

Supersymmetry and dark matter extensions of Higgs-R2 model

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with Hyun Min Lee, Adriana G. Menkara, and Kimiko Yamashita

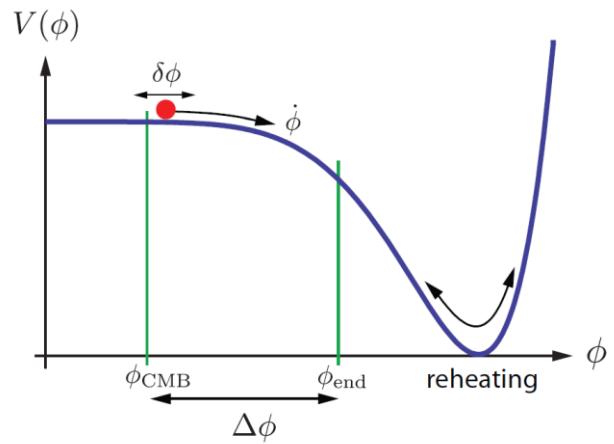
2108.00222, 2202.13063



Introduction

Inflation

- Rapid expansion of early universe
- theoretically & observationally established
- Slow roll inflation (scalar field : **inflaton**)

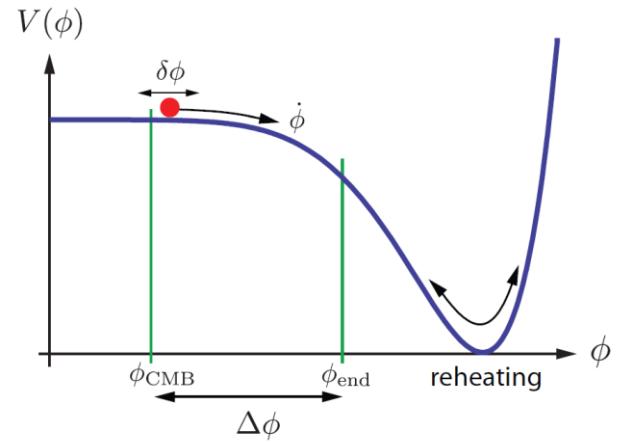


arXiv:0907.5424

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Higgs inflation

Natural idea : inflaton = **SM Higgs boson**

However, the original SM Higgs potential doesn't work

$$V = \lambda_H \left(\mathcal{H}^\dagger \mathcal{H} - \frac{v_H^2}{2} \right)^2 : \text{Not flat}$$

Introduction

Higgs inflation with non-minimal coupling $\xi h^2 R$

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

- ✓ Successful (perfect agreement with Planck data)
- ✓ requires a large $\xi \sim 10^4$

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However, low cutoff scale $\sim M_{pl}/\xi \Rightarrow$ unitarity??

Burgess, Lee, Trott, '09

Barbon, Espinosa, '09

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Solution

- introduce a new d.o.f (like Higgs in SM)
Giudice, Lee '10
- Palatini, Einstein-Cartan, ...
F. Bauer, D. A. Demir, '08
M. Shaposhnikov, A. Shkerin, I. Timiryasov, S. Zell'20
- Critical Higgs inflation
Y. Hamada, H. Kawai, K. y. Oda and S. C. Park '14

Higgs- R^2 inflation model

Salvio & Mazumdar '15, Ema '17, Gorbunov & Tokareva '18, Gundhi & Steinwachs '18,
D. Y. Cheong & S. M. Lee & S. C. Park '21, SA, H. M. Lee, A. G. Menkara,'21 ...

$$\mathcal{L}/\sqrt{-g_J} = \frac{1}{2}(M_{\text{Pl}}^2 + \xi \hat{h}^2)R_J - \frac{1}{2}(\partial_\mu \hat{h})^2 - \frac{\lambda}{4}\hat{h}^4 + \alpha R_J^2$$

$R^2 \supset$ higher derivative of metric

⇒ a new d.o.f (scalaron in Einstein frame)

⇒ scalaron pushes up the cutoff to $\sim M_{pl}$ (solve unitarity problem)

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c.f. pure R^2 case

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

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

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

What to do next?

