Multi-Natural Inflation

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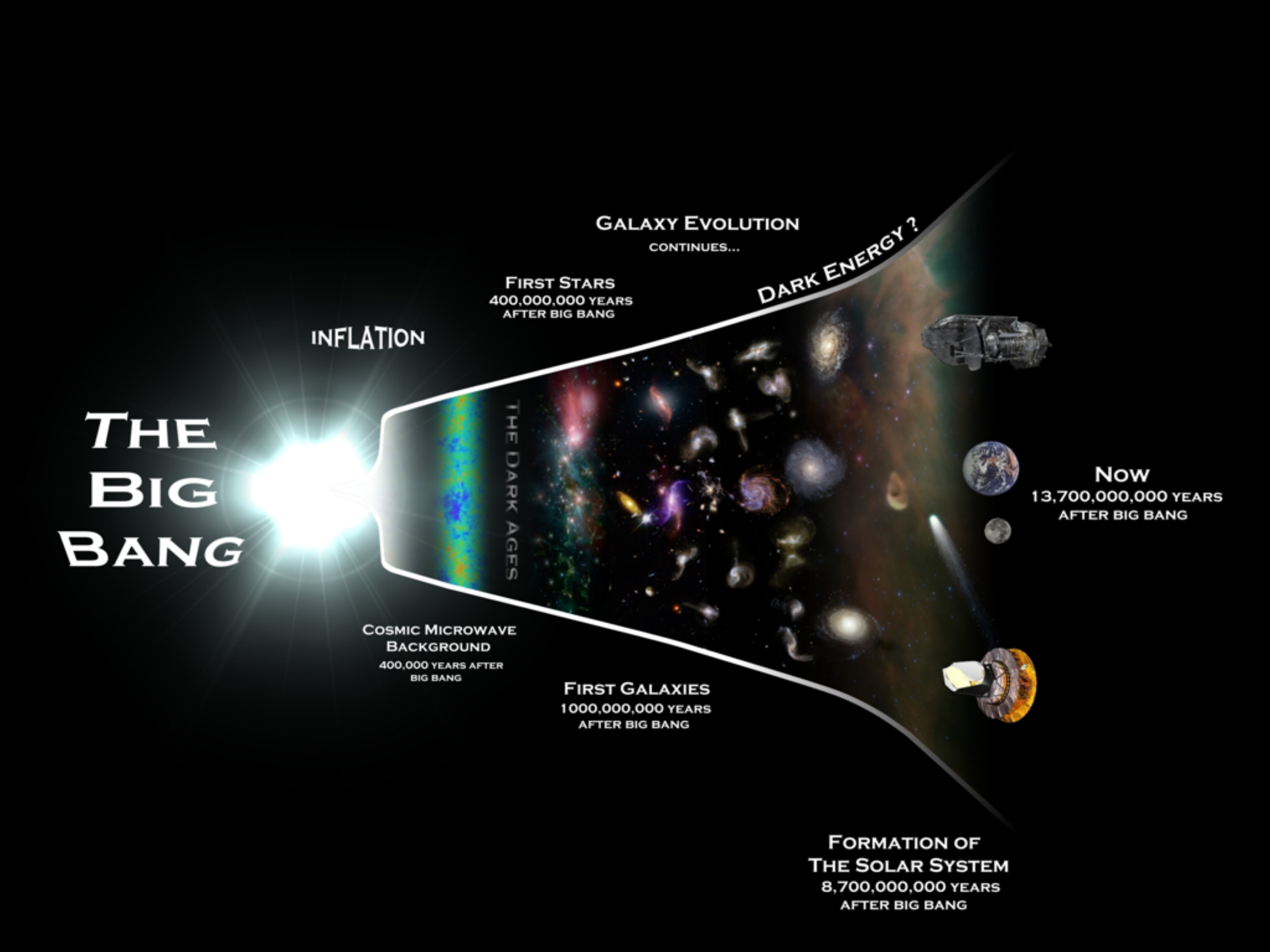
(Tohoku & Kavli IPMU)

based on M. Czerny and FT, 1401.5212
M. Czerny, T. Higaki and FT, in preparation

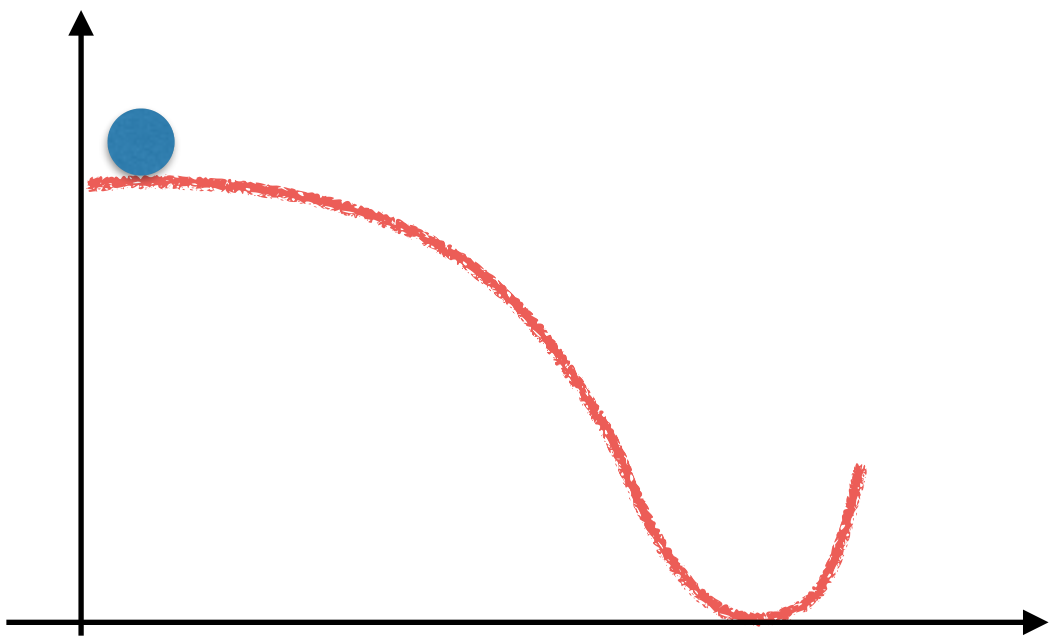


THE BIG BANG
INFLATION
FIRST STARS
400,000,000 YEARS
AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
THE DARK AGES
COSMIC MICROWAVE
BACKGROUND
400,000 YEARS AFTER
BIG BANG
FIRST GALAXIES
1000,000,000 YEARS
AFTER BIG BANG
NOW
13,700,000,000 YEARS
AFTER BIG BANG
FORMATION OF
THE SOLAR SYSTEM
8,700,000,000 YEARS
AFTER BIG BANG

What drives inflation?

The flatness of the inflaton potential could be (partially) due to symmetry.

e.g.) SUSY, conformal symmetry, shift symmetry, etc.



There are many candidates for the inflaton:

SM Higgs, B-L Higgs, right-handed sneutrino, SUSY flat direction, Polonyi field, (pseudo)moduli, **axions**, etc.

There are many inflation models using axion(s):

- Natural inflation Freese, Frieman Olinto,`90
- Pseudo-natural inflation Arkani-Hamed et al `03, Kaplan and Weiner `03
- Racetrack inflation Blanco-Pillado et al `04
- N-flation Dimopoulos et al, `05
- Chromo-natural inflation Adshead and Wyman, `12
- etc.

