IS MINIMAL SUSY DEAD?

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SLAC Theory Seminar, 7 November 2012

SUPERSYMMETRY

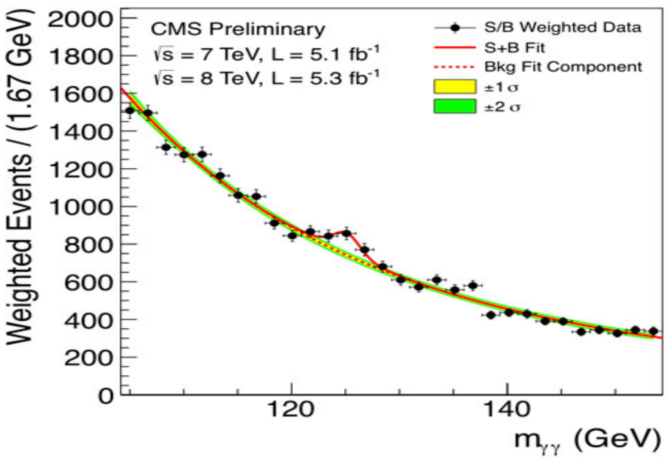
- Weak-scale SUSY has long been the dominant paradigm for new particle physics

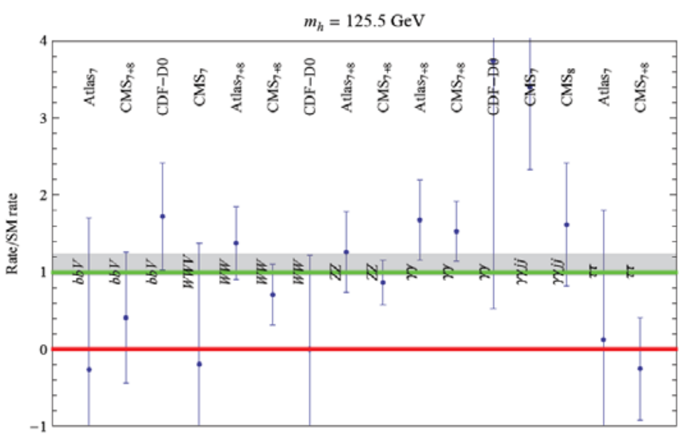
- Longstanding and strong motivations
  - A natural solution to the gauge hierarchy problem
  - Gauge coupling unification
  - An excellent DM candidate
  - …

- Avoid the fallacy of the appeal to novelty

LHC RESULTS

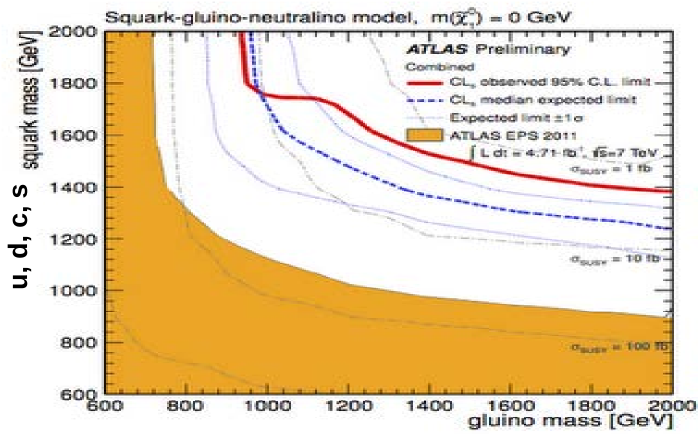
- Higgs discovered





Giardino, Kannike, Raidal, Strumia (2012)

- SUSY not discovered



- Many analyses, many bounds
  - u, d, c, s squarks > 1400 GeV
  - gluinos > 900 GeV
  - top squarks > 350 GeV
  - Winos > 200 GeV
  - sleptons > 150 GeV

- Significant variations possible for different spectra, decay modes

REACTIONS

- These LHC results have led to many interesting statements that I disagree with. The Top 10:

10. SUSY is now excluded
9. Weak-scale SUSY is now excluded
8. The CMSSM is now excluded
7. Naturalness requires light top squarks
6. It's time to stop thinking about naturalness
5. The 125 GeV Higgs requires physics beyond the MSSM
4. Particle physics is in trouble
3. We should all be depressed
2. We shouldn't be depressed, but we should start preparing to be depressed
1. String theory predicts a 125 GeV Higgs

OUTLINE

- Gravity-Mediated Minimal SUSY

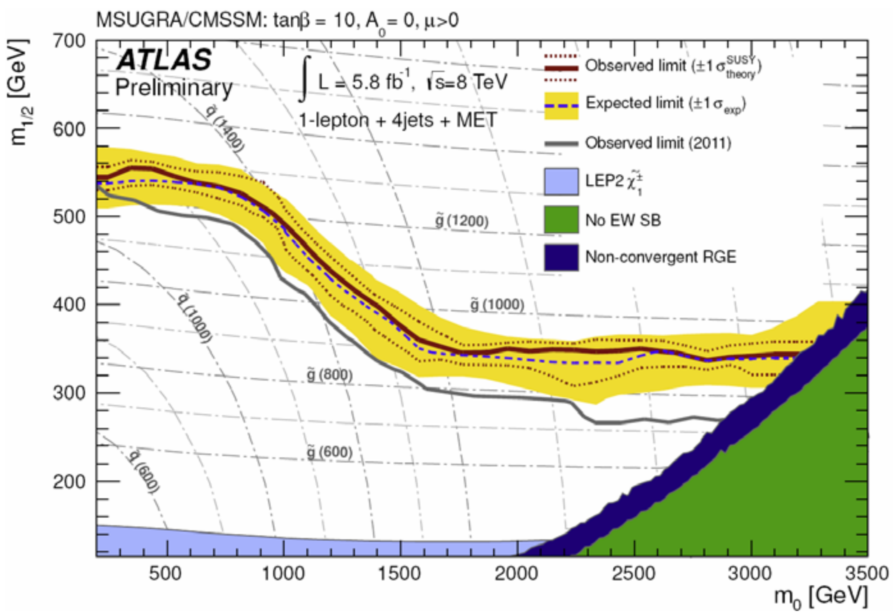
Work with Matchev, Moroi, Wilczek, Cheng, Polonsky (1998-2000)
Feng, Matchev, Sanford (2011-2012)
Draper, Feng, Kant, Profumo, Sanford (in progress)

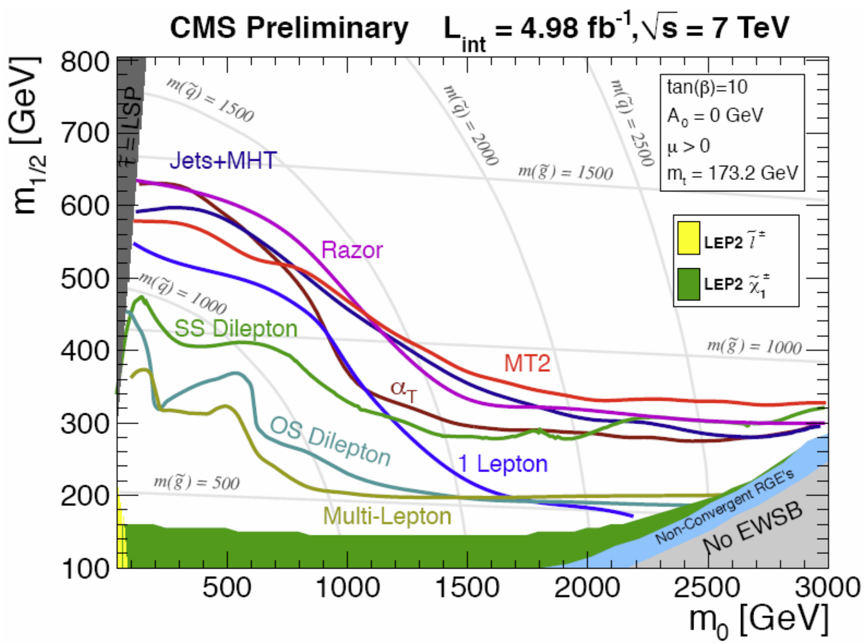
- Gauge-Mediated Minimal SUSY

Work with Rajaraman, Takayama, Smith, Cembranos (2003-2007)
Feng, Surujon, Yu (2012)
Feng, Meng, Yu (in progress)

GRAVITY-MEDIATED MINIMAL SUSY

- Consider mSUGRA / CMSSM ("most difficult" case)
- One often hears now that mSUGRA / CMSSM is excluded by the LHC, but of course, one can always raise the superpartner masses to be viable





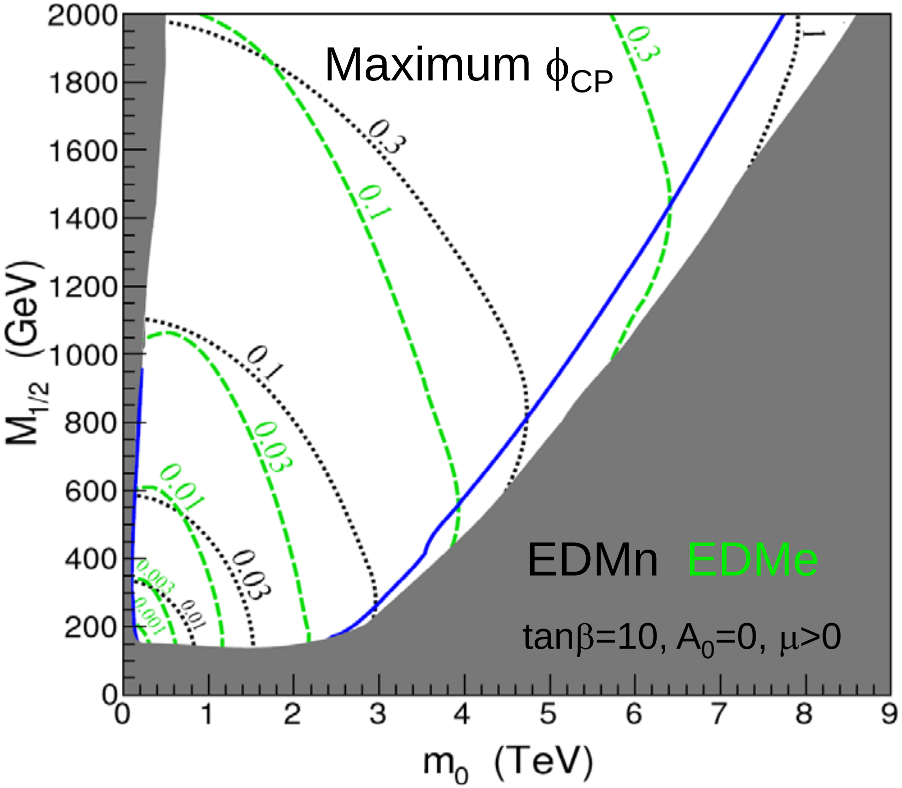
- The question should be refined. There are two aspects:
  - How much has the LHC reduced the parameter space?
  - How appealing is what's left of the parameter space?

