# Landscape Naturalness

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Question:

How in Principle and in Practice Can Predictions be Extracted from a Fundamental Theory with a Landscape of Solutions ?

# (Technical) Naturalness

- Electroweak Symmetry Breaking

Stabilizing Physics < TeV $\rightarrow$ Most General Form in Conflict with ….

| | |
|---|---|
| Precision EW | Four-Fermi Contact Interactions |
| Higgs Mass | Small Neutrino Masses |
| Quark and Lepton FCNC | Proton Stability |
| E and M Dipole Moments | Direct Bounds on New States |

Mechanisms to Avoid …..

Could Standard Model be a Good Theory >> TeV ?

- Vacuum Energy

UV-IR / Holographic Properties of (Virtual) States

. Q-Gravity $\rightarrow \delta\rho \gg \rho$

$\rho \gg 10^{-120} M_p^4$ ?

# Fundamental Theory with a Multiverse

(Landscape of Vacua + Mechanism for Populating)

Landscape Naturalness :

Most Common on Landscape is Most Natural
(Subject to some Constraints)

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Multiverse Wavefunctional $\Psi(\zeta)$ $\zeta$ = Cosmological Trajectory on the Landscape

→ Correlations Among Observables : Necessarily Probabilistic

$$\mathcal{P}(x_i;y_j) = \int D\zeta \; |\Psi(x_i;y_j|\zeta)|^2 \; \mu(\zeta)$$

Observables — Multiverse Measure — External Measure / Restrictions

Note: No Predictions Without (Some Assumptions For)
. Correlations from Underlying Theory $\Psi(x_i;y_j|\zeta)$

$$\mathcal{P}(x_i; y_j) = \int D\zeta \; |\Psi(x_i; y_j|\zeta)|^2 \; \mu(\zeta)$$

- Experimental Priors $y_j$ Ã Versus ! External Restrictions $\mu(\zeta)$

Give up Explaining Relations Among
. Known Observables

May not be clear when to Stop

Selection Effects are Not Physical Principles

But Must Admit that in a Multiverse
there are in Fact Selection Effects

Give up Practical Utility of Program

- Here $y_j$ = { Current Data }

$\mathcal{P}(x_i; y_j)$ No Weighting by "Observers"

Note: No Predictions Without (Some Assumptions For)
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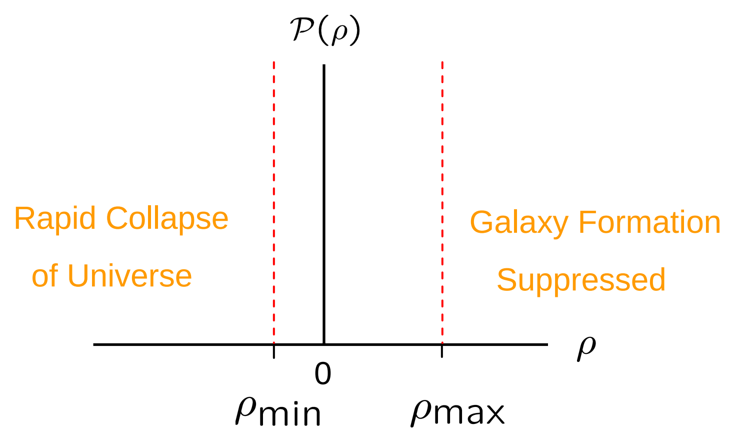
# Vacuum Energy (Banks ; Linde ; Weinberg)




Acceleration Terminates Galaxy Formation

$\rho_{\text{max}} < 100\ \rho_c$ Any Galaxy Forms

$\rho_{\text{max}} <$ few $\rho_c$ Weight by Fraction of Collapsed Baryon

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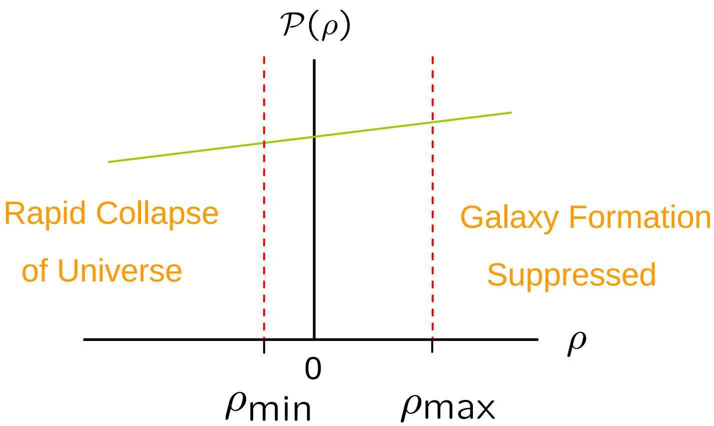


Acceleration Terminates
Galaxy Formation

$\rho_{\text{max}} < 100\ \rho_c$ Any Galaxy Forms

$\rho_{\text{max}} <$ few $\rho_c$ Weight by Fraction of Collapsed Baryon

Assumptions :

i) Hold Everything Fixed but $\rho$ (No Correlations)

ii) $P(\rho)$ smooth near $\rho$ ' 0 (mild)

$$\langle \rho \rangle \sim \frac{1}{2}\rho_{\text{max}} \neq 0$$

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

## Problems with Implementing Landscape Naturalness for Other Observables

- Full Landscape and { $\zeta$ } Unknown
- Full $\Psi(\zeta)$ Unknown
- Much of Landscape may be Incalculable
  .     (Restrict to Representative ?  Samples)
- Measure Problem    D $\zeta$
- Restrict to Local Minima – Unlikely Uniformly Populated
- Can't Calculate Many Observables of Interest Even in a  Single Vacuum
  .     (Limited to Discrete Quantities)

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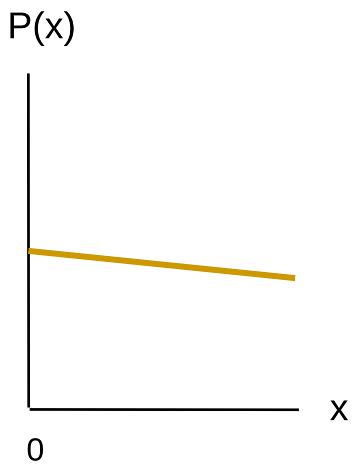
  (Limited to Discrete Quantities)

## Identify Robust Quantities → Classify Distributions of Vacua

- Origin of Small Parameters (Associated with Large Hierarchies)
  on the Landscape - EW Hierarchy, Vacuum Energy, Inflation, ….

