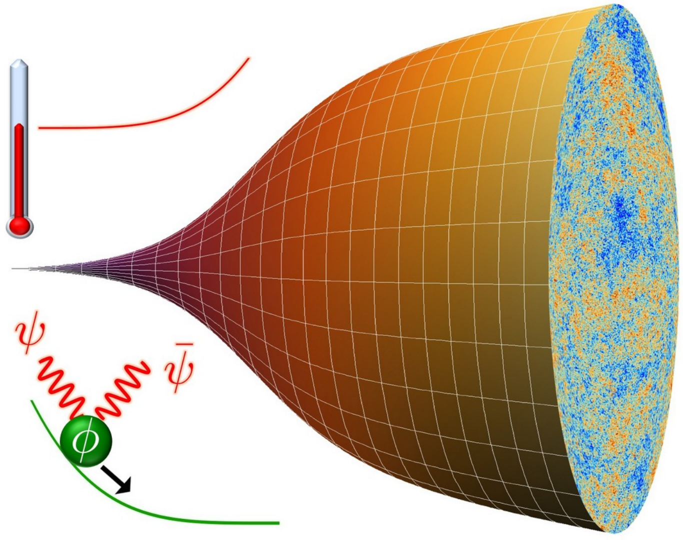
Warm Inflation & Gravitational Waves



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Warm Inflation & Gravitational Waves

Cold inflation/Warm inflation

Model building: dissipative coefficient

Primordial spectrum: PBH & (scalar induced) GW

Expanding Universe

Flatness problem

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

Horizon problem

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

Inflation

Early period of accelerated expansion

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

Primordial spectrum?

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

Unwanted relics...

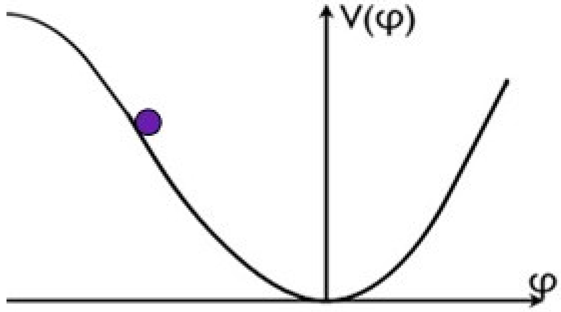
monopoles, moduli, gravitinos,...

[Starobinsky '80; Guth '81; Sato' 81; Albrecht, Steinhardt '82; Linde '82]

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** $(H = \dot{a}/a)$

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

$[\text{No. efolds}: N_e = \ln a/a_i]$

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

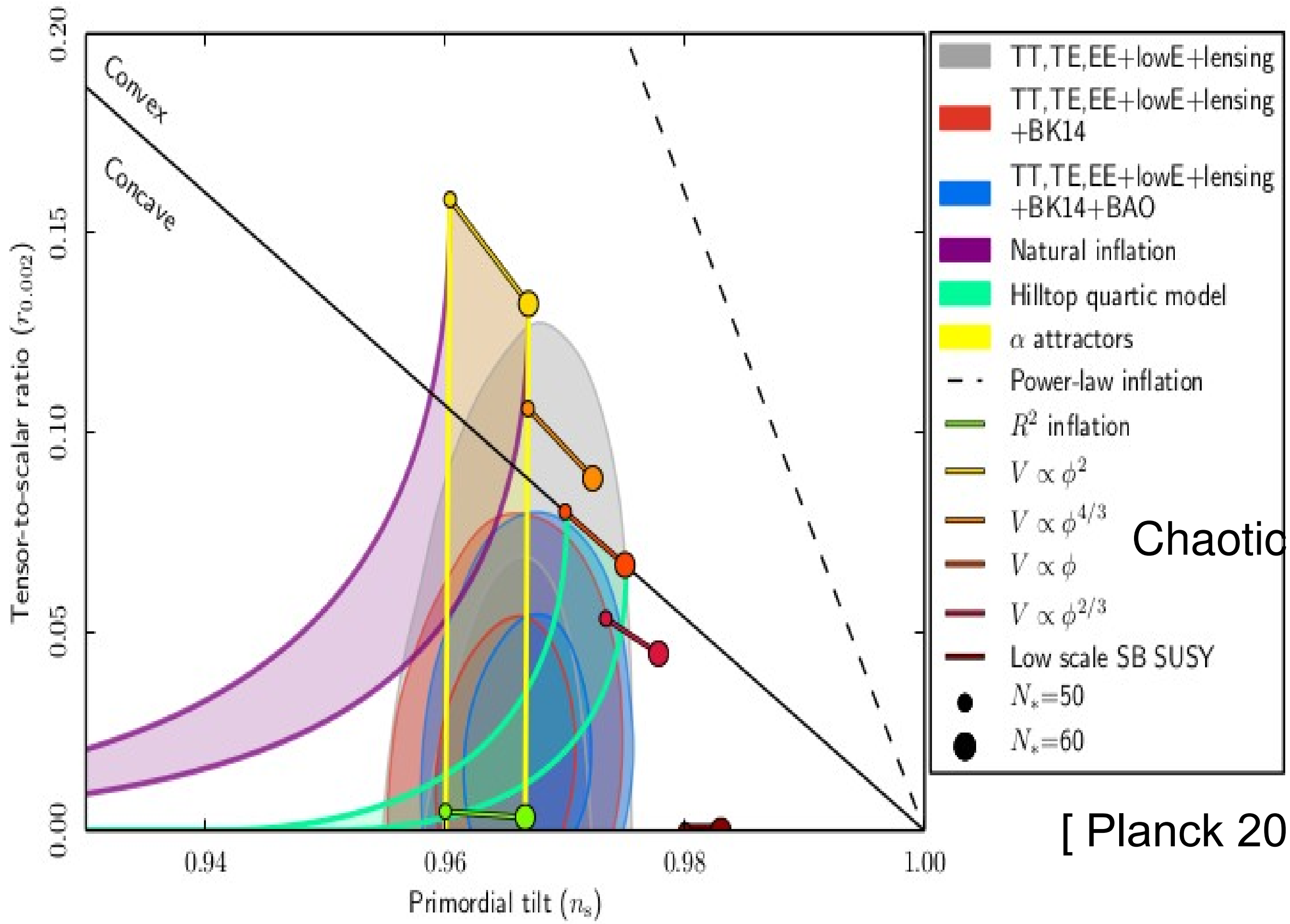
$$P_R \simeq \left(\frac{H}{\dot{\varphi}}\right)^2 \left(\frac{H}{2\pi}\right)^2 \qquad n_s = 1 + 2\eta_\varphi - 6\epsilon_\varphi \qquad r = \frac{P_T}{P_R} \simeq 16\epsilon_\varphi$$ [tensor-to-scalar ratio]

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

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

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1}$ $k_0 = 0.002\,\mathrm{Mpc}^{-1}$

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



$r_{0.002} < 0.07$

Chaotic inflation

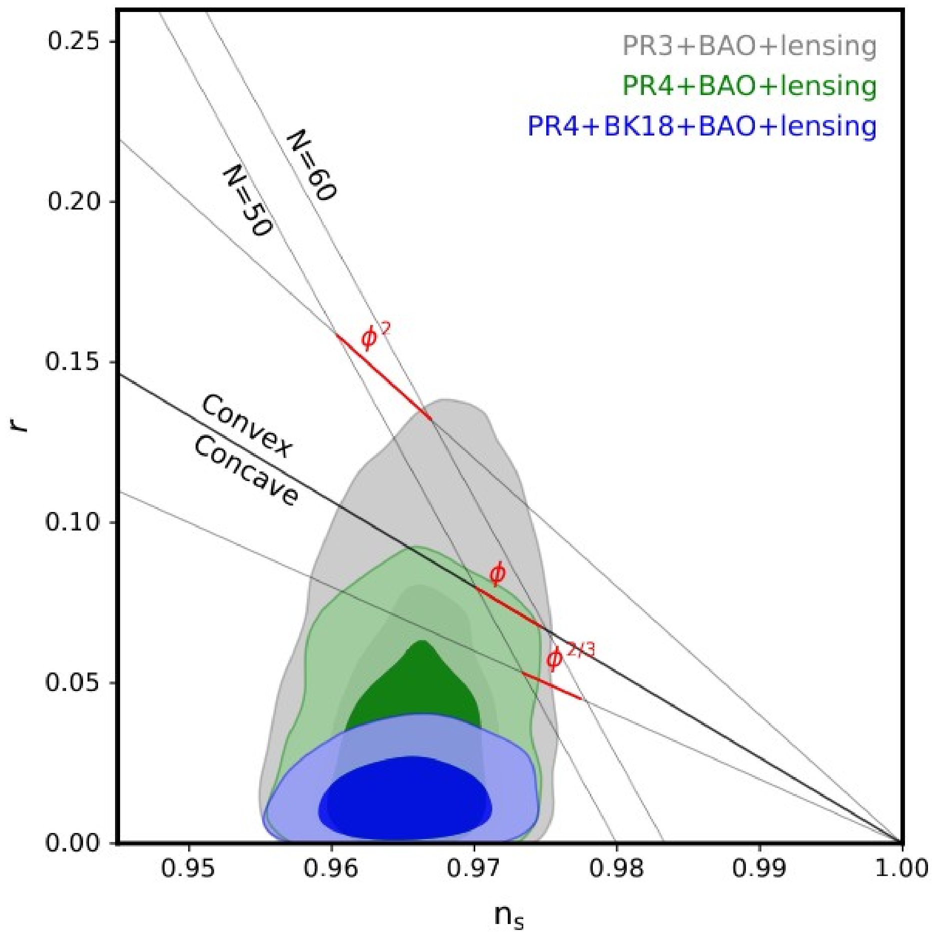
[Planck 2018.: 1807.06211]

CMB constraints ~10 efolds of inflation….

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

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

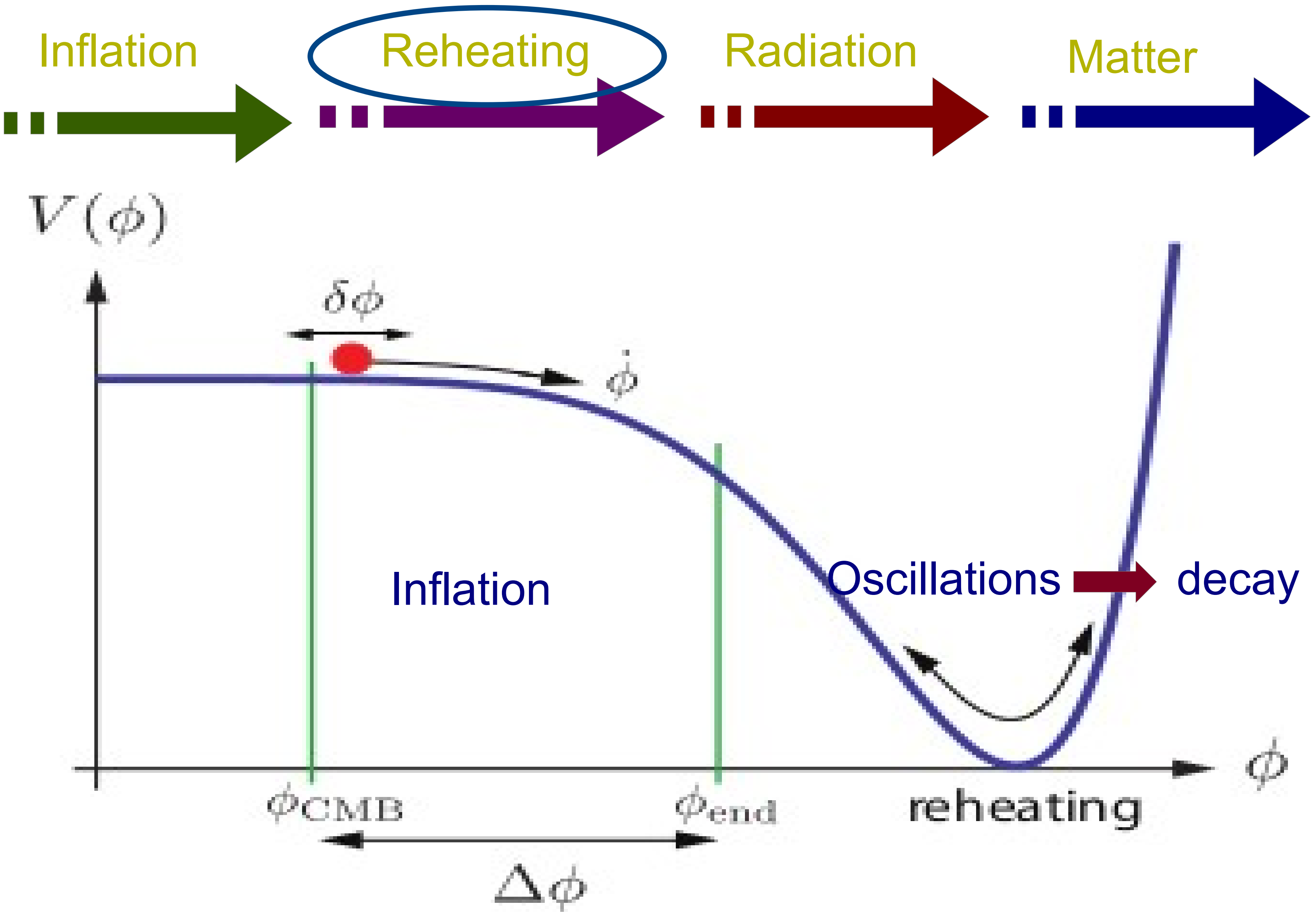
Tensor-to-scalar Ratio: $r = P_T/P_R$ $\quad P_R = 2.2 \times 10^{-9}$



