25/07/2014@ SUSY 2014

Moduli inflation in 5D SUGRA

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arXiv:1405.6520

With
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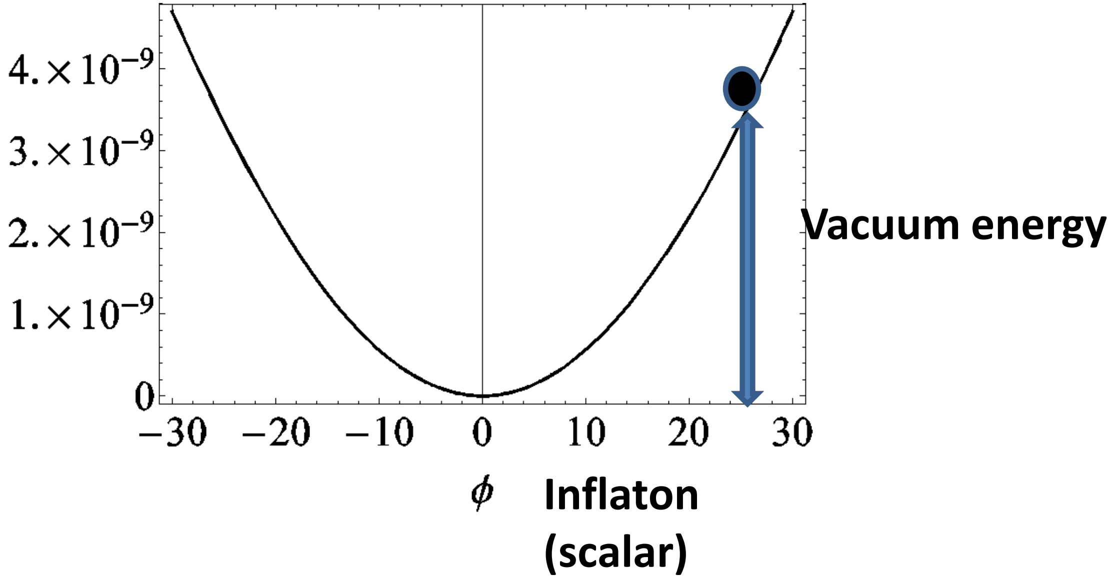
Outline

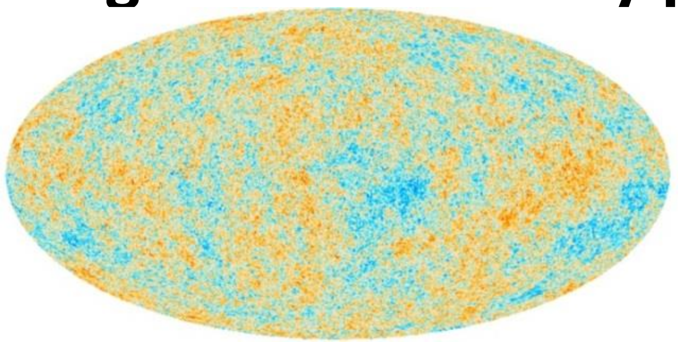
1. **Introduction**
2. **5D SUGRA (five-dimensional supergravity models)**
3. **Moduli inflation in 5D SUGRA**
4. **Conclusion**

Inflation



i) Solving the fine tuning problem
(Horizon problem and flatness problem)

ii) Producing the origin of the density perturbations



$$\frac{\Delta T}{T} \sim 10^{-5}$$

WMAP + Planck

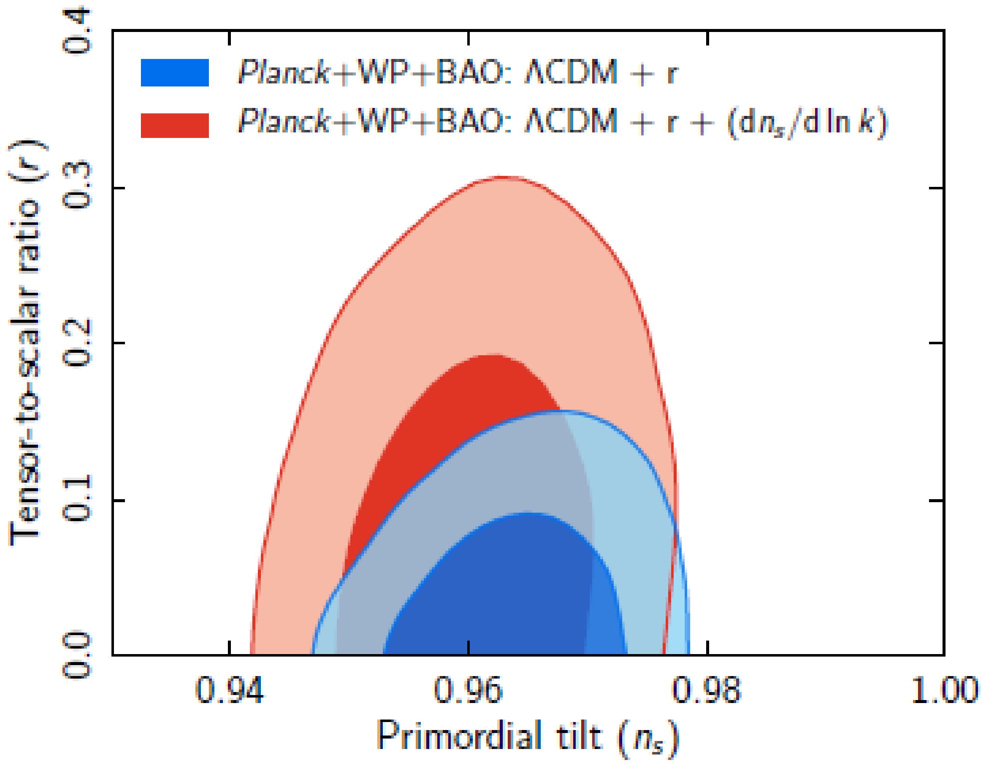
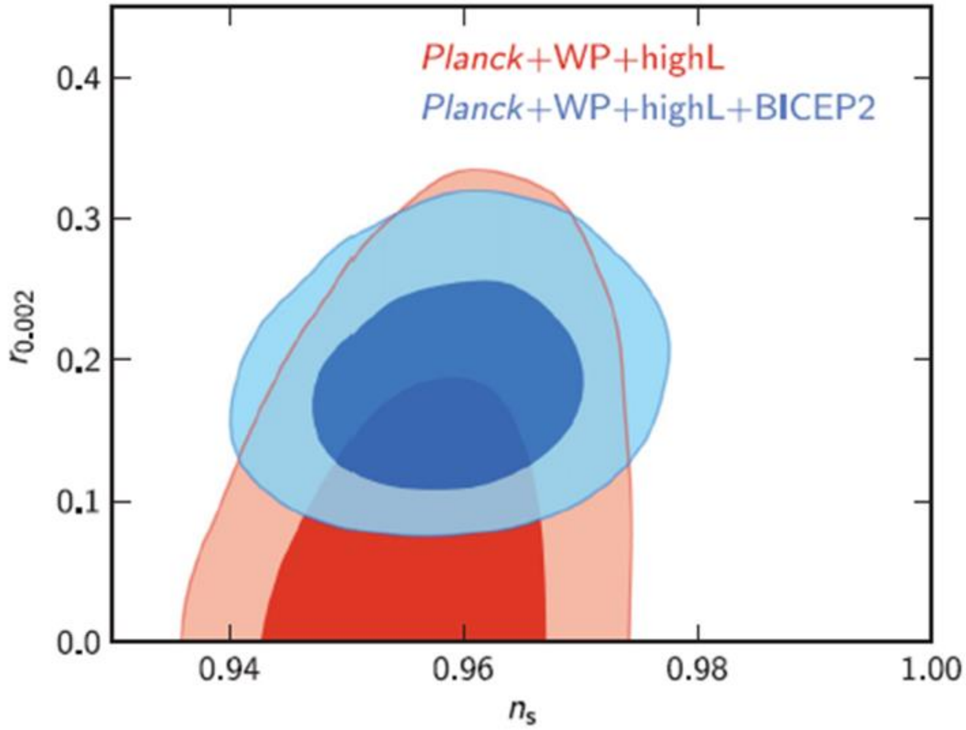


Fig. 4. Marginalized joint 68% and 95% CL regions for (r, n_s), using *Planck*+WP+BAO with and without a running spectral index.

