Dissipation & Viscosities during inflation: warm inflation after Planck

Cold inflation/Warm inflation

Dissipative coefficient: $\Upsilon(T,\phi)$

Dissipation + viscosities: Primordial spectrum

Primordial spectrum & Planck (& BICEP): chaotic models

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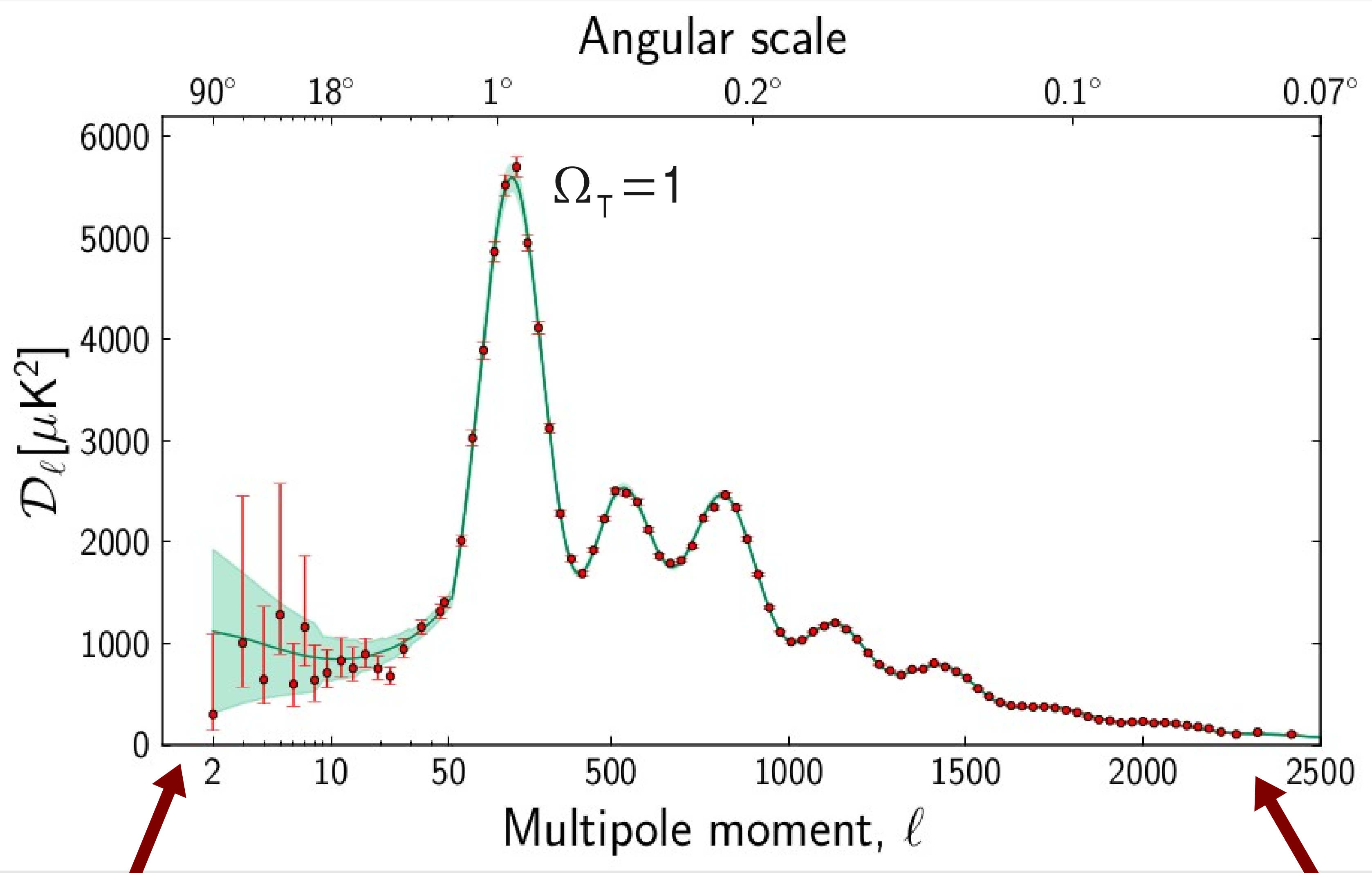
Cosmic Microwave Background Radiation



Largest observable scale O(3000 Mpc)

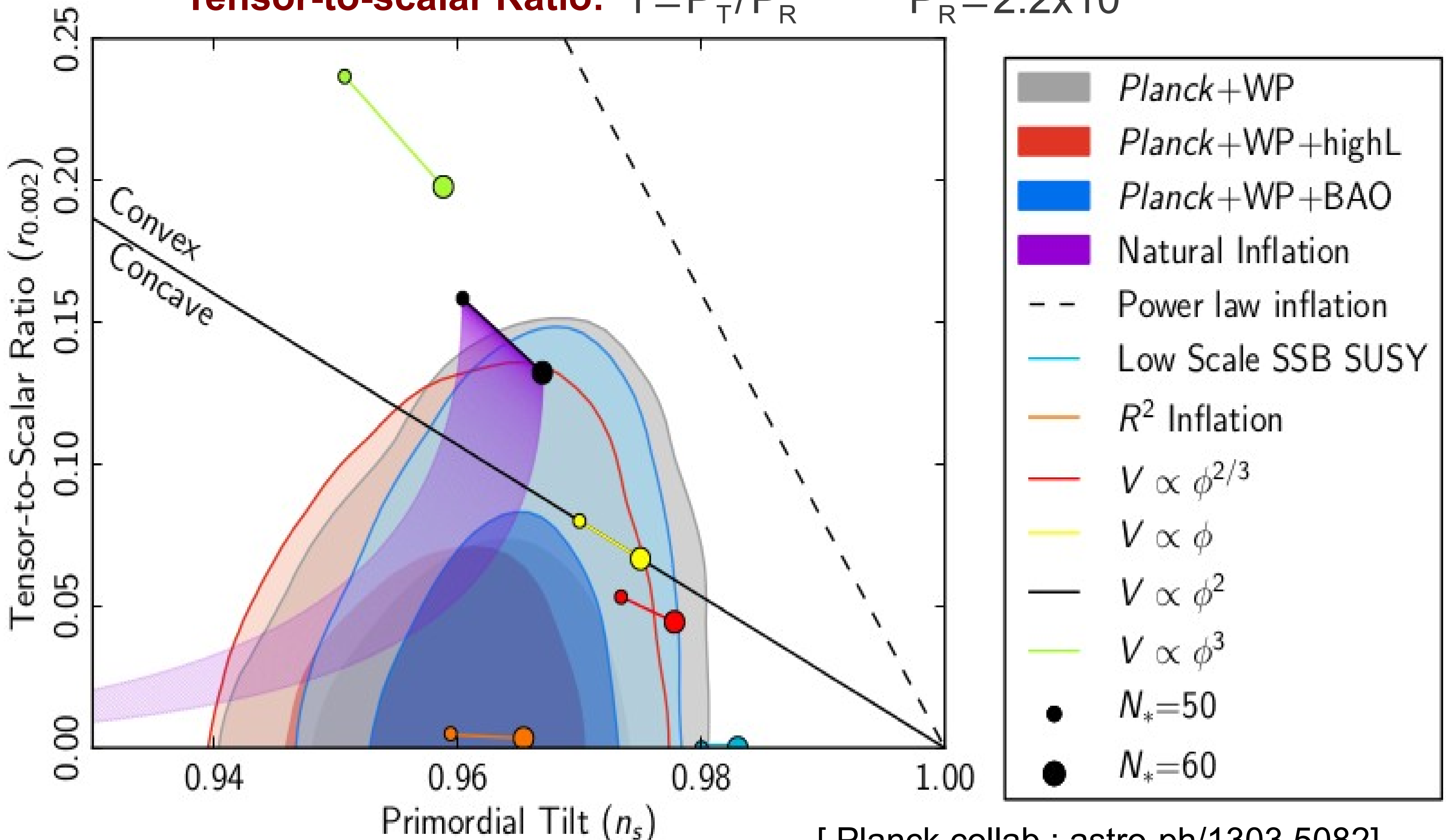
Galaxy scale O(Mpc)

[Planck collab.: astro-ph/1303.5075]

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: $r = P_T/P_R$ $\quad P_R = 2.2\mathrm{x}10^{-9}$



[Planck collab.: astro-ph/1303.5082]

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

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

Super-horizon perturbations?

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

Unwanted relics

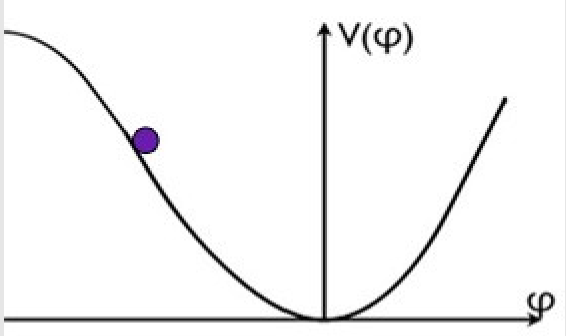
monopoles, moduli, gravitinos,...

