

# Alternative Futures for Particle Physics

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# A tension between naturalness and simplicity

The decades prior to July 4, 2012, saw the triumph of every aspect of the Standard Model – strong interactions, electroweak physics, the CKM theory – but left the question of the origin of electroweak symmetry breaking unanswered.

There have been lots of good arguments to expect that some dramatic new phenomena should appear at the TeV scale. But given the exquisite successes of the Model, the *simplest* possibility has always been the appearance of a single Higgs particle, with a mass not much above the LEP exclusions.

In Quantum Field Theory, *simple* has a precise meaning: a single Higgs doublet is the *minimal* set of additional (previously unobserved) degrees of freedom which can account for the elementary particle masses.

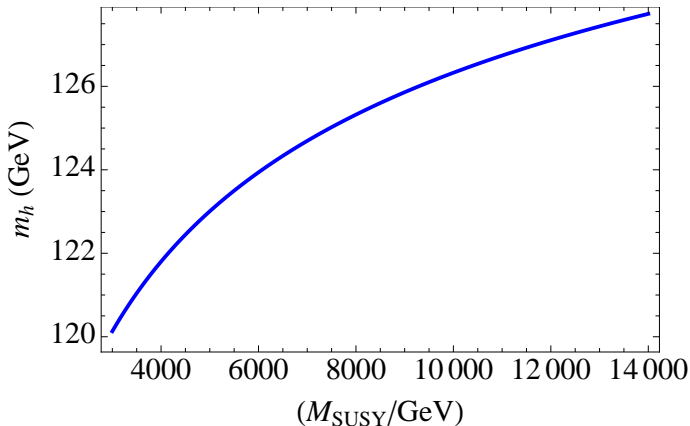
# Higgs Discovery; LHC Exclusions

So far, simplicity appears to be winning. Single light higgs, with couplings which seem consistent with the minimal Standard Model. Exclusion of a variety of new phenomena; supersymmetry ruled out into the TeV range over much of the parameter space. Tunings at the part in 100 – 1000 level.

Most other ideas (technicolor, composite Higgs,...) in comparable or more severe trouble. At least an elementary Higgs is an expectation of supersymmetry. But in MSSM, requires a large mass for stops.

# Top quark/squark loop corrections to observed physical Higgs mass ( $A \approx 0$ ; $\tan \beta > 20$ )

In MSSM, without additional degrees of freedom:



So if 8 TeV, correction to Higgs mass-squared parameter in effective action easily 1000 times the observed Higgs mass-squared.

# Physics in Crisis?

<http://blog.physicsworld.com/2013/09/12/perimeter-institute-welcome-speech-reignites-the-st>

<http://www.math.columbia.edu/~woit/wordpress/?p=6238p>

<http://www.math.columbia.edu/~woit/wordpress/?p=6294>

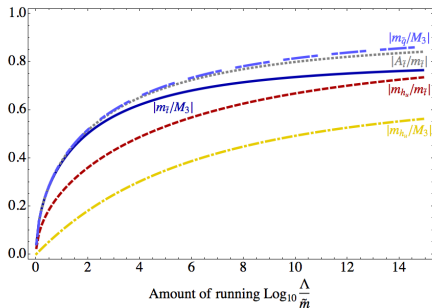
## Possibilities:

- 1 Nature is *natural*. We are on the brink of significant discoveries
- 2 Nature is somewhat tuned (perhaps for reasons we might hope to understand). Higgs mass understood in terms of supersymmetry at 10's to 100's of TeV. We might hope to see deviations in precision measurements, rare processes; perhaps evidence for new physics at much higher energies.
- 3 Nature is extremely tuned. We won't see new physics at accelerators of the highest conceivable energies.

