7/29 基研研究会 素粒子物理学の進展2014

Illustrating SUSY breaking effects on various inflation models

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共同研究者
安倍 博之、青木 俊太朗、長谷川史憲
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H. Abe, S. Aoki, F. Hasegawa and Y. Y, arXiv:1408.XXXX

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Reconsider supergravity inflation from conformal supergravity

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H. Abe, S. Aoki, and Y. Y, work in progress

1. Introduction

SUGRA inflation

Scalar potentialの構造がsupersymmetryで制限される

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SUGRA inflation

Scalar potentialの構造がsupersymmetryで制限される

↓

美しい、しかし、ややこしい。。。

1. Introduction

Scalar potential in “SUSY”

$$\int d^4\theta K(\Phi^I, \bar{\Phi}^{\bar{J}}) + \int d^2\theta W(\Phi^I) + \int d^2\theta f_{AB} \mathcal{W}^{A\alpha}(V)\mathcal{W}^B_\alpha(V) + \mathrm{h.c.}$$

$$V_{\rm global} = K^{I\bar{J}} W_I \bar{W}_{\bar{J}} - \frac{1}{2} \mathrm{Re} f^{-1}_{AB} (K_I k^I_A)(K_J k^J_B)$$

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in SUGRA

$$V_{\text{local}} = e^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2 \right) - \frac{1}{2}\text{Re} f^{-1}_{AB}(K_I k^I_A)(K_J k^J_B)$$

$$D_I W = \partial_I W + \partial_I K W$$

1. Introduction

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$$V_{\text{global}} = K^{I\bar{J}}W_I\bar{W}_{\bar{J}} - \frac{1}{2}\text{Re}f^{-1}_{AB}(K_Ik^I_A)(K_Jk^J_B)$$

in SUGRA

$$V_{\text{local}} = e^K\left(K^{I\bar{J}}D_IWD_{\bar{J}}\bar{W} - 3|W|^2\right) - \frac{1}{2}\text{Re}f^{-1}_{AB}(K_Ik^I_A)(K_Jk^J_B)$$

$$D_IW = \partial_IW + \partial_IKW$$

Supergravitational corrections

1. Introduction

$$V_{\rm global} = K^{I\bar{J}} W_I \bar{W}_{\bar{J}} - \frac{1}{2}{\rm Re} f^{-1}_{AB}(K_I k^I_A)(K_J k^J_B)$$

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"Gravity" mediated effects

ex. SUSY breaking effects on inflation,
"gravity" mediated interaction

SUGRAに"潜んでいる"
compensator multiplet

$$\mathcal{S}_0 = S_0 + \theta\theta F^{S_0}$$

で色々と理解できる

PART 1 S_0

2. SUSY breaking effects on various inflation models

D-term hybrid inflation

$$K = |\Phi|^2 + |S_+|^2 + |S_-|^2$$

$$W = \lambda \Phi S_+ S_-$$

+ 1 loop effective potential

$$V_{\rm eff} = \frac{g^2\chi^2}{2} + \frac{g^4\chi^2}{16\pi^2}\left(1 + \log\frac{\lambda e^{\phi^2}\phi^2}{g^2\chi}\right)$$

$$\phi = |\Phi|$$

P. Binetruy and G. R. Dvali (1996)

E. Halyo (1996)

Universal attractor inflation

$$K = -3\log(-\Omega/3)$$

$$\Omega = -3 - \frac{3}{2}\xi f(\Phi) - \frac{3}{2}\xi f(\Phi) - \frac{1}{2}(\Phi - \bar{\Phi})^2 + g(S, \bar{S})$$

$$W = \lambda f(\phi) S$$

$$V_{\rm eff} = \frac{\lambda^2 f(\phi)^2}{(1 + \xi f(\phi))^2}$$

$$\phi = \frac{{\rm Re}\,\Phi}{\sqrt{2}}$$

R. Kallosh, A. Linde and D. Roest (2013)

2. SUSY breaking effects on various inflation models

D-term hybrid inflation

$$\delta K = |X|^2 - \frac{|X|^4}{\Lambda^2}$$

$$V_{\text{eff}} = \frac{g^2\chi^2}{2} + \frac{g^4\chi^2}{16\pi^2}\left(1 + \log\frac{\lambda e^{\phi^2}\phi^2}{g^2\chi}\right)$$

$$W_{\cancel{\text{SUSY}}} = \sqrt{3}W_0 X + W_0$$

$$\phi = |\Phi|$$

Universal attractor inflation

$$\delta\Omega = |X|^2 - \frac{|X|^4}{\Lambda^2}$$

$$V_{\text{eff}} = \frac{\lambda^2 f(\phi)^2}{(1 + \xi f(\phi))^2}$$

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$$+ e^{\phi^2}\phi^2 W_0^2$$