✓ Further UV embedding = Supersymmetry

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

✓ Study post inflationary dynamics
= Reheating & DM production

SA, H.M. Lee, A. G. Menkara, K.Yamashita
2202.13063

SUSY (SUGRA) embedding

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Strategy

Higgs R² SUGRA =
Higgs inflation in SUGRA + R² SUGRA

MSSM embedding
→ instability

✓ NMSSM

Einhorn, Jones' 10

H.M.Lee' 10

Ferrara, Kallosh, Linde, Marrani, Van Proeyen' 10

✓ Constructed by S. Cecotti' 87

✓ Duality

R² sugra \Leftrightarrow

two chiral superfields $\{T, C\}$

(Non-SUSY : R² \Leftrightarrow scalaron)

Supergravity embedding

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

The diagram shows the Kähler potential K as a sum of two terms. The first term, $-3 \log \left(-\frac{\Omega}{3} \right)$, is associated with the NMSSM part and is highlighted with a blue bracket and an upward arrow labeled "NMSSM". The second term, Ω , is associated with the R^2 SUGRA part and is highlighted with a red bracket and an upward arrow labeled " R^2 SUGRA".

- ✓ NMSSM Fields : singlet S , Higgs doublets H_u, H_d ,
- ✓ Dual scalars T, C (T -sector is completely determined by R^2 structure)
- ✓ Parameters : χ (non-minimal coupling), λ, ρ, α (coefficient of R^2)

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

Unitarity ?? non-trivial after supersymmetrization...

Requires analysis of scattering amplitude,
but can be manifest by (specific) field redefinition & conformal transformation

Scalarmon : $\text{Re}T \rightarrow \sigma$

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

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 χ -parameter**
- ✓ σ linearize NMSSM Higgs inflation
= UV completion

Unitarity ?? non-trivial after supersymmetrization...

Where χ has gone?

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

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Where χ has gone?

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

$\chi / \sqrt{\alpha}$ can be order one

No unitary violation up to Planck scale even after susy extension

Comments on phenomenology

- ✓ Successful inflation ??

$\{\sigma, h\}$ + Many extra fields $\{S, C, \dots\}$

Same as non-susy

should be stabilized



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

Comments on phenomenology

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

✓ SUSY breaking ??

1. Minimal modification: $\Delta\Omega = -\gamma_c (C + \bar{C})$

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

2. Introduce O'Raifeartaigh field Φ $\Delta W = \kappa\Phi + g\Phi C^2$

~~SUSY~~ $\sim F_\Phi = \kappa$: adjustable

Comments on phenomenology

✓ μ -term

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

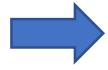
The diagram illustrates the components of the μ -term. It features four nodes: 'NMSSM' on the left, 'Non-minimal coupling' in the center, and 'Giudice-Masiero term' on the right. Above the center node is the equation $\mu = \lambda \langle \tilde{S} \rangle + \frac{3}{2} \chi m_{3/2} - \frac{1}{2} \chi K_{\bar{I}} \bar{F}^{\bar{I}}$. A blue arrow points from 'NMSSM' to 'Non-minimal coupling'. Another blue arrow points from 'Non-minimal coupling' to 'Giudice-Masiero term'. Below the central node is the text 'Lee' 10'. Below the 'Giudice-Masiero term' node is the text 'Giudice, Masiero' 88'.