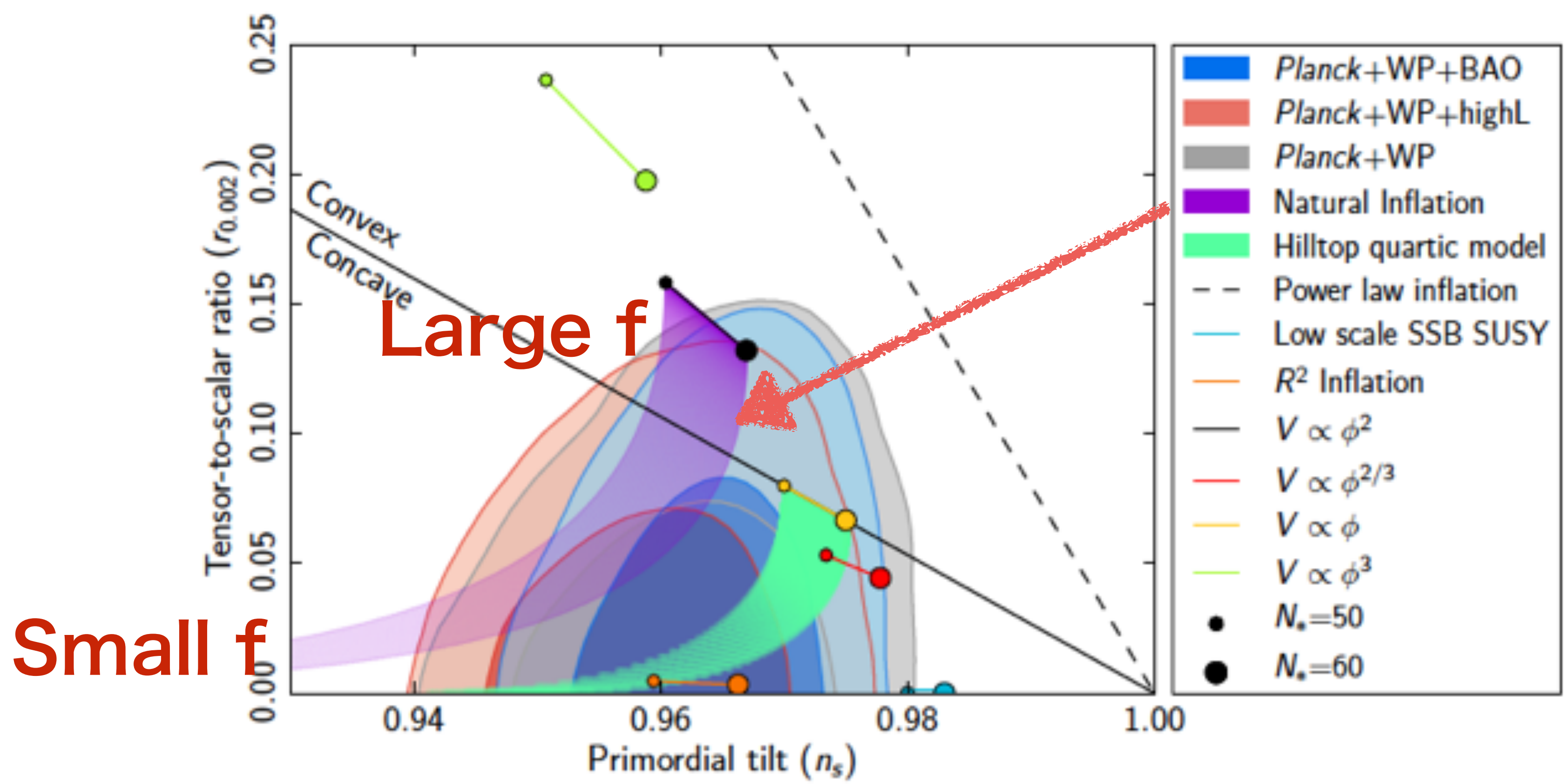
Natural inflation

Freese, Frieman Olinto,`90

The inflaton potential is kept flat by an approximate shift symmetry, whose explicit breaking leads to

$$V(\phi) = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

The lower bound on the decay constant, **$f > 5M_p$**, is required by the Planck data



Multi-natural inflation

M. Czerny and FT, 1401.5212

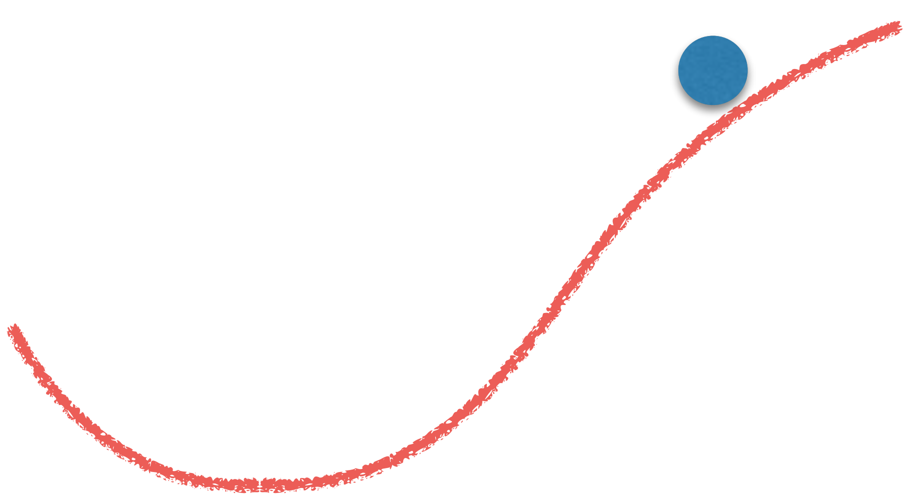
The shift symmetry could be broken by multiple sources.
We consider two comparable sinusoidal functions.

$$V(\phi) = C - \Lambda^4 \cos\left(\frac{\phi}{f}\right) - B\Lambda^4 \cos\left(\frac{\phi}{Af} + \theta\right),$$

$A = \mathcal{O}(1)$
$B = \mathcal{O}(1)$

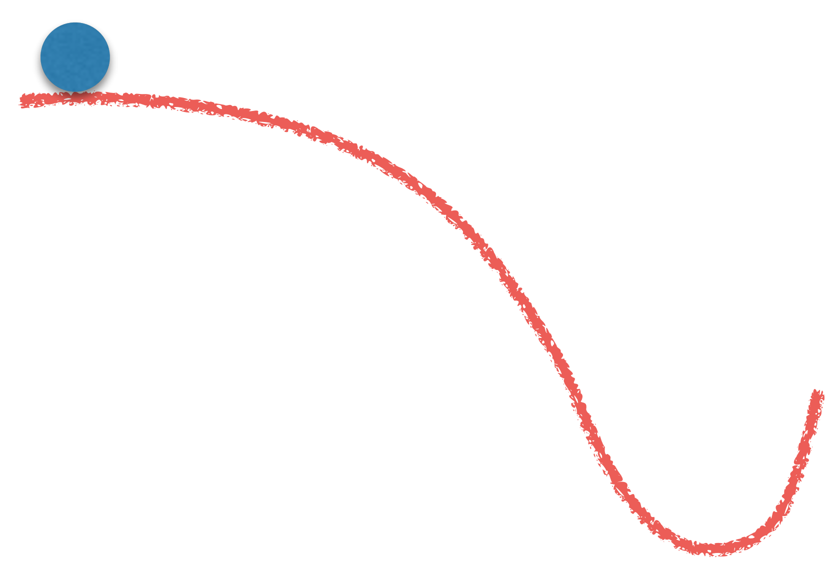
✓ Easy to implement in UV theory such as supergravity/string.

✓ The model is versatile enough to realize both large-field and small field inflation.



