Warm inflation with strong dissipation

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The (cold) inflaton needs to be light

Slow-roll conditions:

$$\epsilon_\phi = \frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$|\eta_\phi| = M_P^2 \frac{|V''|}{V} = \frac{1}{3}\frac{|m_\phi^2|}{H^2} \ll 1$$

There is an "eta-problem" (SUGRA, superstring /M-theory):

$$\Delta V \sim V \frac{\phi^2}{M_P^2} \sim H^2 \phi^2$$

The (cold) inflaton needs to be light

Light scalars are "unnatural" in an EFT:

$$\Delta m_\phi^2 \sim \Lambda^2 \gtrsim H^2$$

- Global symmetries (e.g. shift symmetry) ➡ forbidden in QG?
- Supersymmetry ➡ broken during inflation $\Delta m_\phi^2 \sim H^2$

Swampland conjectures:

[Agrawal, Obied, Ooguri, Steinhardt, Spodyneiko & Vafa (2018)]

$$\Delta\phi \lesssim M_P \ , \qquad M_P|V'|/V \gtrsim 1$$

Can we inflate with a heavy inflaton field?

Warm inflation

[Berera (1995)]

Inflaton dissipates its kinetic energy into the cosmic heat bath:

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

Dissipation is due to non-local terms in effective action:

$$\begin{aligned} \Delta S_\phi &\sim \int d^4x d^4y \phi(x)\Sigma(x-y)\phi(y) \\ &\sim \int d^4x \left[\frac{1}{2}\Delta m_\phi^2 \phi^2 + \Upsilon\dot{\phi}\phi + \ldots\right] \end{aligned}$$

in adiabatic/slow-roll regime where

$$\phi(t') = \phi(t) + \dot{\phi}(t)(t-t')\ldots$$

Warm inflation

[Berera (1995)]

Inflaton dissipates its kinetic energy into the cosmic heat bath:

$$\dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) = -\Upsilon\dot{\phi}^2$$

Dissipation sources radiation/entropy:

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

➡ No need to reheat!
[Luís Ventura's talk]

Slow-roll equations:

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

Slow-roll conditions:

$$\epsilon_\phi < 1 + Q \ , \qquad |\eta_\phi| < 1 + Q$$

➡ Heavy inflaton?

[Berera (1999, 2004)]

Is warm inflation possible?

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

Difficult to keep fields in heat bath light enough:

$$\mathcal{L}_{int} = \frac{1}{2} g^2 \phi^2 \chi^2 \qquad \Rightarrow \qquad m_\chi(\phi) = g\phi$$

Thermal corrections to the inflaton's effective potential:

$$\Delta V_T \subset \frac{1}{24} m_\chi(\phi)^2 T^2 \qquad \Rightarrow \qquad \Delta m_\phi^2 = \frac{1}{12} g^2 T^2 \gtrsim H^2$$

Hard to get significant dissipation for small couplings...

Warm Little Inflaton

[Bastero-Gil, Berera, Ramos & JGR (PRL, 2016)]

Couple inflaton to two light fields:

$$m_1 = gM\cos(\phi/M)\ , \qquad m_2 = gM\sin(\phi/M)$$

Cancellation of leading thermal inflaton mass:

$$\Delta V_T \subset \frac{1}{24}\left(m_1^2 + m_2^2\right)T^2 = \frac{g^2M^2}{24}T^2 \qquad \Rightarrow \qquad \Delta m_\phi^2 = 0$$

Original model with fermions yielded:

$$\Upsilon \propto T$$

Warm Little Inflaton

[Bastero-Gil, Berera, Ramos & JGR (PRL, 2016)]

Inflaton fluctuations follow Langevin equation:

$$\delta\ddot{\phi}_k + 3H(1+Q)\delta\dot{\phi}_k + \left(\frac{k^2}{a^2} + V''(\phi)\right)\delta\phi_k - \frac{d\Upsilon}{dT}\dot{\phi}\delta T_k = \xi_k$$

Thermal fluctuation-dissipation relation:

$$\langle \xi_k \xi_{k'} \rangle = 2(\Upsilon + H)T\frac{(2\pi)^3}{a^3}\delta^3(\mathbf{k}+\mathbf{k}')\delta(t-t')$$