Planck collaboration, XXII arXiv: 1303.5082 [astro-ph.]

BICEP2

BICEP2 collaboration, Phys. Rev. Lett. **112**, 241101, 2014



$$r = 0.16^{+0.06}_{-0.05}$$

Primordial tensor modes can be measured as B-mode polarization of the CMB.

Tensor-to-scalar ratio

Lyth bound

Phys. Rev. Lett. **78** (1997) 1861.

$$r \leq 2.2 \times 10^{-3} \left(\frac{N_*}{60}\right)^{-2} \left(\frac{\Delta\phi}{M_{PL}}\right)^2$$

E-folding number $N_* = \ln \frac{a(t_{\mathrm{end}})}{a(t_*)}$ $a \cdots \text{scale factor}$

BICEP2 : $r \sim O(0.1)$ ⟹ **Large-field inflation**

- **Large-field models are preferred to explain the BICEP2 results.**
- **We propose the large-field inflation mechanism in the higher dimensional theory (5D SUGRA).**

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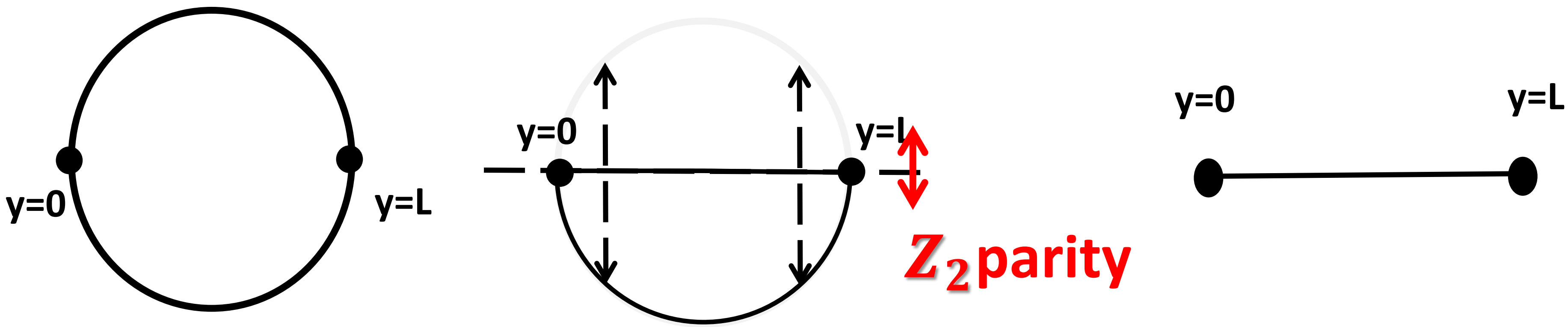
Motivation

5D SUGRA on S^1/Z_2

Fifth direction



Motivation

IIB/M -theory

⇩ Low energy effective theory

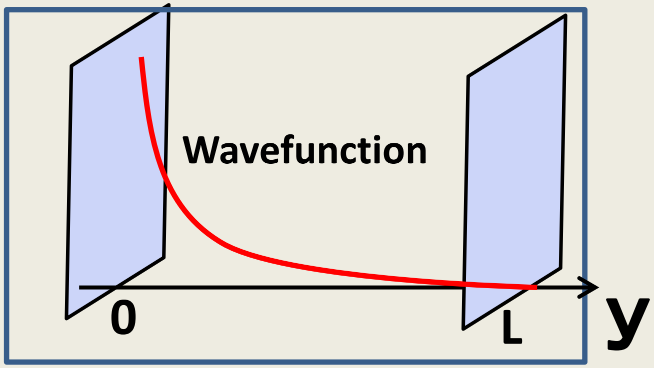
5D SUGRA on S^1/Z_2

- **Wavefunction localization**

  (N. Arkani-Hamed & M. Schmaltz '00)

  ➔ **Yukawa hierarchies**

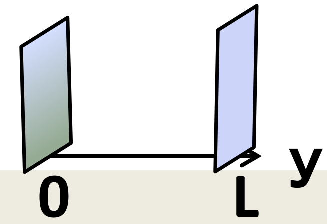
$$m_t/m_u \sim 10^5$$



- **SUSY flavor problems**

  (H. Abe, H.O., Y. Sakamura and Y. Yamada, Eur. Phys. C 72 2012 (2018))

In 5D SUGRA on S^1/Z_2



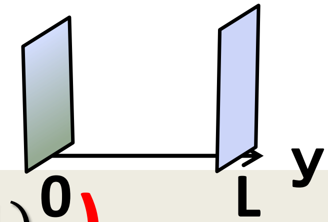
Matter contents

Weyl multiplets (gravity)
Hypermultiplets (matter and compensator)
Vector multiplets (gauge fields)

$$\underline{SU(3)_C \times SU(2)_L \times U(1)_Y} \times \underline{U(1)^n}$$

MSSM
(Minimal Supersymmetric Standard Model)

In 5D SUGRA on S^1/Z_2



Vector multiplets ($SU(3)_C \times SU(2)_L \times U(1)_Y$)

Z_2 parity

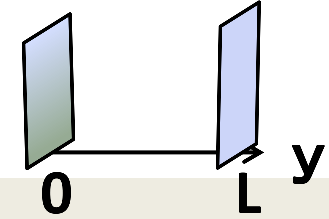
N=2 Vector multiplets	$\mathbf{V} = (V, \ \Sigma)$	$(+, -)$

A_μ^{MSSM} (zero mode) A_y^{MSSM} (massive mode)

$V \cdots$ N=1 vector multiplet

$\Sigma \cdots$ N=1 chiral multiplet

In 5D SUGRA on S^1/Z_2



Vector multiplets ($U(1)^n$)

Z_2 parity

N=2 vector multiplet $(U(1)^n)$	$\mathbf{V}^i = (V^i, \Sigma^i)$	$(-, +)$

$A_\mu^{U(1)^i}$ $A_y^{U(1)^i}$ (zero mode)

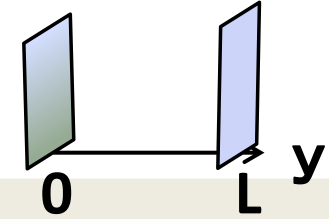
$V^i \cdots$ N=1 vector multiplet

$\Sigma^i \cdots$ N=1 chiral multiplet

Moduli T^i = Zero mode of $\sum^i$ $(i = 1, \cdots n)$

The moduli potential is flat due to the gauge symmetry.

In 5D SUGRA on S^1/Z_2



Hypermultiplets

Z_2 parity

N=2 hypermultiplest	$\mathbf{H}_\alpha = (\mathcal{H}_\alpha,\ \mathcal{H}_\alpha^C)$	$(+,\ -)$

(zero mode)

$\mathcal{H}_\alpha \cdots$ N=1 chiral multiplets

$\mathcal{H}_\alpha^C \cdots$ N=1 chiral multiplets

Stabilizer fields H_α = Zero mode of $\mathcal{H}_\alpha$ $(\alpha = 1, \cdots n)$

We introduce the stabilizer fields to stabilize the moduli.

