Higgs without Supersymmetry

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Outline

- Is there a Higgs naturalness problem?
- What is the LHC telling us?
- Why do we live on the ragged edge of doom?
- Radiative EWSB without SUSY?
- Classically scale invariant modification of the SM?
  - Radiative B-L breaking
  - Dark matter + Higgs portal + radiative EWSB

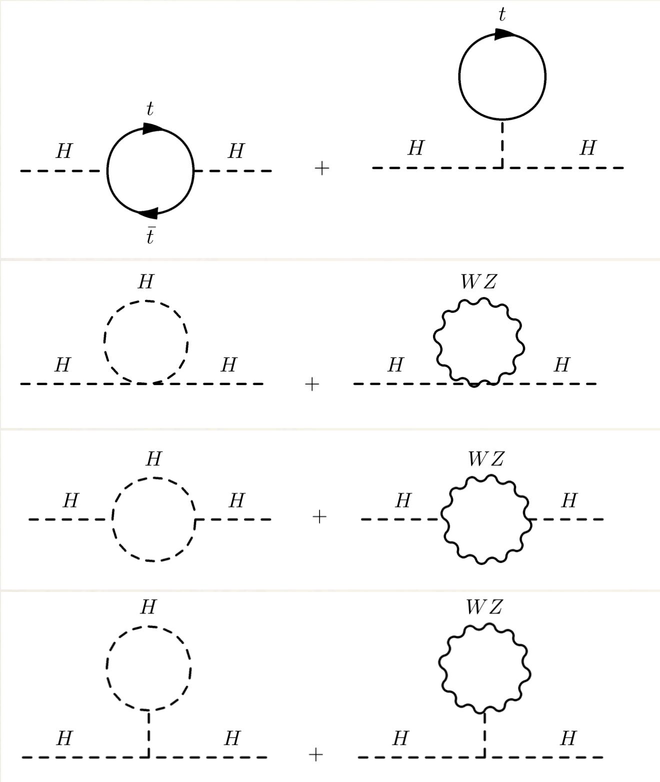
Collaborators:
Wolfgang Altmannshofer, Bill Bardeen, Marcela Carena

is there a Higgs naturalness problem?

- For decades the HEP community has asserted that naturalness is the central issue
- Simply put, we have assumed that either EWSB is natural, in which case we need to explain why, or that it is fine-tuned, in which case we also need to explain why
- I will argue that this is *a false dichotomy*, and that LHC results are hinting at a third path

standard naturalness dogma

The standard argument is simple: start with the SM and start computing radiative corrections to the Higgs mass with an explicit cutoff:



$$M_H^2 = M_0^2 + \frac{3\Lambda_C^2}{8\pi^2 v^2}\left[M_H^2 + 2M_W^2 + M_Z^2 - 4m_t^2\right] + \ldots$$

In the absence of a symmetry or some other conspiracy enforcing cancellations, it would appear that the electroweak scale can only be obtained by fine-tuning a bare parameter against (cut-off)^2 dependent radiative corrections

standard naturalness dogma

- If you accept fine-tuning, you are led down the road to the multiverse and arguments based on anthropic reasoning and/or scanning
- If you want to retain naturalness, then given that the LHC has indeed found a seemingly fundamental lightish Higgs, you are pushed to invoke some kind of heavy partners of SM particles to cancel the apparent quadratic sensitivity to the cut-off
- Thus:
  - SUSY (partners have different spin, symmetry enforces cancellations)
  - Little Higgs (partners have same spin, symmetry enforces cancellations)
  - Lee-Wick SM (partners have same spin but are kinetic ghosts)

naturalness and scale invariance

W. Bardeen, Fermilab-Conf-95-391-T

- If your basic problem is quadratic sensitivity to a cut-off scale, and you are looking for a symmetry to fix the problem, an obvious candidate is scale invariance
- (This is also true for quartic sensitivity to cut-offs, but that is another talk...)
- The Ward Identity associated with the vanishing of the trace of the renormalized stress-tensor will forbid radiative mass generation

$$\boldsymbol{\Theta}^{\mu}_{\mu} = \mathbf{0}$$

naturalness and scale invariance

W. Bardeen, Fermilab-Conf-95-391-T

- There are some obvious objections to this approach:
  - The SM has a built-in scale, the (negative) Higgs mass-squared parameter
  - The SM generates other scales at loop order via dimensional transmutation
  - The SM is not all there is, e.g. superheavy degrees of freedom associated with GUTs and/or gravity could create problems

answering the objections

W. Bardeen, Fermilab-Conf-95-391-T

- The SM is not all there is, e.g. superheavy degrees of freedom associated with GUTs and/or gravity could create problems
    - Gravity per se is not a problem
    - Maybe there aren't any superheavy degrees of freedom, or if there are, they have very special properties