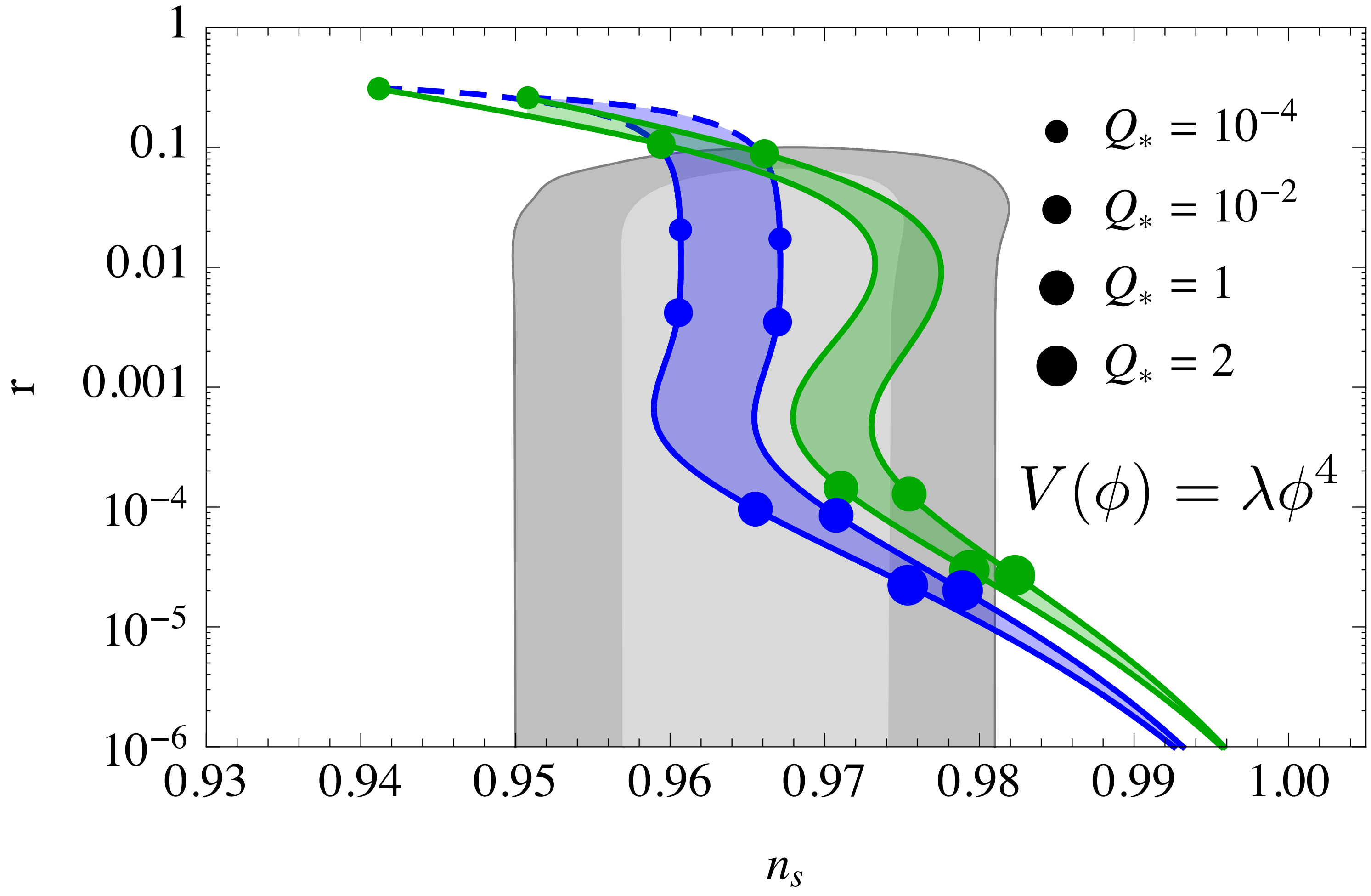
Find growing mode in spectrum for

$$\frac{d\Upsilon}{dT} > 0$$

[Graham & Moss (2009)]

Warm Little Inflaton

[Bastero-Gil, Berera, Ramos & JGR (PRL, 2016)]



Generically low tensor-to-scalar ratio in WI

[Bastero-Gil & Berera (2009)]

Warm Little Inflaton: scalar version

U(1) gauge theory + discrete symmetry $\phi_1 \leftrightarrow i\phi_2$, $\chi_1 \leftrightarrow \chi_2$

$$\mathcal{L}_{\phi\chi} = \frac{1}{2}g^2|\phi_1 + \phi_2|^2|\chi_1|^2 + \frac{1}{2}g^2|\phi_1 - \phi_2|^2|\chi_2|^2 \ ,$$

$$\mathcal{L}_{\chi\psi} = \sum_{\substack{i,j=1,2 \\ i\neq j}} \left[h\chi_i\bar{\psi}_L\psi_R + \text{h.c.} + \frac{\lambda}{2}|\chi_i|^4 + \lambda'|\chi_i|^2|\chi_j|^2\right] .$$

In the ground state (after SSB, unitary gauge):

