# ***Naturalizing SUSY* with the *relaxion* and the *inflaton***

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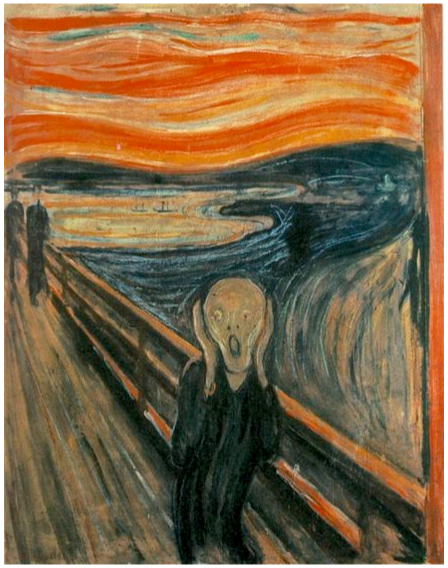
***Gravity, Cosmology and Physics Beyond the Standard Model, UMPC, Paris, France June 15, 2018***

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

# *SUPERSYMMETRY* provides a complete theoretical framework for Beyond the Standard Model

- Stabilizes Planck/weak scale hierarchy
- Dark matter
- Gauge coupling unification
- Low-energy limit of string theory

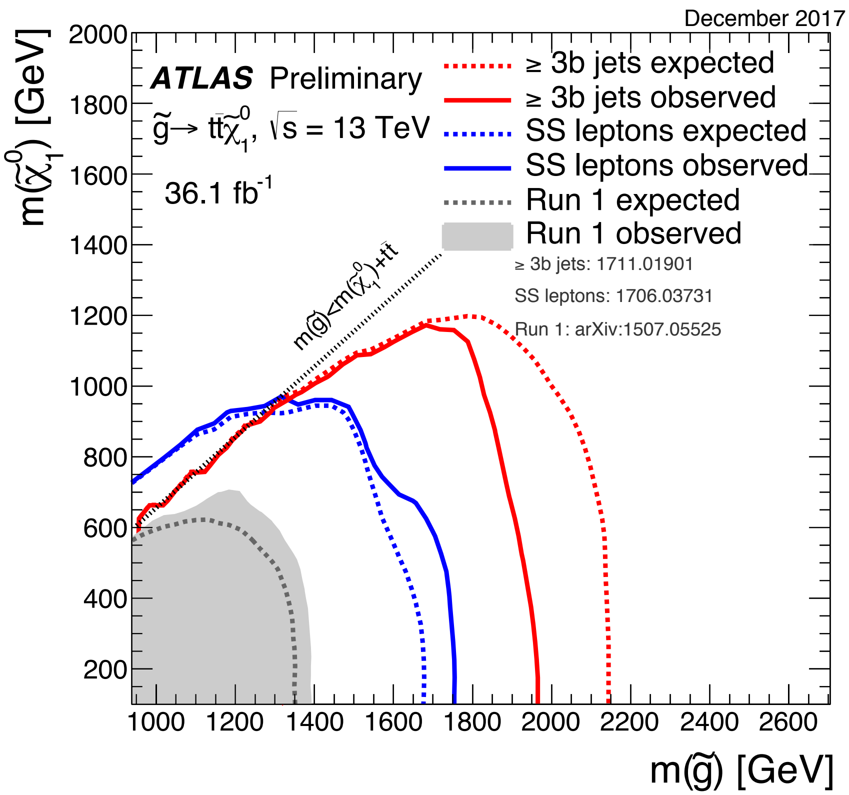
**BUT** where are the superpartners?!?

