Inflation and tachyonic preheating with twin waterfalls

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Classifying inflationary models

1. Initial conditions.

- Both old and new inflation used to rely on **initial thermal equilibrium.**

A.H. Guth, Phys. Rev. D23, 347 (1981)
A.D. Linde, Phys. Lett. 108B

- **Chaotic inflation** studies all possible initial conditions, even outside thermal eq.

2. Shape of the potential.

- Quasiexponential inflation, power law inflation, etc.

3. End of inflation.

- **Slow roll** (e.g. chaotic inflation in the theories ϕ^n)
- **Waterfall phase transition** (e.g. extended inflation scenario, hybrid inflation)

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Today's topic

Natural and Hybrid inflation

Natural inflation **[Phys. Rev. Lett. 65, 3233]**

Inflation = pNGb

$$V(\phi) = \Lambda^4 \left(1 \pm \cos\left(\phi/f\right)\right) \qquad f \sim M_P \qquad \Lambda \sim M_{\mathrm{GUT}}$$

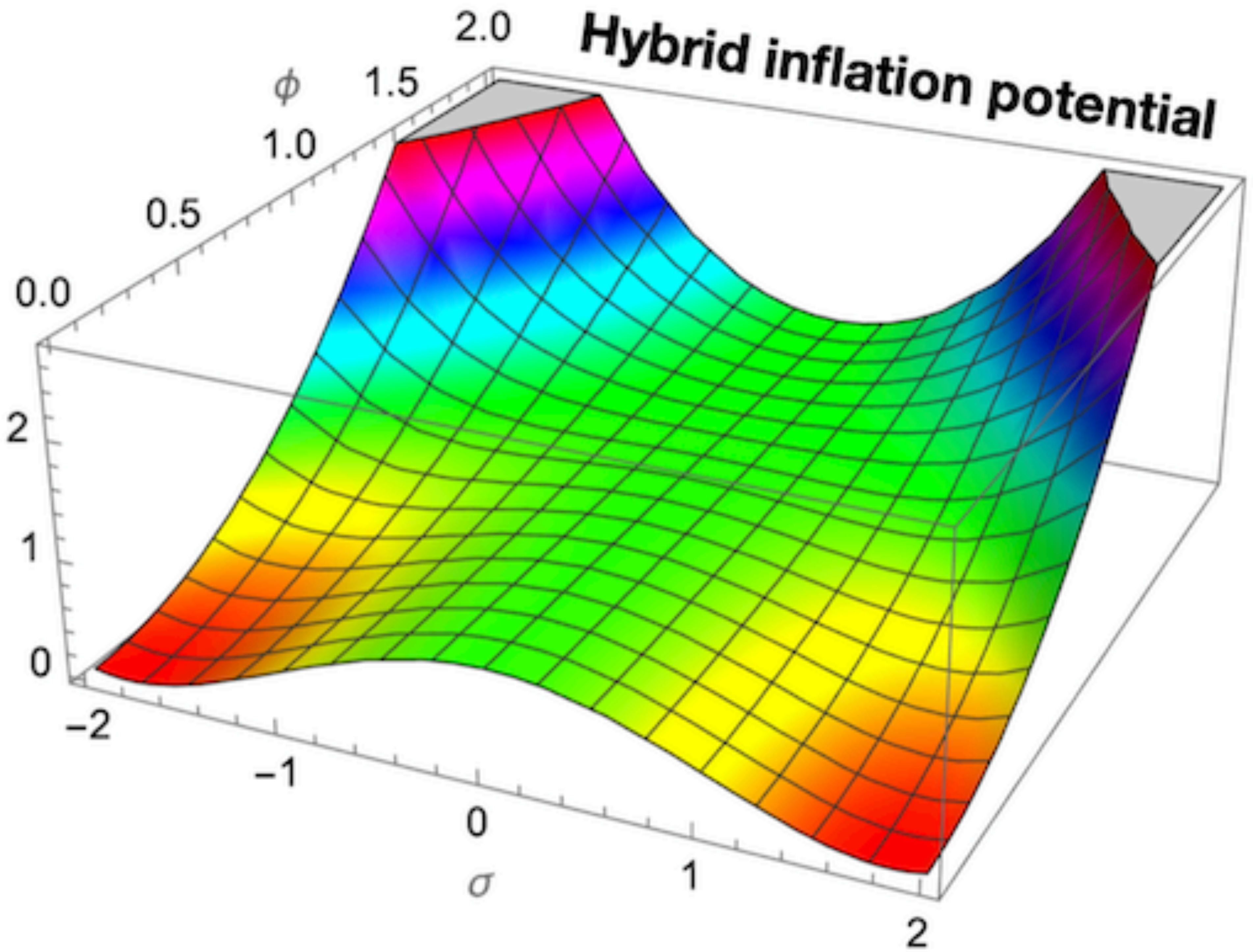
Hybrid inflation

$$V(\sigma,\phi) = \frac{1}{4\lambda}\left(M^2 - \lambda\sigma^2\right)^2 + \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\sigma^2$$

Ending stages **Chaotic inflation**

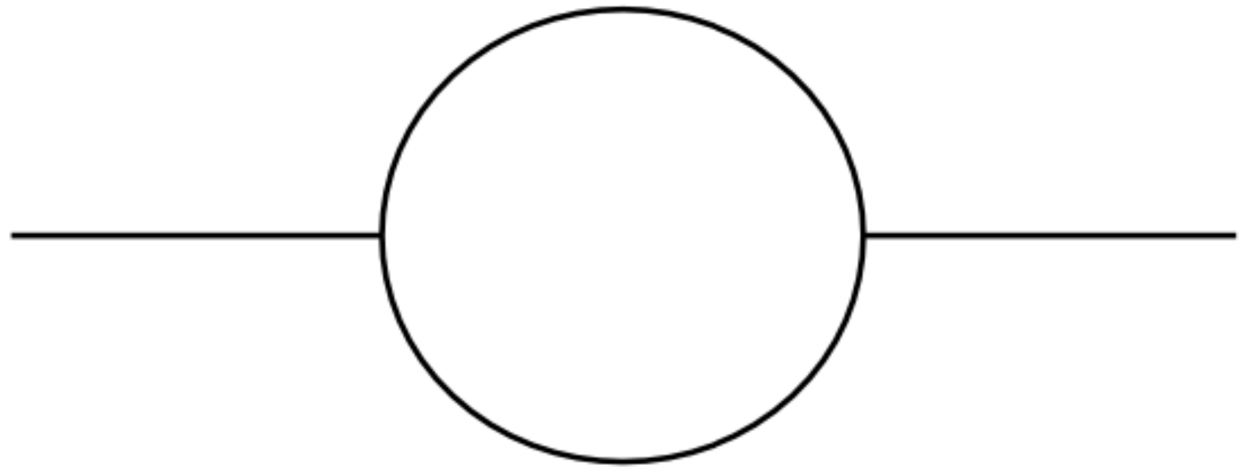
$$V(0,0) = \frac{M^4}{4\lambda}$$

$m_\sigma^2 = -M^2 + g^2\phi^2$ **becomes tachyonic for** $\phi < \phi_c = M/g$



Inflation ends due to a waterfall phase transition

η problem



The coupling $\frac{g^2}{2}\phi^2\sigma^2$ badly breaks the shift symmetry $\longrightarrow$ **Why is the inflation so light?**