Starobinsky PLB91'80; Guth PRD23 '81; Sato MNRAS195 '81; Albrecht & Steinhardt PRL48 '82; Linde PLB108 '82

Slow Roll Inflation

Scalar field rolling down its (flat) potential

$$P = \dot{\phi}^2/2 - V(\phi) \approx -V(\phi)$$ 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

$$|\eta_\phi| = m_P^2 \left| \frac{V''}{V} \right| < 1$$

curvature

$$\epsilon_\phi = \frac{m_P^2}{2} \left(\frac{V'}{V} \right)^2 < 1$$

slope

<u>Inflaton interacts with other particles</u>

"Cold" inflation

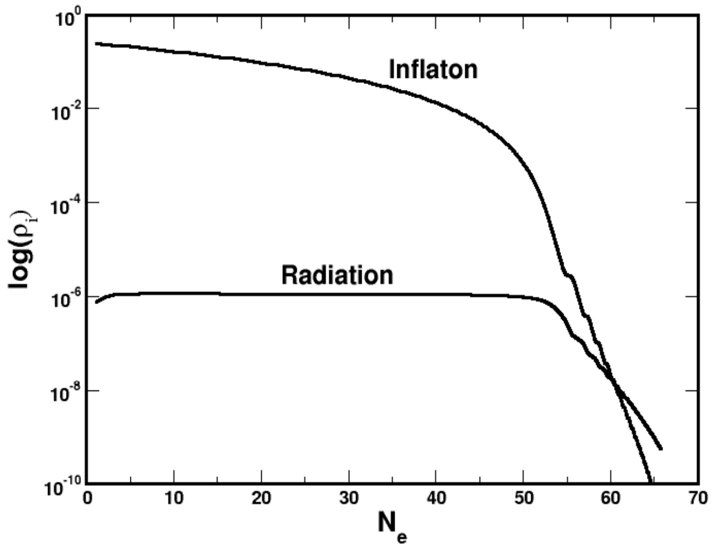
Interactions negligible during Inflation → (Reheating) → Radiation

"Warm" inflation

Inflaton decay into light d. of f. → "Dissipation" → "Radiation"

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

$$\rho = \rho(\phi) + \rho_R , \quad \rho_R \ll \rho(\varphi)$$



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

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

"Decay" into light dof= extra friction

Moss PLB154,'85; Yokoyama & Maeda PLB207 '88; Berera PRL75 '95

Extra friction term: $Q = \Upsilon/(3H)$

- $Q \ll 1$, $T \ll H$ → Standard **C**old **I**nflation
- $Q < 1$, $T > H$ → **Weak Dissipative Regime**

Standard slow-roll

- $Q > 1$, $T > H$ → **Strong Dissipative Regime**

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

$|\eta_{\phi}| < (1+Q)$, $\epsilon_{\phi} < (1+Q)$, $\beta_{\Upsilon} < (1+Q)$, $\delta_T < 1$ (Thermal corrections)

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

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Smaller ϕ values during inflation:

$\phi < m_P$ (chaotic inflation) → non-renorm. interactions under control

smaller inflationary scale → lower tensor-to-scalar ratio

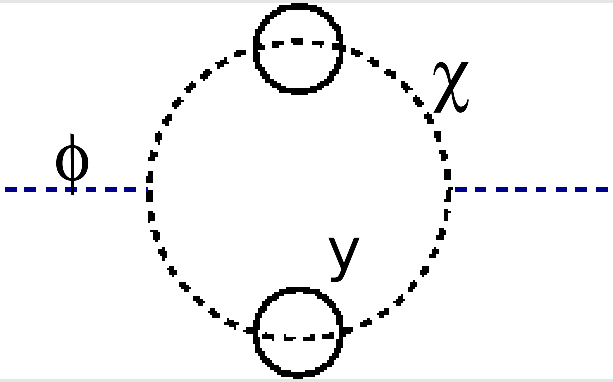
Dissipative coefficient

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

light fermions

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

Inflaton moves down the potential, it excites χ (massive field), which decays into light dof (thermal bath)



$$\ddot{\phi} + \int d^4 x_1 \Sigma_\phi (x - x_1) \delta\phi(t_1) + V_\phi = 0$$

self-energy

Slowly varying:

$$\delta\phi(t_1) = (t_1 - t)\dot{\phi}(t) + \ldots$$

$$\ddot{\phi} + \Upsilon \dot{\phi} + V_\phi = 0$$

$$\Upsilon = -\int d^4 x \, \Sigma_\phi(x) t$$

Dissipative coefficient

Berera and Ramos PRD ‘01, ‘03, ‘05;
Hall and Moss PRD ’05

- Dissipative channel: generic in inflationary models

ex: Chaotic sneutrino inflation

Murayama et al. PRL'93
Ellis, Raidal, Yanagida PLB'04

$$W = \frac{M_R}{2} N_R N_R + h_N H_u L N_R + h_t H_u Q_3 U_3 + \ldots$$

sneutrino → Higgs → (s)top

(light: $M_R < H$) (heavy: $M_{Hu} >> H$) (massless)

- Adiabatic approximation:

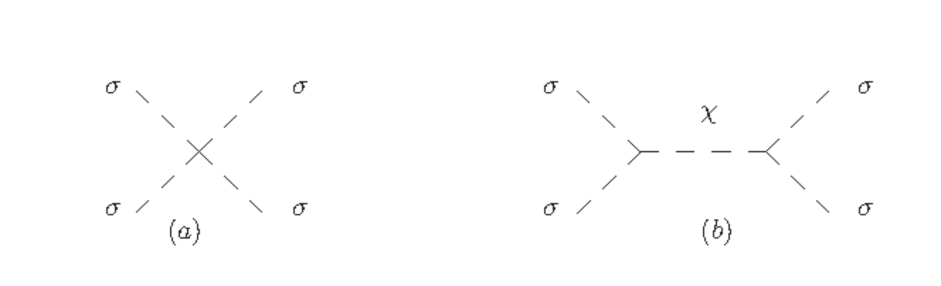
$$\dot{\phi}/\phi < \Gamma_\chi \simeq h^2 m_\chi/(8\pi)$$ Microscopic

Macroscopic $$H < \Gamma_\chi$$

(low T regime: $T > H$, $m_\chi > T$)

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

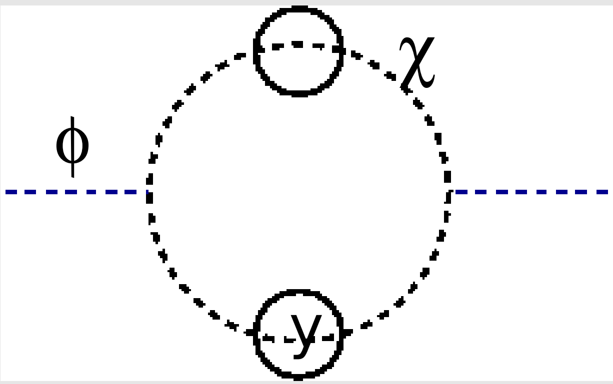
- Thermalization: $n\sigma_i|v| > H$



Moss & Graham 2008

Dissipative coefficient

$$\Upsilon = \frac{4}{T}\left(\frac{g^2}{2}\right)^2 \phi^2 \int \frac{d^4p}{(2\pi)^4}\rho_\chi^2 n_B(1+n_B)$$



Spectral function $\rho_\chi(p,p_0) = \frac{4\omega_p\Gamma_\chi}{(p_0^2-\omega_p^2)^2+4\omega_p^2\Gamma_\chi^2}$

Decay rate $\Gamma_\chi = \frac{h^2 N_Y}{64\pi}\frac{m_\chi^2}{\omega_p}F_T(p,p_0)$

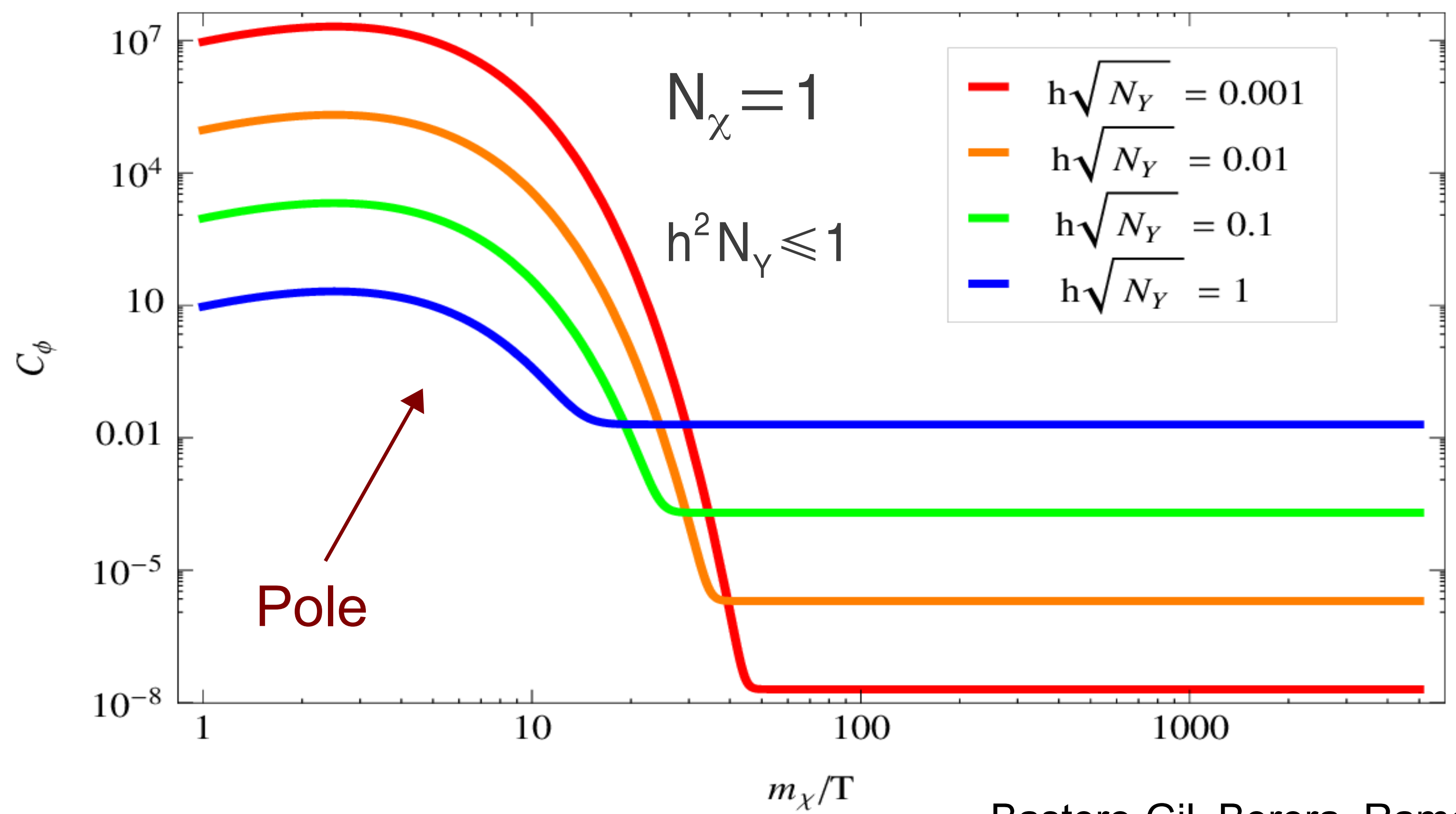
Low T (mχ/T > 1) $\frac{\Upsilon}{g^2 T} \simeq \frac{4}{h^2 N_Y}\left(\frac{m_\chi}{T}\right)^{1/2} e^{-m_\chi/T} + A h^2 N_Y \left(\frac{T}{m_\chi}\right)^2$

