Natural Heavy Supersymmetry

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with G. Giudice and M. McCullough - arXiv:1509.00834

Hidden Naturalness Workshop - April 28-30, 2016

Supersymmetry

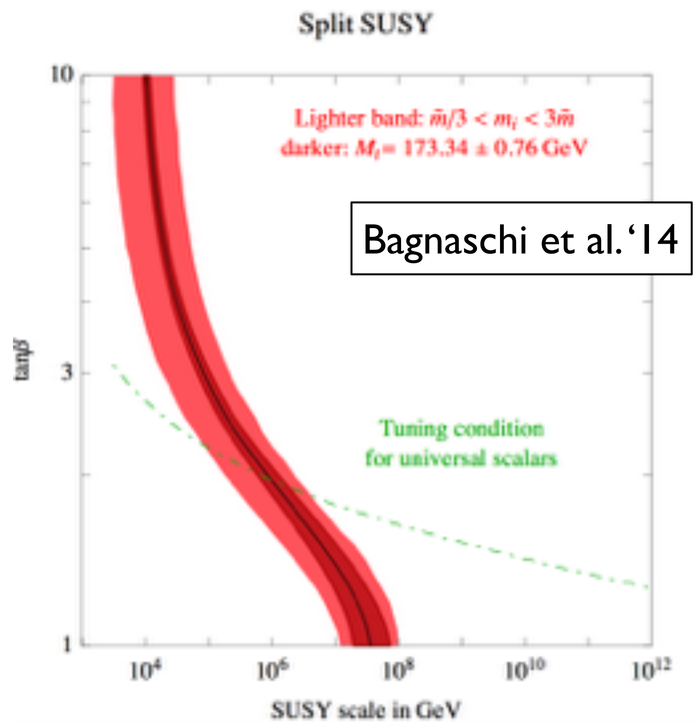
- Naturalness
- Unification
- Dark matter
- Extension of spacetime symmetry
- Quantum gravity, string theory

Is SUSY unnatural?

Arvanitaki, Craig, Dimopoulos, Villadoro
Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski
Bagnaschi, Giudice, Slavich, Strumia
…

Where are the superpartners?

Higgs mass perhaps suggests split or high scale SUSY



Lack of deviations in EWPT, flavor violation, CP-violation, B,L, …

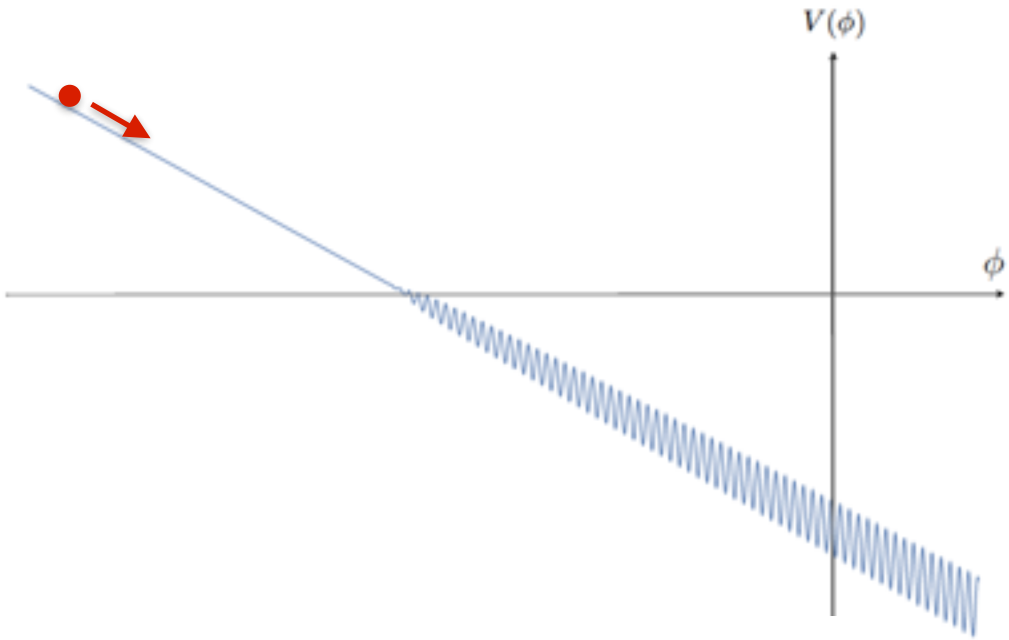
More generally …

Is the Higgs natural?

If yes, then where is the New Physics?

Relaxion

[Graham, Kaplan, Rajendran ’15]



How large can the cutoff be?

In the minimal model, constraints from Vacuum Energy and Classical Rolling imply:

$$M^2/M_P < H_i < (\Lambda^4/f)^{1/3}$$

$$M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{1/6} \simeq 10^7\,\mathrm{GeV}\left(\frac{10^9\,\mathrm{GeV}}{f}\right)^{1/6}$$

- Relaxion: good in the IR, bad in the UV(???)
  - Address little hierarchy
  - UV cutoff $10^{5\text{-}9}$ GeV depending on model
  - Requires UV completion to protect Higgs mass at all scales

- SUSY: bad in the IR, good in the UV
  - No signs of superpartners, Higgs mass suggests heavy scalars
  - Can still address the big hierarchy problem
  - Other UV motivations - unification, quantum gravity, etc.

