Another view of the Higgs Boson and Naturalness

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My philosophy: bottom-up speculative

- Start with the Standard Model, and explore its deficiencies
- Do not assume vast new frameworks of ultra-high energy physics for which there is no experimental evidence
- Be humble about the ability of theorists to predict the unknown
- Don't be quick about abandoning long-held ideas, but pay attention to the data

"It is difficult to make predictions, especially about the future."

- President Chelsea Clinton, second inaugural address, 2037

the Standard Model and naturalness

- **The Standard Model is a really good model**
- It is a renormalizable gauge theory
- **By itself,** is does not have a fine tuning problem
- The trade-off is that the Higgs vev v and the Higgs boson mass M_h **are not predicted**
- Instead you are supposed to impose the measured values as renormalization conditions
- Alternatively, use the measured values to impose boundary conditions on the RG equations for the running couplings $\lambda(\mu)$ and $m_0^2(\mu)$

$$V = m_0^2 H^\dagger H + \frac{1}{2}\lambda |H^\dagger H|^2$$

$$H = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix}$$

$$v = 246.22\ \mathrm{GeV}$$

$$M_h^2 = \frac{\partial^2 V_{eff}}{(\partial h)^2}\Big|_{h=v} + [\Pi_{hh}(M_h^2) - \Pi_{hh}(0)]$$

$$= (126\ \mathrm{GeV})^2$$

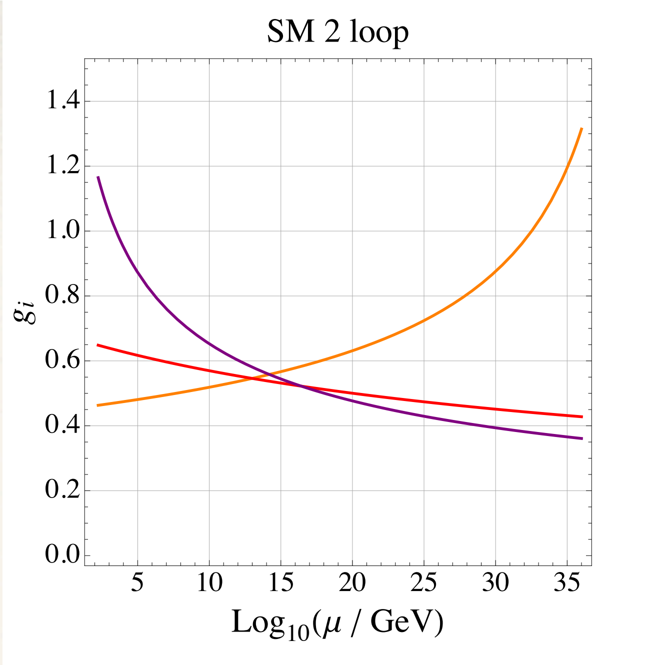
very small

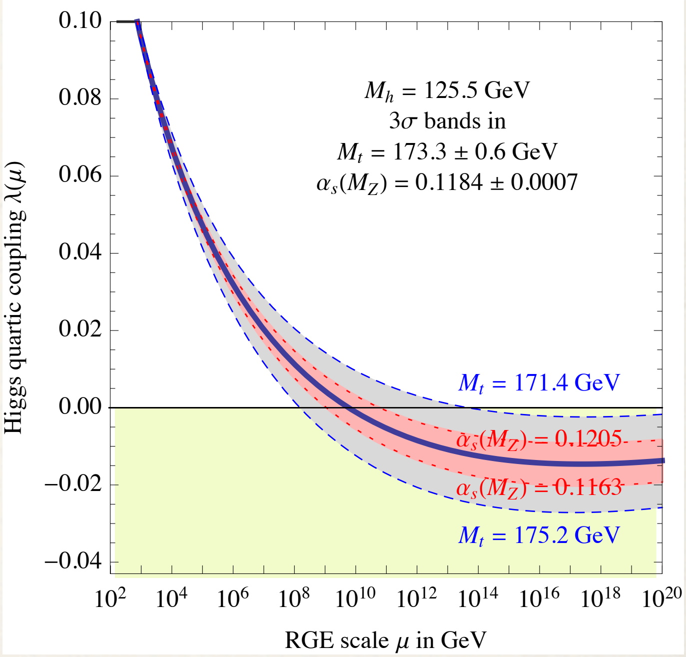
$$V = \frac{1}{2} m_0^2 h^2 + \frac{1}{8}\lambda\, h^4$$