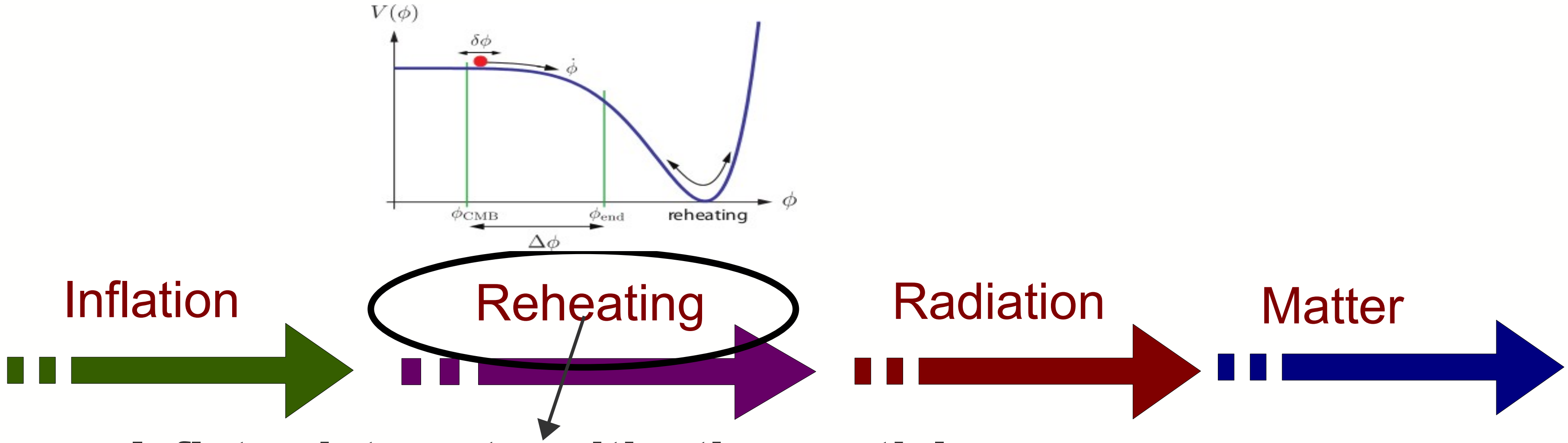
$r < 0.032$

$H_I < 4.4 \times 10^{13}\,\mathrm{GeV}$

[Tristam et al.: 2112.07961]



Inflation
Reheating
Radiation
Matter
$V(\phi)$
$\delta\phi$
$\dot{\phi}$
Inflation
Oscillations
decay
ϕ
ϕ_{CMB}
ϕ_{end}
reheating
$\Delta\phi$



Inflaton interacts with other particles

[Gravitational reheating inconsistent with BBN: limit on GW energy density]

[Figueroa & Tanin 1811.04093]

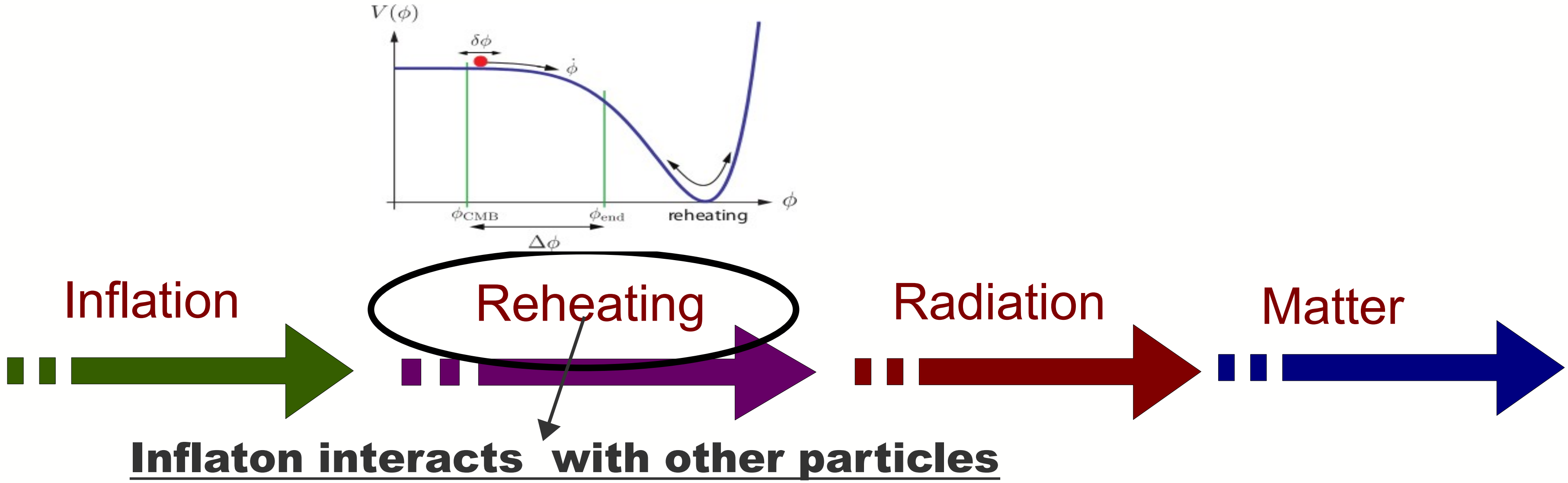
”Cold” inflation: Interactions negligible during Inflation **Reheating** → Radiation

Inflation & Particle production (non-thermal): “Dark photon”

$$L=\frac{1}{2}(\partial_\mu\phi)^2-V(\phi)-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{2}m_A^2A_\mu A^\mu-\frac{\alpha}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

[Anber & Sorbo PRD81 2010]

- Non-Gaussian Primordial spectrum
- Gravitational Waves
- Dark Matter...



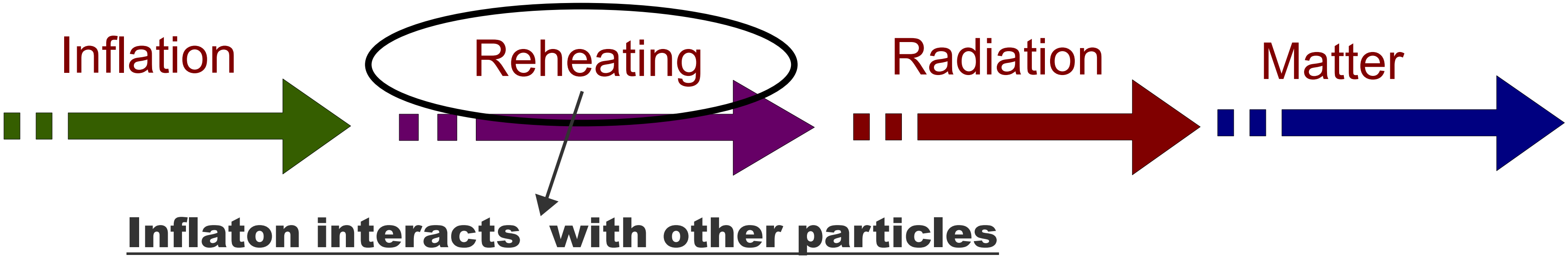
[Gravitational reheating inconsistent with BBN: limit on GW energy density]

[Figueroa & Tanin 1811.04093]

"Cold" inflation:	Interactions negligible during Inflation	**Reheating** →	Radiation
"Warm" inflation:	Inflaton "decay" into light dof (through a mediator)	→ **Dissipation**	Radiation

$$[T > H, \Gamma_\chi > H]$$

[Berera PRD55 '97; Berera, Moss & Ramos RPP72 '07]

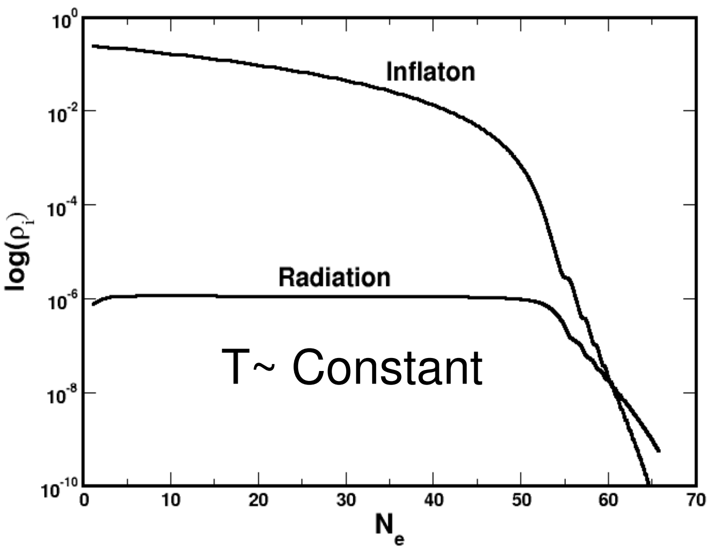


Interactions with the cosmic plasma induce dissipation

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

"Decay" into light dof= extra friction

"Warm" inflation:



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

$$\dot{\rho}_R+4H\rho_R=\Upsilon\dot{\varphi}^2$$ "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: $Q = \Upsilon/(3H), \quad \Upsilon(T, \phi)$

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

} Standard slow-roll

- $Q > 1, T > H$ → **S**trong **D**issipative **R**egime

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

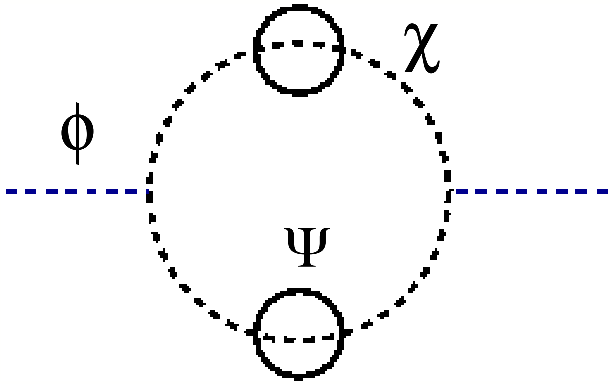
$|\eta_{\varphi}| < (1+Q), \quad \epsilon_{\varphi} < (1+Q), \quad \delta_T = T V_{T\varphi}/V_{\varphi} < 1$ ← Thermal corrections

- Q varies during inflation (WDR → SDR)
- Dissipation induces thermal inflaton fluctuations (**different primordial spectrum**)

- Inflation lasts longer due to extra friction → $H_{60}^{warm} < H_{60}^{cold}$ → $r < 0.1$
- Slow-roll parameters can be larger than 1, when $Q > 1$ (strong dissipative regime)

[no “eta” problem in sugra models]

Interactions & (T-dependent) Dissipative coefficient



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

light fermions,scalars

mediator

•"Heavy" (m > T) mediator: [low-T regime] $\Upsilon \simeq C_\varphi \frac{T^3}{\varphi^2}$ $[T > H]$

Thermal corrections under control (inflaton coupled to heavy fields), but getting 50-60 efolds of inflation typically requires large no. of fields $C_\phi \sim 10^6$

[BG, Berera, Ramos & Rosa 2012; BG, Berera & Kronberg 2015; R. Ayra et al. 2018]

•"Light" (m < T) mediator: [high-T regime] $\Upsilon \simeq C_\varphi T, \; C_\varphi / T$ $[T > H]$

Thermal corrections may spoil inflation! $\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \frac{g^2 \varphi^2}{12} T^2 + \cdots$

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

Solution: use symmetries to protect the inflaton mass

[BG, Berera, Ramos & Rosa 2016; 2019]

- "Little Warm Inflation" :

Inflaton a PNGB of a broken U(1) symmetry + pair of fermions/scalars + exchange symmetry

$$\varphi_1 = \frac{M}{\sqrt{2}} e^{\varphi/M}, \qquad \varphi_2 = \frac{M}{\sqrt{2}} e^{-\varphi/M} \qquad \varphi_1 \longleftrightarrow i\varphi_2 \qquad \Psi_{1L,R} \longleftrightarrow \Psi_{2L,R}$$

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

Fermion masses are bounded!! $[gM < T < M]$

$$\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \frac{g^2 M^2}{12} T^2 + \frac{g^4(\varphi) M^4}{16\pi^2}\left(\log\frac{\mu^2}{T^2} - c_f\right)$$

No thermal mass for the inflaton

Inflaton + pair of fermions

$$\Upsilon \simeq C(h)\frac{g^2}{h^2} T$$

Linear T

Inflaton + pair of scalars

$$\Upsilon \simeq \frac{4g^2}{h^2}\frac{g^2 M^2}{T} F[m_\chi / T]$$

Inverse T

• “Minimal Warm Inflation” :

[Berghaus, Graham, Kaplan 1910.07525]

Axion-like inflation (PNGB of a broken gauge symmetry) + gauge production [SU(N)]

$$L = \cdots - \frac{1}{2g^2}\mathrm{Tr}\,G_{\mu\nu}G^{\mu\nu} - \frac{\phi}{16\pi^2 M}\mathrm{Tr}\,G_{\mu\nu}\tilde{G}^{\mu\nu} - \bar{\Psi}(\gamma^{mu}D_\mu - m_f)\Psi$$

Gauge production ⟶ dissipation

[Mishra, Mohanty & Nautiyal, 1106.3039; Visinelli 1107.3523]

[Ferrerira & Notari 1711.07483; Kamali 1901.01897]

• Axion mass protected by shift symmetry at perturbative level; non-perturbative corrections ~ axion mass, negligible

• Dissipative coefficient

$$\Upsilon \simeq \frac{\Gamma_{sph}}{2TM^2}\frac{C m_f^2/T}{C m_f^2/T + C_R \Gamma_{sph}} \quad \begin{cases} \Upsilon \sim T^3 & (m_f \to \infty) \\ \Upsilon \sim T & (m_f \quad \text{light}) \end{cases}$$

Sphaleron rate $\Gamma_{sph} \simeq N_c^5 \alpha^5 T^4$

• MWI + hybrid inflation ⟶ SDR (Q>>1) at horizon crossing

• Warm inflation is an attractor

- Sphalerons induce (constant) dissipation even with T=0 (vacuum decay Υ ~ Constant)

[Laine & Procacci 2102.09913]

$T=0 \rightarrow T>T_c \rightarrow T>H$

$$\Upsilon \simeq \frac{d_A \alpha^2}{f_a^2}\left(\kappa(\alpha N_c T)^3 F[\omega/T] + (1+n_B(\omega))\frac{\pi\omega^3}{(4\pi)^4}\right) \qquad [\omega \simeq m]$$

Thermal $[\omega \simeq m < \alpha^2 T]$

$$\Upsilon_{IR} \sim \frac{\alpha^5 T^3}{f_a^2}$$

Vacuum $[\omega \simeq m \gg \alpha^2 T]$

$$\Upsilon_{UV} \sim \frac{\alpha^2 \omega^3}{f_a^2} \qquad [\omega \simeq m]$$

$$F[\omega/T] \simeq \frac{1+\frac{\omega^2}{(c_{IR}\alpha^2 N_c^2 T)^2}}{1+\frac{\omega^2}{(c_M \alpha N_c T)^2}}, \quad d_A = N_c^2 - 1, \quad \kappa \simeq 1.5, \quad c_{IR} \simeq 106, \quad c_M \simeq 5.1$$

Fluctuations & primordial spectrum: coupled system

Metric: $ds^2 = -(1+2\alpha)dt^2 - 2a\partial_i\beta\, dx^i dt + a^2[\delta_{ij}(1+2\phi) + 2\partial_i\partial_j\gamma]dx^i dx^j$

Scalar metric eom : Einstein Eqs

Field eom:

$$P_{\delta\varphi} \simeq \left(\frac{H}{2\pi}\right)^2$$

$T \rightarrow 0$

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

fluctuation force ξ

Radiation fluid:

$$\delta\dot{\rho}_r + 4H\delta\rho_r \simeq \frac{k^2}{a^2}\Psi_r + \dot{\varphi}^2\delta\Upsilon + 2\dot{\varphi}\Upsilon\delta\dot{\varphi} + [\text{metric}]$$ Energy density

$$\dot{\Psi}_r + 3H\Psi_r = -\delta\rho_r^{GI}/3 - \dot{\varphi}\Upsilon\delta\varphi + [\text{metric}]$$ Momentum density

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

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Energy density

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Momentum density

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

Tensors:

$$\ddot{h}_{ij} + 3hH_{ij} + \frac{k^2}{a^2}h_{ij} \simeq \frac{2}{m_P^2 a^2}\Pi_{ij}^{TT}$$

[Qui & Sorbo, 2107.09754]

$$P_h = 8\left(\frac{H}{2\pi m_P}\right)^2 + P_h(T) \simeq 8\left(\frac{H}{2\pi m_P}\right)^2$$

$$\left[P_h(T) \sim \frac{T^5}{H m_P^4}\right]$$

Fluctuations & primordial spectrum: coupled system

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

fluctuation force ξ

(light d. of f.)

