Natural Heavy Supersymmetry

G.F. Giudice

Based on 1509.00834 with Brian Batell & Matthew McCullough

Gearing up for LHC13, GGI 14 Oct 2015

Relaxion:

Graham, Kaplan, Rajendran

first concrete example of SOC for ~~EW~~

Not a complete theory

- Naturalness is sensitive to all distance scales

  problem postponed to

  $\Lambda < 10^{7}$ GeV (with $\theta \sim 1$)

  $\Lambda < 10^{4\text{-}6}$ GeV (with $|\theta| \sim 10^{-10}$)

  $\Lambda < 10^{9}$ GeV (with more structure)

  Espinosa, Grojean, Panico, Pomarol. Pujolas, Servant Matsedonskyi

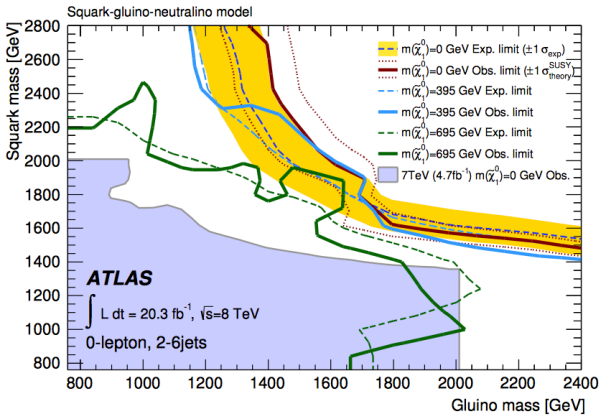
- Solution is specific to EW problem

  naturalness may re-emerge at HE (inflation, GUT, ...)

IR = 😊 UV = 😩

Supersymmetry:

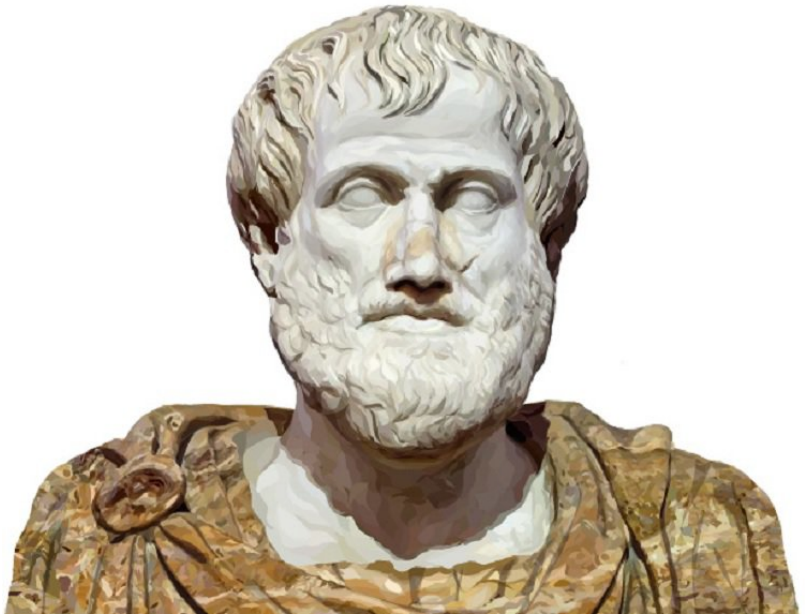
- Elegant solution to naturalness possibly related to unification of forces & quantum gravity
- Cures naturalness at any scale above $\tilde{m}$
- Not part of nature at the EW scale?