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

$$\Rightarrow \quad m_{\chi_1}^2 = g^2M^2\cos^2(\phi/M) \qquad m_{\chi_2}^2 = g^2M^2\sin^2(\phi/M)$$

(+ thermal corrections)

Warm Little Inflaton: scalar version

Dissipation coefficient:

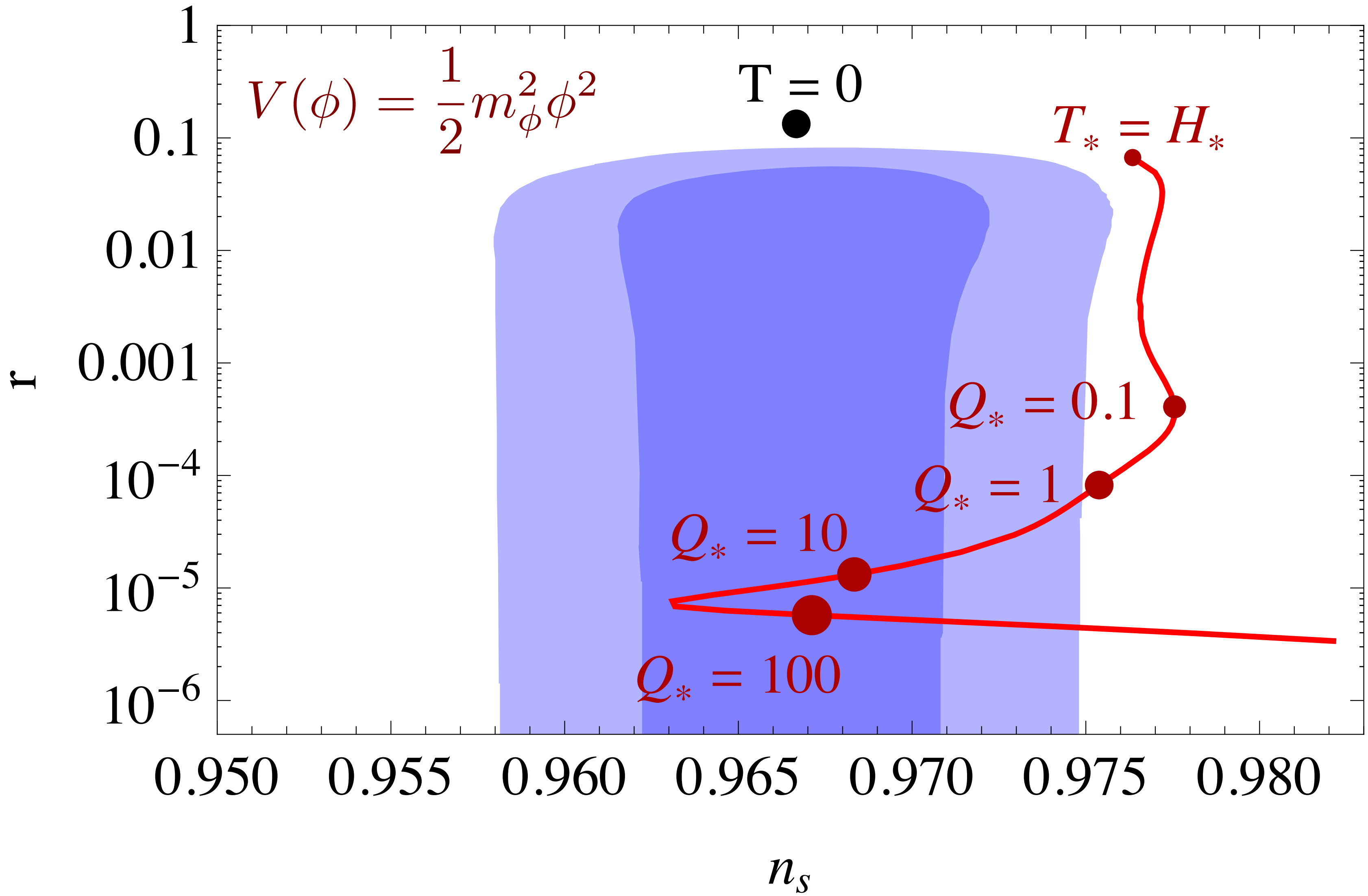
$$\Upsilon \simeq \frac{4Ng^2}{h^2}\frac{M^2T^2}{m_\chi^3}\left[1+\frac{1}{\sqrt{2\pi}}\left(\frac{m_\chi}{T}\right)^{3/2}\right]e^{-m_\chi/T}$$

$$\langle m_\chi^2\rangle = \frac{g^2M^2}{2} + \frac{(h^2+\lambda(N+1)+\lambda' N)}{12}T^2$$

