A Supersymmetric Two-Field Relaxion Model

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Based on J. L. Evans, T. Gherghetta, N. Nagata, Z. Thomas, [arXiv:1602.04812].

Supersymmetry (SUSY)

Leading candidate for physics beyond the Standard Model (SM)

- Solution to the naturalness problem
- SUSY grand unification
- Dark matter candidates

Current constraints on SUSY

- Null results for SUSY searches
- 125 GeV Higgs mass

➡ SUSY scale may be much higher than the EW scale.

➡ Little hierarchy problem??

Relaxion mechanism

P. W. Graham, D. E. Kaplan, S. Rajendran, Phys. Rev. Lett. **115**, 221801 (2015).

Relaxion ϕ

See also L. F. Abbott (1985),
G. Dvali and A. Vilenkin (2013)
G. Dvali (2014)

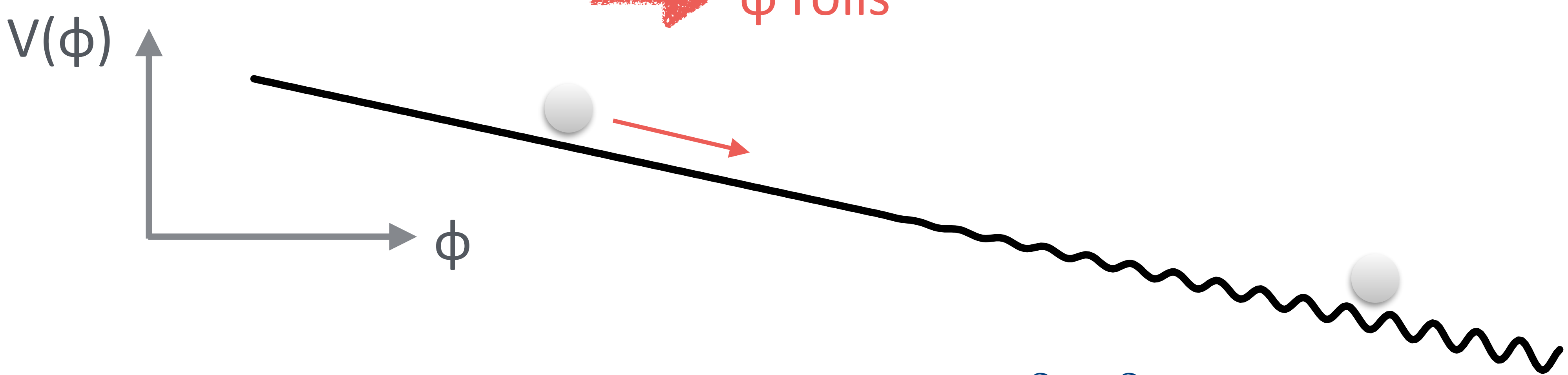
- Axion-like particle
- Scans the Higgs mass parameter

Potential

$$V = -g\Lambda^3\phi + \left(\Lambda^2 - g\Lambda\phi\right)|H|^2 + \frac{\lambda}{2}|H|^4 + f_\pi^2 m_\pi^2 \cos\left(\frac{\phi}{f}\right)$$

Small shift-symmetry breaking → ϕ rolls

∝ Higgs VEV



Barrier generated after EWSB

Small but technically natural → $g \simeq \frac{f_\pi^2 m_\pi^2}{\Lambda^3 f}$

ϕ stops right after EWSB!

Problems in the original model

- Strong CP Problem

The original model uses the Peccei-Quinn axion as the relaxion.

➡ θ_{QCD} is generically too large after the relaxion stops.

- A simple extension

Introduce vector-like fermions charged under new strong (non-QCD) interaction.

➡ Periodic potential is generated by this new interaction.

For the Higgs VEV to give a sizable effect on the periodic potential, the new strong dynamics and the fermions should be the TeV scale.

➡ Coincidence problem

Extensions of the original relaxion model

- Two-field relaxion model

J. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolas, G. Servant (2015).

Second field: σ

Neutralize the periodic potential induced by the new strong dynamics.

