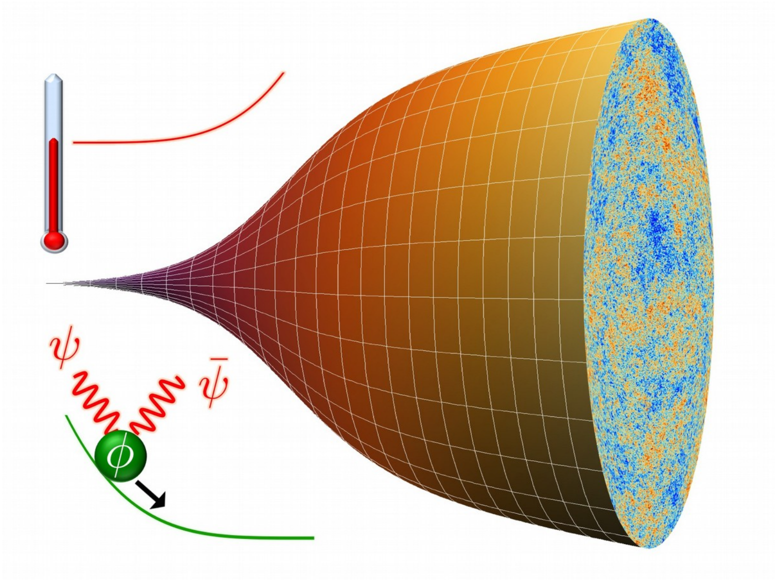
Little Warm Inflation

Cold inflation/Warm inflation



Dissipative coefficient:

High T regime: $\Upsilon(T) = C_T T$

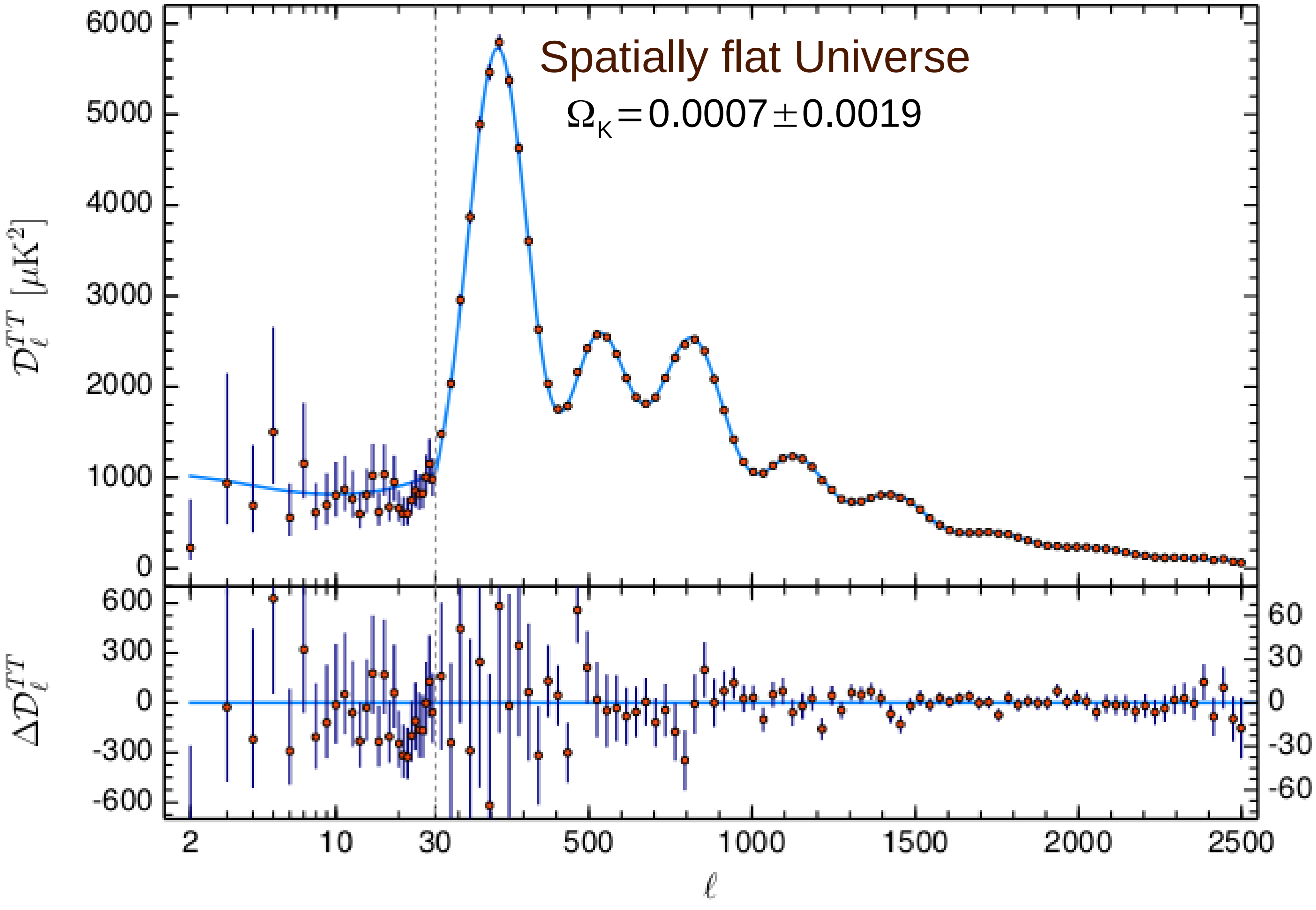
Primordial spectrum: Chaotic models $\lambda\phi^4$

Mar Bastero Gil
University of Granada

MBG, A. Berera, R. Ramos, J. Rosa PRL117 (2016) 151301
MBG S. Bhattacharya, K. Dutta, M. R. Gangopadhyay JCAP 1802 (2018)
MBG, A. Berera, R. Hernández-Jiménez, J. Rosa, arXiv: 1805.07186

Cosmic microwave background radiation (CMB)

Spectrum of T fluctuations



COBE (1992)
Boomerang
Maxima
DASI
CBI
VSA
.....

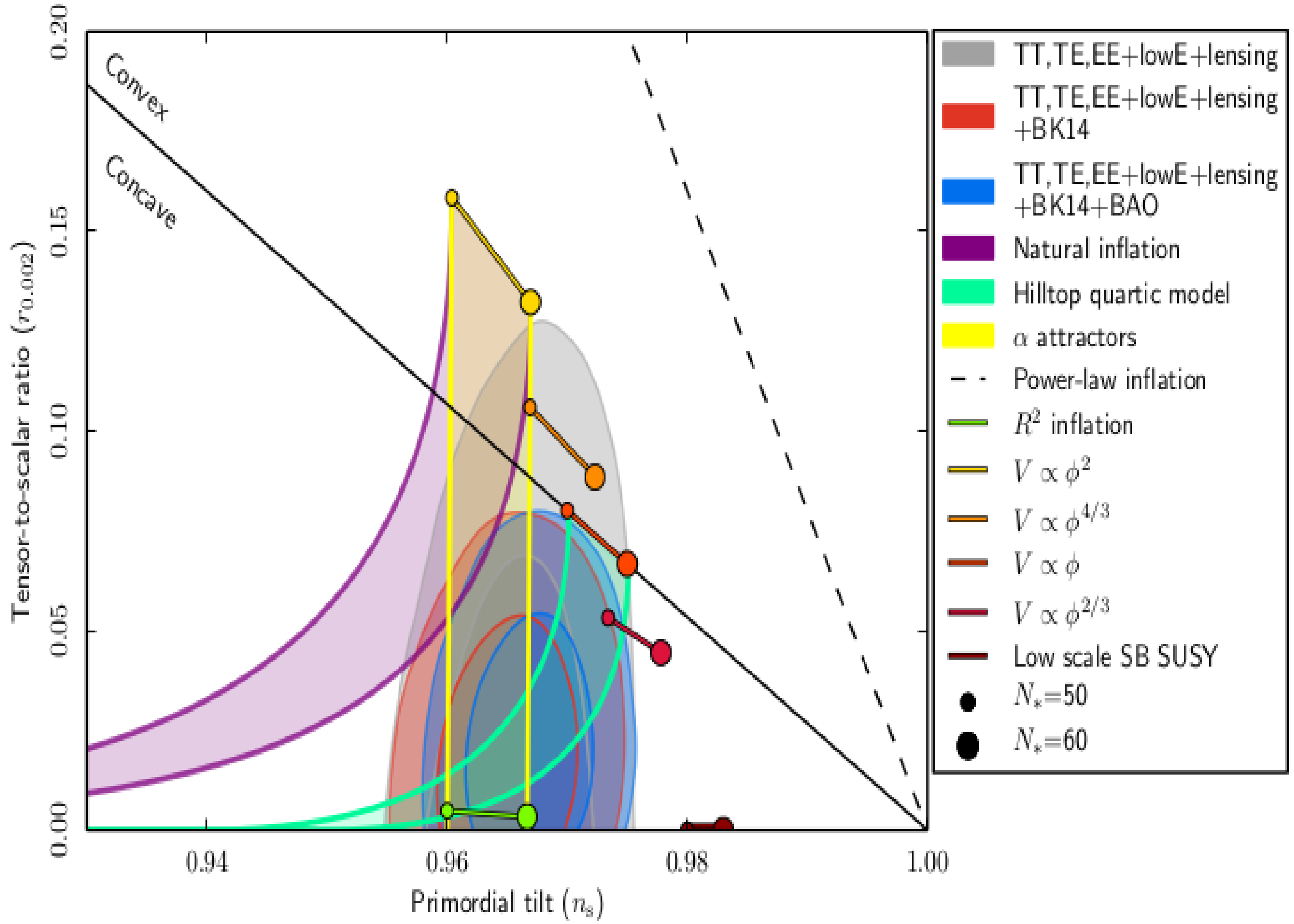
WMAP
SPT
BICEP/KEK
PLANCK
(14/05/09)

[Planck 2018: astro-ph/1807.06211]

Primordial spectrum: ~adiabatic, ~scale-invariant, gaussian?, tensors?

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1}$ $k_0 = 0.05\,\mathrm{Mpc}^{-1}$

Tensor-to-scalar Ratio: $r = P_T/P_R$ $P_R = 2.2 \times 10^{-9}$



$r_{0.002} < 0.07$

[Planck 2018.: 1807.06211]

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1 + \frac{1}{2}\alpha_s \ln k/k_0 + \cdots}$ $\quad k_0 = 0.05\,\mathrm{Mpc}^{-1}$

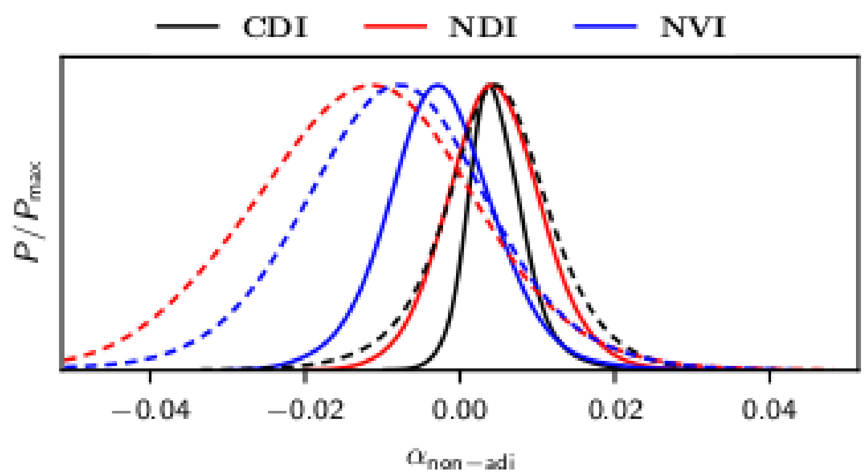
adiabatic, gaussian, ~scale-invariant spectrum

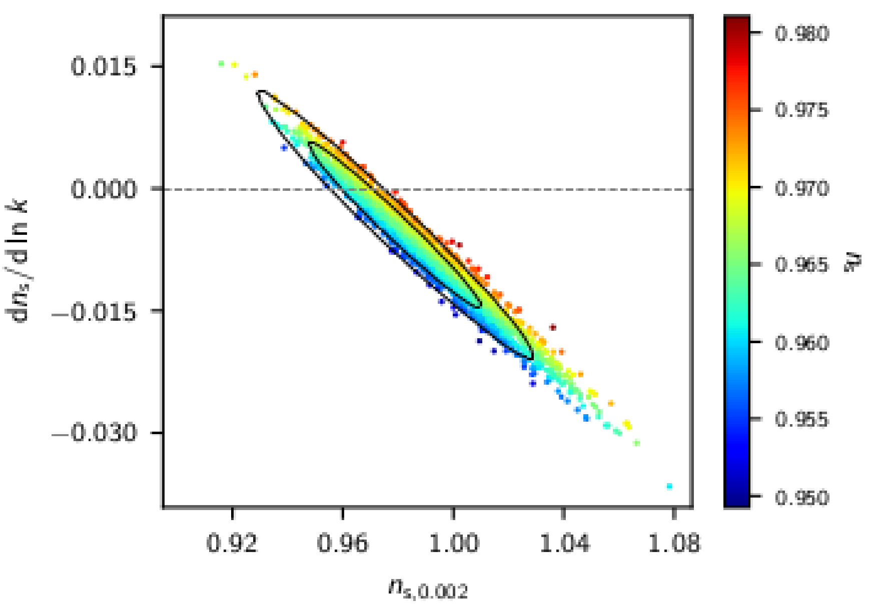
No evidence for:
isocurvature modes, non-gaussianity, or <u>running of the spectral index</u>

$[f_{NL} = 2.5 \pm 5.7]$

$\alpha_s = -0.007 \pm 0.013, \quad r_{0.002} < 0.072$

$[n_t = -r/8 < 0]$





[Planck 2018.: 1807.06211]

Expanding Universe

Flatness problem

$\Omega_T = 1 \Rightarrow \Omega_T(t_{nucl}) - 1 \approx 10^{-16}$

Horizon problem

The observable Universe was larger than the **particle horizon** at LSS

Inflation

Early period of accelerated expansion

$\ddot{a} > 0: \quad P < -\rho/3$

Superhorizon perturbations?