$\Upsilon \sim T^c$ → $\frac{\delta\Upsilon}{\Upsilon} = c\frac{\delta T}{T}$ → Coupled system inflaton-radiation

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

Fluctuations & primordial spectrum: coupled system

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

fluctuation force ξ

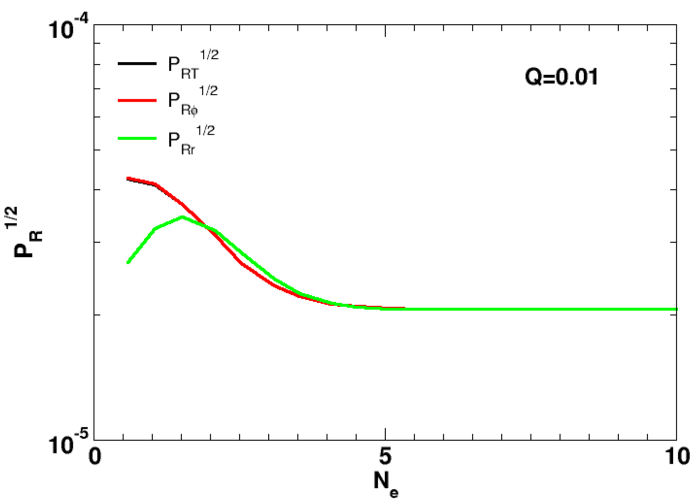
(light d. of f.)

$\Upsilon \sim T^c$ → $\frac{\delta\Upsilon}{\Upsilon} = c\,\frac{\delta T}{T}$ → Coupled system inflaton-radiation

- Weak dissipative regime ($Q=\Upsilon/H<<1$) : field decoupled from radiation

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

$Q=0.01, c=1$



[R is constant after horizon crossing (freeze-out)]

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

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

Dissipative processes may maintain a non-trivial distribution of inflaton particles: $N \simeq n_{BE} = (e^{k/aT}-1)^{-1}$

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

Fluctuations & primordial spectrum: coupled system

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

fluctuation force ξ

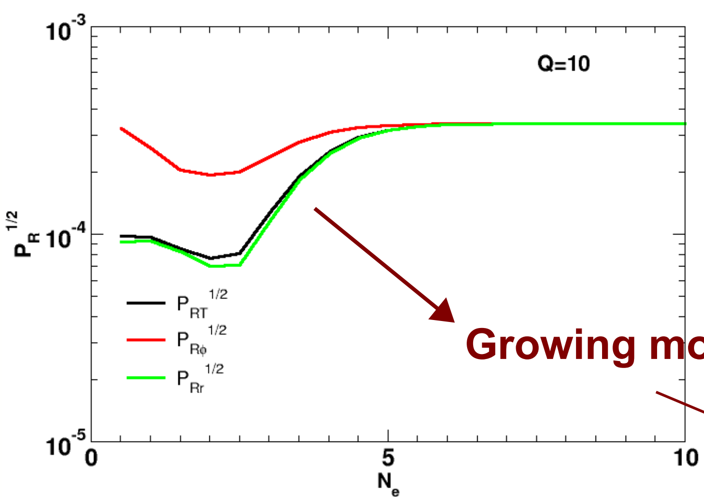
(light d. of f.)

$\Upsilon \sim T^c$ → $\frac{\delta\Upsilon}{\Upsilon} = c\,\frac{\delta T}{T}$ → Coupled system inflaton-radiation

- Strong dissipative regime ($Q=\Upsilon/H > 1$)

[R is constant after horizon crossing (freeze-out)]

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



Growing mode!

Numerical integration

$G[Q] \sim Q^\alpha$

When $c>0$, $\alpha > 0$ → Blue tilted spectrum **Amplification of the primordial spectrum**

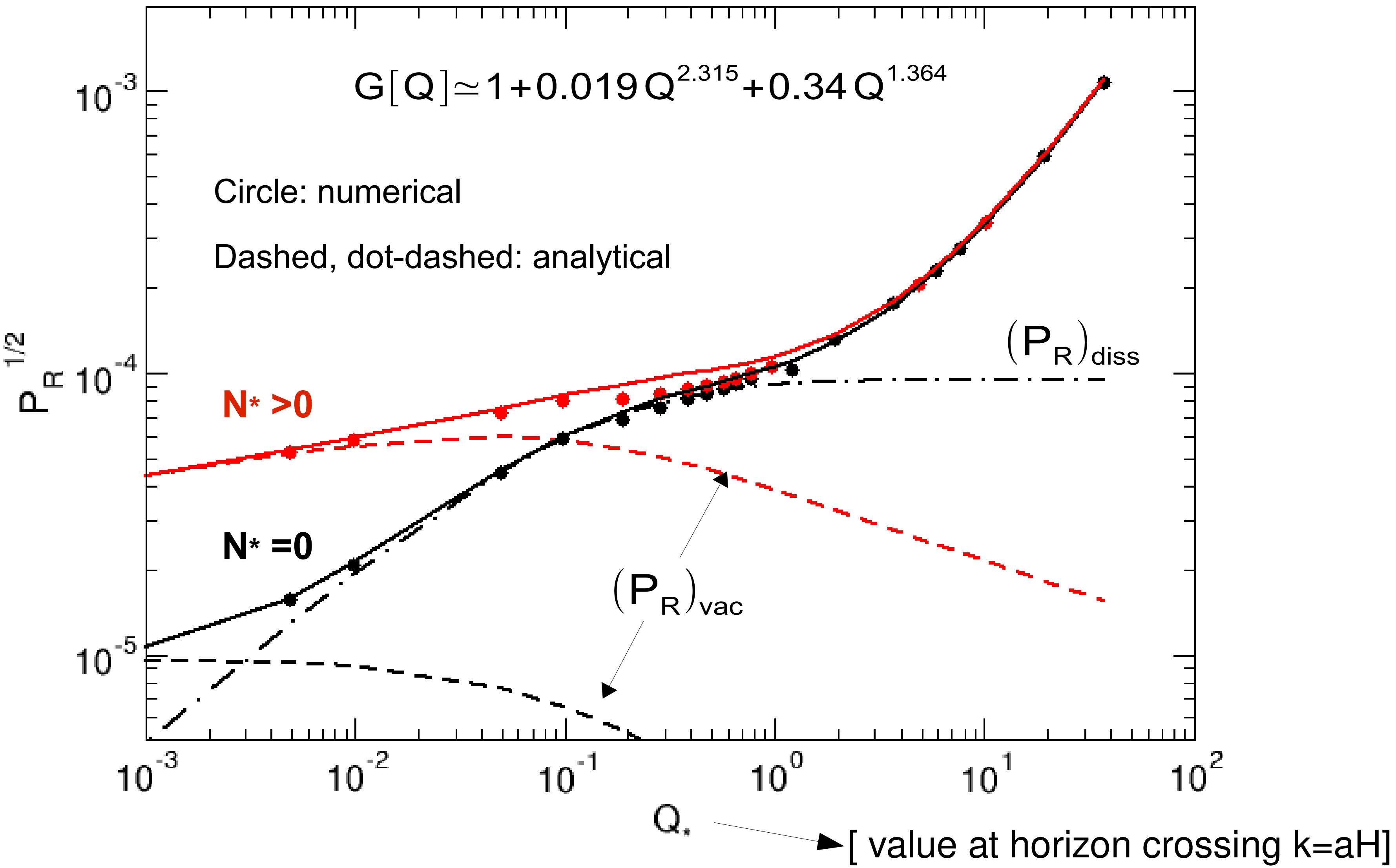
$$P_R \simeq \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2 \left(1 + 2N + \frac{T}{H}\frac{2\pi Q}{\sqrt{1+4\pi Q/3}}\right) G[Q]$$

Cold inflation, Q=0, T/H=0

[Moss & Graham 0905.3500; BG, Berera & Ramos, 1106.0701]

Primordial spectrum: an example, WLI

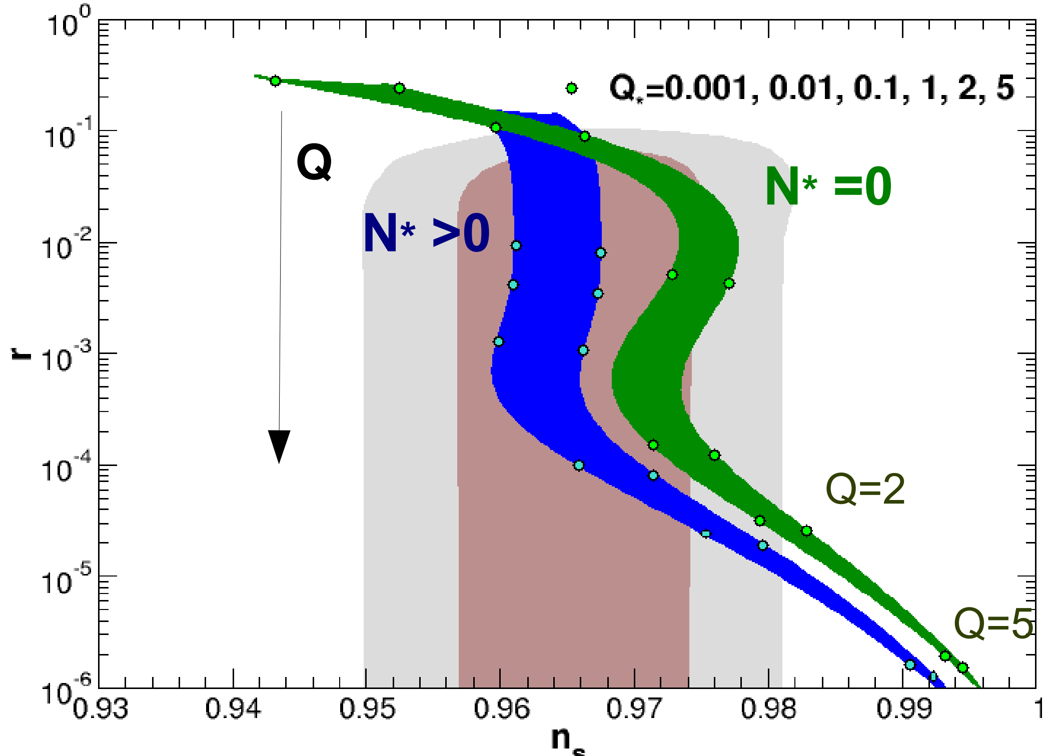
$$P_R \simeq ((P_R)_{vac} + (P_R)_{diss}) G[Q]$$



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

Primordial spectrum: quartic chaotic model LWI

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



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

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

Quartic:

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

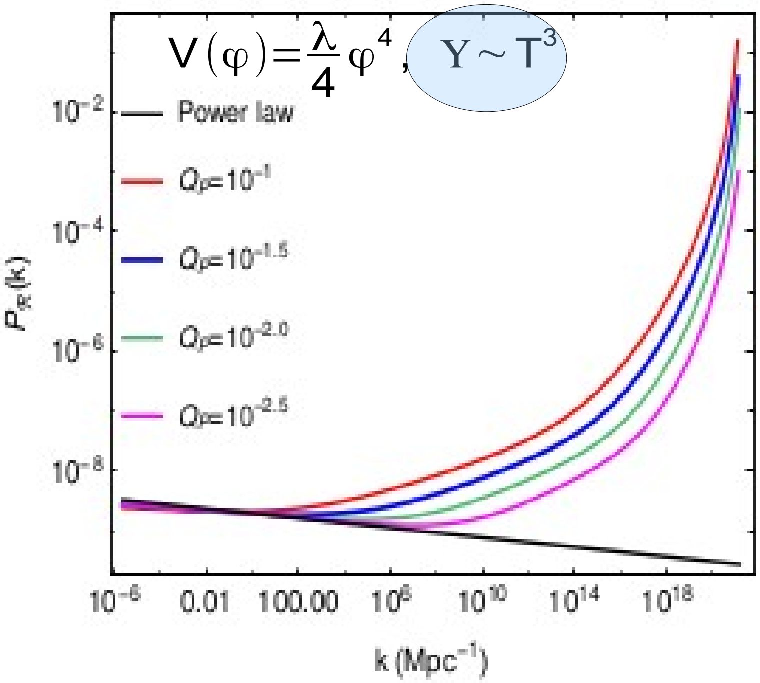
Primordial spectrum: **PBHs & GW**

- CMB constraints the primordial spectrum at scales that leave the horizon 50-60 e-folds before the end:

$$P_R(k_{CMB}) \simeq 2.2 \times 10^{-9}$$

- Dissipative effects amplify the spectrum at smaller scales (near the end)

$$P_R(k) \sim O(0.01 - 0.1)$$ → **PBHs?** **GW?**



$P_R \sim O(0.01\text{-}0.1)$ will lead to PBH formation on re-entry

$$M_{PBH}(k) \simeq \gamma \frac{4\pi m_P^2}{H_M}$$ H on re-entry, close to the end of Inflation, during radiation