→ Combine these frameworks

Natural Heavy Supersymmetry

[BB, Giudice, McCullough]

In addition to a UV completion of the relaxion, we find:

- A novel and economical theory of SUSY breaking
- Relaxation of the SUSY breaking scale
- A natural theory of heavy scalars - Mini-Split SUSY

Setup

srelaxion relaxion relaxino

- MSSM fields + single chiral multiplet: $S = \frac{s + i\,a}{\sqrt{2}} + \sqrt{2}\,\theta\,\tilde{a} + \theta^2 F$

- PQ Shift symmetry: $S \to S + i\alpha, \quad (a \to a + \sqrt{2}\alpha)$

- General EFT below scale f :

$$\begin{aligned}\mathscr{L} \;=\; & \int d^4\theta \left[f^2 K(S+S^\dagger) + Z_i(S+S^\dagger)\,\Phi_i^\dagger e^V \Phi_i\right] + \left[\int d^4\theta\, U(S+S^\dagger)\, e^{-qS} H_u H_d \right. \\ & \left. + \int d^2\theta \left(C_a(S)\,\mathrm{Tr}\mathcal{W}_a\mathcal{W}_a + \mu_0\, e^{-qS} H_u H_d + \text{Yukawa int.}\right) + \text{h.c.}\right],\end{aligned}$$

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

- SUSY and PQ symmetry preserved, axion potential vanishes, no dynamical evolution - must break PQ symmetry…

Breaking the shift symmetry

- Add explicit soft breaking (axion mass)

$$W/f^2 = \frac{m}{2} S^2 \qquad\qquad \mathscr{L}/f^2 = \kappa^{-1}(s) F^* F + m\left[\left(\frac{s+ia}{\sqrt{2}}\right) F + \text{h.c.}\right]$$

$$\Rightarrow \quad \boxed{F \approx ma}$$

The relaxion breaks SUSY

- As the relaxion evolves, it scans SUSY breaking
- Scanning soft masses arise from PQ symmetric couplings
- No additional PQ breaking couplings to Higgs needed (unlike GKR)

Scanning of SUSY breaking

- Gaugino Mass

$$-\frac{c_a g_a^2}{32\pi^2}\int d^2\theta\, S\, W_a\, W_a \quad \longrightarrow \quad M_{\tilde{g}_a} \approx \frac{\alpha_a}{4\pi} F = \frac{\alpha_a}{4\pi}\, m\, a$$

soft masses scan during relaxion evolution

- Scalar Mass

$$\frac{f^2}{M_*^2}\int d^4\theta (S + S^\dagger)^2 \Phi_i^\dagger \Phi_i \quad \longrightarrow \quad \tilde{m}_i \approx \frac{f}{M_*}\, m\, a$$

Cases:

1. $M_* = f$, gauginos lighter than scalars by one loop

2. $M_* \gg 4\pi f/\alpha$, gauginos source SUSY breaking

Relaxation

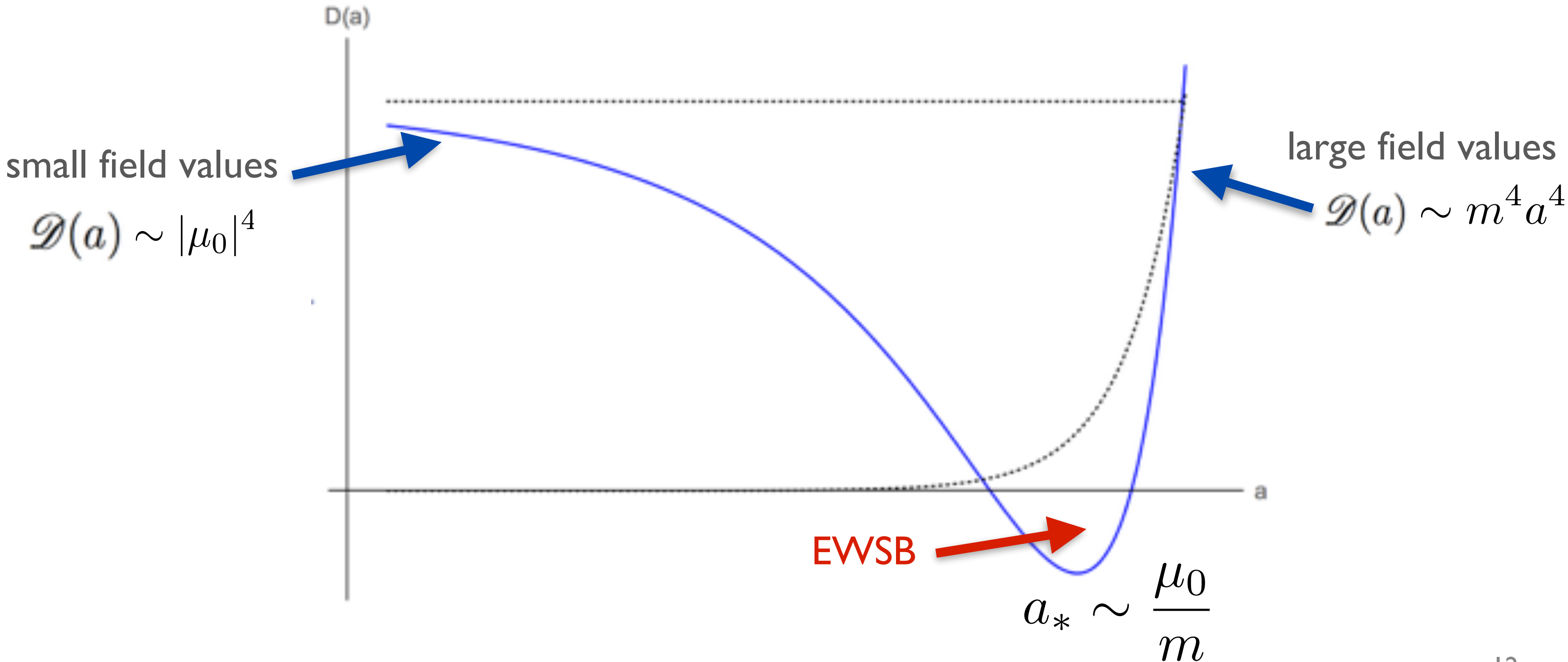
Determinant of Higgs mass matrix - order parameter for EWSB:

