Pseudo-Nambu-Goldstone inflation 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.**

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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)

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- **First-order phase transition** (e.g. extended inflation scenario, hybrid inflation)

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Our topic today

Natural and Hybrid inflation

Inflation ends due to a phase transition

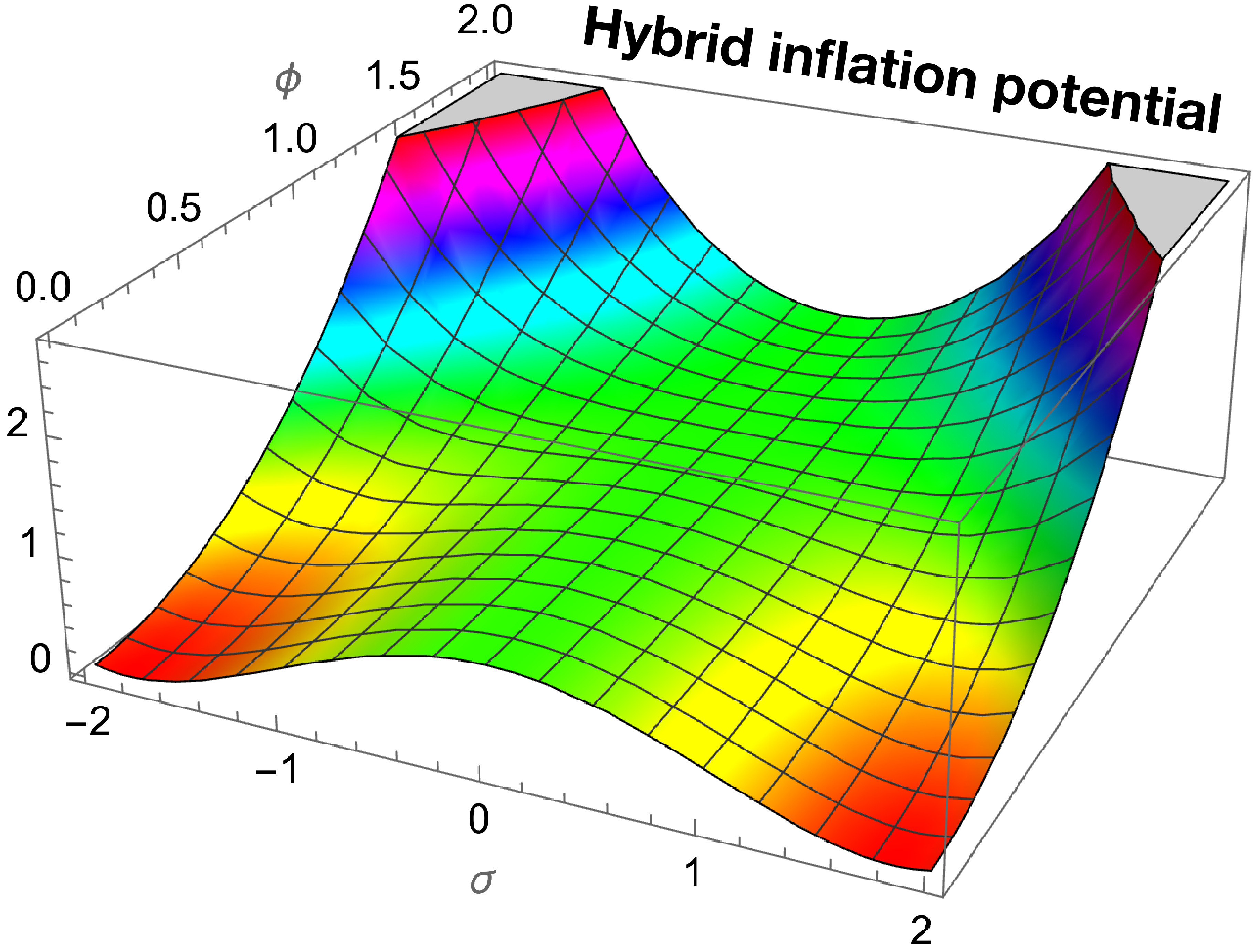
Natural inflation

[Phys. Rev. Lett. 65, 3233]

