Inflation and Supersymmetry Breaking in Higgs-R2 Supergravity

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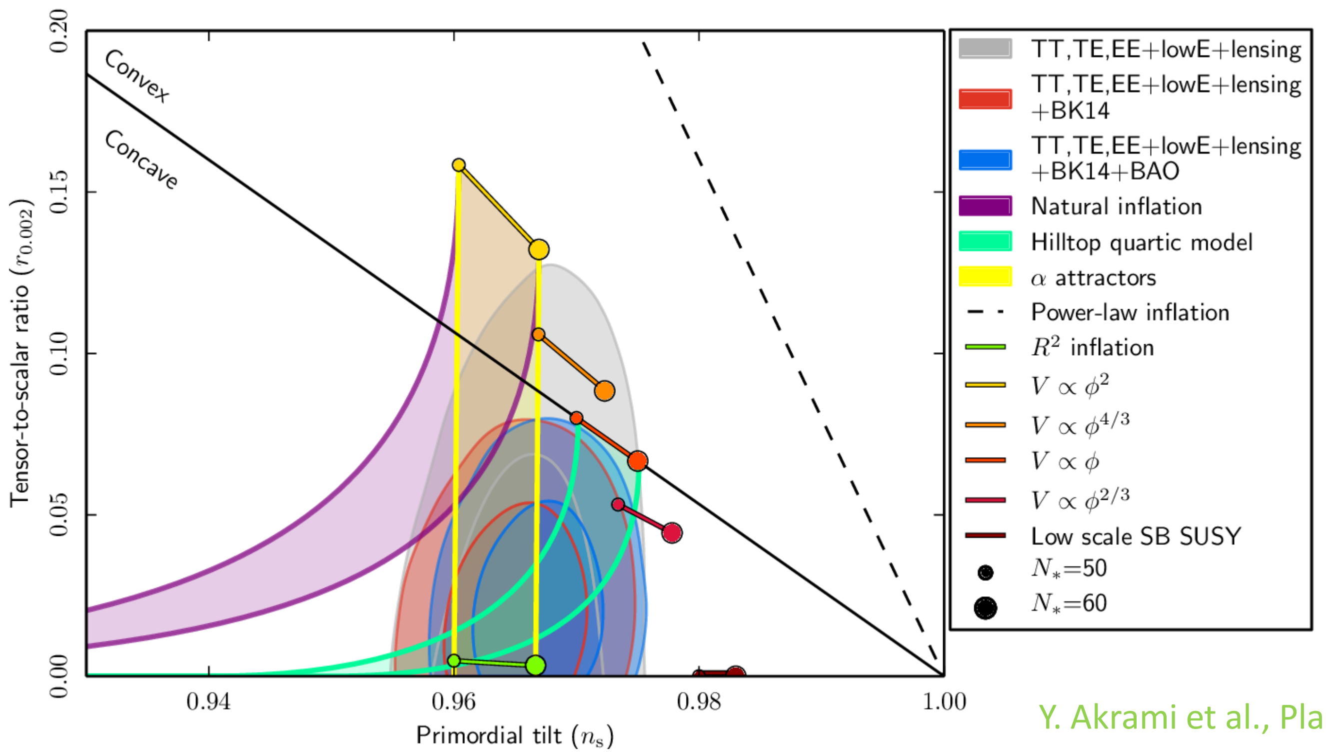
Higgs inflation

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

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



Y. Akrami et al., Planck 2018

Large non-minimal coupling $\xi \sim 10^4$ to Ricci scalar

Unitarity problem in Higgs inflation and Solution

Low cut off scale M_{pl}/ξ ⇒ ? perturbation

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

Cutoff scale depending on the inflaton field value may help

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

Unitarity problem again by preheating

Ema, Jinno, Mukaida, Nakayama' 17

One of solutions : Introduce a new d.o.f, $\boldsymbol{\sigma}$ (c.f., 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
…

Unitarizing Higgs inflation : cut off ⇒ M_{pl}

Higgs-R^2 model

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

"scalaron" in dual picture
can be used for unitarization

Proof by Scattering amplitude

Y. Ema' 19, ...

Renormalizability, RGE

G. 't Hooft, M. Veltman' 74 Y. Ema, K. Mukaida, J. van de Vis' 20 ,...

Inflation, (p)reheating, Dark energy, …

M. He, R. Jinno, K. Kamada, S. C. Park, A. A. Starobinsky, J. Yokoyama '18
D. Y. Cheong, H. M. Lee, S. C. Park '20
H. M. Lee, A. G. Menkara '21
…