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

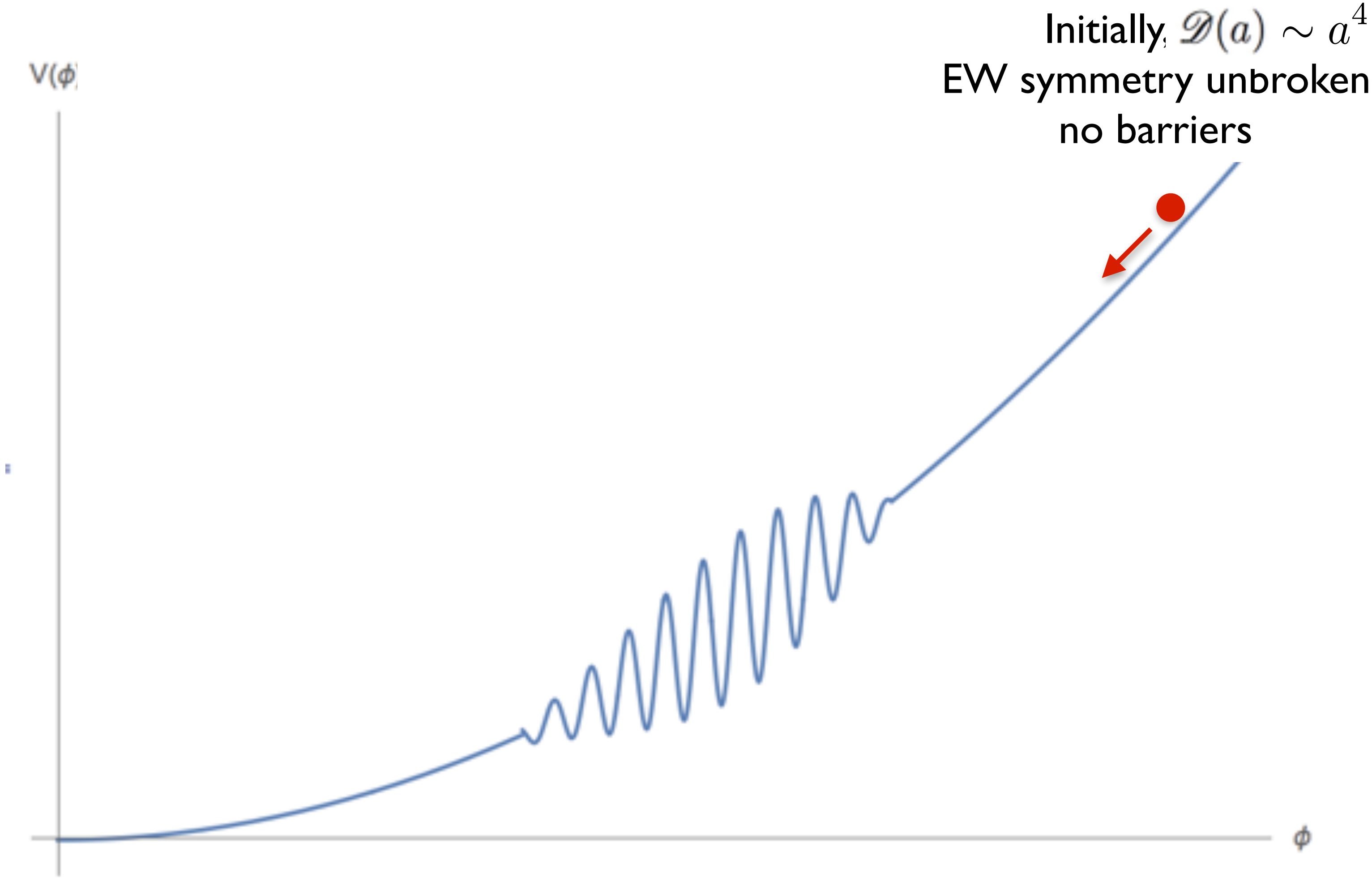
Soft terms (c_i are order one coefficients):

