Naturalizing SUSY with the relaxion and inflaton

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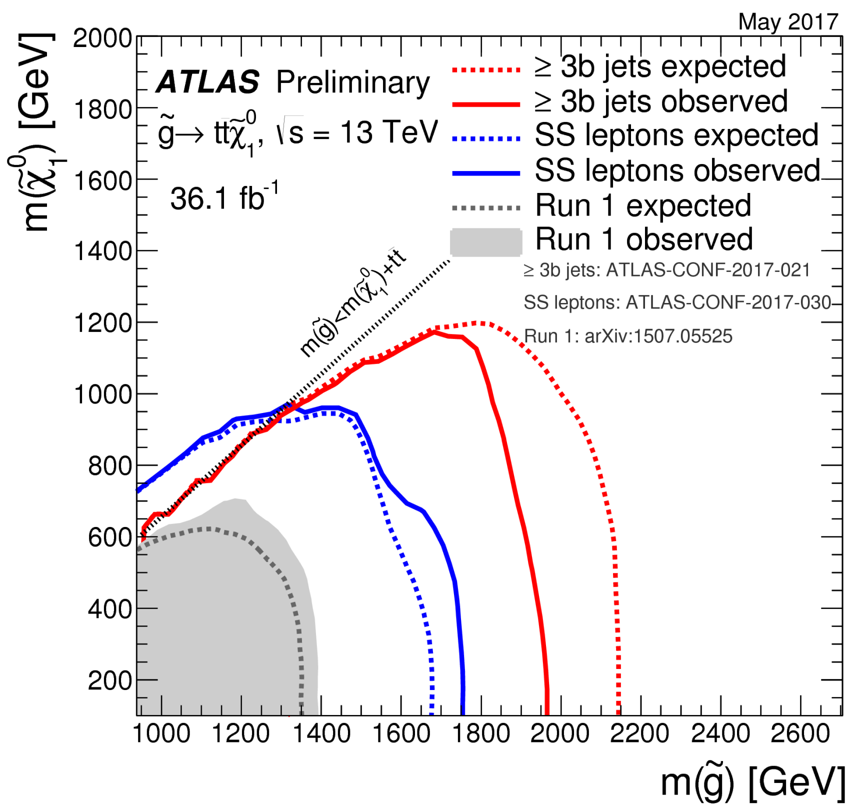
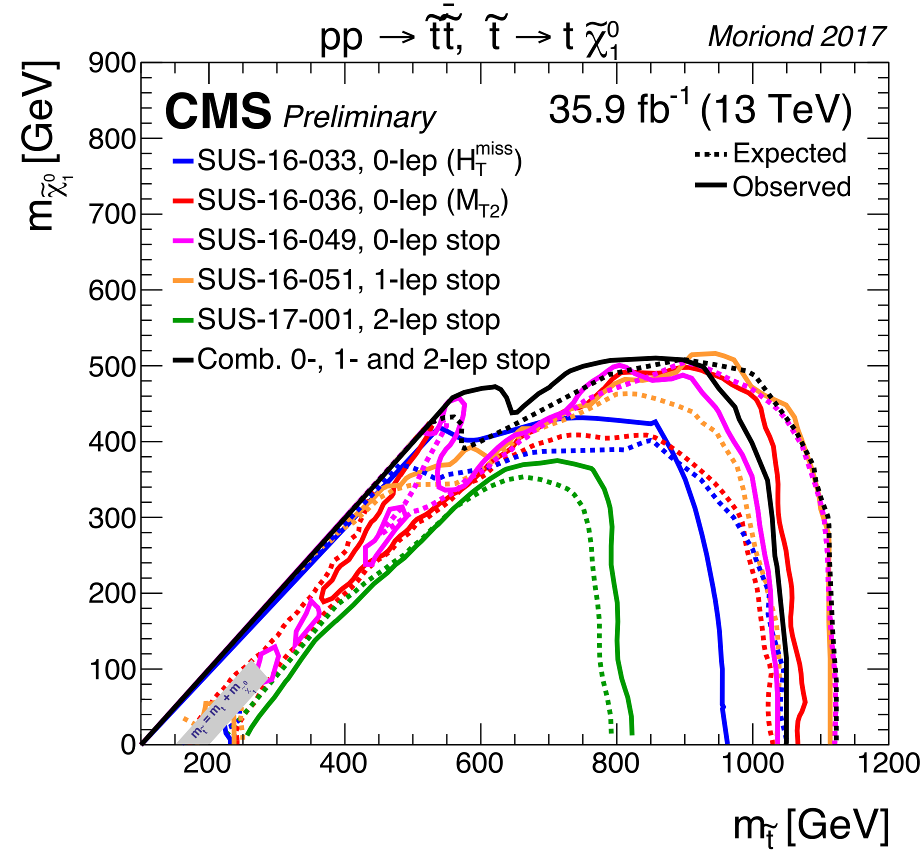
[*Jason Evans, TG, Natsumi Nagata, Zach Thomas,* arXiv:1602.04812]
[*Jason Evans, TG, Natsumi Nagata, Marco Peloso,* arXiv:1704.03695]

