Not so minimal Warm Inflation

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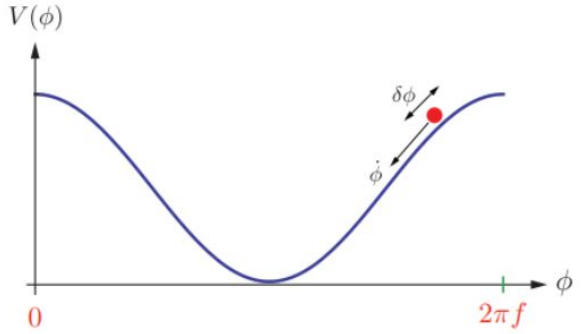
Not so Minimal Warm Inflation

Cold inflation/Warm inflation

$$V = \Lambda^4 \left(1 - \cos \phi / f_b\right)$$



Minimal WI with natural potential

$$L = \cdots - g^2 \frac{\phi}{64\pi^2 f_a} \mathrm{Tr}\, G_{\mu\nu} \tilde{G}^{\mu\nu} \Rightarrow Y \sim \frac{T^3}{f_a^2}$$

Model building constrains:

$$f_a \ll f_b \sim O(3-10) m_P$$

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...

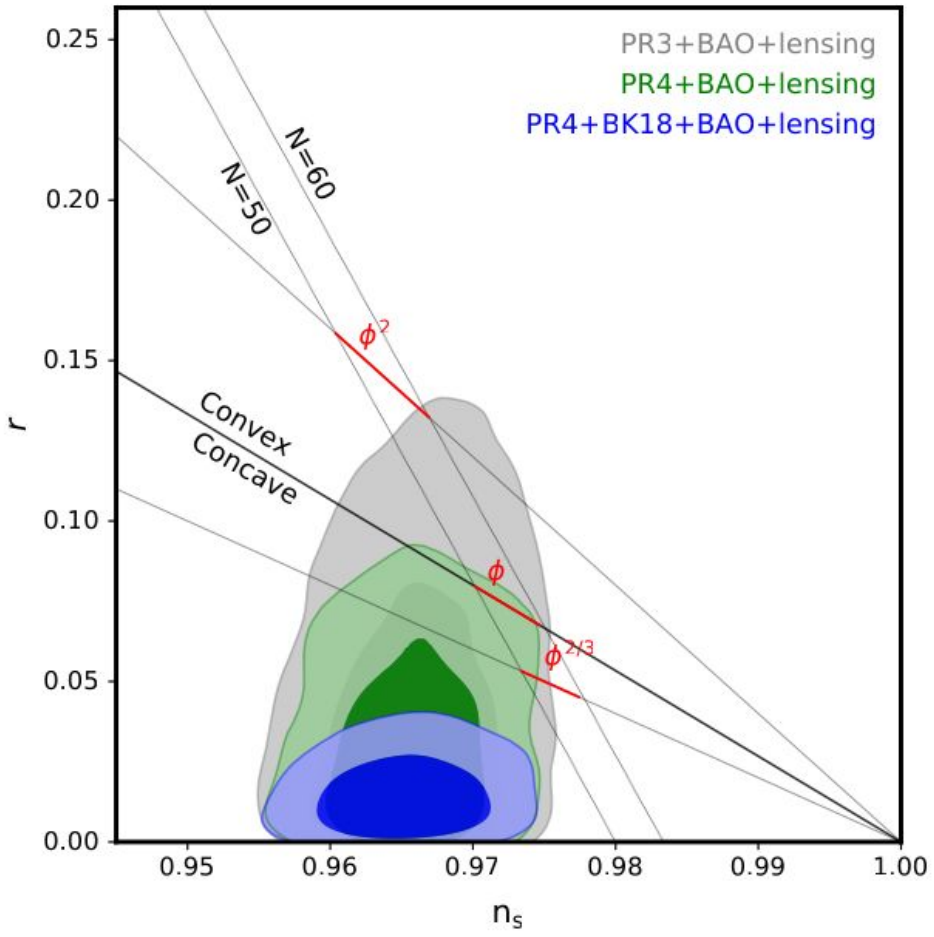
monopoles, moduli, gravitinos,...

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

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: $r = P_T / P_R$



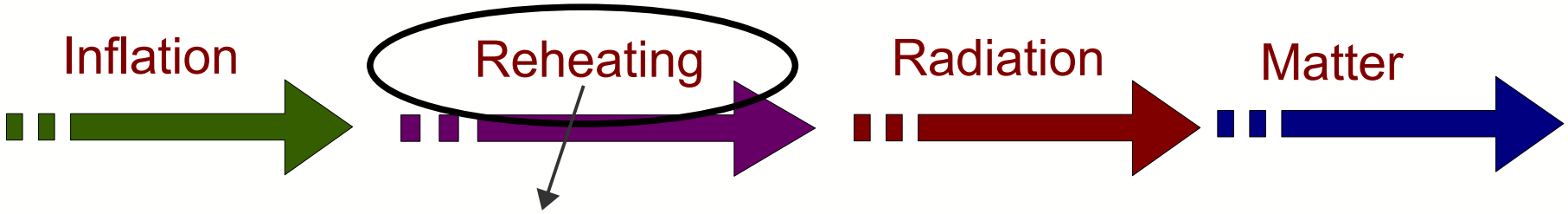
$P_R = 2.2 \times 10^{-9}$

$r < 0.036$

$n_s = 0.9649 \pm 0.0042$

$\alpha_s = -0.013 \pm 0.009$

[Tristam et al.: 2112.07961]



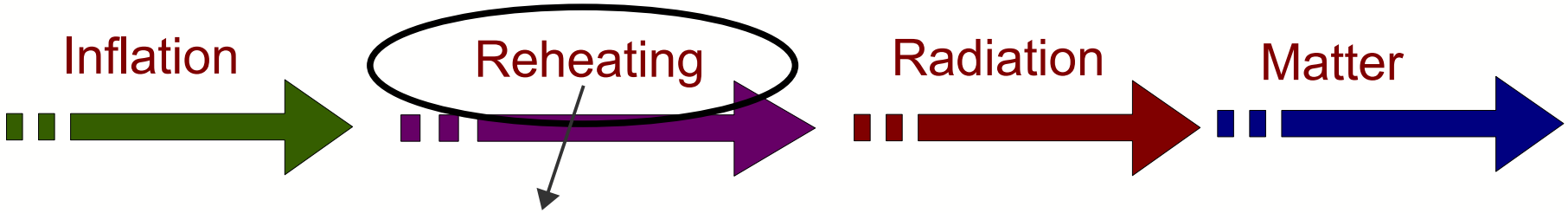
Inflaton interacts with other particles

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

”Warm” inflation: Inflaton “decay” into light dof → Radiation (**Dissipation**)

$[T>H, \Gamma_\chi>H]$ (through a mediator)