# Importance of Symmetries on the Landscape




x Unprotected by Symmetry

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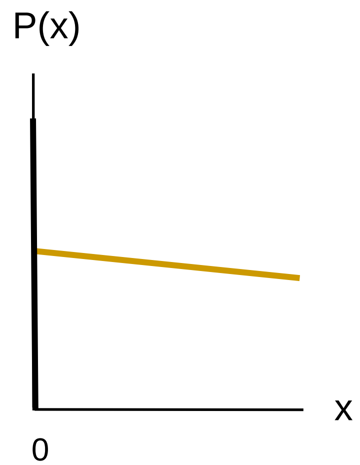


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x Protected by Unbroken Symmetry

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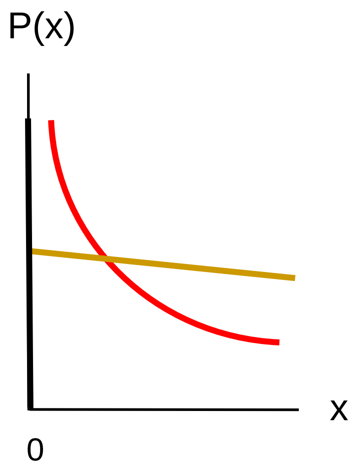


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x Protected by ~~Symmetry~~ -- Power Law  (Froggatt-Nielsen)

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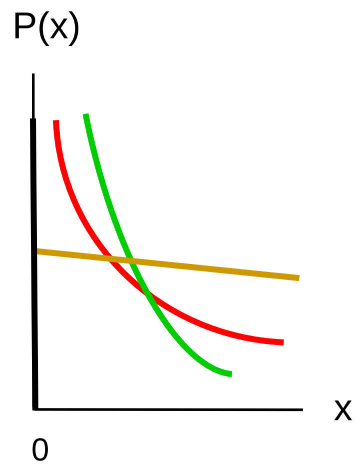


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x Protected by ~~Symmetry~~ -- Power Law (Froggatt-Nielsen)

x Protected by ~~Symmetry~~ – Exponential (Non-Perturbative)

# Importance of Symmetries on the Landscape


Note: Possible that

. P(ε) >> P(ε)

. s P(x) dx << s P(x) dx

x Unprotected by Symmetry

x Protected by Unbroken Symmetry

x Protected by ~~Symmetry~~ -- Power Law (Froggatt-Nielsen)

x Protected by ~~Symmetry~~ – Exponential (Non-Perturbative)

(Technical) Naturalness Are Important Organizing Principles on Landscape

# Landscape Naturalness for Hierarchies

- Symmetries which Protect Hierarchy ?
- Mechanisms for (Hierarchical) ~~Symmetry~~
- Compare Classes of Mechanisms

# The Scale of ~~SUSY~~ on the Landscape V ' 0

(M. Dine, E. Gorbatov, S.T.)

$$V = e^K \left(D_i W K^{ij} (D_j W)^\dagger - 3|W|^2\right) + D_a f^{ab} D_b$$

~~SUSY~~ ~~U(1)~~$_R$ ~~SUSY~~

| ~~SUSY~~ | ~~U(1)~~$_R$ | |
|---|---|---|
| . Classical | Classical | |
| Non-Perturbative | Classical | Non-Renormalization Thms |
| Non-Perturbative | Non-Perturbative | |

Assumptions :

$$\mathcal{P}(|W|^2) \sim \begin{cases} 1 & \text{Classical} \\ 1/|W|^2 & \text{Non-Perturbative} \end{cases}$$

$$\mathcal{P}(|DW|^2) \sim \begin{cases} |DW|^{2n} & \text{Classical} \\ 1/|DW|^2 & \text{Non-Perturbative} \end{cases}$$

Non-Perturbative :

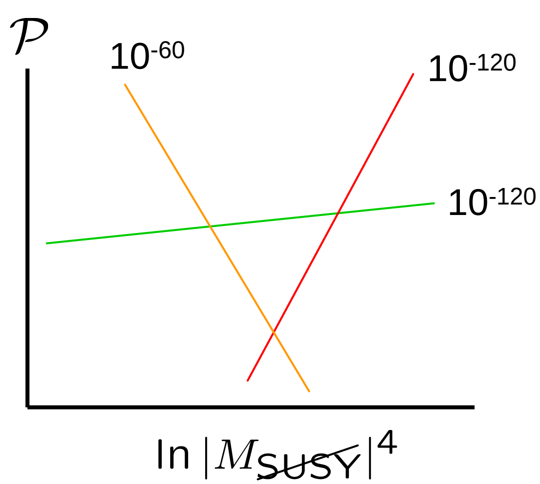
$$|W|^2 \, , \; |DW|^2 \;\sim\; e^{-1/g^2}$$

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

$$\mathcal{P}(|W|^2 < |W_0|^2) = \int_0^{|W_0|^2} d|W|^2 d|DW|^2 \, \mathcal{P}(|W|^2)\mathcal{P}(|DW|^2) \; \delta(|DW|^2 - 3|W|^2)$$