UV = 😊 IR = 😩

Relaxion + Supersymmetry:

Relaxion + Supersymmetry:

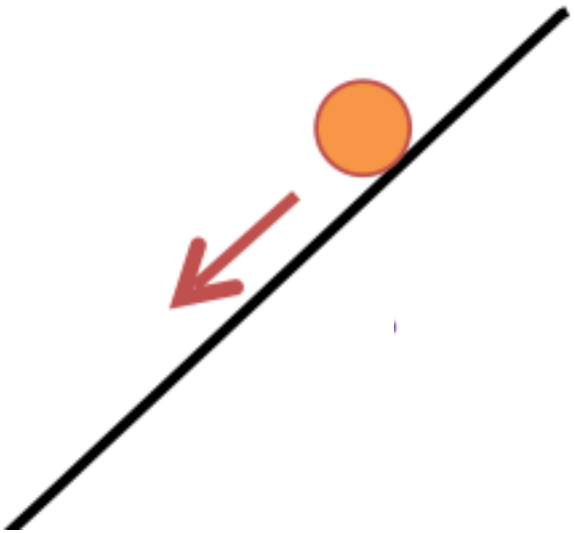


Totality is not a mere heap, but the whole is beyond the sum of its parts, *Metaphysics, Book VIII, 1045a.8-10*

Relaxion:

- (Natural) UV completion $(\Lambda \rightarrow \tilde{m})$
- No need for special relaxion-Higgs couplings (violating shift symmetry)

  a scanning field scans ~~susy~~ scale



$$E_{vac} = \left| \left\langle F_{susy} \right\rangle \right|^2$$

Supersymmetry:

- Little hierarchy explained

- Economical ~~susy~~ sector: only the relaxion superfield
  (bypass theorems on ~~susy~~ with metastable vacua)
  QCD determines the ~~susy~~ scale

Setup:

susy SM + S with shift symmetry $S \to S + i\alpha$

$$S = \frac{s + i\,a}{\sqrt{2}} + \sqrt{2}\,\theta\,\tilde{a} + \theta^2 F$$

srelaxion

relaxion

relaxino (goldstino)

susy breaking

$$\mathscr{L} = \int d^4\theta \left[f^2 K(S+S^\dagger) + Z_i(S+S^\dagger)\,\Phi_i^\dagger e^V \Phi_i \right] + \left[\int d^4\theta\, U(S+S^\dagger)\, e^{-qS} H_u H_d \right.$$

$$\left. + \int d^2\theta \Big(C_a(S)\,\mathrm{Tr}\mathcal{W}_a\mathcal{W}_a + \mu_0\, e^{-qS} H_u H_d + \text{Yukawa int.} \Big) + \text{h.c.} \right] ,$$

$$C_a(S) = \frac{1}{2g_a^2} - \frac{i\,\Theta_a}{16\pi^2} - \frac{c_a\,S}{16\pi^2} .$$

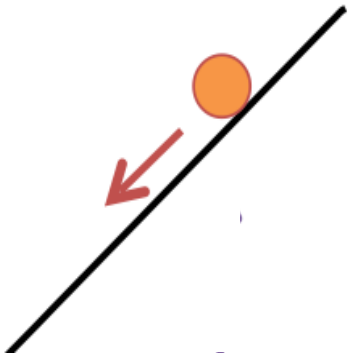
Break the shift symmetry:

$$W/f^2 = \frac{m}{2} S^2 \qquad V/f^2 = \frac{m^2}{2}(s^2 + a^2)\kappa(s)$$

- $m << f$ is (technically) natural
- mimics (rel)axion monodromy
- no shift-breaking Higgs couplings

Assume *a* displaced from its minimum during inflation

Susy breaking: $F \approx ma$



SM feels susy breaking

loop factor

gaugino mass $$W = \frac{c_a}{16\pi^2} S \,\mathrm{Tr}\, \mathcal{W}_a \mathcal{W}_a \quad \Rightarrow \quad M_{\tilde{g}_a} = \frac{c_a \alpha_a}{4\pi} F$$