Large-field inflation

$f \gtrsim M_p$



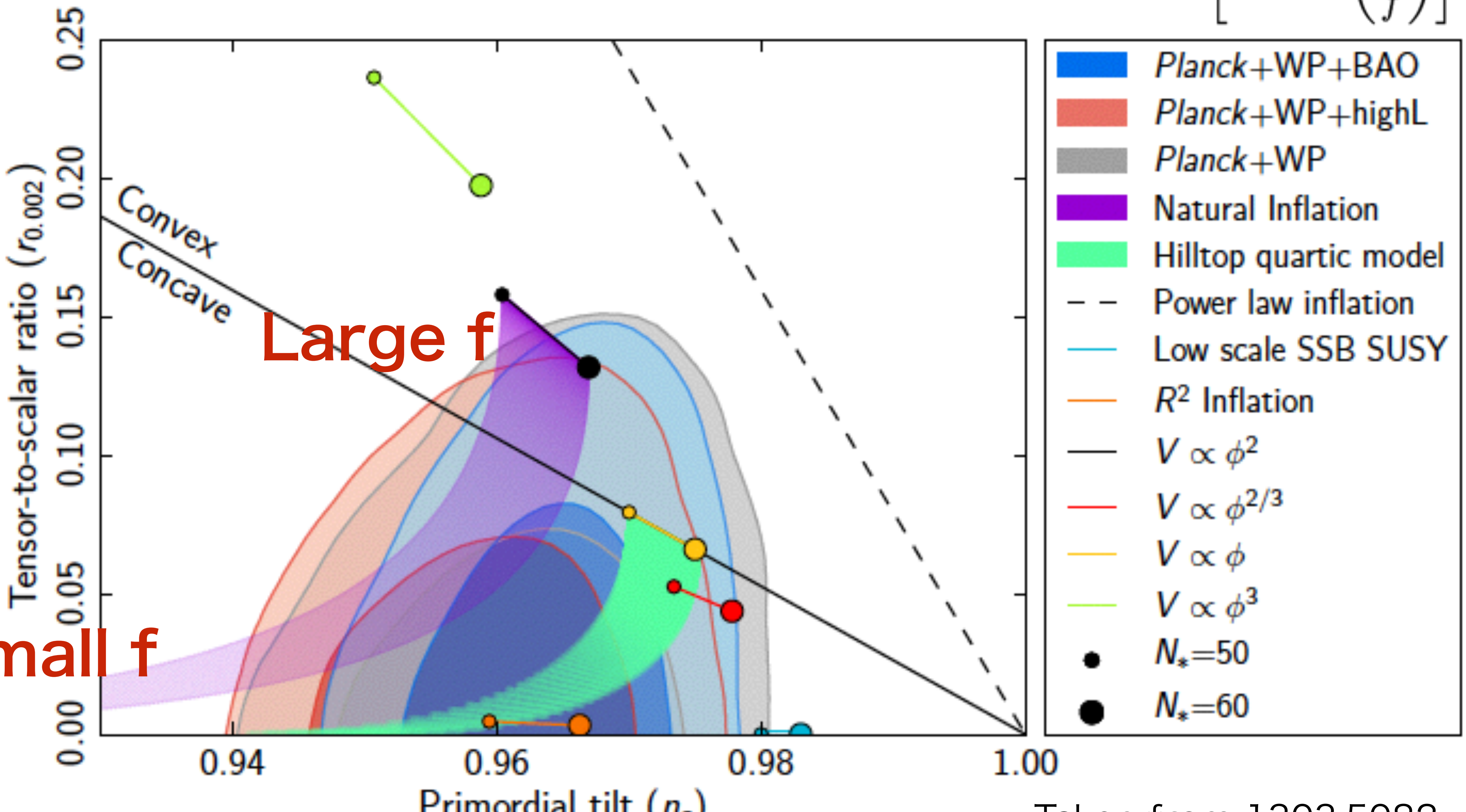
Small-field inflation

$f \lesssim M_p$

Large-field multi-natural inflation

The predicted values of (n_s, r) can be modified from the natural inflation. In particular, the lower bound on f, $f \gtrsim 5M_p$, can be relaxed.

$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$



Taken from 1303.5082

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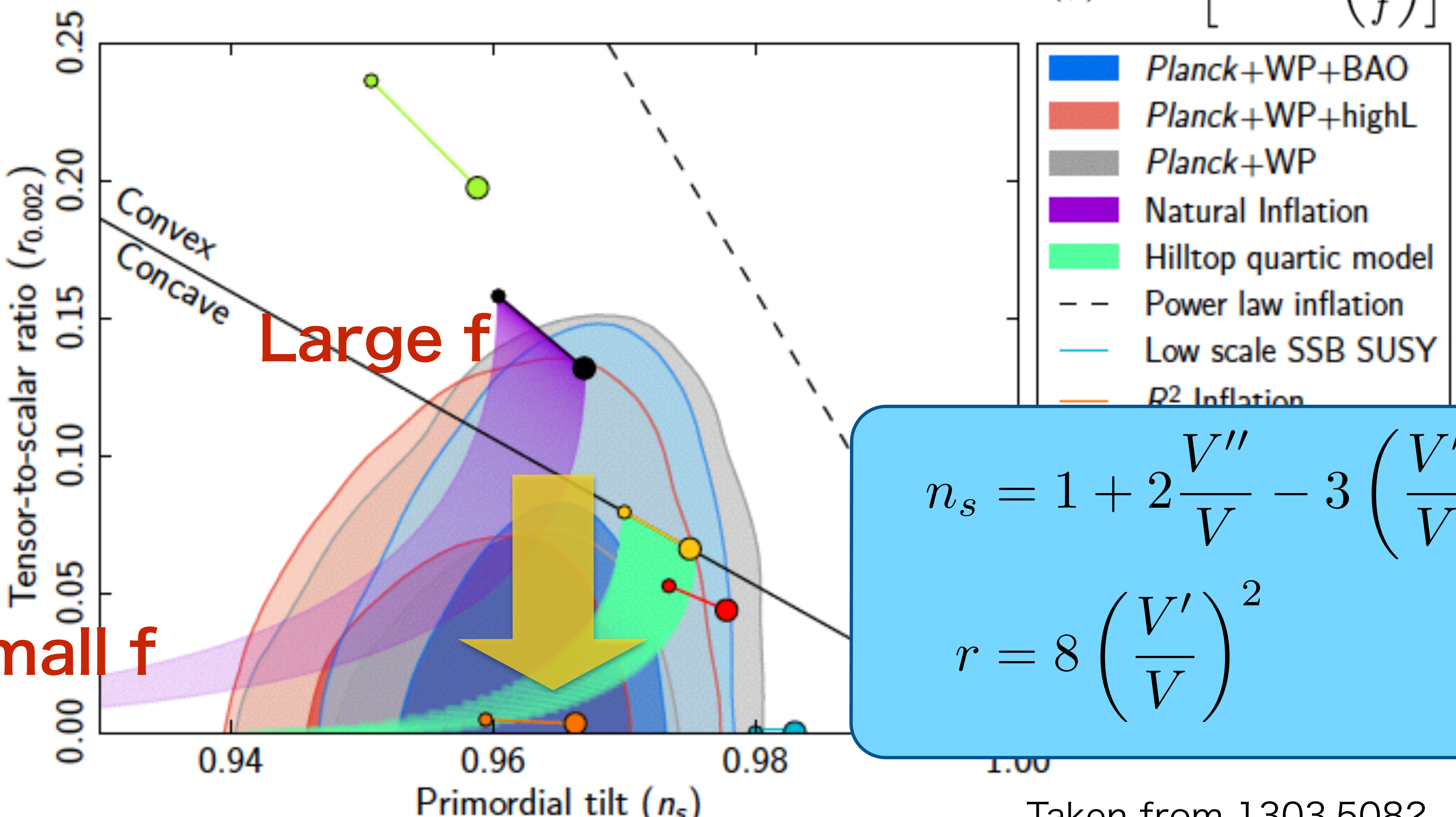