LHC Run 2: *SUSY remains elusive...*



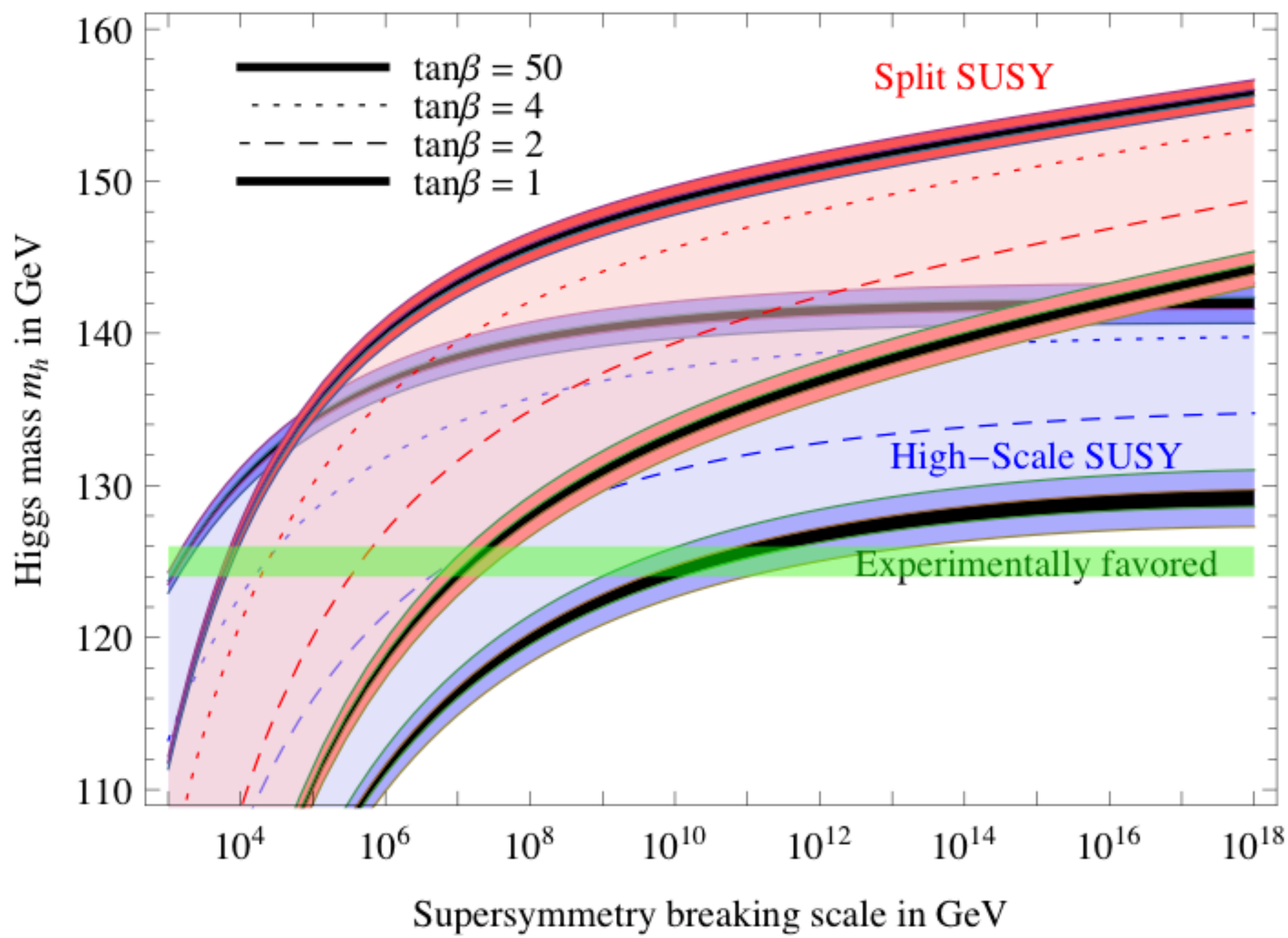


$m_{\tilde{g}} \gtrsim 1900$ GeV

$m_{\tilde{t}} \gtrsim 1050$ GeV

Predicted range for the Higgs mass

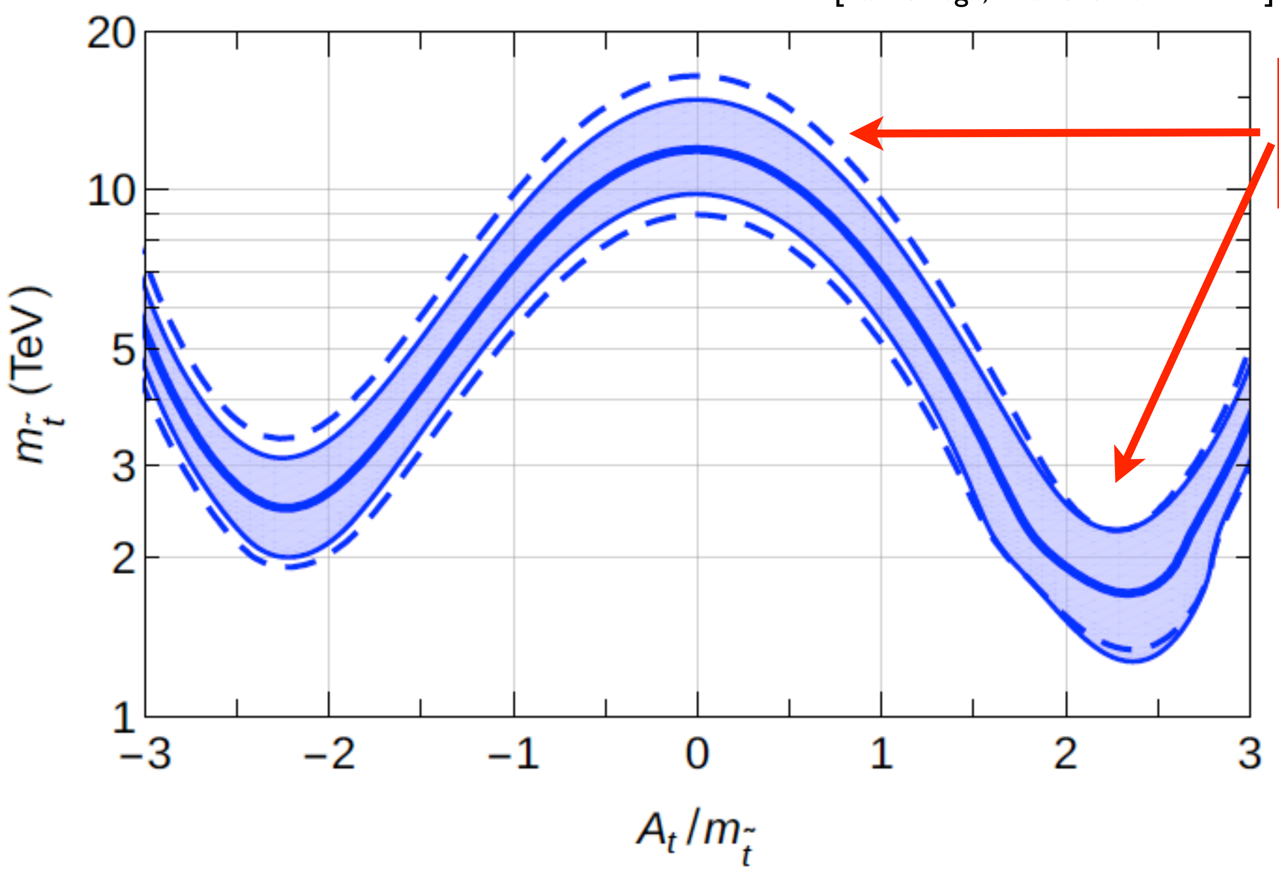
[Giudice, Strumia 1108.6077]



SUSY breaking scale $\lesssim 10^7$ GeV

Higgs mass in minimal SUSY

[Pardo Vega, Villadoro 1504.05200]



Requires large stop masses or large A-terms

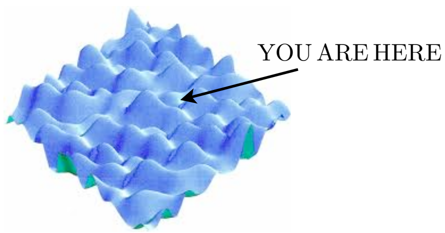
➡ Increases tuning in supersymmetric models

Why is $m_{\tilde{t}} \gtrsim \mathrm{TeV}$ and not near electroweak scale?