Inflaton = PNGB from a broken global symmetry (e.g. axion)

$$V(\phi) = \Lambda^4 \left(1 \pm \cos\left(\phi/f\right)\right)$$

Successful inflation if $f \sim M_p$ and $\Lambda \sim M_{\rm GUT}$



Hybrid inflation

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

Ending stages of inflation — **Chaotic inflation**

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

The later stages of inflation are driven by the vacuum energy density, not the density of the inflation field

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

Our Model

$$V(\phi,\chi_1,\chi_2) = V_I(\phi) \quad + \quad V_W(\phi,\chi_1,\chi_2)$$

Natural inflation ϕ **Hybrid like with two waterfalls** χ_1,χ_2

$$V_I(\phi) = V_0 + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

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

$$V_W(\phi,\chi_1,\chi_2) = -\frac{1}{2}\mu^2 \sin\left(\frac{\phi}{2f}\right)(\chi_1^2 - \chi_2^2) + \frac{1}{2}m_\chi^2(\chi_1^2 + \chi_2^2) - \alpha^2\chi_1\chi_2 + \frac{1}{4}\lambda_\chi(\chi_1^4 + \chi_2^4) + \frac{1}{2}\bar{\lambda}_\chi\chi_1^2\chi_2^2$$

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

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

Exit from inflation

$$V_W(\phi,\chi_1,\chi_2) = -\frac{1}{2}\mu^2 \sin\left(\frac{\phi}{2f}\right)(\chi_1^2 - \chi_2^2) + \frac{1}{2}m_\chi^2(\chi_1^2 + \chi_2^2) - \alpha^2\chi_1\chi_2 + \frac{1}{4}\lambda_\chi(\chi_1^4 + \chi_2^4) + \frac{1}{2}\bar{\lambda}_\chi\chi_1^2\chi_2^2$$

Mass mixing if $\alpha \neq 0$

$$m_1^2(\phi) = m_\chi^2 - \sqrt{\mu^4 \sin^2\left(\frac{\phi}{2f}\right) + \alpha^4} \longrightarrow$$

Tachyonic instability when $m_1^2 < 0$

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

$$m_2^2(\phi) = m_\chi^2 + \sqrt{\mu^2 \sin^2\left(\frac{\phi}{2f}\right) + \alpha^4}$$

Slow roll happens for $\phi < \phi_c$ **with** $\sqrt{m_\chi^4 - \alpha^4} < \mu^2$ $\quad \alpha < m_\chi$

For $\phi = \phi_c$ inflation ends even if the slow-roll conditions still hold

Quantum corrections

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

The quadratic divergent terms are cancelled between the waterfall fields because of the Z_2 symmetry

The log divergence can be ignored during inflation if $\mu^2 \lesssim 8\pi\Lambda$

