Not so minimal Warm Inflation

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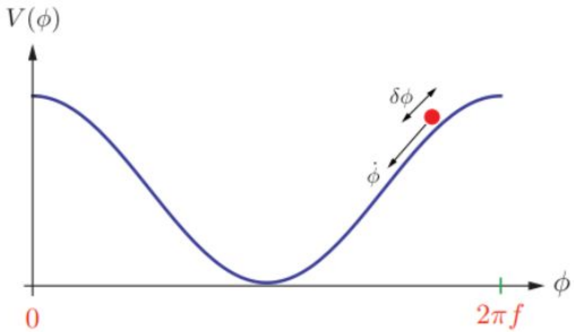
Not so Minimal Warm Inflation

Cold inflation/Warm inflation

Minimal WI with natural potential

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

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



Model building constrains: $f_a \ll f_b$

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...

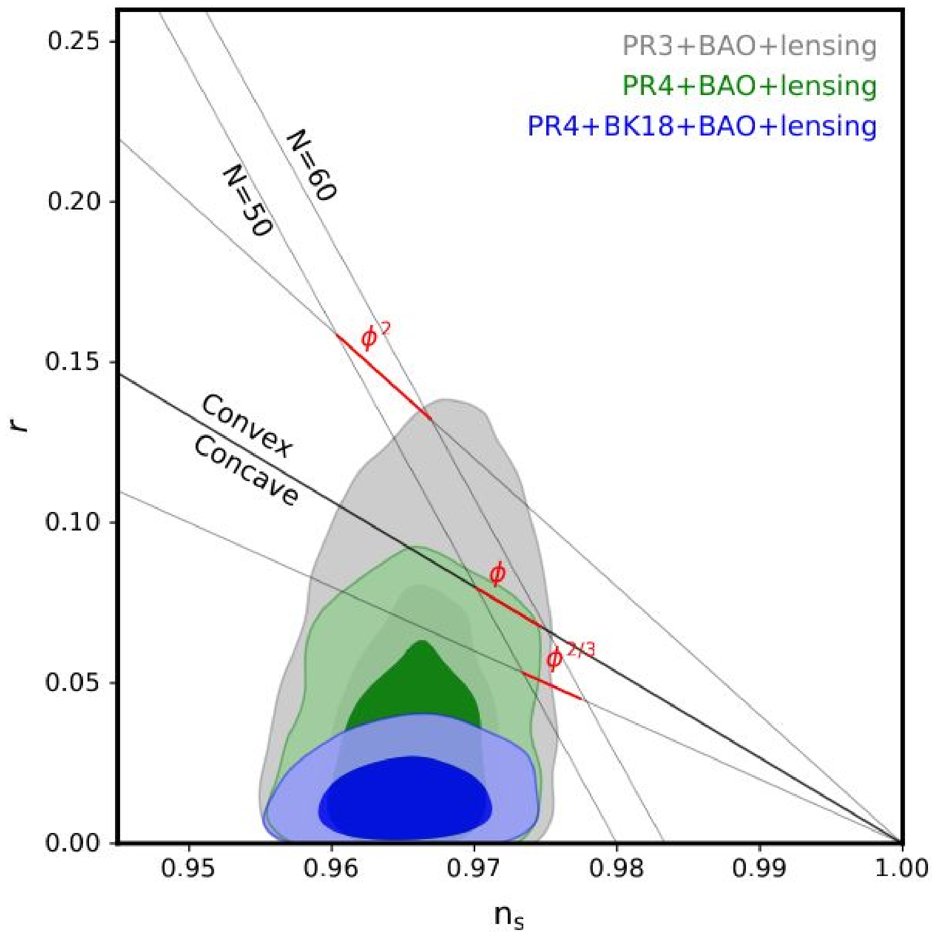
monopoles, moduli, gravitinos,...

