Sneutrino inflation

25th August 2016

@Hokkaido University

Fuminobu Takahashi
(Tohoku)

Murayama, Nakayama, FT, Yanagida, 1404.3857

Nakayama, FT, Yanagida, 1601.00192

Taken from A. Strumia, 1605.09401**v2**

Evidence for BSM

- Neutrino masses, mixings, and CP phases
- Strong CP problem
- Dark energy
- Dark matter
- Baryogenesis
- Inflation
- etc.

from 'Jerry Maguire'

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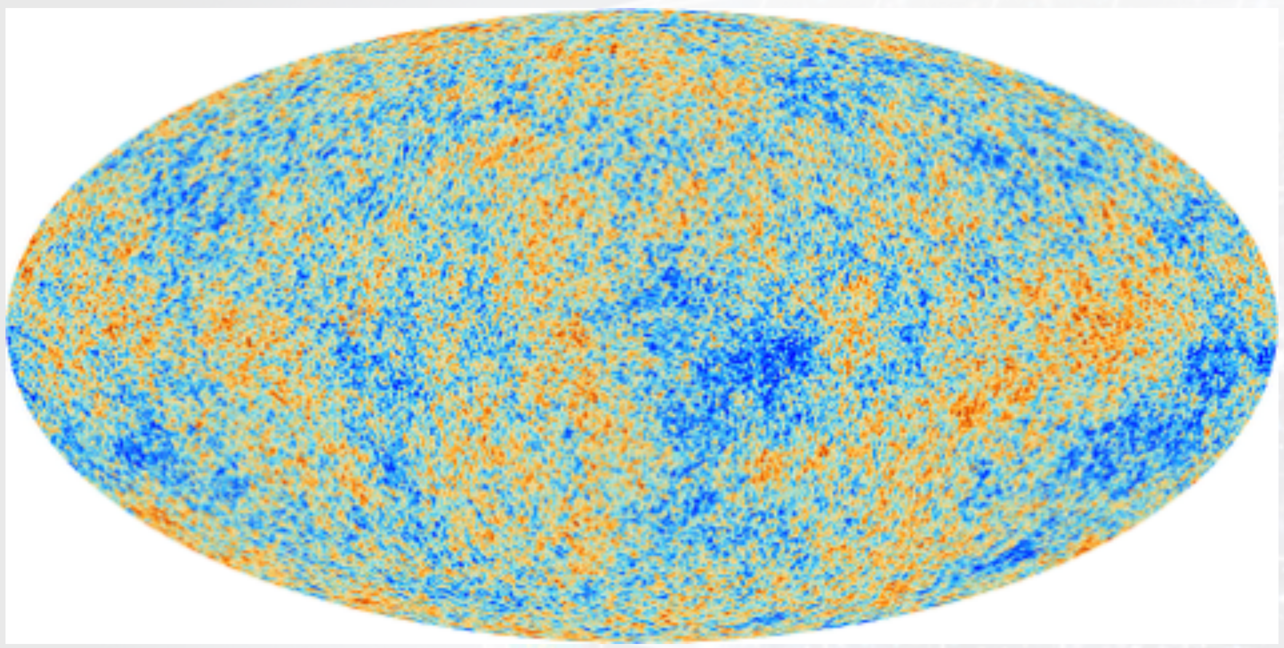
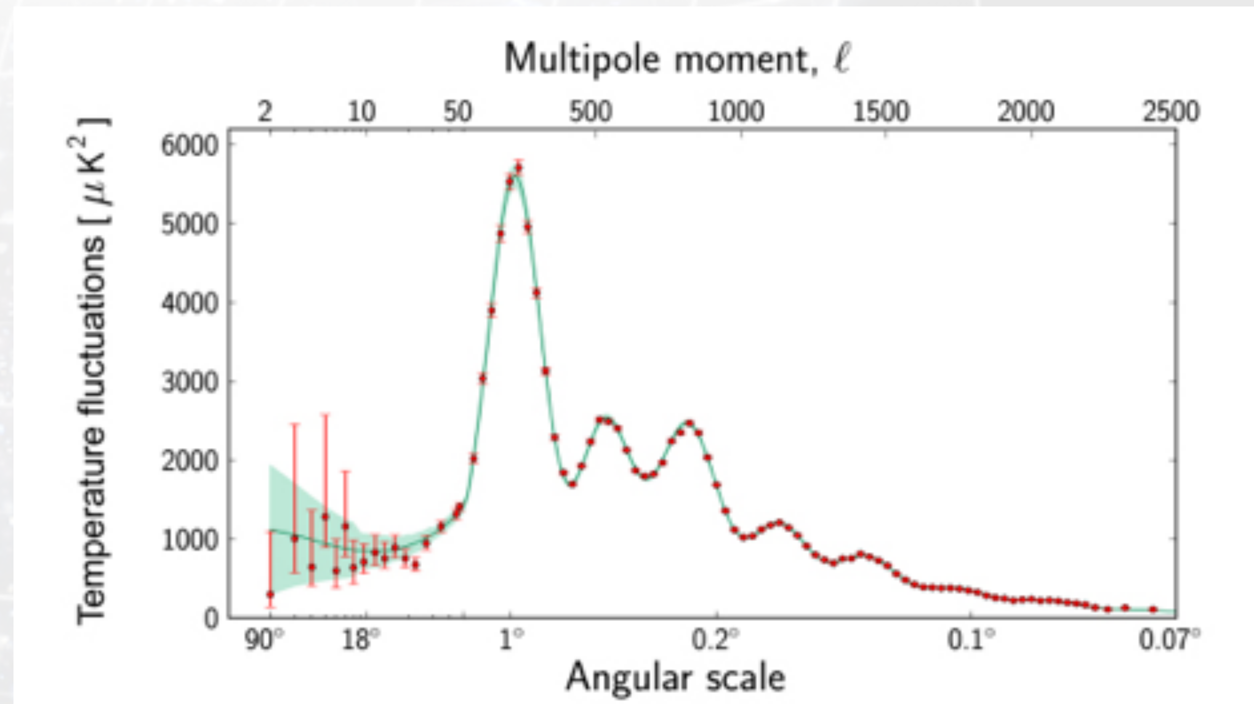
The observed CMB anisotropies strongly suggest inflation at an early stage of evolution.





What is the inflaton?

