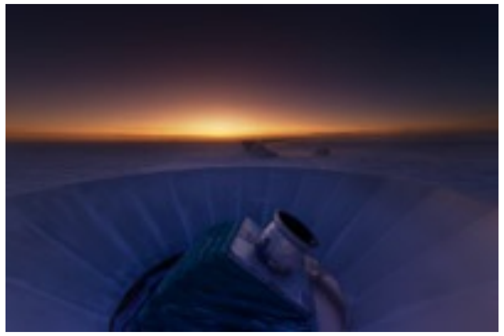
Searching high and low for traces of inflation

8th July 2014

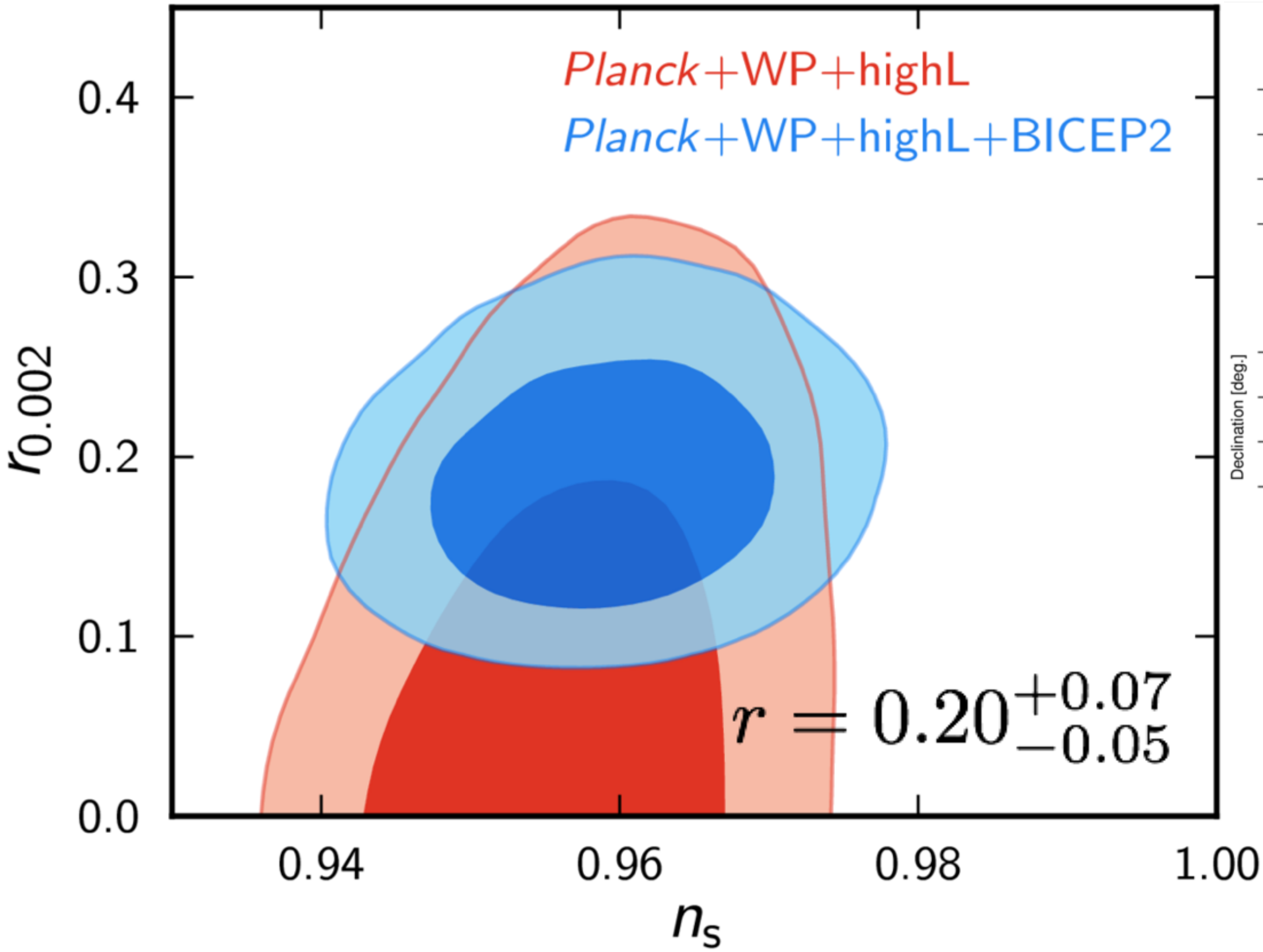
String Pheno 2014 @ICTP

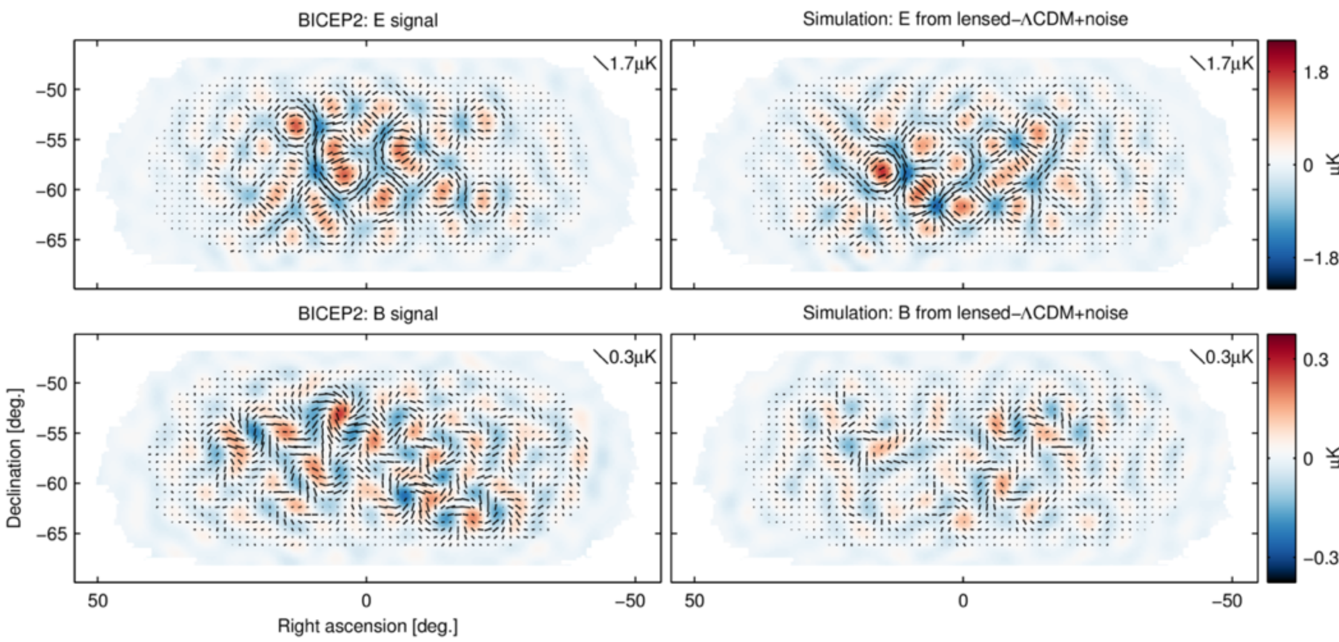
Fuminobu Takahashi
(Tohoku)

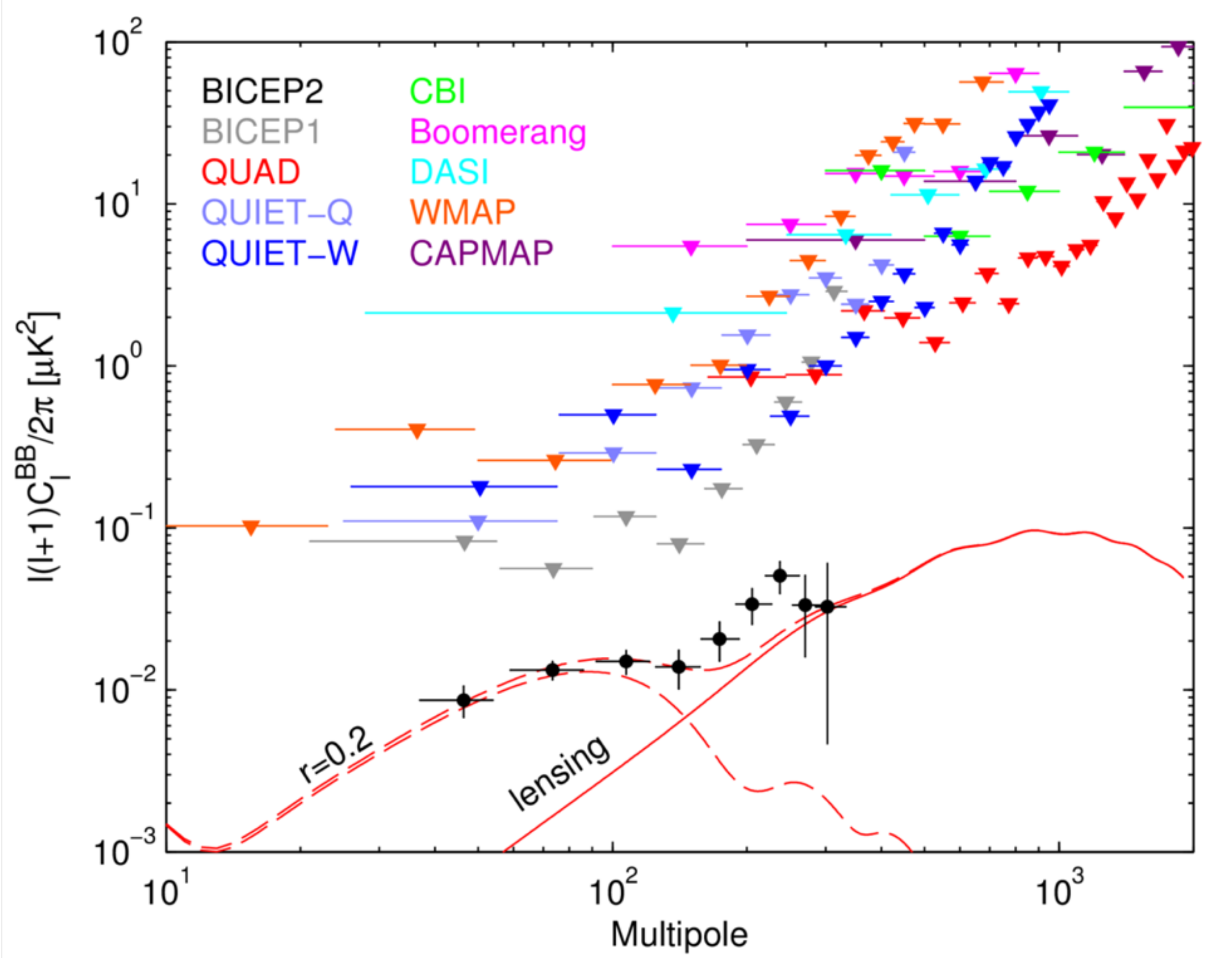


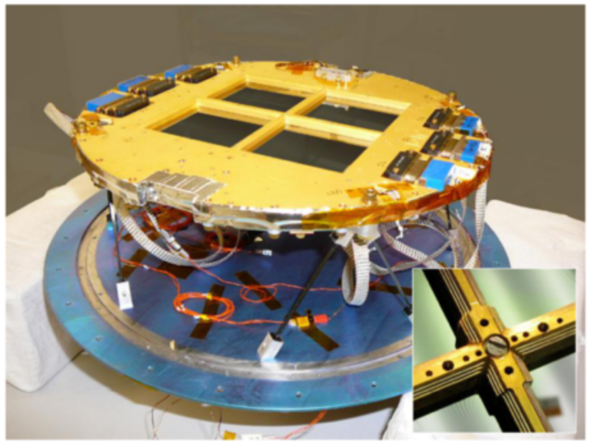
BICEP2

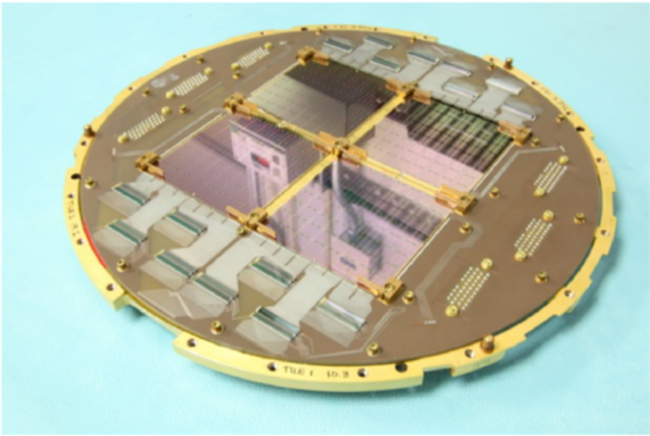
1403.3985





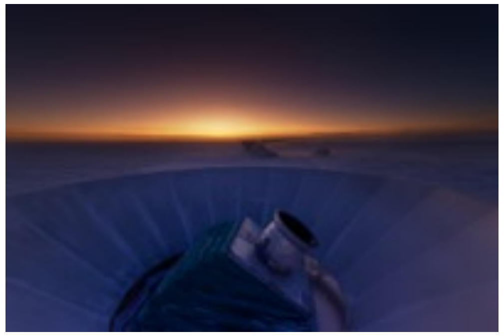


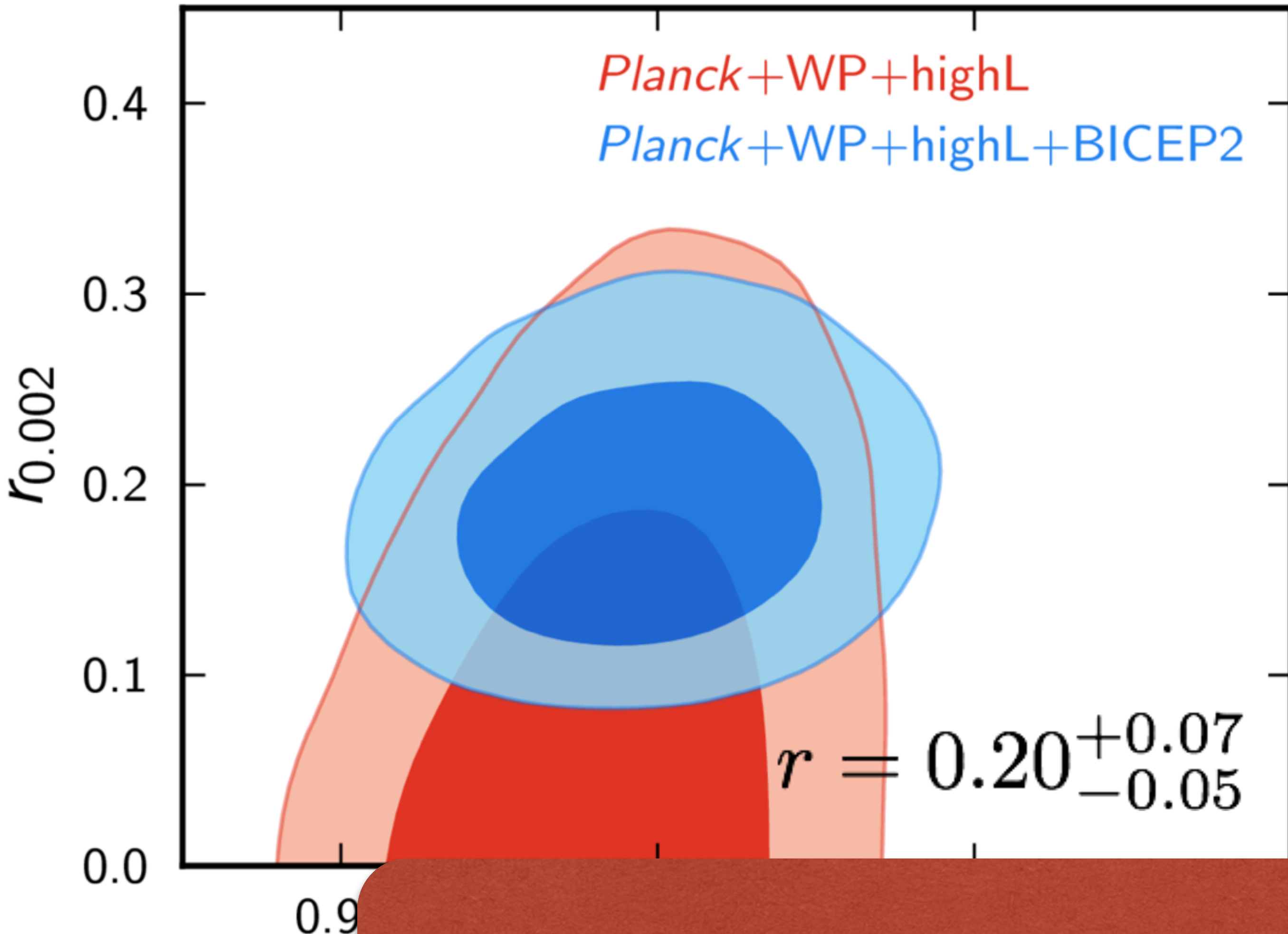


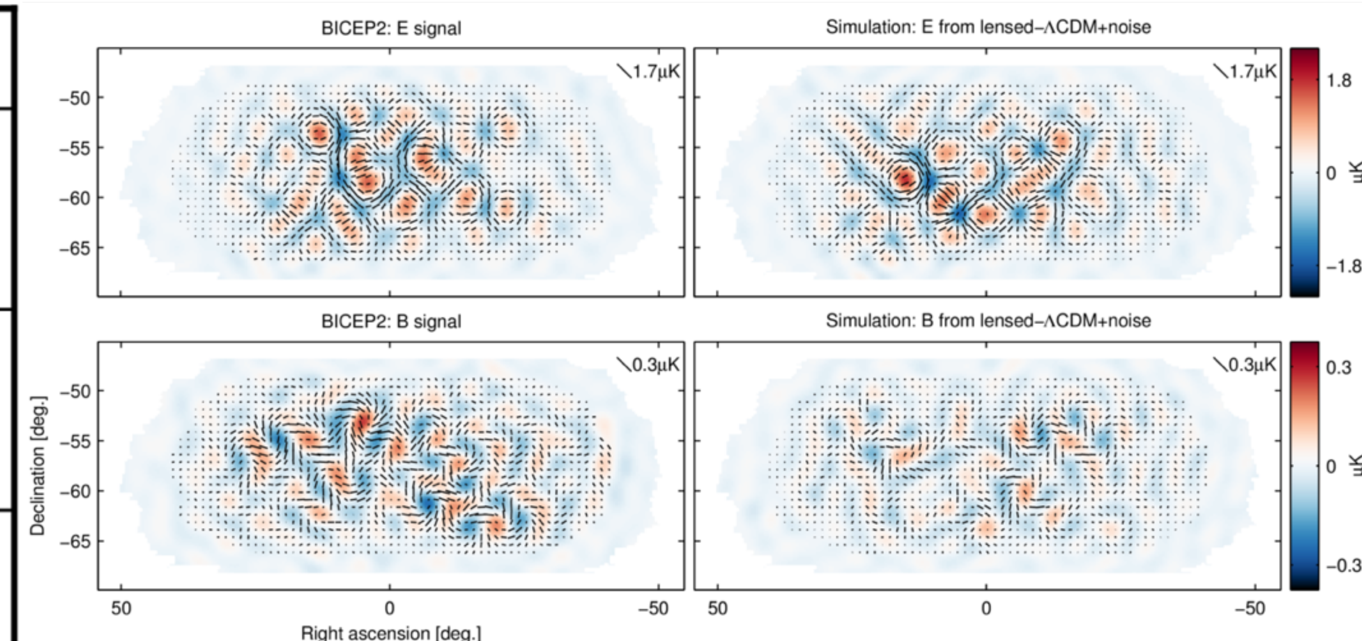


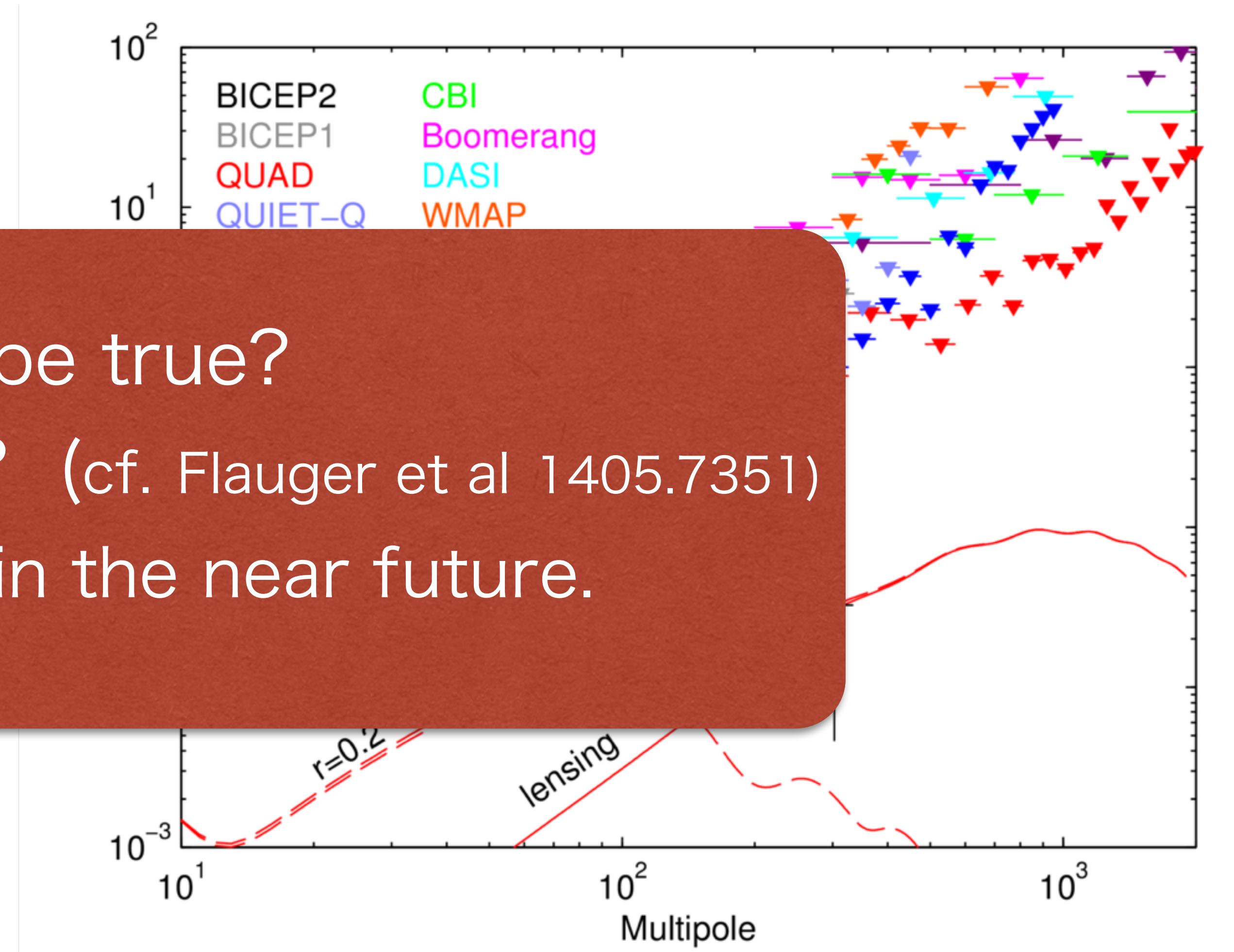
BICEP2

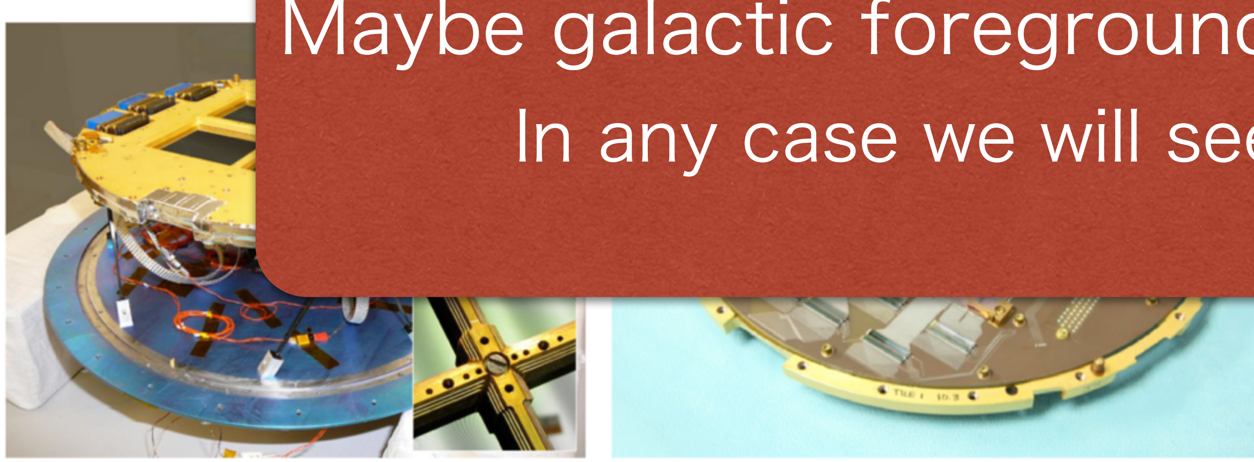
1403.3985











Too good to be true?

Maybe galactic foreground? (cf. Flauger et al 1405.7351)

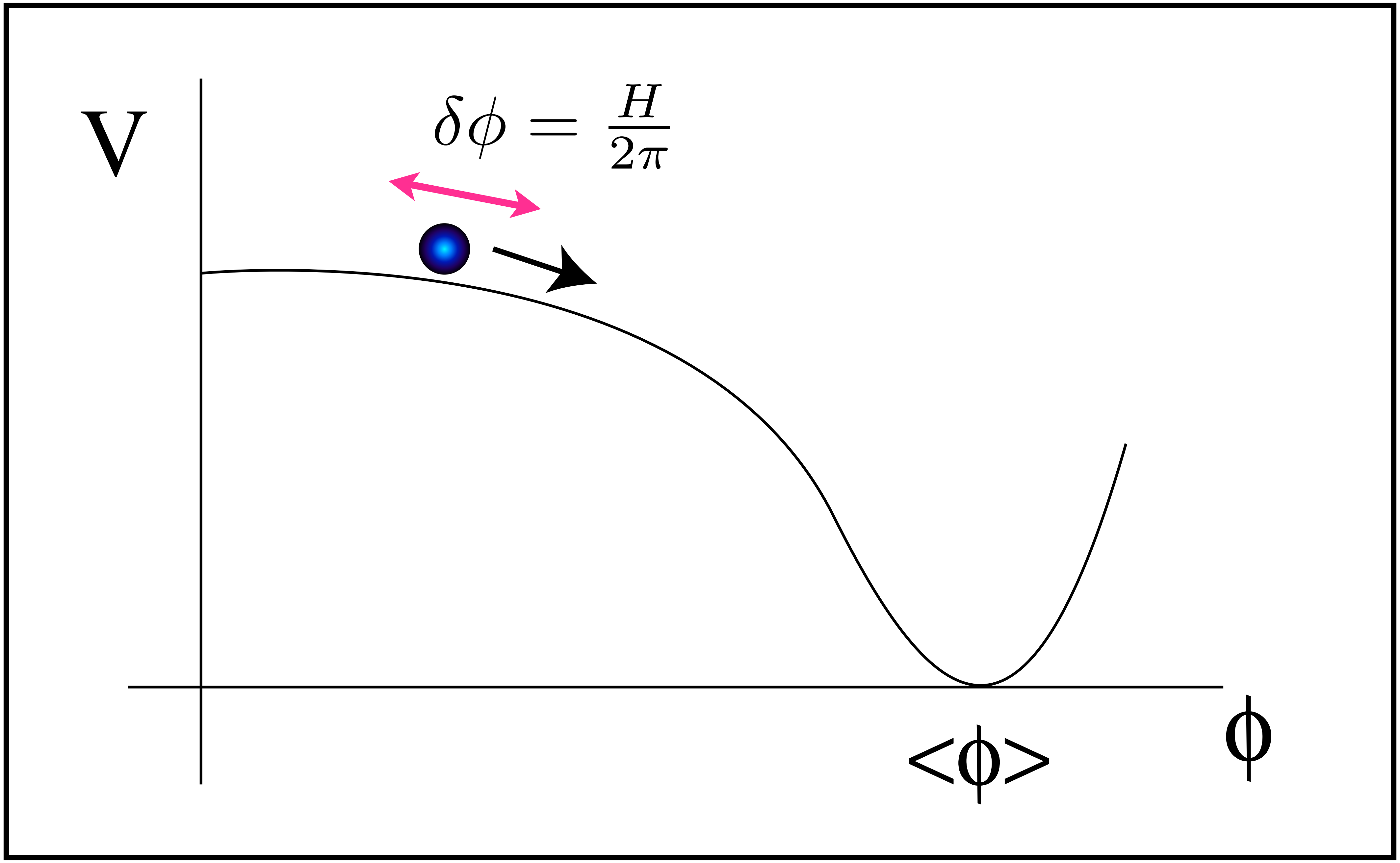
In any case we will see in the near future.

