Inflation and Supersymmetry Breaking in Higgs-R2 Supergravity

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Based on JHEP 10(2021)178

Seminar @ IBS 2022/2/23

Contents

- Introduction

    Unitarity issue in Higgs inflation

    Higgs-R^2 model

- Supergravity embedding

    Unitarity in linear-sigma frame

    Inflation, stabilization

    Supersymmetry breaking

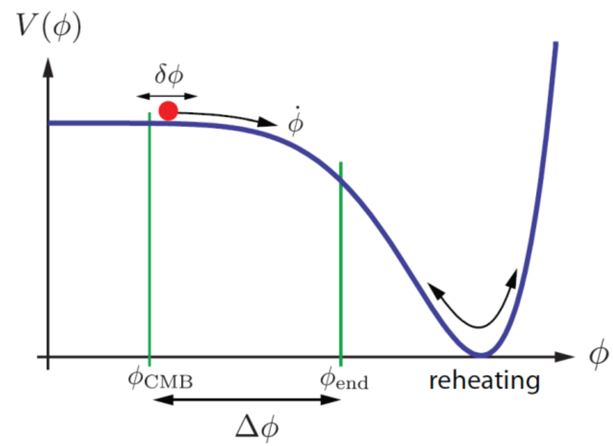
- Summary & Discussion

    How to distinguish from non-susy model?

Introduction

Inflation

- Rapid expansion of early universe
- theoretically & observationally established
  (solve flatness, horizon, monopole problems)
- Slow roll inflation (scalar field)



arXiv:0907.5424

Higgs inflation

Inflaton = SM Higgs boson
The original SM Higgs potential ×

$$V = \lambda_H \left(\mathcal{H}^\dagger \mathcal{H} - \frac{v_H^2}{2} \right)^2$$

$\lambda_H \rightarrow O(10^{-12})$

Higgs inflation

F. L. Bezrukov, M. Shaposhnikov, '08

Non-minimal coupling

$$\mathcal{L}_J = \sqrt{-g_J}\left[\frac{1+\xi h^2}{2}R\left(g_J\right) - \frac{1}{2}\partial_\mu h \partial_\nu h g_J^{\mu\nu} - \frac{\lambda}{4}h^4\right]$$

conformal trans.

$$g_E^{\mu\nu} = \Omega^2 g_J^{\mu\nu} \qquad \Omega^2 = 1+\xi h^2$$

$$\mathrm{d}\psi \equiv \mathrm{d}h\sqrt{\frac{\Omega^2+6\xi^2h^2}{\Omega^4}}$$

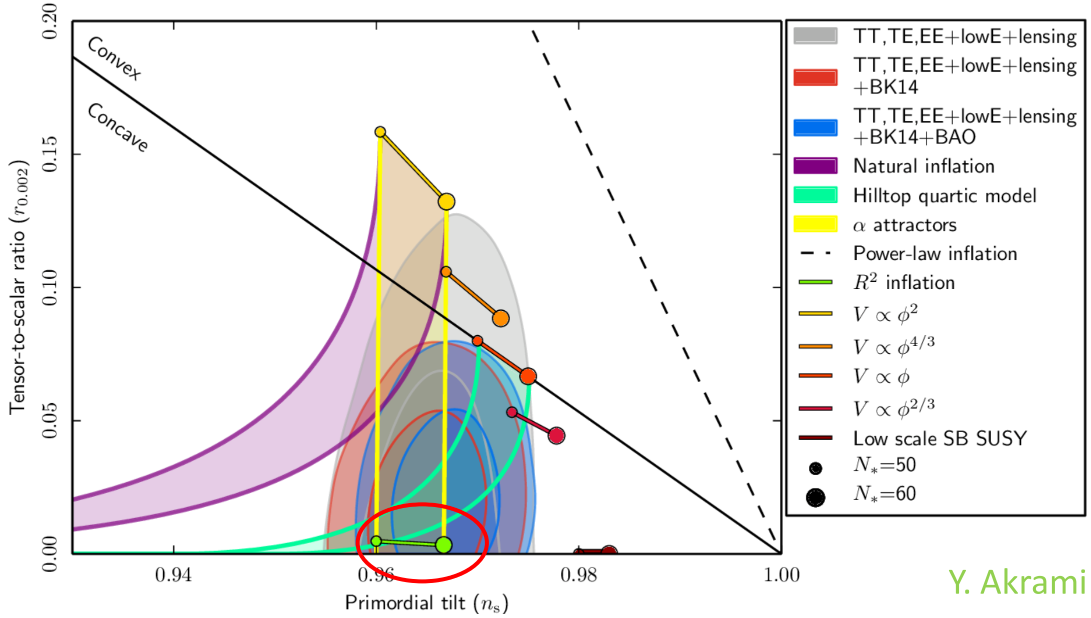
$$\mathcal{L}_E = \sqrt{-g_E}\left(\frac{1}{2}R(g_E) - \frac{1}{2}\partial_\mu\psi\partial_\nu\psi\, g_E^{\mu\nu} - U(\psi)\right)$$

For $h \gg 1/\sqrt{\xi}$ $\qquad U(\psi) \approx \dfrac{\lambda}{4\xi^2}\left(1+\mathrm{e}^{-\frac{2\psi}{\sqrt{6}}}\right)^{-2}$

Higgs inflation

F. L. Bezrukov, M. Shaposhnikov, '08

$$r = 8\left(\frac{V'}{V}\right)^2,\ n_s - 1 = -3\left(\frac{V'}{V}\right)^2 + 2\frac{V''}{V}$$



Y. Akrami et al., Planck 2018

CMB observation ⇒ $\xi^2/\lambda \sim 10^{10}$

⇒ Large non-minimal coupling $\xi \sim 10^4$

Unitarity problem in Higgs inflation

- Low cut off scale : $\Lambda \sim M_{pl}/\xi$ ⇒ ?? perturbation

Burgess, Lee, Trott, '09
Barbon, Espinosa, '09

c.f., $H_{\mathrm{inf}} \sim \sqrt{\lambda}\,\Lambda$,

$h \gg M_{pl}/\sqrt{\xi} \gg \Lambda$

Unitarity problem in Higgs inflation

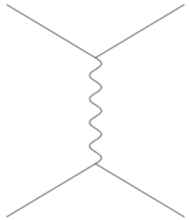
- Low cut off scale : $\Lambda \sim M_{pl}/\xi \Rightarrow$?? perturbation