✓ transmission to visible sector

Sequestered form



vanishing soft mass at tree level



anomaly mediation



tachyonic slepton

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

Reheating & DM production

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

2202.13063

Short summary of reheating

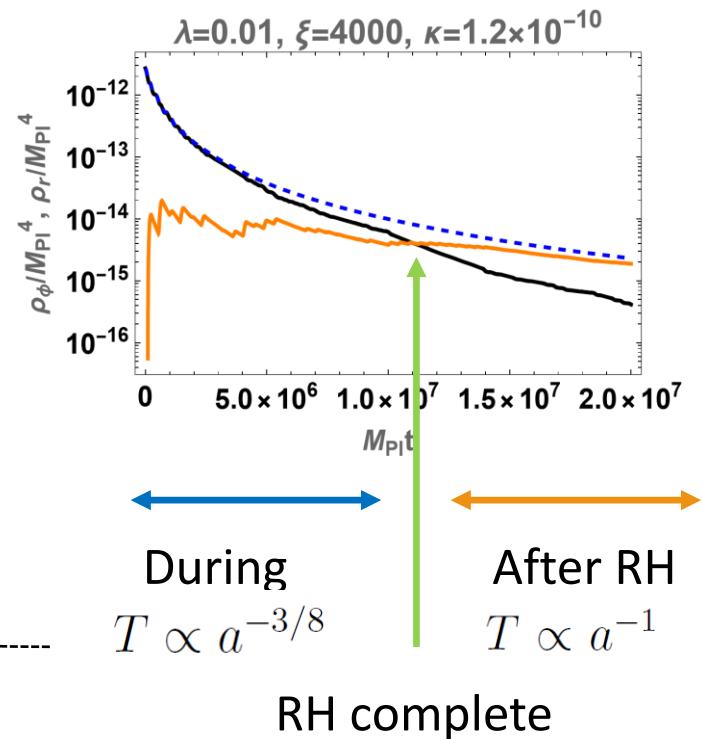
- After inflation, σ and h start oscillation

F. Bezrukov, D. Gorbunov, C. Shepherd and A. Tokareva'19,
M.He '20, SA, H.M.Lee, A.Menkara, K.Yamashita' 22

- dominant channel : $h \rightarrow t + \bar{t} \Rightarrow T_{\text{reh}} \sim 10^{14} \text{ (GeV)}$

- Note: reheating is not instantaneous
 \Rightarrow affect DM production

$$\dot{n}_X + \cancel{3Hn_X} = R(T),$$



FIMP DM scenario

- FIMP = feebly interacting massive particle
- DM never thermalize

Introduce DM (X) as

$$\mathcal{L}/\sqrt{-g_J} = \frac{1}{2}(M_{\text{Pl}}^2 + \xi \hat{h}^2 + \eta \hat{X}^2)R_J - \frac{1}{2}(\partial_\mu \hat{h})^2 - \frac{1}{2}(\partial_\mu \hat{X})^2 - \tilde{V}(\hat{h}, \hat{X}) + \alpha R_J^2 + \mathcal{L}_{\text{SM}}$$

$$\tilde{V}(\hat{h}, \hat{X}) = \frac{\lambda}{4}\hat{h}^4 + \frac{m_X^2}{2}\hat{X}^2 + \frac{\lambda_X}{4}\hat{X}^4 + \frac{\lambda_{hX}}{4}\hat{h}^2\hat{X}^2,$$

- Many Planck suppressed interactions in E-frame
- $|\tilde{\eta}|, |\lambda_{hX}| \sim 0 \Rightarrow$ FIMP

$$\tilde{\eta} \equiv \eta + \frac{1}{6}.$$

Production process

$$\dot{n}_X + 3Hn_X = \underline{R(T)},$$

✓ Thermal production

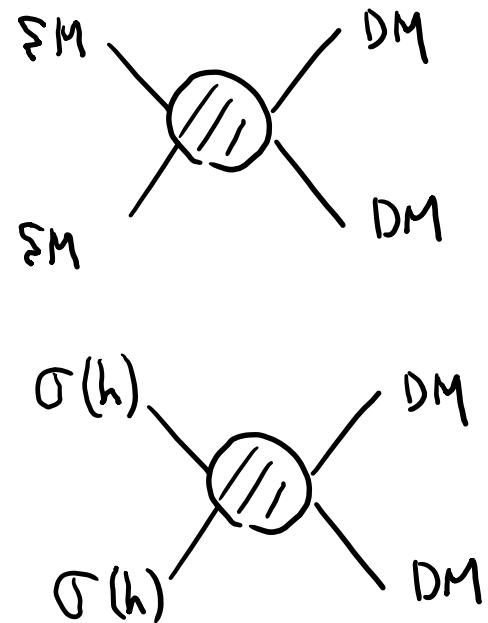
- from radiation (SM particles)
- Efficient both during and after RH

