Warm Inflation as a Way Out of Swampland

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- The Swampland Distance Conjecture [H. Ooguri and C. Vafa, Nucl.Phys.B 2007]

$$\frac{\Delta\phi}{M_{pl}} < \Delta \sim \mathcal{O}(1). \tag{1}$$

- The Swampland de Sitter Conjecture [G. Obied et al., 2018]

$$M_{pl}\left(\frac{|V_\phi|}{V}\right) > c_1 \sim \mathcal{O}(1). \tag{2}$$

- Refined de Sitter Conjecture [H. Ooguri et al., PLB 2018]

$$M_{pl}\left(\frac{|V_\phi|}{V}\right) > c_1 \sim \mathcal{O}(1), \quad \text{or} \quad M_{pl}^2\left(\frac{|V_{\phi\phi}|}{V}\right) < -c_2 \sim \mathcal{O}(1). \tag{3}$$

- Transplanckian Censorship Conjecture (TCC) [A. Bedroya and C. Vafa, JHEP 2019]

$$\frac{a_f}{a_i} < \frac{M_{pl}}{H_f}. \tag{4}$$

while this condition constrains the energy scale of inflation [A. Bedroya et al., PRD 2019]

$$V^{\frac{1}{4}} < 3 \times 10^{-10} M_{pl} \quad \Rightarrow \quad r < 10^{-30}. \tag{5}$$

Warm Vs Cold Inflation

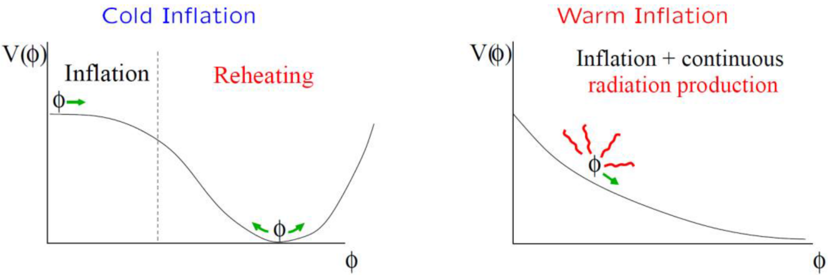

Figure: Warm Vs Cold inflationary dynamics [A. Berera, Contemp.Phys. 2006].

Due to conservation of energy, dynamical equations for warm inflation read as

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V_\phi = 0, \qquad \dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2. \tag{6}$$

Then one can define Hubble slow-roll parameter as follows

$$\epsilon_H \equiv -\frac{\dot{H}}{H^2} = \frac{\epsilon_V}{1+Q}, \qquad \text{(steep potentials)} \tag{7}$$

where $Q = \Upsilon/3H$ and $\epsilon_V = M_{pl}^2(V_\phi/V)^2/2$ and field excursion can be obtained from

$$M_{pl}^{-1}\frac{d\phi}{dN} = \frac{\sqrt{2\epsilon_V}}{1+Q}, \qquad \text{(sub-Planckian)} \tag{8}$$

and radiation to potential energy density ratio is given by

$$\frac{\rho_r}{V} = \frac{\epsilon_H}{2}\frac{Q}{1+Q}, \qquad \text{(no reheating)} \tag{9}$$

Consistency with both swampland de Sitter and distance conjectures imposes a lower bound on the dissipation ratio [M. Motaharfar, V. Kamali and R. Ramos, PRD 2019]

$$1 + Q > \frac{c_1}{\Delta} N \sim N. \tag{10}$$

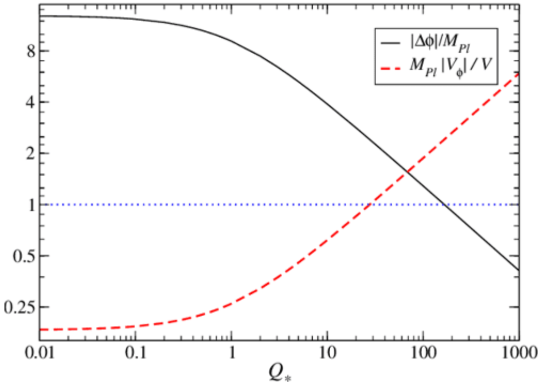

Figure: Field excursion and slop of potential as a function of dissipation ration $Q_\star$

