Induced GW from Warm Inflation

Cold inflation/Warm inflation

Slow-roll warm inflation

Primordial spectrum: PBH & GW

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[arXiv:2105.08045]

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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

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

Primordial spectrum?

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

Unwanted relics...

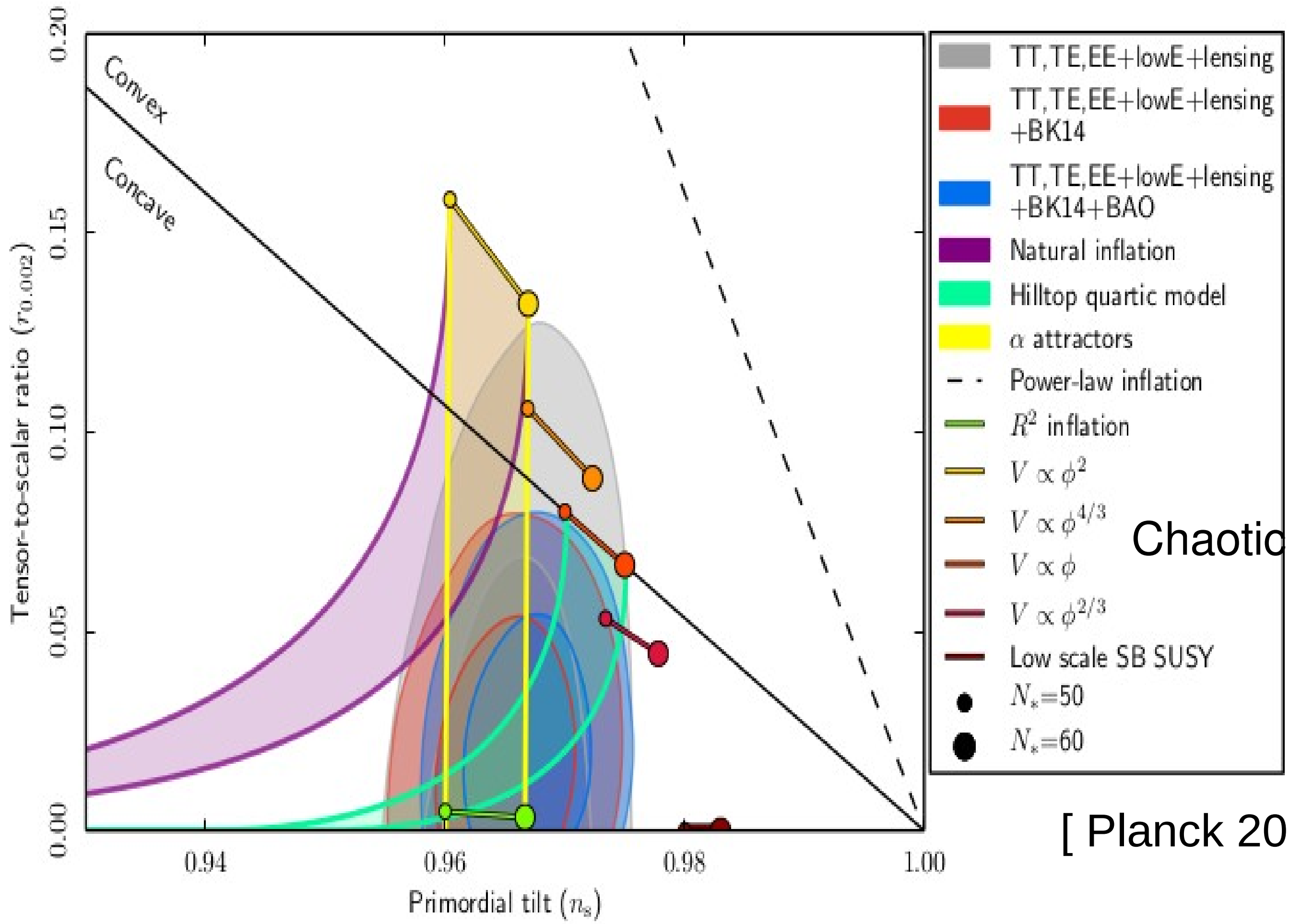
monopoles, moduli, gravitinos,...

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

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

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

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

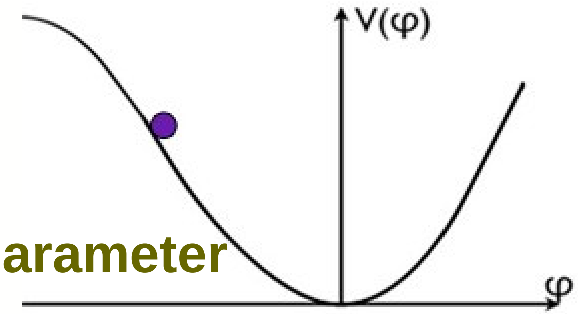


[Planck 2018.: 1807.06211]

CMB constraints ~10 efolds of inflation….