- There is no *low-energy* supersymmetry

- SUSY top partners are uncolored   e.g. Folded SUSY   "Neutral Naturalness"

- Anthropic - we live in a multiverse



Is there an alternative possibility?   *Yes!*

Special point in parameter space:

$m_H^2 = 0$ ***not*** related to symmetry

e.g. supersymmetry $m_H^2 \simeq \Lambda^2 - \Lambda^2 + \ldots$

Instead, $m_H^2 \simeq 0$ related to early-universe dynamics!

e.g. self-organized criticality

Dynamical evolution sets the SUSY scale!

$\longrightarrow$ explains why $m_{\tilde{t}} \gg v$!

$\leftarrow$ This talk

"Hidden" Naturalness

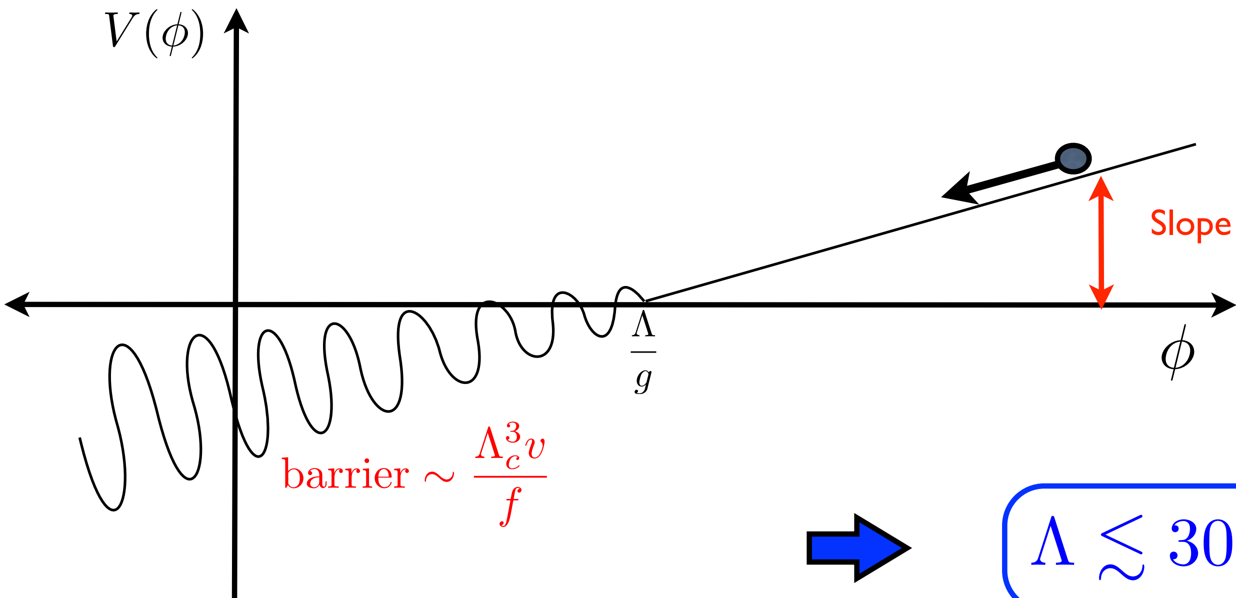
Relaxion mechanism [Graham, Kaplan, Rajendran 1504.07551]

Introduce scalar field (relaxion): ϕ

$$V(\phi, h) = g\Lambda^3\phi - \Lambda^2(1 - \frac{g\phi}{\Lambda})|H|^2 + \lambda_h |H|^4 + \Lambda_c^3 v \cos\frac{\phi}{f}$$

breaks shift symmetry: $\phi \to \phi + c$

back reaction from strong dynamics



$g\Lambda^3 \sim \frac{\Lambda_c^3 v}{f}$

$\Lambda \lesssim 30 - 1000$ TeV

However:

- Relaxion = QCD axion ⟶ large θ_{QCD}!
- Alternatively, non-QCD dynamics requires new fermions near electroweak scale ⟶ coincidence?

In general:

$$V(\phi, h) = g\Lambda^3\phi + \Lambda^2(1 - \frac{g\phi}{\Lambda})|H|^2 + \lambda_h|H|^4 + \Lambda_c^{4-n}v^n \cos\frac{\phi}{f}$$

$n = 1$ Requires new source of EWSB e.g. QCD

$n = 2$ $\Lambda_c^2|H|^2\cos\frac{\phi}{f}$ Gauge invariant - new source not required!

⟶ However, quantum corrections generate: $\Lambda_c^4\cos\frac{\phi}{f},\ \Lambda_c^3 g\phi\cos\frac{\phi}{f}$ Large potential barriers!

Introduce second field, σ [Espinosa et al 1506.09217]

$$V(\phi, \sigma, h) = g\Lambda^3\phi + g_\sigma\Lambda^3\sigma + \Lambda^2(\alpha - \frac{g\phi}{\Lambda})|H|^2 + \lambda_h|H|^4 + \mathcal{A}(\phi, \sigma, H)\cos\frac{\phi}{f}$$