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Moduli Kahler potential

$$K = -\ln\left(C_{ijk}\mathrm{Re}T^i\mathrm{Re}T^j\mathrm{Re}T^k\right) \quad (\text{in the } M_{\mathrm{Pl}} \text{ unit})$$

$$\downarrow \quad C_{112} = 1, \text{otherwise } 0$$

$$K = -\ln\left(\mathrm{Re}T^1\mathrm{Re}T^2\mathrm{Re}T^2\right)$$

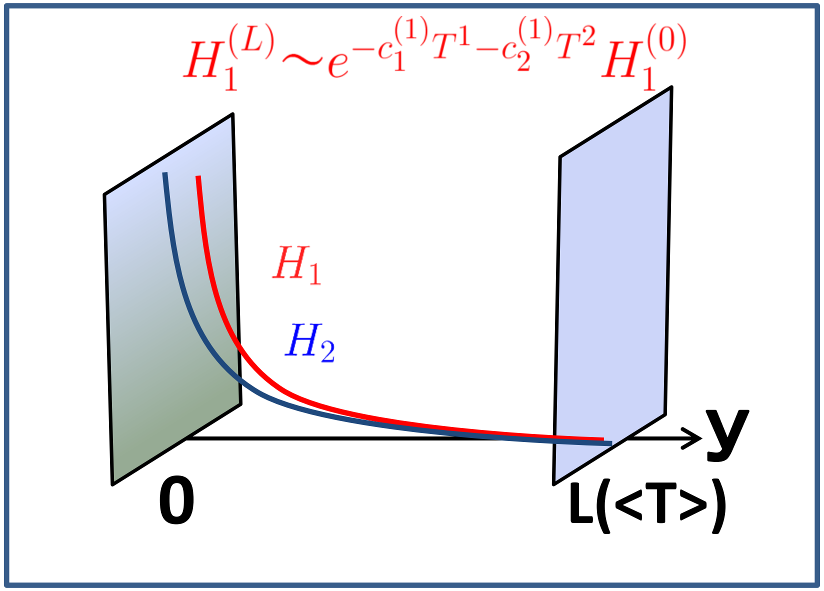
Shift symmetries of moduli

$$T^i \to T^i + i\alpha^i, \quad (i = 1, \cdots, n)$$

$$\mathrm{Im}\, T^i = A_y^{U(1)^i}$$

Superpotential of the stabilizer fields (N. Maru & N. Okada '04)

$$W_0 = J_1^{(0)} H_1^{(0)} + J_2^{(0)} H_2^{(0)}$$



$$W_L = -J_1^{(L)} H_1^{(L)} - J_2^{(L)} H_2^{(L)}$$

$$W = W_0 + W_L = \left(J_1^{(0)} - J_1^{(L)} e^{-c_1^{(1)} T^1 - c_2^{(1)} T^2} \right) H_1 + \left(J_2^{(0)} - J_2^{(L)} e^{-c_2^{(2)} T^2} \right) H_2$$

$$c_1^{(1)} \cdots U(1)^1 \text{charge of } H_1$$

$$c_1^{(2)} \cdots U(1)^2 \text{charge of } H_1$$

$$c_2^{(2)} \cdots U(1)^2 \text{charge of } H_2$$

Stabilizer fields generate the moduli potential.

To analyze the moduli potential, we redefine the moduli as

$$\hat{T}^1 = \frac{c_1^{(1)} T^1 + c_2^{(1)} T^2}{c}$$
$$\hat{T}^2 = T^2$$

In this base, $(\hat{T}^1, H_1)$ and $(\hat{T}^2, H_2)$ have independent superpotential to each other.

$$K = -\ln\left(\mathrm{Re}\hat{T}^1\right) - 2\ln\left(\mathrm{Re}\hat{T}^2 - b\,\mathrm{Re}\hat{T}^1\right)$$

$$W = \left(J_1^{(0)} - J_1^{(L)} e^{-c\hat{T}^1}\right) H_1 + \left(J_2^{(0)} - J_2^{(L)} e^{-c_2^{(2)}\hat{T}^2}\right) H_2$$

$$b = \frac{c\, c_1^{(2)}}{c_2^{(2)} c_1^{(1)}} (> 0)$$

$$W = \left(J_1^{(0)} - J_1^{(L)} e^{-c\hat{T}^1}\right) H_1 + \left(J_2^{(0)} - J_2^{(L)} e^{-c_2^{(2)}\hat{T}^2}\right) H_2$$

Moduli and stabilizer fields are stabilized at the supersymmetric Minkowski minimum.

$$D_I W = W_I + K_I W$$
$$W_I = \partial_I W$$
$$K_I = \partial_I K$$
$$(I = \hat{T}^i, H_i)$$

$$\langle D_{\hat{T}^i} W \rangle = \langle D_{H_i} W \rangle = 0 \quad (i = 1, 2)$$

$$\langle H_1 \rangle = \langle H_2 \rangle = 0$$
$$\langle \hat{T}^1 \rangle = \frac{1}{c} \ln \frac{J_1^{(0)}}{J_1^{(L)}}, \quad \langle \hat{T}^2 \rangle = \frac{1}{c_2^{(2)}} \ln \frac{J_2^{(0)}}{J_2^{(L)}}$$

$$\langle W \rangle = 0$$

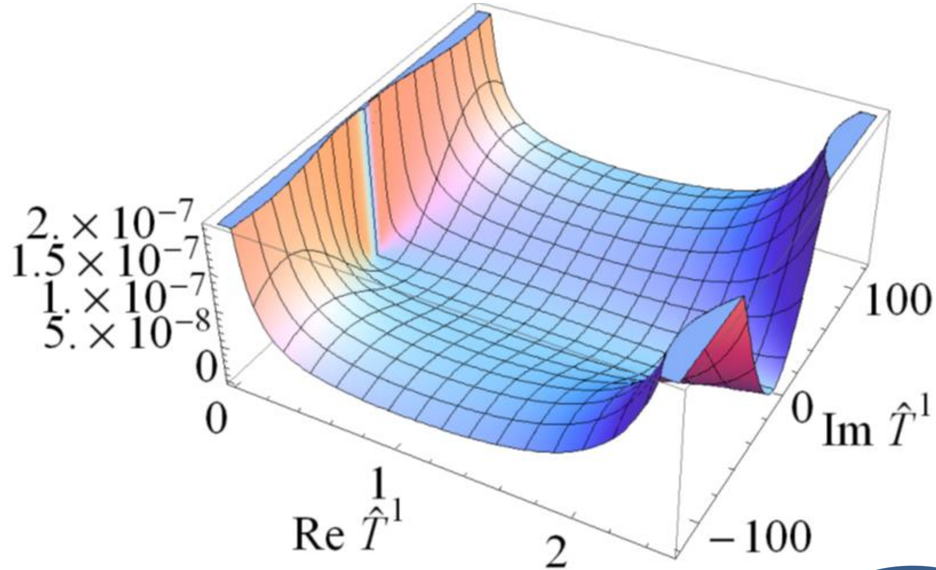
We consider the situation that $(\hat{T}^1, H_1)$ **is lighter than** $(\hat{T}^2, H_2)$ **by assuming** $|J_1^{(0)}|, |J_1^{(L)}| \ll |J_2^{(0)}|, |J_2^{(L)}|$**.**

$$m_{\hat{T}^1} = m_{H_1} \propto c\, J_1^{(L)} e^{-c\,\langle \hat{T}^1 \rangle}$$
$$m_{\hat{T}^2} = m_{H_2} \propto c_2^{(2)}\, J_2^{(L)} e^{-c_2^{(2)}\,\langle \hat{T}^2 \rangle}$$

The pair $(\hat{T}^2, H_2)$ **can be integrated out.**

Effective scalar potential on the $H_1 = 0$ hypersurface

$$V_{\rm eff}(\hat{T}^1, H_1 = 0) = e^K K^{H_1 \bar{H}_1} |W_{H_1}|^2 = \Lambda^4 (1 - \lambda \cos(c\, {\rm Im}\, \hat{T}^1))$$