Slow Roll Inflation

Scalar field rolling down its (flat) potential



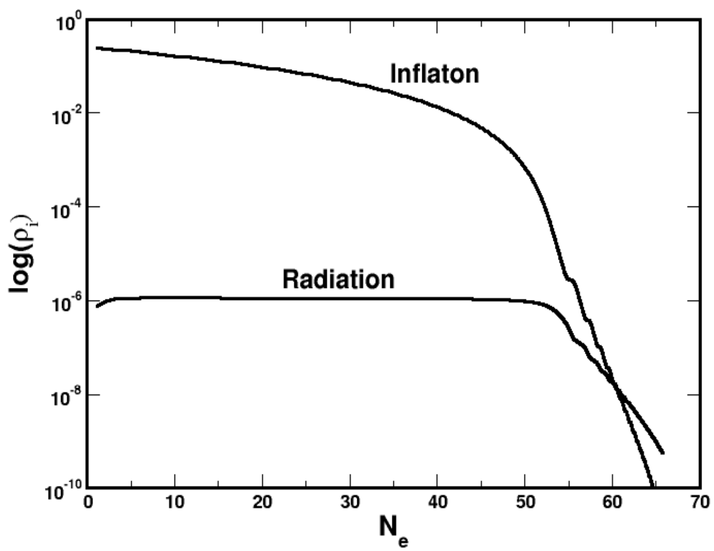
Kinetic energy << potential energy **$H^2 \sim V/3m_P^2$** **Hubble parameter**

Inflation → Reheating → Radiation → Matter

Inflaton interacts with other particles

"Cold" inflation: Interactions negligible during Inflation $\xrightarrow{\text{Reheating}}$ Radiation

"Warm" inflation: Inflaton "decay" into light dof $\xrightarrow[\text{Dissipation}]{}$ Radiation



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

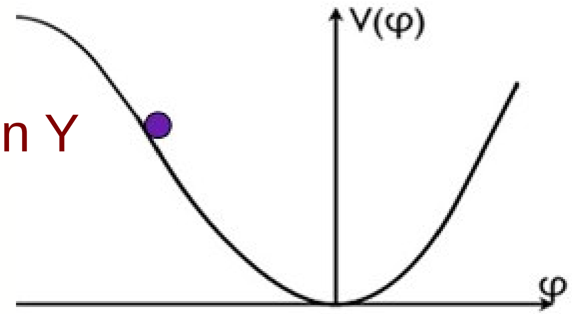
$$\ddot{\varphi} + (3H + \Upsilon)\dot{\varphi} + V_\varphi = 0$$

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

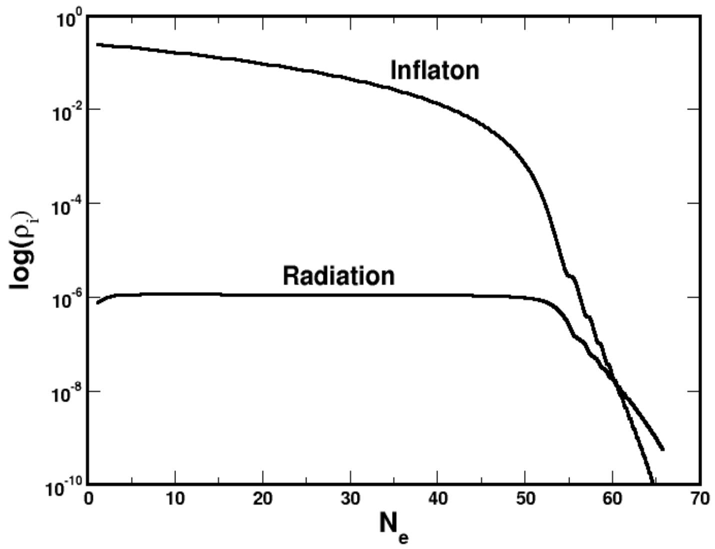
"Decay" into light dof= dissipation= extra friction

[Berera PRD55 '97; Berera, Moss & Ramos Rep. Progr. Physics 72 '07]

Slow Roll Warm Inflation



Scalar field rolling down its (flat) potential+ dissipation Υ



$$Q = \Upsilon / 3H$$

$$\left.\begin{aligned} 3H(1+Q)\dot{\varphi} &\simeq -V_\varphi \\ 4\rho_R &\simeq 3Q\dot{\varphi}^2 \end{aligned}\right\} \qquad \begin{aligned} \epsilon_\varphi &= \frac{m_P^2}{2}\left(\frac{V_\varphi}{V}\right)^2 \ll 1+Q \\ \eta_\varphi &= \frac{V_{\varphi\varphi}}{3H^2} \ll 1+Q \end{aligned}$$

Slow-roll parameters

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 ⬅

η problem : inflaton mass can be larger than H (sugra models)

Swampland conjecture: both slow-roll parameters can be larger than one (inflation & string theory)

[Motharfar, Kamali & Ramos 1810.02816, 1910.06796; Das 1910.02147]

Fluctuations & primordial spectrum: coupled system

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

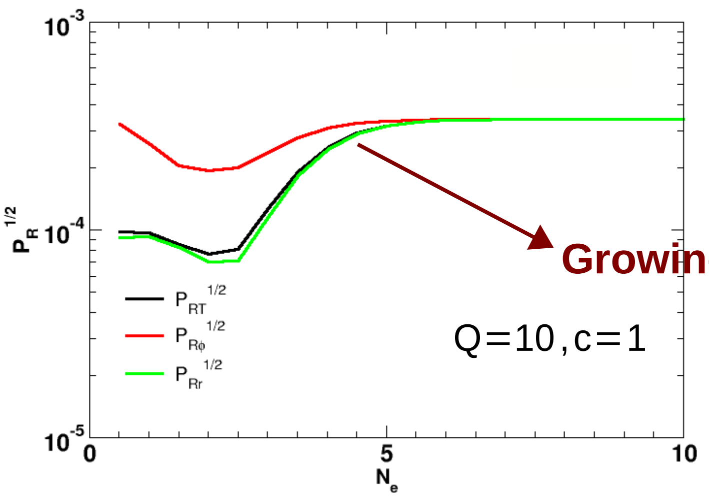
fluctuation force ξ

(light d. of f.)

