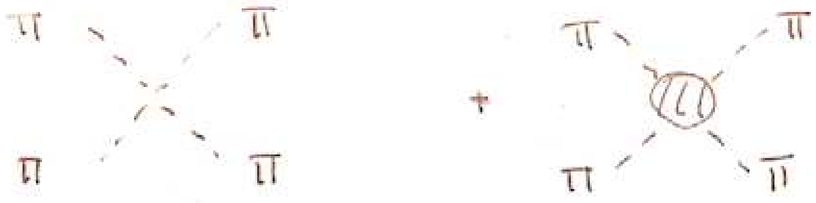
Landscape Naturalness

Scott Thomas

Physics of EWSB

- $W_L W_L \to W_L W_L$ $\quad W_\mu \sim \partial_\mu \pi$



$\frac{E^2}{f}$ $\quad$ Unitarize

- (Technical) Unnaturalness of EW Scale

$\delta m_h^2 \sim \frac{3 h_t^2}{16\pi^2} \Lambda^2$ $\quad$ Cancels Λ^2 div + UV Sensitivity

$\Lambda \lesssim$ TeV

The Concepts ...
Have Guided our
Thinking .. Theories
Fundamental Physics
30 yrs.

If one Steps back
Some ...
Start to look like
epicycles

- (Technical) Naturalness

EWSB - New Physics $\lesssim$ TeV to Stabilize the EW Scale

Most General Forms Can Lead to ---

Precision EW	Four-Fermi Contact
Higgs mass Bounds	Small m_ν
Quark Flavor	Proton Stability
Lepton Flavor	Direct Searches
CP Violation, EDMs	Muon a_μ
⋮	⋮

Mechanisms to Avoid

- Only Direct Evidence for Any Physics Beyond SM - $m_\nu \neq 0$, Gravity (Dark Matter, Baryogenesis, Inflation..)

- Other Hierarchy Problem

? Alternate Framework -- Address Naturalness + Hierarchy Problems

Landscape - Multiverse

- Fundamental Theory with a Landscape of Many Vacua + Mechanism for Populating --

Land Scape Naturalness -
Most Common on Landscape - Multiverse is Most Natural ---

Statistics of Multiverse → Correlations

$$P(x_i | y_j) = \int D\mathfrak{z} \, P(x_i, y | \mathfrak{z}) \, \mu(\mathfrak{z})$$

↑ ↑ Observables — ↑ Multiverse Measure — External Measure, Restrictions

Note: No Predictions without (some Assumptions about) Underlying Theory

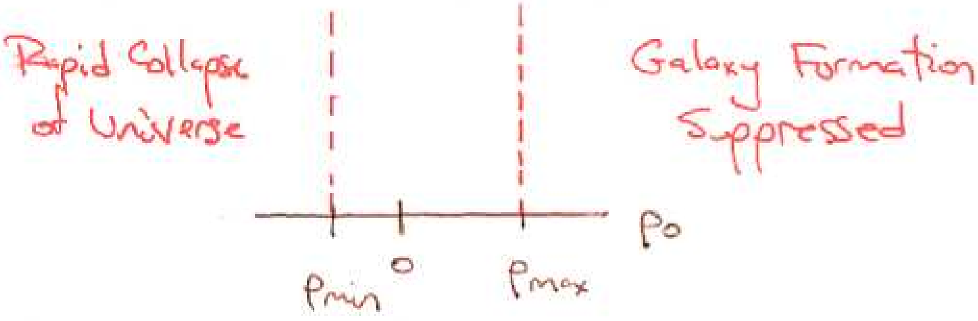
- Priors vs. External Restrictions

  ↳ Anthropic Principle

  ↙ Unsatisfactory: Must Admit that in a Multi-verse There are Selection effects

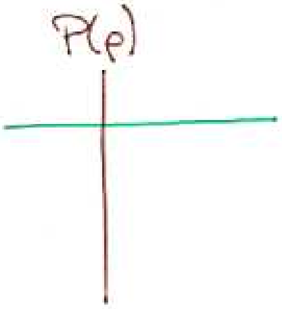
- String/M-Theory - Landscape - SUSY + Evidence for Non-SUSY

Vacuum Energy - Weinberg



$\rho_{max} \sim 2\text{-}3\ \rho_c$

Hold Everything fixed but ρ_0



Assume $P(\rho_0)$ smooth near $\rho_0 \simeq 0$

$\langle \rho_0 \rangle \sim \frac{1}{2} \rho_{max} \neq 0$ ← **

$\rho_{DE} \simeq 0.7 \rho_c$

Dark Energy EoS ...

- As yet no Signal of TeV Scale Physics Beyond Standard Model

- Dark Energy - Interpreted as ρ_0

- String/M-Theory Landscape.