Inflationary predictions

$$\eta_* \simeq -\frac{M_P^2\Lambda^4}{f^2V_0}\cos(\phi_*/f),$$

$$\epsilon_* \simeq \frac{M_P^2\Lambda^8}{2f^2V_0^2}\sin^2(\phi_*/f)$$

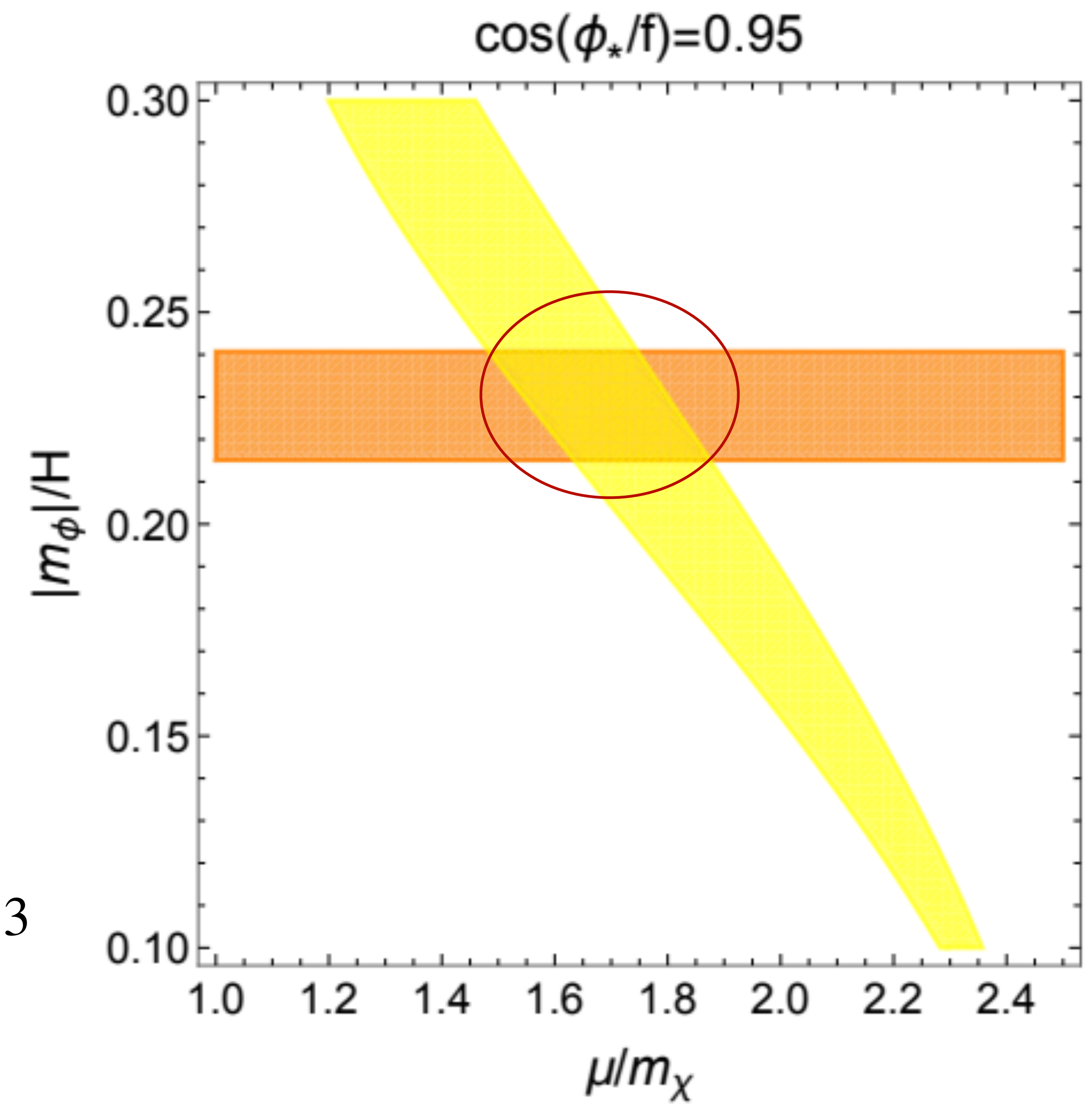
$N = 50 - 60$ **to solve the horizon problem**

$$N \simeq \frac{f^2V_0}{M_P^2\Lambda^4}\ln\left(\frac{\tan(\phi_c/(2f))}{\tan(\phi_*/(2f))}\right)$$