✓ Non-thermal production

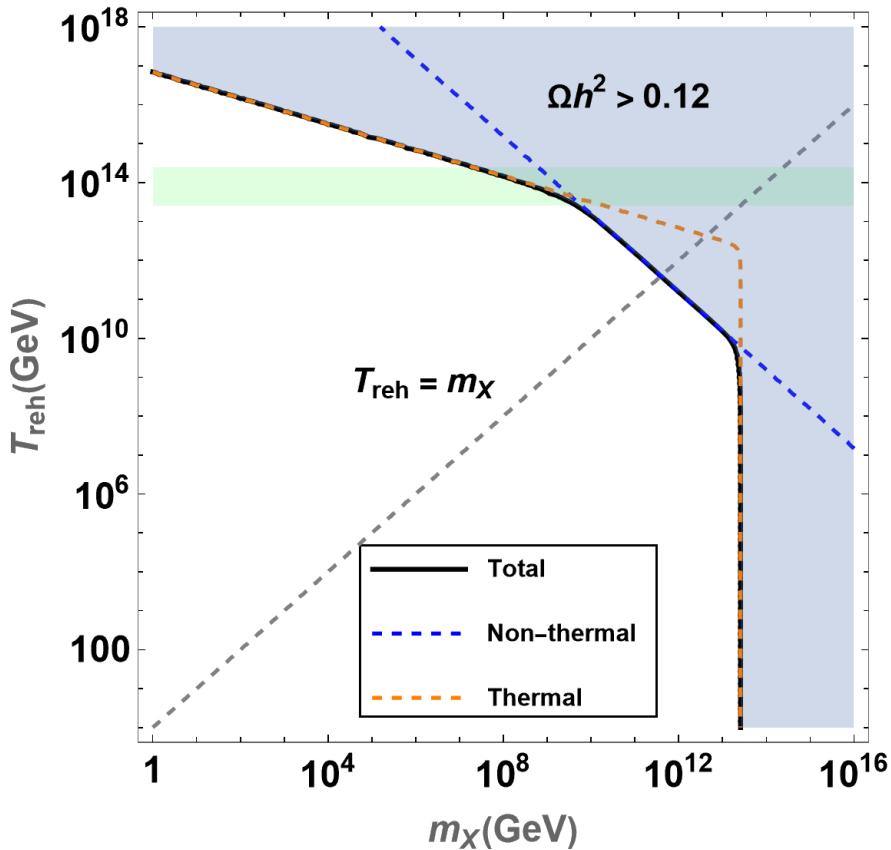
- from inflaton (h and σ)
- Efficient during RH

✓ Graviton exchange S. Clery, Y. Mambrini, K. A. Olive, S. Verner' 21

important for both thermal and non-thermal production



DM abundance



Green band
(predicted RH temp. in this model)

- Non-thermal << Thermal
- $10^7 < m_X < 10^{10}$ (GeV)
can explain DM abundance

Summary

Higgs-R² = UV completion of Higgs inflation

SUGRA embedding of Higgs-R² model

- ✓ no unitarity issue even after supersymmetrization
- ✓ successful inflation with higher curvature modification
- ✓ two SUSY breaking mechanisms & transmission to visible sector

Reheating & FIMP production

- ✓ Scalar FIMP DM ($\tilde{\eta}, \lambda_{hX} \sim 0$)
- ✓ Include thermal/non-thermal production, graviton exchange, temperature evolution, etc
- ✓ Non-thermal << Thermal production
- ✓ $T_{reh} \sim 10^{14}(\text{GeV}) \Rightarrow 10^7 < m_X < 10^{10}$ can explain a correct relic density

Thank you !!

Backup

Higgs- R^2 inflation model

Salvio & Mazumdar '15, Ema '17, Gorbunov & Tokareva '18, Gundhi & Steinwachs '18,
D. Y. Cheong & S. M. Lee & S. C. Park '21, SA, H. M. Lee, A. G. Menkara,'21 ...