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



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

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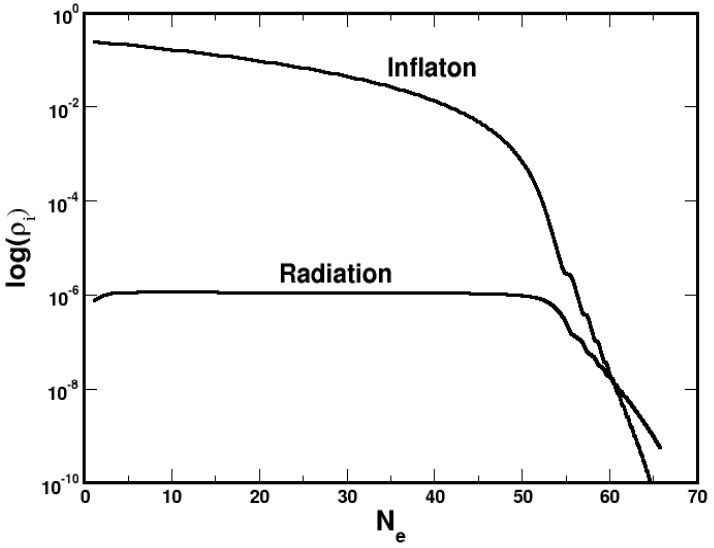
extra friction



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

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

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

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

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

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

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

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

Thermal corrections under control (inflaton coupled to heavy fields)

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

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

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

[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

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

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

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

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

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

Inflaton + single fermion: $\Delta V_T = -\frac{\pi^2}{90} g_R T^4 + \frac{g^2 M^2}{12} T^2 \cos^2(\varphi/M) + \ldots$

[Ferraz & Rosa 2308.0564]

- "Minimal Warm Inflation" : [Berghaus, Graham, Kaplan 1910.07525]

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

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

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

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

Sphaleron rate $\Gamma_{sph} \simeq N_c^5 \alpha^5 T^4$ [Kuzmin, Rubakov & shaposhnikov, PLB '85]

- MWI + hybrid inflation → SDR (Q>>1) at horizon crossing
- Warm inflation is an attractor

- "Warm Inflation within the SM" :

[Berghaus, Drewes, Zell 2503.18829]

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

$$\frac{\alpha}{8\pi f_a}\langle \mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}\rangle \simeq Y_{sph}\left(\dot{\phi}+\frac{6 f_a J_A^0}{N_c T^2}\right)$$

Chiral current $J_A^0 \simeq n_R - n_L \simeq \frac{N_c N_f}{3} T^2 \mu_A$ Chemical potential

$$\begin{cases} \ddot{\phi}+(3H+Y_{sph})\dot{\phi}+V_\phi = -Y_{sph}(2N_f M \mu_A) \\ \dot{\mu}_A+3H\mu_A = \frac{-6 f_a Y_{sph}}{N_c T^2}(\dot{\phi}+2N_f f_a \mu_A) \end{cases} \rightarrow \ddot{\phi}+(3H+Y_{eff})\dot{\phi}+V_\phi = 0$$

- Dissipative coefficient

$$Y_{eff} \simeq \frac{Y_{sph}}{1+4\frac{Y}{H}\left(\frac{f_a}{T}\right)^2 \frac{N_f}{N_c}}$$

- $Y_{eff}+V(\phi)=\lambda\phi^4$ Compatible con observations

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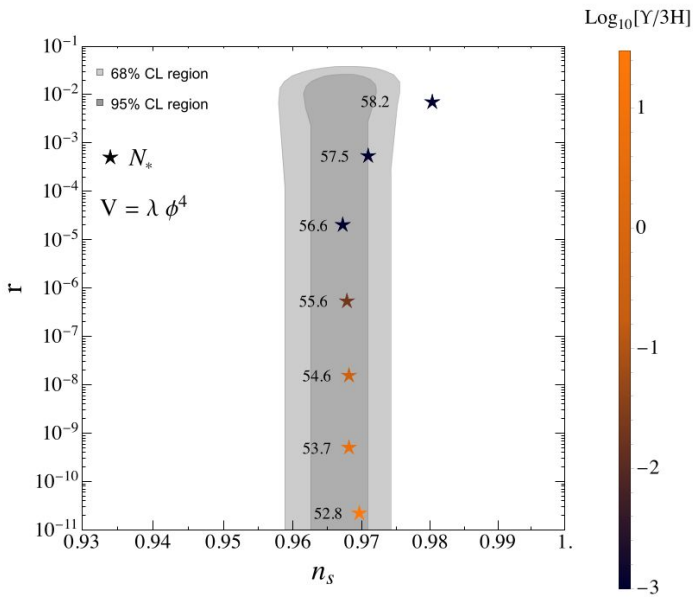

Fluctuations & primordial spectrum: coupled system

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:

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

$$P_{\delta\varphi} \simeq \left(\frac{H}{2\pi}\right)^2 \quad T \to 0$$

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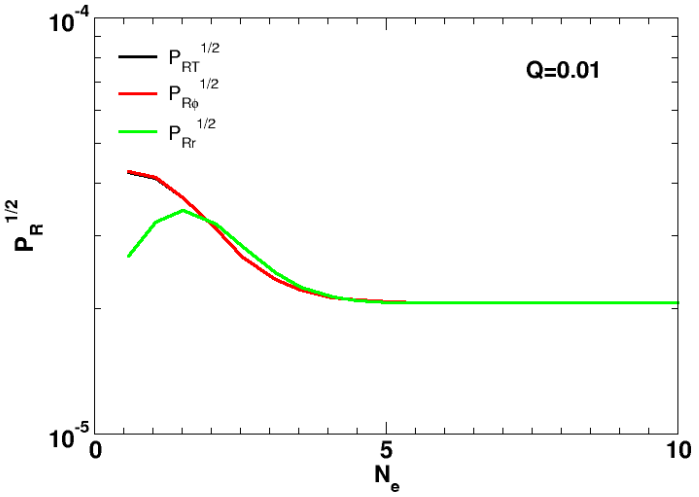
Tensors: $\ddot{h}_{ij} + 3hH_{ij} + \frac{k^2}{a^2}h_{ij} \simeq \frac{2}{m_P^2 a^2}\Pi_{ij}^{TT}$

[Qui & Sorbo, 2107.09754]

$$P_h = 8\left(\frac{H}{2\pi m_P}\right)^2 + P_h(T) \simeq 8\left(\frac{H}{2\pi m_P}\right)^2 \qquad \left[P_h(T) \sim \frac{T^5}{H m_P^4}\right]$$

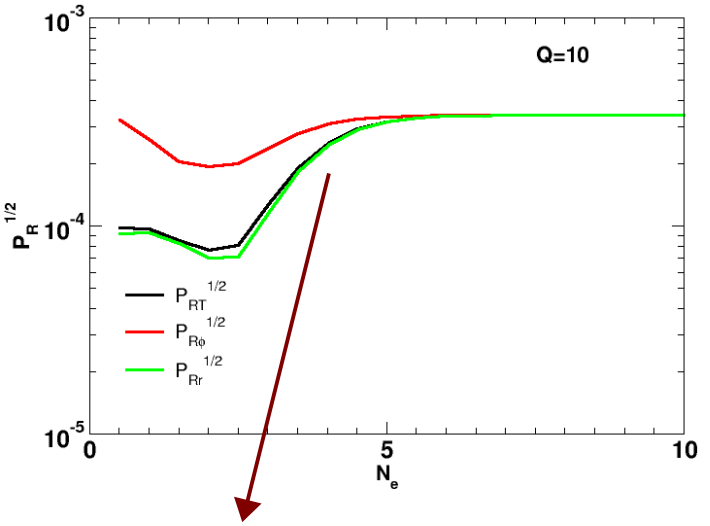
Fluctuations & primordial spectrum: coupled system

- Weak dissipative regime ($Q=\Upsilon/H<<1$)



$$G[Q]\simeq 1$$

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



Growing mode! **Numerical integration**

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

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

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

[Ramos, da Silva, 1302.3544]