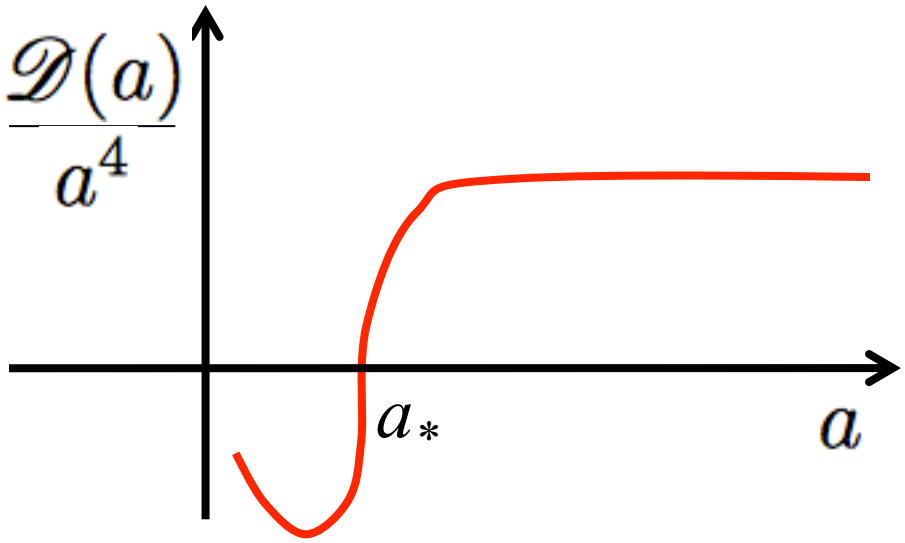
scalar mass $$K = \frac{f^2}{M_*^2}\left(S + S^+\right)^2 \Phi_i^+ \Phi_i \quad \Rightarrow \quad \tilde{m} = \frac{f}{M_*} F$$