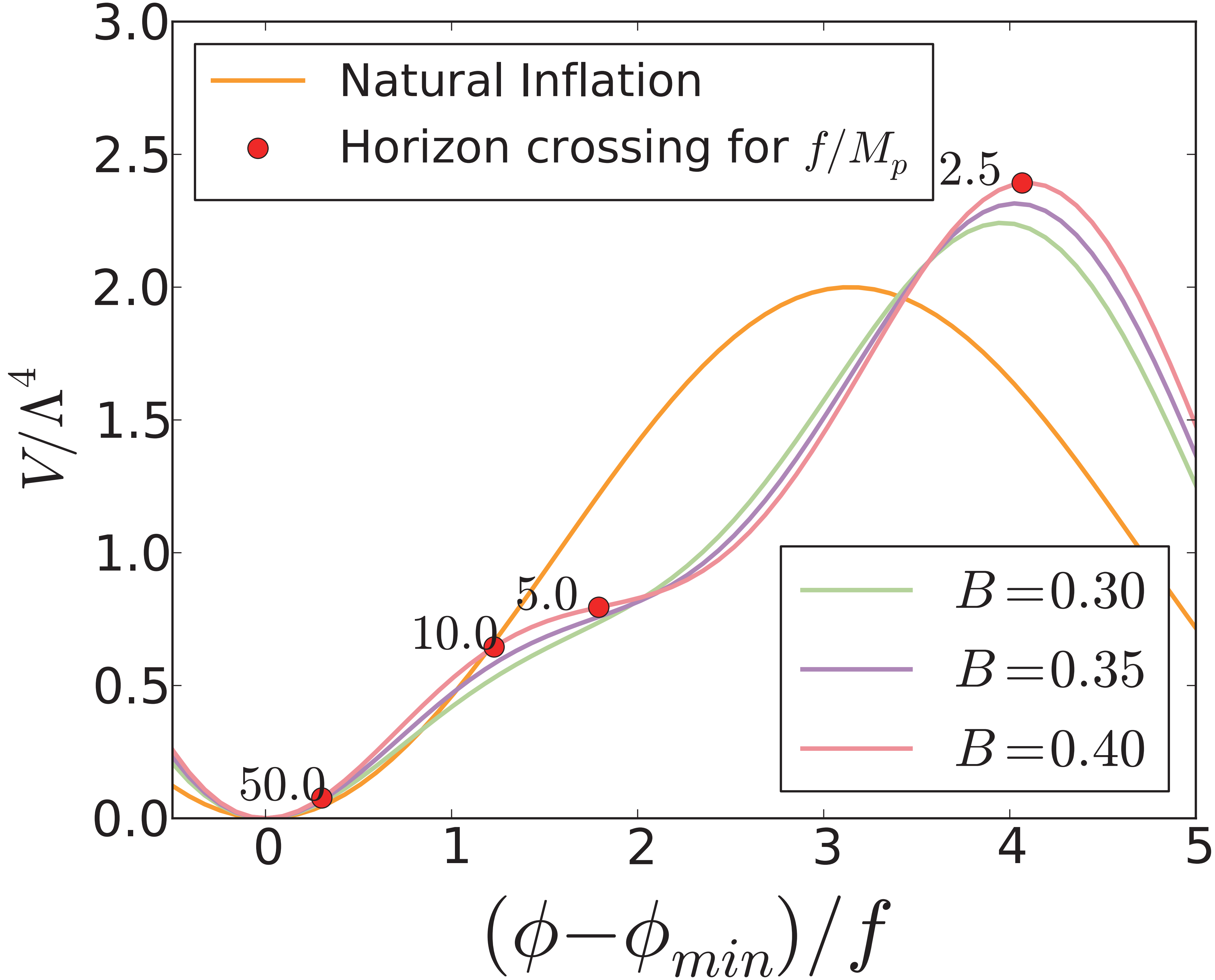
$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2$$

$$r = 8\left(\frac{V'}{V}\right)^2$$

Taken from 1303.5082

Case 1: $A = 1/2, \quad \theta = 2\pi/3$

$$V(\phi) = C - \Lambda^4 \cos\left(\frac{\phi}{f}\right) - B\Lambda^4 \cos\left(\frac{2\phi}{f} + \frac{2\pi}{3}\right)$$