ELECTRIC DIPOLE MOMENTS

- Low-energy constraints are famous problems for new physics
- Flavor violation eliminated by fiat in mSUGRA, but EDMs are flavor-conserving, CP-violating, not eliminated by scalar degeneracy
- Stringent bounds on electron and neutron EDMs

  Regan et al. (2002); Baker et al. (2006)
- O(1) phases → multi-TeV scalars
- Many regions excluded by LHC were already disfavored by EDMs

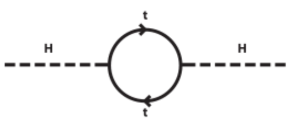
$$d_f = \frac{1}{2} e\, m_f\, g_2^2\, |M_2 \mu|\, \tan\beta\, \sin\phi_{\rm CP}\, K_C(m^2_{\tilde{f}_L}, |\mu|^2, |M_2|^2)$$



Feng, Matchev, Sanford (2011)

HIGGS BOSON

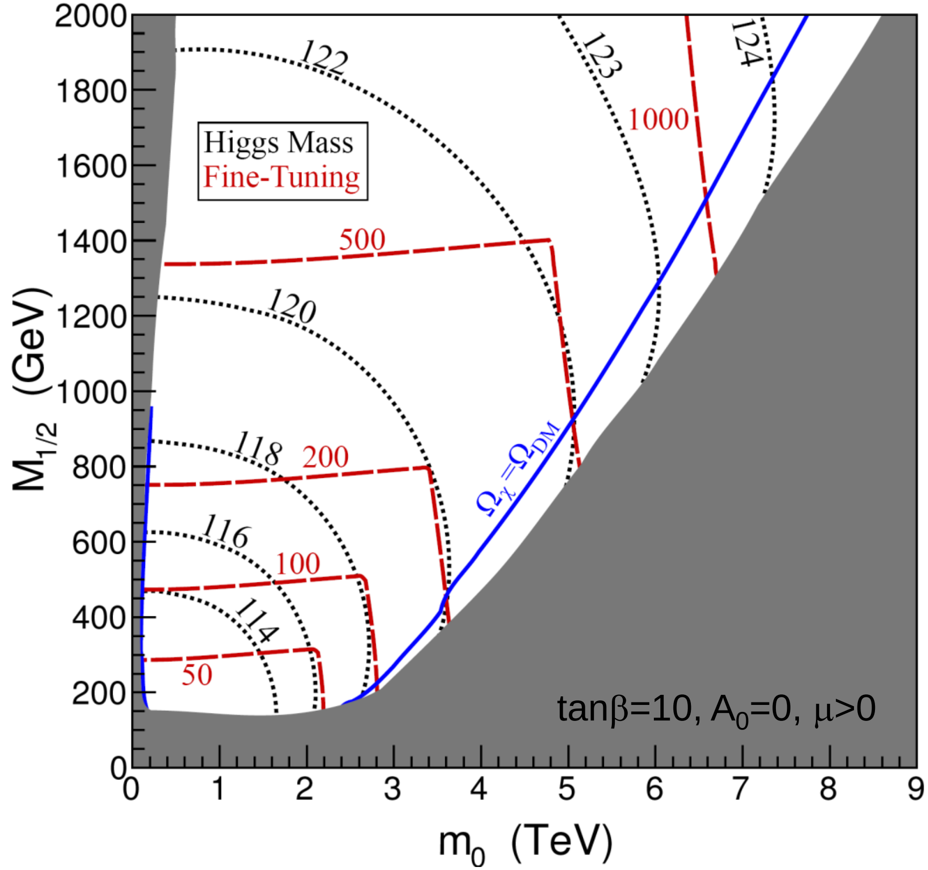
- 40,000 foot view: great for SUSY
- Closer view: challenging for SUSY: need large radiative corrections



$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

  - Expt. uncertainties ~ 1 GeV
  - Theory uncertainties ~ few GeV

- Many regions excluded by LHC were already excluded by (even the LEP 2!) Higgs mass bound

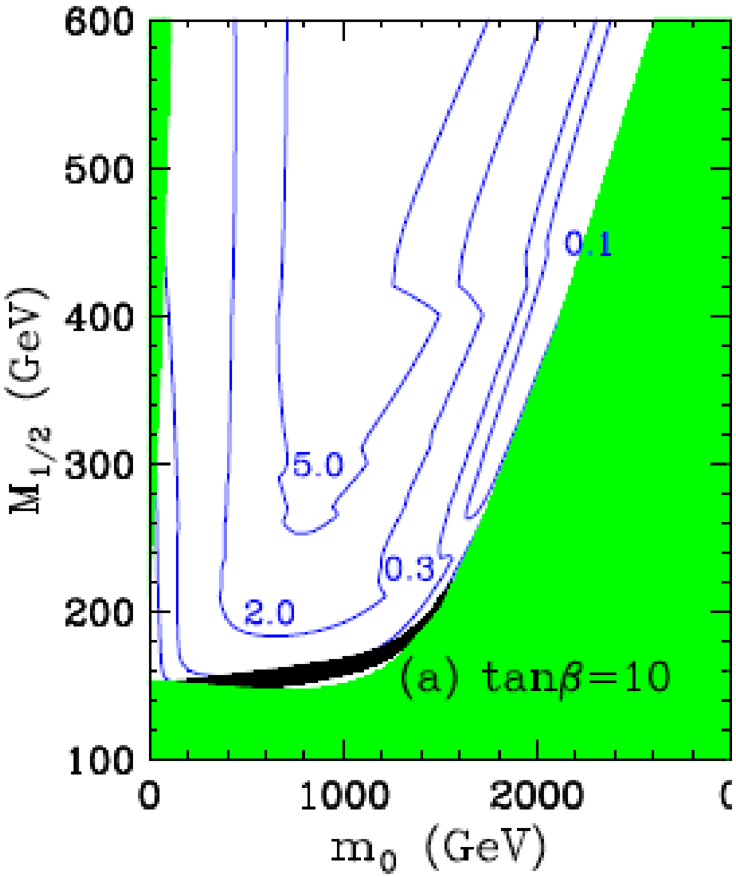


Feng, Matchev, Sanford (2011)

DARK MATTER RELIC DENSITY

- Neutralinos might not be all the dark matter, but they should not overclose the Universe
- They “typically” do, however (Majorana-ness suppresses annihilation)
- Initially used to argue for a cosmological upper bound on superpartner masses in mSUGRA

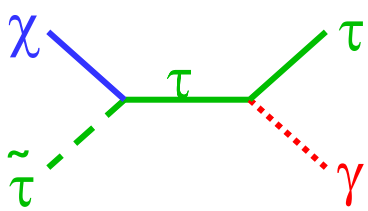
Kane, Kolda, Roszkowski, Wells (1994)



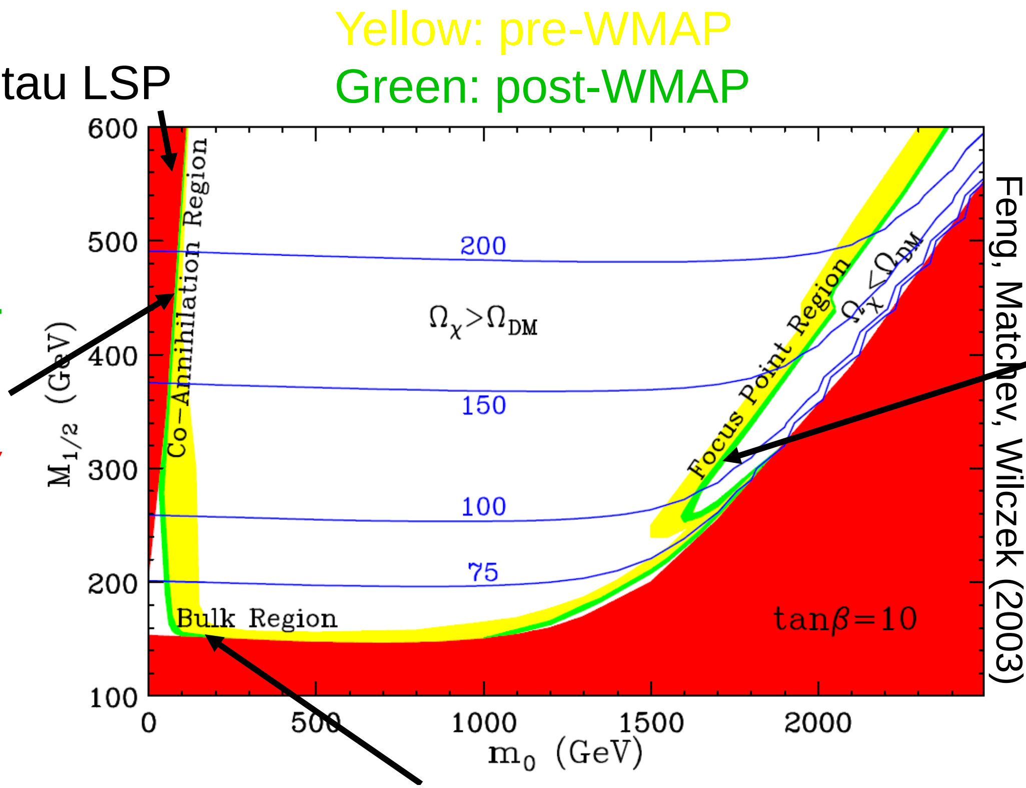
Feng, Matchev, Wilczek (2003)