Take Landscape Seriously ---
Investigate Implications for
Other Observables

Problems with Implementing Landscape Naturalness for Other Observables

- Measure Problem: D_3 — Open Question
- Restrict to Local minima — Unlikely Equally Populated
- Most of Landscape Probably Incalculable — Representative Sample
- Can't Calculate Most Observables Even in Given Vacuum

Identify Robust Quantities in Classes of Vacua - Work out Implications

Scale of SUSY on The Landscape

$$V = e^K \left(|DW|^2 - 3|W|^2 \right)$$

	SUSY	$U(1)_R$
I	Classical	Classical
II	Non-Perturbative	Classical
III	Non-Perturbative	Non-Perturbative

Non-Renormalization Thm. ---

$$P_{|W|^2} \sim \begin{cases} 1 & \text{Classical} \\ \dfrac{1}{|W_0|^2} & \text{Non-Perturbative} \end{cases}$$

$$P_{|DW|^2} \sim \begin{cases} |DW|^{2n} & \text{Classical} \\ \dfrac{1}{|DW|^2} & \text{Non-Perturbative} \end{cases}$$

Non-perturbative: $|W|^2; |DW|^2 \sim e^{-1/g^2}$

$$d(-1/g^2) \sim d \ln |W|^2 \sim \frac{d|W|^2}{|W|^2}$$

• With Constraint of $V \simeq 0$

$$P(|\omega|^2 < |\omega_0|^2) = \int_0^{|\omega_0|^2} d|\omega|^2 \, d|D\omega|^2 \, P_{|\omega|^2} P_{|D\omega|^2} \, \delta(|D\omega|^2 - 3|\omega|^2)$$

Note: Statistics Can Overwhelm Tuning $\Delta n \leq \frac{1}{2}$

	SUSY	$U(1)_R$	$P(\lvert\omega\rvert^2 < \lvert\omega_0\rvert^2)$	$V \simeq 0$	m_Z
High	Classical	Classical	$\lvert\omega_0\rvert^{2n}$	10^{-120}	$1 - 10^{-30}$
Intermediate	NP	Classical	$\ln \lvert\omega_0\rvert^2$	10^{-120}	$1 - 10^{-30}$
Low	NP	NP	$\frac{1}{\lvert\omega_0\rvert^2}$	10^{-60}	1

Note: Lowest Possible SUSY Scale

Tuning Overwhelms Statistics

• Could Try to Study Relative Occurance of Each Branch, $\omega_{tree} = 0$ by Sym or Accident but --

• Implications of Each Branch

Landscape:

- Statistics vs Tuning
- Distributions can Peak
- Careful About Landscape Genericity (Conditional)

  c.f. inflation

- (Technical) Naturalness Enforced by (App) Sym
  Can be important on Landscape

  -- Sharpens Role --

× Landscape is Vast, Somewhere ---

Realizations of Branches

High :
SUSY

Intermediate :
SUSY

Low :
SUSY

· Superpartners ·
· Decays to Goldstino
· Mescoscopic Moduli Forces

Technicolor
Warping
Standard Model

⋮

'Standard' MSSM

⋮

Gauge Mediation
Warping - SUSY
at Bottom of Throat

⋮

• $M_p \gtrsim$ TeV

• $M_p \gtrsim$ TeV

Many are 'Scenarios' - Wide range of Variants
Hard to Calculate without
many Additional Assumptions
- Loose Contact with
Landscape Naturalness

• Landscape Can Suggest New
Directions for Model
Building

The Landscape Standard Model

Conjecture: Standard Model is most common Realization of High Scale Susy Branch of Landscape

