# Naturalizing Supersymmetry with the Relaxion

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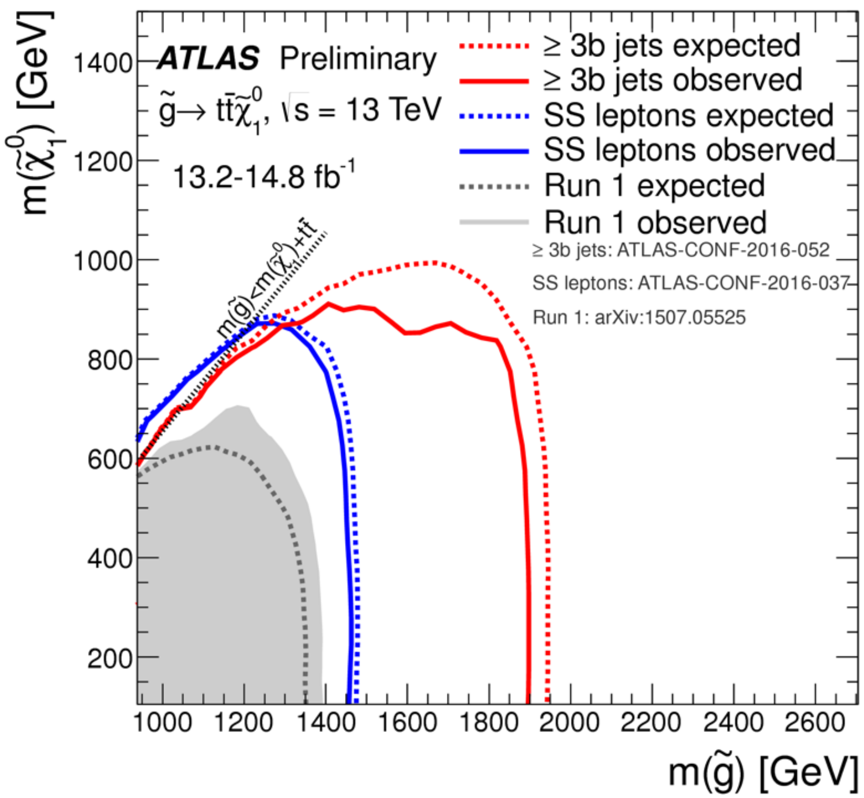
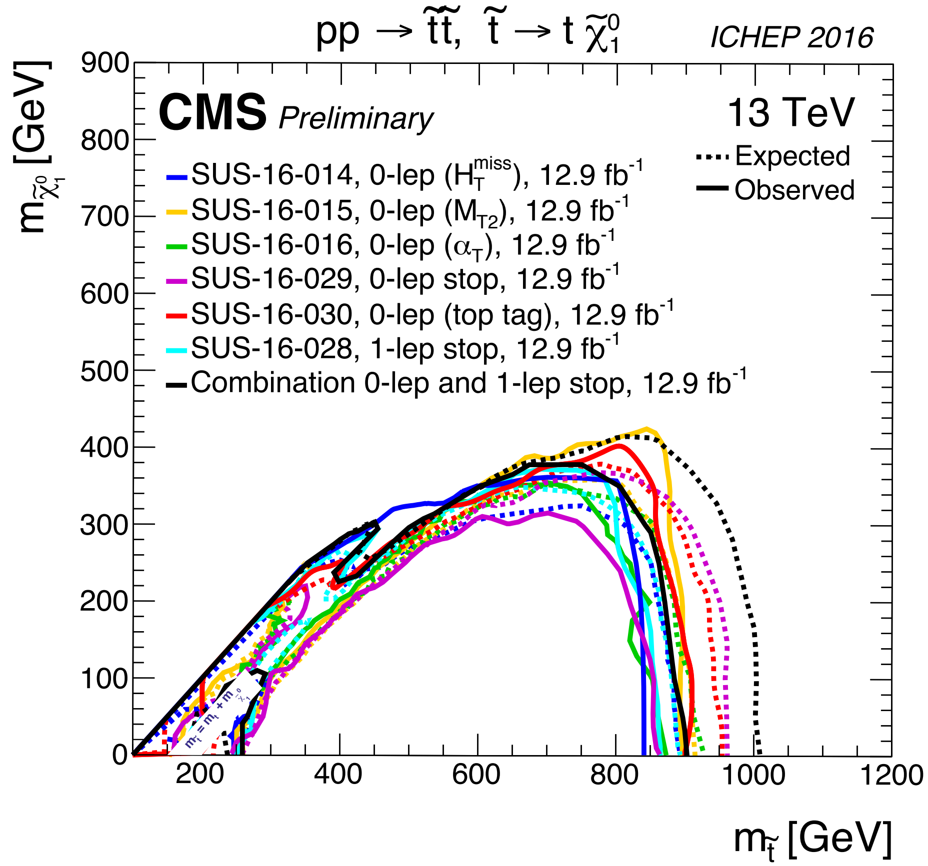
*Jason Evans, TG, Natsumi Nagata, Zach Thomas*
*[1602.04812]*

