Naturalness vs Stringy Naturalness: Predictions for SUSY

arXiv:1906.07741v1 & Phys.Rev.Research 1, 023001

Shadman Salam[1] Howard Baer[1] Vernon Barger[2]

[1]University of Oklahoma
[2]University of Wisconsin

Phenomenology 2020
University of Pittsburgh via Ethernet
5th May, 2020
shadman.salam@ou.edu

The UNIVERSITY of OKLAHOMA

Overview

1. Naturalness
   - -Practical Naturalness
   - -Implications of Practical Naturalness
   - -Stringy Naturalness
   - -Anthropic Justifications
2. Implications of Stringy Naturalness
   - -Why the SM is likely a rare occurrence in the landscape
   - -Why CMSSM/mSUGRA is likely an infrequent occurrence in the landscape
3. Living Dangerously within the String Theory Landscape
   - -Consequence of Living Dangerously
4. Implications for SUSY and DM searches
5. Conclusion

Practical Naturalness

- An observable $\mathcal{O}$ is natural if all *independent* contributions to $\mathcal{O}$ are comparable to or less than $\mathcal{O}$.
- For instance, the Barbieri-Gudice measure of naturalness

$$\Delta_{BG}(\mathcal{O}) \equiv max_i \left| \frac{\partial log\mathcal{O}}{\partial log p_i} \right| = max_i \left| \frac{p_i}{\mathcal{O}} \frac{\partial \mathcal{O}}{\partial p_i} \right|$$

  for an observable, $\mathcal{O} = a_1 p_1 + .. + a_n p_n$.
- If $\mathcal{O} \to m_Z^2$ and for a high-scale cut-off Λ one expands m_Z^2 out in terms of fundamental GUT scale parameters,

$$m_Z^2 \simeq -2.18\mu^2 + 3.84 M_3^2 + 0.32 M_3 M_2 + 0.047 M_1 M_3 - ...$$

  in comparison to usual weak scale SUSY parameters $m_Z^2 \simeq -2m_{H_u}^2 - 2\mu^2$.
- μ hardly evolves with respect to the other terms $\Rightarrow$ need for high fine-tuning for low Δ_{BG}(more natural).
- Δ_{BG} is highly model-dependent, i.e. Δ_{BG} is very different for models with mass universality than those without.

Practical Naturalness

- Another conventional measure of naturalness is Δ_{HS} defined as

$$\Delta_{HS} \equiv \frac{\delta m_{H_u}^2}{m_h^2}$$

where,

$$m_h^2 \simeq m_{H_u}^2(weak) + \mu^2(weak) + mixing + rad.corr.$$

- The issue with this measure is it considers $\delta m_{H_u}^2$ to be independent of $m_{H_u}^2$ by setting several terms to zero in $\frac{dm_{H_u}^2}{dt}$(where $t = logQ^2$),

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2 M_1^2 - .. + 3f_t^2 X_t\right)$$

in particular in $X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$, Δ_{HS} ignores the $m_{H_u}^2$ contribution.

- This simplification predicts top squarks lighter than 500 GeV (LHC excluded) and small A_t terms for low Δ_{HS} fine-tuning.

Practical Naturalness

- A more accurate, **model independent** measure Δ_{EW}, comes to the rescue which relates the Z-boson mass to various SUSY contributions including radiative corrections as,

$$\frac{m_Z^2}{2} \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2})$$

and

$$\Delta_{EW} = |(\max \text{RHS contribution})| / \left(\frac{m_Z^2}{2}\right)$$

is low provided all $weak - scale$ contributions are comparable to $m_Z^2/2$

Implications of Practical Naturalness

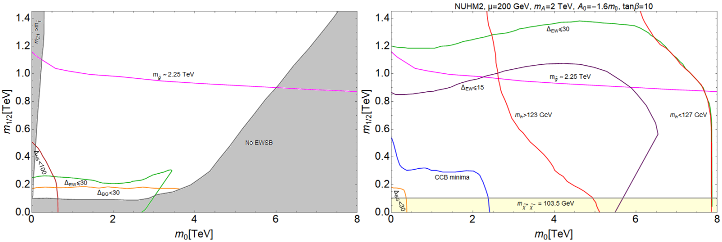


Figure: The m_0 vs $m_{1/2}$ plane for mSUGRA/CMSSM (left) and NUHM2 (right) with various fine-tuning contours

- In the mSUGRA model with $A_0 = 0$, conventional naturalness would dictate the low $m_0 - m_{1/2}$ values to be more natural and excluded by LHC bounds.
- In the NUHM2 model → bigger A_0 term → Δ_{EW} expands out ⇒ bigger m_0 and $m_{1/2}$ values
- Conventional naturalness would still put us in the lower regions of parameter space.