$$m_{H_u}^2 = c_u\, m^2 a^2\,, \quad m_{H_d}^2 = c_d\, m^2 a^2\,,$$

$$\mu = \mu_0 - c_\mu\, m a\,, \quad B_\mu = c_0\, \mu\, m a + c_B\, m^2 a^2\,,$$



$$V(a) = \frac{m^2 f^2}{2} a^2 + \Lambda^4 \cos a$$



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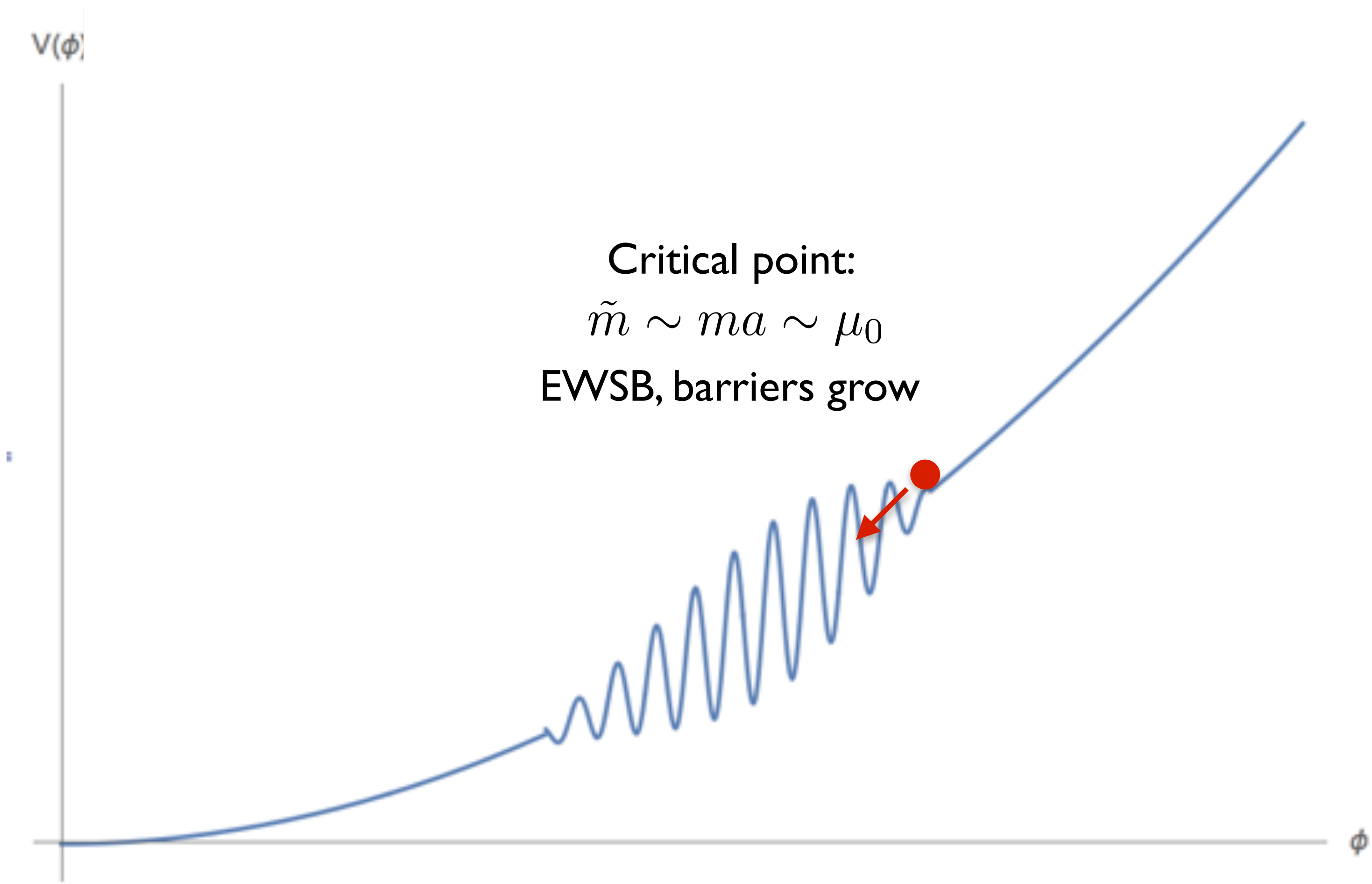
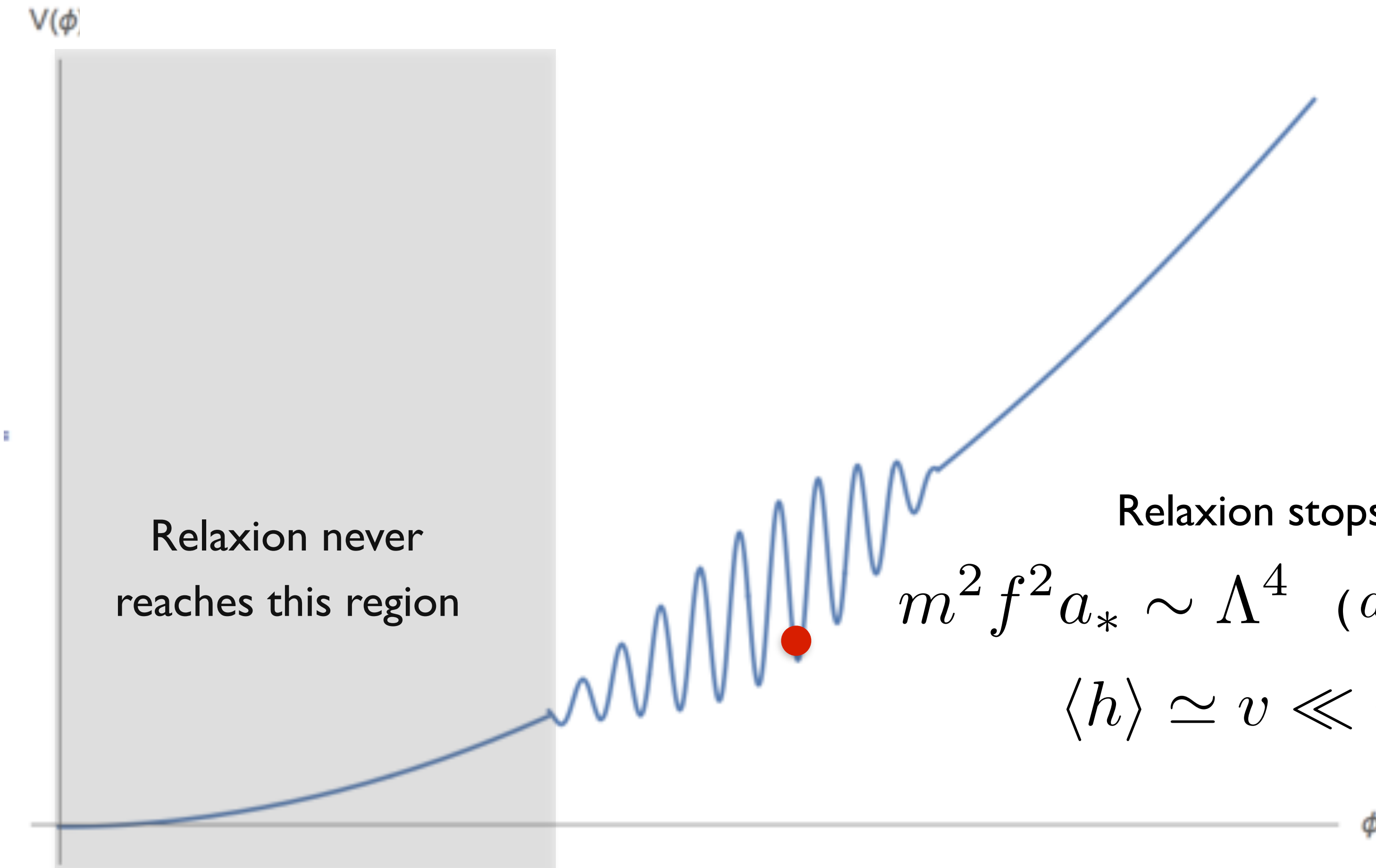