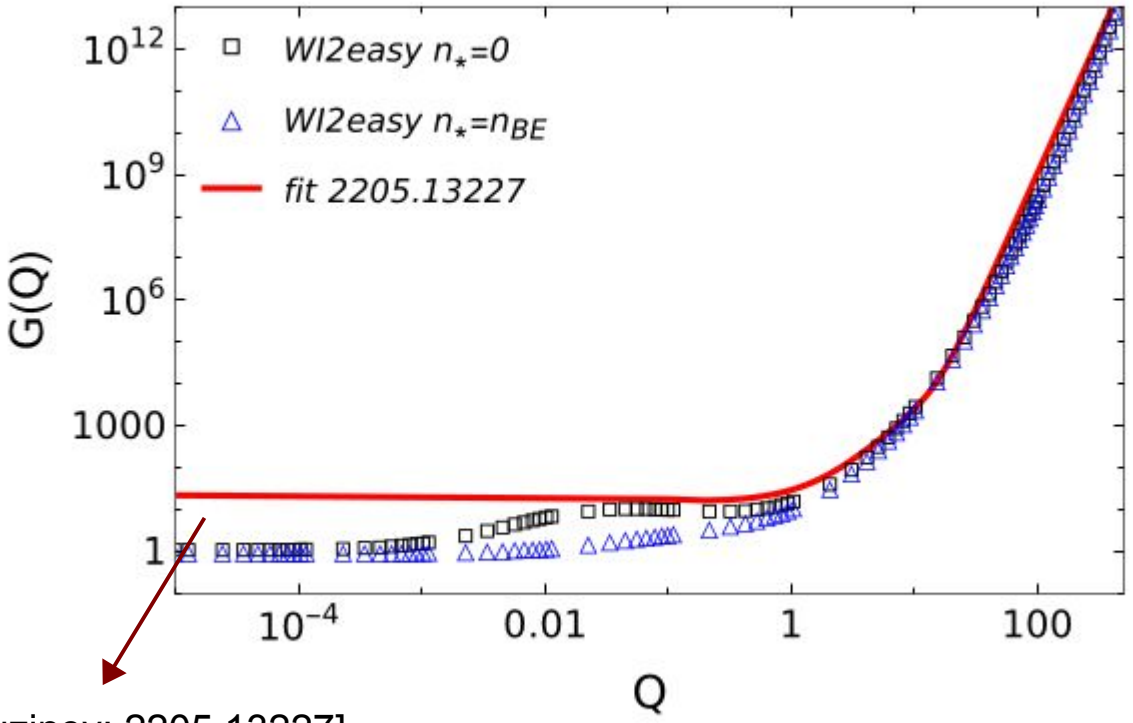
[BG, Berera, Moss & Ramos, 1401.1149]

[WI2easy: Rodrigues, Ramos 2504.17760]

[SWIM: Kumar & Das 2604.24654]

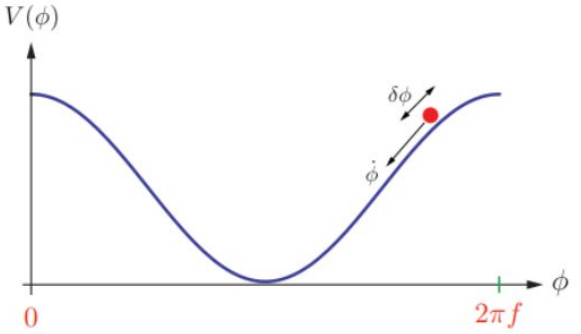
WI2Easy: quartic model + $\Upsilon \sim T^3$

[WI2easy: Rodrigues, Ramos 2504.17760, 2504.20943]



[Mirbabayi & Gruzinov: 2205.13227]

Our setup



- Natural potential: $V = \Lambda^4\left(1-\cos\frac{\phi}{f_b}\right)$

  [Freese, Frieman & Olinto, PRL '90]

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

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

[Laine & Procacci 2102.09913]

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

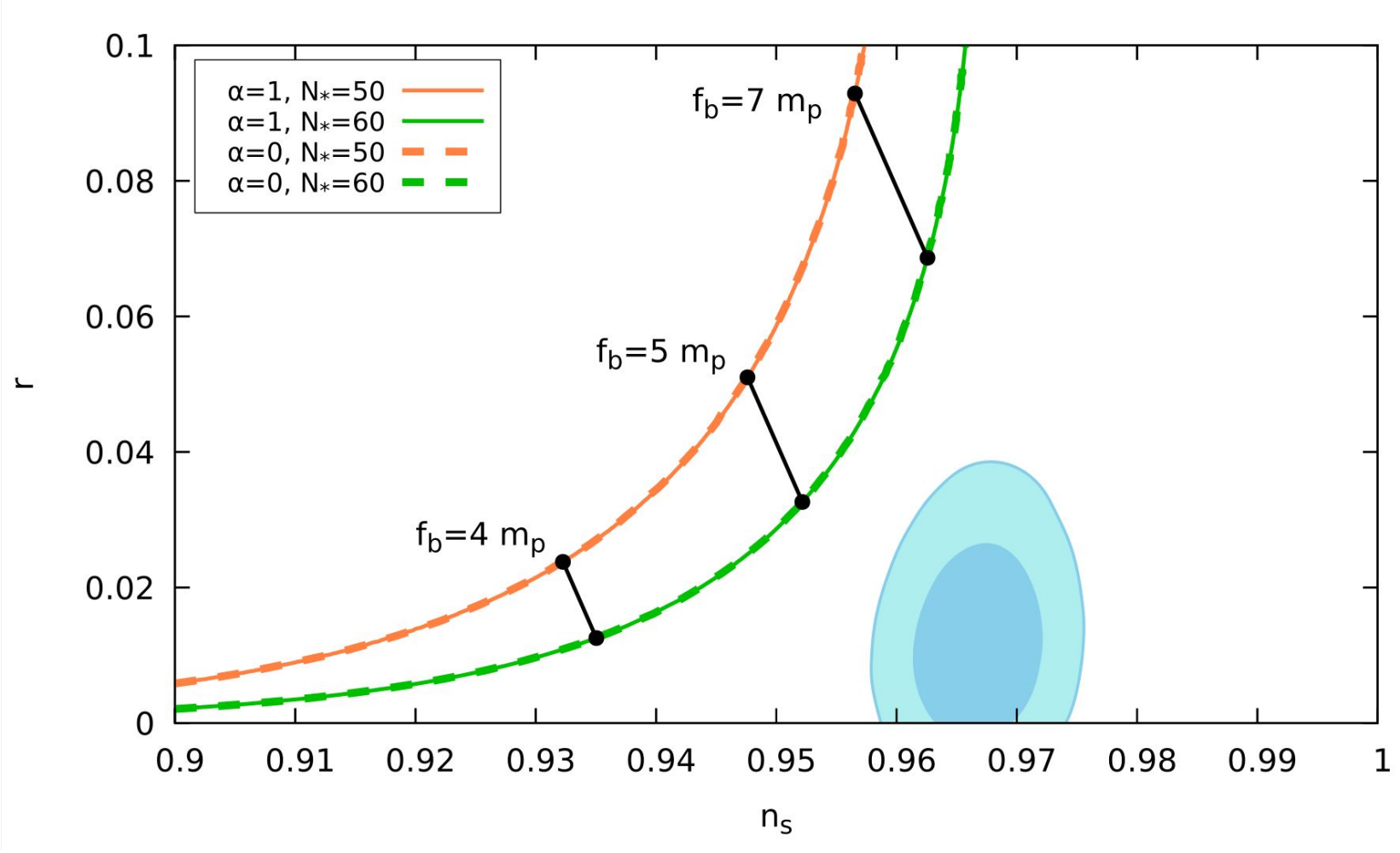
$$\Upsilon_{IR}\sim\frac{\alpha^5 T^3}{f_a^2} \qquad \Upsilon_{UV}\sim\frac{\alpha^2\omega^3}{f_a^2} \qquad [\omega\simeq m]$$