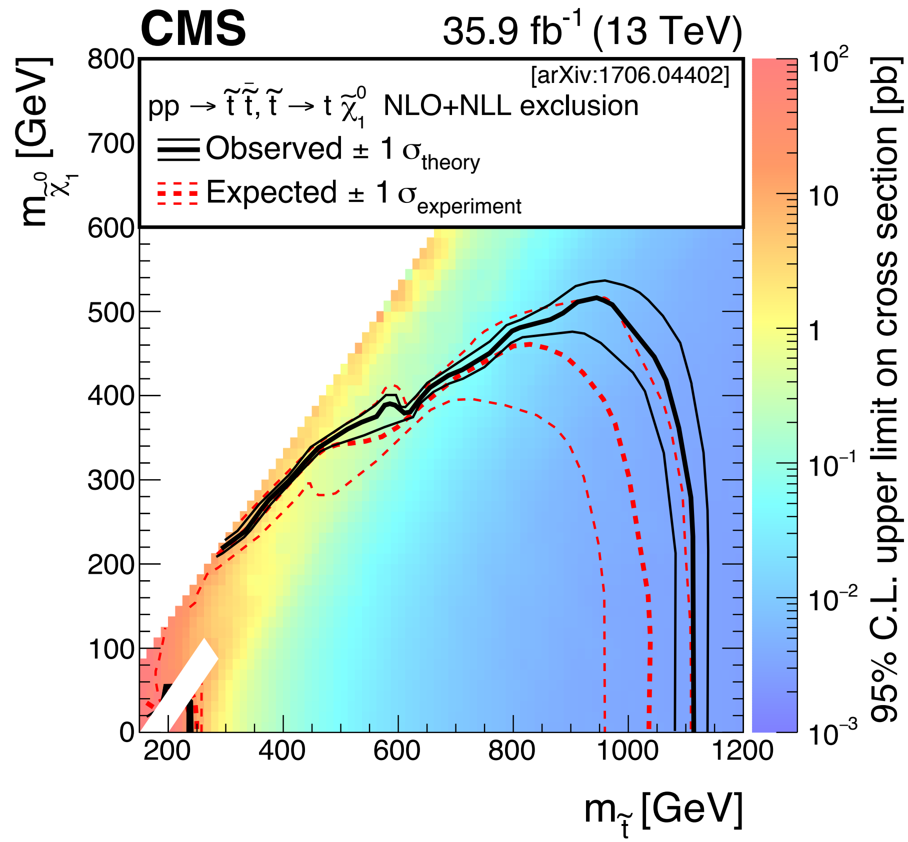


## What we expected....

## What we see....

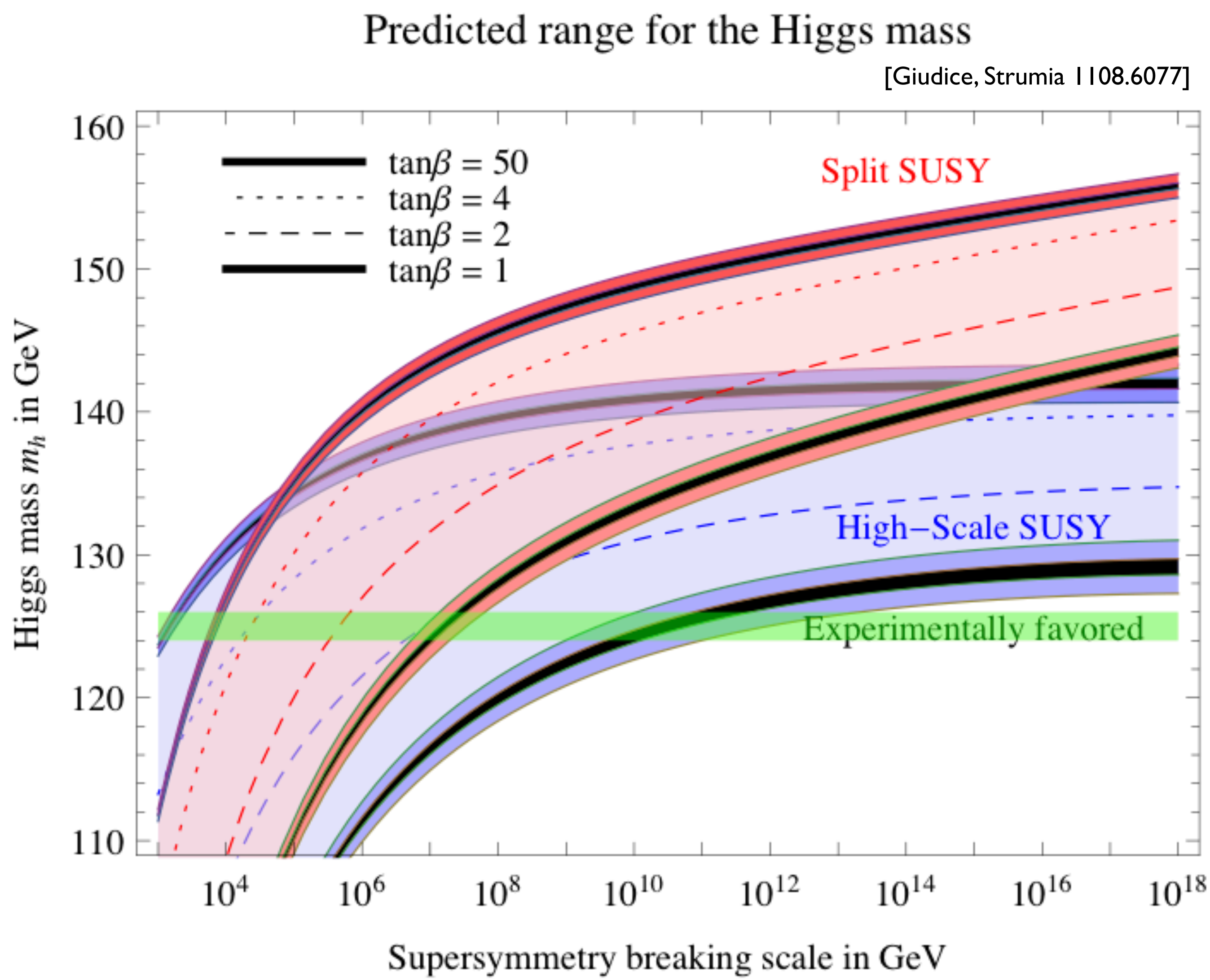
# LHC Run 2 Limits




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