Burgess, Lee, Trott, '09
Barbon, Espinosa, '09

c.f., $H_{\rm inf} \sim \sqrt{\lambda}\,\Lambda$,
$h \gg M_{pl}/\sqrt{\xi} \gg \Lambda$

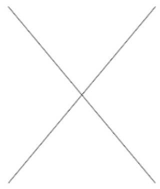
In Jordan frame

$$\sqrt{-g_J}\xi h^2 R_J \supset \boxed{\frac{\xi}{M_p}} h^2 \eta^{\mu\nu} \partial^2 h^J_{\mu\nu}$$



In Einstein frame

$$-g^{\mu\nu}\left[f(D_\mu \mathcal{H})^\dagger (D_\nu \mathcal{H}) + \boxed{\frac{3\,\xi^2 f^2}{2\,M_p^2}} \partial_\mu(\mathcal{H}^\dagger \mathcal{H})\,\partial_\nu(\mathcal{H}^\dagger \mathcal{H})\right]$$



$$f = \left[1 + 2\,\xi(\mathcal{H}^\dagger \mathcal{H})/M_p^2\right]^{-1}$$

Unitarity problem in Higgs inflation

- However, cutoff scale depends on the inflaton field ⇒ $\Lambda' \sim \sqrt{\xi} h$

Bezrukov, Magnin, Shaposhnikov, Sibiryakov' 10
Ferrara, Kallosh, Linde, Marrani, Van Proeyen' 10

- Unitarity problem again in preheating
  (Particles with momentum above the cutoff are generated)

Ema, Jinno, Mukaida, Nakayama' 17

Solution

One of solutions : Introduce a new d.o.f $\boldsymbol{\sigma}$ (like Higgs boson in SM)

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \frac{1}{2}\left(\bar{M}^2 + \underline{\xi\bar{\sigma}^2} + 2\zeta\mathcal{H}^\dagger\mathcal{H}\right)R - \frac{1}{2}\underline{(\partial_\mu\bar{\sigma})^2} - |D_\mu\mathcal{H}|^2$$
$$-\frac{1}{4}\kappa\left(\underline{\bar{\sigma}^2} - \bar{\Lambda}^2 - 2\alpha\mathcal{H}^\dagger\mathcal{H}\right)^2 - \lambda\left(\mathcal{H}^\dagger\mathcal{H} - \frac{v^2}{2}\right)^2.$$

Giudice, Lee '10
...

cut off ⇒ M_{pl}
σ-field linearize Higgs kinetic term = UV completion of Higgs inflation

R^2 (Starobinsky) model

Starobinsky, '80, 83

$$\mathcal{L} = \frac{1}{2}R + \alpha R^2$$

$R^2 \supset$ higher derivative of metric
$\Rightarrow$ a new d.o.f

Rewrite by auxiliary field χ

$$\mathcal{L} = \left(\frac{1}{2} + 2\alpha\chi\right) R - \alpha\chi^2$$

conformal trans.

$g_{\mu\nu} \to \Omega^2 g_{\mu\nu}$ $\quad \Omega^2 = 1 + 4\alpha\chi$ $\quad 1 + 4\alpha\chi = e^{\sqrt{\frac{2}{3}}\phi}$

Einstein frame
(Dual picture)

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{16\alpha}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2$$

ϕ : scalaron

✓ consistent with observation

Higgs-R^2 model

Idea : scalaron for unitarizing Higgs inflation ?

$$\mathcal{L}_J/\sqrt{-g_J} = \frac{1}{2}\left(1+\xi h^2\right)R - \frac{1}{2}(\partial_\mu h)^2 - \frac{\lambda}{4}h^4 + \boxed{\alpha R^2}$$

✓ Yes, it works! Y. Ema' 17, D. Gorbunov and A. Tokareva'18,...

Scalaron pushes up to the unitarity scale to $M_{\rm Pl}$
(I will discuss how it solves in susy case)

✓ $\alpha \sim \xi^2$ emerges by RGE effect

A.Salvio and A. Mazumdar ' 15
X. Calmet and I. Kuntz ' 16
Y. Ema' 17,
D. M. Ghilencea ' 18

Phenomenology of Higgs-R^2 model

✓ inflation

A.Salvio and A. Mazumdar ’ 15
D. Gorbunov and A. Tokareva’18
Y. Ema’ 19,
A. Gundhi and C. F. Steinwachs ’ 20, ...

✓ (p)reheating

M. He, R. Jinno, K. Kamada, S. C. Park, A. A. Starobinsky, J. Yokoyama ’18
F. Bezrukov and C. Shepherd, ’20
M. He, ’20,…

✓ PBH D. Y. Cheong, S. M. Lee, and S. C. Park , ’19

✓ Dark energy H. M. Lee, A. G. Menkara ’21

✓ Dark matter

SA, H. M. Lee, A. G. Menkara, K.Yamashita, in progress

…

S.A., H.M.Lee, A.G.Menkara, 2108.00222

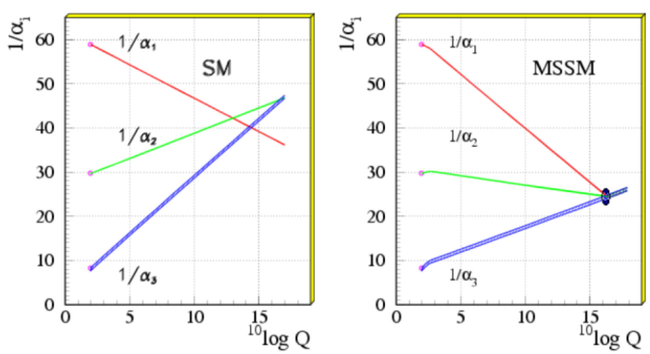
Today's topic
= embed Higgs-R^2 inflation into supergravity

Supersymmetry

- solution of the Hierarchy problem
- unification of the forces
- dark matter candidate

…

hep-ph/9709356



particle data group

SUSY embedding may give an UV completion of Higgs-R^2 inflation

S.A., H.M.Lee, A.G.Menkara,
2108.00222

Today's topic
= embed Higgs-R^2 inflation into supergravity

Questions

- Unitarity?
- maintain successful inflation?
- supersymmetry breaking and phenomenology?
- difference from non-SUSY model?