$$\phi = |\Phi|$$

Universal attractor inflation

$$\delta \Omega = |X|^2 - \frac{|X|^4}{\Lambda^2}$$

$$W_{\not{\text{SUSY}}} = \sqrt{3} W_0 X + W_0$$

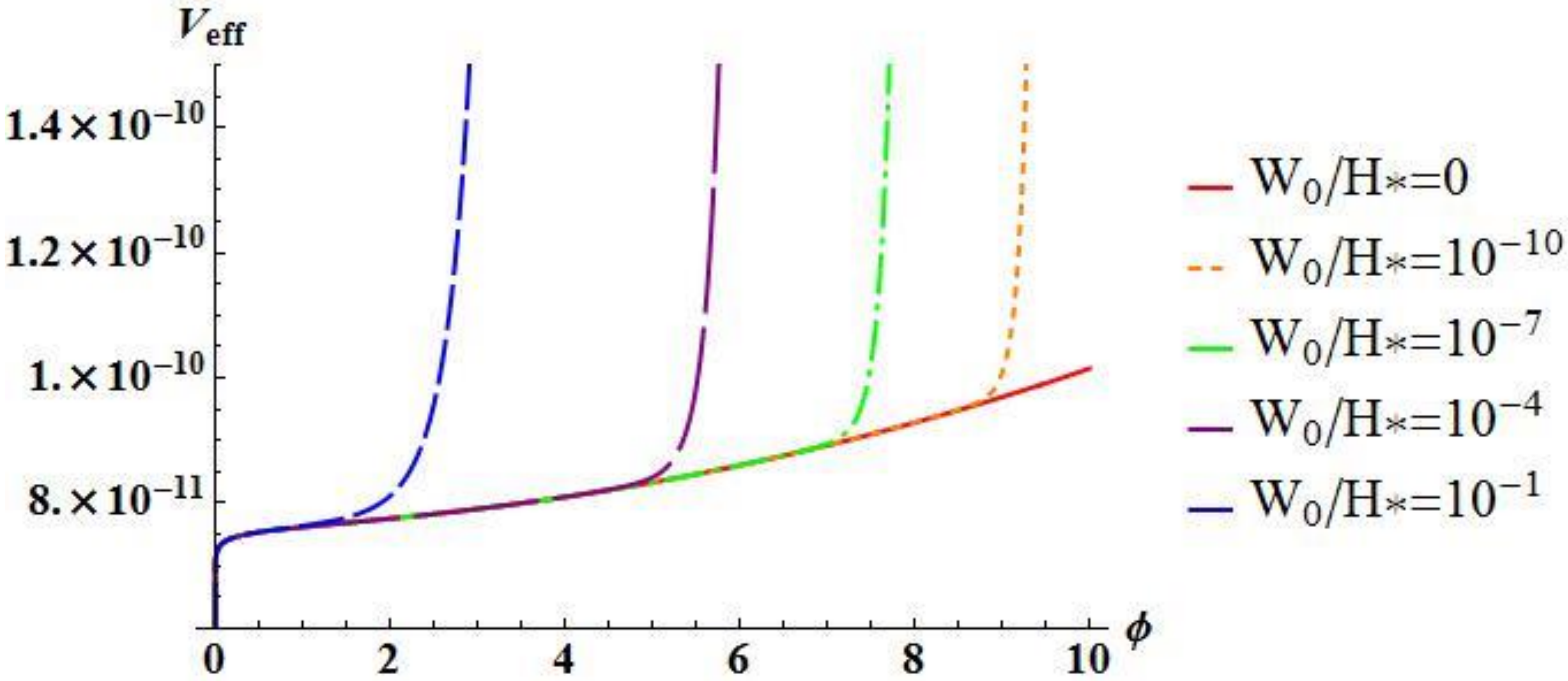
$$\Rightarrow \quad V_{\text{eff}} = \frac{\lambda^2 f(\phi)^2}{(1 + \xi f(\phi))^2}$$

$$\phi = \frac{\text{Re}\, \Phi}{\sqrt{2}}$$

$$+ \frac{3 W_0^2}{(1 + \xi f(\phi))^2} \frac{\xi f(\phi) + \frac{3}{2}\xi^2 f'(\phi)^2}{1 + \xi f(\phi) + \frac{3}{2}\xi^2 f'(\phi)^2}$$