To me the most unnatural feature of the Higgs mass-squared parameter in the SM is not how it runs, but rather that it is tachyonic

“Derived” scales of the SM

- Having fixed the electroweak scale and the Higgs boson mass to their measured values, does the SM hint at any other scales?
- There is of course the approximate gauge coupling unification story, usually taken as a hint of weak scale SUSY
- The hypercharge gauge coupling has a Landau pole at ~ 10^{35} GeV, but who cares?
- There is also the apparent Higgs vacuum instability, possibly related to a UV scale that is 10^{10} GeV or higher



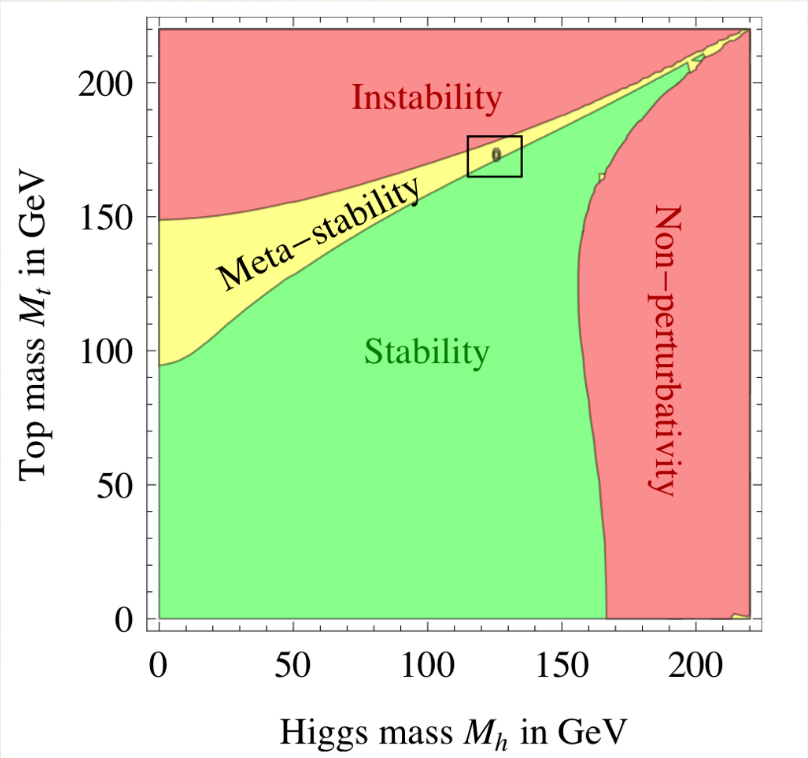


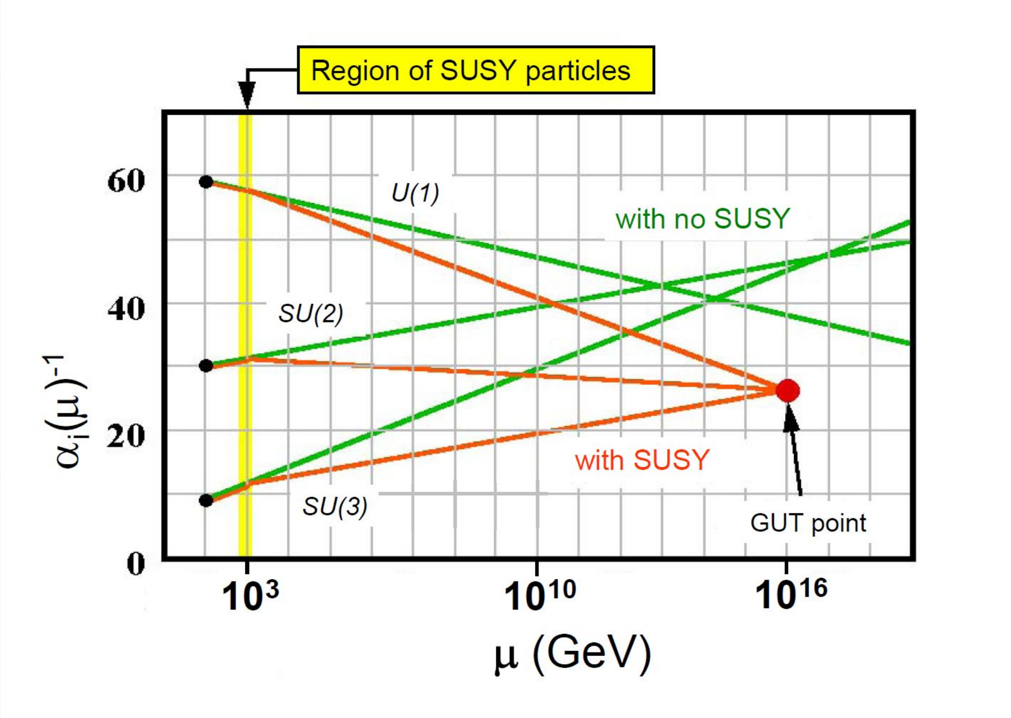
SM 3-loop running with 2-loop matching

A. Strumia, Moriond EW 2013

why do we live on the edge of stability?

or does supersymmetry save us?





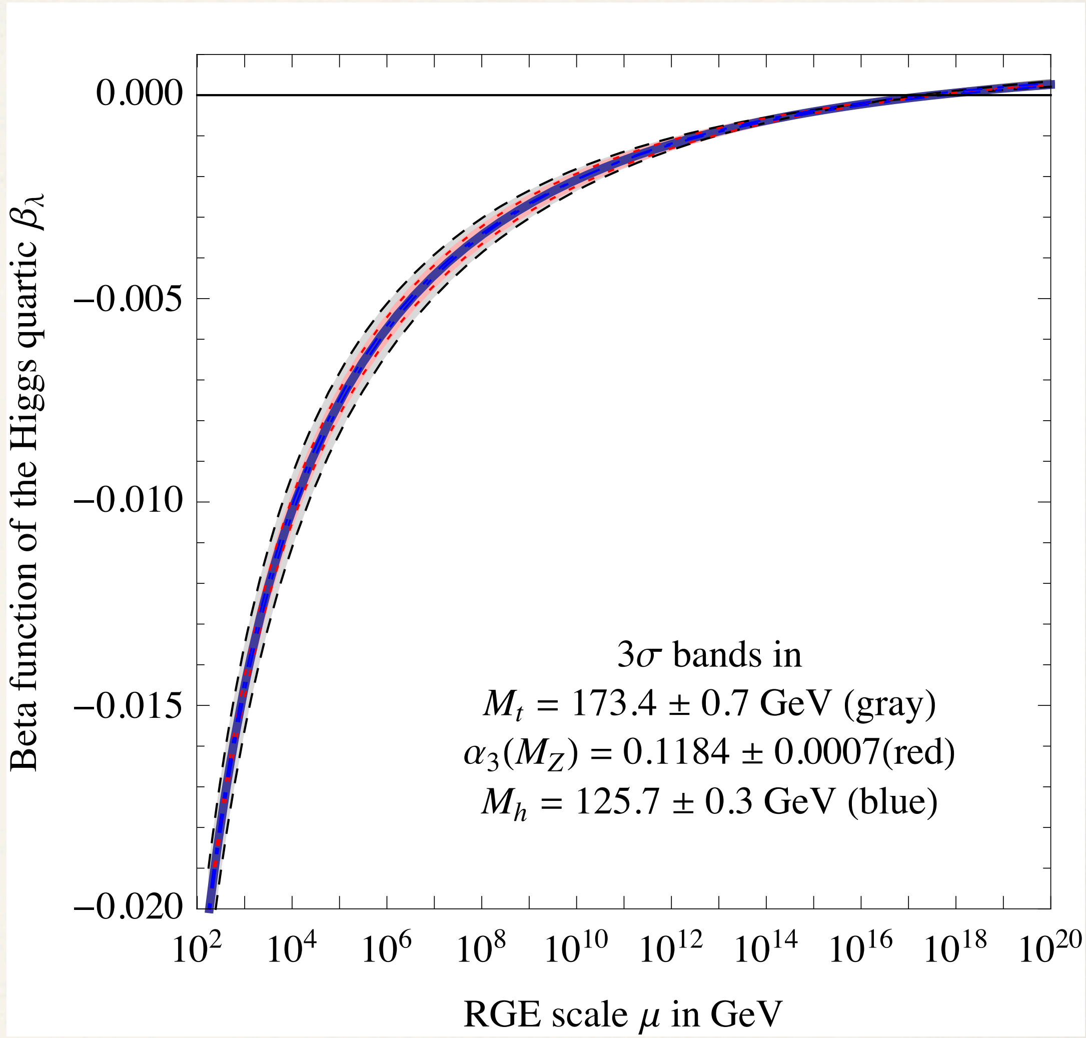
Note that these are mutually exclusive scenarios!