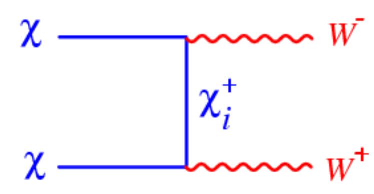
DARK MATTER RELIC DENSITY

Many regions excluded by LHC were already excluded by $\Omega_\chi < 0.23$

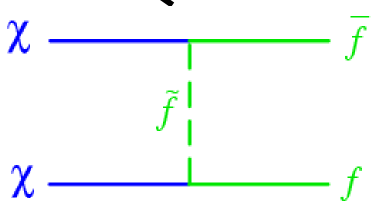


Stau and χ degenerate to within roughly $T \sim m/25$





Mixed Neutralinos



Light sfermions

IMPACT OF LHC BOUNDS

- Much of minimal SUSY parameter space excluded by the LHC so far was already disfavored by existing bounds
  - EDMs (and more generally, flavor bounds)
  - Higgs mass bounds
  - Dark matter overclosure
- From this perspective, much of the favored parameter space remains, and the appeal of minimal SUSY has not changed much
- But are the remaining regions appealing?
  - Naturalness
  - Higgs mass measurement
  - Dark matter signals

NATURALNESS

- Two approaches:
- Option 1: “I know it when I see it.”
- Option 2: Quantify with some well-defined naturalness prescription
- Option 1 acknowledges that naturalness is subjective, but is a non-starter. Option 2 provides an opportunity for discussion and insights, as long as its limitations are appreciated.

A NATURALNESS PRESCRIPTION

- Step 1: Choose a framework with input parameters. E.g., mSUGRA with

$$\left\{P_{\text{input}}\right\} = \left\{m_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\right\}$$

- Step 2: Fix all remaining parameters with RGEs, low energy constraints. E.g., at the weak scale, tree-level,

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- Step 3: Choose a set of parameters as free, independent, and fundamental. E.g., mSUGRA with

$$\{a_i\} = \{m_0, M_{1/2}, A_0, B_0, \mu_0\}$$

- Step 4: Define sensitivity parameters

$$c_i \equiv \left|\frac{\partial \ln m_Z}{\partial \ln a_i}\right|$$

Ellis, Enqvist, Nanopoulos, Zwirner (1986)
Barbieri, Giudice (1988)

- Step 5: Define the fine-tuning parameter

$$c = \max\{c_i\}$$

COMMENTS

- Step 1: Choose a framework with input parameters. E.g., mSUGRA with

$$\{P_{\text{input}}\} = \{m_0, M_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$$

This is a key point: generic SUSY-breaking is excluded, there must be structure leading to correlated parameters, and the correlations impact naturalness. There is no model-independent measure of naturalness.

- Step 2: Fix all remaining parameters with RGEs, low energy constraints. E.g., at the weak scale

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

Important to refine this to include 2-loop RGEs, 1-loop threshold corrections, minimize the potential at some appropriate scale (typically, the geometric mean of stop masses).

COMMENTS

- Step 3: Choose a set of parameters as free, independent, and fundamental. E.g., mSUGRA with $\{a_i\} = \{m_0, M_{1/2}, A_0, B_0, \mu_0\}$

  A popular choice is $\{a_i\} = \{\mu_0\}$, which leads to $c = 2\mu^2/m_Z^2$. This is simple, but completely deficient and misleading: It is equivalent to saying that there is no fine-tuning in a – b + c = 1 if a = 1,000,000,000, b = 1,000,000,001, c = 2, because we can define a – b = d, and d, c ~ O(1).

  Should we include other parameters, like y_t?

  Most say no – the gauge hierarchy problem is related to SUSY breaking parameters, and there are well-known examples in which y_t should not be varied continuously, which is not the case for the SUSY-breaking parameters. This is a subjective choice. Note: this is not an issue of what is measured and what isn't: with our current understanding, if μ were measured to be 1 EeV ± 1 eV, it will be precisely measured, but completely unnatural. Of course, if interesting results emerge that depend on the measured value of y_t, the top mass may be taken as a hint that this is a promising direction to pursue.

COMMENTS

- Step 4: Define sensitivity parameters $c_i \equiv \left| \frac{\partial \ln m_Z}{\partial \ln a_i} \right|$.

Ellis, Enqvist, Nanopoulos, Zwirner (1986)
Barbieri, Giudice (1988)

Why not $c_i \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln a_i} \right|$ (original definition) or $c_i \equiv \left| \frac{\partial \ln m_Z}{\partial \ln a_i^2} \right|$?

Factors of 2 or 4 are completely insignificant.

- Step 5: Define the fine-tuning parameter $c = \max\{c_i\}$.

Why not add in quadrature? What if c is large for all possible parameter choices (cf. Λ_{QCD}).?

De Carlos, Casas (1993); Anderson, Castano (1994)

And finally, what is the maximal natural value for c – 10, 100, 1000, … ?
Many require 10 or 100. But if SUSY reduces c from 10^{32} to 1000, will your research still be devoted to finding a solution to the gauge hierarchy problem?

EFFECTIVE SUSY, 2-1 SUSY, SUPERHEAVY SUSY

- Naturalness only constrains 1st and 2nd generation squarks and sleptons to be < 10-30 TeV
  - Contribution through 1-loop RGE is Yukawa suppressed
  - Dominant contribution is through 2-loop gauge couplings

Drees (1986); Dine, Kagan, Samuel (1990); Dimopoulos, Giudice (1995);
Pomoral, Tomasini (1996); Cohen, Kaplan, Nelson (1996); Dvali, Pomarol (1996);
Mohapatra, Riotto (1997); Zhang (1997); Bagger, Feng, Kolda, Polonsky (1999);
Agashe, Graesser (1999); Hisano, Kurosawa, Nomura (1999); …

- But now the Higgs mass requires heavy top squarks, seemingly in direct conflict with naturalness

WAYS FORWARD

- Light SUSY with Exotic Decays: Introduce new decay modes to make light superpartners compatible with collider constraints

Strassler, Zurek (2006), Fan, Reece, Ruderman (2011), Csaki, Grossman, Heidenreich (2011); …

- Hidden Higgs, Buried Higgs: Make $m_h < 115$ GeV compatible with collider constraints

Dermisek, Gunion (2005); Bellazzini, Csaki, Falkowski, Weiler (2009); …

- Beyond the MSSM (NMSSM, …): Increase particle content to raise m_h naturally, accommodate non-SM Higgs properties

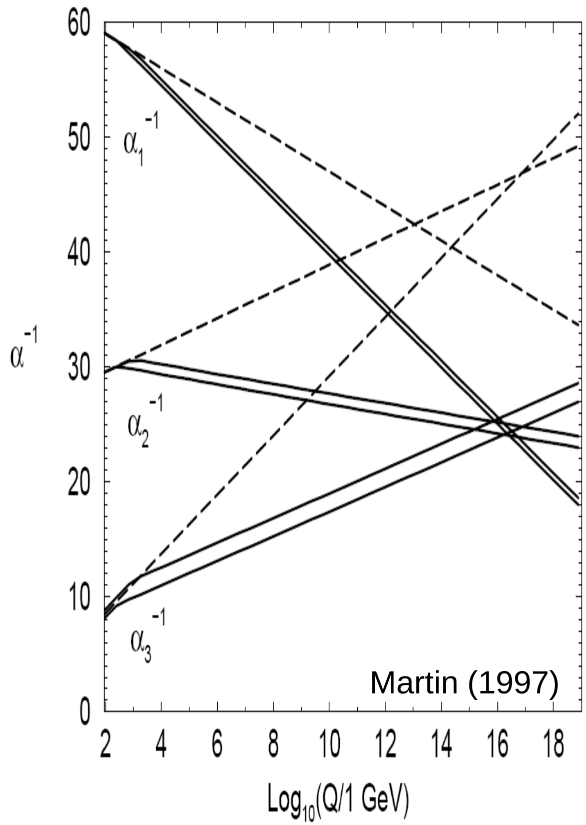
Hall, Pinner, Ruderman (2011); Ellwanger (2011); Arvanitaki, Villadoro (2011);
Gunion, Jiang, Kraml (2011); Perez (2012); King, Muhlleitner, Nevzorov (2012); Kang, Li, Li (2012);…