Too small sub-horizon (**causal**) perturbations

Unwanted relics...

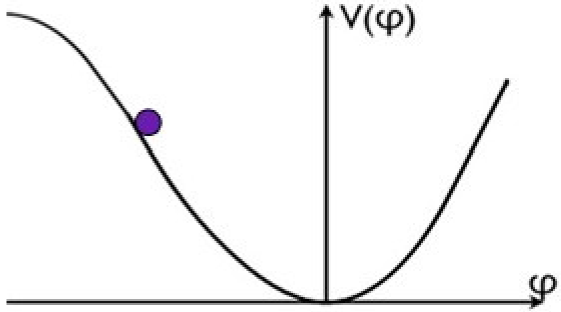
monopoles, moduli, gravitinos,...

Starobinsky '80; Guth '81; Albrecht, Steinhardt '82; Linde 1982

Slow Roll Inflation

Scalar field rolling down its (flat) potential

$$P=\dot{\varphi}^2/2-V(\varphi)\approx -V(\varphi)$$ negative pressure



"Flat" potential The curvature and the slope smaller than the (Hubble) expansion rate H

Kinetic energy << potential energy $H^2 \sim V/3m_P^2$ Hubble parameter $(H=\dot{a}/a)$

$(a=\text{scale factor})$

Slow-roll parameters

$$|\eta_\varphi|=m_P^2\left|\frac{V''}{V}\right|<1 \qquad \epsilon_\varphi=\frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2<1$$

curvature **slope**

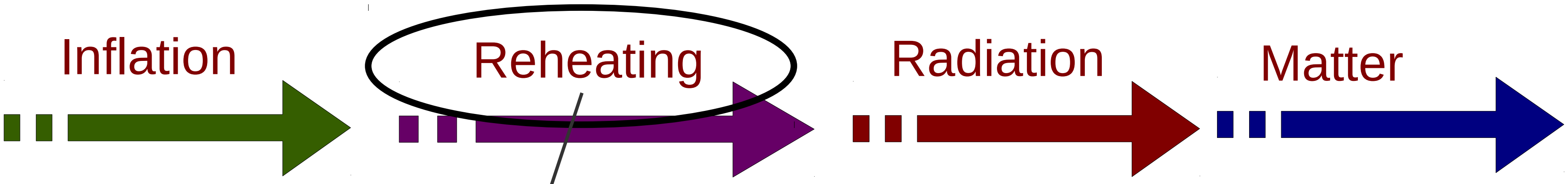
Slow-roll equation

$$\dot{\varphi}\simeq -V'/3H$$

Primordial spectrum

$$P_R\simeq\left(\frac{H}{\dot{\varphi}}\right)^2\left(\frac{H}{2\pi}\right)^2 \qquad n_s=1+2\eta_\varphi-6\epsilon_\varphi \qquad r=16\epsilon_\varphi$$

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



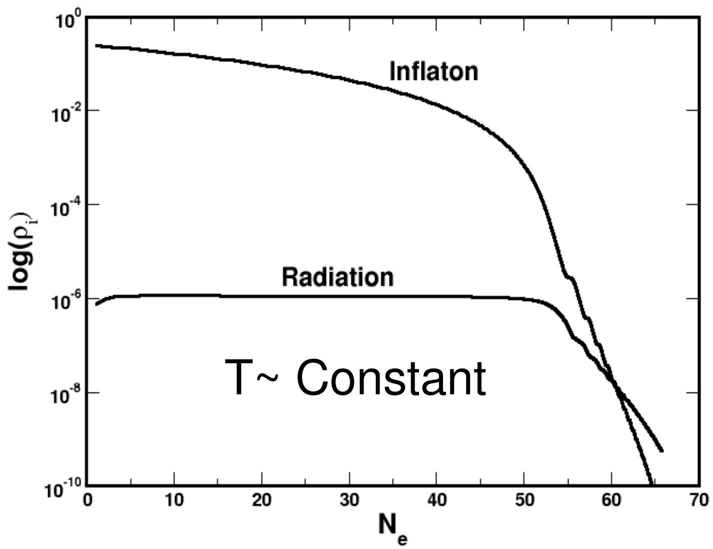
Inflaton interacts with other particles

Interactions with the cosmic plasma induce dissipation

$$\ddot{\varphi}+(3H+\Upsilon)\dot{\varphi}+V_{\varphi}=0$$

“Decay” into light dof= extra friction

”Warm” inflation:



A (small) fraction of the vacuum energy is converted into radiation during inflation

$$\dot{\rho}_R+4H\rho_R=\Upsilon\dot{\varphi}^2 \quad \text{“Source term”}$$

Slow-roll:
$$\begin{cases} (3H+\Upsilon)\dot{\varphi}\simeq -V_{\phi} \\ 4H\rho_R\simeq\Upsilon\dot{\varphi}^2 \end{cases}$$

Extra friction term: $Q = \Upsilon/(3H)$ (Particle production versus Hubble friction)

- $Q \ll 1$, $T \ll H$ ➡ Standard **C**old **I**nflation
- $Q < 1$, $T > H$ ➡ **W**eak **D**issipative **R**egime

  Standard slow-roll

- $Q > 1$, $T > H$ ➡ **St**rong **D**issipative **R**egime

Slow-roll : $3H(1+Q)\dot{\varphi} \simeq -V_\varphi(\varphi, T)$, $\rho_r \simeq \frac{3}{4} Q \dot{\varphi}^2$

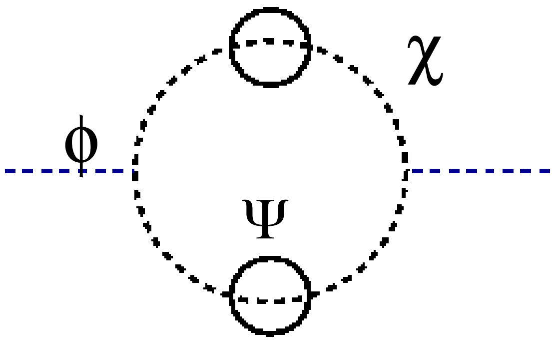
$|\eta_\varphi| < (1+Q)$, $\epsilon_\varphi < (1+Q)$, $\beta_\Upsilon < (1+Q)$, $\delta_T < 1$ **(Thermal corrections)**

$\beta_\Upsilon = m_P^2 (\Upsilon_\varphi V_\varphi)/(\Upsilon V)$ $\delta_T = T V_{T\varphi}/V_\varphi$

- **Q varies during inflation**
- Extra friction prolongs inflation ➡ Smaller ϕ values
- Dissipation induces thermal inflaton fluctuations

Interactions & Dissipative coefficient

Low T regime:



light fermions

$$L = \cdots - \frac{1}{2} m_\varphi^2 \varphi^2 - \frac{g^2}{2} \varphi^2 \chi^2 + h \chi \psi \bar{\psi} + \cdots$$

heavy $m_\chi = g\phi > H, T$

BG, Berera, Ramos & Rosa 2012

$$\boxed{\Upsilon \simeq \frac{32}{\sqrt{2\pi}} \frac{g^2 N_\chi}{h^2 N_Y} (m_\chi T)^{1/2} e^{-m_\chi/T} + 0.02 h^2 N_Y N_\chi \left(\frac{T^3}{\varphi^2}\right) \simeq C_\varphi \frac{T^3}{\varphi^2}}$$

Adiabatic approximation:

$\Rightarrow$ $T>H$

$$\dot{\varphi}/\varphi, \quad H < \Gamma_\chi \simeq h^2 m_\chi/(8\pi)$$

Macroscopic Microscopic

- Easy to fulfill for not too small values of h

$$\frac{\Gamma_\chi}{\dot{\varphi}/\varphi} > \frac{\Gamma_\chi}{H} > \left(\frac{\Gamma_\chi}{m_\chi}\right)\left(\frac{m_\chi}{T}\right)\left(\frac{T}{H}\right) > 1$$

- Thermal corrections under control (inflaton coupled to heavy fields) + susy to control T=0 corrections

Getting 50-60 e-fold of inflation typically requires $C_\phi \sim 10^6$

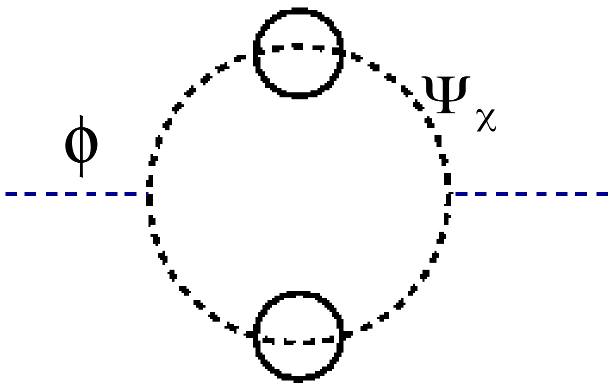
BG, Berera, & Kronberg 2015; R. Ayra et al, JCAP02(2018)

Interactions & Dissipative coefficient

High T regime:

light scalar

$$L = \cdots - \frac{1}{2} m_{\varphi}^2 \varphi^2 - g\, \varphi\, \bar{\psi}_{\chi} \psi_{\chi} - h\, \sigma\, \bar{\psi}_{\chi} \psi_{\chi} + \cdots$$



light $m_{\Psi} = g\phi < H, T$, $g \ll 1$

$$\boxed{\Upsilon \simeq \frac{3}{1 - 0.34 \log h} \frac{g^2}{h^2} T}$$

Linear T coefficient

Adiabatic approximation:

$$T > H$$

$$\dot{\varphi}/\varphi, \quad H < \Gamma_{\chi} \simeq \frac{\pi}{512} h^4 \left(\frac{T}{H}\right)$$

Macroscopic   Microscopic

- Small g coupling to keep fermions light
- Not too small h because of adiabatic condition
- How to avoid thermal corrections to inflaton potential due to light fields?

Thermal potential: $$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \frac{g^2 \varphi^2}{12} T^2 + \cdots$$

Berera, Gleiser &Ramos PRD'98; Yokoyama & Linde PRD '98

Little Higgs ⟺ Little inflaton

Naturalness problem in the SM (and inflation):

- Scalar field masses are not protected against quadratic radiative corrections by any sym. : why m_h = 125 GeV ? (why the inflaton is light $m_\phi < H$?)

(A) Susy : no. fermions = no. bosons

$$\Delta V_{T=0} \sim \Lambda^2 \, \mathrm{STr}\, M^2 + \sum_{F,B} (-1)^{2s_i} (2s_i+1) \frac{M^4}{64\pi^2} \ln \frac{M^2}{Q^2} + \cdots$$

$$\Rightarrow \quad \Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \sum_{F,B} \frac{g_i^2 \varphi^2}{12} T^2 + \cdots \quad \Rightarrow$$

Thermal Higgs mass

(B) Little Higgs: Pseudo-Nambu Goldstone boson of a global symmetry
(m_h ~ soft breaking)

Cancellation of quadratic divergences occurs from particles of the same spin

$$\Rightarrow \quad \Delta V_T = -\frac{\pi^2}{90} g_R T^4 + C\, T^2 + \cdots \quad \Rightarrow$$

No thermal Higgs mass
(high T)

[D. Kaplan & M. Schmaltz JHEP 0310; M. Schmaltz JHEP 0408]

Little warm inflation

- Consider a U(1) gauge theory spostaneously broken by two complex Higgs fields

$$\langle \varphi_1 \rangle = \langle \varphi_2 \rangle = M/\sqrt{2}$$

- One Nambu-Goldstone boson is “eaten” by the gauge field, and the other becomes the physical scalar inflaton field

$$\varphi_1 = \frac{M}{\sqrt{2}} e^{\varphi/M}, \qquad \varphi_2 = \frac{M}{\sqrt{2}} e^{-\varphi/M}$$

- Couple the Higgses to charged and singlet Weyl fermions:

$$L = \frac{g}{\sqrt{2}}(\varphi_1 + \varphi_2)\bar{\Psi}_{1L}\Psi_{1R} - i\frac{g}{\sqrt{2}}(\varphi_1 - \varphi_2)\bar{\Psi}_{2L}\Psi_{2R} + hc$$
$$= gM\cos(\varphi/M)\bar{\psi}_1\psi_1 - gM\sin(\varphi/M)\bar{\psi}_2\psi_2$$

With interchange symmetry: $\varphi_1 \longleftrightarrow i\varphi_2 \qquad \Psi_{1L,R} \longleftrightarrow \Psi_{2L,R}$

Fermion masses are bounded!!

