Stability of the Electroweak Scale

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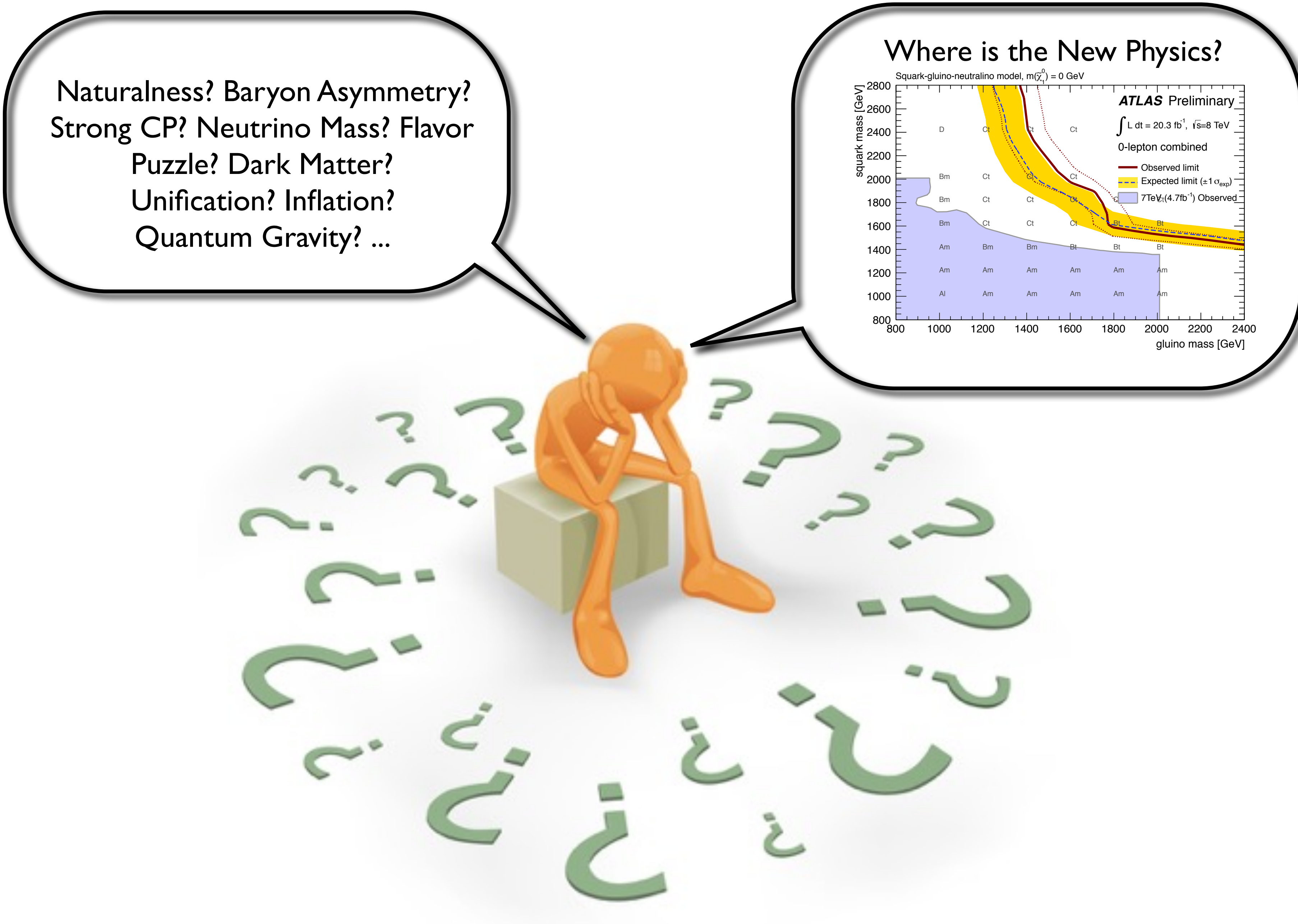
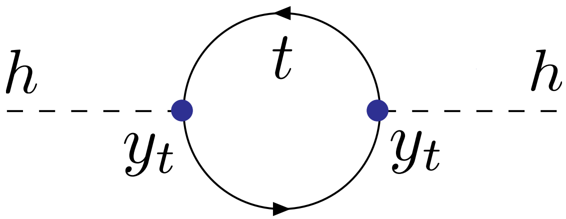
LHCSki
April 10-15, 2016


Naturalness? Baryon Asymmetry?
Strong CP? Neutrino Mass? Flavor
Puzzle? Dark Matter?
Unification? Inflation?
Quantum Gravity? ...
Where is the New Physics?
Squark-gluino-neutralino model, m($\tilde{\chi}_1^0$) = 0 GeV
ATLAS Preliminary
$\int L\,dt = 20.3\ \mathrm{fb}^{-1}$, $\sqrt{s}$=8 TeV
0-lepton combined
Observed limit
Expected limit ($\pm 1\,\sigma_{exp}$)
7TeV (4.7fb^{-1}) Observed
squark mass [GeV]
gluino mass [GeV]

The Hierarchy Problem



$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

(Λ ~ scale of new physics)

Very naively we expect

$$|\delta m_h^2| \lesssim m_h^2 = (125\,\mathrm{GeV})^2$$

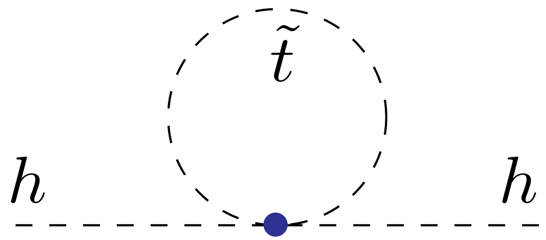
$$\Rightarrow \quad \boxed{\Lambda \lesssim 650\,\mathrm{GeV}}$$

or else we start to tune...

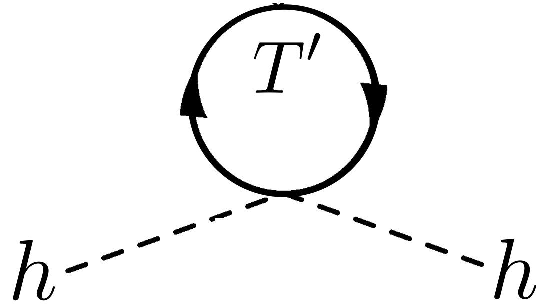
Suggests new dynamics at 100 GeV - 1 TeV!

Naturalness ➡ Top Partners

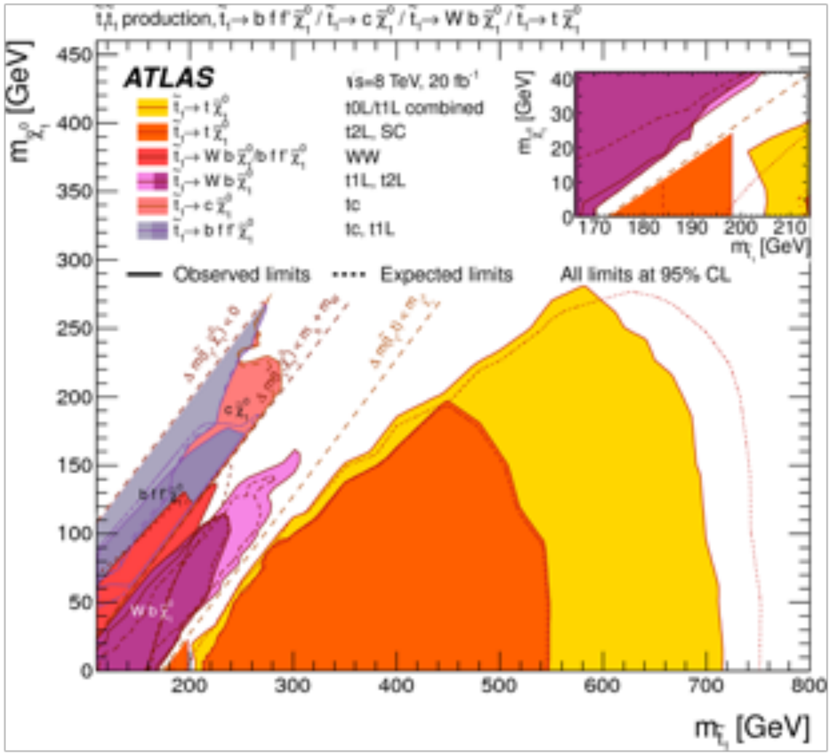
Stops
(SUSY)