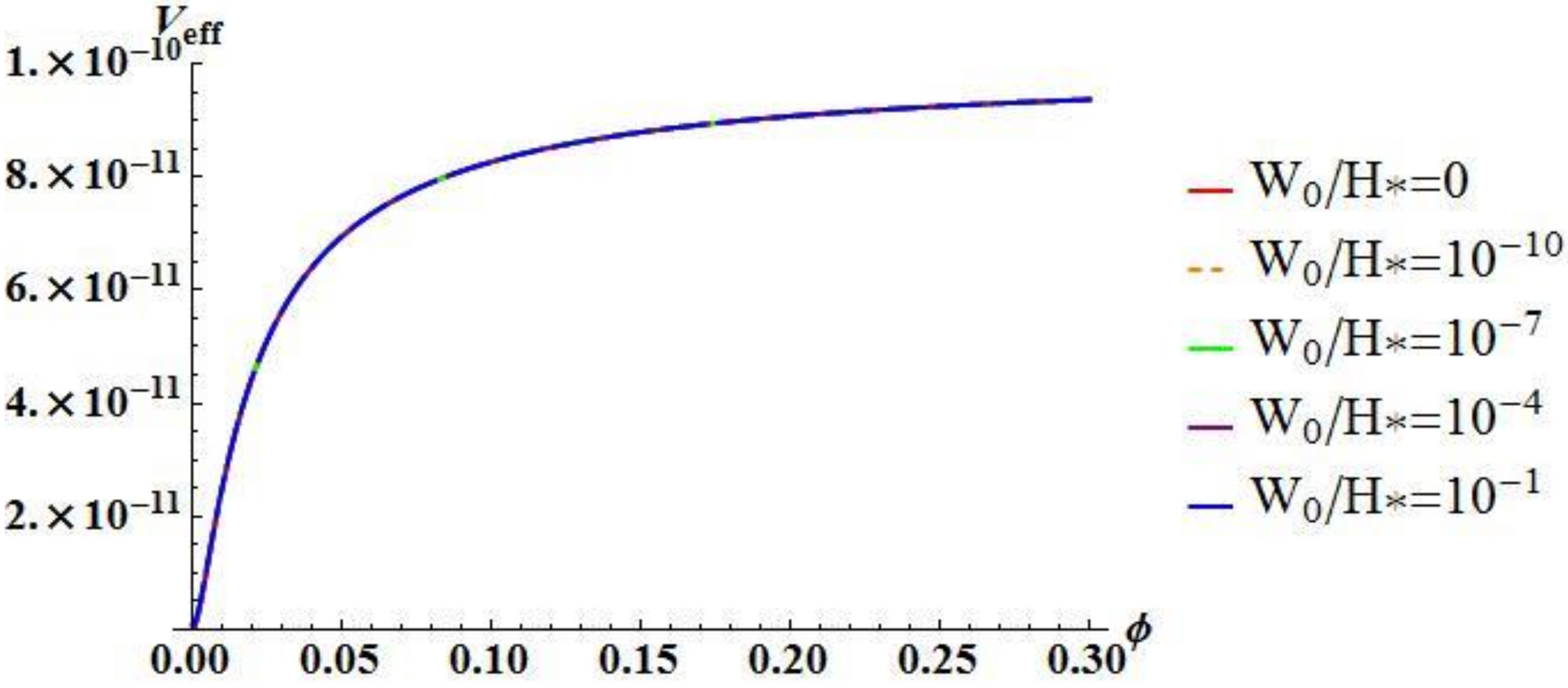
2. SUSY breaking effects on various inflation models

D-term hybrid inflation



2. SUSY breaking effects on various inflation models

Universal attractor inflation



3. Review of conformal SUGRA

Superconformal symmetry

generators	
P	Translation
Q	SUSY
M	Lorentz rotation
D	Dilatation
A	Chiral U(1)
S	S-SUSY
K	Conformal boost

Ex. Dilatation transformation

$$\phi \longrightarrow \phi e^{\sigma}$$

$$g_{\mu\nu} \longrightarrow g_{\mu\nu} e^{-2\sigma}$$

3. Review of conformal SUGRA

Superconformal symmetry

generators	
P	Translation
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D, A, S, K: Gauge fixing

→ Compensator multipletが必要

$$S_0 = S_0 + \theta\theta F^{S_0}$$

→ Poincaré SUSY

generators	
P	Translation
Q	SUSY
M	Lorentz rotation

+global U(1)R, Kahler symmetry

3. Review of conformal SUGRA

General SUGRA action

$$\frac{1}{2}\left[S_0\bar{S}_0\Omega(\phi^I,\bar{\phi}^{\bar{J}})\right]_D+\left[S_0^3W(\phi^I)\right]_F-\frac{1}{4}\left[f_{AB}\mathcal{W}^{\alpha A}\mathcal{W}^B_\alpha\right]$$

T. Kugo and S. Uehara (1983)

S_0 : compensator

$$\Omega=-3e^{-K/3}$$

$$\Rightarrow\quad \mathcal{L}=\frac{1}{6}S_0\bar{S}_0\Omega(\phi^I,\bar{\phi}^{\bar{J}})R+\cdots$$

D-gauge fixing condition

$$S_0\bar{S}_0\Omega(\phi^I,\bar{\phi}^{\bar{J}})=-3\quad\Rightarrow\quad \mathcal{L}_E=-\frac{1}{2}R+\cdots$$ (Einstein frame)

$$S_0\bar{S}_0=1\quad\Rightarrow\quad \mathcal{L}_J=\frac{1}{6}\Omega(\phi^I,\bar{\phi}^{\bar{J}})R+\cdots$$ (Jordan frame)

3. Review of conformal SUGRA

D-gauge fixing condition

$$S_0 \bar{S}_0 \Omega(\phi^I, \bar{\phi}^{\bar{J}}) = -3 \quad \Rightarrow \quad \mathcal{L}_E = -\frac{1}{2}R + \cdots$$