➡ Its scale can be much higher than the electroweak scale! (no coincidence problem).

$$\Lambda \lesssim 10^9 \ \mathrm{GeV}$$

Physics above the cut-off scale?

- Application to the SUSY little hierarchy problem

B. Batell, G. F. Giudice, M. McCullough, JHEP **1512**, 162 (2015).

- Relaxion scans soft masses instead of the Higgs mass parameter
- Succeed the shortcomings in the original model

→ Two-field SUSY relaxion model (this talk)

SUSY two-field relaxion model

Singlet chiral superfields

$$S = \frac{s + i\phi}{\sqrt{2}} + \sqrt{2}\,\widetilde{\phi}\,\theta + F_S\theta\theta\ ,$$

$$T = \frac{\tau + i\sigma}{\sqrt{2}} + \sqrt{2}\,\widetilde{\sigma}\,\theta + F_T\theta\theta\ ,$$

Superpotential

$$W_{S,T} = \frac{1}{2}m_S S^2 + \frac{1}{2}m_T T^2\ ,$$

(shift-symmetry breaking)

$$W_\mu = \mu_0 e^{-\frac{q_H S}{f_\phi}} H_u H_d$$

$$W_{\rm gauge} = \left(\frac{1}{2g_a^2} - i\frac{\Theta_a}{16\pi^2} - \frac{c_a S}{16\pi^2 f_\phi}\right)\mathrm{Tr}(\mathcal{W}_a\mathcal{W}_a)$$

(a: SM, SU(N))

$$W_N = m_N N\bar{N} + ig_S SN\bar{N} + ig_T TN\bar{N} + \frac{\lambda}{M_L}H_u H_d N\bar{N}\ ,$$

(N: charged under SU(N))

Kahler potential does not violate shift symmetries.

Shift symmetries

$$\mathcal{S}_S:\ S \to S + i\alpha f_\phi\ ,\quad T \to T\ ,\quad Q_i \to e^{iq_i\alpha}Q_i\ ,\quad H_u H_d \to e^{iq_H\alpha}H_u H_d\ ,$$

$$\mathcal{S}_T:\ S \to S\ ,\quad T \to T + i\beta f_\sigma\ ,\quad Q_i \to Q_i\ ,\quad H_u H_d \to H_u H_d\ ,$$

σ does not have a renormalizable coupling with the Higgs fields.

See K. Choi and S. H. Im (2015), D. E. Kaplan and R. Rattazzi (2015)

J. L. Evans, T. Gherghetta, N. Nagata, Z. Thomas, [arXiv:1602.04812].

Soft masses

ϕ and σ have large field values during the evolution.

$F_S \neq 0\ , \quad F_T \neq 0\ .$ ➡ SUSY is broken by these fields!

Scalar masses

(e.g.)
$$\int d^4\theta \frac{1}{M_*^2}(S+S^*)^2 Q_i Q_i^* \quad \Rightarrow \quad \widetilde{m} \sim \frac{F_S}{M_*} \sim \frac{m_S \phi}{M_*}$$

Gaugino masses

$$\int d^2\theta \frac{c_a S}{16\pi^2 f_\phi} \mathrm{Tr}(\mathcal{W}_a \mathcal{W}_a) \quad \Rightarrow \quad M_a \sim \frac{c_a F_S}{16\pi^2 f_\phi} \sim \frac{c_a m_S \phi}{16\pi^2 f_\phi}$$

ϕ scans soft masses during the evolution!