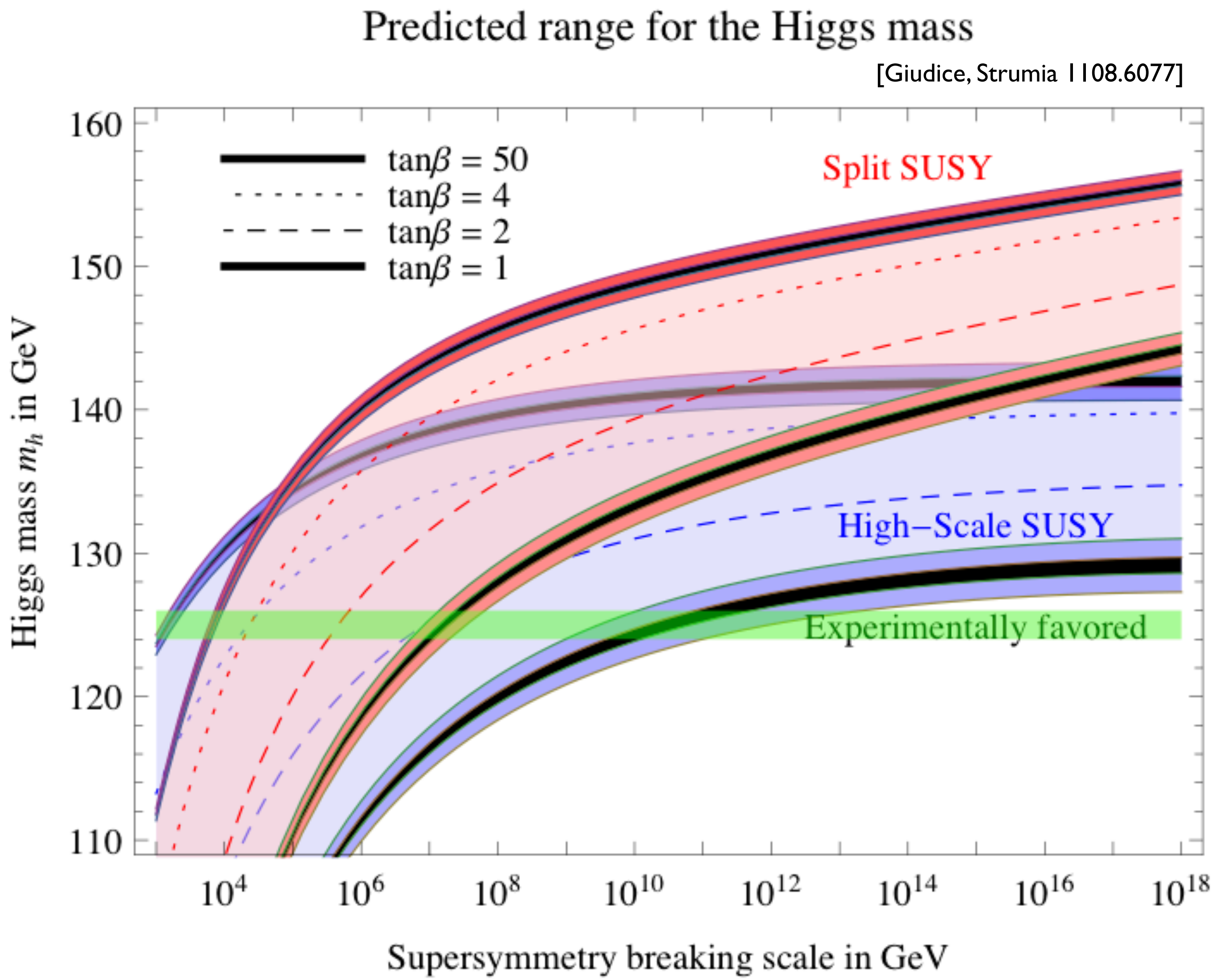
# LHC Run II: *A First Glance....*



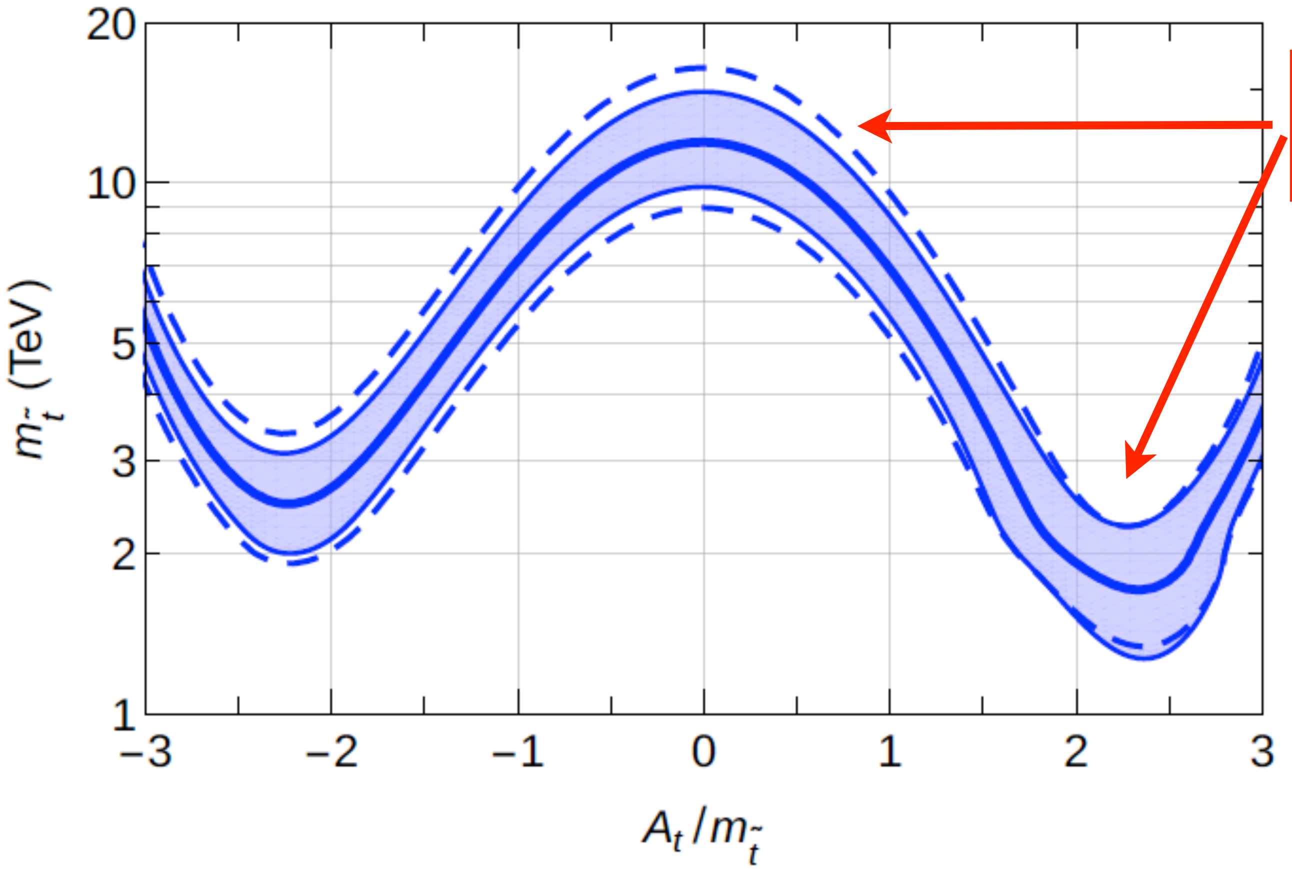

$m_{\tilde{g}} \gtrsim 1900$ GeV

$m_{\tilde{t}} \gtrsim 900$ GeV




⇨ SUSY breaking scale $\lesssim 10^7$ GeV

# ***Higgs mass in MSSM*** [Pardo Vega, Villadoro 1504.05200]




Requires large stop masses or large A-terms

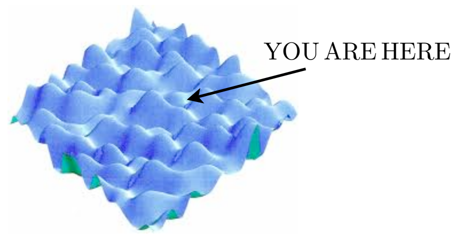
➡ Increases tuning in supersymmetric models