$\boxed{\Upsilon \sim T^c}$ ➡ $\boxed{\dfrac{\delta\Upsilon^{GI}}{\Upsilon} = c\,\dfrac{\delta T}{T}}$ ➡ Coupled system inflaton-radiation

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

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



Growing mode!

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

When c>0, G[Q] ~ Q $^{\alpha}$ ➡ Blue tilted spectrum **Amplification of the primordial spectrum**

We want to have $\Upsilon \sim 1/T$ at CMB scales to avoid the effect on the spectral index of the "growing mode", but to allow $\Upsilon \sim T^c$ later on to amplify the primordial spectrum

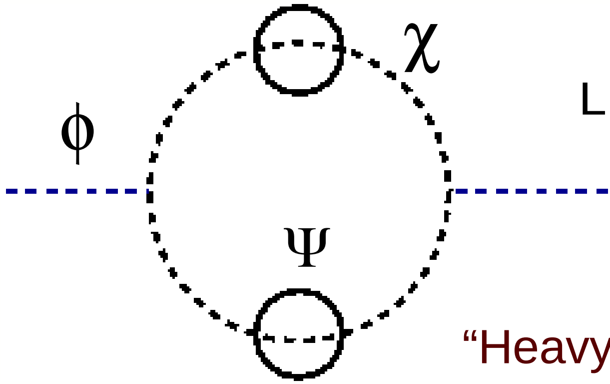
[Green & Liddle PRD56 '97]

PBHs?? [R. Arya 1910.05238]

Second order source of primordial tensors??

[Mollerach, Harari, Matarrese PRD69 '04; Ananda, Clarkson, Wands PRD75 '07]

Interactions & (T-dependent) Dissipative coefficient



light fermions,scalars

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

mediator

[BG, Berera, Ramos & Rosa 2012]

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

Thermal corrections under control (inflaton coupled to heavy fields), but may required large no. of mediator fields

“Light” (m < T) mediator: $\Upsilon\simeq C_\varphi T,\ C_\varphi/T$ [high-T regime]

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

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

Solution: use symmetries to protect the inflaton mass

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

[BG, Berera, Ramos & Rosa 2016]

[BG, Berera, Ramos & Rosa 2019]

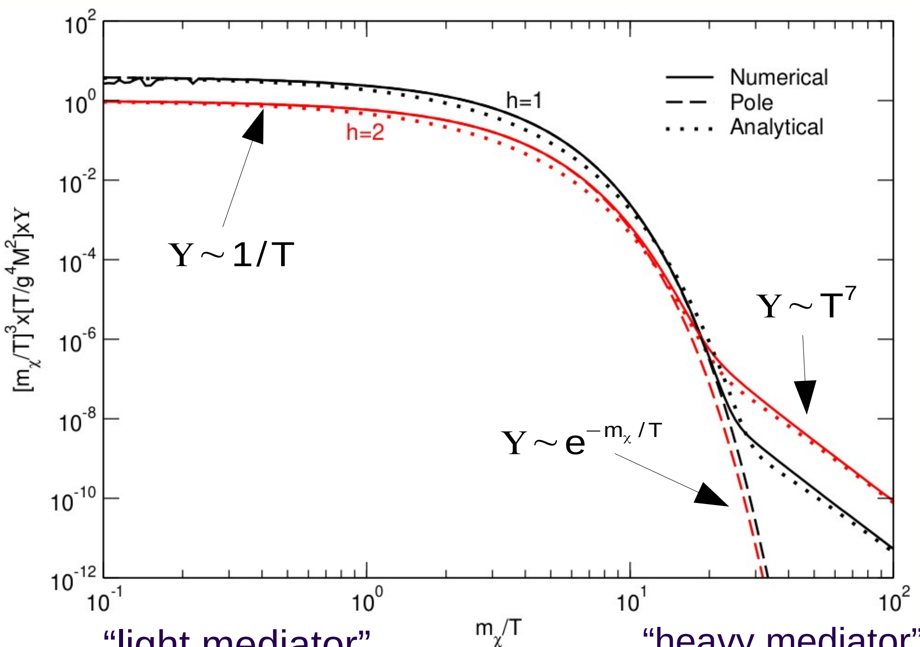
Scalar Little Inflaton Model

$$L = \cdots - g^2 M^2 \cos^2(\varphi/M)\,\chi_1^2 + g^2 M^2 \sin^2(\varphi/M)\,\chi_2^2 + h\sigma \sum_{i=1,2} \chi_i \bar{\psi}_j \psi_k + \cdots$$

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

[M= symmetry breaking scale]

Dissipative coefficient:



"light mediator" m/T<<1

"heavy mediator" m/T>>1

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

During inflation T always decreases:

gM/T << 1 ➡ gM/T >> 1

"High-T" "Low-T"

"No growing mode" "growing mode"