What if r = O(0.001–0.1)?
What can we say about inflation?

Inflation

Guth `81, Linde `82, Albrecht and Steinhardt `82

One way to realize the inflationary expansion is the slow-roll inflation.



Observation vs Theory

Scalar mode

$$P_{\mathcal{R}} = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Tensor mode

$$P_t = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

$$A_s = \frac{V^3}{2\sqrt{3}V'^2},$$

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

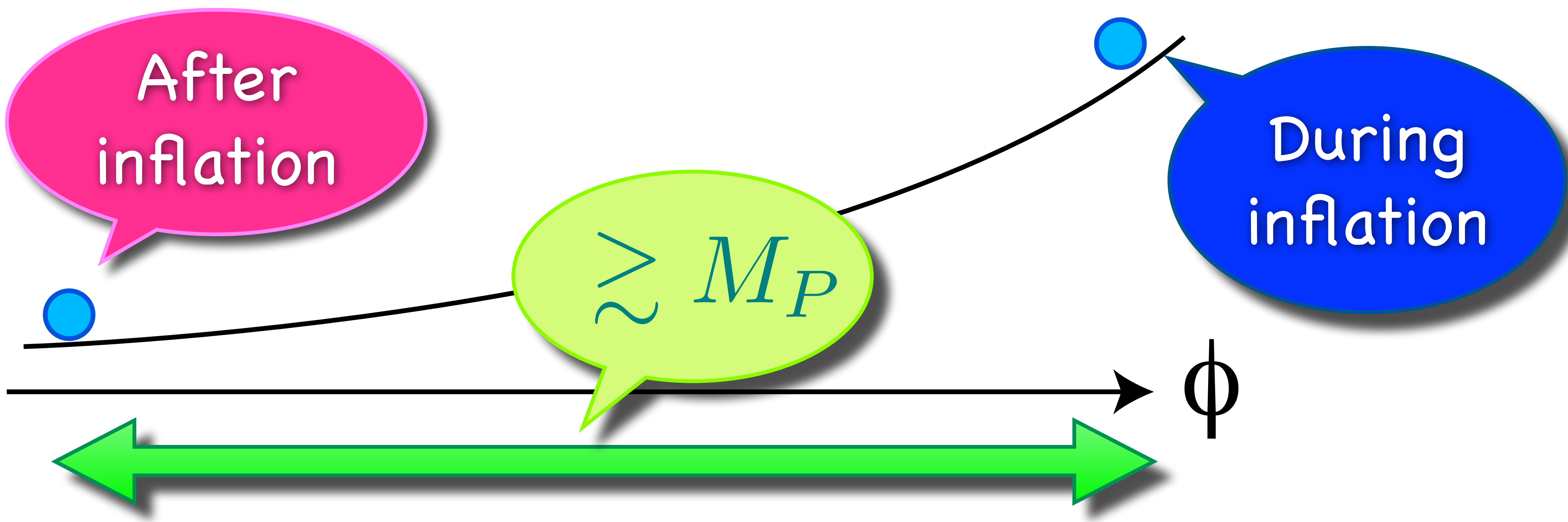
$$r = 8\left(\frac{V'}{V}\right)^2$$

$$A_s,\ n_s,\ r \equiv \frac{A_t}{A_s} \quad \Longleftrightarrow \quad V,\ V', V''$$

V : the inflaton potential

Large-field inflation

The inflaton excursion exceeds the Planck scale.



Lyth bound: $\Delta\phi \gtrsim 8 M_P \left(\frac{r}{0.2}\right)^{\frac{1}{2}} \left(\frac{N}{50}\right)$

Lyth 1997

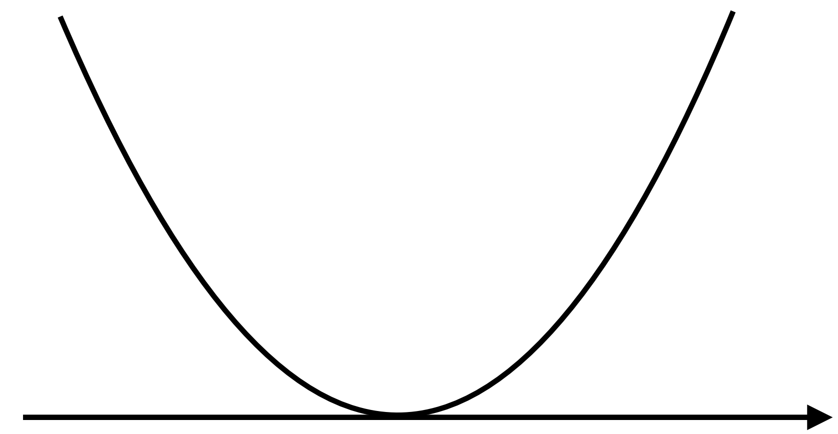
Various large-field inflation models

Quadratic chaotic inflation

Linde `83

$$V = \frac{1}{2}m^2\phi^2$$

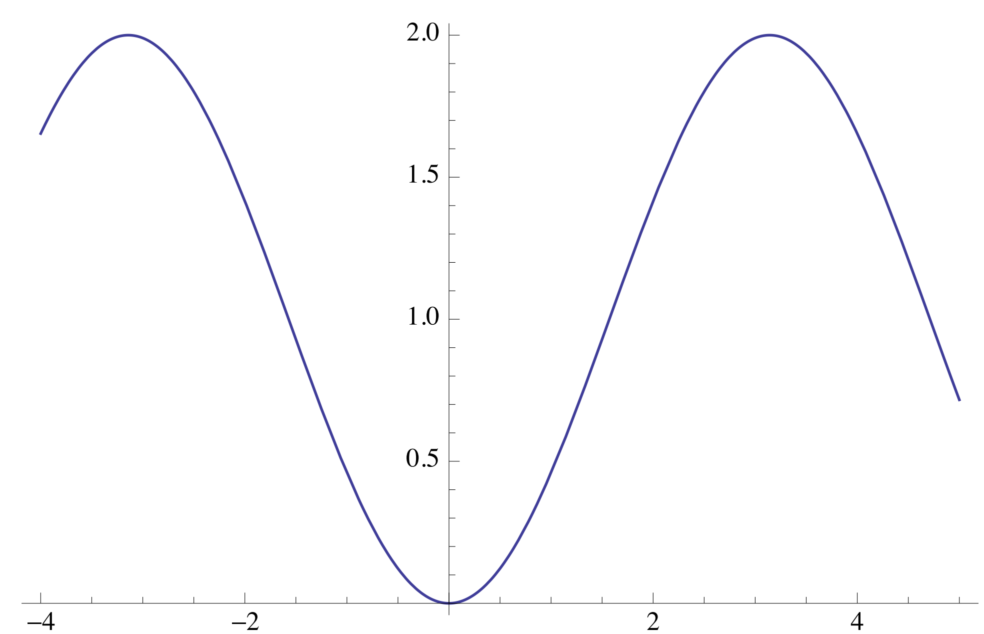
$m \simeq 2 \times 10^{13}\,\mathrm{GeV}$ $\quad \phi_{60} \sim 16 M_P$



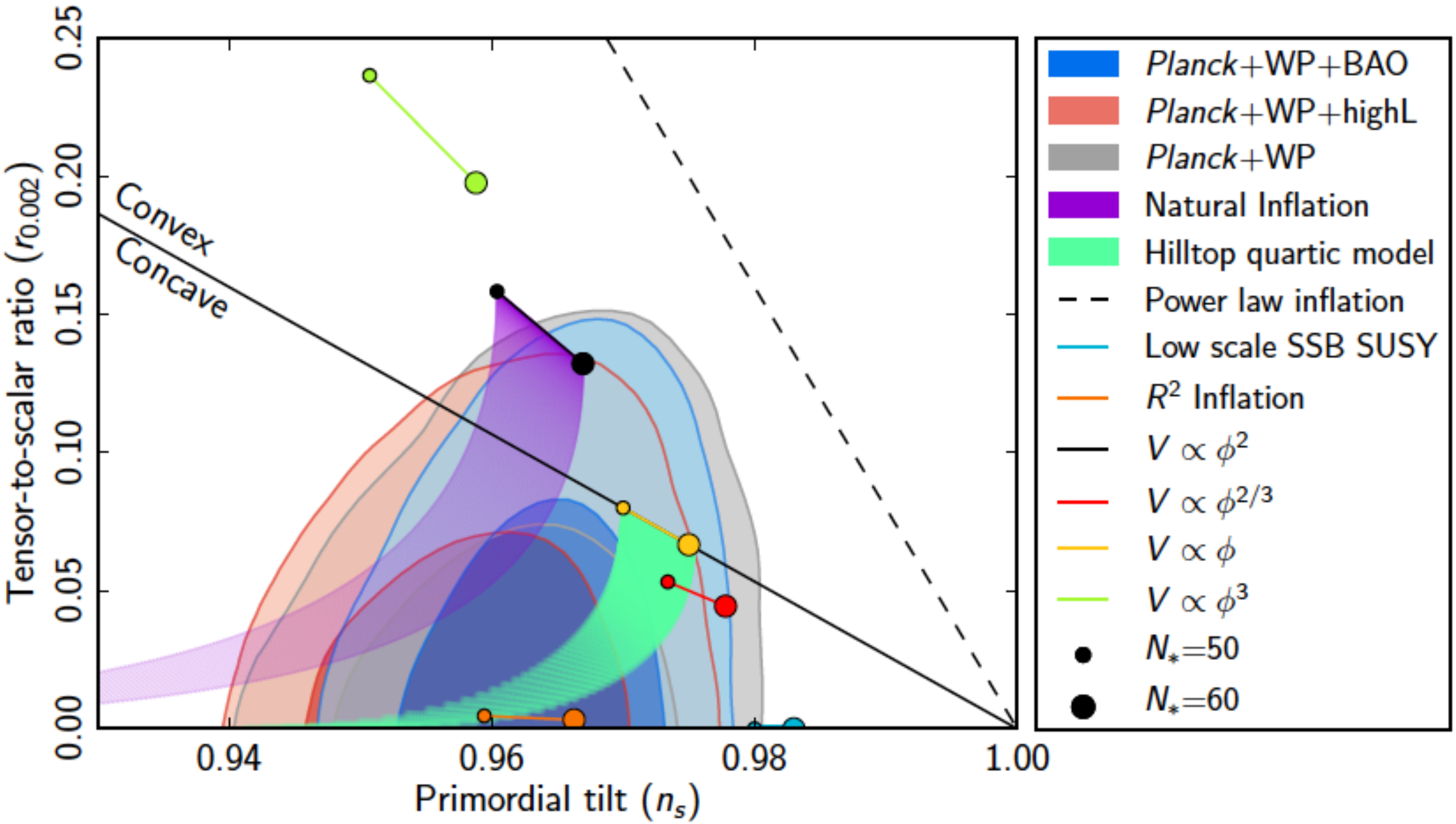
Natural inflation

Freese et al, `90

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

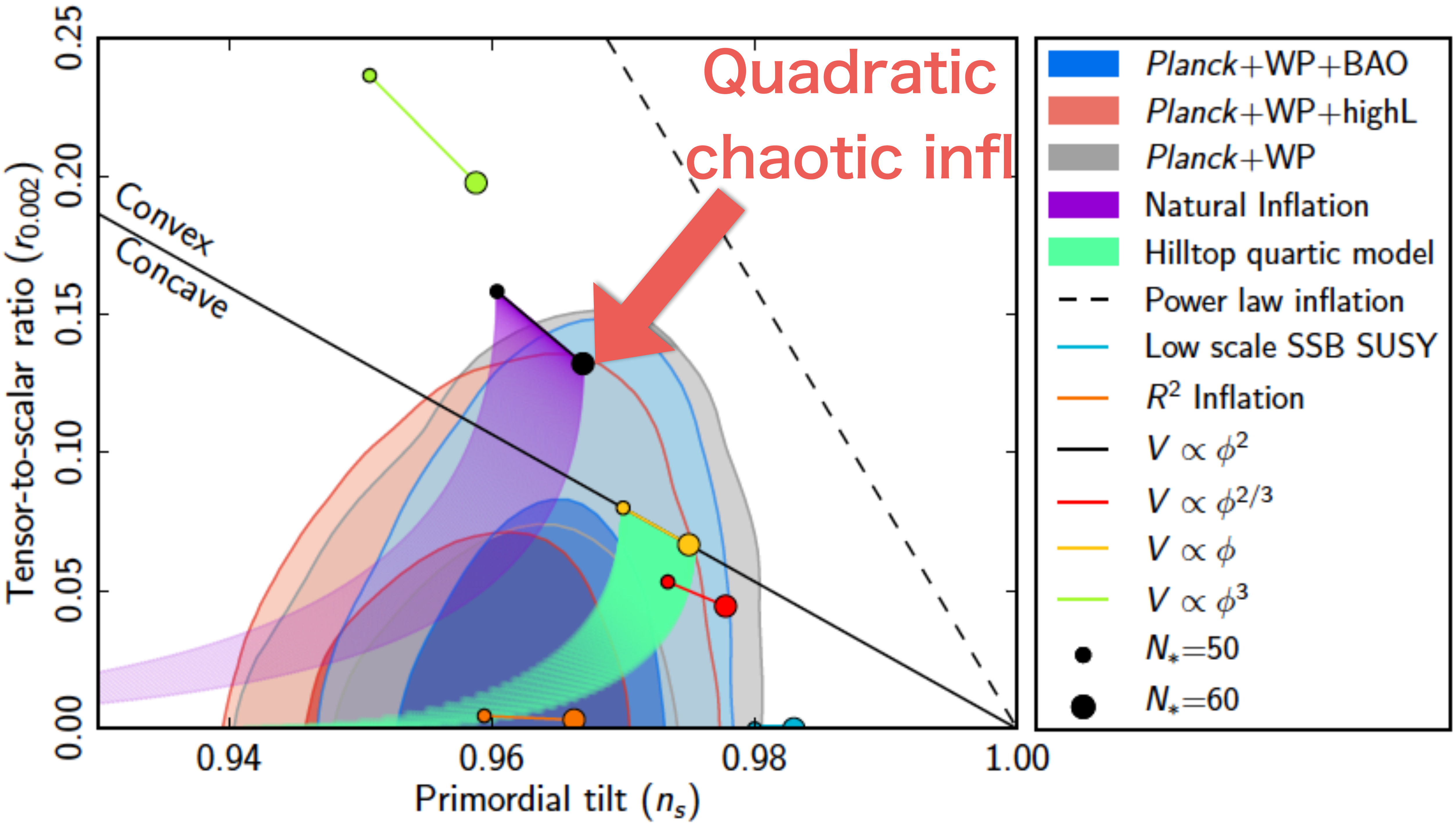


Predicted values of (n_s, r)



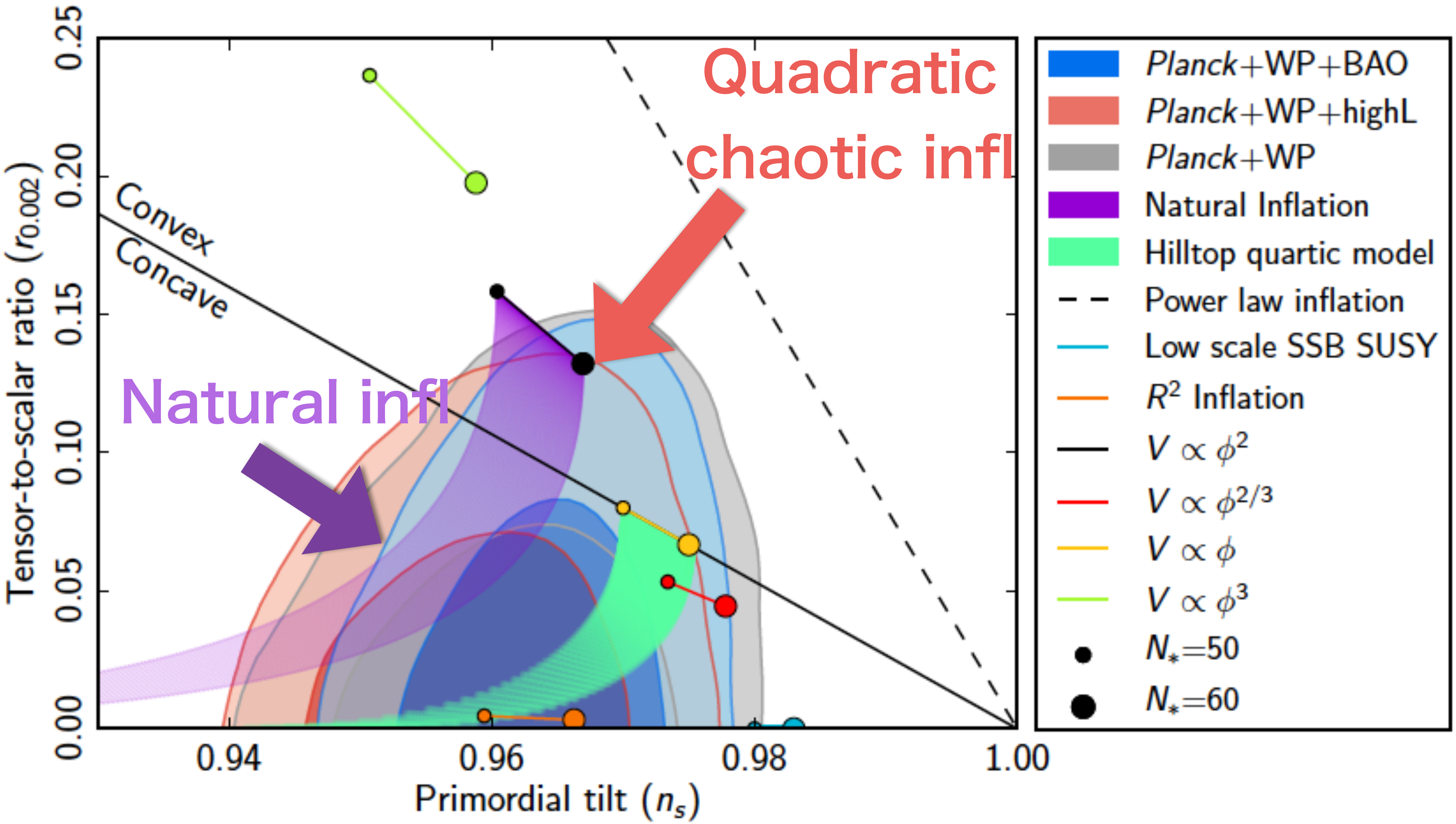
Planck, 1303.5802

Predicted values of (n_s, r)



Planck, 1303.5802

Predicted values of (n_s, r)



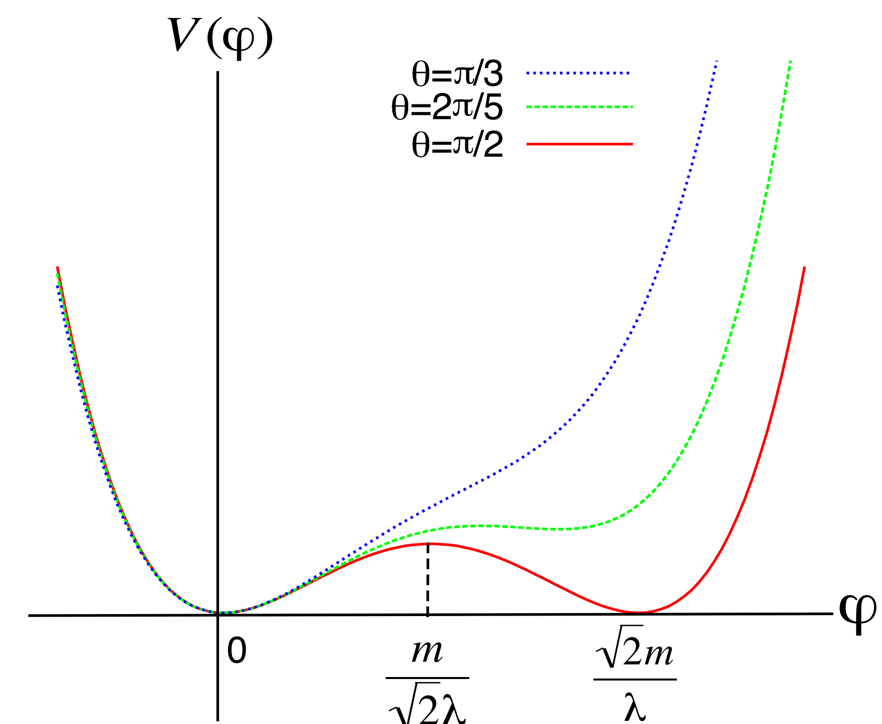
Planck, 1303.5802

Various large-field inflation models

Polynomial chaotic inflation

Destri, de Vega, Sanchez [astro-ph/0703417]
Nakayama, FT, Yanagida 1303.7315
(see also Kobayashi, Seto 1403.5055
Kallosh, Linde, Wesphal 1405.0270)

$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$



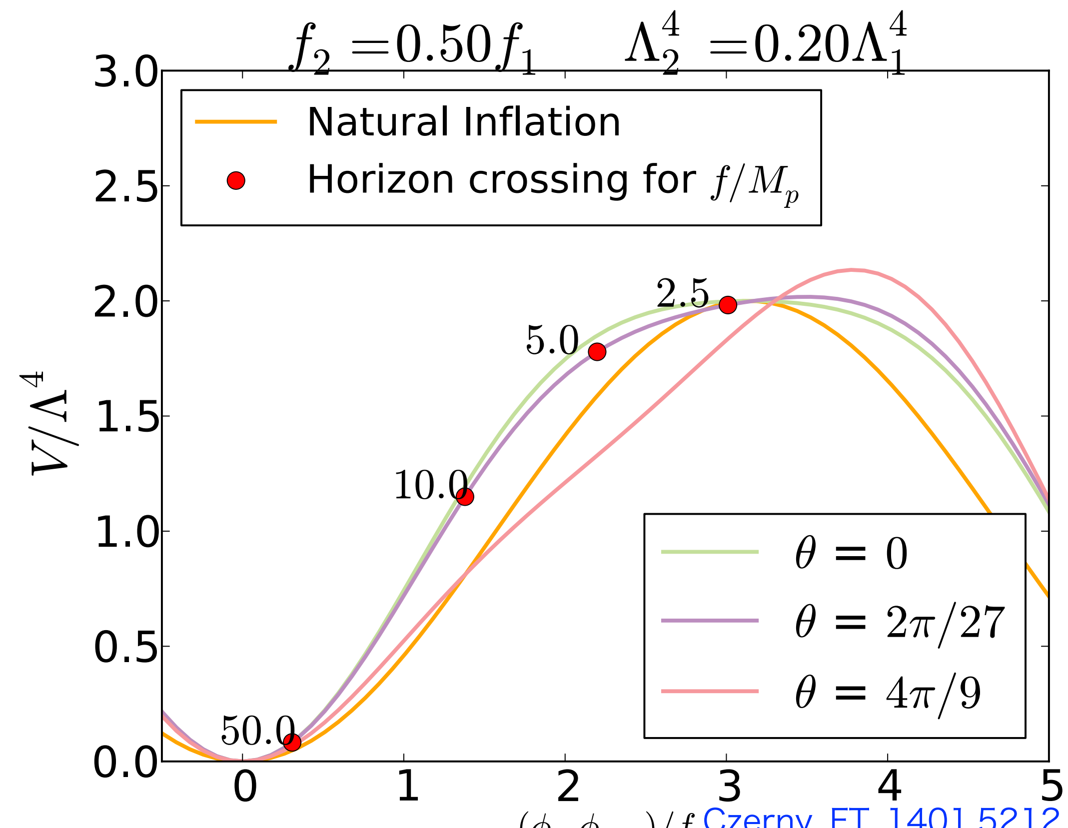
Nakayama, FT, Yanagida, 1303.7315

Multi-Natural inflation (MNI)

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883

$$V(\phi) = C - \Lambda_1^4\cos(\phi/f_1) - \Lambda_2^4\cos(\phi/f_2+\theta),$$

Sub-Planckian decay constants are allowed as hilltop inflation can be realized.



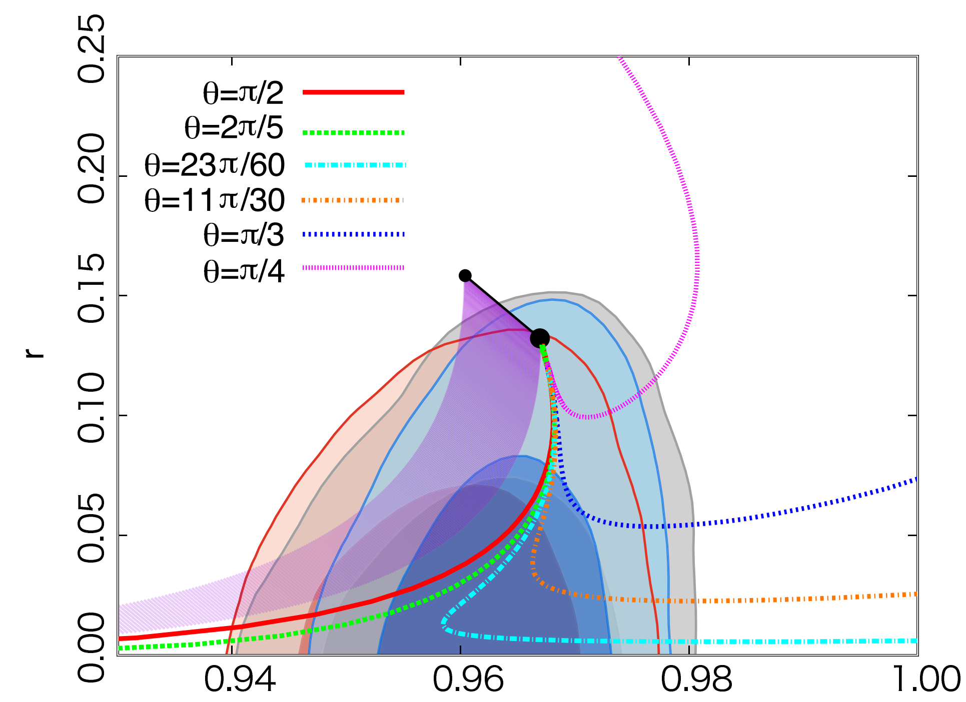
Czerny, FT, 1401.5212

Various large-field inflation models

Polynomial chaotic inflation

Destri, de Vega, Sanchez [astro-ph/0703417]
Nakayama, FT, Yanagida 1303.7315
(see also Kobayashi, Seto 1403.5055
Kallosh, Linde, Wesphal 1405.0270)

$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$



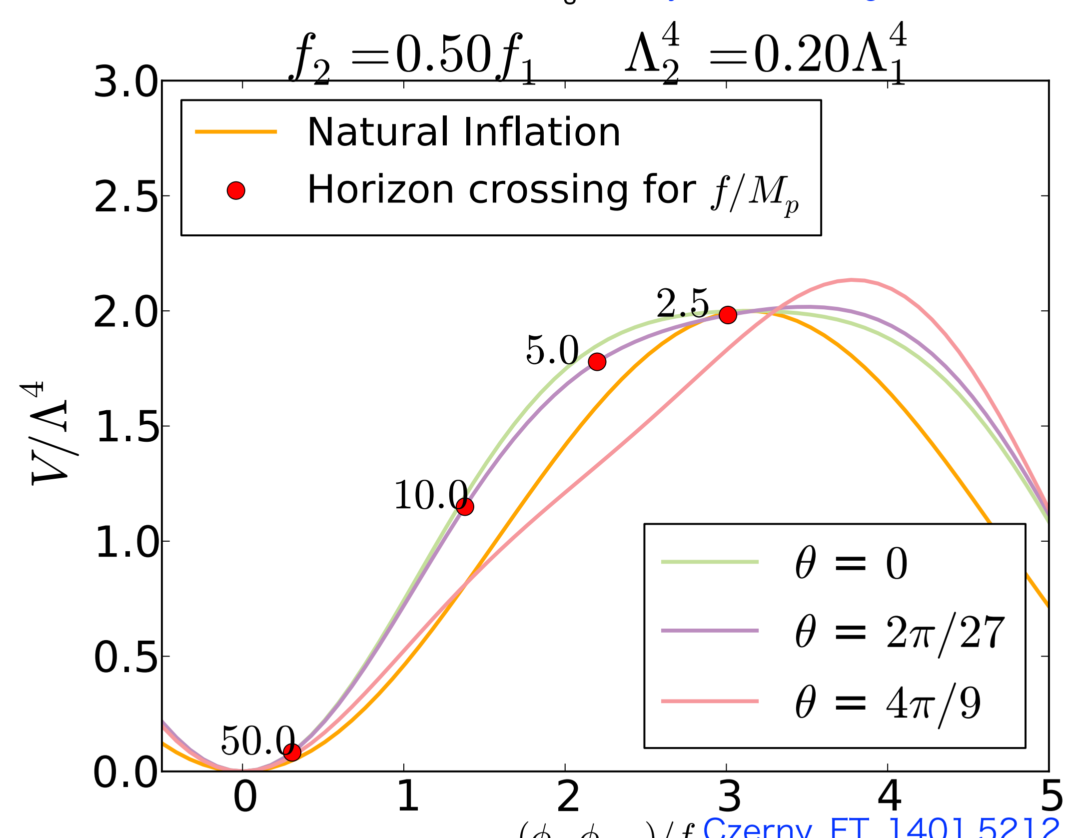
Nakayama, FT, Yanagida, 1303.7315

Multi-Natural inflation (MNI)

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta),$$

Sub-Planckian decay constants are allowed as hilltop inflation can be realized.