- Light fermions: $gM < T < M$

Little warm inflation

High T regime:

Inflaton a PNGB of a broken U(1) symmetry + pair of fermions + exchange sym.

$$L = \cdots - gM\cos(\varphi/M)\bar{\psi}_1\psi_1 - gM\sin(\varphi/M)\bar{\psi}_2\psi_2 - h\sigma\sum_{i=1,2}(\bar{\psi}_i\psi_\sigma + \bar{\psi}_\sigma\psi_i) + \cdots$$

light Ψ: $gM < T < M$, $g<1$

Thermal potential:

$$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \underbrace{\frac{g^2 M^2}{12} T^2}_{\text{No thermal mass for the inflaton}} + \frac{g^4(\varphi) M^4}{16\pi^2}\left(\log\frac{\mu^2}{T^2} - c_f\right)$$

Light dof

No thermal mass for the inflaton

Total energy density:

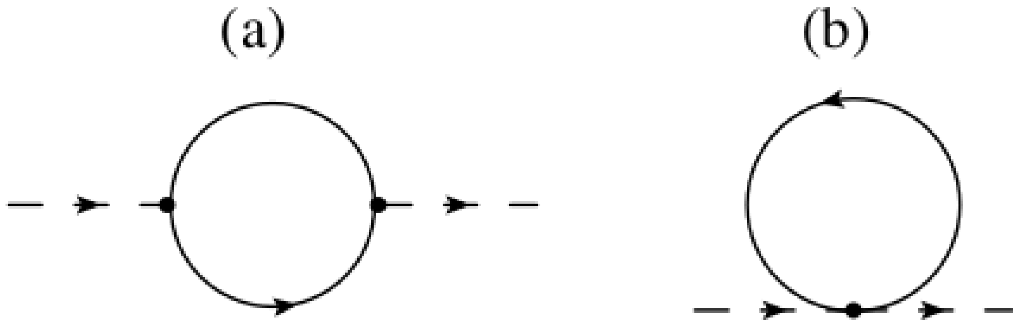
$$\rho_T = \frac{1}{2}\dot{\varphi}^2 + V(\varphi) + \rho_R \qquad \left[\rho_R = \Delta V_T - T\frac{d\Delta V_T}{dT} = \frac{\pi^2}{30} g_R(\varphi, T) T^4\right]$$

Effective no. of dof:

$$g_R(\varphi, T) \simeq g_R - \frac{5}{2\pi^2}\left(\frac{gM}{T}\right)^2 + \frac{15}{16\pi^4}\left(\frac{gM}{T}\right)^4\left(3 + \cos\left(\frac{4\varphi}{M}\right)\right)$$

Inflaton self-energy

$$L = -\sum_i \left(m_i + g_i \delta\varphi + \frac{f_i}{2}\delta\varphi^2 + \cdots\right)\bar{\Psi}_i \Psi_i$$

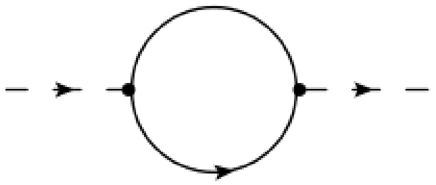


$$\Sigma_\varphi(0) = \sum_i \left(g_i^2 + m_i f_i\right) I_T(0) = g^2\left(-\cos\left(2\frac{\varphi}{M}\right) + \cos\left(\frac{2\varphi}{M}\right)\right) I_T(0) = 0$$

$$I_T(0) = -\frac{\Lambda^2}{2\pi^2} + \frac{T^2}{6}$$

Cancellations of quadratic divergences and thermal masses!!

Dissipation



Dissipation comes from non-local terms (diagram (a))

No cancellation of dissipative terms:

$$\Upsilon = \frac{4}{T}\sum_i \int \frac{d^3p}{(2\pi)^3}\frac{m_i^2}{\Gamma_i\,\omega_p^2} n_F(1+n_F) \simeq \frac{3}{1-0.34\log h}\frac{g^2}{h^2}T$$

Linear T coefficient

Decay rate $\Gamma_i = \frac{h^2}{16\pi}\frac{T^2 m_i^2}{\omega_p |p|} F_T(p/T, \omega_p/T)$ $[L = \cdots - h\sigma \sum_i (\bar{\psi}_i \psi_\sigma + \bar{\psi}_\sigma \psi_i) + \cdots]$

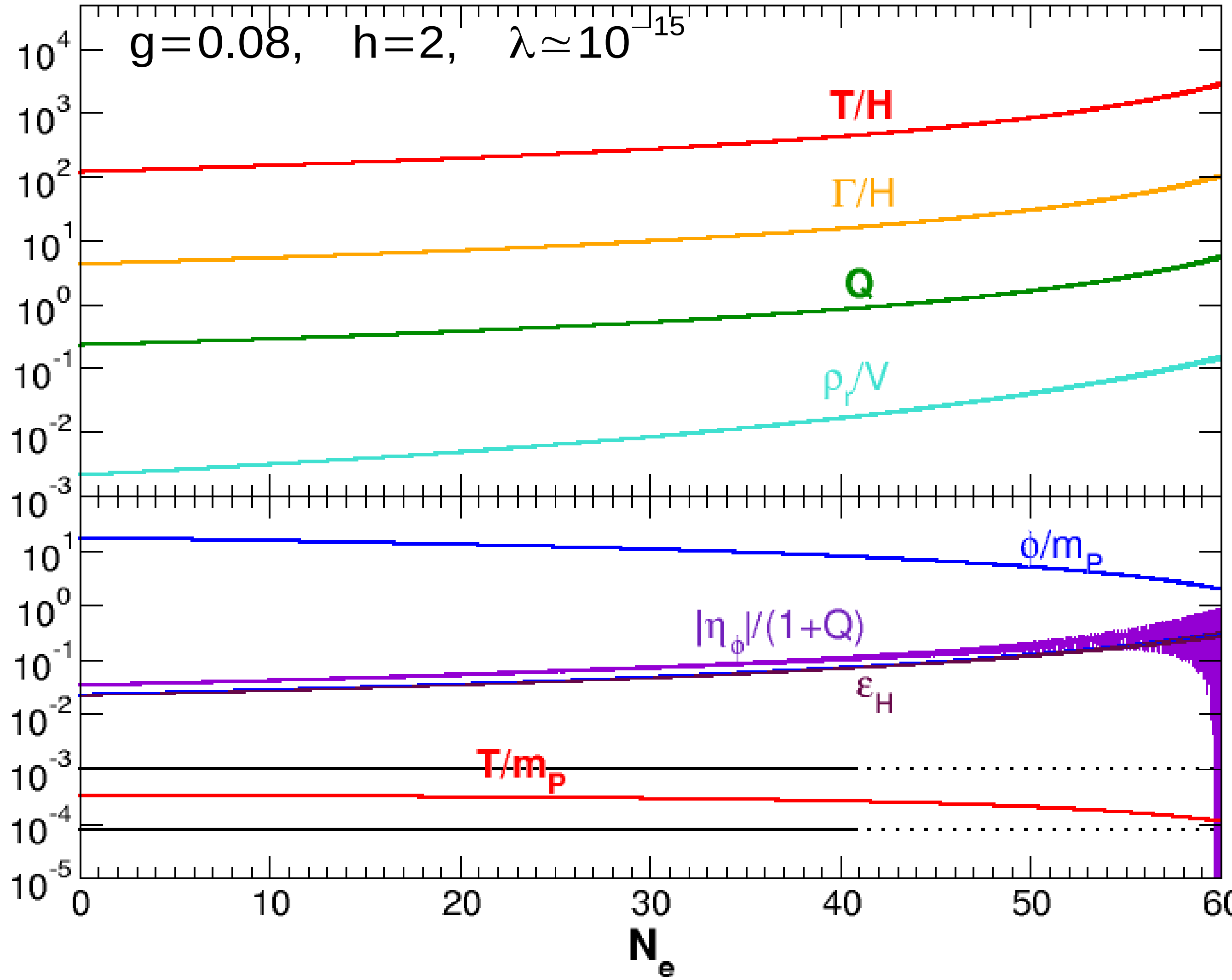
Additional Yukawa interactions with a massless field