$$\left(\delta m_\phi^2\right)_{1\,\text{loop}} \lesssim \left(\delta m_\phi^2\right)_{\text{tree}} \longrightarrow \Lambda^2 \lesssim \left(16\pi^2\eta\right)\frac{H}{g^2}$$ **Cut-off can not be arbitrarily large**

Frozen σ $\quad M^2_{\sigma,\text{eff}} \sim g^2\phi_0^2 \gtrsim H^2 \qquad \phi_0^2 \gtrsim \frac{\Lambda^2}{16\pi^2\eta} \qquad \eta \sim 10^{-2} \qquad \phi_0 \gtrsim \Lambda$

Excursion larger than the cutoff

Even in the marginal case $\quad \phi_0 \sim \Lambda \implies M^2_{\sigma,\text{eff}} \sim H^2 \qquad \langle\sigma\rangle \sim M_P$

EFT requires sub-Planckian fields

The model

$$V(\phi,\chi_1,\chi_2,H) = V_I(\phi) \quad + V_W(\phi,\chi_1,\chi_2) \quad + V_{\rm RH}(\chi_1,\chi_2,H)$$

Natural inflation **Hybrid inflation** **Reheating**

Slow-roll conditions and CMB set the symmetry breaking scale beyond M_P.

But the **Weak Gravity Conjecture** rules out a Trans-planckian axion decay constant f

In the presence of waterfall fields with a Z_2 **mirror symmetry** this can be avoided.

$$\phi \longrightarrow -\phi, \qquad \chi_1 \longleftrightarrow \chi_2$$

The model

$$V(\phi,\chi_1,\chi_2,H) = V_I(\phi) \quad +V_W(\phi,\chi_1,\chi_2) \quad +V_{\mathrm{RH}}(\chi_1,\chi_2,H)$$

Natural inflation — **Hybrid inflation** — **Reheating**

$$V_I(\phi) = V_0 + A(\phi)$$

$$V_{\mathrm{RH}}(\chi_1,\chi_2,H) = \kappa_1(\chi_1^2+\chi_2^2)|H|^2 + \kappa_2\chi_1\chi_2|H|^2 .$$

$$A(-\phi) = A(\phi)$$
$$B(-\phi) = -B(\phi)$$

$$V_W(\phi,\chi_1,\chi_2) = B(\phi)(\chi_1^2-\chi_2^2) + \frac{1}{2}m_\chi^2(\chi_1^2+\chi_2^2) - \alpha^2\chi_1\chi_2$$
$$+\beta(\chi_1^3+\chi_2^3) + \gamma(\chi_1^2\chi_2+\chi_1\chi_2^2)$$
$$+\frac{1}{4}\lambda_\chi(\chi_1^4+\chi_2^4) + \frac{1}{2}\bar{\lambda}_\chi\chi_1^2\chi_2^2 + \frac{1}{3}\lambda'_\chi(\chi_1^3\chi_2+\chi_1\chi_2^3)$$

$\phi^2(\chi_1^2+\chi_2^2)$ **suppressed**

Symmetries $\quad \phi \longrightarrow -\phi, \quad \chi_1 \longleftrightarrow \chi_2$

Z_2 **protects the inflationary potential against quantum corrections**

Origin of the Z2 symmetry $\quad Z_4\times \mathrm{CP}: \quad \phi \to -\phi, \quad \Phi \to i\Phi^*, \quad H \to H$

$$\boxed{\Phi = \frac{1}{\sqrt{2}}(\chi_1 + i\chi_2)}$$

Similar constructions

[JHEP 07 (2021) 147 - Deshpande, Kumar, Sundrum]

[J.O. Gong, K.S. Jeong, Phys.Rev.D 104 (2021)]

Extra Z_2' symmetry

$$Z_2' : \quad \phi \to \phi, \qquad \chi_1 \to \chi_1, \qquad \chi_2 \to -\chi_2,$$

$\alpha = \beta = \gamma = \lambda_\chi' = 0$

$$V_W(\phi, \chi_1, \chi_2) = B(\phi)(\chi_1^2 - \chi_2^2) + \frac{1}{2} m_\chi^2 (\chi_1^2 + \chi_2^2) \cancel{- \alpha^2 \chi_1 \chi_2} \cancel{+ \beta(\chi_1^3 + \chi_2^3)} + \cancel{\gamma(\chi_1^2 \chi_2 + \chi_1 \chi_2^2)}$$
$$+ \frac{1}{4} \lambda_\chi (\chi_1^4 + \chi_2^4) + \frac{1}{2} \bar{\lambda}_\chi \chi_1^2 \chi_2^2 + \cancel{\frac{1}{3} \lambda_\chi' (\chi_1^3 \chi_2 + \chi_1 \chi_2^3)},$$

χ_2 **becomes a stable candidate for DM**

Dark QCD

Microscopic model that realizes inflation

$$\mathscr{L}_{dQCD} = -m_u u_1 u_1^c - m_u u_2 u_2^c - y\Phi_1 u_1^c d - y'\Phi_1 u_1 d^c - iy\Phi_2 u_2^c d - iy'\Phi_2^* u_2 d^c + \mathrm{h.c.}$$

Z_2 **symmetry:** $\Phi_1 \to i\Phi_2$ **and** $\Phi_2 \to -i\Phi_1$

χ_1 **and** χ_2 **in our model are the real parts of** Φ_1 **and** Φ_2

After QCD condensation

$$\mathscr{L}_{\mathrm{eff}} = \frac{1}{2}\mu^2(\chi_1^2 - \chi_2^2)\sin\left(\frac{\phi}{2f}\right)$$

The Z_2 symmetry remains unbroken

Potential for the waterfalls arises from

$$\Delta V_W = m_\chi^2(|\Phi_1|^2 + |\Phi_2|^2) + \lambda_\chi(|\Phi_1|^4 + |\Phi_2|^4) + 2\bar{\lambda}_\chi |\Phi_1|^2 |\Phi_2|^2$$