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

[S. Zell 2408.07746]

- Natural potential+ dissipation: $f_a = f_b$

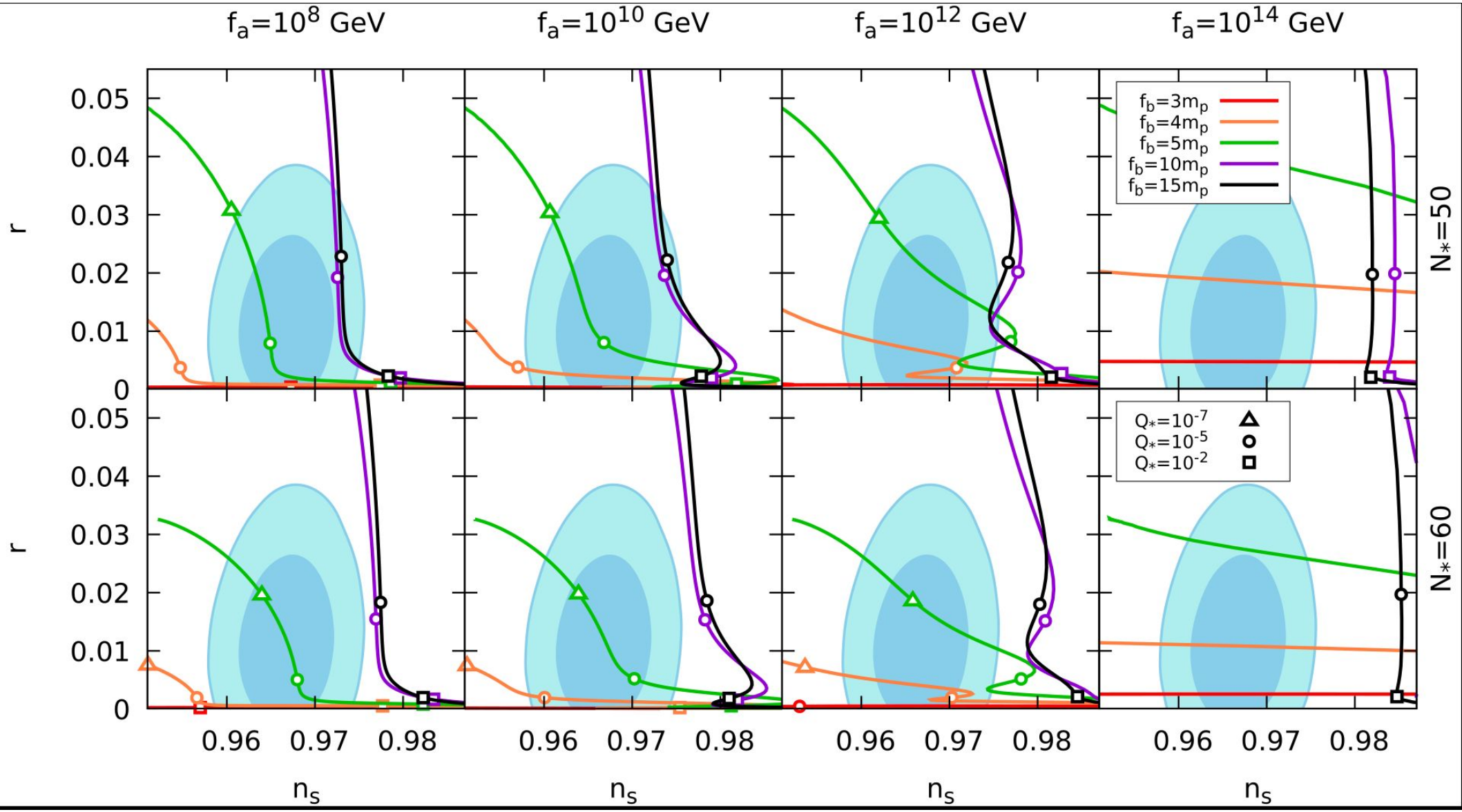
Dissipation suppressed during inflation, excluded by observations



How large the hierarchy between scales?

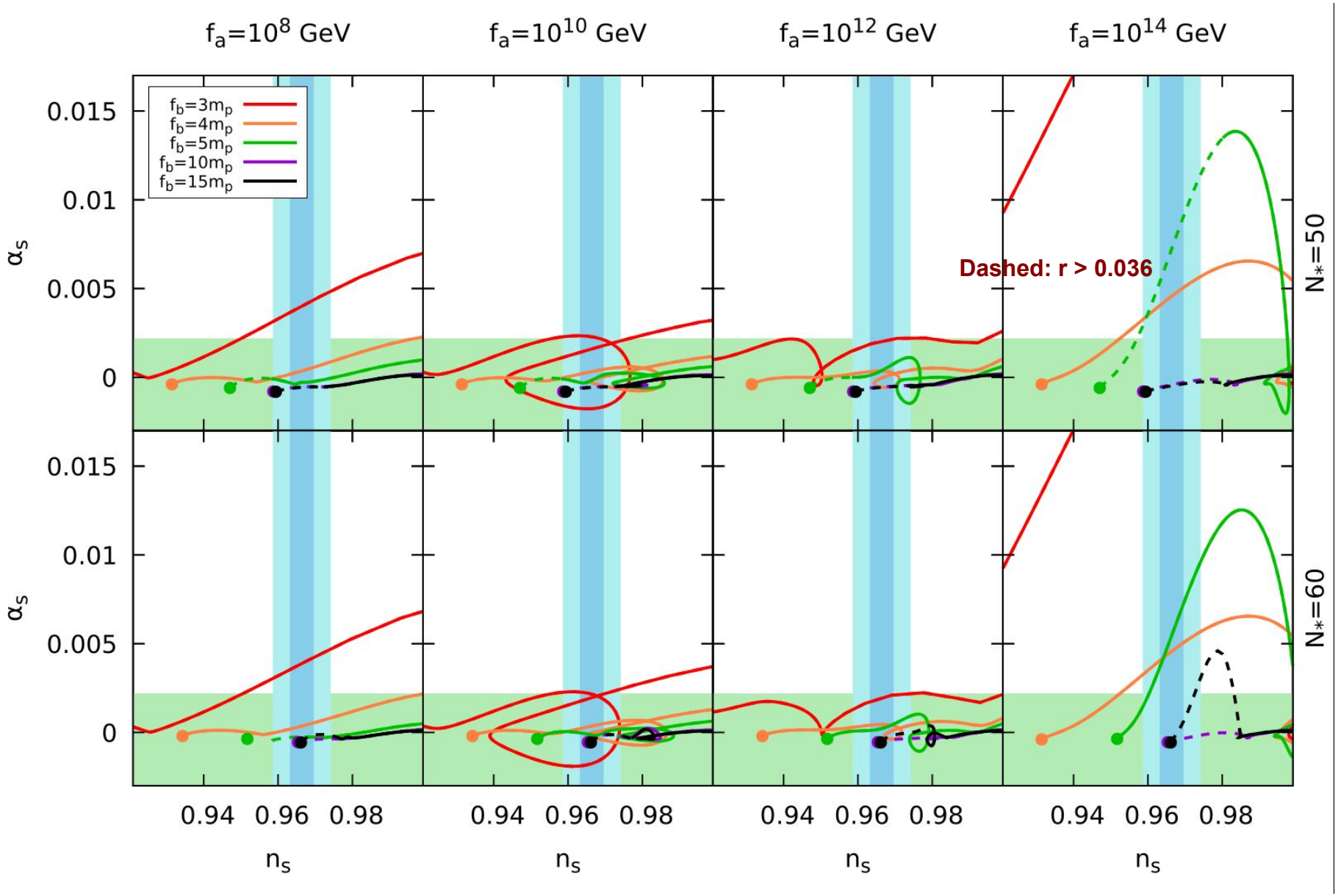
- Natural potential+ dissipation+ thermal inflaton: $f_a << f_b$, weak dissipation, $f_b > m_P$

