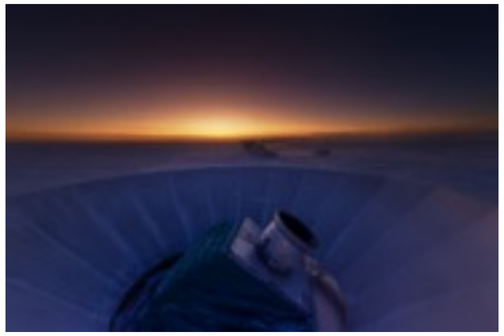
Searching high and low for traces of inflation

29th July 2014

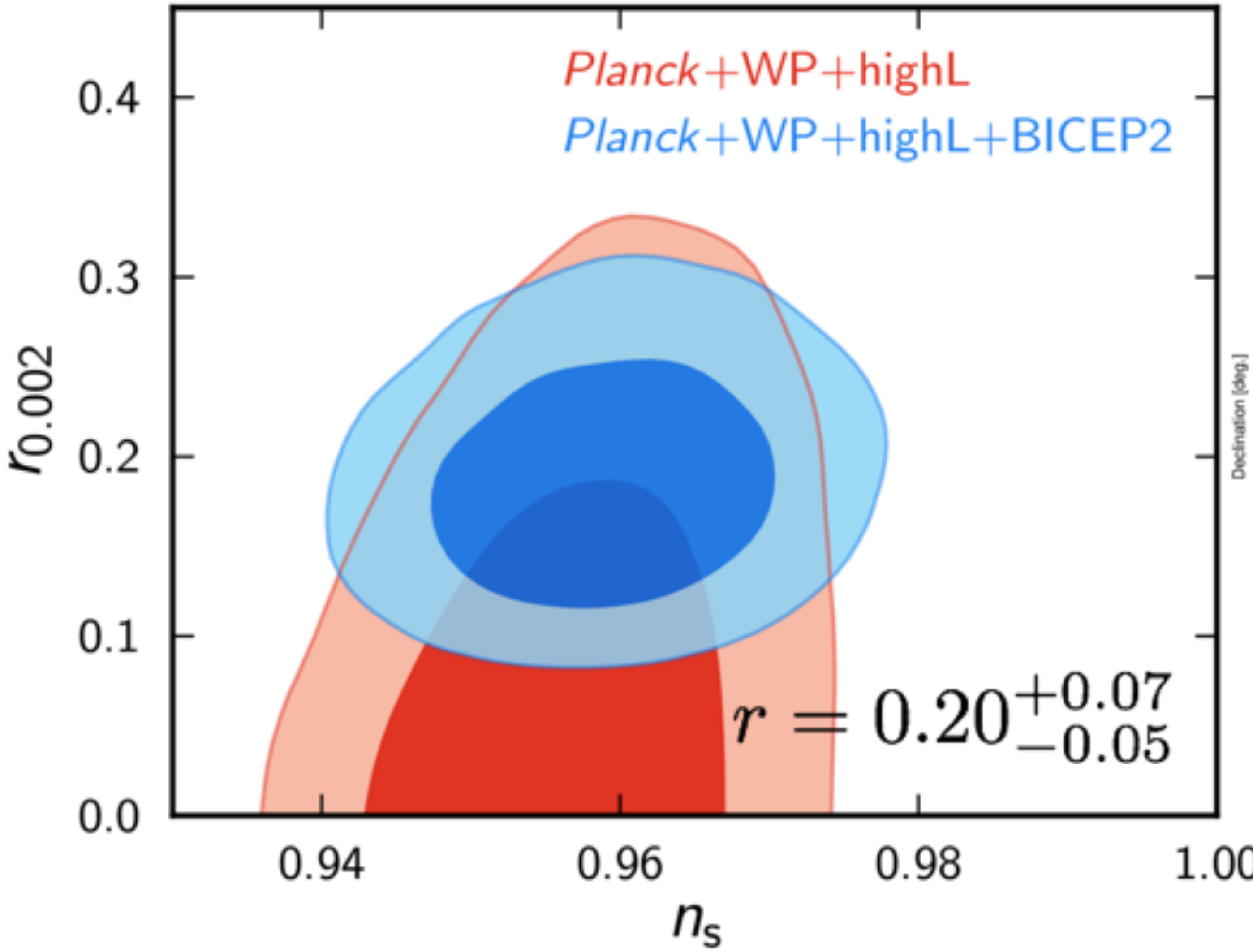
PPP 2014 @YITP

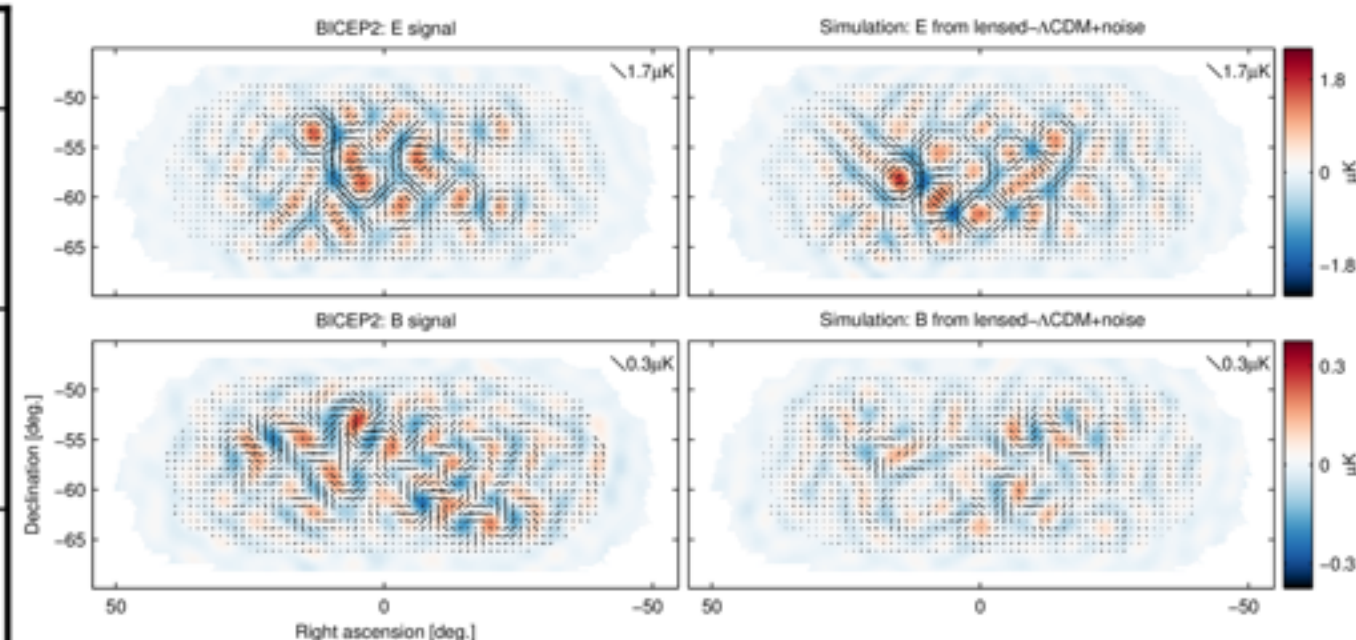
Fuminobu Takahashi
(Tohoku)

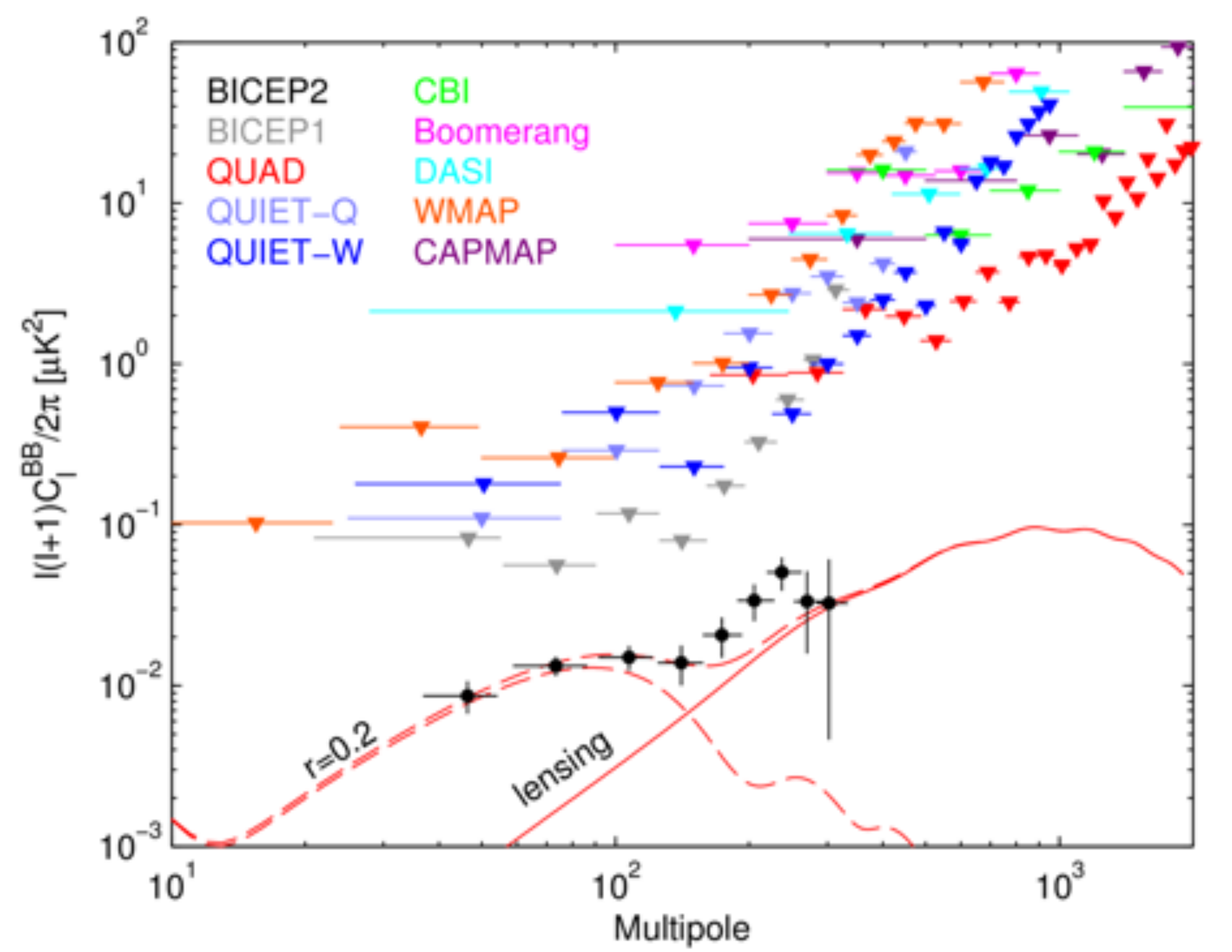


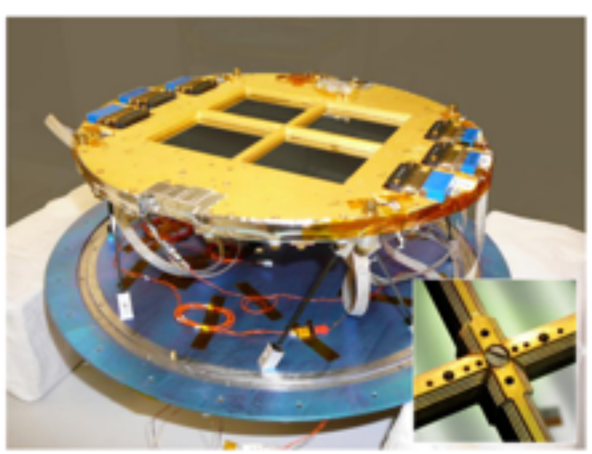
BICEP2

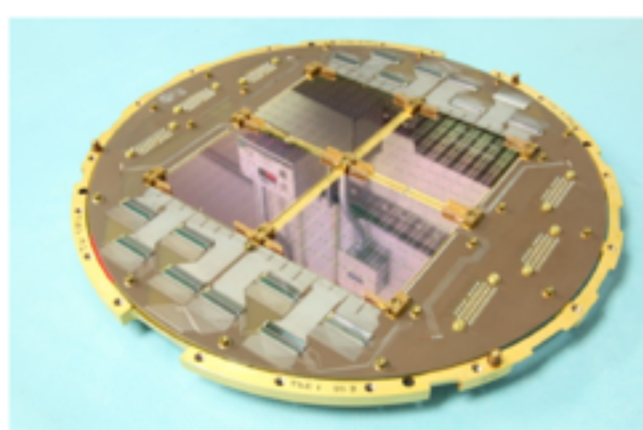
1403.3985

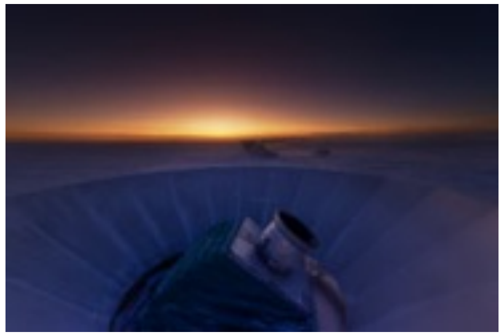












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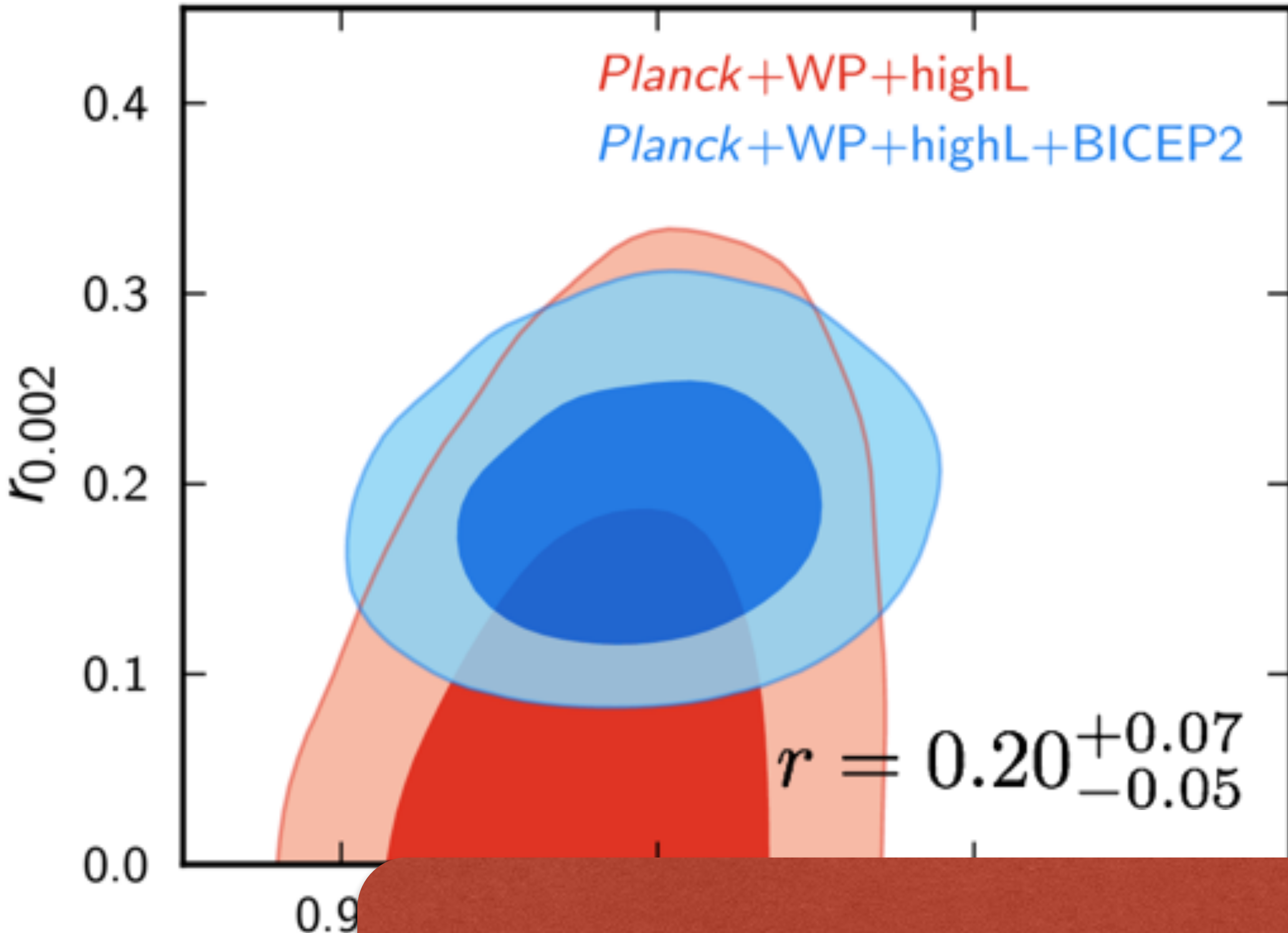

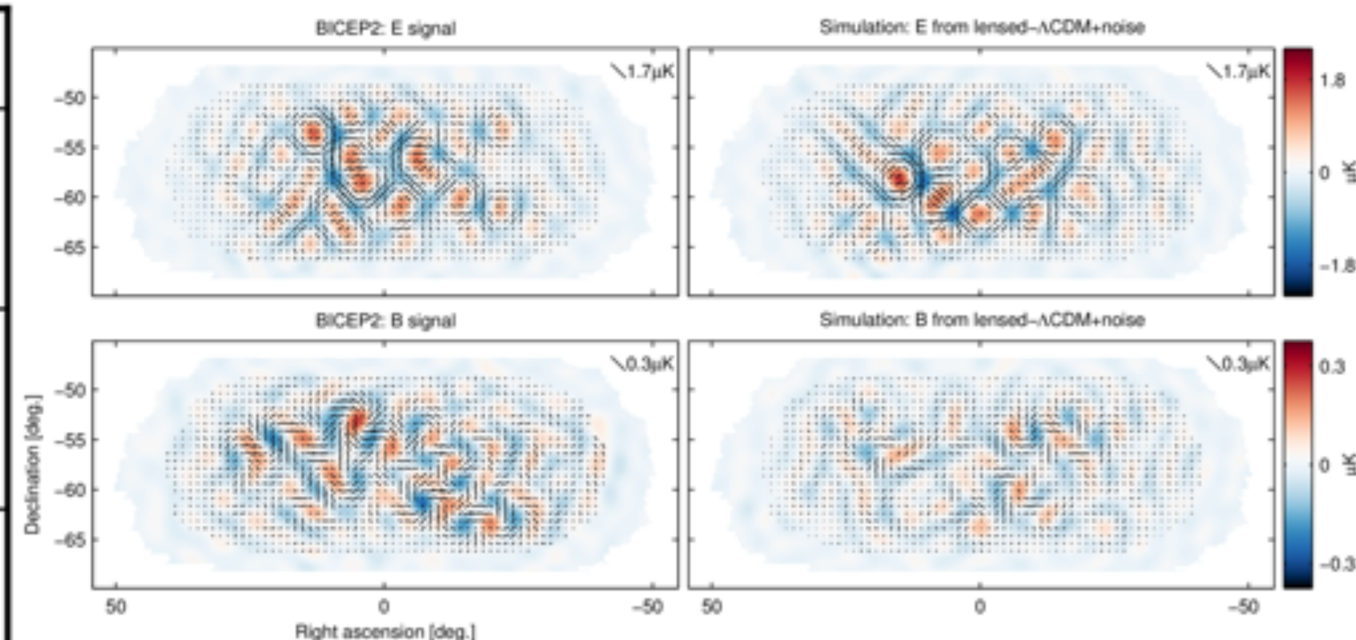

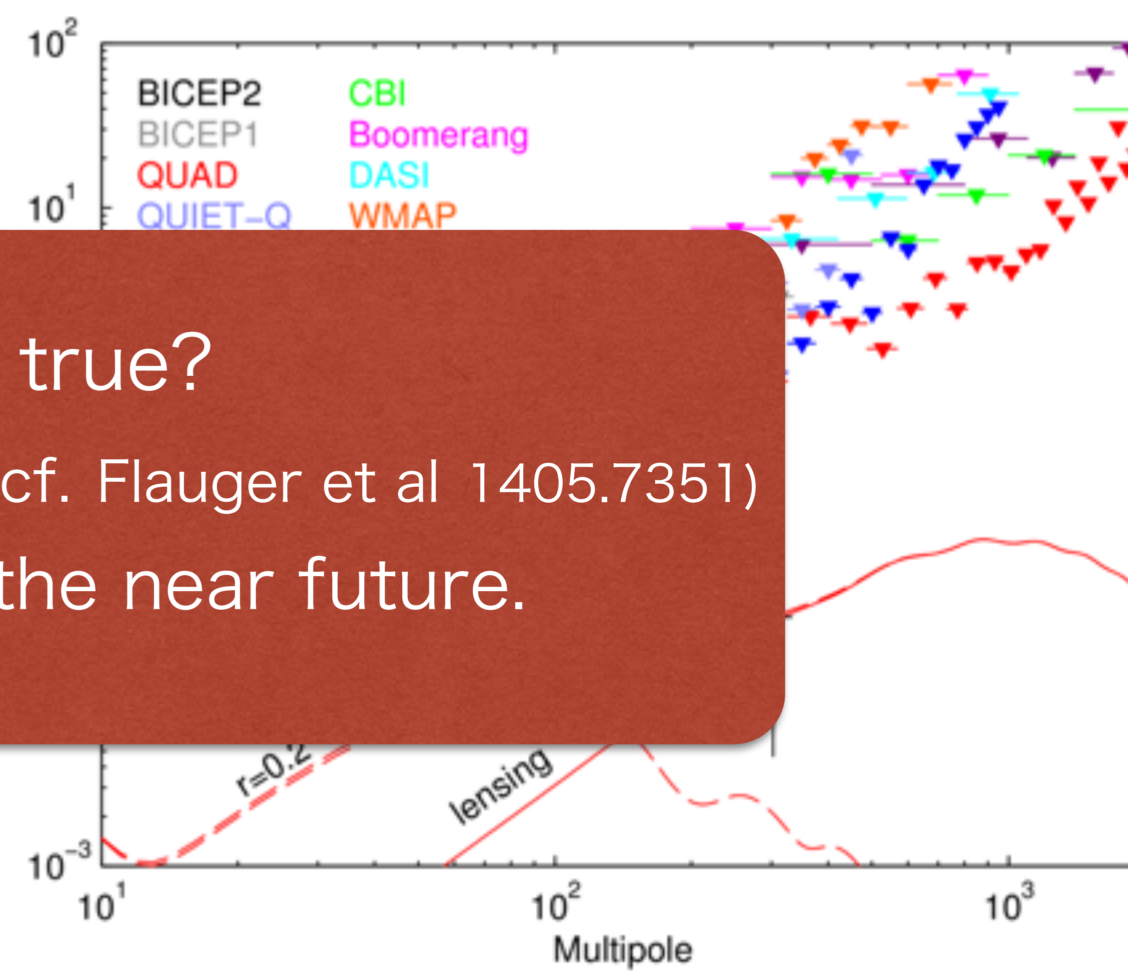

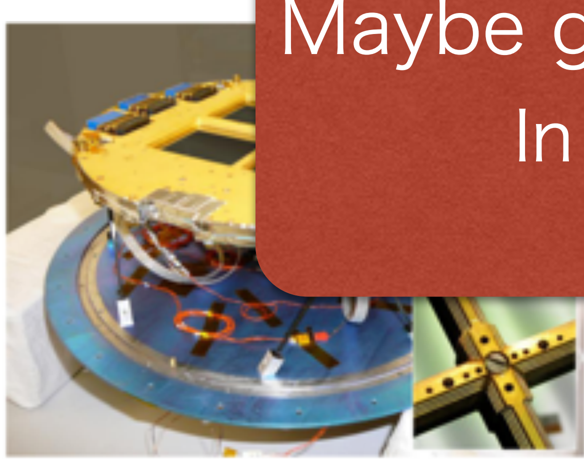

Too good to be true?

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

In any case we will see in the near future.

What if $r = O(10^{-3}\text{–}10^{-1})$?
What can we say about inflation?

It's GUT-scale inflation!

$$V_{\rm inf} \simeq (2.1 \times 10^{16}\,{\rm GeV})^4 \left(\frac{r}{0.16}\right)$$

$$H_{\rm inf} \simeq 1.0 \times 10^{14}\,{\rm GeV} \left(\frac{r}{0.16}\right)^{\frac{1}{2}},$$

GUT-scale, large-field inflation

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See Kitajima's poster

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  - The QCD axion less likely? PQ symmetry restoration?