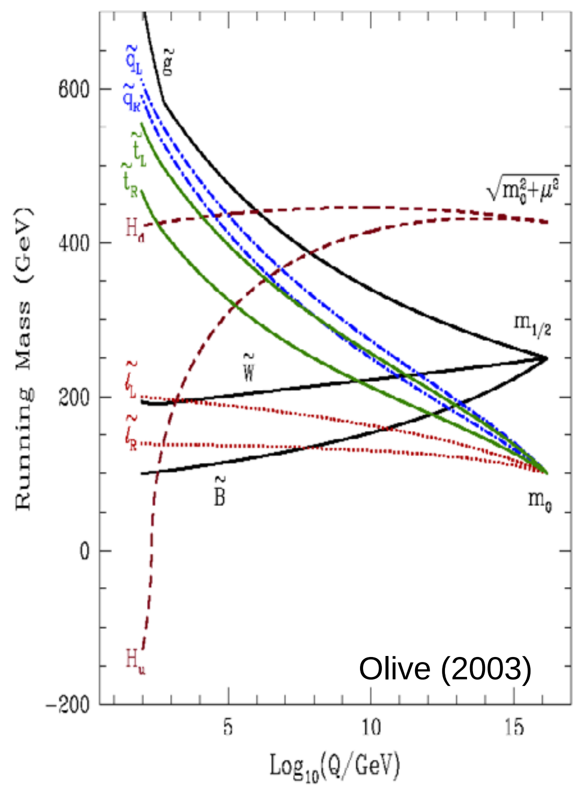
- Focus Point SUSY: Dynamically generated naturalness

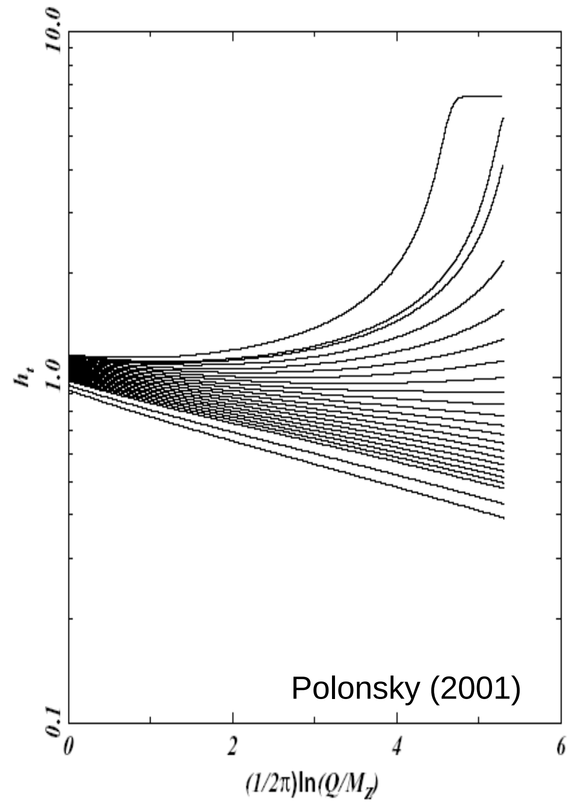
Feng, Matchev, Moroi (1999); Feng, Matchev, Wilczek (2000); Kitano, Nomura (2005); Abe, Kobayashi, Omura (2007);
Horton, Ross (2009); Asano, Moroi, Sato, Yanagida (2011); Akula, Liu, Nath, Peim (2011); Younkin, Martin (2012); …

FOCUS POINT SUSY

- RGEs play a crucial role in almost all of the main motivations for weak-scale SUSY: coupling constant unification, radiative EWSB, top quark quasi-fixed point. What about naturalness?







FP SUSY: ANALYTIC EXPLANATION

- For low and moderate tanβ,

$$\frac{1}{2}m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$
$$\approx -\mu^2 - m_{H_u}^2$$

- So focus on scalar mass $m_{H_u}^2$

- Scalar masses enter only their own RGEs:

$$\begin{aligned} \dot{g} &\sim g^3 \\ \dot{y} &\sim g^2 y - y^3 \\ \dot{M}_{1/2} &\sim g^2 M_{1/2} \\ \dot{A} &\sim -g^2 M_{1/2} - y^2 A \\ \dot{m}^2 &\sim g^2 M_{1/2}^2 - y^2 A^2 - y^2 m^2 \end{aligned}$$

- Assume A, $M_{1/2}$ << m (natural by $U(1)_R$ symmetry).

- If there is one dominant Yukawa,

$$\dot{\boldsymbol{m}}^2 = -\frac{y^2}{16\pi^2}\boldsymbol{N}\boldsymbol{m}^2$$

and the masses evolve as

$$\boldsymbol{m}^2(0) = \sum_i \kappa_i \boldsymbol{e}_i \rightarrow \boldsymbol{m}^2(t) = \sum_i \kappa_i \boldsymbol{e}_i e^{-\lambda_i \int^t \frac{y^2}{16\pi^2} dt'}$$

where $(\boldsymbol{e}_i, \lambda_i)$ are the eigenvectors and eigenvalues of *N*.

LOW AND MODERATE TANβ

$$\begin{bmatrix} \dot{m}^2_{H_u} \\ \dot{m}^2_{U_3} \\ \dot{m}^2_{Q_3} \end{bmatrix} = -\frac{y_t^2}{16\pi^2} \begin{bmatrix} 3 & 3 & 3 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} m^2_{H_u} \\ m^2_{U_3} \\ m^2_{Q_3} \end{bmatrix}$$

$$\begin{bmatrix} m^2_{H_u}(m_W) \\ m^2_{U_3}(m_W) \\ m^2_{Q_3}(m_W) \end{bmatrix} = \kappa_1 \begin{bmatrix} 3 \\ 2 \\ 1 \end{bmatrix} e^{-6\int^{t_W} \frac{y^2}{16\pi^2} dt'} + \kappa_2 \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix} + \kappa_3 \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$$

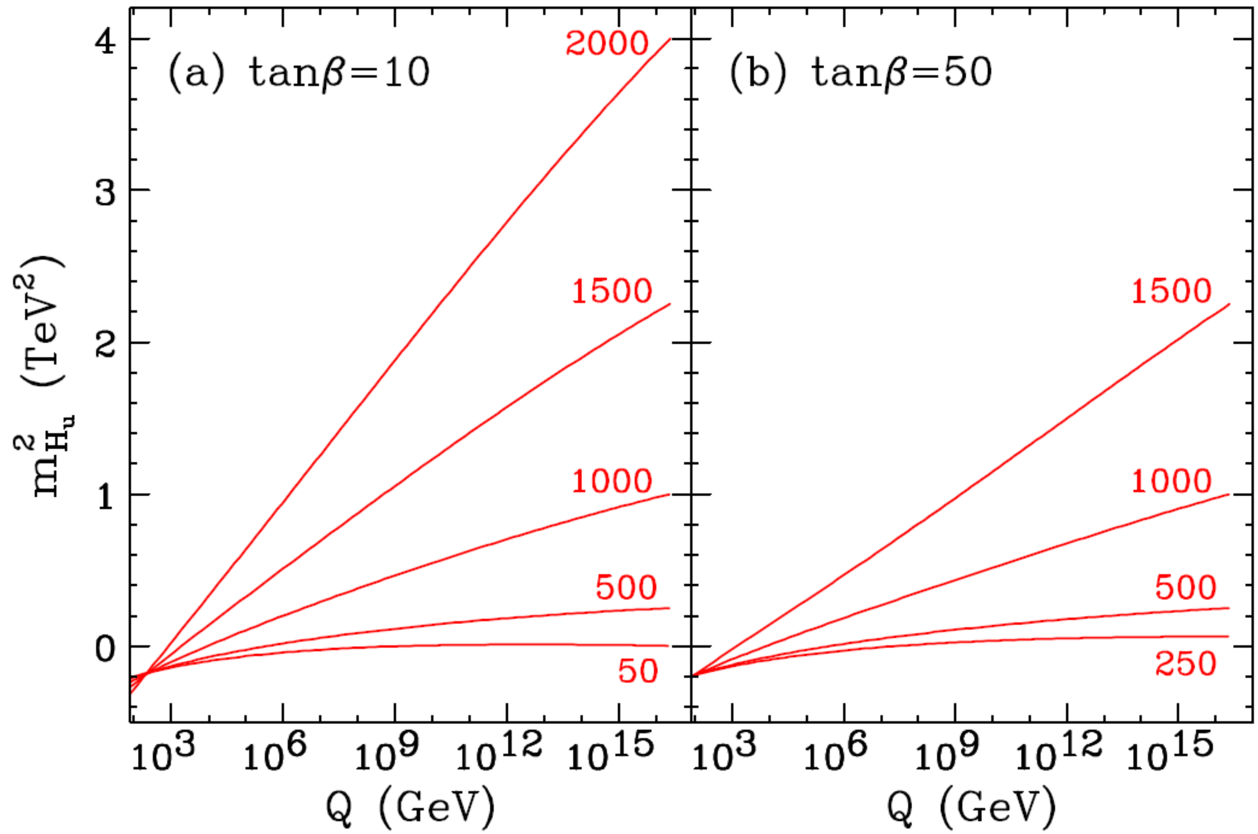
- The exponent is very nearly 1/3, and so

$$\begin{bmatrix} m^2_{H_u}(0) \\ m^2_{U_3}(0) \\ m^2_{Q_3}(0) \end{bmatrix} = m_0^2 \begin{bmatrix} 1 \\ 1+x \\ 1-x \end{bmatrix} \rightarrow \begin{bmatrix} m^2_{H_u}(m_W) \\ m^2_{U_3}(m_W) \\ m^2_{Q_3}(m_W) \end{bmatrix} = m_0^2 \begin{bmatrix} 0 \\ \frac{1}{3}+x \\ \frac{2}{3}-x \end{bmatrix}$$

- m_{Hu} evolves to zero for any (even multi-TeV) m_0, and so the weak scale is natural, even though the stops are heavy
- mSUGRA is a special case, but FP SUSY is much more general