Z_2 and $i\left(\Phi_1\Phi_2^\dagger - \Phi_2\Phi_1^\dagger\right)$ invariant

Exit from inflation

Time dependent waterfall masses

$$m_1^2(\phi) = m_\chi^2 - \sqrt{B^2(\phi) + \alpha^4}$$

$$m_2^2(\phi) = m_\chi^2 + \sqrt{B^2(\phi) + \alpha^4}$$

Mass mixing

$$\sin 2\theta(\phi) = \frac{2\alpha^2}{m_2^2(\phi) - m_1^2(\phi)}$$

No mixing for $\alpha = 0$ $\longrightarrow$ χ_1 **determines the end of inflation**

We take the values $A(\phi) = \Lambda^4 \cos\left(\frac{\phi}{f}\right)$ $\quad B(\phi) = -\frac{1}{2}\mu^2 \sin\left(\frac{\phi}{2f}\right)$ $\longrightarrow$ **Shift symmetry broken to a discrete one**

$$\phi \to \phi + 4\pi f$$

End of inflation $\boxed{\phi_c = 2f \arcsin\left(\sqrt{m_\chi^4 - \alpha^4}/\mu^2\right)}$

***Slow-roll conditions still hold!**

UV insensitivity

$$V_{\rm CW} = \frac{1}{64\pi^2}\sum_{i=1,2}\left[2m_{\chi_i}^2 M_*^2 - m_{\chi_i}^4 \ln\left(\frac{e^{\frac{1}{2}}M_*^2}{m_{\chi_i}^2}\right)\right] \simeq \frac{1}{16\pi^2}m_\chi^2 M_*^2 \qquad -\frac{1}{64\pi^2}\left(m_\chi^4 + 4B^2(\phi) + \alpha^4\right)\ln\frac{M_*^2}{m_\chi^2}$$