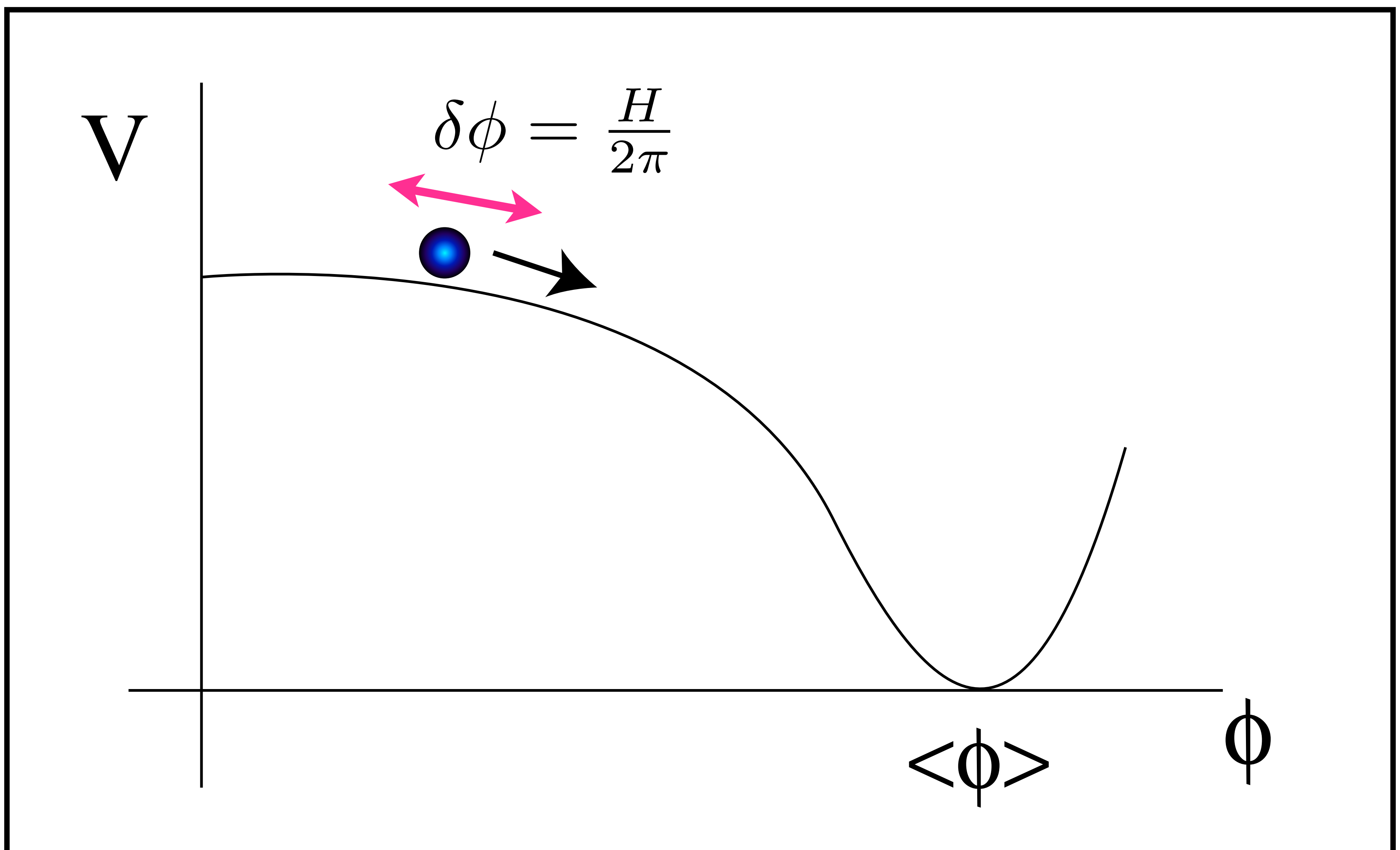
Inflation

Accelerated cosmic expansion solves various theoretical problems of the std. big bang cosmology.

Guth `81, Sato `80, Starobinsky `80, Kazanas `80, Brout, Englert, Gunzig, `79

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

Linde `82, Albrecht and Steinhardt `82



Perturbations of spacetime

Flat FRW Universe:

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+ small perturbations

$$ds^2 = -(1+2A)dt^2 - 2aB_i dt dx^i + a^2 \left(\delta_{ij} + 2H_L \delta_{ij} + 2H_{Tij}\right) dx^i dx^j$$

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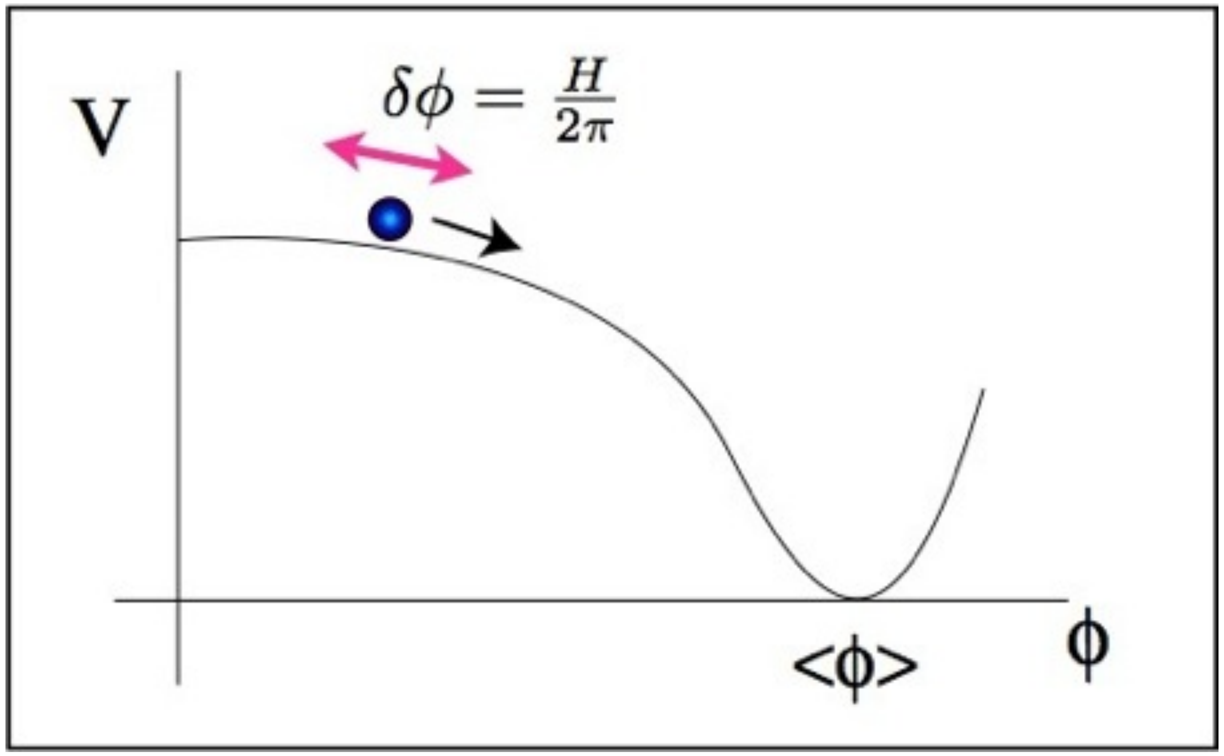
The perturbations can be decomposed into three types.

1. Scalar $ds^2 = -(1+2\Phi)dt^2 + a^2(1+2\Psi)d\mathbf{x}^2$ Inflaton
2. Vector
3. Tensor $ds^2 = -dt^2 + a^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j$ GW

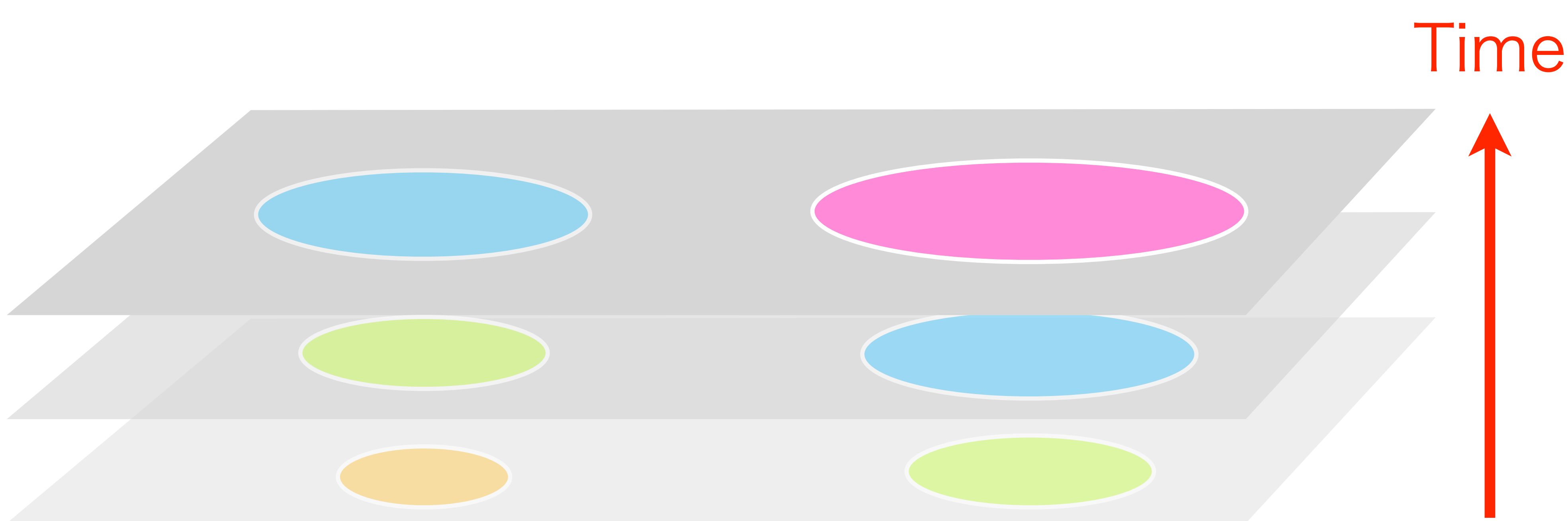
Scalar mode

$$ds^2 = -(1 + 2\Phi)dt^2 + a^2(1 + 2\Psi)d\mathbf{x}^2$$



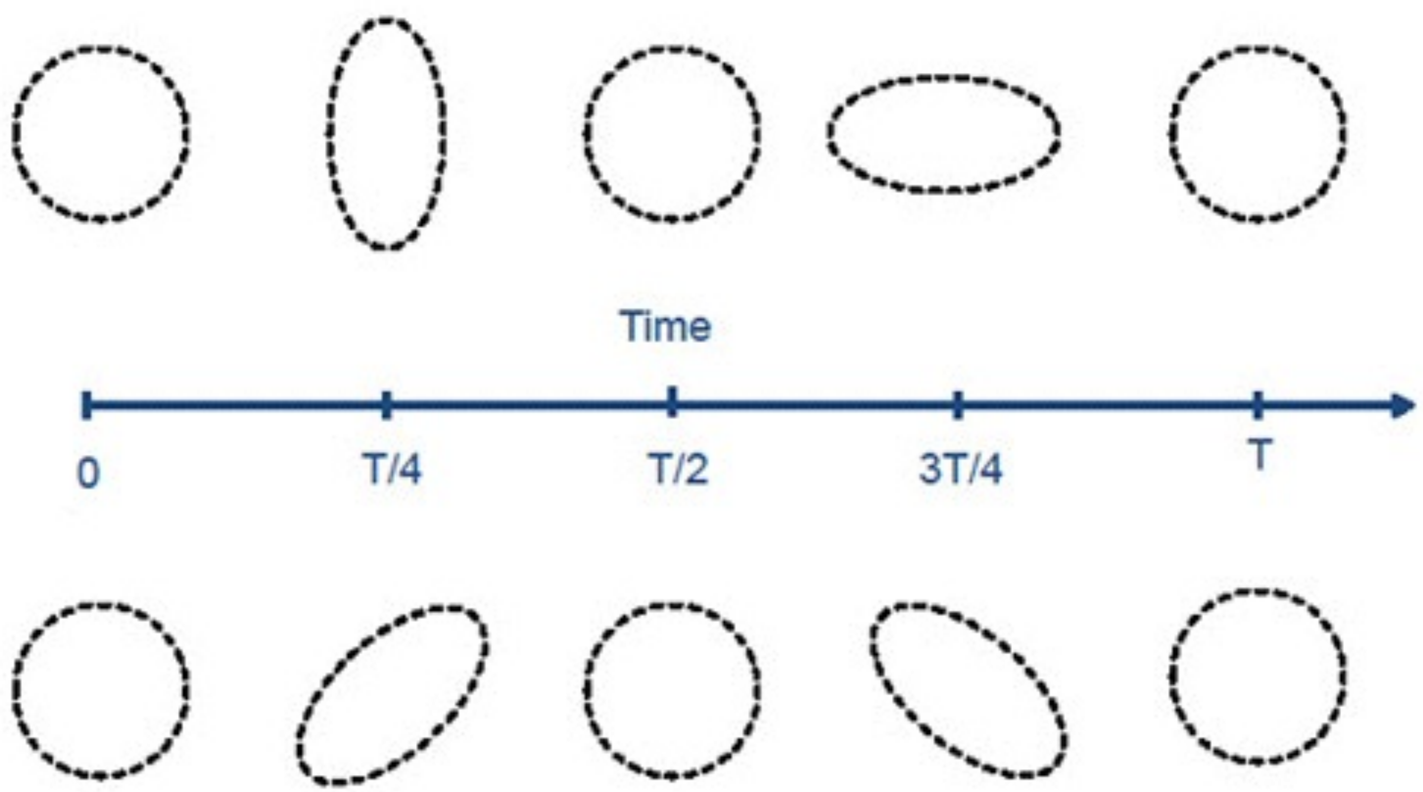
It is due to **fluctuations in time** induced by the inflaton's quantum fluctuation.

$$\Phi \sim \frac{\delta\rho}{\rho} \sim H\delta t \sim H_{\rm inf}\frac{\delta\phi}{\dot\phi} \sim \left|\frac{V^{3/2}}{V' M_P^3}\right|$$



Tensor mode

$$ds^2 = -dt^2 + a^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j$$



It is due to **fluctuations of graviton itself.**

$$h_{ij} \sim \frac{H_{\rm inf}}{M_P}$$

Observation vs Theory

Scalar mode

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

Tensor mode

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

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

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

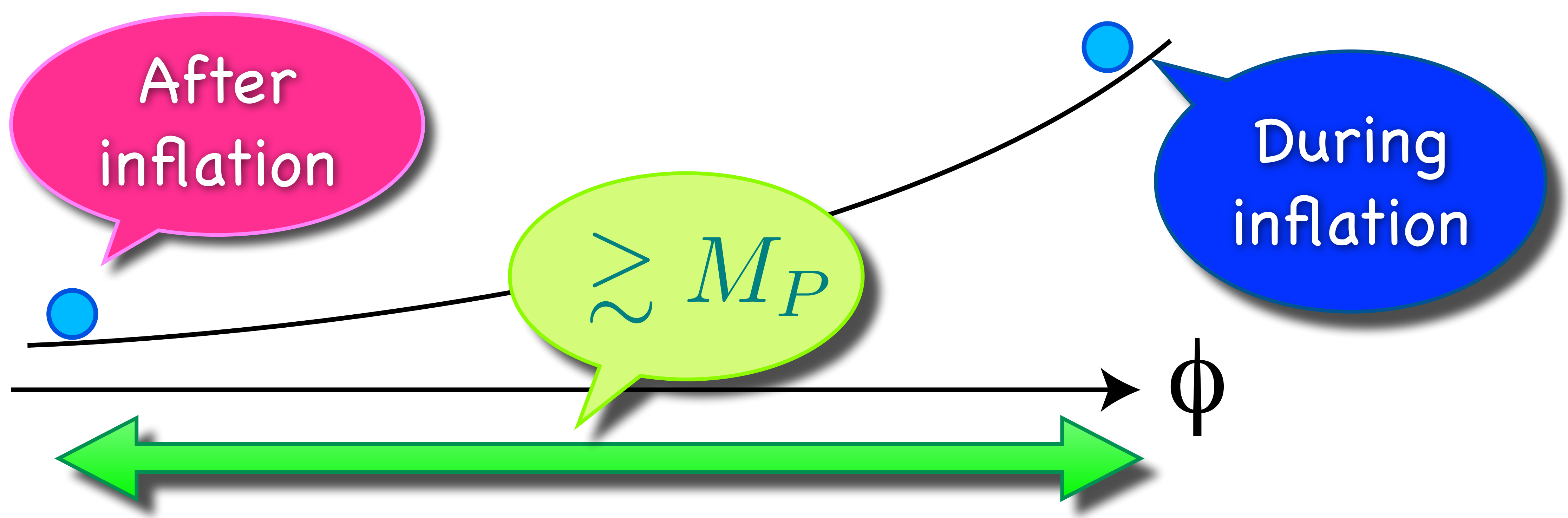
$$r = 8\left(\frac{V'}{V}\right)^2$$

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

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

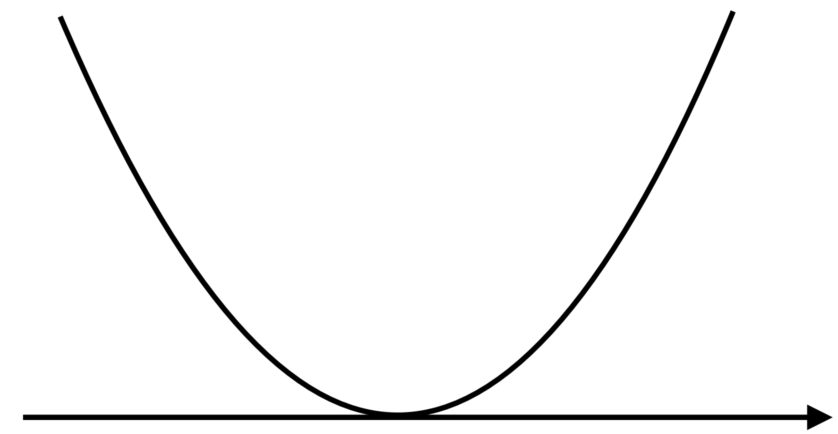
Various large-field inflation models

Quadratic chaotic inflation

Linde `83

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

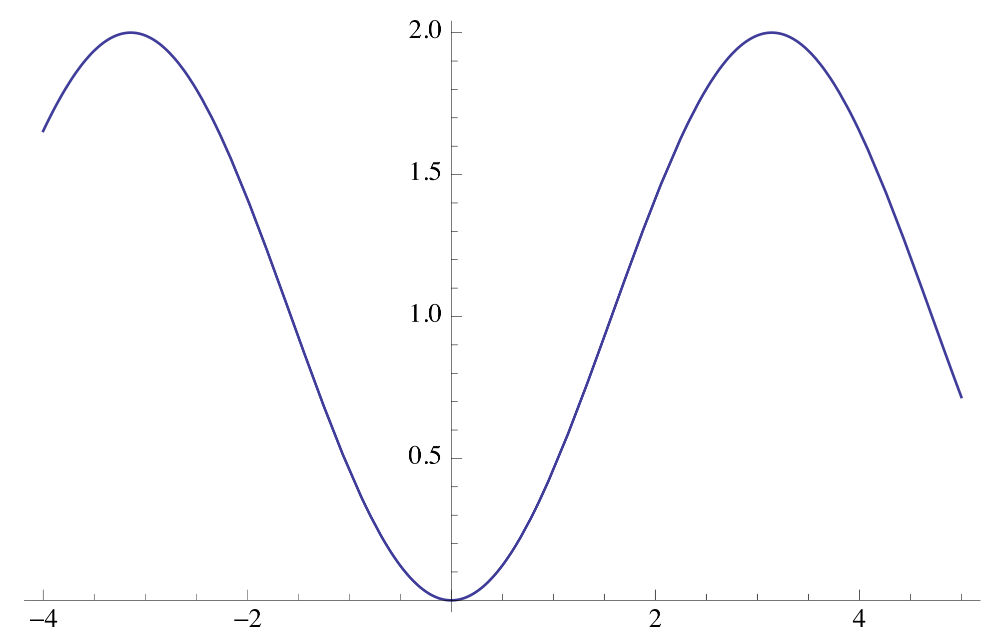
$$m \simeq 2 \times 10^{13}\,\mathrm{GeV} \qquad \phi_{60} \sim 16 M_P$$



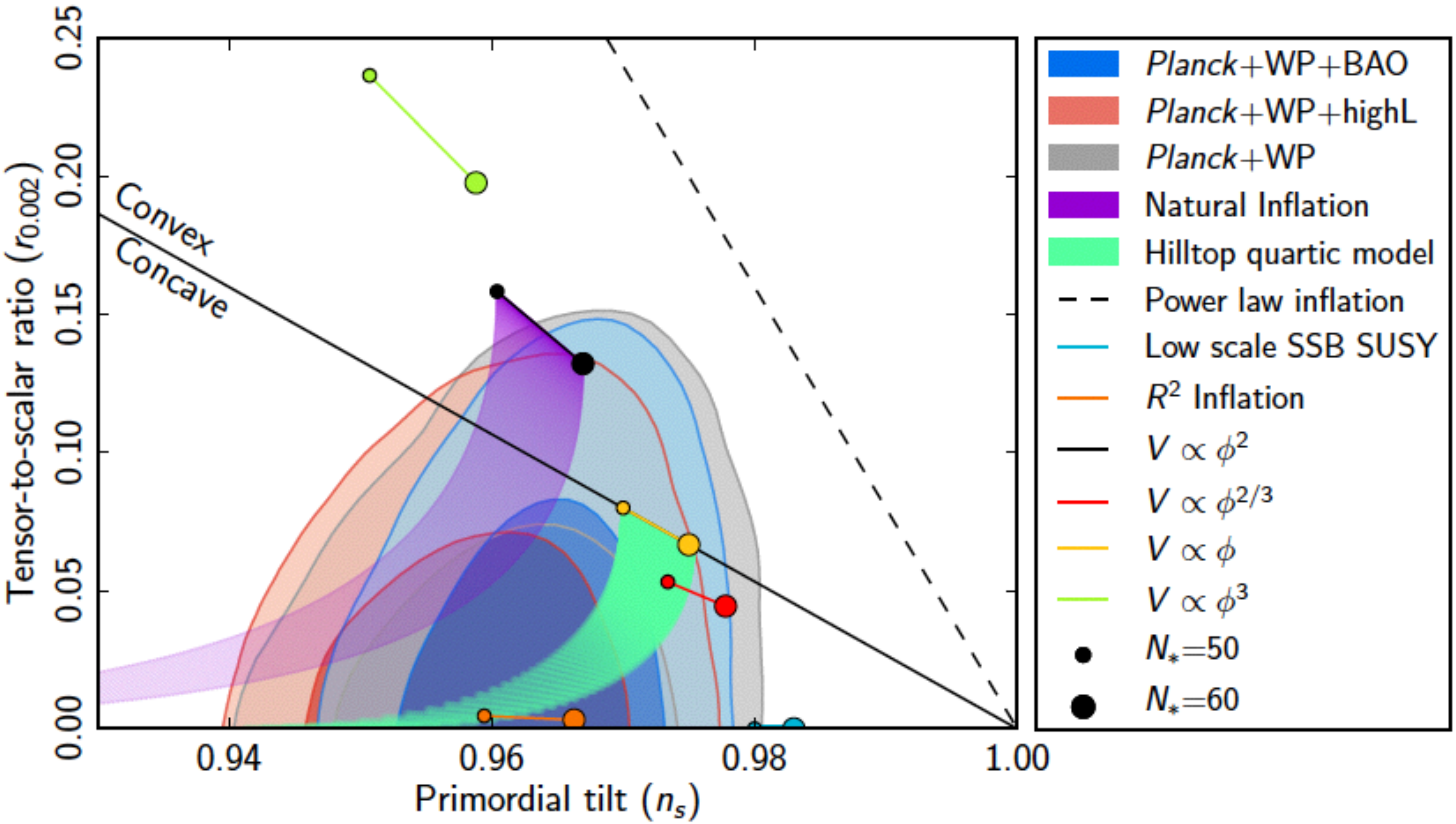
Natural inflation

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

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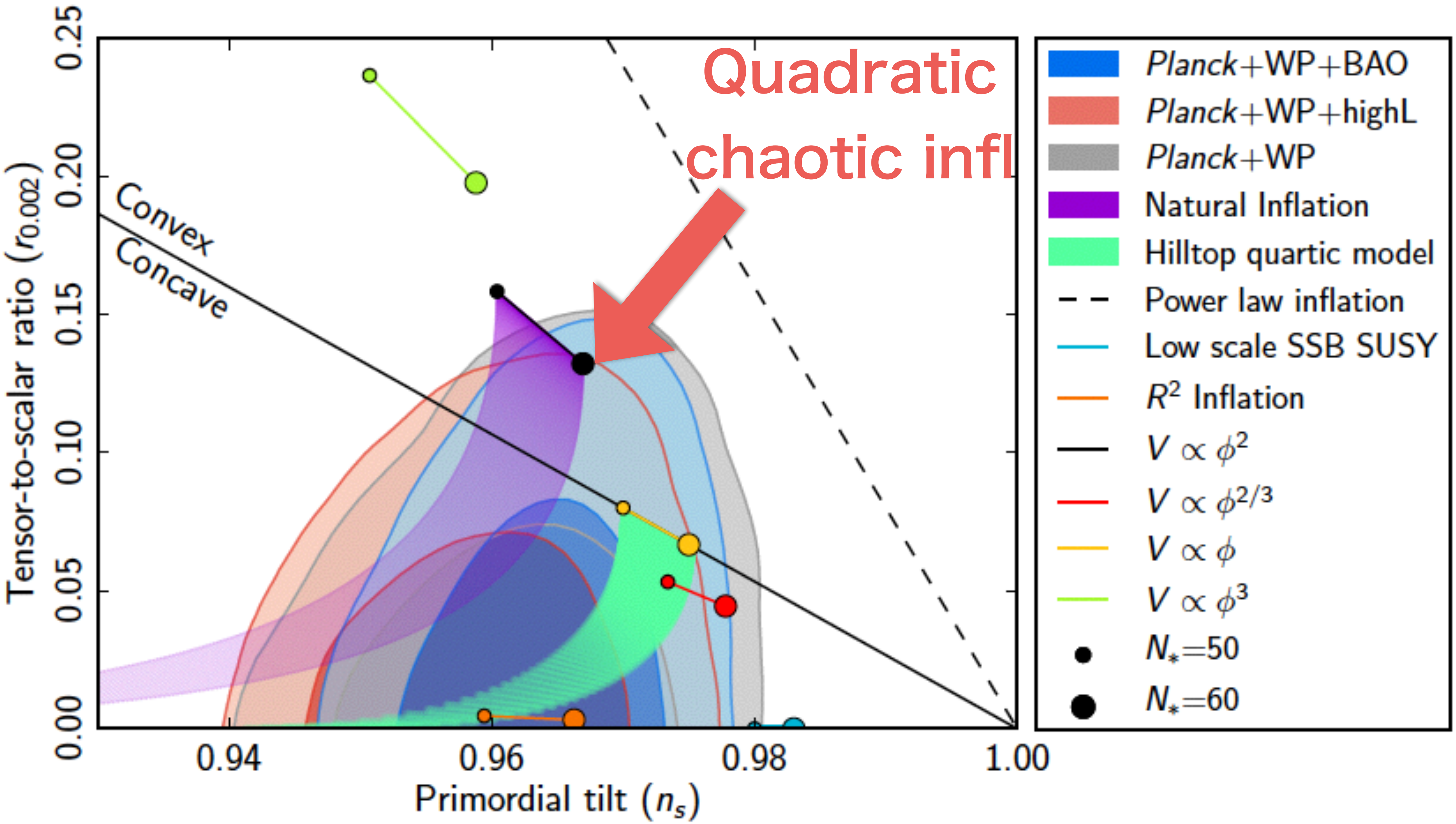