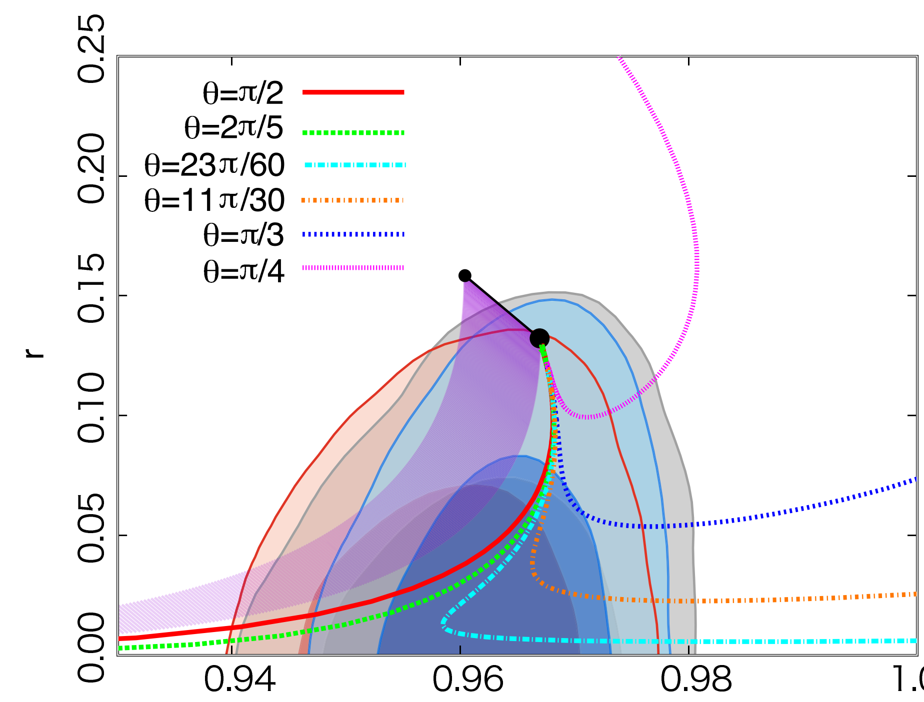


Czerny, FT, 1401.5212

Various large-field inflation models

Polynomial chaotic inflation

Destri, de Vega, Sanchez [astro-ph/0703417]
Nakayama, FT, Yanagida 1303.7315
(see also Kobayashi, Seto 1403.5055
Kallosh, Linde, Wesphal 1405.0270)

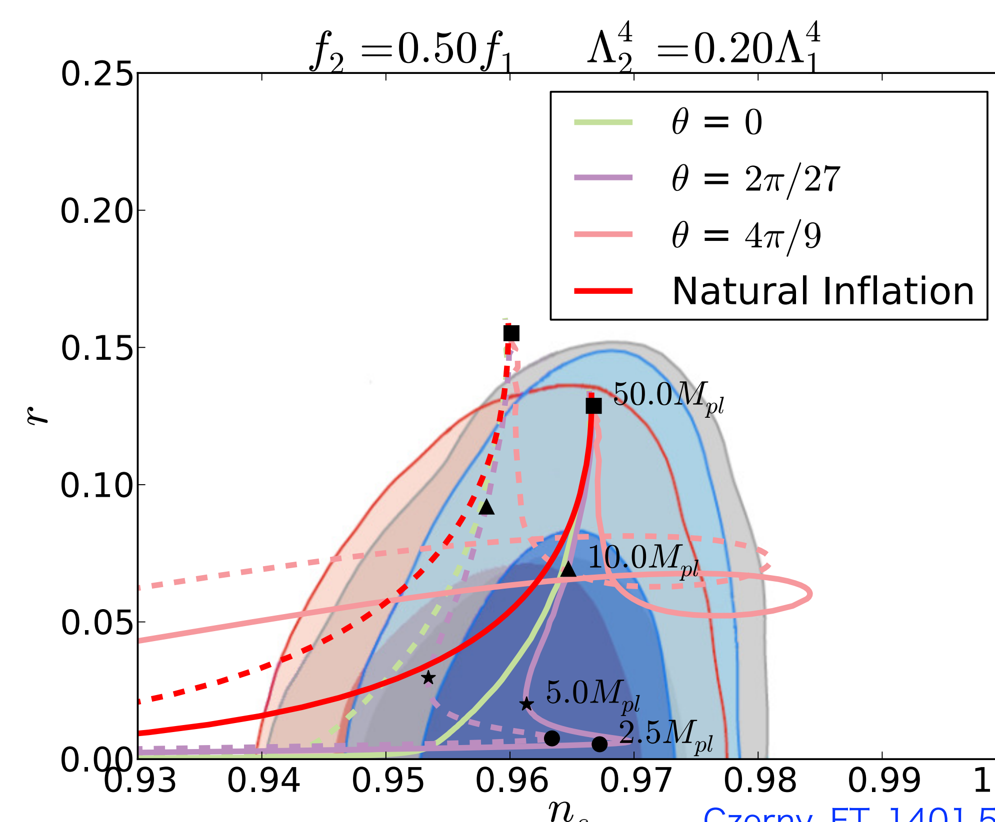


Nakayama, FT, Yanagida, 1303.7315

$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$

Multi-Natural inflation (MNI)

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883



Czerny, FT, 1401.5212

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta),$$

Sub-Planckian decay constants are allowed as hilltop inflation can be realized.

Chaotic inflation in SUGRA

Kawasaki, Yamaguchi, Yanagida, hep-ph/0004243 ,hep-ph/0011104

To have a good control over the inflaton field values greater than the Planck scale, we impose a shift symmetry;

$$\phi \to \phi + iC,$$

which is explicitly broken by the superpotential.

$$K_{\rm inf} = c(\phi + \phi^\dagger) + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

$$V_{\rm sugra} = e^K \left((D_i W) K^{i\bar{j}} (D_j W)^* - 3|W|^2 \right).$$

$$V \simeq \frac{1}{2} m^2 \varphi^2$$

$$\varphi \equiv \sqrt{2}{\rm Im}[\phi]$$

even for $\varphi \gg M_p$

Polynomial chaotic inflation in SUGRA

Nakayama, FT, Yanagida 1303.7315,1305.5099

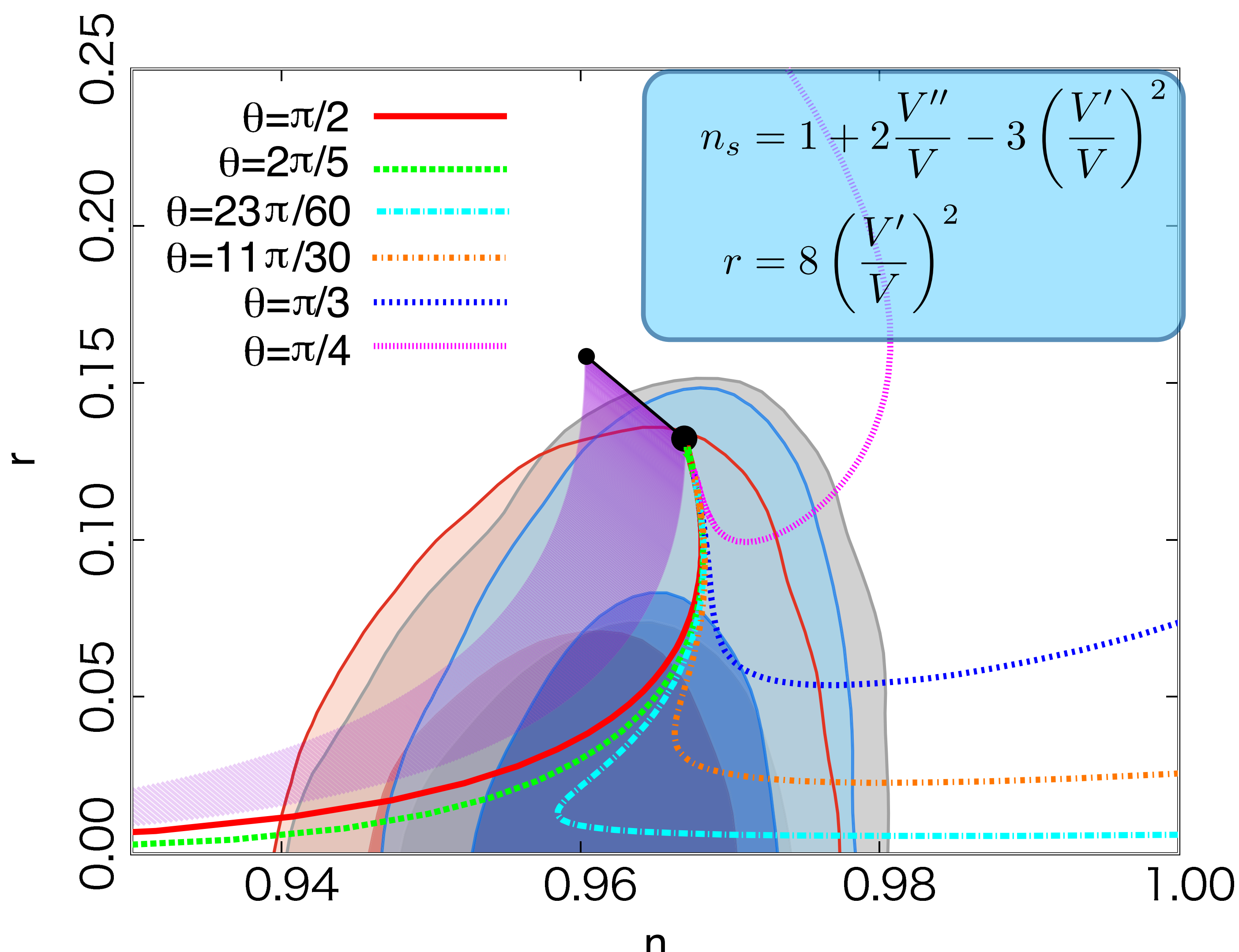
(cf. Kallosh, Linde, Westphal 1405.0270)

$$K = \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 + \cdots,$$

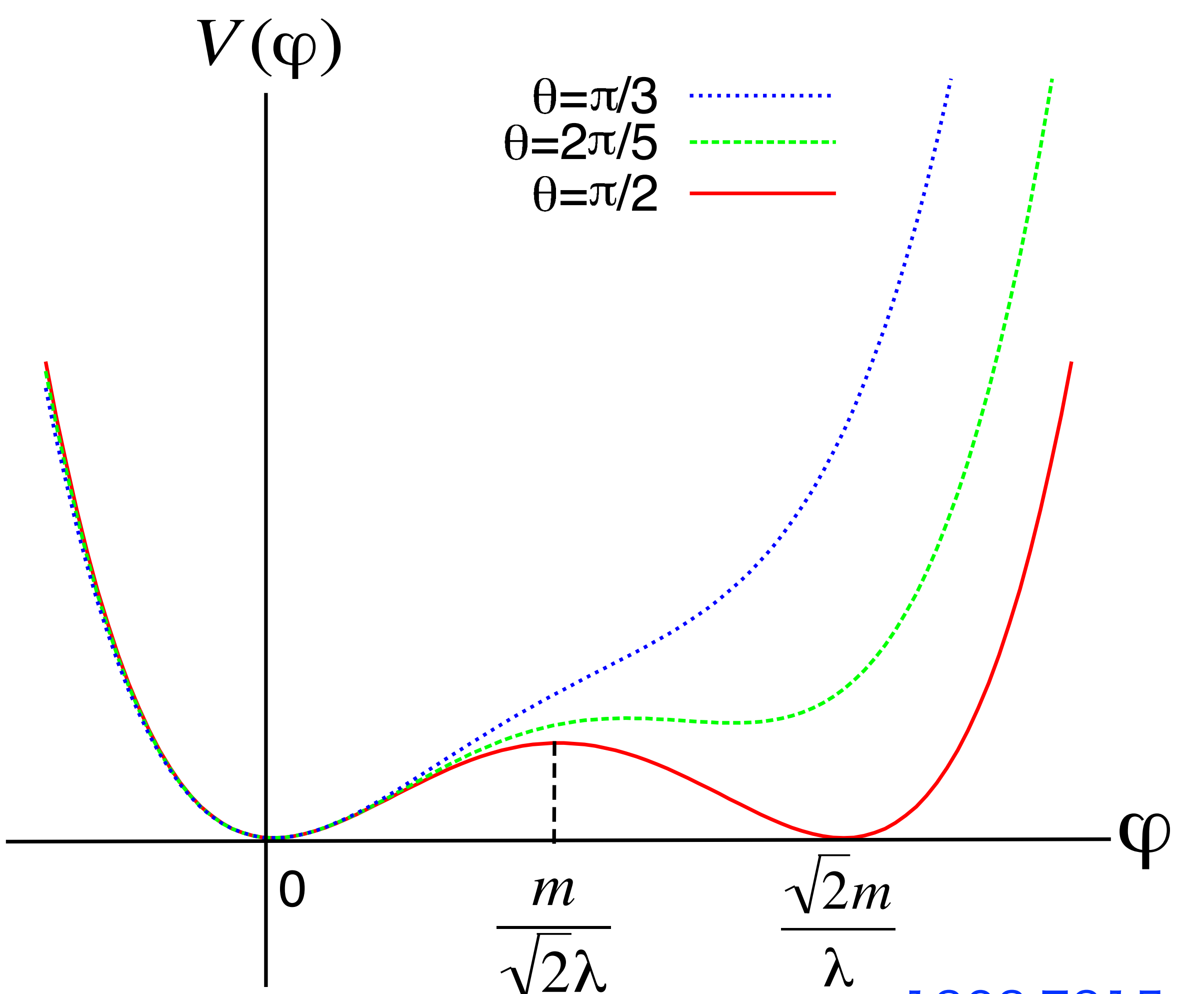
$$W = X\left(m\phi + k_2\phi^2 + \cdots\right),$$

$$V \simeq \frac{1}{2}\varphi^2\left(m^2 - \sqrt{2}m\lambda\sin\theta\,\varphi + \frac{\lambda^2}{2}\varphi^2\right)$$

$$\lambda = |k_2| \quad \theta = \arg[k_2] \quad \mathrm{Re}[\phi] \lesssim 1$$



1303.7315



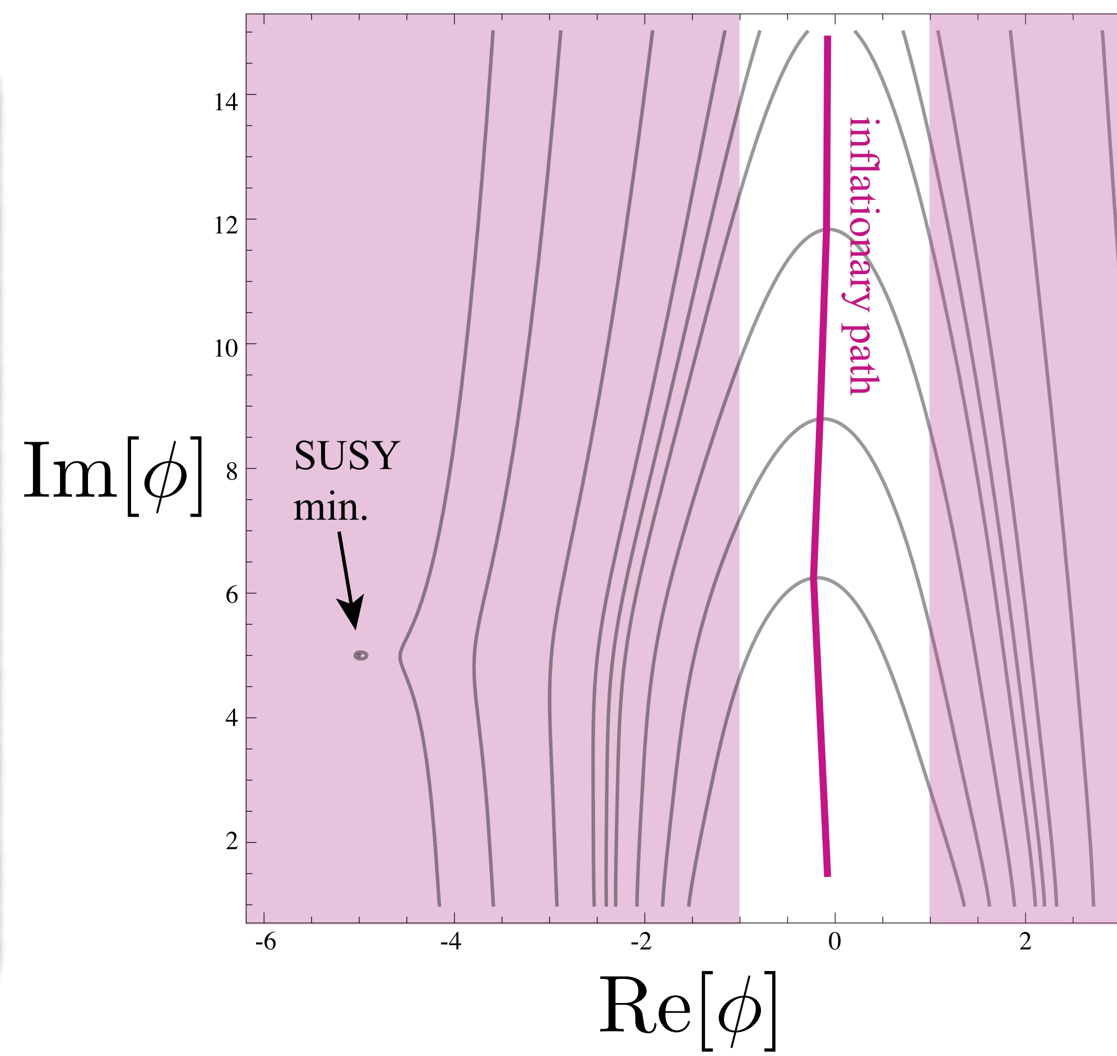
1303.7315

Side remark

Very precisely speaking, the inflaton potential is not exactly polynomial, because $\mathrm{Re}[\phi] \neq 0$ for $\theta \neq 0$.
There is also a SUSY min. at $\mathrm{Re}[\phi] = -\frac{m}{\lambda} e^{-i\theta}$. Linde 1402.0526

- However, the inflaton dynamics can be well approximated by the polynomial potential.
- Numerically confirmed that (n_s,r) remain intact even if this effect is taken into account.

Contour of the inflaton potential



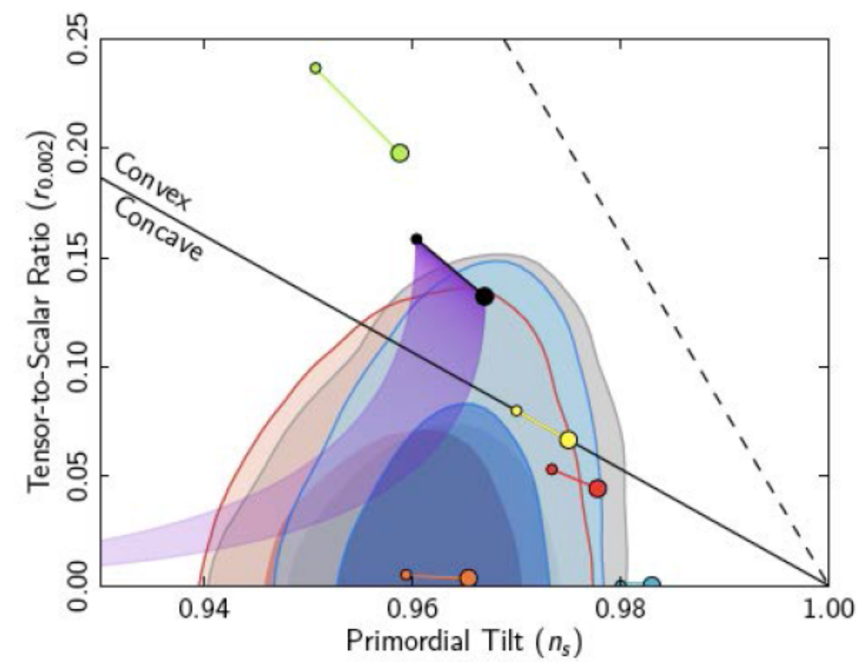
Nakayama, FT, Yanagida, in preparation

Natural and Multi-Natural Inflation

- Natural inflation Freese, Frieman, Olinto `90

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

Only large-field inflation is possible,
and f is bounded below: $f \gtrsim 5 M_P$



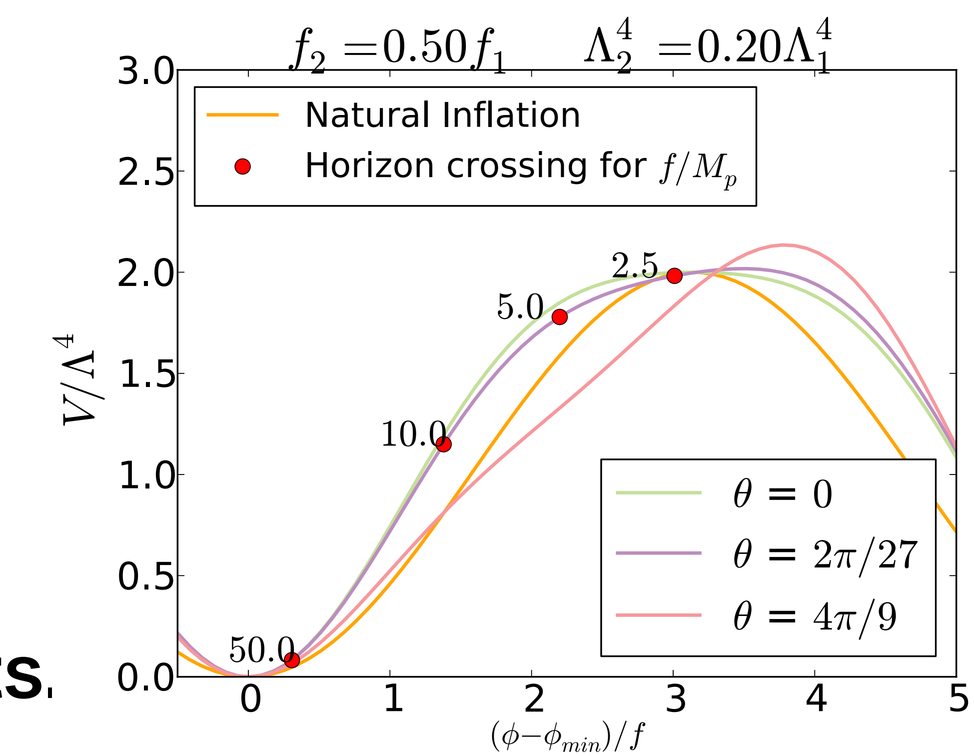
- Multi-Natural inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883

$$V = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\frac{\phi}{f_i} + \theta_i\right) + {\rm const.}$$

For $N_{\rm source} = 2$, various values of (n_s,r) are possible as in the polynomial chaotic inf.

No lower bound on the decay constants.

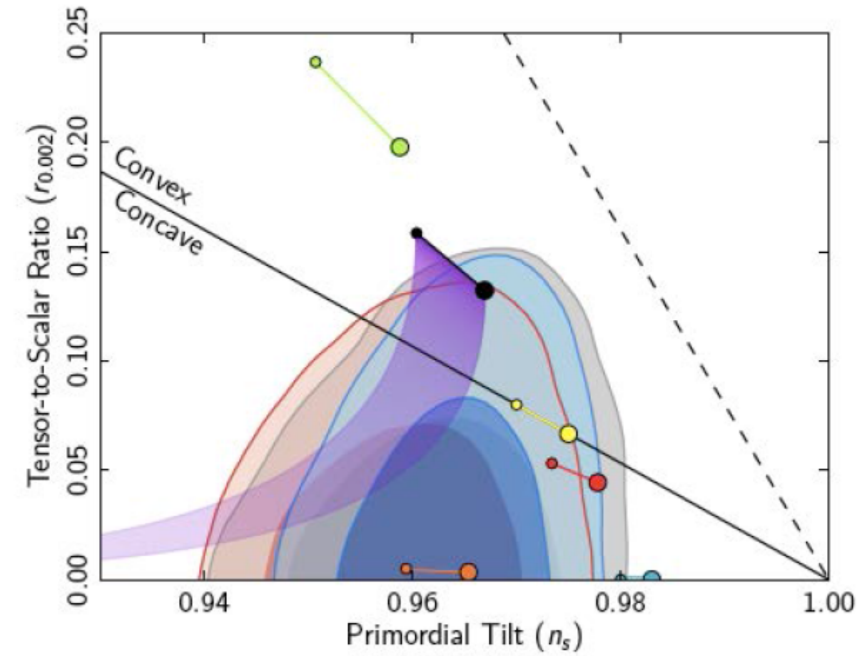


Natural and Multi-Natural Inflation

- Natural inflation Freese, Frieman, Olinto `90

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

Only large-field inflation is possible, and f is bounded below: $f \gtrsim 5M_P$



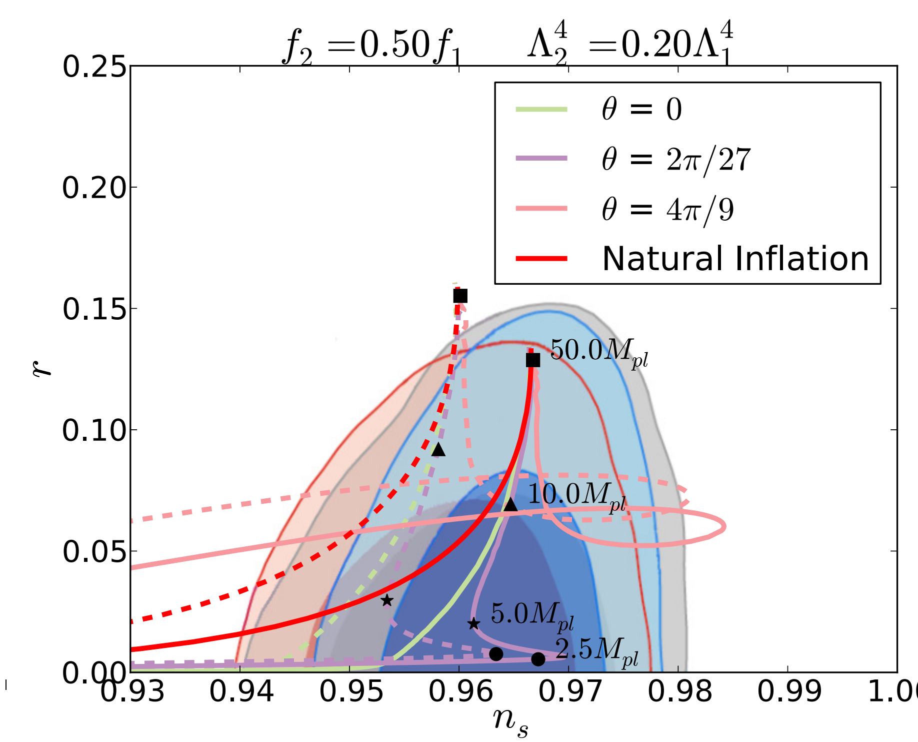
- Multi-Natural inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883

$$V = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\frac{\phi}{f_i} + \theta_i\right) + {\rm const.}$$

For $N_{\rm source} = 2$, various values of (n_s,r) are possible as in the polynomial chaotic inf.