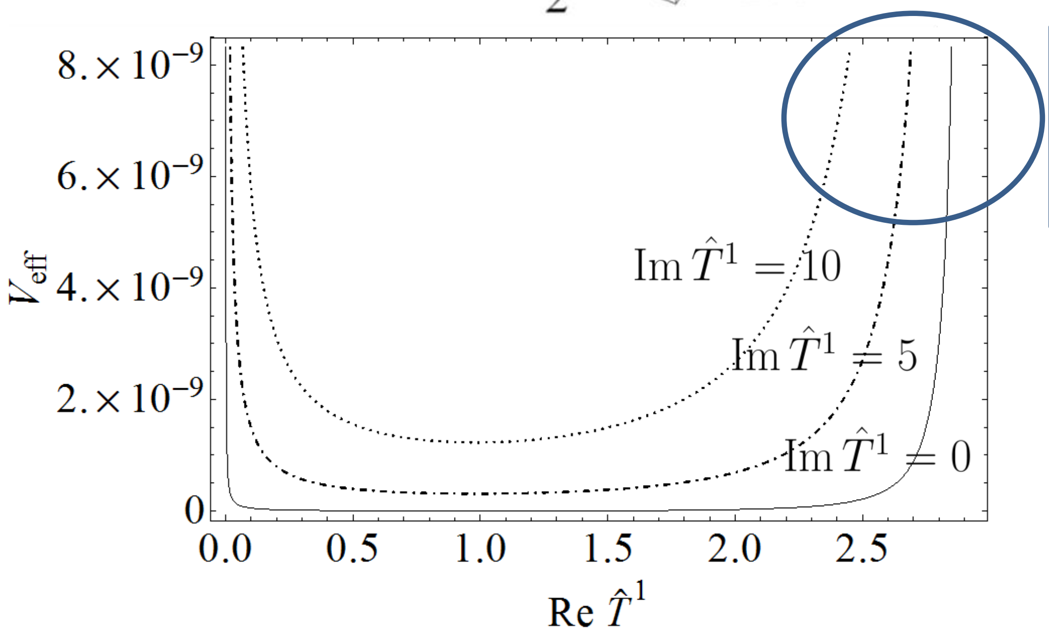


$$\Lambda^4 \equiv \frac{c}{(\langle {\rm Re}\, \hat{T}^2 \rangle - b\, {\rm Re} \hat{T}^1)^2} \frac{(J_1^{(0)})^2 + (J_1^{(L)})^2 e^{-2c\, {\rm Re}\hat{T}^1}}{1 - e^{-2c\, {\rm Re}\hat{T}^1}}$$

$$\lambda \equiv 2 \frac{J_1^{(0)} J_1^{(L)} e^{-c\, {\rm Re}\hat{T}^1}}{(J_1^{(0)})^2 + (J_1^{(L)})^2 e^{-2c\, {\rm Re}\hat{T}^1}}$$

$b = 15 \quad c = 1/30$

$J_1^{(0)} = 4.25 \times 10^{-3} \quad J_1^{(L)} = 4.4 \times 10^{-3}$



$\Lambda \to \infty$

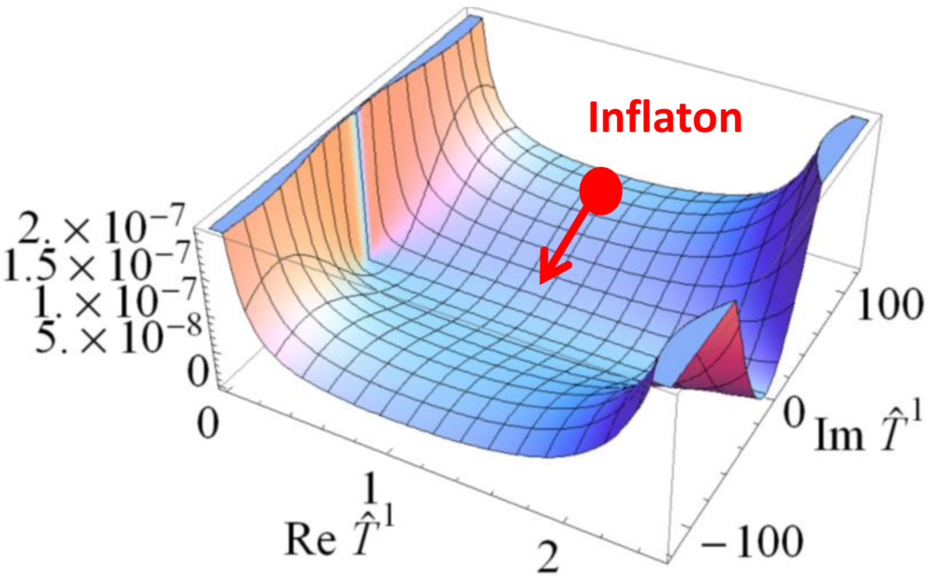
$({\rm Re}\, \hat{T}^1 \to \langle {\rm Re}\, \hat{T}^2 \rangle / b)$

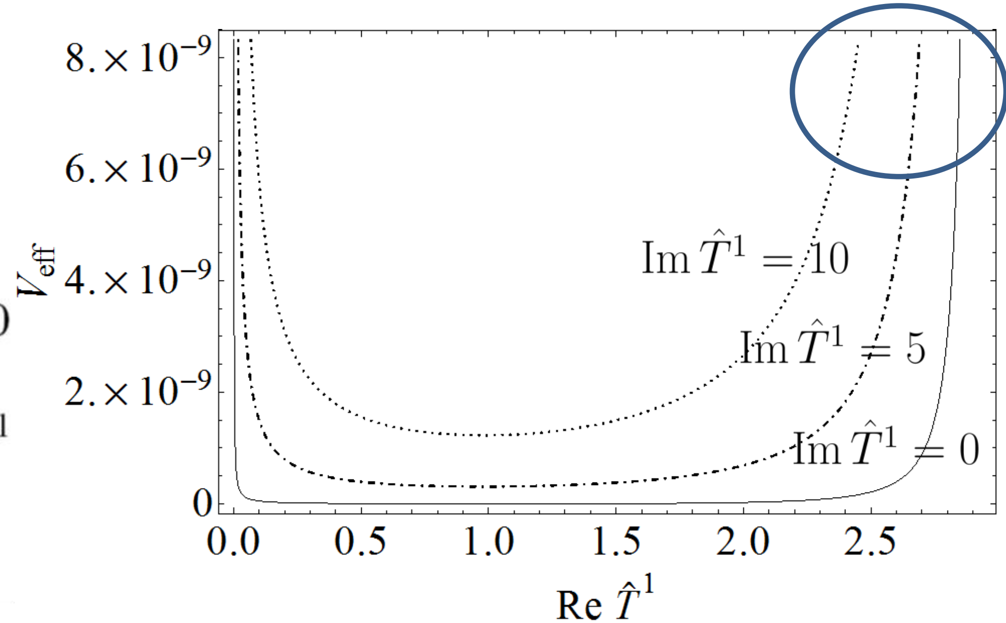
$$K \supset -2 \ln \left(\langle {\rm Re} \hat{T}^2 \rangle - b\, {\rm Re} \hat{T}^1 \right)$$

Effective scalar potential on the $H_1 = 0$ hypersurface

$$V_{\rm eff}(\hat{T}^1, H_1 = 0) = e^K K^{H_1 \bar{H}_1} |W_{H_1}|^2 = \Lambda^4 (1 - \lambda \cos(c \, {\rm Im}\, \hat{T}^1))$$