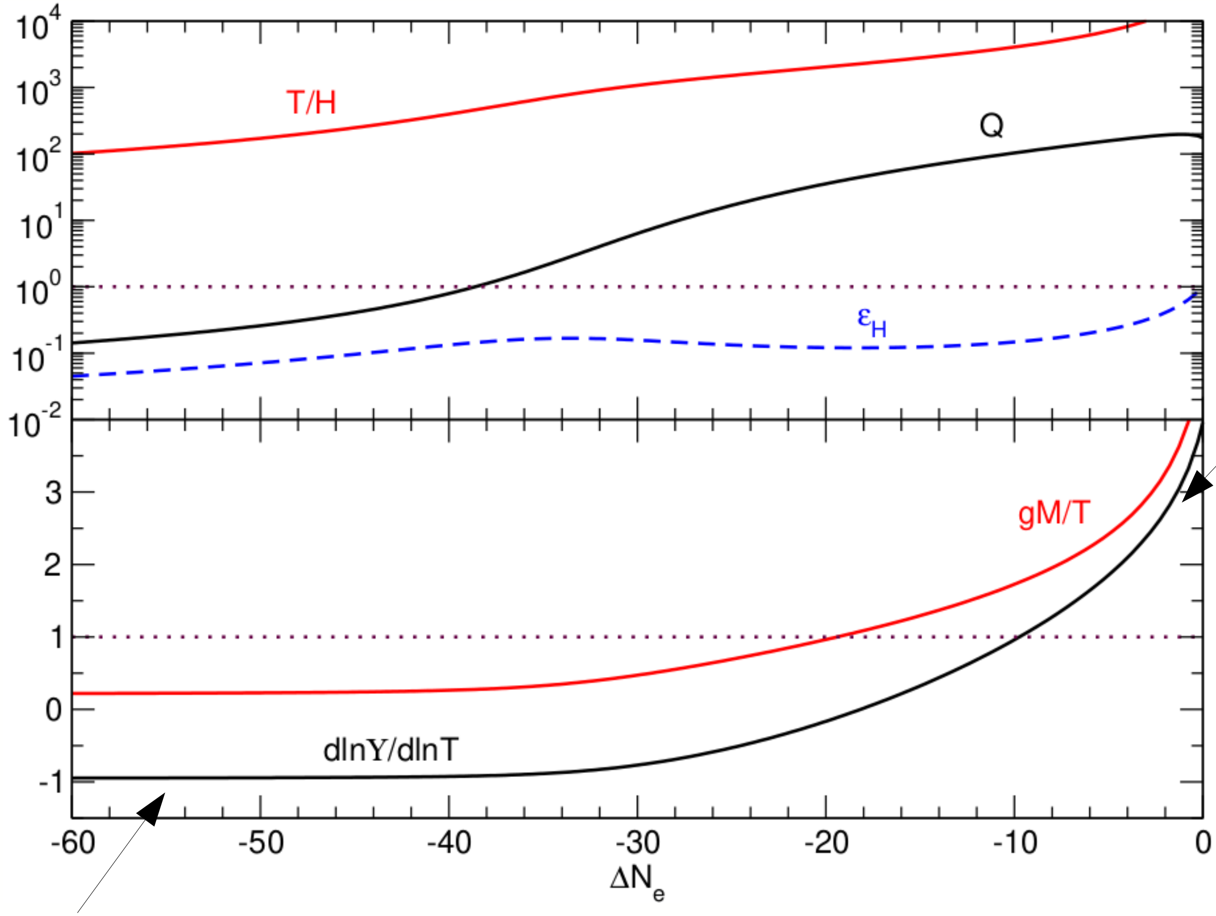
$$\left[m_\chi^2 = \frac{g^2 M^2}{2} + \frac{h^2 T^2}{12} + \frac{h_S^2 T^2}{12}\right]$$

[MBG, Berera, Ramos JCAP1109 '11]