- The SM generates other scales at loop order via dimensional transmutation
    - This is just the trace anomaly. It modifies the Ward Identity to allow multiplicative mass corrections, but not additive ones

$$\mathbf{\Theta}_{\mu}^{\mu} = \beta_{\lambda_\mathbf{i}}(\lambda_\mathbf{i})\ \mathbf{O_i}$$

answering the objections

W. Bardeen, Fermilab-Conf-95-391-T

- The SM has a built-in scale, the (negative) Higgs mass-squared parameter
  - This is an explicit but soft breaking of the scale invariance
  - It should only lead to radiative mass corrections that, at worst, go like

$$\mathbf{m^2(\log\left(\frac{\Lambda^2}{m^2}\right) + c_1)}$$

  - If you compute with a randomly-chosen regulator, you will instead get

$$\mathbf{c_2\Lambda^2 + m^2(\log\left(\frac{\Lambda^2}{m^2}\right) + c_1)}$$

  - But this is the same kind of mistake as choosing a regulator that doesn't respect gauge invariance (and thus appears to violate a Ward Identity)

naturalness and scale invariance

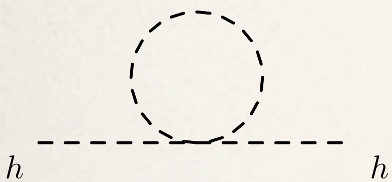
W. Bardeen, Fermilab-Conf-95-391-T

$$\mathbf{c_2 \Lambda^2 + m^2 (\log\left(\frac{\Lambda^2}{m^2}\right) + c_1)}$$

- This is an argument that you should either set $c_2 = 0$, or better use a regulator that is intrinsically free of quadratic divergences.
- The only regulator scheme (that I know of) with this property is dimensional regularization
- Does this mean that dimensional regularization is somehow more “physical” than other regulators?
- Let’s take a brief detour to remind ourselves how dimensional regularization actually regulates UV divergences:

dimensional regularization

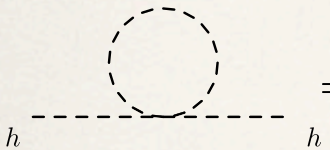
- The regulation of UV divergences in DR really has nothing to do with dimensionality
- We can see this by re-writing a typical one-loop quadratically divergent Higgs mass correction (from the Higgs quartic self-coupling) in terms of a Schwinger proper time integral:



$$= -\mathbf{i}\,\frac{\lambda}{\mathbf{2}}\int \frac{\mathbf{d^d p_E}}{(\mathbf{2}\pi)^{\mathbf{d}}}\,\frac{\mathbf{i}}{\mathbf{p_E^2}+\mathbf{m^2}} \qquad = \frac{\lambda}{\mathbf{32}\pi^{\mathbf{2}}}(\mathbf{4}\pi)^{\frac{\epsilon}{\mathbf{2}}}\int_{\mathbf{0}}^{\infty}\mathbf{d}\tau\;\tau^{\frac{\epsilon}{\mathbf{2}}-\mathbf{2}}\;\mathbf{e}^{-\mathbf{m^2}\tau}$$

- The UV quadratic divergence for $\epsilon = \mathbf{0}$ is now the power divergence of the proper time integral as $\tau \rightarrow \mathbf{0}$
- You could regulate this by explicitly cutting off τ at some minimum value

dimensional regularization



$$= \frac{\lambda}{32\pi^2}(4\pi)^{\frac{\epsilon}{2}} \int_0^\infty \mathbf{d}\tau\ \tau^{\frac{\epsilon}{2}-2}\ \mathbf{e}^{-\mathbf{m}^2\tau} = \frac{\lambda}{32\pi^2}(4\pi)^{\frac{\epsilon}{2}}\ \mathbf{m}^{2-\epsilon} \frac{\mathbf{1}}{\mathbf{2i}\sin\pi(\frac{\epsilon}{2}-\mathbf{1})} \int_{\mathbf{C=Hankel}} \mathbf{dt}\ \mathbf{t}^{\frac{\epsilon}{2}-2}\ \mathbf{e^t}$$