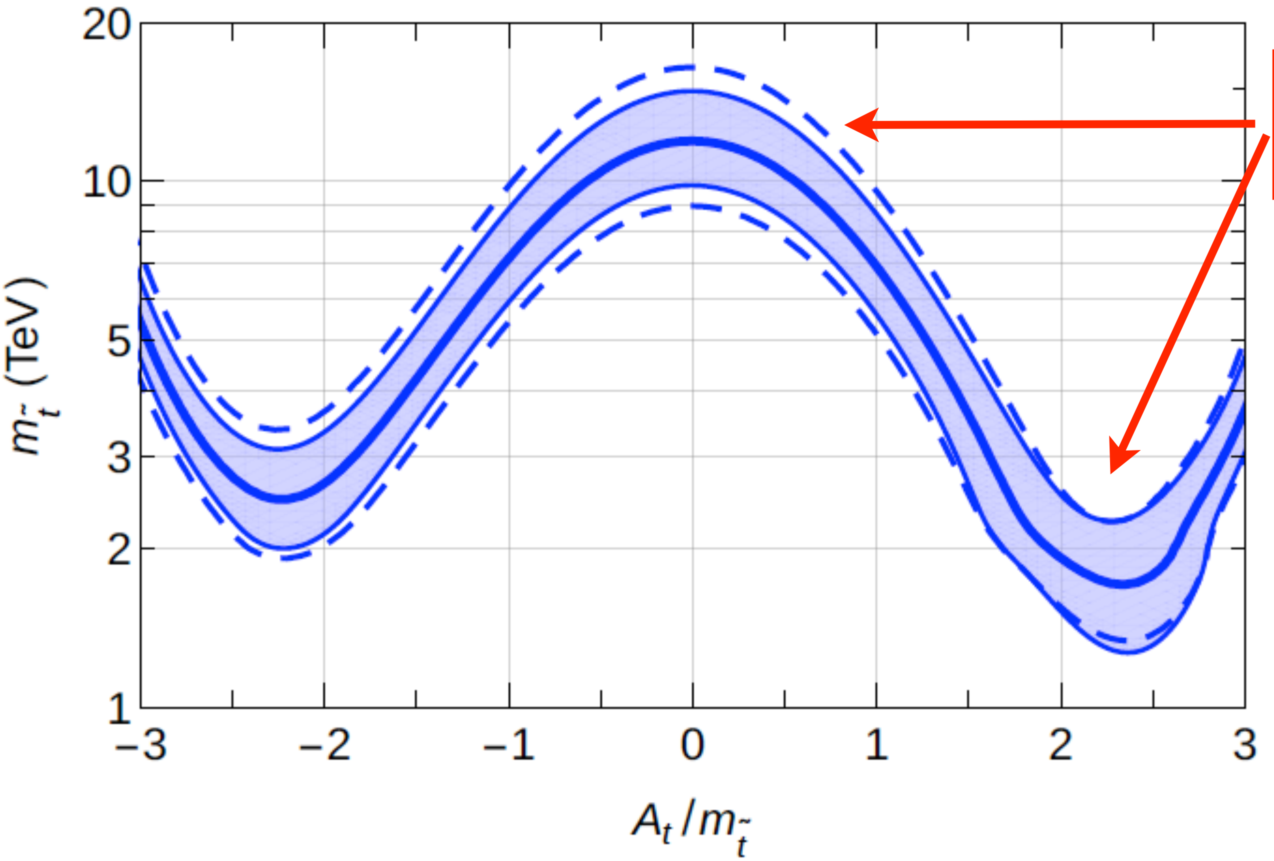
$$m_{\tilde{t}} \gtrsim 1120 \,\text{GeV}$$




➡ 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

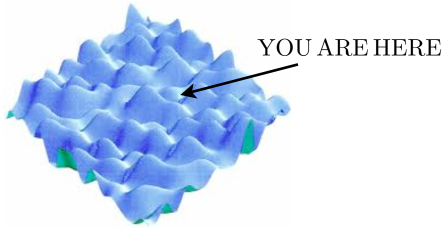
Increases tuning in supersymmetric models