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

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

Supersymmetry

- Hierarchy problem
- gauge coupling unification
- dark matter candidate

…

Questions

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

Higgs R^2 SUGRA =

Higgs inflation in SUGRA + R^2 SUGRA

NMSSM

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

- Construction

S. Cecotti' 87

- Apply to inflation

Kallosh, Linde' 13

Higgs inflation in NMSSM

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

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

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

Contents : $\{H_u, H_d, S\}$

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

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

R^2 (Starobinsky) inflation in supergravity

Remember in non-susy case

ϕ : scalaron

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

susy case S. Cecotti' 87, Kallosh, Linde' 13

$$[(X^0)^2\mathcal{R}]_F + [\alpha\bar{\mathcal{R}}\mathcal{R}]_D \quad \Longleftrightarrow \quad [|X^0|^2\Omega]_D + [(X^0)^3 W]_F$$

$\mathcal{R}$: curvature multiplet

X^0 : compensator multiplet

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

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

ReT : 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)

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

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

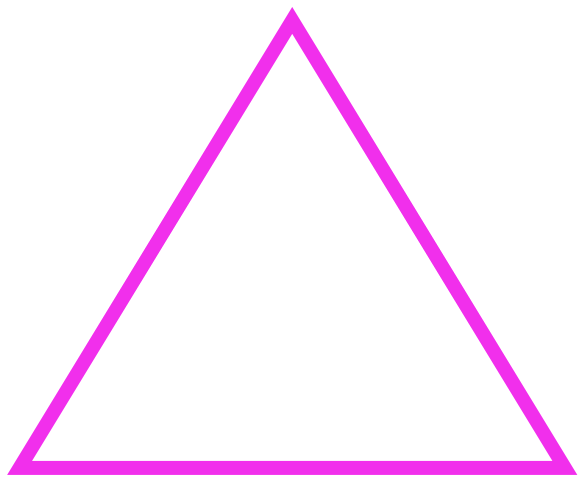
Parameters : χ (non-minimal coupling), λ, ρ, α (coefficient of R^2)

χ ↓ Large

α ↓ Large

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

choose σ s.t.

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

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?

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

Linear Sigma frame

Where χ, α have gone?

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

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

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

Inflation

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

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

Naïve embedding → 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

Inflation

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

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

$$\sigma \simeq -\sqrt{6}\tanh\left(\frac{\phi}{\sqrt{6}}\right)$$

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

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

R^2-like

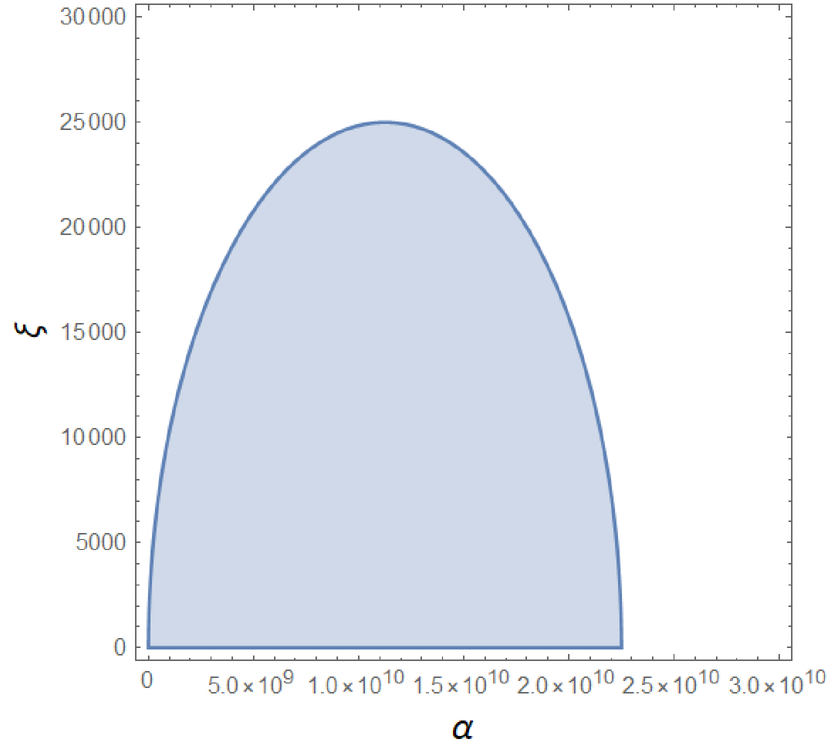
Higgs-like

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

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

R^2 SUGRA

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

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

$$\Omega_{\text{contact}} = C_{\bar{\alpha}\beta}X^\dagger X z^\dagger_{\bar{\alpha}} z_\beta + \text{c.c} \qquad X = C, \Phi,$$

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 light

- go beyond standard analysis (e.g., Running? 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

  Thermal inflation?