Scalar Little Inflaton Model + quartic chaotic

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

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



End of inflation: amplification of the primordial spectrum

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

CMB scales: no growing mode

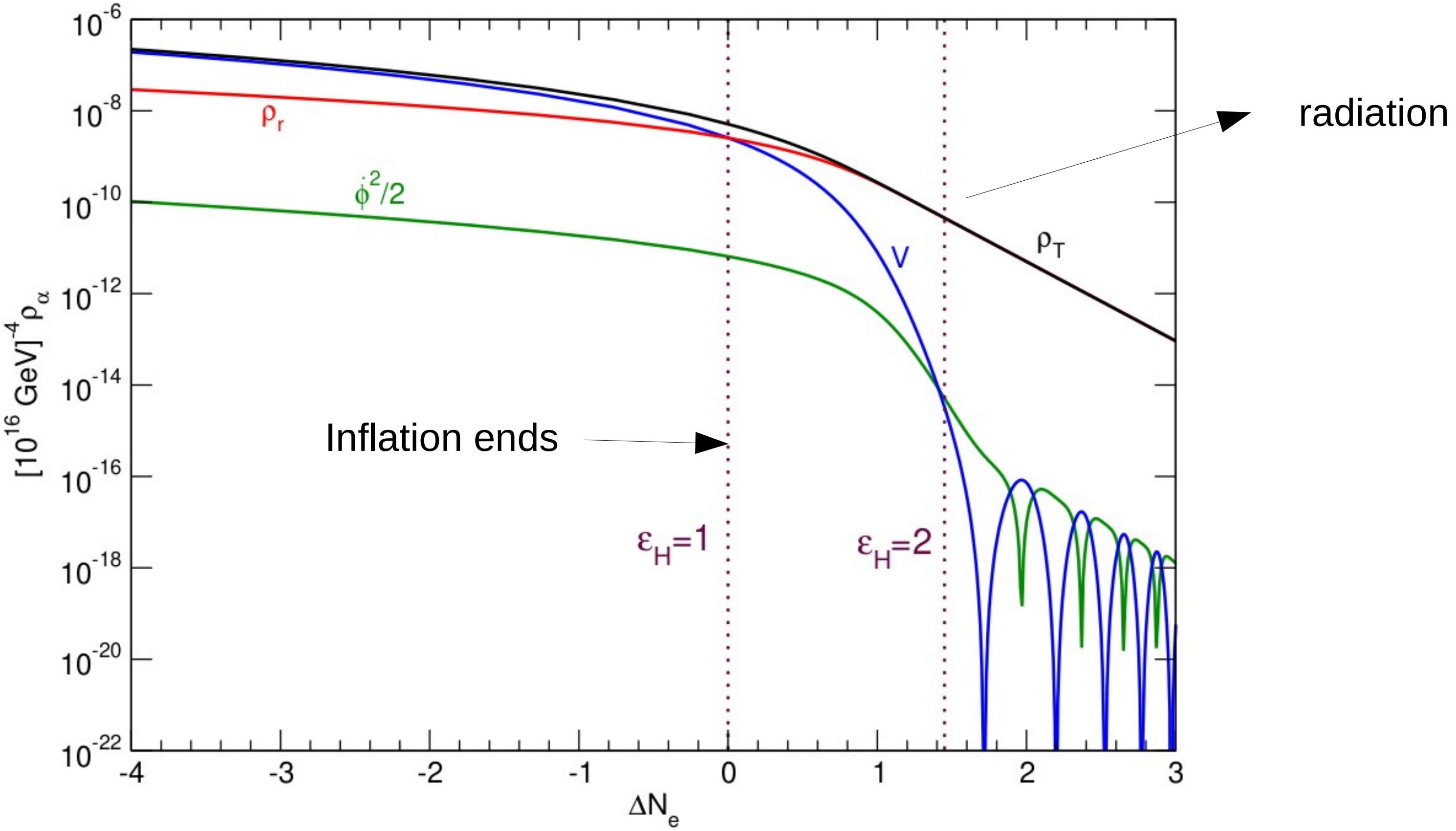
$$\Upsilon \simeq M^2 / T$$

Scalar Little Inflaton Model + quartic chaotic

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

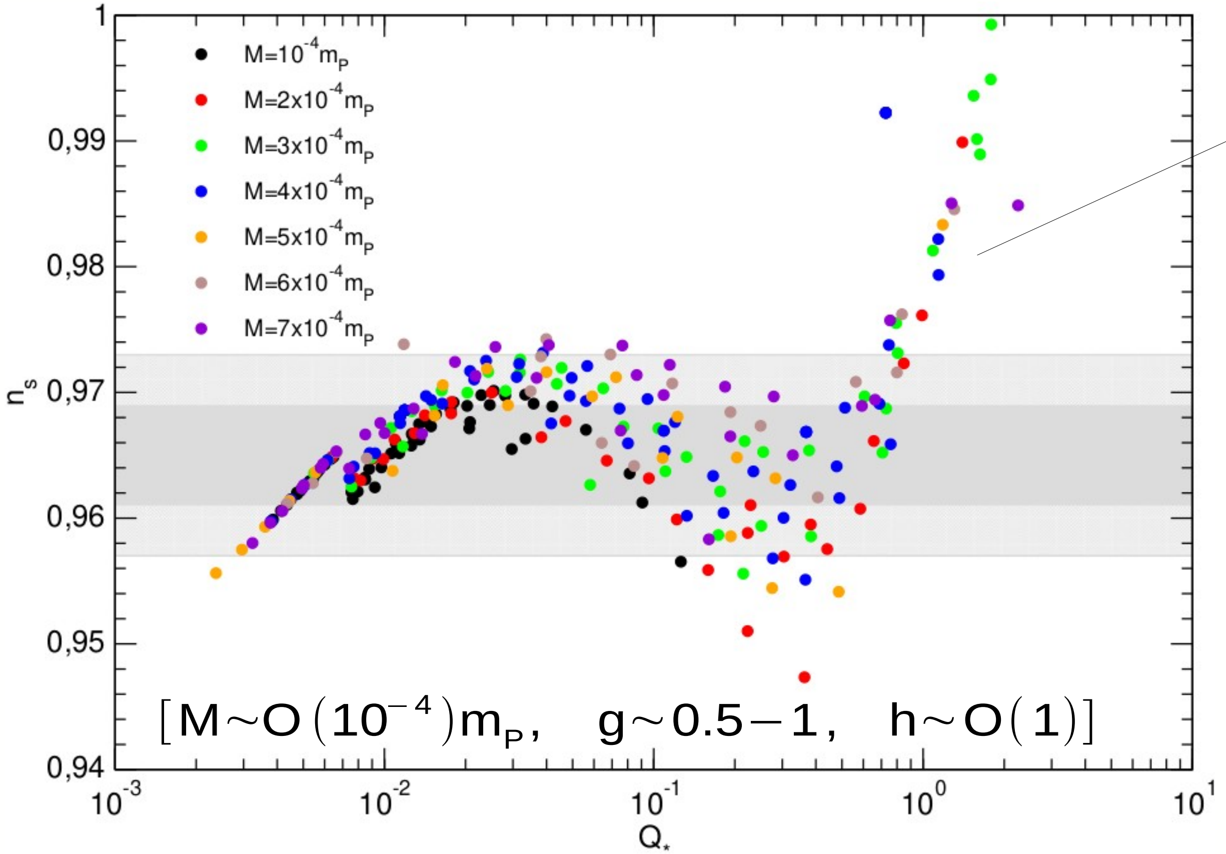
$[M=10^{-4}\,m_P,\quad g=1,\quad h=2.5,\quad \lambda=10^{-14}]$