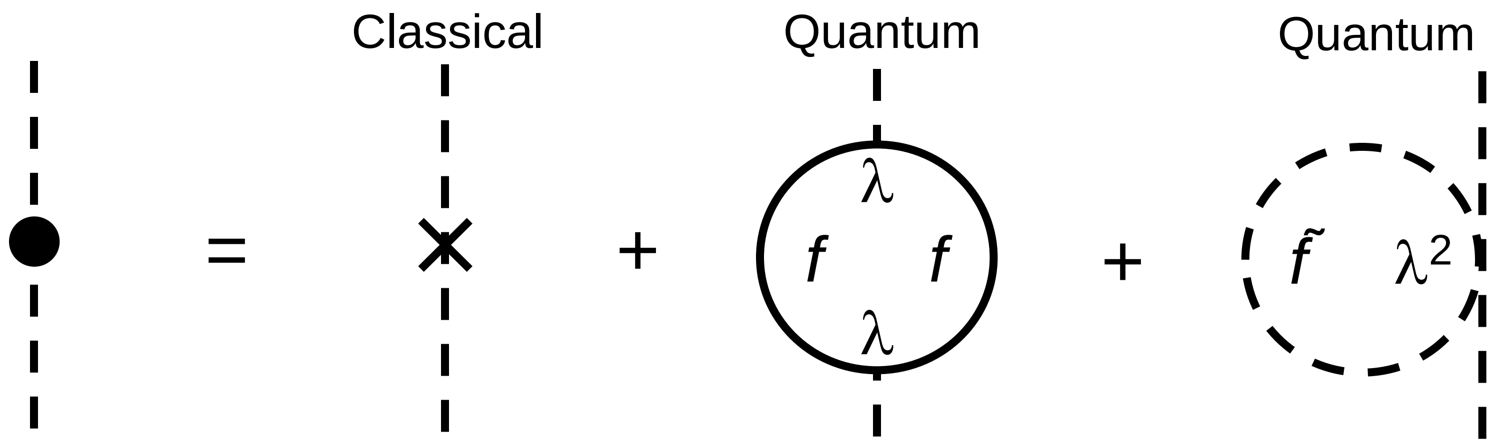
FP SUSY: GRAPHICAL EXPLANATION

- Families of RGEs have a focus point (cf. fixed point)
- Dynamically-generated hierarchy between the stop masses and the weak scale



- The weak scale is insensitive to variations in the fundamental parameters
- All focus point models are natural models with heavy stops, and all natural models with heavy stops are focus point models

FP IN A NUTSHELL



$$m_h^2 = (m_h^2)_0 - \underbrace{\frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2}$$

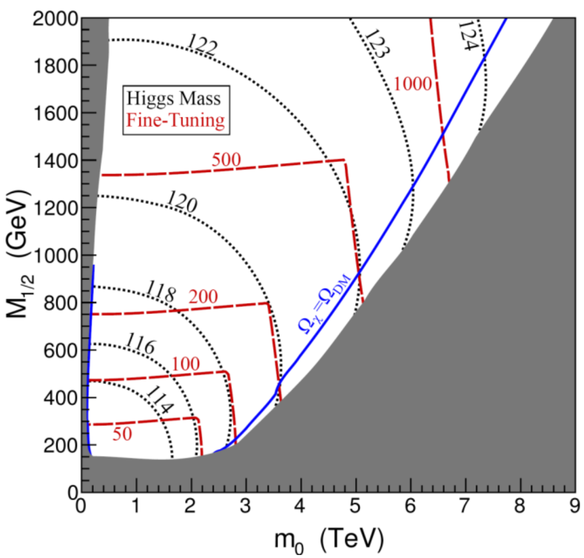
$$+ \frac{2N_f}{16\pi^2}\lambda^2(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_h)$$

- Focus point SUSY does not eliminate fine-tuning, but very roughly reduces it by the logarithm factor ~ 30
- For $\Lambda \sim m_{GUT}$ (m_W), f = top, $N_f = 6$, 1% fine-tuning → $m_{\tilde{t}} < 1$ (5) TeV

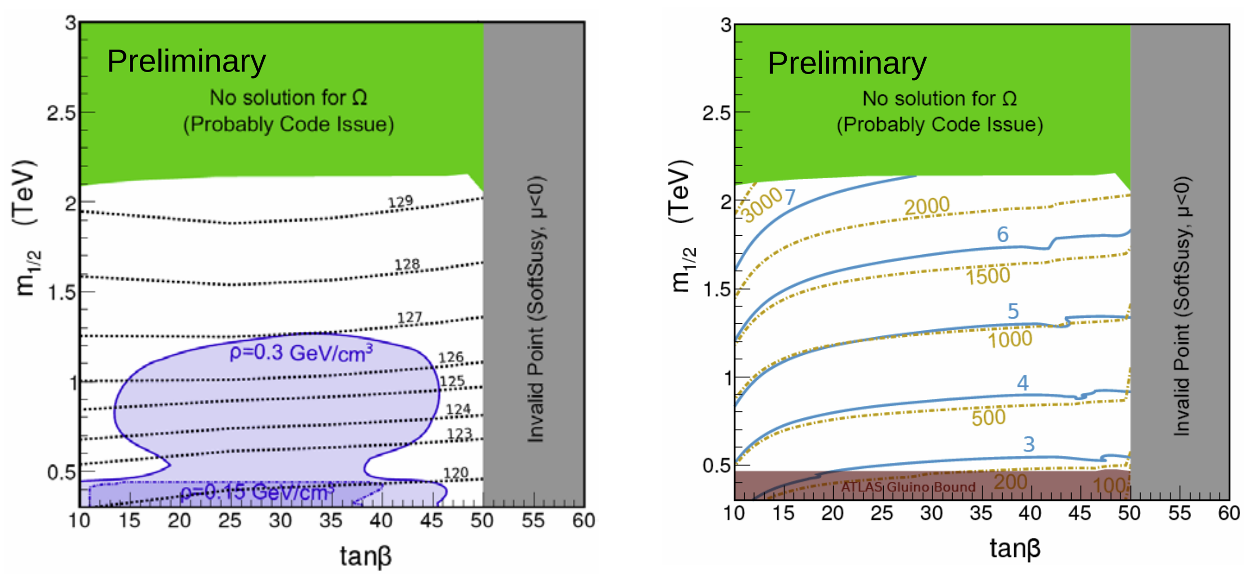
HIGGS MASS MEASUREMENT

- What stop mass is required to get $m_h = 125.5$ GeV?
- In work in progress, we find m_h(3-loop) – m_h(2-loop) ~ 3 GeV in focus point SUSY and others with heavy scalars

Harlander, Kant, Milaila, Steinhauser (2008); Kant, Harlander, Mihaila, Steinhauser (2010)



Feng, Matchev, Sanford (2011)



Draper, Feng, Kant, Profumo, Sanford (in progress)

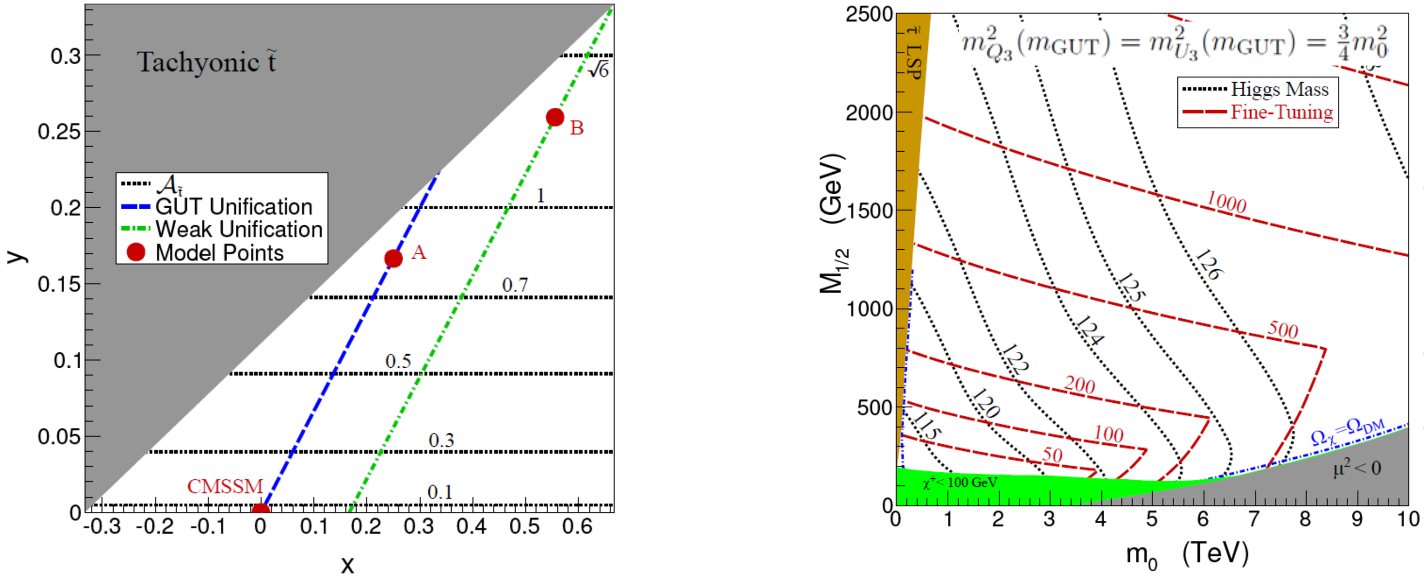
- $m_h = 125.5$ GeV possible with 3-4 TeV squarks, accessible at the LHC

FP WITH A-TERMS

- FP SUSY is much more general than mSUGRA: no specific relations for 1st and 2nd generation sfermion, gaugino masses, A parameters

- The FP solution can be generalized to include A-terms:

$$m_{H_u}^2 : m_{U_3}^2 : m_{Q_3}^2 : A_t^2 = 1 : 1+x-3y : 1-x : 9y$$



Feng, Sanford (2012)

- For example: Model A with correct Higgs mass, fine-tuning ~ 50, gluino at current bound, squarks ~ 2-4 TeV, all with minimal field content

COMMENTS

- FP SUSY provides guidance to go beyond mSUGRA with a few parameters while preserving naturalness, correct Higgs mass
- FP SUSY may emerge from more fundamental theories: e.g., hybrid moduli/anomaly mediation

Kitano, Nomura (2005)

- Alternatively, may be viewed as a bottom-up approach
- FP SUSY is an existence proof that our naïve notions of naturalness may not be accurate: do we really know enough to exclude models by requiring less than 1 or 10% fine-tuning?