No lower bound on the decay constants

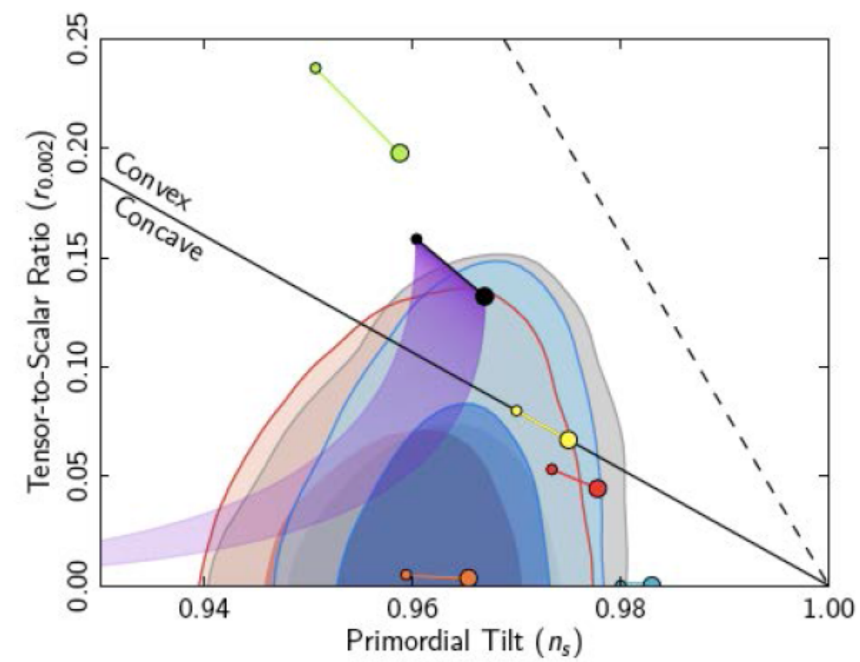


Natural and Multi-Natural Inflation

- Natural inflation Freese, Frieman, Olinto `90

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

Only large-field inflation is possible,
and f is bounded below: $f \gtrsim 5 M_P$



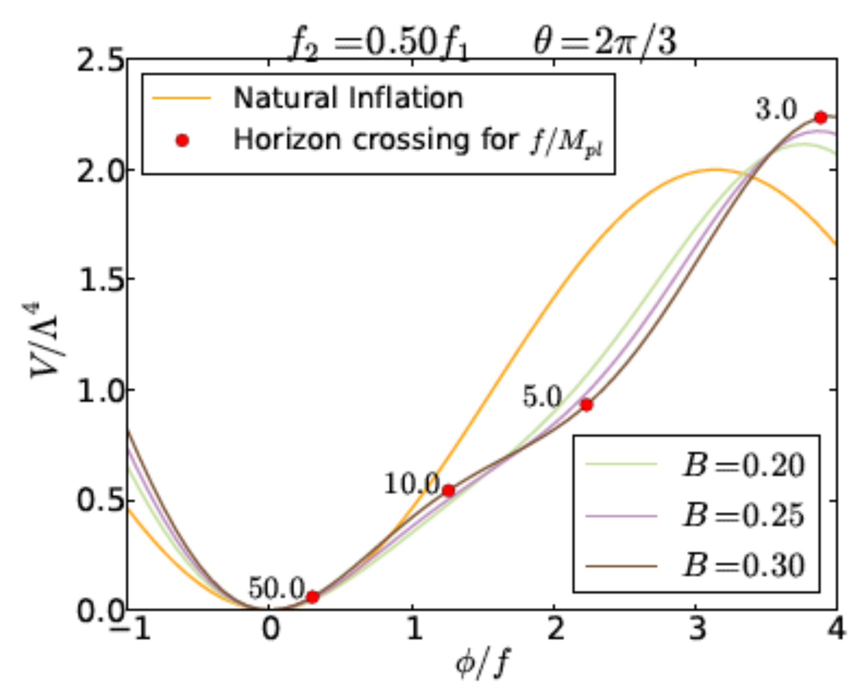
- Multi-Natural inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883

$$V = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\frac{\phi}{f_i} + \theta_i\right) + {\rm const.}$$

For $N_{\rm source} = 2$, various values of (n_s, r) are possible as in the polynomial chaotic inf.

No lower bound on the decay constants.

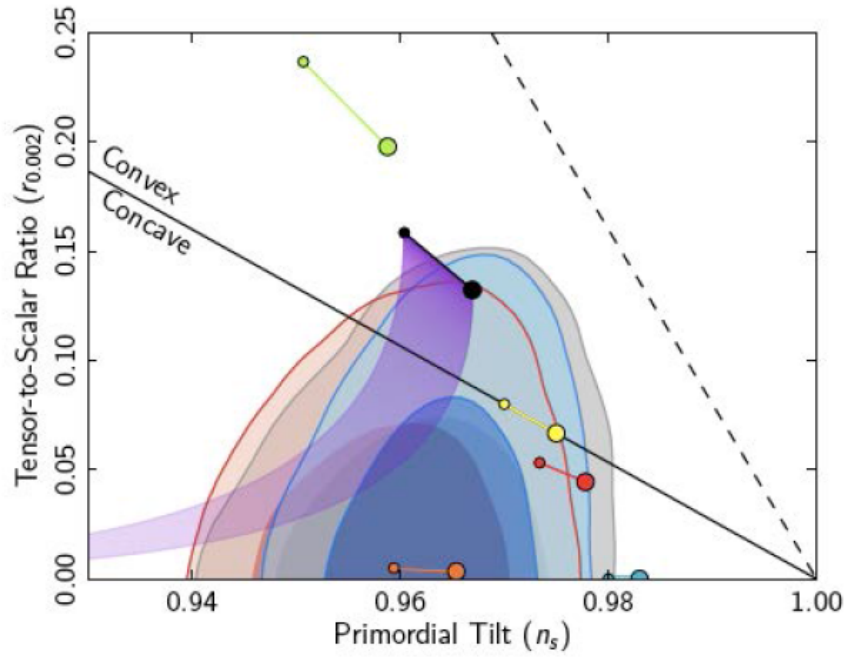


Natural and Multi-Natural Inflation

- Natural inflation Freese, Frieman, Olinto `90

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

Only large-field inflation is possible,
and f is bounded below: $f \gtrsim 5 M_P$



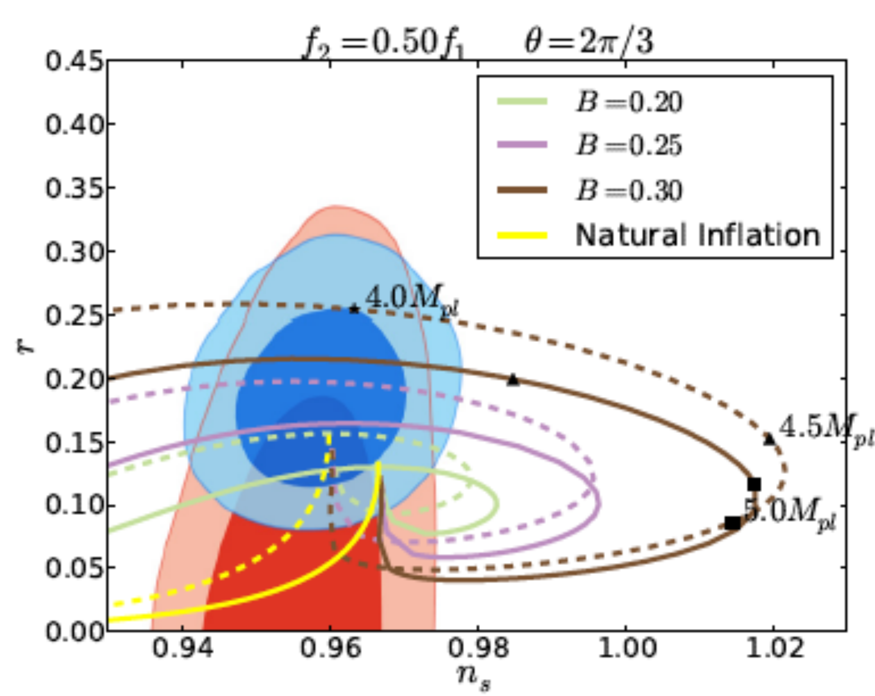
- Multi-Natural inflation

Czerny, FT 1401.5212, Czerny, Higaki, FT 1403.0410, 1403.5883

$$V = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\frac{\phi}{f_i} + \theta_i\right) + {\rm const.}$$

For $N_{\rm source} = 2$, various values of (n_s, r) are possible as in the polynomial chaotic inf.

No lower bound on the decay constants.



Axion hilltop inflation

(Small-field Multi-Natural inflation)

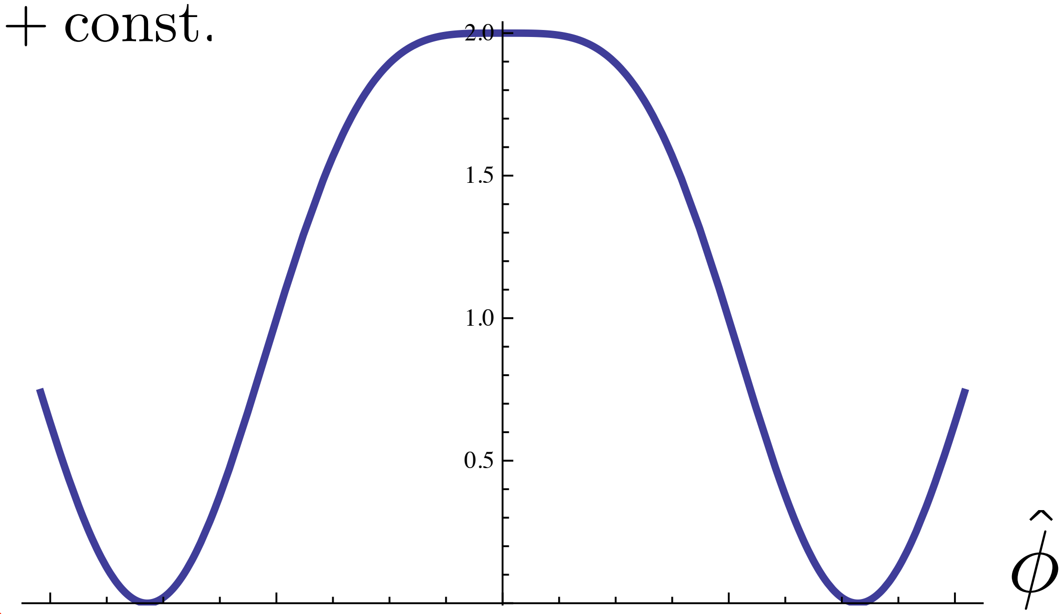
Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410

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

$$V(\phi) = \Lambda_1^4 \left(1 - \cos\left(\frac{\phi}{f_1}\right)\right) + \Lambda_2^4 \left(1 - \cos\left(\frac{\phi}{f_2} + \theta\right)\right) + \text{const.}$$

$$\simeq V_0 - \lambda \hat{\phi}^4 + \cdots \qquad \hat{\phi} \equiv \phi - \pi f_1$$

for $\frac{\Lambda_1^2}{f_1} = \frac{\Lambda_2^2}{f_2}$ and $\theta = -\pi \frac{f_1}{f_2}$



Axion hilltop inflation is possible for $f < M_P$.

- **Simple realization of hilltop inflation by axion.**
- **The potential shape is under control.**
- **Spectral index can give a better fit to the Planck data by a slight shift of the phase.**

Axion hilltop inflation

(Small-field Multi-Natural inflation)

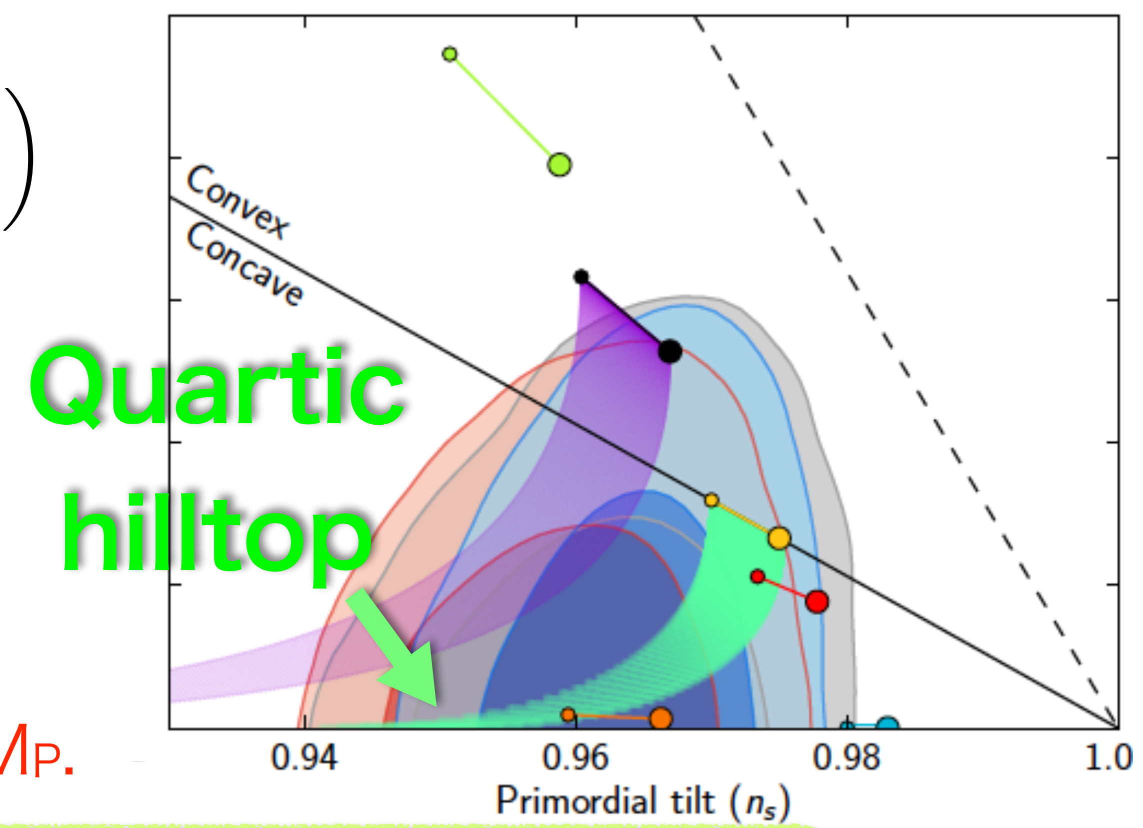
Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410

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

$$V(\phi) = \Lambda_1^4 \left(1 - \cos\left(\frac{\phi}{f_1}\right)\right) + \Lambda_2^4 \left(1 - \cos\left(\frac{\phi}{f_2} + \theta\right)\right)$$

$$\simeq V_0 - \lambda \hat{\phi}^4 + \cdots \qquad \hat{\phi} \equiv \phi - \pi f_1$$

for $\dfrac{\Lambda_1^2}{f_1} = \dfrac{\Lambda_2^2}{f_2}$ and $\theta = -\pi \dfrac{f_1}{f_2}$

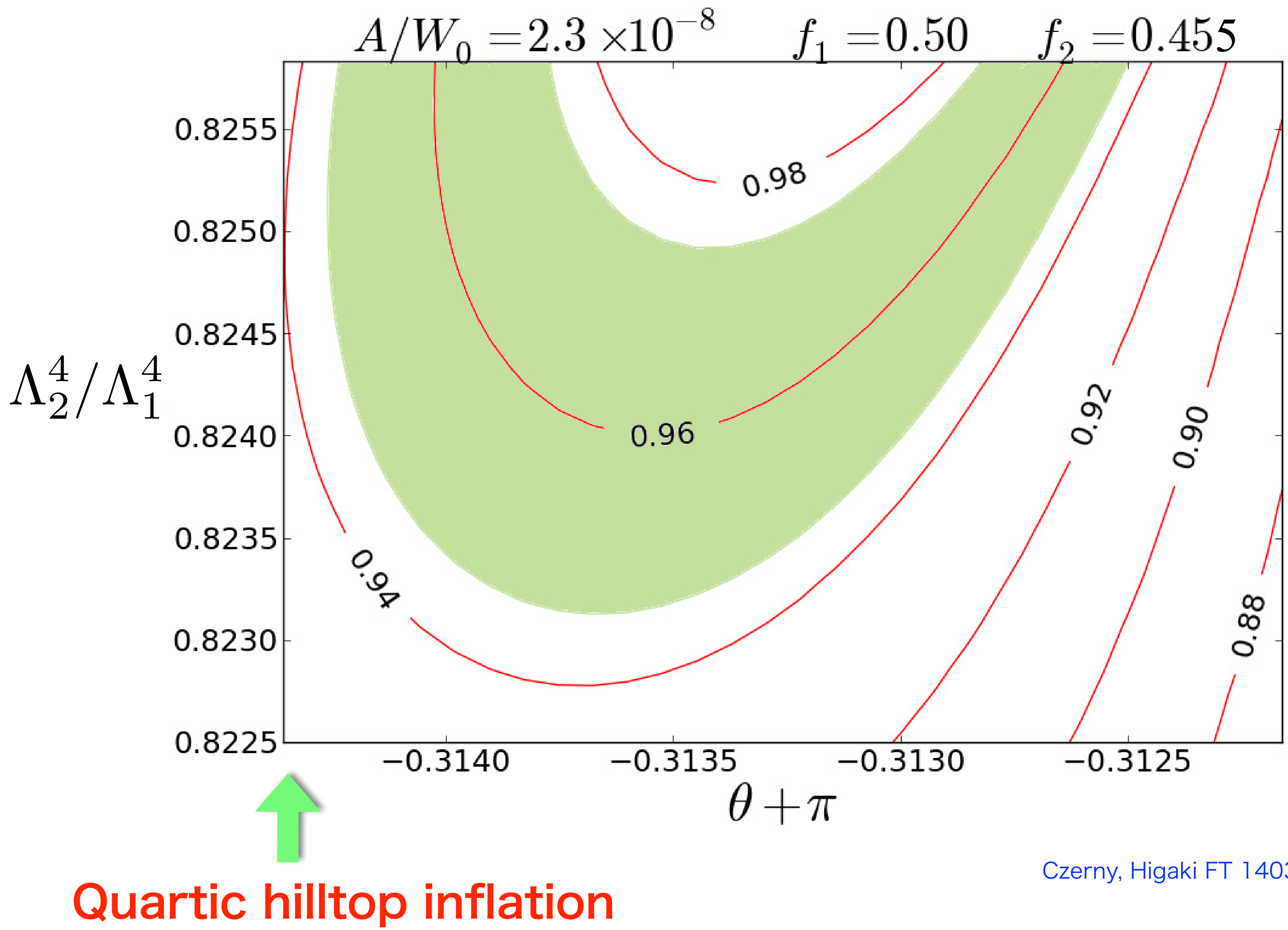


Axion hilltop inflation is possible for f < M_P.

- Simple realization of hilltop inflation by axion.
- The potential shape is under control.
- Spectral index can give a better fit to the Planck data by a slight shift of the phase.

Spectral index of axion hilltop inflation

$$V(\phi) = \Lambda_1^4\left(1-\cos\left(\frac{\phi}{f_1}\right)\right) + \Lambda_2^4\left(1-\cos\left(\frac{\phi}{f_2}+\theta\right)\right) + \text{const.}$$



Relative phase leads to the effective linear term, which affects n_s in hilltop inflation.

cf. FT 1308.4212

Czerny, Higaki FT 1403.0410

Natural and Multi-Natural Inflation in SUGRA

Czerny, Higaki, FT 1403.0410 (before BICEP2) , 1403.5883 (after BICEP2)

$$K = \frac{f^2}{2}(\Phi + \Phi^\dagger)^2 + \cdots$$
$$W = W_0 + Ae^{-a\Phi} + Be^{-i\theta}e^{-b\Phi}$$

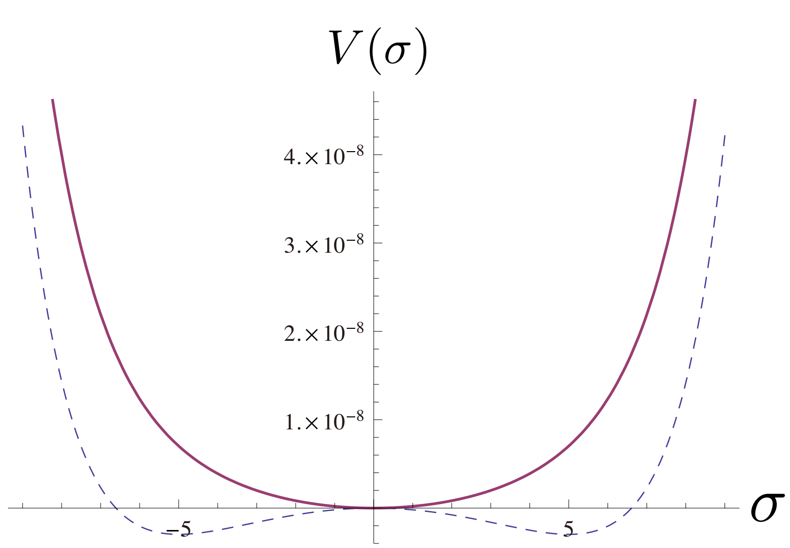
Natural inflation if B=0.
Kallosh, hep-th/0702059

where $A, B \ll W_0 < 1$, $a > 0, b > 0, a \neq b$

$$\Phi = \sigma + i\varphi$$

The saxion is stabilized around the origin by SUSY breaking effect.

$$V = e^{2f^2\sigma^2}\left(4f^2\sigma^2 - 3\right)|W_0|^2 + \Delta V_{\text{up-lift}}$$
$$\simeq 2f^2|W_0|^2\sigma^2 + \cdots ,$$



The saxion mass: $m_\sigma \simeq \sqrt{2}m_{3/2}$

Natural and Multi-Natural Inflation in SUGRA

Czerny, Higaki, FT 1403.0410 (before BICEP2) , 1403.5883 (after BICEP2)

$$K = \frac{f^2}{2}(\Phi + \Phi^\dagger)^2 + \cdots$$

$$W = W_0 + Ae^{-a\Phi} + Be^{-i\theta}e^{-b\Phi}$$

Natural inflation if B=0.
Kallosh, hep-th/0702059

where $A, B \ll W_0 < 1\,,\, a > 0, b > 0, a \neq b$

The axion potential:

$$f_1 \equiv \frac{\sqrt{2}f}{a}, \quad f_2 \equiv \frac{\sqrt{2}f}{b},$$

$$V_{\rm axion}(\phi) \simeq 6AW_0\left[1 - \cos\left(\frac{\phi}{f_1}\right)\right] + 6BW_0\left[1 - \cos\left(\frac{\phi}{f_2} + \theta\right)\right] + \text{const}$$

Large-field NI/MNI requires super-Planckian f_1 and/or f_2.

Small-field MNI possible if $A/B \approx f_1^2/f_2^2$ and $\theta \approx -\pi f_1/f_2$

Natural and Multi-Natural Inflation in SUGRA

Czerny, Higaki, FT 1403.0410 (before BICEP2) , 1403.5883 (after BICEP2)

Effective large decay constant can be realized by the alignment of (more than) two axions.

Kim, Nilles, Peloso, hep-ph/0409138

$$K = \frac{f^2}{2}(\Phi_1 + \Phi_1^\dagger)^2 + \frac{f^2}{2}(\Phi_2 + \Phi_2^\dagger)^2,$$

$$W = W_0 + Ce^{-c(\Phi_1+\Phi_2)} + Ae^{-a(\Phi_1+(1+\Delta_1)\Phi_2)} + Be^{-b(\Phi_1+(1+\Delta_2)\Phi_2)-i\theta},$$

$A \sim B \ll C \ll W_0$

Heavier moduli

$$\sqrt{2}\xi \equiv \phi_1 + \phi_2$$

Lighter one appears with small coefficient due to the alignment.

$$\sqrt{2}\phi \equiv -\phi_1 + \phi_2$$

$$V_{\rm axion}^{(\rm eff)}(\phi) \approx -6W_0 A \cos\left[\frac{\phi}{f_1}\right] - 6W_0 B\cos\left[\frac{\phi}{f_2} + \theta\right] + \text{const.},$$

$$f_1 \equiv \frac{2}{a\Delta_1}f, \quad f_2 \equiv \frac{2}{b\Delta_2}f.$$

$f_1 = \mathcal{O}(10)$ for e.g. $a = \frac{2\pi}{n_1}$, $n_1 = \mathcal{O}(10)$, $\Delta_1 = \mathcal{O}(0.1)$, $f = \mathcal{O}(0.1)$

String-inspired UV completion

Czerny, Higaki, FT 1403.0410 (before BICEP2)
1403.5883 (after BICEP2)

- Three Kahler moduli: T_0, T_1 and T_2

$$K = -2\log(t_0^{3/2} - t_1^{3/2} - t_2^{3/2}); \quad t_i = (T_i + T_i^\dagger) \quad \text{for } i = 0, 1, 2,$$

$$W = W_0 - Ce^{-\frac{2\pi}{N}T_0} - De^{-\frac{2\pi}{M}(T_1+T_2)} + Ae^{-\frac{2\pi}{n_1}T_2} + Be^{-\frac{2\pi}{n_2}T_2},$$

Heavy moduli

Without the last two terms,
Im[T_1-T_2] would be massless.

cf. Conlon, hep-th/0602233
Choi and Jeong, hep-th/0611279

Gaugino condensations in SU(N)xSU(M)xSU(n_1)xSU(n_2) assumed.
Integrating out the heavy moduli, T_0 and T_1+T_2, one obtains

$$K_L \approx \frac{f^2}{2}(\Phi + \Phi^\dagger)^2 + \cdots,$$

$$W_L \approx W_0 + \hat{A}e^{-\frac{\pi}{n_1}\Phi} + \hat{B}e^{-\frac{\pi}{n_2}\Phi - i\theta}.$$

$$\Phi = -T_1 + T_2$$

$$f^2 \equiv \frac{3}{2\sqrt{2}\sqrt{t_1+t_2}\mathcal{V}} \lesssim 1,$$

$$\hat{A} \equiv Ae^{-\frac{\pi}{n_1}\langle T_1+T_2\rangle}, \quad \hat{B} \equiv Be^{-\frac{\pi}{n_2}\langle T_1+T_2\rangle}.$$

KNP mechanism can be similarly implemented. (see 1403.5883)

Aligned Natural Inflation

Kim, Nilles, Peloso, hep-ph/0409138

Czerny, Higaki, FT 1403.5883, Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923, Tye, Won, 1404.6988, Kappl, Krippendorf, Nilles, 1404.7127, Bachlechner et al, 1404.7496, Ben-Dayan, Pedro, Westphal, 1404.7773 ,Long, McAllister, McGuirk 1404.7852

See also talks by Nilles, Westphal, and Ben-Dayan.

The effectively large decay constant can be realized by the alignment of two (or more) axion potentials. Kim, Nilles, Peloso, hep-ph/0409138

- Two axions: $\phi_1 \to \phi_1 + 2\pi f_1 \qquad \phi_2 \to \phi_2 + 2\pi f_2$

$$V(\phi_i) = \Lambda_1^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(m_1 \frac{\phi_1}{f_1} + m_2 \frac{\phi_2}{f_2}\right)\right]$$

For $\Lambda_1 \gg \Lambda_2$, the effective decay constant is

$$f_{\rm eff} = \frac{n_1^2 f_2^2 + n_2^2 f_1^2}{|n_1 m_2 - n_2 m_1|}$$

Some hierarchy among the anomaly coefficients are needed to realize a large enhancement of O(100).

Aligned Natural Inflation

Kim, Nilles, Peloso, hep-ph/0409138

Czerny, Higaki, FT 1403.5883, Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923, Tye, Won, 1404.6988, Kappl, Krippendorf, Nilles, 1404.7127, Bachlechner et al, 1404.7496, Ben-Dayan, Pedro, Westphal, 1404.7773 ,Long, McAllister, McGuirk 1404.7852

See also talks by Nilles, Westphal, and Ben-Dayan.

