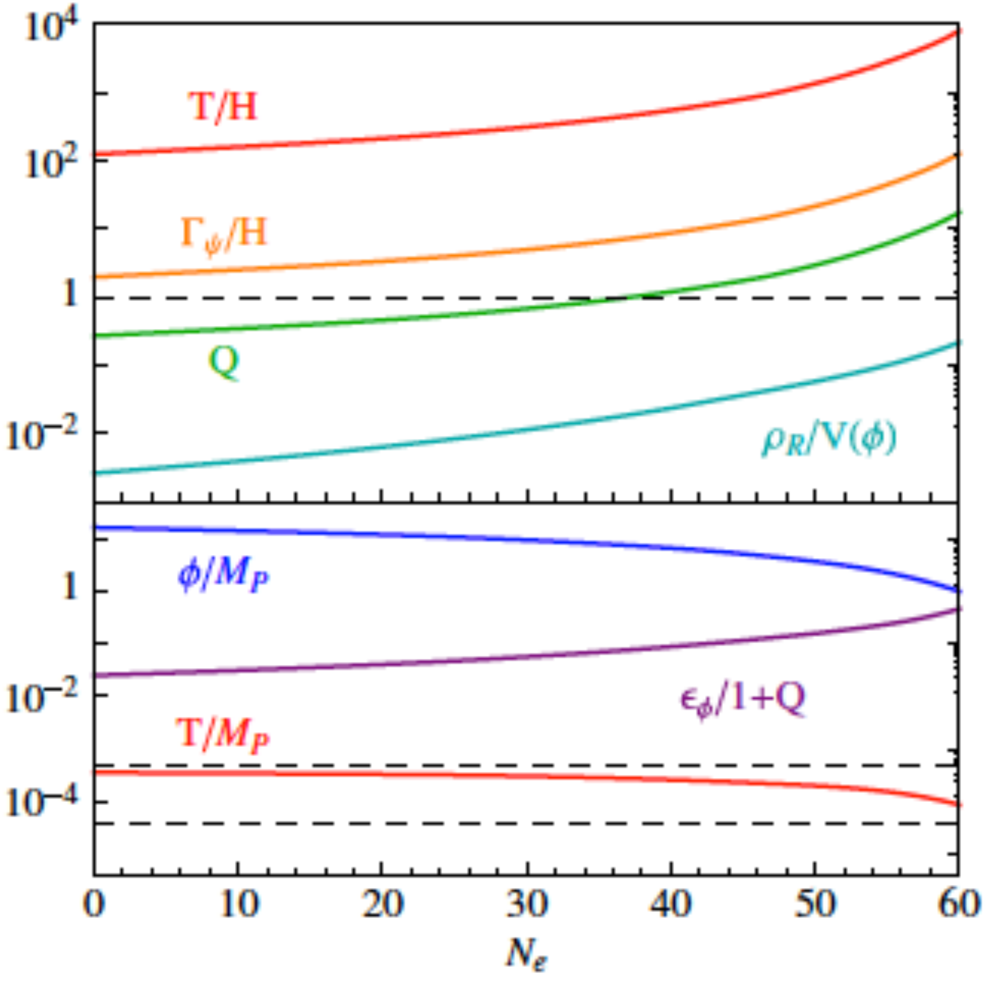
Dynamical example



$$V(\phi) = \lambda\phi^4$$

$$n_s \simeq 0.964 \ ,$$

$$r \simeq 8 \times 10^{-4}$$

$$g = 0.08, \ h = 2, \ M = 10^{15} \text{ GeV}$$

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Summary

- Little inflaton is a pseudo-scalar gauge singlet
- Fields remain light throughout inflation
- No thermal masses and significant dissipative effects
- Observationally consistent chaotic inflation

Warm inflation is possible
and realizable within a simple model