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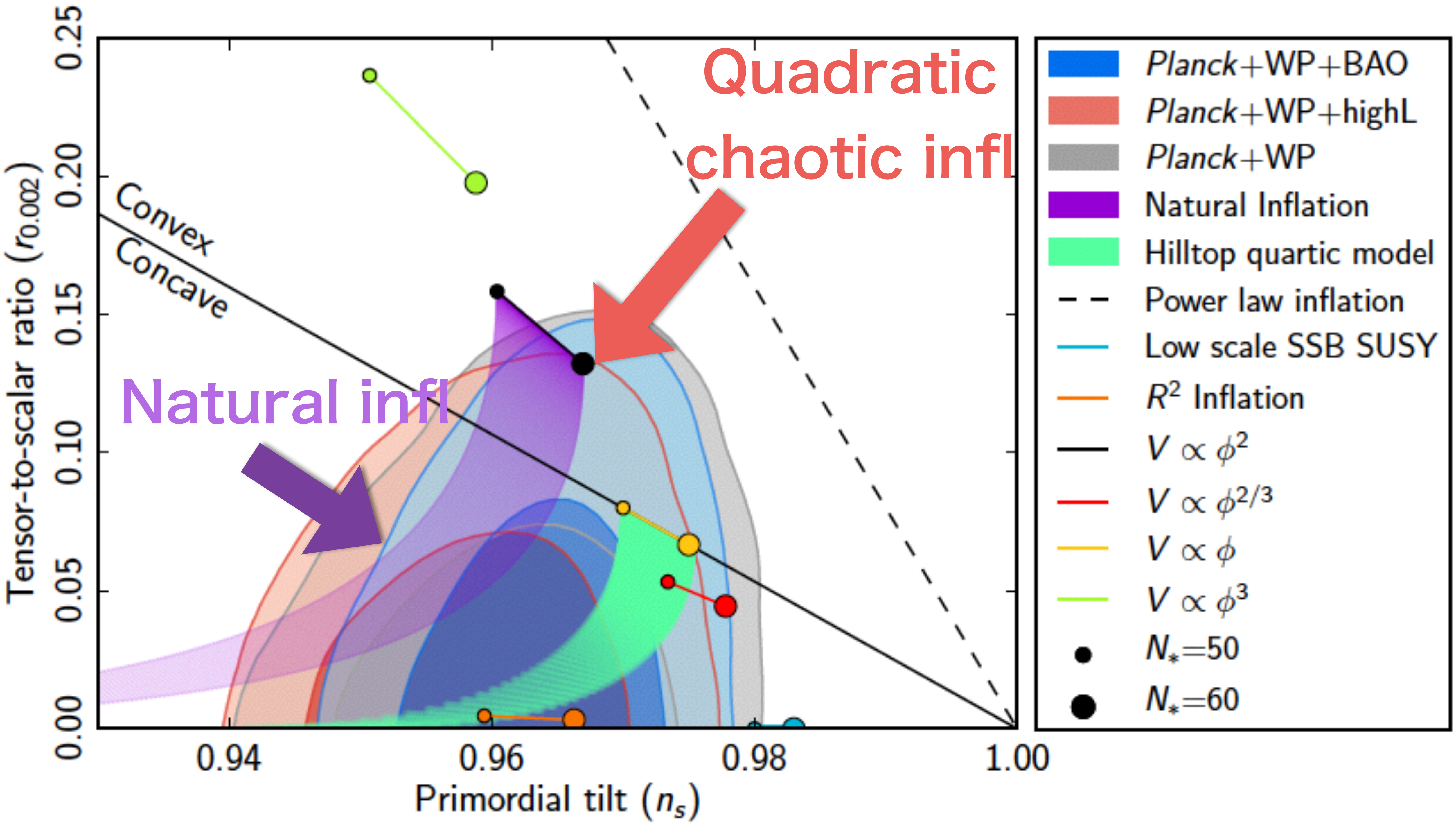

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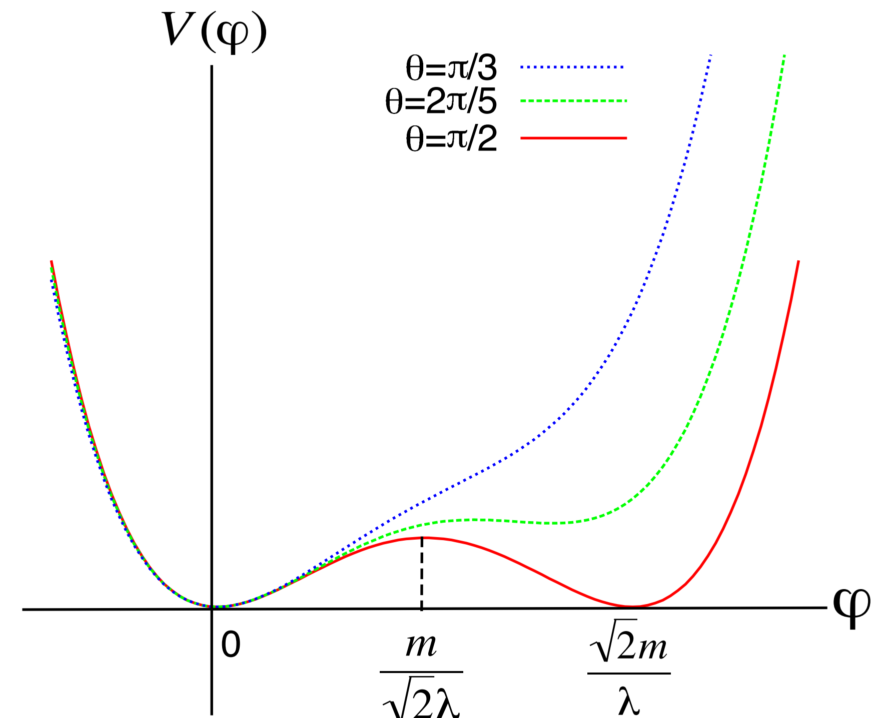
Various large-field inflation models

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)

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



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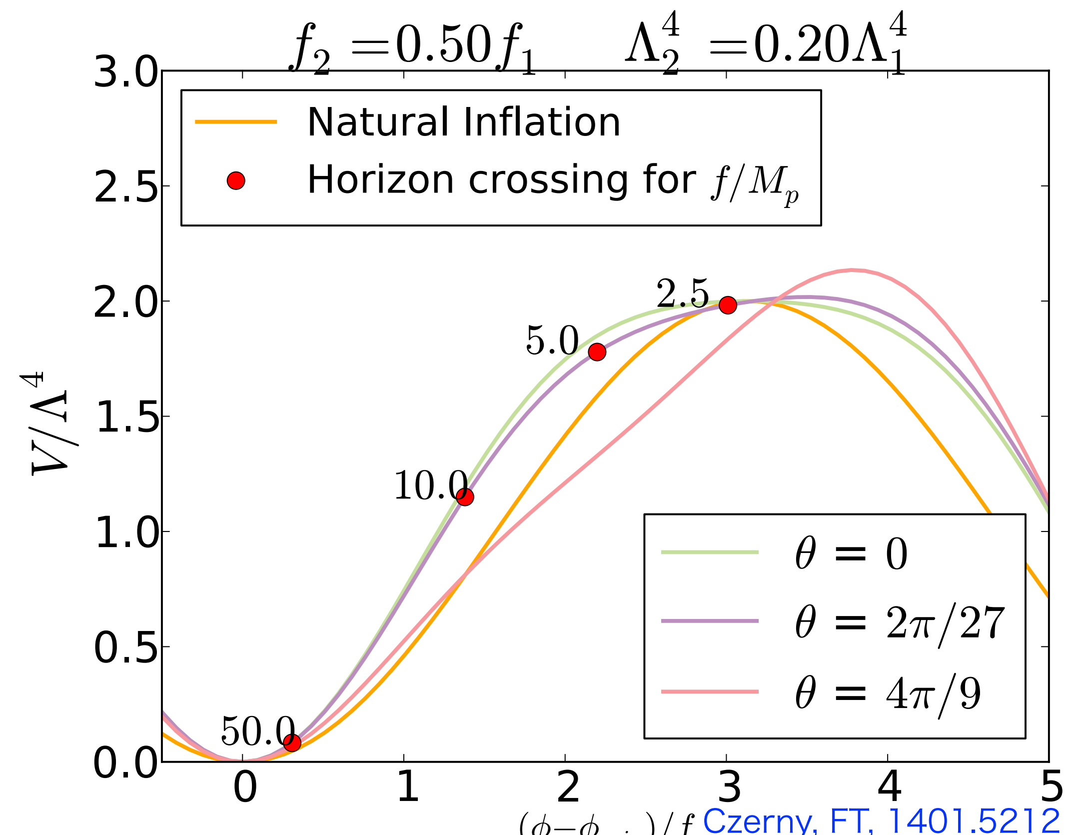
Multi-Natural inflation (MNI)

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.



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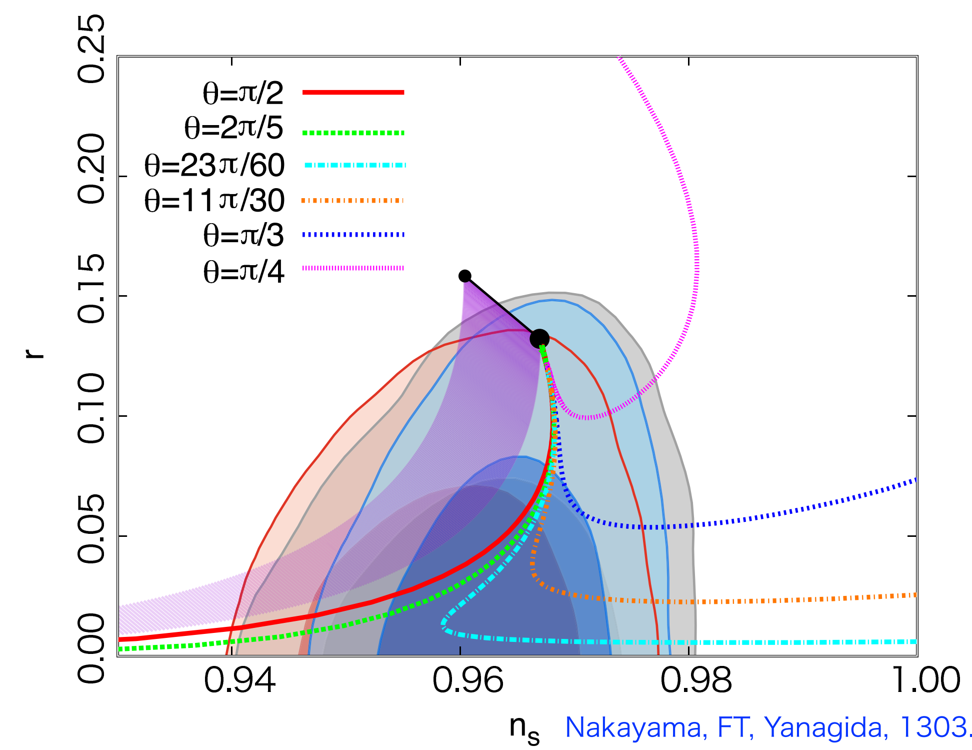

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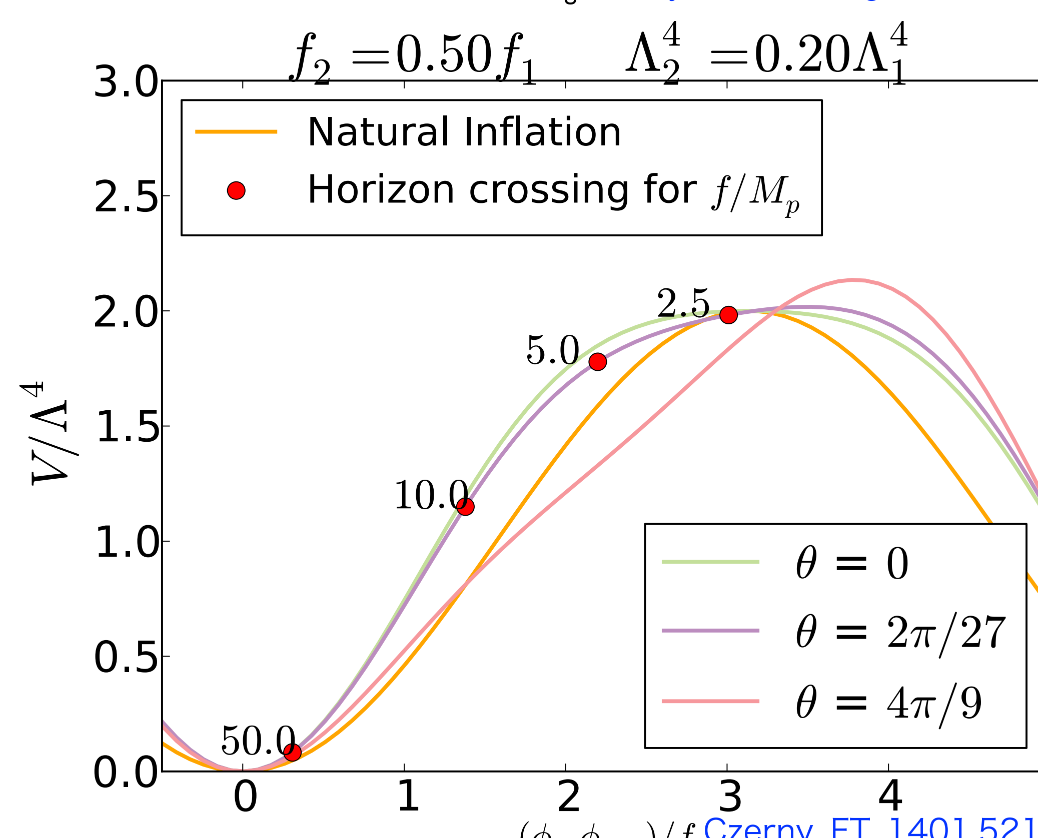

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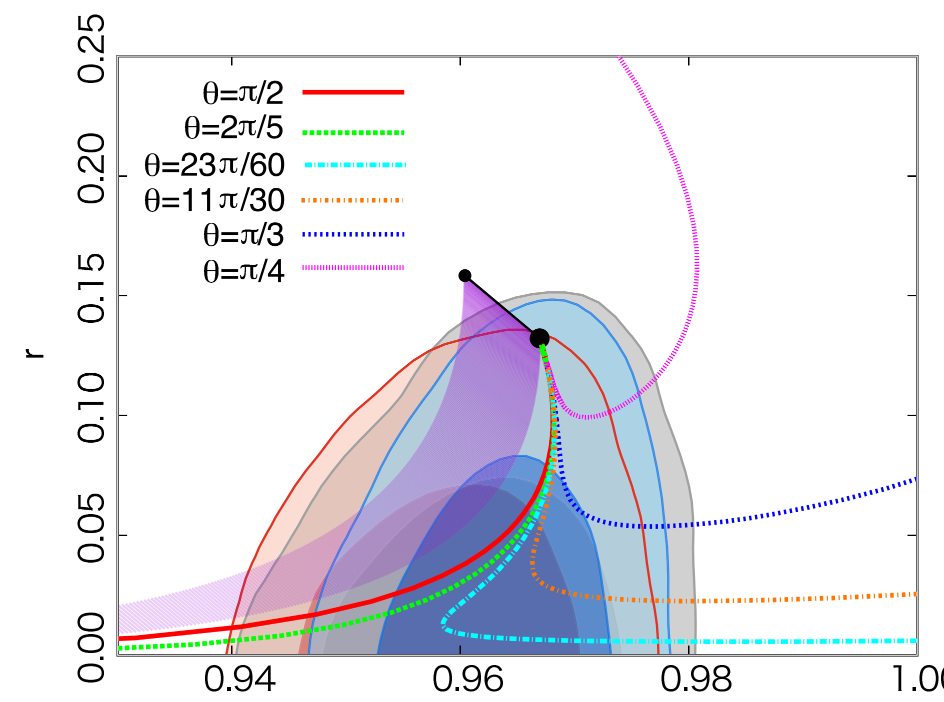

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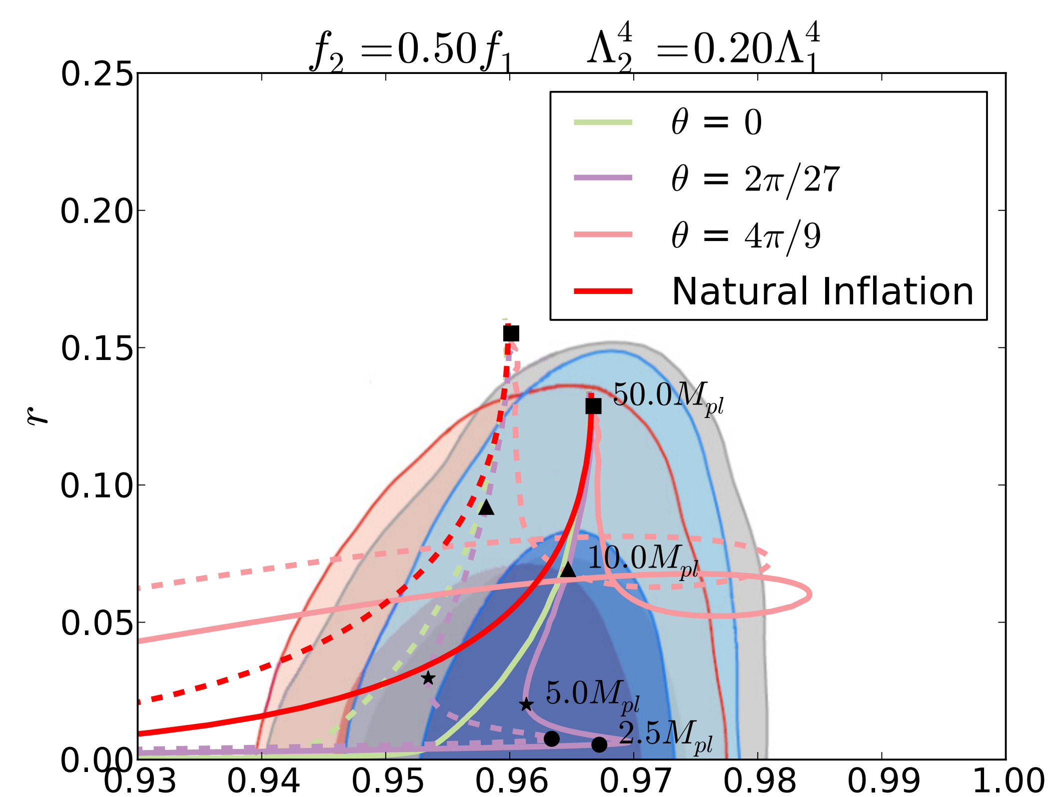


Czerny, FT, 1401.5212

Various large-field inflation models

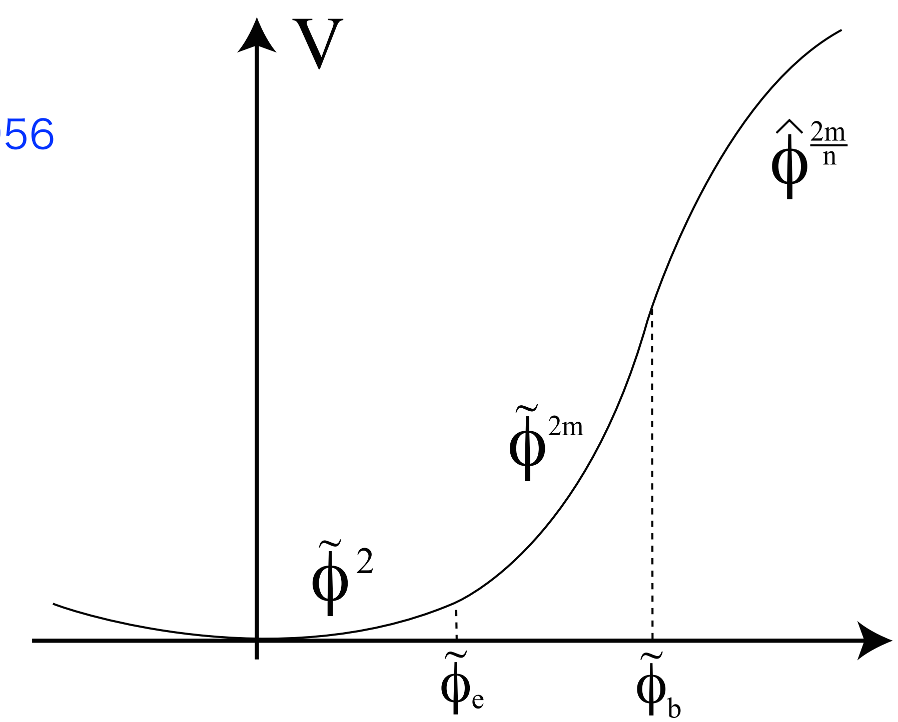
Running kinetic inflation

FT 1006.2801 Nakayama, FT 1008.2956

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \xi(\partial\phi^n)^2 - V(\phi)$$

Linear or fractional-power potential can be realized.

cf. Harigaya, Ibe, Schmitz, Yanagida, 1211.6241 for dynamical realization.



Axion monodromy inflation

Silverstein, Westphal, 0803.3085
McAllister, Silverstein, Westphal, 0808.0706

$$V = \mu^3\phi + \Lambda^4 \cos\left(\frac{\phi}{f_a}\right)$$

Inflation and particle physics

Since early 80's, inflation models have been often designed in response to cosmological issues, not particle physics ones.

However, they are still closely related to each other;

- Realization of inflation in SUGRA/string theory
- Successful reheating (baryogenesis, dark matter, unwanted relics, etc.)
- Inflation dynamics and SUSY breaking

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.

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

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

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

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

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

even for $\varphi \gg M_p$

Z_2 or not Z_2?

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

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

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The inflaton might be right-handed sneutrino.

Murayama, Nakayama, FT, Yanagida,1404.3857

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

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

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

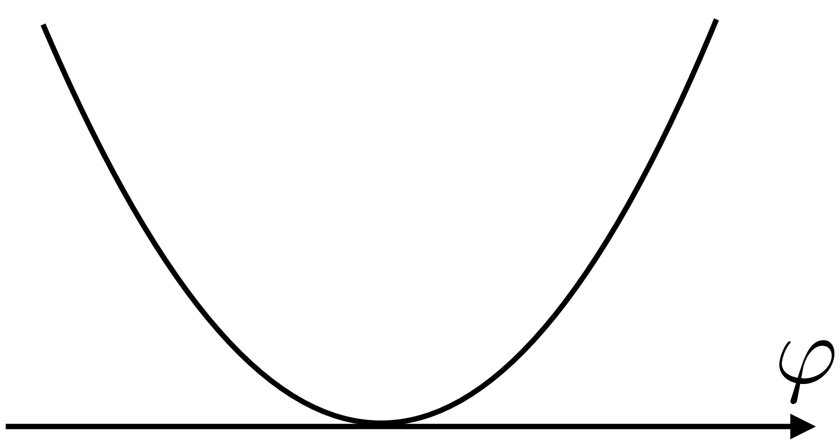
$$W = \frac{1}{2}M_{ij}N_iN_j + h_{i\alpha}N_iL_\alpha H_u$$

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.