Masses $m_i^2 \simeq h^2 T^2/8$

Yokoyama & Linde '98; Moss & Xiong '06; BG, Berera & Ramos '10

Background dynamics

Quartic potential: $V(\varphi) = \frac{\lambda}{4}\varphi^4$



Inflation ends in the strong dissipative regime

$\epsilon_H = -\frac{\dot{H}}{H^2}$

$M \simeq 2 \times 10^{15}\,\mathrm{GeV}$

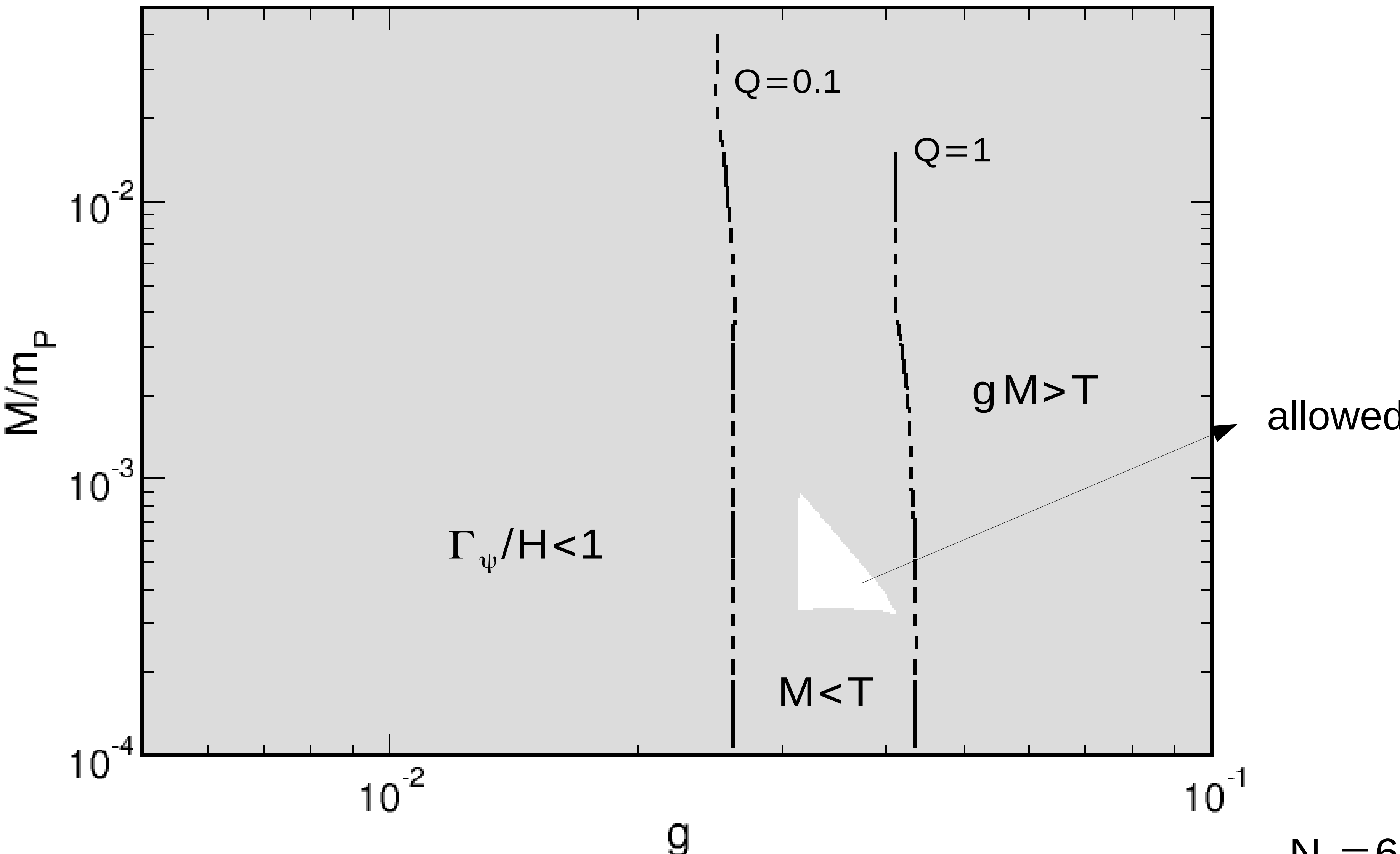
$gM < T < M$

Parameter space: g, h, M

Decay rate: $\frac{\Gamma_\psi}{H} \simeq \frac{\pi}{514} h^4 \frac{T}{H} > 1$

Light fermions: $gM < T < M$

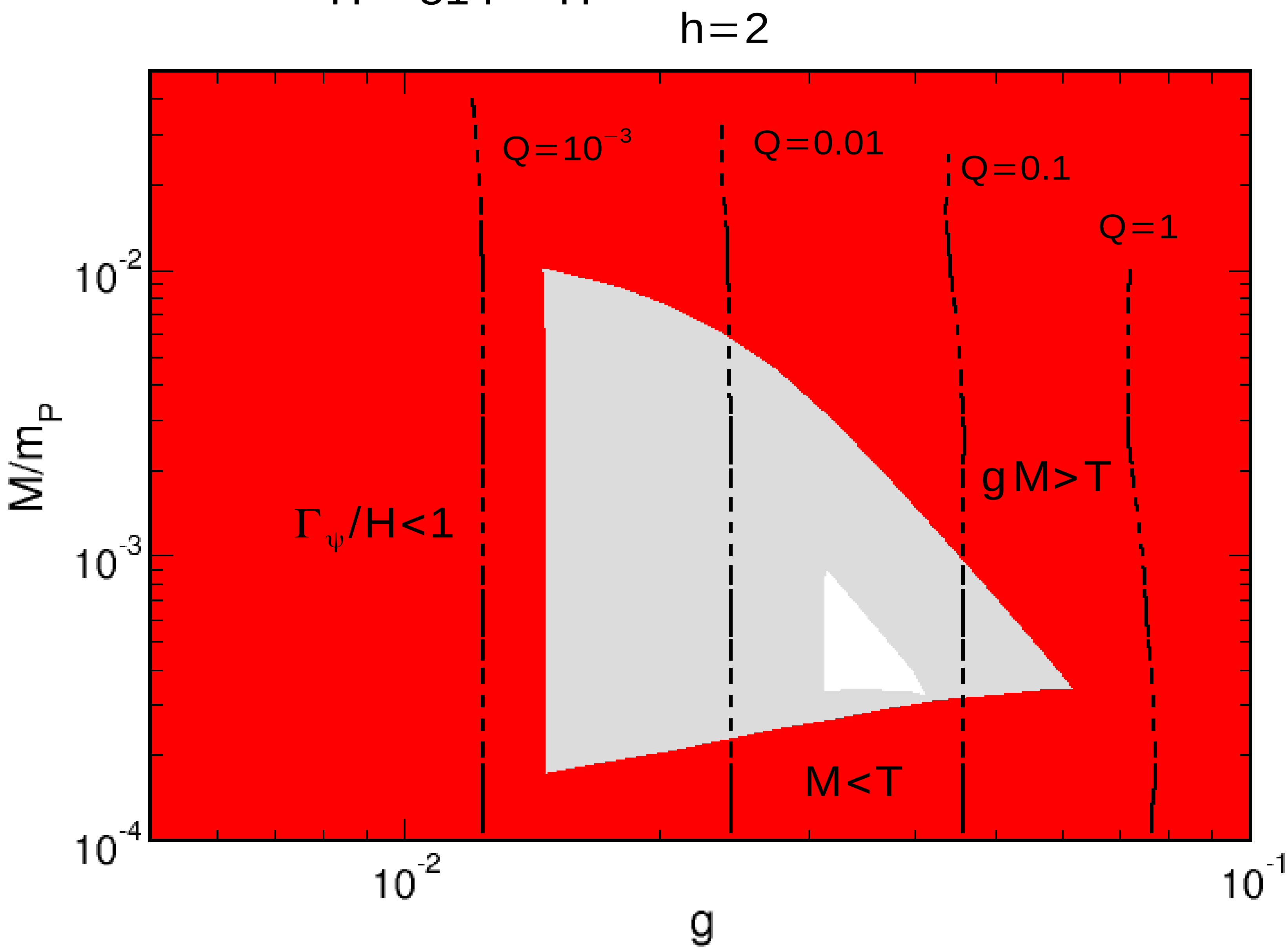
$h = 1$



$N_e = 60$

Parameter space: g, h, M

Decay rate: $\frac{\Gamma_\psi}{H} \simeq \frac{\pi}{514} h^4 \frac{T}{H} > 1$ Light fermions: $gM < T < M$



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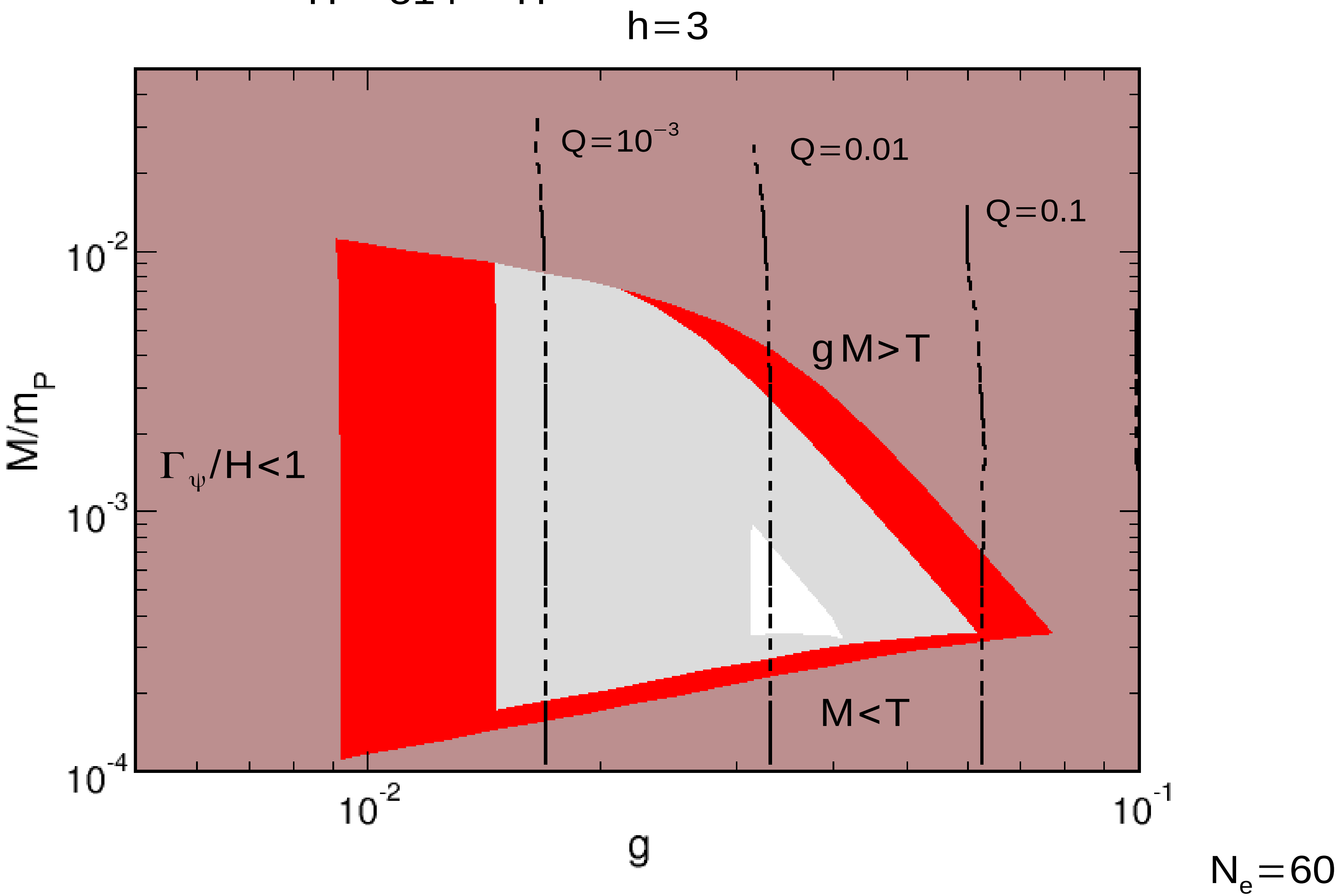
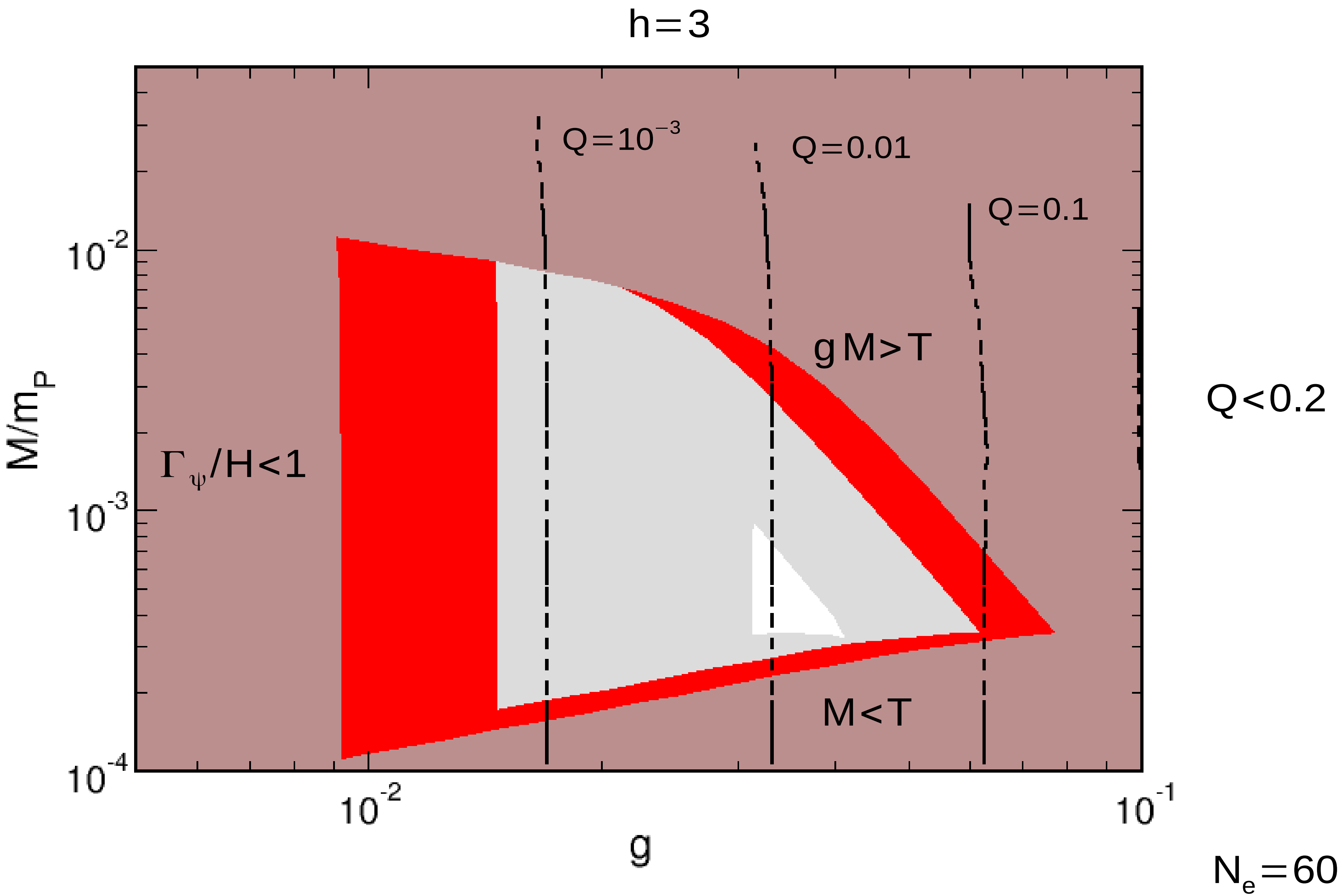


Parameter space: g, h, M

$10^{14}\,\mathrm{GeV} < M < 10^{16}\,\mathrm{GeV}$



Fluctuations & primordial spectrum: coupled system

Field EOM:

$$\delta\ddot{\varphi}_k^{GI} + (3H+\Upsilon)\delta\dot{\varphi}_k^{GI} + \underline{\dot{\varphi}\,\delta\Upsilon^{GI}} + \left(\frac{k^2}{a^2} + V_{\varphi\varphi}\right)\delta\varphi_k^{GI} \simeq (2\Upsilon T)^{1/2}\hat{\xi}_k$$

$$\longrightarrow \boxed{\frac{\delta\Upsilon^{GI}}{\Upsilon} = \frac{1}{4}\frac{\delta\rho_r^{GI}}{\rho_r} \simeq \frac{\delta T}{T}} \longrightarrow$$

<u>Coupled system</u>
inflaton-radiation

Radiation (fluid stress energy-tensor): $T^{\mu\nu}_{rad} = (\rho_r + p_r)u^\mu u^\nu + p_r g^{\mu\nu}$

$$\delta\dot{\rho}_r^{GI} + 4H\delta\rho_r^{GI} \simeq \frac{k^2}{a^2}\Psi_r^{GI} + \underline{\dot{\varphi}^2\,\delta\Upsilon^{GI}} + 2\dot{\varphi}\Upsilon\delta\dot{\varphi}^{GI}$$

$$\dot{\Psi}_r^{GI} + 3H\Psi_r^{GI} \simeq -\delta\rho_r^{GI}/3 - \dot{\varphi}\Upsilon\delta\varphi^{GI}$$ Momentum density

(Gauge invariant perturbations: $\delta\varphi_k^{GI} = \delta\varphi - \frac{H}{\dot{\varphi}}\phi\,,\quad \phi$:metric perturbation)