$\Lambda \to \infty$

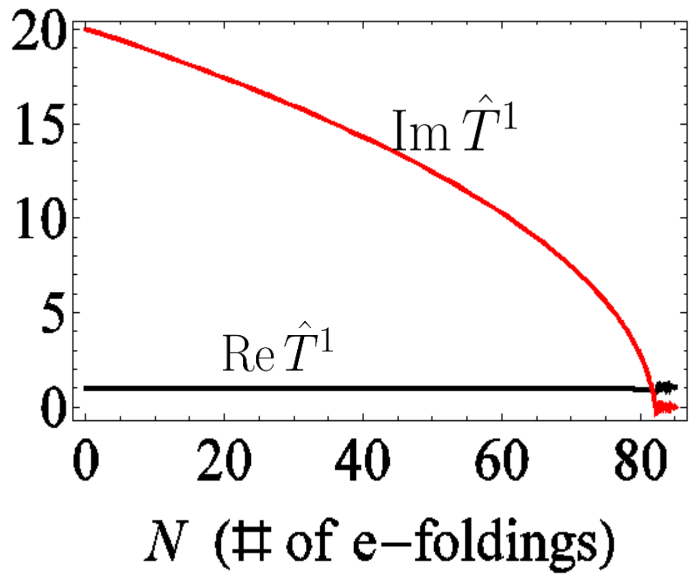


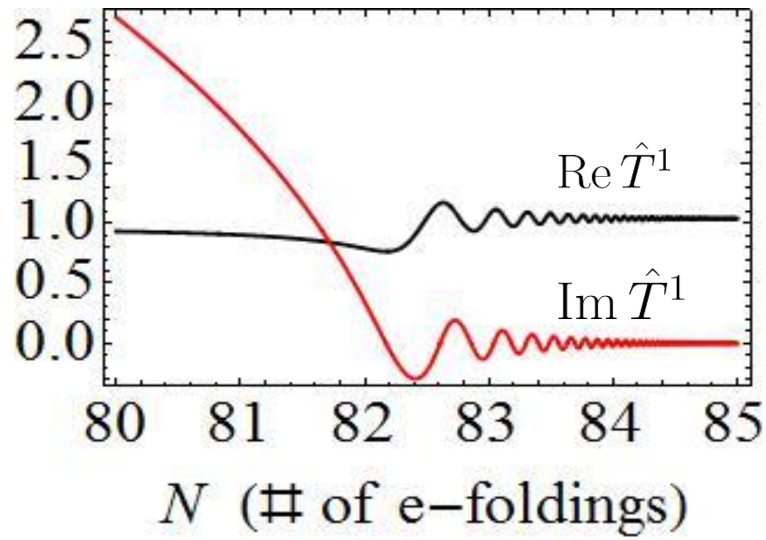


Natural inflation would occur by identifying ${\rm Im}\, \hat{T}^1$ as the inflaton field.
(Axion decay constant corresponds to the inverse of U(1) charge.)

$$f = \frac{1}{c} = 30 \gg 1 \;\; (\text{in the } {\rm M_{Pl}} \text{ unit})$$

By solving the equations of motion (E.O.M.) for $\mathrm{Re}\,\hat{T}^1$ and $\mathrm{Im}\,\hat{T}^1$,



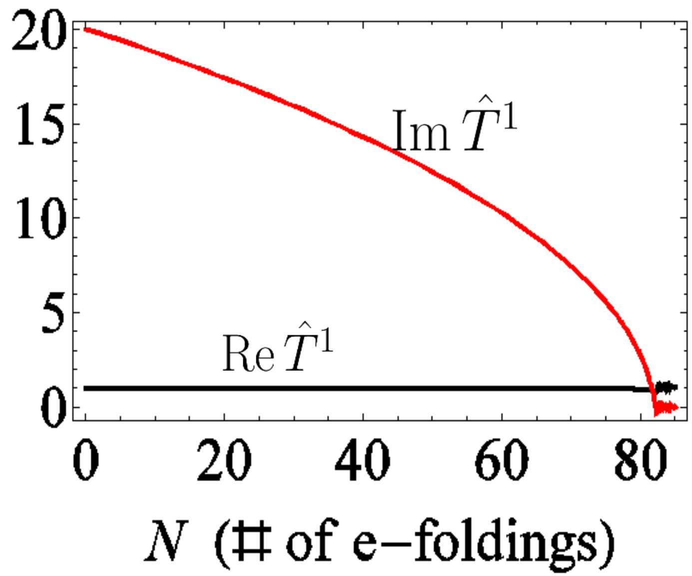


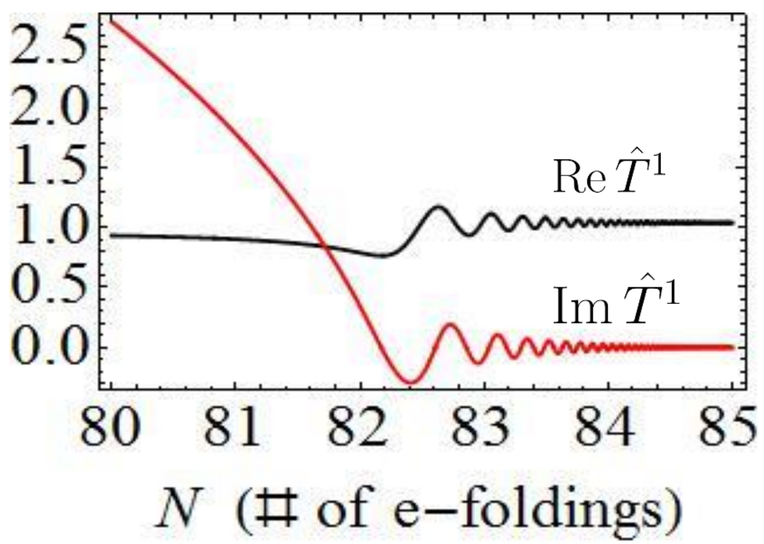
The E.O.M. for $\mathrm{Re}\,\hat{T}^1$ under the slow-roll regime is

$$\frac{d\sigma}{d\,N} \simeq -g^{\sigma\sigma}\left(\frac{2}{\langle \mathrm{Re}\,\hat{T}^2\rangle/b-\ \sigma}-\frac{2c\,e^{-2c\,\sigma}}{1-e^{-2c\,\sigma}}-c\right)+\frac{V_{\mathrm{vac}}(\sigma)}{V_{\mathrm{eff}}},\quad (\sigma=\mathrm{Re}\,\hat{T}^1)$$

$$V_{\mathrm{vac}}(\langle\sigma\rangle)=0$$

By solving the equations of motion (E.O.M.) for $\mathrm{Re}\,\hat{T}^1$ and $\mathrm{Im}\,\hat{T}^1$,





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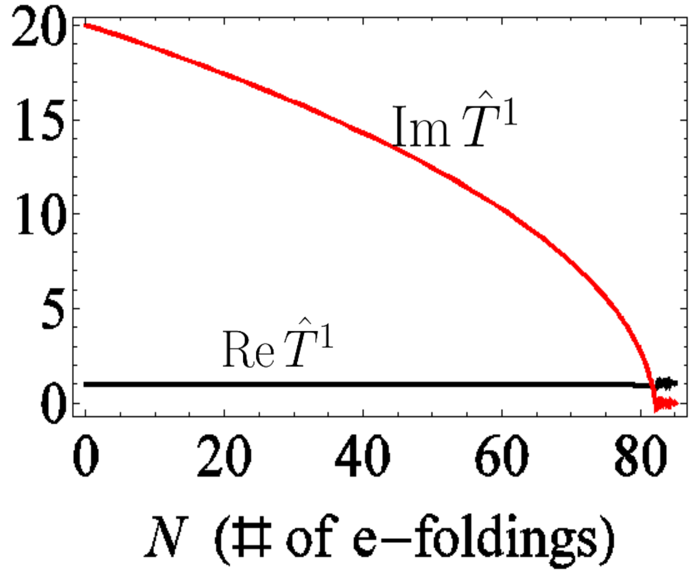
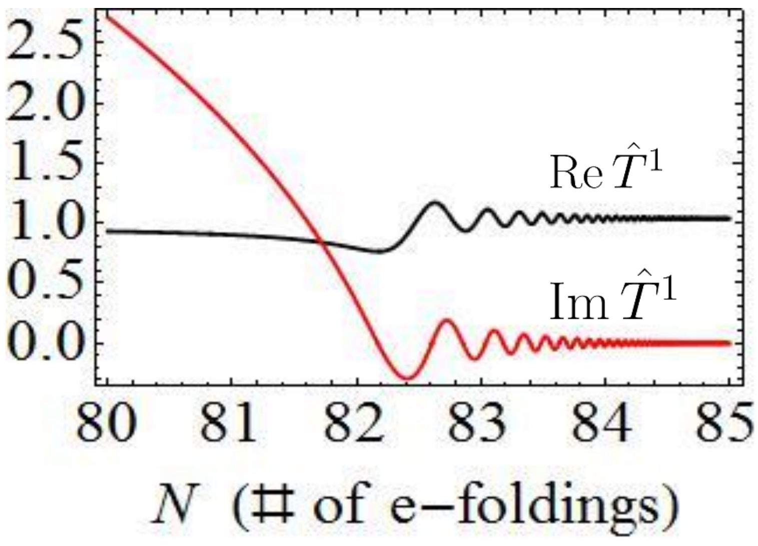
Then we choose $\langle \mathrm{Re}\,\hat{T}^2\rangle/b$ to realize $V_{\mathrm{vac}}(\langle\sigma\rangle) = 0$

$$\frac{2}{\langle \mathrm{Re}\,\hat{T}^2\rangle/b - \langle\sigma\rangle} - \frac{2c\,e^{-2c\,\langle\sigma\rangle}}{1-e^{-2c\,\langle\sigma\rangle}} - c \simeq 0$$