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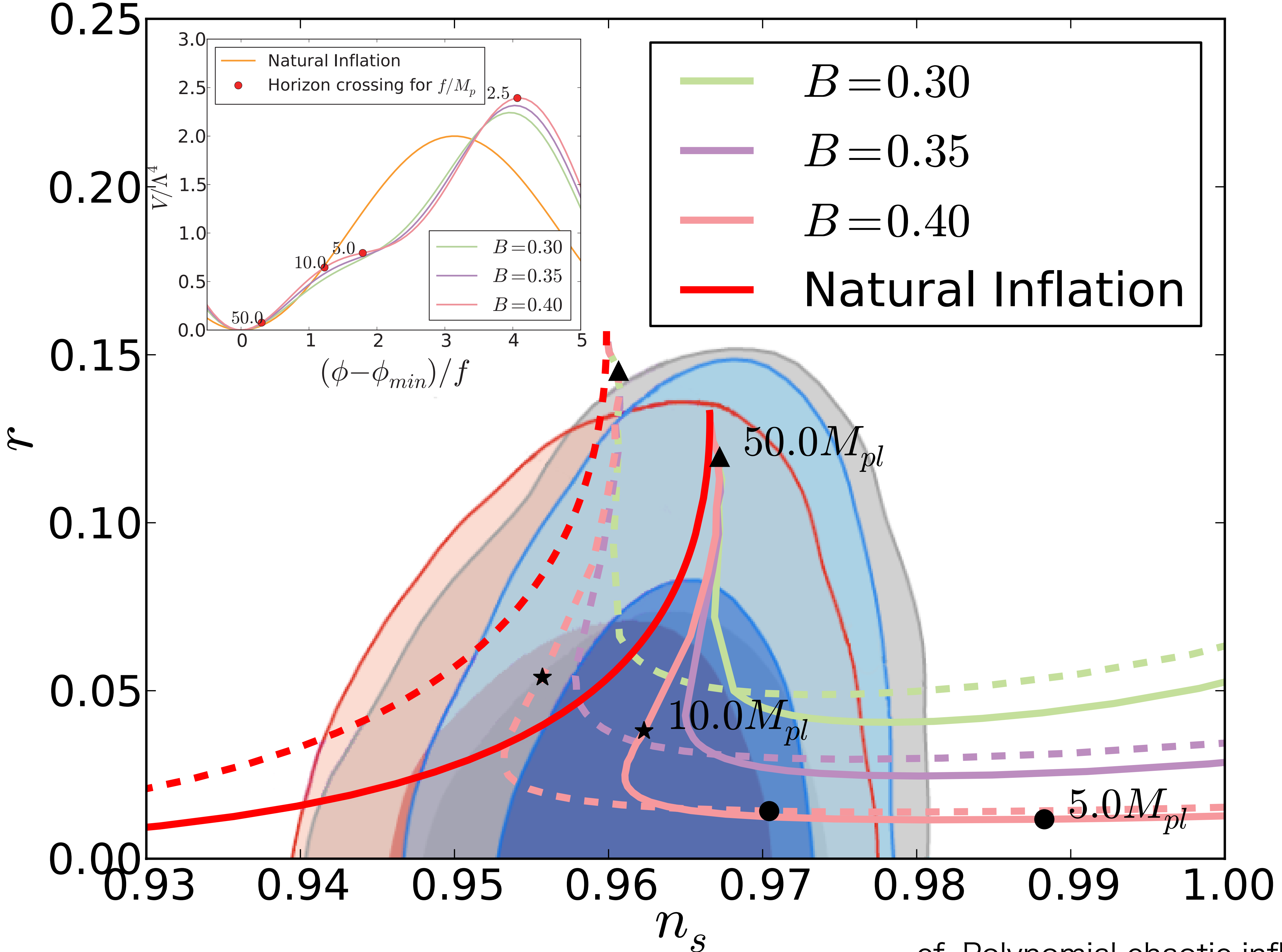
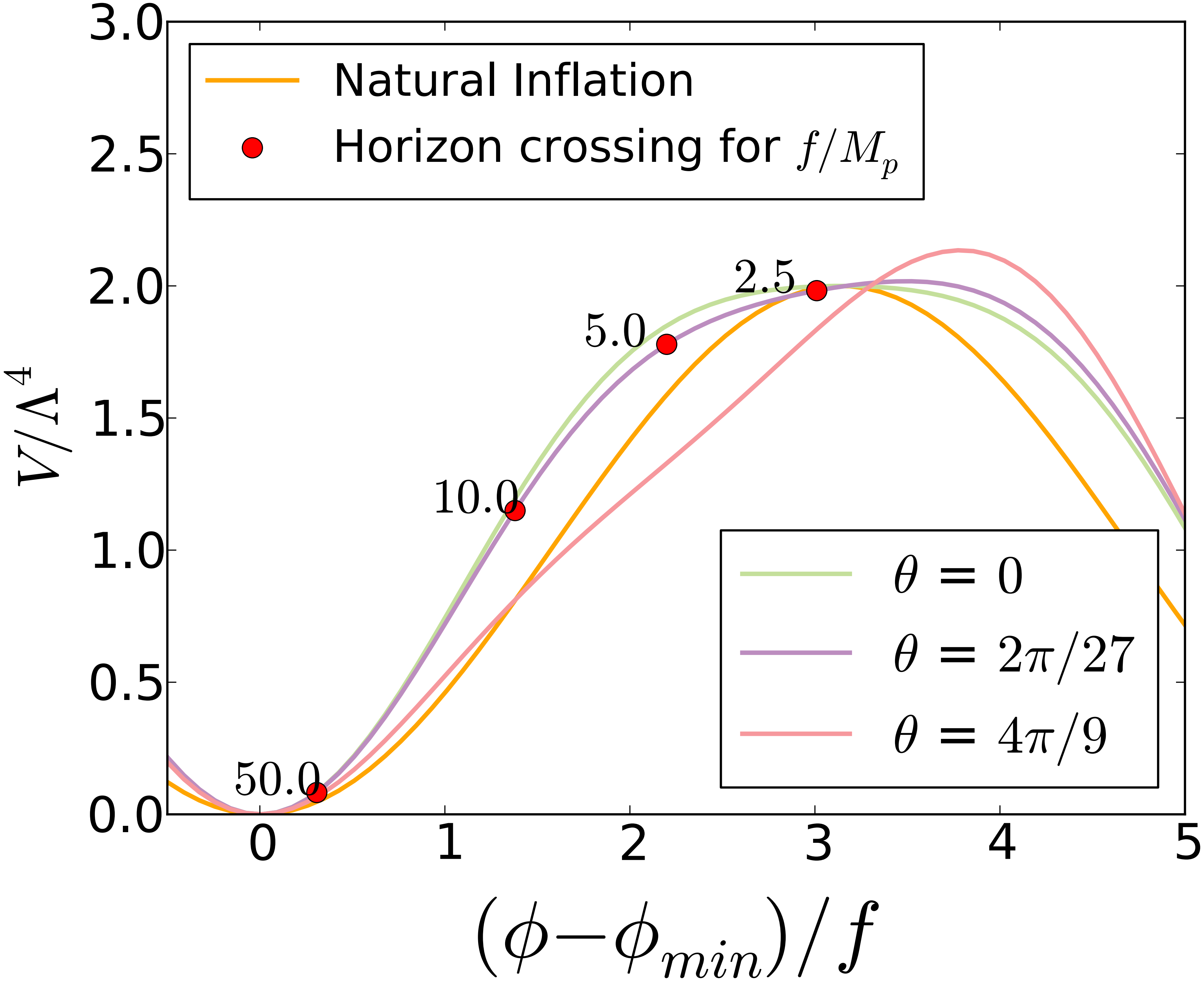


cf. Polynomial chaotic inflation
K. Nakayama, FT, T. Yanagida

Case 2: $A = 1/2, \quad B = 0.2$

$$V(\phi) = C - \Lambda^4 \cos\left(\frac{\phi}{f}\right) - 0.2\Lambda^4 \cos\left(\frac{2\phi}{f} + \theta\right)$$



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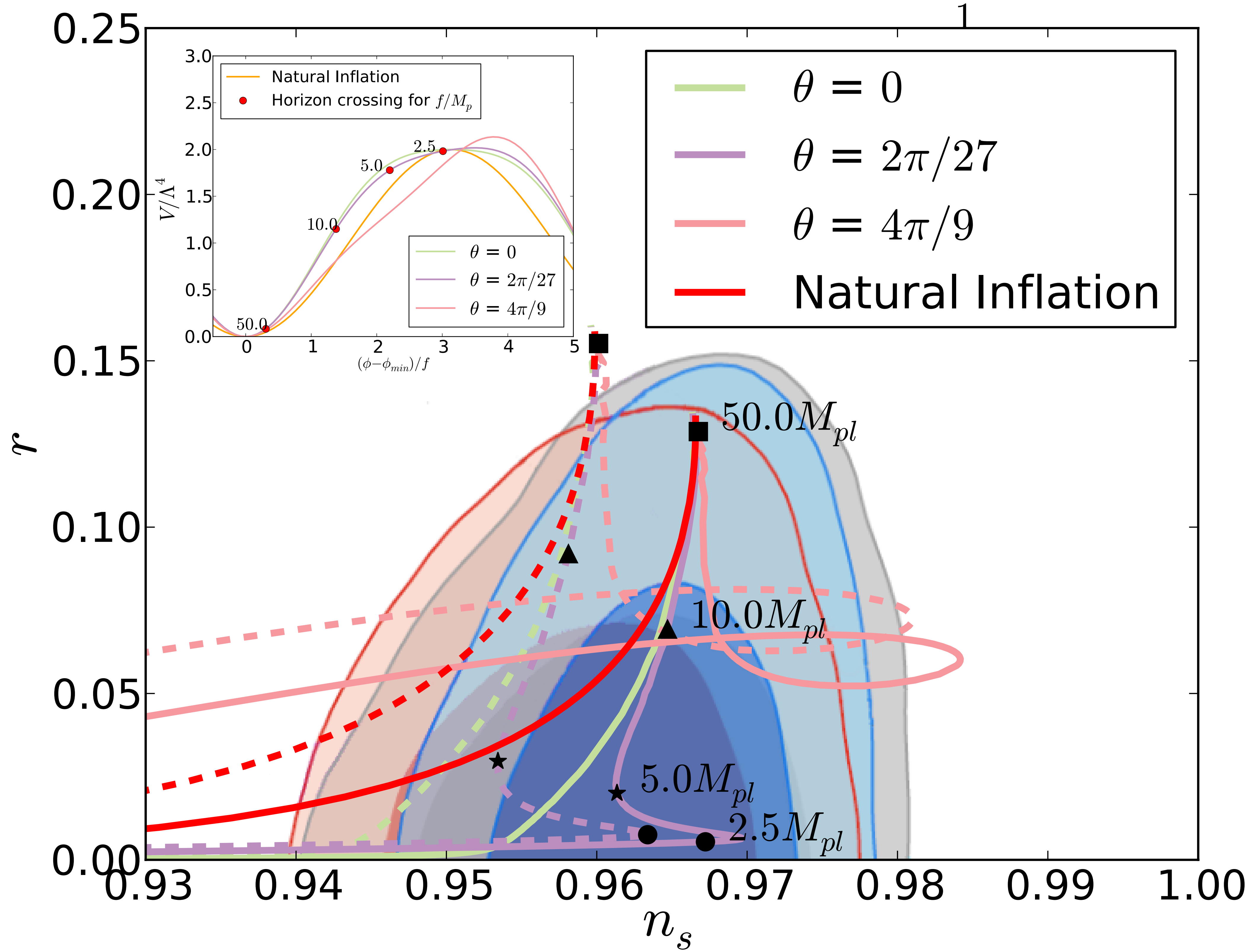