Mass, coupling to the SM sector, ⋯

Obs. vs Theory

Scalar metric perturbations

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

Tensor metric perturbations

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

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

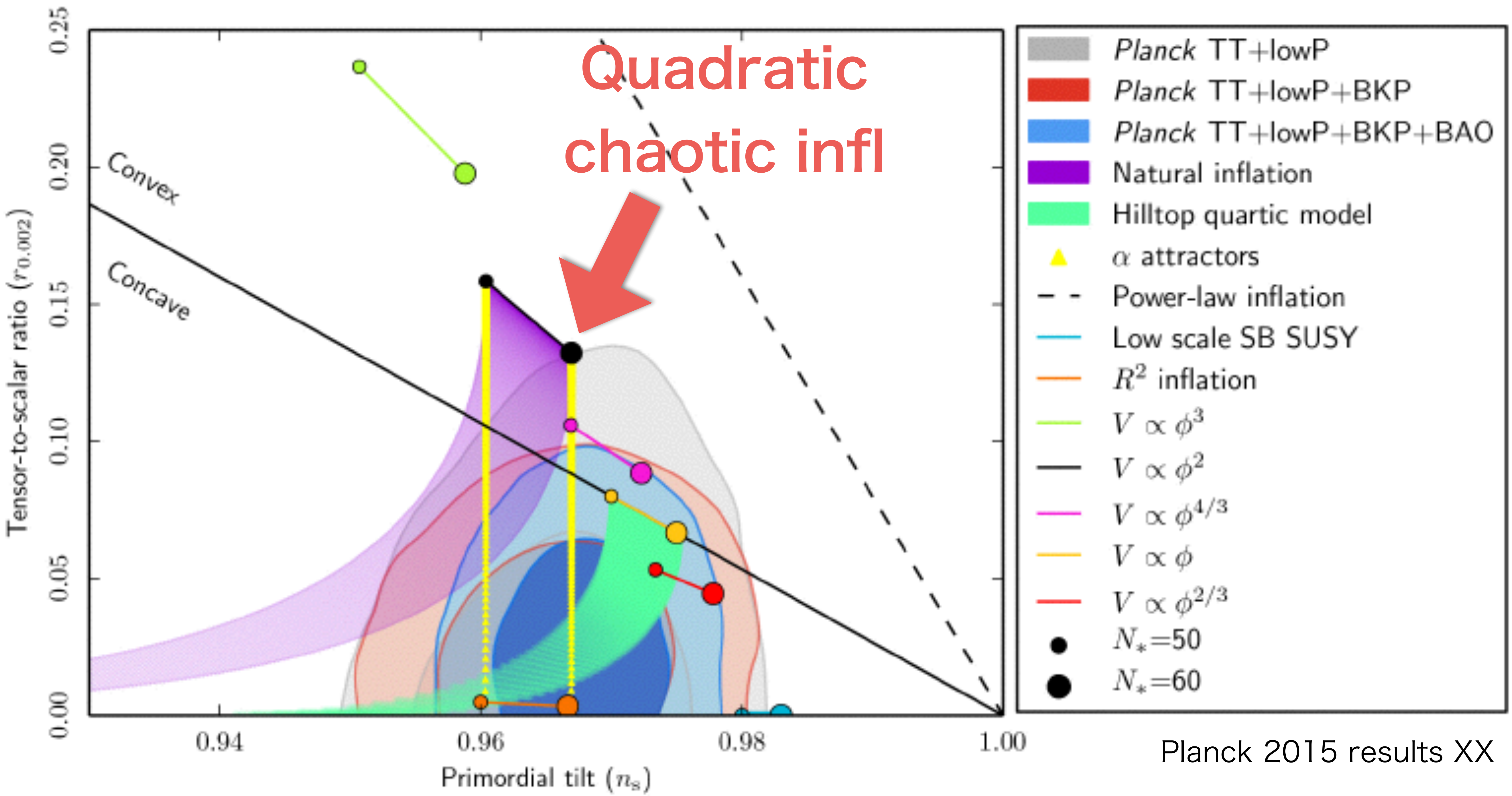
$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2,$$

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

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

V : the inflaton potential

(n_s, r)



Planck 2015 results XX

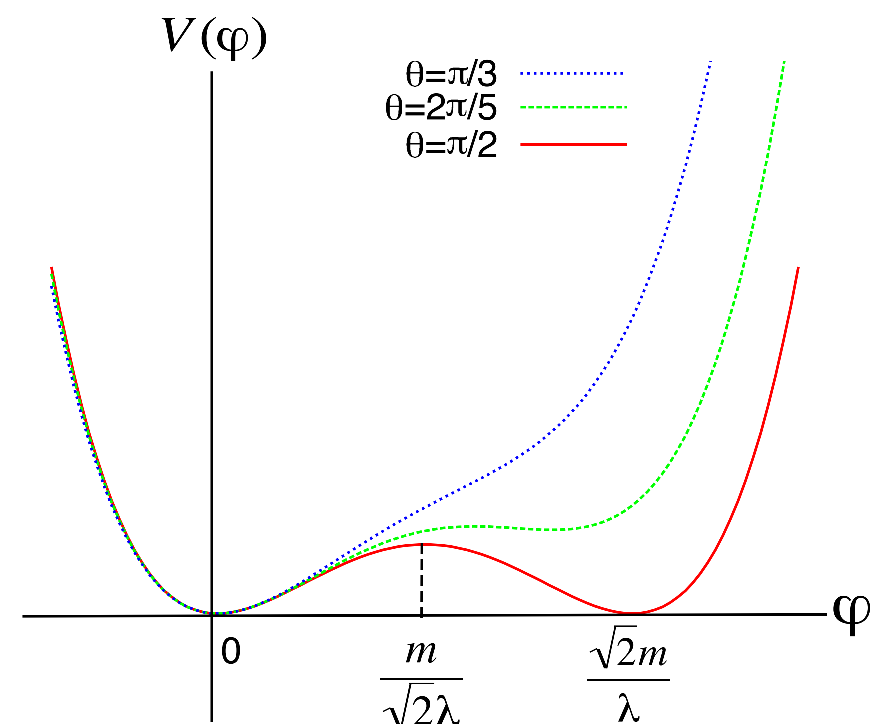
$$V = \frac{1}{2}m^2\phi^2 \quad \text{with} \quad m \simeq 2 \times 10^{13}\,\text{GeV}$$

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)