[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 $\xrightarrow{\text{Reheating}}$ Radiation

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

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

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

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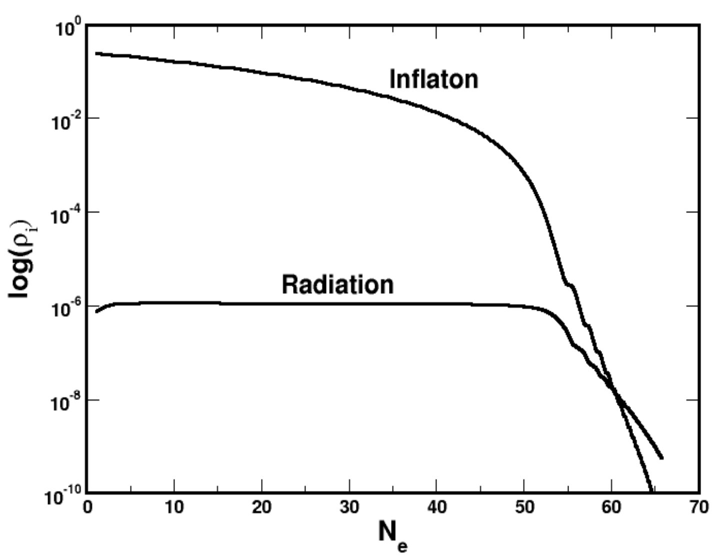
extra friction

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



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

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

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

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

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

$|\eta_{\phi}|<(1+Q)$, $\epsilon_{\phi}<(1+Q)$, $\delta_T = T V_{T\phi}/V_{\phi}<1$ 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_{ϕ}/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

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

Fermion (scalars) masses are bounded ➡ No thermal mass for the inflaton

- "Minimal Warm Inflation" :

[Berghaus, Graham, Kaplan 1910.07525]

Axion-like inflaton+ gauge production [SU(N)]

$$L = \cdots - g^2 \frac{\phi}{64\pi^2 f_a} \mathrm{Tr}\, G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

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

[Ferrerira & Notari 1711.07483; Kamali 1901.01897]

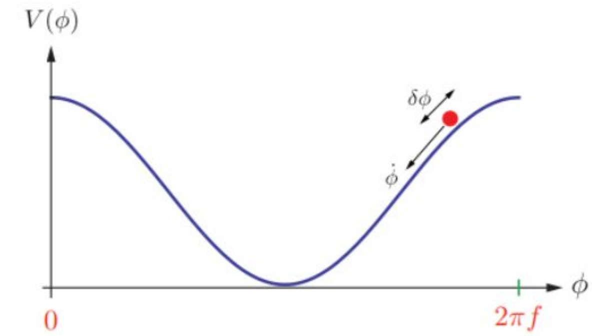
- Axion mass protected by shift symmetry at perturbative level; non-perturbative corrections axion mass ~ negligible

- Dissipative coefficient $\Upsilon \sim \frac{\Gamma_{sph}}{2 T f_a^2}$ 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

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)

[Laine & Procacci 2102.09913]

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

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

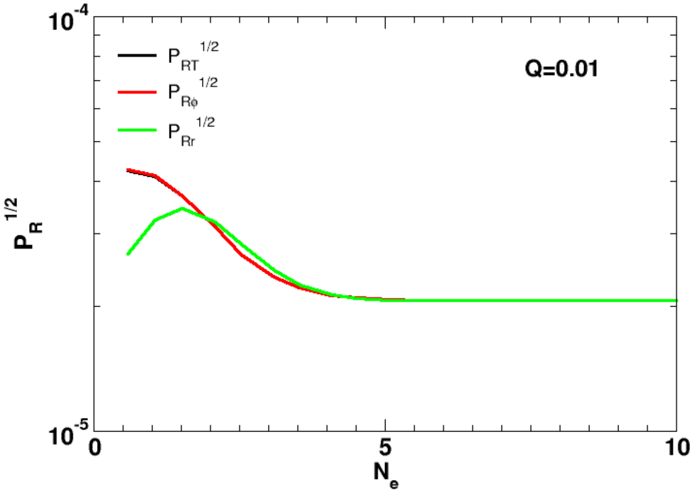
Thermal $[\omega \simeq m < \alpha^2 T]$ Vacuum $[\omega \simeq m \gg \alpha^2 T]$