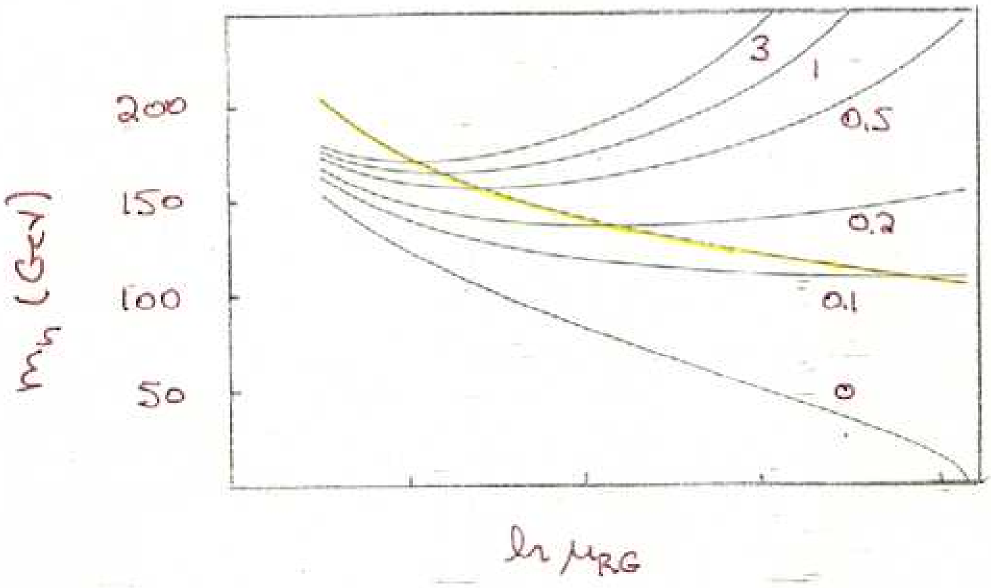
- TeV Scale: Single Higgs

$$V = m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

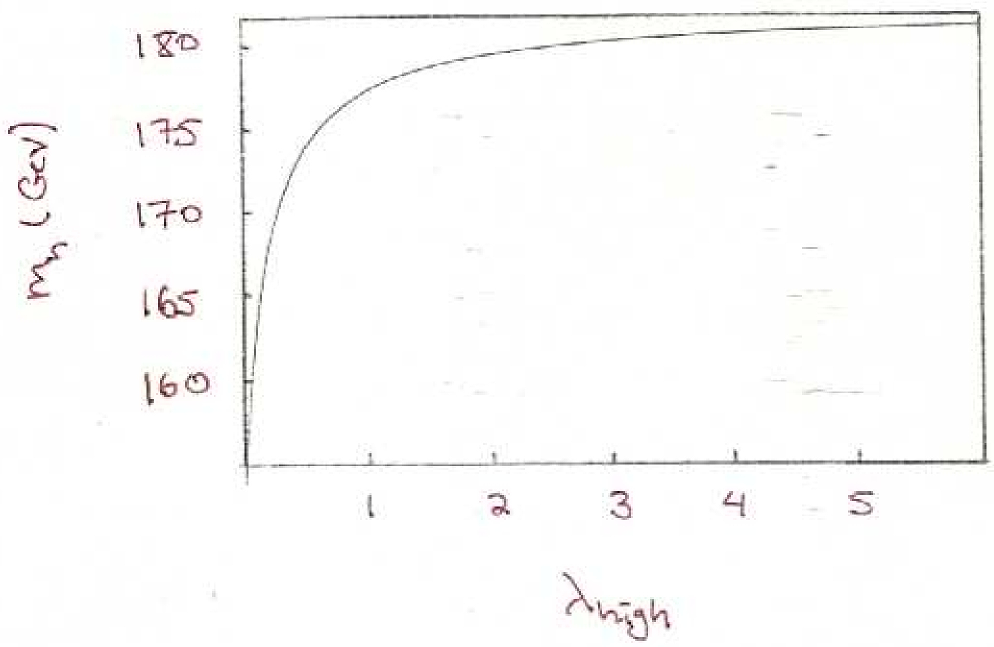
$$m_h^2 = \lambda \langle H \rangle^2$$ Only m_h unknown

↑

•



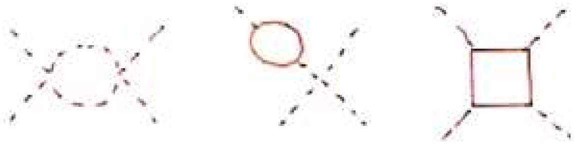
200
150
100
50
m_h (GeV)
3
1
0.5
0.2
0.1
0
ln μ_{RG}