# 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:

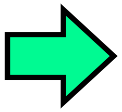
$m_H^2 = 0$ ***not*** related to symmetry

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

Glacial erratic, Yosemite, California

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

e.g. self-organized criticality



Dynamical evolution sets the SUSY scale!

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

$\leftarrow$ This talk

"Hidden" Naturalness

# ***Relaxion mechanism***

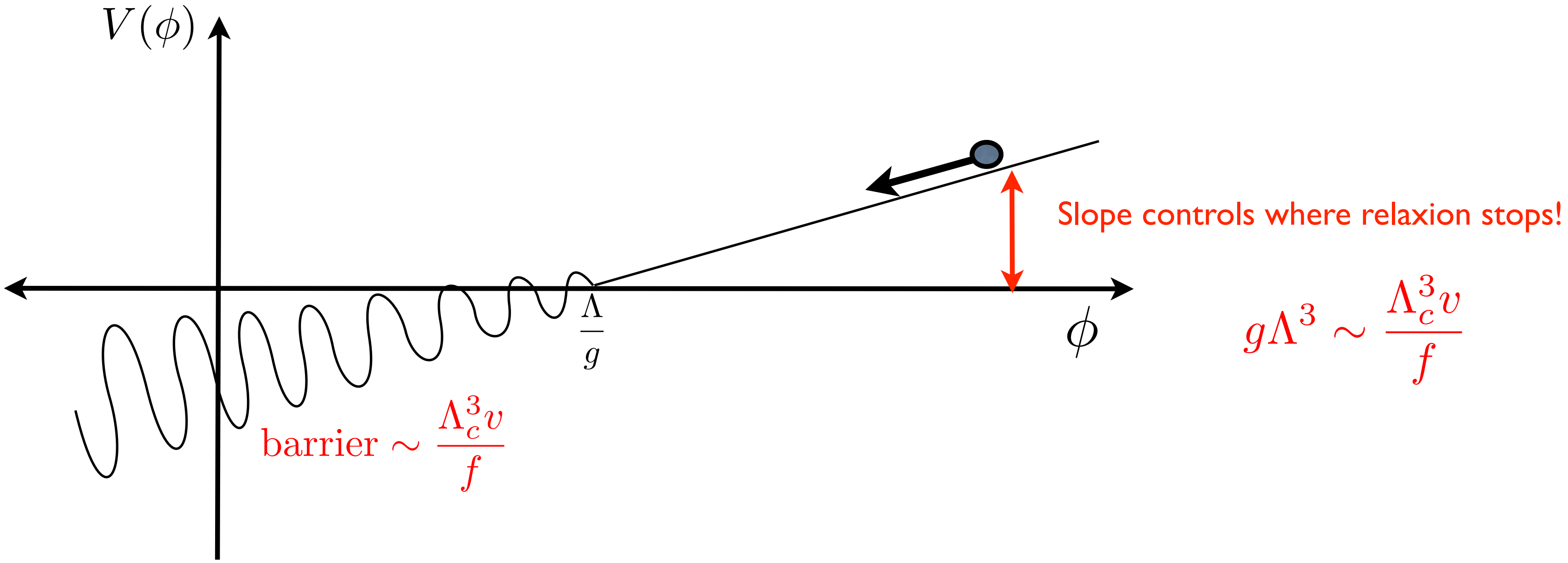
[Graham, Kaplan, Rajendran 1504.07551]

Introduce scalar field (relaxion): $\phi$

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

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

back reaction from strong dynamics




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

$\phi$ = QCD axion ➡ $\Lambda \lesssim 30 - 1000$ TeV

# However:

- ***Relaxion = QCD axion*** $\longrightarrow$ $\frac{\langle\phi\rangle}{f} \neq \theta_{QCD}$ strong CP problem!