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

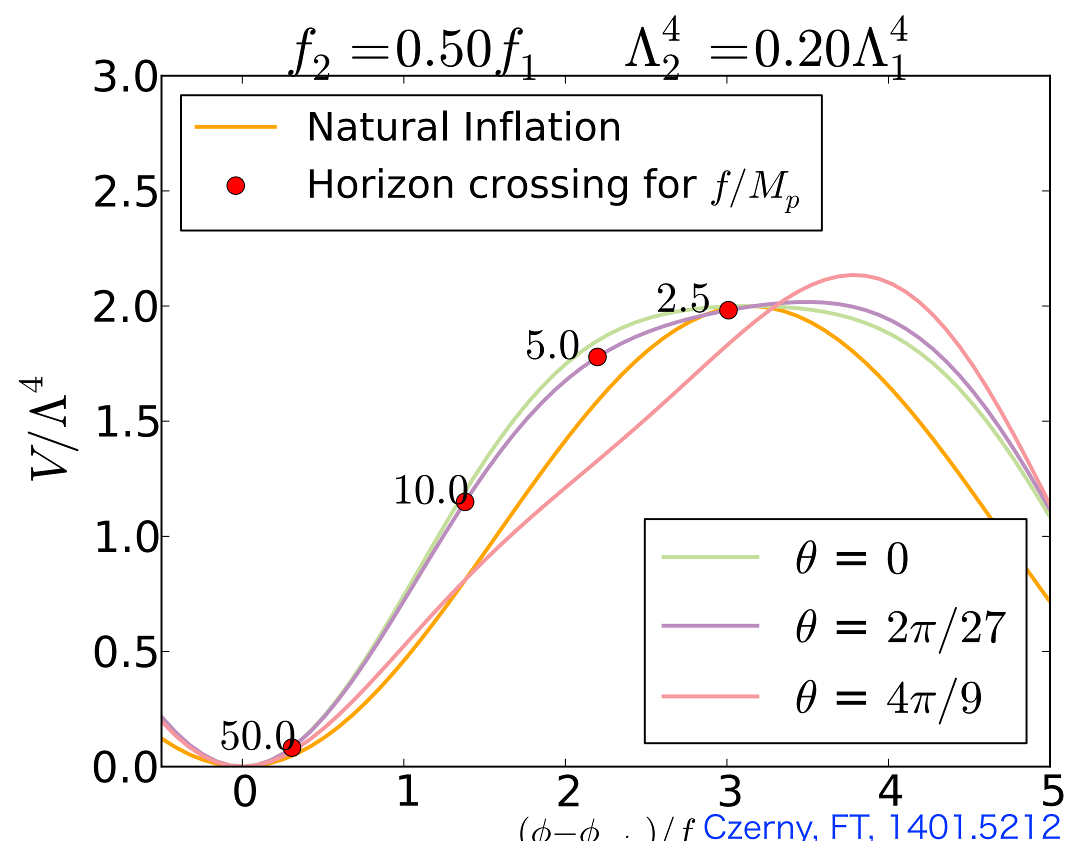


Nakayama, FT, Yanagida, 1303.7315

Multi-Natural inflation

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883

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



Czerny, FT, 1401.5212

N.B. Sub-Planckian decay constants are allowed
as axion hilltop inflation can be realized in a certain limit.

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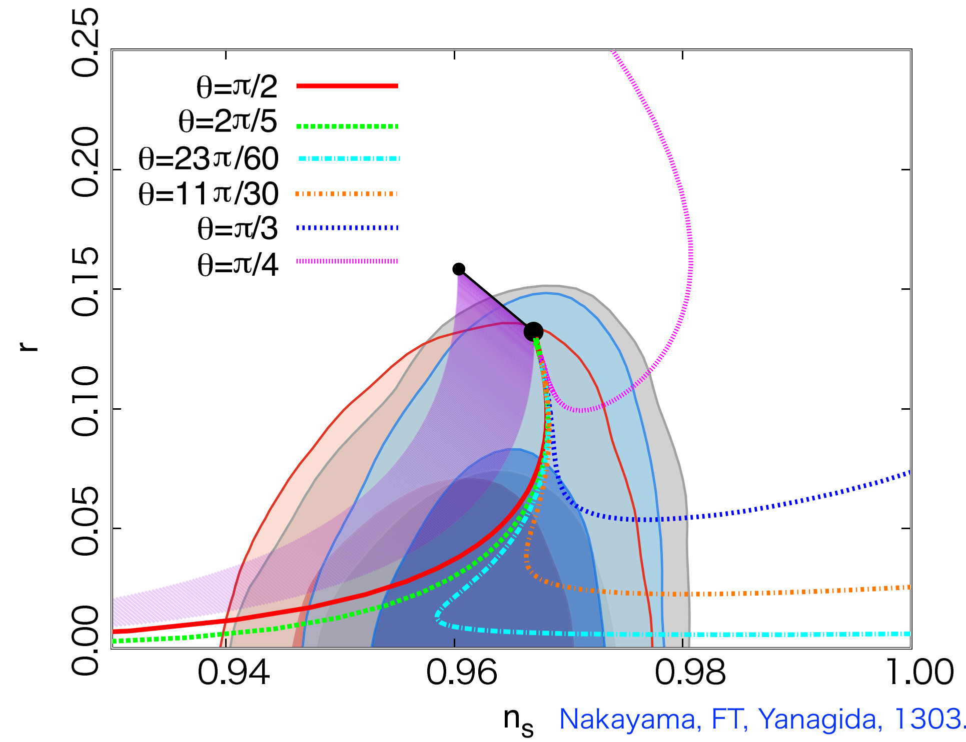

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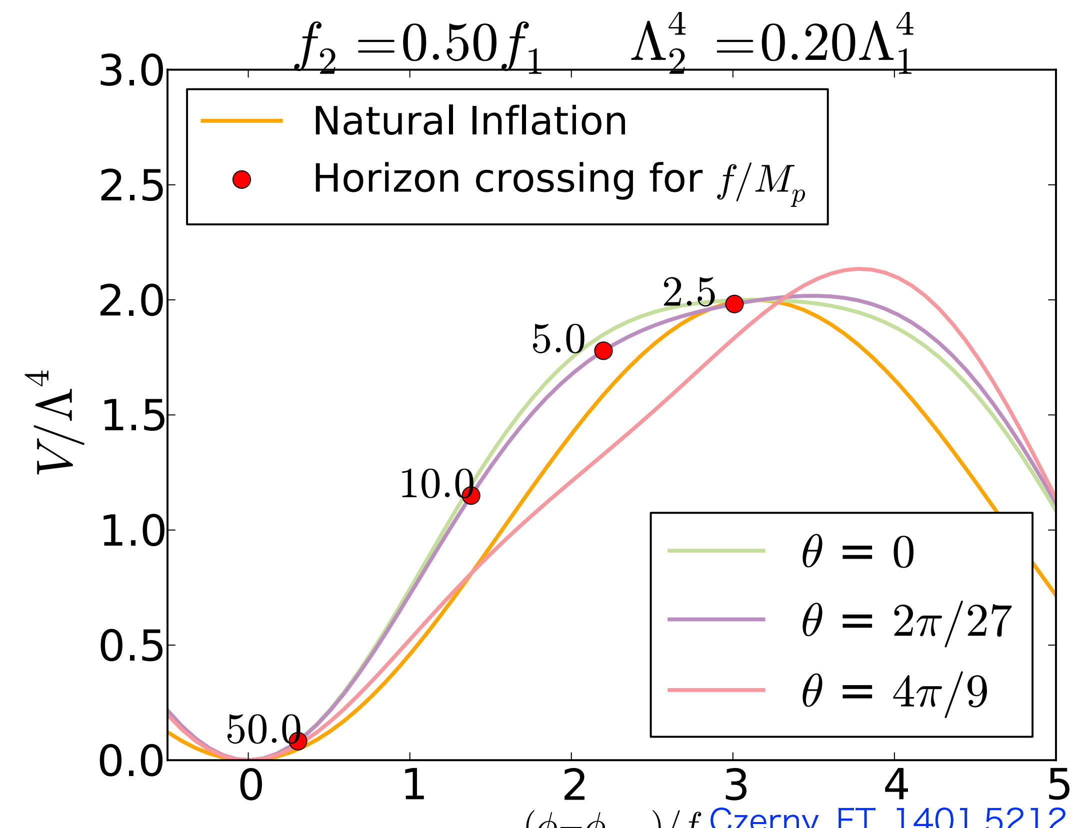