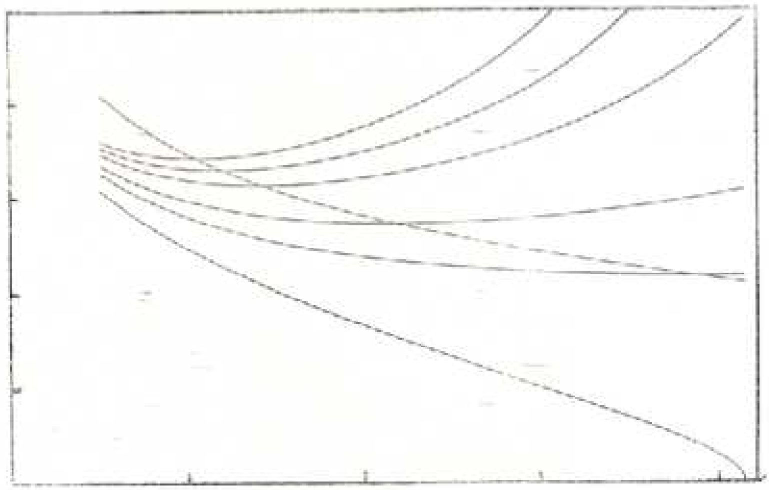


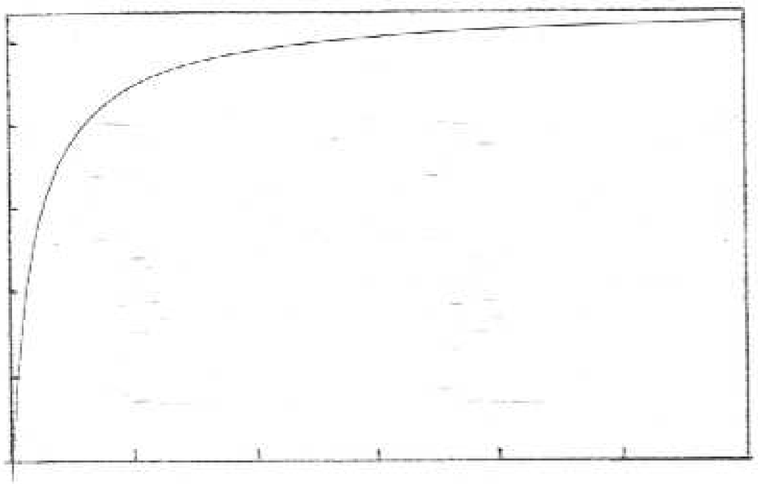
180
175
170
165
160
m_h (GeV)
1
2
3
4
5
λ_{high}

RG Evolution of Higgs Self Coupling

$$16\pi^2 \beta_\lambda = \lambda(24\lambda + 12h_t^2) - 6h_t^4$$

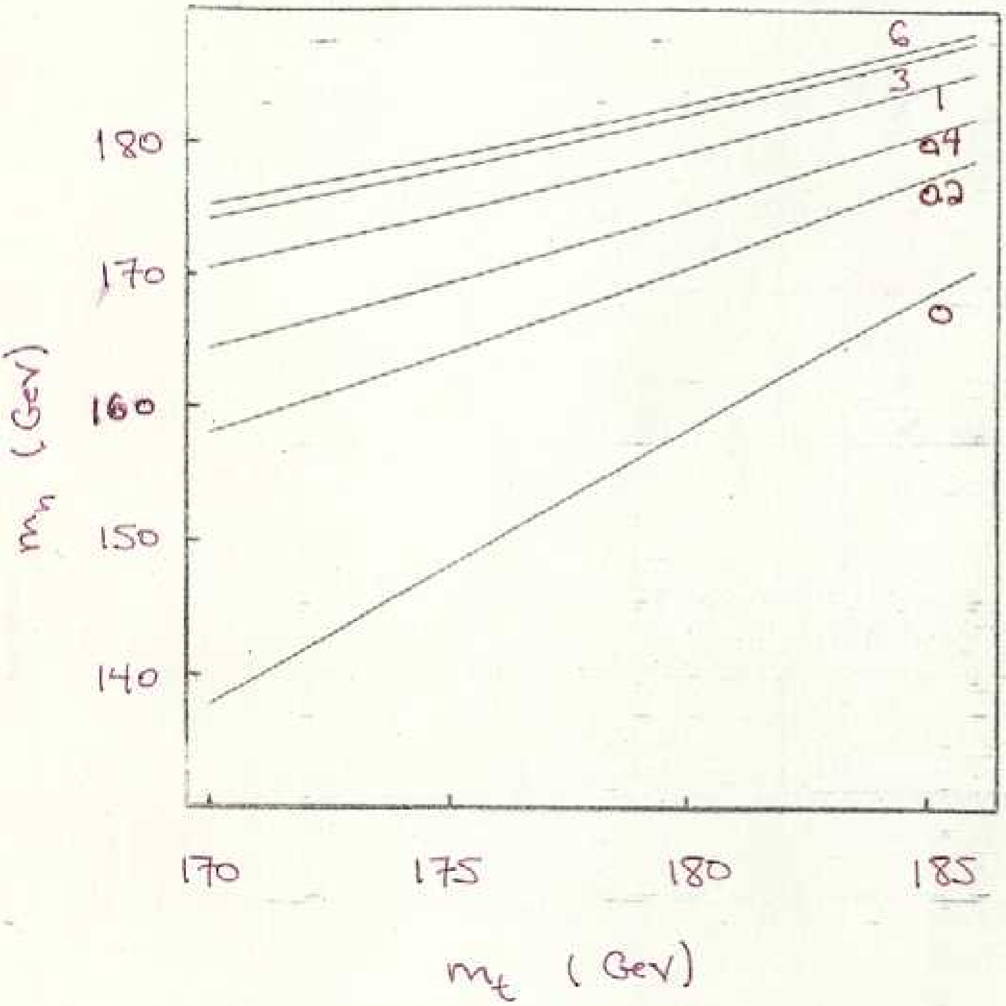






Higgs Mass - Top Mass Relation

Range of Allowed SM Higgs Masses



Uncertainties:

- α_s
- Boundary Scale
- 2-loop
- low-Scale Thresholds
- * top Mass   178 ± 4.3 GeV Tevatron
  ± (1-2) GeV LHC

Scenarios for Landscape Standard Model
on High Scale SUSY Branch

- $m_{SUSY} \ll M$ (cutoff in Distribution)

  - SUSY Boundary Condition for λ_{high}

  - Probability Distribution for soft masses

- $m_{SUSY} \sim M$ (No Cutoff in Distribution)

  - Probability Distribution of SUSY Contributions to λ_{high}

Extension of Weinberg's Ansatz for $P(\rho_\Lambda)$

(Here RG Evolution has dramatic effect.)

$m_{SUSY} \ll M$

$m_{SUSY} < \mu_{RG} < M$ SUSY: H_u Required for large h_t
H_d - - - Anomaly Cancellation

Minimal Particle Content: MSSM
(Assume R-parity, Lepton Flavor Consv)

$\mu_{RG} \sim m_{SUSY}$

$$\begin{pmatrix} m_u^2 + |\mu|^2 & m_{ud}^2 \\ m_{ud}^{*2} & m_d^2 + |\mu|^2 \end{pmatrix}$$

$m_H^2 \simeq 0$ $H = \cos\beta \, H_d^* + \sin\beta \, H_u$

$V_D \to \lambda = \frac{1}{8}\left(\frac{3}{5} g_1^2 + g_2^2\right) \cos^2 2\beta$

└ SUSY Boundary Condition

Higgs Mixing From Soft Masses

$$\frac{c_\mu}{M}\int d^4\theta\, S\, H_u H_d \qquad \mu = c_\mu \frac{F_S}{M}$$

$$\frac{c}{M^2}\int d^4\theta\, S^\dagger S\, H^\dagger H \qquad m^2 = c\,\frac{|F|^2}{M^2}$$

$$\frac{c_d}{M^2}\int d^4\theta\, S^\dagger S\, H_u H_d \qquad m_{ud}^2 = c_{ud}\,\frac{|F|^2}{M^2}$$

Assume c's Uncorrelated, Random $\to P(\cos^2 2\beta)$

$$\cos^2 2\beta = \frac{(m_u^2 - m_d^2)^2}{(m_u^2 - m_d^2)^2 + 4|m_{ud}^2|^2}$$

Large mixing - Small $\cos^2 2\beta$ Most likely

$\langle \cos^2 2\beta \rangle \simeq 0.2$

$\frac{1}{8}\left(\frac{3}{5}g_1^2 + g_2^2\right) \simeq 0.06$

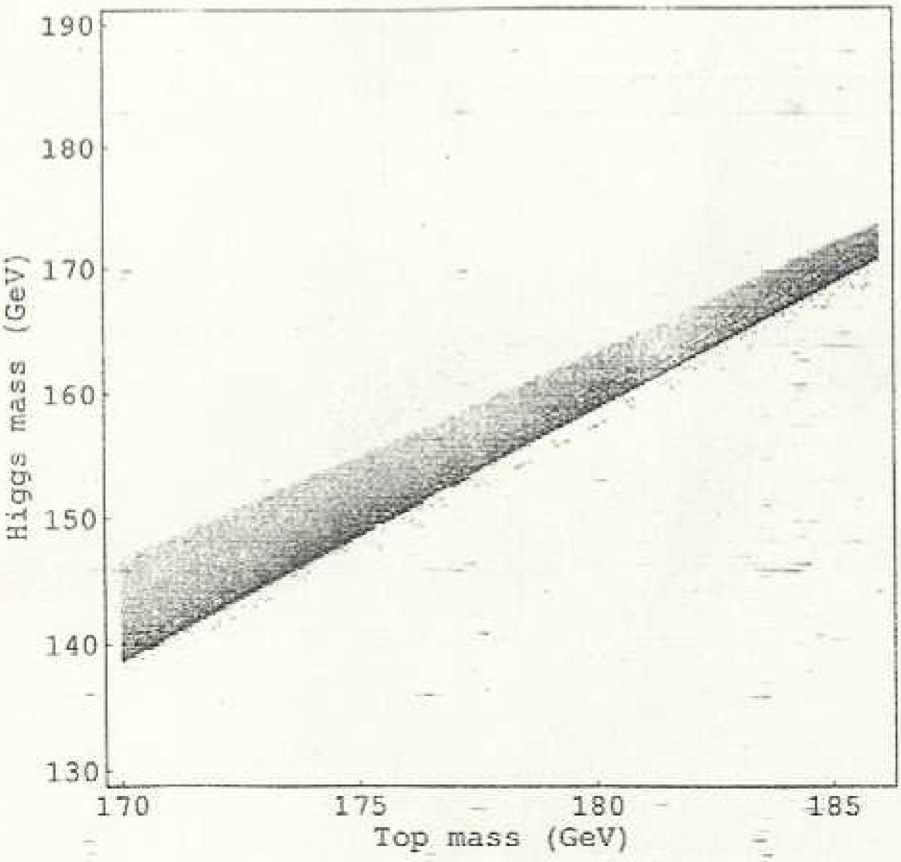
$\therefore \quad \langle \lambda \rangle \simeq 0.01$