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

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

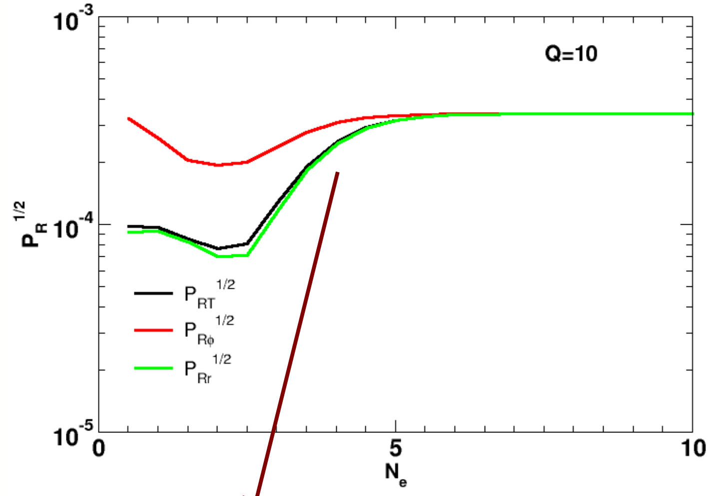
Fluctuations & primordial spectrum: coupled system

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



$G[Q]\simeq 1$

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



Growing mode!

Numerical integration

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

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

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]

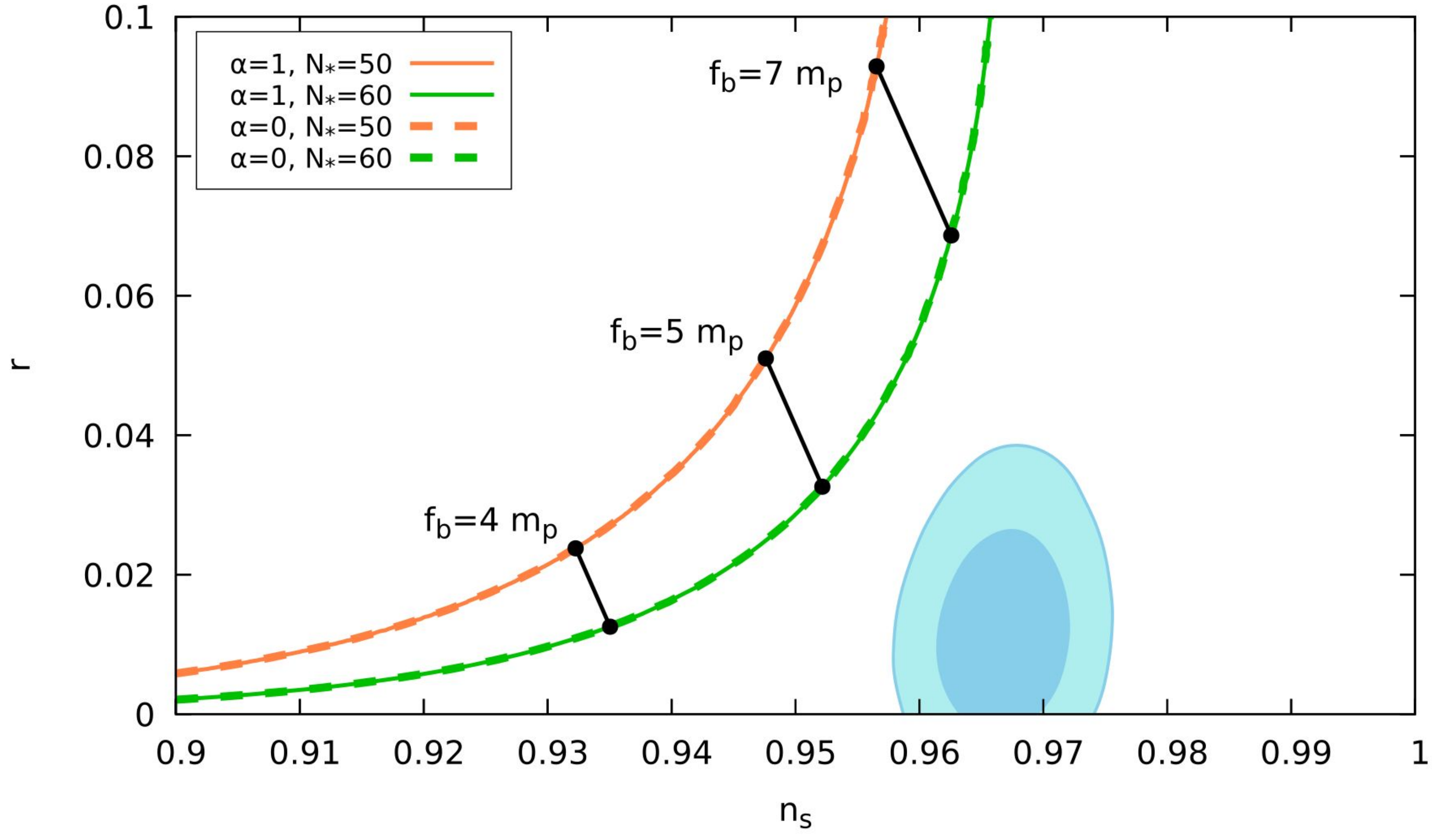
[WI2easy: Rodrigues, Ramos 2504.17760]