$$B^2(\phi) \lesssim 16\pi^2 |A(\phi)|$$

Constant vacuum energy must be renormalized

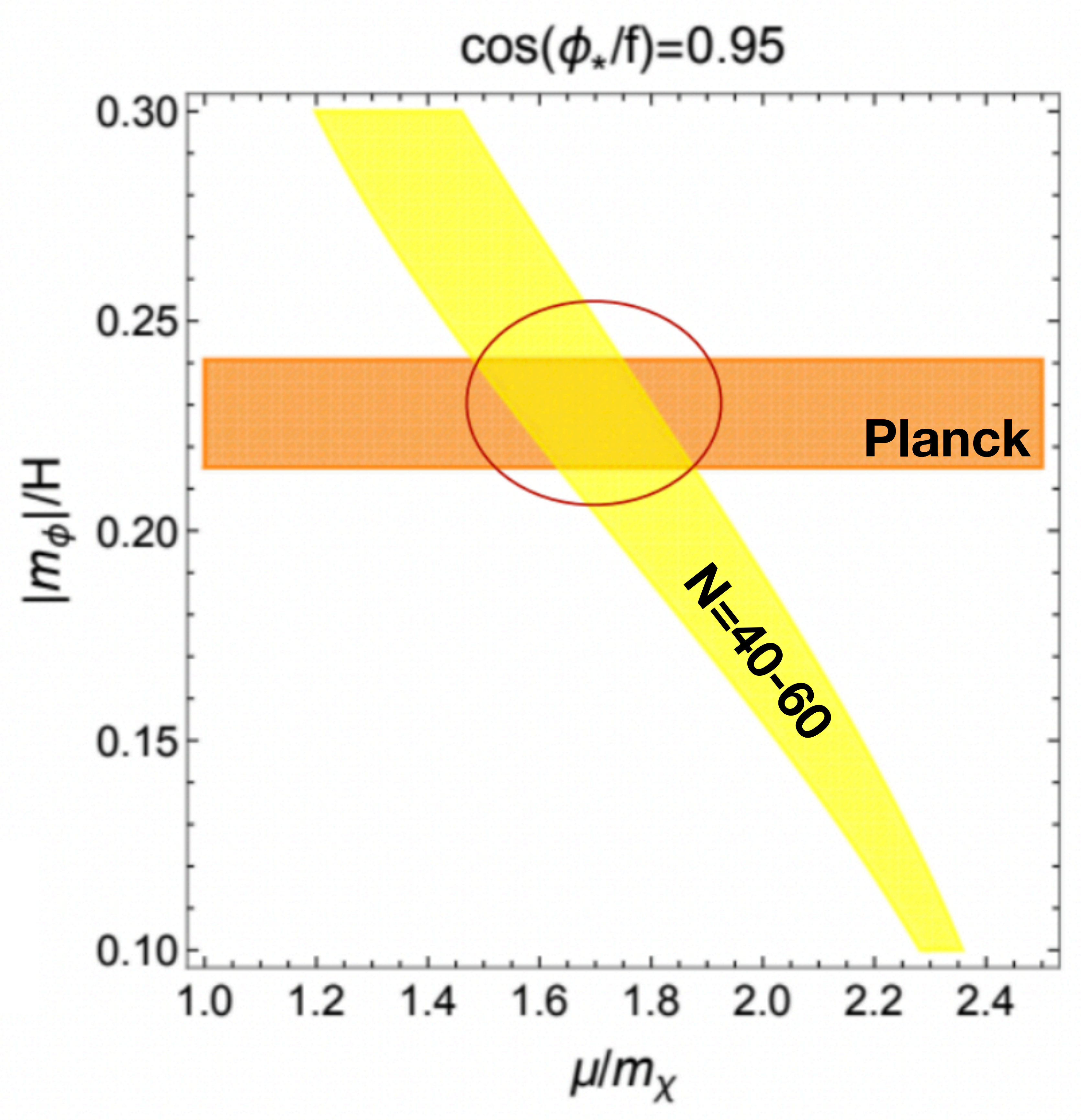
For our particular case

$$A(\phi) = \Lambda^4 \cos\left(\frac{\phi}{f}\right),$$

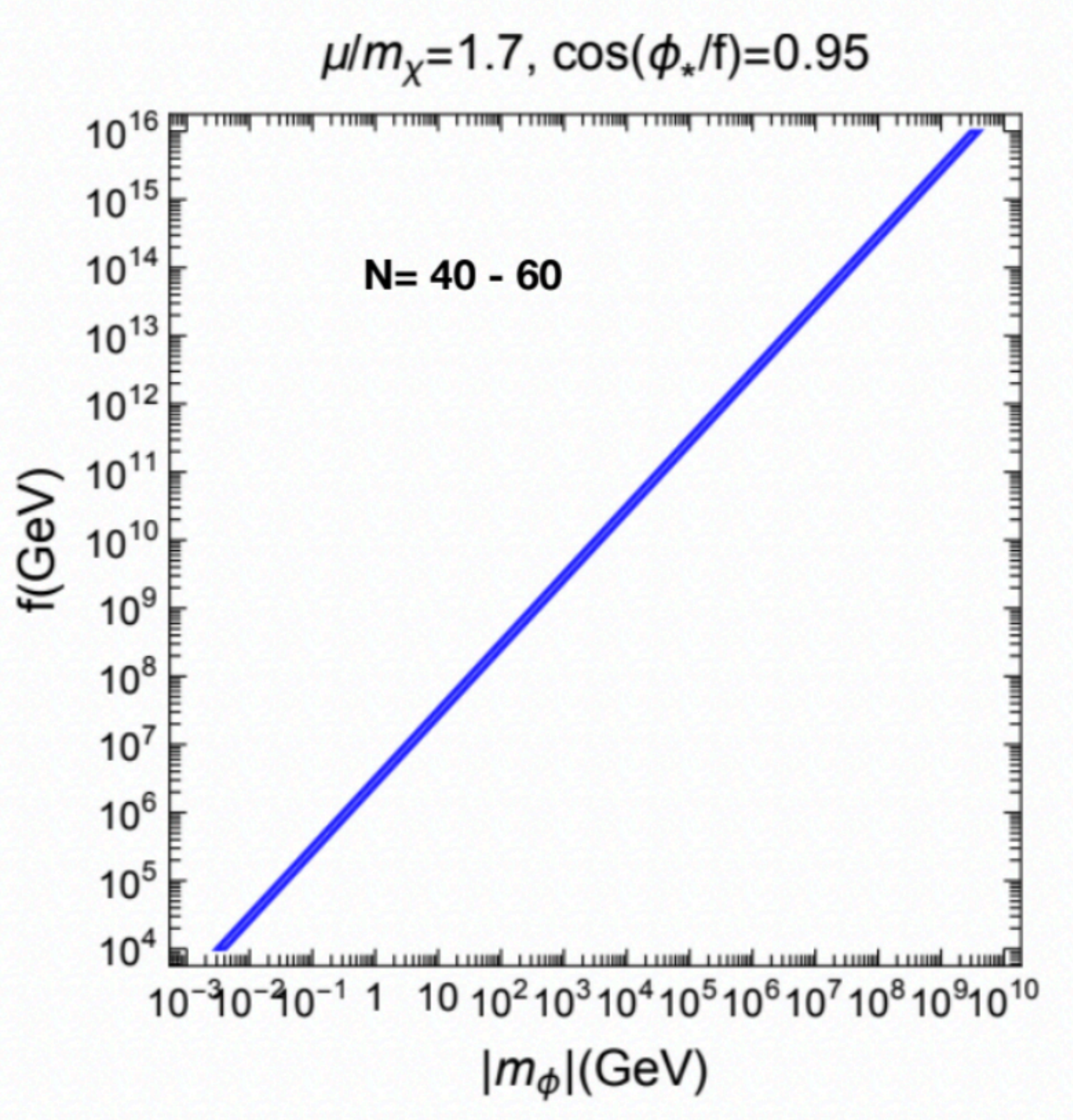
$$B(\phi) = -\frac{1}{2}\mu^2 \sin\left(\frac{\phi}{2f}\right)$$

$\mu^2 \lesssim 8\pi\Lambda^2$ **Ensures control of the log divergences during inflation**

Inflationary predictions



$r < 0.036 \implies H_I < 4.6 \times 10^{13}\,\text{GeV}$



$f \simeq 6.4 \times 10^5 H_I$

The symmetry responsible for the PNGB is broken during inflation

Vacuum structure

$$v_\phi = \pi f$$

Z_2' **symmetry for** χ_2

$$v_\chi = \sqrt{\frac{\mu^2 - m_\chi^2}{\lambda_\chi}}$$

χ_2 **is a DM candidate**

$$\lambda_\chi = \frac{m_1^4}{4V_0} = 1.4 \times 10^{-20}\left(\frac{m_1}{100H_I}\right)^4\left(\frac{H_I}{10^5\,\mathrm{GeV}}\right)^2$$

$$v_\chi = \sqrt{\frac{4V_0}{m_1^2}} = 0.035 M_P\left(\frac{100H_I}{m_1}\right)$$

$H_I \lesssim 1.6 \times 10^{10}\,\mathrm{GeV}$ **for** $f \lesssim 10^{16}\,\mathrm{GeV}$

$\boxed{\lambda_\chi < 10^{-10} \text{ for } m_1 \gtrsim 100H_I}$

$v_\chi \sim 0.035 M_P$

The inflation mass receives corrections from the waterfall couplings

$$m_a^2 = 0.0495 H_I^2 + (3 \times 10^{-9})\left(\frac{r^2}{r^2 - 1}\right)\left(\frac{m_1}{100H_I}\right)^2 v_\chi^2$$

$m_1^2 = \lambda_\chi v_\chi^2$

Inflation mass much heavier → settles fast in the minimum

Preheating

$m_1 \gg H_I$

Preheating takes less than a Hubble time

Right after the end of inflation $\varphi = a\psi$ $\psi = H, \chi_2$

$$\varphi'' - \partial_i^2 \varphi + \left(m_{\psi,\mathrm{eff}}^2 a^2 + (6\zeta_\psi - 1)\frac{a''}{a} \right)\varphi = 0$$

Non minimal coupling

Particles produced during the waterfall transition $n_\psi = \frac{1}{2\pi^2}\int_0^\infty dk\, k^2 n_k^\psi$

$$n_k^\psi = -\frac{g_\psi}{2} + \frac{1}{2\omega_k}\left(|v_k'|^2 + \omega_k^2 |v_k|^2 \right), \quad \omega_k^2 = k^2 + m_{\psi,\mathrm{eff}}^2$$

Ansatz $$m_{\psi,\mathrm{eff}}^2(t) = m_{\psi,0}^2 + \frac{1}{4}c_\psi v_\chi^2 (1 + \tanh \lambda(t - t_*))^2$$

[Garcia-Bellido, Ruiz Morales, Phys. Lett. B 536 (2002)]

Strength of the waterfall transition

$$\lambda = m_1/2 = \sqrt{\lambda_\chi} v_\chi/2$$

Preheating

$$(m_{\psi,\mathrm{eff}}^2 a^2)(\eta) = m_{\psi,0}^2 + \frac{1}{4} c_\psi v_\chi^2 (1 + \tanh \lambda(\eta - \eta_*))^2$$