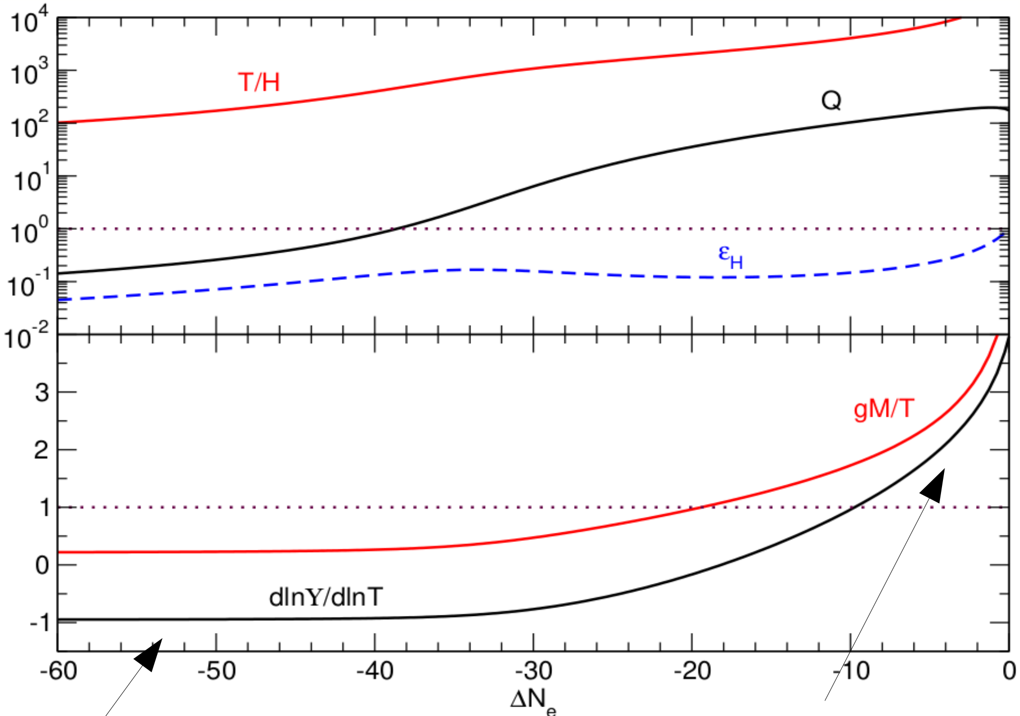
$$M_{PBH} \sim [5 \times 10^4 g, 10^6 g]$$ Light, evaporating black holes

[R. Arya 1910.05238] [R. Arya & K. Mishra 2204.02896]

Scalar Warm Little Inflaton Model + quartic chaotic

$V = \lambda \varphi^4 / 4$

$[M = 10^{-4} m_P, \quad g = 1, \quad h = 2.5, \quad \lambda = 10^{-14}]$



$$Y \simeq \frac{4g^2}{h^2} \frac{g^2 M^2}{T} F[m_\chi / T]$$

- M^2/T "High-T" $gM/T \ll 1$
- T^3/M^2 "Low-T" $gM/T \gg 1$

CMB scales: no growing mode

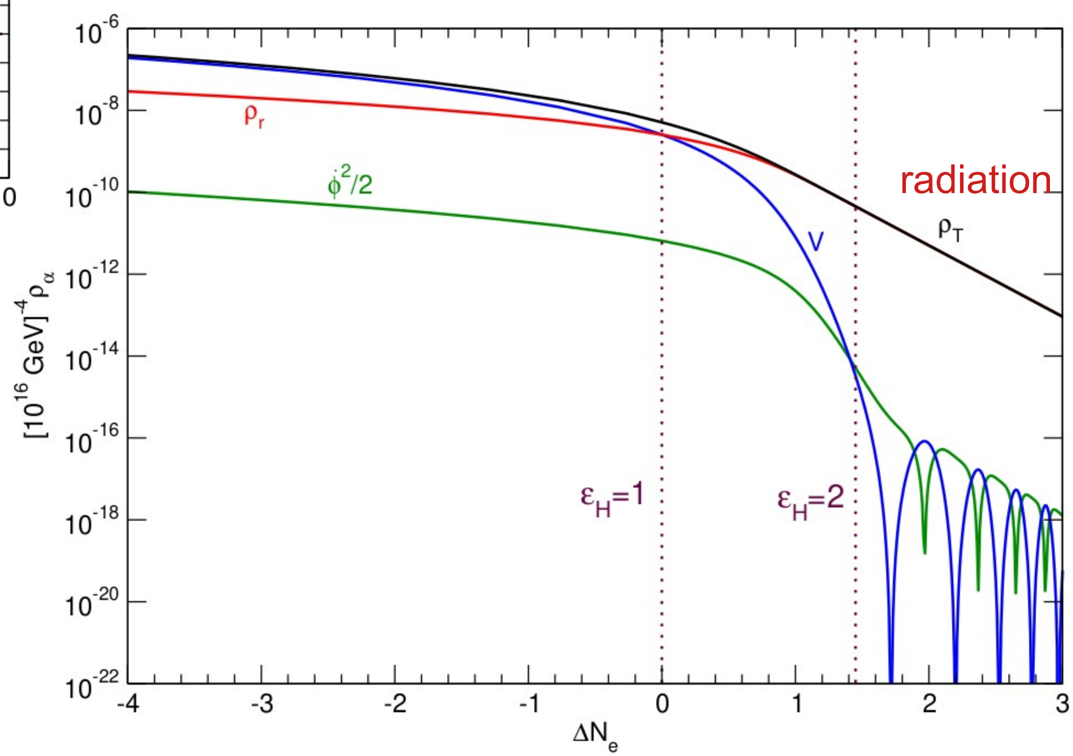
$$Y \simeq M^2/T$$

Primordial spectrum compatible with observations

End of inflation:

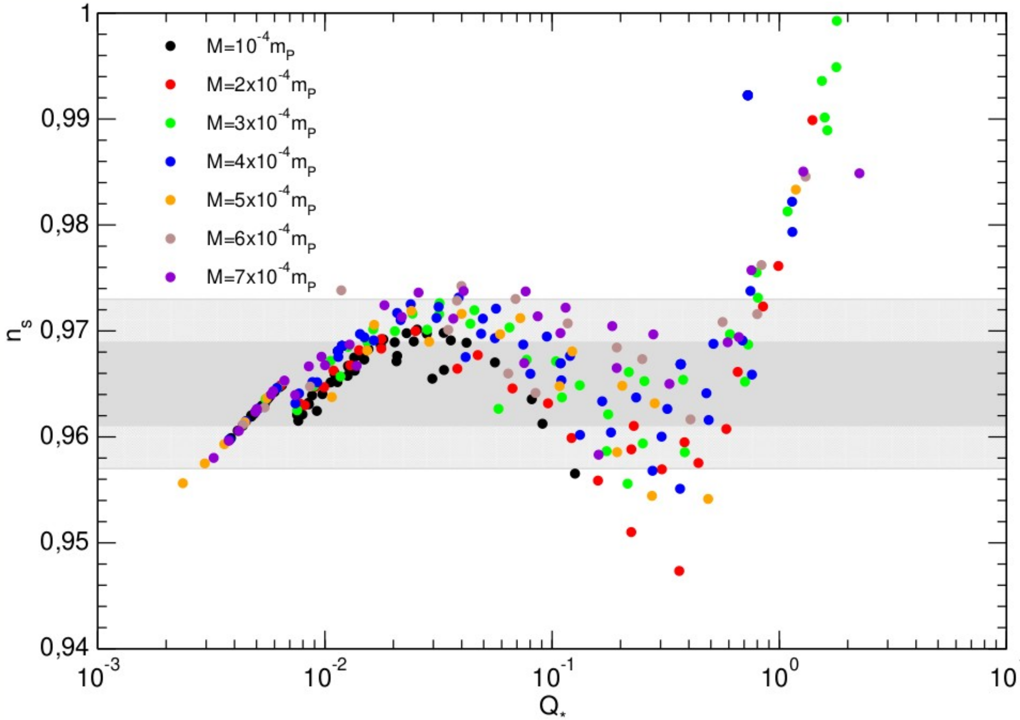
$$Y \simeq T^3/M^2$$

Graceful exit



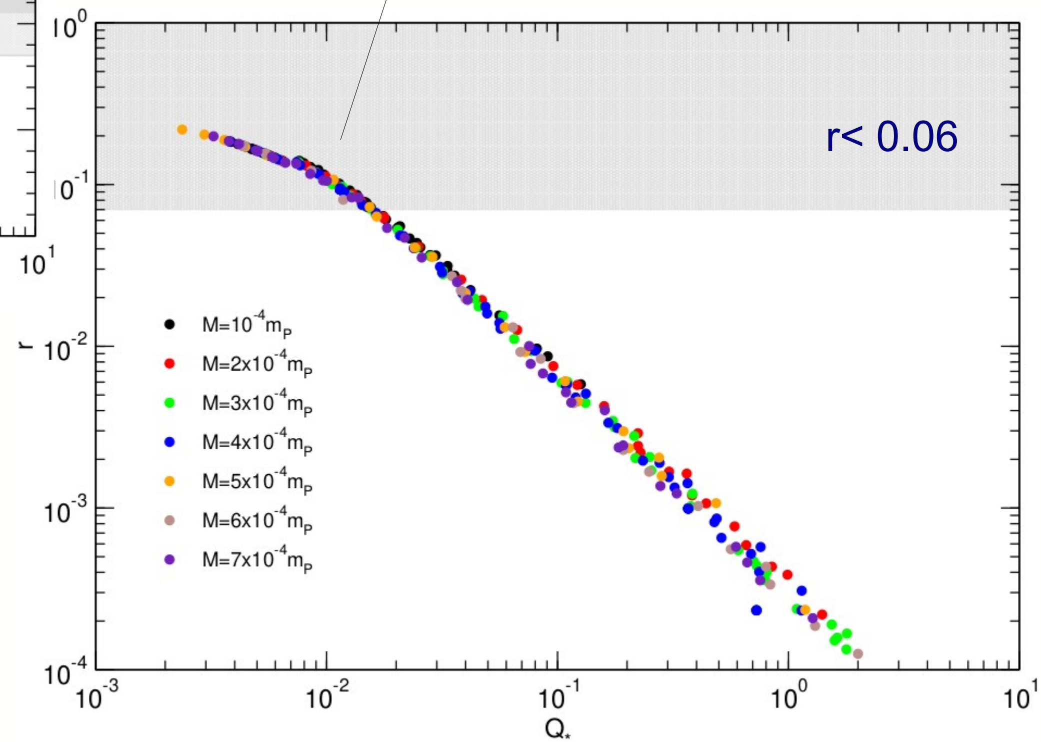
[BG & Subías 2105.08045]