$\Rightarrow$ minimal model ruled out
[requires ad hoc inflaton couplings]

- Alternatively, use non-QCD dynamics $\Lambda_c \neq \Lambda_{QCD}$

$\mathcal{L} \supset m_L L L^c + m_N N N^c + y h L N^c + \tilde{y} h^\dagger L^c N$ $\langle \bar{N} N \rangle \sim \Lambda_c^3$ $f_{\pi'} < v$

$\Rightarrow$ requires new fermions near electroweak scale

$\longrightarrow$ coincidence problem?

How can this be avoided?

# 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-like dynamics

$n = 2$ $\Lambda_c^2|H|^2 \cos\frac{\phi}{f}$ $\longrightarrow$ 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, relaxion cannot move

$\longrightarrow$ *need to remove barrier!*

# Introduce second field, $\sigma$ [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

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

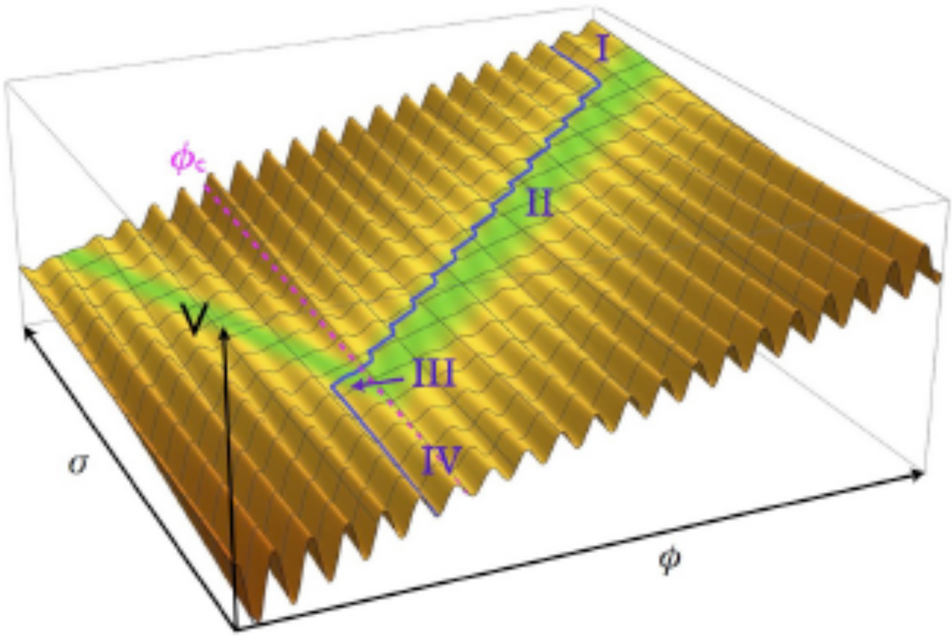
new term

$\sigma$ cancels large potential barrier ⇒ allows $\phi$ to roll!

**Note:** Assumes 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. $\phi$ trapped, $\sigma$ rolls
II. $\mathcal{A} = 0$; both $\phi$ and, $\sigma$ roll
III. EWSB barrier appears
IV. $\phi$ stops, $\sigma$ continues to roll

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

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 $\phi, \sigma$ into chiral superfields $S, T$

relaxion

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

"amplitudon"

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

## Shift symmetries:

$\phi = \text{NG boson}$

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

$\sigma = \text{NG boson}$

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

where $Q_i = \text{MSSM matter superfields}$, $f_\phi, f_\sigma = \text{decay constants}$

$H_u, H_d = \text{MSSM Higgs superfields}$

# Break shift symmetry to generate potential for $\phi, \sigma$

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

where $m_S, m_T$ are 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 $\sigma$ to $H_u, H_d$ !