[SWIM: Kumar & Das 2604.24654]

[S. Zell 2408.07746]

- Natural potential+ dissipation: $f_a = f_b$

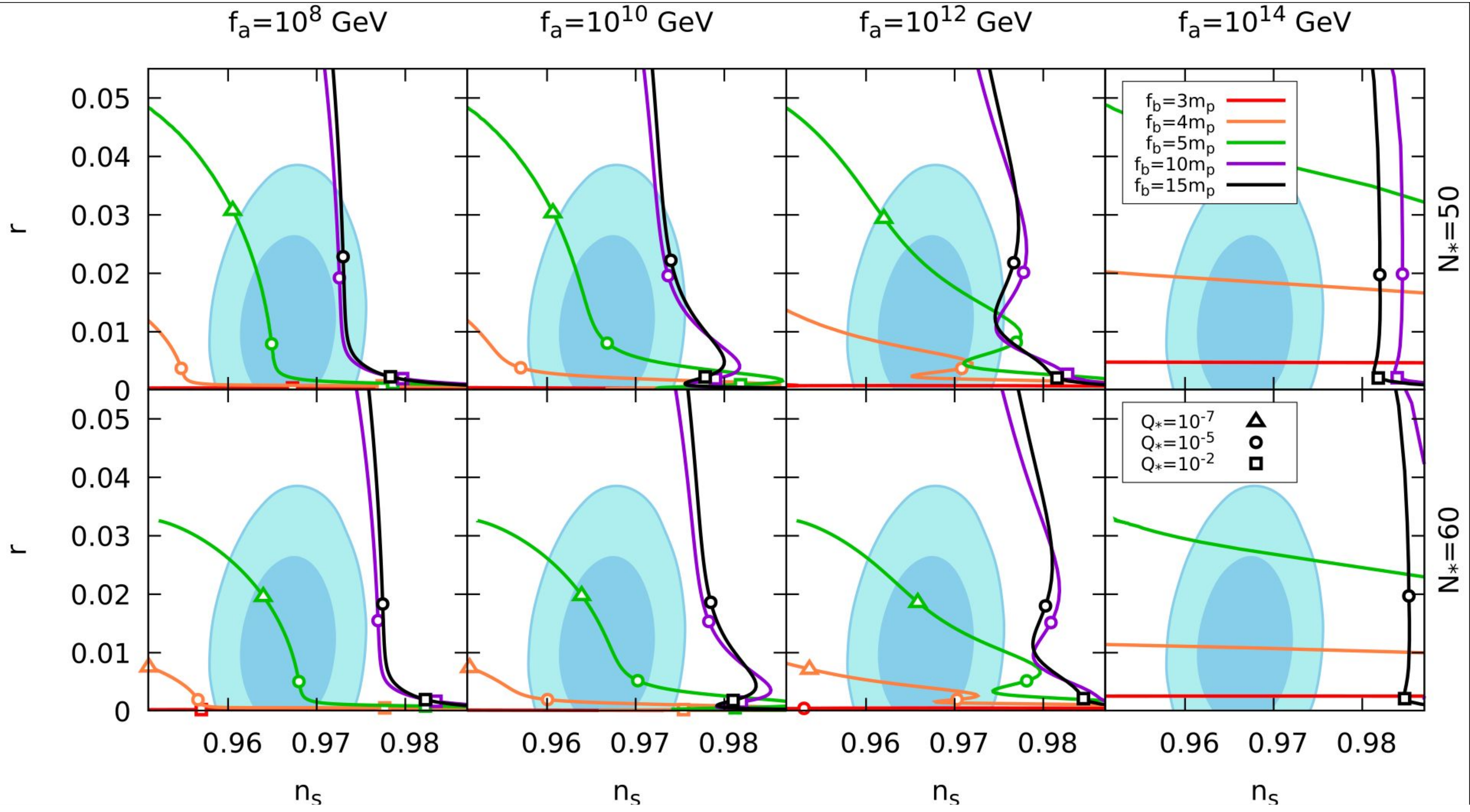
Dissipation suppressed during inflation, excluded by observations



How large the hierarchy between scales?

