Dissipative and Stochastic Effects During Inflation [1]

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Inflation: a window into high energies

Inflation: Early phase of accelerated expansion dominated by vacuum energy $V(\phi)$ ($\phi =$ scalar field – the inflaton) $\ddot{a} > 0, \quad p < -\rho/3$

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

$r =$ tensor-to-scalar curvature perturbation ratio.
Planck TT+BKP 2015: $r \lesssim 0.08$.

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$\Rightarrow$ Can the inflaton be embedded into a fundamental theory ?

$\Rightarrow$ We need to know how it interacts with other fields !

Cold Inflation

Cold Inflation[a]:

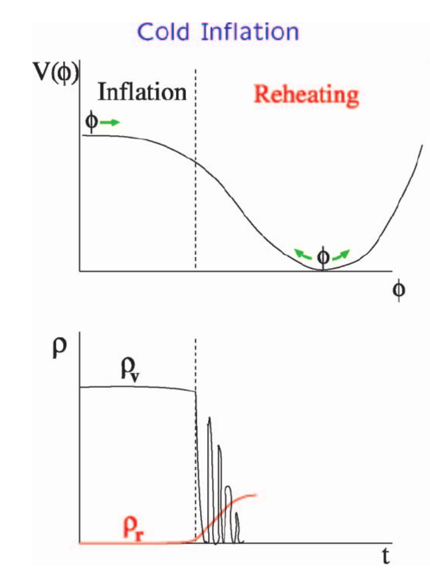
[a] (Starobinsky '80; Guth '81; Albrecht, Steinhardt '82; Linde '82)

$$\text{Inflaton} \implies \text{Reheating} \implies \text{Radiation} \implies \text{Matter}$$

Inflaton interactions with other d.o.f. only important during reheating

$$\dot{\rho}_r + 4H\rho_r = 0, \quad (H = \dot{a}/a \sim cte)$$

$\Rightarrow$ The radiation density during inflation redshifts away: $\rho_r \sim 1/a^4$
$\Rightarrow$ density perturbations sourced by inflaton's quantum fluctuations


Cold Inflation
V(ϕ)
Inflation
Reheating
ϕ
ϕ
ϕ
ρ
ρv
ρr
t

Cold Inflation

$$\begin{array}{ccccc} \text{Inflaton} & \Longrightarrow & \text{Radiation (p)reheating} & \Longrightarrow & \text{Matter} \\ \phi & \longrightarrow & \chi, \psi_\chi & \longrightarrow & \text{SM dof} \end{array}$$

$$\text{for example}: \; \mathcal{L}_I = -V(\phi) - \frac{1}{2} g_\chi^2 \phi^2 \chi^2 - g_\psi \phi \bar{\psi}_\chi \psi_\chi + \mathcal{L}_I[\chi, \psi_\chi, SM]$$

If the universe did not supercool, then...

- can reduce the need for very small couplings
- more opportunities for particle phenomenology
- make structure from thermal fluctuations
- can produce observable amounts of non-gaussianity
- exit nicely

Warm Inflation[a]:

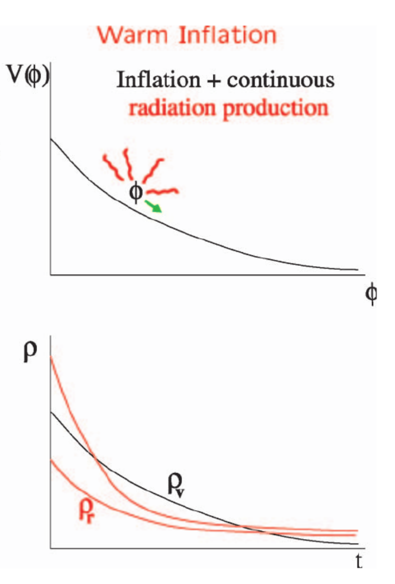
[a] Ian G. Moss PLB154 1985, Yokoyama and Maeda PLB207 1988, A. Berera and L. Z. Fang PRL75 1995

$$\text{Inflaton} \Longrightarrow \text{Decay} \Longrightarrow \text{Radiation} \Longrightarrow \text{Matter}$$