OTHER HEAVY STOP MODELS

- FP SUSY has naturally heavy stops; they can also be unnaturally heavy

- Split SUSY

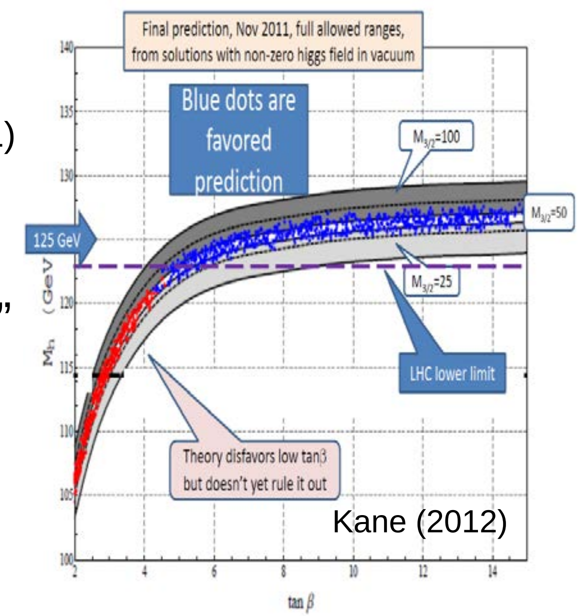
  Arkani-Hamed, Dimopoulos (2004); Giudice, Romanino (2004)

  – Extremely heavy scalars; if above 1 PeV, possibly long-lived gluinos, otherwise, phenomenology essentially identical to FP SUSY
  – Manifestly unnatural, motivated by the anthropic principle

- String-inspired Models

  Feldman, Kane, Kuflik, Lu (2011); Kane, Kumar, Lu, Zheng (2011)

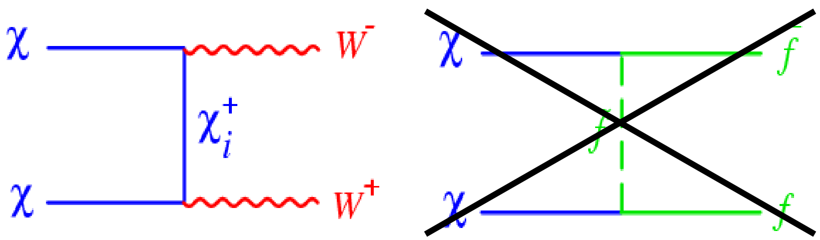
  – "String theory is already or soon being tested in several ways, including correctly predicting the recently observed Higgs boson properties and mass"
  – 30 TeV squarks, phenomenology essentially identical to FP SUSY, but extremely fine-tuned: low μ, but large fine-tuning in m_{Hu}
  – For $\tan\beta > 2$, m_h = 100-127 GeV



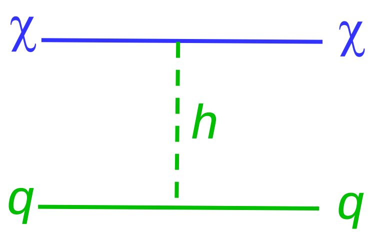
Kane (2012)

DARK MATTER SIGNALS

- The LHC is simplifying SUSY DM. If no co-annihilation, resonances, $M_2 > M_1$, Ω fixes the DM's coupling to Ws

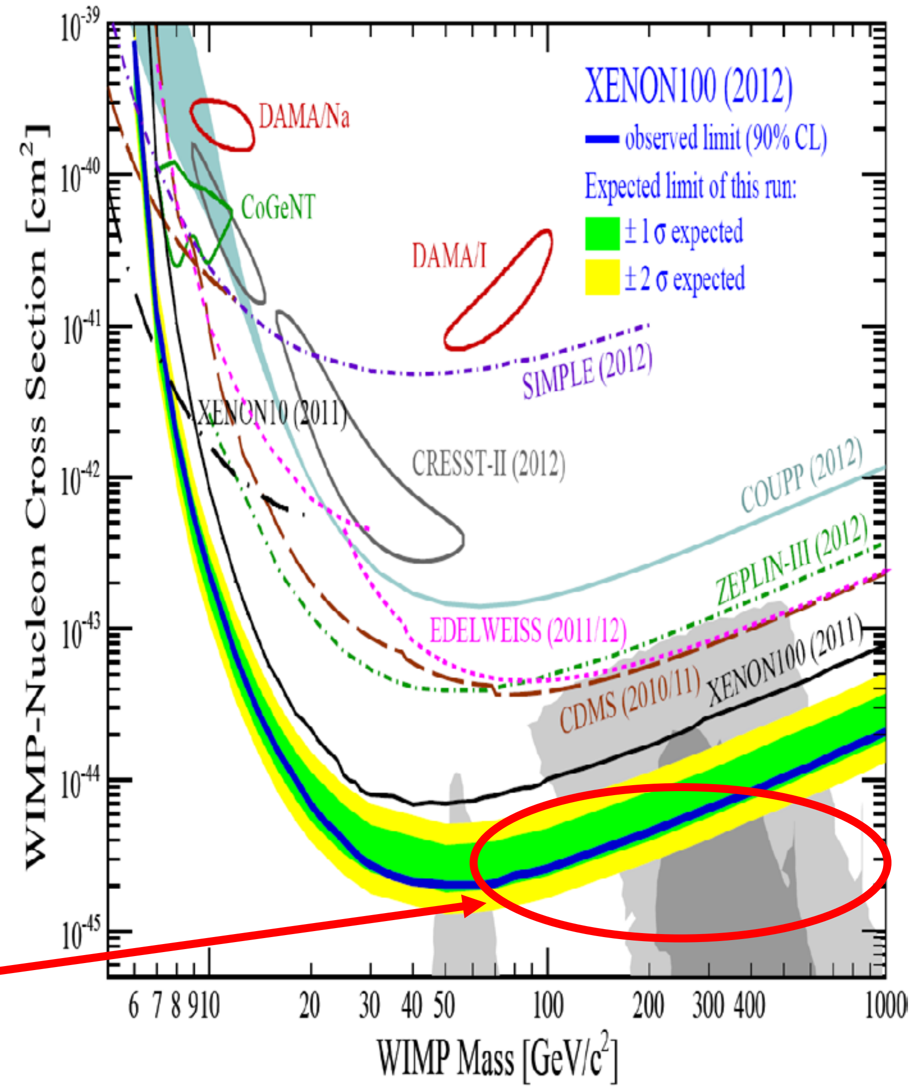


- But this also fixes the DM's coupling to the Higgs boson

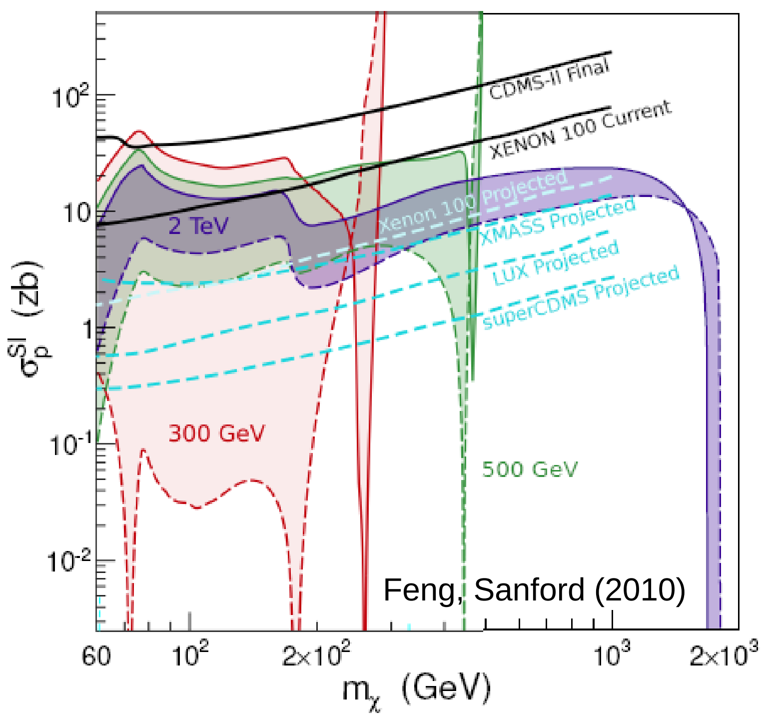


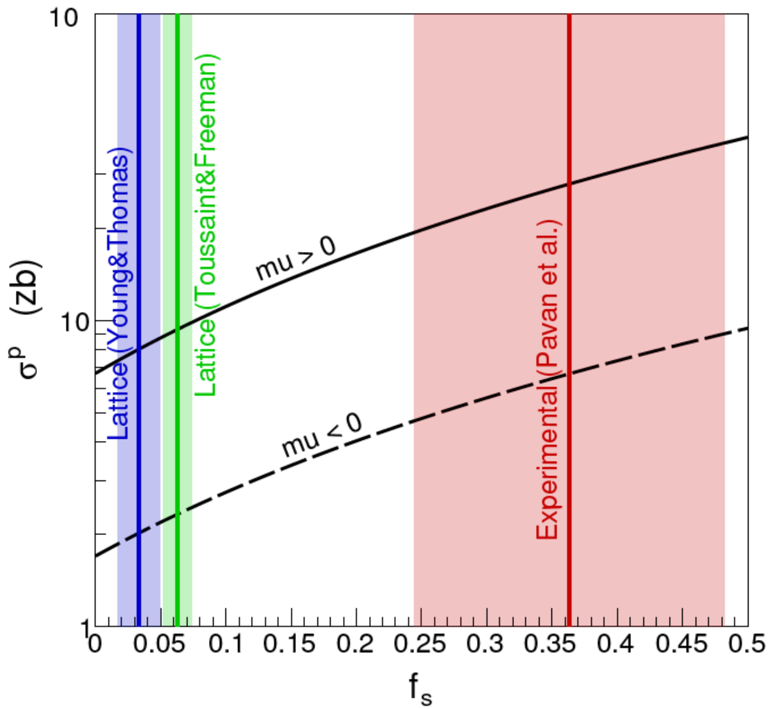
predictions collapse to a small region with σ ~ 1-10 zb