# 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 a 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

$\Rightarrow$ $\boxed{\text{Dynamical evolution sets the SUSY scale!}}$

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

$\leftarrow$ This talk

"Hidden" Naturalness

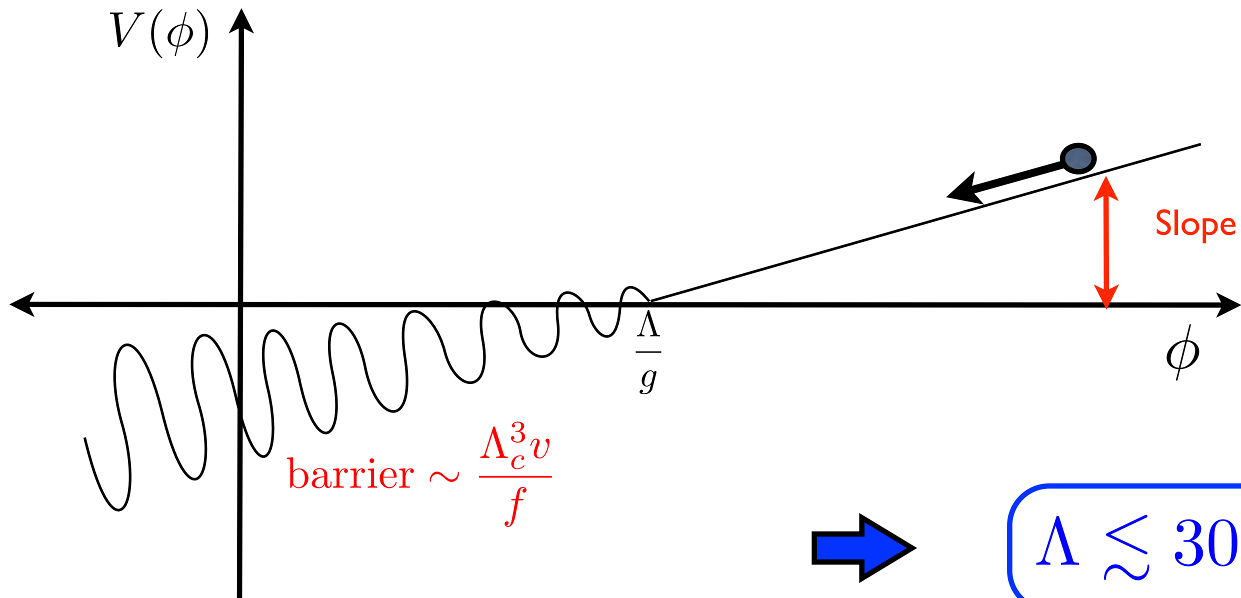
# ***Relaxion mechanism*** [Graham, Kaplan, Rajendran 1504.07551]

Introduce scalar field (relaxion): $\phi$

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

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

back reaction from strong dynamics




Slope controls where relaxion stops!

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

$$\boxed{\Lambda \lesssim 30 - 1000 \text{ TeV}}$$

## ***However:***

- Relaxion = QCD axion $\longrightarrow$ large $\theta_{QCD}$!
- Alternatively, non-QCD dynamics requires new fermions near electroweak scale $\longrightarrow$ 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!

$\longrightarrow$ 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, $\sigma$ [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

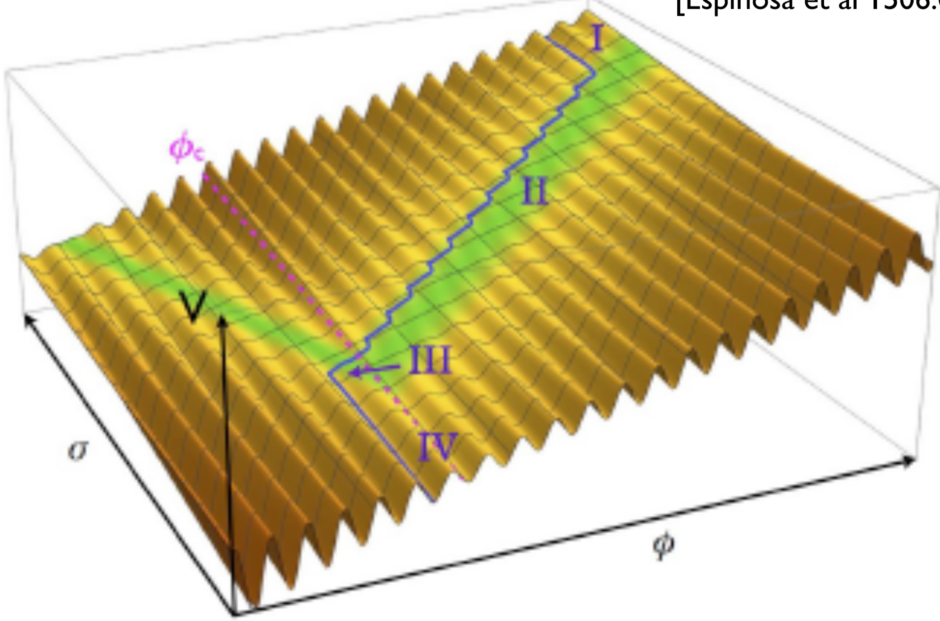
where $\mathcal{A}(\phi,\sigma,H) = \epsilon\left(\beta\Lambda^4 + c_\phi g\Lambda^3\phi - c_\sigma g_\sigma\Lambda^3\sigma + \Lambda^2|H|^2\right)$

new term -- 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. $\phi$ trapped, $\sigma$ rolls
II. $\mathcal{A} = 0$; both $\phi$ and, $\sigma$ roll
III. EWSB barrier appears
IV. $\phi$ stops, $\sigma$ continues to roll