Chaotic inflation w/o Z2

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

- **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

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

Thermal leptogenesis is likely

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- **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.

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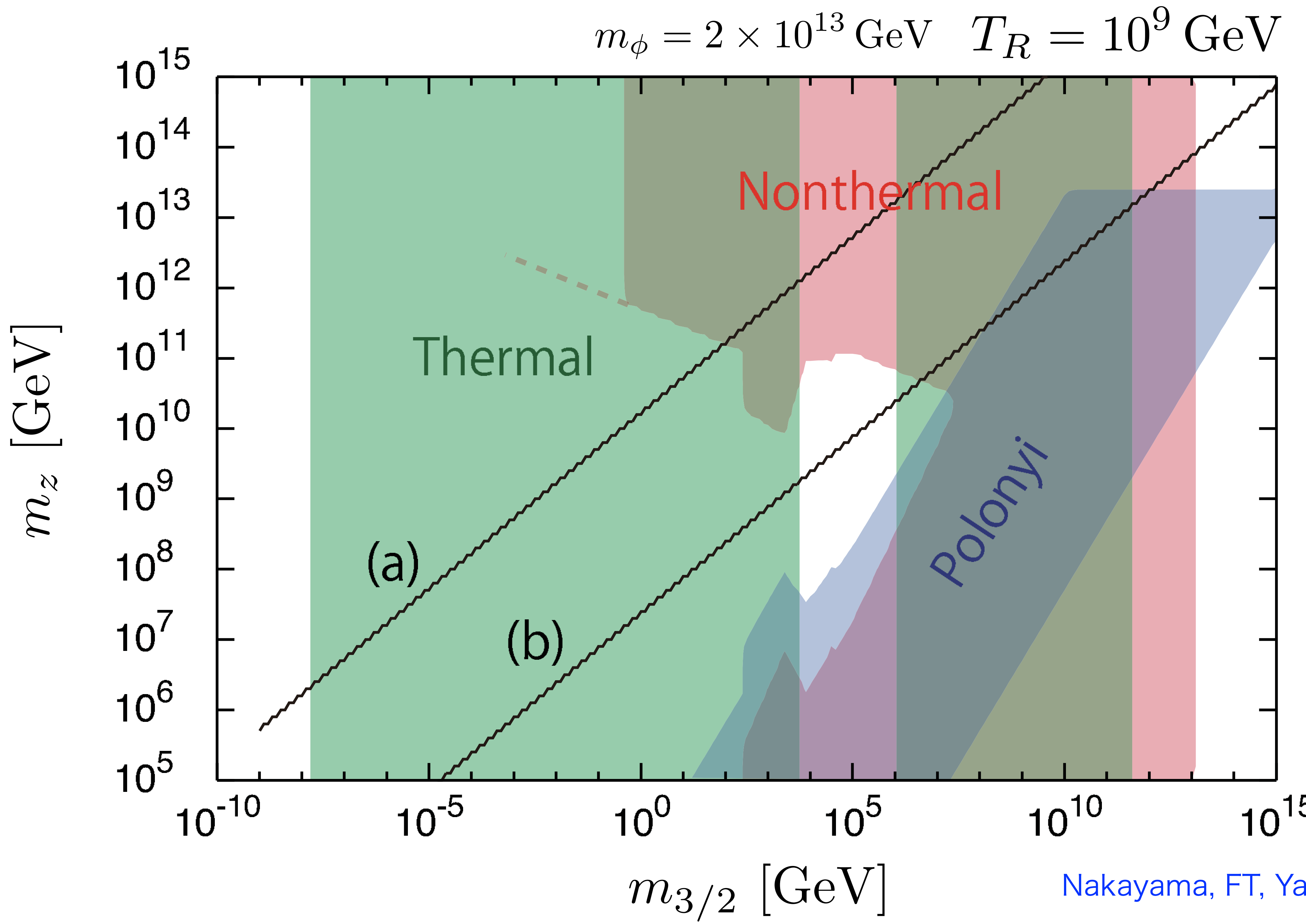
There are various sources for gravitino production;

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

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

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



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

$(a)\lambda = 4\pi$

$(b)\lambda = 1$

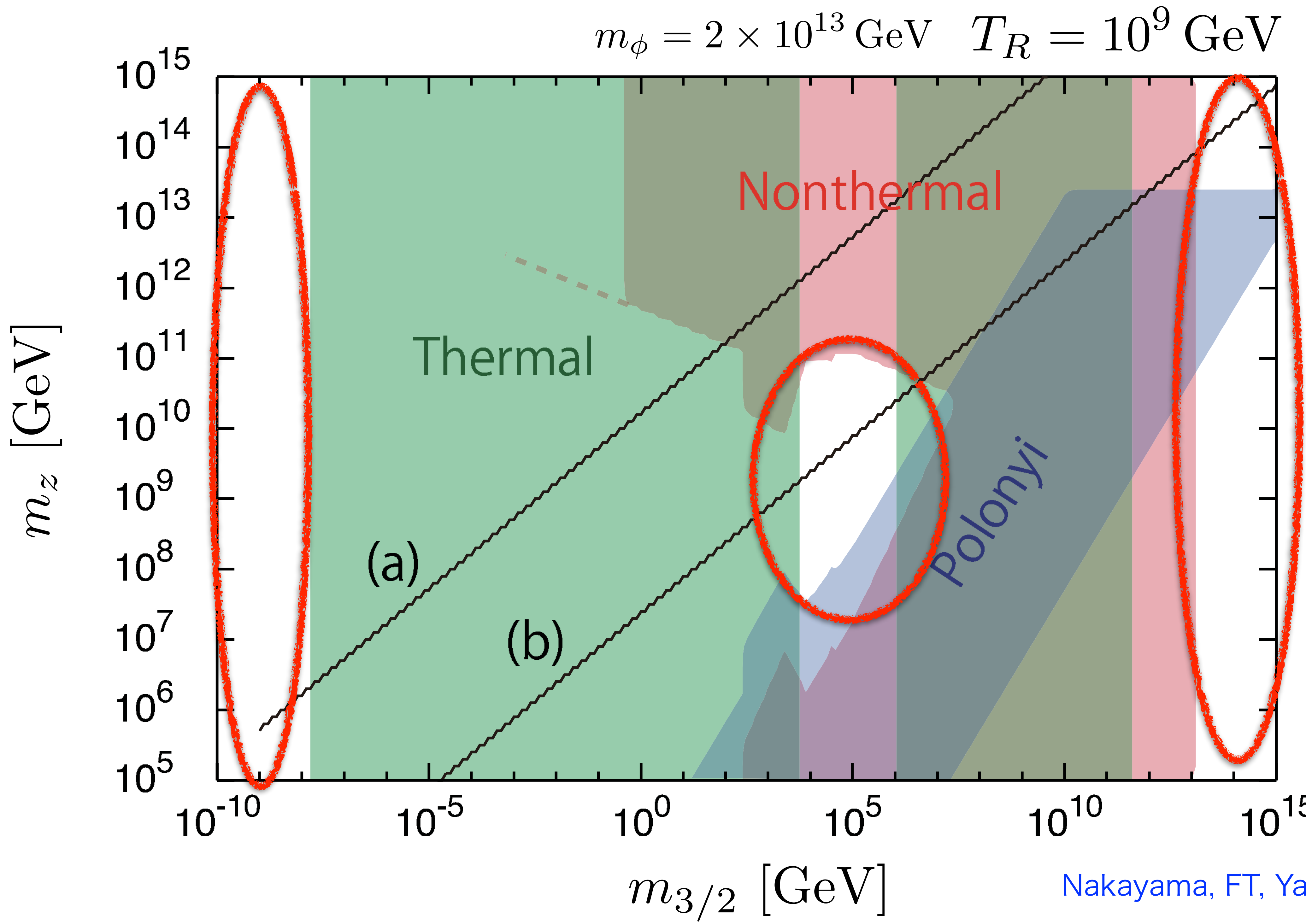
Nakayama, FT, Yanagida,1404.2472

3 allowed regions:

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

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

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



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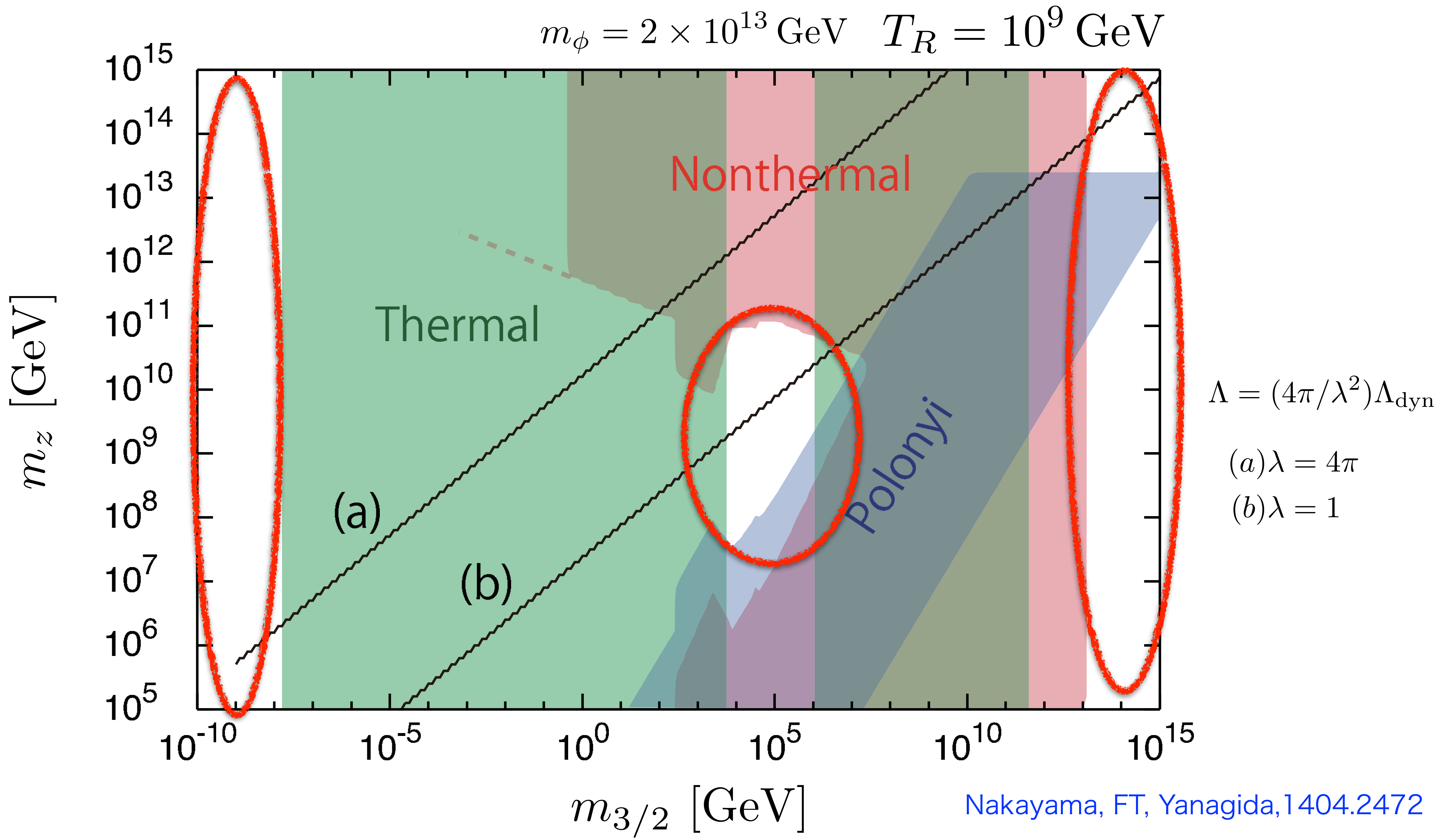


Nakayama, FT, Yanagida,1404.2472

3 allowed regions:

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

(ii) $m_{3/2} = 10 - 1000\mathrm{TeV}$ consistent with 126 GeV Higgs.

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

Polynomial chaotic inflation in SUGRA

Nakayama, FT, Yanagida 1303.7315,1305.5099

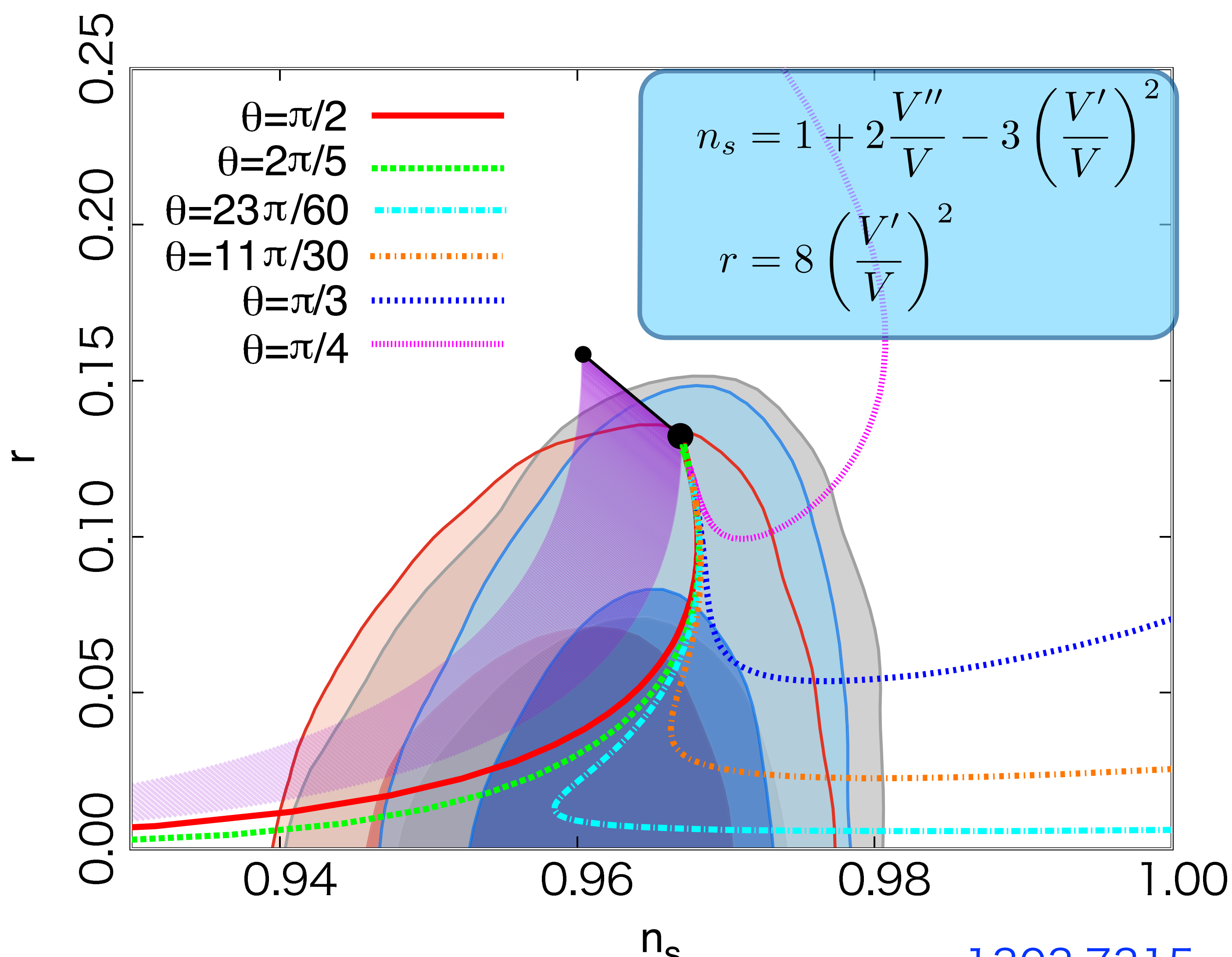
(cf. Kallosh, Linde, Westphal 1405.0270)

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

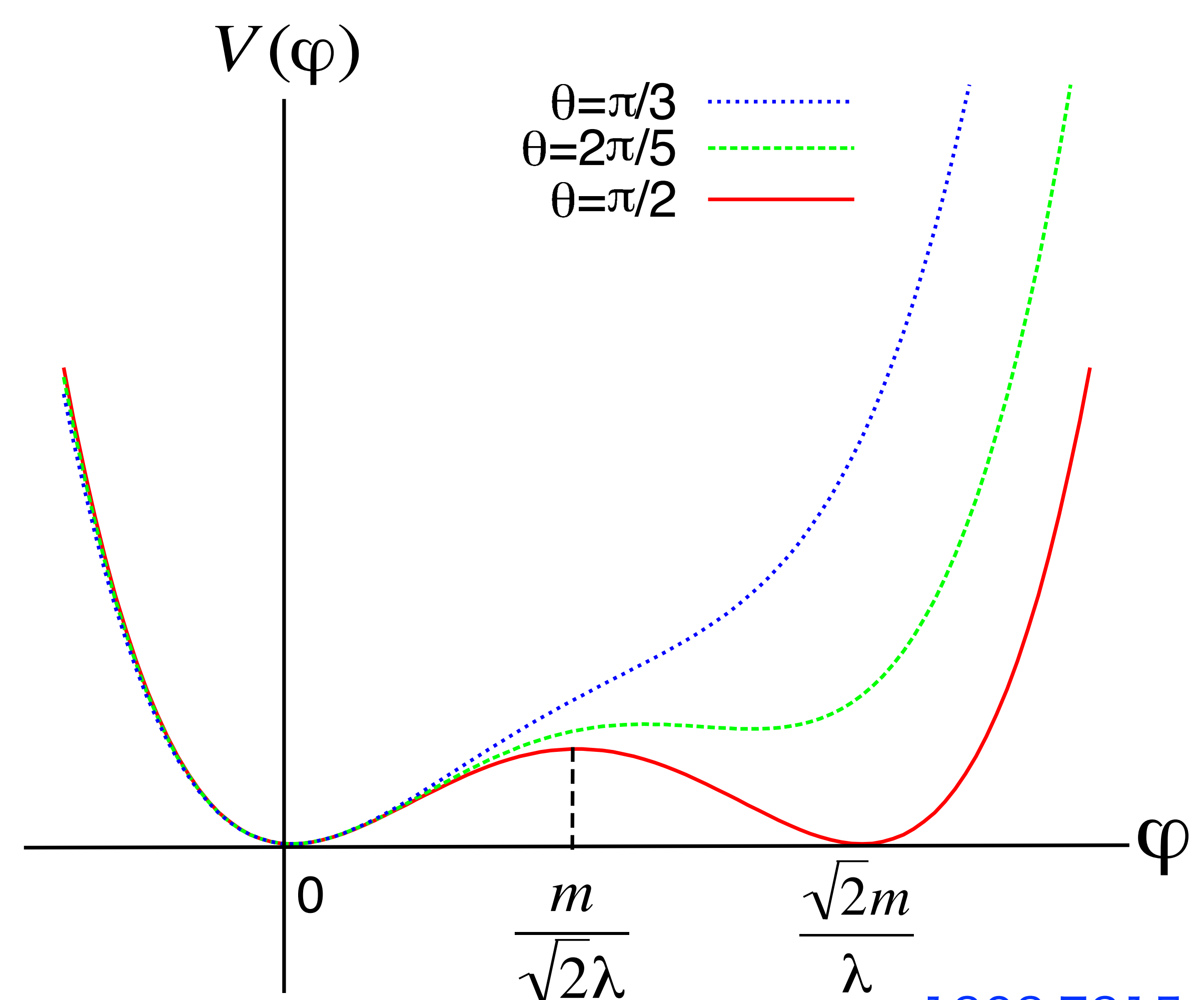
$$W = X\left(m\phi + k_2\phi^2 + \cdots\right),$$

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

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



1303.7315



1303.7315

Side remark

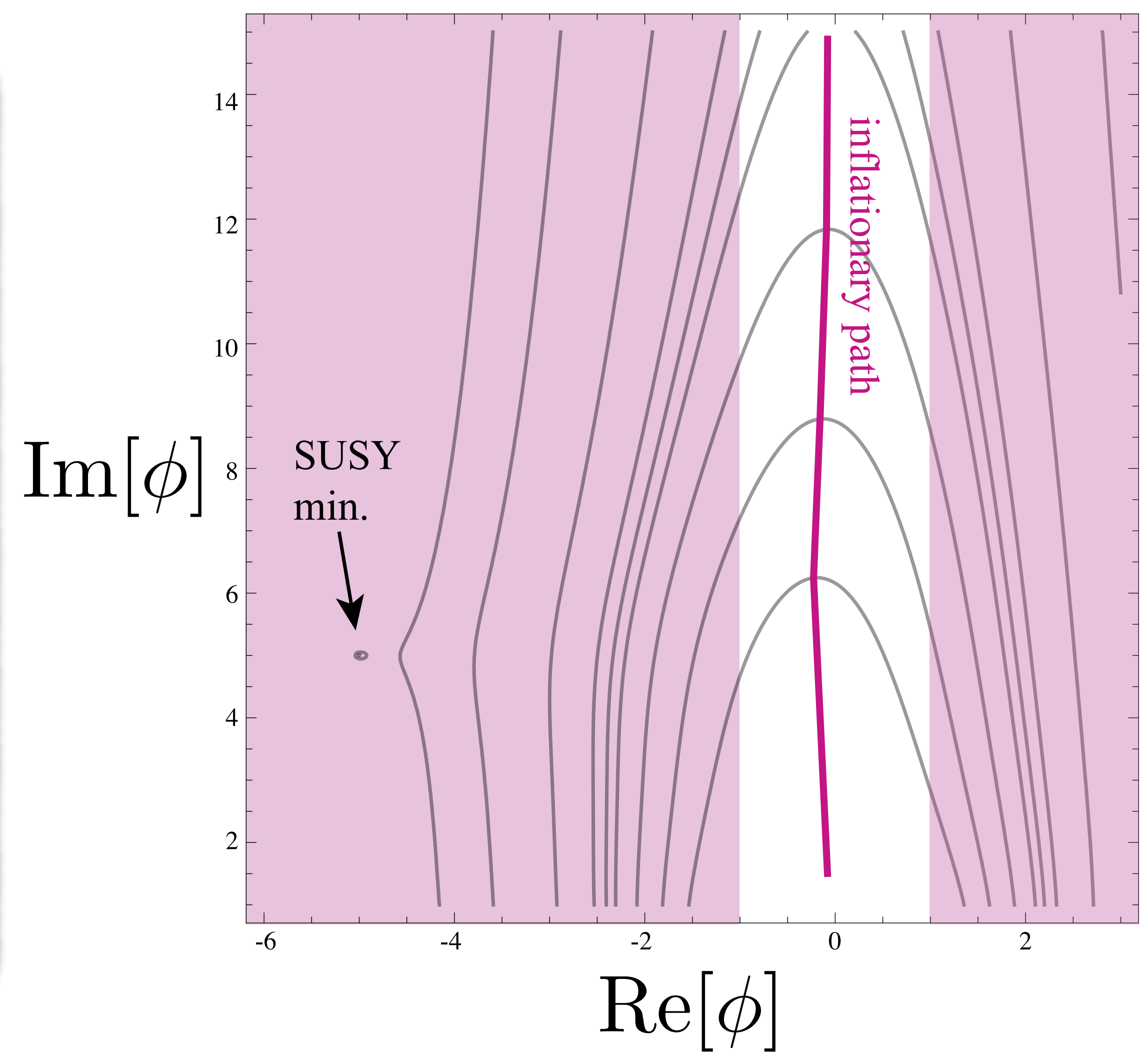
Very precisely speaking, the inflaton potential is not exactly polynomial, because $\mathrm{Re}[\phi] \neq 0$ for $\theta \neq 0$.