The effectively large decay constant can be realized by the alignment of two (or more) axion potentials. Kim, Nilles, Peloso, hep-ph/0409138

- Multiple axions: $\phi_i \equiv \phi_i + 2\pi f_i \quad (i = 1, \cdots, N)$

$$V(\phi_i) = \sum_{i=1}^{N} \Lambda_i^4 \left[1 - \cos\left(\sum_{j=1}^{N} \frac{n_{ij}\phi_j}{f_j}\right)\right]$$

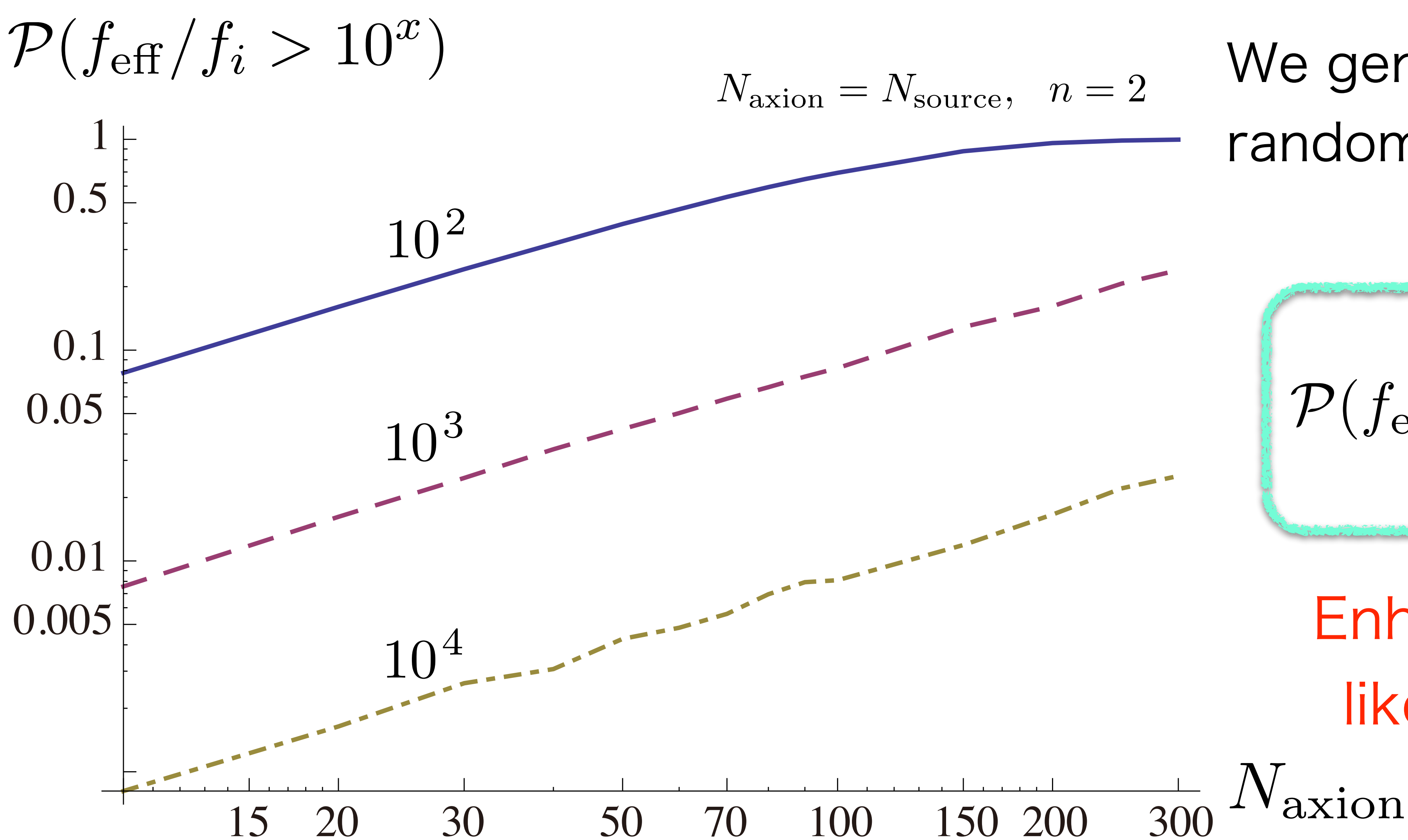
For a moderately large N (> 5 or so), the effective decay constant can be enhanced w/o hierarchy among the anomaly coefficients. Choi, Kim, Yun, 1404.6209

Prob. dist. was studied in detail for various cases incl. $N_{\rm source} \neq N_{\rm axion}$
Higaki, FT, 1404.6923

Aligned Natural Inflation

$$V(\phi_i) = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\sum_{j=1}^{N_{\rm axion}} a_{ij}\frac{\phi_j}{f_j} + \theta_i\right) + V_0$$

- Prob dist for the enhancement of the decay constant



We generated integer-valued random matrix $-n \le a_{ij} \le n$

$$\mathcal{P}(f_{\rm eff}/f_i) \sim N_{\rm axion}\left(\frac{f_i}{f_{\rm eff}}\right)$$

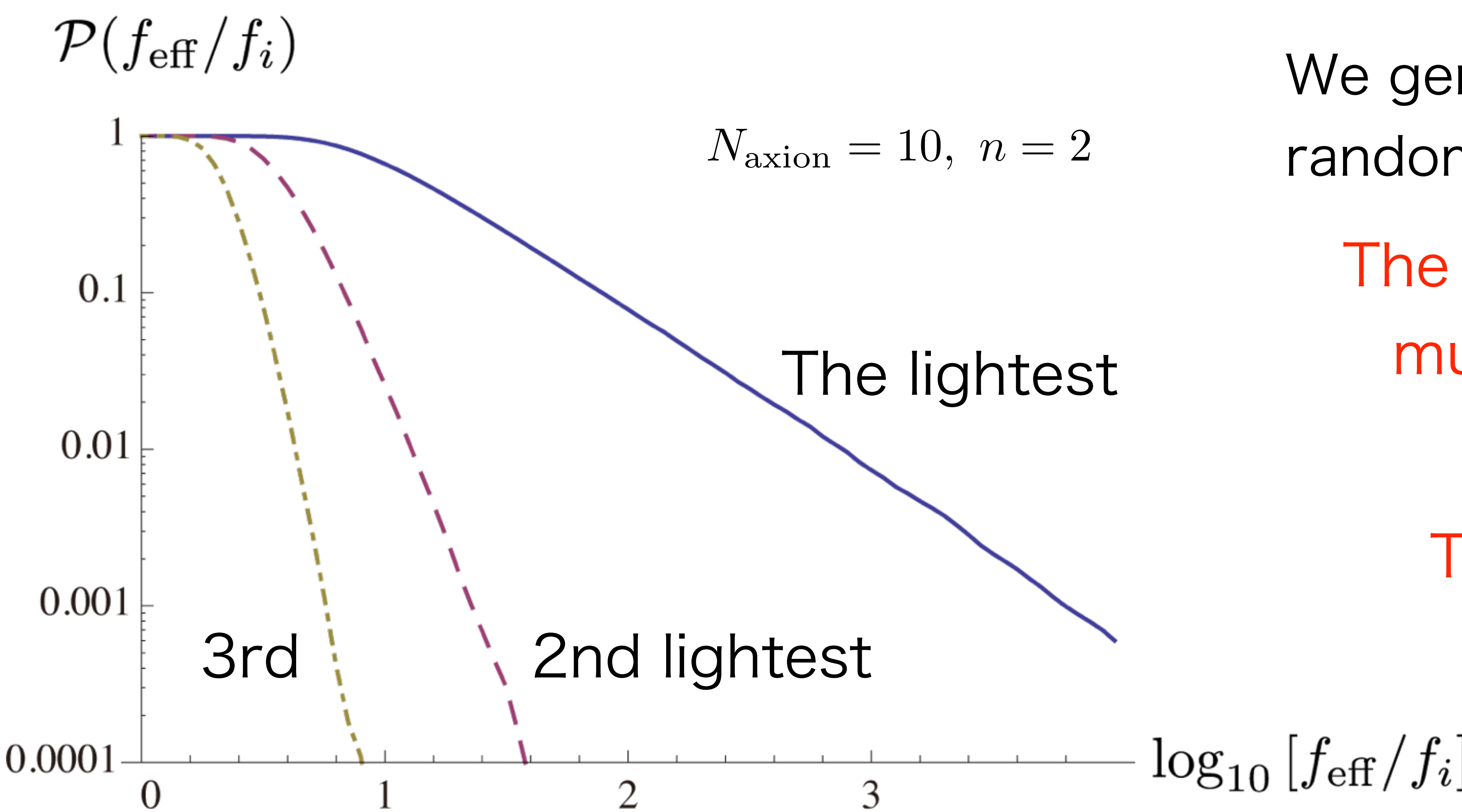
Enhancement becomes likely for larger $N_{\rm axion}$.

Higaki, FT, 1404.6923

Aligned Natural Inflation

$$V(\phi_i) = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\sum_{j=1}^{N_{\rm axion}} a_{ij}\frac{\phi_j}{f_j} + \theta_i\right) + V_0$$

- Prob dist for the enhancement of the decay constant



We generated integer-valued random matrix $-n \le a_{ij} \le n$

The enhancement along multiple directions is highly unlikely.

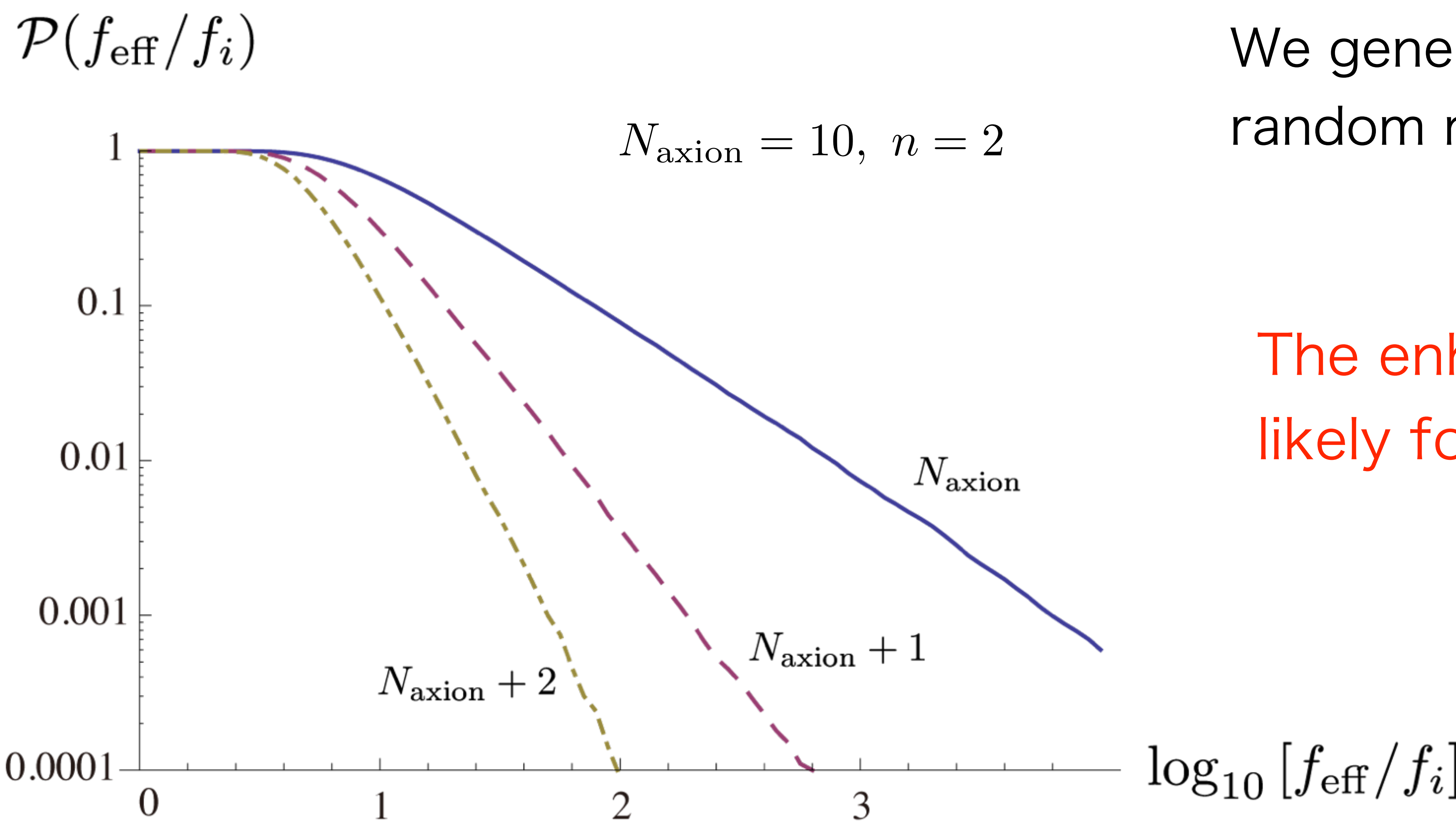
The inflaton is the lightest axion!

Higaki, FT, 1404.6923

Aligned Natural Inflation

$$V(\phi_i) = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\sum_{j=1}^{N_{\rm axion}} a_{ij}\frac{\phi_j}{f_j} + \theta_i\right) + V_0$$

- Prob dist for the enhancement of the decay constant



We generated integer-valued random matrix $-n \leq a_{ij} \leq n$

The enhancement is less likely for larger $N_{\rm source}$.

Higaki, FT, 1404.6923

Axion Landscape

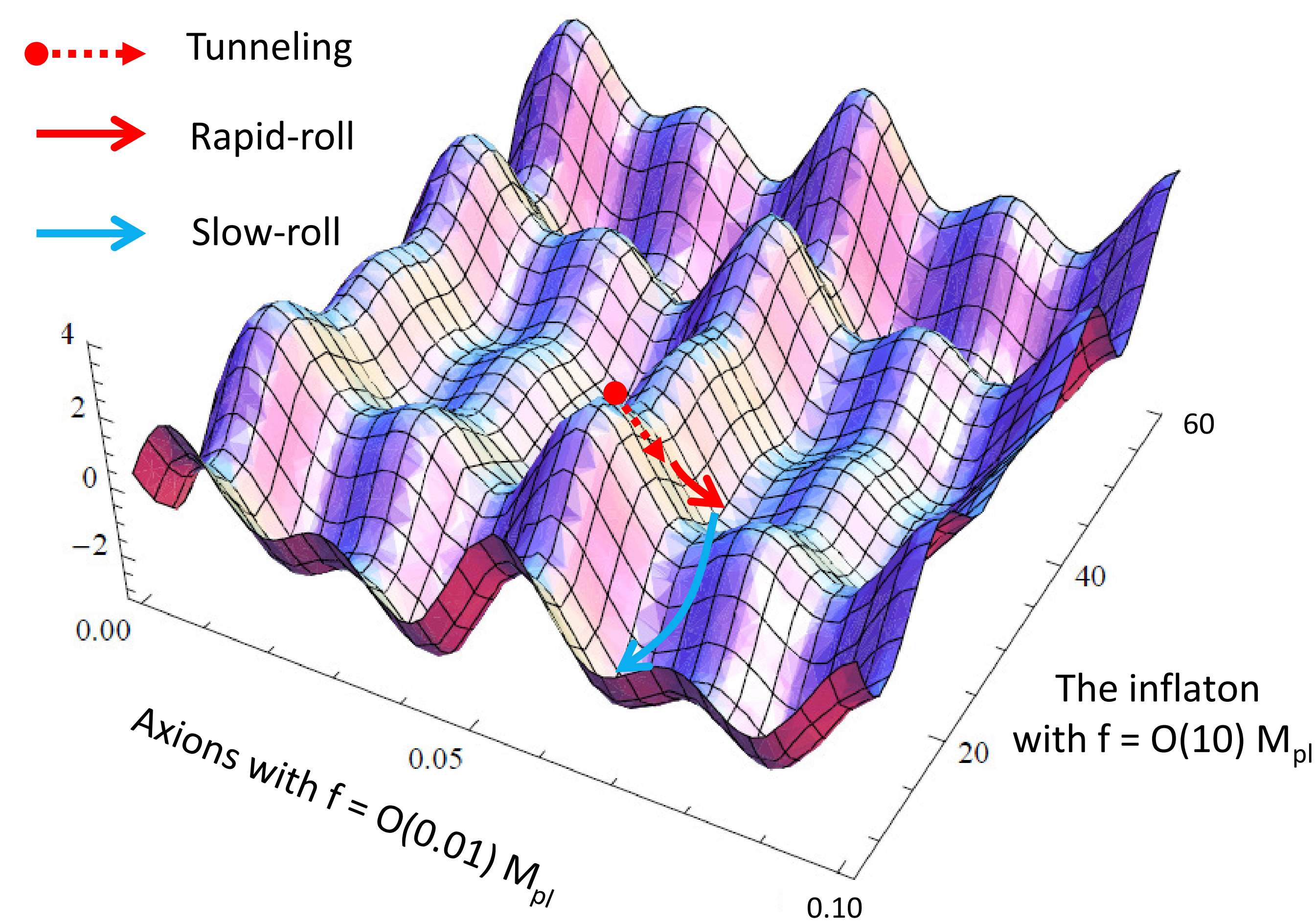
Higaki, FT 1404.6923

For $N_{\rm source} > N_{\rm axion}$, many axions may form a mini-landscape.

$$V(\phi_i) = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\sum_{j=1}^{N_{\rm axion}} a_{ij}\frac{\phi_j}{f_j} + \theta_i\right) + V_0$$

- Eternal inflation takes place in a local minimum.
- A flat direction arises by the KNP mechanism.
- Slow-roll inflation starts along the flat direction after the tunneling event.
- Negative curvature/suppression at large scales if the total e-folding is just 50-60.

Linde `95, Freivogel et al `05, Yamauchi et al `11, Bousso et al `13



Any little something extra?

- Running spectral index
- Isocurvature perturbations

Running spectral index

The spectral index depends on scales, but its running is too small to be detected in many cases.

Spectral index $$n_s - 1 = \frac{d\ln P_\zeta}{d\ln k} \simeq 2\eta - 6\epsilon$$

Running of spectral index $$\frac{dn_s}{d\ln k} = -24\epsilon^2 + 16\epsilon\eta - 2\xi$$

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \; \eta \equiv M_p^2\frac{V''}{V}, \; \xi \equiv M_p^4\frac{V'V'''}{V^2}.$$

$$\frac{dn_s}{d\ln k} = -0.0134 \pm 0.0090$$

Planck 1303.5802

If the running is O(0.01), the inflation soon ends with N_e<30.

Easther and Peiris, astro-ph/0604214

Running spectral index

The spectral index depends on scales, but its running is too small to be detected in many cases.

Spectral index
$$n_s - 1 = \frac{d \ln P_\zeta}{d \ln k} \simeq 2\eta - 6\epsilon$$

Running of spectral index
$$\frac{dn_s}{d \ln k} = -24\epsilon^2 + 16\epsilon\eta - 2\xi$$

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \ \eta \equiv M_p^2 \frac{V''}{V}, \ \xi \equiv M_p^4 \frac{V'V'''}{V^2}.$$

$$\frac{dn_s}{d \ln k} = -0.0134 \pm 0.0090$$

Planck 1303.5802

If the running is O(0.01), the inflation soon ends with N_e<30.

Easther and Peiris, astro-ph/0604214

Large-field inflation with modulations

Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589

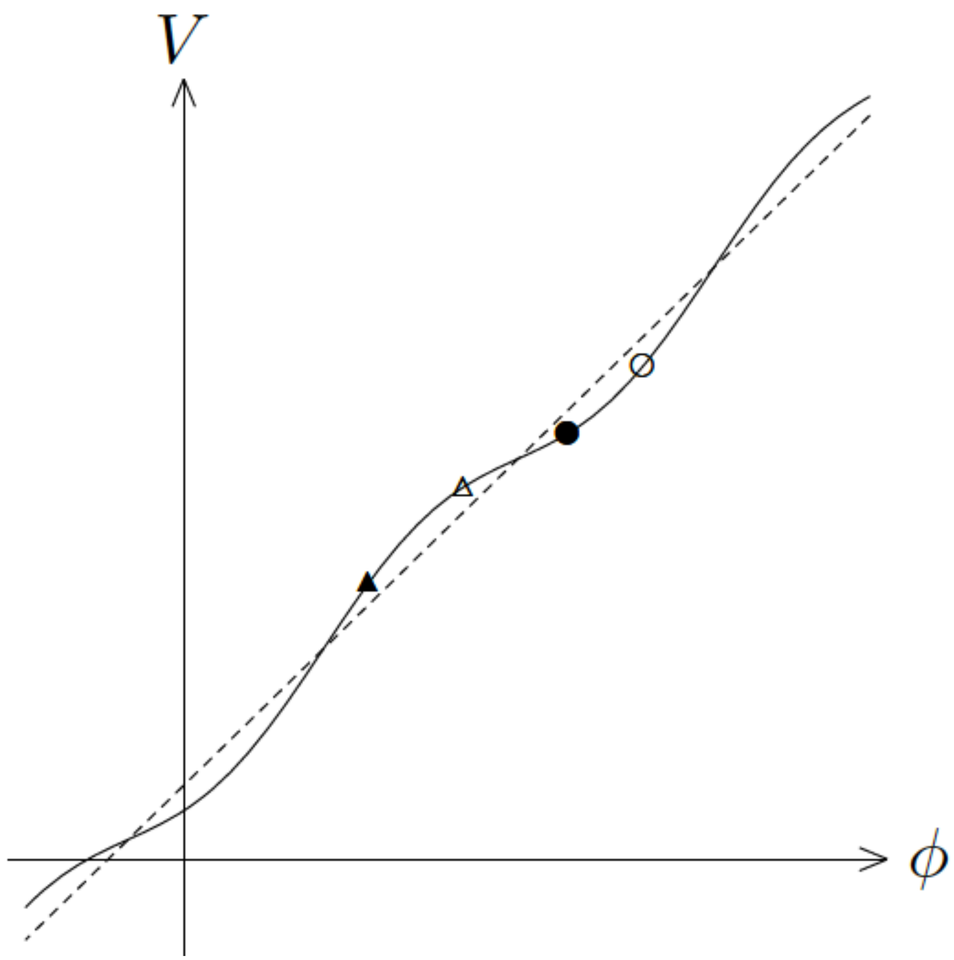
Let us add small modulations to the inflaton potential,

$$V(\phi) = V_0(\phi) + V_{mod}(\phi),$$

s.t.

$$\begin{aligned} |V_0(\phi)| &\gg |V_{mod}(\phi)|, \\ |V_0'(\phi)| &> |V_{mod}'(\phi)|. \\ |V_0''(\phi)| &\lesssim |V_{mod}''(\phi)|, \\ |V_0'''(\phi)| &\ll |V_{mod}'''(\phi)|. \end{aligned}$$

(Both sides represent typical values)

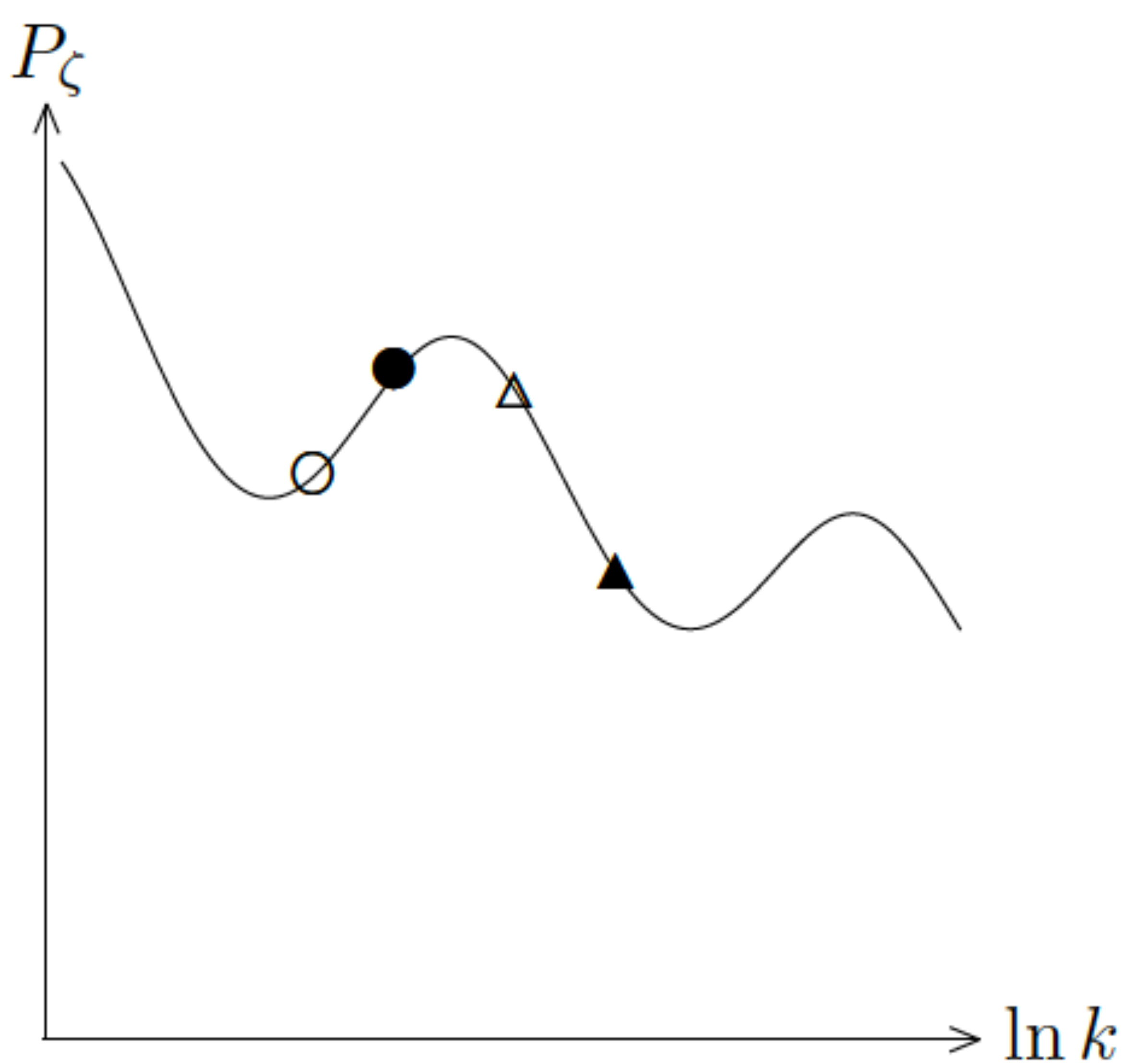


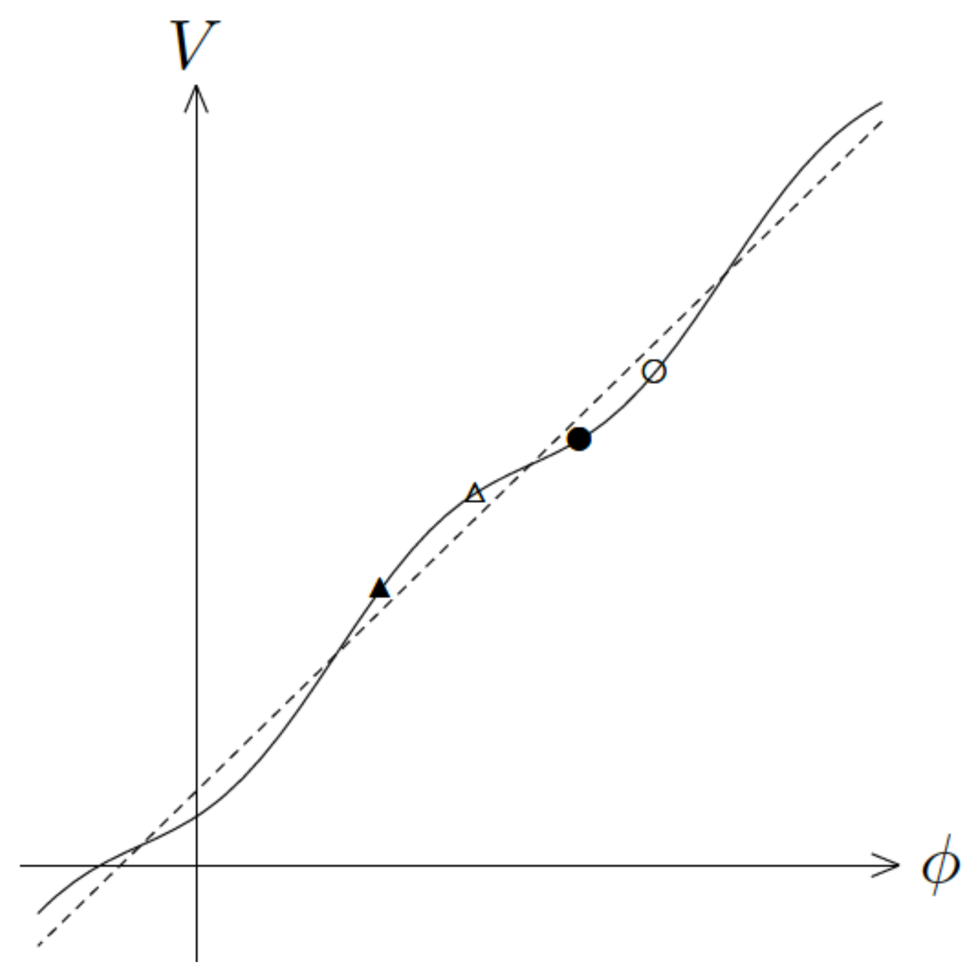
Then the spectral index and its running are significantly affected by modulations, while the inflaton dynamics and the normalization of density perturbations remain intact.

Large-field inflation with modulations

Let us add small modulations to the inflaton potential.

Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589

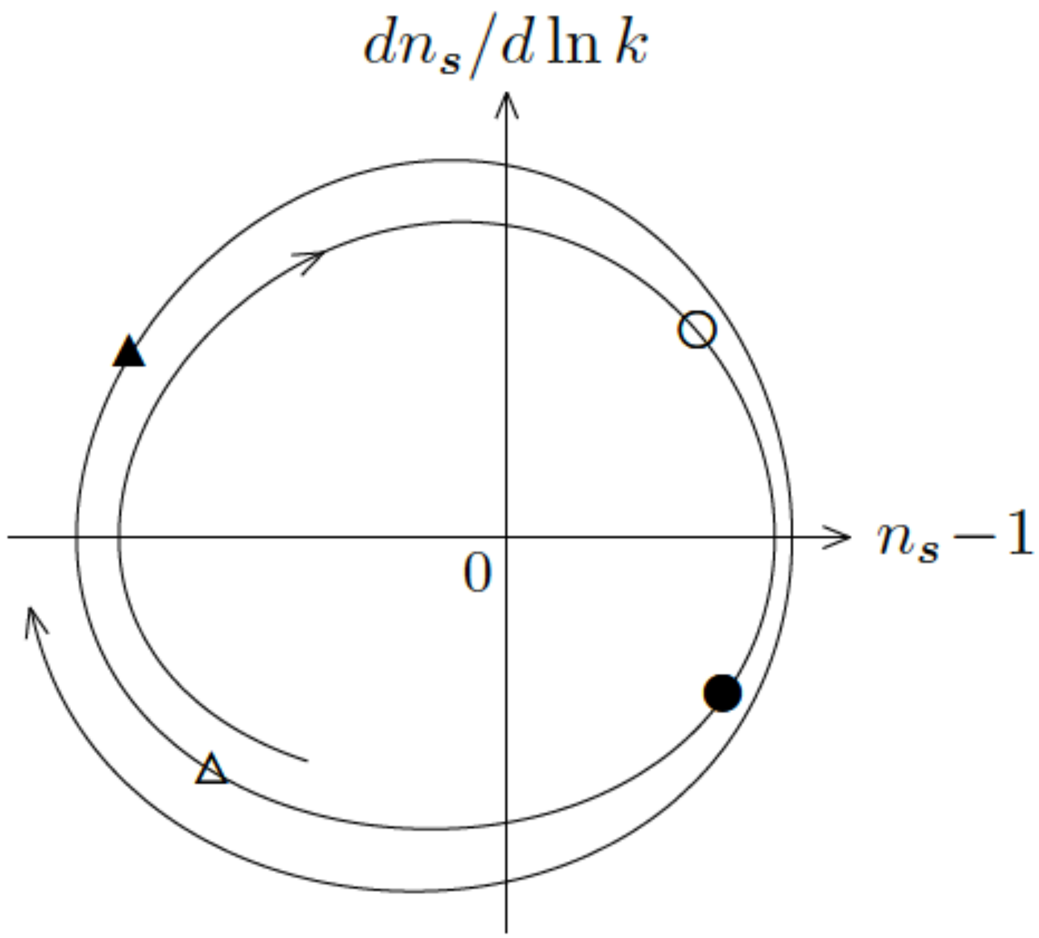


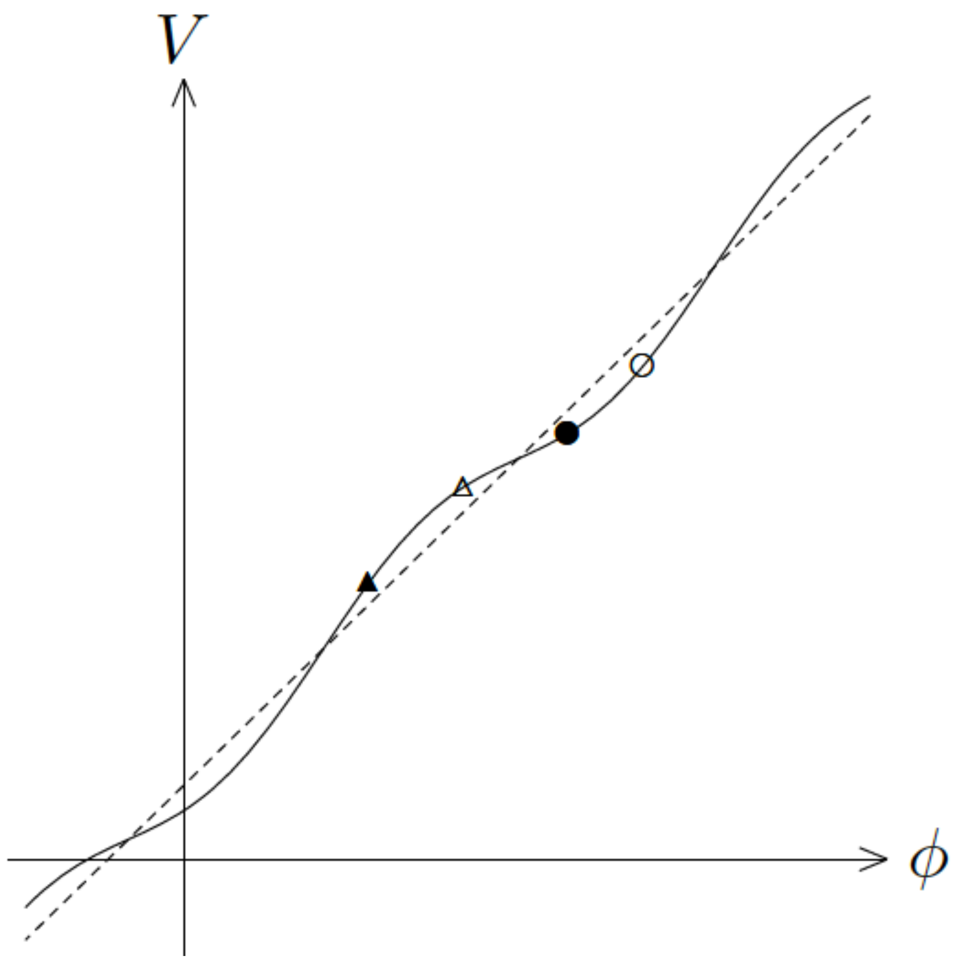


Large-field inflation with modulations

Let us add small modulations to the inflaton potential.

Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589





Such small modulations are present in the axion monodromy inflation, and built-in feature of the multi-natural inflation model.

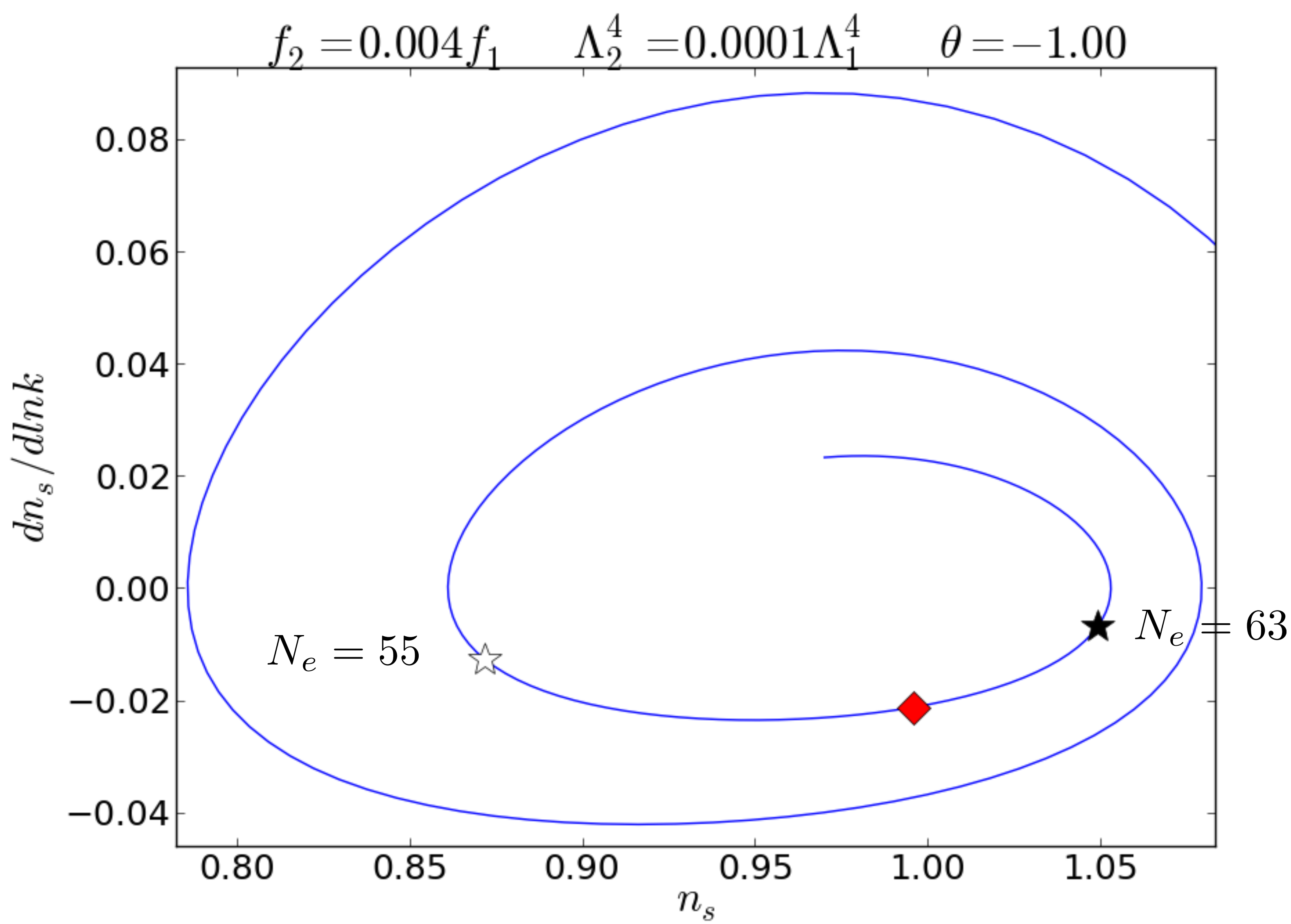
McAllister, Silverstein, Westphal, 0808.0706

Large-field inflation with modulations

Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589

e.g. Multi-natural inflation

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta),$$

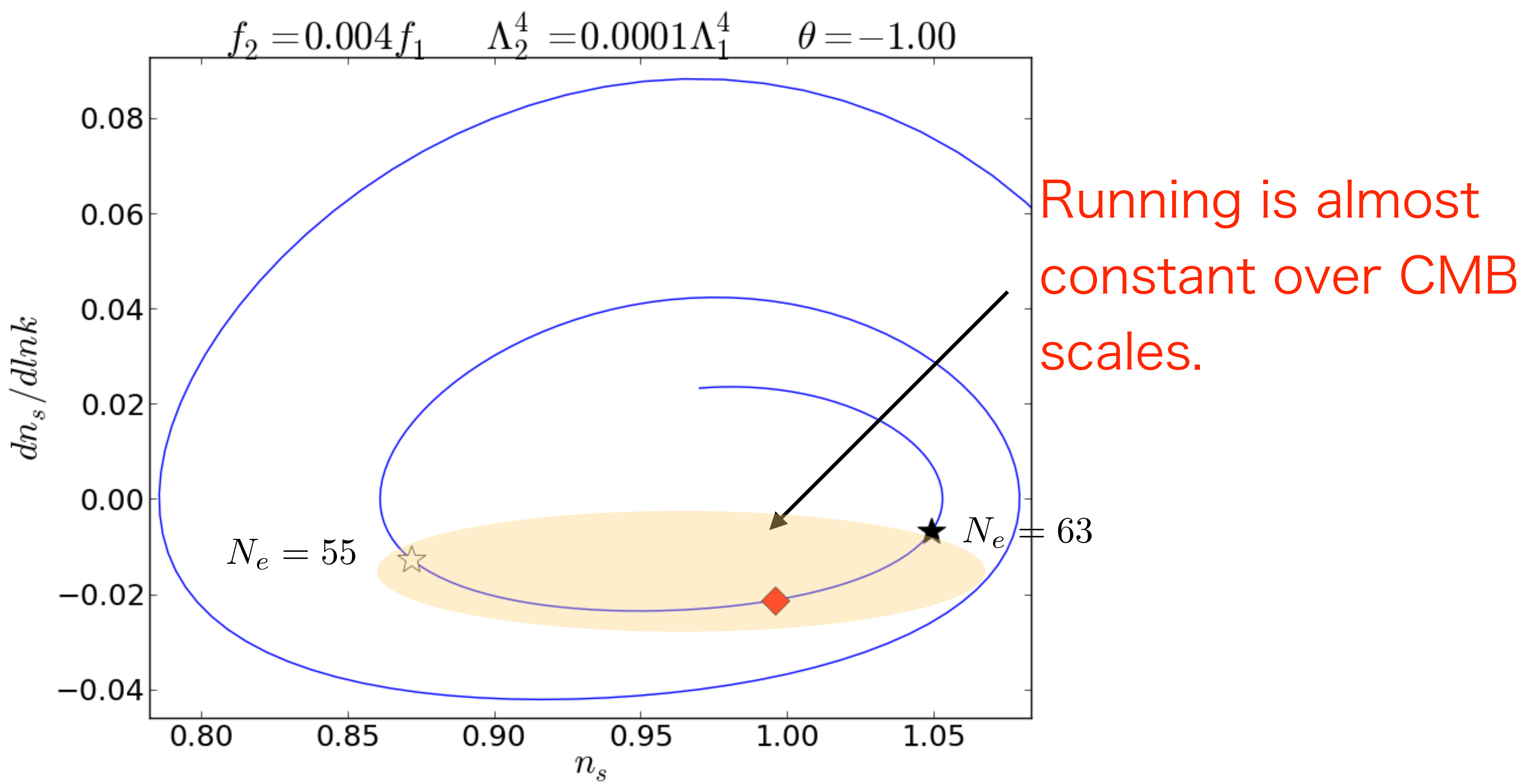


Large-field inflation with modulations

Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589

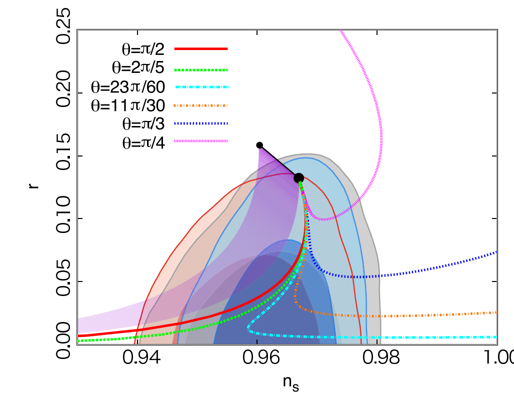
e.g. Multi-natural inflation

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta),$$

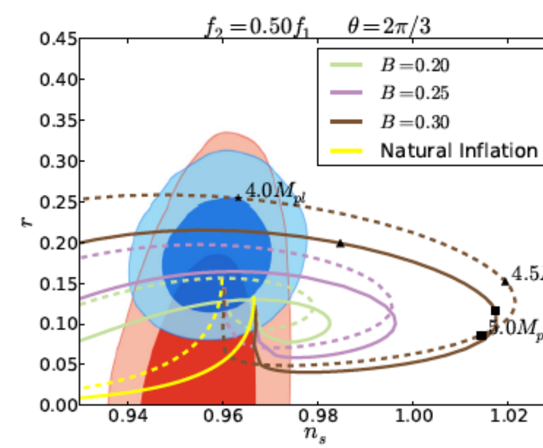


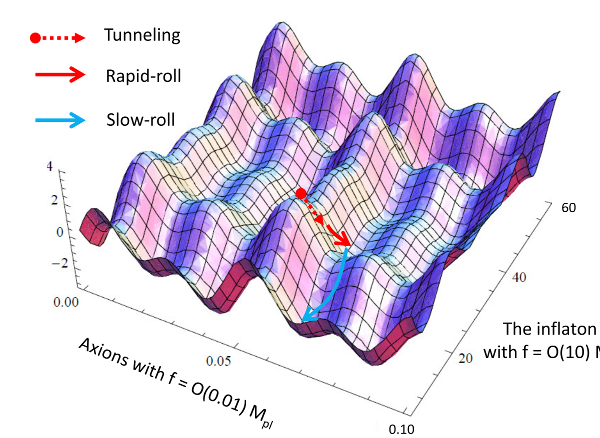
Conclusions

- **Polynomial chaotic inflation**
  - Simple extension of the quadratic potential leads to various values of (n_s, r).



- **Multi-Natural inflation**
  - Various values of (n_s,r) are possible.
  - Axion hilltop inflation can be realized for sub-Planckian f.
  - f >> 1 can be realized by the KNP mechanism.
  - Axion landscape leads to natural/multi-natural inflation after eternal inflation.





- **Anything extra?**
  - Running spectral index easily realized by small modulations to the inflaton potential.
  - Isocurvature perturbations/non-Gaussianity/curvature, etc.

Back-up slides

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

Z_2: $\quad \phi \to -\phi \quad X \to -X$

$$K_{\rm inf} = c(\phi + \phi^\dagger) + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

Z_2: $\phi \to -\phi \quad X \to -X$

$$K_{\rm inf} = c(\phi + \phi^\dagger) + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

$$Z_2: \quad \phi \to -\phi \quad X \to -X$$

$$K_{\rm inf} = c(\phi + \phi^\dagger) + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

The visible sector particles must be also charged under Z_2 for successful reheating.

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

Z_2: $\phi \to -\phi \quad X \to -X$

$$K_{\rm inf} = \cancel{c(\phi + \phi^\dagger)} + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

The visible sector particles must be also charged under Z_2 for successful reheating.

The Z_2 might be the matter parity! $W_{\not R} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

Z_2: $\quad \phi \to -\phi \qquad X \to -X$

$$K_{\rm inf} = \cancel{c(\phi + \phi^\dagger)} + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

The visible sector particles must be also charged under Z_2 for successful reheating.

The Z_2 might be the matter parity! $\quad W_{R\!\!\!/} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

The inflaton might be right-handed sneutrino.

Murayama, Nakayama, FT, Yanagida,1404.3857

$$W = \phi L H_u \quad \Rightarrow \quad \mathcal{L} \sim \frac{(LH_u)^2}{M}$$

(-) (-)

Neutrino mass is a low-E consequence of the inflaton!

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

$$Z_2: \quad \phi \to -\phi \qquad X \to -X$$

$$K_{\rm inf} = \cancel{c(\phi + \phi^\dagger)} + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

The visible sector particles must be also charged under Z_2 for successful reheating.

The Z_2 might be the matter parity! $W_{\not R} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

The inflaton might be right-handed sneutrino.

Murayama, Nakayama, FT, Yanagida,1404.3857

$$W = \phi L H_u \quad \Rightarrow \quad \mathcal{L} \sim \frac{(LH_u)^2}{M}$$

(-) (-)

Neutrino mass is a low-E consequence of the inflaton!

- In the absence of Z_2, inflaton decays into gravitinos, constraining the gravitino mass to be around 10-1000TeV, or <16eV.

Nakayama, FT, Yanagida,1404.2472

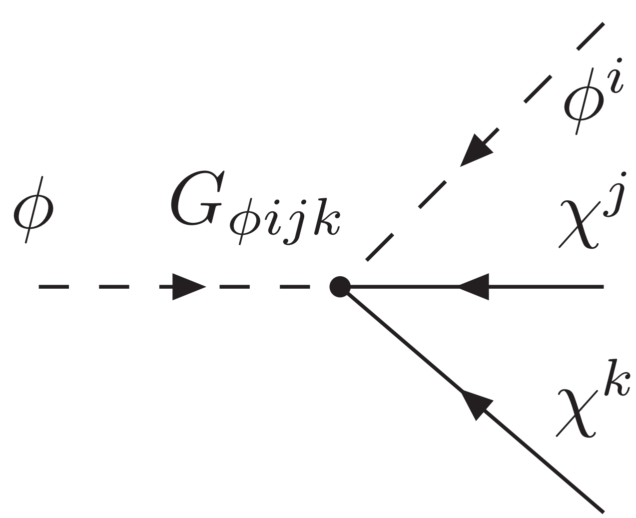
Chaotic inflation w/o Z2

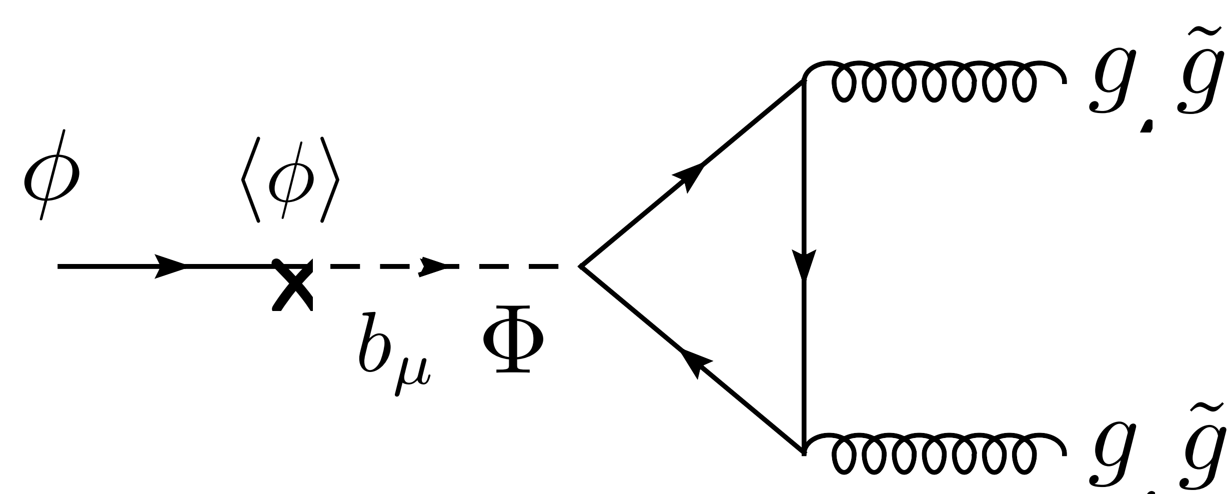
$$K = c(\phi + \phi^\dagger) + \cdots \quad \Rightarrow \quad \langle K_\phi \rangle = c = \mathcal{O}(1)$$

- **Pro**

  The inflaton automatically decays into the visible sector w/o introducing ad hoc couplings.

Endo, Kawasaki, FT, Yanagida, hep-ph/0607170
Endo, FT, Yanagida,hep-ph/0701042





Chaotic inflation w/o Z_2

$$K = c(\phi + \phi^\dagger) + \cdots \quad \Rightarrow \quad \langle K_\phi \rangle = c = \mathcal{O}(1)$$

- **Pros**

  The inflaton automatically decays into the visible sector w/o introducing ad hoc couplings.

  Endo, Kawasaki, FT, Yanagida, hep-ph/0607170
  Endo, FT, Yanagida,hep-ph/0701042

$$\Gamma \sim \frac{m^3}{M_P^2}, \quad T_R \sim 10^9\,\mathrm{GeV}$$

high enough for thermal leptogenesis

Chaotic inflation w/o Z_2

$$K = c(\phi + \phi^\dagger) + \cdots \quad \Rightarrow \quad \langle K_\phi \rangle = c = \mathcal{O}(1)$$

- **Pros**

  The inflaton automatically decays into the visible sector w/o introducing ad hoc couplings.

  Endo, Kawasaki, FT, Yanagida, hep-ph/0607170
  Endo, FT, Yanagida,hep-ph/0701042

$$\Gamma \sim \frac{m^3}{M_P^2}, \quad T_R \sim 10^9\,\mathrm{GeV}$$

  high enough for thermal leptogenesis

- **Cons**

  The inflaton decays into hidden sectors, producing too many gravitinos.

$$\Gamma(\phi \to 2\psi_{3/2}) \sim \frac{m^3}{M_P^2}$$

  Endo, Hamaguchi, FT, `06
  Nakamura, Yamaguchi, `06
  Kawasaki, FT, Yanagida,`06
  Dine, Kitano, Morisse, Shirman,`06
  Endo, FT, Yanagida,`06,`07

Gravitino production in chaotic inflation w/o Z_2

Nakayama, FT, Yanagida,1404.2472

Let us add a SUSY breaking field z;

$$K = K_{\rm inf} + |z|^2 - \frac{|z|^4}{\Lambda^2},$$
$$W = W_{\rm inf} + \mu^2 z + W_0,$$

$$m_z^2 \simeq \frac{12 m_{3/2}^2}{\Lambda^2}.$$
$$\langle z \rangle \simeq 2\sqrt{3}\left(\frac{m_{3/2}}{m_z}\right)^2 \simeq \frac{m_{3/2}}{m_z}\Lambda.$$

There are various sources for gravitino production;

- Thermal production
- Non-thermal production
  - Inflaton decays into gravitinos
  - Inflaton decays into z.
  - The z coherent oscillations.

Gravitino production in chaotic inflation w/o Z_2

Nakayama, FT, Yanagida,1404.2472

Let us add a SUSY breaking field z;

$$K = K_{\rm inf} + |z|^2 - \frac{|z|^4}{\Lambda^2},$$
$$W = W_{\rm inf} + \mu^2 z + W_0,$$

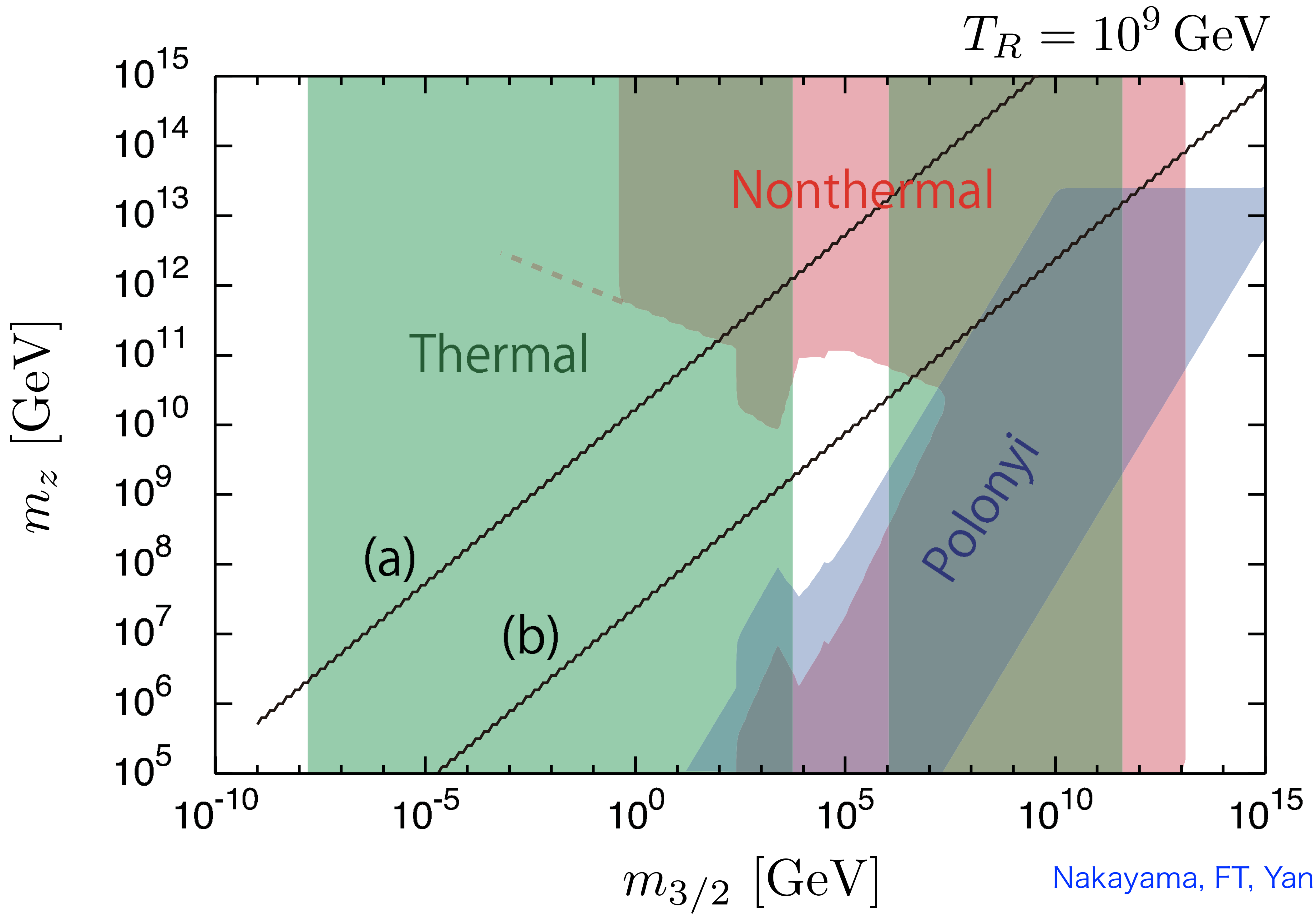
$$m_z^2 \simeq \frac{12 m_{3/2}^2}{\Lambda^2}.$$
$$\langle z \rangle \simeq 2\sqrt{3}\left(\frac{m_{3/2}}{m_z}\right)^2 \simeq \frac{m_{3/2}}{m_z}\Lambda.$$