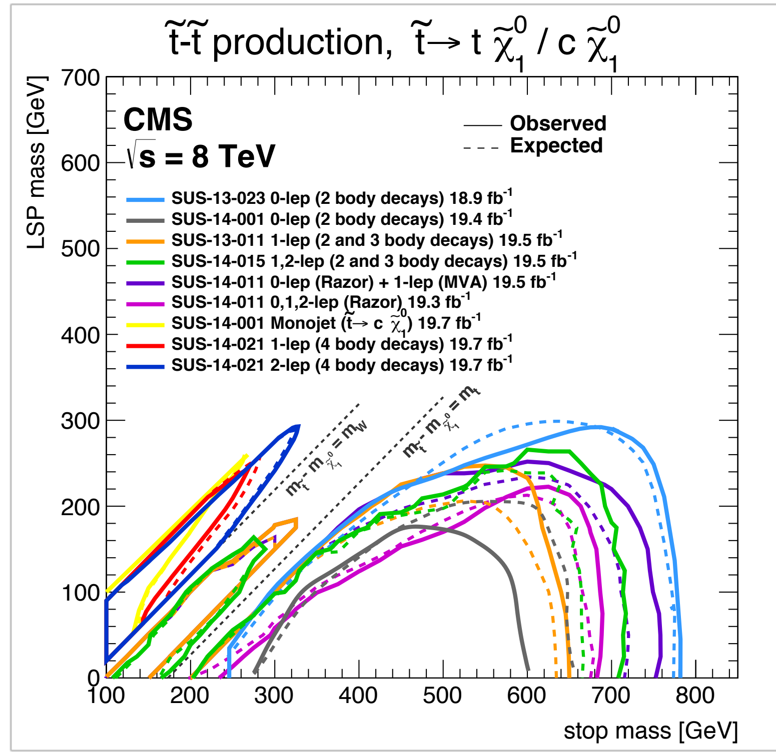


Fermionic T’
(Little/Composite/pNGB
Higgs)



Where are the Top Partners?

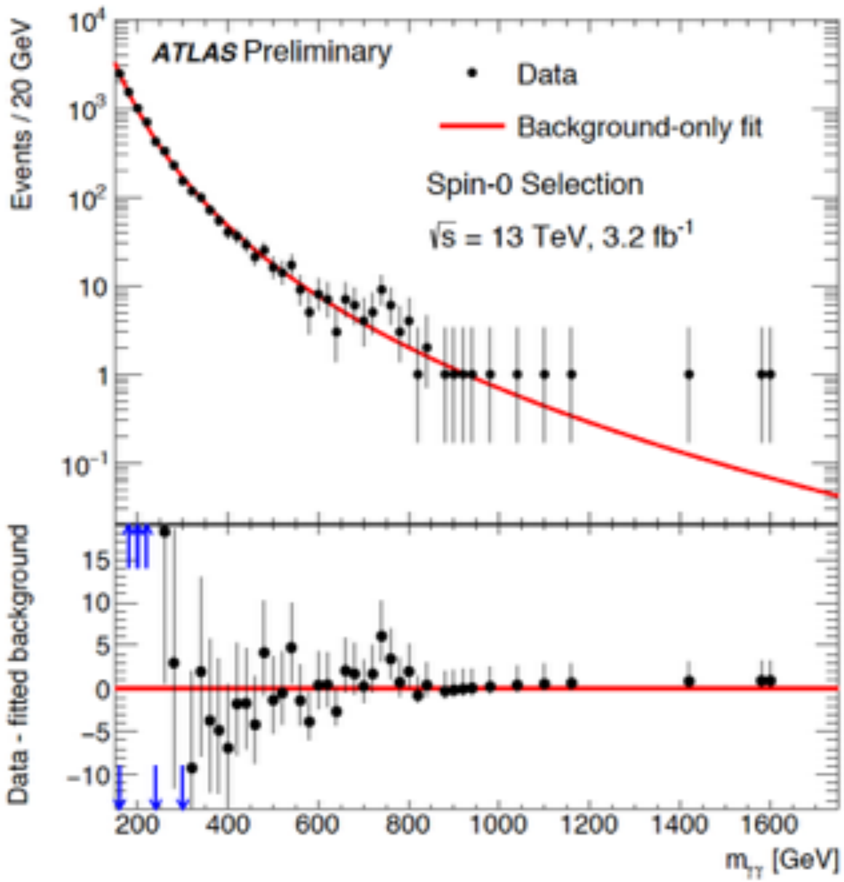


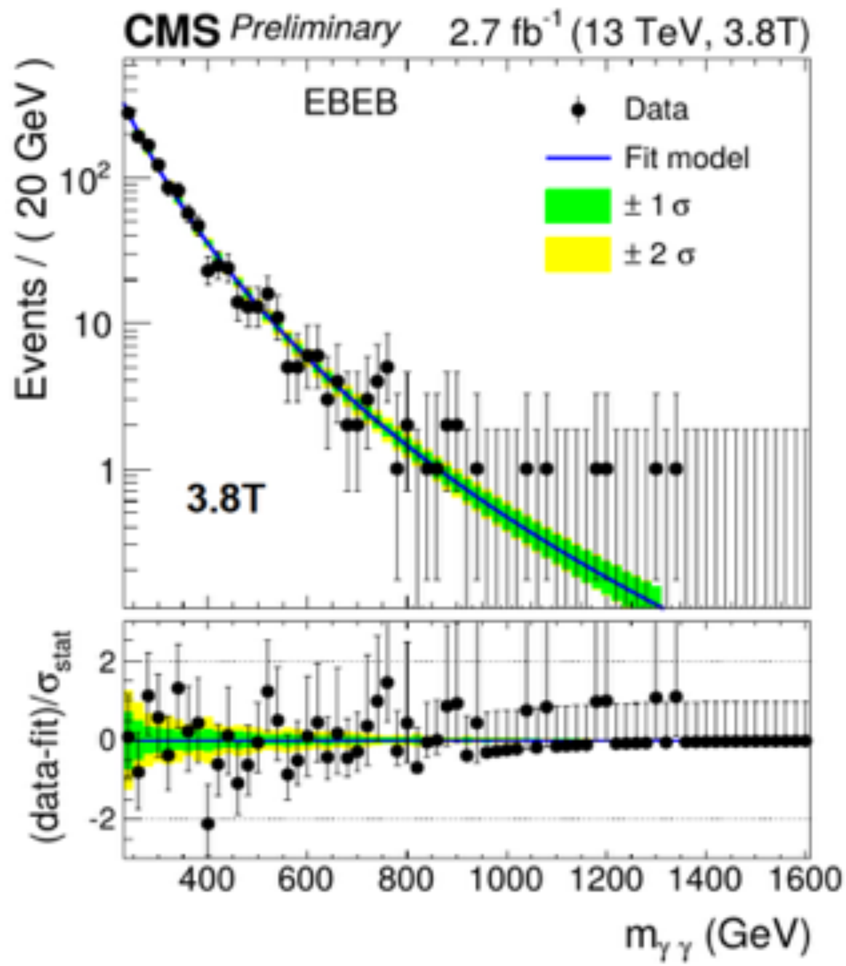


Is the Higgs natural?

If yes, then where is the New Physics?

Maybe this is what we've all been waiting for!