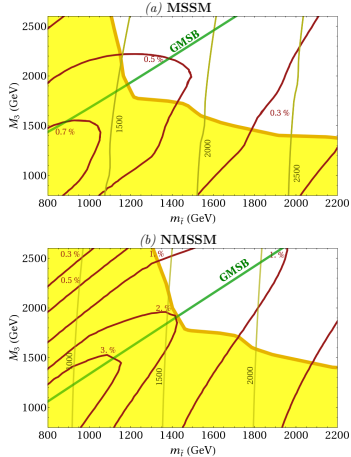
# Natural Supersymmetry

Being tightly squeezed. Requires light stops. NMSSM or other type structure to account for Higgs mass. Appears at least somewhat tuned if true. Problem is that gluino limits are quite strong, and gluino mass (of order 1.4 TeV) feeds into stop. Typically leads to few percent fine tuning (Arvinalaki, Villadoro, et al survey review recently; others)

But perhaps our ideas for realization of supersymmetry not quite right; there are various assumptions in these analyses, some stated, some perhaps hidden. Maybe there are models which are not tuned, or only very slightly. An exciting possibility. Could yet emerge in future LHC runs.



**Figure 1.** The *gluino sucks* effect: Even starting with vanishing boundary conditions for all scalar soft terms at the scale  $\Lambda$ , they are quickly generated in the IR by the gluino mass contributions. Already after one decade of running the average stop mass  $m_{\tilde{t}} = \sqrt{(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2)/2}$  is almost a factor 2 below the gluino and after three decades also  $|m_{H_u}|$  is within a factor of 4 from the gluino. Few decades of running are enough for the soft masses to saturate their IR fixed values.



**Figure 2.** Contours of tuning in the stop-gluino mass plane for the (a) MSSM and the (b) NMSSM models. The vertical golden contours refer to the low energy values of the squark masses generated by universal boundary conditions at the messenger scale  $M = 300$  TeV. The green line corresponds to the GMSB boundary conditions for the stop masses with  $N = 5$  messengers. The  $\mu$  term has been fixed to 400 GeV. The yellow region is excluded by the LHC [12].

Discovering evidence of supersymmetry, and these additional degrees of freedom, would be extremely exciting.

New symmetry of nature, new particles, new dynamics, *orthodox* ideas of naturalness will be vindicated.

More generally, *any* discovery of degrees of freedom beyond that of the simplest Standard Model will be revolutionary.

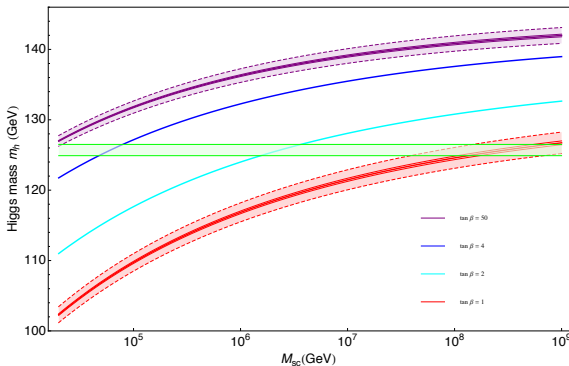
Particle physics will have a clearcut program of elucidating these new phenomenon for many years.

The happiest outcome.

# Slightly Tuned Supersymmetry

For moderate to large  $\tan \beta$ , stop masses of order 10 – 100 TeV can account for the observed Higgs mass. Tuning at part in  $10^4$  level or more.

From Arkani-Hamed et al:



Even at the lower end, experimentally challenging. Out of reach of LHC. Possibly might observe rare processes ( $\mu \rightarrow e + \gamma$ ,  $d_n$ ). Only the lower end accessible directly even at a 100 TeV collider.

# ("Mini") Split Supersymmetry

Some (Arkani-Hamed et al, Dimopoulos et al) have advocated a higher scale.

- 1 Argue that if breaking scale of order  $10^4$  TeV, flavor problems of supersymmetric theories solved.
- 2 Argue that gauginos are naturally light compared to scalars, governed by anomaly mediated formula

$$m_\lambda = \frac{\beta(g)}{g} m_{3/2}.$$

- 3 Small  $\tan \beta$  (some additional tuning) then consistent with observed  $m_H$ .
- 4 Unification, dark matter ok. Conceivably gauginos light enough that observable.

# An aside: simplified understanding of anomaly mediation

Usually presented with “superconformal compensators” and other rather obscure features of supergravity theories. A simple, low energy argument (Wilsonian!) [P. Draper, M.D.]