But $\phi$ 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 $\phi, \sigma$ field value

$V = \vec{F}^\dagger \mathcal{K}^{-1} \vec{F}$ and $\sigma \sim \phi, f_\sigma \sim f_\phi, m_T \sim m_S$

⇨ $m_\phi \sim m_\sigma \sim m_S$ $\quad$ $\boxed{F_S \sim F_T \sim m_S \phi}$

SUSY is broken by relaxion!

*Soft terms:*

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

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

Assume $m_T \ll m_S$ or $F_T \ll F_S$ [avoids SUSY-breaking $\sigma$-Higgs coupling]

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

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

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

Solves little hierarchy problem!

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

may be super-Planckian!

# Generation of periodic potential

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

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

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

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

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

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

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

# Cosmological Evolution

$\phi, \sigma$ evolution determined by

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

where $\mathcal{A}(\phi,\sigma,H_uH_d) = \bar{m}_N - \frac{g_S}{\sqrt{2}}\phi + \frac{|g_T|}{\sqrt{2}}\sigma + \frac{\lambda}{M_L}H_uH_d \qquad (\bar{m}_N, g_S > 0, g_T < 0)$

Initially: $\phi, \sigma \gg f_\phi$, $|m_S|^2 \ll g_S\frac{\Lambda_N^3}{f_\phi}$ $\Rightarrow$ $H_u = H_d = 0$, $\phi$ fixed, $\sigma$ free to roll

When $\mathcal{A} = 0, \phi$ decreases, tracking $\sigma$ evolution $\quad (|m_T| < |m_S|)$

Finally: $|m_S|^2\phi \lesssim \frac{\Lambda_N^3}{f_\phi}|\mathcal{A}(\phi,\sigma,\frac{v^2(\phi)}{4}\sin 2\beta)|$ $\Rightarrow$ $\phi \sim \phi_* \quad \sigma \sim 0$, $H_u = v_u, H_d = v_d$

EW symmetry broken!