CMB normalization $r = 3.2\times10^7 \cdot \frac{V_0}{M_P^4}$

Planck bounds $n_s = 0.967 \pm 0.0037 \implies 2\eta_* \simeq -0.0033$

$r < 0.036 \implies H_I < 4.6\times10^{13}\,\mathrm{GeV}$



Inflationary predictions

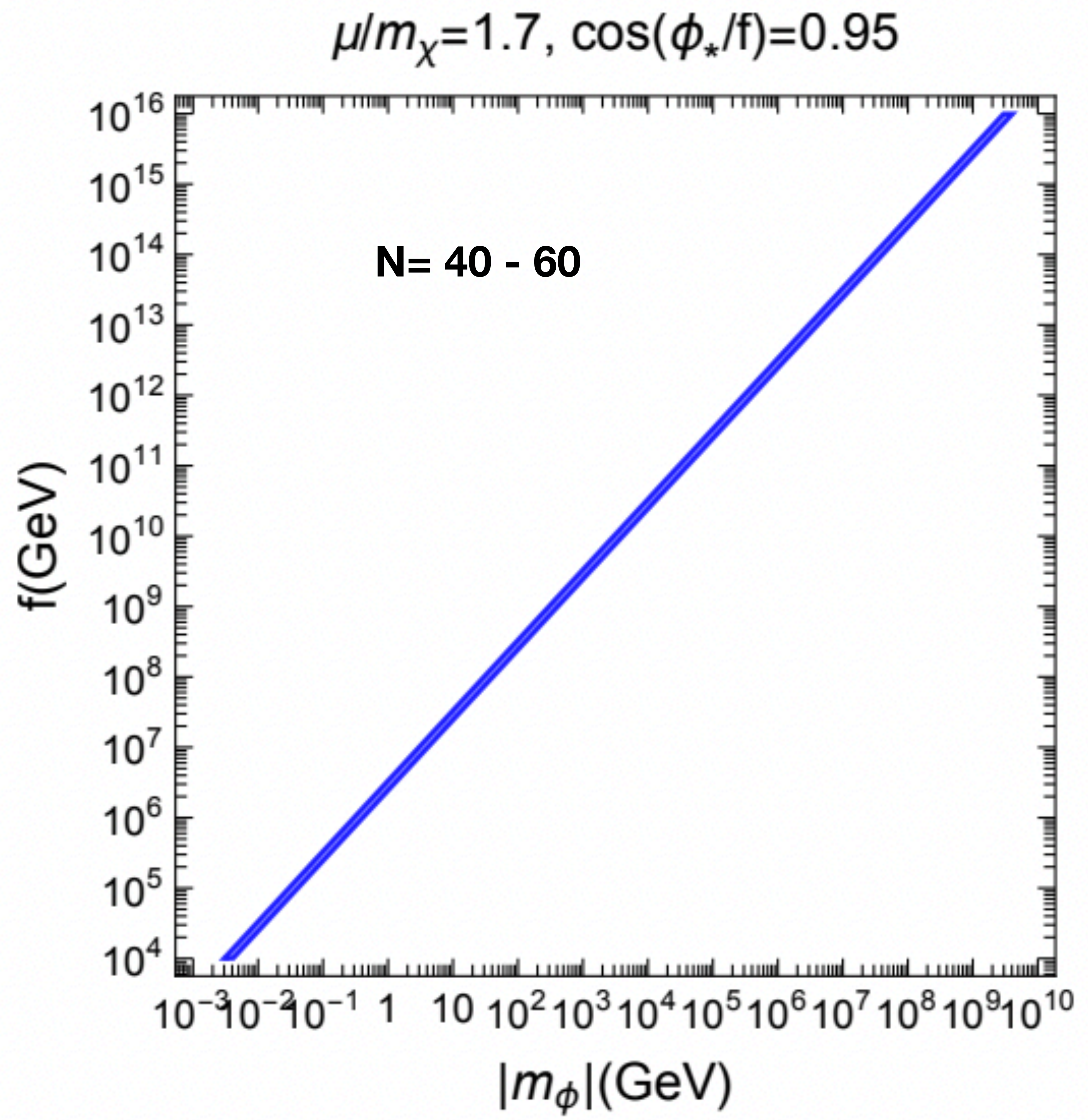
$$\frac{H_I}{f} = 2.9 \times 10^{-4} \left| \eta_* \tan(\phi_*/f) \right|$$