Take a pure susy gauge theory.  $\langle\lambda\lambda\rangle \neq 0$ . Mass gap. Couple to gravity, and include, at high scales, a constant in  $W$ ,  $W_0$ . Well known that gaugino condensation generates a contribution to the superpotential:

$$W = W_0 + \frac{1}{32\pi^2} \langle\lambda\lambda\rangle. \quad (1)$$

At low energies,  $\mathcal{L}_{eff}$  should include:

$$V = \dots - 3|W|^2. \quad (2)$$

Arises if, more microscopically:

$$\mathcal{L}_{eff} \subset -\frac{3N}{32\pi^2} \lambda \lambda W_0^*. \quad (3)$$

Extensions of this argument fill out the gauge mediation formula for more general groups and representations.

Plausibly there is some anthropic reason for the Higgs mass to be comparable to what we have now observed (specifically the weak scale – stellar processes, nucleosynthesis).



Just one light Higgs. No new physics up to extremely high energy scales (scale of r.h. neutrino masses?). Rather bleak prospect.

# Extremely tuned (non-existent?) supersymmetry

Perhaps anthropic considerations account for huge tuning of Higgs mass (Donoghue, Hall, Nomura, Dimopoulos et al, Arkani-Hamed et al). Underlying scale large.

But a price.

Supersymmetry has (often) several features which are quite appealing:

- 1 Solution of hierarchy problem: cancellation of quadratic divergences.
- 2 Solution of hierarchy problem: dynamical supersymmetry breaking as origin of hierarchy
- 3 Coupling constant unification
- 4 Natural dark matter candidates

# Landscape as a Model for Questions of Naturalness

Landscape models have many limitations. But they have the virtue that they make sharp questions of naturalness. [Otherwise, what are we worried about? We don't want the entity responsible for the laws of nature to have to work too hard?] Well defined notion of measure on the space of theories. Impose priors (anthropics? just existing data?). With sufficient understanding, could decide, e.g., low energy susy more or less likely.



# A Non-Standard argument for some degree of supersymmetry

Apart from the standard arguments, there is another argument for some degree of supersymmetry: vacuum stability.

In a landscape context, might expect supersymmetry rather special. Many have argued that Higgs mass then explained anthropically.

Two issues with this picture. First, naive intuition itself is questionable. Model by flux vacua in string theory. For fixed choice of fluxes, some effective potential. Study stationary points. In general, many non-susy points if large number of fields.

But McAlister et al: only an exponentially small fraction (meta) stable. Study random supergravity potentials using techniques of random matrix theory. In their model, find

$$\mathcal{N}_{vacua} \approx \mathcal{N}_{cp} e^{-0.08 N^{1.3}} \quad (4)$$

where  $N$  is number of fields.

Lesson: non-susy states more rare than expected. SUSY states sometimes more stable. E.g. if susy breaking scale low, so approximately globally supersymmetric theory.

Overall, states sparse. In a flux landscape, might expect order one stable state for any choice of fluxes. Still could be a very large number. No particular reason to think, for example, that lowest energy state for a given choice of fluxes is (approximately) supersymmetric.

# “Non-perturbative stability”

In a landscape picture, our “vacuum” is a state of accidentally small c.c. surrounded by a vast number of lower c.c. states. Need to suppress decays to *every* state. Small coupling (string coupling), large volume: don’t help significantly. Problem emphasized recently by Greene, Weinberg.

They considered a model with multiple fields, a random potential expanded to quartic order. Find that the fraction of states with a tunneling exponent greater than some value  $B$  behaves as

$$f(B) \approx \exp(-\beta N^{2.7} B) \quad (5)$$

$$\beta \sim 10^{-3}.$$

Some issues in reconciling these various models. Study in progress.

Simplest way to account for stability?

(Approximate) Supersymmetry!

With exact supersymmetry in flat space, the vacuum is stable. This can be understood as a consequence of the existence of global supercharges, obeying the familiar algebra:

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2P^\mu (\sigma_\mu)_{\alpha\dot{\beta}} \quad (6)$$

With (slightly) broken supersymmetry, expect still true or suppressed. Generally true.

For a broad class of models (Festuccia, Morisse, M.D.), one has a general formula:

$$\Gamma \propto e^{-2\pi^2 \left( \frac{M_p^2}{m_{3/2}^2} \right)} \quad (7)$$

# Branches of the Landscape

Studies of landscape models (e.g. Type II flux vacua—Douglas, Denef; Dine, Sun) suggest existence of branches with

- 1 No supersymmetry
- 2 Supersymmetry, no (discrete)  $R$  symmetries
- 3 Supersymmetry, discrete  $R$  symmetries.