By solving the equations of motion (E.O.M.) for $\mathrm{Re}\,\hat{T}^1$ and $\mathrm{Im}\,\hat{T}^1$,





The E.O.M. for $\mathrm{Re}\,\hat{T}^1$ under the slow-roll regime is

$$\frac{d\sigma}{d\,N} \simeq -g^{\sigma\sigma}\left(\frac{2}{\langle \mathrm{Re}\,\hat{T}^2\rangle/b-\ \sigma} - \frac{2c\,e^{-2c\,\sigma}}{1-e^{-2c\,\sigma}} - c\right) + \frac{V_{\mathrm{vac}}(\sigma)}{V_{\mathrm{eff}}}, \quad (\sigma = \mathrm{Re}\,\hat{T}^1)$$

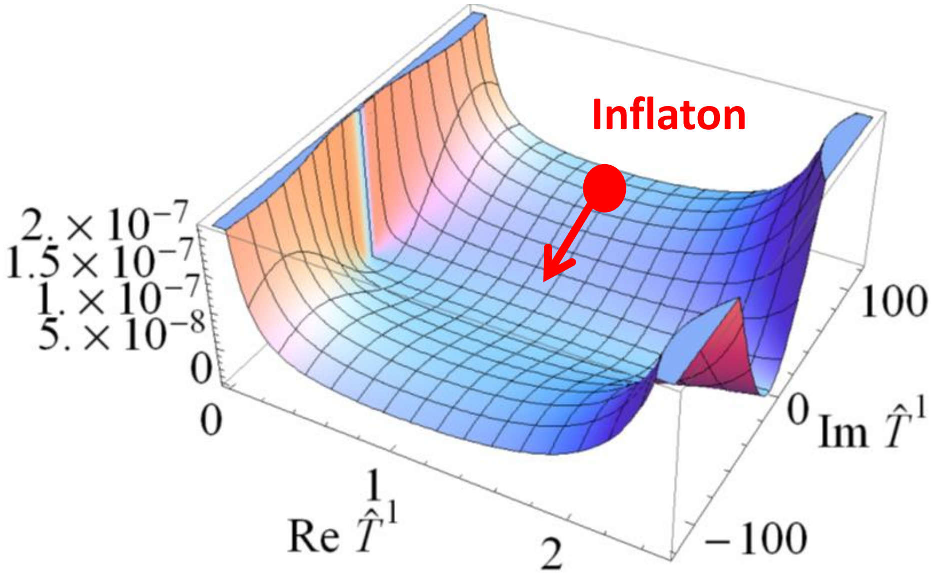
In this case,

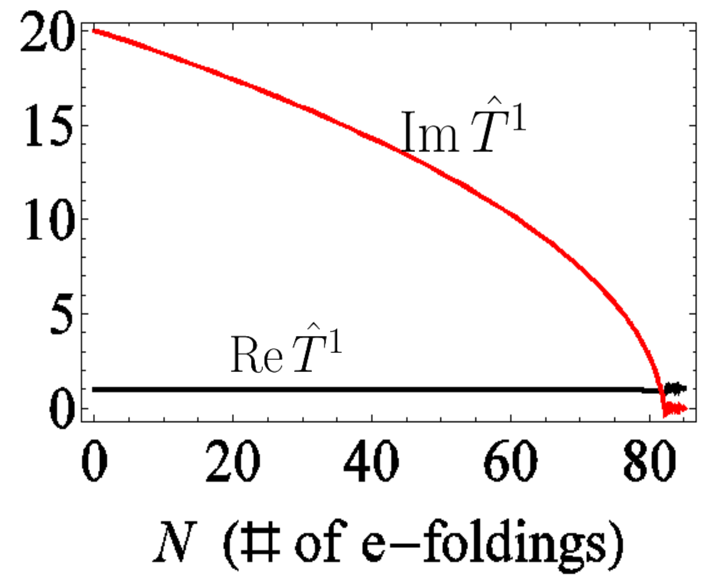
$$\frac{d\sigma}{d\,N} \simeq 0, \quad \mathrm{at}\,\sigma \simeq \langle\sigma\rangle$$

$$V_{\mathrm{vac}}(\langle\sigma\rangle) = 0$$

$$\frac{2}{\langle \mathrm{Re}\,\hat{T}^2\rangle/b-\ \langle\sigma\rangle} - \frac{2c\,e^{-2c\,\langle\sigma\rangle}}{1-e^{-2c\,\langle\sigma\rangle}} - c \simeq 0$$

By solving the equations of motion (E.O.M.) for $\mathrm{Re}\,\hat{T}^1$ and $\mathrm{Im}\,\hat{T}^1$,





The E.O.M. for $\mathrm{Re}\,\hat{T}^1$ under the slow-roll regime is

$$\frac{d\sigma}{dN} \simeq -g^{\sigma\sigma}\left(\frac{2}{\langle \mathrm{Re}\,\hat{T}^2\rangle/b - \sigma} - \frac{2c\,e^{-2c\,\sigma}}{1-e^{-2c\,\sigma}} - c\right) + \frac{V_{\rm vac}(\sigma)}{V_{\rm eff}} \simeq 0$$

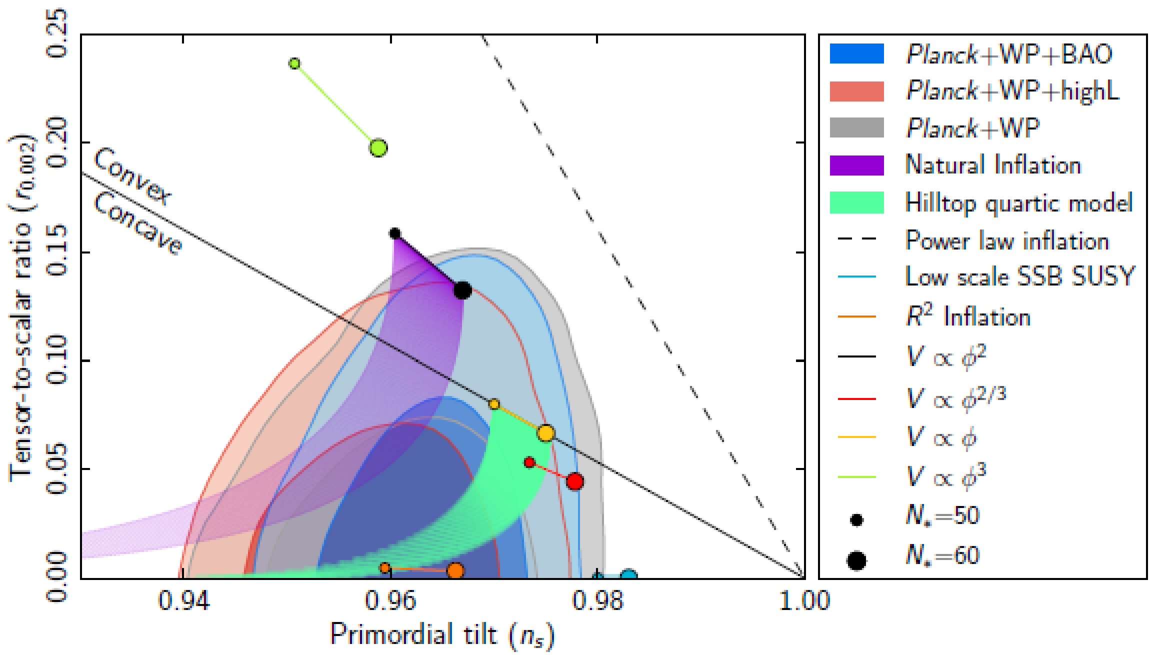
$\mathrm{Re}\,\hat{T}^1$ **is "stabilized" at $\langle \mathrm{Re}\,\hat{T}^1\rangle$ during the inflation.**