- Improvement by factors of a few will discover/exclude neutralino DM in minimal SUSY



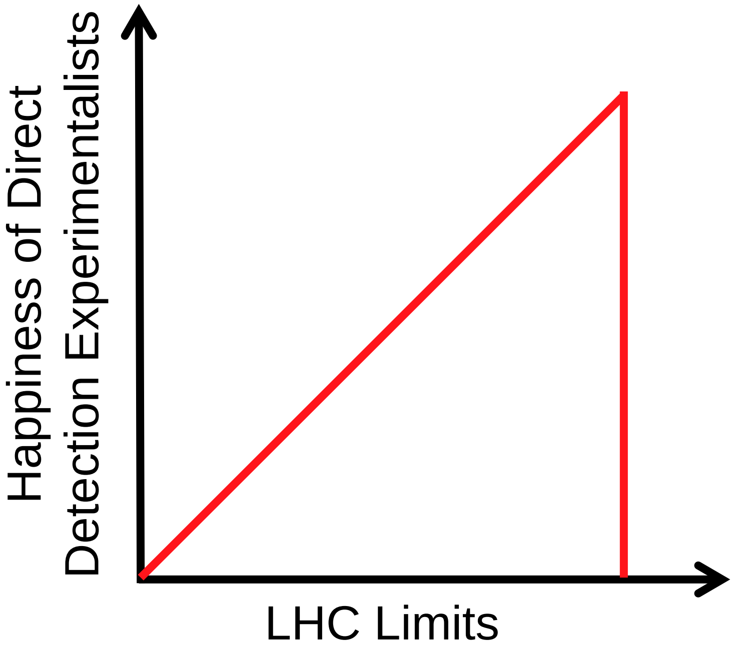
NEUTRALINO DETECTION PROSPECTS

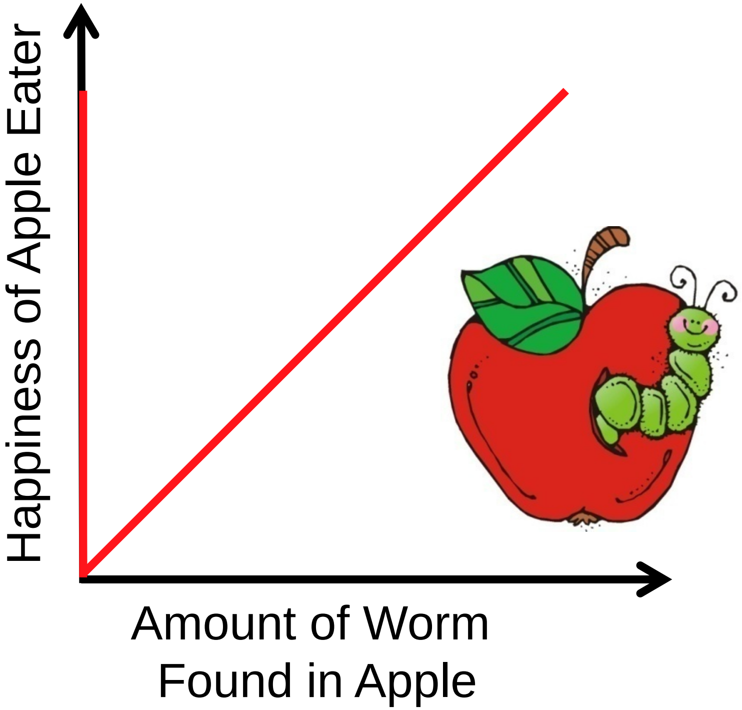




- Direct detection cross section: strong dependence on strange content
- Predicted cross sections not excluded, but very close to current bounds; a signal should be seen soon

NEUTRALINO DM IN MINIMAL SUSY





GAUGE-MEDIATED MINIMAL SUSY

Feng, Smith, Takayama (2007); Feng, Surujon, Yu (2012)
Kitano, Low (2005); Ibe, Kitano (2007)

- Let's reconsider gauge-mediated supersymmetry breaking: a beautiful framework that suppresses flavor violation

- In GMSB, Higgs is a special problem: X_t is small → heavy top squarks

Draper, Meade, Reece, Shih (2011); Evans, Ibe, Shirai, Yanagida (2012)

- But GMSB also has other difficulties:

EDMs

– GMSB suppresses flavor, but not CP violation (e.g., from μ, $M_{1/2}$ phase difference)
– Electron EDM → selectrons > 2 TeV, GMSB relations → squarks > 5 TeV

Dark Matter

– No WIMP miracle: neutralinos decay to gravitinos
– keV gravitino DM not viable: $\Omega_{\tilde{G}} h^2 \approx 0.1 (m_{\tilde{G}} / 80 \text{ eV})$, but Lyman-$\alpha$ → $m_{\tilde{G}} > 2$ keV

Viel et al. (2006); Seljak et al. (2006)

MINIMAL GMSB

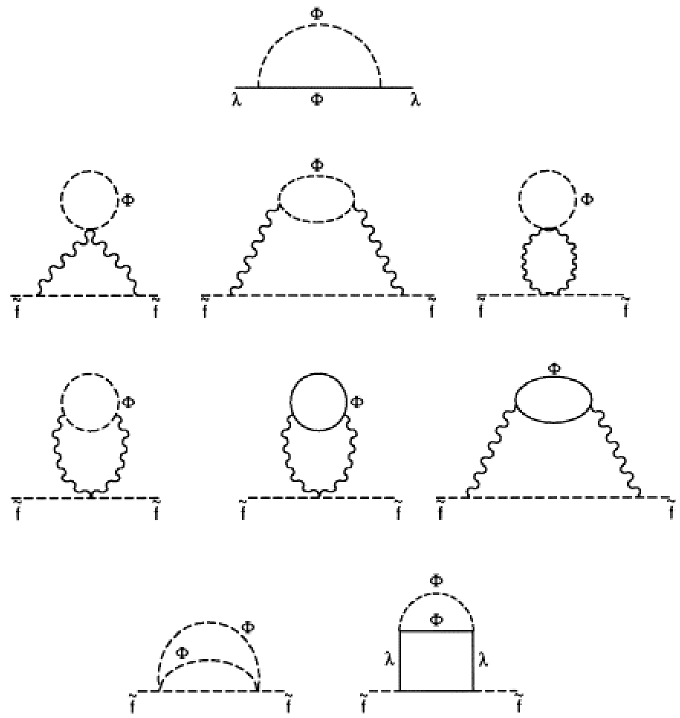
- Let's simply take all the data at face value, and see where it leads us. For simplicity, consider minimal GMSB
- 5 parameters: $m_{\tilde{G}}$, Λ, $\tan\beta$, N_5, sign(μ); set $N_5 = 1$, $\mu > 0$

$$m_{\tilde{G}} = \frac{F}{\sqrt{3} M_*}$$

$$\Lambda = F/M_m$$

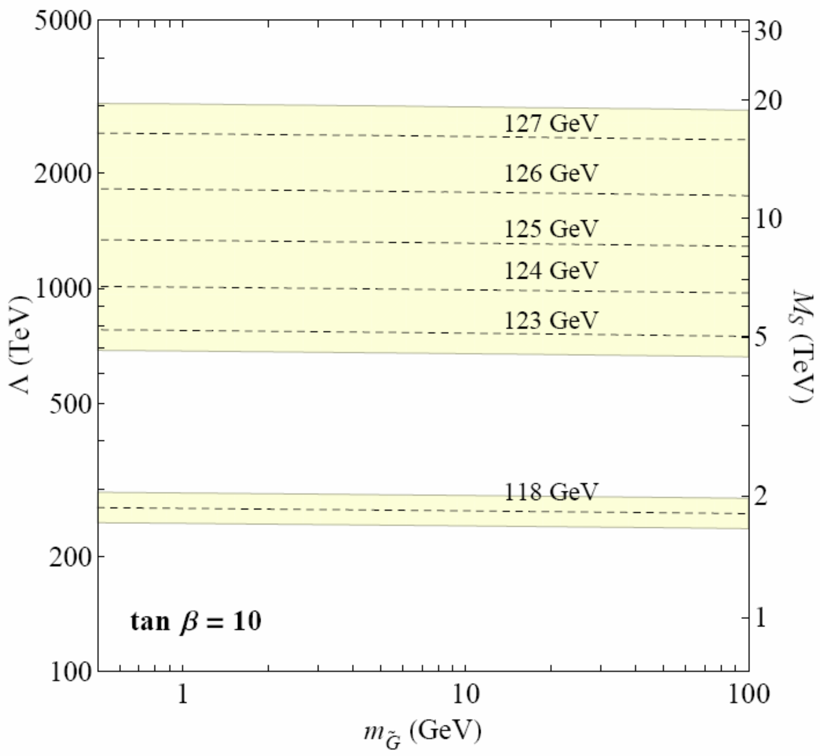
$$m_{\tilde{f}}^2(M_m) = 2 N_5 \Lambda^2 \sum_{a=1}^{3} C_a^f \left[\frac{\alpha_a(M_m)}{4\pi} \right]^2$$