New Approaches to Higgs Naturalness

1. Neutral Naturalness

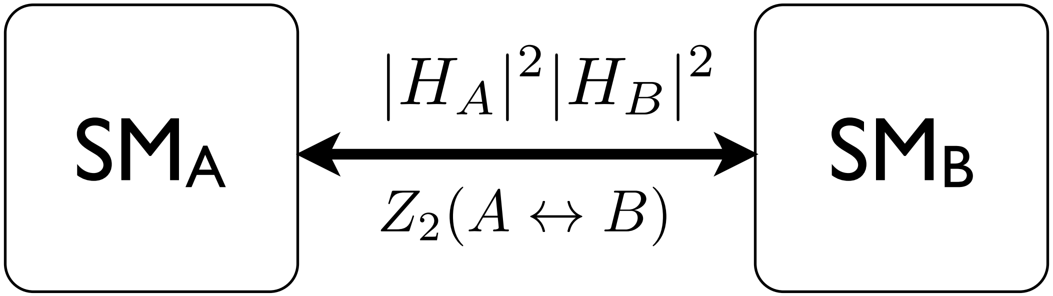
2. Relaxation

Unifying theme: no guarantee to see signals of naturalness at LHC :-(

Neutral Naturalness

Basic idea: Top partners do not cary color charge

The Twin Higgs [Chacko, Goh, Harnik ‘05]



- Mirror copy of the Standard Model
- Higgs sector has an approximate global SU(4) symmetry

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- The SM Higgs is a pseudo-Nambu-Goldstone Boson

$$\langle H \rangle = f \qquad SU(4) \to SU(3)$$

$n_G = 15 - 8 = 7$ pNGBs -- 4 of these (H_A) make up SM Higgs

Twin Top

- Enlarge color to $SU(3)_A \times SU(3)_B \times Z_2$

- Yukawa: $\lambda_t \, H_A \, Q_A \, t^c_A + \lambda_t \, H_B \, Q_B \, t^c_B$

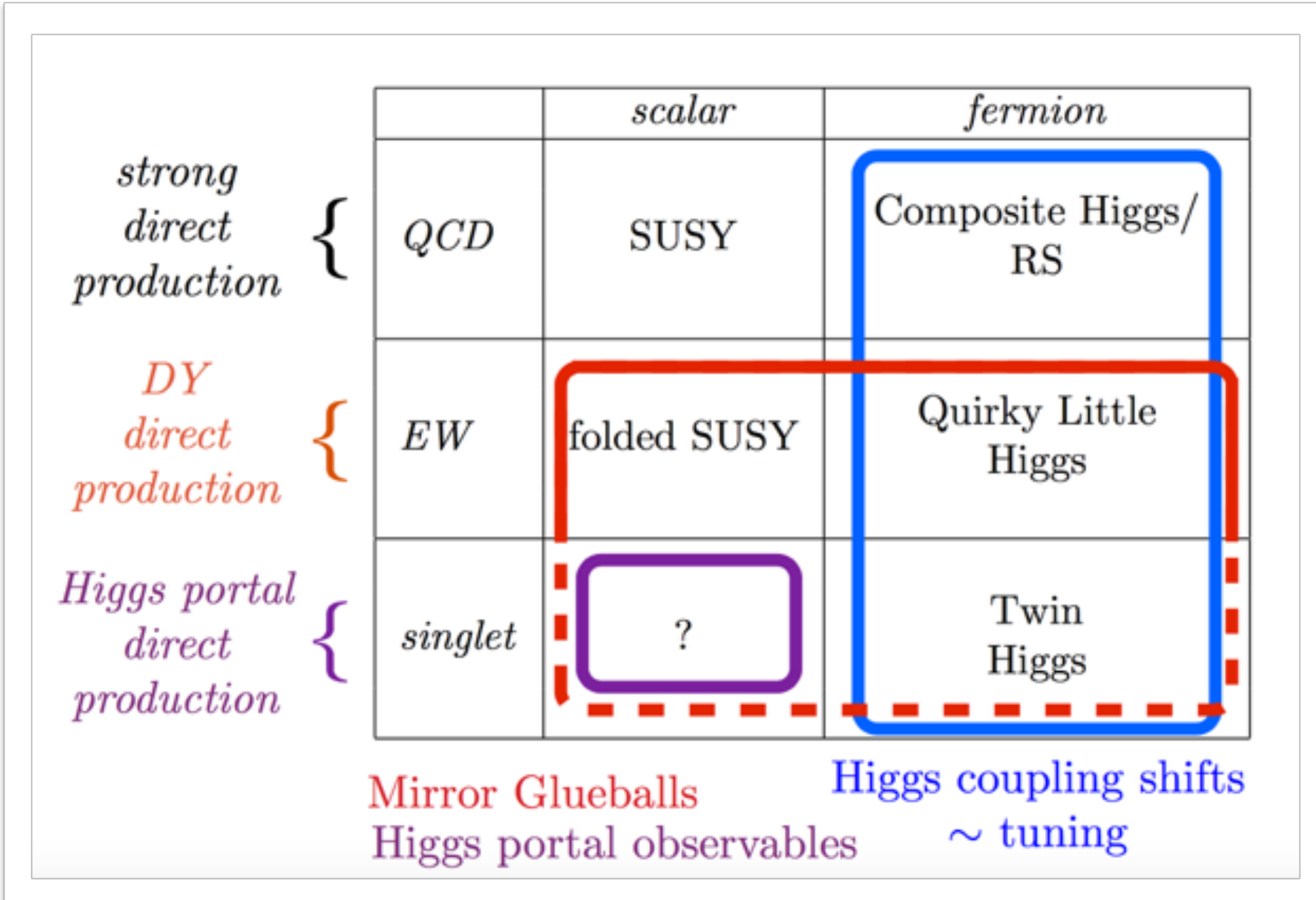
Coupling equality enforced by Z_2

Quadratic divergences: $$-\frac{3\lambda_t^2}{8\pi^2}\Lambda^2(|H_A|^2 + |H_B|^2) = -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2|H|^2$$

Λ^2 respects $SU(4)$ - No mass induced for the pNGB Higgs

Color neutral neutral fermionic top partners!

Direct searches for top partners evaded



[Curtin, Verhaaren '15]

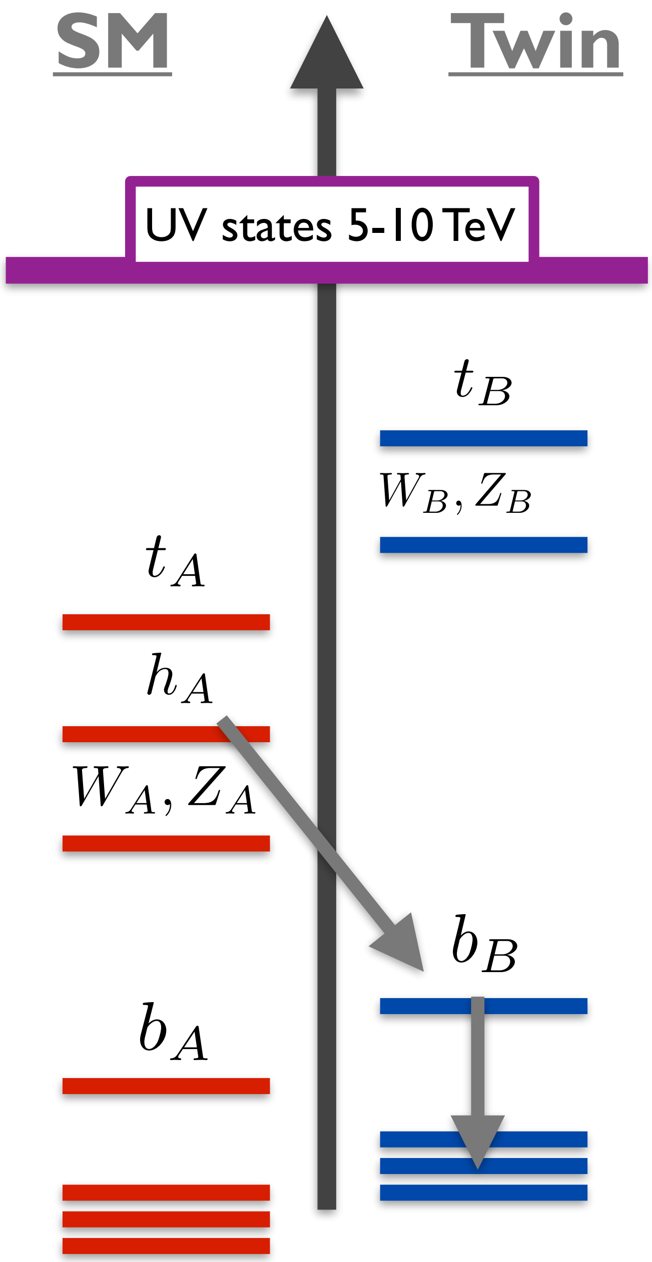
Exotic Higgs Decays

- Mirror symmetric Twin Higgs:

  [Chacko, Goh, Harnik '05]

- Higgs portal coupling $|H_A|^2|H_B|^2$

➡ $h_A \to b_B \bar{b}_B \to \text{invisible}$



Exotic Higgs Decays

- Fraternal Twin Higgs

  [Craig,Katz,Strassler, Sundrum '14]

  - Naturalness does not require light twin states
  - Cosmology constraints light twin states

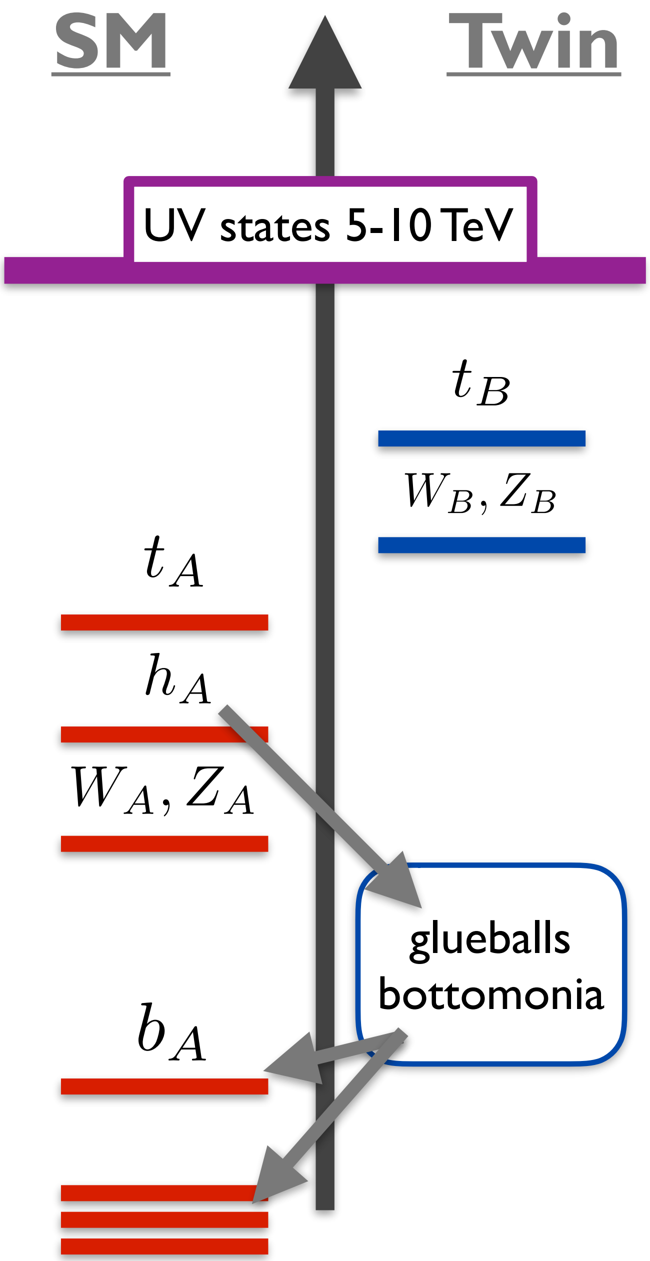
$$h_A \to G_B \to b_A \bar{b}_A, \ldots$$

  - Twin hadron decays can be displaced

- Similar glueball signatures possible in Folded SUSY models

  [Curtin, Verhaaren, '15]

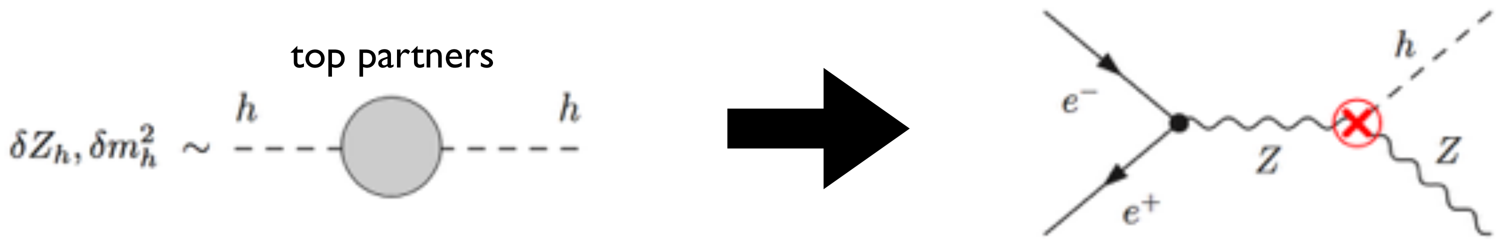
  - Higgs decays mediated by EW charged top partner loops



Future colliders

- Naturalness implies irreducible shift in $e^+e^- \rightarrow Zh$

[Craig, Englert, McCullough, 13]



- Future precision electroweak tests:
  - Twin Higgs: v/f corrections to Higgs couplings; $f > 1 - 5\,\mathrm{TeV}$
  - Folded SUSY: folded stop contributions to T parameter; 500 -1000 GeV

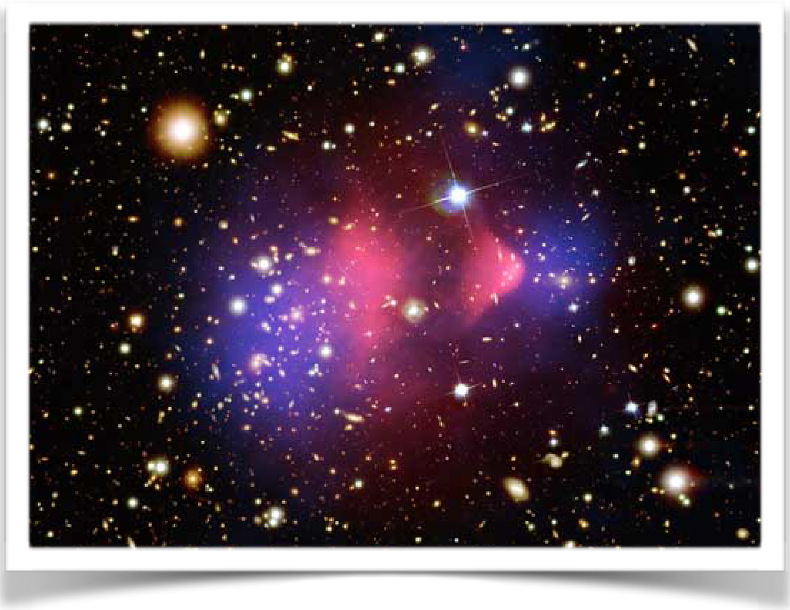
[Fan, Reece, Wang, '14]

- Future hadron collider can probe colored states in the UV completions

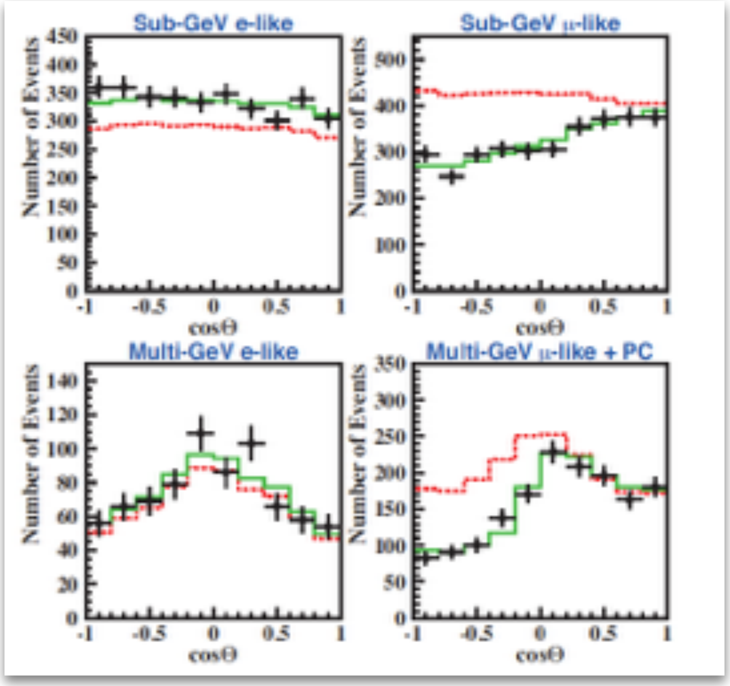
[see, e.g. Curtin, Saraswat '15]

There are other compelling empirical hints for new neutral particles in Nature!