(Einstein frame)

A-gauge fixing condition

$$S_0 = \bar{S}_0 \quad \Rightarrow \quad S_0 = \sqrt{-\frac{3}{\Omega(\phi^I, \bar{\phi}^{\bar{J}})}} (= e^{K/6})$$

compensatorはfundamentalな場ではなくなる

3. Review of conformal SUGRA

F-term scalar potential in conformal SUGRA

$$V_F = |S_0|^4 \mathcal{M}^{I\bar{J}} \left(W_I - \frac{3\Omega_I}{\Omega} W \right) \left(\bar{W}_{\bar{J}} - \frac{3\Omega_{\bar{J}}}{\Omega} \bar{W} \right) + \frac{9|S_0|^4}{\Omega} |W|^2,$$

$$\mathcal{M}_{I\bar{J}} = \Omega_{I\bar{J}} - \frac{\Omega_I \Omega_{\bar{J}}}{\Omega}$$

$S_0 = \sqrt{-\frac{3}{\Omega}}$ & $\Omega = -3e^{-K/3}$

⇒ $$V_F = e^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2 \right)$$

3. Review of conformal SUGRA

F-term scalar potential in conformal SUGRA

$$V_F = |S_0|^4 \mathcal{M}^{I\bar{J}} \left(W_I - \frac{3\Omega_I}{\Omega} W \right) \left(\bar{W}_{\bar{J}} - \frac{3\Omega_{\bar{J}}}{\Omega} \bar{W} \right) + \frac{9|S_0|^4}{\Omega} |W|^2,$$

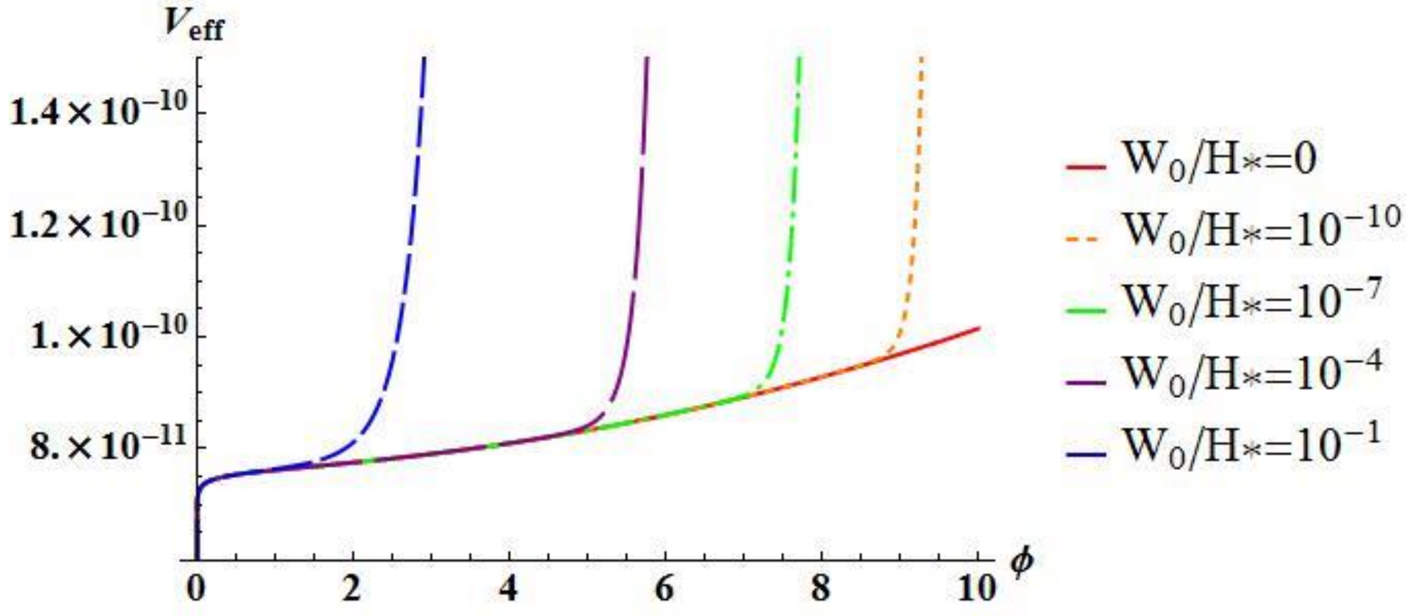
$$S_0 = \sqrt{-\frac{3}{\Omega}} \quad \& \quad \Omega = -3e^{-K/3}$$

$$\mathcal{M}_{I\bar{J}} = \Omega_{I\bar{J}} - \frac{\Omega_I \Omega_{\bar{J}}}{\Omega}$$