Pole: $p_0 \simeq \omega_p$ Low momentum: $p, p_0 \ll m_\chi$

Moss & Xiong 2006; BG, Berera & Ramos 2010; BG, Berera, Ramos & Rosa 2012

Dissipative (T-dependent) coefficient

$$\Upsilon \simeq \frac{4g^2}{h^2 N_Y}(m_\chi T)^{1/2} e^{-m_\chi/T} + A h^2 N_Y \left(\frac{T^3}{\phi^2}\right) \simeq C_\phi \frac{T^3}{\phi^2}$$

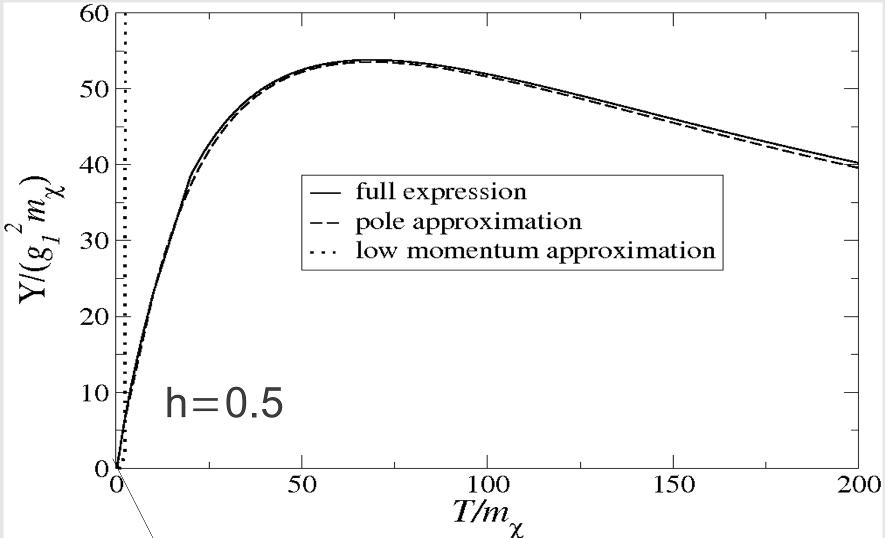


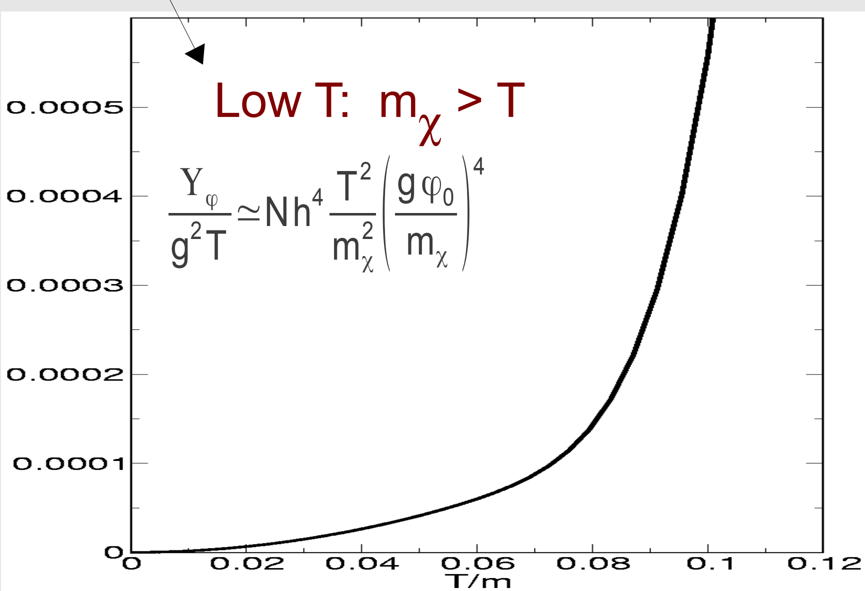
Bastero-Gil, Berera, Ramos & Rosa 2012

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

A too low value of h in conflict with $\frac{\Gamma_\chi}{H} \simeq \frac{h^2 N_Y}{64\pi}\left(\frac{m_\chi}{T}\right)\left(\frac{T}{H}\right) > 1$

Dissipative (T-dependent) coefficient
(Adiabatic, close-to-equilibrium approx.)





<u>T/H > 1</u>

$\Upsilon \propto T^3/\phi^2$ Low T, $m\chi/T > 10$

$\Upsilon \propto T$ High T, $m\chi/T \sim 1$

$\Upsilon \propto T^{-1}$ Very high T, $m\chi/T << 1$

Large thermal corrections, a few e-folds....

(Berera, Gleiser, Ramos '98; Yokoyama & Linde '98)

General: c=-1,0,1,3 $\Upsilon \propto \left(\frac{T}{\phi} \right)^c \phi$

Fluctuations & primordial spectrum

Thermal fluctuations become the source for the adiabatic perturbations

(inflaton) System ⟷ Environment (light d. of f.)

transfer of energy

Dissipation Υ fluctuation force ξ

$$\delta\ddot{\phi}_k + (3H+\Upsilon)\delta\dot{\phi}_k + \dot{\phi}\,\delta\Upsilon + \left(\frac{k^2}{a^2} + V_{\phi\phi}\right)\delta\phi_k = \xi_k$$

Fluctuation-Dissipation rel.:

$$\langle \xi(k)\xi(k')\rangle = 2\Upsilon T a^{-3}(2\pi)^3\delta^{(3)}(k-k')\delta(t-t')$$

Berera & Fang PRL74 (1995); Taylor& Berera PRD62 (2000);
Oliveira & Joras, PRD64 (2001); Hall, Moss &Berera PRD69 (2004)

Fluctuations & primordial spectrum: coupled system

Field EOM:

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

$$\boxed{\frac{\delta\Upsilon^{GI}}{\Upsilon} = \frac{c}{4}\frac{\delta\rho_r^{GI}}{\rho_r} + (1-c)\frac{\delta\phi^{GI}}{\phi}}$$

→ Coupled system inflaton-radiation

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

$$\delta\dot{\rho}_r^{GI} + 4H\delta\rho_r^{GI} \simeq \frac{k^2}{a^2}\Psi_r^{GI} + \underline{\dot{\phi}^2\delta\Upsilon^{GI}} + 2\dot{\varphi}\Upsilon\delta\dot{\phi}^{GI} - \underbrace{\dot{\phi}D^{1/2}\hat{\xi}_k}$$

Energy density

? $\nabla_\mu[T^{\mu\nu}_\phi + T^{\mu\nu}_{rad} + \ldots] = 0$

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

Momentum density

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

BG, Berera, Moss & Ramos, 1401.1149

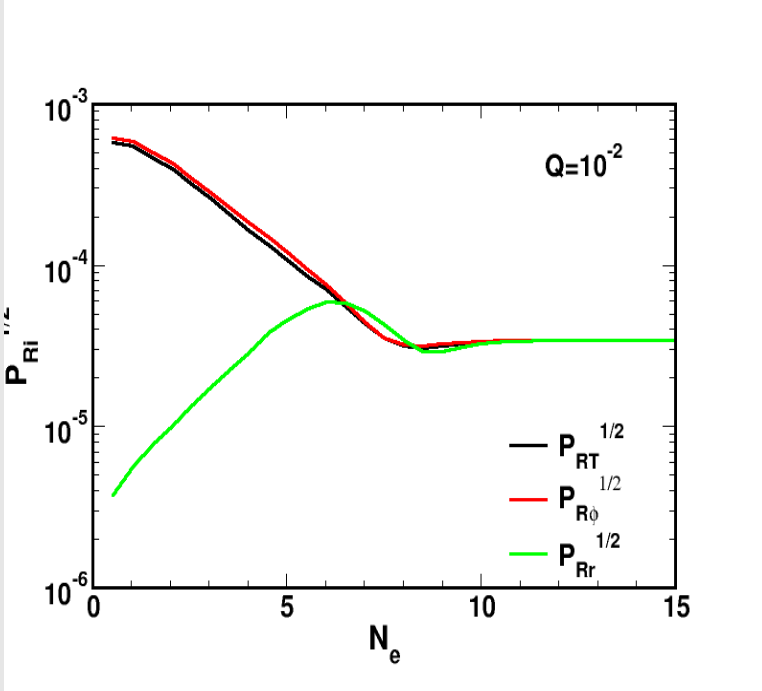
Fluctuations & primordial spectrum: coupled system

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

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

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

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



R is constant after horizon crossing (freeze-out)