Spectral index & tensor-to-scalar ratio



$Q_* < 1$, CMB scales

$Q_* > 0.02$

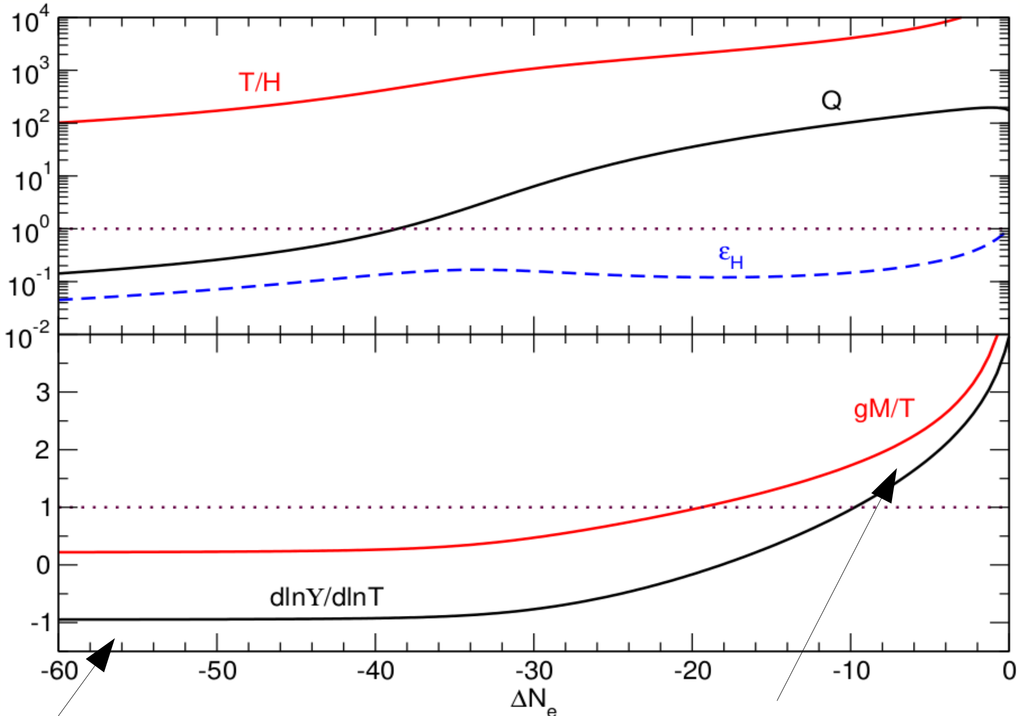


$$[M \sim O(10^{-4})m_P, \quad g \sim 0.5-1, \quad h \sim O(1)]$$

Scalar Warm Little Inflaton Model + quartic chaotic

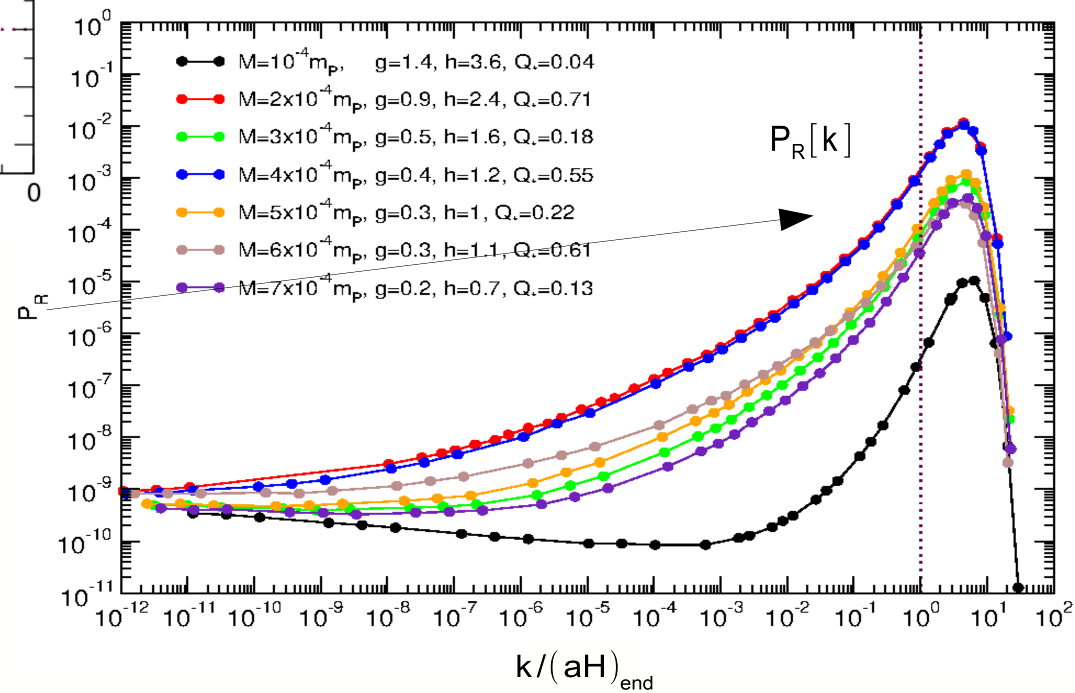
$V = \lambda \varphi^4/4$

$[M = 10^{-4} m_P, \quad g = 1, \quad h = 2.5, \quad \lambda = 10^{-14}]$



$$Y \simeq \frac{4g^2}{h^2}\frac{g^2 M^2}{T} F[m_\chi/T] \quad \begin{cases} M^2/T & \text{“High-T”} \\ T^3/M^2 & \text{“Low-T”} \end{cases}$$

Numerical integration upto $\epsilon_H = 2$



CMB scales: no growing mode

$Y \simeq M^2/T$

Primordial spectrum compatible with observations

End of inflation: amplification of the primordial spectrum

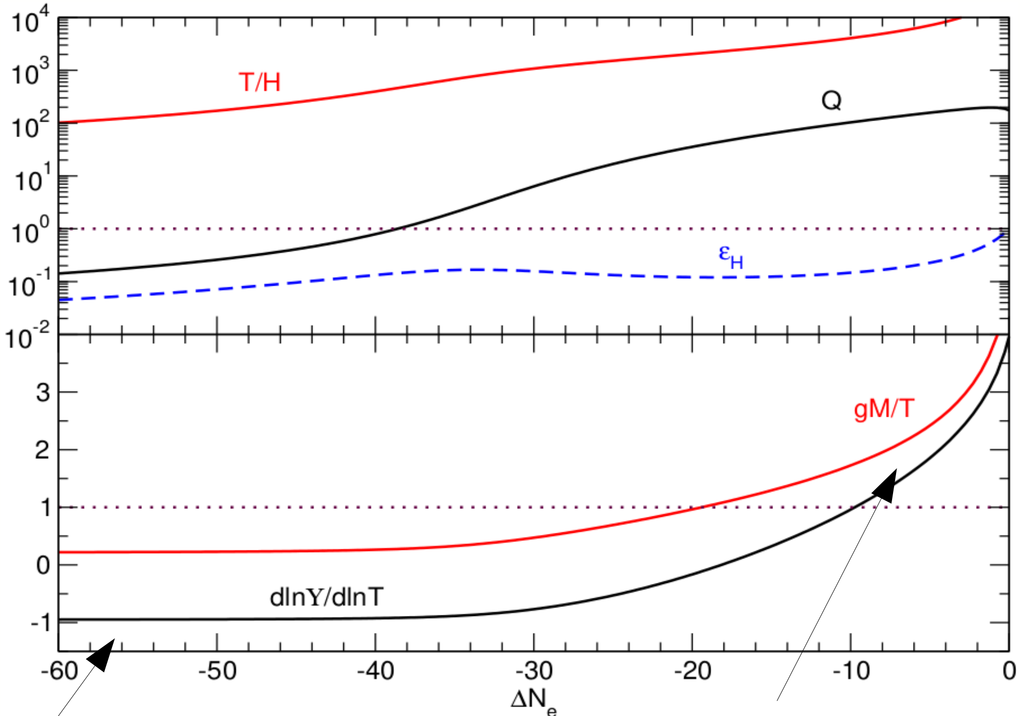
$Y \simeq T^3/M^2$

[BG & Subías 2105.08045]

Scalar Warm Little Inflaton Model + quartic chaotic

$V = \lambda \varphi^4/4$

$[M = 10^{-4} m_P, \quad g = 1, \quad h = 2.5, \quad \lambda = 10^{-14}]$



$$\Upsilon \simeq \frac{4g^2}{h^2}\frac{g^2M^2}{T} F[m_\chi/T] \begin{cases} M^2/T & \text{“High-T”} \\ T^3/M^2 & \text{“Low-T”} \end{cases}$$

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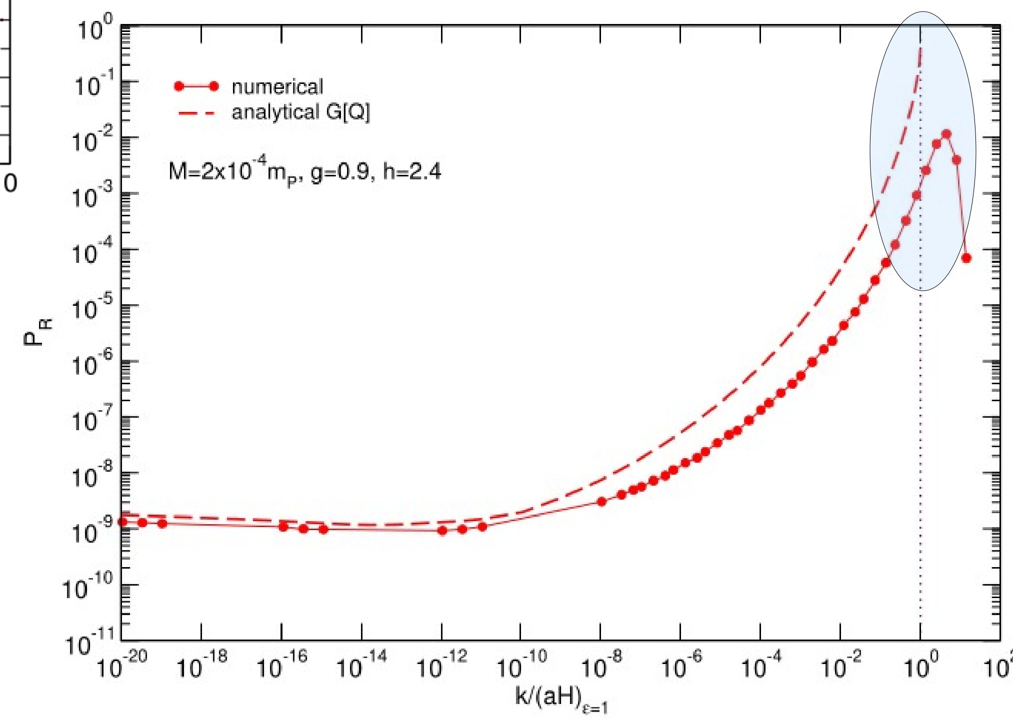
Numerical versus analytical G[Q] at CMB scales



[BG & Subías 2105.08045]

Scalar Warm Little Inflaton Model + quartic chaotic $V=\lambda\varphi^4/4$

$[M=10^{-4}m_P,\quad g=1,\quad h=2.5,\quad \lambda=10^{-14}]$

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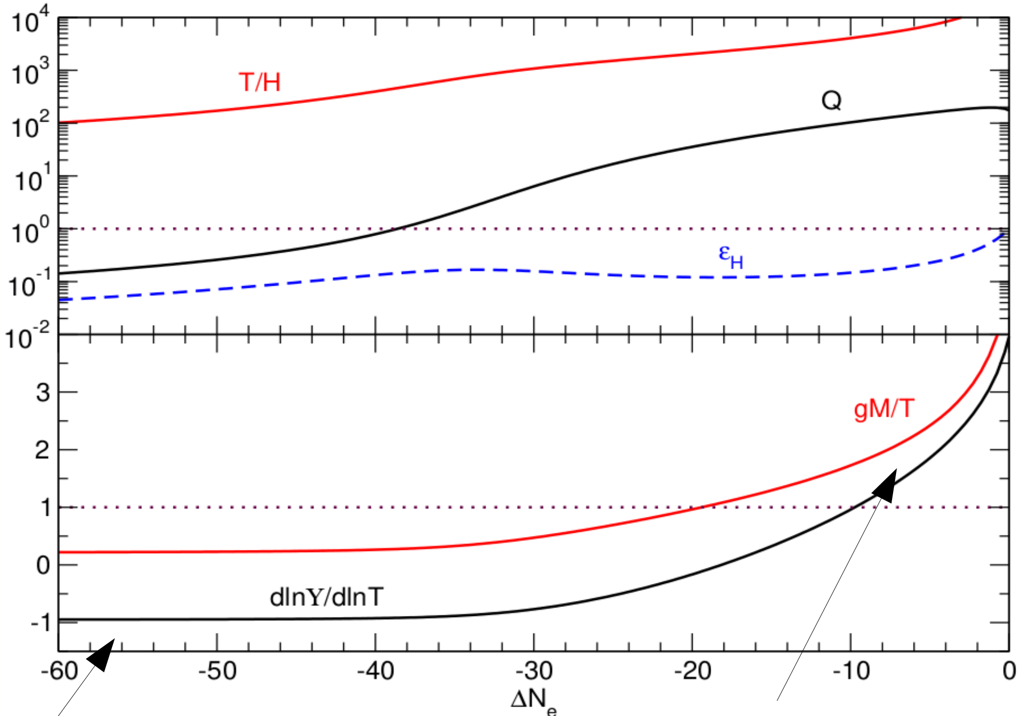
PBHs?

[R. Arya 1910.05238]

Light, evaporating PBHs: M_{PBH} ~ $O(10^3\text{-}10^6)$ g



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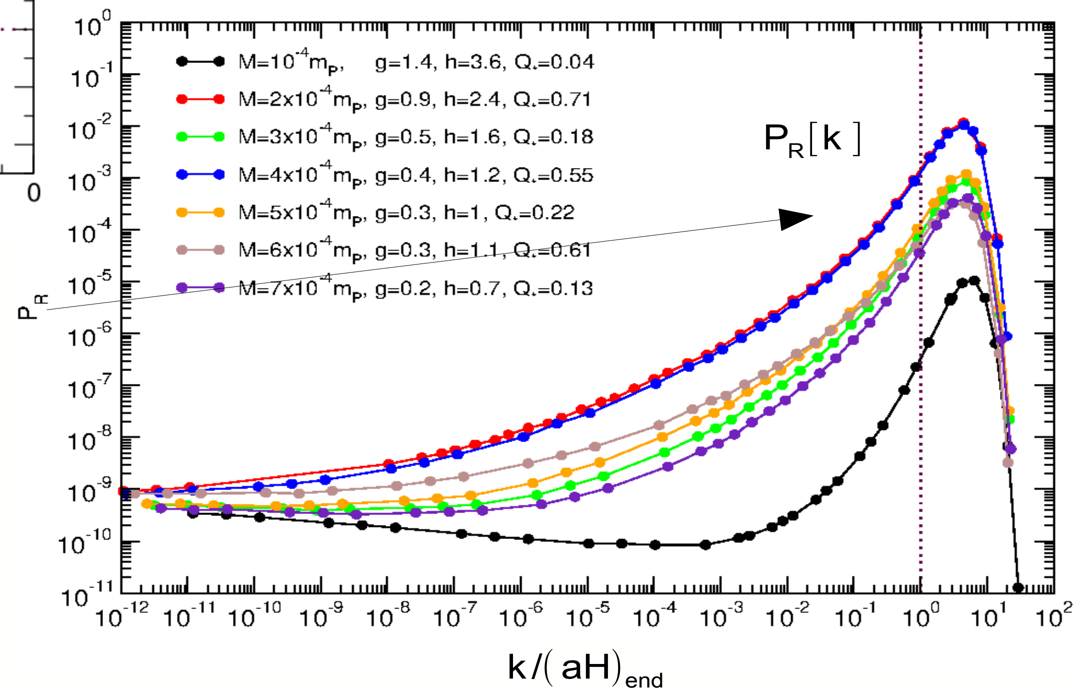

[BG & Subías 2105.08045]