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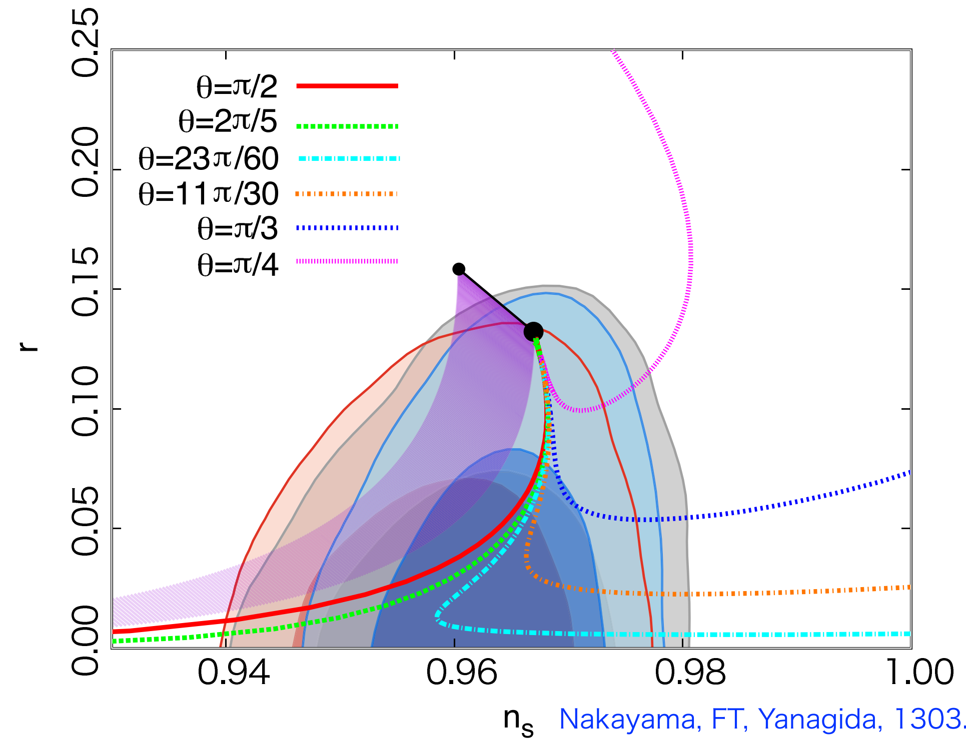

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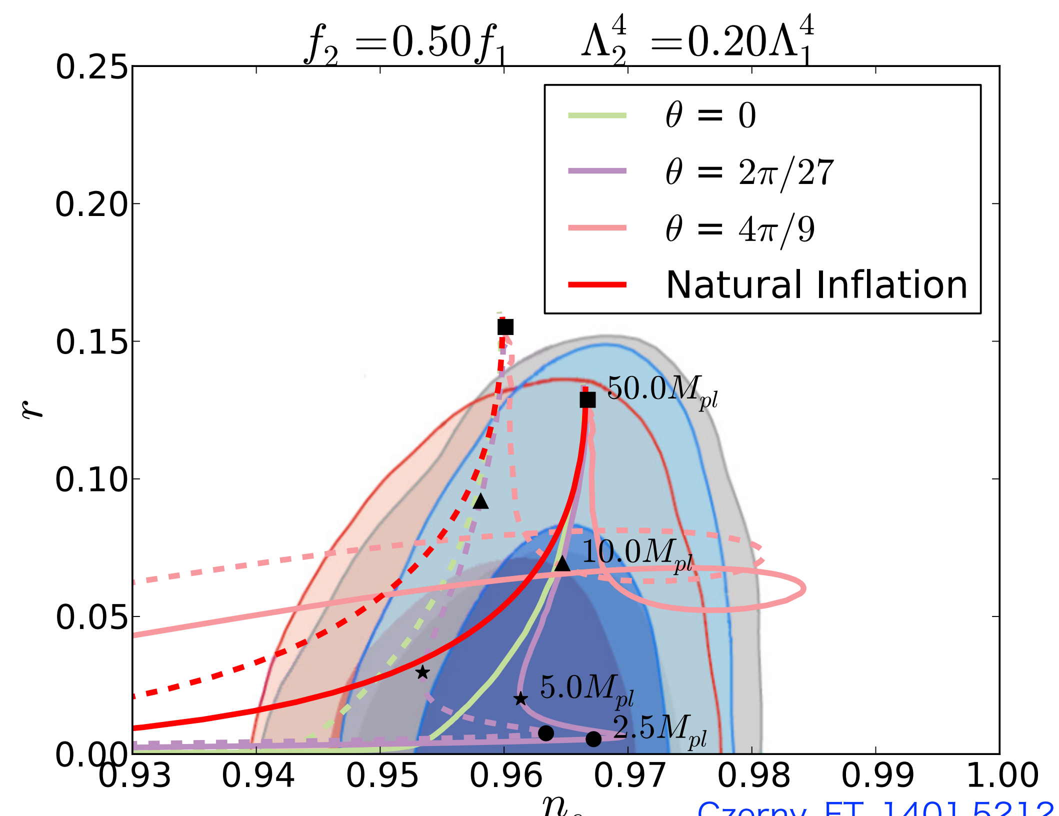

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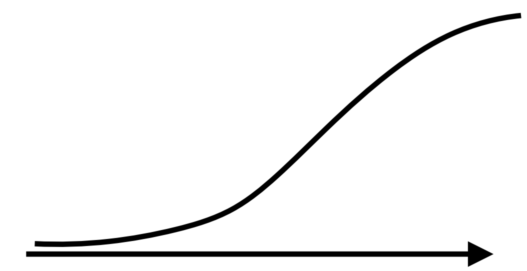
Classification of inflationary models

1. Extensions of quadratic chaotic inflation or natural inflation

r ~ 0.01-0.1



$|V''|_{\rm inf} \sim V''_{\rm present} \sim 10^{13}\,{\rm GeV}$ is the typical curvature of the potential.

$m_{\rm inf} \sim 10^{13}\,{\rm GeV}?$

Intriguingly close to the seesaw scale!