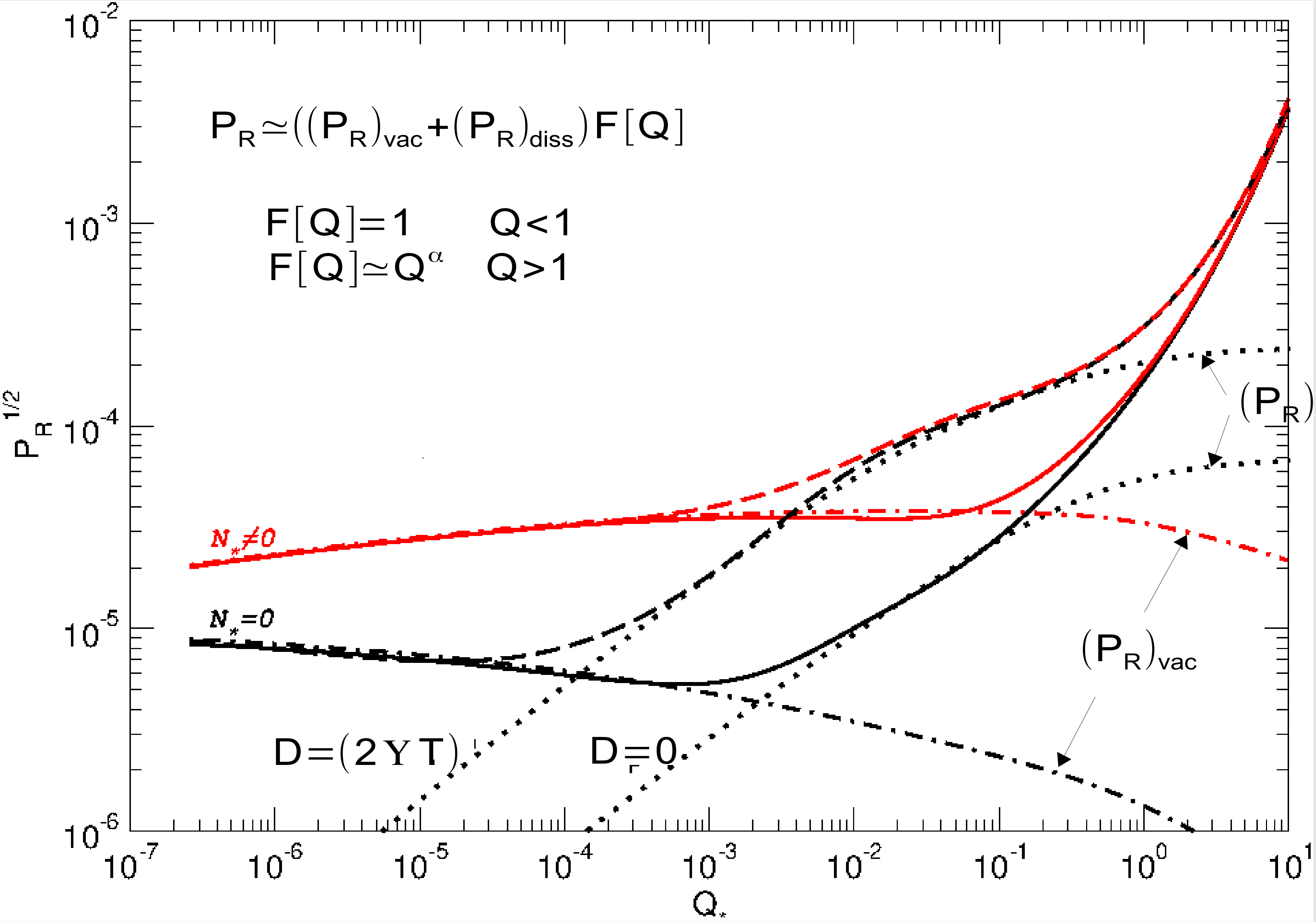
$$P_R\simeq(P_R)_{Q=0}\left(\underbrace{1+2N}+\frac{T}{H}\frac{2\pi Q}{\sqrt{1+4\pi Q/3}}\right)$$

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

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

ϕ particles also produced in χ decays: $\Gamma(\chi\to\phi y y)=g^2/(4\pi)\Gamma(\chi\to y y)$