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



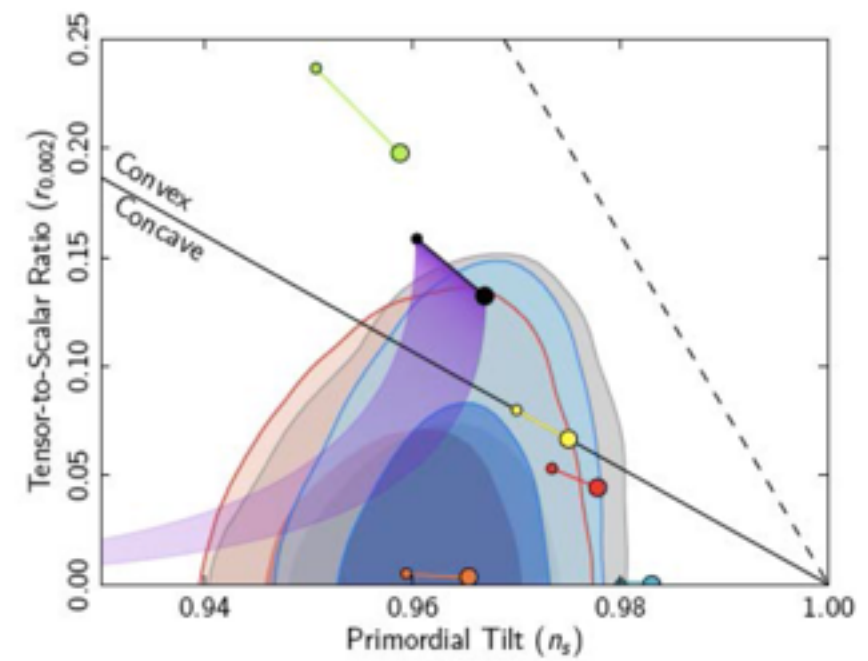
Nakayama, FT, Yanagida, in preparation

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: $f \gtrsim 5 M_P$



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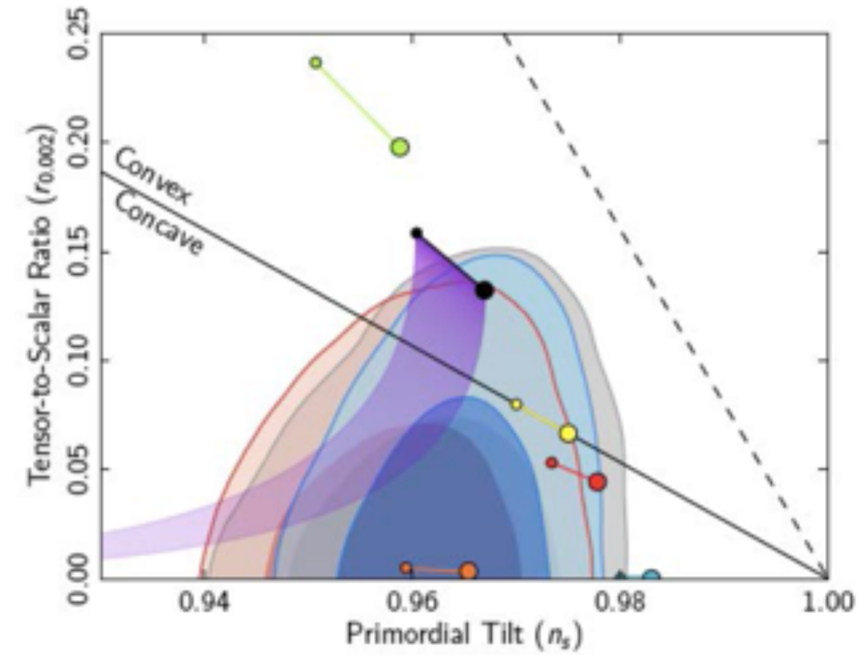


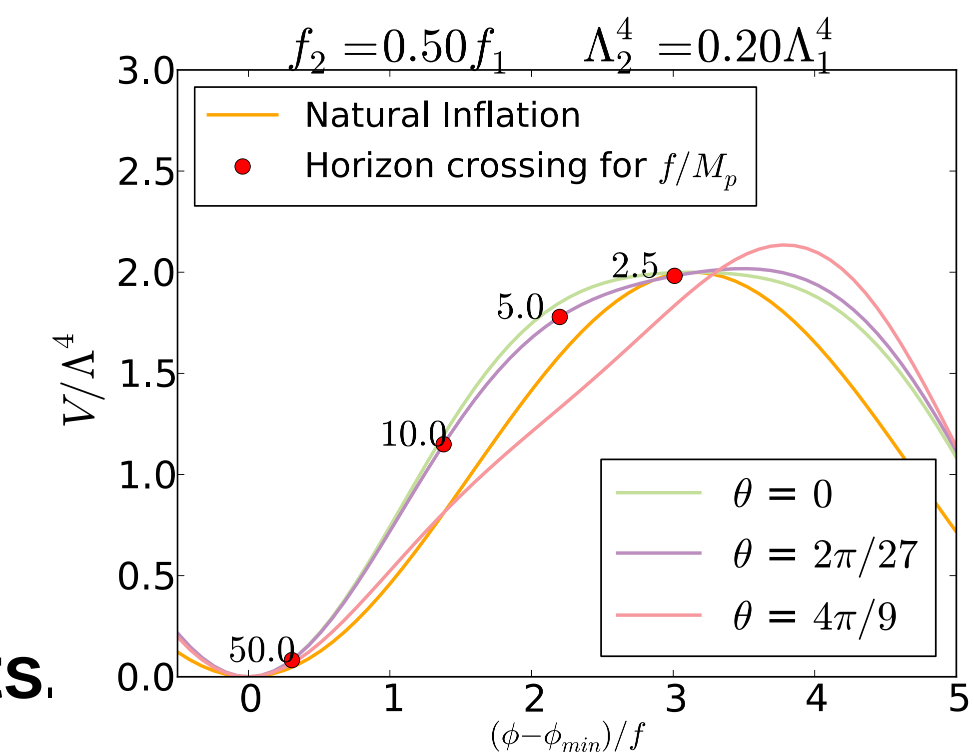
- Multi-Natural inflation

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.



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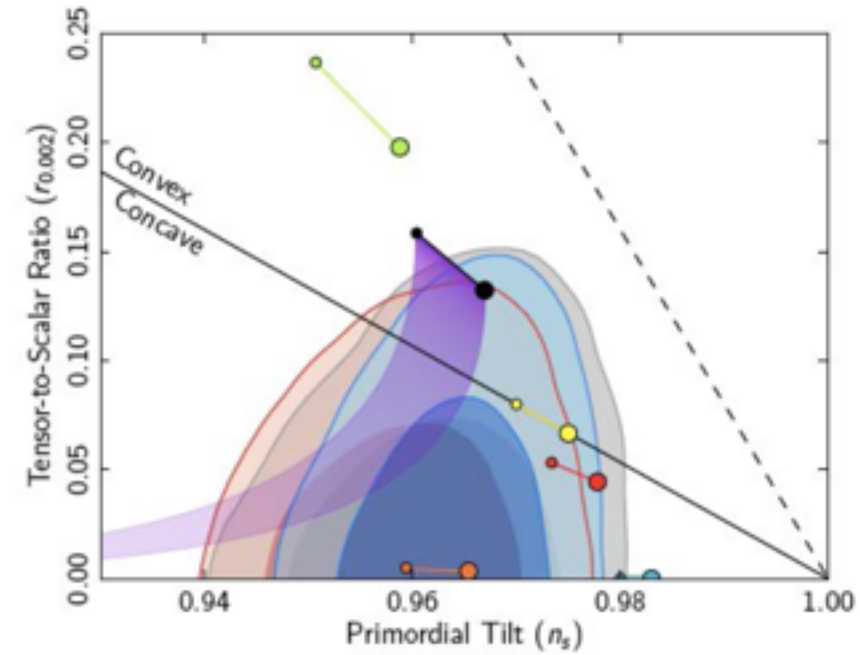

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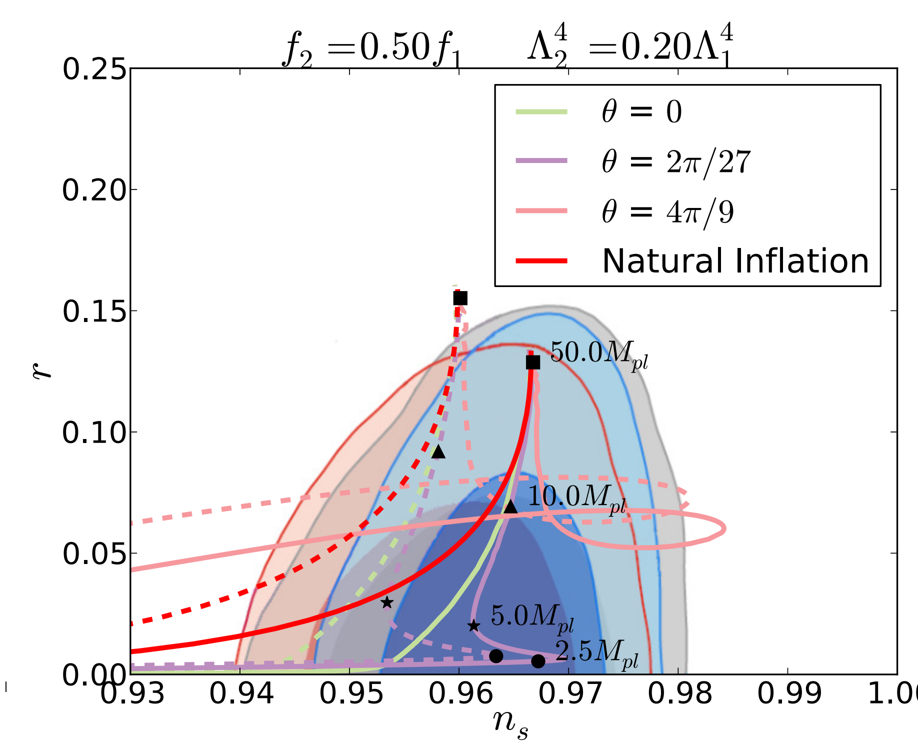

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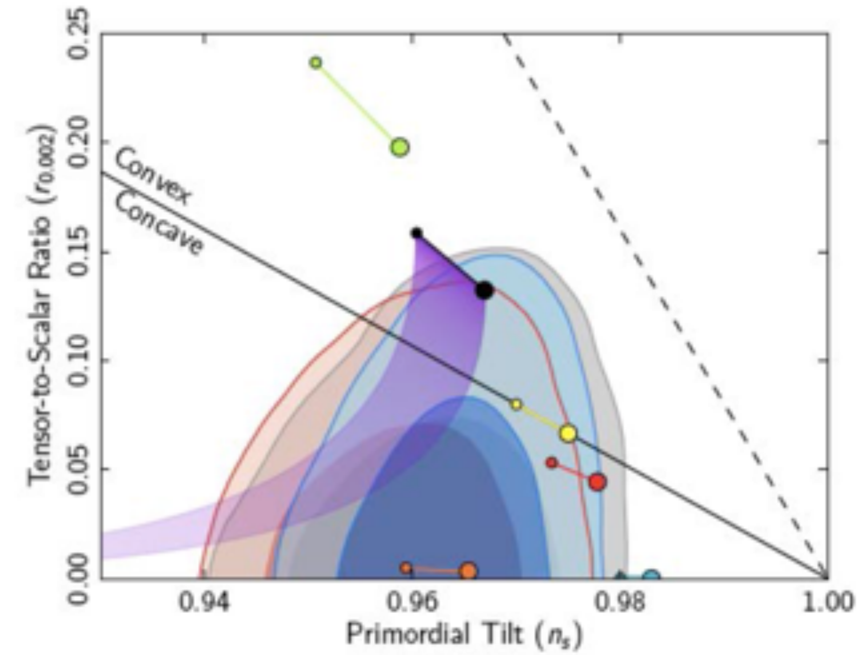

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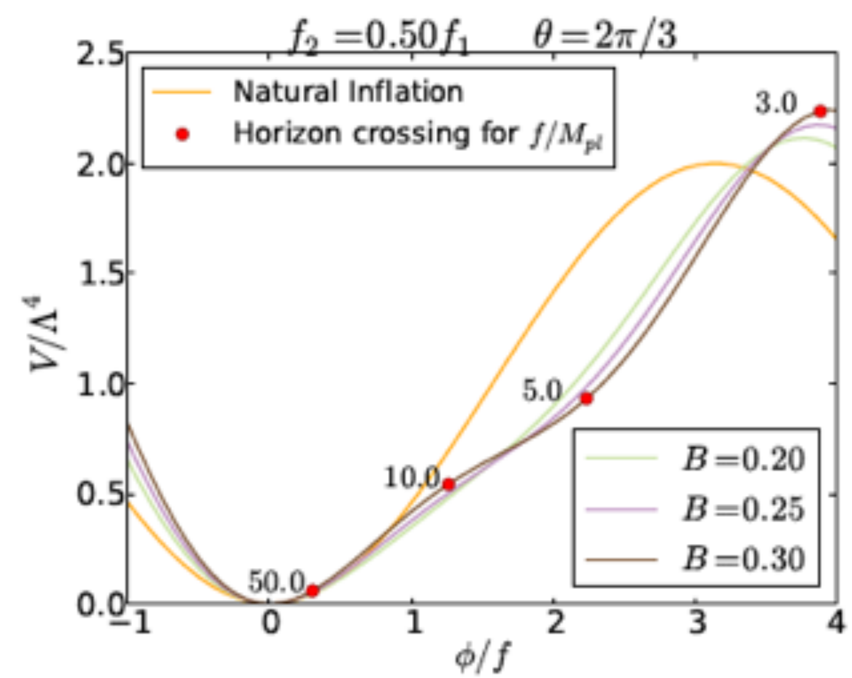

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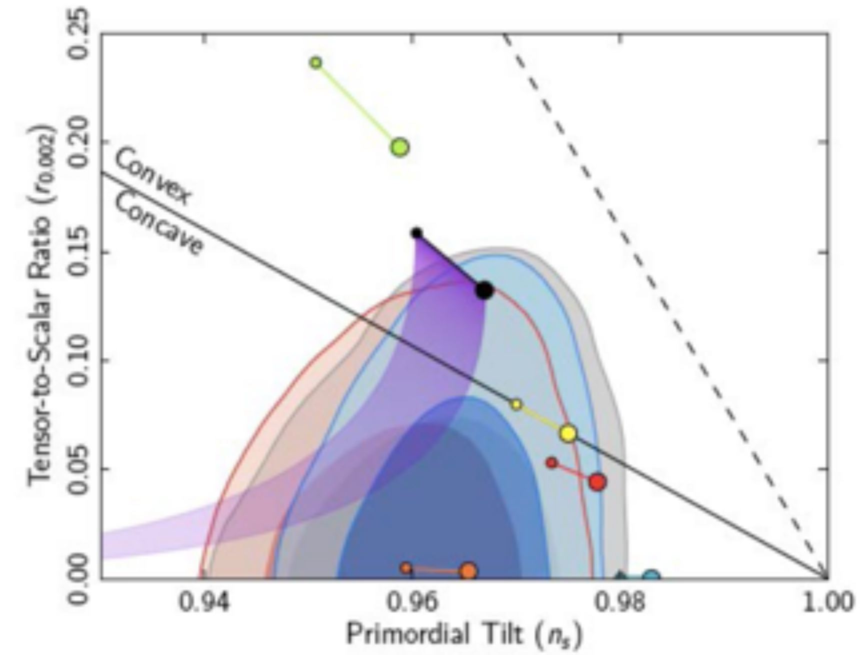

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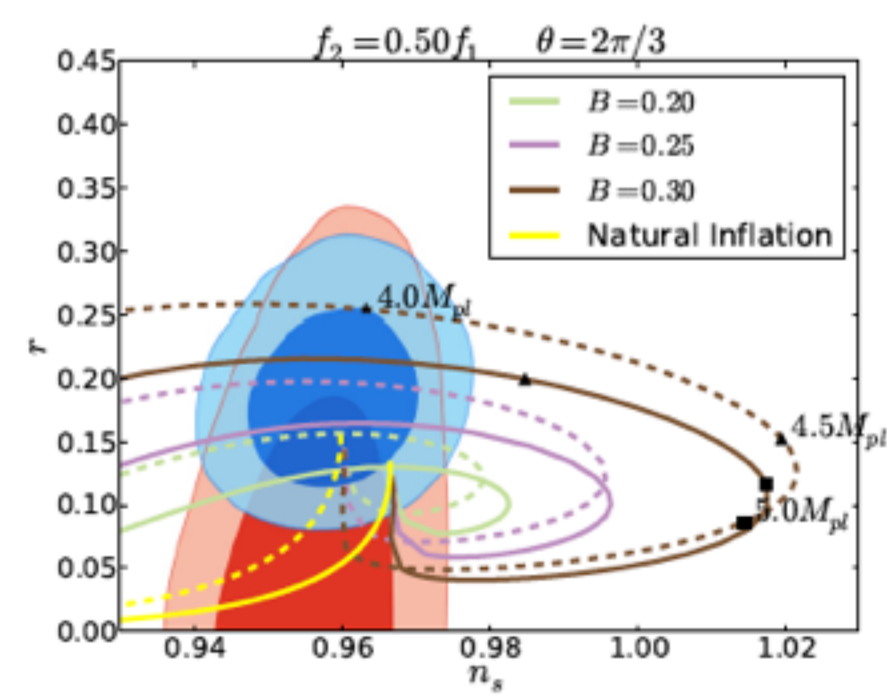


Axion hilltop inflation

(Small-field Multi-Natural inflation)

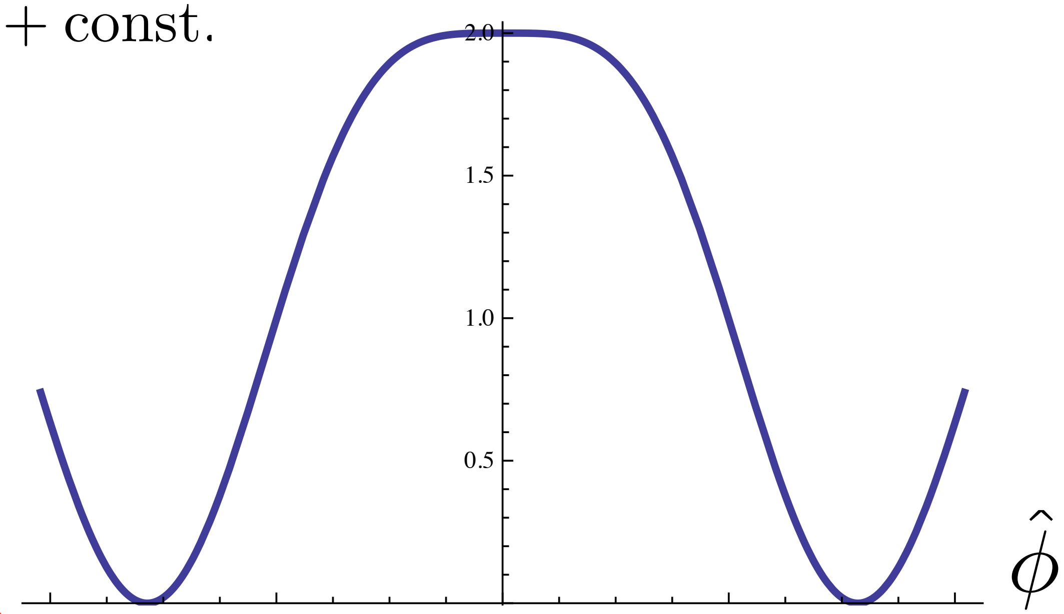
Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410

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 $\dfrac{\Lambda_1^2}{f_1} = \dfrac{\Lambda_2^2}{f_2}$ 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.**

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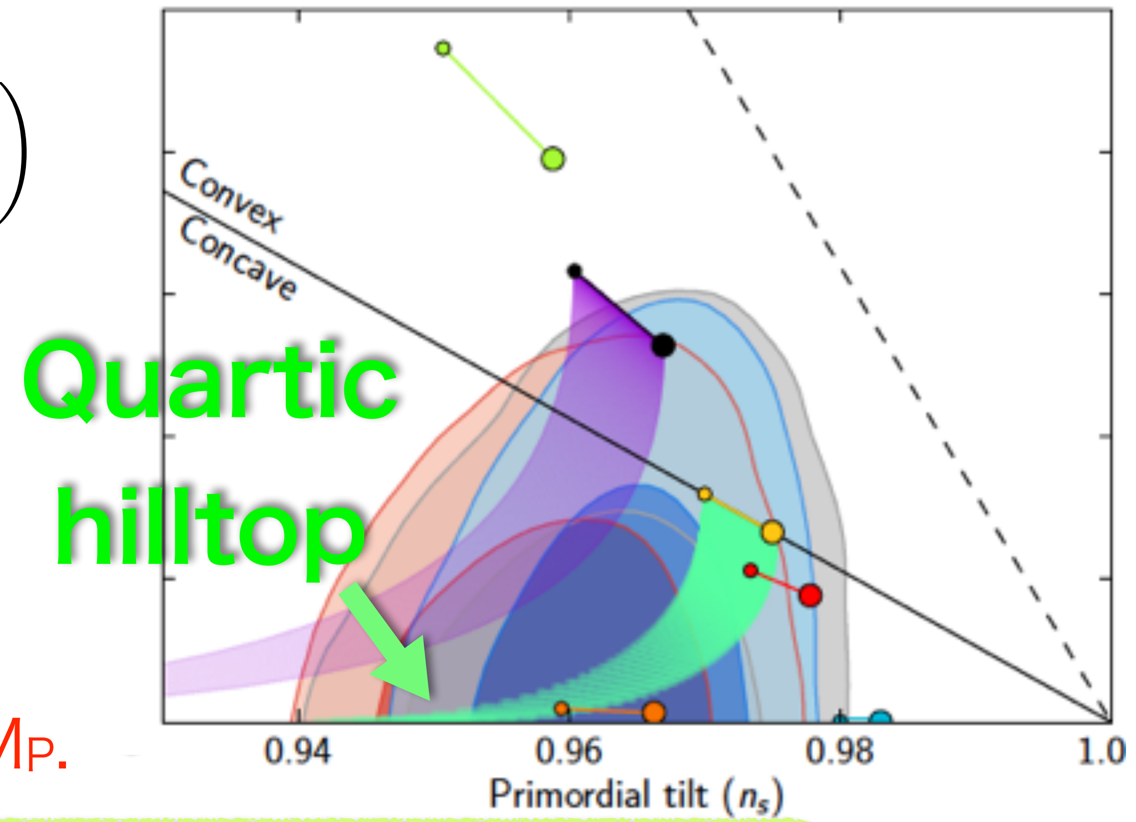

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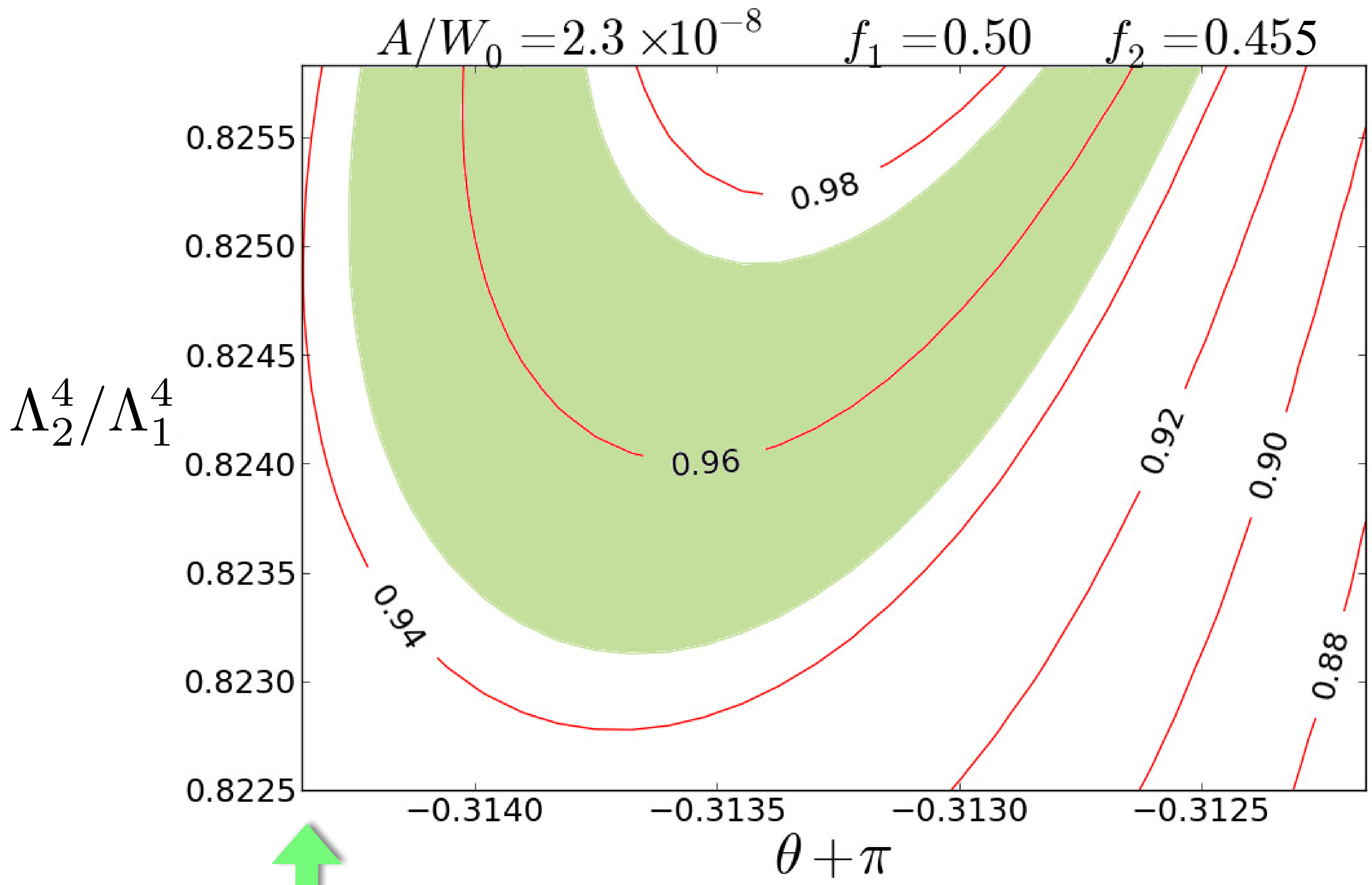
Spectral index of axion hilltop inflation

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



Quartic hilltop inflation

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)

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

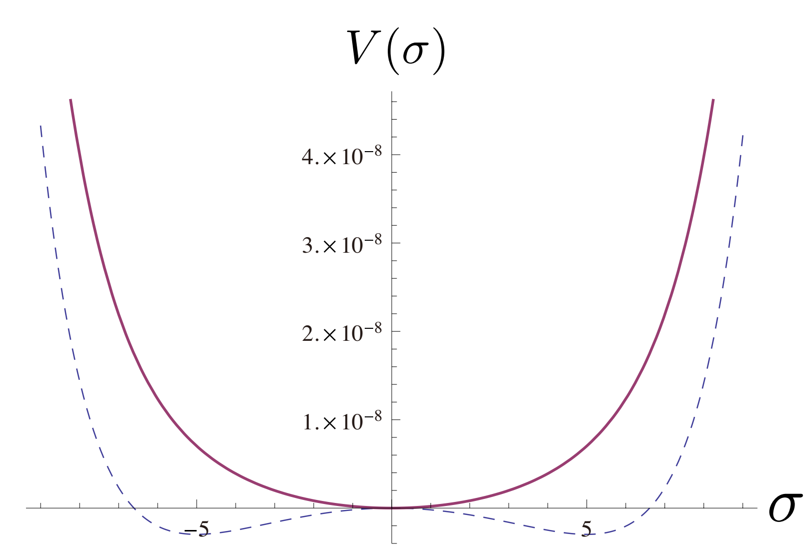
Natural inflation if B=0.
Kallosh, hep-th/0702059

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.