So one (or both) of these is just a coincidence at the few % level

"Derived" scales of the SM

- The Higgs self coupling beta function vanishes at ~ 10^{18} GeV
- Is this a hint connecting the SM to the Planck scale, or just a coincidence?

See papers by M. Shaposhnikov



D. Buttazzo et al, arXiv:1307.3536

The Standard Model is not all there is (right?)

A general argument:

- The SM is just a stand-in for an effective field theory that flows down from some fancy "UV completion" associated to (at least one) actual high energy scale
- If you start with this UV theory, you will have to fine tune to get to something that looks like the SM at lab energies
- This is the fine tuning/naturalness/hierarchy problem that needs to be explained

S. Weinberg, J. Polchinski, K. Wilson, ...

This is a good argument, but...

- We believed this argument so much that we have spent billions of dollars of the taxpayers money over 30 years looking for evidence of the higher dimension operators
- **So far we have seen no such evidence**, with the notable exception of neutrino masses
- Neutrino masses may be explained by the Weinberg operator, the unique dimension 5 operator extension of the Standard Model

$$\frac{y_\nu}{M_{\rm new}}(\bar{L}H)^2 \to \frac{y_\nu v^2}{M_{\rm new}}\bar{\nu}_L \nu_L^c$$

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Conclusion: you should come to Fermilab and do neutrino physics

The Standard Model is not all there is (right?)

Popular arguments:

- **Gravity exists!** (but we don't understand it)
- **Dark matter exists!** (more on this later)
- Dark energy exists! (but we don't understand it or what it means)
- The strong CP problem of the SM implies either a mysterious tuning of $\theta_{\rm CP}$, or a new high scale to explain the axion
- What about inflation? BICEP2, etc

multiverse?

- **If you accept fine tuning**, you are led down the road to the multiverse and arguments based on anthropic reasoning
- I am not a fan of the multiverse, but multiverse proponents do have a few strong points in their favor:
  - ★ Their is increasing experimental evidence for primordial cosmic inflation with a high scale and a large field excursion: the basic ingredients of the eternal inflation picture
  - ★ The history of science favors those who suggest that the universe is much larger than previously supposed (kudos to William Herschel)
  - ★ Attempts to explain the Higgs naturalness problem (e.g. SUSY) **fail miserably** when applied to the cosmological constant problem

moving SUSY to higher ground?