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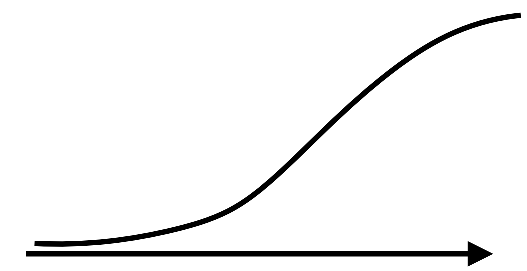

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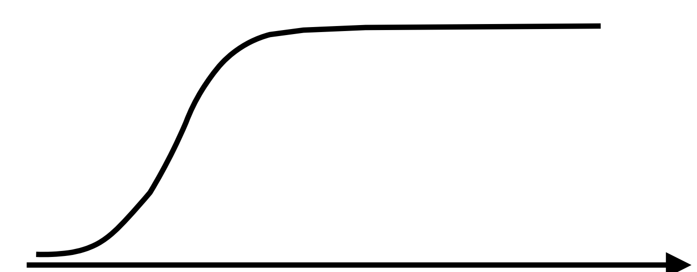
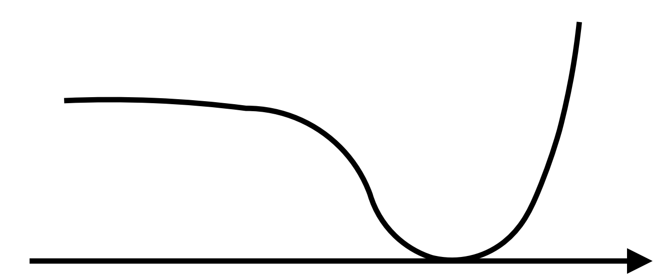
2. R^2 inflation, Higgs inflation

r ~ 10^{-3}



3. Small-field inflation (e.g. new inflation)

r << 10^{-3}



Chaotic inflation in SUGRA

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

We impose a shift symmetry;

$$\Phi \to \Phi + iC$$

which is explicitly broken by the superpotential with inflaton and stabilizer fields.

$$K = \frac{1}{2}\left(\Phi + \Phi^\dagger\right)^2 + |X|^2 + \cdots$$

Φ : inflaton

X : stabilizer field

$$W = MX\Phi \qquad M \sim 10^{13}\,\mathrm{GeV}$$

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

$$\Rightarrow \quad V \simeq \frac{1}{2} M^2 \varphi^2$$

$\varphi = \sqrt{2}\mathrm{Im}[\Phi]$

even for $\varphi \gg M_p$

Our basic idea:

Viable chaotic inflation in SUGRA requires two gauge singlets, inflaton and stabilizer fields. Being singlets, they are naturally coupled to LHu.

$$K = \frac{1}{2}\left(\Phi + \Phi^{\dagger}\right)^{2} + |X|^{2} + \cdots$$

$$W = MX\Phi + \boxed{y_{\Phi}\Phi L H_u + y_X X L H_u}$$

$$M \sim 10^{13}\,\mathrm{GeV}$$

The F-term of X is not absorbed by LHu if y = O(0.1).

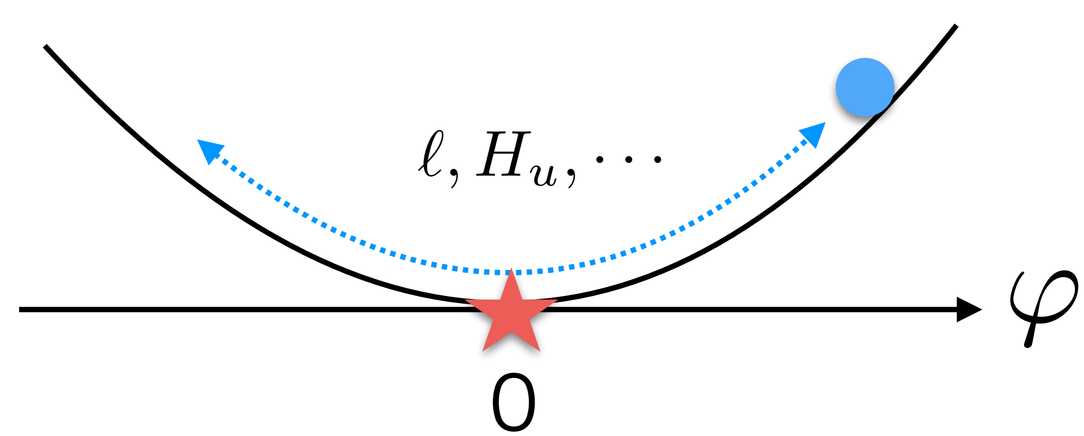
The inflaton potential can be made flatter to be consistent with the CMB obs. (later).

Then, integrating out the inflaton and stabilizer fields, we are left with the neutrino mass terms thru the seesaw mechanism:

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

Minkowski `77, Yanagida `79, Ramond `79, Glashow `80

Inflaton also decays into leptons and Higgs via preheating and T_R is of order 10^{13} GeV. Successful leptogenesis is possible.



Minimal Sneutrino Chaotic inflation

Nakayama, FT, Yanagida, 1601.00192 cf. Murayama, Nakayama, FT, Yanagida,1404.3857

Logic:

Viable chaotic inflation in SUGRA

→ Two singlets needed (inflaton and stabilizer)

→ Being singlets, naturally coupled to LH_u

→ Leptogenesis & seesaw mechanism

Seesaw and leptogenesis are natural outcomes of viable chaotic inflation in supergravity!

Minimal Sneutrino Chaotic inflation

Nakayama, FT, Yanagida, 1601.00192 cf. Murayama, Nakayama, FT, Yanagida,1404.3857

- Deviation from quadratic potential required.
- At inflaton field values > $10M_p$, the lepton and Higgs become heavier than the Planck mass and effective field theory description breaks down.

$$W = MX\Phi + y_\Phi \Phi L H_u + y_X X L H_u$$

$$y = \mathcal{O}(0.1)$$

These can be avoided if there remains unbroken discrete shift symmetry:

$$\varphi \to \varphi + 2\pi f \qquad f = \mathcal{O}(10)M_p$$

Minimal Sneutrino Chaotic inflation

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Let us rewrite $\Phi \to N_1, \quad X \to N_2$

$$K = \frac{1}{2}(N_1 + N_1^\dagger)^2 + |N_2|^2 - k_2 \frac{|N_2|^4}{M_P^2} + |L_\alpha|^2 + |H_u|^2,$$

$$W = MN_2 \sum_{n=1} \frac{g_n}{2n} f \left(e^{\frac{\sqrt{2}nN_1}{f}} - e^{\frac{-\sqrt{2}nN_1}{f}} \right)$$

$$+ \left[y_{1\alpha} \sum_{n=1} \frac{g_n'}{2n} f \left(e^{\frac{\sqrt{2}nN_1}{f}} - e^{\frac{-\sqrt{2}nN_1}{f}} \right) + y_{2\alpha} N_2 \right] L_\alpha H_u,$$

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$$W = M N_2 \sum_{n=1} \frac{g_n}{2n} f \left(e^{\frac{\sqrt{2} n N_1}{f}} - e^{\frac{-\sqrt{2} n N_1}{f}} \right)$$

$$+ \left[y_{1\alpha} \sum_{n=1} \frac{g'_n}{2n} f \left(e^{\frac{\sqrt{2} n N_1}{f}} - e^{\frac{-\sqrt{2} n N_1}{f}} \right) + y_{2\alpha} N_2 \right] L_\alpha H_u,$$

Multi-natural inflation

invariant under $\varphi \to \varphi + 2\pi f$

Yukawa does not blow up.