There are various sources for gravitino production;

$$Y_{3/2} = Y_{3/2}^{(\rm th)} + Y_{3/2}^{(\phi)} + Y_{3/2}^{(z)}.$$

$$Y_{3/2}^{(\rm th)} \simeq \begin{cases} \min\left[2\times 10^{-12}\left(1+\frac{m_{\tilde g}^2}{3m_{3/2}^2}\right)\left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right),\ \frac{0.42}{g_{*s}(T_{3/2})}\right] & \text{for } T_{\rm R} \gtrsim m_{\rm SUSY}, \\ 0 & \text{for } T_{\rm R} \lesssim m_{\rm SUSY}, \end{cases}$$

$$Y_{3/2}^{(\phi)} = \frac{3T_{\rm R}}{4m}\frac{2\Gamma(\Phi\to\tilde z\tilde z) + 4\Gamma(\Phi\to z z^\dagger)}{\Gamma_{\rm tot}}, \qquad Y_{3/2}^{(z)} \simeq \frac{2}{m_z}\frac{\rho_z}{s}.$$



$\Lambda = (4\pi/\lambda^2)\Lambda_{\rm dyn}$

$(a)\lambda = 4\pi$

$(b)\lambda = 1$

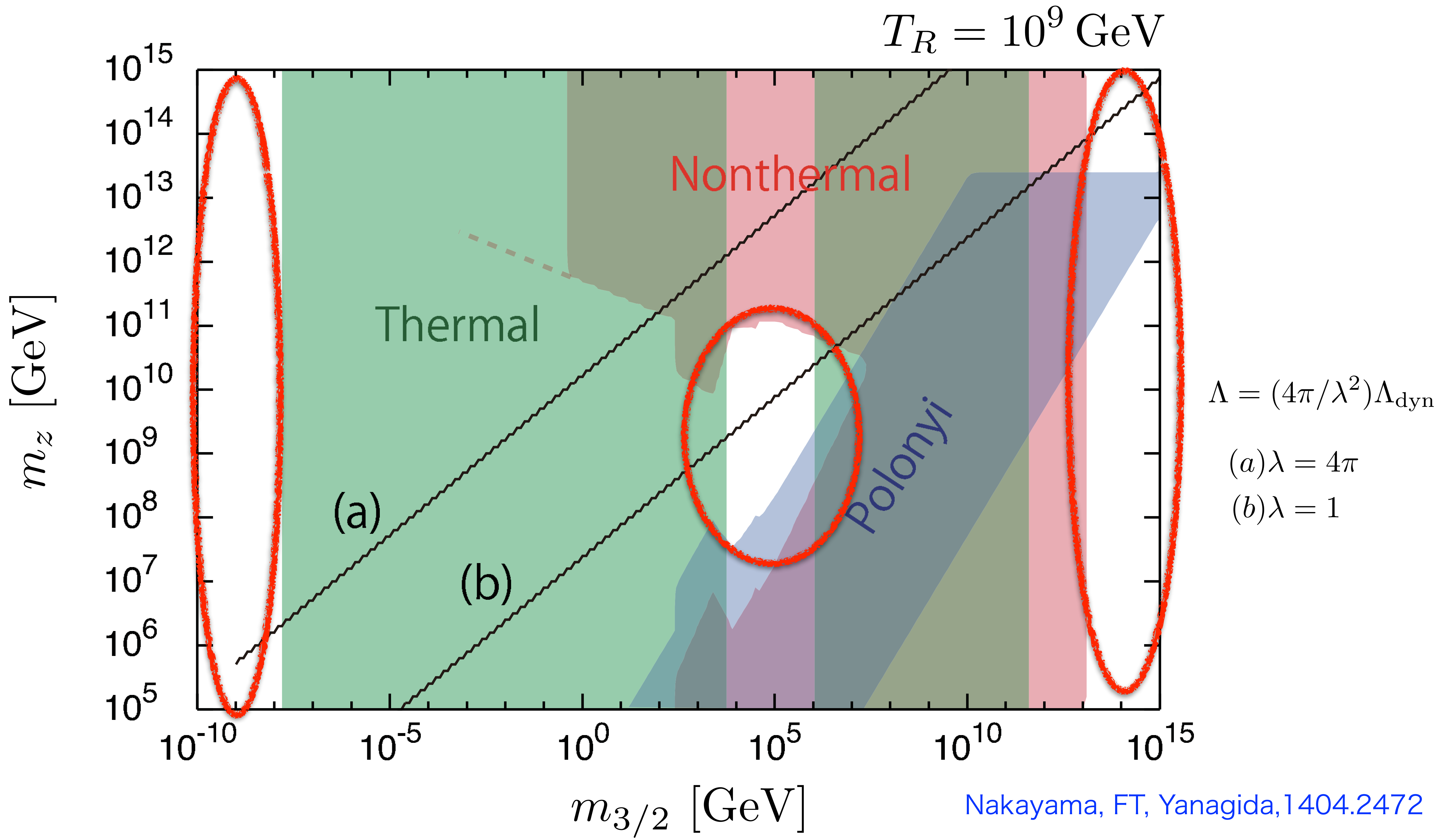
Nakayama, FT, Yanagida,1404.2472

3 allowed regions:

(i) $m_{3/2} \lesssim 16\text{eV}$

(ii) $m_{3/2} = 10 - 1000\text{TeV}$

(iii) $m_{3/2} \gtrsim 10^{13}$ GeV

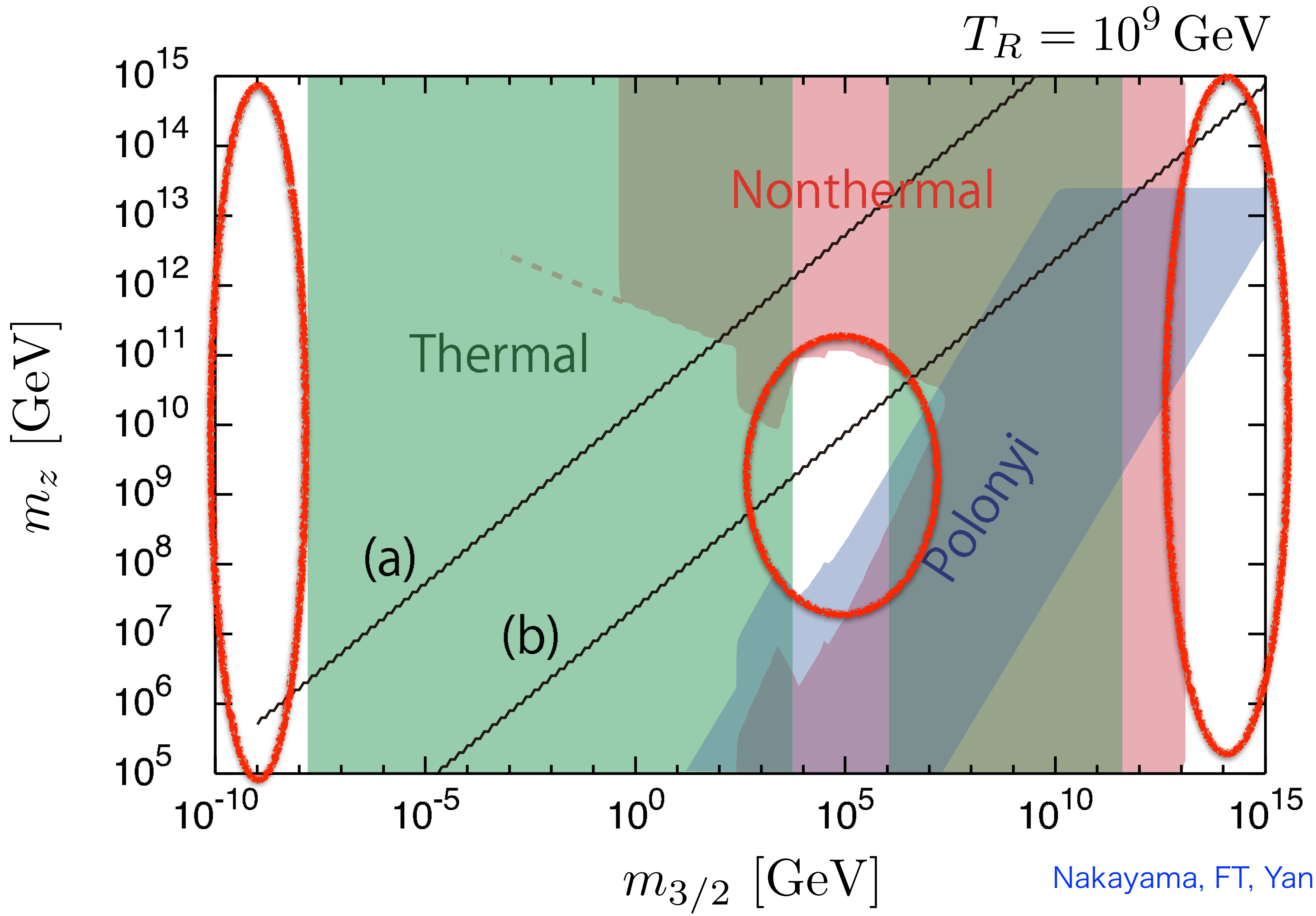


3 allowed regions:

(i) $m_{3/2} \lesssim 16\text{eV}$

(ii) $m_{3/2} = 10 - 1000\text{TeV}$

(iii) $m_{3/2} \gtrsim 10^{13}$ GeV



$\Lambda = (4\pi/\lambda^2)\Lambda_{\rm dyn}$

$(a)\lambda = 4\pi$

$(b)\lambda = 1$

Nakayama, FT, Yanagida,1404.2472

3 allowed regions:

(i) $m_{3/2} \lesssim 16\text{eV}$

(ii) $m_{3/2} = 10 - 1000\text{TeV}$

(iii) $m_{3/2} \gtrsim 10^{13}\,\text{GeV}$

consistent with 126 GeV Higgs.

Chaotic inflation with Z_2

$$K = \frac{1}{2}(\phi + \phi^\dagger)^2 + \cdots \quad \Rightarrow \quad \langle K_\phi \rangle = 0$$

- **Pros**

  Non-thermal gravitino production is forbidden.

- **Cons(?)**

  Reheating the visible sector is non-trivial.

  If Z_2 symmetry is unbroken, one needs to assign the Z_2 charge on the SM and their SUSY partners; otherwise the inflaton will be stable.
  Or, Z_2 must be broken.

What is the Z_2 symmetry, under which visible particles are charged?

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity!

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity! $W_{\not{R}} = udd, LLe, QdL$

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity! $W_{\not R} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity! $W_{\not R} = udd, LLe, QdL$

Then, the inflaton is one of the matter fields of mass about 10^{13}GeV⋯.

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity! $W_{\not R} = \sout{udd}, \sout{LLe}, \sout{QdL}$

Then, the inflaton is one of the matter fields of mass about 10^{13}GeV….

It's right-handed sneutrino!

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity! $W_{\not{R}} =$ ~~udd~~, ~~LLe~~, ~~QdL~~

Then, the inflaton is one of the matter fields of mass about 10^{13}GeV⋯.

It's right-handed sneutrino!

$$W = \Phi L H_u$$ is then allowed.

(-)(-)

What is the Z_2 symmetry, under which visible particles are charged?

It could be the matter parity! $W_{\not R} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

Then, the inflaton is one of the matter fields of mass about 10^{13}GeV⋯.

It's right-handed sneutrino!

$$W = \underset{(-)}{\Phi}\underset{(-)}{L}H_u$$ is then allowed.

$$\mathcal{L} \sim \frac{(LH_u)^2}{M}$$

Neutrino mass is a low-E consequence of the inflaton!

Sneutrino Chaotic inflation

Murayama, Nakayama, FT, Yanagida, 1404.3857

We impose an approximate shift symmetry on one of N_i

$$K = |N_1|^2 + |N_2|^2 + \frac{1}{2}(N_3 + N_3^\dagger)^2 + \cdots$$

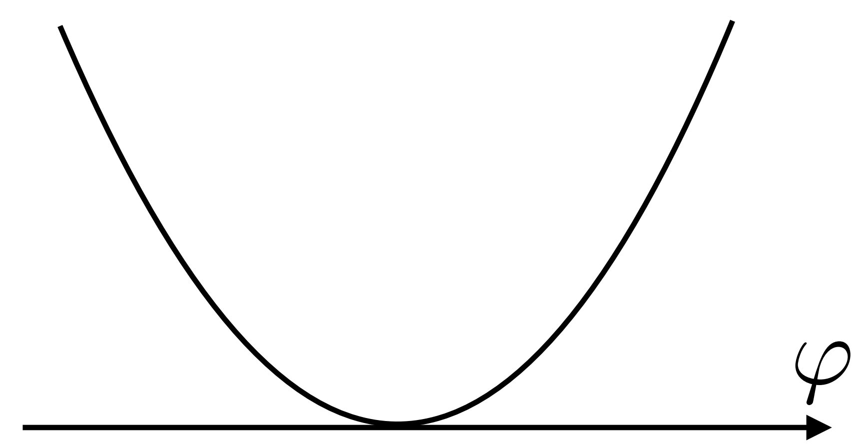
$$W = \frac{1}{2}M_{ij}N_iN_j + h_{i\alpha}N_iL_\alpha H_u$$

with

$$M_{ij} = \begin{pmatrix} m & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

The inflaton is $\varphi = \sqrt{2}\mathrm{Im}N_3$

$$V = \frac{1}{2}M^2\varphi^2$$



All the other directions can be stabilized during inflation.

- The seesaw mechanism for light neutrino masses works.

- High reheating temperature.

$$\Gamma \sim \frac{h^2}{8\pi} M \qquad T_R \sim g_*^{-\frac{1}{4}} \sqrt{\Gamma M_P} \sim 10^{13}\,\mathrm{GeV}$$

- Thermal leptogenesis by N_1 works successfully.

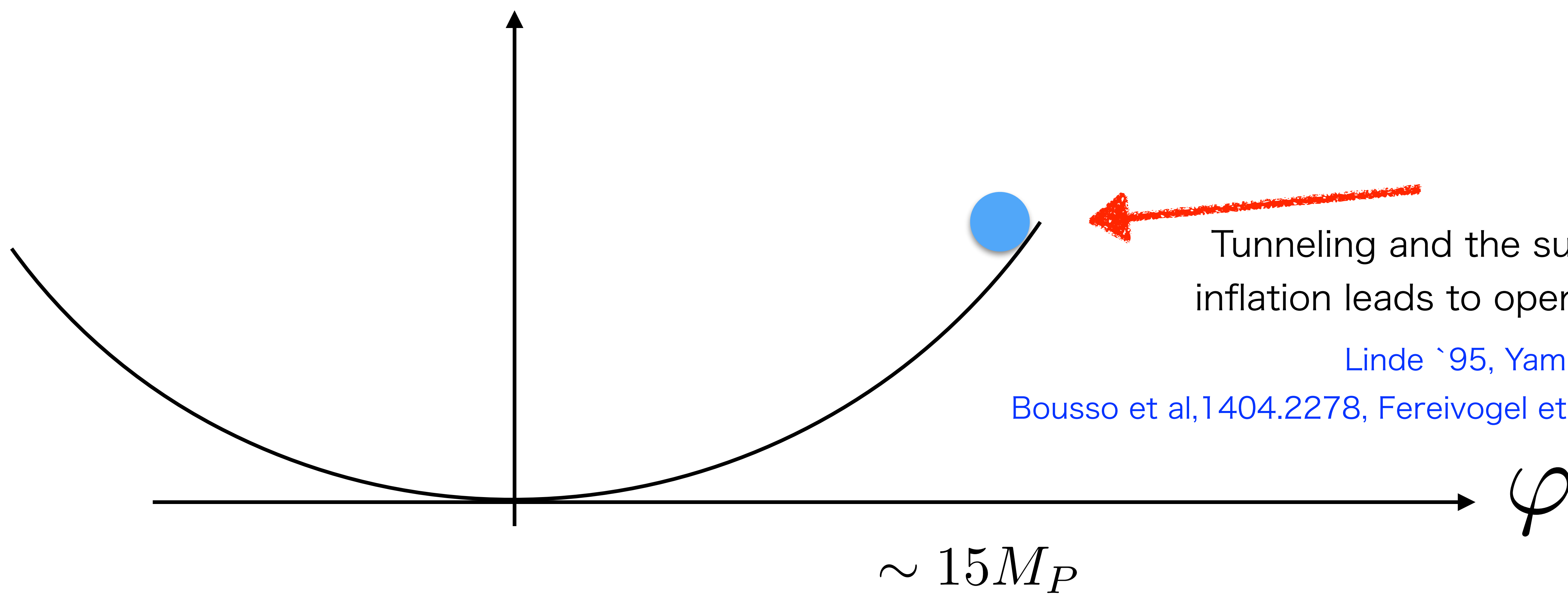
- Many gravitinos from thermal scatterings.

  R-parity (matter parity) violation for $m_{3/2} > 30$TeV
  or light gravitinos with mild entropy production, or $m_{3/2} < 16$eV.

- $n_s \simeq 0.967, \quad r \simeq 0.13 \;\; \text{for} \;\; N_e = 60.$

The shift symmetry must be broken by the neutrino Yukawa couplings for successful inflation, and $h_{3\alpha} \sim 0.1$ is suggested by the neutrino mass & seesaw.

$$W \supset N_2 \left(\frac{1}{2} M N_3 + h_{2\alpha} L_\alpha H_u \right) + h_{3\alpha} N_3 L_\alpha H_u$$

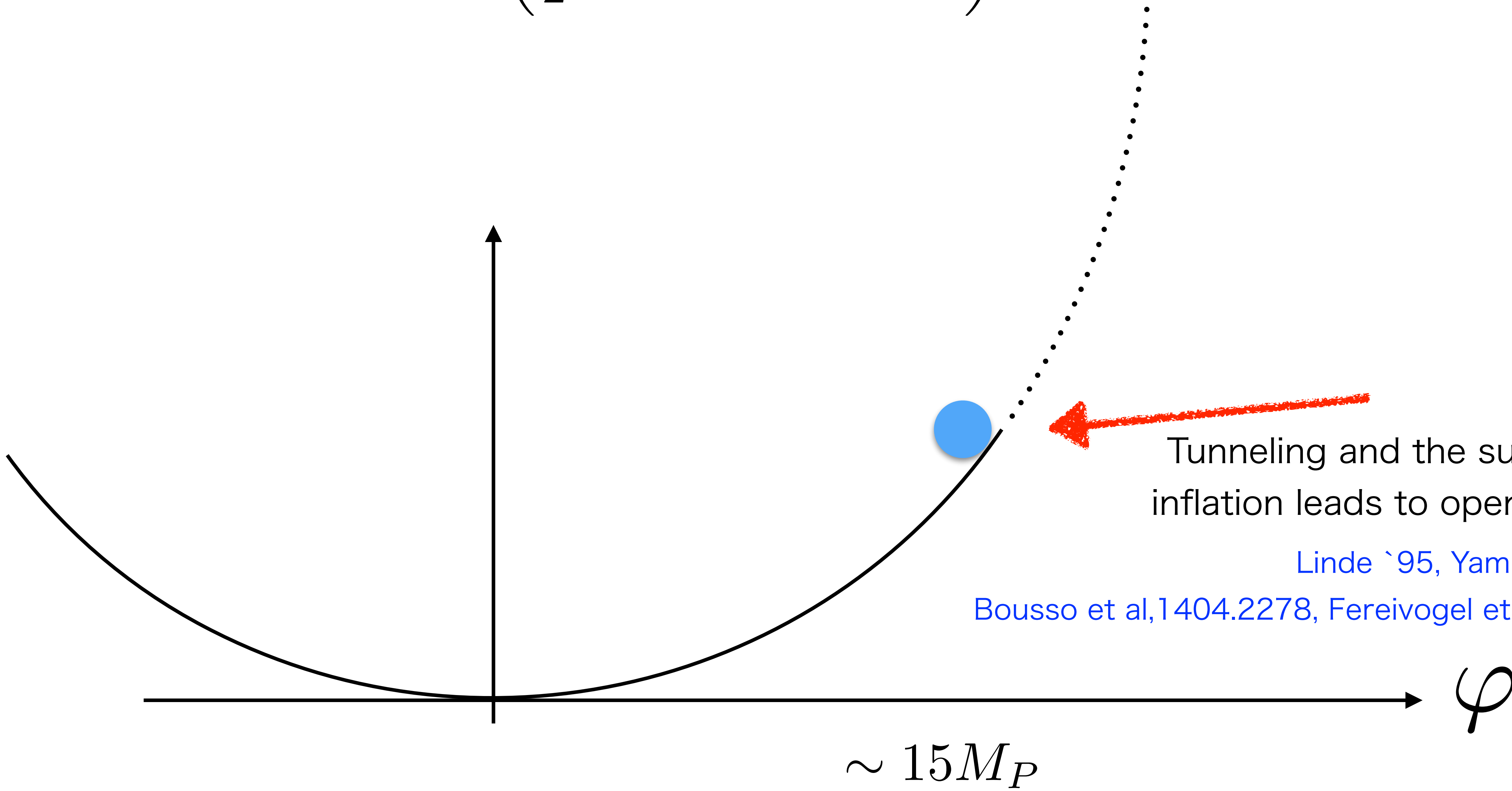


Linde `95, Yamauchi et al `11

Bousso et al,1404.2278, Fereivogel et al, 1404.2274

The shift symmetry must be broken by the neutrino Yukawa couplings for successful inflation, and $h_{3\alpha} \sim 0.1$ is suggested by the neutrino mass & seesaw.

$$W \supset N_2 \left(\frac{1}{2} M N_3 + h_{2\alpha} L_\alpha H_u \right) + h_{3\alpha} N_3 L_\alpha H_u$$



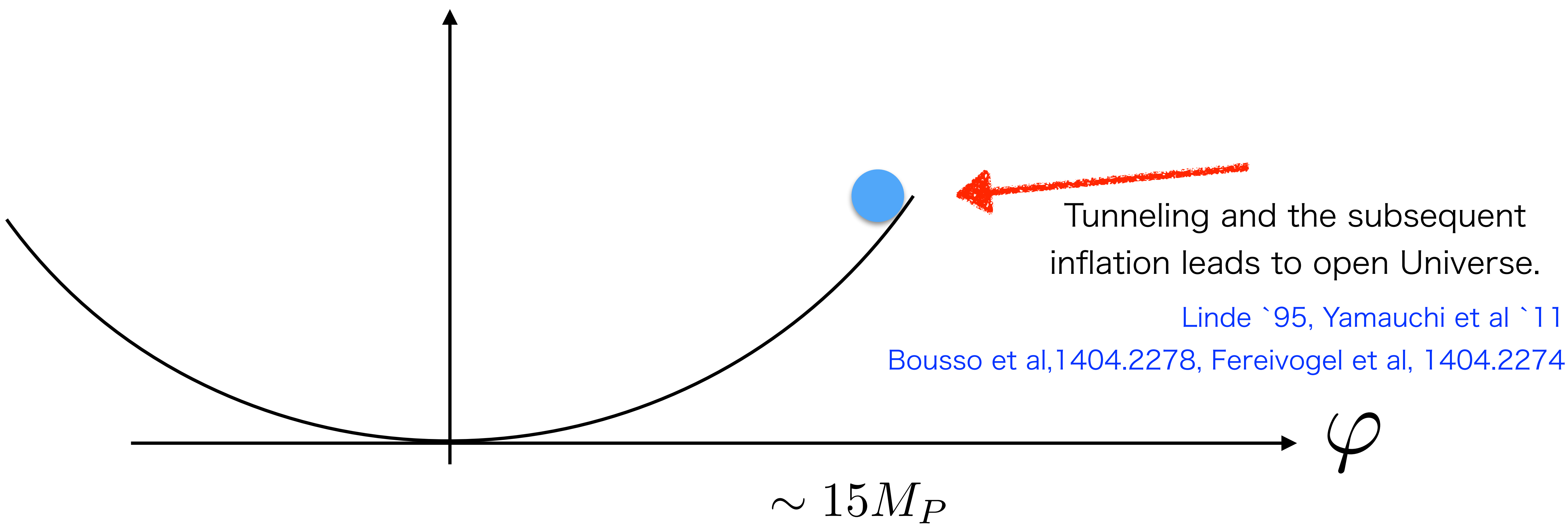
Tunneling and the subsequent inflation leads to open Universe.

Linde `95, Yamauchi et al `11

Bousso et al,1404.2278, Fereivogel et al, 1404.2274

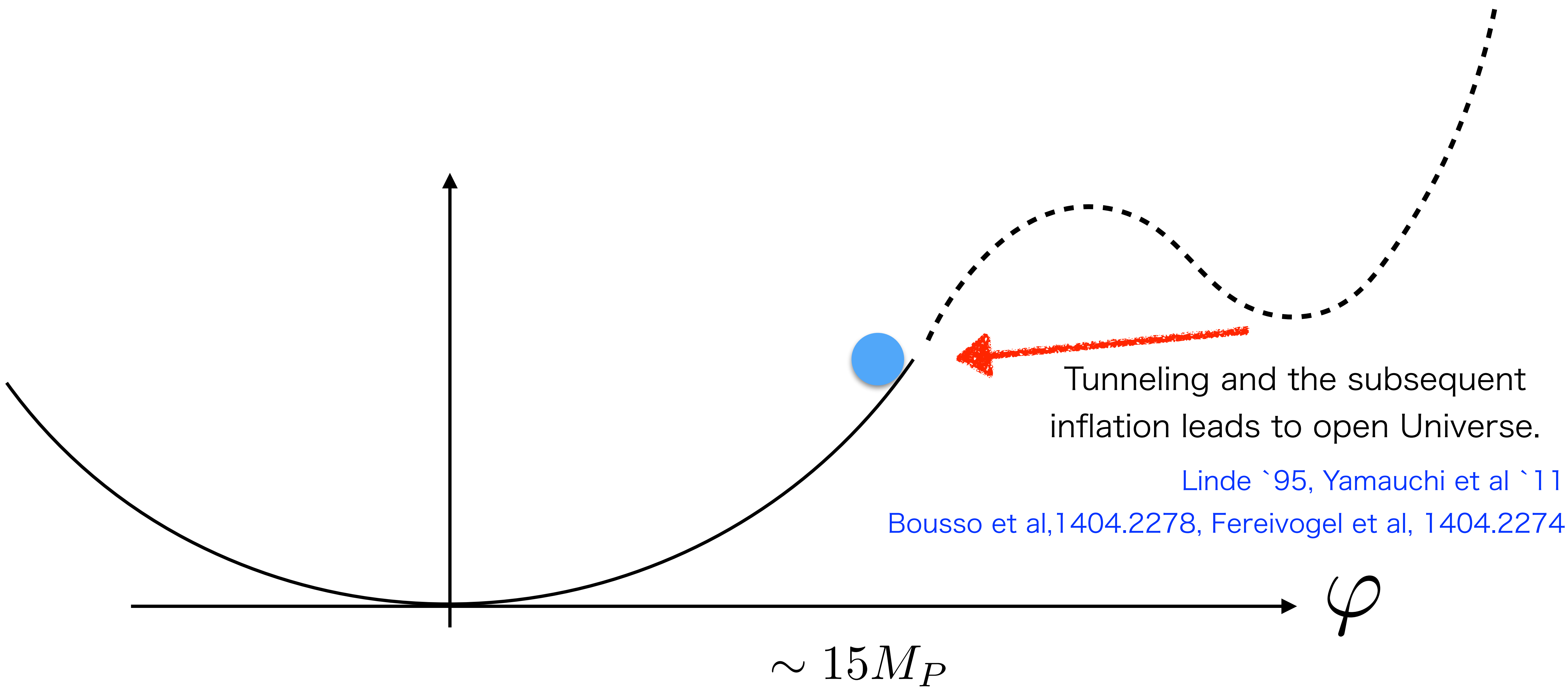
The shift symmetry must be broken by the neutrino Yukawa couplings for successful inflation, and $h_{3\alpha} \sim 0.1$ is suggested by the neutrino mass & seesaw.

$$W \supset N_2 \left(\frac{1}{2} M N_3 + h_{2\alpha} L_\alpha H_u \right) + h_{3\alpha} N_3 L_\alpha H_u$$