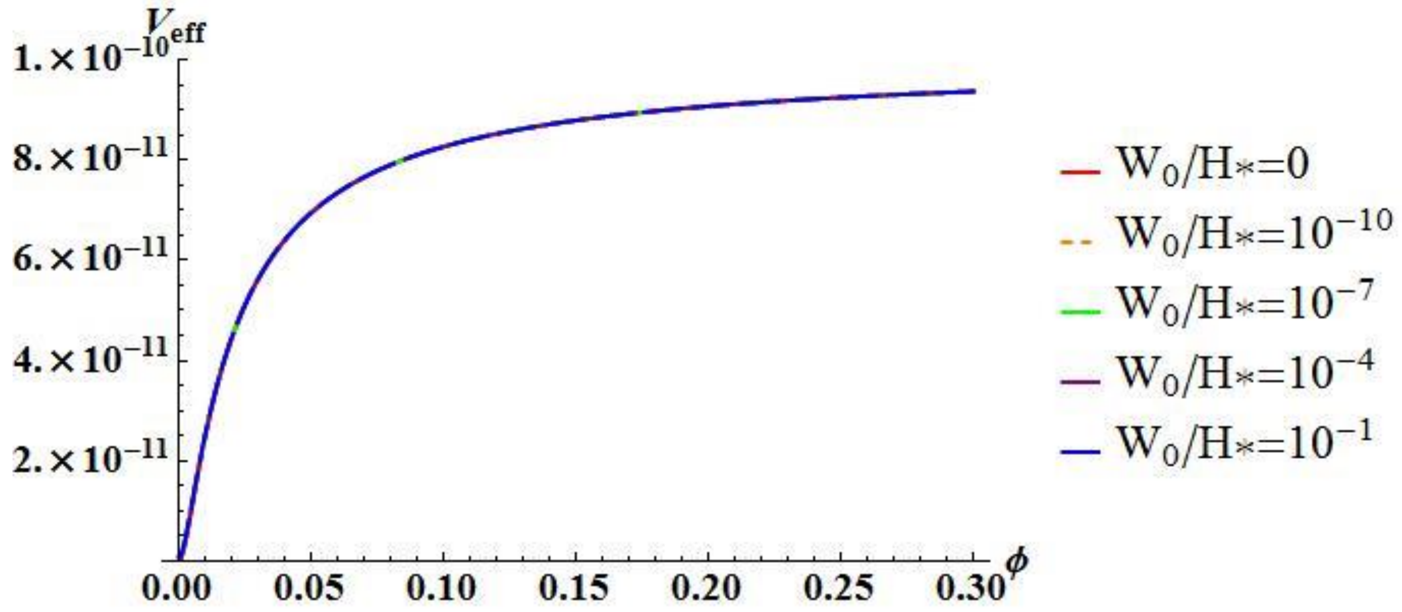
$$\Rightarrow \quad V_F = e^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2 \right)$$

4. SUSY breaking effects from conformal SUGRA view point

D-term hybrid inflation



Universal attractor inflation



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$$V_{\mathrm{eff}} = \frac{g^2\chi^2}{2} + \frac{g^4\chi^2}{16\pi^2}\left(1 + \log\frac{\lambda e^{\phi^2}\phi^2}{g^2\chi}\right) - \frac{27W_0^2}{\Omega^3}\phi^2$$

$\Omega = -3e^{-\phi^2/3}$ ➡ enhancement

Universal attractor inflation

$$V_{\mathrm{eff}} = \frac{9\lambda^2 f(\phi)^2}{\Omega^2} + \frac{27W_0^2}{\Omega^2}\,\frac{\xi f(\phi) + \frac{3}{2}\xi^2 f'(\phi)^2}{1 + \xi f(\phi) + \frac{3}{2}\xi^2 f'(\phi)^2}$$

$\Omega = -3(1 + \xi f(\phi))$ ➡ suppression

4. SUSY breaking effects from conformal SUGRA view point

$$S_0\bar{S}_0 = 1 \quad \Rightarrow \quad \mathcal{L}_J = \frac{1}{6}\Omega(\phi^I, \bar{\phi}^{\bar{J}})R + \cdots$$

実効的なPlanck massの変化

⟺ "Gravity" mediated couplingsのenhancement/suppression

"compensated" terms → enhancement/suppression effectsが生じる

Minimal Kahler models: $\Omega = -3e^{-|\Phi|^2/3}$ ⇒ η-problem

$$K = |\Phi|^2$$

Higher derivative extensionをしても同様の議論が出来る！ (青木くんのポスター)

PART 2 F^{S_0}

6. SUGRA inflation without SUGRA corrections

補助場を消去する前のF-termポテンシャル

$$V_F = -S_0\bar{S}_0\Omega_{I\bar{J}}F^I\bar{F}^{\bar{J}} - \left(S_0^3 W_I F^I + \mathrm{h.c.}\right) + \Omega\tilde{F}^{S_0}\bar{\tilde{F}}^{\bar{S}_0}$$

$$\tilde{F}^{S_0} = -\frac{1}{\Omega}\left(\bar{S}_0\Omega_I F^I + 3\bar{S}_0^2\bar{W}\right)$$

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$$\tilde{F}^{S_0} = -\frac{1}{\Omega}\left(\bar{S}_0\Omega_I F^I + 3\bar{S}_0^2\bar{W}\right)$$