- λ_{low} Mostly from h_t^4 RG Contribution

Higgs Mass - Top Mass Relation:

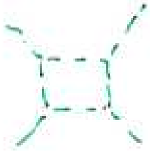
$m_{3/2} \ll M$

Random Uncorrelated Soft masses $\rightarrow P(\lambda)$



λ_{high} Modified by

- High Scale Thresholds



$$\delta\lambda = \frac{3h_t^4}{16\pi^2} a_t^2 \left(1 - \frac{a_t^2}{12}\right) \qquad a_t = \frac{A_t - \mu\cot\beta}{m_{\tilde{t}}}$$

$$\lesssim 0.007$$

- Hard SUSY Breaking

$$\frac{c_1}{M^2} \int d^2\theta \, S \, (H_u H_d)^2$$

$$\frac{c_2}{M^4} \int d^4\theta \, S^\dagger S \, (H_u H_d)^2$$

$$\delta\lambda = c_1 \frac{|F|}{M^2} + c_2 \frac{|F|^2}{M^4}$$

Parametrically $m_{SUSY} \lesssim 10^{-2} M$ -(but might be less stringent)

- Lepton ~~Flavor~~

$$H = U_{H,u} H_u + U_{H,d} H_d^* + \sum_{i=1}^{3} U_{H,i} L_i^*$$

Generic Mixing - No Qualitative Effect

- R-~~Parity~~

$$W = h'_{ij} L_i L_j \bar{e} + h'_2 \bar{Q} L \bar{d} + h_3 \bar{u} \bar{d} \bar{d}$$

└ Antisym - No effect

- Additional States Coupled to Higgs / sleptons

$$W = N H_u H_d + N H_u L_i + m^2 N^2$$

Can Modify Results - Only for Vector Matter

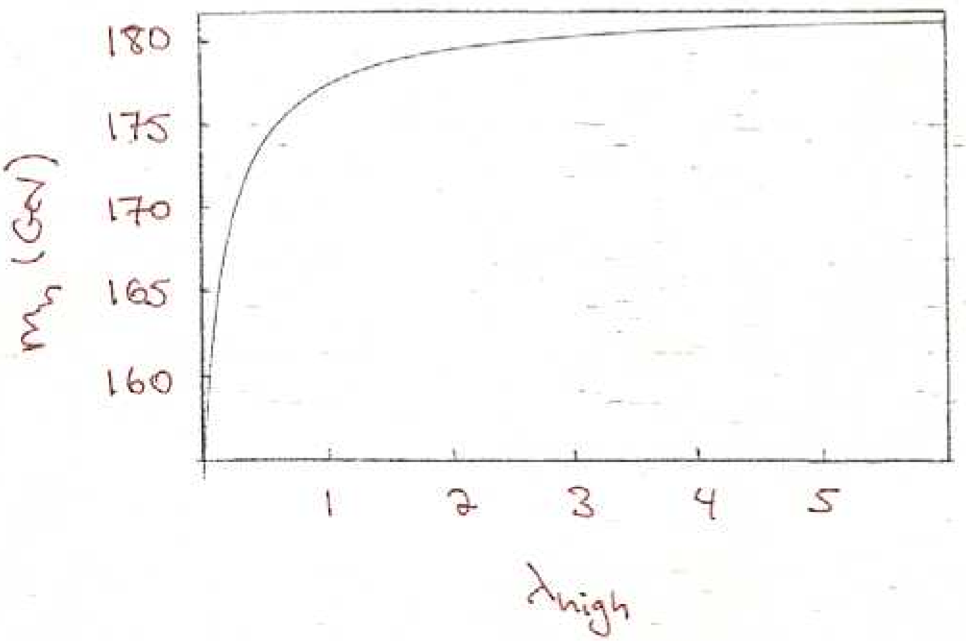
– Fairly Robust Probabilistic Prediction for Relation between m_h and m_t