$$M_a(M_m) = N_5 \Lambda \frac{\alpha_a(M_m)}{4\pi}$$

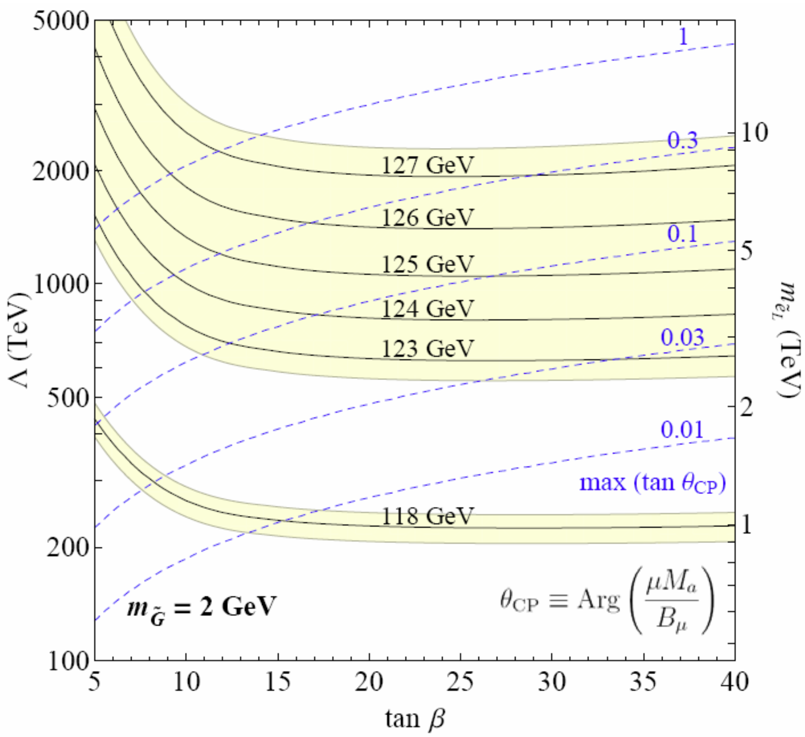


HIGGS AND EDMS

- Higgs Mass



- Electron EDM

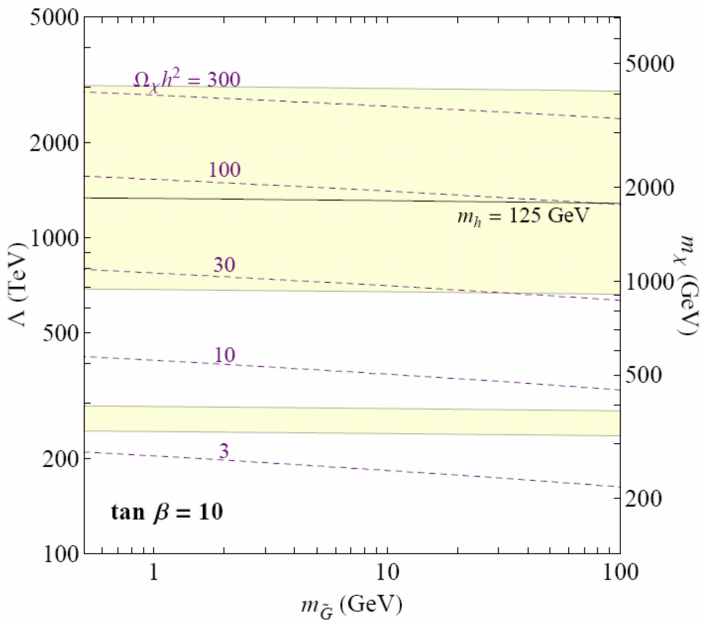


- The Higgs and EDM constraints point to the same region of parameter space

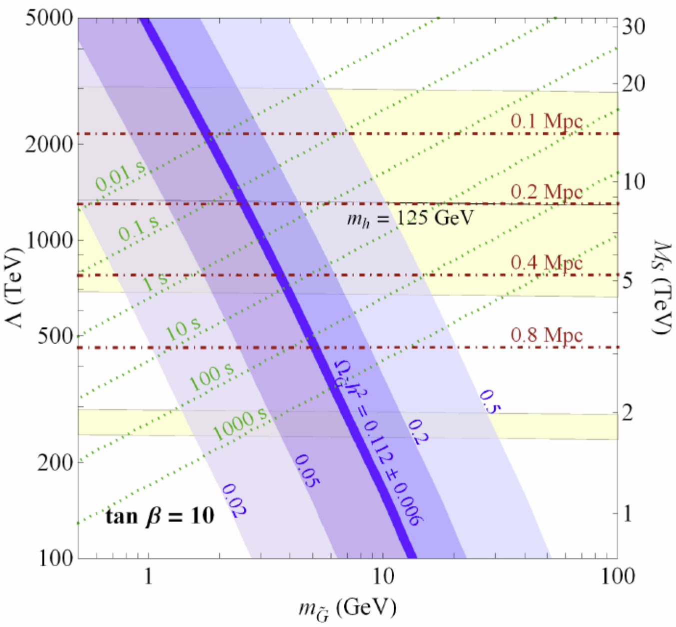
DARK MATTER

- Such large masses → TeV neutralinos are vastly over-produced in the early universe with Ωh^2~100. But then they decay to GeV gravitinos that have the right relic density!

Neutralino Ω



Gravitino Ω



- Goldilocks SUSY
  – Gravitinos are light enough to solve the flavor problem
  – Gravitinos are heavy enough to be all of DM

GOLDILOCKS COSMOLOGY

- Dark matter is non-thermal gravitinos from late decays

- Several constraints
  - Relic density

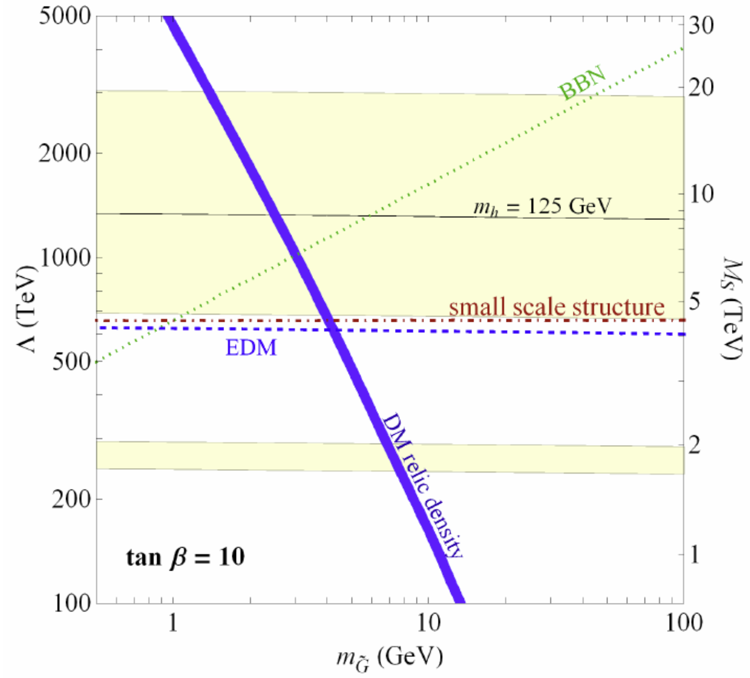
$$\Omega_{\tilde{G}} h^2 = (m_{\tilde{G}}/m_\chi)\Omega_\chi h^2$$

  - Decays before BBN (1 s)

$$\tau_\chi \simeq \frac{48\pi m_{\tilde{G}}^2 M_*^2}{m_\chi^5} \simeq 0.02 \text{ sec} \left(\frac{m_{\tilde{G}}}{1 \text{ GeV}}\right)^2 \left(\frac{2 \text{ TeV}}{m_\chi}\right)^5$$

  - Cold enough (λ_{FS} < 0.5 Mpc)

$$\lambda_{FS} \simeq 1.0 \text{ Mpc} \left[\frac{u_\tau^2 \tau}{10^6 \text{s}}\right]^{1/2} \left[1 - 0.07 \ln\left(\frac{u_\tau^2 \tau}{10^6 \text{ s}}\right)\right]$$



- All constraints point to the same region of parameter space
- Naturalness? Perhaps focus point SUSY

Agashe (1999)

SUMMARY

- SUSY with minimal field content remains viable
- Gravity-mediated minimal SUSY: Focus Point SUSY
  - The original motivations of Higgs mass, EDMs, dark matter,... are stronger than ever
  - mSUGRA, rather than being excluded, is in fact, more useful than ever as an effective theory for viable SUSY models
  - Signals: gluino, squark pair production with bottom-rich cascades, EDMs, dark matter direct detection
- Gauge-mediated minimal SUSY: Goldilocks SUSY
  - Constraints from EDMs, dark matter, Higgs mass all point to same parameter space
  - Signals: none at LHC, direct, indirect DM detection, but promising EDMs, warm DM with $\lambda_{FS} \sim 0.1 – 0.5$ Mpc