new term

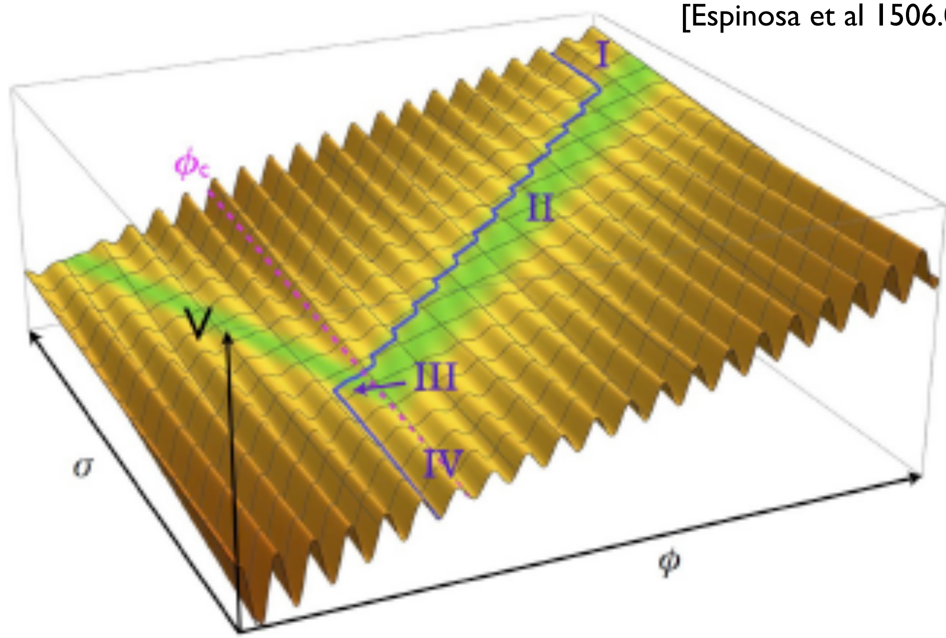
where $$\mathcal{A}(\phi, \sigma, H) = \epsilon\left(\beta\Lambda^4 + c_\phi g\Lambda^3\phi - c_\sigma g_\sigma\Lambda^3\sigma + \Lambda^2|H|^2\right)$$

new term -- cancels large potential barrier!

[Assuming no $\sigma|H|^2$ coupling and $\epsilon^2\Lambda^4\cos^2\frac{\phi}{f}$ terms]

Obtain:

[Espinosa et al 1506.09217]



Cosmological Evolution Stages:

I. ϕ trapped, σ rolls
II. $\mathcal{A} = 0$; both ϕ and, σ roll
III. EWSB barrier appears
IV. ϕ stops, σ continues to roll

$$\Lambda \lesssim 2 \times 10^9 \text{ GeV} \quad \text{for } g_\sigma = 0.1 g \simeq 10^{-27}$$

But $\Lambda \ll M_P$, so still require a UV completion....

Instead, apply to SUSY “little” hierarchy!

Supersymmetric *two-field* relaxion mechanism

[Evans, TG, Nagata, Thomas 1602.04812]

Embed ϕ, σ into chiral superfields S, T

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

relaxion

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

"amplitudon"

Shift symmetries:

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

$\phi = \mathrm{NG\ boson}$

$$\begin{aligned} \mathcal{S}_T:\ \ S &\to S\,, \\ T &\to T + i\beta f_\sigma\,, \\ Q_i &\to Q_i\,, \\ H_u H_d &\to H_u H_d\,, \end{aligned}$$

$\sigma = \mathrm{NG\ boson}$

where $Q_i = \mathrm{MSSM\ matter\ superfields}$, $f_\phi, f_\sigma = \mathrm{decay\ constants}$
$H_u, H_d = \mathrm{MSSM\ Higgs\ superfields}$

Break shift symmetry to generate potential for ϕ, σ

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

⇨ $$V(\phi, \sigma) = \frac{1}{2}|m_S|^2 \phi^2 + \frac{1}{2}|m_T|^2 \sigma^2$$

Kahler potential: $$K = K(S + S^*, T + T^*)$$ shift invariant

⇨ no renormalisable coupling of σ to H_u, H_d!

But ϕ can couple to MSSM Higgs fields via $U(S + S^*, T + T^*) e^{-\frac{q_H S}{f_\phi}} H_u H_d$

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

Scanning of soft mass parameters

[Batell, Giudice, McCullough 1509.00834]

Assume large initial ϕ, σ field value and $\sigma \sim \phi, f_\sigma \sim f_\phi, m_T \sim m_S$

$\Rightarrow$ $m_\phi \sim m_\sigma \sim m_S$ $\quad$ $F_S \sim F_T \sim m_S \phi$

SUSY is broken by relaxion!

Soft terms:

$$\int d^4\theta \frac{1}{M_*^2}[(S+S^*)^2 + (T+T^*)^2]\Phi^\dagger\Phi \Rightarrow \tilde{m} \sim B \sim A_{ijk} \sim \frac{m_S \phi}{M_*}$$

varies as relaxion evolves!

$$\int d^2\theta \frac{c_a S}{16\pi^2 f_\phi} \mathrm{Tr} W_a W_a \xRightarrow{f_\phi \sim M_*} M_a \sim \frac{\alpha_a}{4\pi}\frac{m_S \phi}{M_*}$$

only S shift symmetry induces chiral anomaly

Electroweak symmetry breaking

Obtain: $m_{H_u}^2 = c_u |m_S|^2 \phi^2, \qquad m_{H_d}^2 = c_d |m_S|^2 \phi^2,$ [assuming $m_T \ll m_S (F_T \ll F_S)$]

$$\mu = c_{\mu 0}\mu_0 + c_\mu m_S^* \phi\ , \qquad B\mu = c_{B0}\mu_0 m_S \phi + c_B |m_S|^2 \phi^2 + \frac{\lambda \Lambda^3}{M_L} \cos\frac{\phi}{f}$$

assume subdominant $\lesssim v^2$

Order parameter: $\mathcal{D}(\phi) \equiv \left(m_{H_u}^2 + |\mu|^2\right)\left(m_{H_d}^2 + |\mu|^2\right) - |B\mu|^2$

decreases until $\mathcal{D}(\phi) < 0$ → EWSB

Critical value: $\mathcal{D}(\phi_*) = 0$ occurs when $\mu_0 \sim \frac{m_S \phi_*}{f_\phi} \sim m_{SUSY}$

For: $m_S \sim 10^{-7}\ \mathrm{GeV} \times \left(\frac{m_{\mathrm{SUSY}}}{10^5\ \mathrm{GeV}}\right)\left(\frac{f_\phi}{10^5\ \mathrm{GeV}}\right)\left(\frac{10^{17}\ \mathrm{GeV}}{\phi_*}\right)$

⇒ $\mu \sim m_{SUSY}, \quad m_{H_u}^2 \sim m_{H_d}^2 \sim B\mu \sim m_{SUSY}^2$

Solves little hierarchy problem!