$$V(a) = \frac{m^2 f^2}{2} a^2 + \Lambda^4 \cos a$$



Relaxion stops

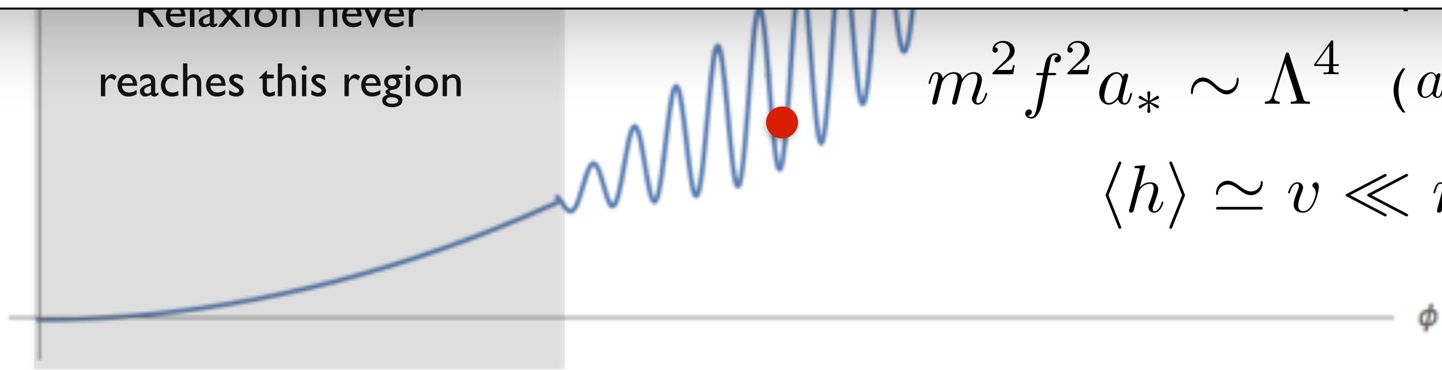
$$m^2 f^2 a_* \sim \Lambda^4 \quad (a_* \sim \mu_0/m)$$