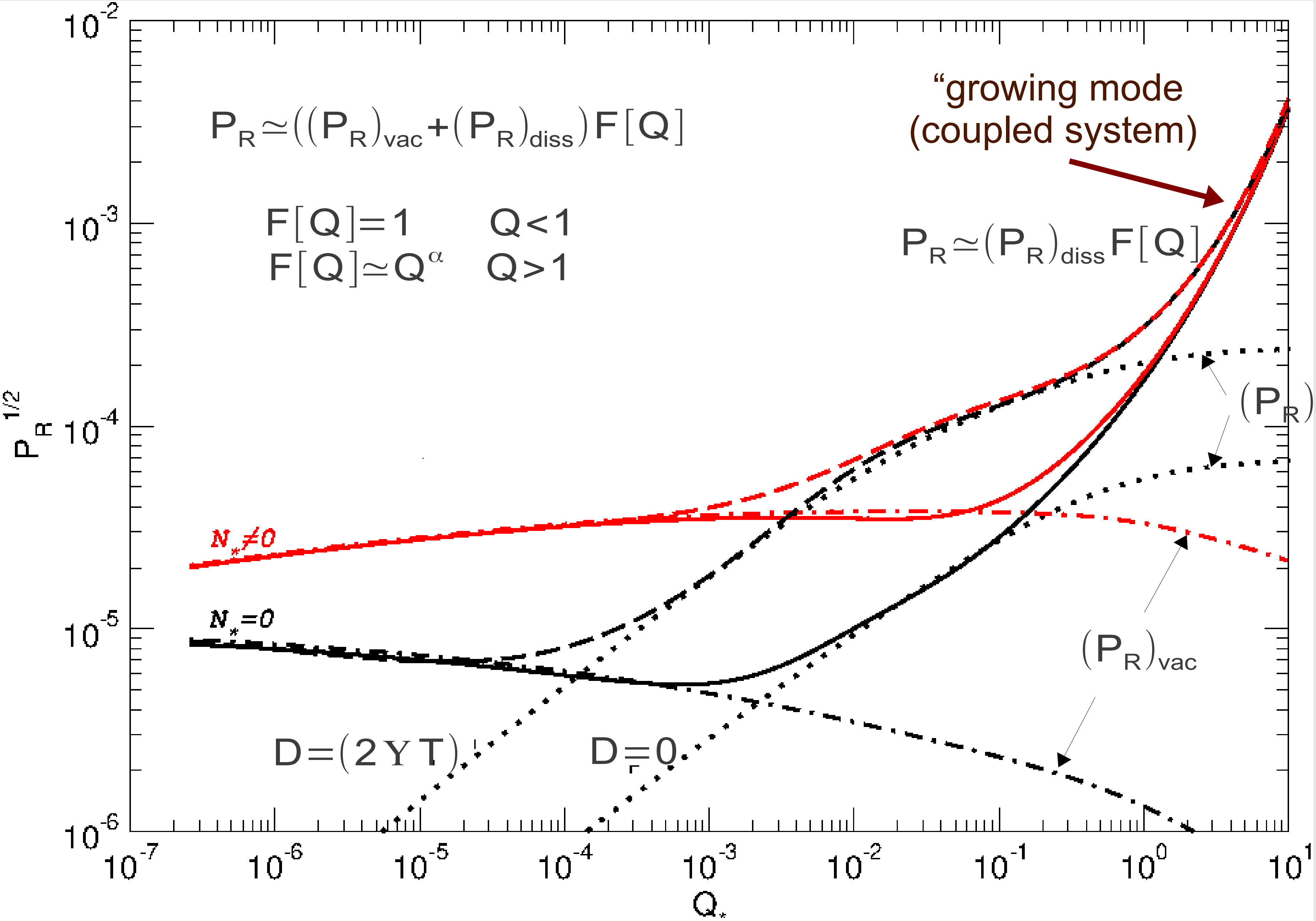
Primordial spectrum



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

BG, Berera, Moss & Ramos, 1401.1149

Primordial spectrum



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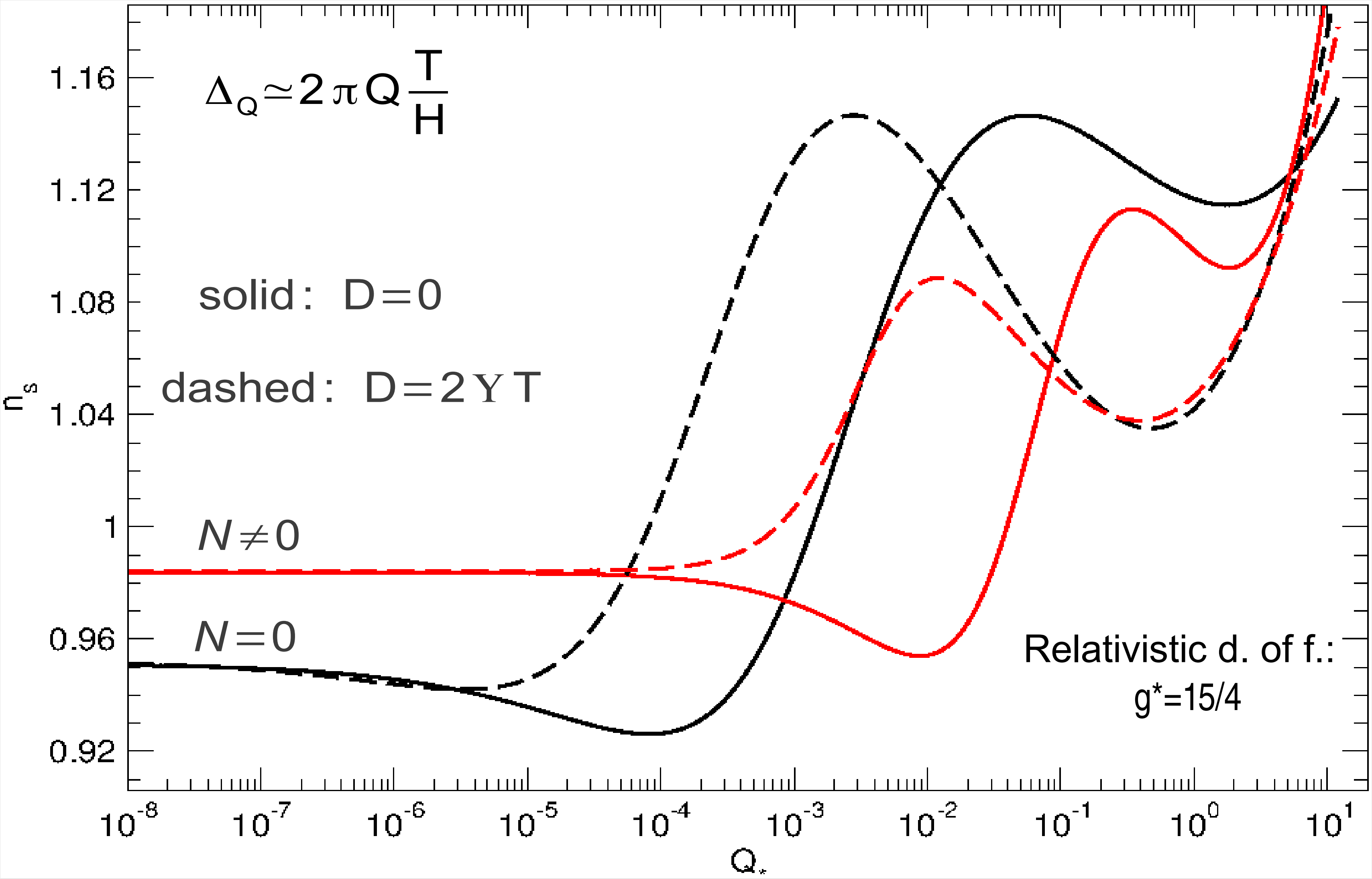
BG, Berera, Moss & Ramos, 1401.1149

Spectral index

$$n_s - 1 \simeq 2\eta_\phi - 6\eta_\phi + \frac{4N}{1+2N+\Delta_Q}(2\epsilon_\phi - \eta_\phi + \sigma_\phi) + \frac{2\Delta_Q}{1+2N+\Delta_Q}(7\epsilon_\phi - 4\eta_\phi + 5\sigma_\phi)$$



Chaotic model: $V(\phi) = \lambda\phi^4/4$, $\lambda = 10^{-14}$, $\sigma_\phi = m_P^2 \frac{V_\phi/\phi}{V}$, $\rho_r = \frac{\pi^2}{30} g_* T^4$

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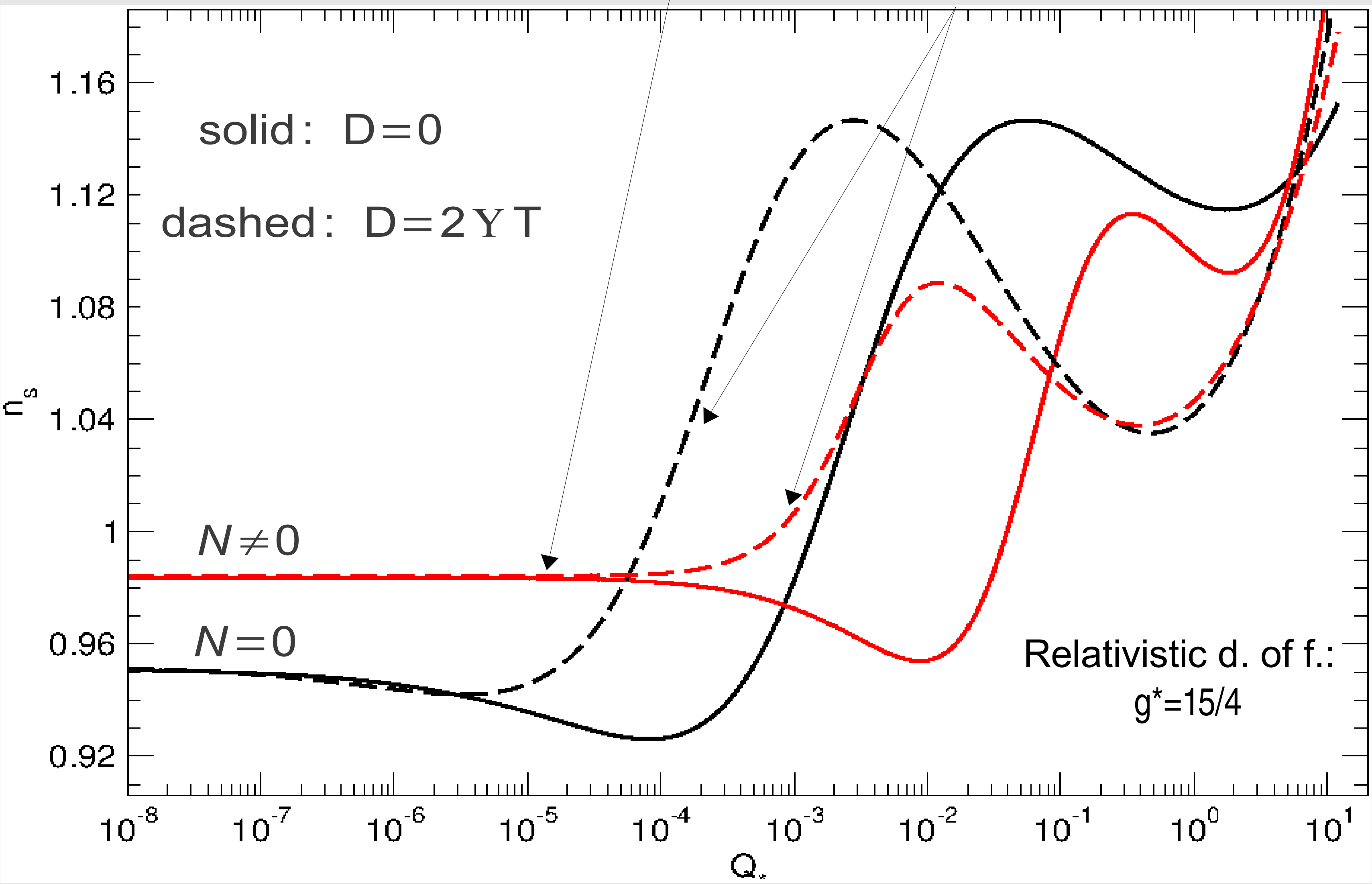

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Dissipation & Viscosity

- The radiation bath is expected to depart from a perfect fluid due to particle production

(u_σ=fluid flow velocity)

$$T^{\mu\nu}=(\rho+p)u^\mu u^\nu+p\,g^{\mu\nu}+\pi_b(u^\mu u^\nu+g^{\mu\nu})+\pi^{\mu\nu}+\Sigma^{\mu\nu}$$

Adiabatic pressure $p\sim T^4$,

Bulk vis. $\pi_b\simeq-3\zeta_b\theta$ $(\theta=\text{expansion rate})$

Shear vis. $\pi_{\mu\nu}\simeq-2\zeta_s\sigma_{\mu\nu}$ $(\sigma_{\mu\nu}=\text{shear})$

Stochastic source

- Bulk vis. can affect both background & fluctuations dynamics: $\pi_b<0$

-More e-folds of inflation

- More radiation

Mimoso, Nunes, Pavón PRD73 '06; Del Campo, Herrera, Pavón PRD75 '07; Del Campo et al. 1007.0103; Bastero et al. 1209.0712

- Shear vis. enters in the EOM for the fluctuations

Light fields: $\zeta_b(T),\zeta_s(T)\propto T^3$

Jeon & Yaffe PRD53 ('96)

Shear viscosity: fluctuations & primordial spectrum

Field EOM:

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

Radiation (fluid stress energy-tensor):