# The Branches of the Landscape

| | SUSY | $U(1)_R$ | $\mathcal{P}(\lvert W\rvert^2 < \lvert W_0\rvert^2)$ | V ' 0 |
|---|---|---|---|---|
| High | Classical | Classical | $\lvert W_0\rvert^{2n}$ | $10^{-120}$ |
| Intermediate | NP | Classical | $\ln \lvert W_0\rvert^2$ | $10^{-120}$ |
| Low | NP | NP | $\frac{1}{\lvert W_0\rvert^2}$ | $10^{-60}$ |



# The Branches of the Landscape

Statistics Overwhelms Tuning

| | SUSY (struck through) | U(1)$_R$ (struck through) | $\mathcal{P}(\lvert W\rvert^2 < \lvert W_0\rvert^2)$ | V ' 0 |
|---|---|---|---|---|
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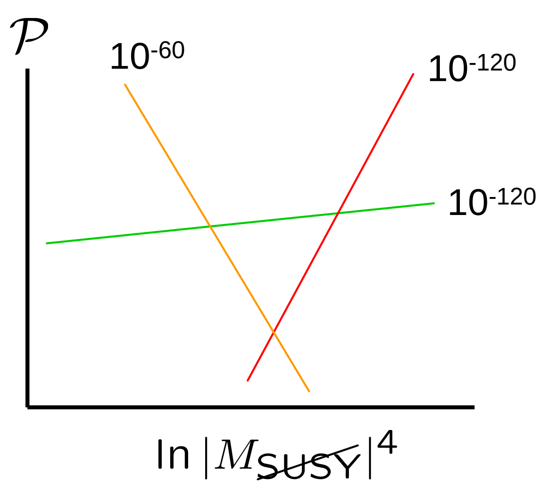
Tuning Overwhelms Statistics



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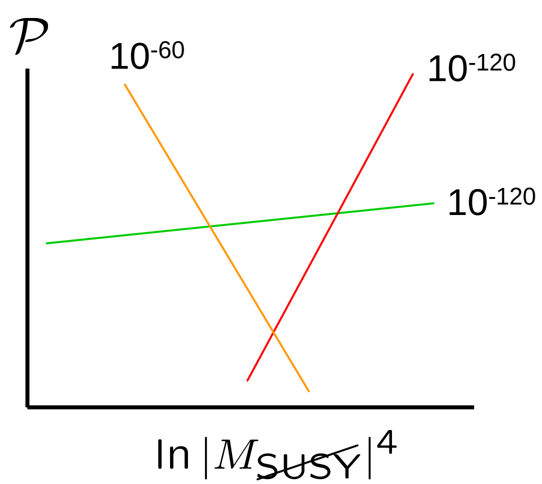
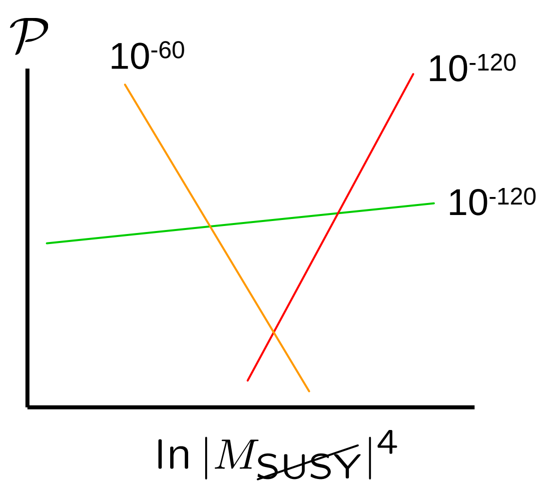



- Robust Feature of Local Supersymmetry
- Relative Occurrence Each Branch

# The Branches of the Landscape

| | ~~SUSY~~ | ~~U(1)~~$_R$ | $\mathcal{P}(\lvert W\rvert^2 < \lvert W_0\rvert^2)$ | V ' 0 | $m_Z^2$ | $\Delta$ n |
|---|---|---|---|---|---|---|
| High | Classical | Classical | $\lvert W_0\rvert^{2n}$ | $10^{-120}$ | $1\text{-}10^{-32}$ | 0-1/2 |
| Intermediate | NP | Classical | $\ln\lvert W_0\rvert^2$ | $10^{-120}$ | $1\text{-}10^{-32}$ | 0-1/2 |
| Low | NP | NP | $\frac{1}{\lvert W_0\rvert^2}$ | $10^{-60}$ | 1 | 0 |




- Robust Feature of Local Supersymmetry
- Relative Occurrence Each Branch
- Sub-Branches …..

# <u>The Structure of the Landscape</u>

- Realization and Breaking of Symmetries
- (Technical) Naturalness Enforced by (Approximate) Symmetries
- Distributions can (Dramatically) Peak
- Careful About Landscape Genericity – <u>Conditional</u> Correlations
- Statistics versus Tuning
- ~~SUSY~~ Branches

. Feature of Any Theory with Local Supersymmetry – Robust

. Step Towards a Priori (Probabilistic) Prediction of ~~SUSY~~ Scale

- Realizations of Branches
- Sub-Branches
- Experimental Signatures
- ……….

# Universality Classes of Landscape Correlations

Correlations $P(x_i;y_j)$ which are Insensitive to

. Details of $\Psi(x_i;y_j|\zeta)$ Within Some Wide Class of Vacua

Predictive if 8 $\{\zeta\}$ ¾ Class Vacua 9 P(x_i ; y_j) So Narrow ) $x_i$ ' $f(y_j)$

Universality Class of Predictions from Landscape Naturalness

Opportunity to Extract Real Predictions from Landscape Naturalness

. Within Classes of Vacua – Possible with Current Technology

# Realizations of EWSB on High Scale ~~SUSY~~ Branch

Technicolor
Warped Throat
Elementary Higgs
…………..