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



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

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

<u>The axion potential:</u>

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

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

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

Aligned Natural Inflation

Kim, Nilles, Peloso, hep-ph/0409138
Czerny, Higaki, FT 1403.5883, Harigaya and Ibe 1404.3511, 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

The effectively large decay constant can be realized by the alignment of two (or more) axion potentials.

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

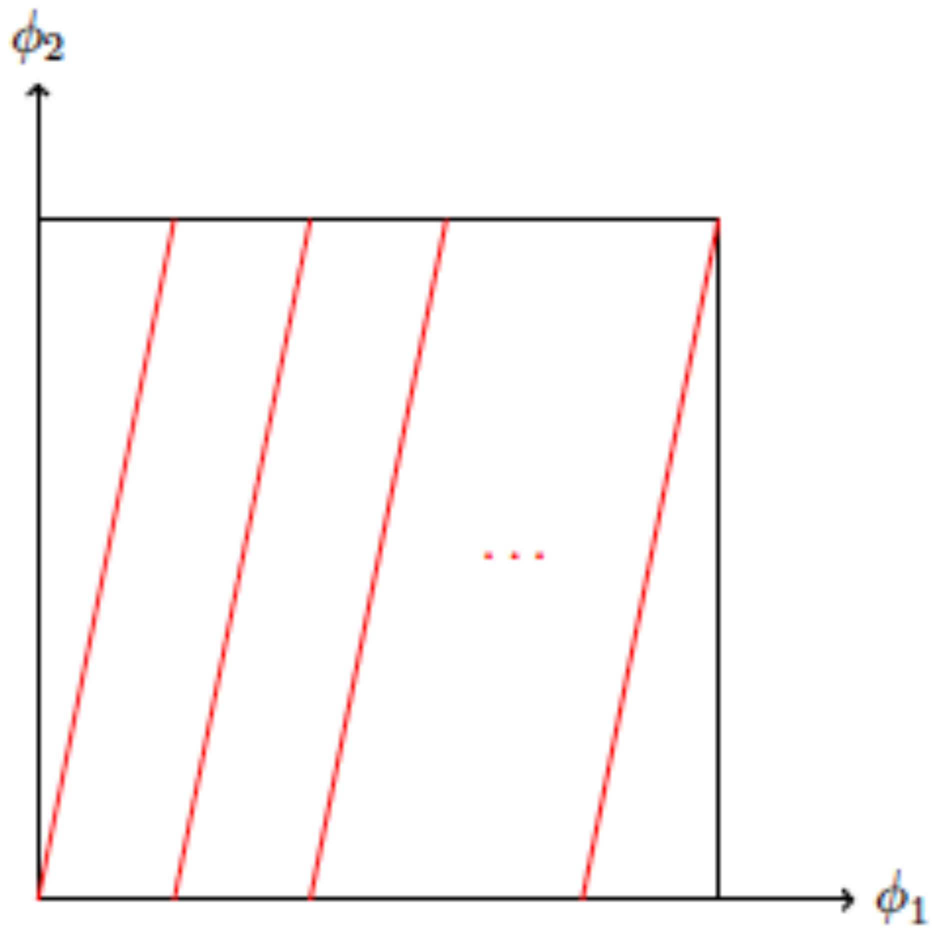
$$\boxed{V(\phi_i) = \Lambda_1^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(m_1 \frac{\phi_1}{f_1} + m_2 \frac{\phi_2}{f_2}\right)\right]}$$

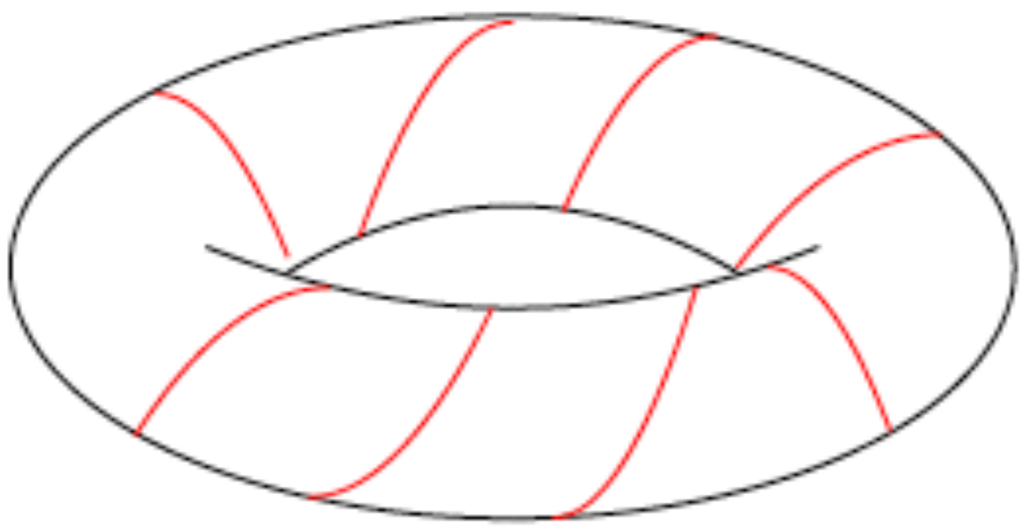
If $n_1/n_2 = m_1/m_2$, there is a flat direction; the corresponding decay constant would be infinite.

If $n_1/n_2 \approx m_1/m_2$, there is a relatively light direction; the corresponding decay constant can be larger than f_1 or f_2.

Aligned Natural Inflation

Kim, Nilles, Peloso, hep-ph/0409138





Taken from 1404.6209 by Choi, Kim, Yun

Aligned Natural Inflation

e.g.) $n_2 \gg n_1 \sim m_2 \sim \mathcal{O}(1)$ and $m_1 = 0$

$f_1 = f_2,\ \Lambda_1 = \Lambda_2$

Tye, Won, 1404.6988

Ben-Dayan, Pedro, Westphal,1404.7773

See also Harigaya's talk

$$V(\phi_i) = \Lambda^4 \left[2 - \cos\left(n_1 \frac{\phi_1}{f} + n_2 \frac{\phi_2}{f} \right) - \cos\left(m_2 \frac{\phi_2}{f} \right) \right]$$

$$M_{ij}^2 = \frac{\Lambda^4}{f^2} \begin{pmatrix} n_1^2 & n_1 n_2 \\ n_1 n_2 & n_2^2 + m_2^2 \end{pmatrix}$$

$$\sqrt{\det M^2} = n_1 m_2 \frac{\Lambda^4}{f^2}$$

$$\mathrm{Tr}[\mathrm{M}^2] = (n_1^2 + n_2^2 + m_2^2) \frac{\Lambda^4}{f^2}$$

$$\Rightarrow \quad \boxed{M_{\rm light} \sim \frac{\Lambda^2}{n_2 f}, \qquad f_{\rm eff} \sim n_2 f}$$

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$$M_{\rm light} \sim \frac{\Lambda^2}{n_2 f}$$

$$f_{\rm eff} \sim n_2 f$$

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Ben-Dayan, Pedro, Westphal,1404.7773

See also Harigaya's talk

$$V(\phi_i) = \Lambda^4 \left[2 - \cos\left(n_1 \frac{\phi_1}{f} + n_2 \frac{\phi_2}{f}\right) - \cos\left(m_2 \frac{\phi_2}{f}\right)\right]$$

$$M_{ij}^2 = \frac{\Lambda^4}{f^2} \begin{pmatrix} n_1^2 & n_1 n_2 \\ n_1 n_2 & n_2^2 + m_2^2 \end{pmatrix}$$

$$\sqrt{\det M^2} = n_1 m_2 \frac{\Lambda^4}{f^2}$$

$$\mathrm{Tr}[\mathrm{M}^2] = (n_1^2 + n_2^2 + m_2^2)\frac{\Lambda^4}{f^2}$$

$$M_{\rm light} \sim \frac{\Lambda^2}{n_2 f}$$

$$f_{\rm eff} \sim n_2 f$$

Aligned Natural Inflation

e.g.) $n_2 \gg n_1 \sim m_2 \sim \mathcal{O}(1)$ and $m_1 = 0$

$f_1 = f_2, \ \Lambda_1 = \Lambda_2$

Tye, Won, 1404.6988

Ben-Dayan, Pedro, Westphal, 1404.7773

See also Harigaya's talk

$$V(\phi_i) = \Lambda^4 \left[2 - \cos\left(n_1 \frac{\phi_1}{f} + n_2 \frac{\phi_2}{f} \right) - \cos\left(m_2 \frac{\phi_2}{f} \right) \right]$$

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$$f_{\text{eff}} \sim n_2 f$$

Aligned Natural Inflation

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

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

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

Aligned Natural Inflation

- 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

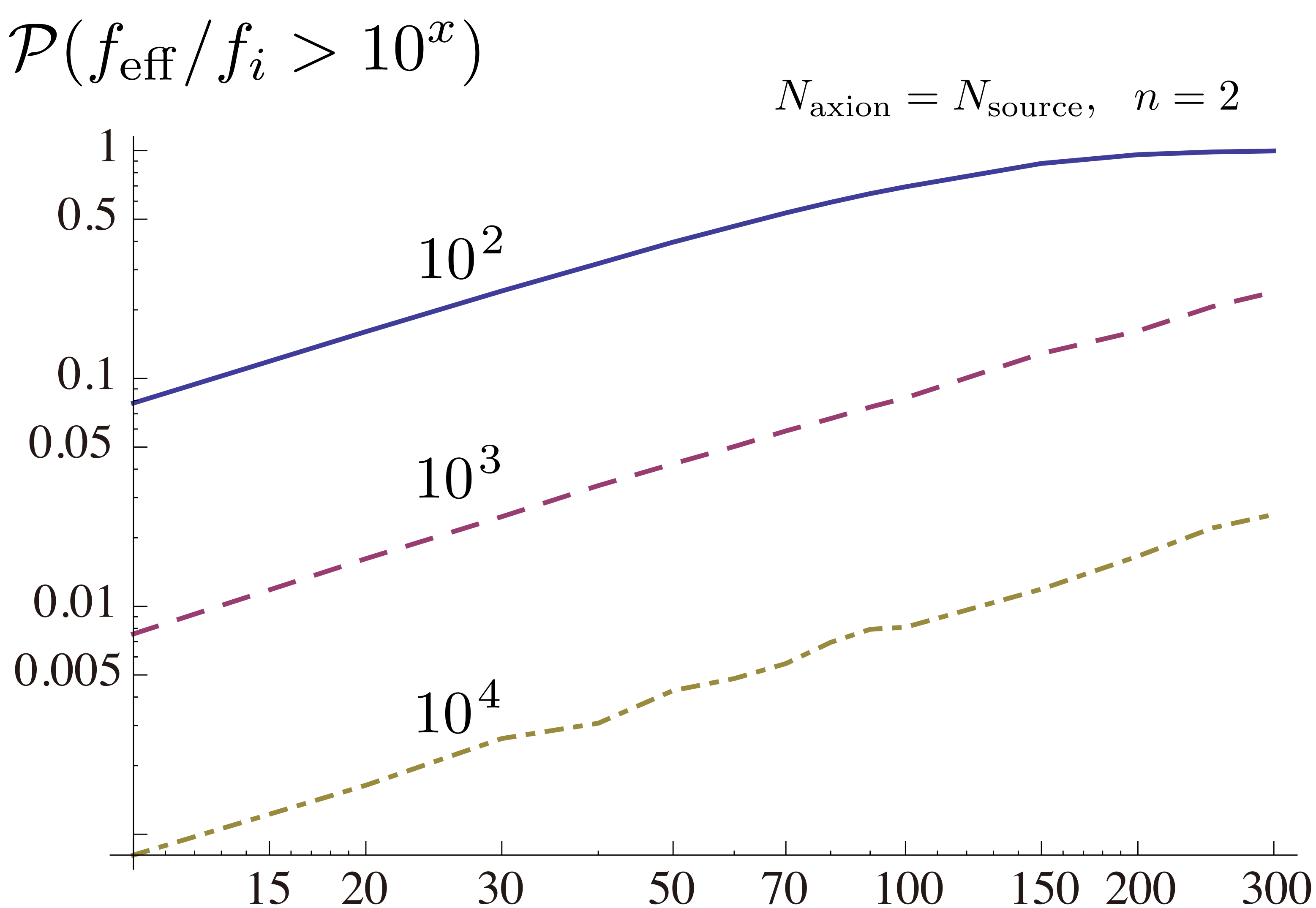
Prob. dist. was studied in detail for various cases incl. $N_{\rm source} \neq N_{\rm axion}$

Higaki, FT, 1404.6923

Aligned Natural Inflation

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

- <u>Prob dist for the enhancement of the decay constant</u>



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

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

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

Higaki, FT, 1404.6923

Aligned Natural Inflation

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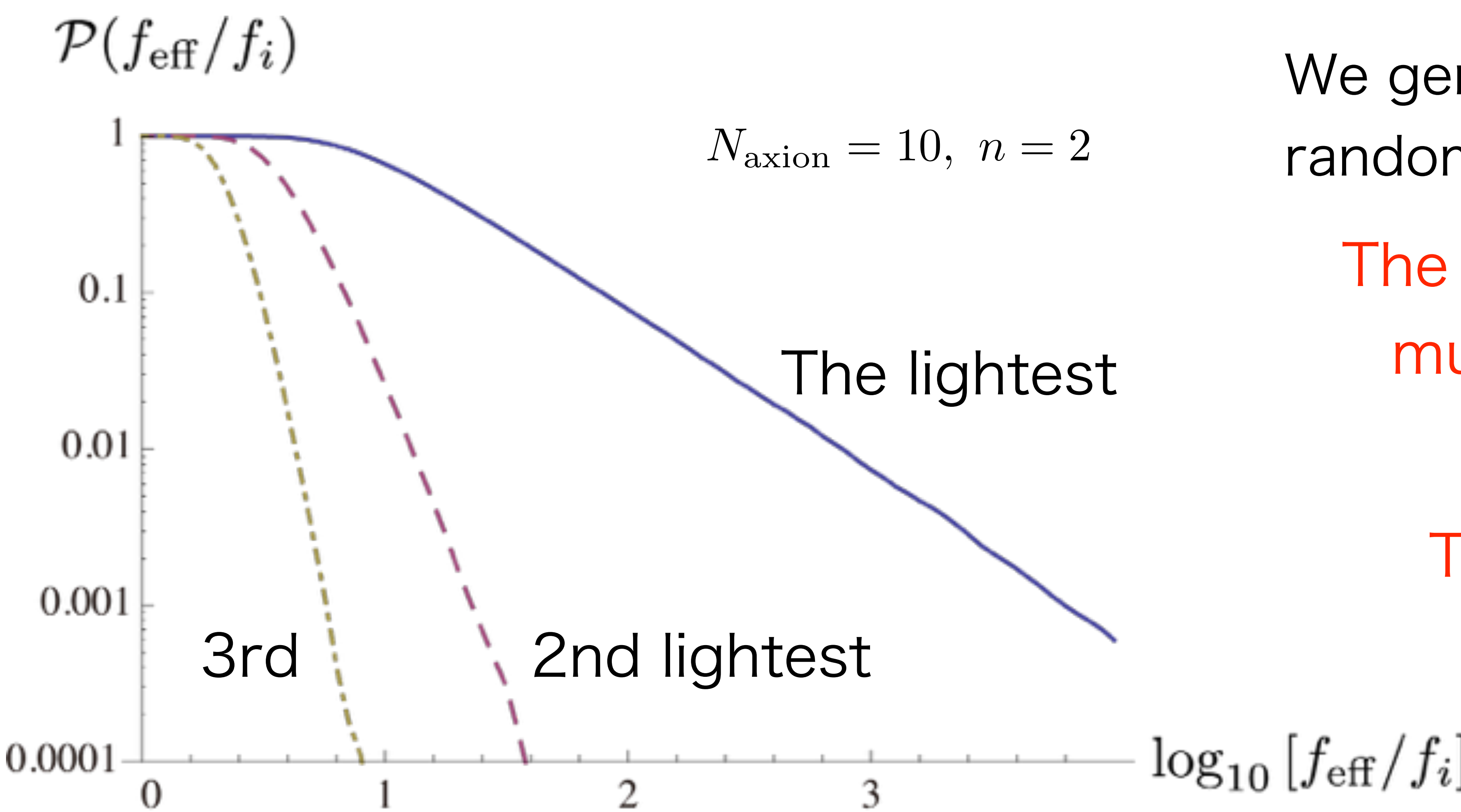

We generated integer-valued random matrix $-n \leq a_{ij} \leq n$

The enhancement along multiple directions is highly unlikely.

The inflaton is the lightest axion!

Higaki, FT, 1404.6923

Aligned Natural Inflation

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

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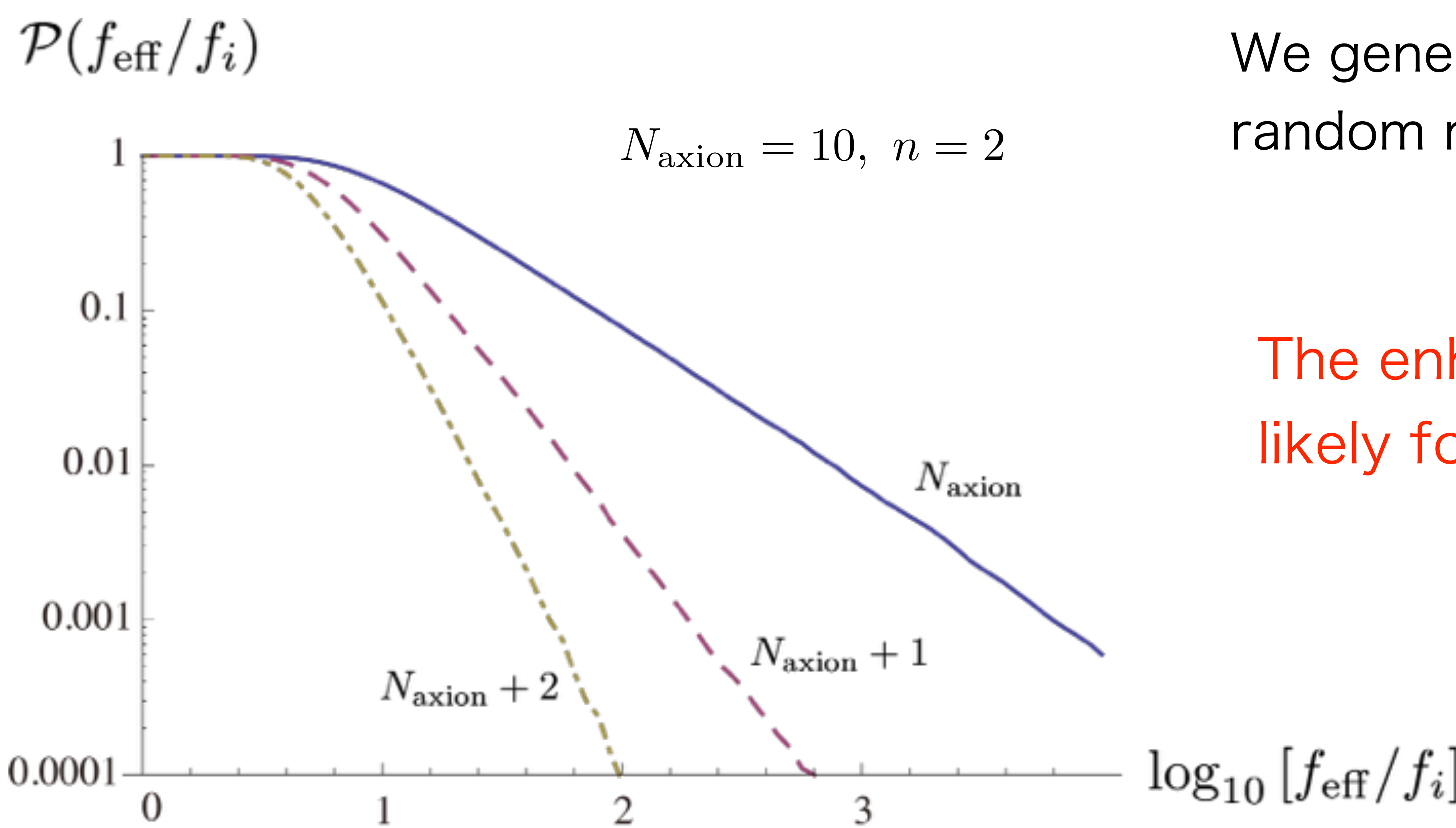


We generated integer-valued random matrix $-n \leq a_{ij} \leq n$

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

Higaki, FT, 1404.6923

Axion Landscape

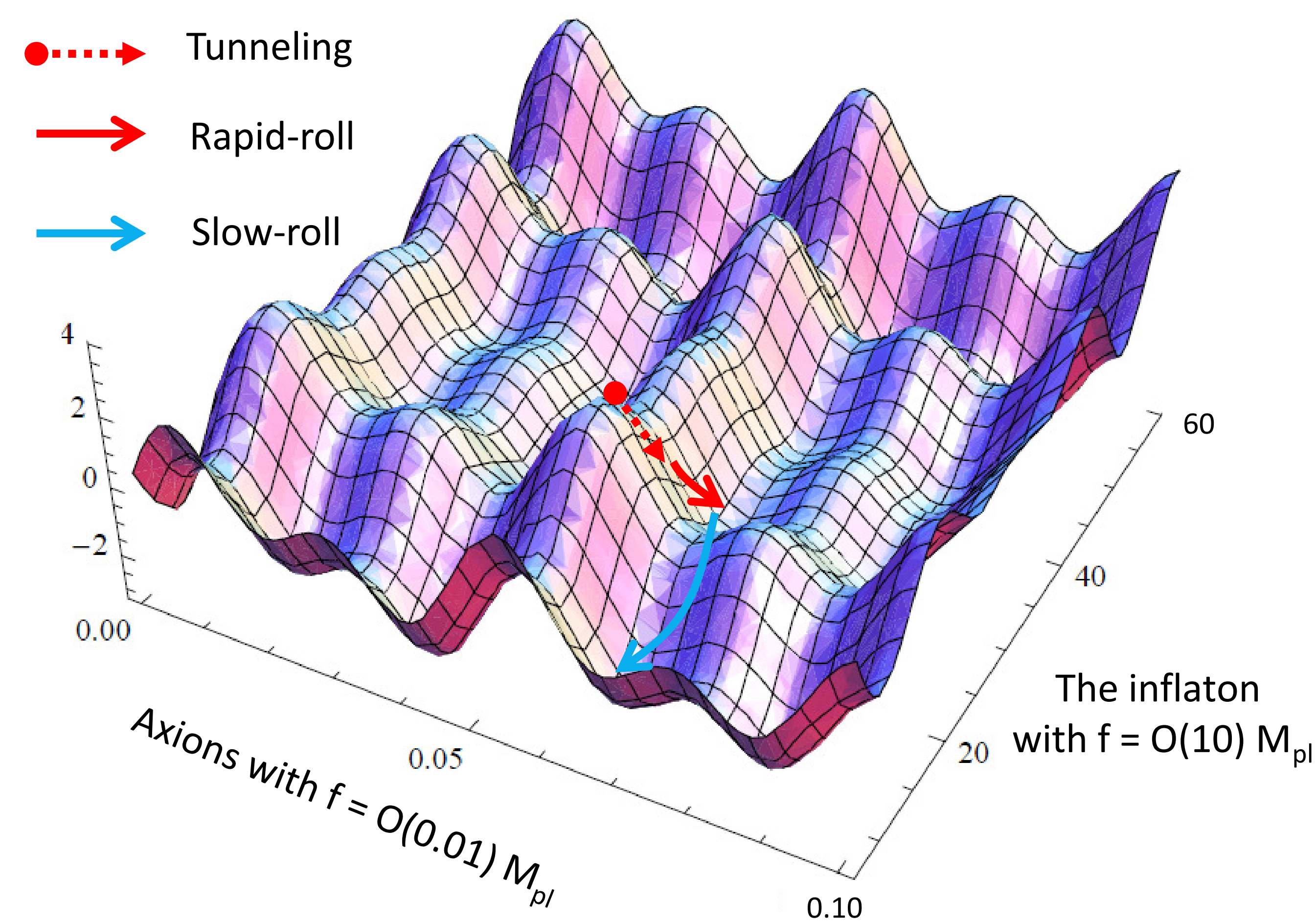
Higaki, FT 1404.6923

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

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

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

Planck 1303.5802

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

Easther and Peiris, astro-ph/0604214

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Large-field inflation with modulations