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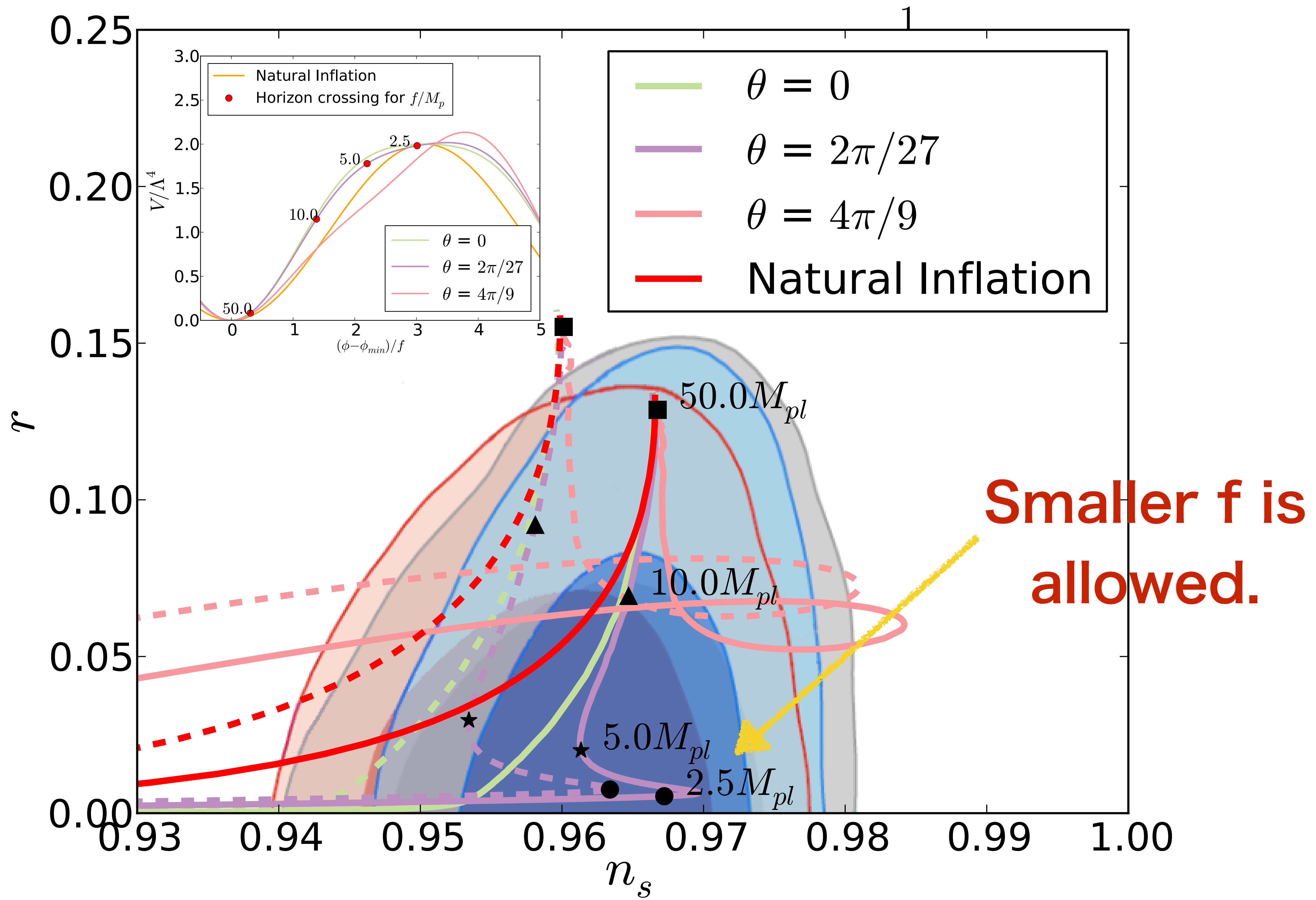
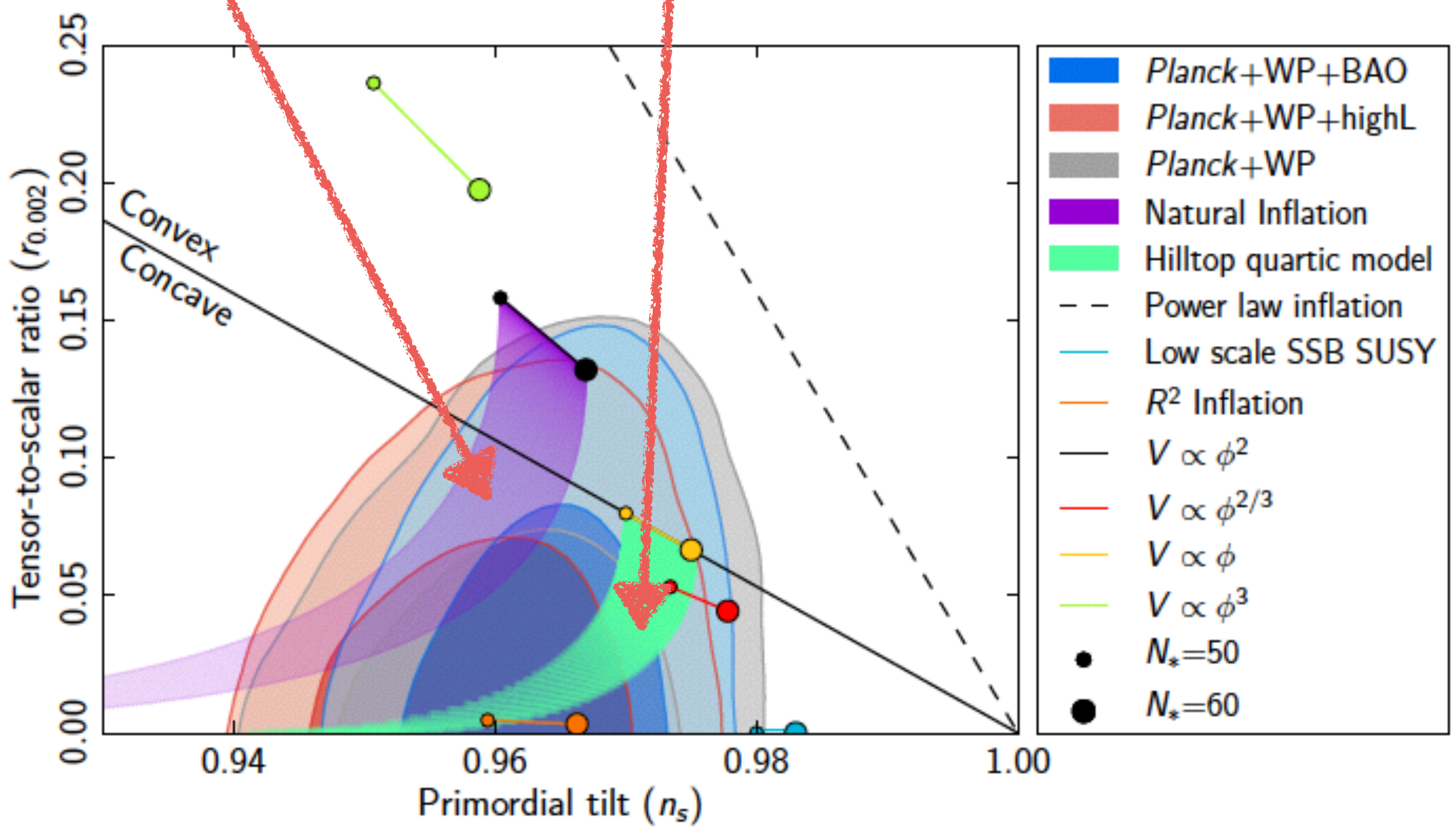


For certain parameters, multi-natural inflation can interpolate natural inflation and hilltop quartic inflation (or new inflation).