BG, Berera, Moss & Ramos, JCAP1405

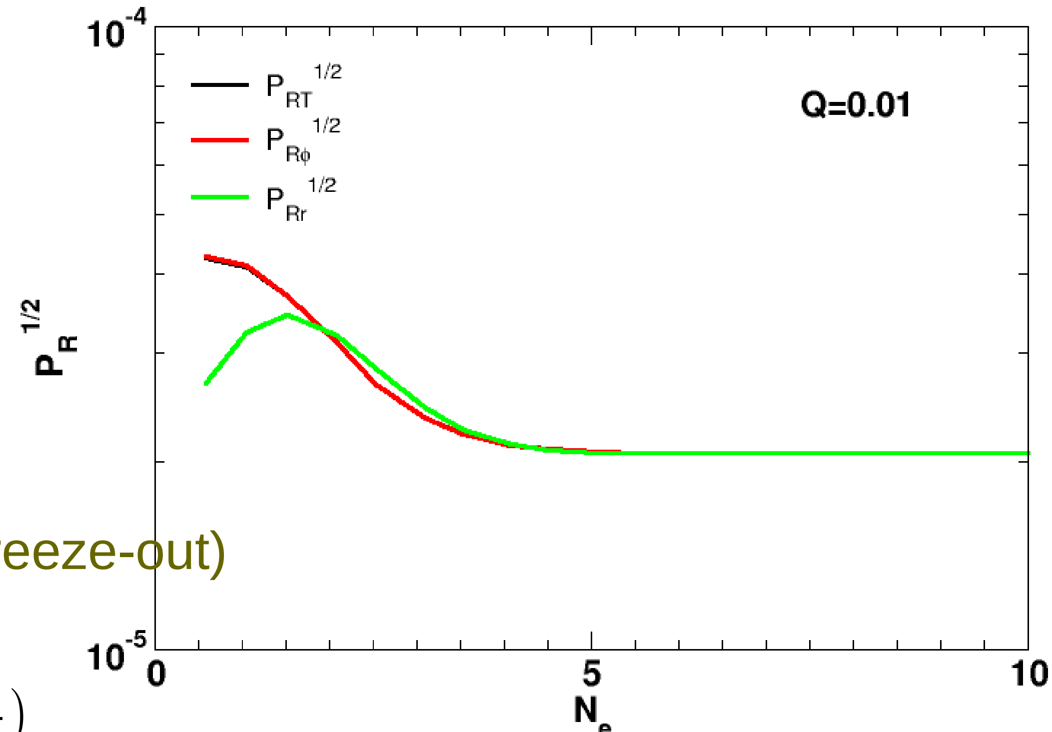
Fluctuations & primordial spectrum: coupled system

Weak dissipative regime (Q=Υ/H<<1) : field decoupled from radiation

$$\delta\ddot{\varphi}_k^{GI} + (3H+\Upsilon)\delta\dot{\varphi}_k^{GI} + \left(\frac{k^2}{a^2} + V_{\varphi\varphi}\right)\delta\varphi_k^{GI} \simeq (2\Upsilon T)^{1/2}\hat{\xi}_k$$

$$P_{\delta\varphi} \simeq \frac{HT}{2\pi}\frac{Q}{\sqrt{1+4\pi Q/3}}$$

Primordial spectrum: $P_R \simeq \left(\frac{H}{\dot{\varphi}}\right)^2 P_{\delta\varphi}$



R is constant after horizon crossing (freeze-out)

$$P_R \simeq (P_R)_{Q=0}\underbrace{(1+2\mathcal{N}}_{} + \frac{T}{H}\frac{4\pi Q}{\sqrt{1+4\pi Q/3}})$$

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

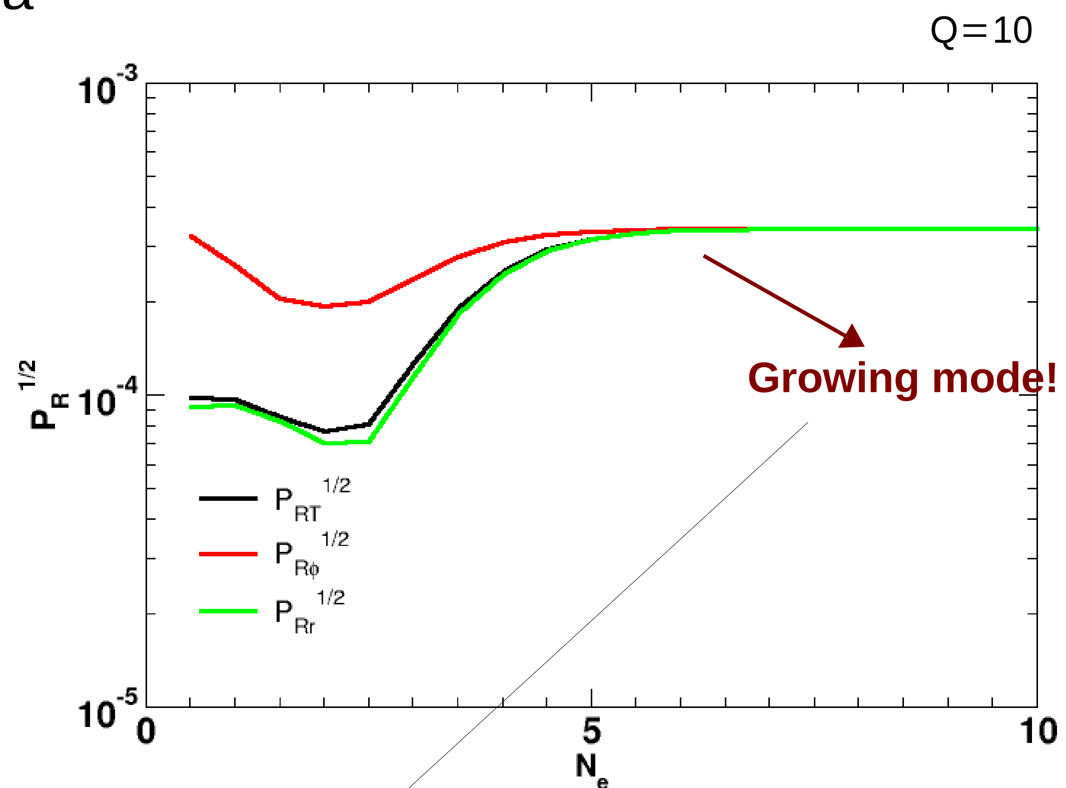
$$\mathcal{N} \simeq n_{BE} = (e^{k/aT}-1)^{-1}$$

Ramos, da Silva, 1302.3544; BG, Berera, Moss & Ramos, 1401.1149

Fluctuations & primordial spectrum: coupled system

Strong dissipative regime ($Q=\Upsilon/H>1$) : coupled system

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



Primordial spectrum:

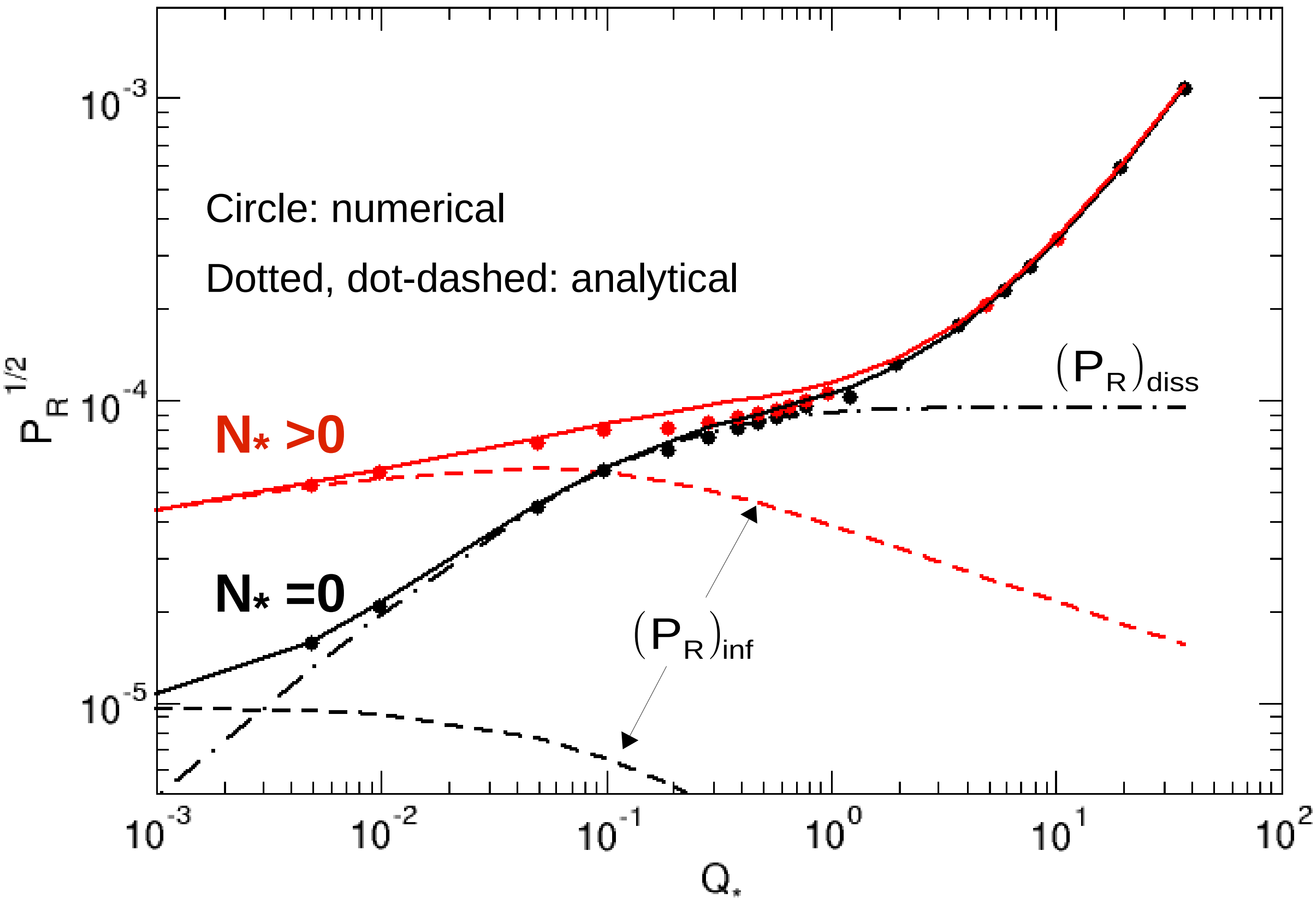
$$P_R = \frac{h_\varphi}{h_T}P_{R_\varphi} + \frac{h_r}{h_T}P_{R_r} \simeq P_{R_r} \simeq P_{R_\varphi}, \qquad (h_i = \rho_i + p_i)$$

R is constant after horizon crossing

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

Primordial spectrum

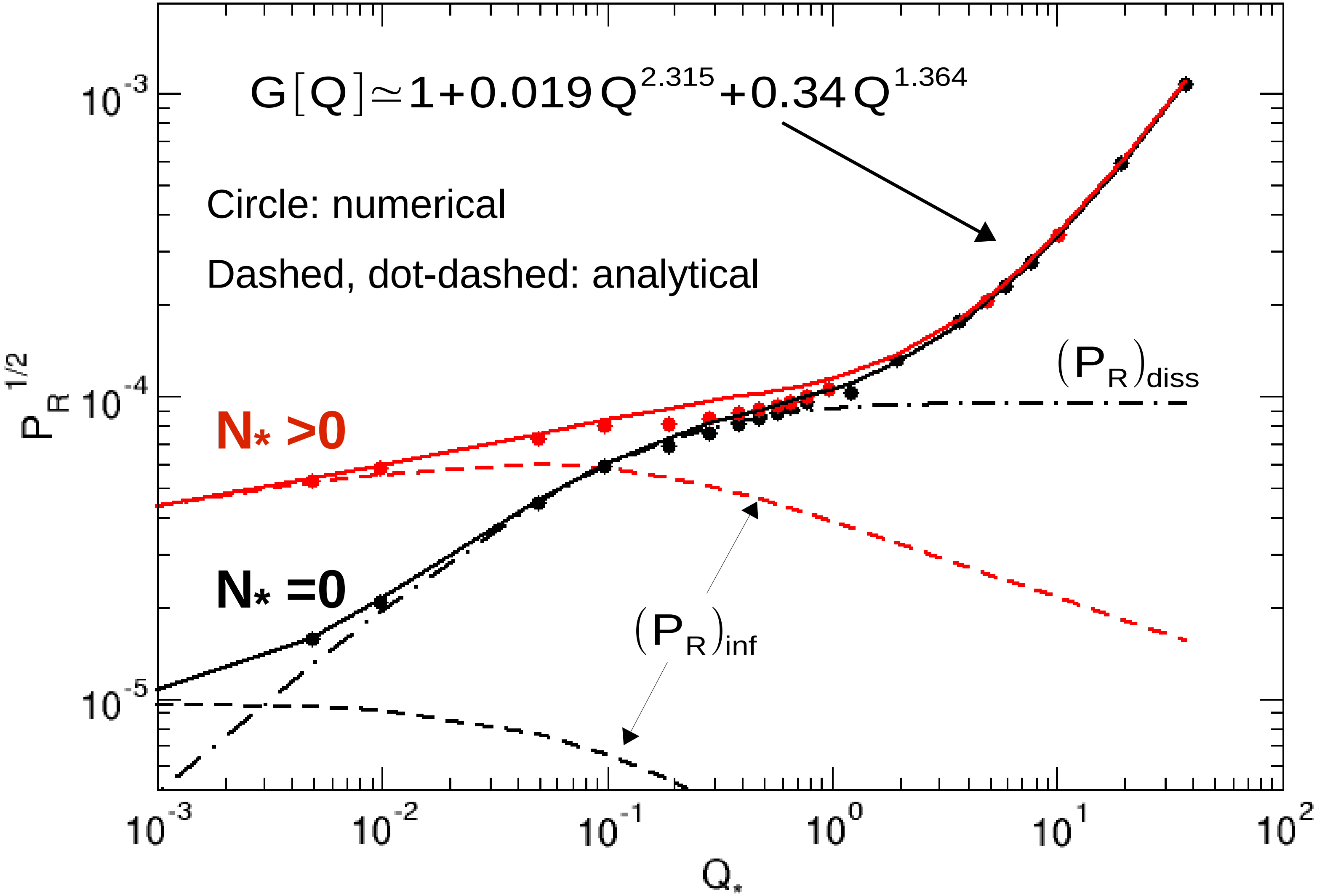
$$P_R \simeq ((P_R)_{vac} + (P_R)_{diss}) G[Q]$$