Higgs R^2 SUGRA =

Higgs inflation in SUGRA + R^2 SUGRA

NMSSM

Einhorn, Jones' 10
H.M.Lee' 10
Ferrara, Kallosh, Linde, Marrani, Van Proeyen' 10

- Construction

S. Cecotti' 87

- Apply to inflation

Kallosh, Linde' 13, …

Higgs inflation in NMSSM

$$\mathcal{L} = -\frac{1}{6}\Omega R - \Omega_{I\bar{J}}\partial_\mu z^I \partial^\mu \bar{z}^{\bar{J}} - V$$

Ω : frame function

$$K = -3\log\left(-\frac{\Omega}{3}\right)$$

$$\xi \equiv -\frac{1}{6} + \frac{\chi}{4}$$

Contents : $z^I = \{H_u, H_d, S\}$

$$\begin{cases} \Omega = -3 + |S|^2 + |H_u|^2 + |H_d|^2 + \left(\frac{3}{2}\chi H_u \cdot H_d + \text{h.c.}\right) \\ W = \lambda S H_u \cdot H_d + \frac{\rho}{3} S^3 \end{cases}$$

Einhorn, Jones' 10
H.M.Lee' 10
Ferrara, Kallosh, Linde, Marrani, Van Proeyen' 10

Higgs inflation in NMSSM

Truncate every field other than h

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ h/2 \end{pmatrix}, H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \rightarrow \begin{pmatrix} h/2 \\ 0 \end{pmatrix}, S \rightarrow 0$$

➡ Realize Higgs inflation with $\chi/\lambda \sim 10^4$

CMB ➡ $\chi/\lambda \sim 10^4$ ➡ **Large non-minimal coupling χ**

R^2 (Starobinsky) inflation in supergravity

$\int d^4\theta$

$$[\alpha\bar{\mathcal{R}}\mathcal{R}]_D = \alpha R^2 + \cdots$$

S. Cecotti' 87

- $\mathcal{R} = (X^0)^{-1}\Sigma(\bar{X}^{\bar{0}})$: curvature superfield
- X^0 : compensator
- Σ : chiral projection ($\sim \bar{D}^2$)

R^2 (Starobinsky) inflation in supergravity

Introduce auxiliary superfield T and C

$$[\alpha\bar{\mathcal{R}}\mathcal{R}]_D = [\alpha\bar{C}C]_D + [T(C-\mathcal{R})]_F$$

$[\ ]_F \to \int d^2\theta$

$$= [TC - \Sigma(T(X^0)^{-1}\bar{X}^{\bar{0}})]_F$$

$$= [TC]_F - [T(X^0)^{-1}\bar{X}^{\bar{0}} + \text{c.c.}]_D$$

&

$T \to T(X^0)^2$ and $C \to CX^0$

$C \to C/\sqrt{\alpha}$,

$$= [|X^0|^2\Omega]_D + [(X^0)^3 W]_F$$

$$\begin{cases} \Omega = |C|^2 - (T+\bar{T}) \\ W = \dfrac{1}{\sqrt{\alpha}}TC \end{cases}$$

R^2 SUGRA = SUGRA + two chiral multiplets (T, C)

R^2 (Starobinsky) inflation in supergravity

Kallosh, Linde' 13

$$\mathrm{Im}T \to 0, C \to 0$$

➡ Realize R^2 inflation with $\mathrm{Re}T$ identified as inflaton (scalaron)

CMB ➡ $\alpha \sim 10^{10}$ ➡ **Large coefficient α**

Supergravity embedding

Higgs R^2 SUGRA =
NMSSM inflation in SUGRA + R^2 SUGRA (⇒ dual scalars T, C)

$$
\begin{cases}
K = -3\log\left(-\frac{\Omega}{3}\right) \\
\Omega = \underline{-3 + |S|^2 + |H_u|^2 + |H_d|^2 + \left(\frac{3}{2}\chi H_u \cdot H_d + \text{h.c.}\right)} + \underline{|C|^2 - (T + \bar{T})} \\
W = \underline{\lambda S H_u \cdot H_d + \frac{\rho}{3} S^3} + \underline{\frac{1}{\sqrt{\alpha}} T C}
\end{cases}
$$

✓ Fields : NMSSM singlet S, Higgs doublets H_u, H_d, Dual scalars T, C

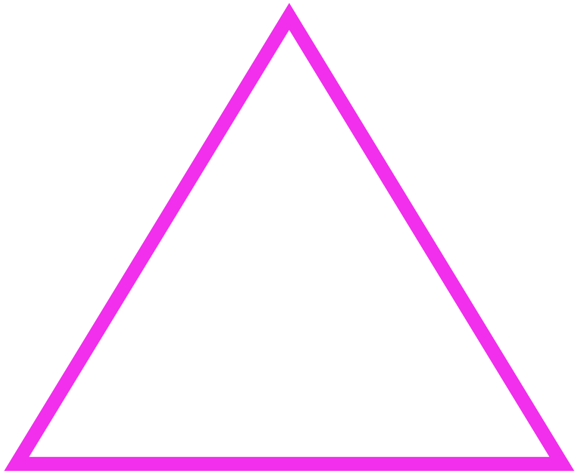
✓ Parameters : χ (non-minimal coupling), λ, ρ, α (coefficient of R^2)

↓ χ: Large ↓ α: Large

✓ By construction, it has R^2 origin (T-sector is fixed by R^2 structure)

Three frames

Linear sigma frame (for unitarity)



Jordan frame
(for SUGRA construction)

$$\mathcal{L}_J = -\frac{1}{6}\Omega R + \cdots$$

Einstein frame
(for physics)

$$\mathcal{L}_E = \frac{1}{2} R + \cdots$$

Linear Sigma frame

Conformal trans. $g^J_{\mu\nu} = \left(1 + \frac{1}{\sqrt{6}}\sigma\right)^2 g_{\mu\nu}$