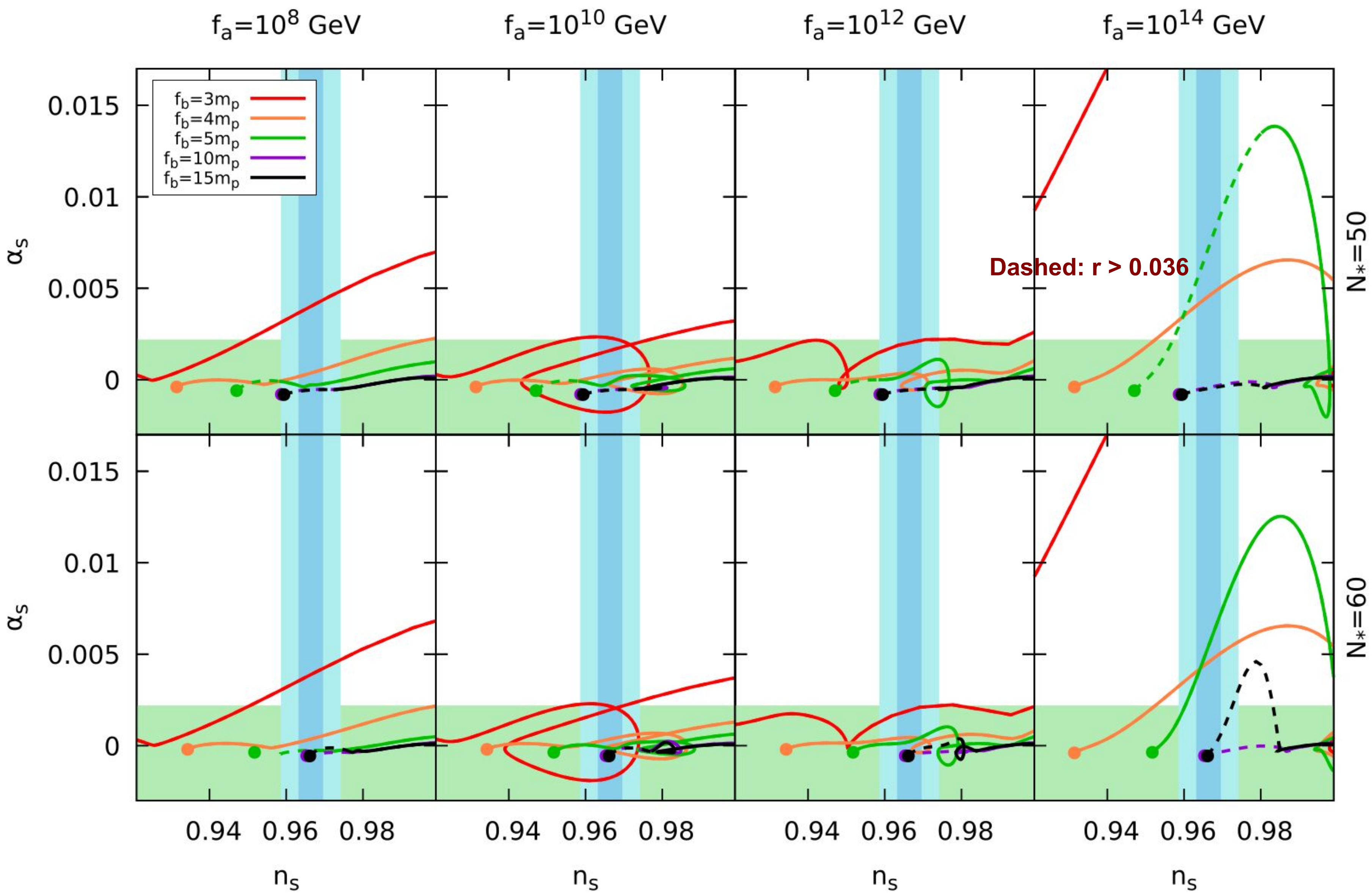
- Natural potential+ dissipation: $f_a << f_b$, weak dissipation, $f_b > m_P$