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

Primordial spectrum

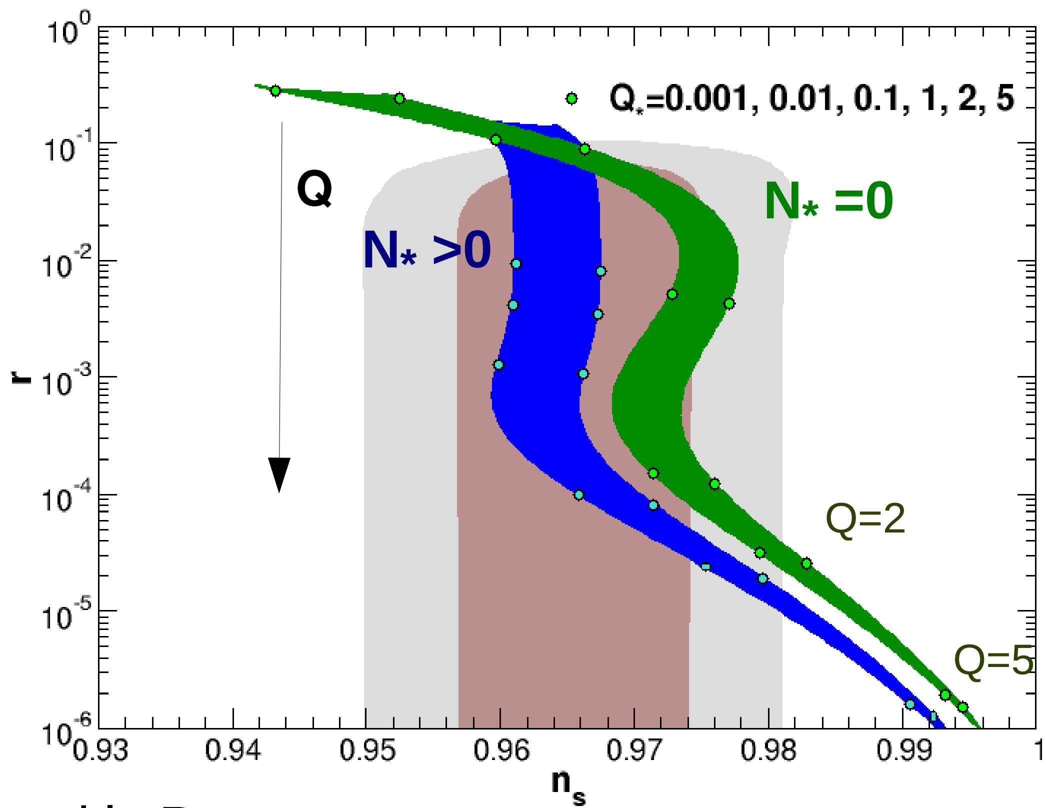
$$P_R \simeq ((P_R)_{vac} + (P_R)_{diss})\, G[Q]$$



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

Primordial spectrum: quartic chaotic model

$$V(\varphi)=\frac{\lambda}{4}\varphi^{4}, \quad N_e=50-60$$



$$n_s-1=\frac{d\ln P_R}{dN_e}=(n_s-1)_N+(n_s-1)_{diss}+(n_s-1)_G, \quad (n_s-1)_G>0$$

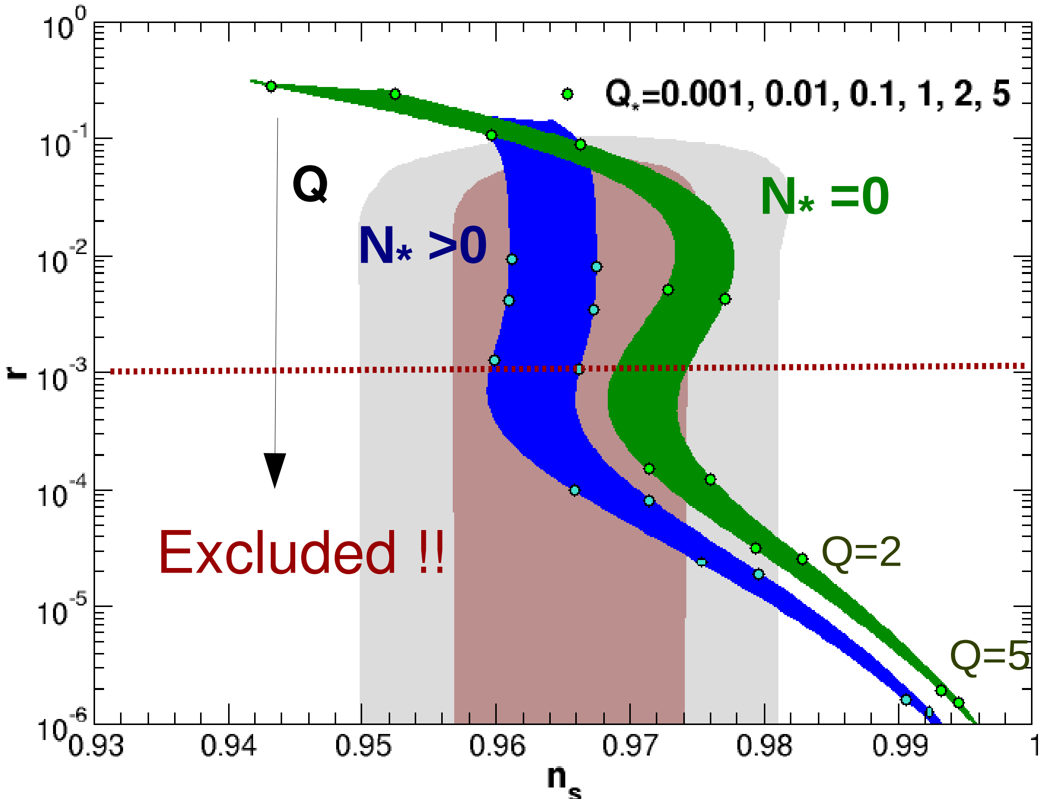
$$r\simeq\frac{16\,\epsilon_\phi}{(1+2N+\Delta_Q)\,G[Q]}\leq 16\,\epsilon_\varphi$$

Quartic:

$$\boxed{N\neq 0,\ Q<1:\ n_s\simeq 1-2/N_e, \quad r\simeq 16\,\epsilon_\varphi\left(\frac{H}{T}\right)\ll 0.1}$$

Primordial spectrum: quartic chaotic model

$$V(\varphi) = \frac{\lambda}{4}\varphi^{4}, \quad N_e = 50 - 60$$



Q > 0.1, r> 0.001

$$n_s - 1 = \frac{d \ln P_R}{dN_e} = (n_s - 1)_N + (n_s - 1)_{diss} + (n_s - 1)_G, \quad (n_s - 1)_G > 0$$

$$r \simeq \frac{16\,\epsilon_\phi}{(1 + 2N + \Delta_Q)\,G[Q]} \le 16\,\epsilon_\varphi$$

Quartic:

$$\boxed{N \neq 0,\ Q < 1:\ n_s \simeq 1 - 2/N_e, \quad r \simeq 16\,\epsilon_\varphi\left(\frac{H}{T}\right) \ll 0.1}$$

Little warm inflation & CMB data

$$V(\varphi)=\lambda\varphi^4, \qquad Q=C_T(T/3H), \qquad \rho_R=\pi^2 g_r/30\,T^4=C_r T^4$$

- CosmoMC: 6 parameters fit

  ΛCDM: $\Omega_b h^2,\ \Omega_c h^2, 100\,\theta_{MC},\ \tau,\ \ln(A_s\times 10^{10}),\ n_s,\ r,$

  WLI: $\Omega_b h^2,\ \Omega_c h^2, 100\,\theta_{MC},\ \tau,\ \underline{\lambda,\ C_T,\ g_r}$

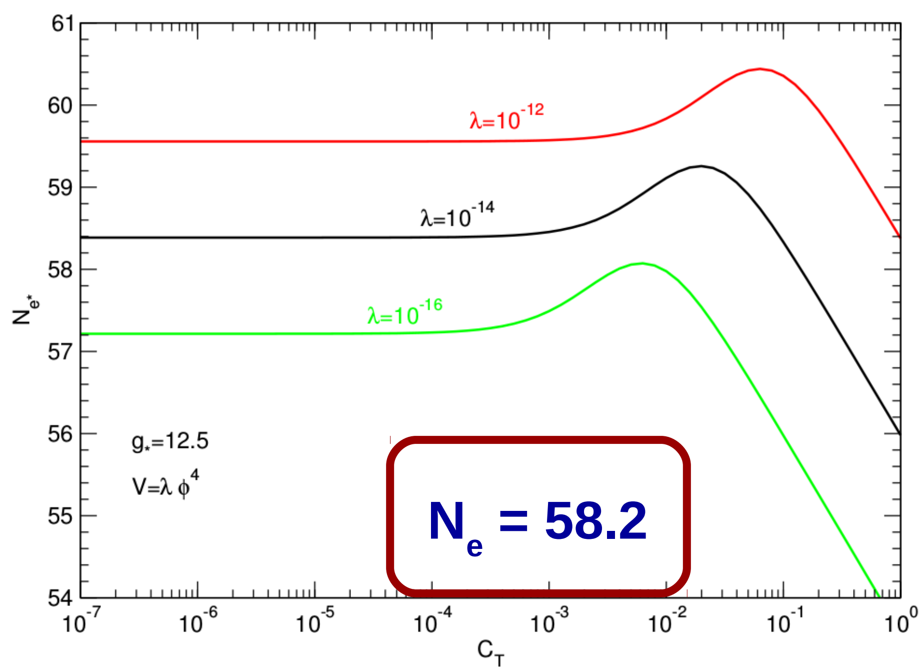
- Input: $P_R[N_e]\simeq\left(\frac{H}{\dot\varphi}\right)^2\left(\frac{H}{2\pi}\right)^2\left(1+2N+\frac{T}{H}\frac{4\pi Q}{\sqrt{1+4\pi Q/3}}\right)\times G[Q] \Rightarrow P_R[k]$

- $$N_e=56.12-\ln\frac{k}{k_0}+\frac{1}{3(1+\widetilde{w})}\ln\frac{2}{3}+\ln\frac{V_k^{1/4}}{V_{end}^{1/4}}+\frac{(1-3\widetilde{w})}{3(1+\widetilde{w})}\ln\frac{\rho_{RH}^{1/2}}{V_{end}^{1/4}}+\ln\frac{V_k^{1/4}}{10^{16}\,\mathrm{GeV}}$$

$\widetilde{w}$: Effective equation of state during reheating

$\Rightarrow$ $\widetilde{w}=1/3$ for a quartic chaotic model

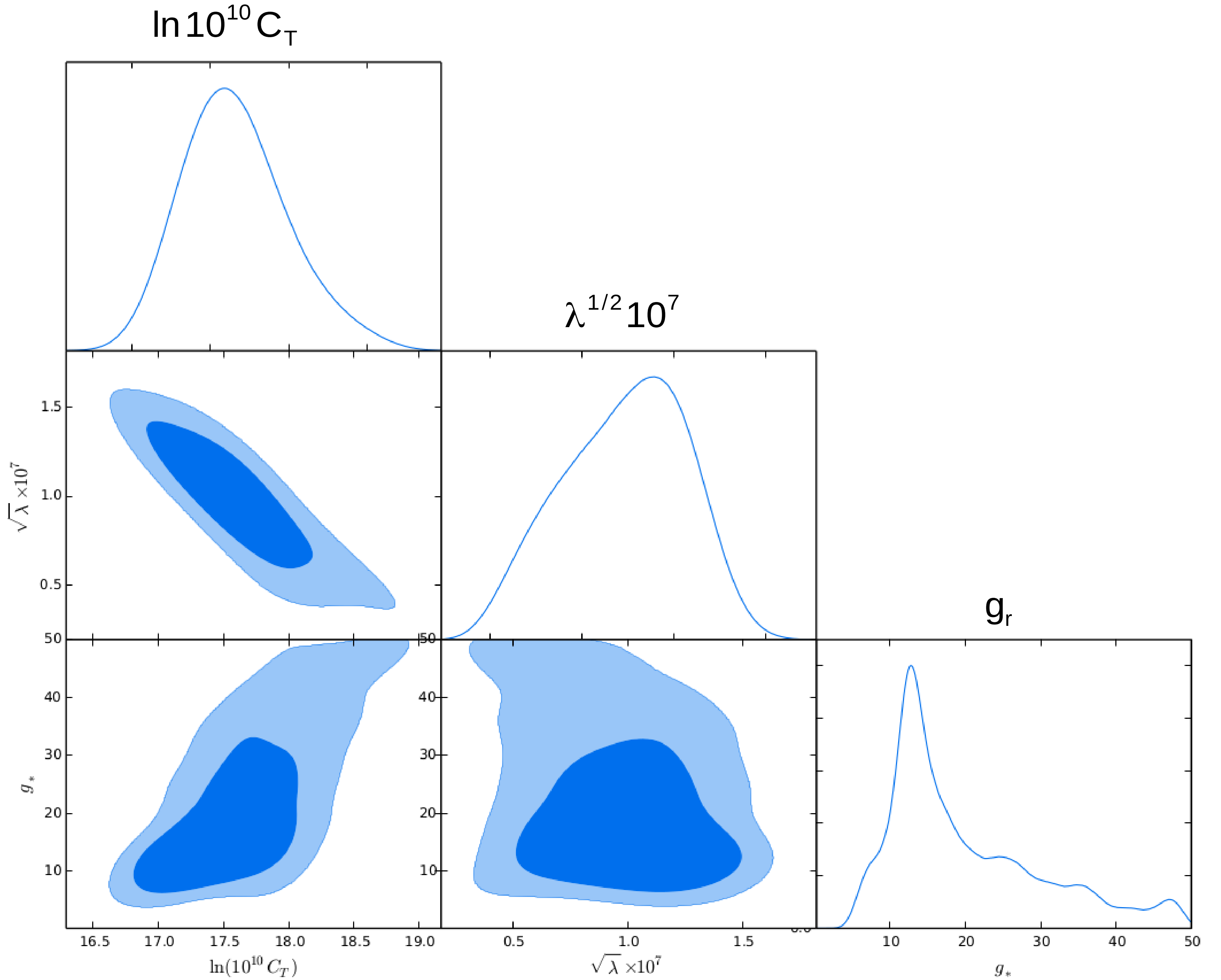
$\Rightarrow$ $N_e[k]$ Independent of T_{RH}