⇨ **We can realize the single-field inflation model.**

Cosmological observations

$$P_\xi = 2.18\times10^{-9},\ \ n_s = 0.967,\ \ dn_s/d\ln k = -5.3\times10^{-4},\ \ r = 0.12,\ \ N_* = 64.6$$

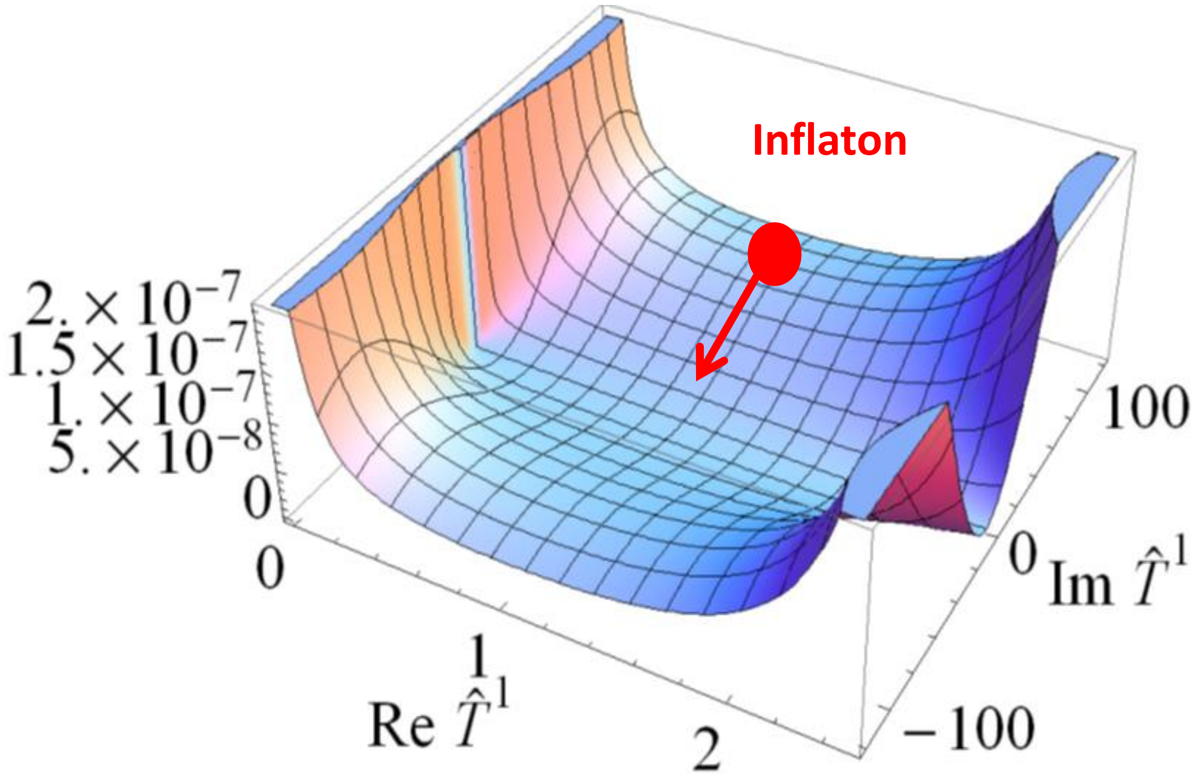
○All results are consistent with the WMAP, Planck and BICEP2 data.
○There is no eta problem peculiar to the supergravity model.
(Kahler potential have a shift symmetry for the inflaton.) $\hat{T}^1 \to \hat{T}^1 + i\alpha^1$



Planck collaboration, XXII
arXiv: 1303.5082 [astro-ph.]

Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

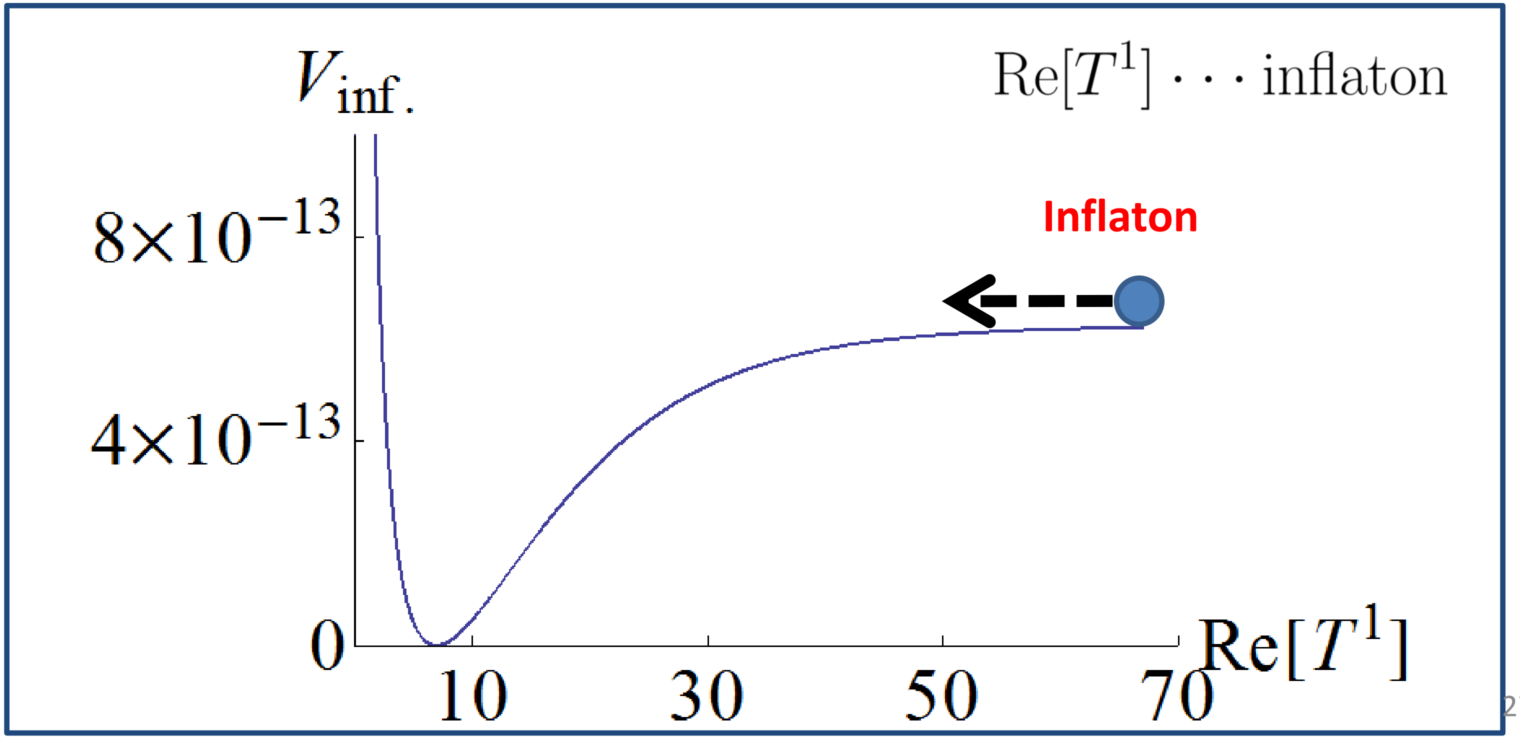
$$K \supset -2\ln\left(\langle \mathrm{Re}\hat{T}^2\rangle - b\,\mathrm{Re}\hat{T}^1\right)$$