- Maybe SUSY is a great idea and does indeed have something to do with electroweak physics
- But maybe we are also missing something, e.g. there is another higher scale (and tuning?) involved: 10 TeV? 100 TeV?
- Putting squark masses at 100 TeV, whatever the motivation, is a good playground for the idea that flavor-violating effects may be intrinsically O(1), but with a big mass suppression

Higgs and the WIMP miracle

what if there is no SUSY or compositeness at or around the TeV scale?

- In that case I would assert that among the best-motivated new particles at or around the TeV scale are some kind of WIMP dark matter
- Since the electroweak scale exists and is of unknown origin, why not try to connect it to the dark sector?
- This is not so different from what we do in SUSY, where the electroweak scale is related to the SUSY breaking scale, which in turn **is assumed** to be generated by (hidden sector) quantum dynamics not unlike the QCD scale
- Perhaps the scale of the dark sector is generated by quantum dynamics, and the electroweak scale inherits from this

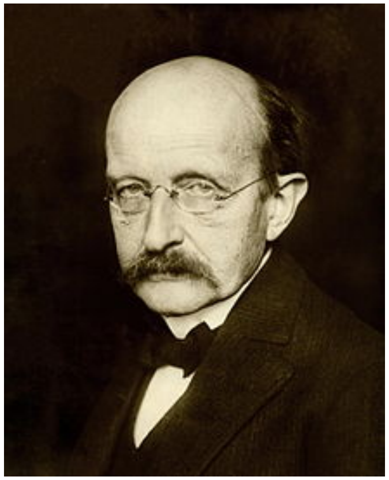
Higgs portal

- Assume that the SM, with the Higgs mass-squared parameter set to zero, connects directly to the dark sector via a **Higgs portal coupling** to a complex scalar field Σ that is a singlet under the SM

$$V_0 = \frac{1}{2}\lambda|H|^4 + \lambda_{\Sigma H}|H|^2|\Sigma|^2 + V_\Sigma(\Sigma)$$

- Assume that Σ gets a vev, and that $\lambda_{\Sigma H}$ is somewhat small and negative (
- In this case the vev of the dark sector scalar triggers electroweak symmetry breaking
- **So now the dark scale and electroweak scale are linked**

Conjecture:



Max Planck

All mass is a quantum phenomenon.

Murraypalooza talk:
Christopher T. Hill , hep-th/0510177

- The QCD scale is generated from UV quantum dynamics
- How about the electroweak scale? (Coleman-Weinberg, Gildener-Weinberg)

In the actual Standard Model this isn't happening, so we will need to extend the SM in some way to get radiative breaking

generating the electroweak scale AND the dark matter scale radiatively

- Hambye and Strumia have a simple model where the dark matter scale is generated radiatively, then the Higgs portal coupling induces EWSB
- The dark sector is just a simple Coleman-Weinberg: an SU(2) gauge field and a complex scalar doublet with a scale -invariant potential
- Once the “dark scalar” gets a CW-induced vev, the “dark” gauge bosons become heavy and stable: they are viable dark matter candidates!