$\Rightarrow$ $\boxed{\Lambda \lesssim 2 \times 10^9 \ \text{GeV}}$ 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 $\phi, \sigma$ 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:

$\phi = \text{NG boson}$

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

$\sigma = \text{NG boson}$

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

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

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

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

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

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

***Kahler potential:*** $K = K(S + S^*, T + T^*)$ $\boxed{\text{shift invariant}}$

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

# Generation of periodic potential

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

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

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

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

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

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

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

$g_S, g_T$ real

$\bar{m}_N \equiv m_N + \frac{i}{\sqrt{2}}(g_S s + g_T \tau)$

$= \text{effective mass}$

# Scanning of soft mass parameters

[Batell, Giudice, McCullough 1509.00834]

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

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

SUSY is broken by relaxion!

## *Soft terms:*

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

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

varies as relaxion evolves!

only S shift symmetry induces chiral anomaly

# Electroweak symmetry breaking

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

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

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 $\mathcal{D}(\phi) < 0$ $\longrightarrow$ EWSB

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

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

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

**Solves little hierarchy problem!**

# 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*

$$\boxed{m_{3/2} = \frac{F}{\sqrt{3}M_P} \simeq 20 \times \left(\frac{F}{F_S}\right)\left(\frac{m_{\rm SUSY}}{10^6~\text{GeV}}\right)\left(\frac{f_\phi}{10^8~\text{GeV}}\right)~\text{keV}}$$

sub-Planckian $F = F_S$ relaxino eaten by gravitino

super-Planckian $F > F_S$ relaxino, no longer Goldstino, remains light

Can be dark matter!

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

Identify “amplitudon” $\sigma$ as the inflaton!

D-term inflation

$$D = \underbrace{g}_{\text{U(1) gauge coupling}} \left(|\phi_+|^2 - |\phi_-|^2 - \underbrace{\xi}_{\text{F-I term}}\right)$$

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

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

Local minimum: $\phi_\pm = 0 \quad \left(\sigma \gg \sigma_c = \frac{g}{\kappa}\sqrt{2\xi}\right)$

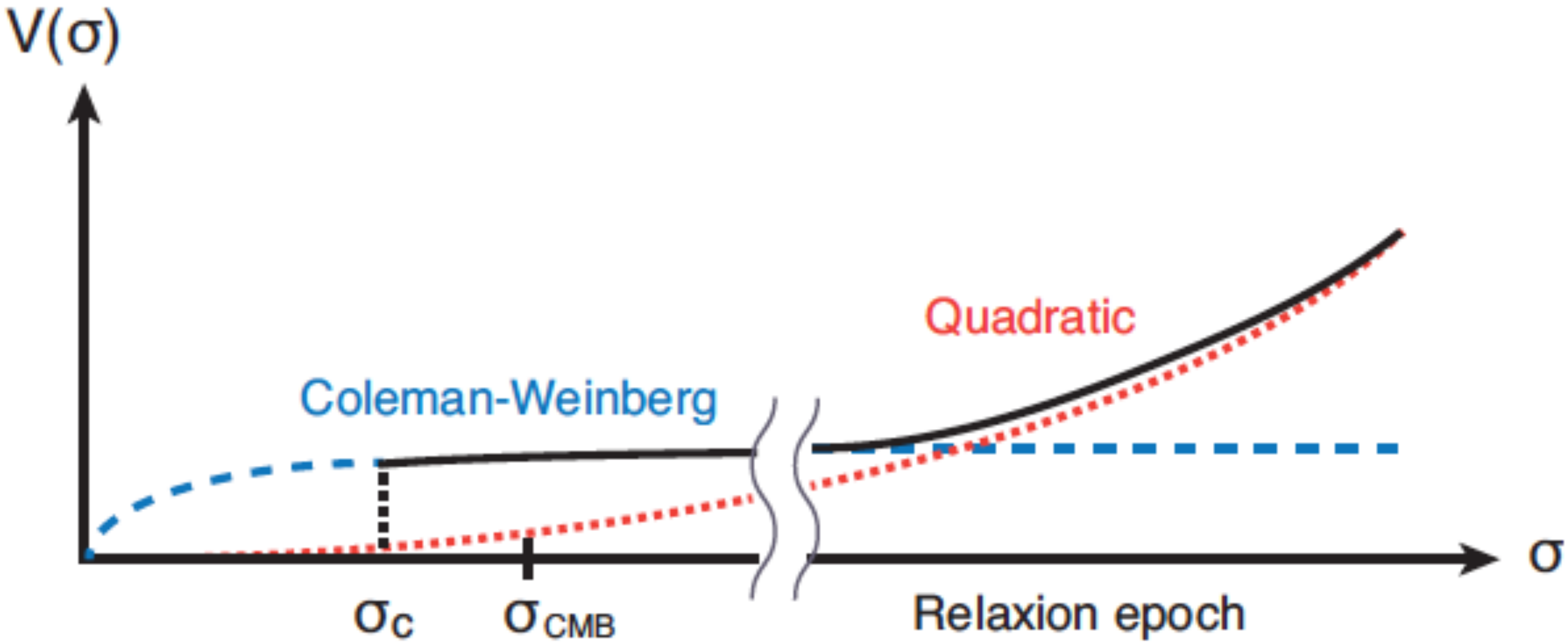
$$\boxed{V \simeq \frac{g^2 \xi^2}{2}\left[1 + \frac{g^2}{8\pi^2} \ln\left(\frac{\kappa^2 \sigma^2}{2Q^2}\right)\right] + \frac{1}{2}|m_T|^2 \sigma^2 + \frac{1}{2}|m_S|^2 \phi^2}$$