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

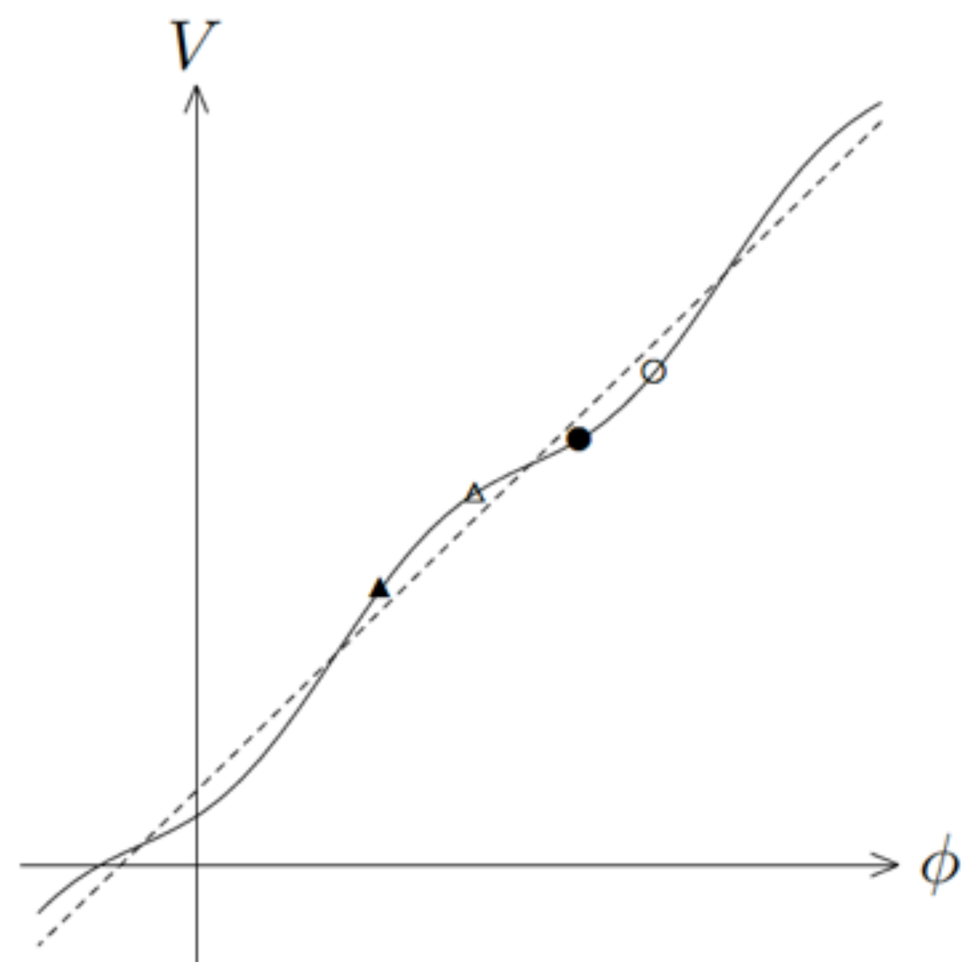
Let us add small modulations to the inflaton potential,

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

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

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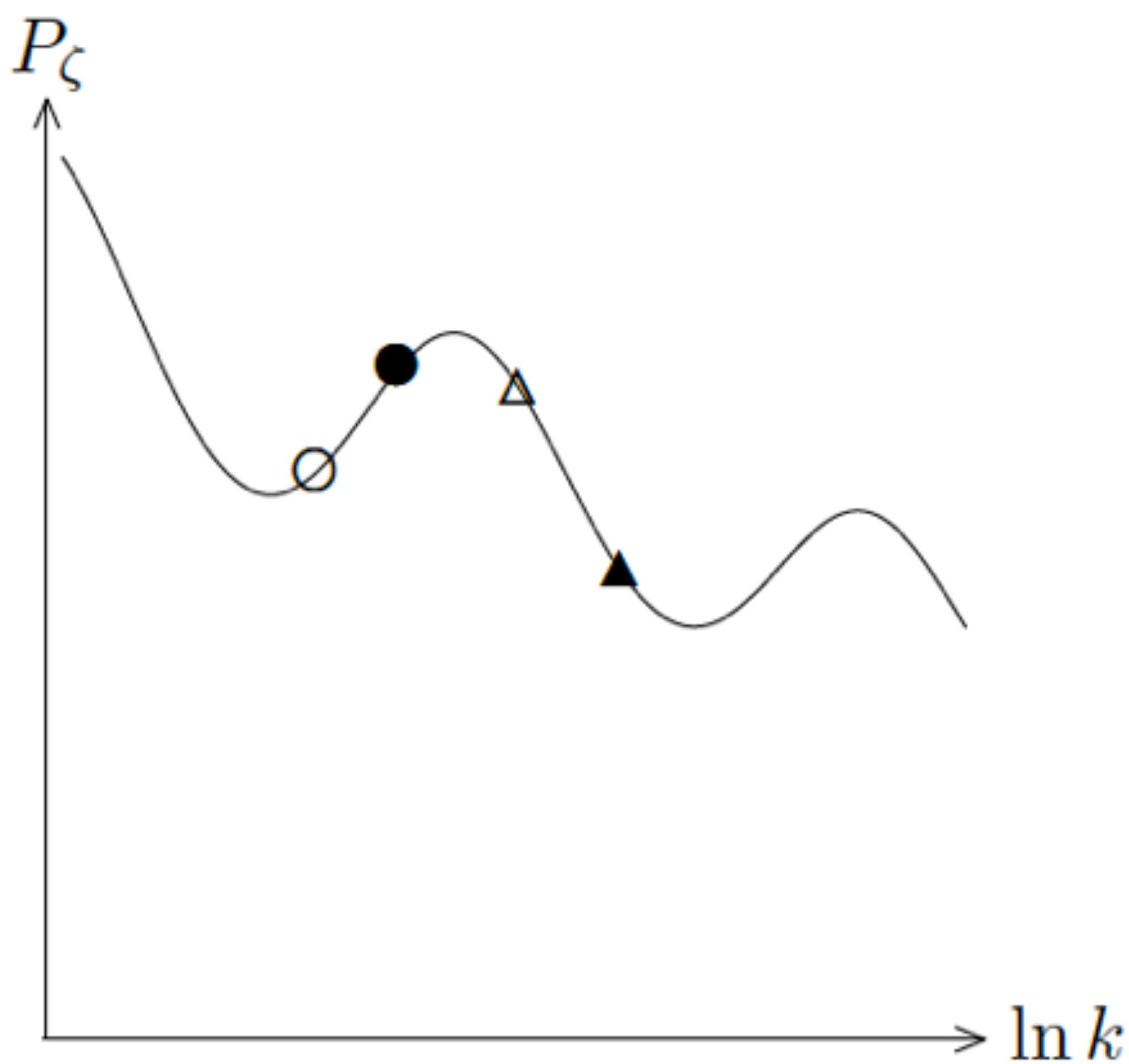
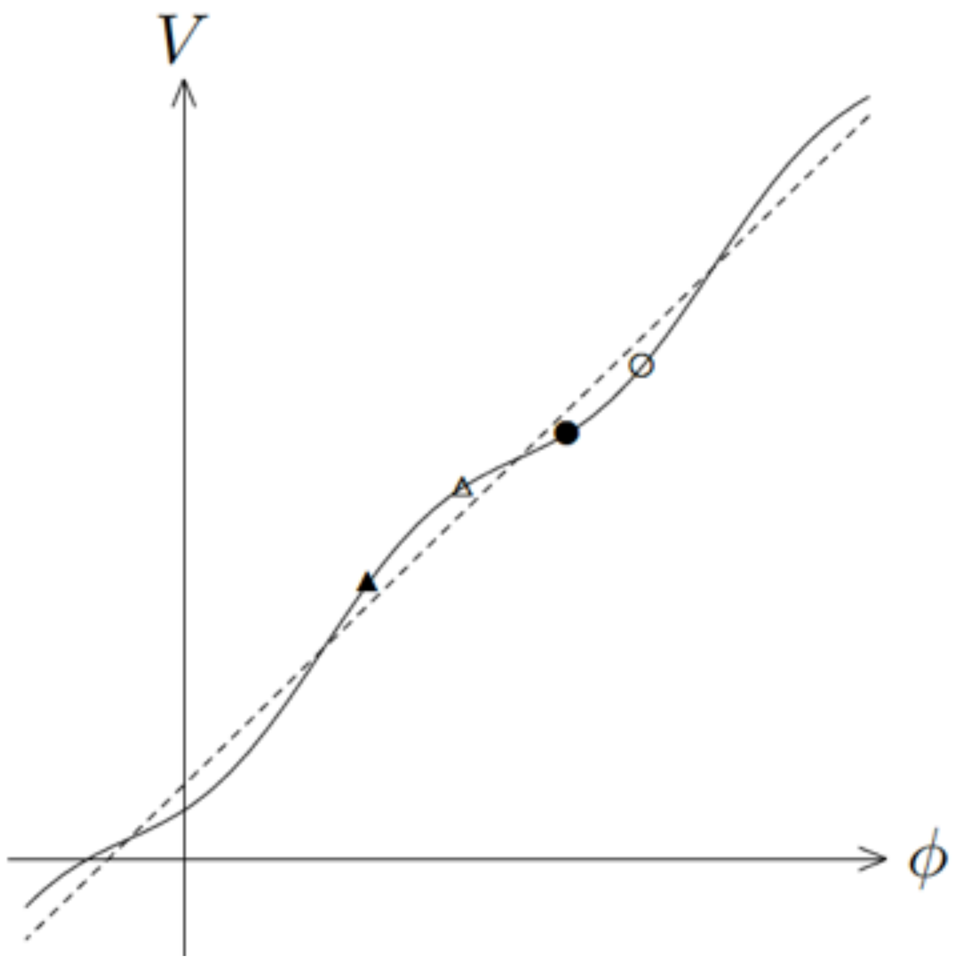
Kobayashi, FT, 1011.3988
Czerny, Kobayashi, FT, 1403.4589





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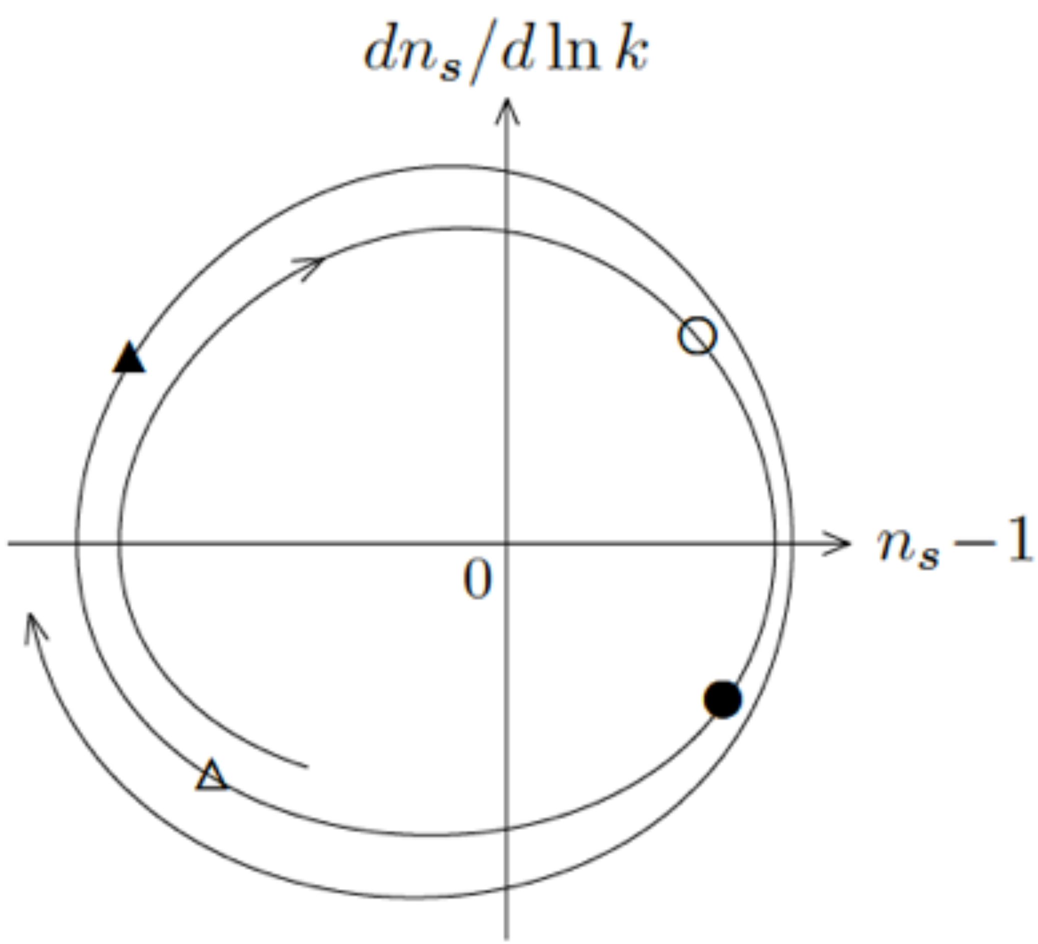
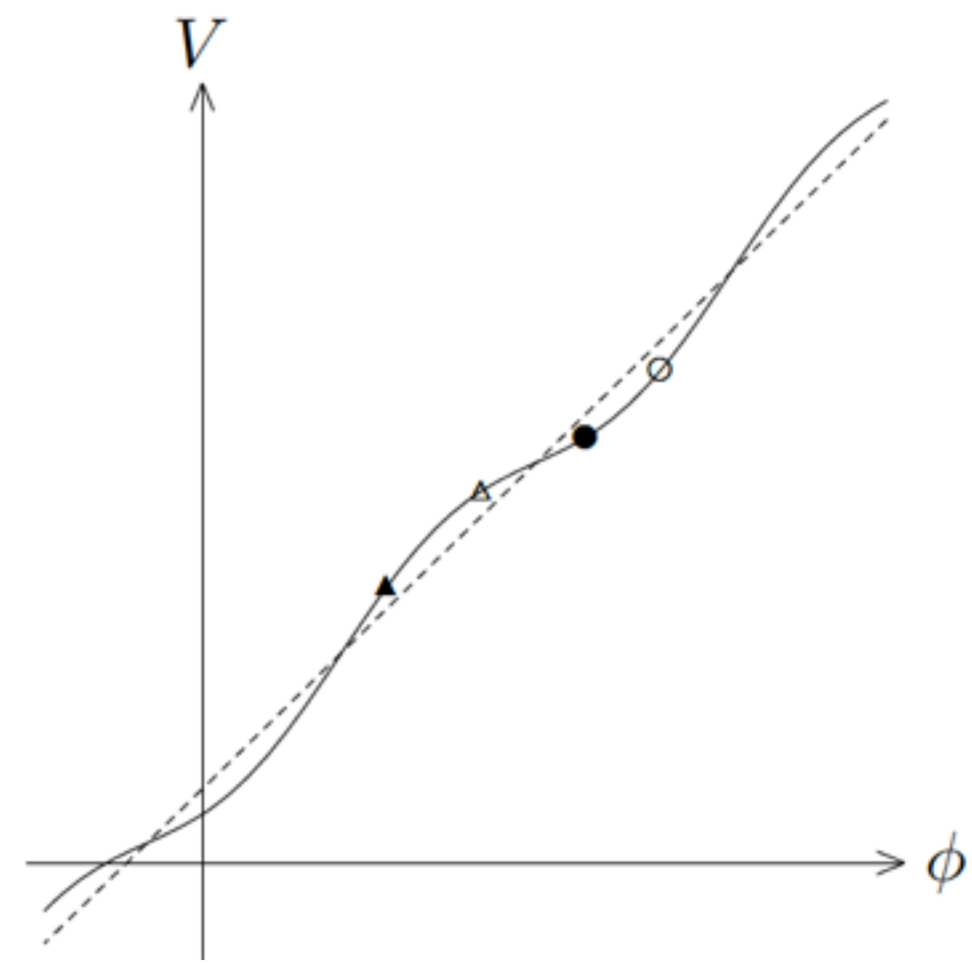




Such small modulations are present in the axion monodromy inflation, and built-in feature of the multi-natural inflation model.

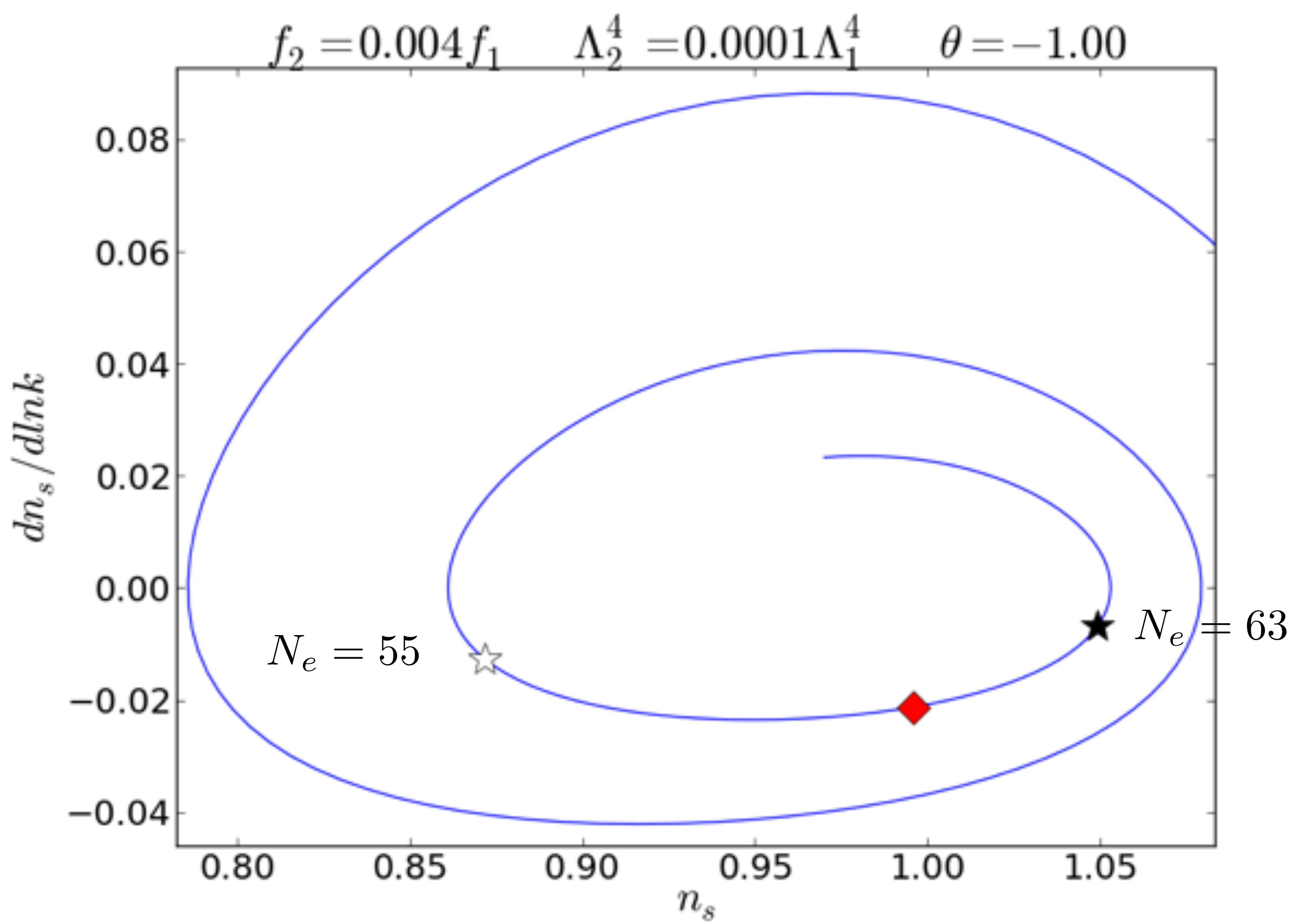
McAllister, Silverstein, Westphal, 0808.0706

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

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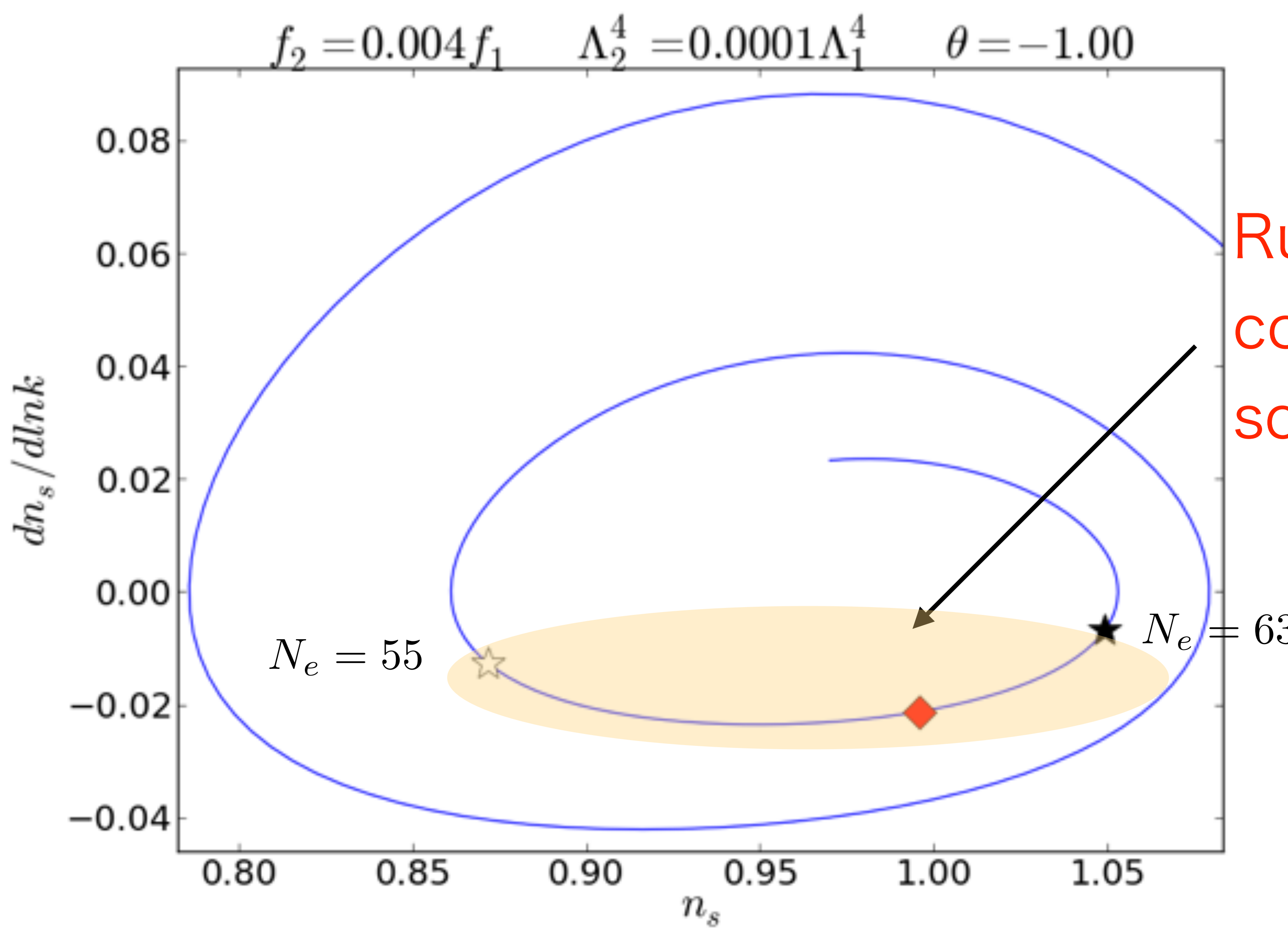
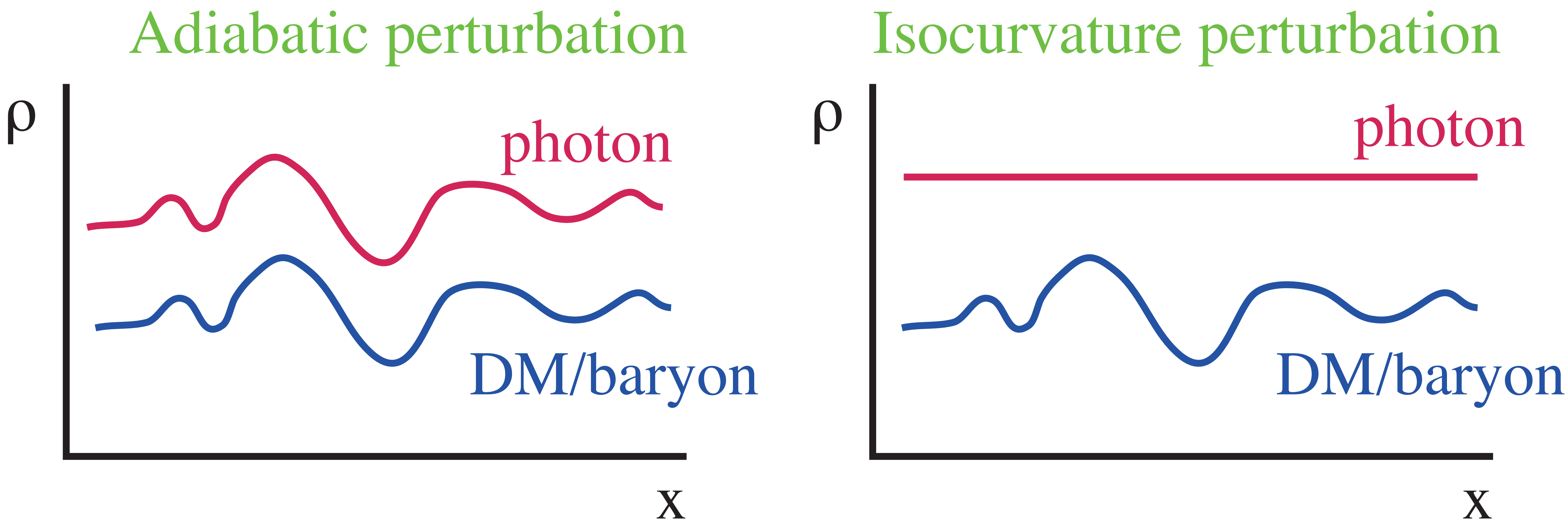


Running is almost constant over CMB scales.