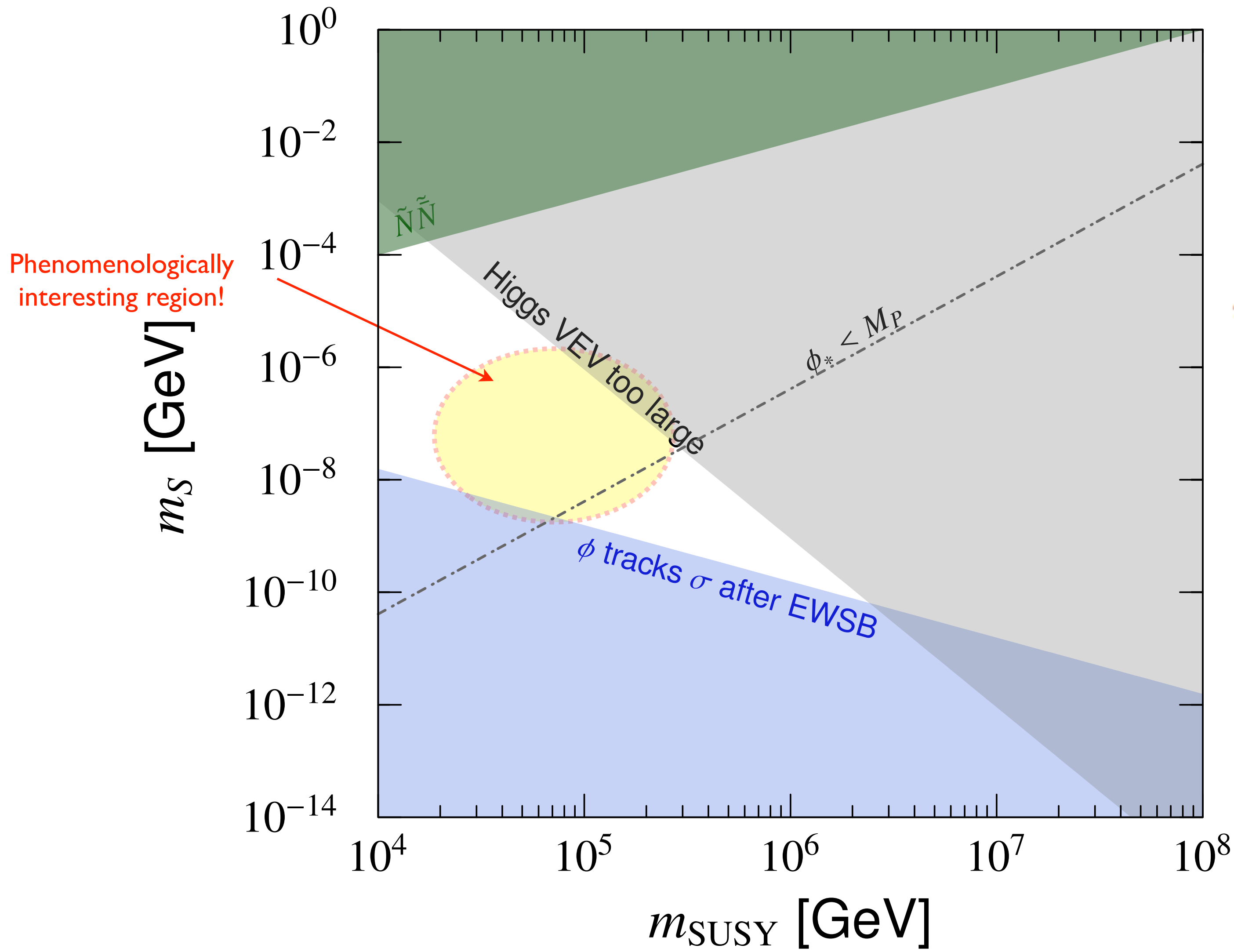
# Constraints

Assume de-Sitter phase with Hubble parameter $H_I$

- Inflaton dominates vacuum energy $\frac{1}{2}|m_S|^2\phi^2\ ,\ \frac{1}{2}|m_T|^2\sigma^2 \ll 3H_I^2M_P^2$
- $\phi$, $\sigma$ slow roll $|m_S| \ll H_I$
- Classical rolling $\frac{d\phi}{dt}H_I^{-1} > H_I$ ⇨ $H_I^3 \ll \frac{g_S}{|g_T|}|m_T|^2\phi_*$
- Sufficient number of e-folds $N_e \simeq \frac{H_I\Delta\phi}{\left|\frac{d\phi}{dt}\right|} \gtrsim \frac{H_I^2}{|m_S|^2} = 10^{14}\times\left(\frac{H_I}{1\text{ GeV}}\right)^2\left(\frac{10^{-7}\text{ GeV}}{|m_S|}\right)^2$
- Inflaton SUSY-breaking subdominant

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

[Evans, TG, Nagata, Thomas 1602.04812]