$\underline{m_{SUSY} \sim M}$

Hard SUSY $\quad \frac{c}{M} \int d^2\theta \; S (H_u H_d)^2$

Assume c's Uncorrelated, Random

$P(\lambda) \sim$ Uniform

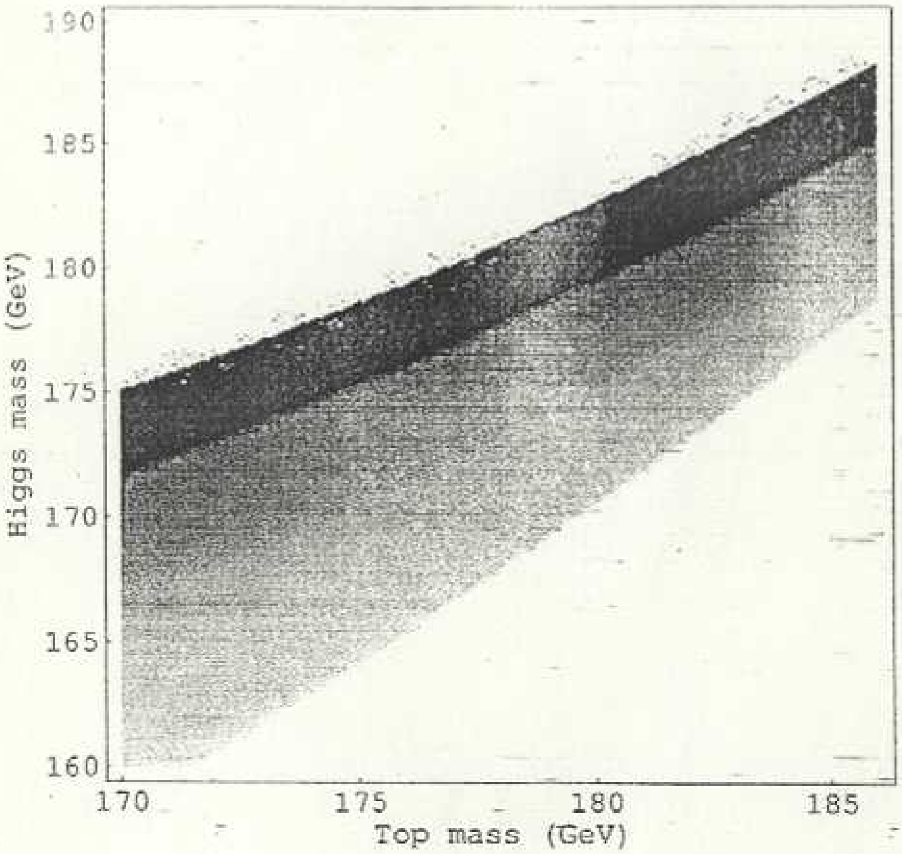


180
175
170
165
160
m_h (GeV)
1
2
3
4
5
λ_{high}

Higgs Mass - Top Mass Relation

$m_{SUSY} \sim M$

Random Uncorrelated Hard SUSY → $P(\lambda) \sim$ Uniform



SUSY Gauge Coupling Unification	Landscape SM Higgs Mass
Desert (No Split GUT μ-plets)	Desert (No Significant Additional Coupling to Higgs)
Only One Number	Only One Number
% Level Prediction	% Level Prediction
High Scale Thresholds Can Modify	High Scale Thresholds Can Modify
Requires (Slightly) Small Parameter $M_U / M_{S,P}$	Requires (Slightly) Small Parameter M_{SUSY} / M
Numerically Successful (As yet no other evidence for SUSY)	? ('Easily' disproved)

LHC:

- $t\bar{t}$ Production Rate ~ 1 Hz

Kinematic m_t Determination
Limited by Final State Gluon Radiation

$\Delta m_t = \pm (1-2)$ GeV

- $H \to ZZ^* \to 4\ell$ Gold Plated Mode

$Br(H \to ZZ^*) = (2-8)\%$. Only Need a few Events.