$$r \simeq 16\epsilon_H/(1+n_{BE}) < 16\epsilon_H$$



Running of the spectral index

- Natural potential+ dissipation: $f_a << f_b$, weak dissipation, $f_b >\sim 3m_P$, $f_b/f_a > 10^6$



How large the hierarchy between scales?

- "Clockwork" : $V = \Lambda^4 \left(1 - \cos \frac{\phi}{j f_a}\right)$, $j < f_b/\Lambda$, $\Lambda \downarrow < f_a$

[Choi & Im 1511.00132; Kaplan & Rattazzi 1511.01827]

- Partial waves unitarity bounds (scattering of gauge fields and inflaton) :

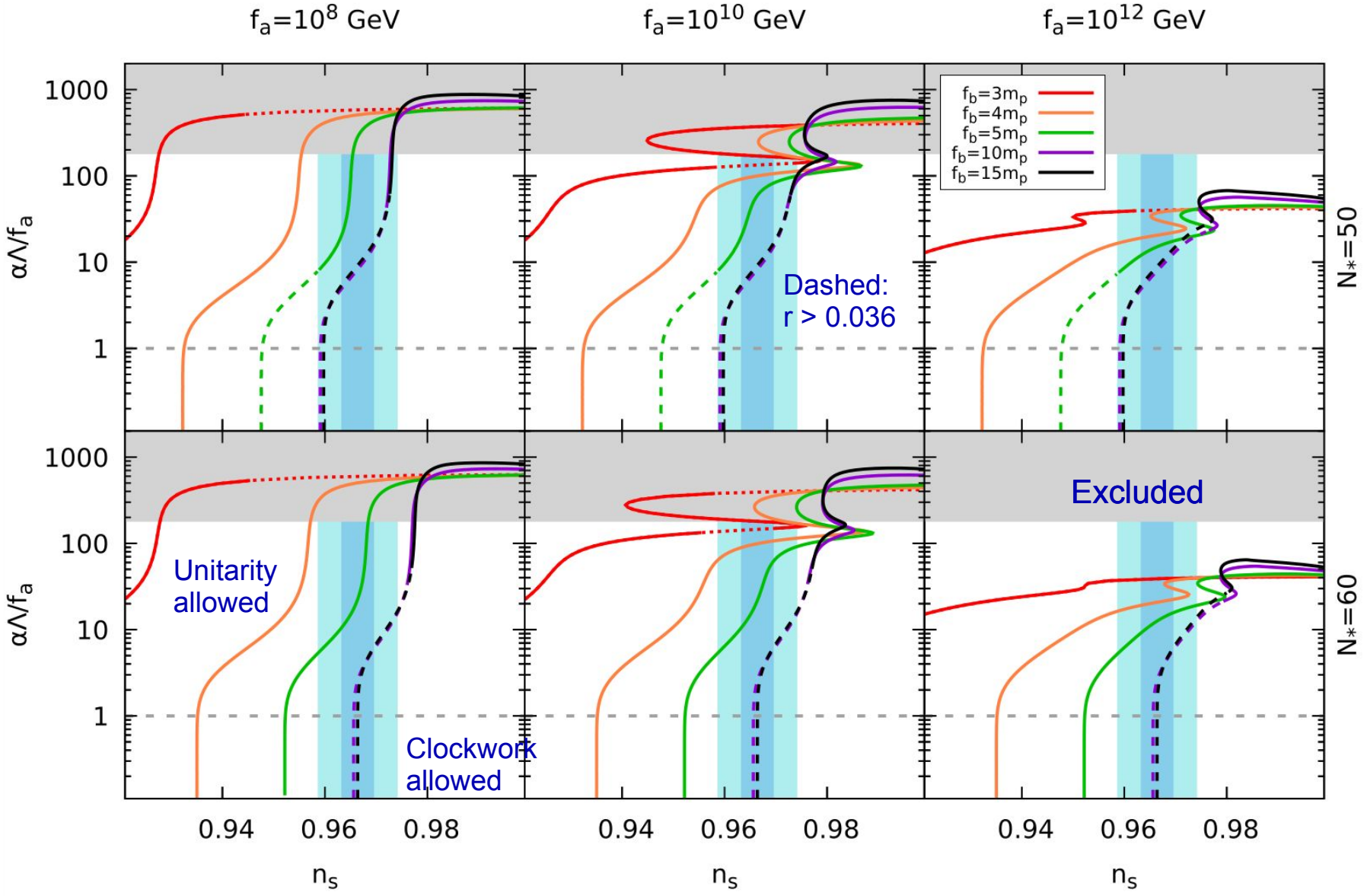
$$\Lambda < 32\pi^{3/2} \frac{f_a}{\alpha}$$

[Bagherian, Reece & Xu 2207.11262]

The value of Λ is set from the amplitude of the primordial spectrum

How large the hierarchy between scales?