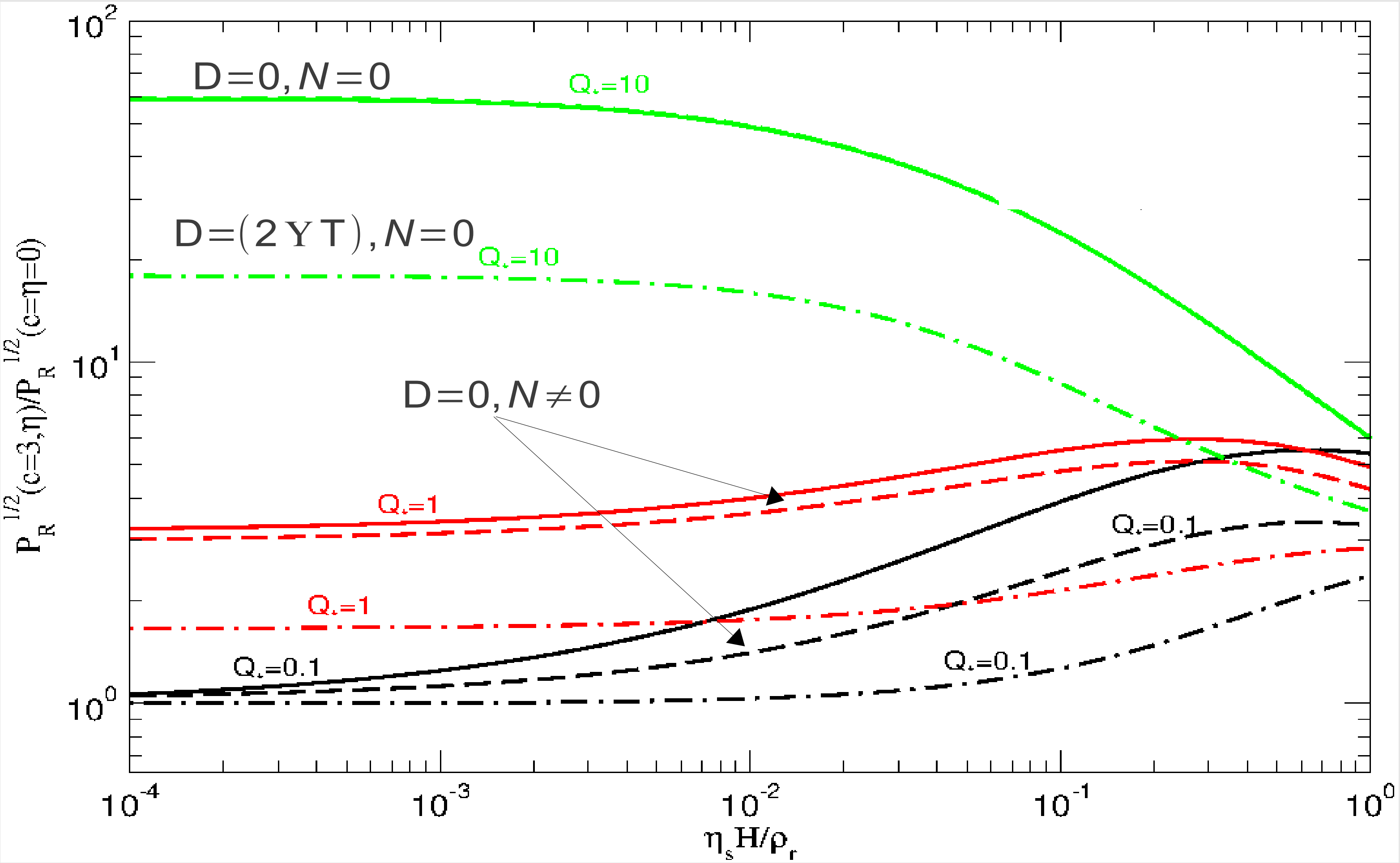
$$\delta\dot{\rho}_r^{GI}+4H\delta\rho_r^{GI}\simeq\frac{k^2}{a^2}\Psi_r^{GI}+\dot{\phi}^2\delta\Upsilon^{GI}+2\dot{\varphi}\,\Upsilon\,\delta\dot{\phi}^{GI}-\dot{\phi}\,D^{1/2}\hat{\xi}_k$$ Energy density

$$\dot{\Psi}_r^{GI}+3H\left(1+\frac{k^2}{a^2H^2}\bar{\zeta}_s\right)\Psi_r^{GI}\simeq-\delta\rho_r^{GI}/3-\dot{\phi}\,\Upsilon\,\delta\phi^{GI}+\left(\frac{8}{3}\zeta_s T\right)^{1/2}\hat{\xi}_s$$ Momentum density

Shear parameter

$$\left(\bar{\zeta}_s=\frac{4}{9}\frac{\zeta_s H}{\rho_r+p_r}\right)$$

Primordial spectrum & shear

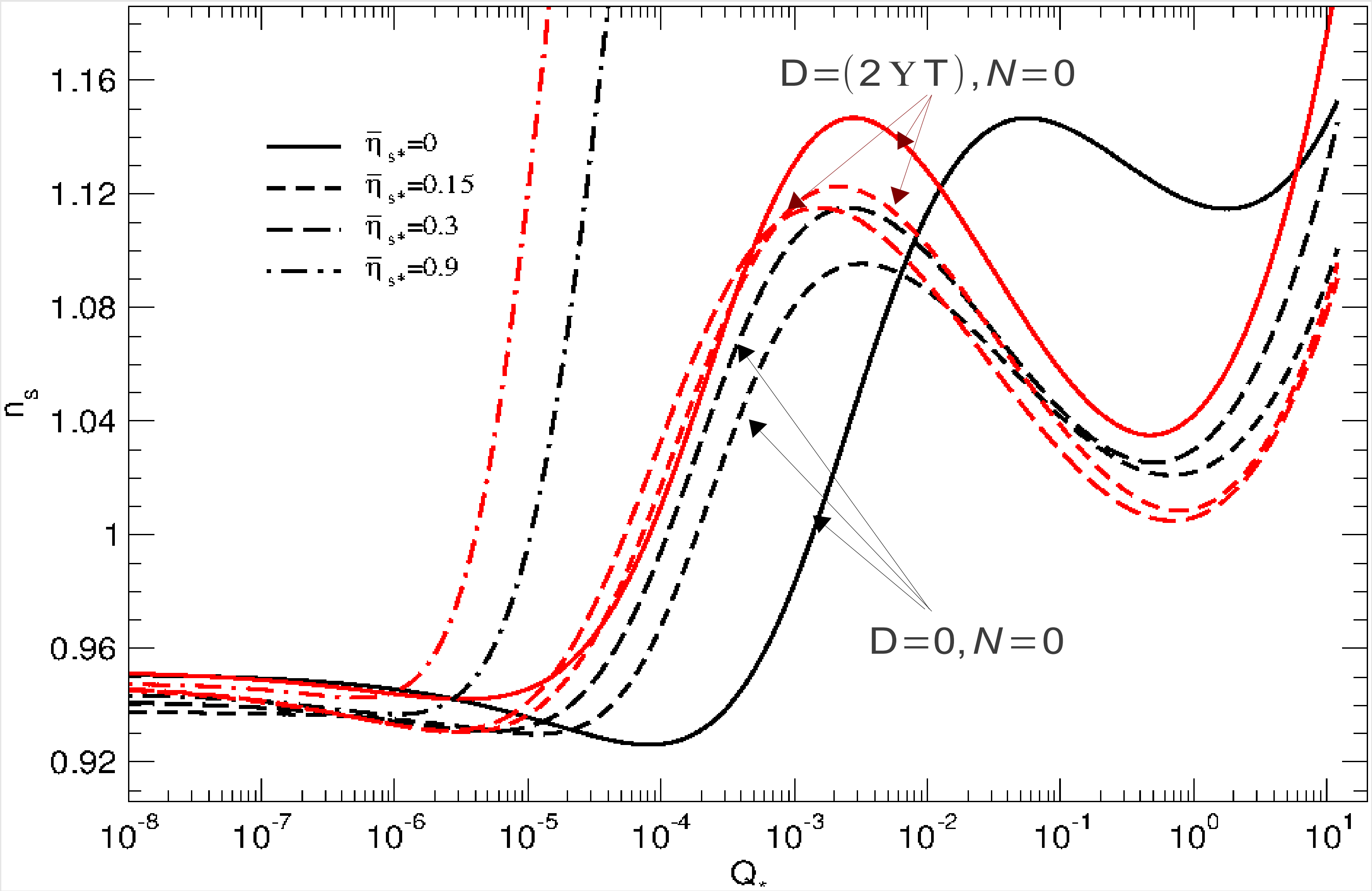


Shear tends to damp the growth of the radiation fluctuations (before freeze-out), and therefore that of the field only for Q >1.

Otherwise the stochastic viscous noise acting as a source in the radiation fluid will enhance the amplitude.