R^2 model

Starobinsky, ‘80, 83

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

↓

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

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

Dual picture

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

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

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

Detail of duality in sugra

$$[\alpha\bar{\mathcal{R}}\mathcal{R}]_D = [\alpha\bar{C}C]_D + [T(C-\mathcal{R})]_F \qquad \mathcal{R} = (X^0)^{-1}\Sigma(\bar{X}^{\bar{0}})$$

$$\Downarrow$$

$$\begin{aligned}[T(C-\mathcal{R})]_F &= [TC - \Sigma(T(X^0)^{-1}\bar{X}^{\bar{0}})]_F \\ &= [TC]_F - [T(X^0)^{-1}\bar{X}^{\bar{0}} + \text{c.c.}]_D\end{aligned}$$

$$\Downarrow \quad T \to T(X^0)^2 \text{ and } C \to CX^0 \quad C \to C/\sqrt{\alpha},$$

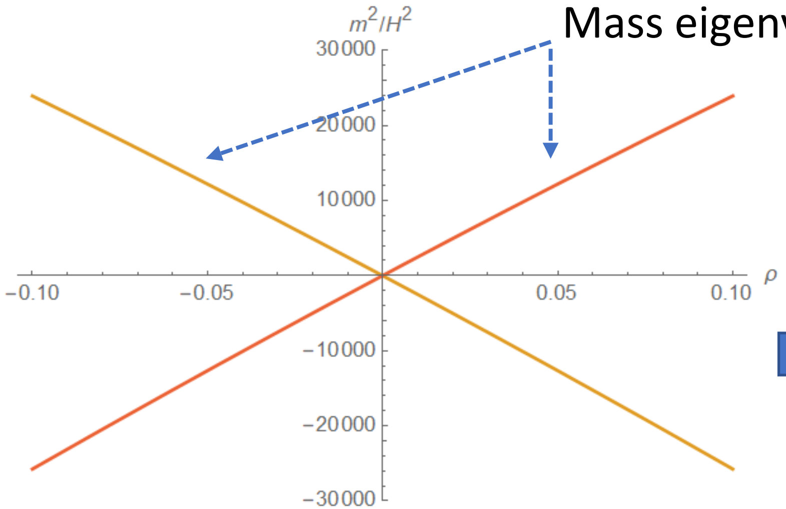
$$[|X^0|^2\Omega]_D + [(X^0)^3W]_F$$

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

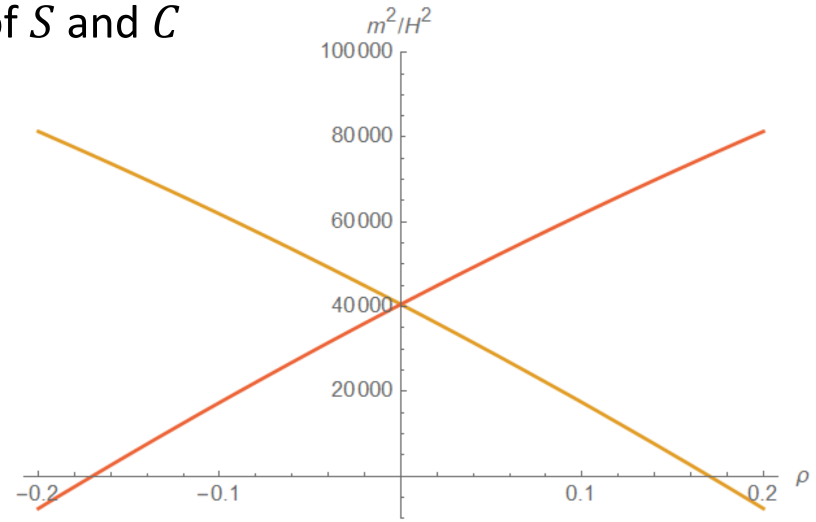
Effects of quartic couplings

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

Mass eigenvalues of S and C



(ζ_s, ζ_c)=(0,0)



(ζ_s, ζ_c)=(3,0.4)