Field redef. $\hat{z}^i \equiv \left(1 + \frac{1}{\sqrt{6}}\sigma\right) z^i, \quad \hat{T} \equiv \left(1 + \frac{1}{\sqrt{6}}\sigma\right)^2 T, \qquad z^i = \{S, H_u, H_d, C\}$

choose σ s.t.

$$\left(1 + \frac{1}{\sqrt{6}}\sigma\right)^2 + \left(-\frac{1}{2}\chi \hat{H}_u \cdot \hat{H}_d + \text{h.c.}\right) + \frac{2}{3}\text{Re}\hat{T} = 1 - \frac{1}{6}\sigma^2.$$

Convert Re$\hat{T}$ (scalaron) → σ

Linear Sigma frame

Conformal trans. $g^J_{\mu\nu} = \left(1 + \frac{1}{\sqrt{6}}\sigma\right)^2 g_{\mu\nu}$

Field redef. $\hat{z}^i \equiv \left(1 + \frac{1}{\sqrt{6}}\sigma\right) z^i, \quad \hat{T} \equiv \left(1 + \frac{1}{\sqrt{6}}\sigma\right)^2 T, \qquad z^i = \{S, H_u, H_d, C\}$

choose σ s.t.

$$\left(1 + \frac{1}{\sqrt{6}}\sigma\right)^2 + \left(-\frac{1}{2}\chi \hat{H}_u \cdot \hat{H}_d + \text{h.c.}\right) + \frac{2}{3}\text{Re}\hat{T} = 1 - \frac{1}{6}\sigma^2.$$

Convert Re$\hat{T}$ (scalaron) → σ

$$\mathcal{L}/\sqrt{-g} = \frac{1}{2}\left(1 - \frac{1}{3}|\hat{S}|^2 - \frac{1}{3}|\hat{H}_u|^2 - \frac{1}{3}|\hat{H}_d|^2 - \frac{1}{3}|\hat{C}|^2 - \frac{1}{6}\sigma^2\right) R$$

conformal

$$- |\partial_\mu \hat{S}|^2 - |\partial_\mu \hat{H}_u|^2 - |\partial_\mu \hat{H}_d|^2 - |\partial_\mu \hat{C}|^2 - \frac{1}{2}(\partial_\mu \sigma)^2 - V$$

canonical

No-large couplings χ, α

Linear Sigma frame

Where χ, α have gone?

$$
\begin{aligned}
V =& |\lambda \hat{H}_u \cdot \hat{H}_d + \rho \hat{S}^2|^2 + \lambda^2 |\hat{S}|^2 (|\hat{H}_u|^2 + |\hat{H}_d|^2) + \frac{1}{4\alpha}\left(\sigma^2 + \sqrt{6}\sigma - \left(\frac{3}{2}\chi \hat{H}_u \cdot \hat{H}_d + \text{h.c.}\right)\right)^2 \\
&+ \frac{1}{\alpha}(\text{Im}\hat{T})^2 + \frac{3}{2}\frac{\chi\lambda}{\sqrt{\alpha}}(\hat{S}\bar{\hat{C}} + \bar{\hat{S}}\hat{C})(|\hat{H}_u|^2 + |\hat{H}_d|^2) \\
&+ \frac{1}{\alpha}|\hat{C}|^2 \left\{3 + 2\sqrt{6}\sigma + \frac{3}{2}\sigma^2 + \frac{9}{4}\chi^2(|\hat{H}_u|^2 + |\hat{H}_d|^2)\right\} \\
&+ \frac{g'^2}{8}\left(|\hat{H}_u|^2 - |\hat{H}_d|^2\right)^2 + \frac{g^2}{8}\left((\hat{H}_u)^\dagger \vec{\tau} \hat{H}_u + (\hat{H}_d)^\dagger \vec{\tau} \hat{H}_d\right)^2 .
\end{aligned}
$$

Linear Sigma frame

Where χ, α have gone?

$$
\begin{aligned}
V =& |\lambda \hat{H}_u \cdot \hat{H}_d + \rho \hat{S}^2|^2 + \lambda^2 |\hat{S}|^2 (|\hat{H}_u|^2 + |\hat{H}_d|^2) + \frac{1}{4\alpha}\left(\sigma^2 + \sqrt{6}\sigma - \left(\frac{3}{2}\chi \hat{H}_u \cdot \hat{H}_d + \text{h.c.}\right)\right)^2 \\
&+ \frac{1}{\alpha}(\mathrm{Im}\hat{T})^2 + \frac{3}{2}\frac{\chi\lambda}{\sqrt{\alpha}}(\hat{S}\bar{\hat{C}} + \bar{\hat{S}}\hat{C})(|\hat{H}_u|^2 + |\hat{H}_d|^2) \\
&+ \frac{1}{\alpha}|\hat{C}|^2 \left\{3 + 2\sqrt{6}\sigma + \frac{3}{2}\sigma^2 + \frac{9}{4}\chi^2(|\hat{H}_u|^2 + |\hat{H}_d|^2)\right\} \\
&+ \frac{g'^2}{8}\left(|\hat{H}_u|^2 - |\hat{H}_d|^2\right)^2 + \frac{g^2}{8}\left((\hat{H}_u)^\dagger \vec{\tau} \hat{H}_u + (\hat{H}_d)^\dagger \vec{\tau} \hat{H}_d\right)^2 .
\end{aligned}
$$

$$\chi / \sqrt{\alpha}$$

can be order one

- no unitary violation up to Planck scale even after susy extension
- perturbativity requires $\frac{\chi}{\sqrt{\alpha}} < 1$

Inflation

SUGRA Higgs-R^2 system ⊃ $\underbrace{\sigma, h}_{}, \underbrace{S, C, \ldots}_{}$

= non-susy   Extra fields due to susy (should be stabilized)