$$\langle h \rangle \simeq v \ll \tilde{m}$$

$$V(a) = \frac{m^2 f^2}{2} a^2 + \Lambda^4 \cos a$$

Metastable SUSY-breaking minimum formed by the competition of QCD instantons and explicit PQ breaking :

“QCD breaks SUSY”



$$m^2 f^2 a_* \sim \Lambda^4 \quad (a_* \sim \mu_0/m)$$

$$\langle h \rangle \simeq v \ll \tilde{m}$$

Constraints on inflation

Inflaton dominates energy density:

$$H^2 M_P^2 > m^2 f^2 a^2 \sim \mu_0^2 f^2$$

$$H > \mu_0 f / M_P \qquad \text{(vacuum energy)}$$

Classical rolling dominates over quantum fluctuations

$$\delta a_{cl} \sim \dot{a}/H \sim V'/f^2 H^2$$

$$\delta a_{qu} \sim H/f$$

$$H < (V'/f)^{1/3} \sim (\Lambda^4/f)^{1/3} \qquad \text{(classical beats quantum)}$$

How large can the cutoff be?

(vacuum energy) and (classical beats quantum) imply:

$$\frac{\mu_0 f}{M_P} < H < \left(\frac{\Lambda^4}{f}\right)^{1/3}$$

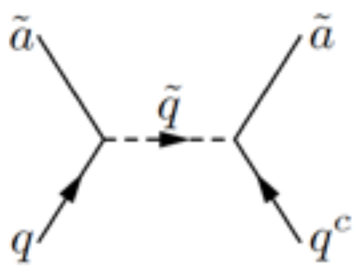
$$\mu_0 < M_P \left(\frac{\Lambda}{f}\right)^{4/3} \sim 5 \times 10^5\,\mathrm{GeV} \times \left(\frac{\Lambda}{300\,\mathrm{MeV}}\right)^{4/3} \left(\frac{10^9\,\mathrm{GeV}}{f}\right)^{4/3}$$

$$\Rightarrow \quad \tilde{m} \sim m a_* \sim \mu_0 < 1000\,\mathrm{TeV}$$

Relaxino = Goldstino

- Since the relaxion breaks SUSY, the relaxino must be the goldstino
- Relaxino mass is non-trivial - Contribution from QCD instantons:

Integrate out squarks to generate 4 – Fermi operator



$$-\frac{1}{2\sqrt{2}am}\left(im_q e^{ia/\sqrt{2}} q^c q + \text{h.c.}\right)\left(\tilde{a}\tilde{a} + \text{h.c.}\right)$$

Match to chiral Lagrangian: $m_q \langle q^c q \rangle \to \Lambda^4/2$

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos\frac{a}{\sqrt{2}} \quad \Rightarrow \quad m_{\tilde{a}}(a) = m - \frac{\Lambda^4 \sin\frac{a}{\sqrt{2}}}{\sqrt{2}\, a m f^2} \to 0$$