The Inflaton-Relaxion model [Evans, TG, Nagata, Peloso 1704.03695]

Identify "amplitudon" σ as the inflaton!

D-term inflation

$$D = g\left(|\phi_+|^2 - |\phi_-|^2 - \xi\right)$$

U(1) gauge coupling (g); F-I term (ξ)

where $\Phi_\pm$ charged under U(1)

$$W = \kappa T \Phi_+ \Phi_- + \frac{1}{2} m_T T^2 + \frac{1}{2} m_S S^2 + \left(m_N + i g_S S + i g_T T + \frac{\lambda}{M_L} H_u H_d\right) N \bar{N}$$

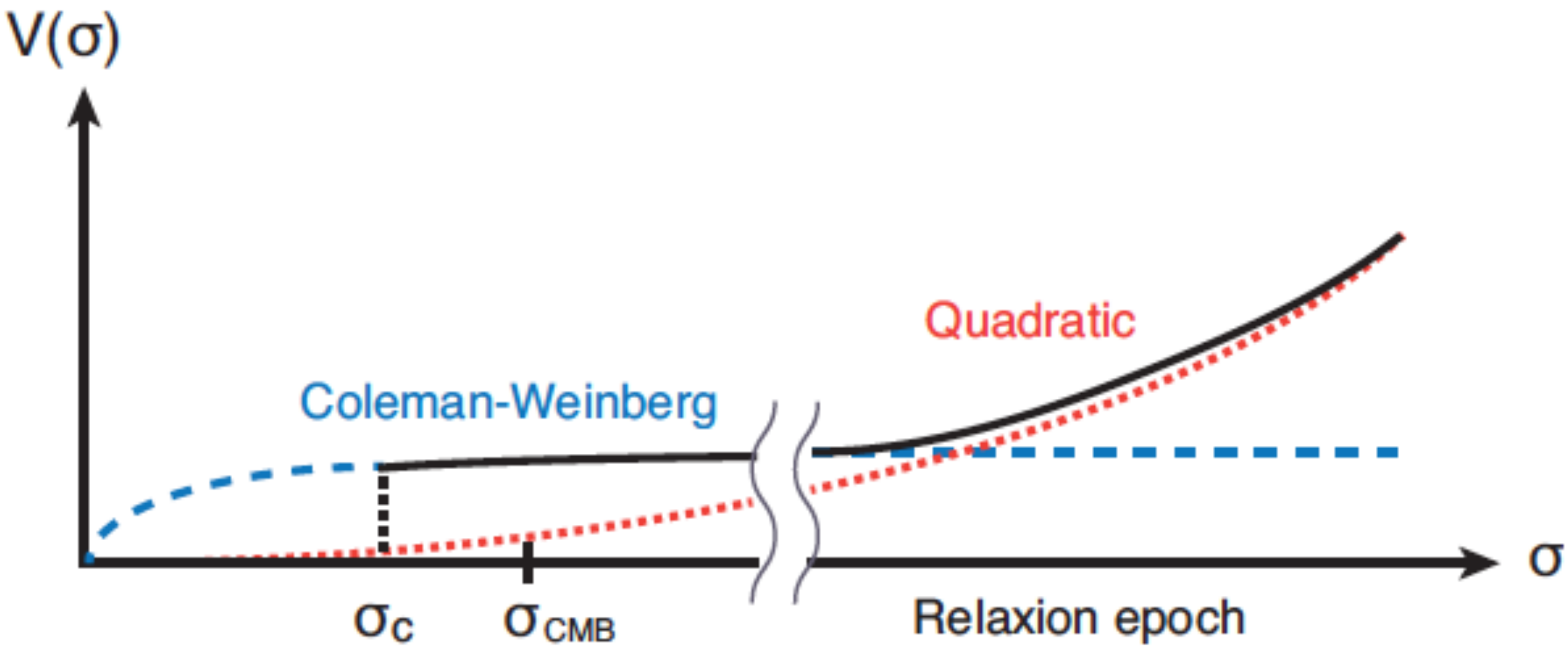
$$\Rightarrow \quad V \simeq \frac{g^2 \xi^2}{2}\left[1 + \frac{g^2}{8\pi^2} \ln\left(\frac{\kappa^2 \sigma^2}{2Q^2}\right)\right] + \frac{1}{2}|m_T|^2 \sigma^2 + \frac{1}{2}|m_S|^2 \phi^2$$

vacuum energy: $\frac{g^2 \xi^2}{2}$

CMB epoch: $\frac{g^2}{8\pi^2} \ln\left(\frac{\kappa^2 \sigma^2}{2Q^2}\right)$

relaxion epoch: $\frac{1}{2}|m_S|^2 \phi^2$

Scalar potential



Slow-roll parameters: $\epsilon \equiv \frac{M_P^2}{2V^2}\left(\frac{\partial V}{\partial \sigma}\right)^2 \simeq \frac{g^4}{32\pi^4}\left(\frac{M_P}{\sigma}\right)^2 , \quad \eta \equiv \frac{M_P^2}{V}\frac{\partial^2 V}{\partial \sigma^2} \simeq -\frac{g^2}{4\pi^2}\left(\frac{M_P}{\sigma}\right)^2$

$\Rightarrow$ $\epsilon_{\rm CMB} = \frac{g^2}{16\pi^2}\frac{1}{N_{\rm CMB}} , \quad \eta_{\rm CMB} = -\frac{1}{2N_{\rm CMB}}$ i.e. $\epsilon \ll |\eta|$

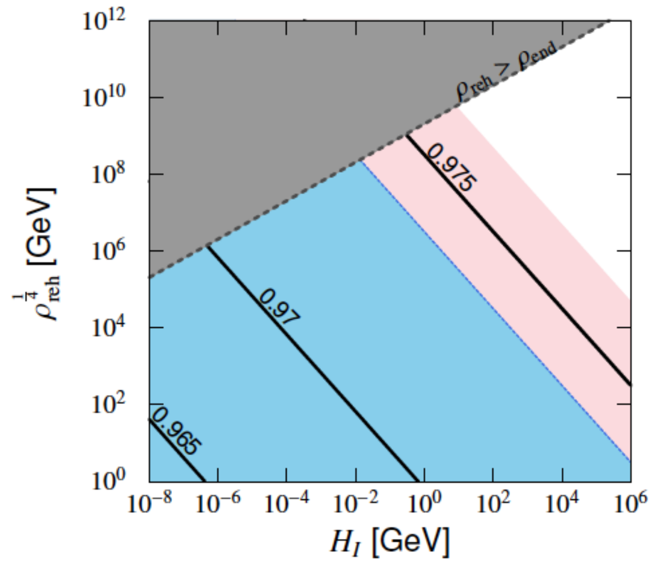
Inflation check list

✔ Spectral tilt

$$n_s - 1 \simeq 2\eta = -0.026\left(\frac{39}{N_{CMB}}\right)$$

$$N_{\rm CMB} \simeq 38.9 + \frac{1}{3}\ln\left(\frac{H_I}{10^5\ {\rm GeV}}\right) + \frac{1}{3}\ln\left(\frac{\rho_{\rm reh}^{1/4}}{100\ {\rm GeV}}\right)$$

⇒ $H_I \lesssim 10^5\ {\rm GeV}$ Low-scale inflation!