See also:
M. Benetti, R. Ramos, PRD95 (2017)
R. Ayra et al, JCAP02(2018)

MBG, S. Bhattacharya, K. Dutta, M. R. Gangopadhyay JCAP 1802 (2018)

Little warm inflation & CMB data:
non thermal inflaton



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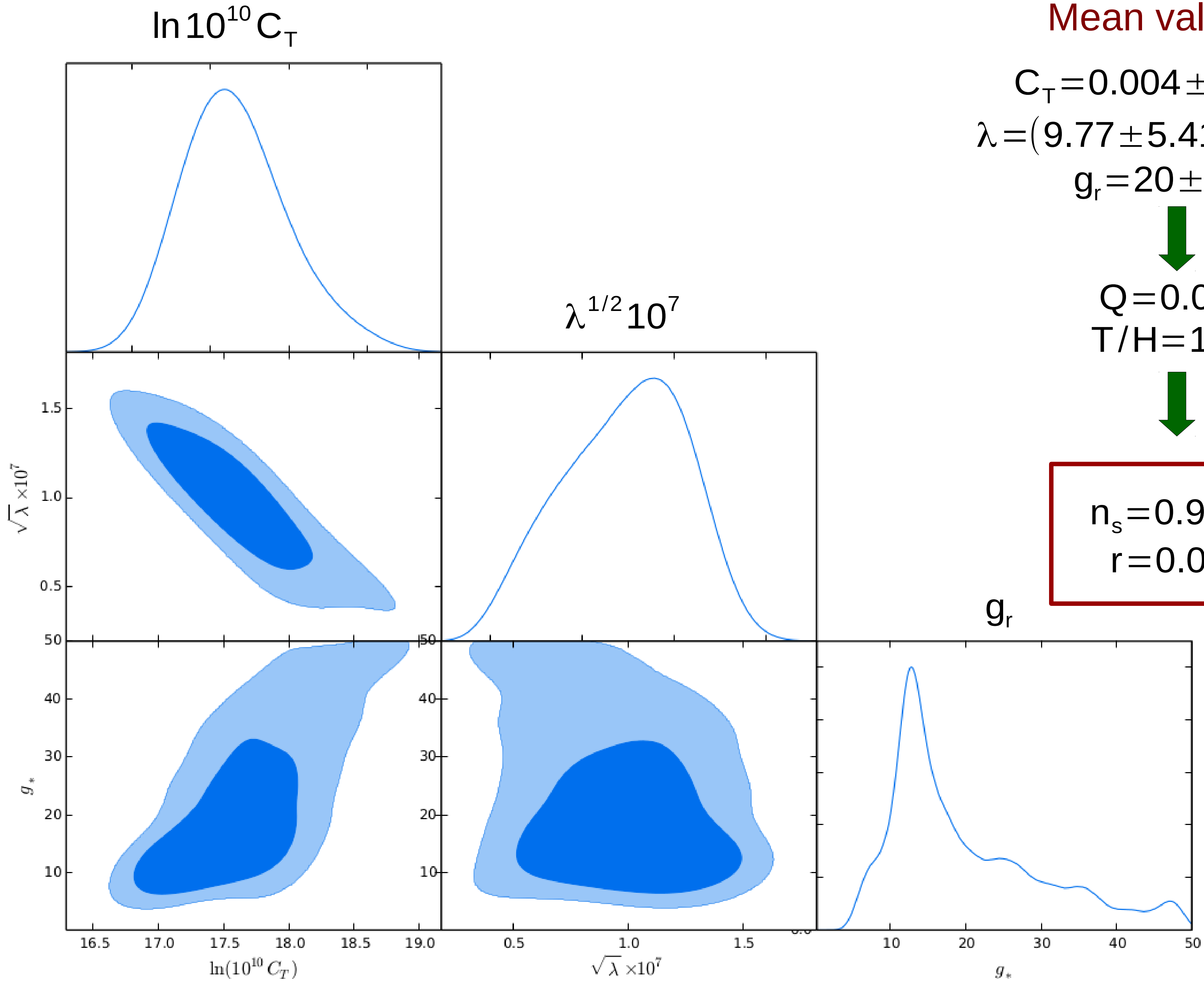


Mean values

$C_T = 0.004 \pm 0.002$

$\lambda = (9.77 \pm 5.41) \times 10^{-15}$

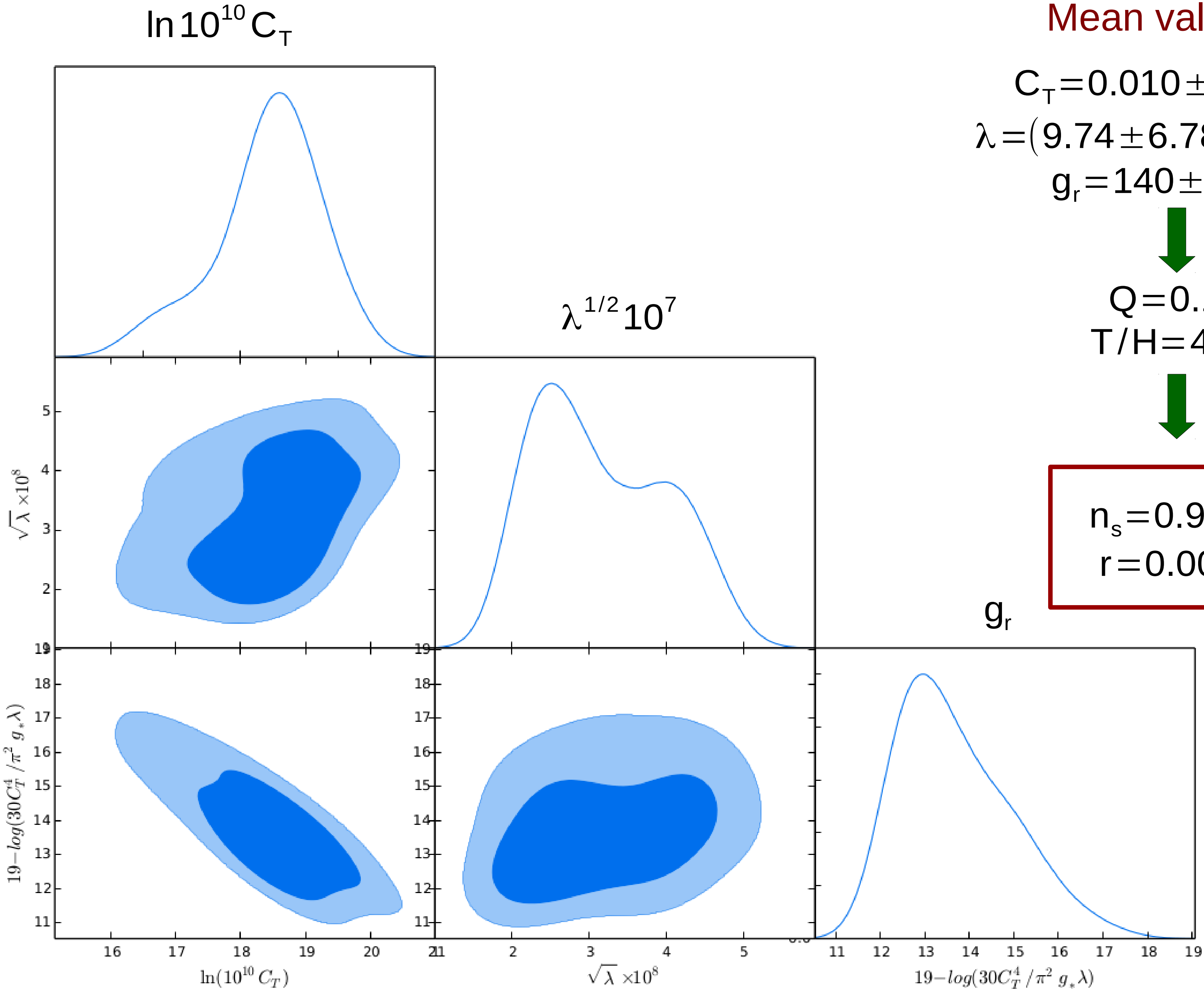
$g_r = 20 \pm 10$

$Q = 0.019$

$T/H = 19.3$

$$\boxed{\begin{gathered} n_s = 0.974 \\ r = 0.06 \end{gathered}}$$

Little warm inflation & CMB data:
thermal inflaton



Mean values

$C_T = 0.010 \pm 0.008$

$\lambda = (9.74 \pm 6.78) \times 10^{-16}$

$g_r = 140 \pm 488$

$Q = 0.14$

$T/H = 40.7$

$$\boxed{\begin{array}{c} n_s = 0.965 \\ r = 0.006 \end{array}}$$

Summary

- <u>Dissipative effects</u> due to decaying fields can be relevant during inflation, and modify the inflationary predictions

- "Low T" regime for dissipation (massive scalar χ decaying into light dof): thermal corrections under control, but required <u>large number of fields</u> $N_\chi \sim 10^6$

- "High T" regime for dissipation (light fermion ψ decaying into light dof): $\Upsilon = C_T\, T$

  Inflaton a PNGB of a broken U(1) symmetry + pair of fermions + exchange sym.

  Light fermions: gM < T + thermal corrections under control + <u>minimal matter content</u>

$$\boxed{\lambda\phi^4 \text{ compatible with data, } Q^* \sim 0.01\text{-}0.1,\ r \sim 0.1\text{-}10^{-3}}$$

- For a T dependent dissipative coefficient, the field and radiation perturbation EOM form a coupled system: Field fluctuations are amplified before freeze-out (Q < 1)

  Blue-tilted spectrum for Q >> 1

- Non-gaussianity compatible with observations for both weak and strong dissipative regime, with a <u>characteristic shape</u>

Warm inflation &Non-gaussiantiy : T dependent diss. coefficient

- **Bispectrum:** $B_R(k_1, k_2, k_3) = \sum_{cyc} \langle R_1(k_1) R_1(k_2) R_2(k_3) \rangle = A_B(k) \bar{B}(k_1, k_2, k_3)$

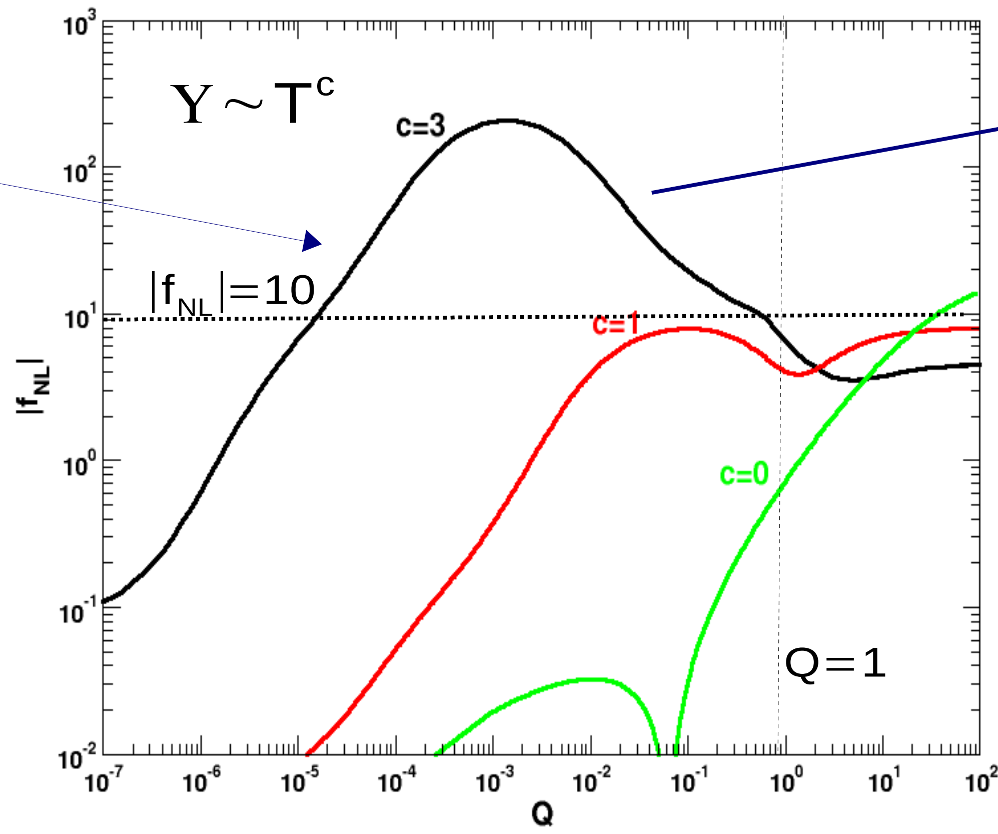
shape

$$f_{NL} = \frac{18}{5} \frac{A_B(k)}{P_R(k)^2}$$

Non-linear parameter

$$P_R \simeq ((P_R)_{vac} + (P_R)_{diss}) F[Q]$$

$(P_R)_{vac} > (P_R)_{diss}$



$(P_R)_{vac} < (P_R)_{diss}$

(Planck: f_{NL}<~O(10))

f_{NL}^{local} = 2.7 +- 5.8 ($k_3 << k_1 \sim k_2$)

f_{NL}^{equil} =-42 +- 75 ($k_3 \sim k_1 \sim k_2$)