vacuum energy

CMB epoch

relaxion epoch

# Scalar potential




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

$$\Rightarrow \quad \epsilon_{\rm CMB} = \frac{g^2}{16\pi^2}\frac{1}{N_{\rm CMB}} , \qquad \eta_{\rm CMB} = -\frac{1}{2N_{\rm CMB}}$$

i.e. $\epsilon \ll |\eta|$

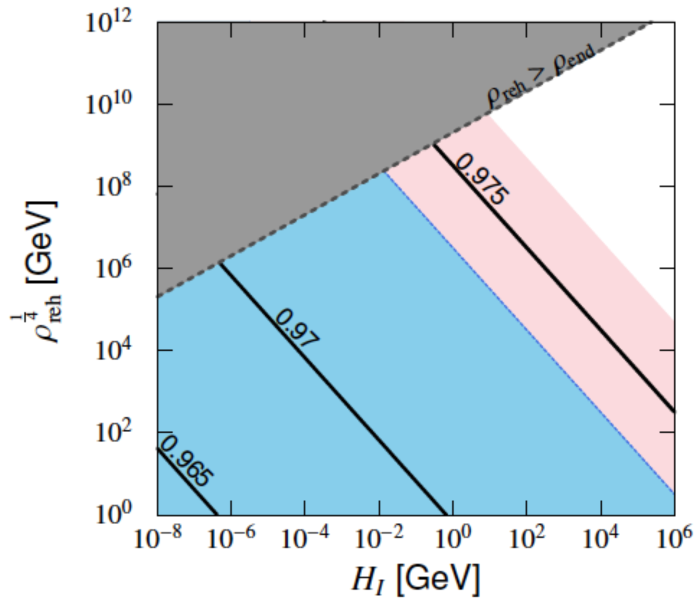
# Inflation check list

## ✓ Spectral tilt

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

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

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




## ✓ 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

Energy stored in $\phi_+$ requires cancellation of large $\langle\phi_+\rangle$: $-\mathcal{L} \supset \frac{1}{2}\kappa_1\kappa_2 \sin 2\beta \langle M_-\rangle \phi_+ h^2$