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Multi-natural inflation

invariant under $\varphi \to \varphi + 2\pi f$

Yukawa does not blow up.

To see how (ns,r) changes, we focus on the first two terms.

$$V = M^2 \left| \sum_n \frac{g_n}{n} \sin\left(\frac{n\varphi}{f}\right) \right|^2$$

$$= \frac{1}{2} M^2 f^2 \sin^2\left(\frac{\varphi}{f}\right) \left[1 + 2C \cos\theta \cos\left(\frac{\varphi}{f}\right) + C^2 \cos^2\left(\frac{\varphi}{f}\right) \right] + \cdots$$

Minimal Sneutrino Chaotic inflation

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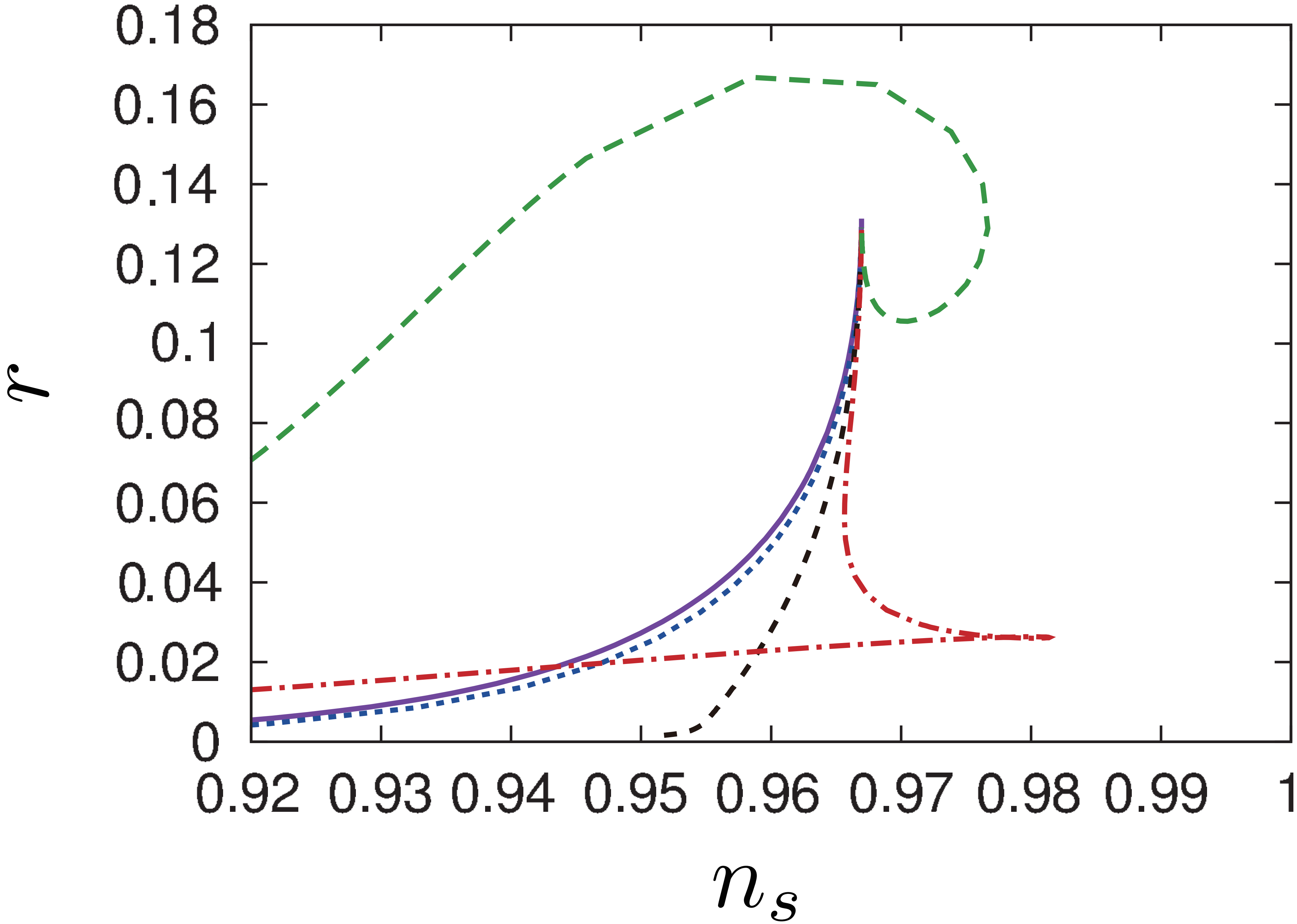
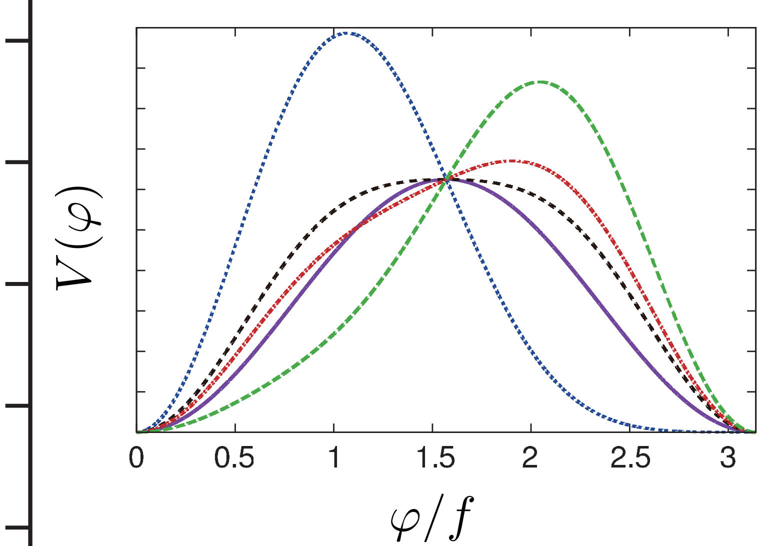




Neutrino masses

Seesaw with two RH neutrinos leads to $m_1 = 0$.