Stringy Naturalness

- The value of an observable $\mathcal{O}_2$ is more natural than a value $\mathcal{O}_1$ if more *phenomenologically viable* vacua lead to $\mathcal{O}_2$ than to $\mathcal{O}_1$ (Douglas).
- *Phenomenologically viable* $\Rightarrow$ anthropically veto any vacua wildly dissimilar to ours $\Rightarrow$ CCB, no EWSB or too large m_Z^{PU}.
- *PU* refers to Pocket Universes in the multiverse of the string landscape of vacua $\sim 10^{500}$.
- Nuclear physics calculations by Agrawal *et al.* $\Rightarrow m_{weak}^{PU}$ should not differ by more than a factor 2-5 from our measured value of the weak scale $\Rightarrow \Delta_{EW} \lesssim 30$.

Anthropic Justifications

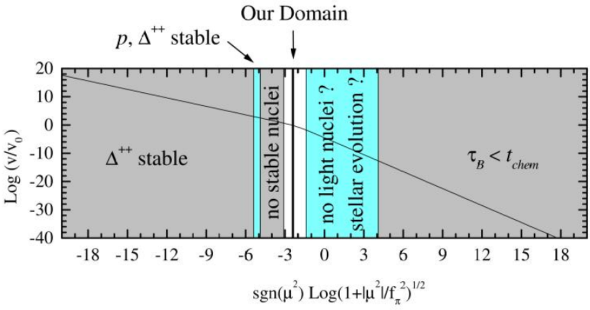
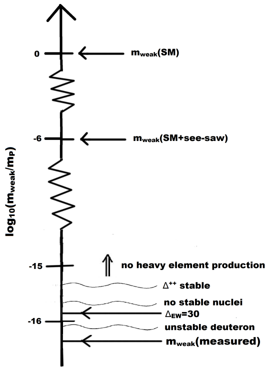


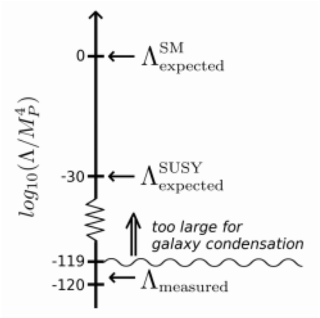
Figure: Figure summarizing anthropic arguments (Agrawal, Barr, Donoghue, Seckel, 1998).

- We live in a narrow band with conditions just right for formation of complex nuclei and hence to support life.

Anthropic Justifications



(a) Several anthropic bounds on m_{weak}



(b) Anthropic argument for the cosmological constant

Stringy vs Practical Naturalness

- Douglas's notion of stringy naturalness however prefers a mild draw to larger soft terms according to the ansatz,

$$f_{SUSY}\left(m^2_{hidden}\right) \sim \left(m^2_{hidden}\right)^{2n_F+n_D-1}$$

where n_F is the number of F-breaking terms, n_D is the number of D-breaking terms and $n = 2n_F + n_D - 1$.

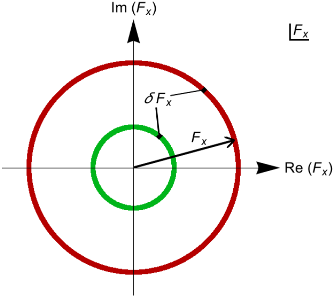


Figure: Statistically more likely to lie on the outer (red) circle due to larger area.

Stringy vs Practical Naturalness

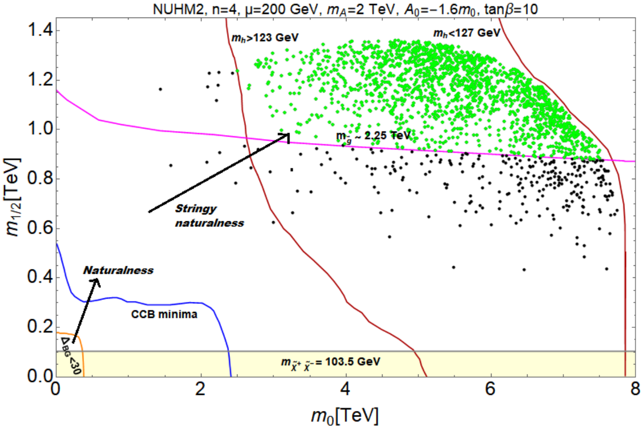


Figure: Stringy naturalness puts us in the green region while conventional naturalness would put us in the unlivable corner.