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

$$V = V_0 - \lambda\phi^4 + \cdots$$



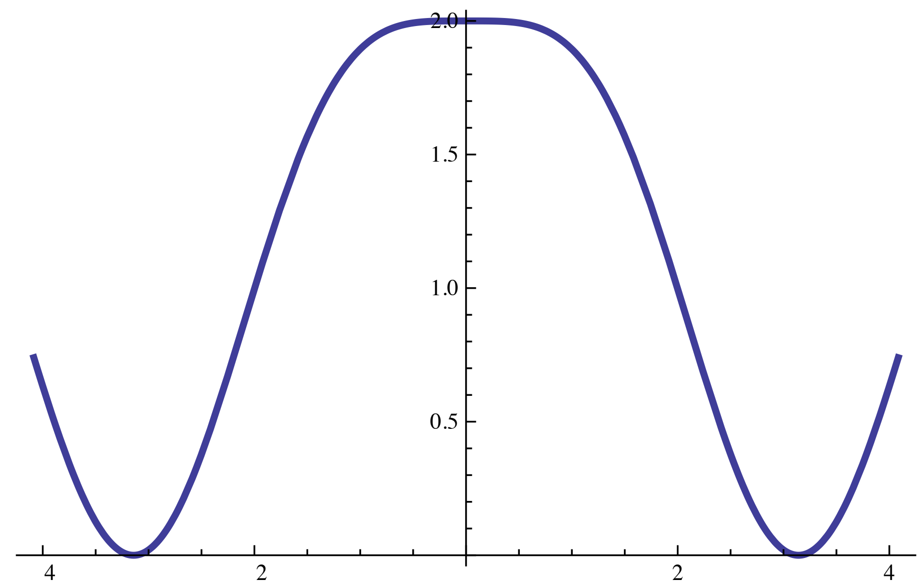
As the hilltop quartic inflation can describe small-field inflation, the lower bound on the decay constant no longer exists.

Small-field multi-natural inflation

Hilltop quartic inflation (new inflation) can also be realized by requiring a flat-top potential.

$$V(\phi) = C - \Lambda^4 \cos\left(\frac{\phi}{f}\right) - B\Lambda^4 \cos\left(\frac{\phi}{Af} + \theta\right)$$
$$= V_0 - \lambda\phi^4 + \cdots$$

for $B \approx A^2, \quad \theta \approx -\pi/A$



- **Simple realization of axion inflation.**
- **The potential shape is under control.**
  - No radiative correction, no extra high-dim operator.
- **Spectral index can fit the Planck result.**

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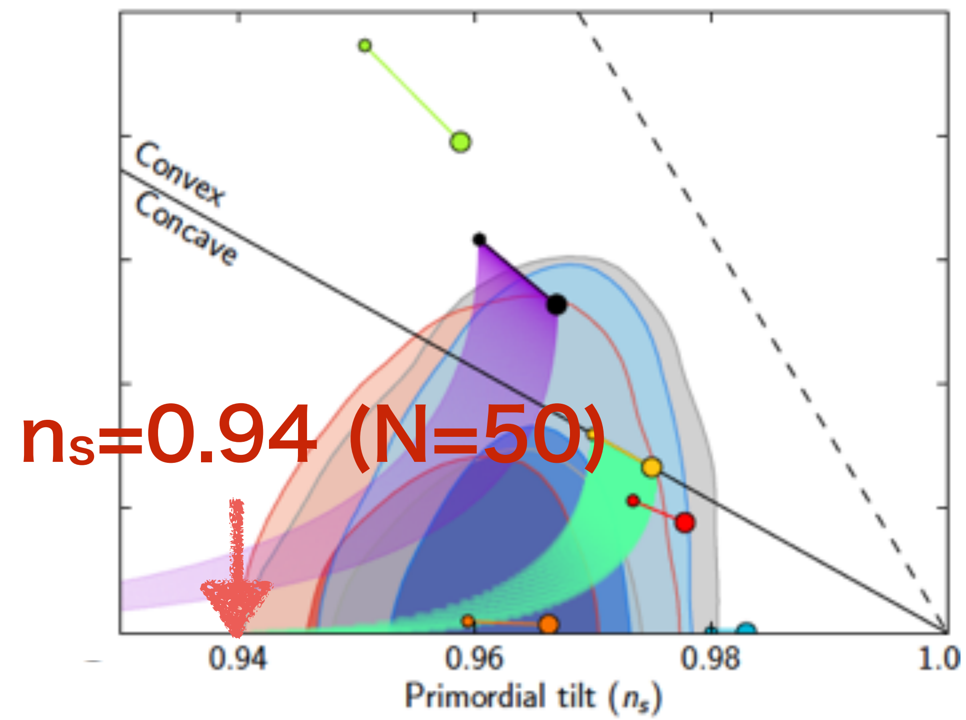