Frampton, Glashow, Yanagida 2002

$$W = \frac{1}{2}\tilde{M}_i \tilde{N}_i \tilde{N}_i + \tilde{y}_{i\alpha}\tilde{N}_i L_\alpha H_u,$$

Variables in the mass eigenstate basis are shown with tildes:

$$\tilde{M}_1 = \tilde{M}_2 = M,$$

$$\tilde{y}_{1\alpha} = \frac{1}{\sqrt{2}}(y_{1\alpha} + y_{2\alpha}), \quad \tilde{y}_{2\alpha} = \frac{i}{\sqrt{2}}(-y_{1\alpha} + y_{2\alpha}),$$

$$\tilde{N}_1 = \frac{1}{\sqrt{2}}(N_1 + N_2), \quad \tilde{N}_2 = \frac{i}{\sqrt{2}}(N_1 - N_2),$$

$$m^{(\nu)}_{\alpha\beta} = \frac{v^2 \sin^2\beta}{M}\tilde{y}_{i\alpha}\tilde{y}_{i\beta},$$

Neutrino masses

$$m^{(\nu)}_{\alpha\beta} = \frac{v^2 \sin^2\beta}{M} \tilde{y}_{i\alpha}\tilde{y}_{i\beta},$$

Rotation phases
of charged lepton
$\ell_\alpha \to e^{i\theta_\alpha}\ell_\alpha$

<u># of degrees of freedom in UV</u>

A general 2 RHN model: $2 + (2 \times 3) \times 2 - 3 = \boxed{11}$

M_1, M_2
2RH neutrino masses

neutrino Yukawa

complex
(real + imaginary)

More precisely, $2r + (2 \times 3) \times (r + i) - 3i = 8r + 3i$

In our 2 RHN model, RH neutrino masses are degenerate, and the mass scale is (almost) fixed by the Planck norm.
Thus, $11 - 2 = \boxed{9} \quad (8r + 3i - 2r = 6r + 3i)$

Neutrino masses

$$m^{(\nu)}_{\alpha\beta} = \frac{v^2 \sin^2\beta}{M} \tilde{y}_{i\alpha}\tilde{y}_{i\beta},$$

# of degrees of freedom in UV

$$11 - 2 = \boxed{9} \quad (8r + 3i - 2r = 6r + 3i)$$

# of degrees of freedom in IR

$$\underbrace{6 \times 2}_{m^{(\nu)}_{\alpha\beta}} - \underbrace{3}_{\text{Rotation phases of charged lepton}} - \underbrace{2}_{\det\left[m^{(\nu)}_{\alpha\beta}\right] = 0} = \boxed{7} \quad (6 \times (r + i) - 3i - (r + i) = 5r + 2i)$$

2 masses,
3 mixing angles,
one Dirac and one Majorana phase.

Therefore there are two unfixed parameters in out set-up.

Neutrino mass eigenvalues

$$m^{(\nu)}_{\bar\alpha}\delta_{\bar\alpha\bar\delta} = U^{(\mathrm{MNS})T}_{\bar\alpha\beta} m^{(\nu)}_{\beta\gamma} U^{(\mathrm{MNS})}_{\gamma\bar\delta}$$

$$U^{(\mathrm{MNS})}_{\alpha\bar\beta} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \mathrm{diag}\left(1, e^{i\alpha/2}, 1\right)$$

$$\tilde{y}_{i\alpha}\tilde{y}_{i\beta} = \frac{M}{v^2\sin^2\beta} U^{(\mathrm{MNS})*}_{\alpha\bar\gamma} m^{(\nu)}_{\bar\gamma}\delta_{\bar\gamma\bar\delta} U^{(\mathrm{MNS})\dagger}_{\bar\delta\beta}$$

Casas-Ibarra parametrization:

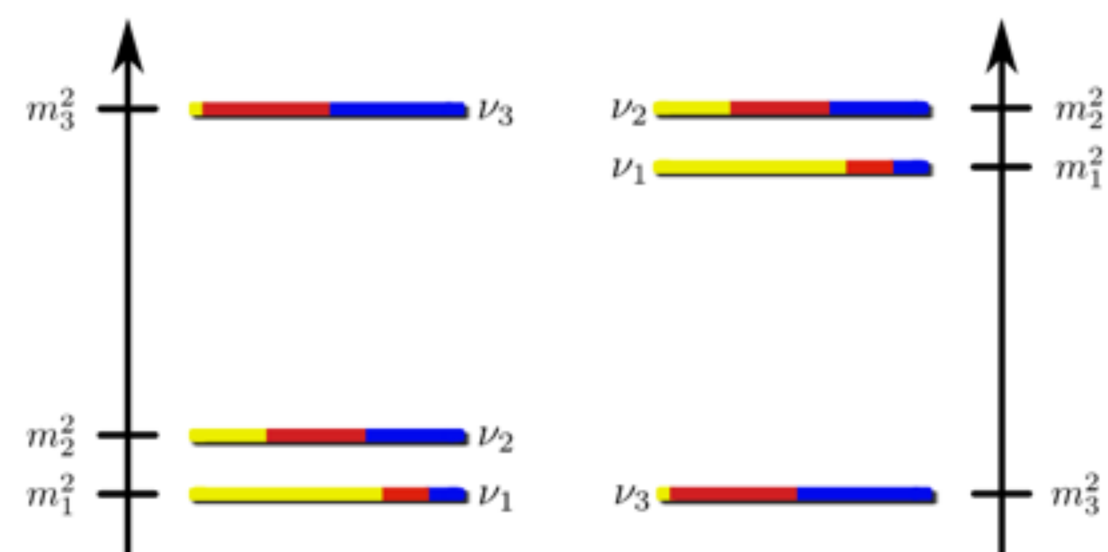
$$\tilde{y}_{i\alpha} = \frac{M^{1/2}}{v\sin\beta} R_{i\bar\gamma}\sqrt{m^{(\nu)}_{\bar\gamma}}\,\delta_{\bar\gamma\bar\delta} U^{(\mathrm{MNS})\dagger}_{\bar\delta\alpha}$$

$$R_{i\bar\gamma} = \begin{pmatrix} 0 & \cos z & -\sin z \\ 0 & \sin z & \cos z \end{pmatrix} \quad \text{for} \quad \mathrm{NH}$$

$$R_{i\bar\gamma} = \begin{pmatrix} -\sin z & \cos z & 0 \\ \cos z & \sin z & 0 \end{pmatrix} \quad \text{for} \quad \mathrm{IH},$$

z : complex parameter

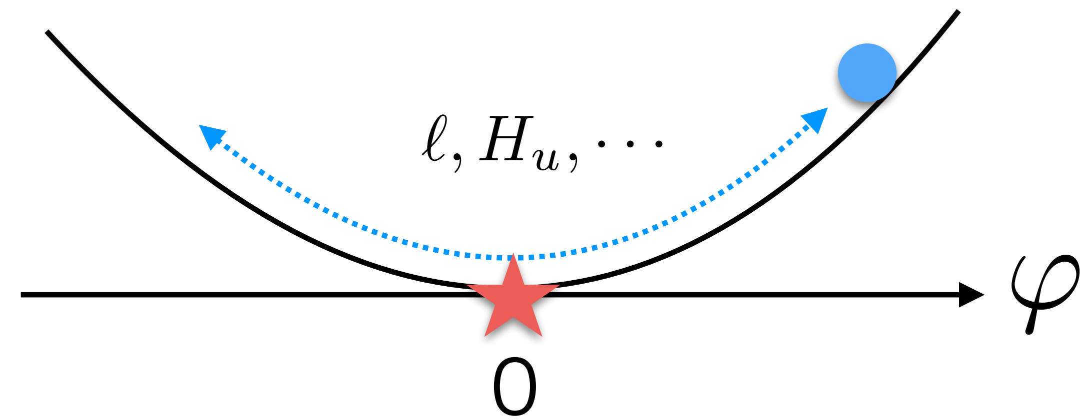
Both NH and IH are possible.