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

# 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 $\quad |m_S| \lesssim \frac{v^4}{m_{\mathrm{SUSY}} f_\phi^2}$

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

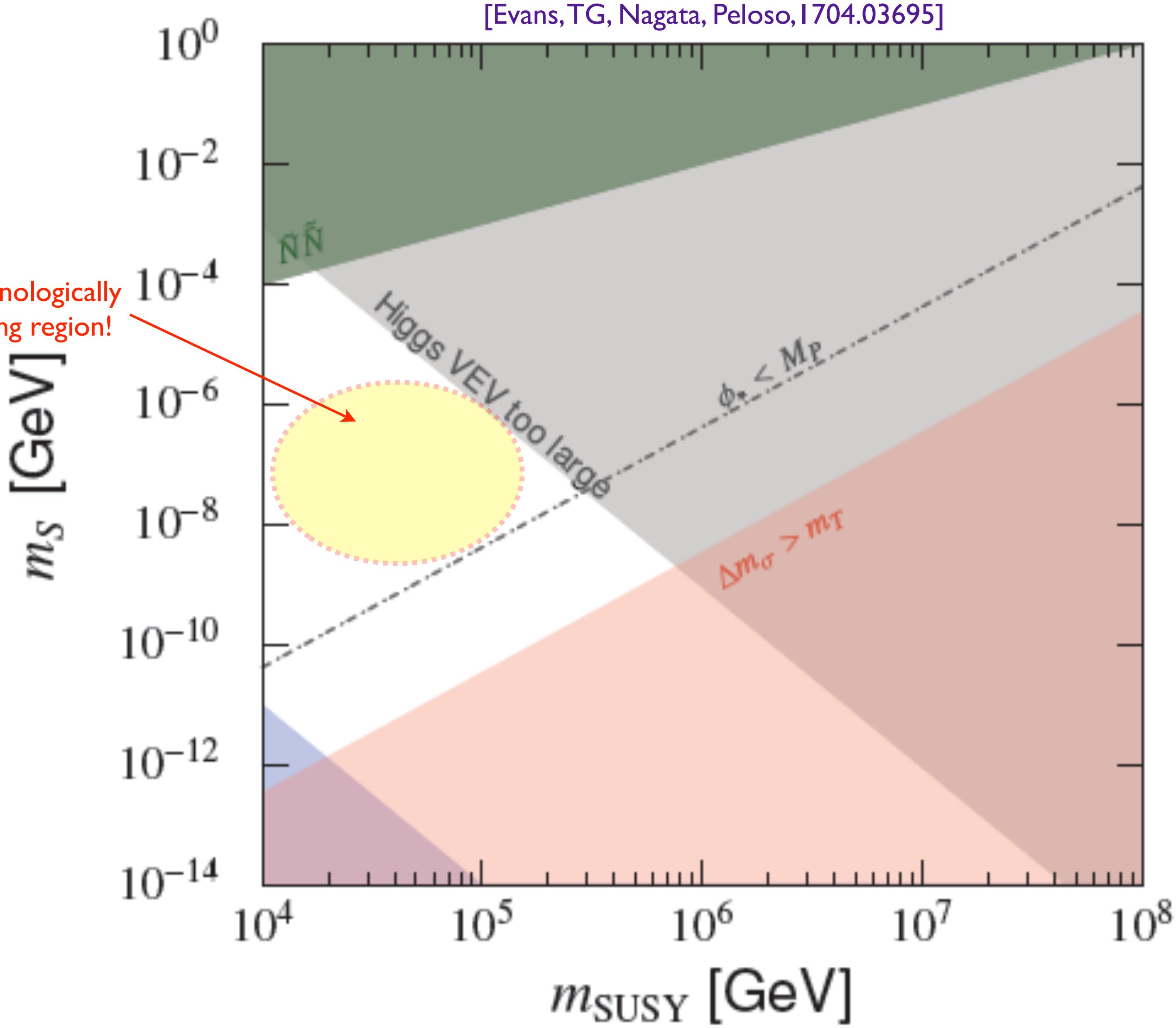
- Sufficient number of e-folds $\quad N_e \simeq \frac{H_I \Delta\phi}{\left|\frac{d\phi}{dt}\right|} \gtrsim \frac{H_I^2}{|m_S|^2} = 10^{14} \times \left(\frac{H_I}{1\ \mathrm{GeV}}\right)^2 \left(\frac{10^{-7}\ \mathrm{GeV}}{|m_S|}\right)^2$

- Loop corrections to inflaton mass

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

[Evans, TG, Nagata, Peloso, 1704.03695]

Phenomenologically interesting region!




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

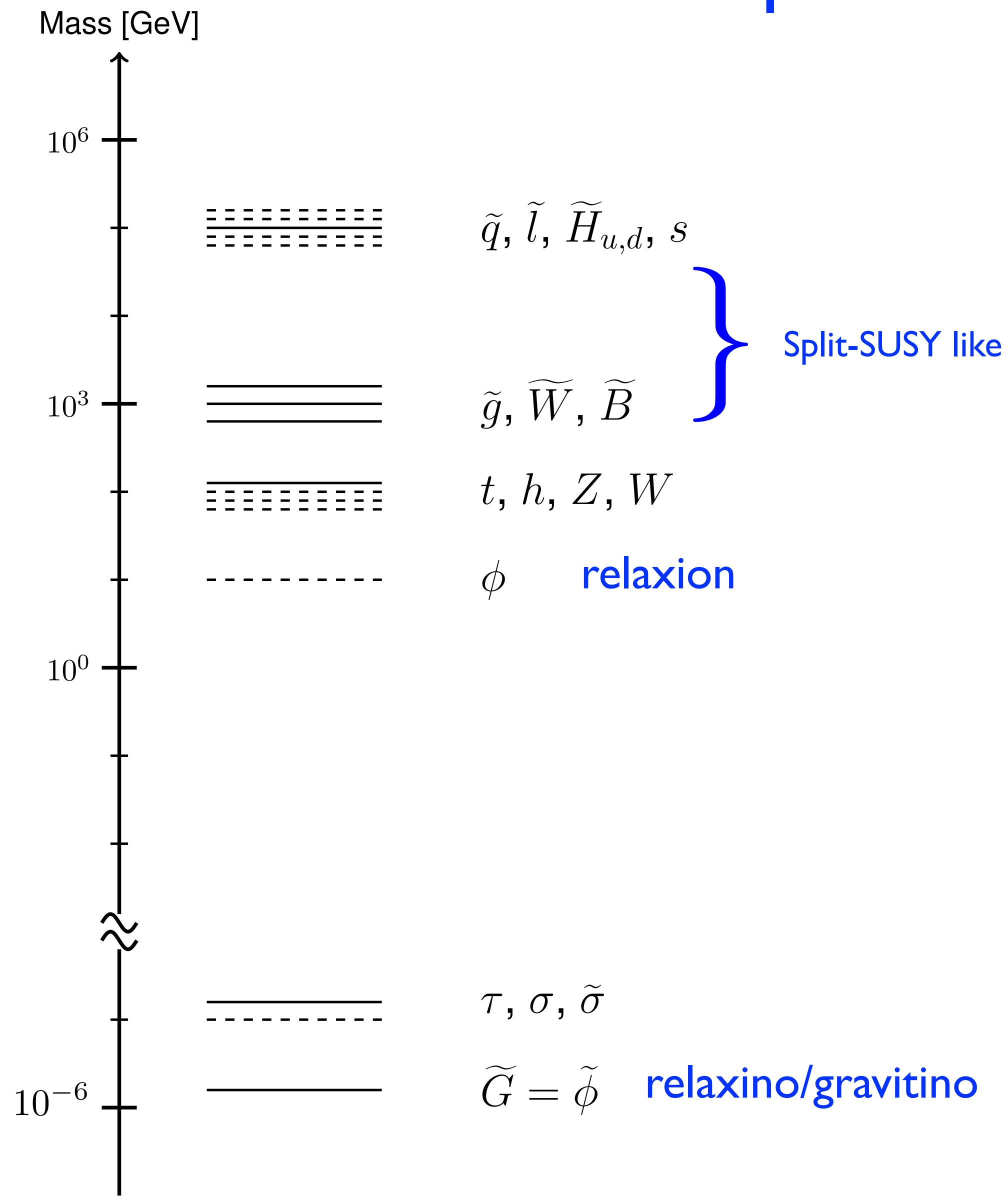
$$r_{TS} \equiv \frac{m_T}{m_S}, \quad r_\Lambda \equiv \frac{\Lambda_N}{f}, \quad r_{\rm SUSY} \equiv \frac{m_{\rm SUSY}}{f},$$