In addition to the solution of unitarity issue,

- keep successful inflation (Higgs inflation + Starobinsky inflation)
- predictive
- Supported by RGE
- Solve vacuum instability problem

R^2 (Starobinsky) inflation in supergravity

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

$\int d^4\theta$



S. Cecotti' 87

$$\left[\begin{array}{l} \mathcal{R} = (X^0)^{-1} \Sigma (\bar{X}^{\bar{0}}) \quad : \text{curvature superfield} \\ X^0 : \text{compensator} \\ \Sigma : \text{chiral projection } (\sim \bar{D}^2) \end{array} \right]$$

R^2 (Starobinsky) inflation in supergravity



Introduce auxiliary superfield T and C

$$[\alpha \bar{R} R]_D = [\alpha \bar{C} C]_D + [T(C - \bar{R})]_F \xrightarrow{\int d^2\theta}$$

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



&

$$T \rightarrow T(X^0)^2 \text{ and } C \rightarrow CX^0$$

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

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

$$\left\{ \begin{array}{l} \Omega = |C|^2 - (T + \bar{T}) \\ W = \frac{1}{\sqrt{\alpha}} TC \end{array} \right.$$

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

Linear Sigma frame

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

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

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 $\text{Re}\hat{T}$ (scalarmon) $\rightarrow \sigma$

$$\begin{aligned} \rightarrow \mathcal{L}/\sqrt{-g} = & \frac{1}{2} \left(1 - \frac{1}{3}|\hat{S}|^2 - \frac{1}{3}|\hat{H}_u|^2 - \frac{1}{3}|\hat{H}_d|^2 - \frac{1}{3}|\hat{C}|^2 - \frac{1}{6}\sigma^2 \right) R \\ & - |\partial_\mu \hat{S}|^2 - |\partial_\mu \hat{H}_u|^2 - |\partial_\mu \hat{H}_d|^2 - |\partial_\mu \hat{C}|^2 - \frac{1}{2}(\partial_\mu \sigma)^2 - V \end{aligned}$$