Conjecture: (Statistics Overwhelm Tuning)

The Higgs Sector Responsible for EWSB is a Single Elementary Scalar Higgs Doublet at or not too Far Below the Fundamental Scale

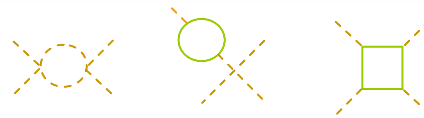
# The Landscape Standard Model (P. Graham, S.T.)

The Entire Visible Sector is the Three Generation Standard Model at or not too Far Below the Fundamental Scale

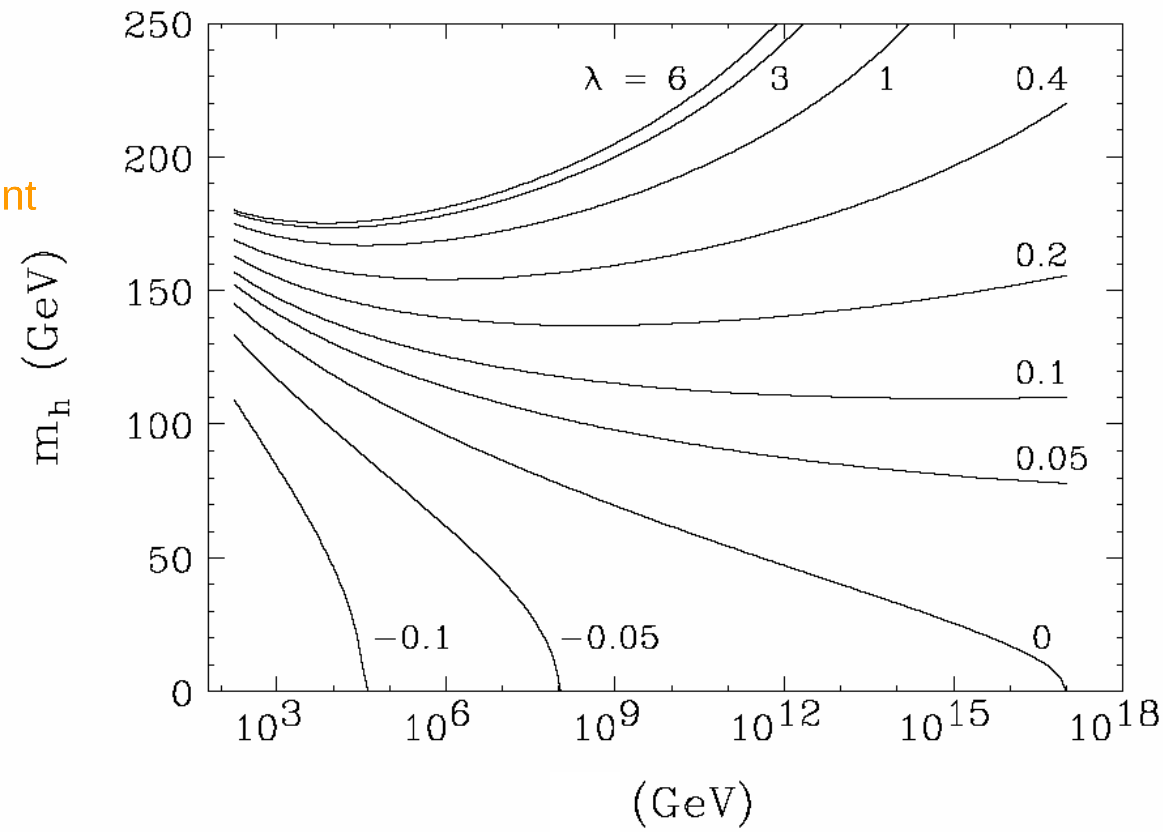
The Only Remaining Observable of EW Scale Physics is the
. Higgs Mass