Dark Matter



Neutrino Mass



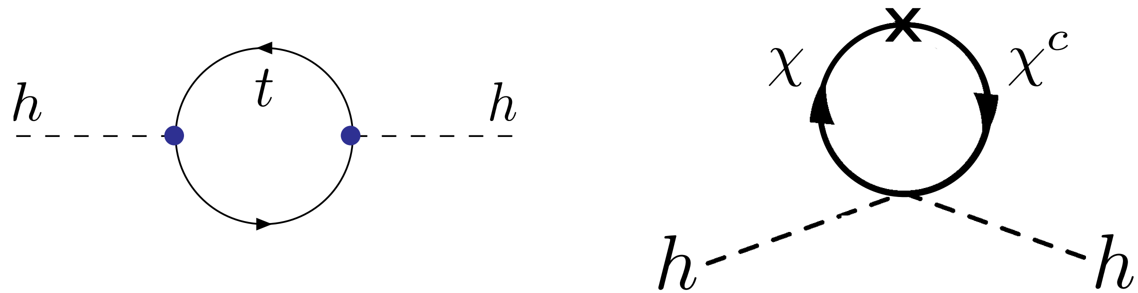
Can the new neutral states responsible for naturalness explain these empirical mysteries?

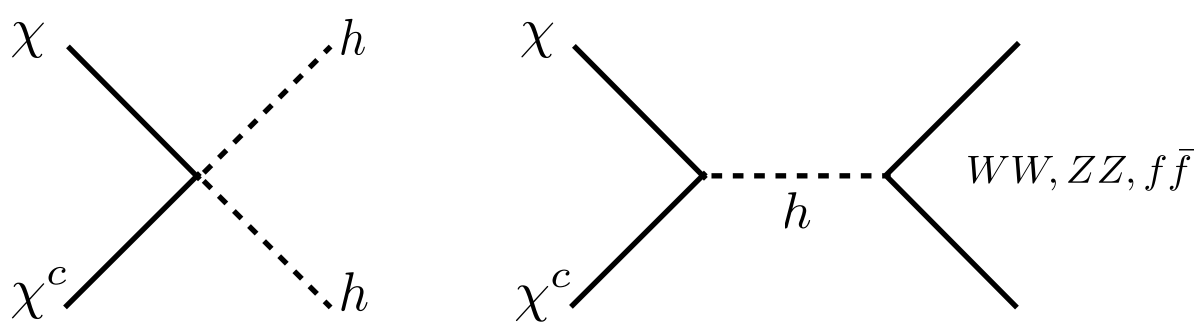
The Dark Top

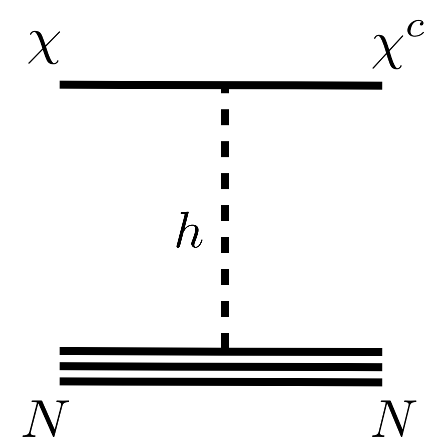
[Poland, Thaler ’08]

Dark Matter particles are the Top Partners

Naturalness







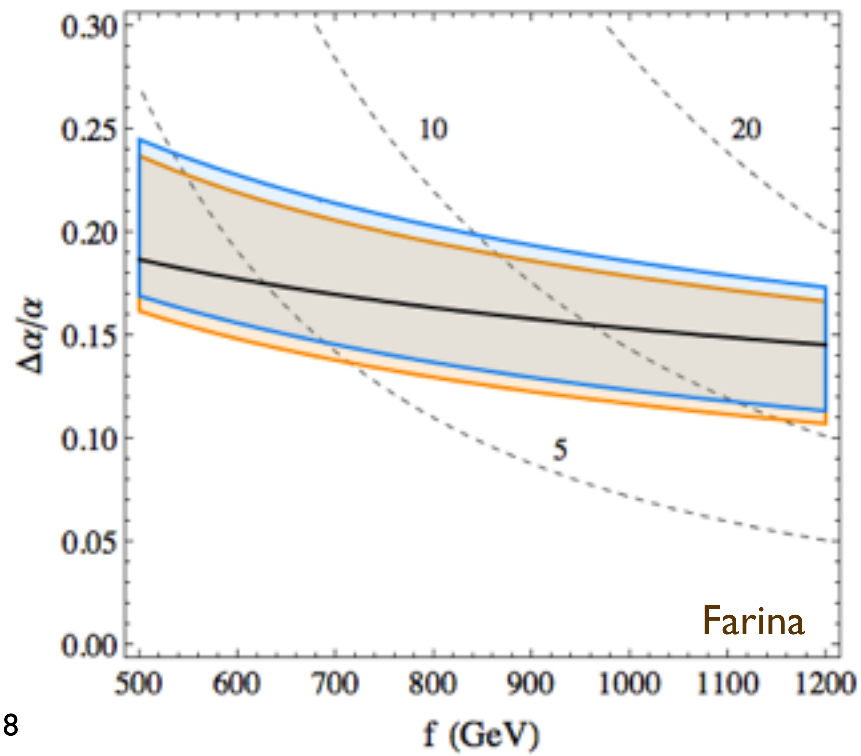
Annihilation

Scattering

Twin Dark Matter

[Garcia Garcia, Lasenby, March-Russell]
[Craig, Katz]
[Farina]
[see also earlier work on Mirror-DM by Foot, ...]

- Many potential DM candidates in the Twin sector
  - Twin τ, twin baryons, twin atoms, ...
- Provides an attractive framework for Asymmetric Dark Matter
  - Z_2 symmetry provides rationale for the similarity of QCD and dark QCD confinement scales
  - UV completion required at ~ 10 TeV scale; can provide transfer operators

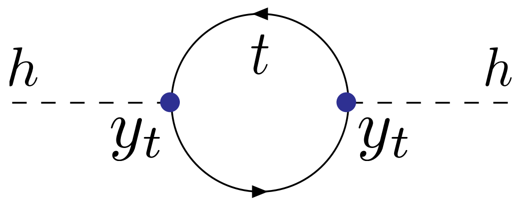


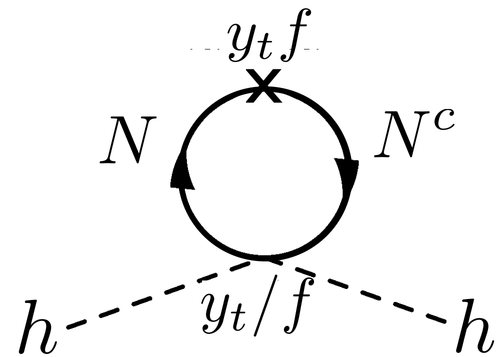
Natural Neutrinos

[BB, McCullough '15]