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

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

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

# 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

# Long-lived Particles [in preparation]

- Higgs can mix with the relaxion-inflation sector

relaxion

Higgs-scalar: $\mathcal{L} \supset 2\lambda' \sin\left(\frac{\phi_0}{f} + \delta\right) \frac{v^2}{f} h^2 \phi$ $\qquad -\mathcal{L} \supset \kappa_2' m_{\phi_+} \phi_+ h^2 + h.c.$

"waterfall" field

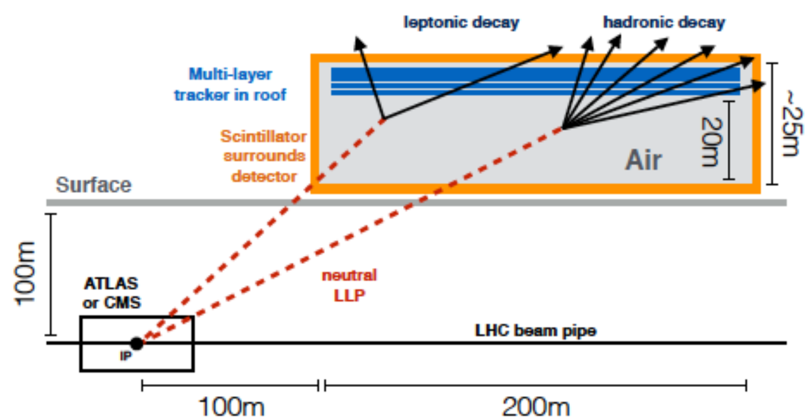
Higgsino-relaxino: $\mathcal{L} \supset \kappa_2 \tilde{R} \left(v_u \tilde{H}_d + v_d \tilde{H}_u\right) + h.c.$

$$\Rightarrow \quad \Gamma_{\lambda_3 \to h\tilde{R}} \simeq (150\ \mathrm{m})^{-1} \left(\frac{|\kappa_2|}{10^{-7}}\right)^2 \left(\frac{10\ \mathrm{TeV}}{\mu}\right)^2 \left(\frac{c_{2\beta}}{0.5}\right)^2 \left(\frac{M_2}{1\ \mathrm{TeV}}\right)$$

- Direct axion-like coupling: $\mathcal{L} \supset \int d^2\theta \frac{C}{32\pi^2} \frac{S}{f} W^{a\alpha} W^a_\alpha + h.c.$

$$\Rightarrow \quad \Gamma_{\lambda^a \to \tilde{S} + \gamma/Z} = (171\ \mathrm{m})^{-1} \left(\frac{|C|}{1}\right)^2 \left(\frac{M_{\lambda^a}}{1\ \mathrm{TeV}}\right)^3 \left(\frac{3 \times 10^8\ \mathrm{GeV}}{f}\right)^2$$

Possible signal at MATHUSLA experiment!



# UV completion [Based on Kaplan, Rattazzi:1511.01827]

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

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

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 $\Rightarrow$ $f_\phi \sim f_0 \qquad V_\phi \sim V_0 \propto \cos \frac{\phi}{f_\phi}$

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

$= |m_S|^2$!

Similarly:

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

$= g_S$ !

# Summary

- Inflaton-relaxion dynamics can explain SUSY scale up to $10^6$ 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 array, MATHUSLA….