Energy densities



Smooth transition from inflation to radiation

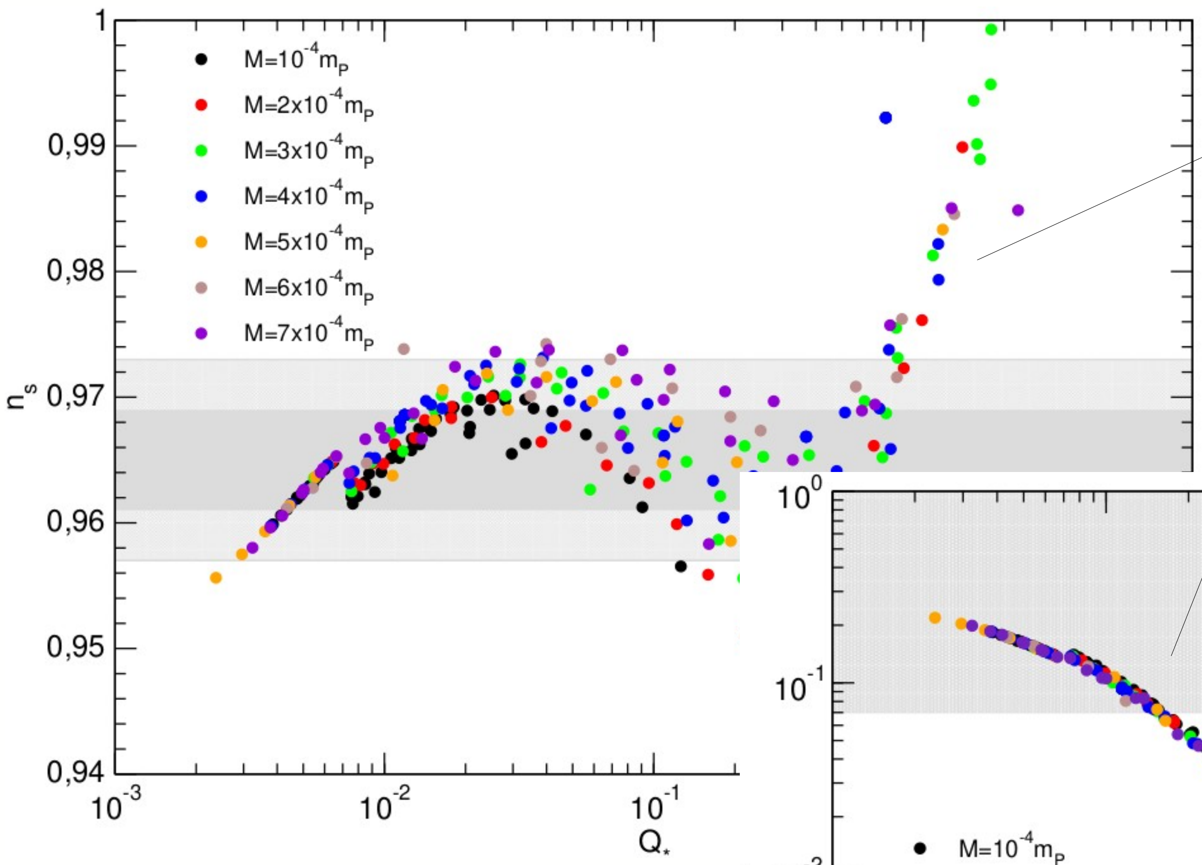
Spectral index & tensor-to-scalar ratio



$Q_* < 1$, CMB scales

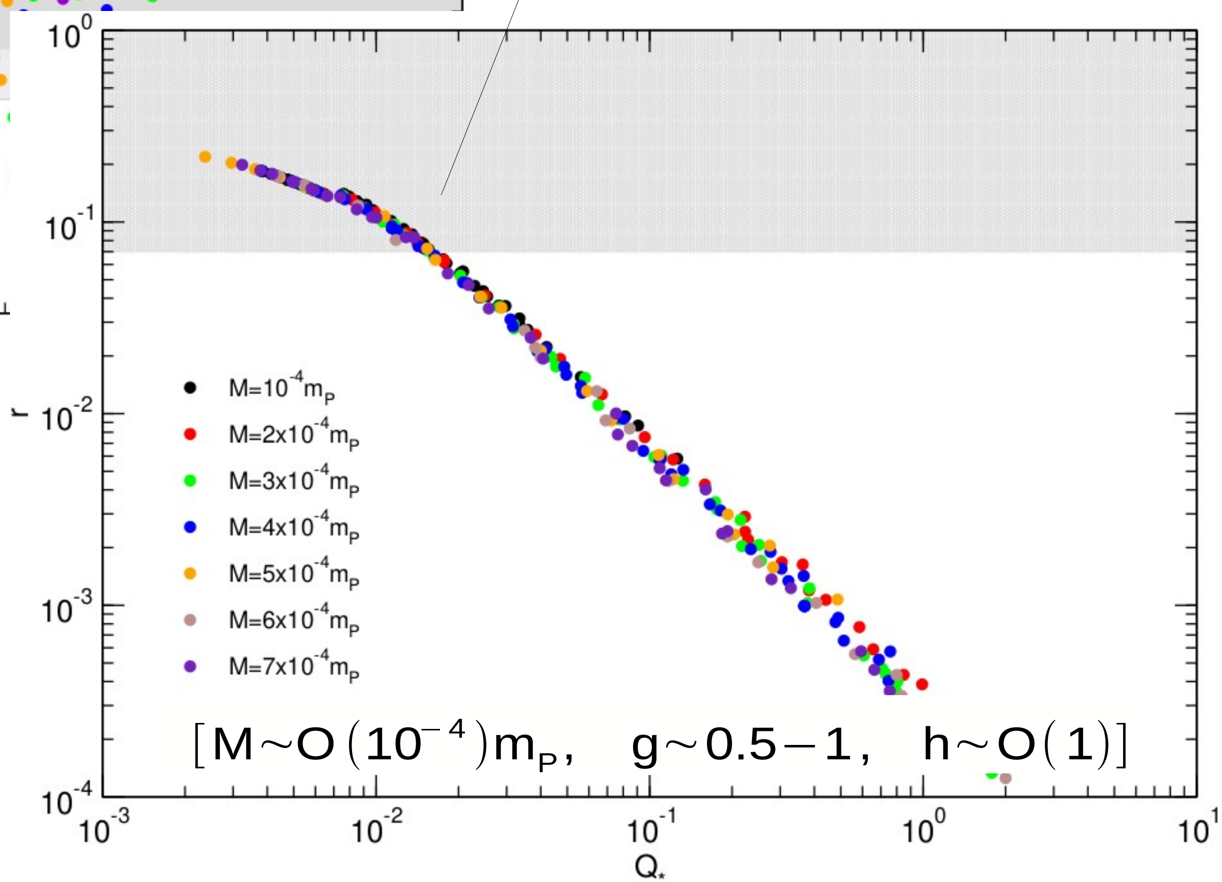
[λ fixed using Planck normalization of the primordial spectrum]