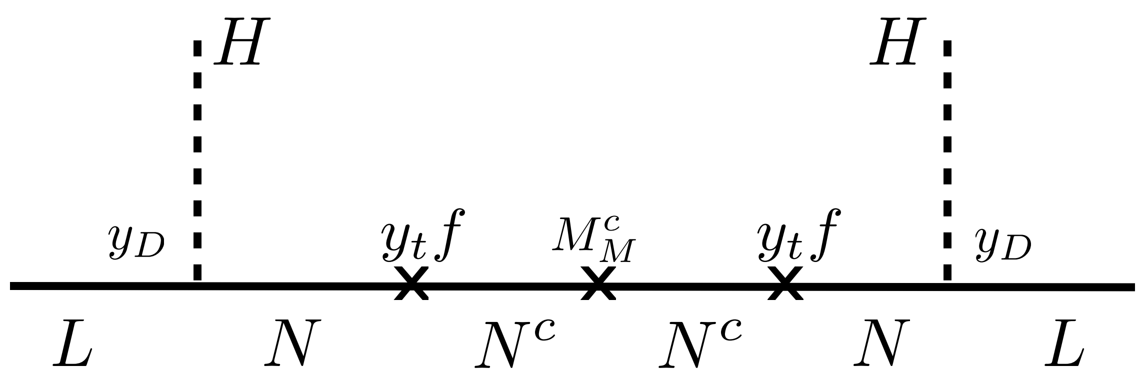
Right Handed Neutrinos are the Top Partners

Naturalness





See-saw



Neutrino mass ➡ twin color SU(3) broken

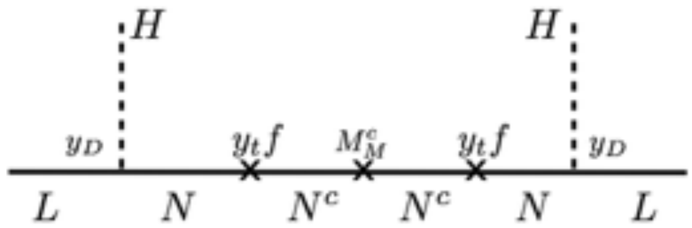
- 2 loop top-gluon contribution to Higgs mass: $$\delta\mu^2 = \frac{3y_t^2 g_3^2}{4\pi^4}\Lambda^2$$ ⇨ Mild tuning of order 10% for $\Lambda \sim 5\,\mathrm{TeV}$

- Naturalness robustly predicts TeV-scale see-saw:

$$\mathcal{L} \supset M_N N N^c + \mathrm{h.c.}, \quad M_N = \lambda_t f + \mathcal{O}(v^2/f) \lesssim \mathrm{TeV}$$

- Collective breaking of Lepton number

$$m_\nu \sim \frac{y_D^2\, v^2\, M_M^c}{M_N^2}$$



- Large neutrino Yukawa couplings are possible - PMNS non-unitarity
  - W, Z boson decays (including invisible Z width), Z-pole asymmetries, W-boson mass, Weak mixing angle measurements, Lepton flavor universality tests (W, tau-lepton and meson decays), Lepton Flavor violating decays, Quark Flavor CKM parameters

Relaxation of Electroweak Scale

Basic idea: Natural weak scale a consequence of dynamics in the early universe, not symmetries

- First proposal in context of hierarchy problem is the Cosmic Attractor scenario (see talk by G. Dvali)

[Dvali, Vilenken '03]
[Dvali '04]

Relaxion

[Graham, Kaplan, Rajendran '15]

- "Bare" Higgs mass is natural - at the cutoff $M \gg v$
- A field ϕ couples to $|h|^2$ and evolves in the early universe

$$m_h^2 = -M^2 + g\phi(t) \quad \Rightarrow \quad \phi \text{ scans the Higgs mass}$$

- After EWSB ($m_h^2(\phi) < 0$) the Higgs backreacts on ϕ

  and stops its evolution, fixing $\langle h \rangle \approx v \ll M$

Minimal Model: SM + QCD axion ϕ

$$(-M^2 + g\phi)|h|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

- ϕ has a shift symmetry broken by two effects:
  - QCD instantons break $\phi \to \phi + 2\pi f$
  - Explicit breaking by the coupling g (technically natural)

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4\cos(\phi/f)$$

Axion potential

$$\Lambda^4 \sim f_\pi^2 m_\pi^2$$

$$m_\pi^2 \sim 4\pi f_\pi (m_u + m_d) \propto v$$

Barrier height depends on the Higgs field

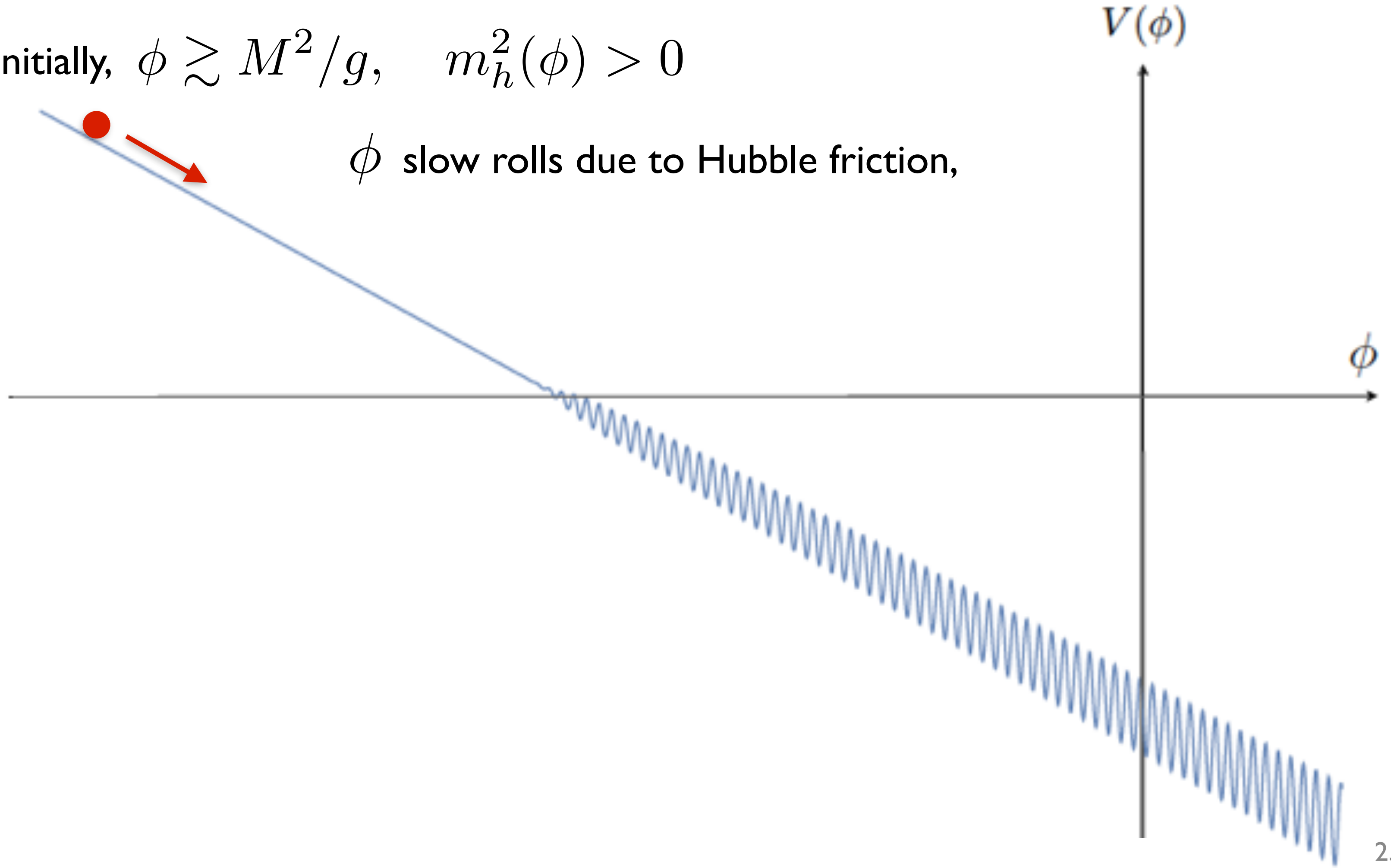
$$\Lambda^4 \sim f_\pi^2 m_\pi^2 \, \frac{h}{v}$$