B. Batell, G. F. Giudice, M. McCullough, JHEP **1512**, 162 (2015).

EWSB condition

$$\mathcal{D}(\phi) \equiv (m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B\mu|^2 < 0$$

Critical value [D(ϕ*) = 0]

$$\mu_0 \sim \frac{m_S \phi_*}{f_\phi} \equiv m_{\mathrm{SUSY}}$$

Cosmological evolution

Potential

$$V_{\phi,\sigma}(\phi,\sigma,H_uH_d) = \frac{1}{2}|m_S|^2\phi^2 + \frac{1}{2}|m_T|^2\sigma^2 + \mathcal{A}(\phi,\sigma,H_uH_d)\,\Lambda_N^3 \cos\left(\frac{\phi}{f_\phi}\right) ,$$

Λ_N^3 ← $\langle \overline{\psi_N}\psi_N \rangle$

with

$$\mathcal{A}(\phi,\sigma,H_uH_d) = \overline{m}_N - \frac{g_S}{\sqrt{2}}\phi - \frac{g_T}{\sqrt{2}}\sigma + \frac{\lambda}{M_L}H_uH_d\ .$$

$(\overline{m}_N, g_S > 0,\ g_T < 0,\ \lambda < 0)$

Two-field relaxion mechanism

I: ϕ stuck. σ rolls.

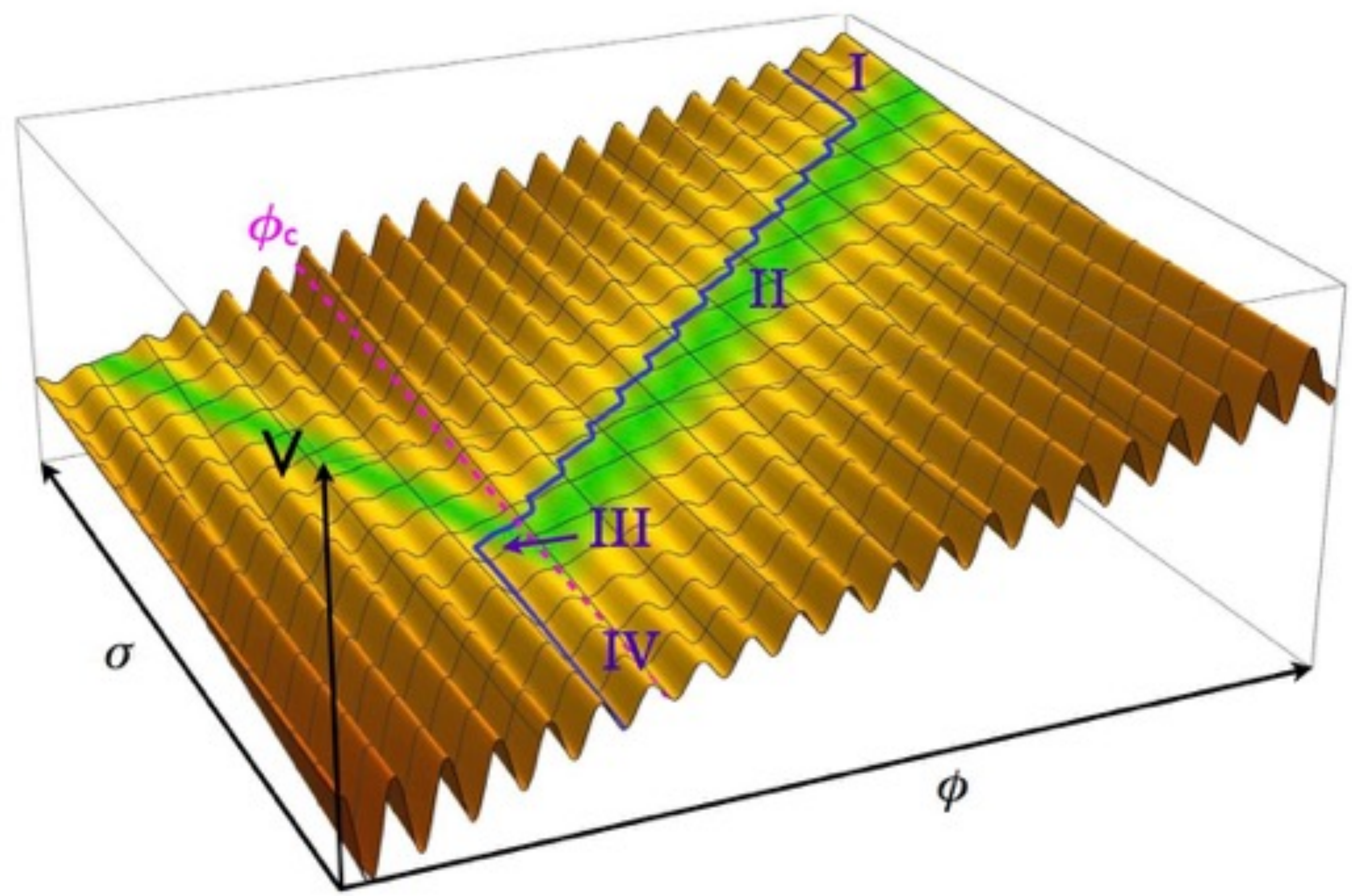
II: Both ϕ and σ evolve. A = 0.