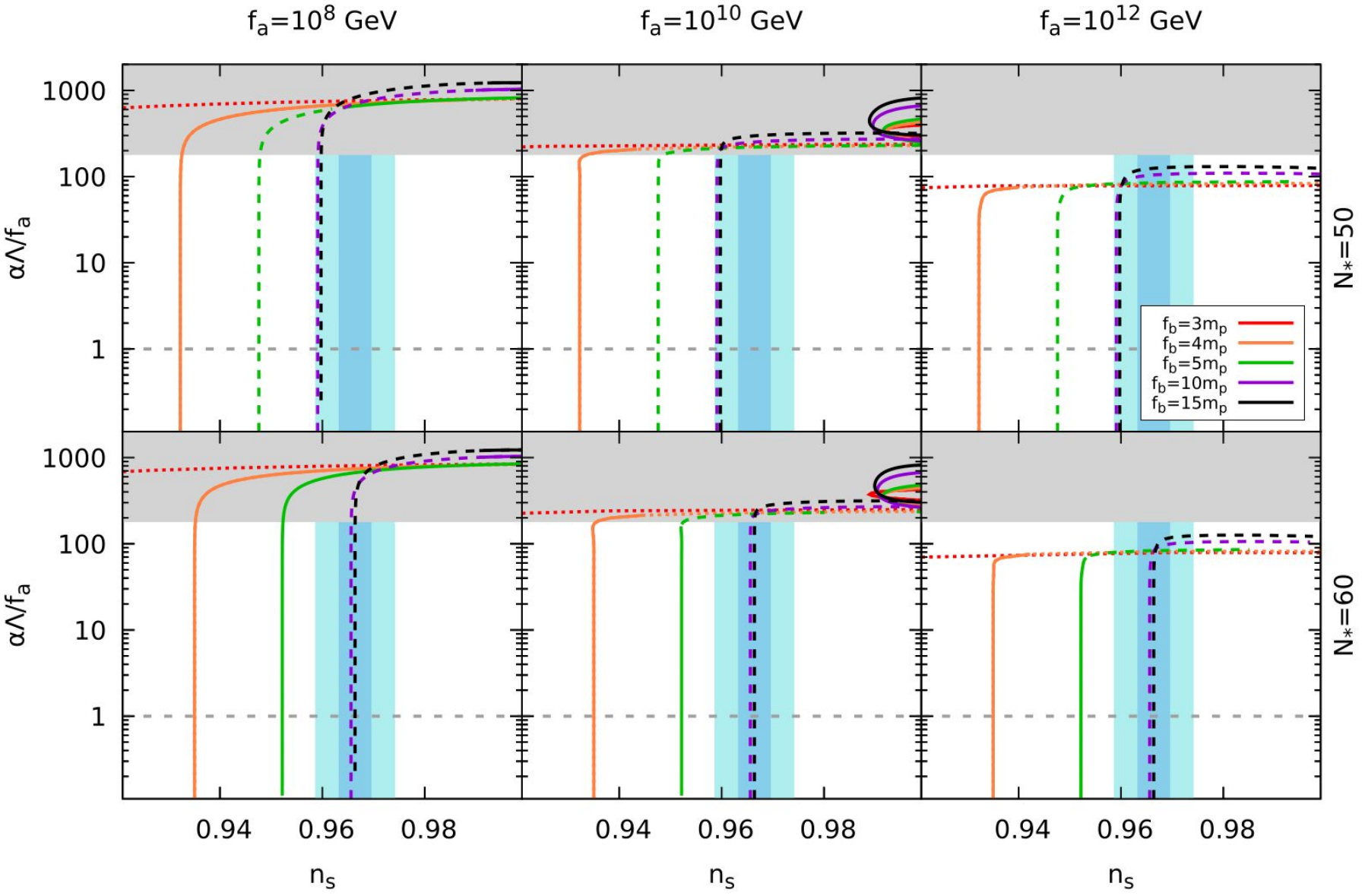
- Clockwork : $\Lambda < f_a \quad (\alpha<1)$
- Unitarity bound : $\Lambda < 32\pi^{3/2} f_a/\alpha$



There are no values compatibles with "clockwork" mechanism to generate the hierarchy

Non-thermal inflaton

- Clockwork : $\Lambda < f_a \quad (\alpha<1)$
- Unitarity bound : $\Lambda < 32\pi^{3/2} f_a/\alpha$



No values compatibles with "clockwork" & unitarity constraints

Summary

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

- 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 + shift symmetry + gauge field production (non perturbative)