On (2), cosmological constant requirement (ignoring Higgs) suggests uniform distribution of susy scales on a log scale. For (3), concentration at low scales.

How populated? Counting/cosmology? Argument above suggests that, for (1), non-susy states might not be so common (how to quantify?). Simple considerations for flux vacua suggest that states with symmetries are rare.

# Aside: Landscape and Symmetries

Naive landscape counting in flux models: states exhibiting symmetries are rare!

Only an exponentially small fraction of fluxes allow symmetry (Z. Sun, M.D.).

Challenges accepted wisdom that symmetries are natural.

But perhaps *too* naive. (Festuccia, Morisse, M.D.)  
Cosmological considerations *might* favor symmetries.

# Phenomenological Pointers for the Scale of Supersymmetry Breaking

In any case, a strong argument for some degree of low energy supersymmetry, possibly at low scales. How low?

For a broad range of  $\tan \beta$ , susy at 10's-100's of TeV accounts for the Higgs mass.

A phenomenological argument against  $10^4$  TeV: proton decay

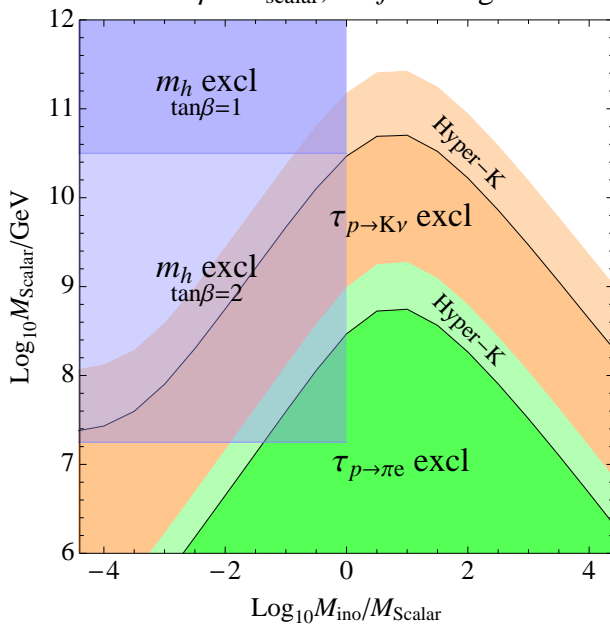
If soft breakings anarchic, a problem with proton decay through *dimension five* operators.

# Proton Decay Through Dimension Five Operators

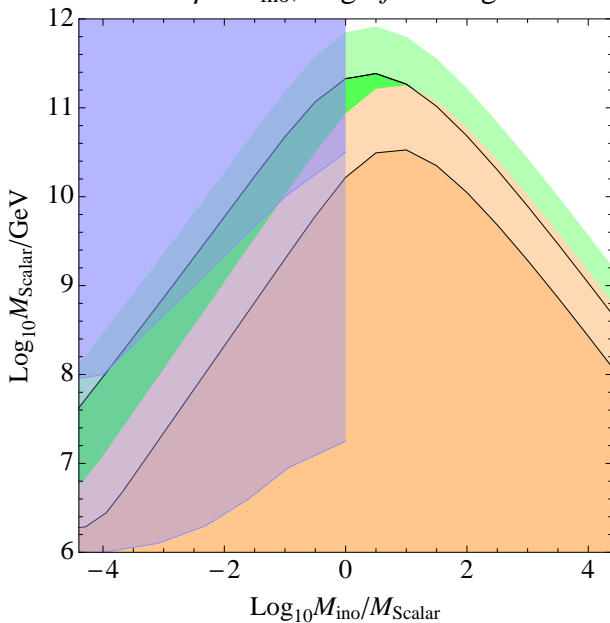
SU(5) models: usually assumed that dimension five operators arise through exchange of color triplet Higgs, and that corresponding Yukawa's related by SU(5) symmetry (simple Higgs structure). Results in suppression of dimension five operators by products of light quark, lepton masses; still not consistent with existing limits.