✔ Density perturbations

$$\sqrt{\xi} \simeq 9.0\times 10^{15}\ {\rm GeV}\times\left(\frac{1-n_s}{0.03}\right)^{\frac{1}{4}}\left(\frac{A_s}{2.1\times 10^{-9}}\right)^{\frac{1}{4}}$$

⇒ $$g \simeq 7.4\times 10^{-9}\times\left(\frac{H_I}{10^5\ {\rm GeV}}\right)\left(\frac{1-n_s}{0.03}\right)^{-\frac{1}{2}}\left(\frac{A_s}{2.1\times 10^{-9}}\right)^{-\frac{1}{2}}$$

✔ Cosmic strings

U(1) broken during inflation via dynamical D-terms

✔ Reheating

$$-\mathcal{L} \supset \frac{1}{2}\kappa_1\kappa_2 \sin 2\beta\langle M_-\rangle\phi_+ h^2$$

⇒ $$T_R = 485\ {\rm GeV}\times\left(\frac{106.75}{g_\rho}\right)^{1/4}\left(\frac{\langle M_-\rangle}{10^{16}\ {\rm GeV}}\right)\left(\frac{10^8\ {\rm GeV}}{m_{\phi_+}}\right)^{1/2}\left(\frac{\kappa_1}{10^{-9}}\right)\left(\frac{\kappa_2}{10^{-8}}\right)$$

Constraints

- Inflaton, relaxion slow roll

$$|m_S| \ll H_I \qquad \frac{d\sigma}{dt} = -\frac{1}{3H_I}\frac{\partial V}{\partial \sigma} = -\frac{1}{3H_I}\left[m_T^2\sigma - \frac{g_T}{\sqrt{2}}\Lambda_N^3 \cos\left(\frac{\phi}{f_\phi}\right)\right] \Rightarrow m_T^2\sigma \gg \frac{g_T}{\sqrt{2}}\Lambda_N^3$$

- Stability of relaxion minimum $\quad |m_S| \lesssim \frac{v^4}{m_{\rm SUSY} f_\phi^2}$

- Classical rolling $\quad \frac{d\phi}{dt}H_I^{-1} > H_I \Rightarrow H_I^3 \ll \frac{g_S}{|g_T|}|m_T|^2\phi_*$

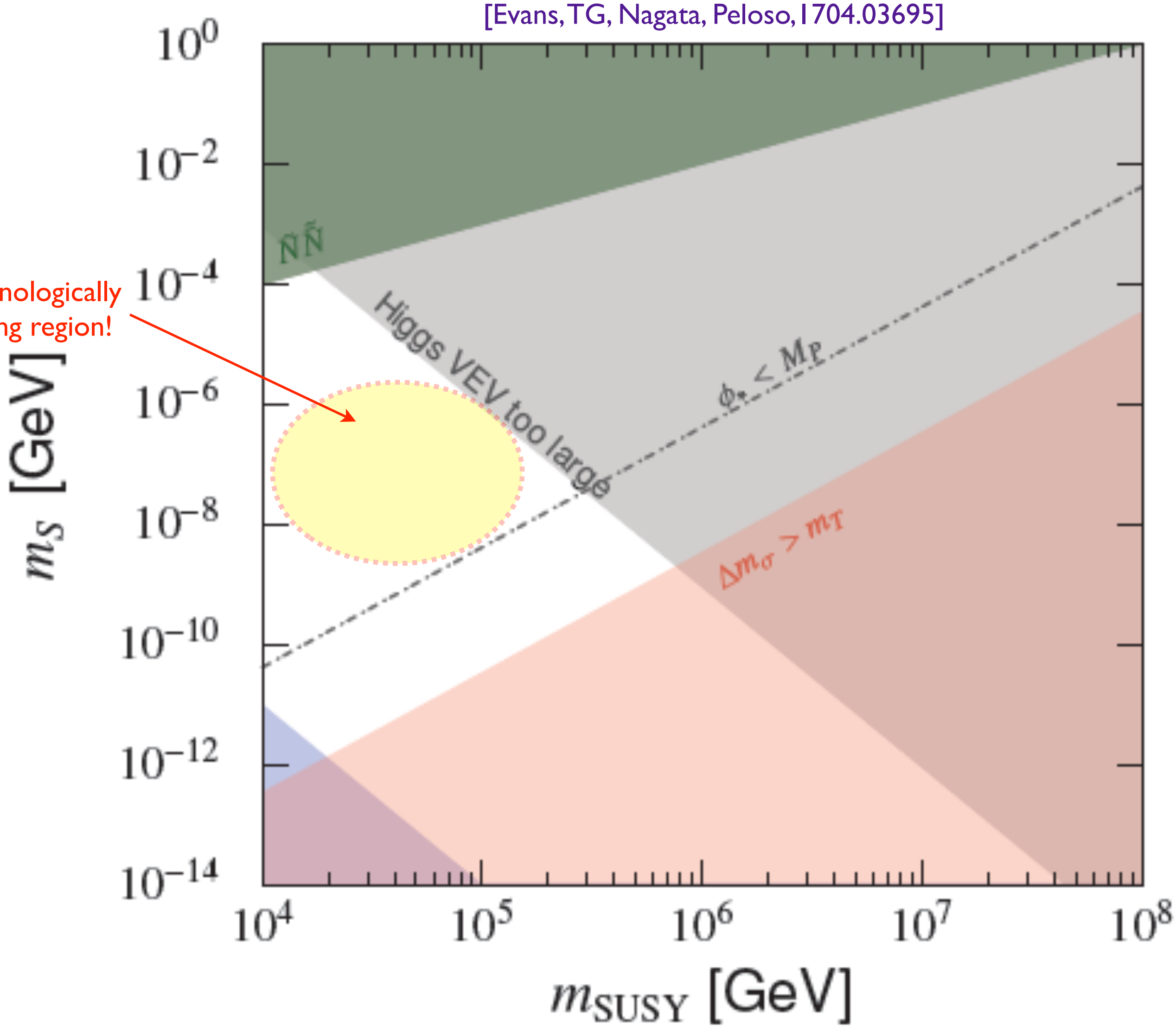
- Sufficient number of e-folds $\quad N_e \simeq \frac{H_I \Delta\phi}{\left|\frac{d\phi}{dt}\right|} \gtrsim \frac{H_I^2}{|m_S|^2} = 10^{14} \times \left(\frac{H_I}{1\ \text{GeV}}\right)^2 \left(\frac{10^{-7}\ \text{GeV}}{|m_S|}\right)^2$