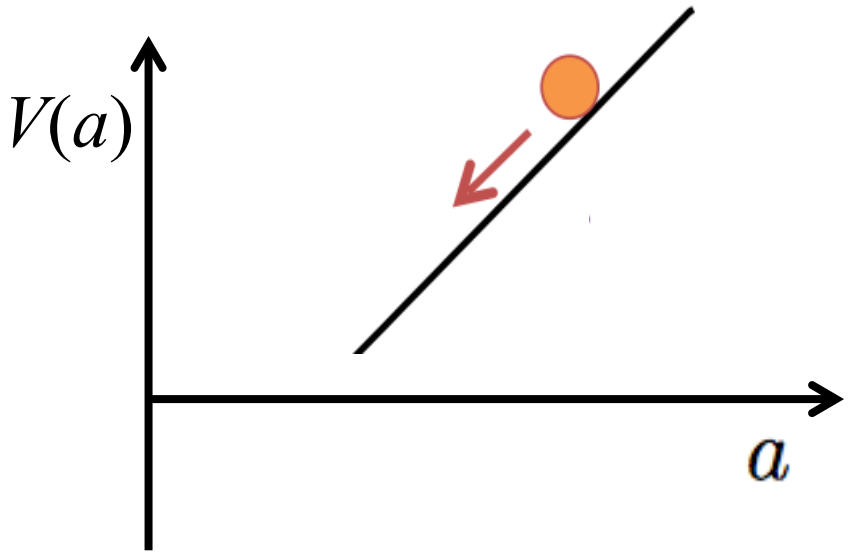
messenger scale $M_* \geq f$

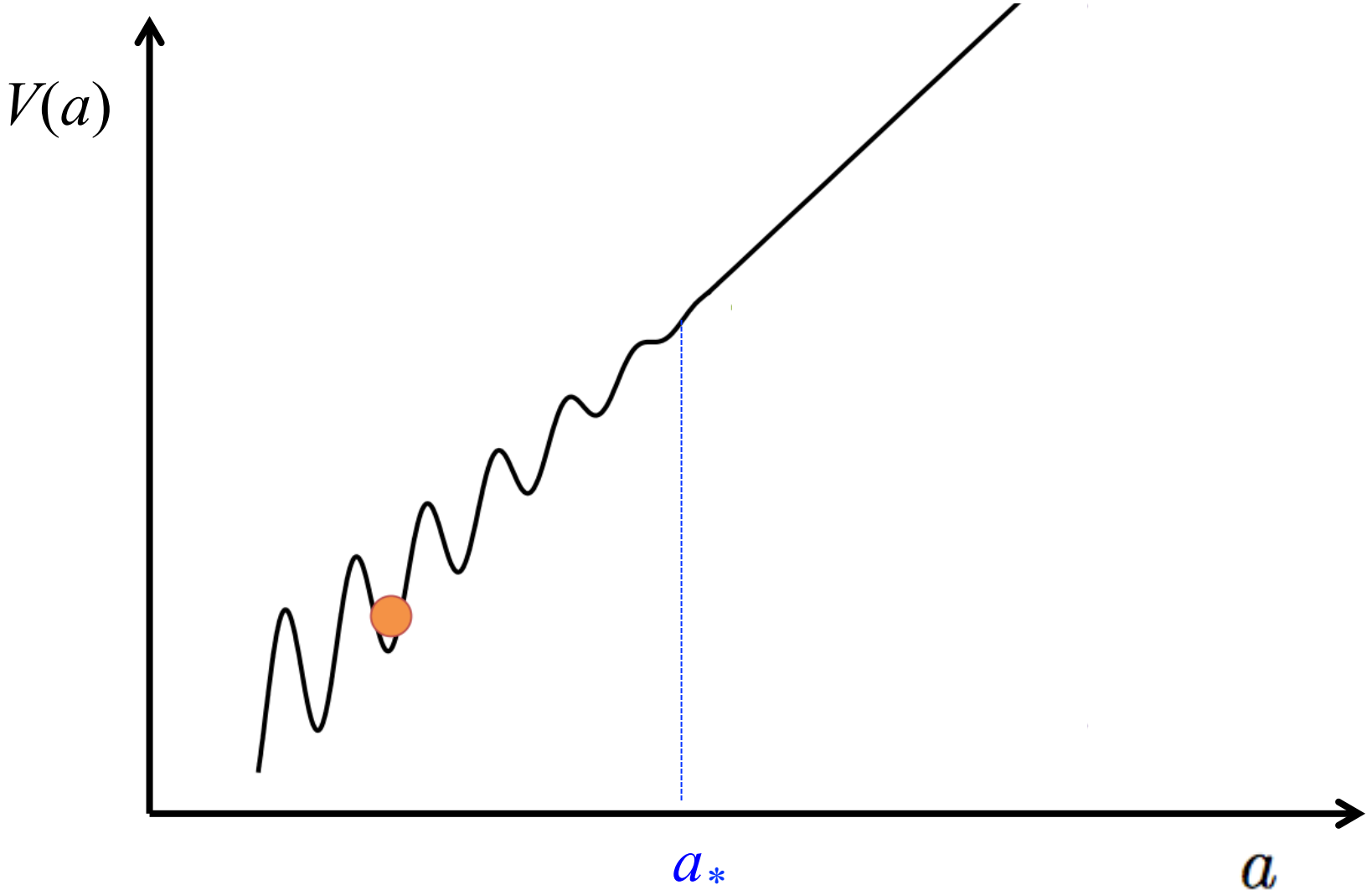
Relaxation of susy breaking

EW order parameter

$$\mathscr{D}(a) \equiv \left(m_{H_u}^2 + |\mu|^2\right)\left(m_{H_d}^2 + |\mu|^2\right) - |B_\mu|^2$$





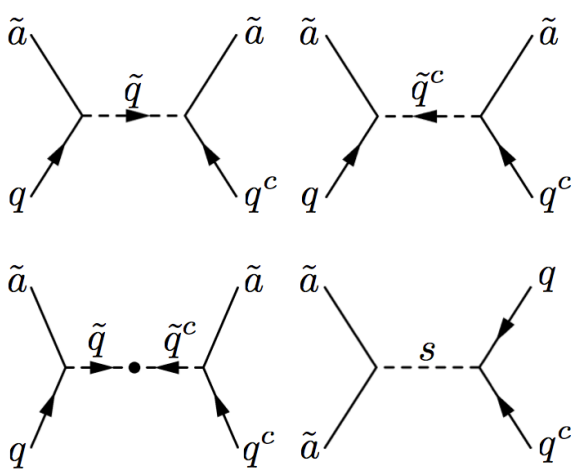


- $a_* \approx \mu / m$
- Higgs vev parametrically uncorrelated with susy scale ($v << F$)

Deep interplay between different scales

(Susy broken by QCD)