But if no underlying flavor structure, might expect, in general, dimension five operators  $QQQL, \bar{u}\bar{u}\bar{d}\bar{e}$  with "anarchic" coefficients. In order that adequately suppressed, need very high scale of supersymmetry breaking,  $10^{10}$  TeV or so. [P. Draper, W. Shepherd, M.D.]

$\mu = M_{\text{scalar}}, \text{ no } \tilde{f} \text{ mixing}$



$\mu=M_{\text{ino}}, \text{ large } \tilde{f} \text{ mixing}$



Even simple models of horizontal symmetry (“alignment”), with susy breaking scale at 10 TeV, more than adequately suppress flavor changing neutral currents, B, L violation. So argument for very high scale of susy breaking is not compelling. [Leurer, Nir, Seiberg; Ben-Hamo, Nir,; Draper, Shepherd, M.D.]

# Genericity of Split Spectrum

Usual argument: Gauginos are fermions, fermion masses can be protected by chiral symmetries.

But *argument suspect*: any such symmetry is an R symmetry. Necessarily broken to account for small cosmological constant. (This breaking is reflected in the usual anomaly-mediated mass formula).

Need to look more microscopically at mechanism of supersymmetry breaking,  $R$  breaking.

# Retrofitting: A generic form of (metastable) dynamical supersymmetry breaking

Would like to understand supersymmetry breaking dynamically. Most discussions of metastable DSB performed in framework of gauge mediation. But can consider gravity mediation as well [M.Bose, M.D.]

Simplest possibility: field  $X$  with coupling  $XW_\alpha^2$ .  $X$  a pseudomodulus. If couples to other fields, naturally stabilized at point where these are light.

In such models,  $F_X \neq 0$ , naturally couples to SM fields as well (no suppression of gaugino masses).

So not clear that “split” is generic [M.Bose, M.D.], but might be true.

Can generate  $\mu$  term, other dimensionful couplings through retrofitting as well.

# A pointer to Scales: The Cosmological Moduli Problem

Ibanez et al, Banks, Kaplan and Nelson: moduli in string theory lead to cosmological difficulties.

Require: reheating to temperatures of order 10 MeV or higher.

$$\Gamma \approx \frac{m_{3/2}^3}{4\pi M_p} \quad T_{rh} \approx m_{3/2} \frac{m_{3/2}}{M_p}^{1/2}. \quad (8)$$

Requires moduli masses (assuming decay through Planck suppressed operators) 30 TeV or higher.

If operative, suggests a high scale of supersymmetry breaking. Dark matter not produced thermally. Late generation of baryon asymmetry.

# Moduli as Controlling Element in Realization of Supersymmetry

[M. Bose, P. Draper, M.D.]

Can consider (at least) three possibilities:

- 1 No moduli
- 2 Supersymmetric moduli (moduli with small  $F$  terms, as in KKLT)
- 3 Non-supersymmetric moduli

Which of these three is realized controls realization of supersymmetry, critical features of cosmology.

# No moduli

Conventional cosmology possible. Universe was once very hot. No additional constraints on scale of supersymmetry breaking.

But: unless supersymmetry broken at very high scales, no axion (and understanding axion challenging without supersymmetry).

Supersymmetric moduli: Still no axion. Moduli can be quite heavy. Readily decay to particles and superpartners.

# Aside: A Theorem About Decay Rates in Supersymmetric Theories

The literature on moduli decays suffers from confusions about the relative decay rates to different channels. One can avoid these starting with the following simple observation:

With unbroken supersymmetry, can often prove exact statements about decay of particles (moduli scalars in this case) to pairs of particles, superpartners. Follows from supersymmetric ward identities. Ex:

$$W = \frac{1}{2}M\Phi^2 + \lambda\Phi\phi\phi. \quad (9)$$

Supersymmetry relates the Green's functions:

$$\langle F_{\Phi}^*(x_1)\psi_{\alpha}(x_2)\psi_{\beta}(x_3)\rangle\epsilon^{\alpha\beta} = 2\langle\Phi(x_1)^*\partial_{\mu}\phi(x_2)\partial^{\mu}\phi(x_3)\rangle. \quad (10)$$

E.g. from

$$\langle\Phi^*(x_1,\theta_1)\phi(x_2,\theta_2)\phi(x_3,\theta_3)\rangle \quad (11)$$

The left hand side of the Ward i.d. is the coefficient of  $\bar{\theta}_1^2\theta_2\theta_3$  in this Green's function; translating by  $\theta_1$  in superspace, relates to

$$\langle\Phi^*(x_1,0)\phi(x_2,\theta_2-\theta_1)\phi(x_3,\theta_3-\theta_1)\rangle \quad (12)$$

and now the coefficient of  $\bar{\theta}_1^2\theta_2\theta_3$  is the right-hand side of the equation.