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

The global symmetry for the PNG is broken during inflation

For $f = 10^4\,\mathrm{GeV} - 10^{16}\,\mathrm{GeV}$, successful inflation is achieved for:

$$3.5 \times 10^9\,\mathrm{GeV} > |m_\phi| = \Lambda^2/f > 3.5 \times 10^{-3}\,\mathrm{GeV}$$



Vacuum structure

$$\langle\alpha\rangle = \langle\chi_2\rangle = 0 \qquad \phi = v_\phi + a$$

$$v_\phi = \pi f \qquad v_\chi = \sqrt{\frac{\mu^2 - m_\chi^2}{\lambda_\chi}}$$

The Z_2 symmetry is broken in the vacuum

The inflation mass gets a large contribution from the waterfall fields

$$m_a^2 = \frac{1}{f^2}\left(\Lambda^4 + \underline{\frac{1}{8}\mu^2 v_\chi^2}\right)$$

$$m_1^2 = 2\lambda_\chi v_\chi^2 = 2(\mu^2 - m_\chi^2),$$

$$m_2^2 = \mu^2 + m_\chi^2 + \bar{\lambda}_\chi v_\chi^2 = \mu^2 + m_\chi^2 + \frac{\bar{\lambda}_\chi}{\lambda_\chi}(\mu^2 - m_\chi^2)\,.$$

$m_2 > m_1$ **Is favored by the number of e-foldings**

Reheating

Z_2 invariant **couplings of the waterfalls with the Higgs**

$$\mathscr{L}_H = -\kappa_1(\chi_1^2+\chi_2^2)|H|^2 - \kappa_2\chi_1\chi_2|H|^2$$

$$T_{\rm RH} = \left(\frac{90}{\pi^2 g_{\rm RH}}\right)^{1/4}\sqrt{M_P\Gamma_{\chi_1}} \longrightarrow \quad T_{\rm RH} \simeq \left(\frac{90}{\pi^2 g_{\rm RH}}\right)^{1/4}\left(\frac{\kappa_1^2}{4\pi\lambda_\chi}\right)^{1/2}\sqrt{M_P m_1}$$

taking $H_I \lesssim 1.6\times10^{10}\,\mathrm{GeV}$ **for** $f \lesssim 10^{16}\,\mathrm{GeV}$

$$T_{\rm RH} \ll 10^{14}\,\mathrm{GeV}$$

$$N = 61.1 + \Delta N - \ln\left(\frac{V_0^{1/4}}{H_k}\right) - \frac{1}{12}\ln\left(\frac{g_{\rm RH}}{106.75}\right)$$

$$\Delta N = \frac{1}{12}\left(\frac{3w-1}{w+1}\right)\ln\left(\frac{45V_0}{\pi^2 g_{\rm RH}T_{\rm RH}^4}\right)$$

$$\longrightarrow \quad N = 51.3 + \frac{1}{3}\ln\left(\frac{H_I}{1.6\times10^{10}\,\mathrm{GeV}}\right) + \frac{1}{3}\ln\left(\frac{T_{\rm RH}}{10^{14}\,\mathrm{GeV}}\right)$$

Wide range of parameter space **for successful inflation with sufficiently large reheating temperature**

Dark QCD

Microscopic model that realizes inflation

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

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

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

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**

Summary

- We presented a natural inflation model in which the inflation is a PNGB.
- There is no need for a trans-Planckian axion decay constant or fine tuned initial conditions.
- The Z_2 symmetry protects the CW potential from quantum corrections.
- Assuming Z_2 invariant coupling to the SM Higgs, the reheating temperature is sufficiently large.
- We provided a microscopic model from which our inflationary model arises.

Thank you!