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



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

[Choi & Im 1511.00132; Kaplan & Rattazzi 1511.01827]

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

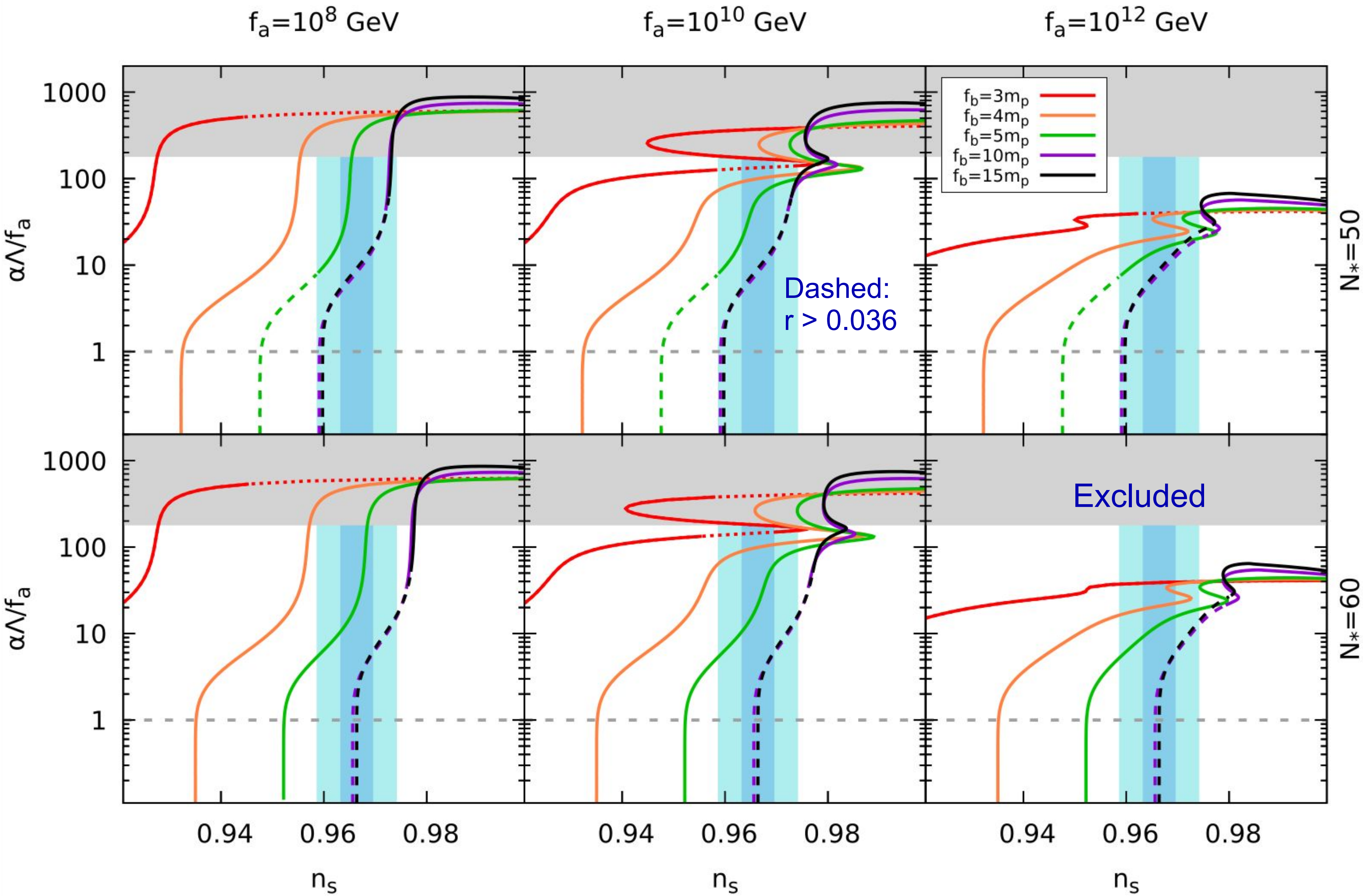
$$\Lambda < 32\pi^{3/2}\frac{f_a}{\alpha}$$

[Bagherian, Reece & Xu 2207.11262]

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

How large the hierarchy between scales?