Inflaton interactions with other d.o.f. is important during inflation generate dissipation/viscosity terms ⇒ small fraction of vacuum energy density can be converted to radiation

$$\dot{\rho}_r + 4H\rho_r = \Upsilon\dot{\phi}^2$$

⇒ The radiation density during inflation stabilises: $\Rightarrow \rho_r \sim \Upsilon\dot{\phi}^2/(4H)$


Warm Inflation
V(ϕ)
Inflation + continuous
radiation production
ϕ
ϕ
ρ
ρv
ρr
t

Warm Inflation

- The production of radiation is associated with a friction term in the inflaton equation,

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} + \Upsilon\dot{\phi} = \xi$$

- $\Upsilon\dot{\phi}$ (friction term) describes how inflaton's interactions with other fields backreact on the inflaton dynamics.
- ξ describes quantum and thermal stochastic fluctuations. Dynamics for the inflaton is similar to a Langevin equation with quantum and thermal noise terms (stochastic process w/ Gaussian noises)[2]
- Effectiveness of warm inflation measured by $Q = \frac{\Upsilon}{3H}$
- Cold or warm inflation: $T \lesssim H$ or $T \gtrsim H$
- adiabatic density fluctuations are sourced by thermal fluctuations: amplitude $\delta\phi^2 \sim H^2 + HT + \Upsilon T$, (WI: $T > H$), curvature perturbations $\zeta = H\delta\phi/\dot{\phi}$.

[2] M. Gleiser and ROR, PRD50, 2441 (1994); A. Berera, M. Gleiser and ROR, PRD58, 123508 (1998); ROR and L. A. da Silva, JCAP 03 (2013) 032

Warm Inflation Model Building

Challenges:

- Coupling the inflaton to light particles is hard
  Berera, Gleiser & ROR (1998); Yokoyama & Linde (1998),

$$\mathcal{L}_{\rm int} = -g\phi\bar{\psi}\psi \quad \Rightarrow \quad m_\psi = g\phi \gtrsim T$$

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

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- Need very small couplings $\Rightarrow$ results in very little dissipation ...

PHYSICAL REVIEW D, VOLUME 60, 083509

Is warm inflation possible?

Jun'ichi Yokoyama*
Department of Physics, Stanford University, Stanford, California 94305-4060
and Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

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Department of Physics, Stanford University, Stanford, California 94305-4060
(Received 25 August 1998; published 24 September 1999)

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VOLUME 83, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1999

A First Principles Warm Inflation Model that Solves the Cosmological Horizon and Flatness Problems

Arjun Berera,[1] Marcelo Gleiser,[2] and Rudnei O. Ramos[3]
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(Received 30 September 1998; revised manuscript received 2 November 1998)

A quantum field theory warm inflation model is presented that solves the horizon and flatness problems. The model obtains, from the elementary dynamics of particle physics, cosmological scale factor trajectories that begin in a radiation dominated regime, enter an inflationary regime, and then smoothly exit back into a radiation dominated regime, with non-negligible radiation throughout the evolution.

Is warm inflation possible ? YES !

The inflaton does not need to be coupled directly to the radiation fields: It can couple indirectly through heavy mediator fields
Berera & ROR (2001); Berera & ROR (2003); Moss & Xiong (2006); Bastero-Gil, Berera & ROR (2011); Bastero-Gil, Berera, ROR & Rosa (2014,2015), For a review: Berera, Moss and ROR, Rep. Prog. Phys. **72**, 026901 (2009)

Working model: the two-stage decay model:

ϕ	$\longrightarrow$	χ, ψ_χ	$\longrightarrow$	ψ_σ, σ
inflaton		heavy field		light fermions or scalars
		$(m_X \gg T)$		$(m_Y \ll T)$

for example : $\mathcal{L}_I = -\frac{\lambda}{4}\phi^4 - \frac{1}{2}g_\chi^2\phi^2\chi^2 - g_\psi\phi\bar{\psi}_\chi\psi_\chi - h_\sigma M\chi\sigma^2 - h_\psi\chi\bar{\psi}_\sigma\psi_\sigma$

very same interactions found/needed in (p)reheating in cold inflation !