- Loop corrections to inflaton mass

$$\Delta K \simeq \frac{\kappa^2}{16\pi^2}|T|^2 \Rightarrow \Delta m_\sigma \simeq 3.3 \times 10^{-12}\ \text{GeV} \times \left(\frac{\kappa}{10^{-2}}\right)\left(\frac{m_{\rm SUSY}}{10^5\ \text{GeV}}\right)\left(\frac{f_\phi}{10^5\ \text{GeV}}\right) < m_T$$

[Evans, TG, Nagata, Peloso, 1704.03695]

Phenomenologically interesting region!



$$g_S = \zeta \frac{m_S}{f_\phi}, \quad g_T = \zeta \frac{m_T}{f_\sigma}, \quad f \equiv f_\phi = f_\sigma,$$

$$r_{TS} \equiv \frac{m_T}{m_S}, \quad r_\Lambda \equiv \frac{\Lambda_N}{f}, \quad r_{\rm SUSY} \equiv \frac{m_{\rm SUSY}}{f},$$

$$\zeta = 10^{-8}, r_{TS} = 0.1$$

$$r_\Lambda = 1, \; r_{\rm SUSY} = 1, \; \kappa = 10^{-2}$$

$$\max\left\{|m_S|,\; 4\times 10^{-9}\ {\rm GeV} \times \left(\frac{m_{\rm SUSY}}{10^5\ {\rm GeV}}\right)^2 \left(\frac{1}{r_{\rm SUSY}}\right)\right\} < H_I < 4.6\ {\rm GeV} \times \left(\frac{r_{TS}}{0.1}\right)^{\frac{1}{3}} \left(\frac{1}{r_{\rm SUSY}}\right)^{\frac{1}{3}} \left(\frac{|m_S|}{10^{-7}\ {\rm GeV}}\right)^{\frac{1}{3}} \left(\frac{m_{\rm SUSY}}{10^5\ {\rm GeV}}\right)^{\frac{2}{3}}$$

Supergravity effects

For super-Planckian field excursions

$$V = e^{K/M_P^2}\left(\underbrace{D^i W^* D_i W}_{\sim m_T^2\sigma^2} - \underbrace{\frac{3|W|^2}{M_P^2}}_{\sim \frac{m_T^2\sigma^4}{M_P^2}}\right)$$

Requires no-scale SUSY breaking with field X

$$V = e^{K/M_P^2}\left(W^{*i}W_i + \frac{1}{M_P^2}(\underbrace{W^{*i}K_i W}_{W_X \simeq 0} + \text{h.c.}) + (\underbrace{K^i K_i - 3M_P^2}_{\simeq 0})\frac{|W|^2}{M_P^4}\right)$$