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

Spectral index & shear

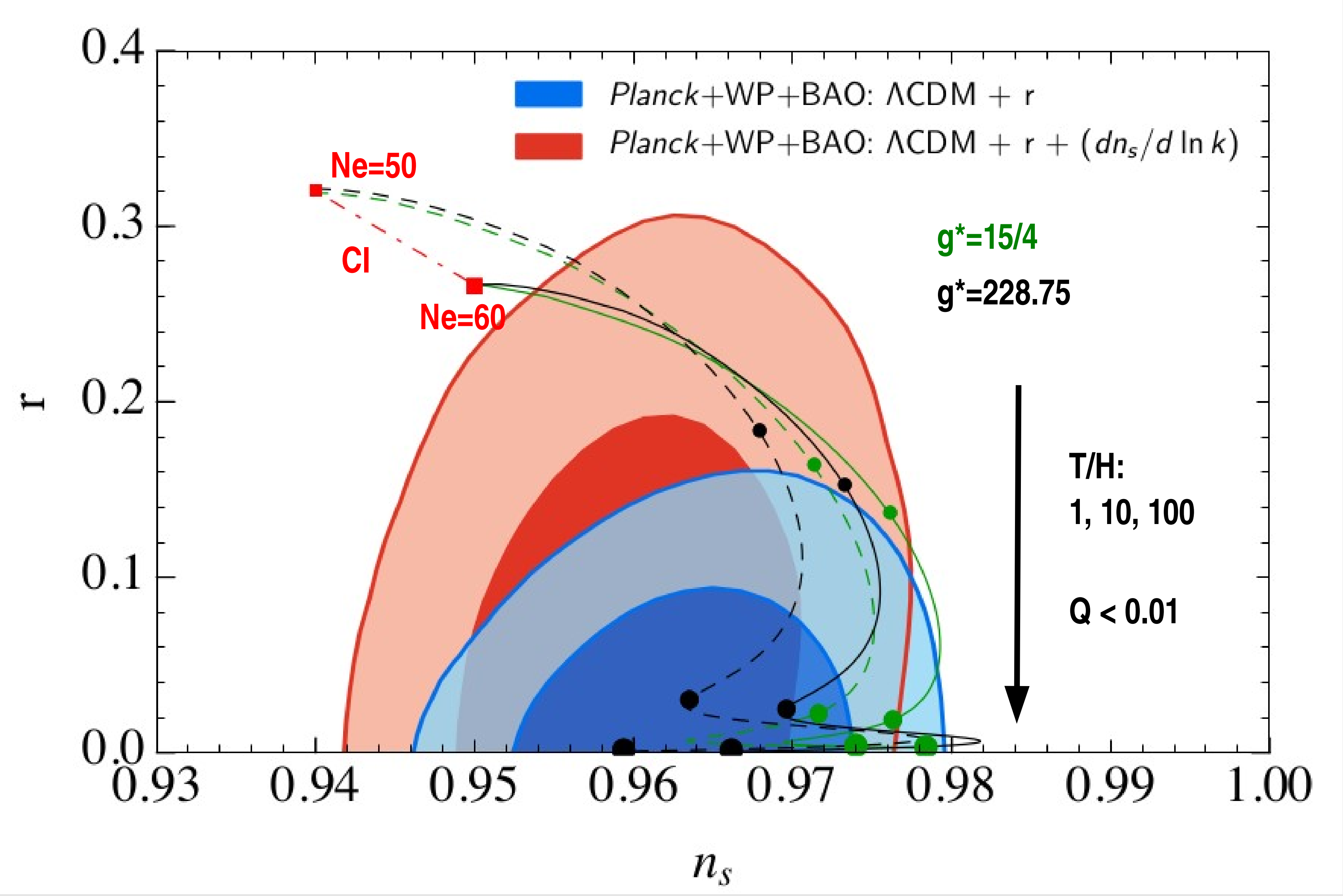


Shear will set more power on larger wavenumbers, increasing the tilt of the spectrum for smaller values of Q.

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

Weak dissipation: $\lambda\phi^4$ potential

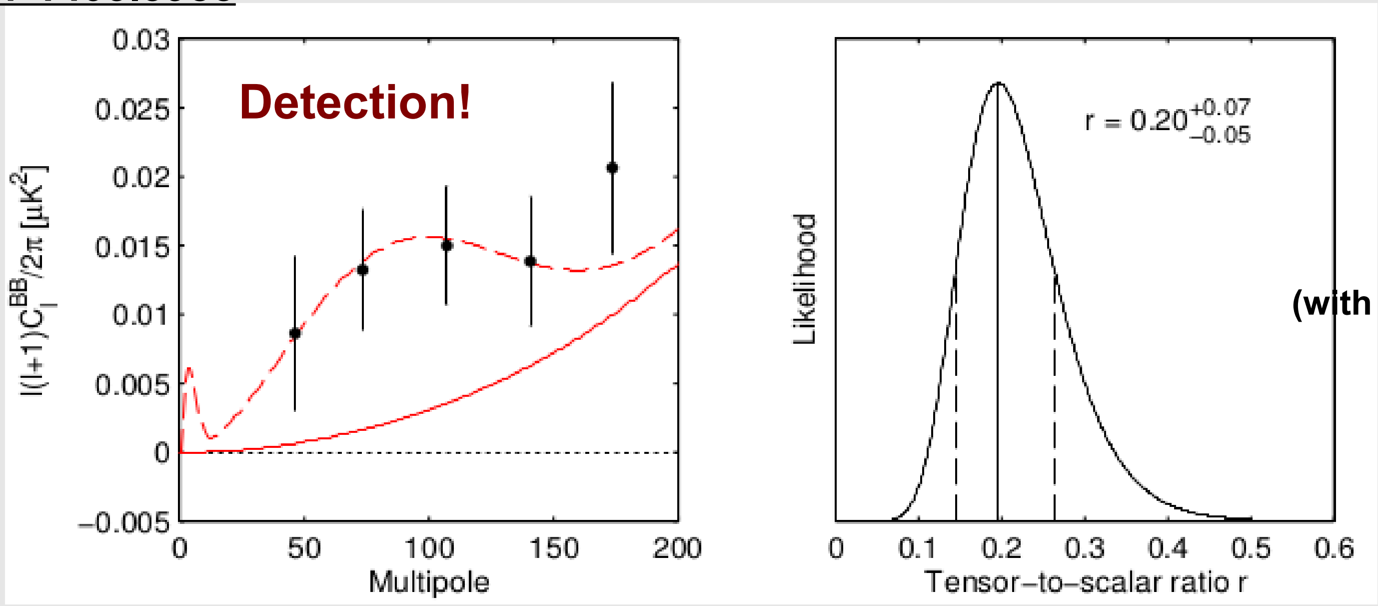
$$N \neq 0: \quad n_s \simeq 2\sigma_\phi - 2\epsilon_\phi, \qquad r \simeq \frac{16\,\epsilon_\phi}{1+2\pi Q}\frac{H}{T}$$



Low T regime: $\lambda \sim 10^{-14}$ $\qquad C_\phi \sim (T/H)\, g_* N_e^2 \sim 10^6$

BICEP2 & PLANCK

BICEP2: arXiv 1403.3985



$(r<0.2)$

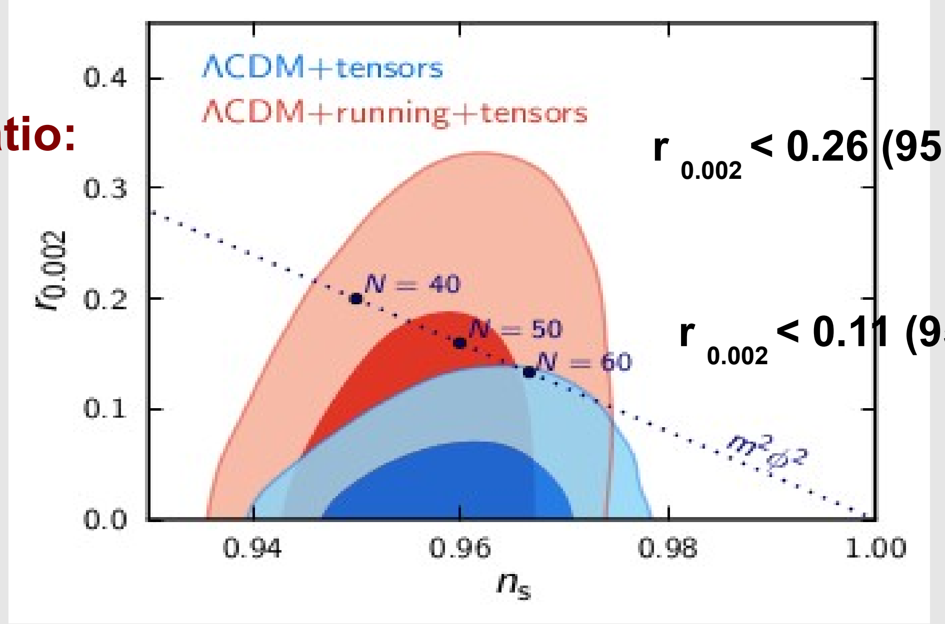
(with foreground dust subt.)

Primordial spectrum: $P_R = P_R(k_0)(k/k_0)^{n_s - 1 + n'_s \ln k/k_0/2}$ $k_0 = 0.002\,\mathrm{Mpc}^{-1}$

Tensor-to-scalar Ratio:

$r = P_T/P_R$

$P_T = P_T(k_0)(k/k_0)^{n_T}$



PLANCK: arXiv 1303.5076

$r_{0.002} < 0.26$ (95 % CL) (with running)

$r_{0.002} < 0.11$ (95 % CL) (no running, no iso)

BICEP2 & PLANCK: how to reconcile both results?
(while waiting for confirmation & Planck new analyses....)

- Negative running of the spectral index: $n'_S \simeq -0.0134 \pm 0.009$

Czerny, Higaki & Takahashi, 1403.5883

Ashoorioon, Dimopoulos, Sheikh-Jabbari, Shiu,1403.6099

- Blue-tilted tensor spectrum: $n_T > 0$

(String gas cosmology)

Wang & Xue 1403.5817

Brandenberger, Nayeri & Patil 1403.4927

- Sterile neutrinos (extra relativistic dof.)

(tension between different data sets, CMB & LSS)

Zhang, Li & Zhang 1403.7028

Dvorkin, Wyman, Rudd & Hu 1403.8049

See also: Leistedt, Peiris & Verde 1404.5950

- Cosmic strings?

Lizarraga et al., 1403.4924

- ➡ (Anticorrelated) isocurvature perturbations

Kawasaki & Yokoyama 1403.5823

Kawasaki, Sekiguchi, Takahashi & Yokoyama 1404.2175

CMB T anisotropies and isocurvature perturbations

Isocurvature pert.: $B_m = S_m/\zeta$

$$\langle (\Delta T/T)^2 \rangle \sim \underbrace{P_\zeta}_{\text{adiabatic}} \left(1 + \overbrace{4B_m^2 + 4B_m}^{} + \underbrace{\frac{5}{6} r}_{\text{tensors}}\right) \sim P_\zeta \left(1 + \frac{5}{6} r_{eff}\right)$$

$$B_m = \frac{\Omega_c}{\Omega_m} B_c + \frac{\Omega_b}{\Omega_m} B_b$$ ~ CDM + baryons ⬅

- Anticorrelated iso: $\underbrace{r_{eff}}_{\text{PLANCK}} = r + \frac{24}{5} B_m (B_m + 1) < \underbrace{r}_{\text{BICEP2}}, \quad [B_m < 0]$

$r_{0.002}$ < 0.11 (95 % CL) (no running, no iso) $r \sim 0.2$

- Chaotic (warm) models: $r \simeq 0.2, \quad B_m \simeq \frac{\Omega_b}{\Omega_m} B_b \simeq 0.02$ ➡ $r_{eff} \simeq 0.1$

  (large field models)