Spectral index & tensor-to-scalar ratio

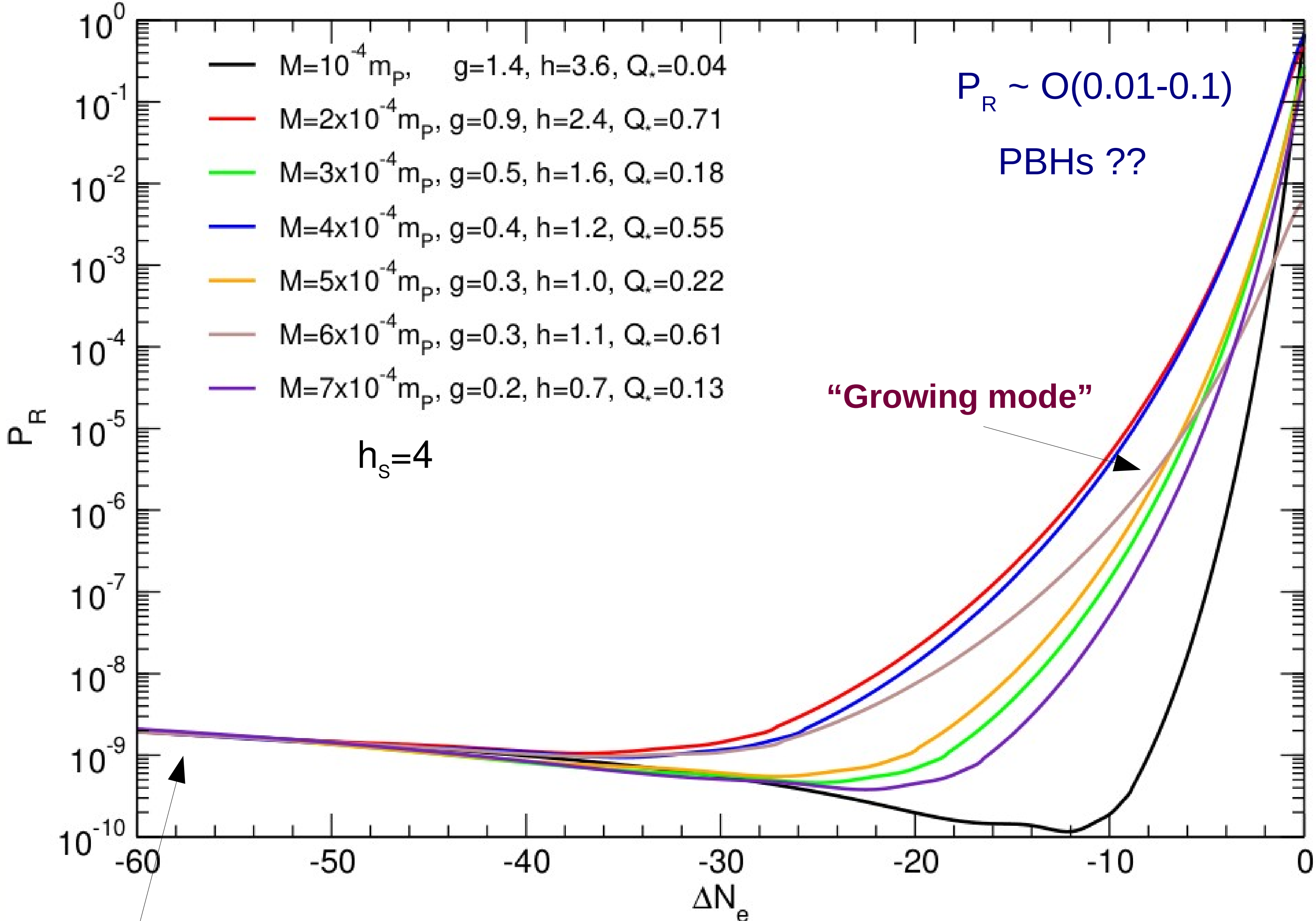


$Q_* < 1$, CMB scales

$Q_* > 0.05$



Primordial scalar spectrum



The spectrum is amplified around the last 10-20 efolds of inflation

CMB scales

Primordial Black Holes

P_R~O(0.01-0.1) will lead to PBH formation on re-entry

$$M_{PBH}(k) \sim \frac{4\pi m_P^2}{H_M}$$

H on re-entry, close to the end of inflation

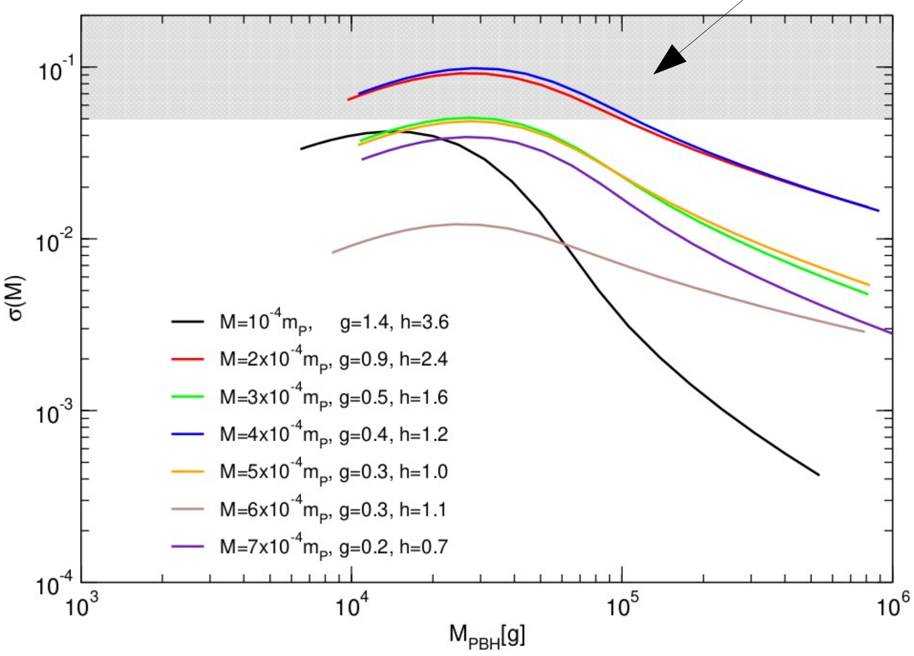
$$M_{PBH} \sim [5\times 10^4\,g, 10^6\,g]$$

Light, evaporating black hole

Planck relics may be produced during their evaporation

To avoid the overclosure of the universe: $\sigma(M) < 0.05$ Variance of the density fluctuations

[Carr et al. PRD81 '10]



$$\boxed{P_R \leqslant 0.1}$$

Induced 2nd order GW

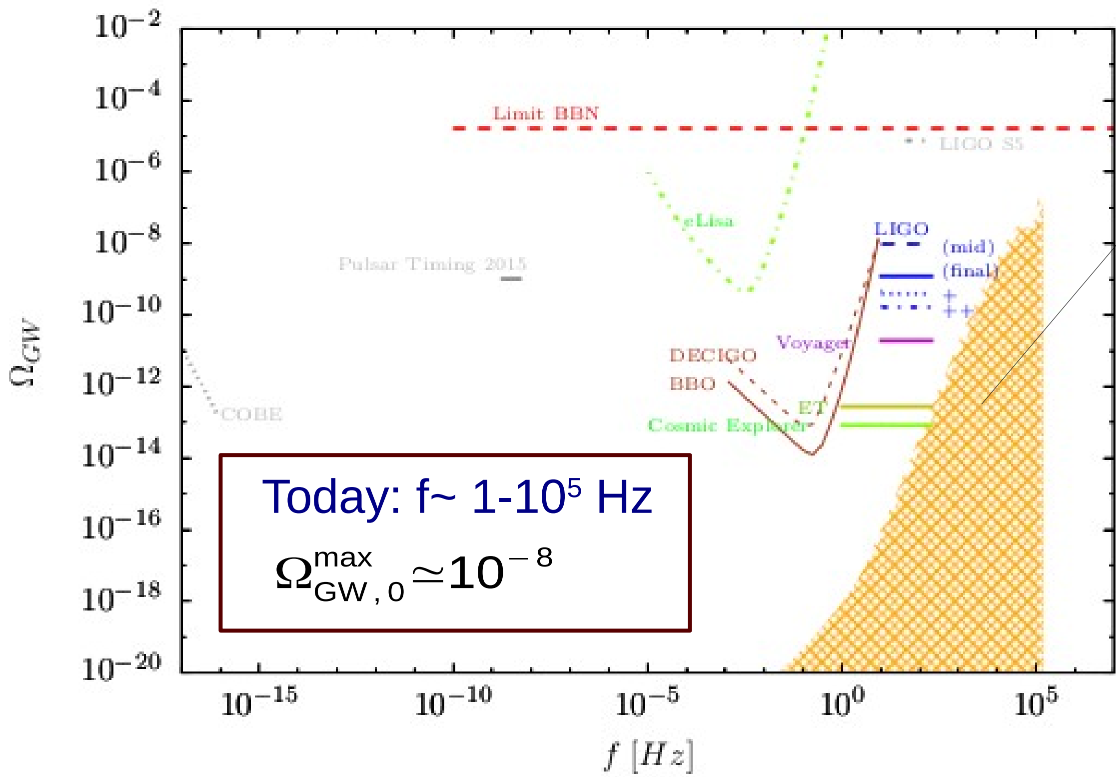
Although at linear order scalar, vector and tensor perturbations decouple,
large scalar fluctuations source tensors at second order

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

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~ 1-10^5 Hz

$\Omega^{max}_{GW,0} \simeq 10^{-8}$

Consistent with all constraints (CMB, PBHs)

Summary

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

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

- "High T" regime at CMB scales, compatible with observations: $\Upsilon = C_T/T$

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

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

$$\boxed{\lambda\phi^4 \text{ compatible with data, } Q_* \sim 0.01\text{-}1,\ r \sim 0.1\text{-}10^{-4}}$$

- "Low T" regime before the end of inflation: $\Upsilon = C_T\, T^c$ ➡ amplification of the primordial spectrum $P_R \sim O(0.01\text{-}0.1)$ (last 10-20 efolds)

- On re-rentry:
  - Light, evaporating PBHs: $M_{PBH} \sim O(10^4\text{-}10^6)$ g
  - Primordial GW: f~ $O(1\text{-}10^5)$ Hz, $\Omega^{max}_{GW,0} \simeq 10^{-8}$