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- decouple the radiation from the inflaton $(m_\chi, m_{\psi_\chi} \gg T, m_{\sigma,\psi_\sigma} \ll T)$
- couplings between fields of order 0.1
- SUSY to reduce vacuum corrections, e.g., $W = g\Phi X^2 + hXY^2$ where Φ, X, Y are superfields with scalar and fermion components given by $(\phi,\ \psi_\phi)$, $(\chi,\ \psi_\chi)$ and $(\sigma,\ \psi_\sigma)$ respectively.

Let $\phi \equiv \phi(x,t)$ and average out (integrate over) the other fields. This gives a stochastic (Langevin-like) system[3],

$$\ddot{\phi}(\mathbf{x},t)+3H\dot{\phi}(\mathbf{x},t)+\int d^4x'\Sigma_R(x,x')\phi(x')+V_{,\phi}-\frac{1}{a^2}\nabla^2\phi(\mathbf{x},t)=\xi(\mathbf{x},t).$$

The kernel:

$$\begin{aligned}\Sigma_R(x') &= -i\left(\frac{g_1^2}{2}\right)^2\varphi^2\sum_{i=1}^{2}\theta(t-t')\langle[\chi_i^2(x'),\chi_i^2(0)]\rangle \\ &\quad -i\frac{g_2^2}{2}\theta(t-t')\mathrm{tr}\left\{\langle[\bar{\psi}_\chi(x')\psi_\chi(x'),\bar{\psi}_\chi(0)\psi_\chi(0)]\rangle\right\}\ ,\end{aligned}$$

is connected to the two-point correlation function of the noise term $\xi(\mathbf{x},t)$: generalized fluctuation-dissipation relation

[3] M. Gleiser and ROR, PRD50, 2441 (1994)

The self-energy contribution is a dissipative term[4] (in the adiabatic approximation, $\dot{\phi}/\phi, H, \dot{T}/T < \Gamma_\chi \approx h^2 m_\chi/(8\pi)$),

$$\int d^4x' \Sigma_R(x, x')\phi(x') \approx \Upsilon \dot{\phi}(x, t)$$

$$\begin{aligned} \Upsilon &= \frac{2}{T}\left(\frac{g_1^2}{2}\right)^2 \varphi^2 \int \frac{d^4p}{(2\pi)^4}\, \rho_\chi(p_0, \mathbf{p})^2 \; n_B(p_0)\,[1 + n_B(p_0)] \\ &+ \frac{g_2^2}{2T} \int \frac{d^4p}{(2\pi)^4} \mathrm{tr}\left[\rho_{\psi_\chi}(p_0, \mathbf{p})^2\right] n_F(p_0)\,[1 - n_F(p_0)] \;, \end{aligned}$$

where ρ_χ and ρ_{ψ_χ} are the spectral functions for the intermediate fields χ and ψ_χ

The dissipation coefficient Υ can be explicitly computed in QFT once the interactions are given.

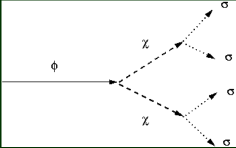
[4] A. Berera, I. G. Moss and ROR, PRD76, 083520 (2007)