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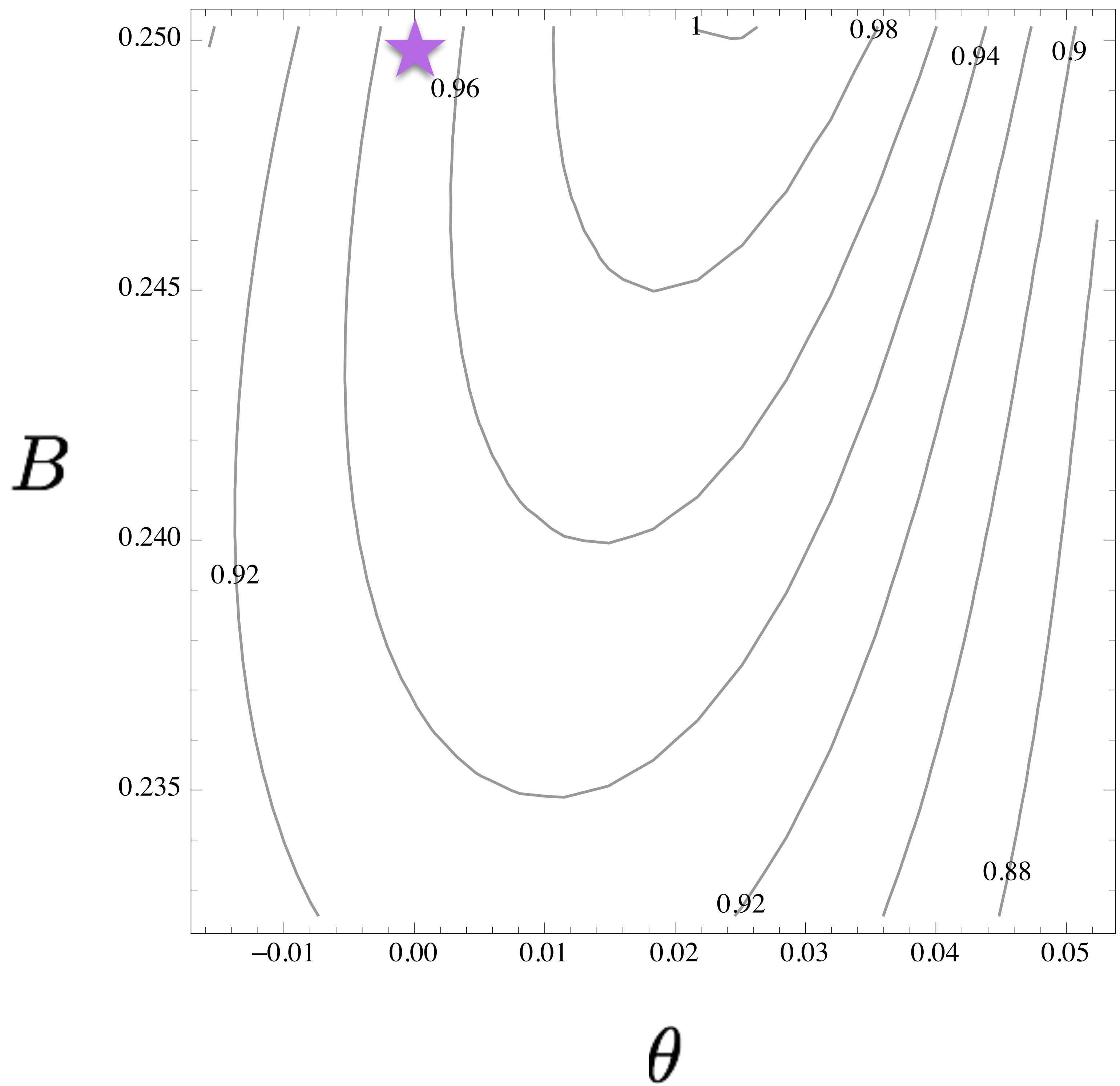
Spectral index

Hilltop quartic

$$V(\phi) = C - \Lambda^4 \cos\left(\frac{\phi}{f}\right) - B\Lambda^4 \cos\left(\frac{\phi}{Af} + \theta\right),$$

$$f = 0.5 M_p \quad A = 0.5$$



Relative phase leads to effective linear term.

cf. FT 1308.4212

UV completion

1. Field theoretic axion

Consider a complex scalar field coupled to two kinds of quarks charged under SU(N_1) and SU(N_2).

$$\mathcal{L} = \sum_{i=1}^{n_q} y_i \Phi q_i \bar{q}_i + \sum_{j=1}^{n_Q} Y_j \Phi Q_j \bar{Q}_j,$$

Assuming Φ develops a vacuum expectation value, we can identify the NG boson with the inflaton.

$$\Phi = \frac{v + \hat{s}}{\sqrt{2}} \exp\left[i\frac{\phi}{v}\right]$$

In the low energy, both gauge interactions become strong, leading to the axion potential:

$$V(\phi) = \Lambda_1^4 \cos\left(\frac{\phi}{f_1}\right) + \Lambda_2^4 \cos\left(\frac{\phi}{f_2} + \theta\right)$$

$$f_1 = \frac{v}{n_q}, \qquad f_2 = \frac{v}{n_Q}.$$

2. String-inspired axion

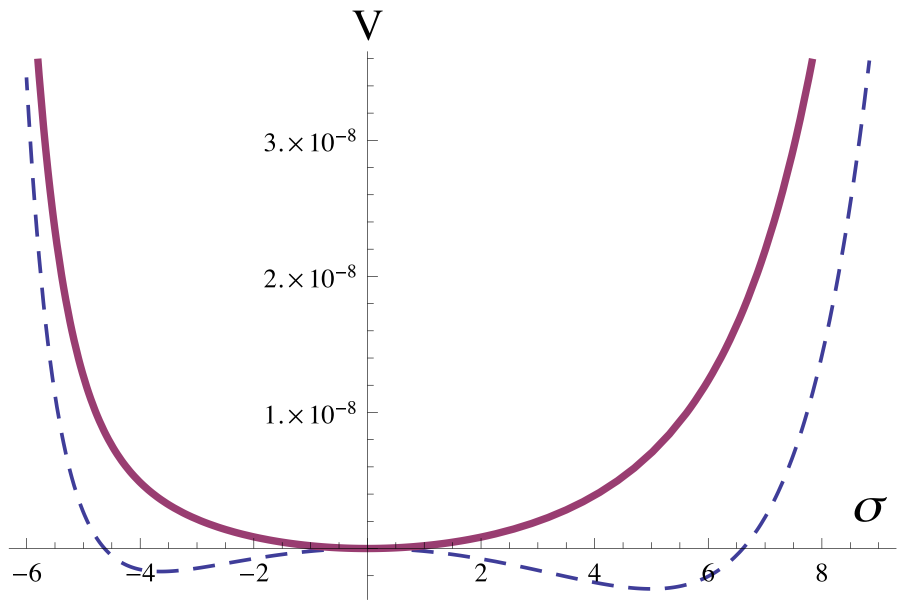
M. Czerny, T. Higaki and FT, in preparation.

The multi-natural inflation model can be easily realized based on any string QCD axion models.

Let us consider low-energy effective sugra model

$$K = K(\Phi + \Phi^\dagger),$$
$$W = W_0 + Ae^{-a\Phi} + Be^{-b\Phi}. \qquad \Phi = \sigma + i\phi$$

For $K = \frac{f^2}{2}(\Phi + \Phi^\dagger)^2$, the saxion is stabilized at the origin with a mass of order the gravitino mass.



2. String-inspired axion

After integrating out the saxion, we obtain

$$V_{\rm axion}(\phi) = 6AW_0\left[1-\cos\left(\frac{\phi}{f_1}\right)\right] + 6BW_0\left[1-\cos\left(\frac{\phi}{f_2}+\theta\right)\right]$$
$$-2AB\left(\frac{2}{f_1 f_2}-3\right)\left[1-\cos\left[\left(\frac{1}{f_1}-\frac{1}{f_2}\right)\phi-\theta\right]\right].$$

where $\hat{\phi} \equiv \frac{\phi}{\sqrt{2}f}; \quad f_1 = \frac{\sqrt{2}f}{a}, \quad f_2 = \frac{\sqrt{2}f}{b},$

- **Simple realization of string axion inflation.**
- **Implication for moduli stabilization**

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Reheating

Reheating

The inflaton decays into the SM gauge fields through

$$\mathcal{L} = \frac{\alpha}{8\pi}\frac{\phi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

with the decay rate $\Gamma(\phi \to gg) \simeq \frac{\alpha^2}{32\pi^2}\frac{m_\phi^3}{f^2}$

The reheating temperature is given by

$$T_R \sim 10^9\,\mathrm{GeV}\left(\frac{m}{10^{13}\,\mathrm{GeV}}\right)^{\frac{3}{2}}\left(\frac{f}{M_p}\right)^{-1}$$

Sufficiently high for (non-)thermal leptogenesis.

Summary

◉ We have proposed **multi-natural inflation**, which can realize both large-field and small-field inflation.

- Large-field inflation

✓ The predicted n_s and r can be closer to the center value of the Planck results.

- Small-field inflation (hilltop quartic inflation)

✓ Simple realization of axion inflation with $f < M_p$

✓ Potential under good control against radiative corr.

✓ Spectral index can explain the Planck data.

◉ **Easy to implement in supergravity and string theory.**