III: EWSB occurs (D(ϕ)<0).

IV: ϕ stops. σ keeps rolling.

ϕ needs to track σ

$$|m_T| < |m_S|$$



J. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolas, G. Servant (2015).

Constraints

Slow-roll conditions

$$|m_S| \ll H_I$$

(H_I : Hubble parameter)

We assume inflation is driven by another inflaton field.

ϕ and σ should not dominate vacuum energy

$$\frac{1}{2}|m_S|^2\phi^2 \ , \ \frac{1}{2}|m_T|^2\sigma^2 \ll 3H_I^2 M_P^2$$

(M_P : Planck mass)

SUSY-breaking from inflation sector is sub-dominant

$$H_I \lesssim v$$

Low-scale inflation

[or *D*-term inflation??]

Classical rolling

$$\left|\frac{d\sigma}{dt} H_I^{-1}\right| \sim \frac{|m_T|^2\sigma}{3H_I^2} \gg H_I$$

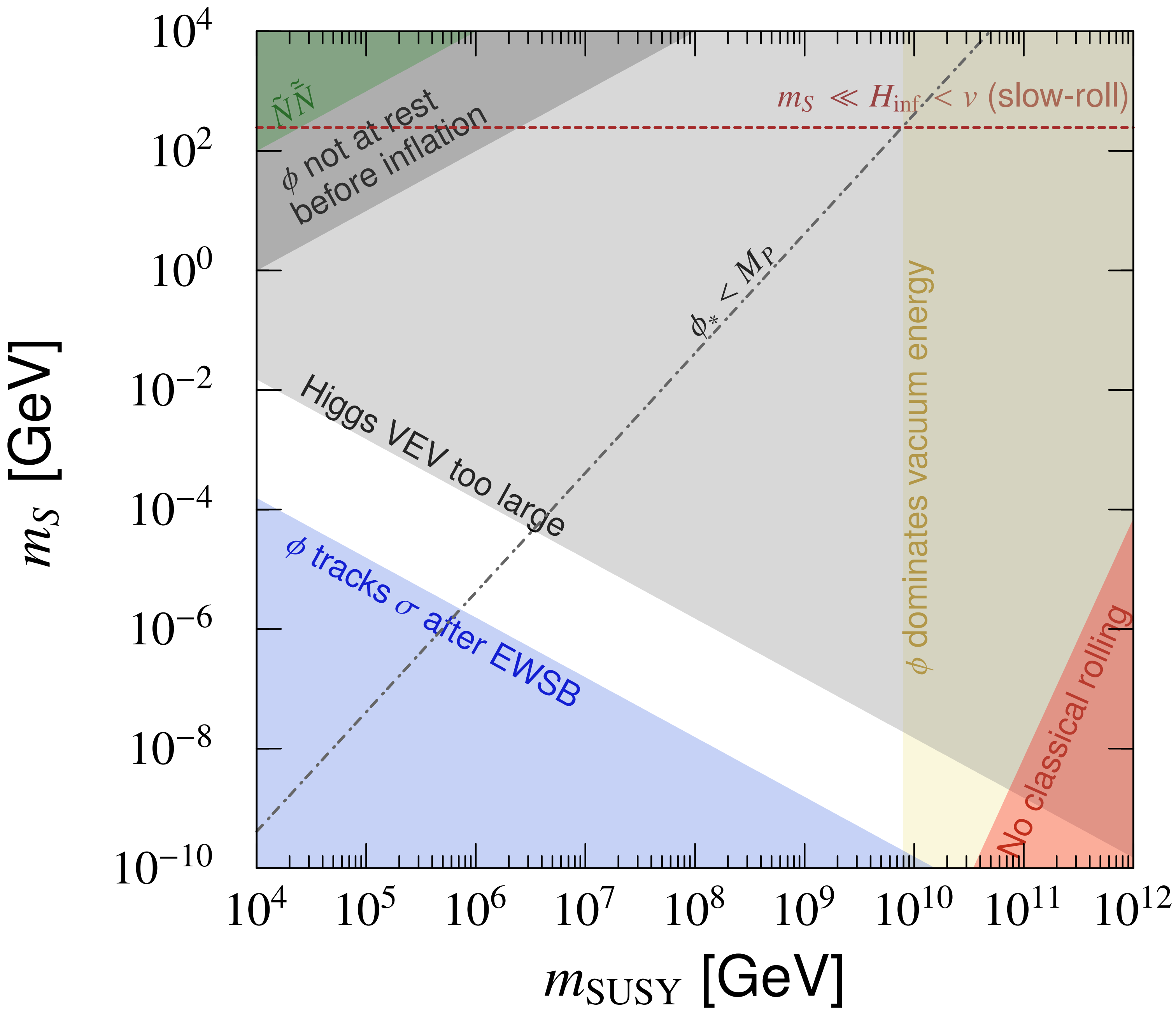
Change of σ during Hubble time

Typical size of quantum fluctuations

Number of *e*-folds

$$N_e \simeq \frac{H_I \Delta\phi}{\left|\frac{d\phi}{dt}\right|} \gtrsim \frac{H_I^2}{|m_S|^2} = 10^{12} \times \left(\frac{H_I}{100 \ \mathrm{GeV}}\right)^2 \left(\frac{10^{-4} \ \mathrm{GeV}}{|m_S|}\right)^2$$

Results



$$m_{\rm SUSY} = \Lambda_N = M_L = 0.1 f_\phi$$

$$f_\phi = f_\sigma \quad m_T = 0.1 m_S$$

$$\frac{g_S f_\phi}{m_S} = \frac{g_T f_\sigma}{m_T} = 0.01$$

$$\phi_* \sim \frac{m_{\rm SUSY} f_\phi}{m_S}$$

PeV-scale SUSY can be naturalized with sub-Planckian excursion!