Naïve embedding → tachyonic instability in one of mixed state of S and C

Solution: $\Delta\Omega = -\zeta_s|S|^4 - \zeta_c|C|^4$

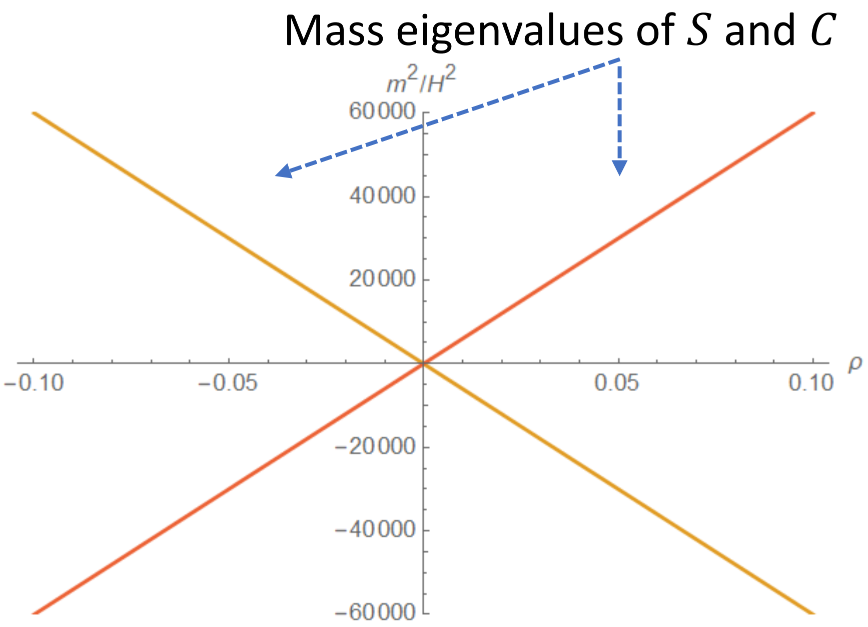
↓

$-[\zeta_c \alpha^2 |X^0|^{-2} (\bar{\mathcal{R}}\mathcal{R})^2]_D$ in dual side

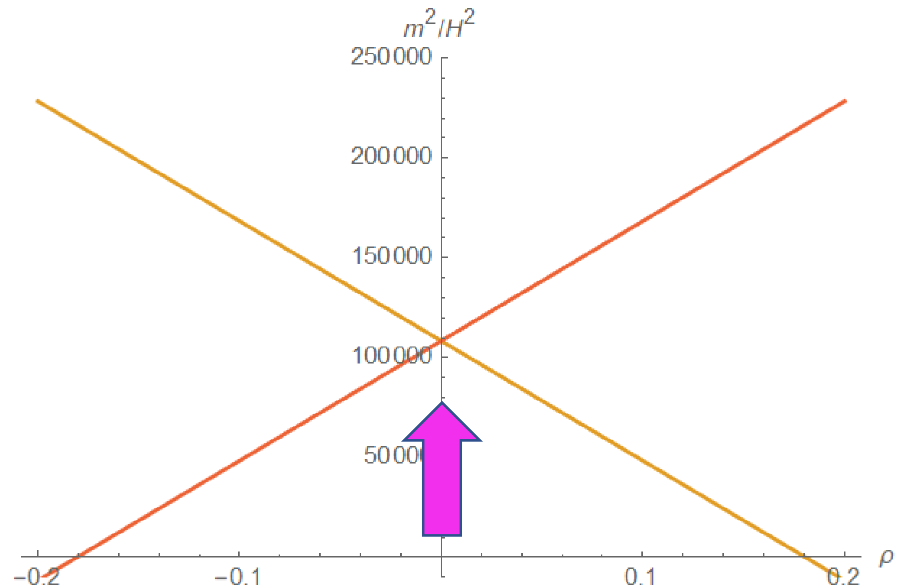
Note : doesn't destroy R^2 structure in component

Stabilization of S and C

ρ : cubic coupling of S



(ζ_s, ζ_c)=(0,0)



(ζ_s, ζ_c)=(3,0.4)

$(\lambda, \xi, \alpha) = (4 \times 10^{-5}, 1, 10^2)$

Inflation

EFT of σ and h = same as non-susy case

Integrate out h : $\hat{h}^2 = \dfrac{\frac{1}{\alpha}\sigma(\sigma+\sqrt{6})\left(\sigma - 3\left(\xi+\frac{1}{6}\right)(\sigma-\sqrt{6})\right)}{\frac{\lambda^2}{4}(\sigma-\sqrt{6}) - \frac{3}{\alpha}\left(\xi+\frac{1}{6}\right)\left(\sigma - 3\left(\xi+\frac{1}{6}\right)(\sigma-\sqrt{6})\right)}$

Canonical normalization : $\sigma \simeq -\sqrt{6}\tanh\left(\dfrac{\phi}{\sqrt{6}}\right)$

$$V_{\rm eff}(\phi) = \frac{9}{4\alpha}\left(1-e^{-\frac{2}{\sqrt{6}}\phi}\right)^2\left[1+\frac{1}{\lambda^2\alpha}\left(6\xi+e^{-\frac{2}{\sqrt{6}}\phi}\right)^2\right]^{-1} \qquad \xi \equiv -\frac{1}{6}+\frac{\chi}{4}$$