Minimize potential

Massless relaxino

Gravitino

- Relaxino = Goldstino is eaten by gravitino, with mass

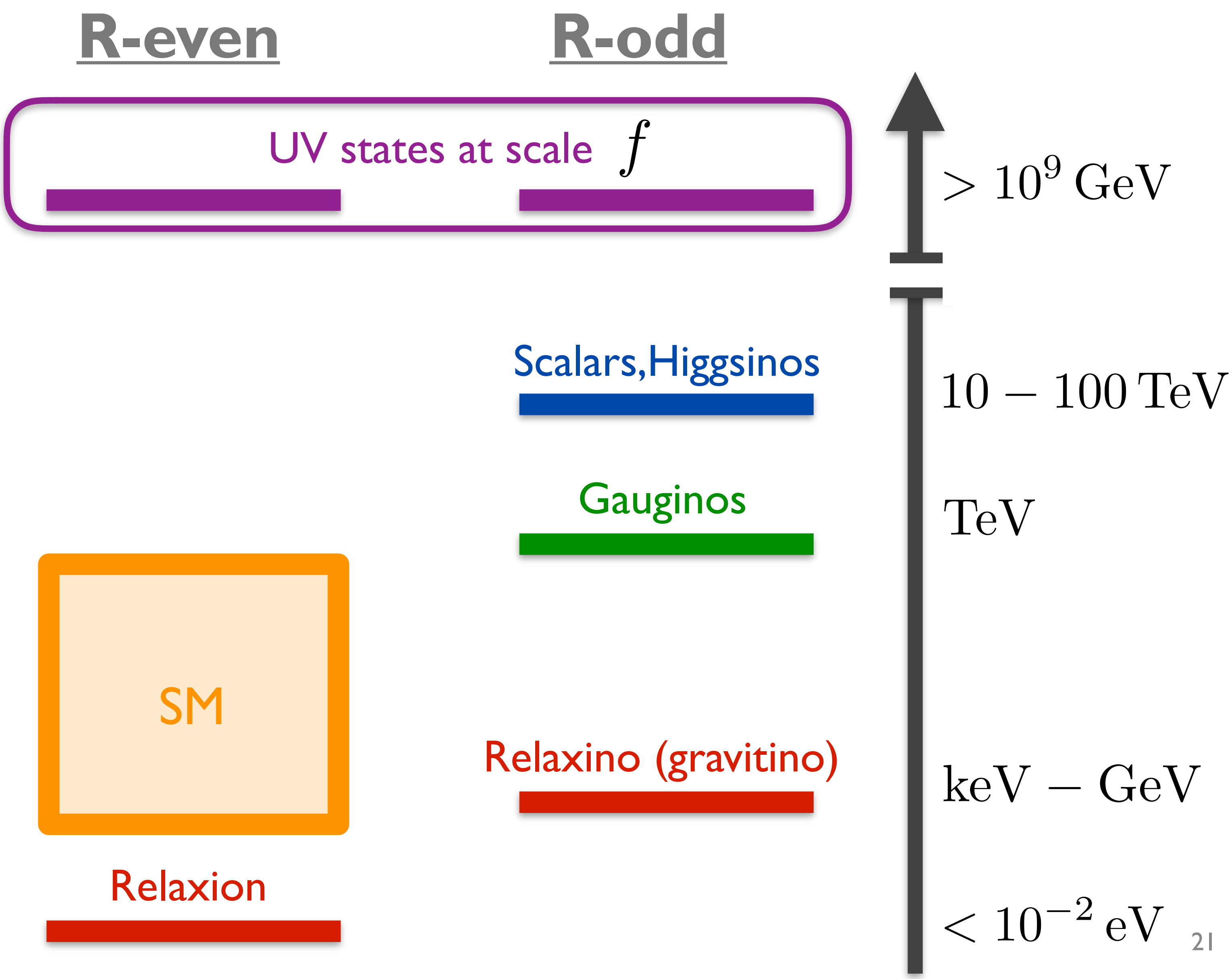
$$m_{3/2} \sim \frac{F\,f}{M_P} \sim \frac{\tilde{m} f}{M_P} \simeq 10\,\mathrm{keV}\left(\frac{\tilde{m}}{10^5\,\mathrm{GeV}}\right)\left(\frac{f}{10^9\,\mathrm{GeV}}\right)$$

- Gravitino is LSP - $m_{3/2} \sim \mathrm{keV} - \mathrm{GeV}$ depending on assumptions regarding parameters and inflation constraints

- Gravitino relic abundance places a bound on reheat temperature

$$T_{RH} < M_{\tilde{g}_a} \sim \frac{\alpha_a}{4\pi}\tilde{m}$$

Natural Split-SUSY



LHC Phenomenology

- Scalars, Higgsinos are expected to be heavy, out of reach at LHC
- Gaugino mass are in the TeV range, potentially within reach of LHC

$$
\begin{aligned}
M_{\tilde{g}} &\approx c_3 \left(\frac{\tilde{m}/k}{10^5\ \mathrm{GeV}}\right) 700\ \mathrm{GeV} \\
M_{\tilde{W}} &\approx c_2 \left(\frac{\tilde{m}/k}{10^5\ \mathrm{GeV}}\right) 250\ \mathrm{GeV} \\
M_{\tilde{B}} &\approx c_1 \left(\frac{\tilde{m}/k}{10^5\ \mathrm{GeV}}\right) 120\ \mathrm{GeV}
\end{aligned}
$$

- Lightest gaugino is NLSP - it decays to SM + relaxino.

$$
\Gamma(\tilde{P} \to P\tilde{a}) = \frac{\tilde{m}_P^5}{48\pi\, m_{3/2}^2 M_P^2} \quad \longrightarrow \quad \tau_{\mathrm{NLSP}} = \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{NLSP}}}\right)^5 1.7 \times 10^2\ \mathrm{meters}/c
$$

- ℓ_{NLSP} between 100 microns and collider stable

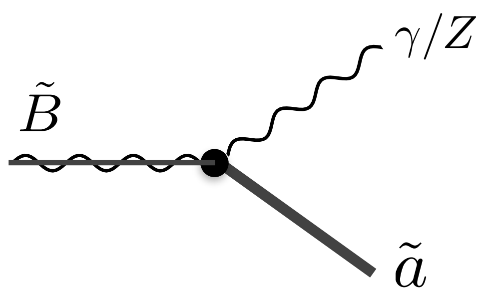
Bino NLSP

- Gluino decays through off shell squarks, $\tilde{g} \to q\bar{q}\tilde{B}$

$$\tau_{\tilde{g}\to q\bar{q}\tilde{B}} \approx \left(\frac{\tilde{m}}{10^5\,\mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{M_{\tilde{g}}}\right)^5 10^{-1}\ \mu\mathrm{m}/c\,.$$