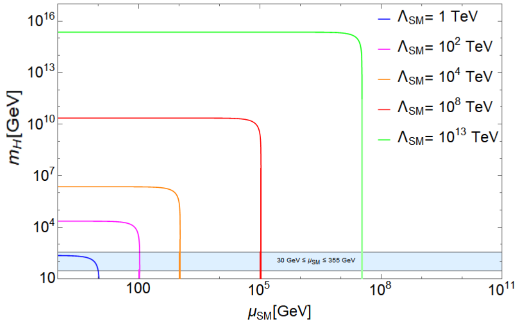
SM is likely a rare occurrence in the landscape

- In the SM, the Higgs mass with quadratic divergent radiative corrections is

$$m_H^2 \simeq m_H^2(tree) + \delta m_H^2$$

where, $m_H^2(tree) = 2\mu_{SM}^2$ and

$$\delta m_H^2 = \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8cos\theta_W} + \lambda_{SM}\right)\Lambda_{SM}^2.$$



- Hence $\Lambda \gg m_{weak} \Rightarrow$ teensy range of μ gives $m_{weak} \sim 100$ GeV.

CMSSM/mSUGRA is likely an infrequent occurrence in the landscape

- A large range of μ gives $m_{weak} \sim 100$ GeV.

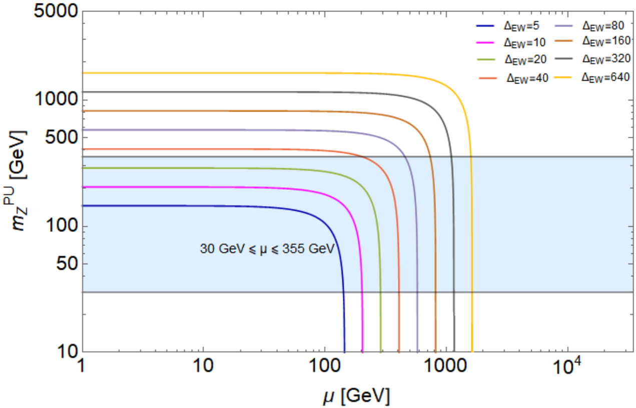
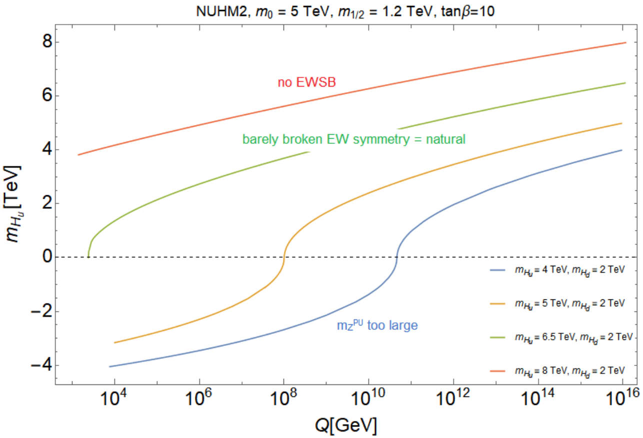


Figure: As Δ_{EW} increases, the weak scale for a pocket universe lies well beyond the allowed anthropic zone.

Living Dangerously

- *Living Dangerously*, a phrase coined by Arkani-Hamed *et al.* $\Rightarrow$ "Anthropic reasoning leads to the conclusion that we live dangerously close to violating an important but fragile feature of the low-energy world"-in our case, this is appropriate EWSB with $m_{weak}^{PU} < 4m_{weak}^{OU}$.



Living Dangerously

- As $A(t)$ gets large negative, then $\tilde{t}_1, \tilde{t}_2$ contributions to the weak scale falls below anthropic requirement.