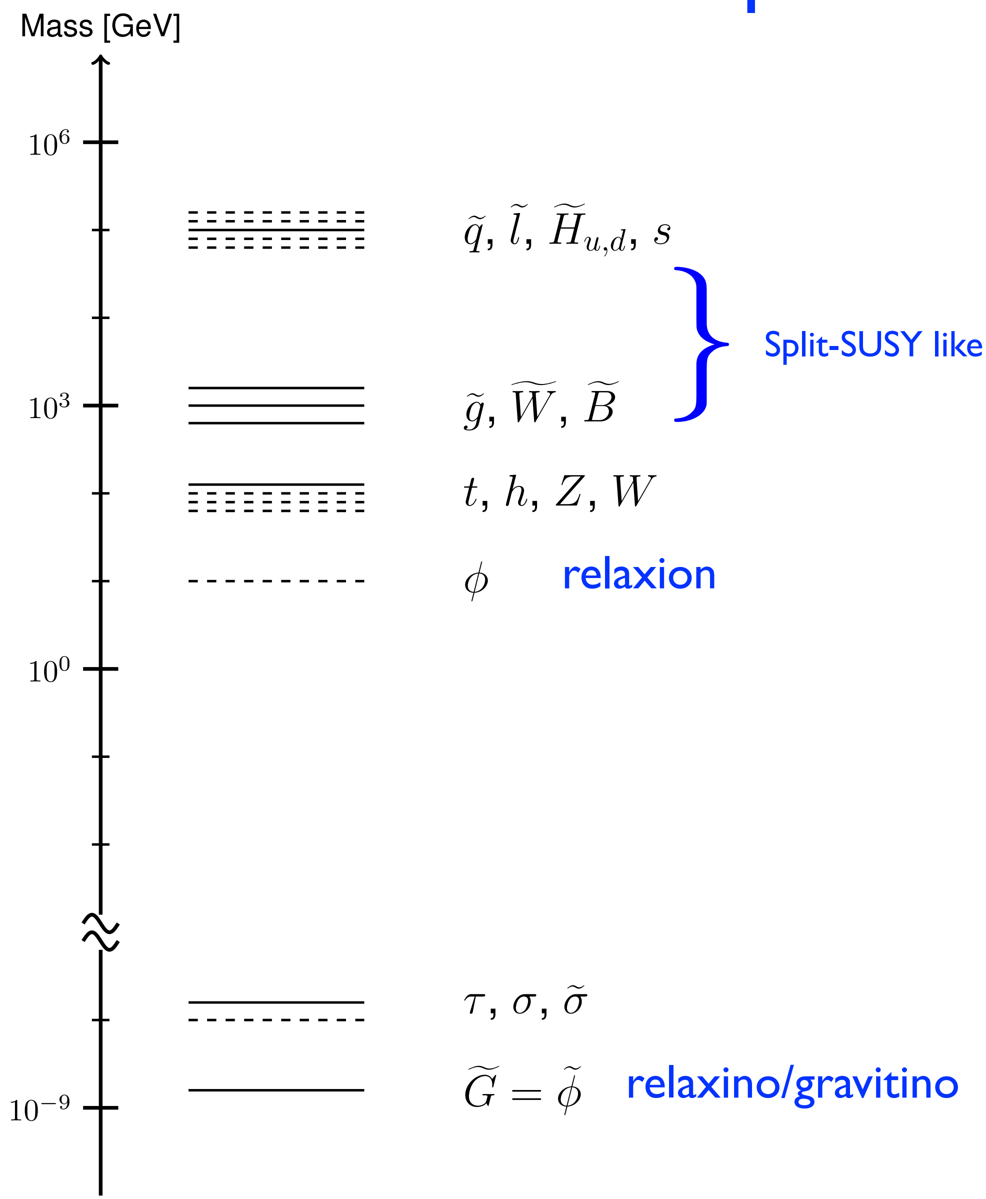
Gravitino

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} \simeq 2\times\left(\frac{F}{F_S}\right)\left(\frac{m_{\rm SUSY}}{10^5\ \text{GeV}}\right)\left(\frac{f_\phi}{10^5\ \text{GeV}}\right)\ \text{eV}$$

sub-Planckian	$F = F_S$	relaxino eaten by gravitino
super-Planckian	$F > F_S$	relaxino, no longer Goldstino, remains light

} Can be dark matter!

Generic particle spectrum:



Features:

i) No SUSY flavor problem
ii) Preserves gauge coupling unification
iii) Relaxino/Gravitino dark matter
iv) Collider signal long-lived NLSP decay
v) Higgs-relaxion mixing

Summary

- Inflaton-relaxion dynamics can explain SUSY-breaking scale up to 10^9 GeV
  - --- preserves QCD axion solution to strong CP problem
  - --- “naturalizes” supersymmetry
- Predicts split-SUSY-like + “invisible” spectrum
  - --- relaxino/gravitino = dark matter
  - --- “invisible” spectrum = sign of dynamical relaxation!
- UV completion possible with multi-axion/ clockwork fields

Questions/Future Work

- What fixes the scale of the explicit breaking?

  --- PeV scale: $10^{-10}\ \mathrm{GeV} \lesssim m_S \lesssim 10^{-4}\ \mathrm{GeV}$

- Alternate ways to generate periodic potential?

- Other ways to incorporate inflation? e.g. F-term inflation

- Cosmological constant

  --- how to reconcile large number of vacua?

  --- requires non-anthropic solution?

- Ways to search for "invisible" sector

  --- beam dump experiments, superradiance, pulsar timing arrays....

Extra slides

Generation of periodic potential

Assume SU(N) gauge theory with singlet superfields $N, \bar{N}$

$$W_N = m_N N\bar{N} + i g_S S N\bar{N} + i g_T T N\bar{N} + \frac{\lambda}{M_L} H_u H_d N\bar{N}$$

$$\Rightarrow \quad \mathcal{L}_N = -m_N \bar{\psi}_N \psi_N - \frac{i}{\sqrt{2}} g_S (s + i\phi)\bar{\psi}_N \psi_N - \frac{i}{\sqrt{2}} g_T (\tau + i\sigma)\bar{\psi}_N \psi_N - \frac{\lambda}{M_L} H_u H_d \bar{\psi}_N \psi_N + \text{h.c.}$$

Fermion condensate: $\langle \bar{\psi}_N \psi_N \rangle \simeq \Lambda_N^3$ $\quad \Lambda_N = \text{confinement scale}$

$$\bar{\psi}_N \psi_N \to e^{i\frac{\phi}{f_\phi}} \bar{\psi}_N \psi_N \qquad (\text{eliminates } \tfrac{\phi}{f_\phi} G'_{\mu\nu} \tilde{G}'^{\mu\nu})$$

$$\Rightarrow \quad V_{period} = \mathcal{A}(\phi, \sigma, H_u H_d) \Lambda_N^3 \cos\left(\frac{\phi}{f_\phi}\right)$$

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

g_S, g_T real

$\bar{m}_N =$ effective mass

UV completion [Based on Kaplan, Rattazzi:1511.01827]

Consider set of chiral superfields $\phi_i, \bar{\phi}_i, S_i (i = 0, \dots N)$

$$W_{\rm UV} = \sum_{i=0}^{N} \lambda_i S_i \underbrace{(\phi_i \bar{\phi}_i - f_i^2)}_{\text{spontaneous breaking}} + \epsilon \sum_{i=0}^{N-1} (\bar{\phi}_i \underbrace{\phi_{i+1}^2 + \phi_i \bar{\phi}_{i+1}^2}_{\text{explicitly breaks } U(1)^{N+1} \text{ to } U(1)}) \qquad \phi_i = f_i e^{\frac{\Pi_i}{f_i}} , \qquad \bar{\phi}_i = f_i e^{-\frac{\Pi_i}{f_i}}$$

Massless mode: relaxion $\phi \supset S = c_N \sum_{i=0}^{N} \frac{f_i}{2^i f_0} \Pi_i$

Identify remnant $U(1)$ as shift symmetry $\mathcal{S}_S$

$y \phi_0 \bar{\psi}_0 \psi_0$ coupling ➡ $f_\phi \sim f_0 \qquad V_\phi \sim V_0 \propto \cos \frac{\phi}{f_\phi}$

$y' \phi_N \bar{\psi}_N \psi_N$ coupling ➡ $V_N \propto \tilde{\Lambda}_N^4 \cos\left(\frac{\phi}{2^N f_\phi}\right) \simeq \tilde{\Lambda}_N^4 - \frac{1}{2} \frac{\tilde{\Lambda}_N^4}{4^N f_\phi^2} \phi^2 + \dots$

$= |m_S|^2$!

Similarly:

$i \frac{\kappa}{\widetilde{M}_N^2} \int d^4\theta N \bar{N} \Xi^* \bar{\Xi}^* + \text{h.c.}$ ➡ $i \frac{\kappa}{\widetilde{M}_N^2} \int d^2\theta \, \tilde{\Lambda}_N^3 e^{\frac{\Pi_N}{f_N}} N \bar{N} + \text{h.c.} \simeq \int d^2\theta \frac{i\kappa \tilde{\Lambda}_N^3}{f_\phi 2^N \widetilde{M}_N^2} S N \bar{N} + \text{h.c.}$

$= g_S$!