Evolution of ϕ during inflation

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$

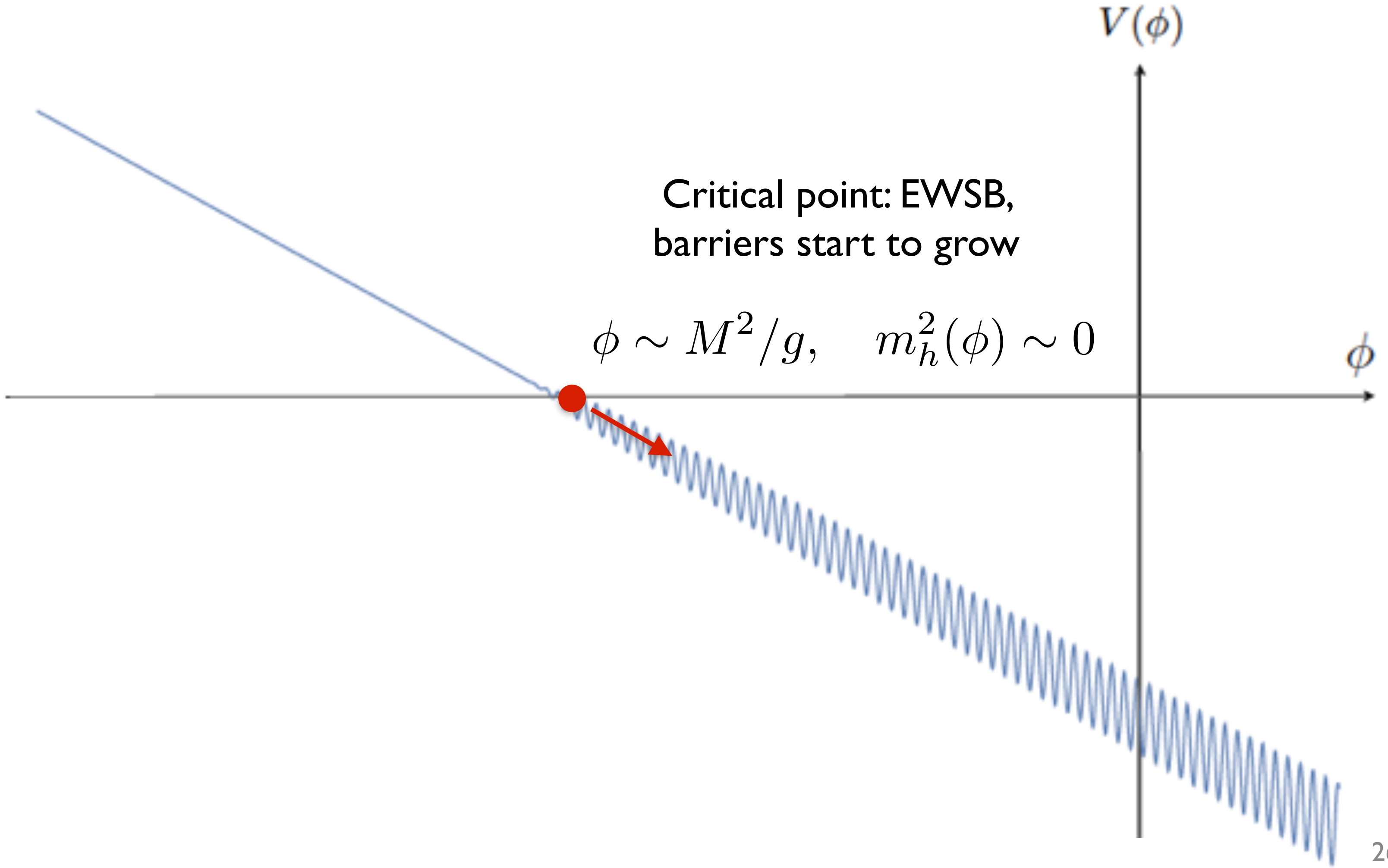
Initially, $\phi \gtrsim M^2/g, \quad m_h^2(\phi) > 0$

ϕ slow rolls due to Hubble friction,



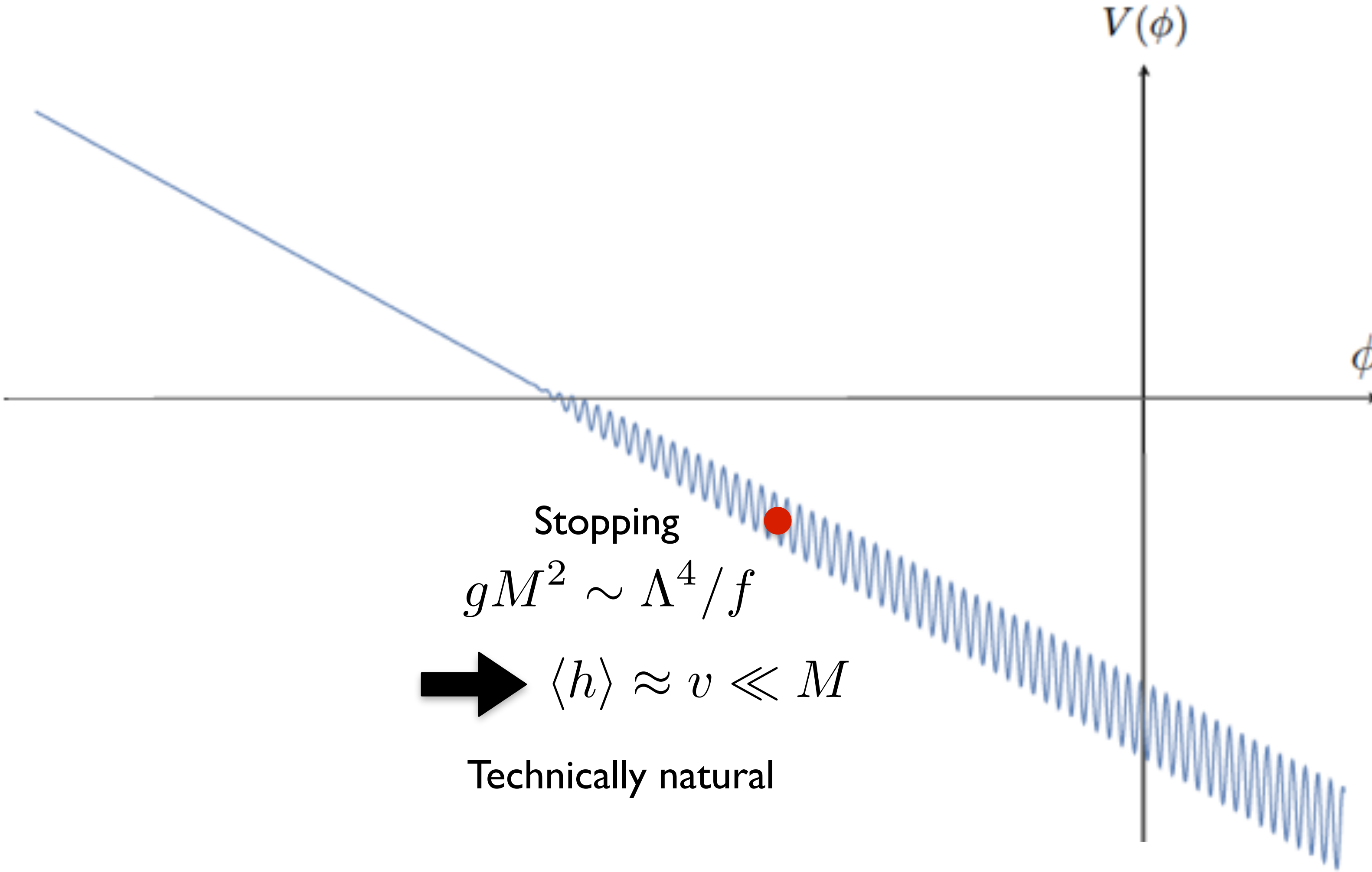
Evolution of ϕ during inflation

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4 \cos(\phi/f)$$



Evolution of ϕ during inflation

$$(-M^2 + g\phi)|h|^2 + \left(gM^2\phi + g^2\phi^2 + \cdots\right) + \Lambda^4\cos(\phi/f)$$



Stopping

$$gM^2 \sim \Lambda^4/f$$

$$\Rightarrow \langle h\rangle \approx v \ll M$$

Technically natural

How large can the cutoff be?