(P)reheating

1. Instant preheating

$$\Gamma_\phi \sim \frac{2y^2 M}{\pi^{7/2} g} \equiv bM$$



$$T_{\rm R} \sim 10^{15}\,{\rm GeV} \left(\frac{b}{0.01}\right)^{1/2} \left(\frac{M}{2\times 10^{13}\,{\rm GeV}}\right)^{1/2}$$

2. Dissipation (evaporation)

$$\Gamma_\phi^{(\rm dis)} \sim \frac{b' y \alpha_W^2 T^2}{\tilde{\varphi}},$$

$$T_{\rm R} \sim \mathcal{O}(0.01) \times \sqrt{M M_P} \sim 10^{14}\,{\rm GeV} \left(\frac{M}{2\times 10^{13}\,{\rm GeV}}\right)^{1/2}.$$

Leptogenesis

In the limit of degenerate RH neutrino masses, the CP asymmetry in the RH nu decay vanishes.

This is because one can absorb the CP phase in nu Yukawa by $N_i \to e^{\pm i\alpha} N_i$ without affecting $W = M N_1 N_2$

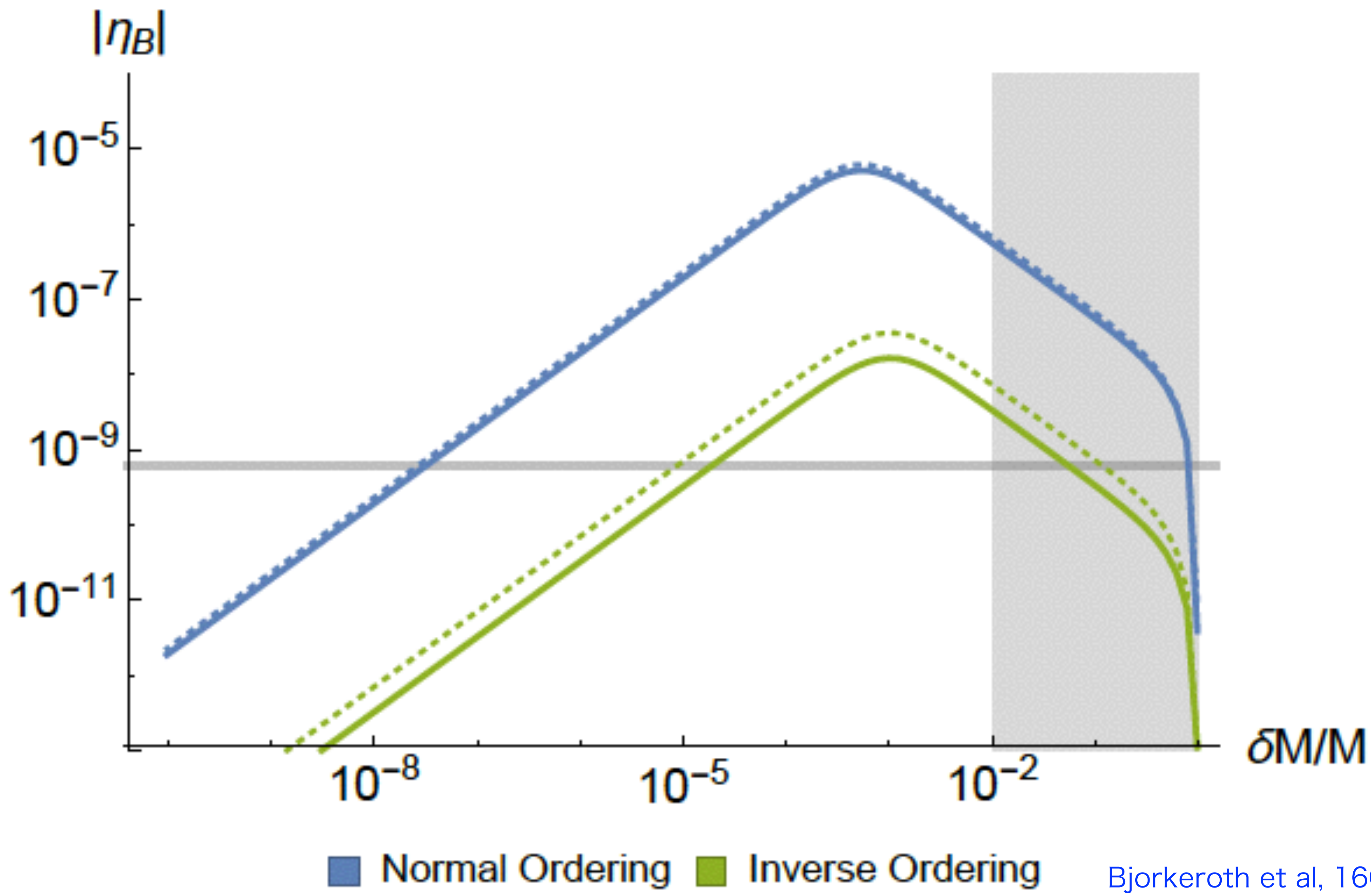
$$\epsilon_i = \frac{\mathrm{Im}\left[(\tilde{y}_{i\alpha}\tilde{y}^\dagger_{\alpha j})^2\right]}{8\pi(\tilde{y}_{i\alpha}\tilde{y}^\dagger_{\alpha i})} \frac{\tilde{M}_i\tilde{M}_j(\tilde{M}_i^2 - \tilde{M}_j^2)}{(\tilde{M}_i^2 - \tilde{M}_j^2)^2 + R^2},$$

One has to add a small breaking term to lift the degeneracy,

$$W' = \delta M N_2 N_2$$

Then, resonant leptogenesis takes place, and a large amount of baryon asymmetry can be produced.

Leptogenesis



Bjorkeroth et al, 1608.04911

$\delta M/M \sim 10^{-8}$ is required for a right amount of baryon asymmetry.

Summary

✓The viable chaotic inflation in sugra requires two gauge singlets, which can be naturally identified with the right-handed neutrinos.

✓Seesaw mechanism & leptogenesis are natural outcomes of the chaotic inflation.

- Deviation from the quadratic potential as well as the blow-up of the neutrino Yukawa couplings can be avoided by unbroken discrete shift symmetry.

- Multi-natural inflation.

- Gravitino overproduction must be solved by violating R-parity.