$\psi = H, \chi_2$

Analytic

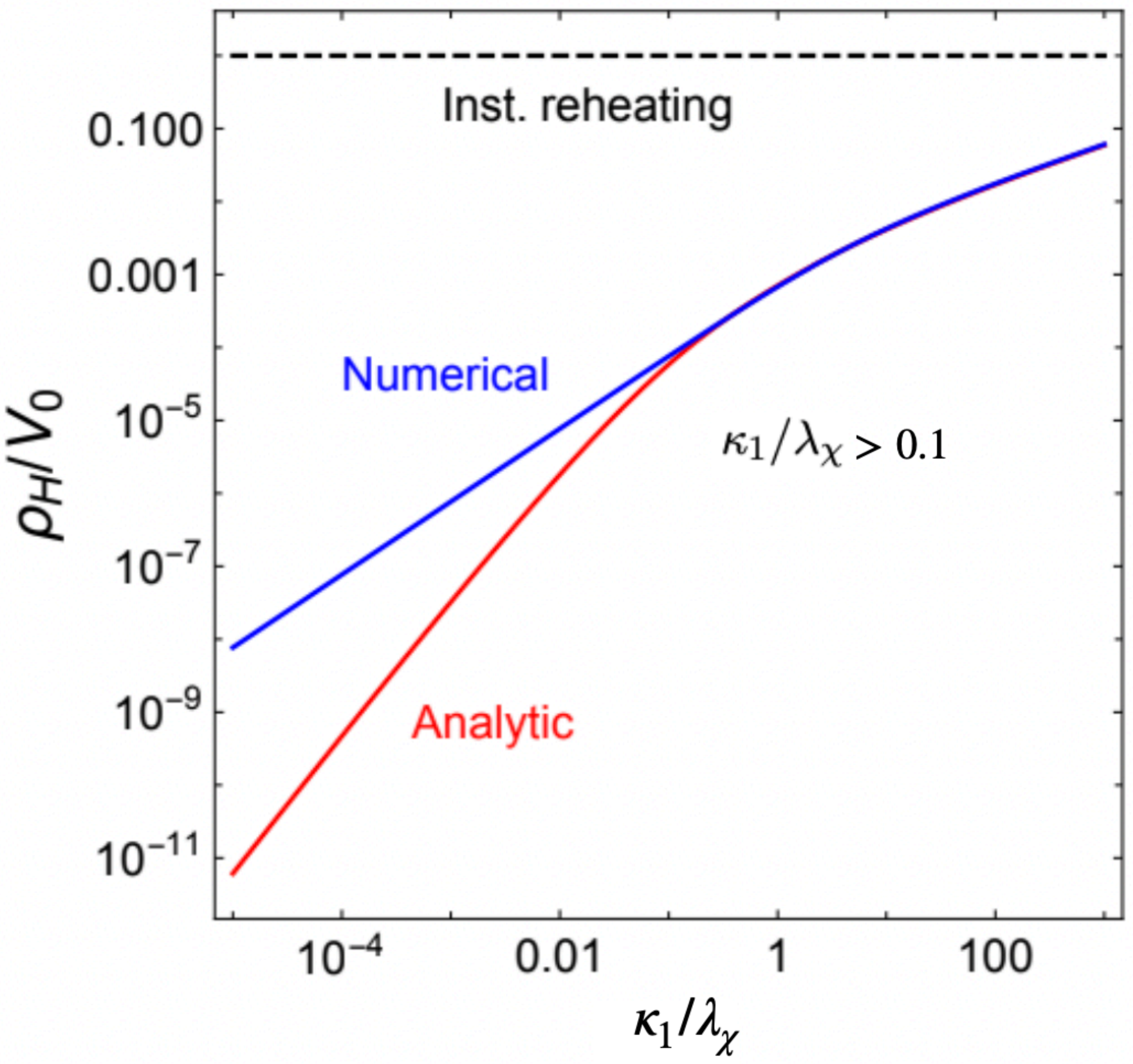
$$\frac{\rho_\psi}{V_0} = \frac{2 g_\psi \lambda_\chi}{\pi^2} \int_0^\infty d\kappa\, \kappa^2 n_k^\psi \sqrt{\kappa^2 + \frac{m_{\psi,0}^2}{m_1^2} + \alpha_\psi}$$

Numerical

$$\frac{\rho_\psi}{V_0} = 2 \times 10^{-3} g_\psi \lambda_\chi \underline{f(\alpha_\psi, 1.3)}$$

Fitting function

$$f(\alpha, \gamma) = \sqrt{\alpha + \gamma^2} - \gamma$$



Perturbative reheating

$$\mathscr{L}_{\rm int} = \frac{\mu^2}{8f^2} v_\chi a^2 \tilde{\chi}_1 + \frac{\mu^2}{16f^2} a^2(\tilde{\chi}_1^2 - \chi_2^2) - \bar{\lambda}_\chi v_\chi \tilde{\chi}_1 \chi_2^2 - \kappa_1 v_\chi \tilde{\chi}_1 h^2 + \cdots$$

$\tilde{\chi}_1 \nrightarrow aa$

$\tilde{\chi}_1 \nrightarrow \chi_2\chi_2$

Closed channels

$\chi_1 \rightarrow hh$ **Reheating**

For non instantaneous reheating

$$N = 51.3 - \frac{1}{3}\ln\left(\frac{H_I}{1.6\times 10^{10}\,\mathrm{GeV}}\right) - \boxed{\frac{1}{12}\ln\left(1 - \frac{\rho_R(t_*)}{V_0}\right)} + \frac{1}{3}\ln\left(\frac{\boxed{T_{\rm RH}}}{10^{14}\,\mathrm{GeV}}\right)$$

Radiation produced during preheating

$T_{\rm RH} \ll 10^{14}\,\mathrm{GeV}$ **for** $f \lesssim 10^{16}\,\mathrm{GeV}$