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

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



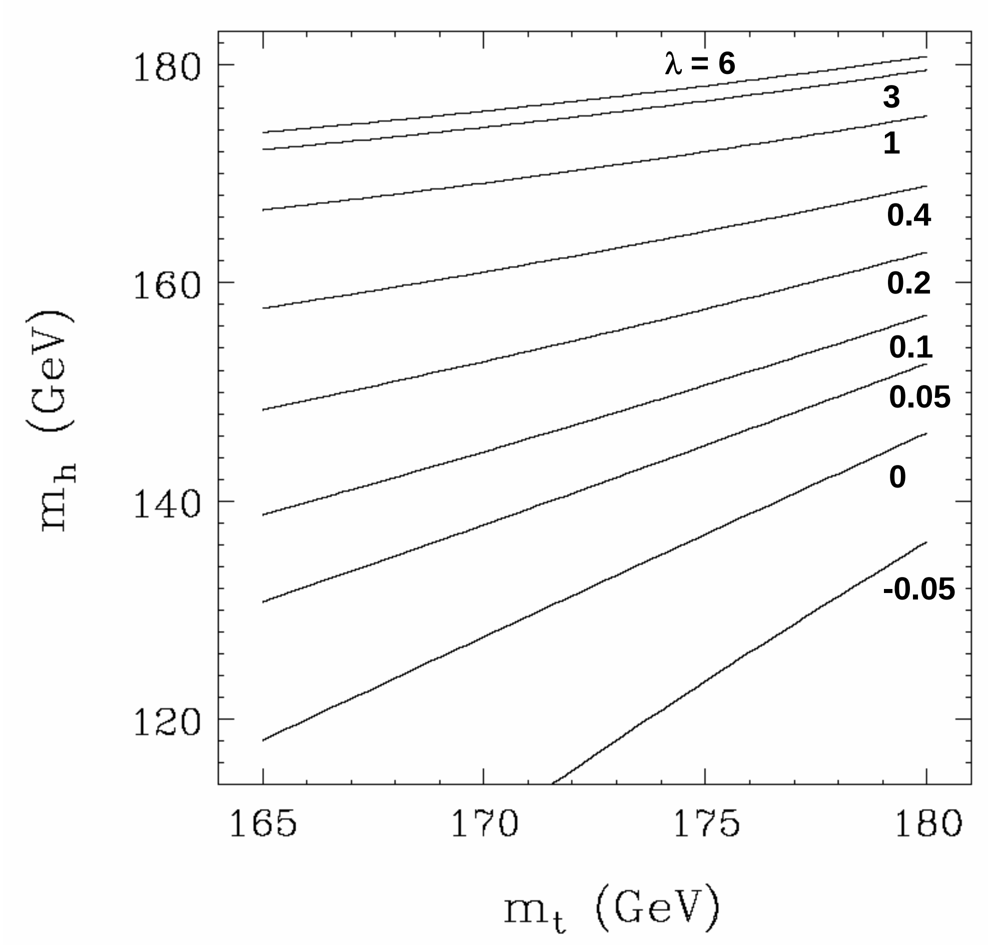
Quasi-fixed Point




$m_h^2 = 4\lambda / (2^{3/2} G_F)$

$m_t$ = 173 GeV

# Correlation Between $m_h$ and $m_t$




M = $10^{16}$ GeV

# Higgs Self Coupling

- $M_{\not{\text{SUSY}}}$ » M
- $M_{\not{\text{SUSY}}}$ < M (Cutoff in Distribution)

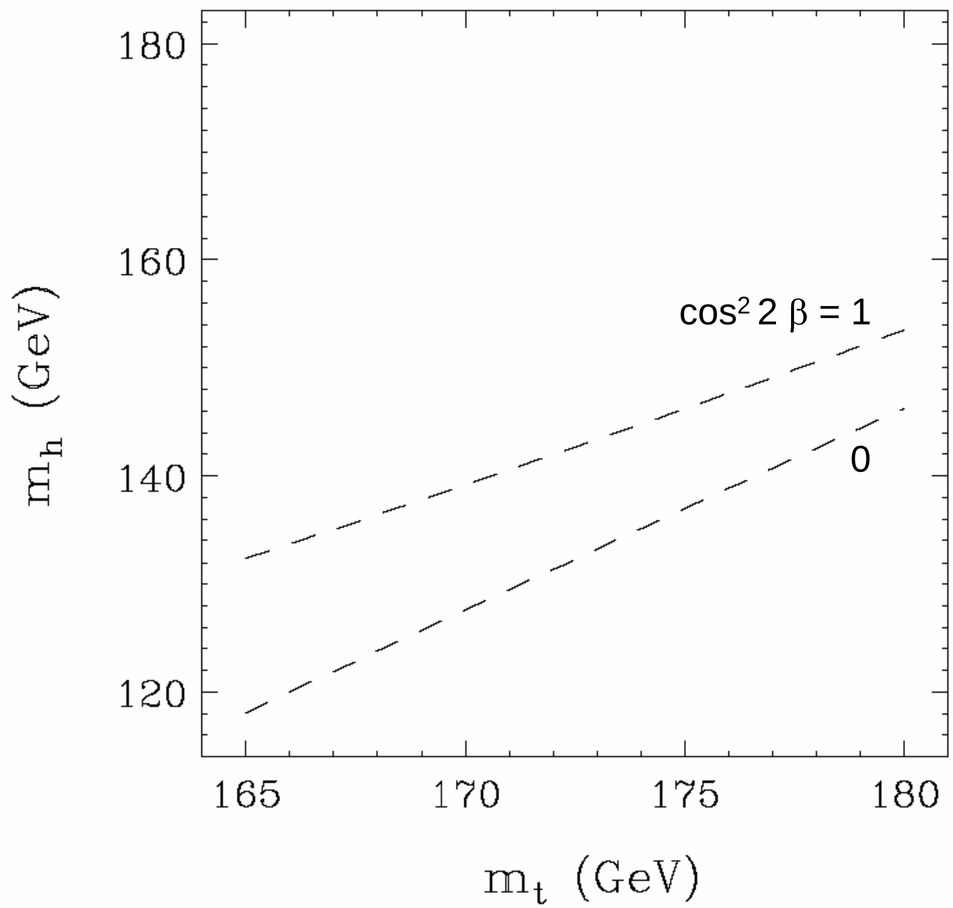
SUSY Boundary Condition for λ at Matching Scale