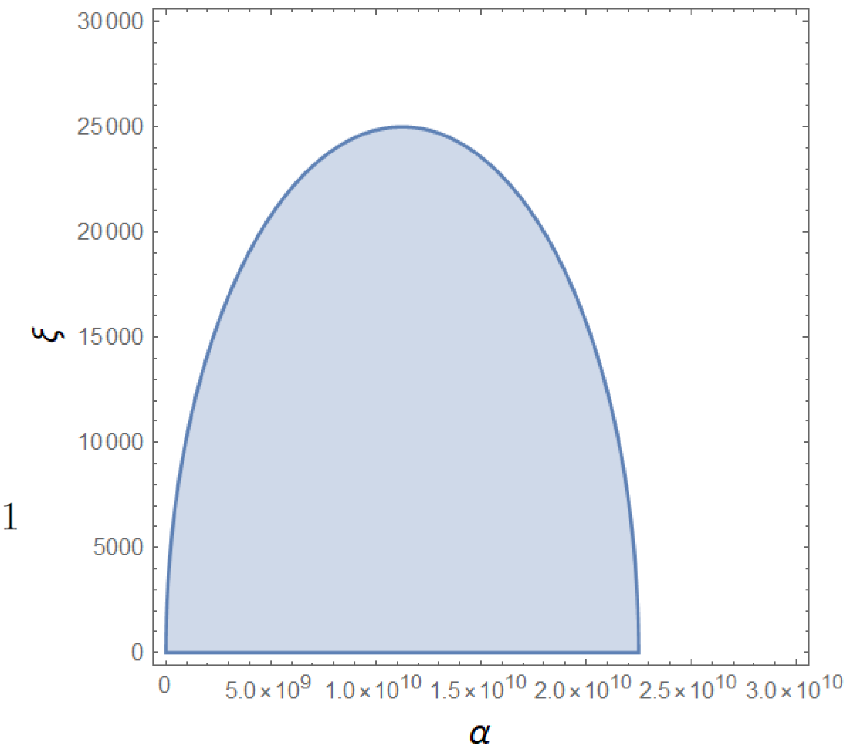
$$V_{\rm eff}(\phi) \approx \begin{cases} \frac{9}{4\alpha}\left(1-e^{-2\phi/\sqrt{6}}\right)^2, & \frac{\xi^2}{\alpha} \ll \lambda^2 \quad R^2\text{-like} \\ \frac{\lambda^2}{16\xi^2}\left(1-e^{-2\phi/\sqrt{6}}\right)^2. & \frac{\xi^2}{\alpha} \gg \lambda^2 \quad \text{Higgs-like} \end{cases}$$

Inflationary observables

CMB :
$$\frac{\lambda^2 + \frac{36\xi^2}{\alpha}}{\lambda^2/\alpha} = 2.25 \times 10^{10}$$

Perturbativity :

$$\frac{\lambda^2}{4} + \frac{9}{\alpha}\left(\xi + \frac{1}{6}\right)^2 \leq 1, \quad 0 < \frac{1}{\alpha} \leq 1, \quad \frac{6}{\alpha}\left(\xi + \frac{1}{6}\right) \leq 1$$



(n_s, r)

$$\begin{cases} n_s = 1 - \frac{2}{N} - \frac{9}{2N^2} + \frac{3}{\alpha N^2}\frac{(-\lambda^2 + 12\lambda^2\xi + 72\xi^2(1+6\xi)/\alpha)}{(\lambda^2 + 6\xi(1+6\xi)/\alpha)^2} \\ r = 16\epsilon_* = \frac{12}{N^2} \end{cases}$$

✓ Consistent with Planck observation

SUSY breaking

1. SUSY breaking by higher curvature effects

I. Dalianis, F. Farakos, A. Kehagias, A. Riotto, R. von Unge, '14

$$\Omega = \underbrace{-3 + (T + \bar{T}) + |C|^2}_{\text{R^2 SUGRA}} - \gamma_c (C + \bar{C}) - \zeta_c |C|^4$$

γ_c: new

ζ_c: already added

In dual picture,

$$-3 + \alpha |\mathcal{R}/X^0|^2 - \gamma_c \alpha \left(\mathcal{R}/X^0 + \text{c.c.}\right) - \zeta_c \alpha^2 |\mathcal{R}/X^0|^4$$

⇨ $\langle T \rangle \neq 0, \langle C \rangle \neq 0$

~~SUSY~~ $\sim M_P/\sqrt{\alpha} \gtrsim 10^{13}\,\text{GeV}$: High scale SUSY breaking

($\gtrsim$: perturbativity constraint)

SUSY breaking

2. O'Raifeartaigh model

$$\Omega = -3 - (T + \bar{T}) + |C|^2 + |\Phi|^2 - \gamma\,|\Phi|^4,$$
$$W = \frac{1}{\sqrt{\alpha}} TC + \kappa\,\Phi + g\,\Phi C^2 + \lambda\Phi^3 + \kappa' C + g'\Phi^2 C + \lambda' C^3$$

← Z_{4R} R-symmetry with $R[\Phi] = R[C] = +2 \quad R[T] = 0$

SUSY breaking scale ~ $F_\Phi = \kappa$: adjustable

Implication for phenomenology

μ-term

$$\mu = \lambda\langle\tilde{S}\rangle + \frac{3}{2}\chi m_{3/2} - \frac{1}{2}\chi K_{\bar{I}}\bar{F}^{\bar{I}}$$

NMSSM

Non-minimal coupling

Lee' 10

Giudice-Masiero term

Giudice, Masiero' 88

Sequestered form

Randall, Sundrum' 99

- vanishing soft mass at tree level
- anomaly mediation
- tachyonic slepton

$$\Omega_{\rm contact} = C_{\bar{\alpha}\beta}X^{\dagger}Xz^{\dagger}_{\bar{\alpha}}z_{\beta} + {\rm c.c} \qquad X = C, \Phi,$$

Summary

- embed Higgs-R^2 inflation into SUGRA
- interpolate NMSSM inflation and R^2 inflation in SUGRA
- Three frames (Jordan, Einstein, Linear sigma)
- no unitarity issue even after supersymmetrization
- successful slow-roll inflation with quartic couplings (higher curvature terms)
- two SUSY breaking mechanisms & transmission to visible sector

Discussion & Future

No distinction in inflationary observables (n_s, r) of susy/non-susy models ⇒ How to distinguish?

- S, C contributions to inflation if they are light
- SUSY breaking effect on inflation
- go beyond standard analysis (e.g., Non-Gaussianity?)

↓

$\mathrm{Im}T$: relatively light $\sim 2H$

- gravitino problem

T_r should be $\leq\ 10^{8,9}$ GeV ⇔ naïve estimation $\sim 10^{13}$ GeV

For pure R^2 SUGRA ⇒ T. Terada, Y. Watanabe, Y. Yamada and J. Yokoyama, JHEP 02, 105 (2015)

Thank you for your attention !!