In the case of $b=0$, we can realize the **small-field Inflation** on the hypersurface $\mathrm{Im}\, T^1 = H_1 = 0$.

$$V \simeq e^K K^{H_1 \overline{H_1}} |W_{H_1}|^2 \propto \frac{|J_0 - J_L e^{-c^1 T^1}|^2}{1 - e^{-2c\,\mathrm{Re}T^1}}$$

$$K_{H_1 \bar{H}_1} = \frac{1 - e^{-2c\mathrm{Re}T^1}}{c\,\mathrm{Re}T^1}$$



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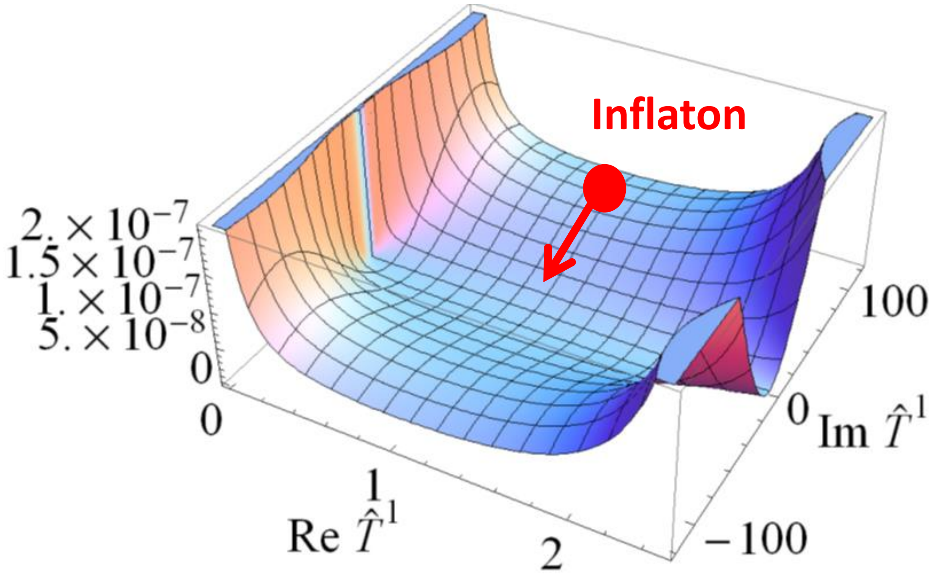
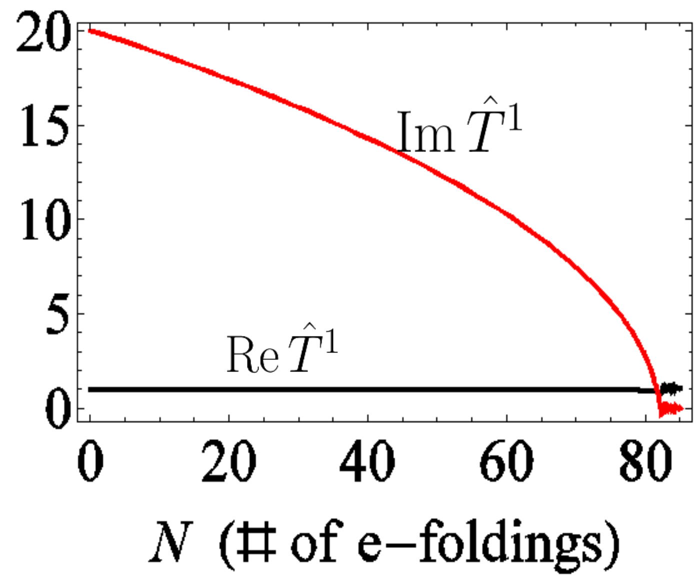
Conclusion





○ **We can realize the large-field inflation in the framework of 5D SUGRA.**

$$P_\xi = 2.18\times10^{-9}, \ \ n_s = 0.967, \ \ dn_s/d\ln k = -5.3\times10^{-4}, \ \ r = 0.12$$

○ **The real part of the modulus is "stabilized" during the inflation.**

○ **There are no eta problem and cosmological moduli problem (moduli-induced gravitino problem).**

Appendix

SUSY breaking sector

We add the following Kahler potential and superpotential of the SUSY breaking sector.

$$K = K_{\text{inf}} + K_{\cancel{\text{SUSY}}}$$

$$W = W_{\text{inf}} + W_{\cancel{\text{SUSY}}}$$

We estimate the deviations from the SUSY preserving minimum.
The F-terms of the moduli and stabilizer fields, in the limit of $m_{3/2} \ll m_{\text{inf}}$ **, are estimated as**

$$m_{3/2} = e^{\langle K \rangle /2} \langle W_{\cancel{\text{SUSY}}} \rangle$$

$$\sqrt{K_{\hat{T}^1 \bar{\hat{T}}^1}} F^{\hat{T}^1} = -e^{K/2} \sqrt{K_{\hat{T}^1 \bar{\hat{T}}^1}} K^{\hat{T}^1 \bar{J}} \overline{D_J W} \simeq \mathcal{O}\left(\frac{(m_{3/2})^3}{(m_{\text{inf}})^2} \right)$$

$$\sqrt{K_{H_1 \bar{H}_1}} F^{H_1} = -e^{K/2} \sqrt{K_{H_1 \bar{H}_1}} K^{H_1 \bar{J}} \overline{D_J W} \simeq \mathcal{O}\left(\frac{(m_{3/2})^3}{(m_{\text{inf}})^2} \right)$$

SUSY breaking sector do not affect the inflation mechanism and the realated cosmology (cosmological moduli problem).

Moduli-induced gravitino problem

Endo, Hamaguchi, Takahashi (2006)
Nakamura,Yamaguchi (2006)

○Overproduction of gravitinos from moduli decay

Moduli and stabilizer fields decay into the gravitino pair.

$$\Gamma(\mathrm{Im}\,\hat{T}^1 \to \Psi_{3/2}\Psi_{3/2}) = \frac{1}{288\pi\sqrt{K_{\hat{T}^1\hat{T}^1}}}\left|\frac{D_{\hat{T}^1}W}{W}\right|^2 \frac{m^5_{\mathrm{Im}\,\hat{T}^1}}{m^2_{3/2}M^2_{\mathrm{Pl}}},$$
$$\simeq 10^{-17}\left(\frac{m_{\mathrm{Im}\,\hat{T}^1}}{10^{13}\,[\mathrm{GeV}]}\right)\left(\frac{m_{3/2}}{10^5\,[\mathrm{GeV}]}\right)^2$$

$$\Gamma_{\mathrm{tot}} \simeq \sum_{a=1}^{3}\Gamma(\mathrm{Im}\,\hat{T}^1 \to g^{(a)} + g^{(a)}) \simeq \sum_{a=1}^{3}\frac{N^a_G}{128\pi}\left\langle\frac{\xi^1_a}{\sqrt{K_{\hat{T}^1\bar{\hat{T}}^1}}\mathrm{Re}\,f_a}\right\rangle^2 \frac{m^3_{\mathrm{Im}\,\hat{T}^1}}{M^2_{\mathrm{Pl}}}$$
$$\simeq 98\ \mathrm{GeV}$$

The decay channel from the inflaton to gravitinos is highly suppressed.

$$\mathrm{Br}_{3/2} = \frac{\Gamma(\mathrm{Im}\,\hat{T}^1 \to \Psi_{3/2}\Psi_{3/2})}{\Gamma_{\mathrm{tot}}} \sim 10^{-19}$$

$$T_{\mathrm{reh}} \simeq 0.45 \times \sqrt{\Gamma_{\mathrm{tot}} M_{\mathrm{Pl}}} \simeq 6.8 \times 10^9\,[\mathrm{GeV}]$$