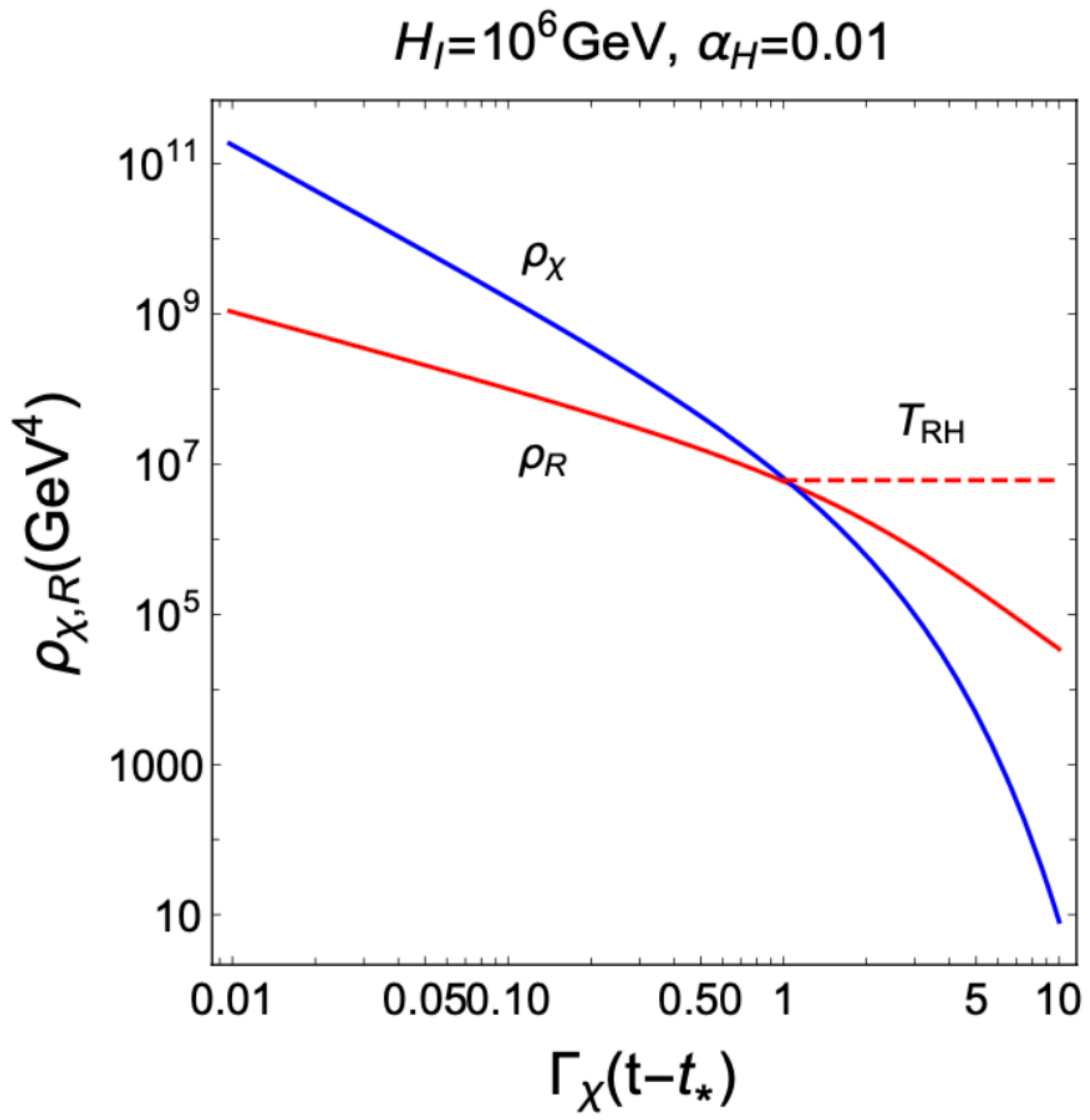
Radiation energy density

After preheating

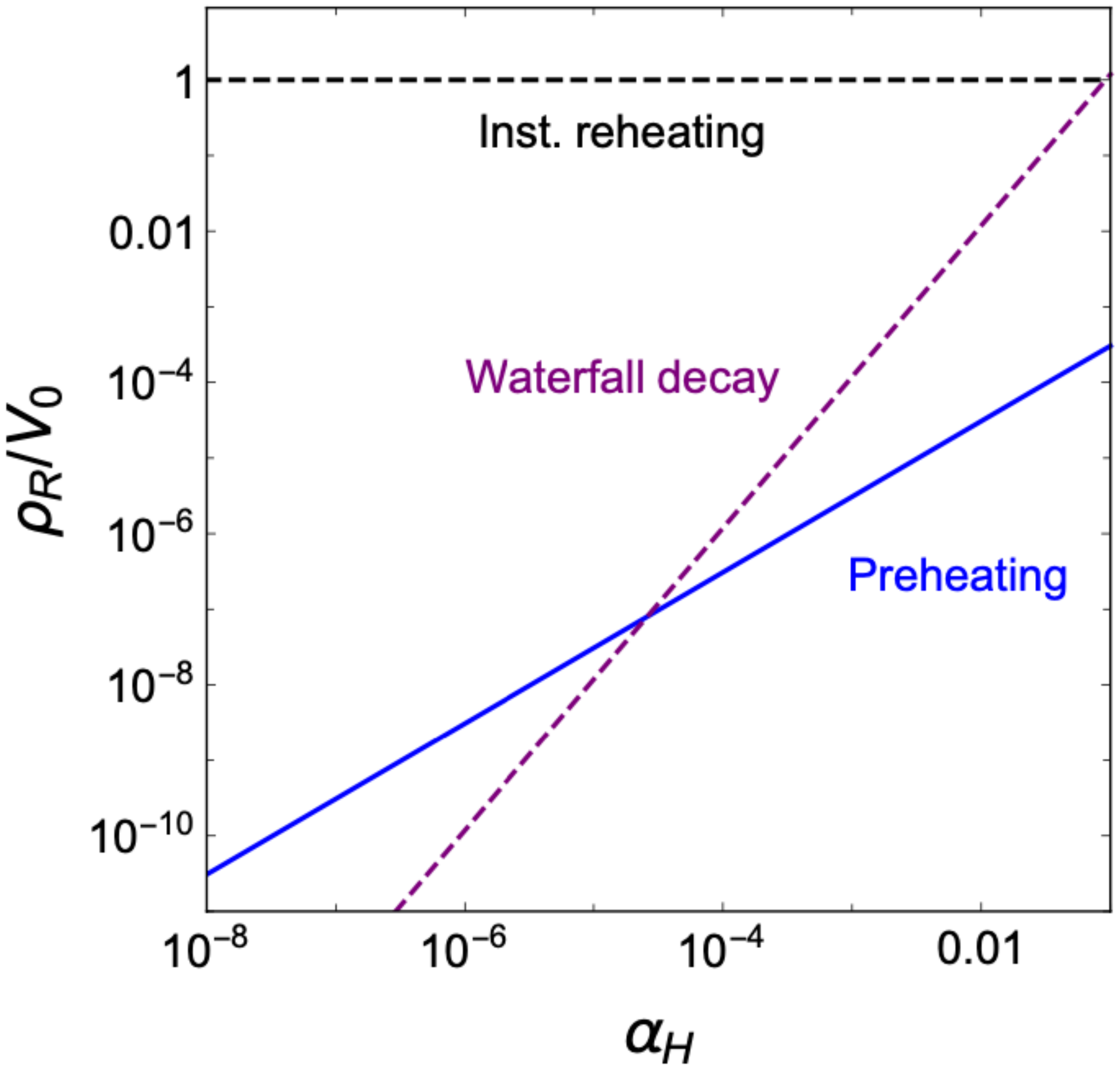
$$\rho_R(t) = \rho_{\chi_1}(t_*)\left(1+\frac{v}{A}\right)^{-8/3}\left[\frac{\rho_R(t_*)}{\rho_{\chi_1}(t_*)} + \boxed{\int_0^v \left(1+\frac{v'}{A}\right)^{2/3} e^{-v'}\,dv'}\right]$$