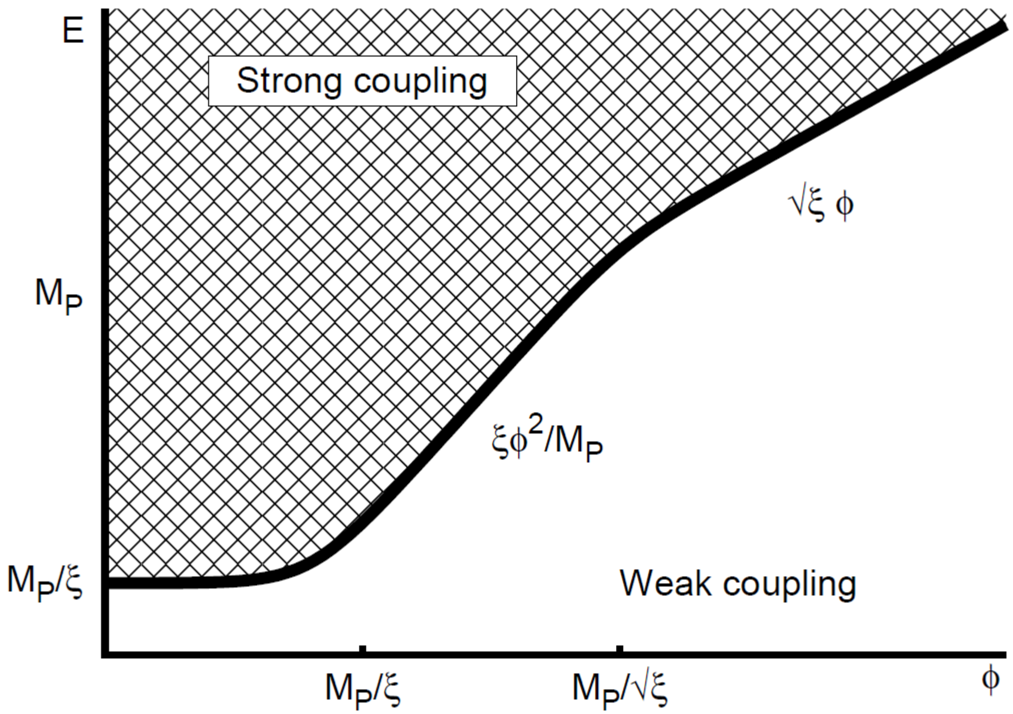
Backup

Cut off depends on the background field value

F. Bezrukov, A. Magnin, M. Shaposhnikov, S. Sibiryakov [arXiv:1008.5157]

$$\Lambda^J(\bar{\phi}) = \frac{M_P^2 + \xi\bar{\phi}^2 + 6\xi^2\bar{\phi}^2}{\xi\sqrt{M_P^2 + \xi\bar{\phi}^2}}$$

$\bar{\phi} \gg M_P/\sqrt{\xi}$, large fields (inflationary period) ⇒ $\Lambda^J \simeq \sqrt{\xi}\bar{\phi}$


E
Strong coupling
M_P
$\sqrt{\xi}\,\phi$
$\xi\phi^2/M_P$
M_P/ξ
Weak coupling
M_P/ξ
$M_P/\sqrt{\xi}$
ϕ

Jordan frame supergravity

S. Ferrara, R. Kallosh, A. Linde, A. Marrani and A. Van Proeyen,
Phys. Rev. D 82, 045003 (2010)

$$\mathcal{L}/\sqrt{-g} = -\frac{1}{6}(X^0)^2\Omega R - \Omega(\partial_\mu X^0)^2 - X^0\partial^\mu X^0\left(\Omega_I\partial_\mu z^I + \Omega_{\bar{I}}\partial_\mu\bar{z}^{\bar{I}}\right) + \left(X^0\right)^2\Omega\mathcal{A}_\mu^2 \\ - (X^0)^2\Omega_{I\bar{J}}\partial_\mu z^I\partial^\mu\bar{z}^{\bar{J}} - V, \tag{2.16}$$

where

$$\mathcal{A}_\mu = -\frac{\mathrm{i}}{2\Omega}\left(\partial_\mu z^I\Omega_I - \partial_\mu\bar{z}^{\bar{I}}\Omega_{\bar{I}}\right). \tag{2.17}$$

$$V^F = \left(X^0\right)^4\left(\Omega_{I\bar{J}} - \frac{\Omega_I\Omega_{\bar{J}}}{\Omega}\right)^{-1}\left(W_I - \frac{3\Omega_I}{\Omega}W\right)\left(\bar{W}_{\bar{J}} - \frac{3\Omega_{\bar{J}}}{\Omega}\bar{W}\right) + \frac{9}{\Omega}\left(X^0\right)^4|W|^2 \\ = \left(X^0\right)^4 e^{\mathcal{K}/3}\left[\mathcal{K}^{I\bar{J}}\left(W_I + \mathcal{K}_I W\right)\left(\bar{W}_{\bar{J}} + \mathcal{K}_{\bar{J}}\bar{W}\right) - 3|W|^2\right], \tag{2.18}$$

$$V^D = \frac{\left(X^0\right)^4}{2}(\mathrm{Re}f)^{-1AB}\Omega_\alpha k_A^\alpha\Omega_{\bar{\beta}}k_B^{\bar{\beta}}, \tag{2.19}$$

R^2 frame

$$S = [|X^0|^2\tilde{\Omega}(z^\alpha, \bar{z}^{\bar{\beta}})]_D + [(X^0)^3\tilde{W}(z^\alpha)]_F + [f_{AB}(z^\alpha)\bar{\mathcal{W}}^A\mathcal{W}^B]_F + [\alpha\bar{\mathcal{R}}\mathcal{R}]_D,$$

$$\mathcal{R} = (X^0)^{-1}\Sigma(\bar{X}^{\bar{0}}),$$

Σ is a chiral projection operator

$$\begin{aligned}\mathcal{L}/\sqrt{-g} =& -\tilde{\Omega}_{\alpha\bar{\beta}}\partial_\mu z^\alpha\partial^\mu\bar{z}^{\bar{\beta}} + (-i\tilde{\Omega}_\alpha\partial_\mu z^\alpha\mathcal{A}^\mu + \text{c.c.}) + \tilde{\Omega}(-\mathcal{A}^2 + \left|F^0\right|^2) + (3F^0\tilde{W} + \text{c.c.})\\ &+ \left(-\frac{\tilde{\Omega}}{6} + \frac{\alpha}{6}|F^0|^2 + \frac{\alpha}{3}\mathcal{A}^2\right)R + \frac{\alpha}{36}R^2 + \alpha\left(\mathcal{A}^2 + \left|F^0\right|^2\right)^2 + \alpha(\nabla_\mu\mathcal{A}^\mu)^2\\ &- \alpha\left|\partial_\mu F^0 - 3i\mathcal{A}_\mu F^0\right|^2 - \tilde{\Omega}^{\alpha\bar{\beta}}(\tilde{\Omega}_\alpha\bar{F}^{\bar{0}} + \tilde{W}_\alpha)(\tilde{\Omega}_{\bar{\beta}}F^0 + \bar{\tilde{W}}_{\bar{\beta}})\\ &- \frac{1}{2}(\text{Re}f)^{-1AB}\tilde{\Omega}_\alpha k_A^\alpha\tilde{\Omega}_{\bar{\beta}}k_B^{\bar{\beta}}, \qquad (2.3)\end{aligned}$$