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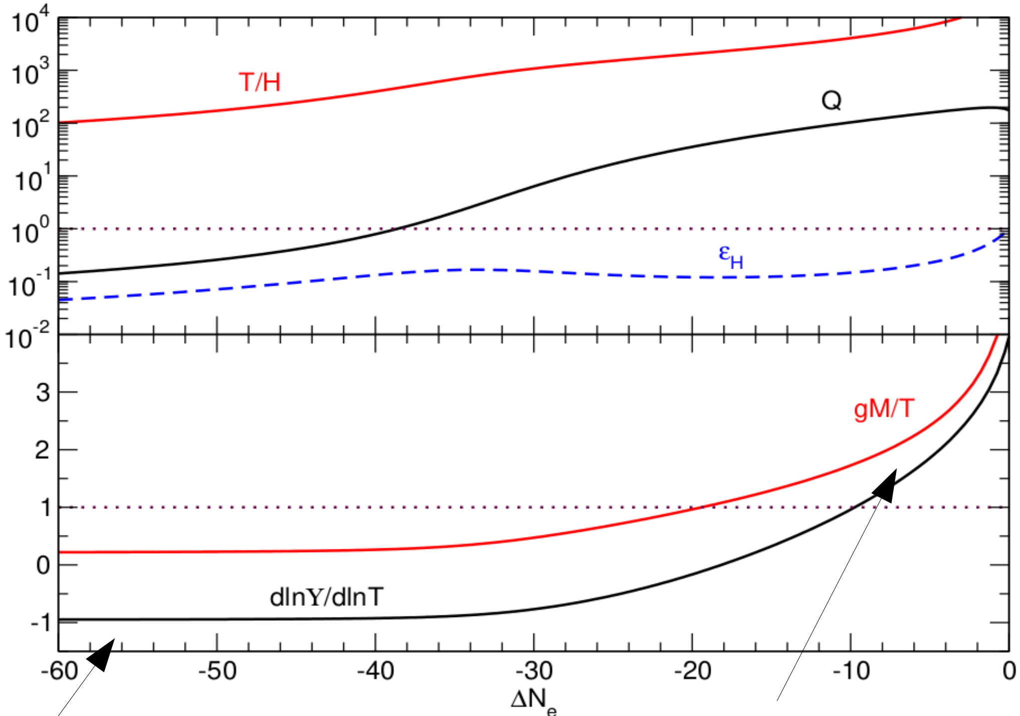
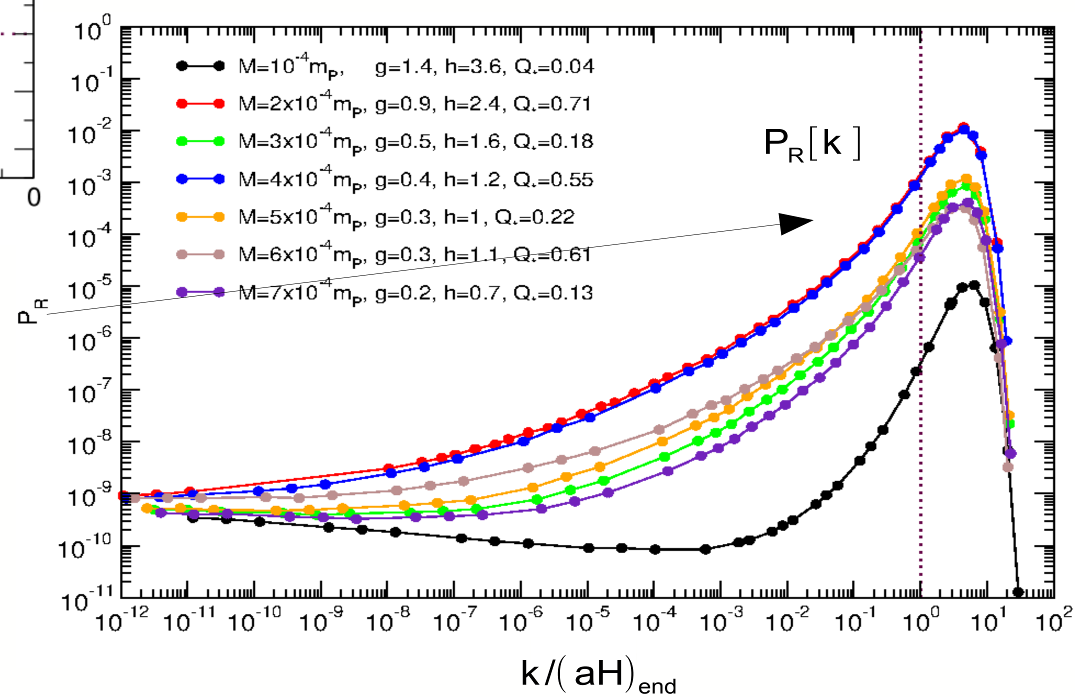


$$Y \simeq \frac{4g^2}{h^2}\frac{g^2 M^2}{T} F[m_\chi/T] \begin{cases} M^2/T & \text{"High-T"} \\ T^7/M^6 & \text{"Low-T"} \end{cases}$$

2^{nd} order source of primordial tensors?



CMB scales: no growing mode

$Y \simeq M^2/T$

Primordial spectrum compatible with observations

End of inflation: amplification of the primordial spectrum

$Y \simeq T^3/M^2$

[BG & Subías 2105.08045]

Induced 2nd order GW

Although at linear order scalar, vector and tensor perturbations decouple,
large scalar fluctuations source tensors at second order

$$\ddot{h}_k + 3H\dot{h}_k + \frac{k^2}{a^2} h_k = S_k[\Phi_k]$$

Primordial spectrum

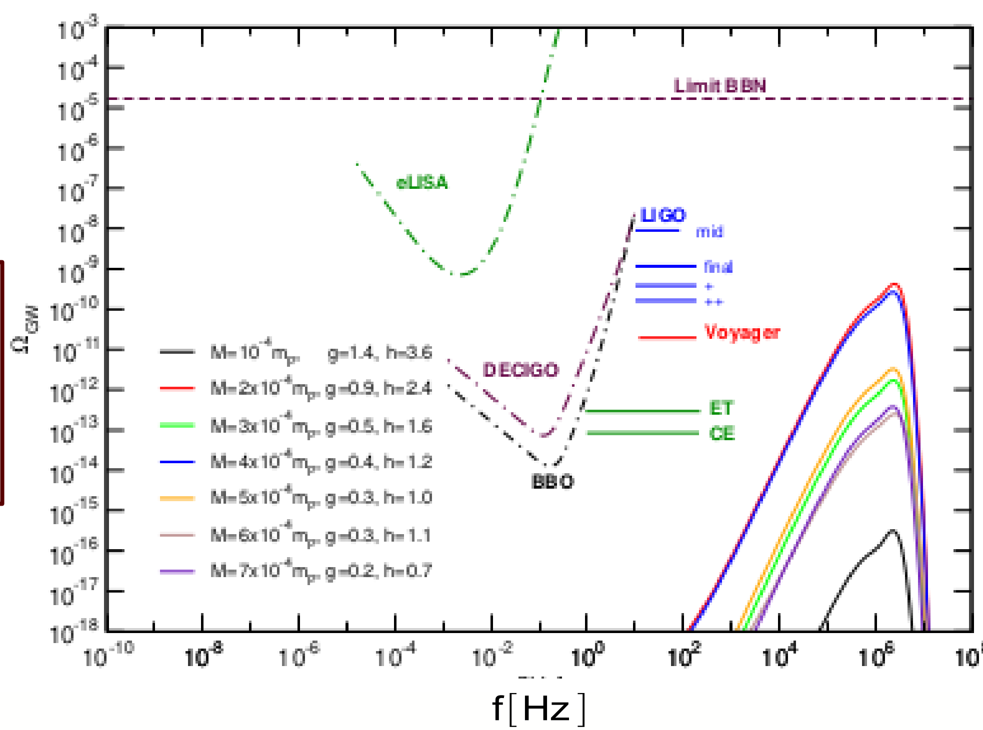
Gravitational potential: $\Phi_k = T[k\tau]\phi_k , \quad \langle \phi_k \phi_q \rangle = \delta(\vec{k}+\vec{q}) \frac{2\pi^2}{k^3} \left(\frac{3+3w}{5+3w}\right)^2 P_\zeta(k)$ [w=1/3 radiation]

GW spectral density: $\Omega_{GW,0}(k) \simeq 0.4\,\Omega_{r,0} \times \frac{1}{24} \left(\frac{k}{aH}\right)^2 P_h(k,\tau_c)$ [Kohri & Terada 1804.08577]

Today: f~ 10^5 -10^6 Hz

$$\Omega^{max}_{GW,0} \simeq 10^{-9}$$

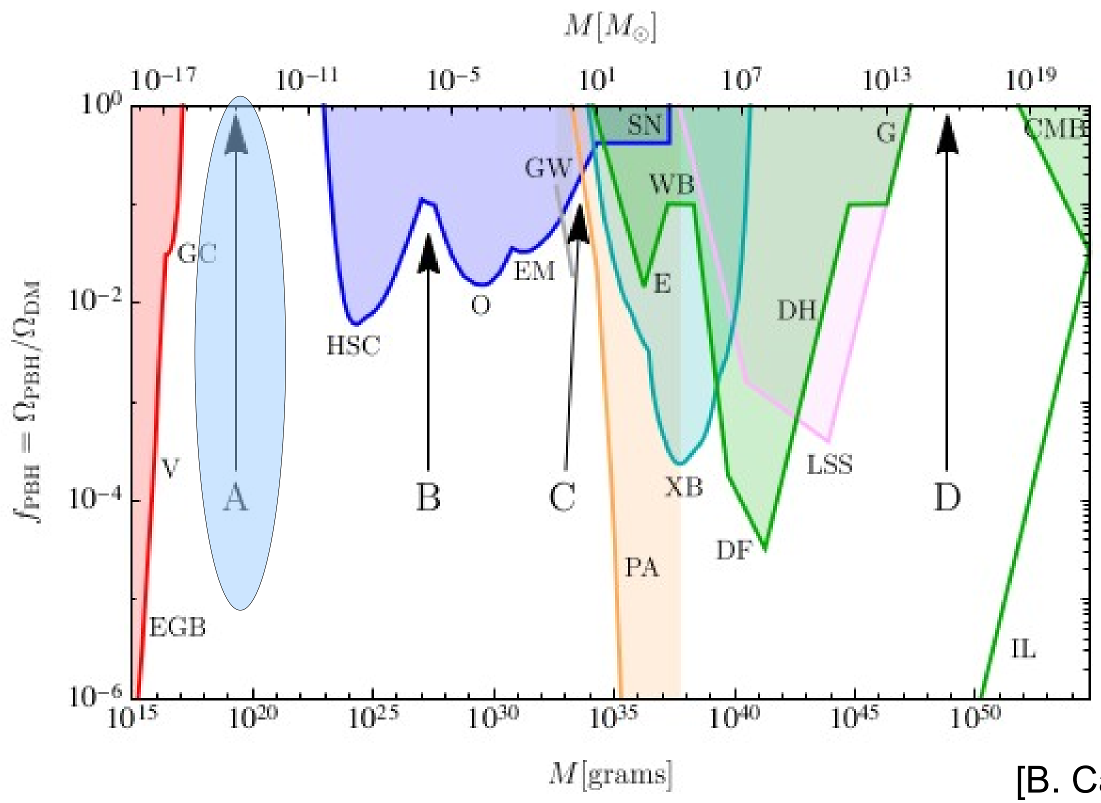
$$[\Omega_{GW,0} \propto f^3 \ln^2 f/f_P]$$



Consistent with all constraints (CMB, PBHs)

[BG & Subías 2105.08045]

PBHs as DM



[B. Carr & F Kuhnel 2006.02838]

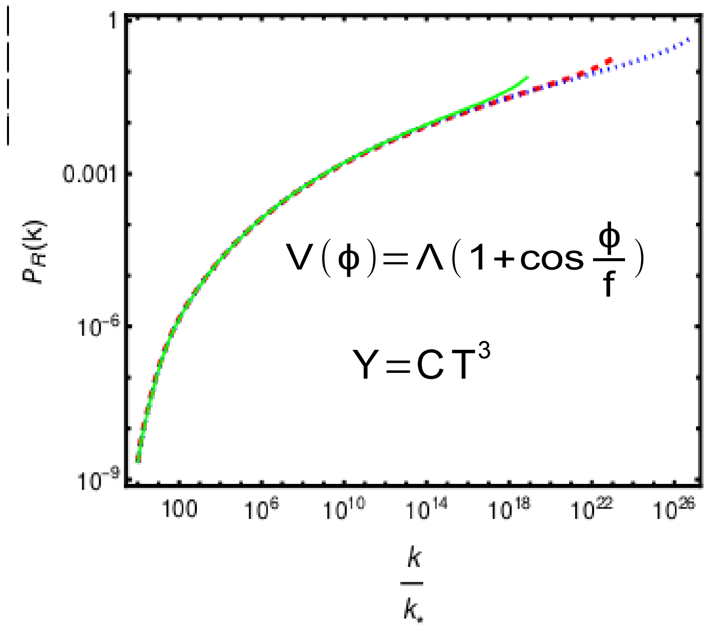
$$M_{PBH}(k) \sim \frac{4\pi m_P^2}{H_M} \sim 10^{-16} - 10^{-11} M_{sun} \;\Longrightarrow\; f_{PBH} \sim O(1)$$

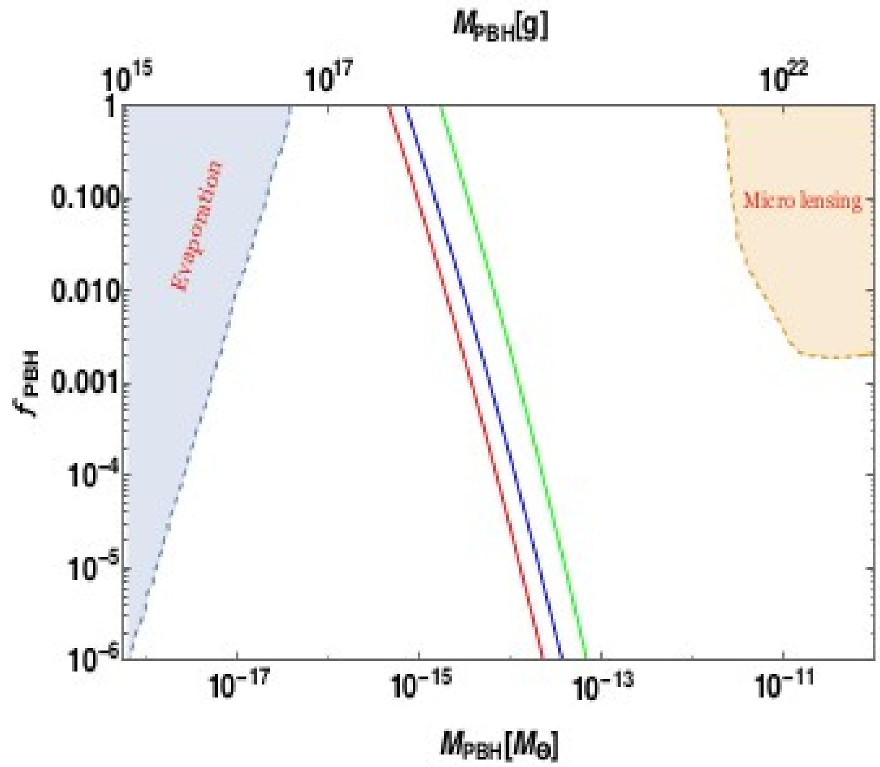
- We need $P_R(k) \sim O(0.01 - 0.1)$ 20 - 30 efolds before the end