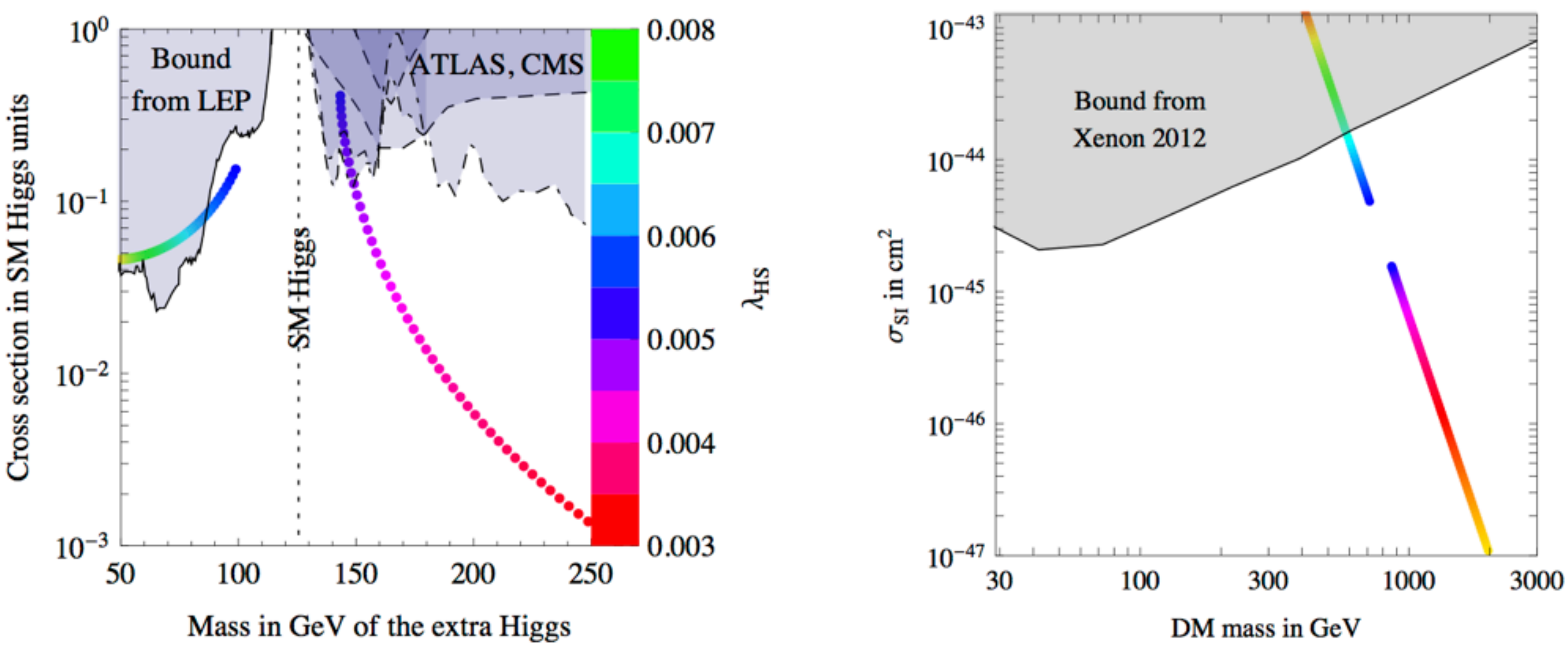
T. Hambye and A. Strumia, arXiv:1306.2329

Experimental implications

1) New scalar s: like another h with suppressed couplings; $s \to hh$ if $M_s > 2M_h$.
2) Dark Matter coupled to s, h. Assuming that DM is a thermal relict

$$\sigma v_{\rm ann} + \frac{1}{2}\sigma v_{\rm semi-ann} = \frac{11 g_X^2}{1728\pi w^2} + \frac{g_X^2}{64\pi w^2} \approx 2.3 \times 10^{26}\,\frac{\rm cm^3}{\rm s}$$

fixes $g_X = w/1.9\,\text{TeV}$, so all is predicted in terms of one parameter λ_{HS}:



(Insignificant hint in ZZ and $\gamma\gamma$ data around 143 GeV)