Relaxion-relaxino EFT below QCD scale



$$\mathscr{L} = -V(a) - \frac{m_{\tilde{a}}(a)}{2} f^2 \left(\tilde{a}\tilde{a} + \text{h.c.}\right)$$

$$m_q \langle q^c q \rangle \to \Lambda^4/2$$

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos\frac{a}{\sqrt{2}}\,, \qquad m_{\tilde{a}}(a) = m - \frac{\Lambda^4 \sin\frac{a}{\sqrt{2}}}{\sqrt{2}\, a m f^2}$$

$$V'(a)|_{a=\langle a\rangle} = 0 \qquad \Rightarrow \qquad m^2 f^2 \langle a\rangle = \frac{\Lambda^4}{\sqrt{2}} \sin\frac{\langle a\rangle}{\sqrt{2}}$$

Constraints

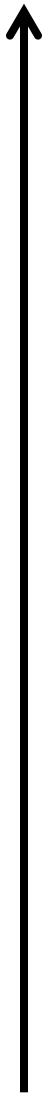
- slow-roll relaxion $\Rightarrow \quad m < \dfrac{\mu f}{M_P}$
- $V_{relaxion} << V_{inflaton} \approx H^2 M_P^2 \quad \Rightarrow \quad H > \dfrac{\mu f}{M_P}$
- relaxion-induced >> inflaton-induced $\Rightarrow \; H < \mu$

  soft terms soft terms ($\approx H$)
- inflaton does not disturb $\Rightarrow \quad H < \Lambda_{QCD}$

  QCD-induced potential
- relaxion evolves classically $\Rightarrow \quad H^3 < mf\mu$

$\mu < 500$ TeV

Mass spectrum



$\tilde{q}, \tilde{\ell}, \tilde{H}, s \sim 100$ TeV

$\tilde{g}, \tilde{W}, \tilde{B} \sim 1$ TeV

$SM \sim 100$ GeV $\leftrightarrow$ MeV

$\tilde{a}\,(\tilde{G}) \sim$ keV $\leftrightarrow$ GeV

$a \sim 10^{-2} \leftrightarrow 10^{-5}$ eV

Mass spectrum Phenomenology

$\tilde{q}, \tilde{\ell}, \tilde{H}, s \sim 100$ TeV OK for m_H, flavor, dim-5 p-decay

$\tilde{g}, \tilde{W}, \tilde{B} \sim 1$ TeV could be within LHC reach

$SM \sim 100$ GeV $\leftrightarrow$ MeV

$\tilde{a}\,(\tilde{G}) \sim$ keV $\leftrightarrow$ GeV LSP, DM for $T_{RH} \sim \tilde{m}$

$a \sim 10^{-2} \leftrightarrow 10^{-5}$ eV DM for $f \sim 10^{11\text{-}12}$ GeV

(rel)axion couplings related to soft terms

LHC phenomenology

- Only gauginos ⇒
  like anomaly-med mini-Split (but natural!)
- NLSP prompt decay, displaced vertex, or stable ⇒
  like gauge-med
- Characteristic and unique signatures

Gluino NLSP: $pp \to \tilde{g}\tilde{g} \to gg\tilde{a}\tilde{a}$

- MET with low jet multiplicity
- displaced vertices
- long-lived color particles

$\tilde{W}$ or $\tilde{B}$ NLSP: $pp \to \tilde{g}\tilde{g}, \quad \tilde{g} \to q\bar{q}(\tilde{B}, \tilde{W}^{\pm}, \tilde{W}^{0})$

$$\tilde{B} \to (\gamma, Z)\tilde{a}$$

$$\tilde{W}^{\pm} \to \pi^{\pm}\tilde{W}^{0}$$

$$\to W^{\pm}\tilde{a}$$

$$\tilde{W}^{0} \to (\gamma, Z)\tilde{a}$$

- variety of signals
- disappearing tracks
- chain of displaced vertices

Conclusions

Supersymmetry: excellent candidate for UV completing the relaxion

- Scanning of Higgs mass through (automatic) scanning of susy-breaking scale
- Relaxion superfield is the susy-breaking sector
- Susy scale determined by QCD
- Natural version of mini-Split or high-scale susy
- New characteristic LHC signals

Open problems: strong CP
non-compact axion
super-Planckian excursion
cosmology