PBHs as DM

- Natural WI + T^3 dissipation: the spectrum is amplified ~ 20 efolds before the end

[Correa, Gangopadhyay, Jaman, Mathews, 2207.10394]



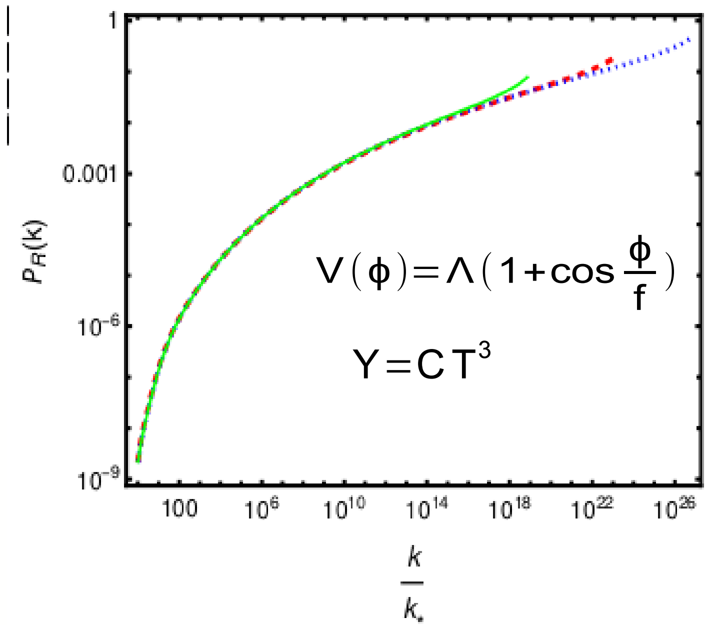


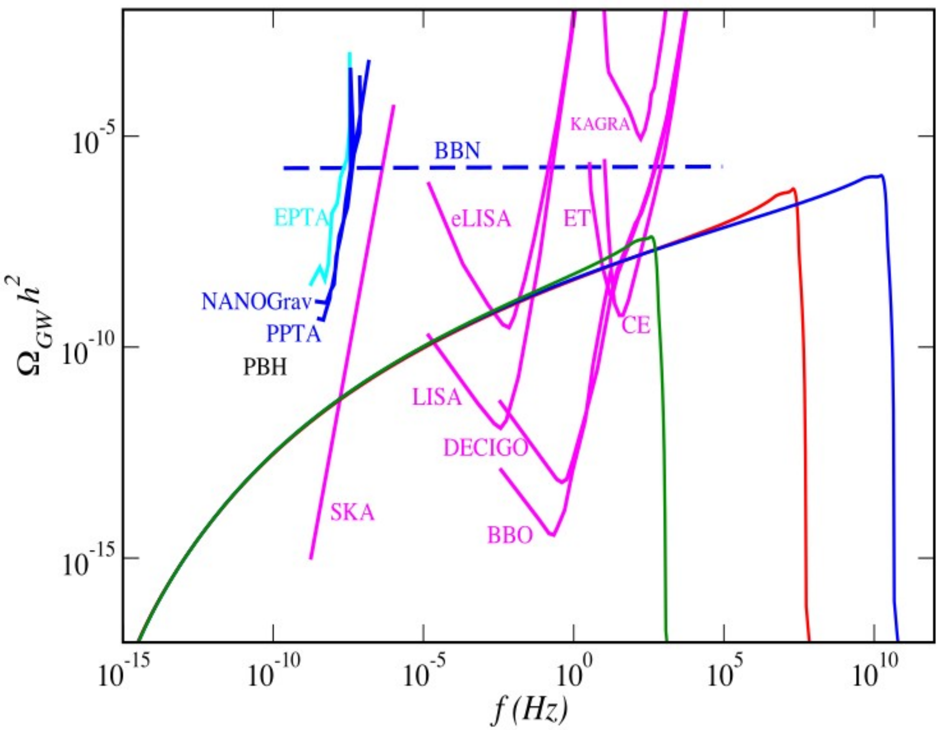
$$M_{PBH}(k) \sim \frac{4\pi m_P^2}{H_M} \sim 10^{-16} M_{sun} \Rightarrow f_{PBH} \sim O(1)$$

PBHs as DM

- Natural WI + T^3 dissipation: the spectrum is amplified ~ 20 efolds before the end

[Correa, Gangopadhyay, Jaman, Mathews, 2306.09641]





PBHs as DM

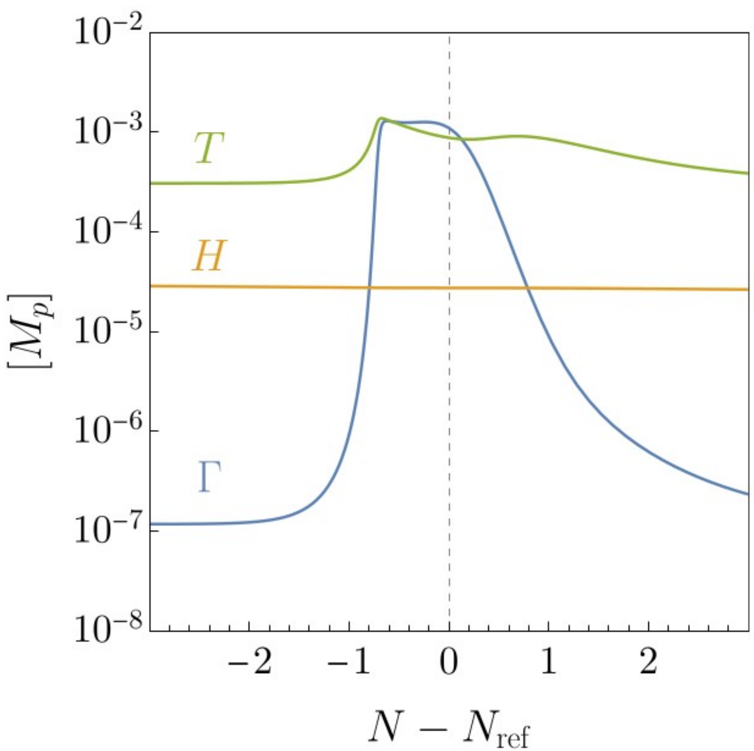
- Transient dissipation : peak in Q ➡ peak in the spectrum ~ 20-30 efolds before the end

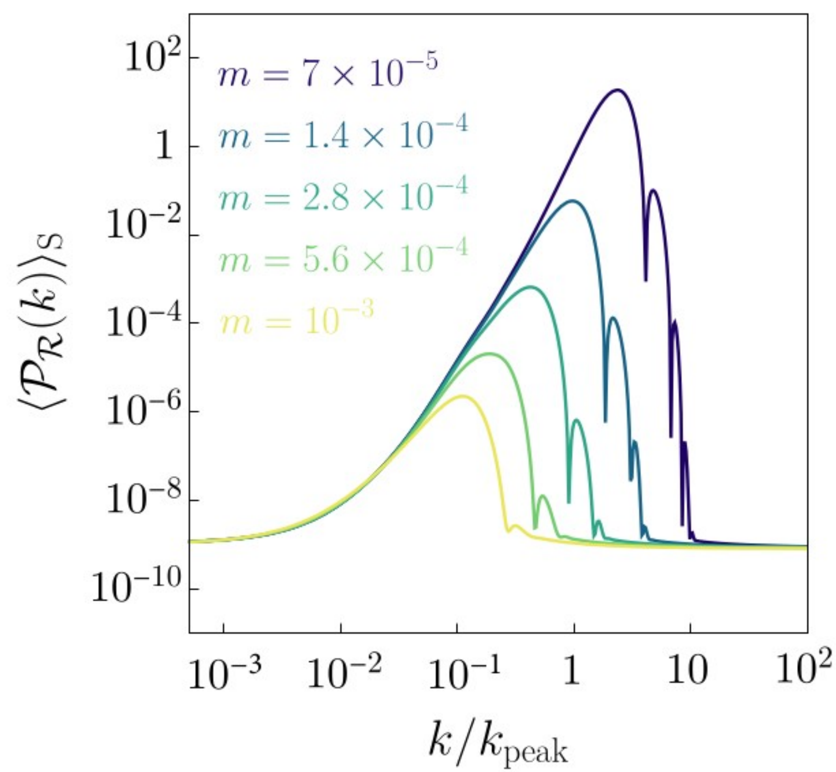
[Ballesteros, García, Pérez-Rodríguez, Pierre, Rey 2208.14978]

$$\Upsilon(\phi, T) = \frac{T^3}{m^2 + M^2 \tanh^2((\phi - \phi_c)/\Lambda)}$$

[Non-minimal kinetic term]

$V = \lambda \varphi^4 / 4$





$[M = 10^{-2} m_P, \ \Lambda = 0.1 m_P, \ \lambda = 2.5 \times 10^{-15}]$

PBHs as DM

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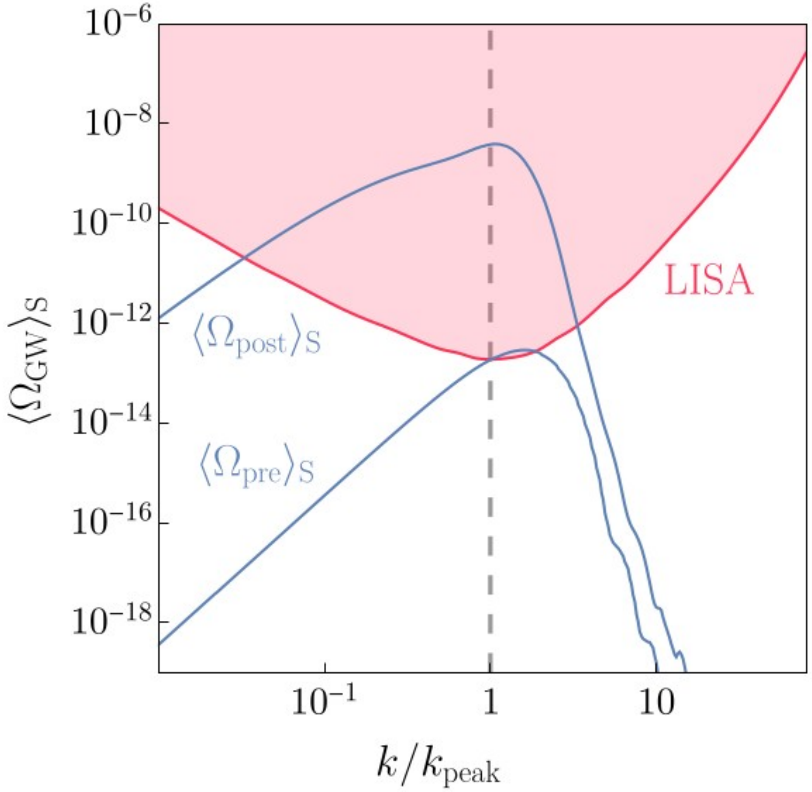
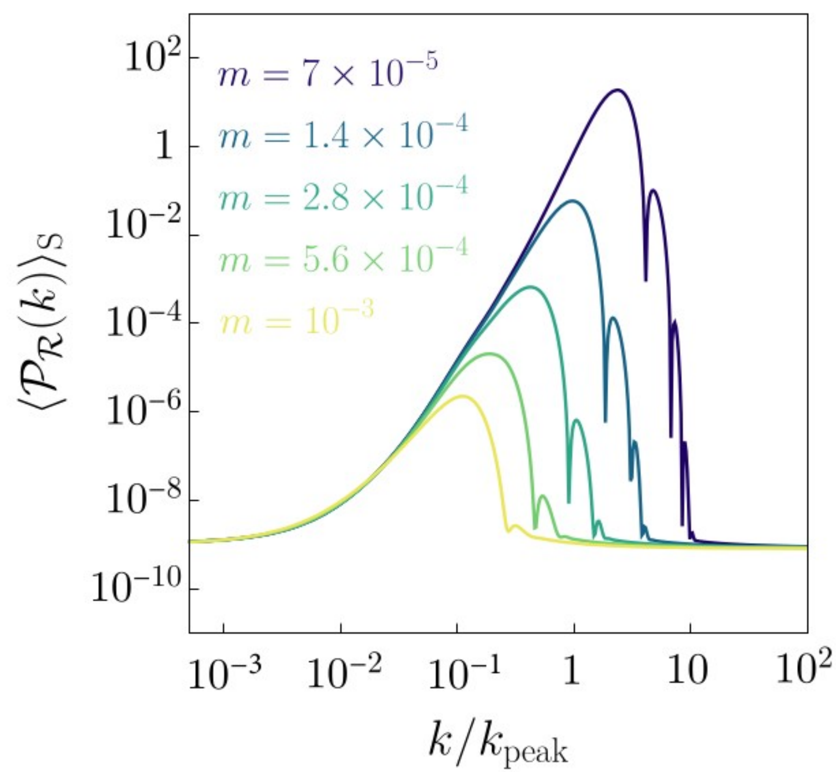




$[M = 10^{-2} m_P, \ \Lambda = 0.1 m_P, \ \lambda = 2.5 \times 10^{-15}]$

Summary

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

$\lambda\phi^4$ compatible with data (WDR)

Other models (hybrid, running inflaton….) compatible with data in the SDR (Y>> H)

- Thermal corrections to inflation potential under control with symmetries:

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

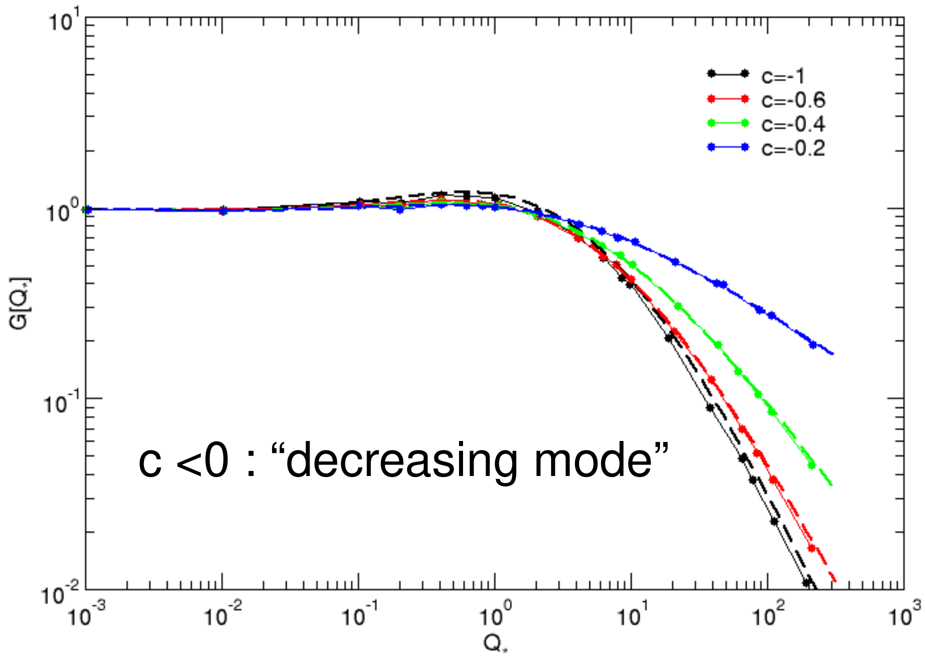
MWI: Inflaton a PNGB of a broken U(1) symmetry + gauge field production

- Warm inflation: amplification of the spectrum → PBHs, 2^{nd} order GW, ….