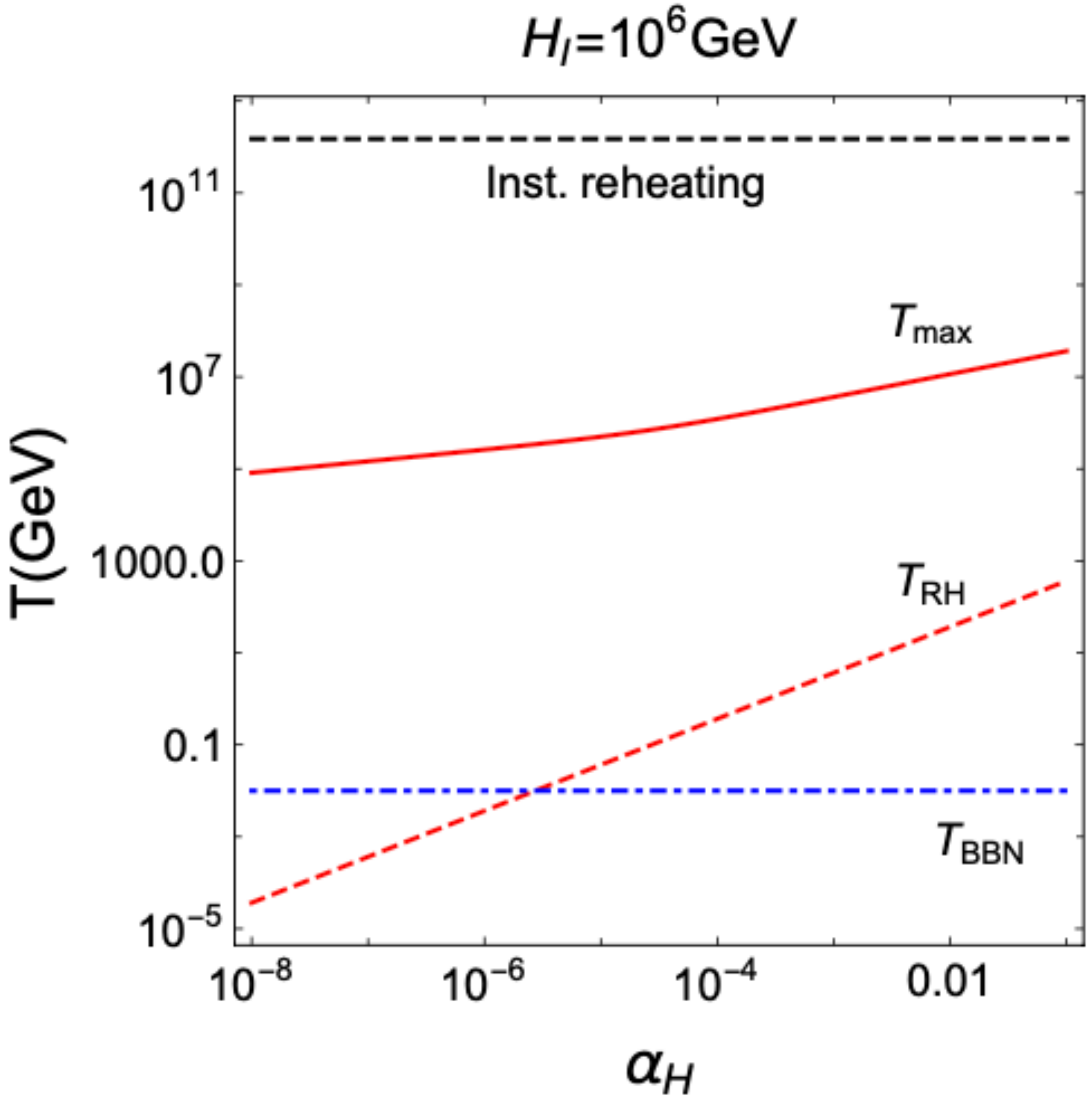
$$\rho_R(t_{\max}) = 1.8^{-8/3}\left(\rho_R(t_*) + 1.0A\rho_{\chi_1}(t_*)\right)$$

$$A = 4\sqrt{\frac{2}{3}}\frac{\Gamma_{\chi_1}}{m_{\chi_1}}\left(\frac{v_\chi}{M_P}\right)^{-1}$$