$\mathcal{L}_I$	dissipation Υ
$-g_1^2\phi^\dagger\phi\chi^\dagger\chi - h_1 M[\chi^\dagger\sigma^2 + \chi(\sigma^\dagger)^2]$	$0.026 g_1^4 h_1^4 \varphi^2 T^3 M^4/m_{R,\chi}^8$
$-g_1^2\phi^\dagger\phi\chi^\dagger\chi - h_2[\chi^\dagger\bar{\psi}_\sigma P_R\psi_\sigma + \chi\bar{\psi}_\sigma P_L\psi_\sigma]$	$0.11 g_1^4 h_2^4 \varphi^2 T^7/m_{R,\chi}^8$
$-g_1^2\phi^\dagger\phi\chi^\dagger\chi - h_1 M[\chi^\dagger\sigma^2 + \chi(\sigma^\dagger)^2]$ $-h_2[\chi^\dagger\bar{\psi}_\sigma P_R\psi_\sigma + \chi\bar{\psi}_\sigma P_L\psi_\sigma]$	$0.015 g_1^4 h_1^2 h_2^2 \varphi^2 T^5 M^2/m_{R,\chi}^8$
$-\frac{1}{\sqrt{2}} g_2\varphi\bar{\psi}_\chi\psi_\chi - h_3[\sigma^\dagger\bar{\psi}_\chi P_R\psi_\sigma + \sigma\bar{\psi}_\chi P_L\psi_\sigma]$	$0.22 g_2^2 h_3^4 T^5/m_{R,\psi_\chi}^4$

Table 1. A summary of all the dissipation coefficients in the low-temperature regime coming from each of the interaction cases involving a heavy intermediate field (all expressions evaluated with $m_{\chi_1} = m_{\chi_2}$).

$\Rightarrow$ leading friction coefficient for $T \ll m_\chi$ is:

$$\Upsilon \sim g^2 h^4 (T^3/m_\chi^2),$$



Going back to the old WI model

New Motivation: Little Higgs model[5]. The Higgs is a PNGB of some spontaneously broken global symmetry: $G \rightarrow H$, with a property of collective symmetry breaking. Global symmetry is explicitly broken by two sets of interactions, with each preserving a subset of the symmetry:

$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

$\mathcal{L}_0$ symmetric part, $\mathcal{L}_{1,2}$ are explicit symm. breaking terms.

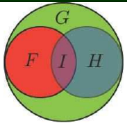


Fig. 3. A global symmetry G is spontaneously broken down to a subgroup H. A subgroup F of G is gauged and it is broken down to the intersection of F and H, $I = F \cap H$, which is identified as the SM electroweak gauge symmetry. The number of uneaten PNGBs is given by the number of generators of $(N(G) - N(H)) - (N(F) - N(I))$. They are identified as the Higgs.

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

The Warm Little Inflaton

Bastero-Gil, Berera, ROR & Rosa, PRL (2016)

Consider a $U(1)$ gauge theory spontaneously broken by *two complex scalar fields*:

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

Only one Nambu-Goldstone boson is "eaten" by the gauge field, while the other remains as a physical singlet scalar (inflaton):

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

The Warm Little Inflaton

Couple the inflaton to charged and singlet Weyl fermions:

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

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!

$$gM \lesssim T \lesssim M$$

The Warm Little Inflaton

Effective potential at high temperature:

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

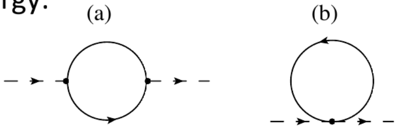
No thermal inflaton masses!

Alternatively, expand Lagrangian to quadratic order:

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

The Warm Little Inflaton

Inflaton self-energy:



$$\Sigma_\phi(0) = \left[\left(g_1^2 + m_1 f_1\right) + \left(g_2^2 + m_2 f_2\right)\right] I_T$$
$$= g^2 \left[-\cos(2\phi/M) + \cos(2\phi/M)\right] I_T = 0 \ ,$$

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

Cancellation of quadratic divergences and thermal masses!

The Warm Little Inflaton

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

No cancellation of dissipative terms!