もし $\tilde{F}^{S_0} = 0$ なら

$$V_F|_{\tilde{F}^{S_0}=0} = |S_0|^4\Omega^{I\bar{J}}W_I\bar{W}_{\bar{J}}$$

Global SUSY like scalar potential !

c.f.

$$\begin{aligned} V_F &= |S_0|^4\mathcal{M}^{I\bar{J}}\left(W_I - \frac{3\Omega_I}{\Omega}W\right)\left(\bar{W}_{\bar{J}} - \frac{3\Omega_{\bar{J}}}{\Omega}\bar{W}\right) \\ &+ \frac{9|S_0|^4}{\Omega}|W|^2 \end{aligned}$$

$$V_{\mathrm{global}} = K^{I\bar{J}}W_I\bar{W}_{\bar{J}}$$

6. SUGRA inflation without SUGRA corrections

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$$V_{\text{global}} = K^{I\bar{J}}W_I\bar{W}_{\bar{J}}$$

こんなことが起こるのか？

6. SUGRA inflation without SUGRA corrections

Chaotic inflation in SUGRA

$$K = \frac{1}{2}(\Phi + \bar{\Phi})^2 + |S|^2 + \cdots$$

$$W = f(\Phi)S$$

M. Kawasaki, M. Yamaguchi, and T. Yanagida(2000)
R. Kallosh, A. Linde, and T. Rube (2010)

⇒

インフレーション中

$$S = \mathrm{Re}\Phi = 0$$

$$\begin{aligned} V &= K^{S\bar{S}} W_S \bar{W}_{\bar{S}} \\ &= f^2(\mathrm{Im}\Phi) \end{aligned}$$

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インフレーション中

$$S = \mathrm{Re}\Phi = 0$$

$$\begin{aligned} V &= K^{S\bar{S}} W_S \bar{W}_{\bar{S}} \\ &= f^2(\mathrm{Im}\Phi) \end{aligned}$$

$$\begin{aligned} \tilde{F}^{S_0} &= \frac{e^{K/3}}{3}\left(\bar{S}_0 e^{-K/3}(\Phi + \bar{\Phi})F^{\Phi} + \bar{S}_0 e^{-K/3}\bar{S}F^S + 3\bar{S}_0^2 \bar{f}(\bar{\Phi})\bar{S}\right) \\ &= 0 \end{aligned}$$

① inflation trajectoryによってSUGRA correctionを消去

6. SUGRA inflation without SUGRA corrections

No-scale model

$$\Omega = -3(T + \bar{T}) + \hat{\Omega}(\Phi, \bar{\Phi})$$

$$W = W(\Phi)$$

6. SUGRA inflation without SUGRA corrections

No-scale model

$$\Omega = -3(T+\bar{T}) + \hat{\Omega}(\Phi, \bar{\Phi})$$

$$W = W(\Phi)$$

⇒ $\tilde{F}^{S_0} \equiv 0$ No SUGRA corrections

② No-scale structureでSUGRA correctionを消去

6. SUGRA inflation without SUGRA corrections

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$$\Omega = -3(T+\bar{T}) + \hat{\Omega}(\Phi, \bar{\Phi})$$

$$W = W(\Phi)$$

⇒ $\tilde{F}^{S_0} \equiv 0$ No SUGRA corrections

② No-scale structureでSUGRA correctionを消去

apploximately No-scale model (e.g. LARGE volume scenario

V. Balasubramanian et al. (2005)

J. P. Conlon et al. (2005)

$$\Omega = -3(T+\bar{T}) + \hat{\Omega}(\Phi, \bar{\Phi}) + \frac{\xi}{(T+\bar{T})^2}$$

$$W = W(\Phi)$$

⇒ $\langle T+\bar{T}\rangle \gg 1$ のとき

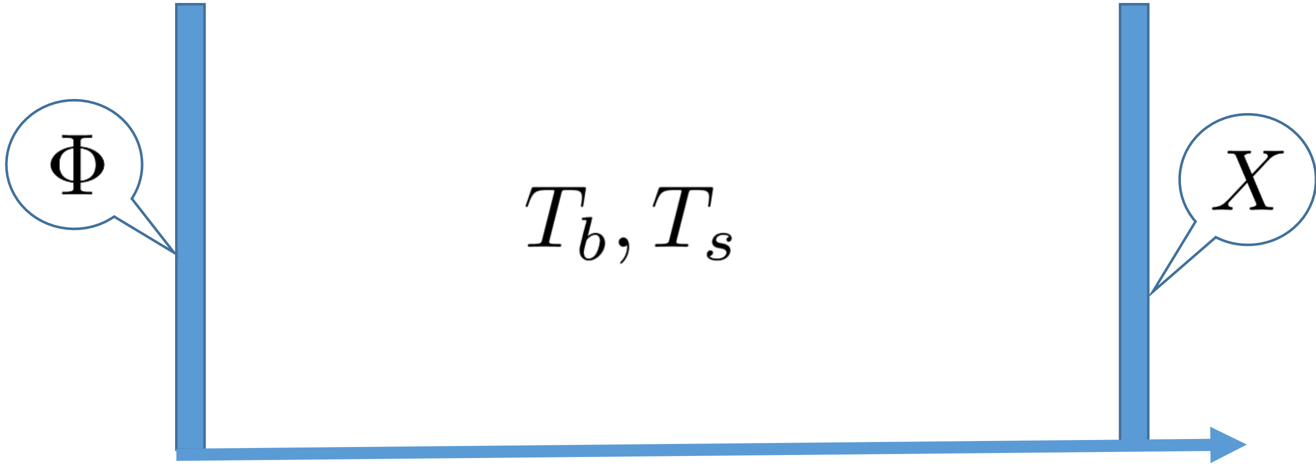
SUGRA corrections $\propto \dfrac{\xi}{(T+\bar{T})^3}$