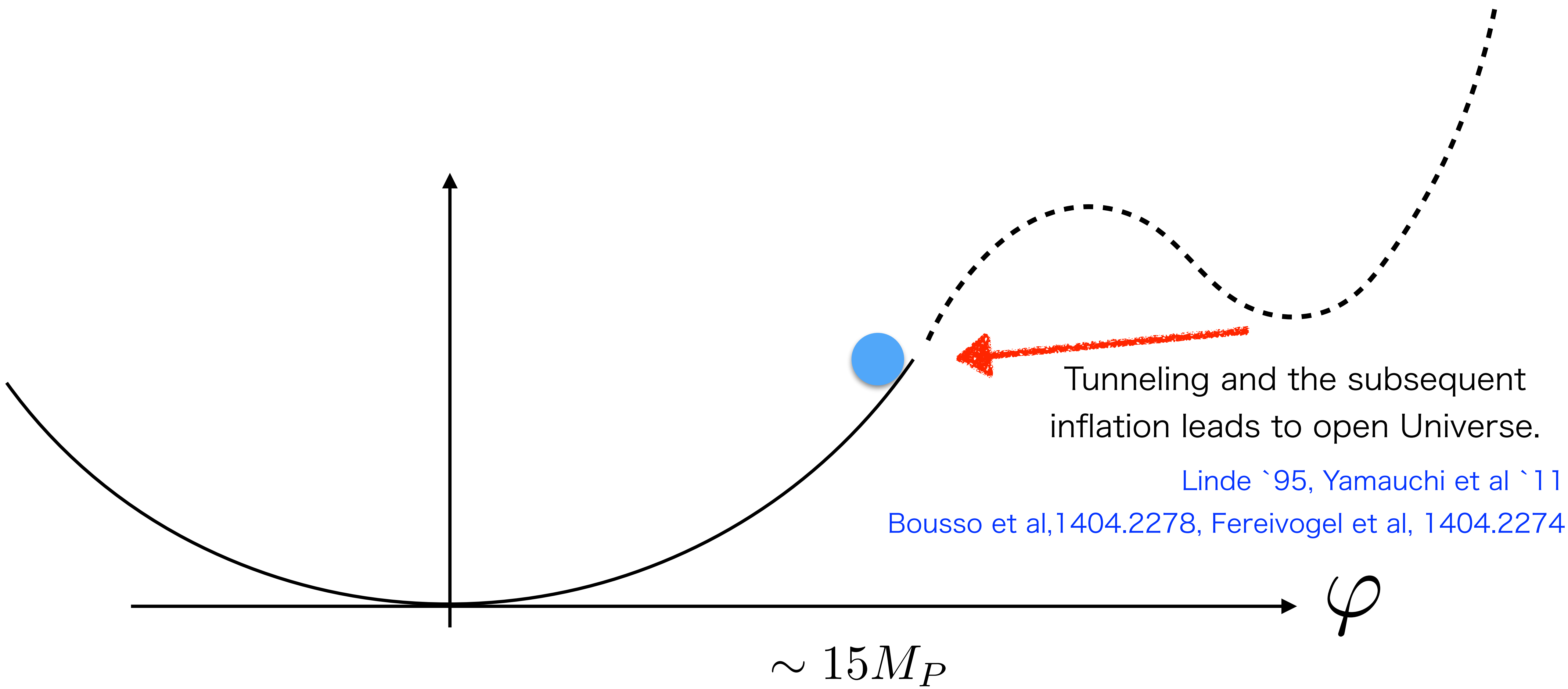
The shift symmetry must be broken by the neutrino Yukawa couplings for successful inflation, and $h_{3\alpha} \sim 0.1$ is suggested by the neutrino mass & seesaw.

$$W \supset N_2 \left(\frac{1}{2} M N_3 + h_{2\alpha} L_\alpha H_u \right) + h_{3\alpha} N_3 L_\alpha H_u$$



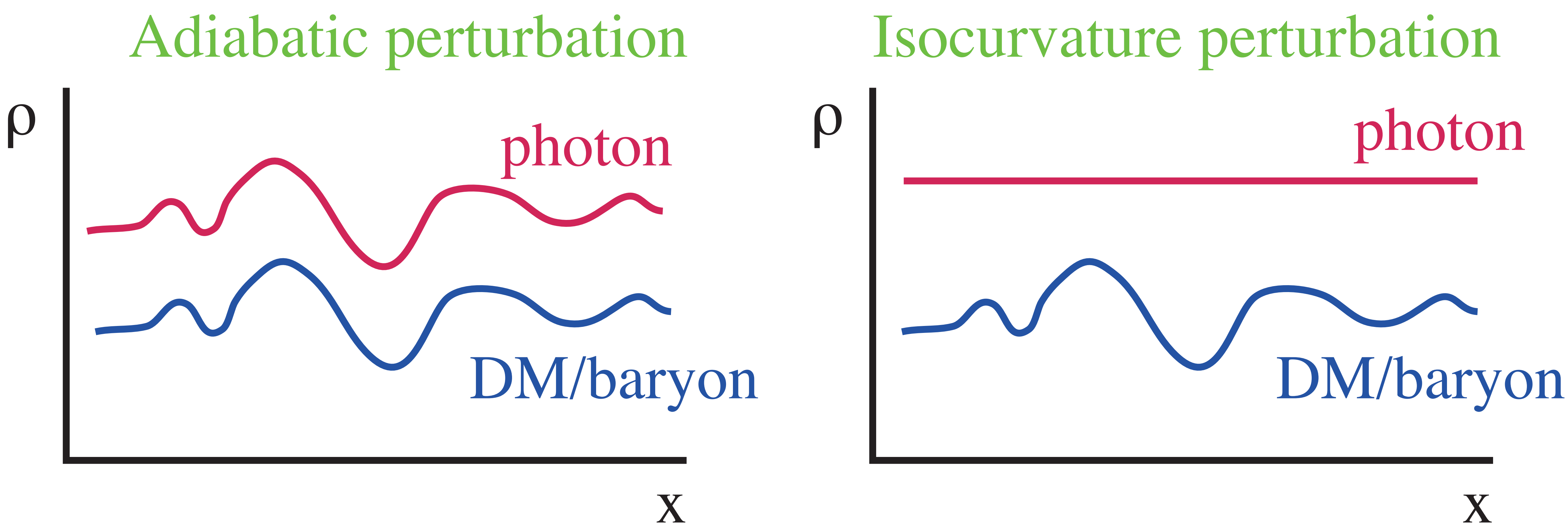
The shift symmetry must be broken by the neutrino Yukawa couplings for successful inflation, and $h_{3\alpha} \sim 0.1$ is suggested by the neutrino mass & seesaw.

$$W \supset N_2 \left(\frac{1}{2} M N_3 + h_{2\alpha} L_\alpha H_u \right) + h_{3\alpha} N_3 L_\alpha H_u$$



Sneutrino as a portal to the mother Universe.

Axion isocurvature perturbations

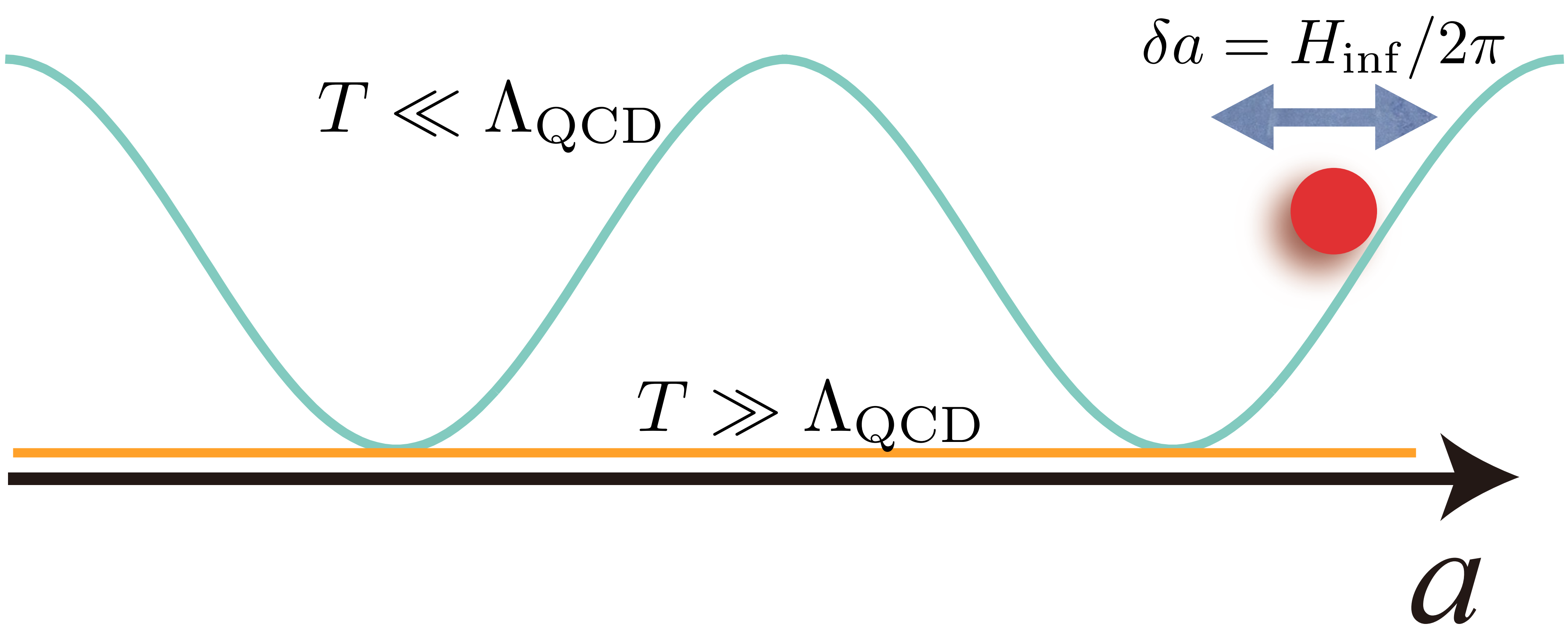


$$\alpha \equiv \frac{P_S}{P_{\mathcal{R}}} \lesssim 0.041 \quad (95\%\mathrm{CL})$$

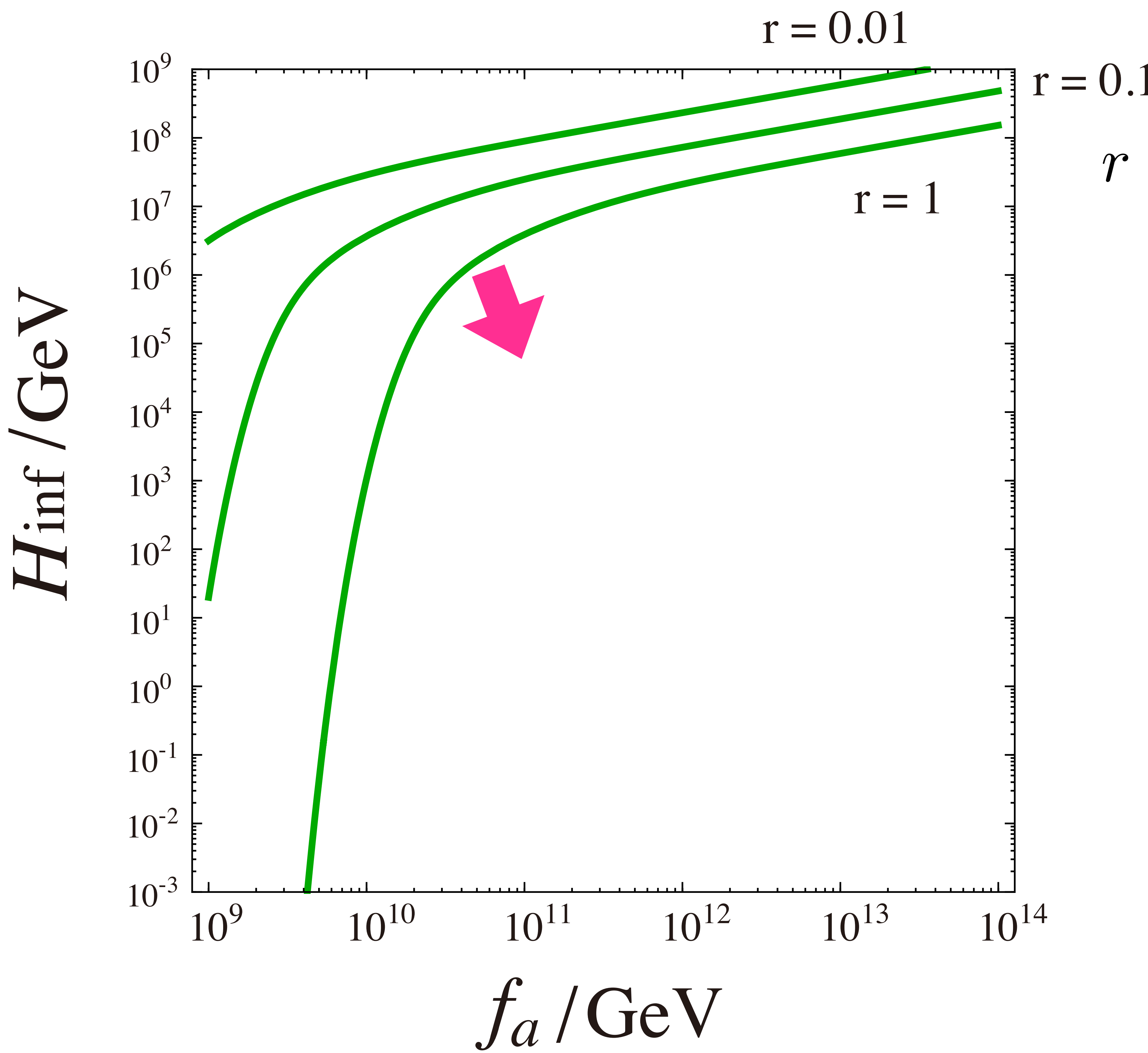
(Planck+WMAP polarization)

The QCD axion is a plausible candidate for DM with isocurvature perturbations.

$$\mathcal{L} = \left(\theta + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi^2} G^{\mu\nu} \tilde{G}_{\mu\nu}$$



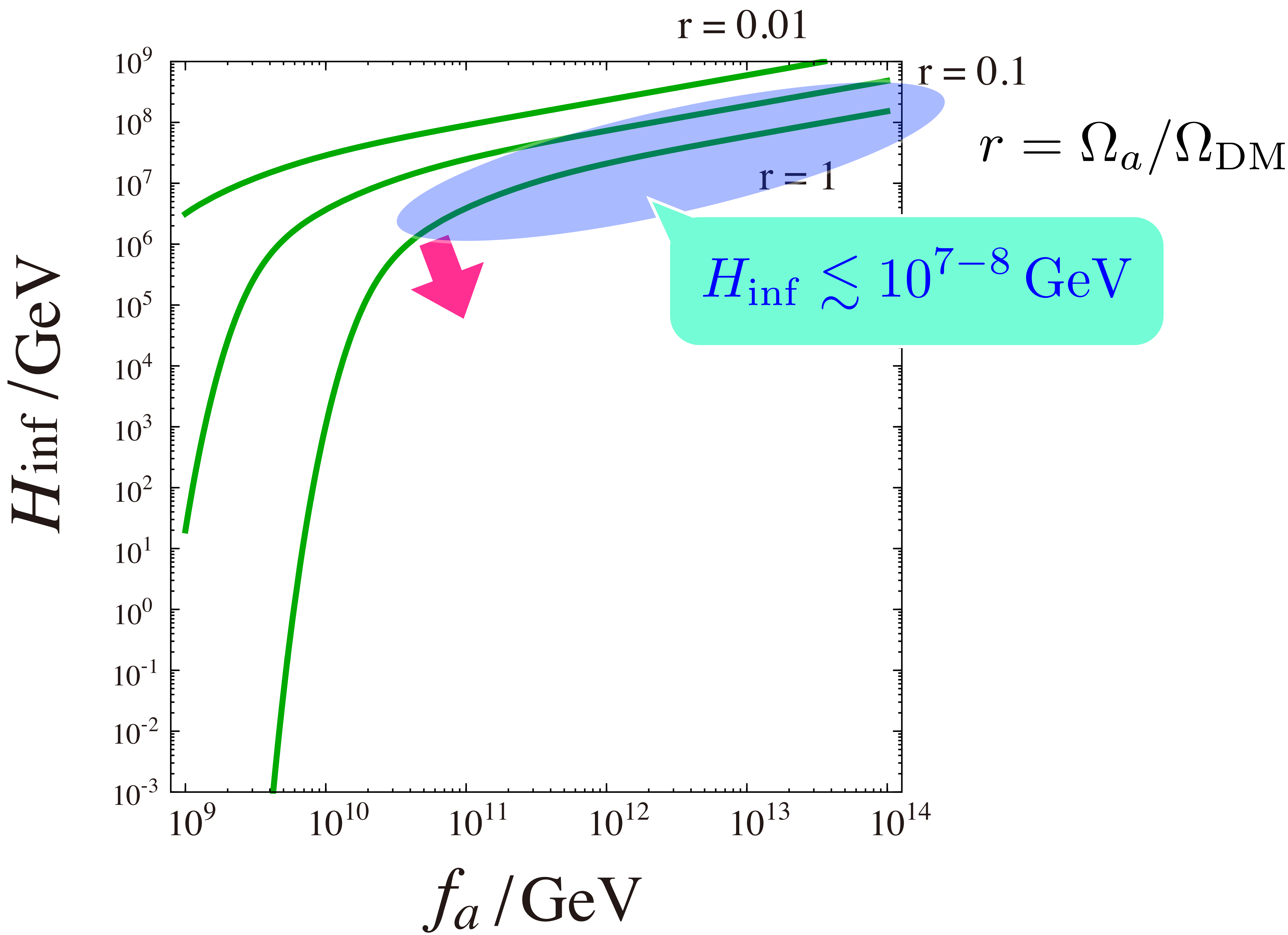
Isocurvature constraint on H_{inf}



$$r = \Omega_a / \Omega_{\rm DM}$$

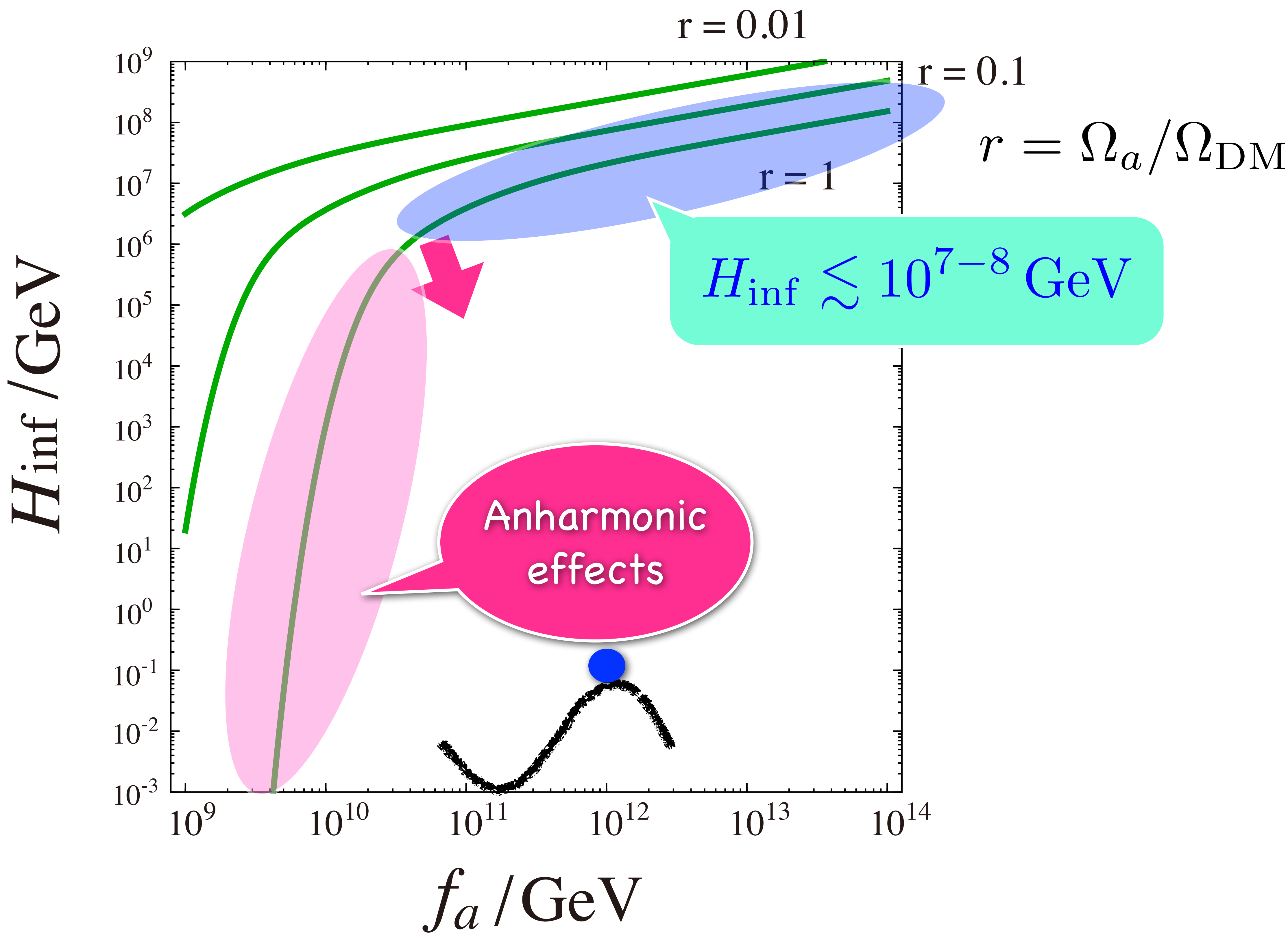
Kobayashi, Kurematsu, FT, 1304.0922

Isocurvature constraint on H_{inf}



Kobayashi, Kurematsu, FT, 1304.0922

Isocurvature constraint on H_{inf}

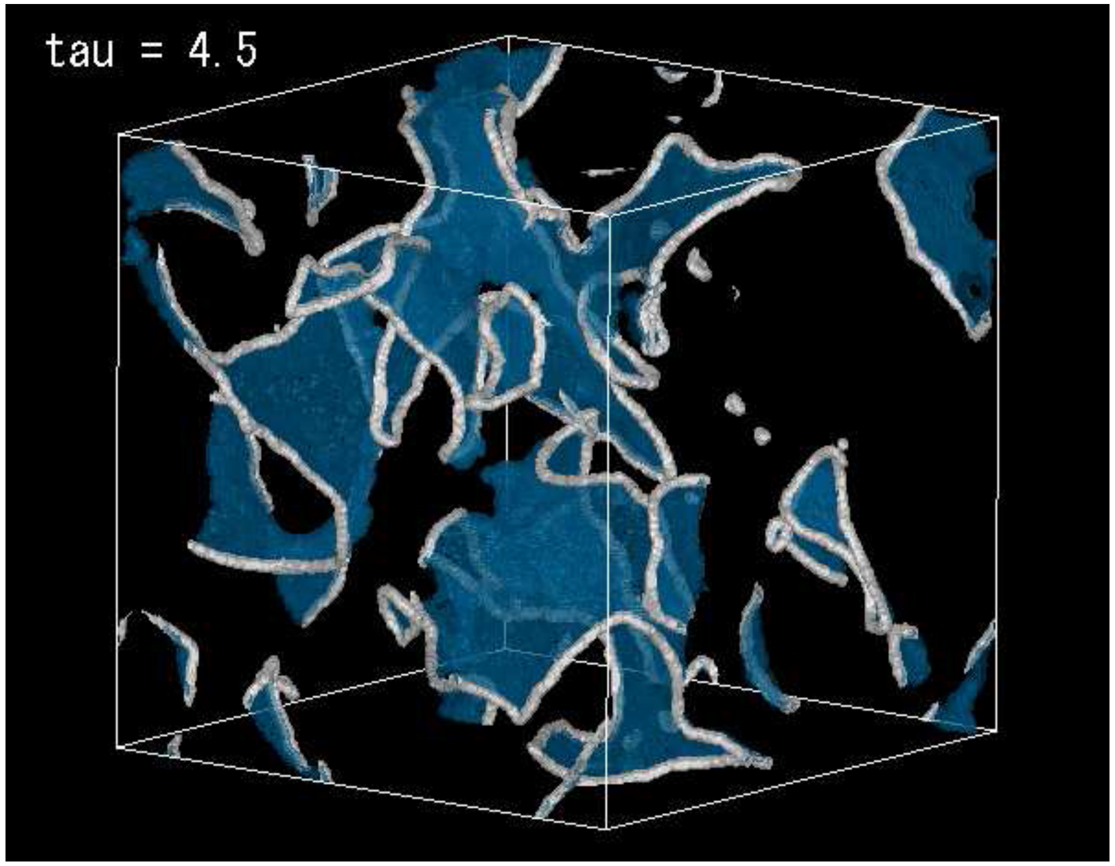


Kobayashi, Kurematsu, FT, 1304.0922

Solutions

- Restoration of Peccei-Quinn symmetry during inflation.
  - Axions are produced from domain walls and axion DM is possible for fa = 10^{10}GeV.

Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

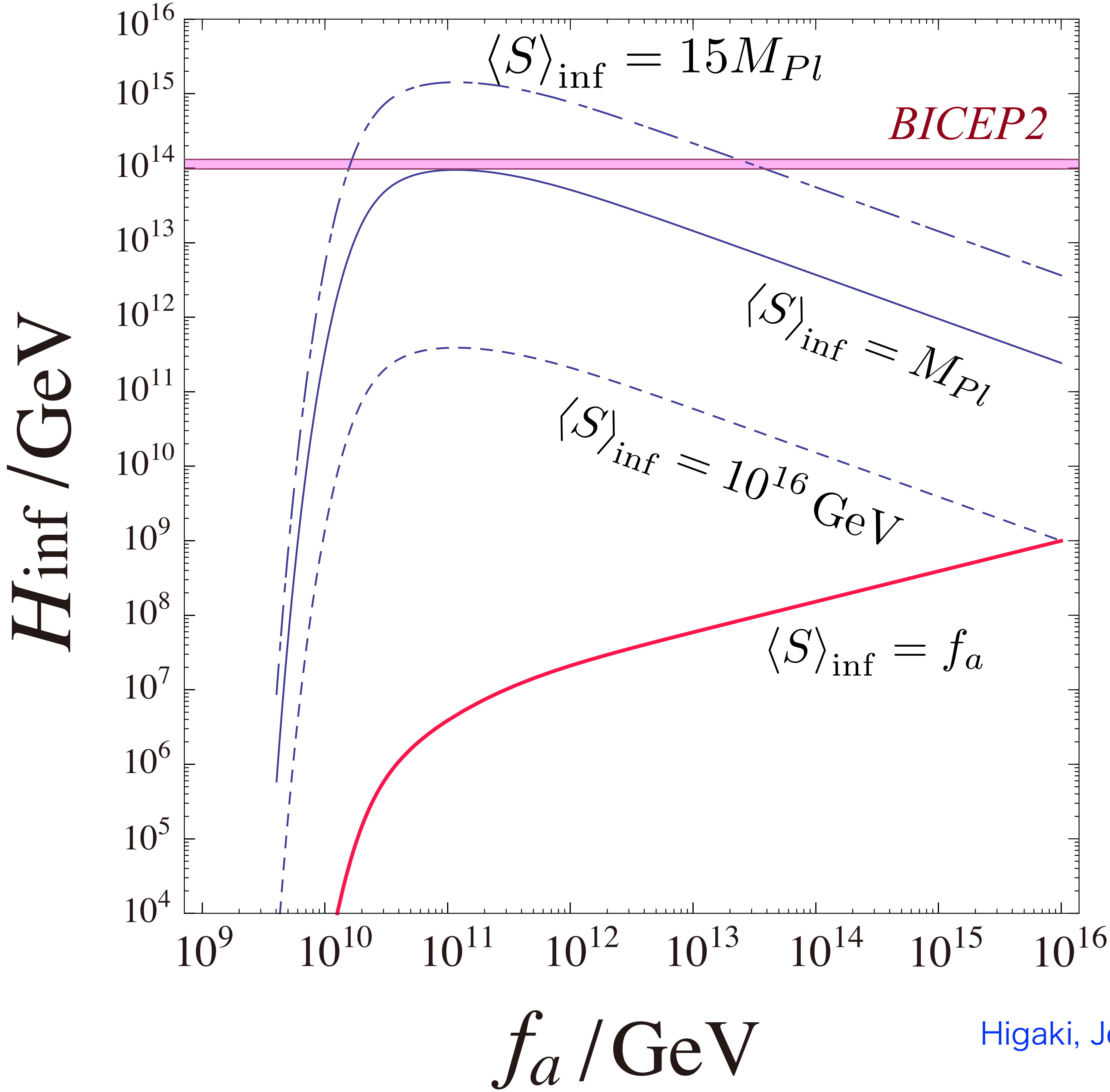


Solutions

- Restoration of Peccei-Quinn symmetry during inflation.
  - Axions are produced from domain walls and axion DM is possible for fa = 10^{10}GeV.

Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

- Super-Planckian saxion field value during inflation. (Saxion could be the inflaton)



axion CDM
is assumed.

Higaki, Jeong, FT, 1403.4186

Solutions

- Restoration of Peccei-Quinn symmetry during inflation.
  - Axions are produced from domain walls and axion DM is possible for fa = 10^{10}GeV.

Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

- Super-Planckian saxion field value during inflation. (Saxion could be the inflaton)
- Heavy axions during inflation. $m_a^2 \gtrsim H_{\rm inf}^2$
  - Stronger QCD during inflation Jeong, FT 1304.8131
  - Enhanced explicit PQ breaking Higaki, Jeong, FT, 1403.4186