J. L. Evans, T. Gherghetta, N. Nagata, Z. Thomas, [arXiv:1602.04812].

Particle spectrum

SUSY particles

- $M_* \sim f_\phi$ → Gaugino masses are suppressed by a loop factor compared with scalar masses (mini-split type)
- $M_* \gg f_\phi$ → Soft masses are induced by gaugino masses. (similar to gaugino mediation/no-scale scenario)

Relaxion sector

- ϕ $\cdots$ Determined by the height of periodic potential. $m_\phi^2 \simeq \frac{\Lambda_N^3 \mathcal{A}}{f_\phi^2}$
- $\tilde{\phi}$ $\cdots$ Eaten by gravitino (goldstino).

$$m_{3/2} = \frac{F}{\sqrt{3} M_P} \simeq 2 \times \left(\frac{m_{\rm SUSY}}{10^6 \ {\rm GeV}} \right) \left(\frac{f_\phi}{10^8 \ {\rm GeV}} \right) \ {\rm keV}$$

Gravitino problem
- Low reheating temperature
- Late-time entropy production

- s $\cdots$ As heavy as SUSY particles.
- $\tau, \ \tilde{\sigma}$ $\cdots$ Depending on Kahler potential. Can be as light as gravitino.
- σ $\cdots$ m_T

Conclusion

- We proposed a SUSY two-field relaxion model.
- Strong CP problem and coincidence problem are evaded thanks to the two-field relaxion mechanism.
- PeV-scale SUSY can be naturalized with sub-Planckian field excursion.
- There are several issues to study more in cosmology side (inflation model, low H_{inf}, gravitino problem, …).