If thermal mass dominates: $m_\chi \propto T$

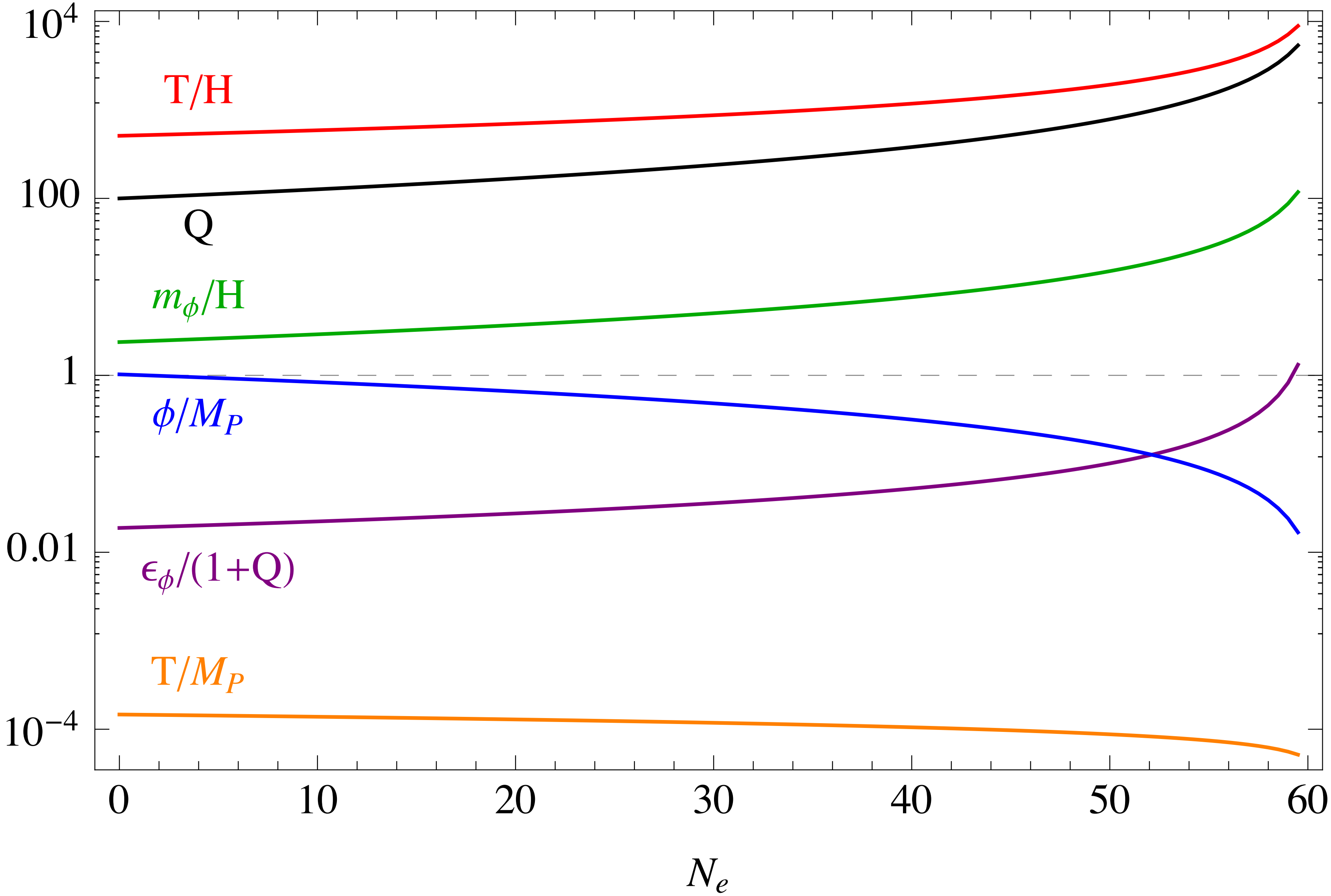
$\Upsilon \propto T^{-1}$ ➡ Fluctuation damping!

Warm Little Inflaton: scalar version



$$gM \simeq 5 \times 10^{13}\ \text{GeV}\ , \quad m_\phi \simeq 10^{12}\ \text{GeV}\ , \quad \alpha^2 = 1/12$$

Warm Little Inflaton: scalar version



Summary

First consistent QFT model of warm inflation w/ strong dissipation:

- simple quadratic potential + renormalizable interactions
- sub-Planckian field excursions
- super-Hubble inflaton mass
- observational agreement with Planck legacy data
- classical thermal inflaton fluctuations
  (no vacuum ambiguities, transplanckian problem, etc)

A warm spot in a cold inflationary swampland?