- Case of study: natural inflation + gauge dissipative coefficient

$$V = \Lambda^4 \left(1 - \cos \phi / f_b\right) \qquad \Upsilon \sim \frac{T^3}{f_a^2} F_3[\omega] + F_0[\omega]$$

- Observations (CMB spectrum): only compatible in the WDR (Q << 1) + thermal inflaton

Large hierarchy required $f_b \sim O(m_P) >> f_a$

Clockwork mechanism not enough to explain the hierarchy

Compatible with unitarity bounds, but only with a thermal inflaton

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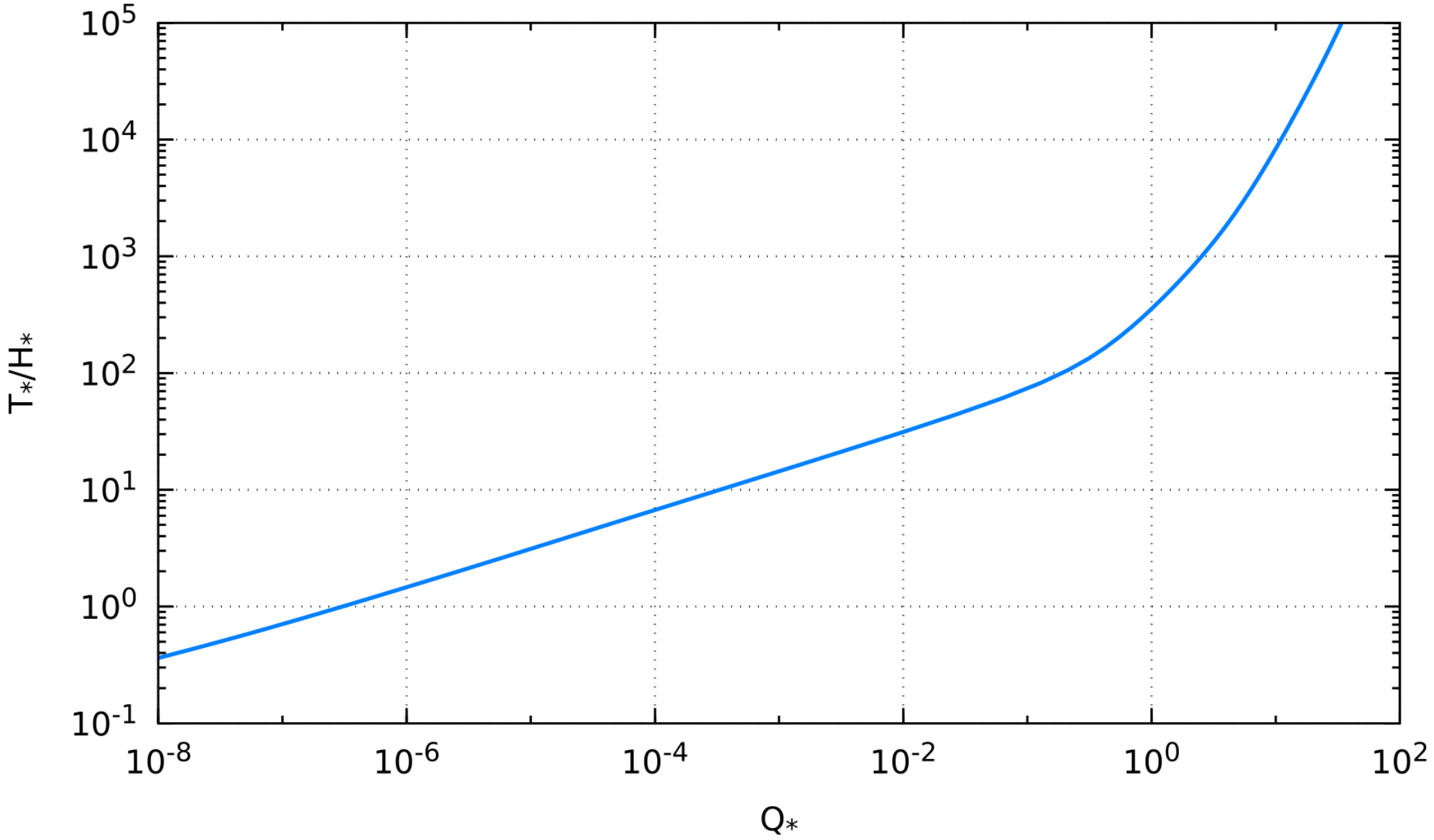
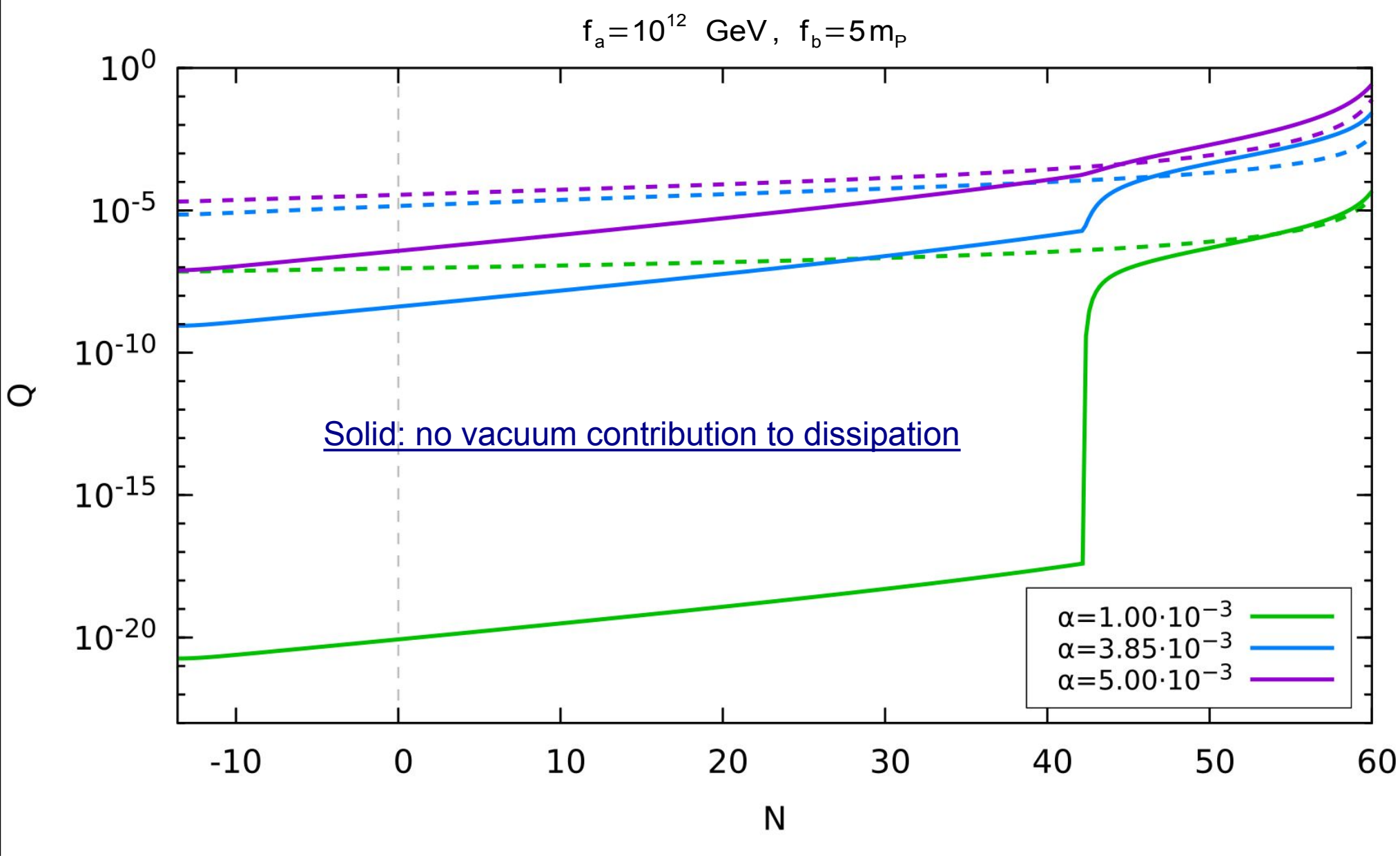
Thank you!