R^2 frame

$$\tilde{\Omega}(z^\alpha, \bar{z}^{\bar{\beta}}) = -3 + |S|^2 + |H_u|^2 + |H_d|^2 + \left(\frac{3}{2}\chi H_u \cdot H_d + \text{h.c.}\right),$$

$$\tilde{W}(z^\alpha) = \lambda S H_u \cdot H_d + \frac{\rho}{3} S^3,$$

$$\mathcal{L}/\sqrt{-g} = \left\{\frac{1}{2} - \frac{1}{6}|S|^2 - \frac{1}{6}|H_u|^2 - \frac{1}{6}|H_d|^2 + \left(-\frac{1}{4}\chi H_u \cdot H_d + \text{h.c.}\right)\right\} R$$
$$- |\partial_\mu S|^2 - |\partial_\mu H_u|^2 - |\partial_\mu H_d|^2 + \frac{\alpha}{36} R^2 + \cdots,$$

Unitarity issue for $\mathbf{Im}T$

$$\mathcal{L}_{LS}/\sqrt{-g} = \frac{1}{2}\left(1 - \frac{1}{3}|\hat{S}|^2 - \frac{1}{3}|\hat{H}_u|^2 - \frac{1}{3}|\hat{H}_d|^2 - \frac{1}{3}|\hat{C}|^2 - \frac{1}{6}\sigma^2\right) R$$
$$- |\partial_\mu \hat{S}|^2 - |\partial_\mu \hat{H}_u|^2 - |\partial_\mu \hat{H}_d|^2 - |\partial_\mu \hat{C}|^2 - \frac{1}{2}(\partial_\mu \sigma)^2 + \boxed{\Omega \mathcal{A}_\mu^2} - V_{LS},$$

$$\Omega \mathcal{A}_\mu^2 = -\frac{1}{4\Omega}\Big[(X^0)^{-1}\Big((\bar{\hat{C}}\partial_\mu \hat{C} + \bar{\hat{S}}\partial_\mu \hat{S} + \bar{\hat{H}}_u \partial_\mu \hat{H}_u + \bar{\hat{H}}_d \partial_\mu \hat{H}_d - \text{c.c}) - 2i\partial_\mu b\Big)$$
$$-4ib\, \partial_\mu (X^0)^{-1}\Big]^2.$$

$$X^0 = 1 + \tfrac{1}{\sqrt{6}}\sigma,$$

$$\hat{T} - \bar{\hat{T}} - \frac{3}{2}\chi(\hat{H}_u \cdot \hat{H}_d - \bar{\hat{H}}_u \cdot \bar{\hat{H}}_d) = 2ib,$$ convert $\mathrm{Im}\hat{T} \to b$

$$\Rightarrow \quad V_{LS}^F \supset \frac{1}{\alpha}(\mathrm{Im}\hat{T})^2 = \frac{1}{\alpha}\left(b - \frac{3}{4}i\chi(\hat{H}_u \cdot \hat{H}_d - \bar{\hat{H}}_u \cdot \bar{\hat{H}}_d)\right)^2.$$

perturbative as long as $\boxed{\frac{\chi}{\alpha} \lesssim 1, \qquad \frac{\chi^2}{\alpha} \lesssim 1.}$

Effective mu-term

H.M.Lee' 10
Ferrara, Kallosh, Linde, Marrani, Van Proeyen' 10

$$\mathcal{K}(z,\bar{z}) = -3M_P^2 \log\left[1 - \frac{\phi^a\bar{\phi}_a}{3M_P^2} - \frac{J(\phi)}{3M_P^2} - \frac{\bar{J}(\bar{\phi})}{3M_P^2} - \dots\right] \qquad J(\phi) = -\chi\, C_{ab}\phi^a\phi^b.$$

$$\Rightarrow \quad \mathcal{K}(z,\bar{z}) = \phi^a\bar{\phi}_a + J(\phi) + \bar{J}(\bar{\phi}) + \dots$$

Kaehler transformation

$$W_{\text{eff}} \to W \mathrm{e}^{J(\phi)/M_P^2} \approx W + \frac{\langle W_{\text{hid}}\rangle}{M_P^2} J(\phi) \approx W + \boxed{m_{3/2} J(\phi)}$$

$$\left(m_{3/2} = \mathrm{e}^{\frac{\mathcal{K}}{2M_P^2}} \frac{\langle W\rangle}{M_P^2} \approx \frac{\langle W_{\text{hid}}\rangle}{M_P^2} \right)$$

Z_M^R-symmetry

M. Lee, S. Raby, M. Ratz, G. G. Ross, R. Schieren, K. Schmidt-Hoberg and P. K. S. Vaudrevange, Nucl. Phys. B 850, 1-30 (2011)

$$\left\{\begin{array}{l} \mathscr{W} \;\to\; \mathrm{e}^{2\pi\,\mathrm{i}\,q_{\mathscr{W}}/M}\,\mathscr{W} \qquad \text{with } q_{\mathscr{W}} = 2. \\ \theta \;\to\; \mathrm{e}^{2\pi\,\mathrm{i}/M}\,\theta \\ \Phi^{(f)} \;\to\; \mathrm{e}^{2\pi\,\mathrm{i}\,q^{(f)}/M}\,\Phi^{(f)} \end{array}\right.$$

Our case :

Z_{4R} R-symmetry with $R[\Phi] = R[C] = +2 \quad R[T] = 0$