A. Strumia, Madrid workshop

Extension with fermion dark matter

W. Altmannshofer, W. Bardeen, M Bauer, M. Carena, JL

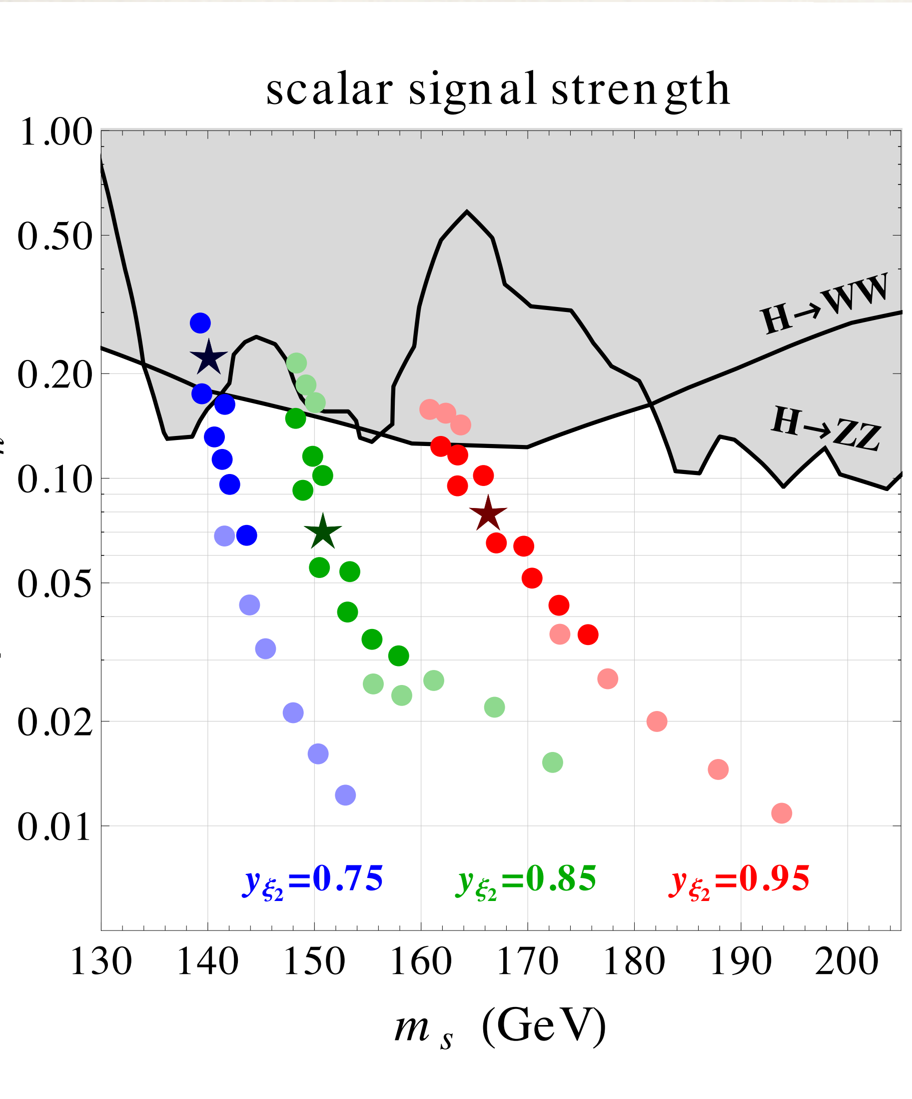
- Dark matter doesn't have to be heavy gauge bosons, or scalars, it could be chiral fermions