Backup

Lagrangian

Kahler potential

$$K = \kappa(S+S^*, T+T^*) + Z_i(S+S^*, T+T^*)\Phi_i^* e^{2V}\Phi_i$$
$$+ \left[U(S+S^*, T+T^*) e^{-\frac{q_H S}{f_\phi}} H_u H_d + \text{h.c.} \right] ,$$

where $\Phi_i = Q_i, H_u, H_d, N, \bar{N}$

Super potential

$$W_{\text{gauge}} = \left(\frac{1}{2g_a^2} - i\frac{\Theta_a}{16\pi^2} - \frac{c_a S}{16\pi^2 f_\phi} \right) \text{Tr}\mathcal{W}_a\mathcal{W}_a ,$$

$$W_{\text{Yukawa}} = y_u Q\overline{U}H_u + y_d Q\overline{D}H_d + y_e L\overline{E}H_d ,$$

$$W_\mu = \mu_0 e^{-\frac{q_H S}{f_\phi}} H_u H_d ,$$

$$W_{S,T} = \frac{1}{2}m_S S^2 + \frac{1}{2}m_T T^2 ,$$

$$W_N = m_N N\bar{N} + ig_S SN\bar{N} + ig_T TN\bar{N} + \frac{\lambda}{M_L}H_u H_d N\bar{N} .$$

Scalar potential

Lagrangian for S and T

$$\mathcal{L} = \boldsymbol{F}^{\dagger}\mathcal{K}(s,\tau)\boldsymbol{F} + \left(\boldsymbol{m}\cdot\boldsymbol{F} + i\boldsymbol{g}\cdot\boldsymbol{F}\widetilde{N}\widetilde{\bar{N}} + \text{h.c.}\right) ,$$

where

$$\mathcal{K} = \frac{1}{2}\begin{pmatrix} \frac{\partial^2\kappa}{\partial s^2} & \frac{\partial^2\kappa}{\partial s\partial\tau} \\ \frac{\partial^2\kappa}{\partial s\partial\tau} & \frac{\partial^2\kappa}{\partial\tau^2} \end{pmatrix}, \quad \boldsymbol{F} = \begin{pmatrix} F_S \\ F_T \end{pmatrix}, \quad \boldsymbol{g} = \begin{pmatrix} g_S \\ g_T \end{pmatrix}, \quad \boldsymbol{m} = \frac{1}{\sqrt{2}}\begin{pmatrix} m_S(s+i\phi) \\ m_T(\tau+i\sigma) \end{pmatrix} .$$

$$\boldsymbol{F} = -\mathcal{K}^{-1}\left(\boldsymbol{m} + i\boldsymbol{g}\widetilde{N}\widetilde{\bar{N}}\right)^{*} .$$

Scalar potential

$$V = \boldsymbol{m}^{\dagger}\mathcal{K}^{-1}\boldsymbol{m} .$$

Minimum for s and τ

$$\frac{\partial}{\partial s}\mathcal{K}^{-1}(s,\tau) \simeq \frac{\partial}{\partial\tau}\mathcal{K}^{-1}(s,\tau) \simeq 0 ,$$

The minimum does not depend on ϕ and σ as long as they have large value, since the condition is independent of these fields.

s and τ are constant.

Absence of the σ-Higgs coupling

In the two-field relaxion mechanism, σ should not have a direct coupling to the Higgs fields. (Otherwise, the late time excursion of σ changes the Higgs mass.)

⇒ In our model, there is no such a coupling at renormalizable level.

(The Kahler potential depends on $T + T^*$.)

The σ-Higgs couplings are generated by SUSY-breaking effects.