Cosmological Perturbations and Growing Mode Behavior

Curvature power spectrum for warm inflation is given by [M. Bastero-Gil, A. Berera and R. Ramos, JCAP 2011]

$$P_{\mathcal{R}} = \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2 \left[1 + 2n_\star + \frac{2\sqrt{3}\pi Q_\star}{\sqrt{3+4\pi Q_\star}} \frac{T_\star}{H_\star}\right] G(Q_\star). \tag{11}$$

- Thermal fluctuations rather quantum fluctuations ($T > H \sim m_\phi$)
- Bose-Einstein distribution, i.e. $n_\star = 1/[\exp[H_\star/T_\star] - 1]$ (thermally excited states)
- Modification due to dissipation coefficient
- Growing mode behaviour due to coupling between inflaton and radiation fluctuations, i.e. $G(Q_\star) \sim Q_\star^{3c}$, where $c = d\ln\Upsilon/d\ln T > 0$ (blue spectrum)

Tensor power spectrum is the same as cold inflation, therefore,

$$r = \frac{16\epsilon_H}{1+Q}\mathcal{F}^{-1}\left(\frac{k}{k_\star}\right). \tag{12}$$

So TCC requires larger dissipation ratio than lower bound found in Eq. (11).

How to build warm inflation with large dissipation ratio still consistent with observation?

- Modifying the dynamics of warm inflation
- Building particle physics models

We consider warm inflation in Randall-Sundrum brane-world cosmology with exponential potential [V. Kamali, M. Motaharfar and R. Ramos, PRD 2019]

$$3M_{pl}^2H^2 = \rho\left(1+\frac{\rho}{\lambda}\right), \qquad V(\phi) = V_0\exp(-\alpha\phi/M_{pl}), \qquad \Upsilon(\phi,T) = C\frac{T^3}{\phi^2}, \tag{13}$$

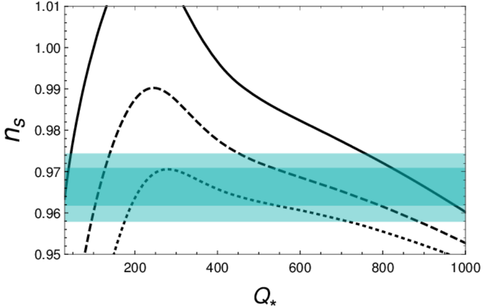

Figure: The spectral index n_s as a function of the dissipation ratio $Q_\star$ for the cases of $\lambda/V_0 = 10^{-5}$ (solid line), $\lambda/V_0 = 5\times10^{-5}$ (dashed line) and $\lambda/V_0 = 10^{-4}$ (dotted line), for the fixed value of $\alpha = 40$. The shaded areas are for the 68% and 95% C.L. results from Planck 2018 (TT+TE+EE+lowE+lensing+BK15+BAO data).

Warm Dirac-Born-Infeld (DBI) inlfation

We consider warm inflation with Driac-Born-Infeld (DBI) kinetic term as follows [M. Motaharfar and R. Ramos, PRD 2021]

$$\mathcal{L}_{DBI} = f^{-1}(\phi)\left[1-\sqrt{1-2Xf(\phi)}\right]-V(\phi), \qquad X=-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi, \quad (14)$$

$$c_s \equiv \sqrt{1-2f(\phi)X}, \qquad f(\phi)=f_0\phi^{-4}. \quad (15)$$

and one will find analytically that $G(Q_\star) \sim Q_\star^{3cc_s^2}$.

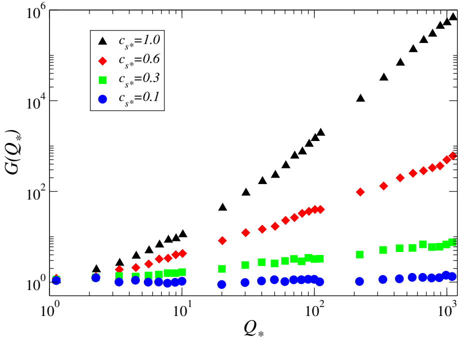

Figure: Growing mode function $G(Q_\star)$ for different value of sound speed $c_{s_\star}$ and linear dissipation coefficient $\Upsilon \propto T$.

- Swampland conjectures require smaller energy scale inflationary models which is achievable for large dissipation ratio in warm inflation.
- Large dissipation ratio makes the power spectrum blue titled due to coupling between inflaton and radiation fluctuations.
- Combination of high energy correction from brane-world cosmology with exponential potential results in red-tilted power spectrum for large dissipation ratio.
- Smaller sound speed will suppress growing mode resulting in warm inflation with high dissipation ratio consistent with swampland conjectures.