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

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

The Warm Little Inflaton

Fermion decay from additional Yukawa interactions:

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

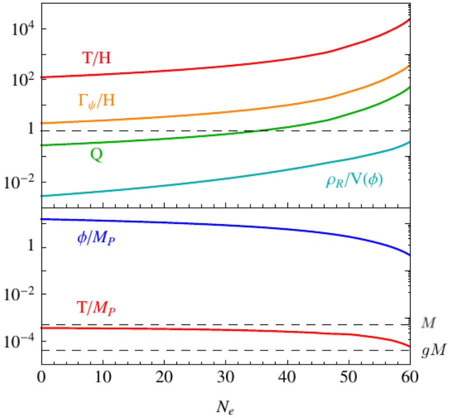
Dissipation coefficient proportional to the temperature:

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

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

The Warm Little Inflaton

satisfies the conditions $gM \lesssim T \lesssim M$ for $M \simeq 10^{15}$ GeV



Example of the dynamical evolution in warm inflation with a quartic potential. The dashed lines in the bottom plot correspond to M and gM (in Planck units).

ROR & da Silva (2013), Bastero-Gil, Berera, Moss & ROR (2014)

Fluctuations & primordial spectrum: coupled system

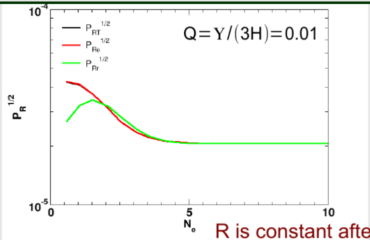
Field EOM: $$\delta\ddot{\phi}_k^{GI} + (3H+\Upsilon)\delta\dot{\phi}_k^{GI} + \dot{\phi}\,\delta\Upsilon^{GI} + \left(\frac{k^2}{a^2} + V_{\phi\phi}\right)\delta\phi_k^{GI} \simeq (2\Upsilon T)^{1/2}\hat{\xi}_k$$

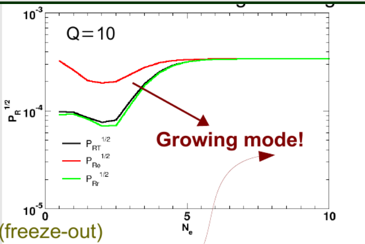
fluctuation force ξ

(light d. of f.)

$$\rightarrow \quad \frac{\delta\Upsilon^{GI}}{\Upsilon} = \frac{1}{4}\frac{\delta\rho_r^{GI}}{\rho_r} = \frac{\delta T}{T} \quad \rightarrow$$

Coupled system inflaton-radiation





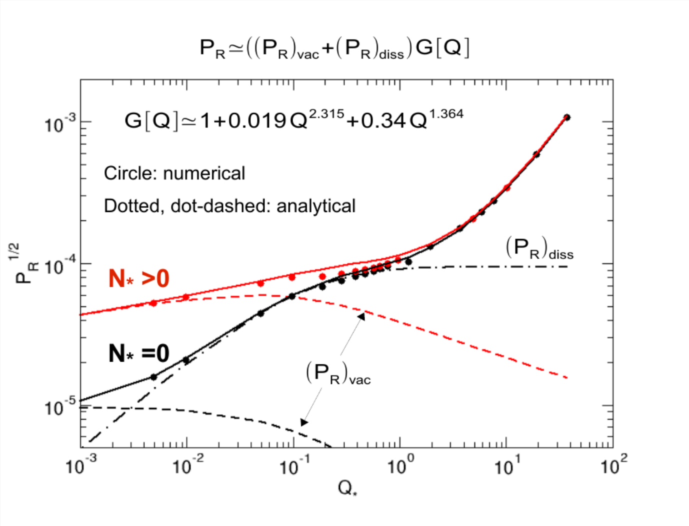
R is constant after horizon crossing (freeze-out)

$$P_R \simeq \left(\frac{H}{\dot{\phi}}\right)^2 \left(\frac{H}{2\pi}\right)^2 \left(1 + 2\mathcal{N} + \frac{T}{H}\frac{4\pi Q}{\sqrt{1+4\pi Q/3}}\right) \times G[Q], \qquad Q = \Upsilon/(3H)$$