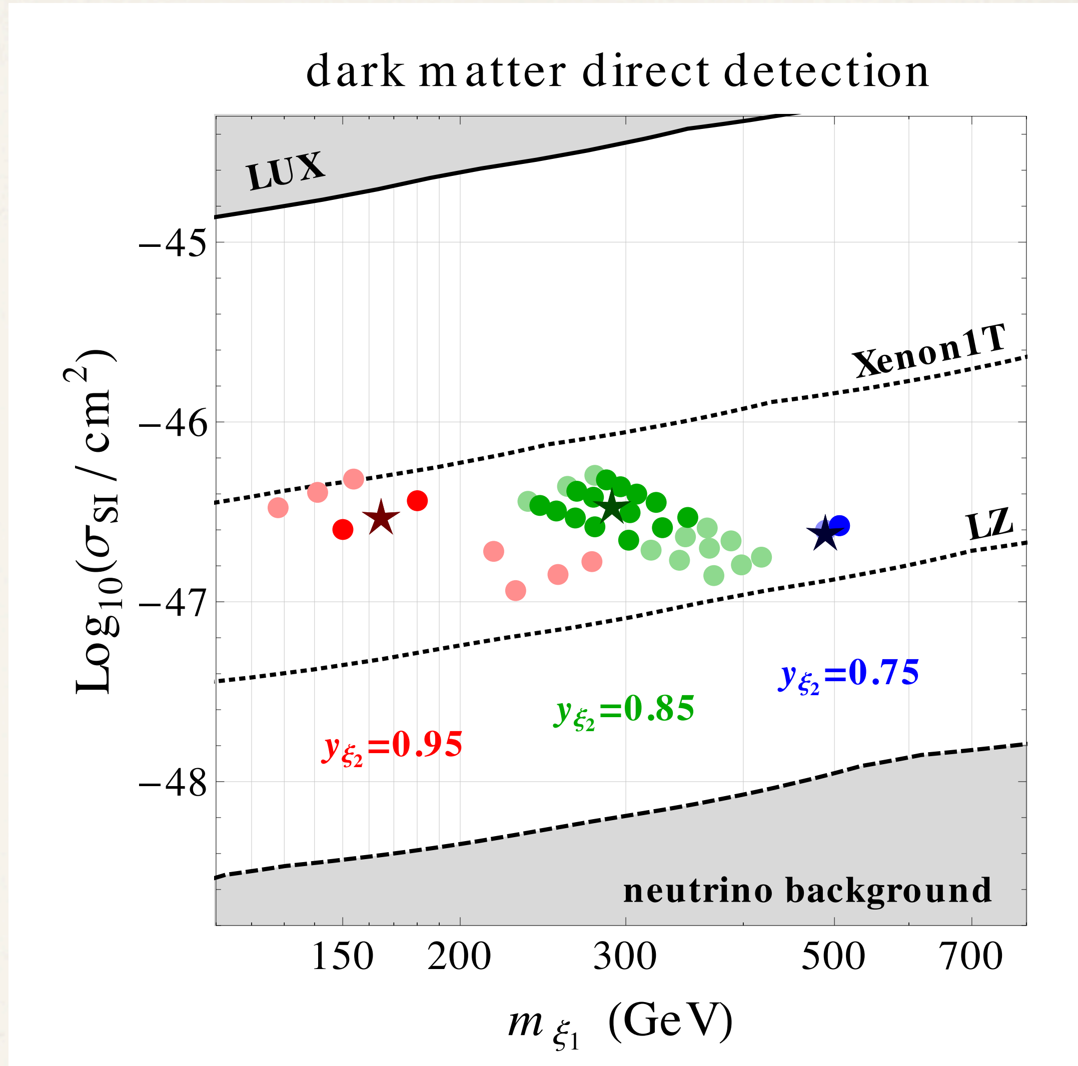
- Dark sector has Yukawa couplings, gauge couplings, and one scalar self-coupling, but no explicit mass parameter

- In addition to the spontaneously broken dark SU(2) of Hambye and Strumia, you can add a dark "hypercharge" U(1), such that the radiative breaking preserves a massless dark photon

- Basically this is Weinberg's original "Theory of Leptons", but all on the dark side, and with no explicit tachyonic mass parameter (and duplicating the fermion content to cancel anomalies)

An extra Higgs and detectable dark matter





Summary

- Maybe there will be SUSY at the LHC, or maybe not
- We do not understand the naturalness problem
- Maybe the electroweak scale is determined by a radiatively generated dark scale
- Discoveries from the LHC and direct dark matter detection will clarify this picture!!!