(Typically prompt)

- Following gluino decay, Bino decays to relaxino $\tilde{B} \to \gamma/Z + \tilde{a}$



$$\frac{\Gamma(\tilde{B}\to Z\tilde{a})}{\Gamma(\tilde{B}\to\gamma\tilde{a})} = \tan^2\theta_W \left(1 - \frac{m_Z^2}{m_{\tilde{B}}^2}\right)^4$$

If measured, could confirm NLSP = bino

- Signatures can be quite striking, e.g. $jjjj + \gamma\gamma + \mathrm{MET}$, with photons displaced

Strong CP #1 - inflaton dependent slope

$$W = (m - \lambda I)\,\frac{f^2 S^2}{2} + \frac{m_I\, I^2}{2}\,.$$

I - inflaton superfield

- Effective axion mass and F-term:

$$m^2_{\rm eff}(\varphi_I) = (m - \lambda\varphi_I)^2 + \lambda m_I \varphi_I$$
$$F_{\rm eff}(\varphi_I) = i(m + \lambda\varphi_I)\,\frac{a}{\sqrt{2}}\,.$$

- Require $m^2/m_I \ll \lambda\varphi_I \ll m$

$$\Rightarrow \quad F_{\rm eff}(\varphi_I) \approx F_{\rm eff}(0)$$
$$m^2_{\rm eff}(\varphi_I) \approx \lambda m_I \varphi_I$$

SUSY breaking same before and after inflation

Relaxion mass can be much larger during inflation

- To address Strong CP, we require $\theta \approx \frac{m_{\text{eff}}^2(0)}{m_{\text{eff}}^2(\varphi_I)} \ll 1$
- Demanding that the inflaton dominates the potential, we find

$$H > \left(\frac{f}{10^9 \text{ GeV}}\right)\left(\frac{\mu_0}{10^5 \text{ GeV}}\right)\left(\frac{10^{-10}}{\theta}\right)^{1/2} \text{GeV}$$

- Can satisfy the condition that barriers form
- Cannot satisfy the condition that classical rolling dominates

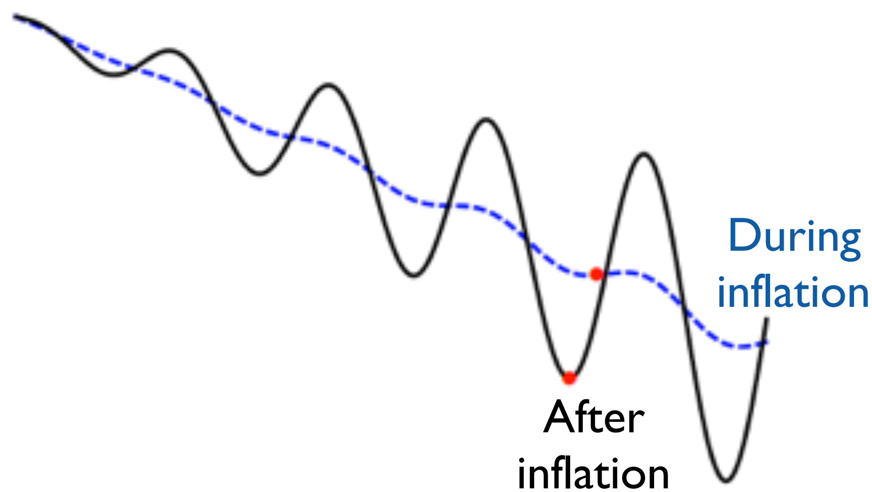
Strong CP # 2 – inflaton dependent barriers

- Consider inflation in the regime $H_I > \Lambda_{\rm QCD}$
- Barriers still form, but are exponentially suppressed

$$V(a) = \frac{m^2 f^2}{2} a^2 + \Lambda^4 \Theta(T_H) \cos a$$

- During inflation, $\Theta \lesssim \theta \sim 10^{-10}$ while after $\Theta \sim \mathcal{O}(1)$

- The condition for classical evolution is not satisfied



Open questions

- Strong CP problem
- Inflation, cosmology
- UV issues - PQ symmetry, non-compact axion, super-Planckian field excursions, SUGRA

See talks by P. Graham & T. Gherghetta

Conclusions

- SUSY + Relaxion make a great team
  - Relaxion addresses the little hierarchy problem

    SUSY takes care of the big hierarchy problem
- The relaxion breaks SUSY
  - Metastable SUSY breaking vacuum formed from explicit PQ breaking vs. QCD instantons (i.e., QCD breaks SUSY)
  - SUSY breaking is scanned
  - Relaxino = goldstino
- Natural Heavy SUSY
  - Mini-Split spectrum, Relaxino = LSP,
  - Variety of striking signals possible at LHC