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

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

$$\zeta = 10^{-8}, r_{TS} = 0.1, r_\Lambda = 1, r_{SUSY} = 1$$

# 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

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

***Gravitino***

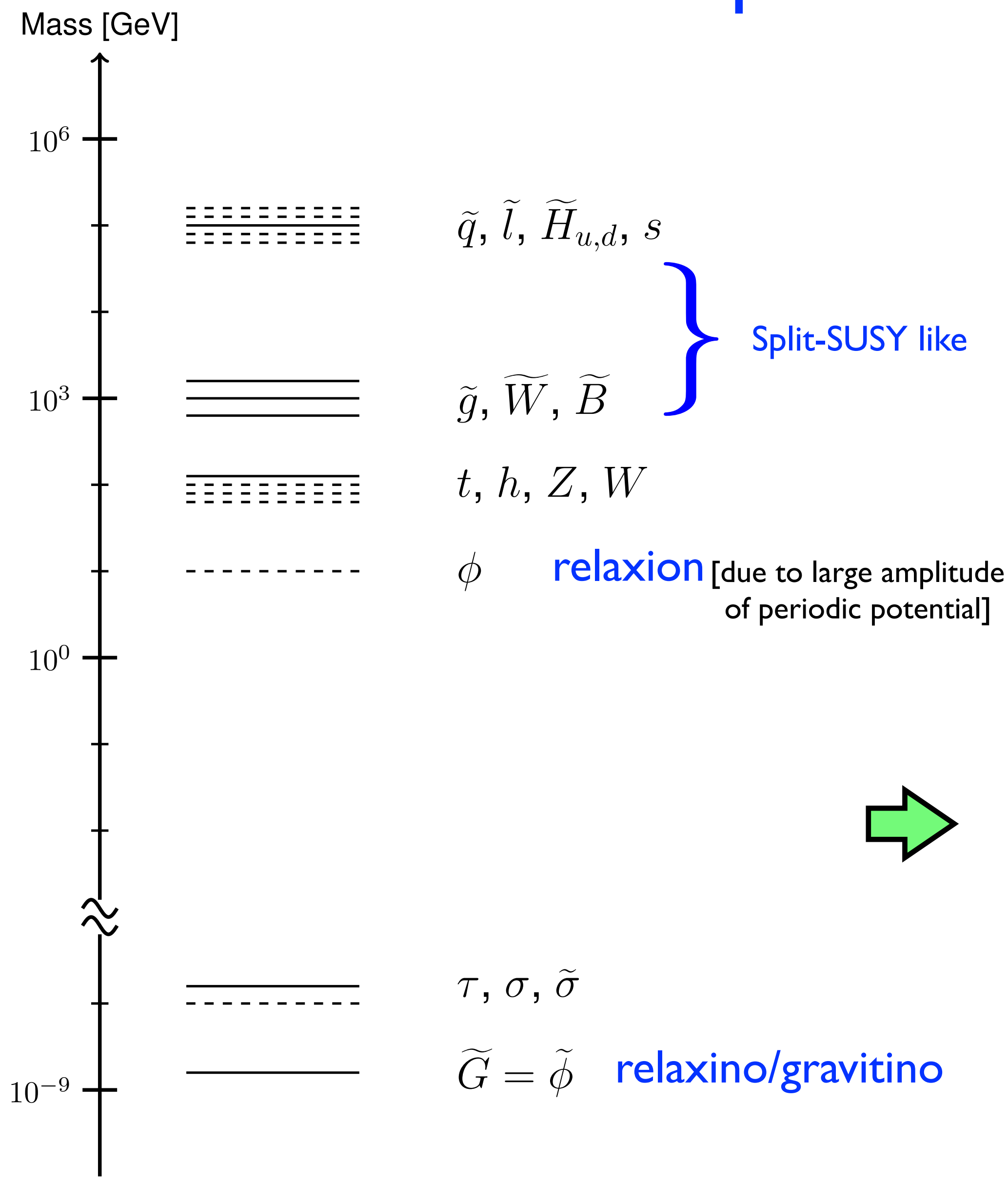
$$m_{3/2} = \frac{F}{\sqrt{3}M_P} \simeq 2\times\left(\frac{F}{F_S}\right)\left(\frac{m_{\rm SUSY}}{10^5~\text{GeV}}\right)\left(\frac{f_\phi}{10^5~\text{GeV}}\right)~\text{eV}$$

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) Relaxino/Gravitino dark matter

ii) No SUSY flavor problem

iii) Preserves gauge coupling unification

iv) Collider signal long-lived NLSP decay

# UV completion

[Based on Kaplan, Rattazzi:1511.01827]

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

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

## 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:

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

$= g_S$ !

# Summary

- Dynamical relaxation with two fields can explain heavy superpartner scale up to $10^9$ GeV
  - --- preserves QCD axion solution to strong CP problem
  - --- “naturalizes” supersymmetry
- Sparticle spectrum is split-SUSY like
- Relaxino/gravitino = dark matter
- UV completion possible with multi-axion like fields

# Questions/Future Work

- What fixes the scale of the explicit breaking?

  --- PeV scale: $10^{-17}\ \mathrm{GeV} \lesssim m_S \lesssim 10^{-9}\ \mathrm{GeV}$

- Alternate ways to generate periodic potential?

- How to incorporate inflation?

  --- identify "amplitudon" with inflaton e.g. D-term inflation [in preparation]

- Cosmological constant

  --- how to reconcile large number of vacua?

- .......