(In string theory)

Application to the tadpole problem in hybrid inflation
T. Higaki, K. S. Jeong, F. Takahashi (2012)

D7-brane chaotic inflation
A. Hebecker, S. C. Kraus, L. T. Witkowski

6. SUGRA inflation without SUGRA corrections



5D: S^1/Z_2

LVS in effective theory of 5D SUGRA

Y. Sakamura and Y. Y (2013), (2014)

$$\Omega_{\rm eff} = -3({\rm Re}T_b) + \frac{\xi}{({\rm Re}T_b)^2} + \frac{C({\rm Re}T_s)^3}{({\rm Re}T_b)^3} + \Omega_{\rm brane} + \cdots$$

$$\Omega_{\rm brane} = \hat{\Omega}(\Phi, \bar{\Phi}) + |X|^2 - \frac{|X|^4}{\Lambda^2}$$

$$W_{4D} = W_0 + Ae^{-aT_s} + \hat{W}(\Phi) + \mu^2 X$$

$$\langle ({\rm Re}T_b)^3 \rangle \propto e^{a\langle {\rm Re}T_s \rangle}$$

$$\frac{\xi}{\langle {\rm Re}T_b^3 \rangle} \ll 1$$

Approximately No-scale !

6. SUGRA inflation without SUGRA corrections

T_b, T_s, X をintegrate out

$$V_{\rm eff} = \frac{1}{\langle\tau_b^2\rangle}\Omega_{\Phi\bar{\Phi}}^{-1}|\hat{W}_\Phi|^2\left(1+\frac{2\hat{\Omega}}{3\langle\tau_b\rangle}\right) - \frac{4C\langle\tau_s^3\rangle|W_0|}{\Omega_{\Phi\bar{\Phi}}\langle\tau_b^6\rangle}\left(\Omega_\Phi\bar{\hat{W}}_{\bar{\Phi}} + \text{h.c.}\right) - \frac{6(C\langle\tau_s^3\rangle-\xi)|W_0|}{\langle\tau_b^6\rangle}(\hat{W}(\Phi)+\text{h.c.}) + \frac{6\xi}{\langle\tau_b^6\rangle}|\hat{W}(\Phi)|^2$$

Global SUSY like parts

Suppressed SUGRA corrections

SUGRA inflation without SUGRA corrections!

※compensatorからの寄与は残る

6. SUGRA inflation without SUGRA corrections

Example: chaotic inflation

$$\hat{\Omega}(\Phi,\bar{\Phi}) = \frac{1}{2}(\Phi+\bar{\Phi})^2$$

$$\hat{W}(\Phi) = \frac{1}{2}m\Phi^2$$

$$\Rightarrow$$

$$V_{\text{eff}} \;=\; \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}m_\chi^2\chi^2 + \frac{3\xi\tilde{m}^2}{8\langle\tau_b^3\rangle}(\phi^4+\chi^4),$$

$$m_\phi^2 \;\equiv\; \tilde{m}^2 + \frac{27M}{(a\langle\tau_s\rangle+2)}\left(1-\frac{1}{2(a\langle\tau_s\rangle+2)}\right)\tilde{m},$$

$$m_\chi^2 \;\equiv\; \frac{2}{3}\tilde{m}^2(\phi^2+\frac{3}{2}) - \frac{M\tilde{m}}{8} - \frac{27M\tilde{m}}{(a\langle\tau_s\rangle+2)}\left(1-\frac{1}{2(a\langle\tau_s\rangle+2)}\right) + \frac{3\xi\tilde{m}^2\phi^2}{4\tau_b^3},$$

$$\tilde{m} \equiv m/\langle\tau_b^{1/2}\rangle \qquad M \equiv C\langle\tau_s^3\tau_b^{-9/2}\rangle \qquad \Phi \equiv (\chi+i\phi)/\sqrt{2}\langle\tau_b^{1/2}\rangle$$