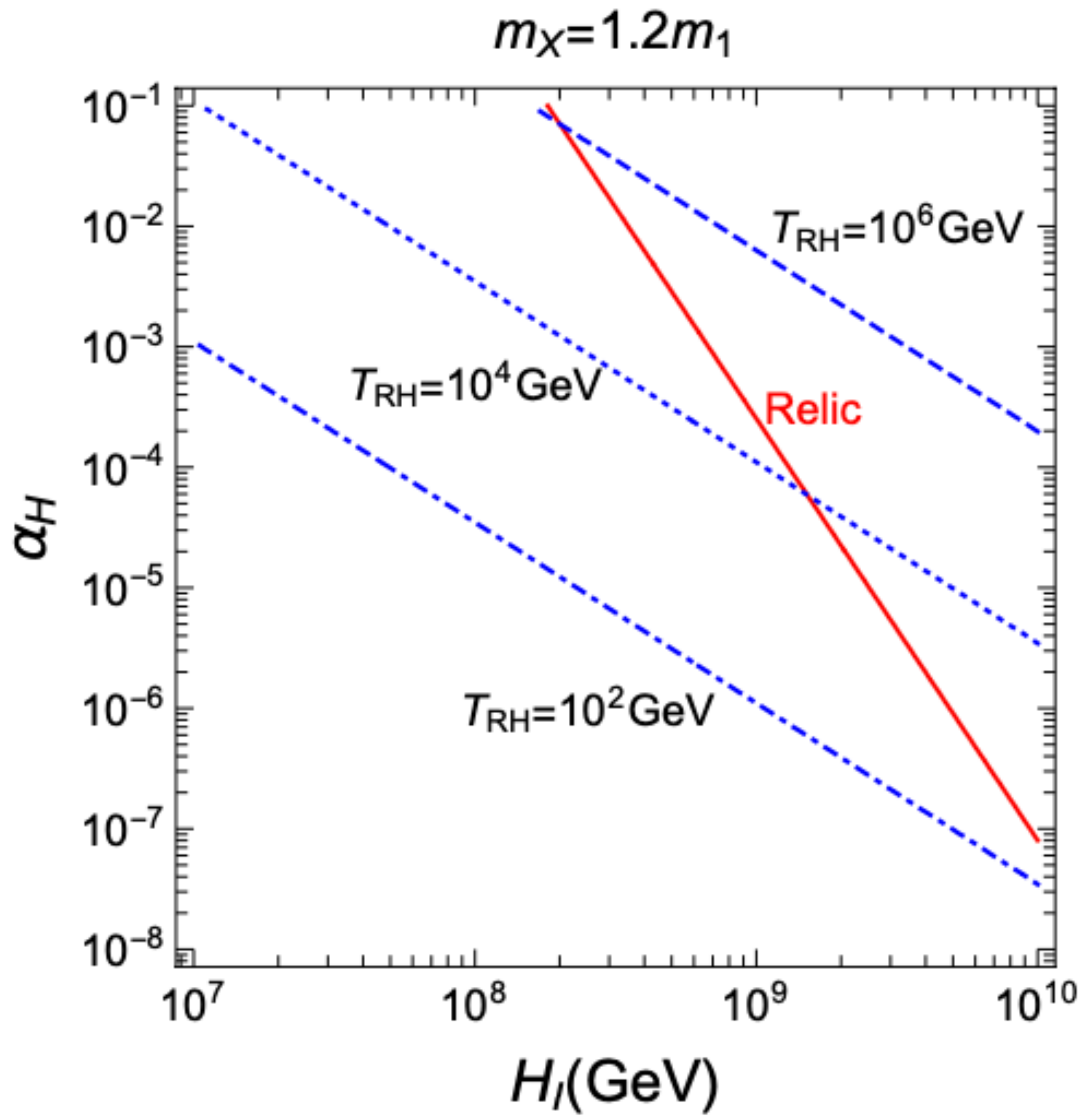
Preheating vs reheating



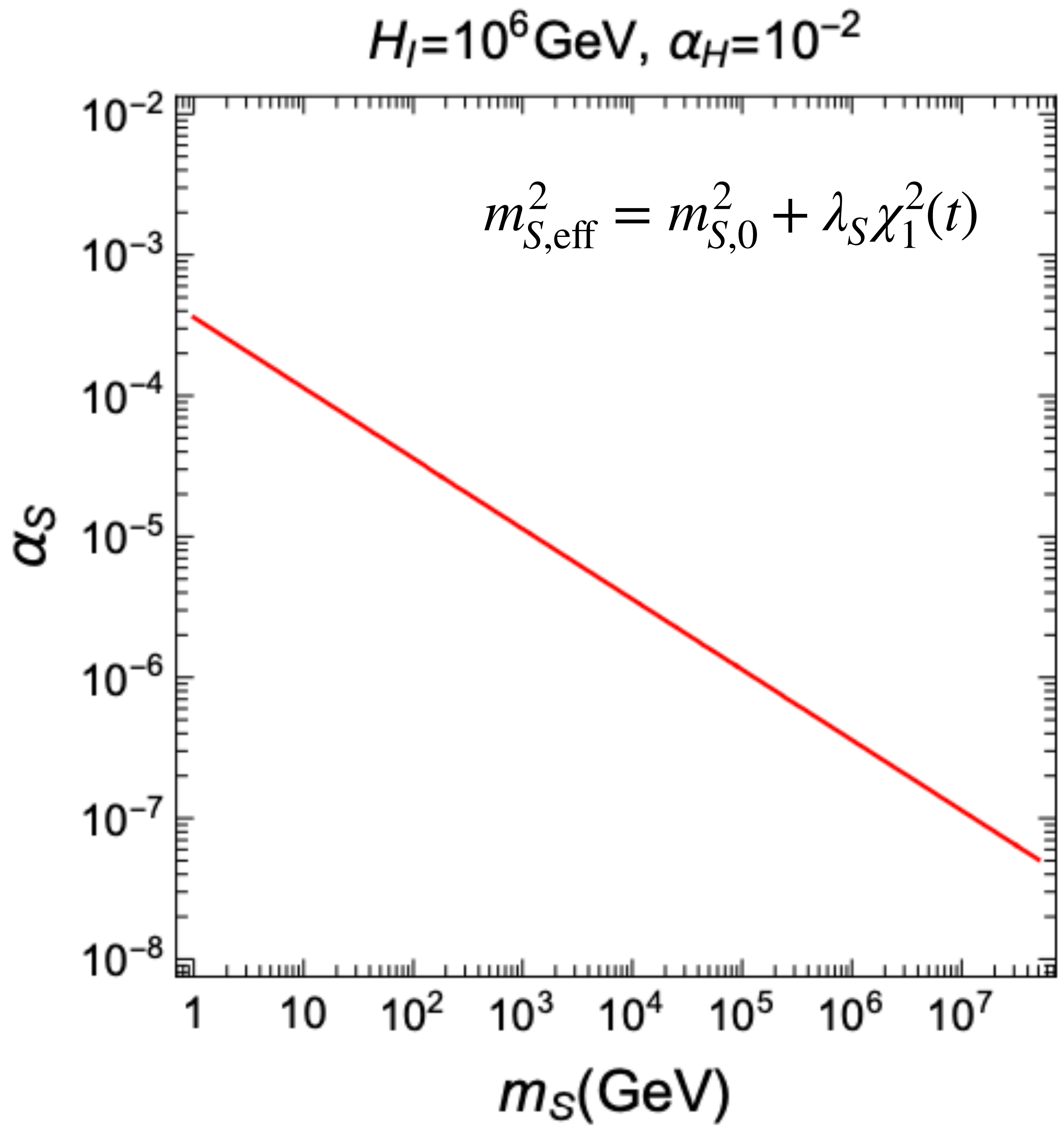


Dark Matter Production

χ_2 **Dark Matter**



Another scalar candidate



Summary

- We presented a natural inflation model, in which the inflation is a PNGB. **Phys.Lett.B 834 (2022)**
- We showed how the Z2 symmetry arises from a larger Z4 symmetry
- Large parameter space for successful inflation
- We studied the possibility of preheating, but reheating is dominant.
- We studied Dark Matter production