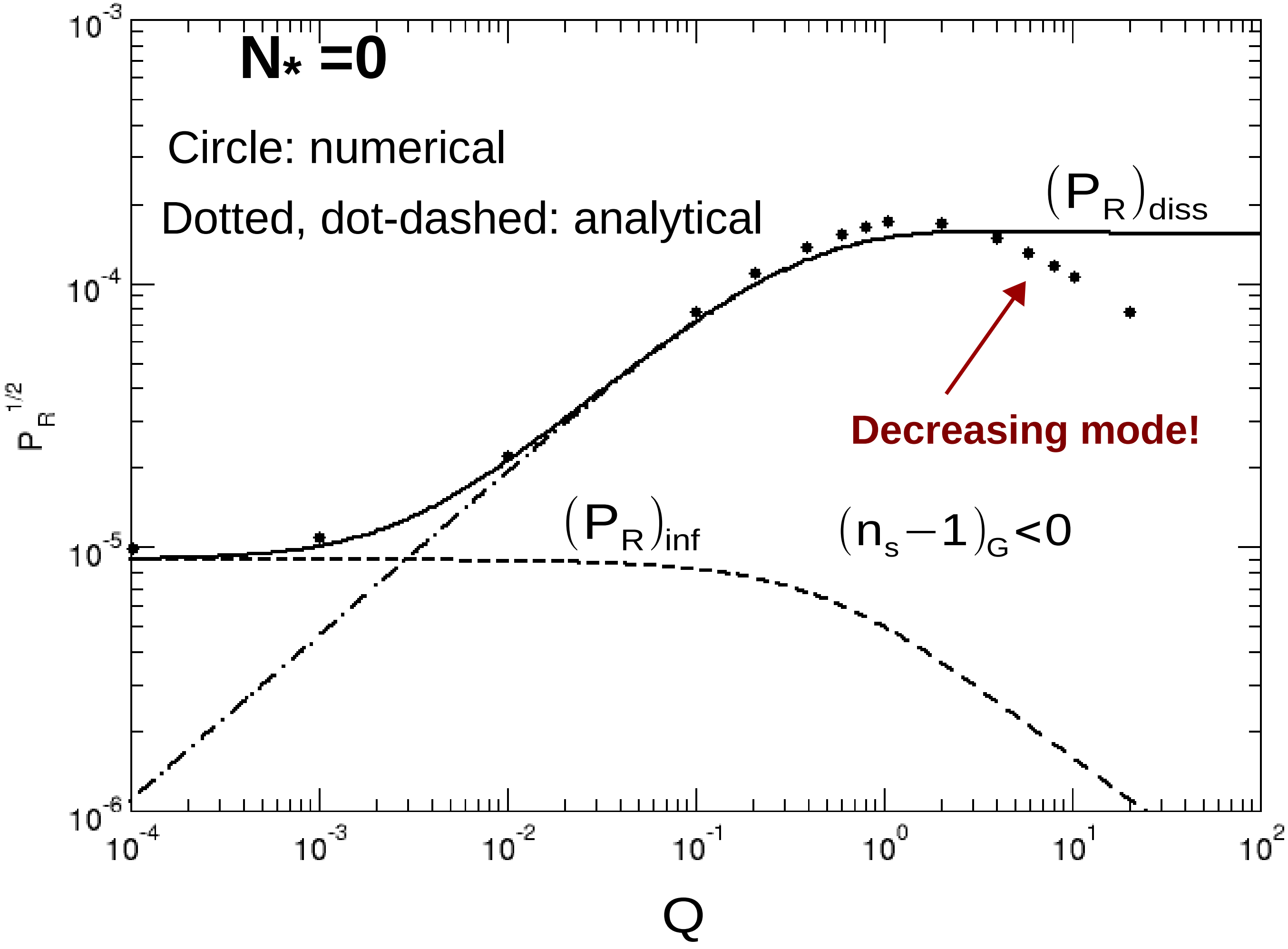
f_{NL}^{warm} = 4 +- 33

[BG, Berera, Moss, Ramos '14]

Primordial spectrum: Υ = C/T

Light bosons decaying into light dof

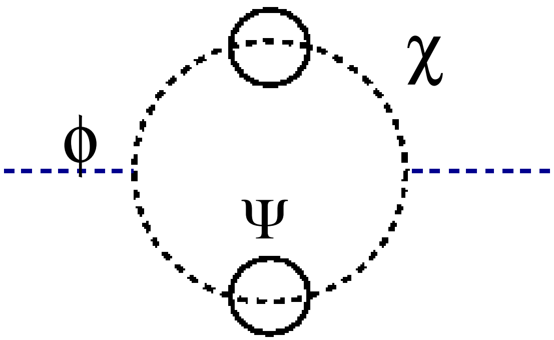
$$P_R \simeq ((P_R)_{vac} + (P_R)_{diss})\, G[Q]$$



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

Interactions & Dissipative coefficient

Low T regime: (no thermal corrections)



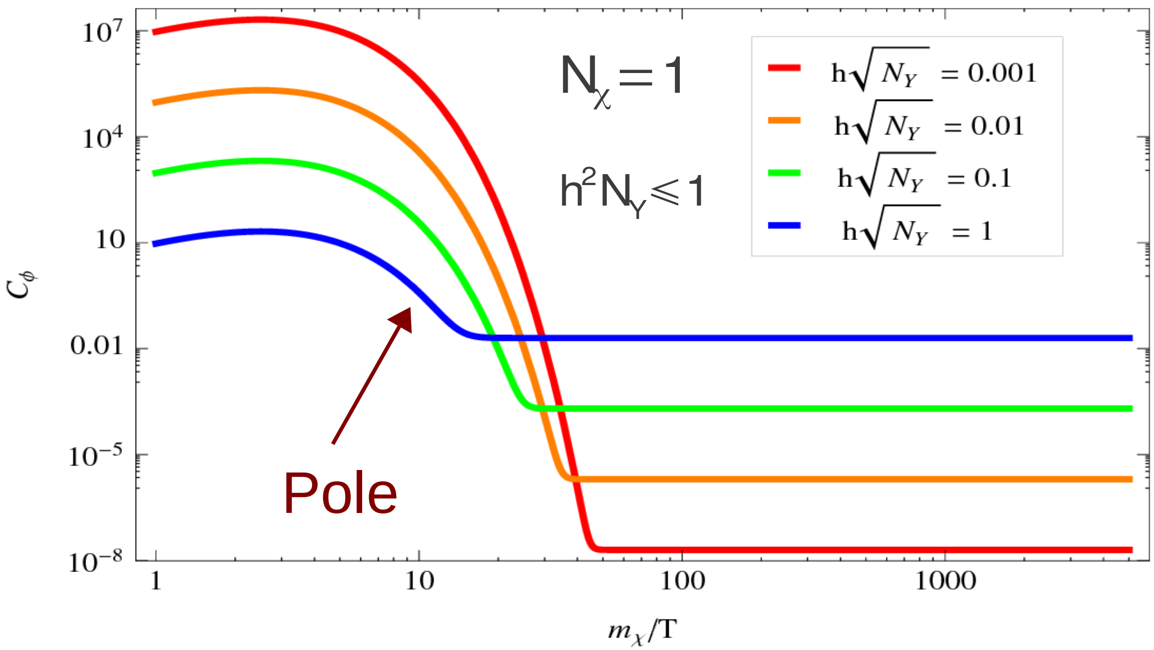
light fermions

$$L = \cdots - \frac{1}{2} m_\varphi^2 \varphi^2 - \frac{g^2}{2} \varphi^2 \chi^2 + h \chi \psi \bar{\psi} + \cdots$$

heavy $m_\chi = g\phi > H, T$

BG, Berera, Ramos & Rosa 2012

$$\Upsilon \simeq \frac{32}{\sqrt{2\pi}} \frac{g^2 N_\chi}{h^2 N_Y} (m_\chi T)^{1/2} e^{-m_\chi/T} + 0.02 h^2 N_Y N_\chi \left(\frac{T^3}{\varphi^2}\right) \simeq C_\varphi \frac{T^3}{\varphi^2}$$



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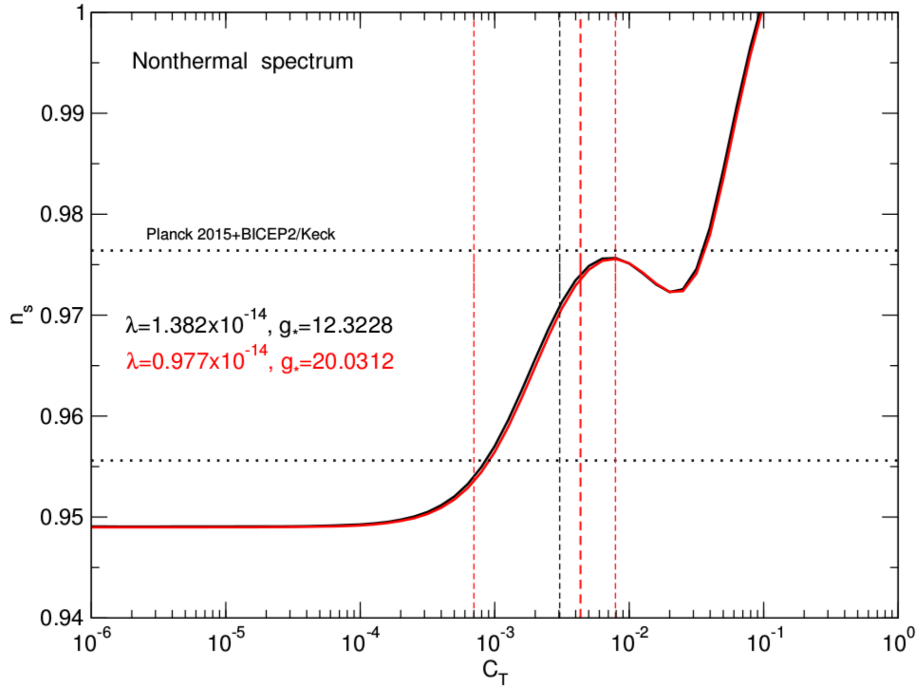

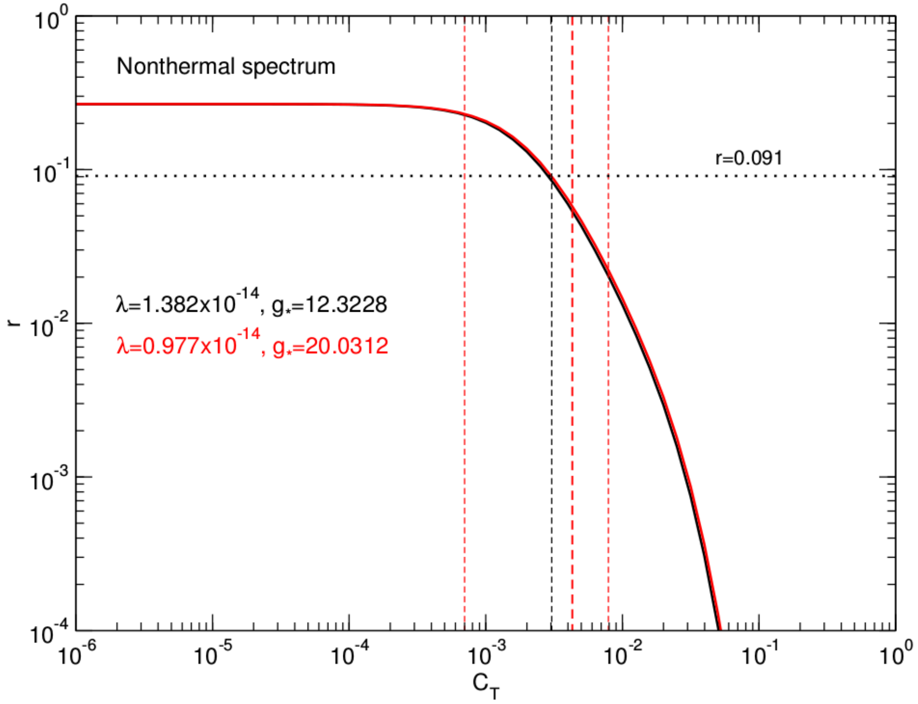

Little warm inflation & CMB data:
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