Dissipative processes may maintain a non-trivial distribution of inflaton particles:

$$\mathcal{N} \simeq n_{BE} = (e^{k/aT} - 1)^{-1}$$

Primordial spectrum



Chaotic model: $V(\phi) = \lambda \phi^4/4, \quad \lambda = 10^{-14}, \quad N_e = 50$

Spectral tilt n_s × Tensor-to-Scalar ratio r PRD95, 023517 (2017)

$Q \equiv \Upsilon/(3H)$

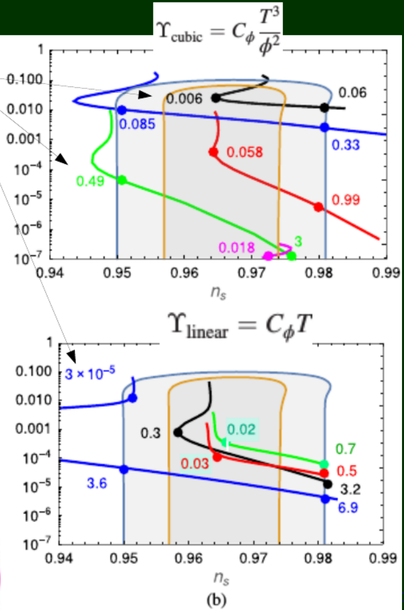
$$V_{\rm quartic}(\phi) = \frac{\lambda}{4}\phi^4$$

$$V_{\rm sextic}(\phi) = \frac{\lambda}{6M_p^2}\phi^6$$

$$V_{\rm hilltop}(\phi) = \frac{\lambda M_P^4}{2}\left[1 - \frac{\gamma}{2}\left(\frac{\phi}{M_p}\right)^2\right]^2$$

$$V_{\rm Higgs}(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$$

$$V_{\rm plateau}(\phi) = \frac{\lambda v^6}{12M_P^2}\left(1 - 3\frac{\phi^2}{v^2} + 2\frac{\phi^6}{v^6}\right)$$



(b)

Breaking Degeneracies

WARM INFLATION DISSIPATIVE EFFECTS: … PHYSICAL REVIEW D **95,** 023517 (2017)

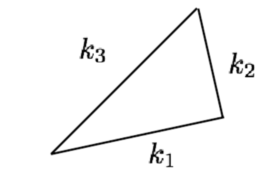
TABLE I. The values of dissipation ratio Q_* and T_*/H_*, along also the values of r, α_s and β_s, and the $\Delta\chi^2$ with respect to the minimal ΛCDM model when n_s is fixed at the value $n_s \simeq 0.9655$, for each model considered in this work.

$V(\phi)$	Υ	Q_*	T_*/H_*	r	α_s	β_s	$\Delta\chi^2_{\rm min}$
Quartic		1.697×10^{-3}	7.246	36×10^{-3}	-9.840×10^{-4}	-2.557×10^{-5}	-0.2
Sextic		0.187	41.945	5.225×10^{-3}	1.540×10^{-3}	1.972×10^{-4}	$+0.3$
Hilltop	$\propto \frac{T^3}{\phi^2}$	0.186	41.656	1.741×10^{-4}	-9.997×10^{-5}	-3.101×10^{-6}	$+0.1$
Higgs		1.417	214.829	2.317×10^{-6}	-1.857×10^{-4}	-4.333×10^{-6}	-0.1
Plateau sextic		5.645×10^{-3}	10.766	1.085×10^{-7}	-4.692×10^{-4}	3.369×10^{-5}	0
Quartic		1.256	273.472	1.276×10^{-4}	-3.019×10^{-4}	4.156×10^{-6}	0
Sextic		4.966	769.074	1.064×10^{-5}	3.731×10^{-3}	8.381×10^{-4}	$+0.7$
Hilltop	$\propto T$	0.028	50.303	1.092×10^{-4}	-1.588×10^{-4}	-1.028×10^{-5}	0
Higgs		0.020	44.492	2.947×10^{-4}	-2.505×10^{-4}	-1.424×10^{-5}	-0.1
Plateau sextic		0.810	210.187	4.448×10^{-9}	-3.862×10^{-4}	-2.708×10^{-6}	0