$$H = \cos\beta \; H_d^* + \sin\beta \; H_u$$

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

$V_D$ Potential

# Correlation Between $m_h$ and $m_t$ – SUSY Boundary Condition




$M = 10^{16}$ GeV

# Higgs Self Coupling on the Landscape - SUSY Boundary Condition

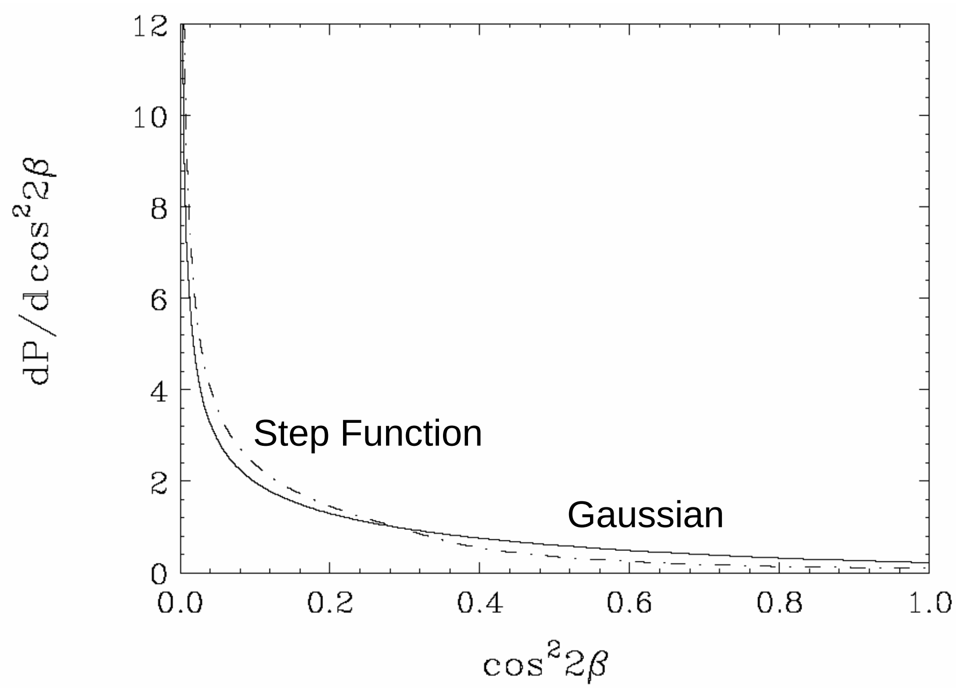
$$V_2 = \left(H_u^\dagger\ H_d\right)\begin{pmatrix} m_u^2+|\mu|^2 & m_{ud}^{*2} \\ m_{ud}^2 & m_d^2+|\mu|^2 \end{pmatrix}\begin{pmatrix} H_u \\ H_d^\dagger \end{pmatrix}$$

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

$$\mathcal{P}(\cos^2 2\beta) = \int d\bar{m}_u^2\ d\bar{m}_d^2\ d|\bar{m}_{ud}^2|^2\ d|\bar{\mu}|^2\ \mathcal{P}(\bar{m}_u^2,\bar{m}_d^2,|\bar{m}_{ud}^2|^2,|\bar{\mu}|^2)\ \delta(\bar{m}_H^2)\ \delta\left(\cos^2 2\beta - \frac{(\bar{m}_u^2-\bar{m}_d^2)^2}{(\bar{m}_u^2-\bar{m}_d^2)^2+4|\bar{m}_{ud}^2|^2}\right)$$

Assumption : Random,
. Uncorrelated

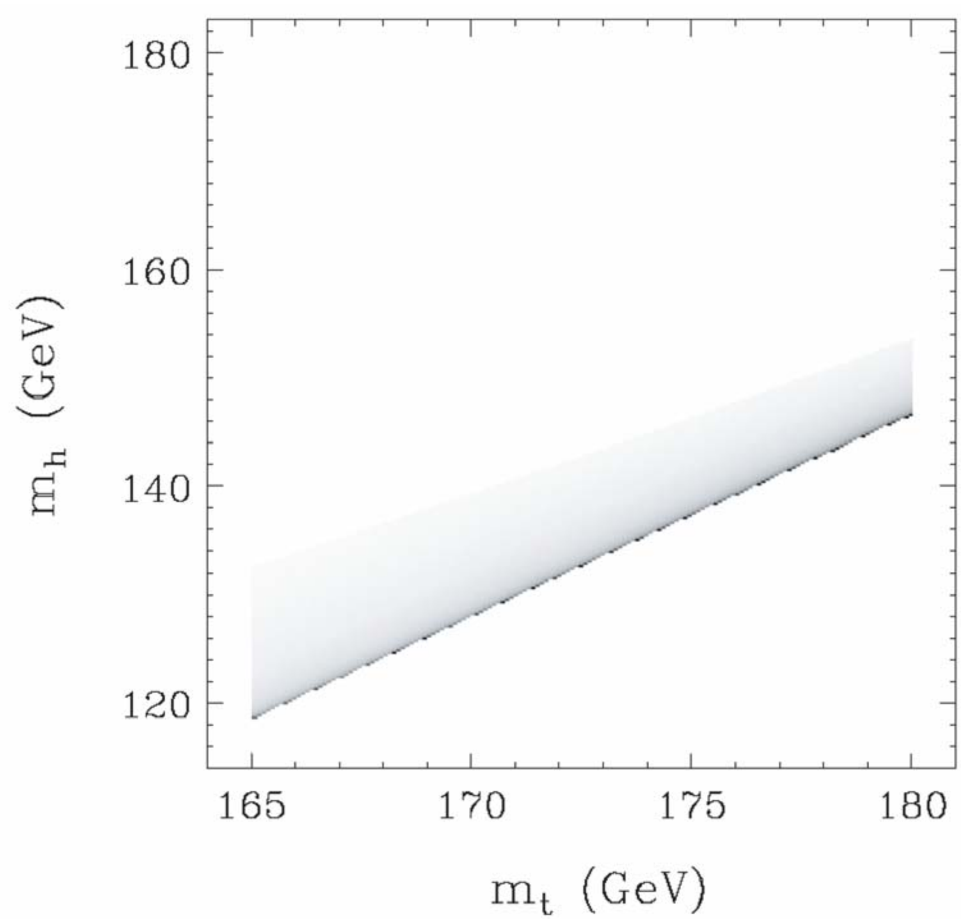
$$\mathcal{P}(\bar{m}_u^2,\bar{m}_d^2,|\bar{m}_{ud}^2|^2,|\bar{\mu}|^2) = \mathcal{P}(\bar{m}_u^2)\mathcal{P}(\bar{m}_d^2)\mathcal{P}(|\bar{m}_{ud}^2|^2)\mathcal{P}(|\bar{\mu}|^2)$$