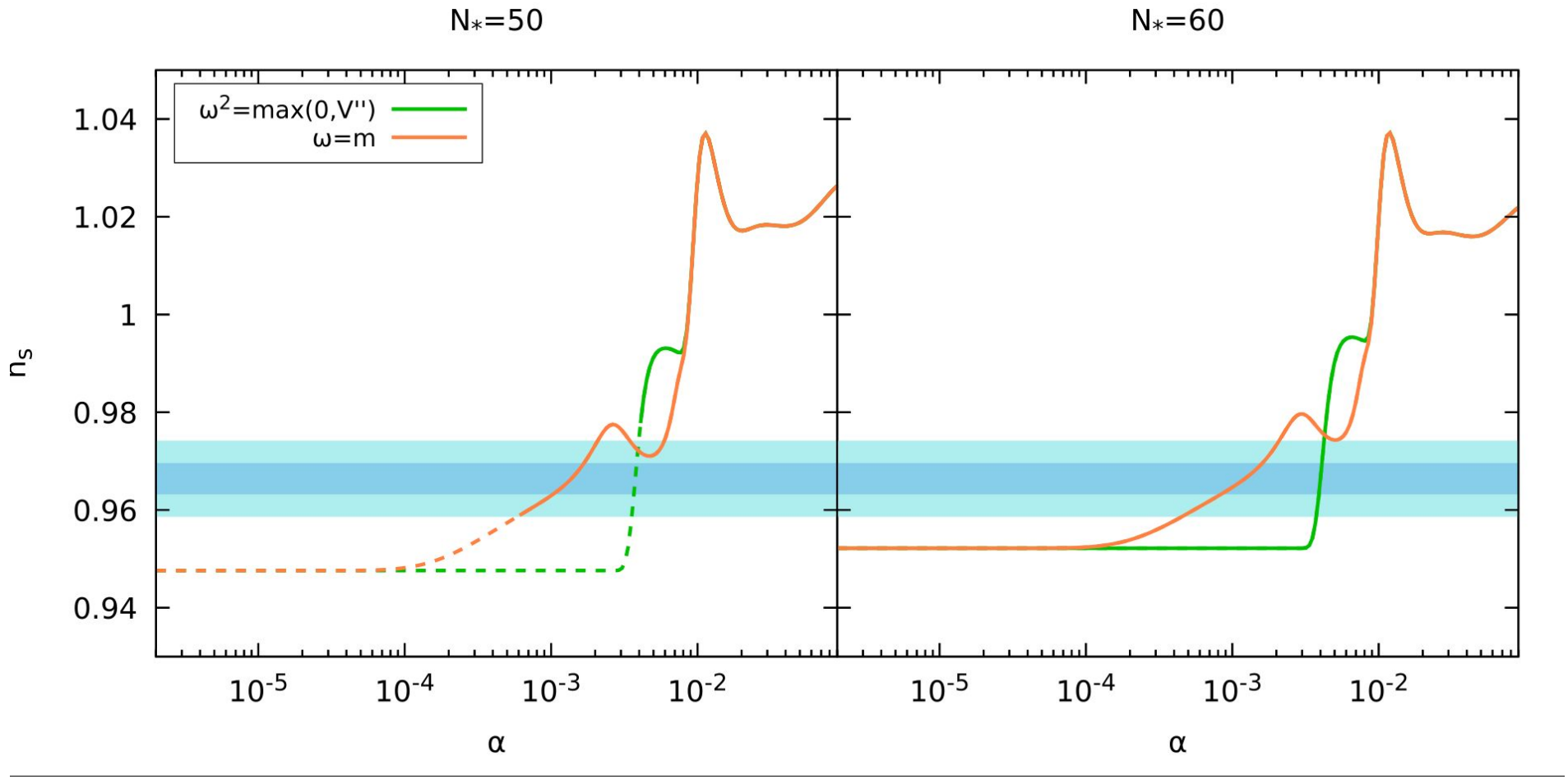
Backup slides

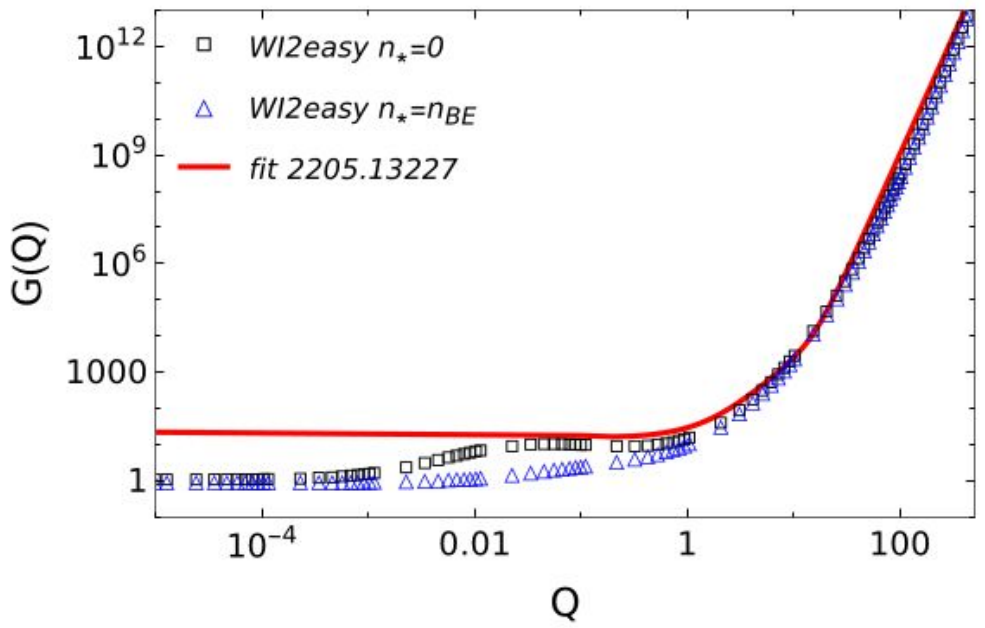
General relation from spectrum at horizon crossing , independent of the potential



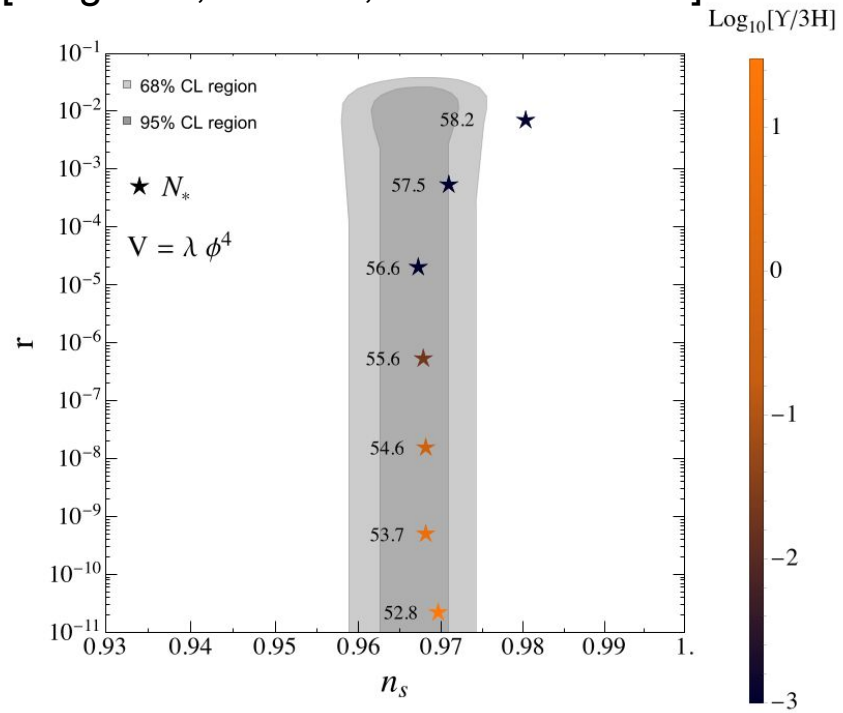
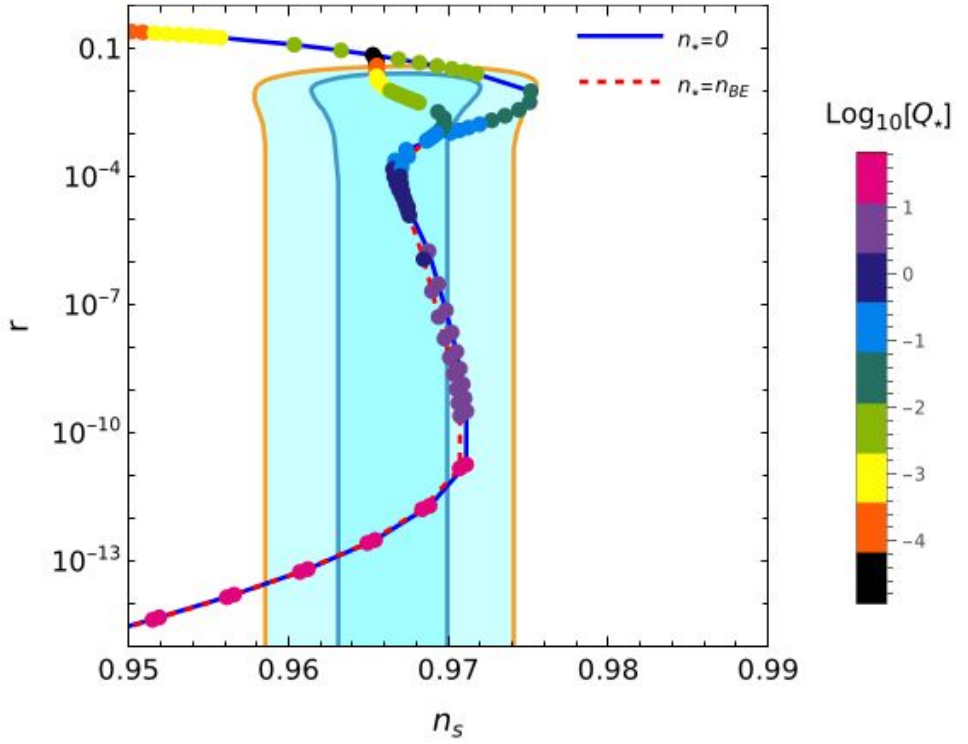

$f_a = 10^{12}$ GeV, $f_b = 5 m_P$
10^0
10^{-5}
10^{-10}
10^{-15}
10^{-20}
Q
Solid: no vacuum contribution to dissipation
$\alpha = 1.00 \cdot 10^{-3}$
$\alpha = 3.85 \cdot 10^{-3}$
$\alpha = 5.00 \cdot 10^{-3}$
-10
0
10
20
30
40
50
60
N

$f_a = 10^{12}$ GeV, $f_b = 5 m_P$





[Berghaus, Drewes, Zell 2503.18829]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