To extract the decay amplitudes, we can apply the LSZ formalism. First we note the relations for the Green's functions, in momentum space,

$$\langle F^\dagger F \rangle = p^2 \langle \phi^\dagger \phi \rangle. \quad (13)$$

Follows from examining  $\theta_1 \bar{\theta}_1 \theta_2 \bar{\theta}_2$  coefficient on both sides of:

$$\langle \Phi(\theta_1, \bar{\theta}_1) \Phi^\dagger(\theta_2, \bar{\theta}_2) \rangle = \langle \Phi(\theta_1 - \theta_2, 0) \Phi^\dagger(0, \bar{\theta}_2 - \bar{\theta}_1) \rangle. \quad (14)$$

So we can relate the single particle matrix elements needed for LSZ; those of  $\phi$  and  $F$  differ by a factor of  $m^2$ , the physical on-shell mass. There are two possible initial states (which can be thought of as the scalar and its antiparticle) and two possible final states in either the two boson or two fermion channel. Combining the Ward identity for the Green's functions and the result for the single particle matrix elements demonstrates the equality of the two boson and two fermion matrix elements. The result is readily verified at tree level.

Similarly, for a scalar coupled to  $W_\alpha^2$ , one can prove an equality for the matrix elements (and hence the rates) for the decays:  $\phi \rightarrow A_\mu + A_\mu$  and  $\phi \rightarrow \lambda\lambda$ . When supersymmetry is broken these equalities will fail, but, except for tuned values of the parameters, we expect the rates to be comparable.

# Supersymmetric moduli: decays to WIMPs

In light of above, if there is a stable WIMP, will be produced copiously in decays of supersymmetric moduli. To avoid overproduction, require that temperature after decay high enough that WIMPs in thermal equilibrium. Implies a very large mass for the moduli,  $10^6$  GeV or larger.

# Non-supersymmetric Moduli

It has been argued that WIMP dark matter might be produced in moduli decays. But in light of the equality of decays to particles and superpartners, except in special kinematic regions, one expects an order one fraction of the energy density, immediately after moduli decays, to be in WIMPs, and this is problematic.

Avoid, e.g., if moduli are lighter than WIMPs. Note this is probably not compatible with split spectrum. Alternatively avoid if no WIMPs (broken R parity).

# Ways one might understand a modest hierarchy

- 1 In inflationary models, if inflaton and susy breaking dynamics connected, may have countervailing pressures: low inflation scale tuned, light higgs with high susy breaking scale tuned.
- 2 Dark matter, moduli problems may provide pressure to higher scales.
- 3 Limitations of discrete tuning (M. Bose, Dine)

None of these is convincing at this stage, nor do they point reliably to a particular scale for supersymmetry breaking.

# An exciting and Remarkable Present

- 1 Exquisite understanding of the laws of nature. Higgs discovery and measurement of its production and decay the culmination of five decades of study of the Standard Model. Triumph for the *principle of simplicity*.
- 2 Tools on the horizon for precision studies of the Higgs, search for very high energy physics (“intensity frontier”, rare processes like  $\mu \rightarrow e + \gamma$ , CP,...)

# Alternative futures

- ① Naturalness triumphs – new physics discoveries at 14 TeV.
- ② Naturalness fails a little bit: Higgs clue to the next important energy scales.
  - Split supersymmetry: LHC discovery of long-lived gluino
  - Unsplit – Intensity frontier provides evidence for a new scale at 10's of TeV ( $\mu \rightarrow e + \gamma$ ;  $d_n$ ). *Eventually* able to probe this scale.
- ③ Big failure of naturalness