(1/8)((3/5)$g_1^2$+$g_2^2$) ' 0.06

h λ i ' 0.01 +- 0.01

## Universality Class of $P(m_h:m_t)$ Correlation – SUSY Boundary Condition



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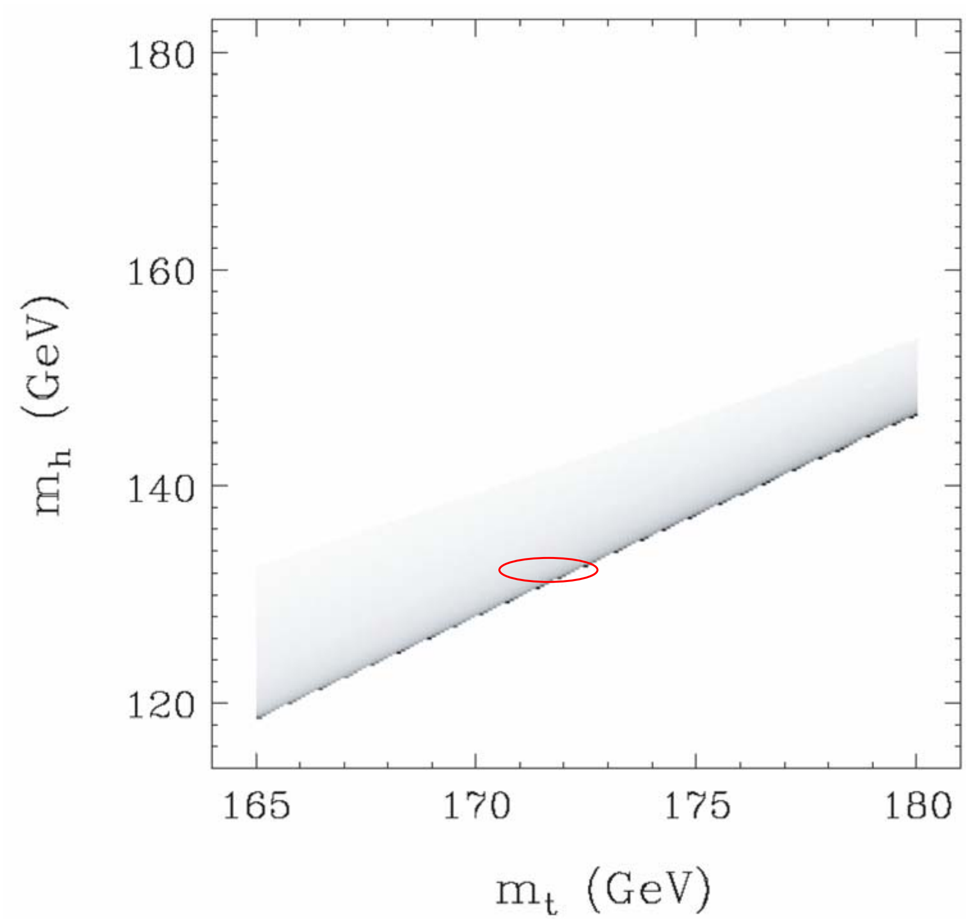


LHC : > 30 $fb^{-1}$

$h^0$ ! $ZZ^*$ , $\gamma\ \gamma$

$\Delta\ m_h$ ' 1 GeV

$\Delta\ m_t$ ' 1 GeV

# Corrections and Uncertainties in $m_h$ Correlation

## Corrections :

| | | $\Delta m_h / m_h$ |
|---|---|---|
| Renormalization Group Running | | + 100 % |
| Finite $m_t^{pole}$ Corrections | | |
| | QCD 1-Loop | -10.8 % |
| | QCD 2-Loop | - 3.3 % |
| | $G_F m_t^2$ 1-Loop | + 3.7 % |
| | $G_F m_h^2$ 1-Loop | - 3.5 % |
| Finite $m_h^{pole}$ Corrections | | |
| | $(G_F m_t^2)^{1,2}$ 1-Loop | + 2.9 % |
| | $G_F m_h^2$ 1-Loop | + 1.4 % |

## Uncertainties :

| | | |
|---|---|---|
| $\Delta \alpha_s(m_z)$ | +- 1 % | |
| 2-Loop Running | +- 1-2 % | (estimate) |
| Landscape Statistical | +- 1.3 % | |
| Boundary Scale $10^{15} - 10^{18}$ GeV | +- 0.4 % | (Near $\beta_\lambda$ ' 0) |

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Level of Irreducible Uncertainties

# Robustness of Universality Class to UV Completion

$\lambda$ ' 0    Delicate Boundary Condition

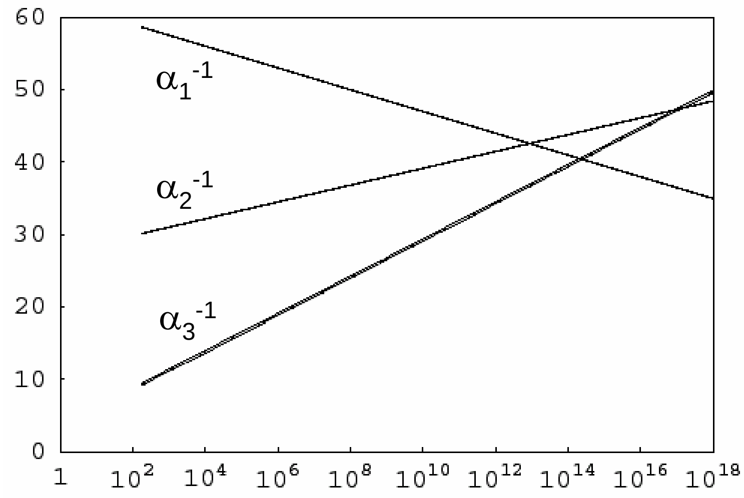
- ✓ High Scale Thresholds
- ✓ Hard SUSY   $m_{\not{SUSY}} < 10^{-(1-2)}$ M
- ✓ Slepton Flavor Violation $H_u$ , $H_d$ , $L_i$
- ✓ R-Parity Violation
- X Additional Vector Rep States Coupled to Higgs/Sleptons