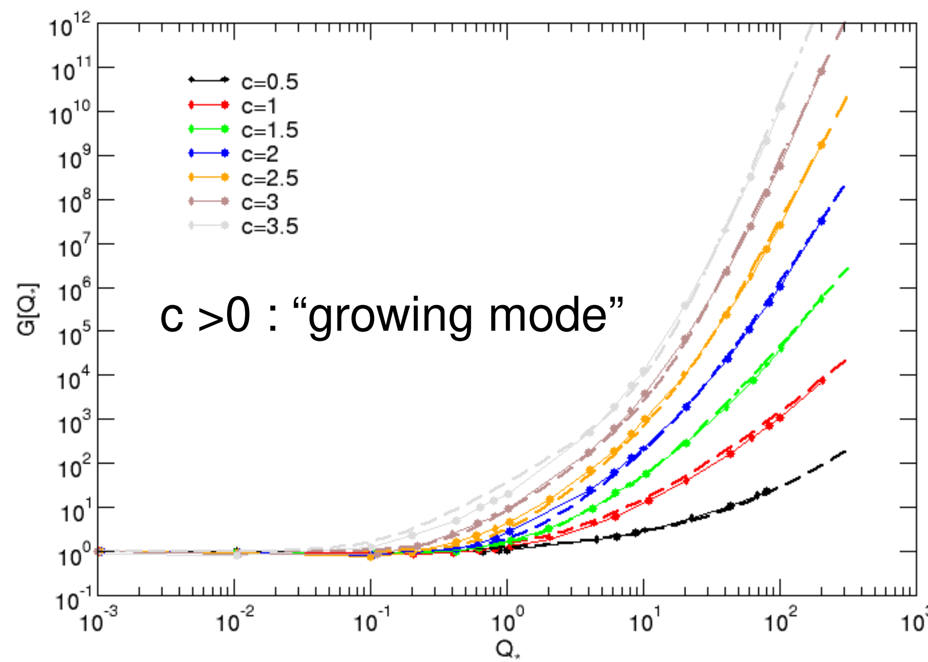
Thank you!

Backup slides

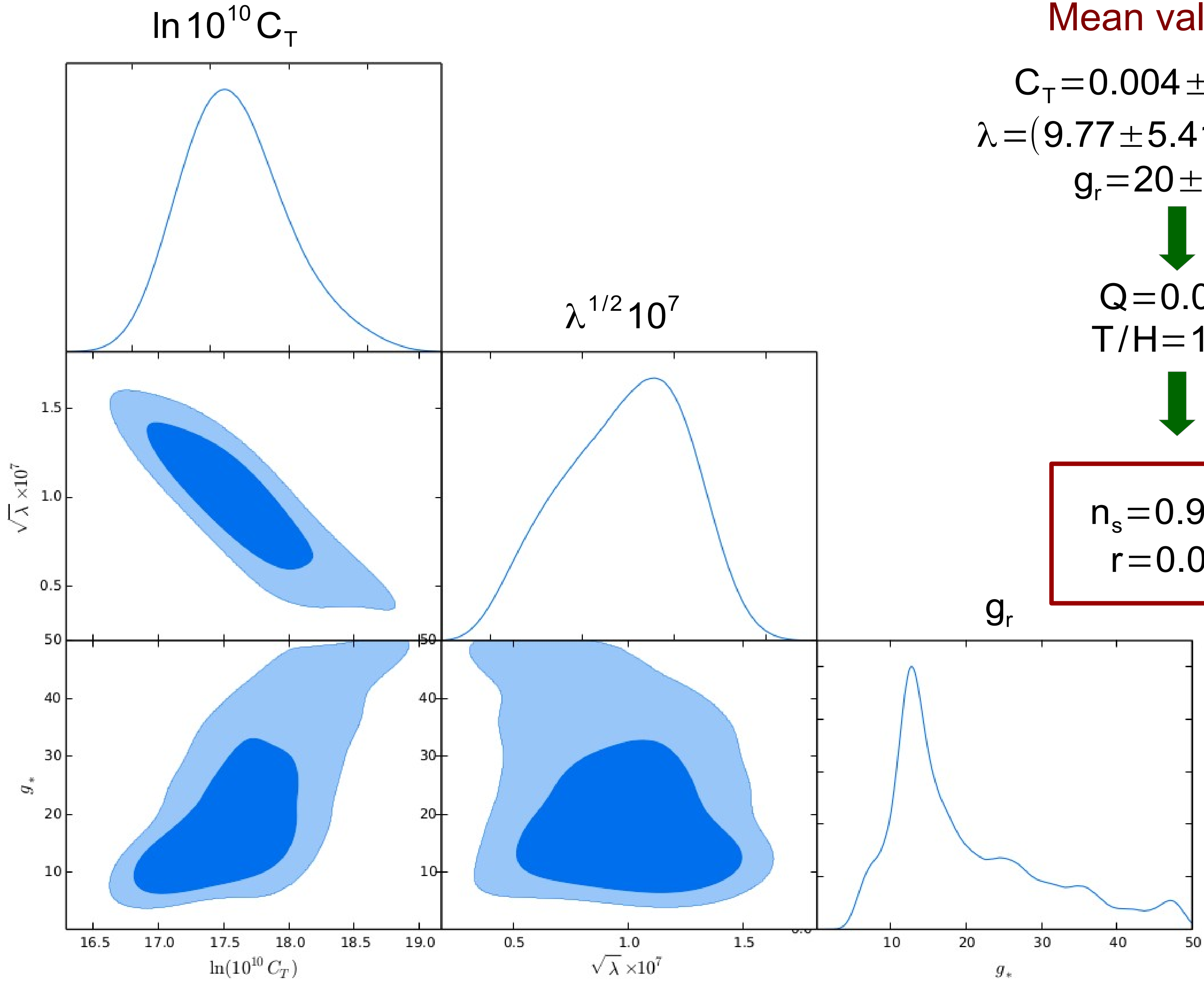
Primordial spectrum: growing/decreasing mode $\Upsilon \propto T^c$



$$G[Q]=\frac{P_R[num.]}{((P_R)_{vac}+(P_R)_{diss})}$$



Little warm inflation & CMB data:
non thermal inflaton



Mean values

$C_T = 0.004 \pm 0.002$

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

$g_r = 20 \pm 10$

↓

$Q = 0.019$

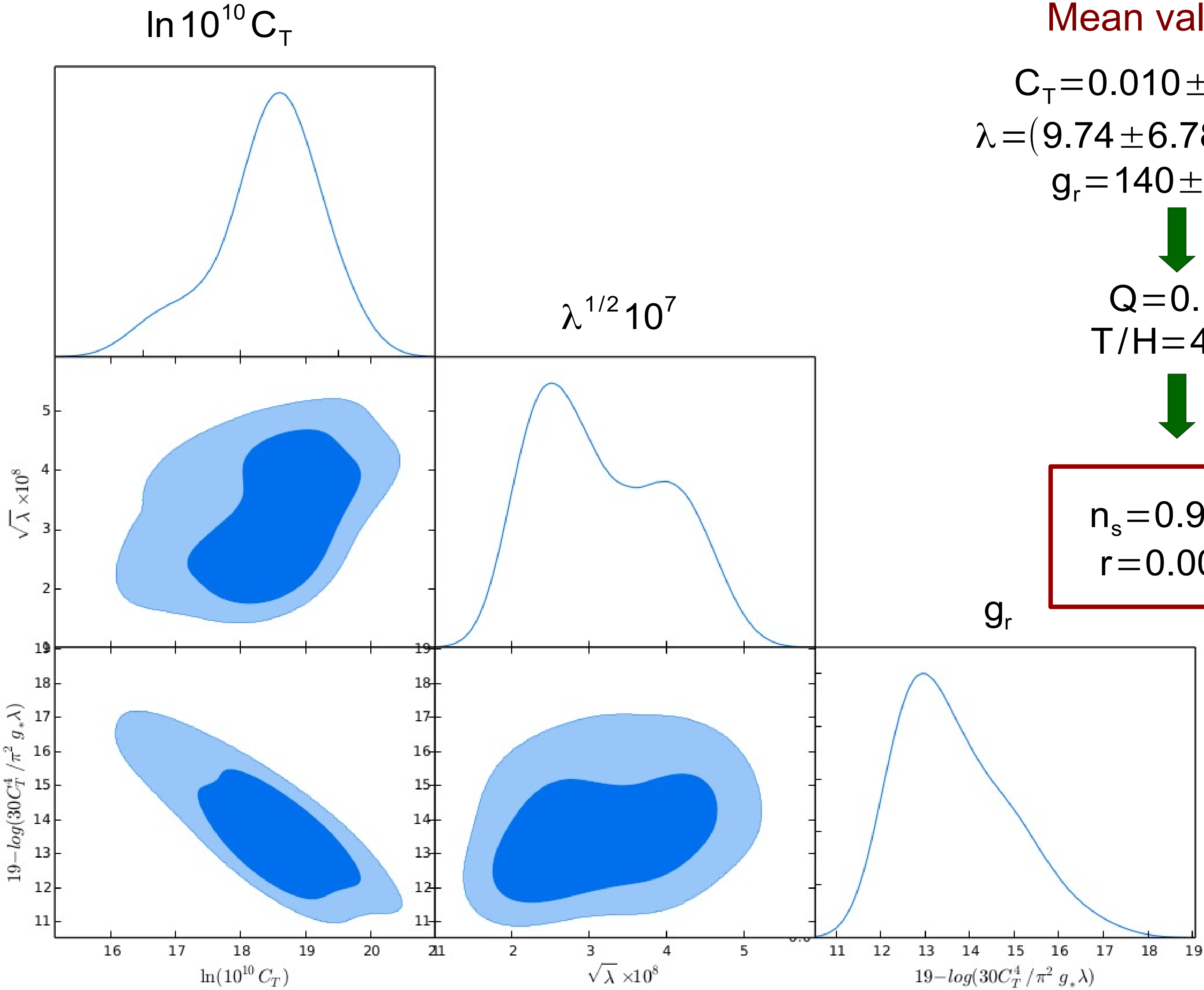
$T/H = 19.3$

↓

$n_s = 0.974$

$r = 0.06$

Little warm inflation & CMB data:
thermal inflaton



Mean values

$C_T = 0.010 \pm 0.008$

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

$g_r = 140 \pm 488$

$Q = 0.14$

$T/H = 40.7$

$n_s = 0.965$

$r = 0.006$

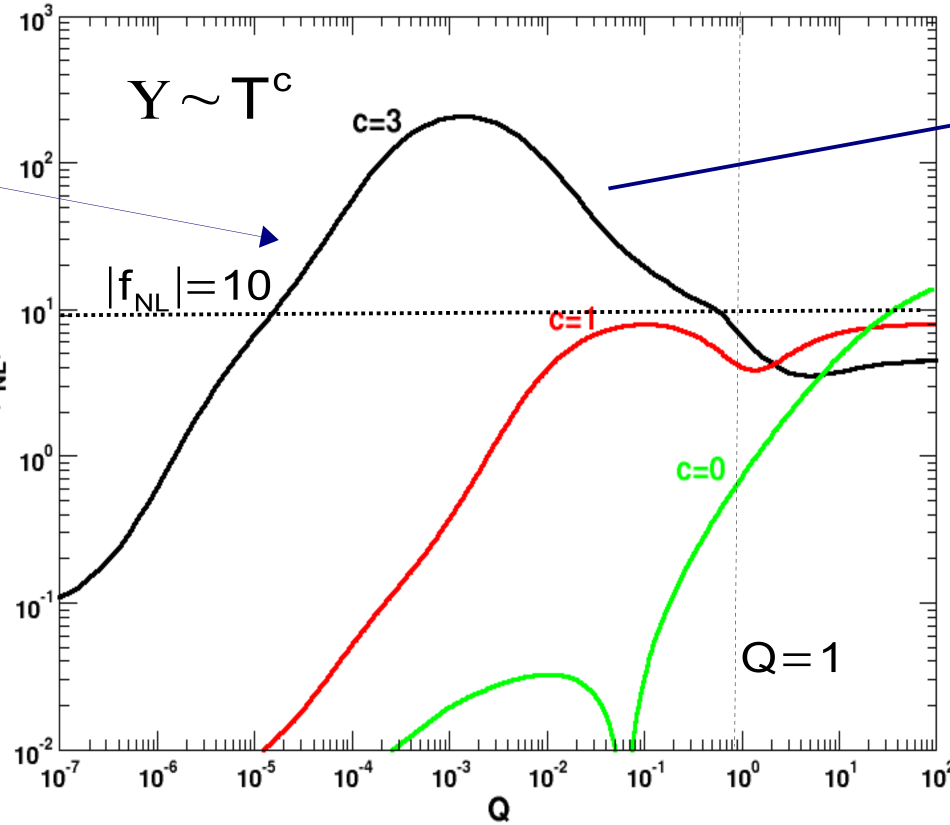
Warm inflation &Non-gaussiantiy : T dependent diss. coefficient

- **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]