6. SUGRA inflation without SUGRA corrections

$$|W_0| = |A| = 1, \quad a = 4\pi^2, \quad \xi = 0.03, \quad C = 1$$

$$\Rightarrow \langle \tau_b^3 \rangle \sim 6019, \quad \langle \tau_s \rangle \sim 0.345, \quad M \sim 8.80 \times 10^{-8} \ll \tilde{m} \sim 6 \times 10^{-6}$$

$$V_{\rm eff} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_\chi^2 \chi^2 + \frac{3\xi \tilde{m}^2}{8\langle \tau_b^3 \rangle} (\phi^4 + \chi^4),$$

$$\sim \boxed{\frac{1}{2} \tilde{m}^2 \phi^2}$$ Simple chaotic inflation

$$m_\phi^2 \equiv \tilde{m}^2 + \frac{27M}{(a\langle \tau_s \rangle + 2)} \left(1 - \frac{1}{2(a\langle \tau_s \rangle + 2)} \right) \tilde{m},$$

$$m_\chi^2 \equiv \frac{2}{3} \tilde{m}^2 (\phi^2 + \frac{3}{2}) - \frac{M\tilde{m}}{8} - \frac{27M\tilde{m}}{(a\langle \tau_s \rangle + 2)} \left(1 - \frac{1}{2(a\langle \tau_s \rangle + 2)} \right) + \frac{3\xi \tilde{m}^2 \phi^2}{4\tau_b^3},$$

$$M \equiv C \langle \tau_s^3 \tau_b^{-9/2} \rangle$$

7. Summary

Supergravitational corrections
= couplings between compensator and matters

S_0 ➡ 全ての“compensated” termのEnhancement/Suppression effects

F^{S_0} ➡ “gravity” mediated interactionsの原因

SUGRA potential without SUGRA corrections

① $\tilde{F}^{S_0}$ vanishing trajectory

② No-scale (or approximately No-scale) model

Backup slides

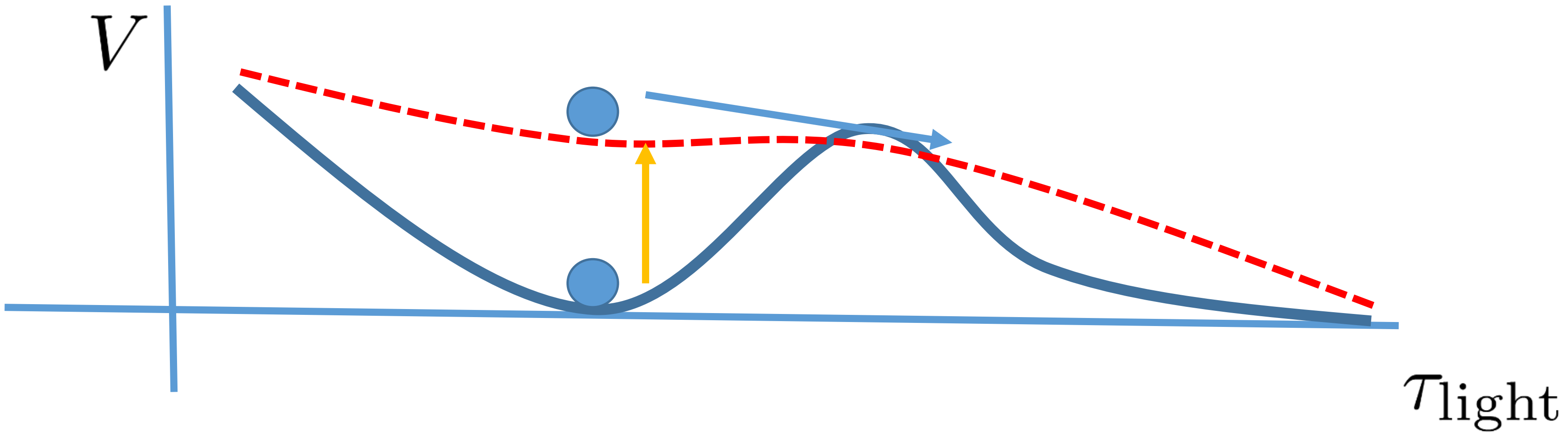
Effective theory of 5D SUGRA

5D multiplet	Hypermultiplet		Vector multiplet			
Role in 4D	Chiral		Vector		Moduli (chiral)	
Superfield in 4D	$\mathcal{Q}_a$ (chiral)	$\mathcal{Q}_a^c$ (chiral)	V^{I_e} (vector)	Σ^{I_e} (chiral)	V^{I_o} (vector)	Σ^{I_o} (chiral)
Z_2 parity	$+$	$-$	$+$	$-$	$-$	$+$
Zero mode	Q_a		V^{I_e}			T^{I_o}

$T_{b,s}$

Constraint on approximately no-scale inflation & SUSY breaking scale

最も軽いmodulus($\tau_{\rm light}$)のovershooting problemを避ける



Hubble correctionによって、$\tau_{\rm light}$がポテンシャル障壁を超えないためには次の条件が必要

$$m_{\rm light} \sim \langle \tau_b^{-3} \rangle > H_{\rm inf}$$

$$\Rightarrow \quad m_{3/2} = \langle e^{K/2} W \rangle \sim \langle \tau_b^{-3/2} \rangle > \sqrt{H_{\rm inf}}$$

High scale SUSY breaking !