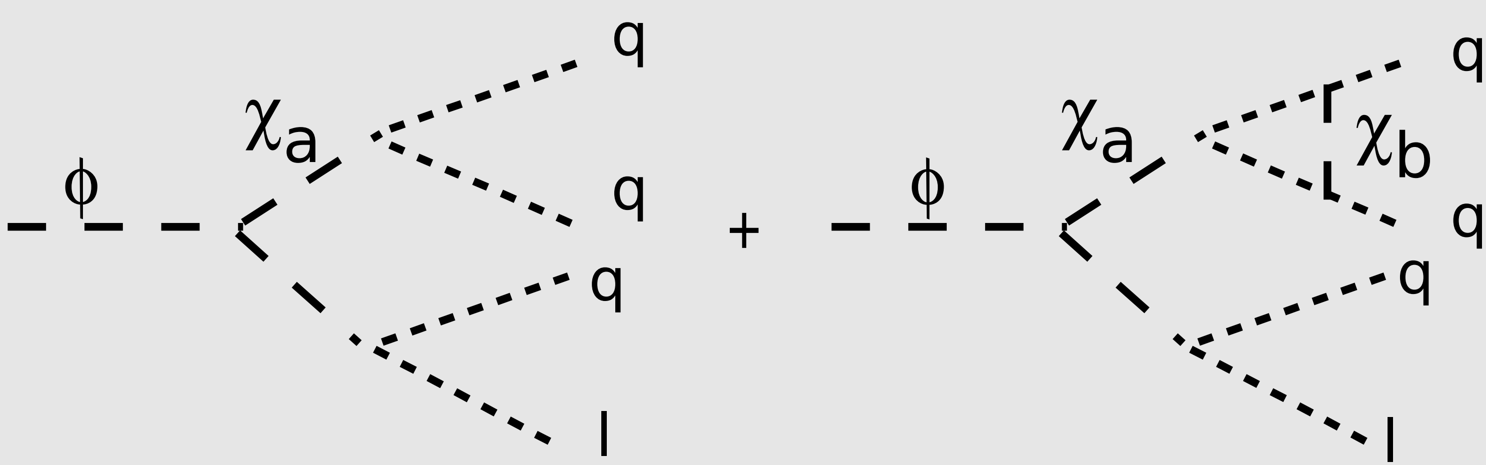
[MBG, Berera, Ramos & Rosa 1404.4976]

Baryogenesis & Dissipation

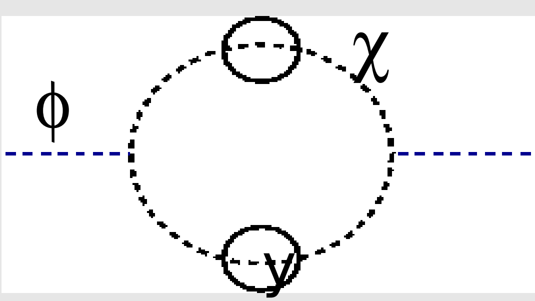
$$W = g_a \Phi X_a^2 + h_a^{ij} X_a Q_i Q_j + \lambda_a^{ij} X_a Q_i^c L_j$$

leptons

quarks



- B violating interactions
- CP violation: complex couplings $h_a^{ij}, \ \lambda_a^{ij}$ ➡ δ = CP phase
- Out-of-equilibrium conditions : <u>dissipation</u> in the low T regime $T < m_X$



(Low T : $\Upsilon \propto T^3/m_\chi^2 \propto T^3/\phi^2$)

[MBG, A. Berera, R. Ramos, J. Rosa PLB '12]

Baryon Isocurvature Perturbations

Baryon-to-entropy ratio $\eta \propto \frac{T^2}{\phi^2}$ ⇒ $\frac{\delta\eta}{\eta} = 2\left(\frac{\delta T}{T} - \frac{\delta\phi}{\phi}\right) \propto \frac{\delta\phi}{\phi}$

Baryons are subdominant during inflation, but later they contribute to the CMB and LSS

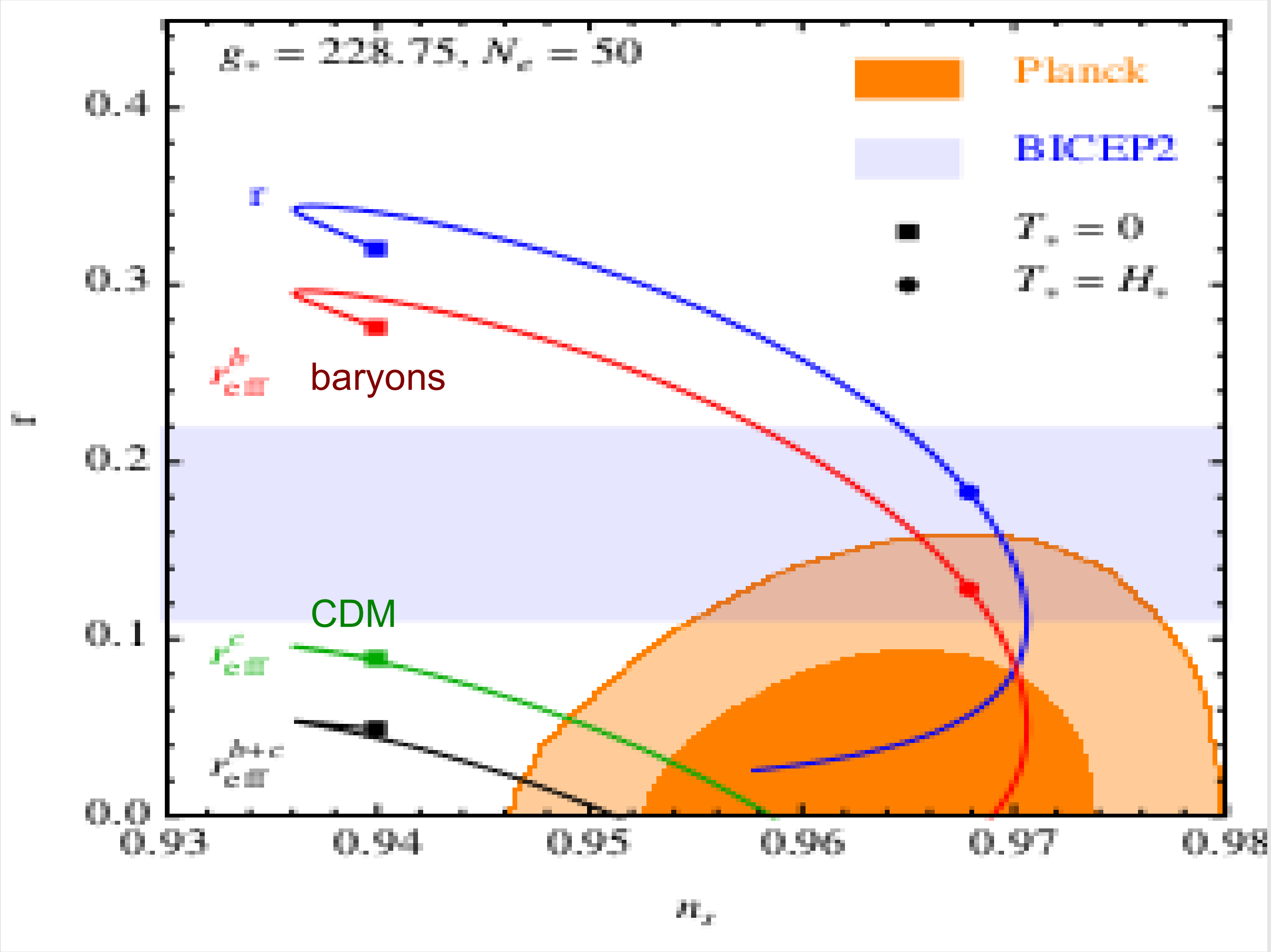
$$B_B = \frac{S_B}{\zeta} = \frac{\delta\eta}{\eta} \simeq \begin{cases} 2(2\eta_\phi - 5\sigma_\phi - \epsilon_\phi)/(7Q^2), & Q \gg 1 \quad \text{SDR} \\ 4\eta_\phi - 6\sigma_\phi - 6\epsilon_\phi, & Q \ll 1 \quad \text{WDR} \end{cases}$$

Fully correlated/ anti-correlated

Chaotic models: anti-correlated

PLANCK: $|B_B| < 0.51$ (95% CL) [Planck collab., arXiv:1303.5082]

Quartic (warm) models, n ~n_{BE}: r_{eff}



- r consistent with Planck & BICEP2 with BIPs, for T/H ~1.5

- $B_m = \frac{\Omega_{ci}}{\Omega_m} B_{ci} < \frac{\Omega_c}{\Omega_m} B_c$ asymm. only in a fraction of the CDM, better agreement

Summary

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

Extra friction $\Upsilon(T,\phi)$ $(Q=\Upsilon(T,\phi)/(3H))$:

slow roll: $\eta_\phi < 1+Q\,,\ \epsilon_\phi < 1+Q\,,\ \beta_\Upsilon < (1+Q)$ Field values below m_P

For a T dependent dissipative coefficient, the field and radiation perturbation EOM form a coupled system: Field fluctuations are amplified before freeze-out (Q > 0.1)

$P_R \simeq P_R(c=0) \times Q^\alpha$ Blue-tilted spectrum in models where Q> 0.1 increases

The radiation bath is expected to depart from a perfect fluid due to particle production:
Shear (fluctuations) + bulk viscosity (backg. + fluctuations)

$P_R \simeq P_R(c=0)$ when $\bar{\zeta}_s > 1$ Shear curtails growth

Too large value of the shear?

Summary

"Low T" regime for dissipation (thermal corrections under control):

QFT solutions are perturbative but have large number of fields $N_X \sim 10^6$

Expected fewer fields in pole-dominated dissipative regime/intermediate T regime

<u>Chaotic models</u>: (WDR)

smaller values of the inflationary scale are needed to fit the primordial spectrum

→ smaller tensor-to-scalar ratio

$\lambda\phi^4$ compatible with data

Thermal inflaton spectrum?