Inflaton dominates energy density:

$$H_i > M^2/M_P$$

Classical rolling dominates over quantum fluctuations:

$$H_i < (V')^{1/3} \sim (\Lambda^4/f)^{1/3}$$

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

Strong CP problem

- Relaxion displaced from the minimum of the periodic potential:

$$V'(\phi) = gM^2 - \frac{\Lambda^4}{f}\sin\phi/f = 0$$

$$\Rightarrow \quad \boxed{\theta = \phi/f \sim \mathcal{O}(1)}$$

Two solutions:

1. Slope ("g") comes from relaxion-inflaton coupling. After inflation, slope relaxes, relaxion rolls to the minimum of the periodic potential
2. Non-QCD model. Relaxion is not a QCD axion

Numbers

- Coupling:

$$g \sim 10^{-27}\,\mathrm{GeV}$$

- Field excursion (super-Planckian):

$$\Delta\phi \sim 10^{41}\,\mathrm{GeV}$$

- Number of periods (non-compactness):

$$\Delta\phi/f \sim 10^{32}$$

- Hubble (low scale inflation):

$$H_i \sim 10^{-4}\,\mathrm{GeV}$$

- Number of e-folds of inflation

$$N \sim H\Delta t \sim H\Delta\phi/\dot{\phi} \sim H^2\Delta\phi/V' \sim H^2/g^2 \sim 10^{46}$$

see recent works:
[Kaplan, Rattazzi]
[Choi, Im]
[Ibanez, Montero, Uranga, Valenzuela]

see recent work by
[Patil, Schwaller]

Recap

- Relaxion: good in the IR, bad in the UV
  - Address little hierarchy and more
  - UV cutoff 10^7 GeV (10^5 GeV in non-QCD 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

But wait, there is more…

Natural Heavy SUSY

[BB, Giudice, McCullough '15]

- MSSM fields + single chiral multiplet: $S = \frac{s + i\,a}{\sqrt{2}} + \sqrt{2}\,\theta\,\tilde{a} + \theta^2 F$ (srelaxion: s, relaxion: a, relaxino: $\tilde{a}$)
- PQ Shift symmetry: $S \to S + i\alpha, \quad (a \to a + \sqrt{2}\alpha)$
- General EFT below scale f :

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

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

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

Scanning of SUSY breaking

- Add explicit soft breaking (axion mass)

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

$$\boxed{F \approx m a}$$

The relaxion breaks SUSY!

- As the relaxion evolves, it scans SUSY breaking
- Relaxino is goldstino (eaten by gravitino)
- Scanning of SUSY breaking $\Rightarrow$ scanning of Higgs mass matrix determinant (EW order parameter)

Scanning Soft Masses

- Gaugino Mass

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

soft masses scan during relaxion evolution

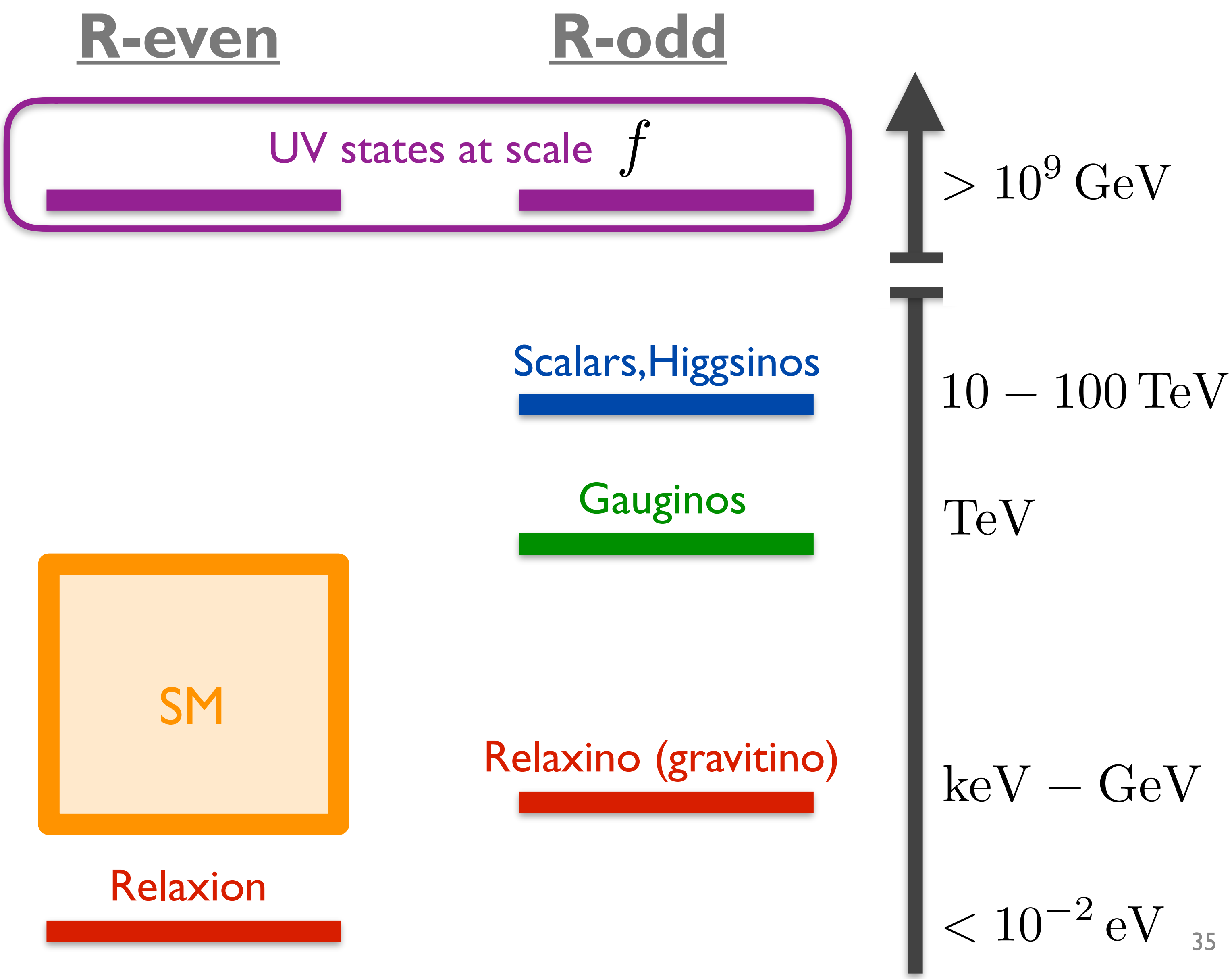
- Scalar Mass

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

Cases:

1. $M_* = f$, gauginos lighter than scalars by one loop
2. $M_* \gg 4\pi f/\alpha$, gauginos source SUSY breaking

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.

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

- ℓ_{NLSP} “between 100 microns and journey to the moon”

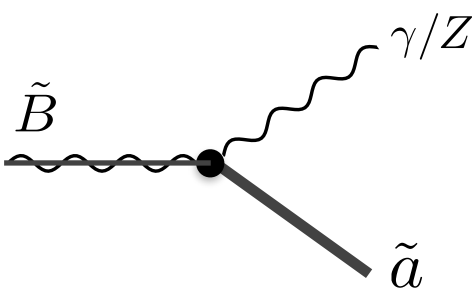
e.g. Bino NLSP

- 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

Outlook

- Higgs Naturalness is being put to the test at the LHC
- Traditional approaches (SUSY, Composite Higgs) are more and more constrained/tuned. Maybe the weak scale is (mildly) tuned?
- Novel approaches: Neutral Naturalness & Relaxation
- Can lead to striking new experimental signals, but no guarantees!
- May play a role in understanding other empirical mysteries: dark matter, neutrino mass, baryogenesis, SUSY breaking, …
- Future experiments are needed to thoroughly test these theories