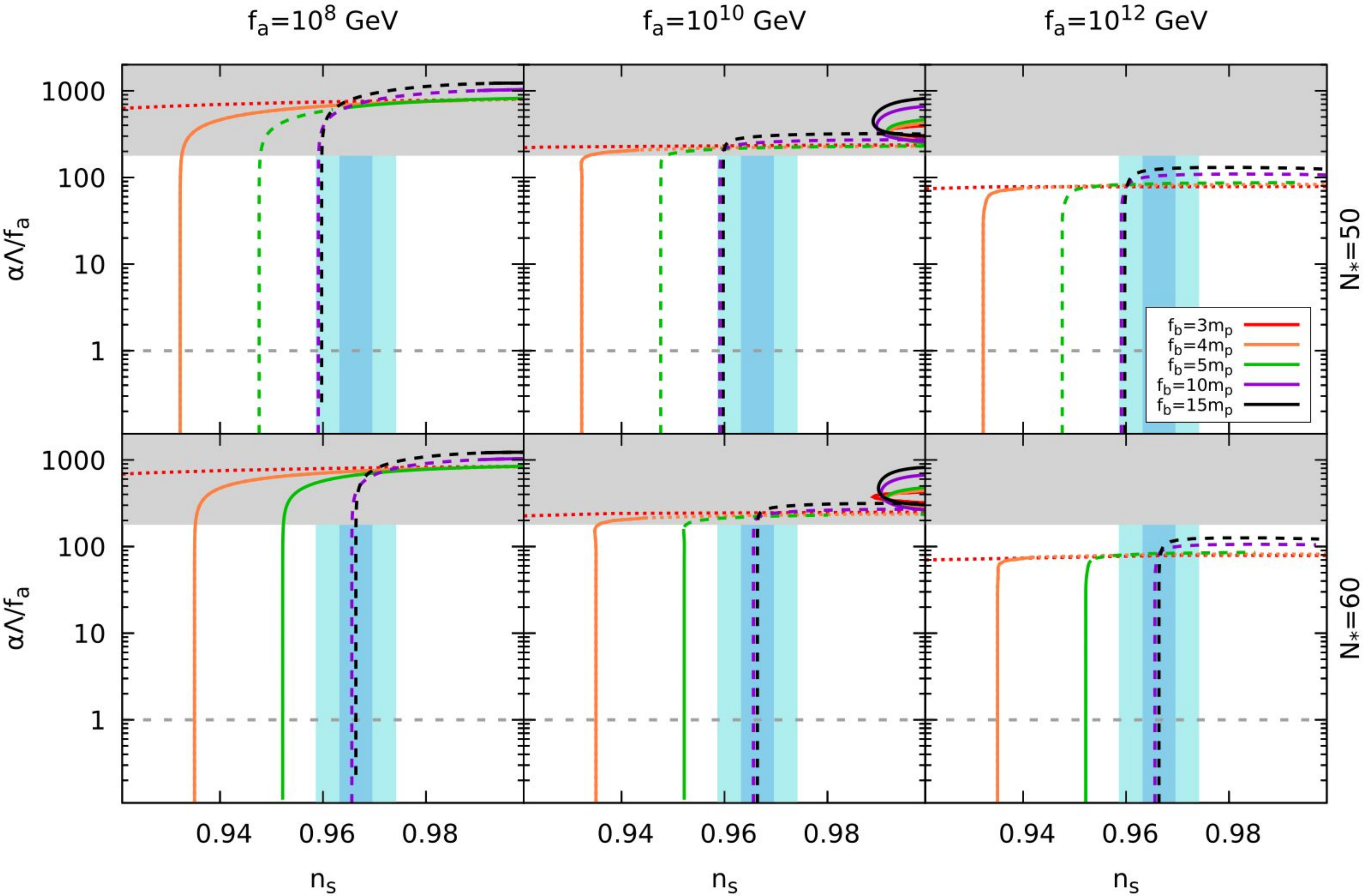
- Clockwork : $\Lambda < f_a \quad (\alpha < 1)$
- Unitarity bound : $\Lambda < 32\pi^{3/2} f_a/\alpha$



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

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

- Observations (CMB spectrum): only compatible in the WDR ($Q \ll 1$)

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

Clockwork mechanism not enough to explain the hierarchy

Compatible with unitarity bounds, but only with a thermal inflaton

Thank you!