Non-Gaussianities

$$\langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle = (2\pi)^3\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\Phi(k_1,k_2,k_3)$$

$\Phi \equiv (3/5)\zeta$, $\zeta =$ comoving curvature perturbation



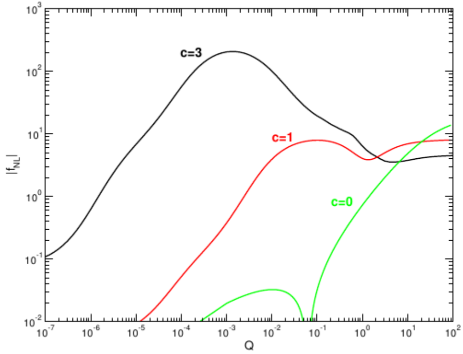
Nonlinearity parameter f_{NL}:

$$B_\Phi(k_1,k_2,k_3) = f_{NL}F(k_1,k_2,k_3)$$

function $F(k_1,k_2,k_3)$ depends on the shape (type of triangle)

Warm Inflation and Non-Gaussianity[6]

f_{NL} relative to the equilateral shape: $f_{NL} = \frac{18}{5}\frac{B(k,k,k)}{P(k)^2}$

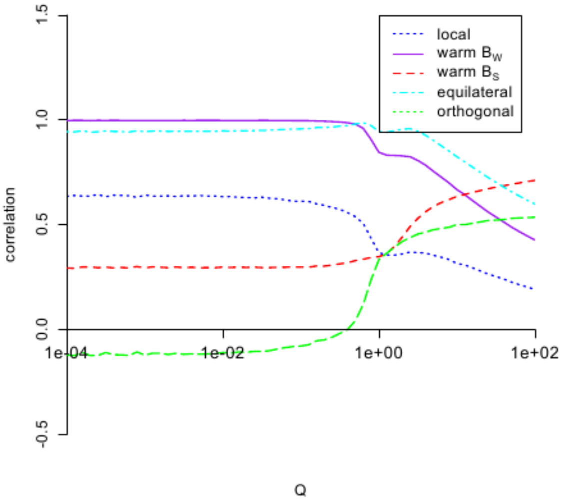


Non-linearity parameter $|f_{NL}|$ versus Q for different values of c ($\Upsilon \propto T^c$) as indicated in the plot.

Planck constraints:

$f_{NL}^{\rm local} = 2.7 \pm 5.8\,,\;\; f_{NL}^{\rm equi} = -42 \pm 75\,,\;\; f_{NL}^{\rm warm} = 4 \pm 33$

[6] M. Basteiro-Gil, A. Berera, I. G. Moss, R.O.R., JCAP12, 008 (2014)



(a)The correlation between the numerical bispectrum and the template shapes plotted as a function of the dissipation strength parameter Q.

Summary

- Dissipative and stochastic effects due to interactions can be relevant and modify the inflationary predictions (r, n_s, f_{NL}, etc).
- Warm inflation has been previously successfully constructed in the low-T regime for dissipation (inflaton+mediator fields+radiation fields), but requires large number of heavy mediators ($N_\chi \sim 10^6$).
- Warm inflation in the high-T regime for dissipation has been considered "impossible".
- Little Higgs like model for the inflaton (PNGB of a broken U(1) symmetry + exchange symmetry) demonstrates for the first time that this is not true.
- Cancellation of thermal masses and quadratic divergences but not of dissipative effects: a warm inflation model with minimal matter content (only two light fermions !).
- Both low-T and high-T particle physics models for WI lead to consistent dynamics with observables well within the Planck values.