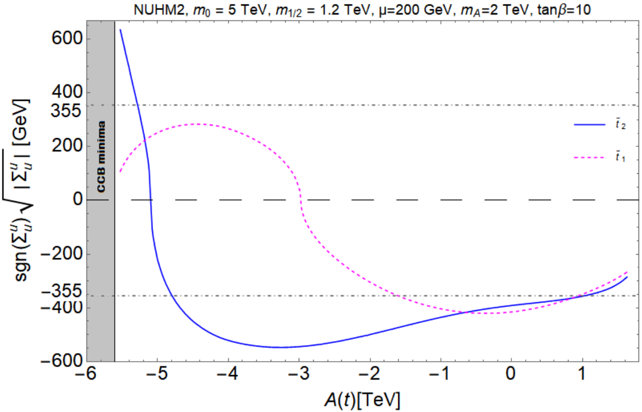
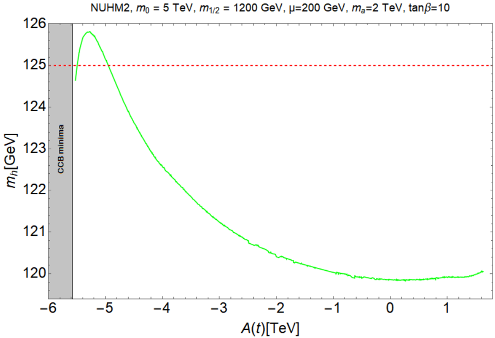


Figure: Contributions of $\sqrt{\Sigma_u^u(\tilde{t}_{1,2})}$ to weak scale vs $A(t)$ in NUHM2 model.

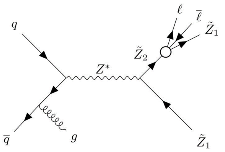
Consequence of Living Dangerously



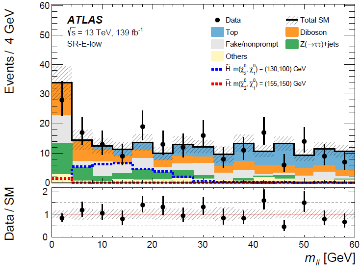
- Large $A_0 \Rightarrow$ large mixing in the top-squark sector $\Rightarrow$ maximizing m_h.
- Unnatural $A_0 \sim 0$ TeV $\Rightarrow m_h \sim 119$ GeV.
- Natural selection of large $A_0 \Rightarrow m_h \sim 124 - 126$ GeV in accord with measured higgs mass.

Implications for SUSY and DM searches

- Stringy naturalness $\Rightarrow \mu$ parameter to be close to weak scale $\Rightarrow$ light higgsinos with mass range $m(higgsinos) \sim 100 - 300$ GeV.
- Interesting signatures should emerge slowly as more data accures at the LHC from



(a) Dilepton plus jet channel promising for SUSY signal at the LHC and beyond.

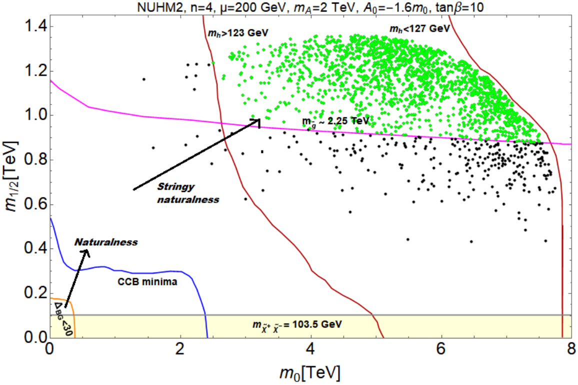


(b) ATLAS Collaboration Data, $arXiv$: $1911.12606v2$

Implications for SUSY and DM searches

- Gluino and top-squark signatures might emerge at HL-LHC but may require HE-LHC since $m_{\tilde{g}} \lesssim 6$ TeV and $m_{\tilde{t}_1} \lesssim 3$ TeV.
- Higgsino-like WIMPS are expected at multi-ton noble liquid dark matter detectors but will be difficult to detect since these make up $\sim 10\%$ of dark matter (90% axions).

Conclusion



- String theory landscape $\Rightarrow m_{weak}$ and Λ_{cc} are environmentally determined from anthropic requirements.
- Statistical draw to large soft terms $\rightarrow$ *Radiative Natural SUSY* is the most likely scenario.
- Stringy naturalness $\Rightarrow m_h \sim 125$ GeV with no sight of Sparticles (with current search limits).