Axion isocurvature perturbations

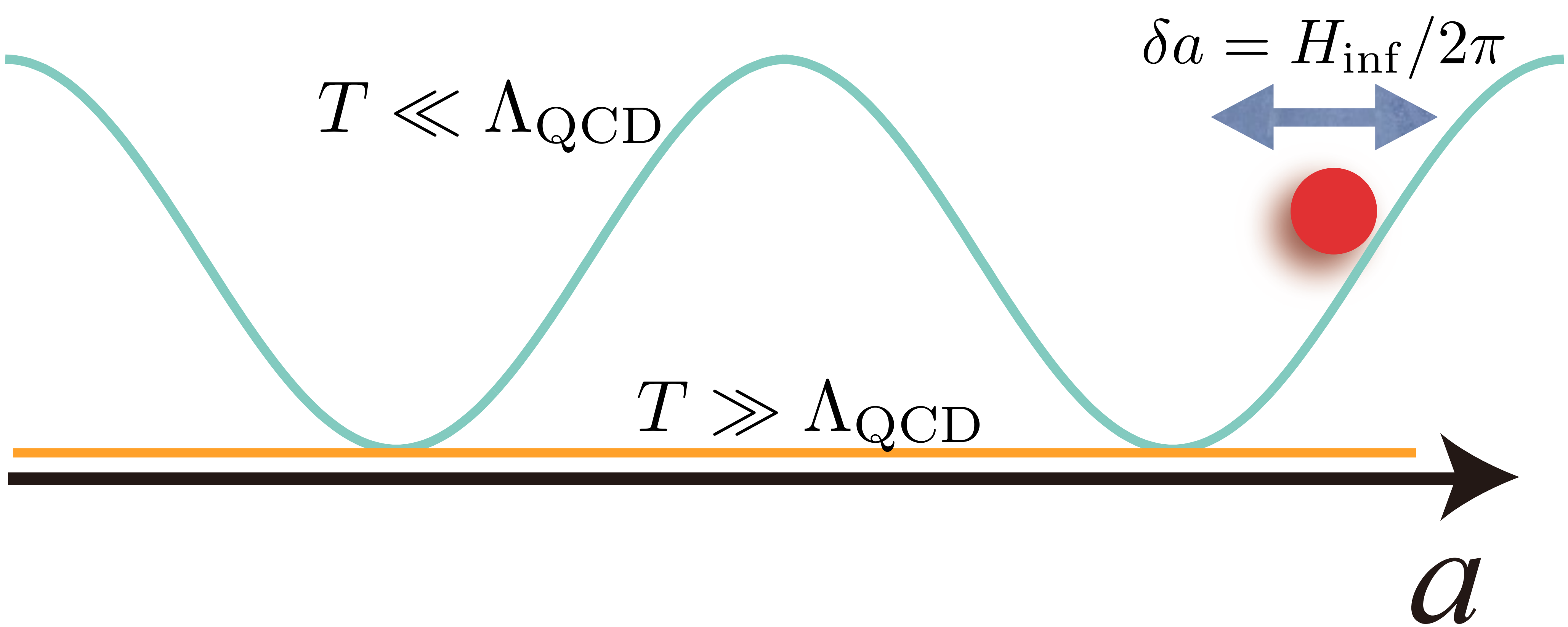


$$\alpha \equiv \frac{P_S}{P_{\mathcal{R}}} \lesssim 0.041 \quad (95\%\mathrm{CL})$$

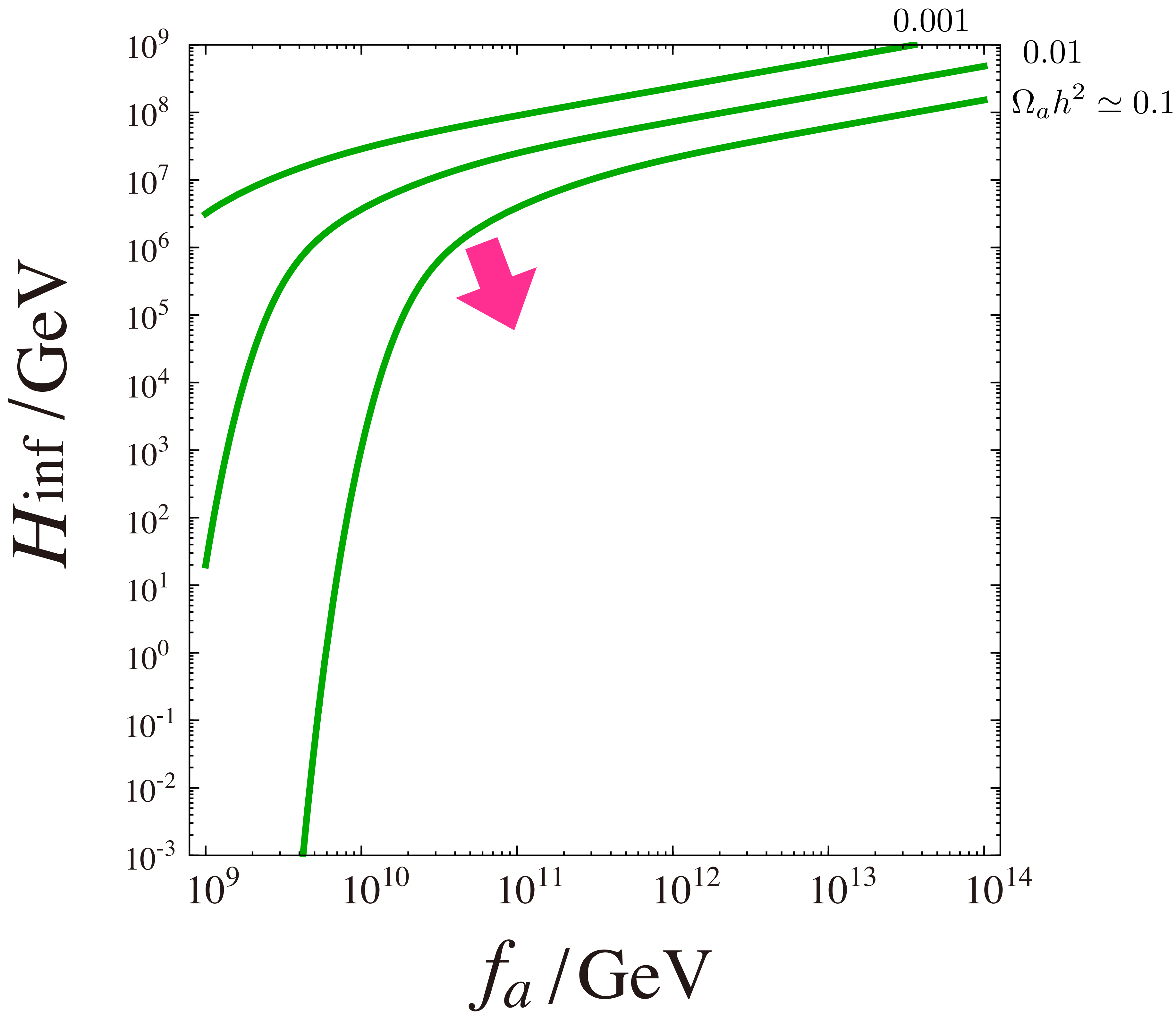
(Planck+WMAP polarization)

- 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}



Kobayashi, Kurematsu, FT, 1304.0922

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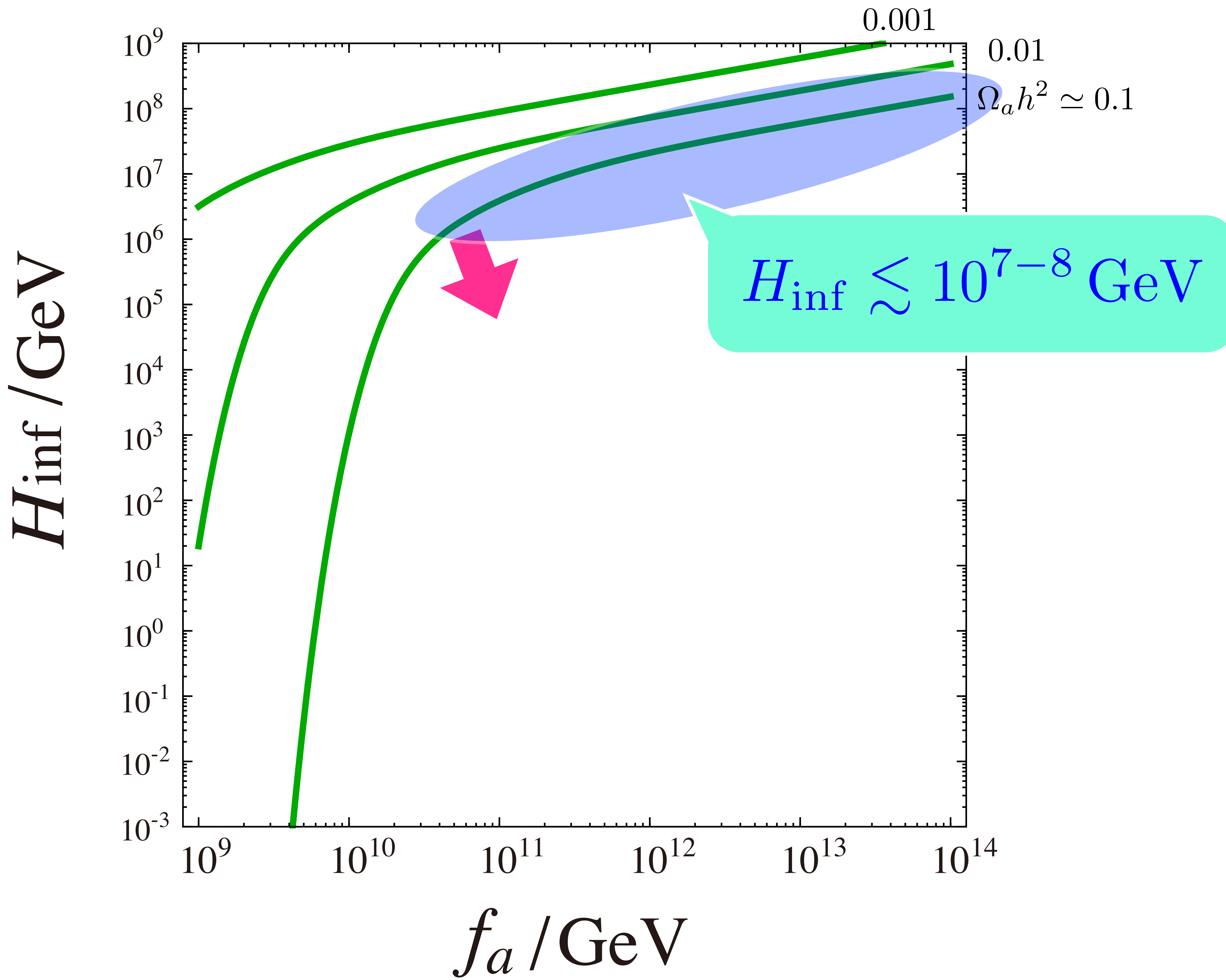

Kobayashi, Kurematsu, FT, 1304.0922

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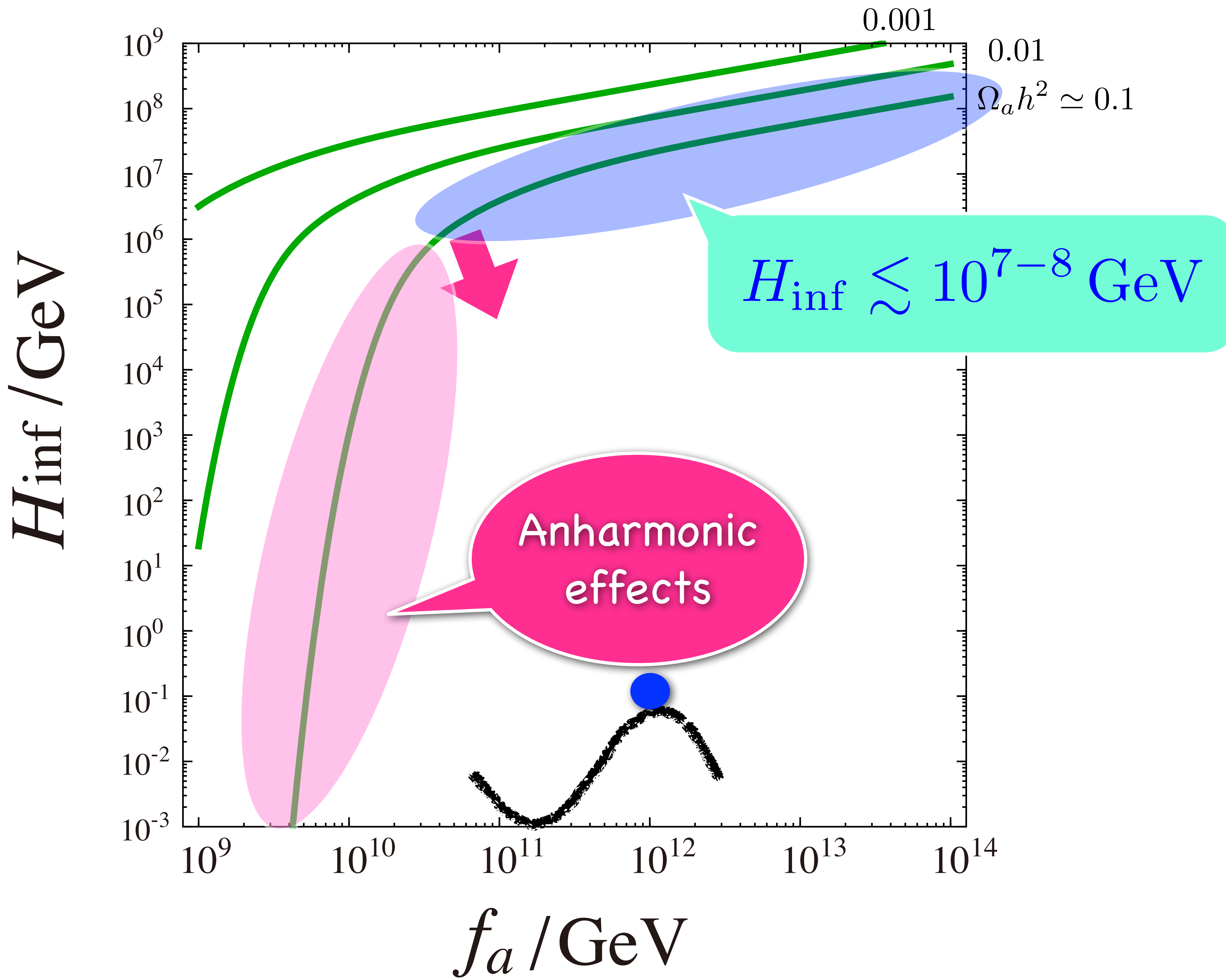
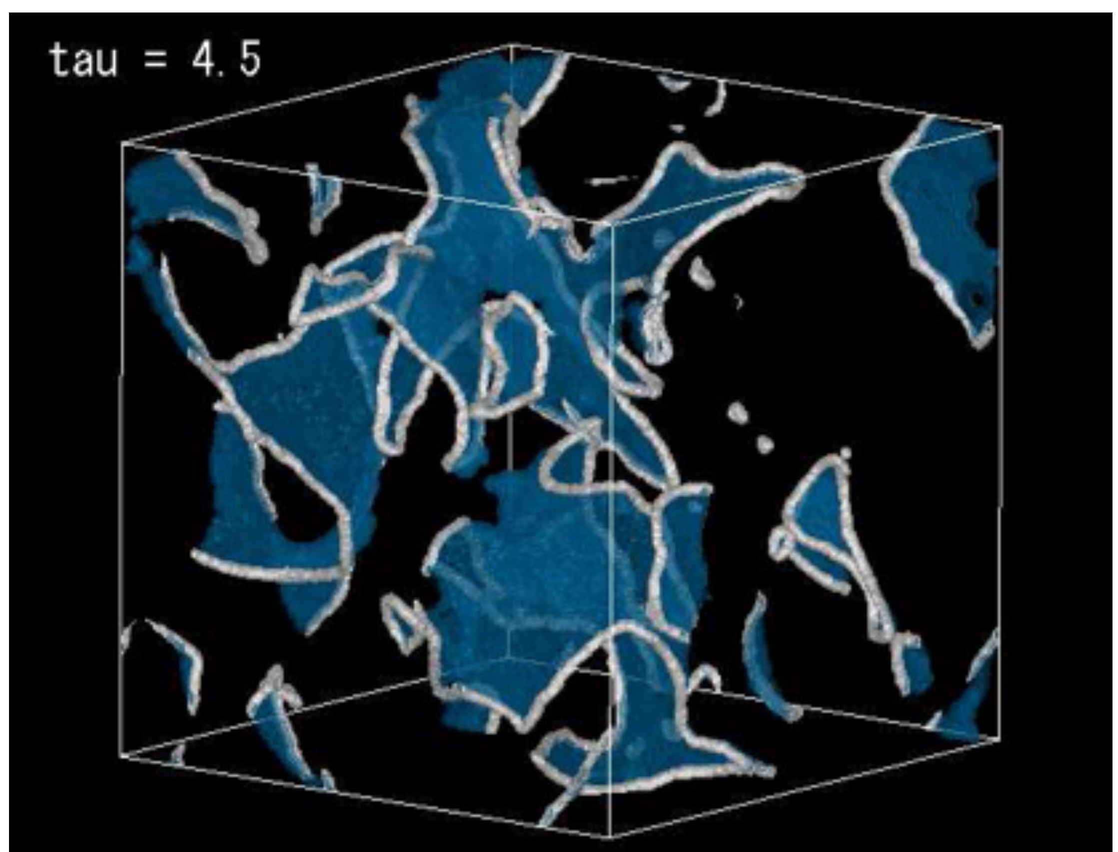


Kobayashi, Kurematsu, FT, 1304.0922

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



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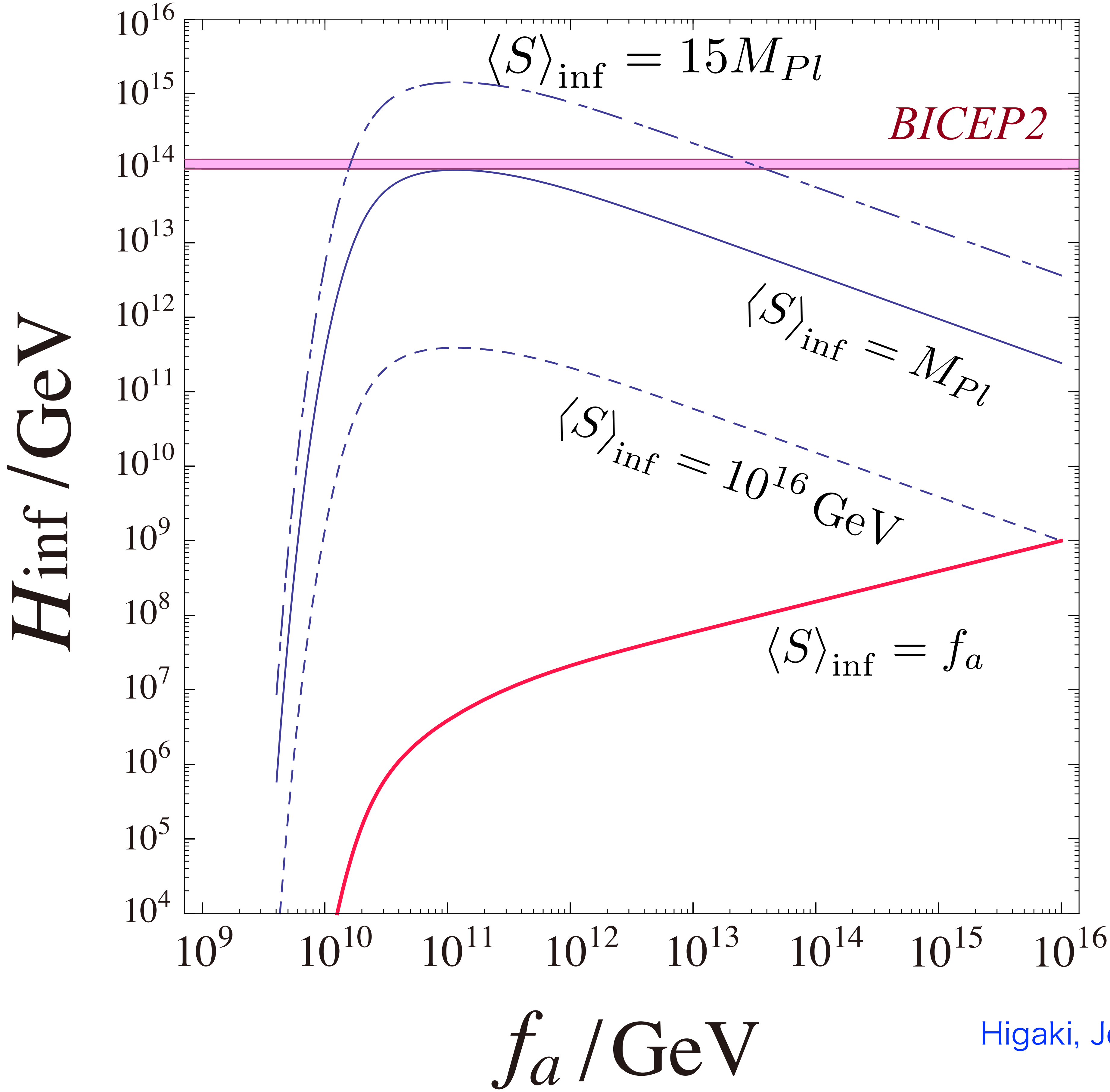
Hiramatsu, Kawasaki, Saikawa and Sekiguchi, 1202.5851,1207.3166

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



axion CDM
is assumed.

Higaki, Jeong, FT, 1403.4186

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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

Conclusions

- **If r =O(0.001-0.1)**, we can get information of the very early Universe at the GUT-scale.
- **Large-field inflation** realized by shift symmetry.
  - Polynomial chaotic inflation/multi-natural inflation lead to various values of (n_s,r).
- **Axion landscape**
  - Eternal inflation and subsequent slow-roll inflation realized in a unified manner.
  - (Multi-)natural inflation by the KNP mechanism
  - Just 50-60 e-foldings may lead to negative curvature.
- **Anything extra?**
  - Running spectral index realized by small modulations.
  - Isocurvature/non-Gaussianity/spatial curvature, etc.