Invariant Mass Reconstruction

$\Delta m_h = \pm (1-2)$ GeV

Neutrino Masses

Atmospheric: $\nu_\mu \to \nu_\tau$ $\quad \Delta m^2 \sim 3\times10^{-3}\ eV^2$

Solar : $\nu_e \to \nu_\mu, \nu_\tau$ $\quad \Delta m^2 \sim 5\times10^{-5}\ eV^2$

$m_3 \gtrsim 50\ meV$

$m_2 \gtrsim 7\ meV$

$\frac{1}{M} \psi_L H \psi_L H$ $\qquad m_\nu = \frac{2 H^2}{M}$

$M_3 \lesssim 3\times10^{15}\ GeV$

$M_2 \lesssim 2\times10^{16}\ GeV$

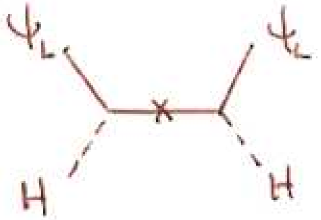
Approximate $U(1)_R$ Sym

- $m_\lambda \lesssim m_\phi$

  With General Lepton Flavor in m^2_{ij}

  $$H = U_{H,u} H_u + U_{H,d} H_d^* + \sum_{i=1}^{3} U_{H,i} L_i^*$$

- Gaugino Exchange



$$\frac{g^2}{m_{bino}} \psi_L H \psi_L H$$

Singlet Channel - Bino Only

$\therefore$ Single Neutrino Heavier other two $U_{3,i} = U_{H,i}$

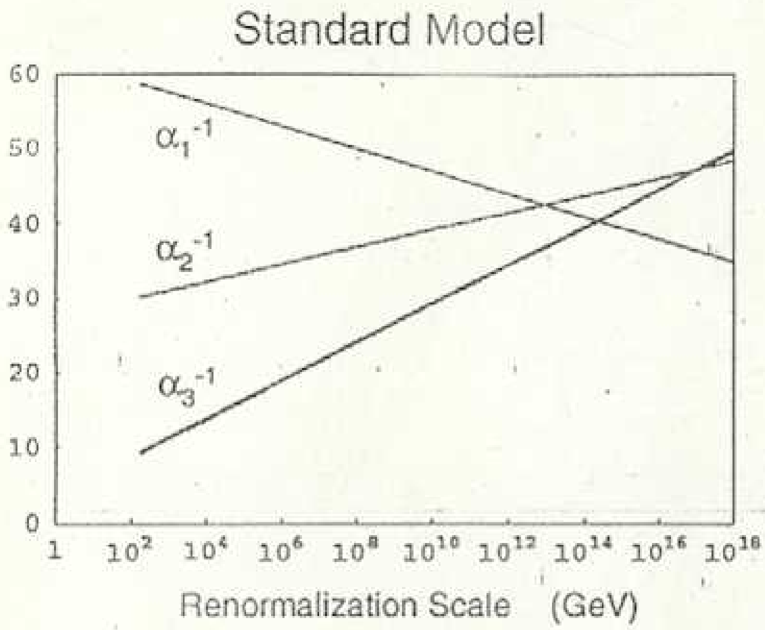
$m_{bino} \sim 5 \times 10^{13}$ GeV

$M_2 \sim 2 \times 10^{16}$ GeV → High Energy Completion

- Proton Decay - No effect from Light Gauginos

  $$\frac{1}{M_2} \bar{\psi} \gamma^\mu \psi \bar{\psi} \gamma_\mu \psi \qquad \tau(p \to \pi e) \sim 5 \times 10^{35} yr$$

Gauge Coupling Non-Unification



$M \sim 10^{17}$ GeV $\quad \sin^2\theta \sim \frac{3}{7}$

- $U(1)_Y$ Normalization
- Brane Realizations

Non-Unification may be Landscape Natural

Additional Light States ?

Gauginos - $U(1)_R$ Badly $\langle W \rangle \neq 0$ $m_\lambda \gtrsim m_{3/2}$

Requirements: $F_S = F_T = F_\Phi \equiv 0$

$D>S$ below M_4

$m_{3/2}$ Soft.

(Tune ..)

Heterotic M-Theory Doesn't Work

Higgsinos - $U(1)_{PQ}$ Generally

Model Building

← Traditional Sense

Feature(s) → 'Explain' Known Physics + Predictions

EW Hierarchy
Gauge Couplings
Flavor Hierarchies
Lepton Hierarchies
Baryon Asym
Dark Matter
⋮

(The Landscape is Vast ...)

+ Avoid All Bounds

Conclusions

- Landscape - Suggests a New Concept of Naturalness

- Scale of SUSY -

  Vacua Classified in Terms of Distinct Branches

- High Scale SUSY Branch -

  One Realization - Landscape Standard Model

  - Rather tight Probabilistic Predictions for Correlation between m_t and m_h

  LHC will Test ✓ $\Delta m_t = \pm (1-2)$ GeV
  $\Delta m_h = \pm (1-2)$ GeV

- If verified and nothing else found may have to rethink our previous notions of naturalness