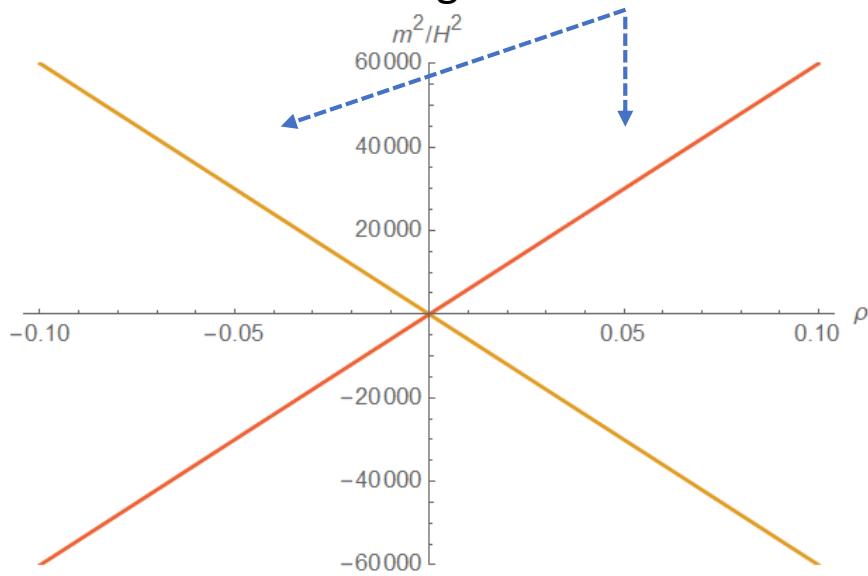
conformal
canonical

No-large couplings χ, α

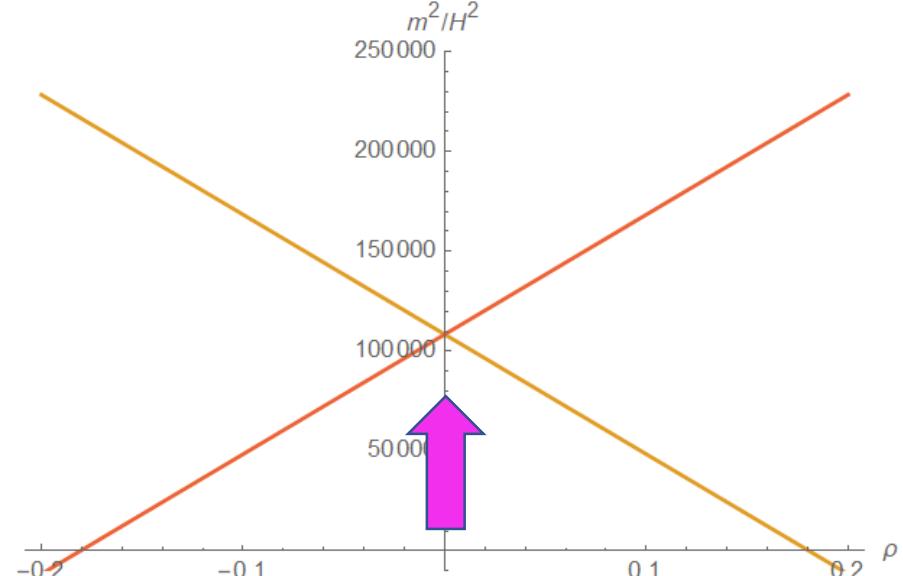
Stabilization of S and C

ρ : cubic coupling of S

Mass eigenvalues of S and C



$$(\zeta_s, \zeta_c) = (0,0)$$

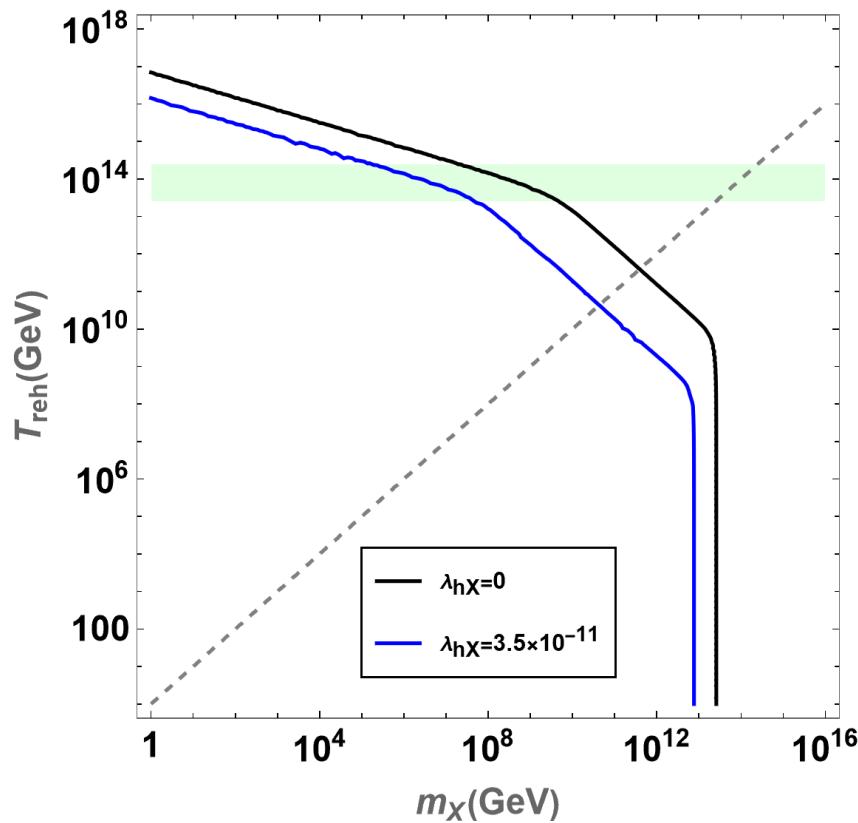


$$(\zeta_s, \zeta_c) = (3,0.4)$$

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

Effects of $\tilde{\eta}$ and λ_{hX}

To avoid overproduction \Rightarrow $|\lambda_{hX}| \lesssim 10^{-10}$ & $|\tilde{\eta}| \lesssim 10^{-6}$



Smaller DM mass
for correct relic abundance