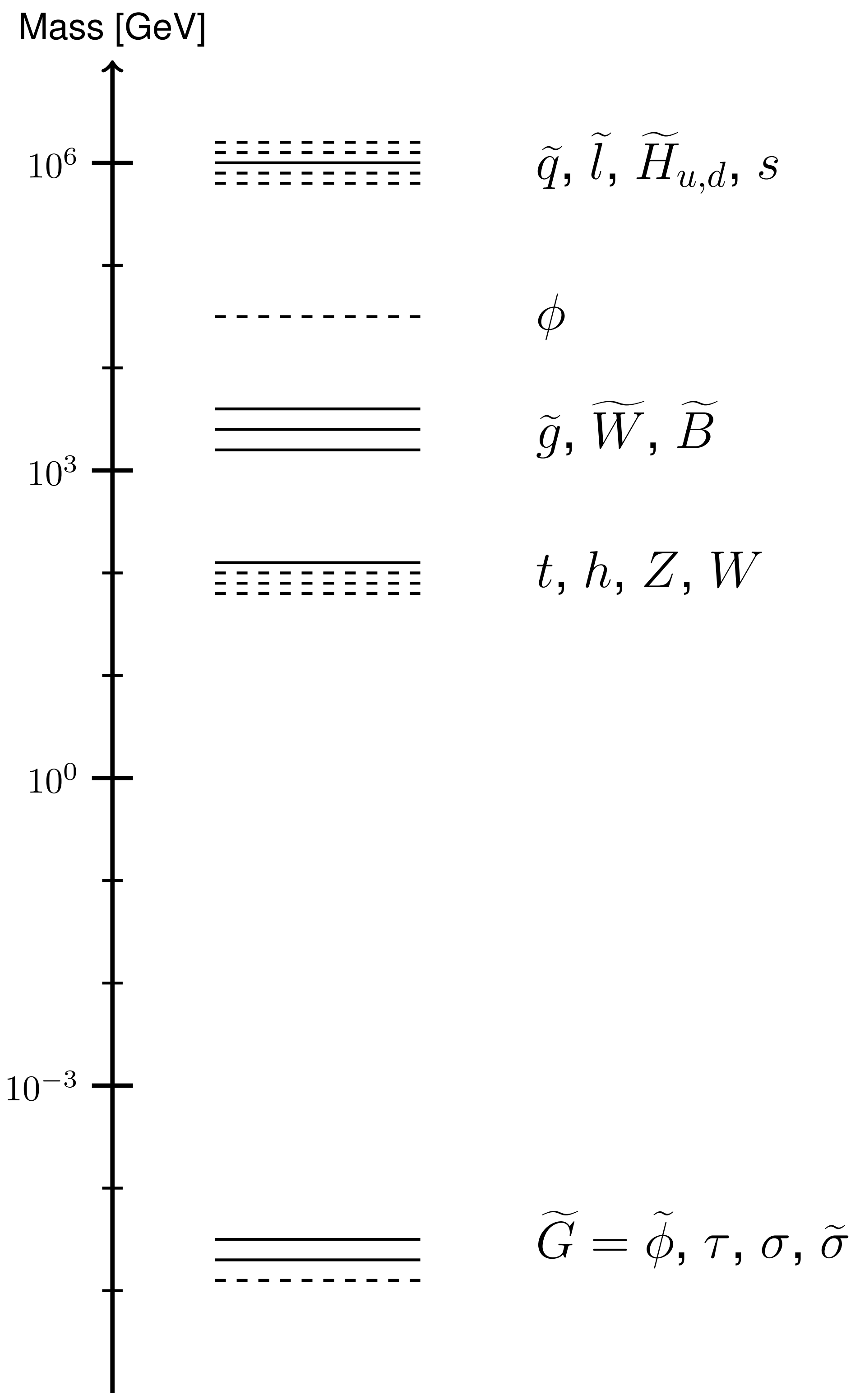
- $m_T \ll m_S$

  $F_T \ll F_S$. In this case, F_S is the dominant source of the SUSY-breaking.

- $M_* \gg f$

  Again, F_S is the dominant source of the SUSY-breaking.

Particle spectrum



$$m_{\rm SUSY} = 10^6\ \text{GeV}$$

$$M_* \sim f_{\phi,\sigma} = 10^6\ \text{GeV}$$