Slightly small Parameter   $m_{\not{SUSY}} / M$   →

Robust Universality Class of $m_h$ ' $f(m_t)$ Correlation

.   Rather Insensitive to UV Physics + $\Psi(m_h;m_t \mid \zeta)$

# Gauge Coupling (Non)-Unification



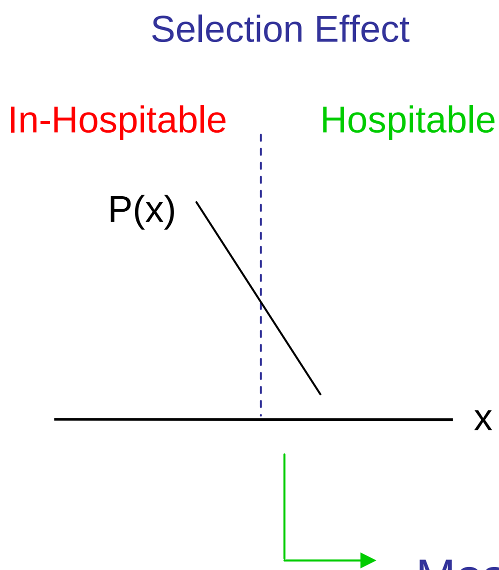

$\sin^2 \theta_W \simeq 3/7$

$U(1)_Y$ Normalization

Brane Realizations : $g_{4,i}^{-2} = V_{D-4}\, g_{D,i}^{-2}$

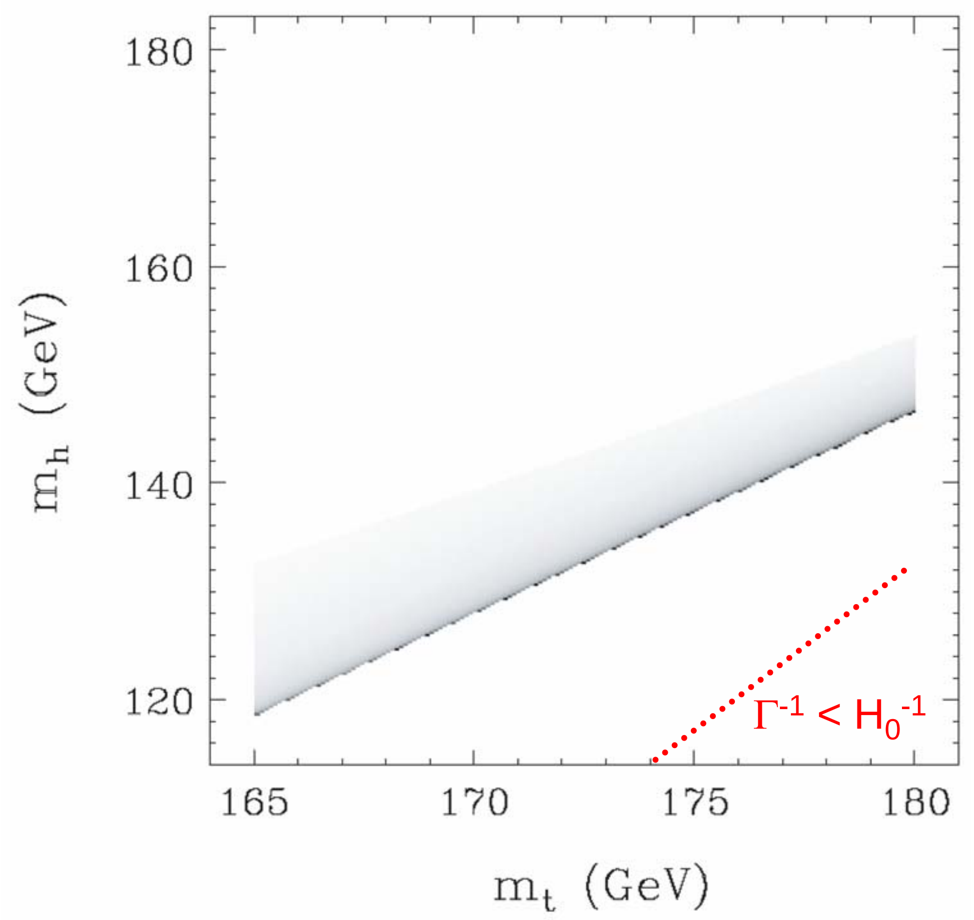
Gauge Coupling Unification May Not be Landscape Natural

# Living Dangerously




Most Likely Value Near Boundary of
In-Hospitable Region

# Living Dangerously Versus Comfortably



# Conclusions

• Fundamental Theory with Many Vacua →
. Landscape Naturalness

• (Conditional) Correlations Among Observables from $\Psi(\zeta)$

• Symmetries Organize Structure of Landscape

Supersymmetry: Non-Renormalization Thms + V ' 0 →
. Low, Intermediate, High Scale ~~SUSY~~ Branches

Additional Symmetries: Sub-Branches …..

• Universality Classes of Correlations → Path to Predictions

Landscape Standard Model + SUSY B.C. →
. $m_h$ ' $f(m_t)$ Correlation Wide Class of Vacua
. Landscape Uncertainties » Irreducible Uncertainties in Calculation .
Well Tested by LHC

Other Universality Classes ………