- With a cut-off you would conclude that $\epsilon = \mathbf{2}$ corresponds to a log UV divergence, while $\epsilon = \mathbf{0},\ -\mathbf{2}, \ldots$ correspond to *increasingly bad* power divergences
- Dimensional regularization corresponds to recognizing that the integral is really the Euler integral, replacing it by a Gamma function for $\epsilon > \mathbf{2}$, then analytically continuing back to the singularity
- Of course in this approach all of the singularities are of *the same* type: they are just simple poles in ϵ

summary so far

- The SM may in fact be technically natural
- But we also need a deeper understanding of regulating power versus log UV divergences
- In its minimal form, this idea does not make any predictions, other than that the SM may be all there is up to Planck scale
- This prediction has to be reconciled with the existence of dark matter and whatever new physics is responsible for neutrino masses and solving the strong CP problem
- This motivates a systematic study of simple non-SUSY extensions of the SM that are also technically natural

what is the LHC telling us?

- There is a Higgs-like boson with mass 125.5 +- 1 GeV
- No sign (so far) of any other new physics
- Knowing the Higgs mass, we can run all of the SM couplings up to large scales, and we can compute the Higgs effective potential over a large range of field values
- Near or above the Planck scale we would have to worry about gravitational corrections
- Below this scale we can consistently assume just the SM

SM Higgs effective potential

J. Casas, J. Espinosa, M. Quiros, hep-ph/9409458
G. Degrassi, S. Di Vita, J. Elias-Miro, J. Espinosa, G. Giudice, G. Isidori, A. Strumia, arXiv:1205.6497

The state-of-the-art is to compute the 2-loop form of the effective potential, insert the 3-loop running couplings of the SM, and use 2-loop matching to relate the top quark pole mass and Higgs pole mass to the running top Yukawa $\mathbf{y_t}$ (evaluated at m_t) and the Higgs quartic self-coupling λ (also evaluated at m_t)

$$\mathbf{V}(\phi) = \mathbf{V_0}(\phi) + \mathbf{V_1}(\phi) + \mathbf{V_2}(\phi) + \ldots$$

$$\mathbf{V_0}(\phi) = \frac{\mathbf{1}}{\mathbf{2}}\mathbf{m_0^2}\phi^{\mathbf{2}} + \frac{\mathbf{1}}{\mathbf{8}}\lambda\phi^{\mathbf{4}}$$

$$\mathbf{V_1}(\phi) = \frac{\mathbf{1}}{\mathbf{64}\pi^{\mathbf{2}}}\Big[-\mathbf{12m_t^4}(\log\left(\frac{\mathbf{m_t^2}}{\mu^{\mathbf{2}}} - \frac{\mathbf{3}}{\mathbf{2}}\right) + \mathbf{6m_W^4}(\log\left(\frac{\mathbf{m_W^2}}{\mu^{\mathbf{2}}} - \frac{\mathbf{5}}{\mathbf{6}}\right) + \mathbf{3m_Z^4}(\log\left(\frac{\mathbf{m_Z^2}}{\mu^{\mathbf{2}}} - \frac{\mathbf{5}}{\mathbf{6}}\right)$$
$$+\mathbf{m_h^4}(\log\left(\frac{\mathbf{m_h^2}}{\mu^{\mathbf{2}}} - \frac{\mathbf{3}}{\mathbf{2}}\right) + \mathbf{3m_\chi^4}(\log\left(\frac{\mathbf{m_\chi^2}}{\mu^{\mathbf{2}}} - \frac{\mathbf{3}}{\mathbf{2}}\right)\Big]$$

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The resulting RG-improved SM Higgs potential resums the next-to-next-to leading logs, and is sufficiently scale invariant that one can extract the features of the potential for field values varying from the weak scale up to the Planck scale

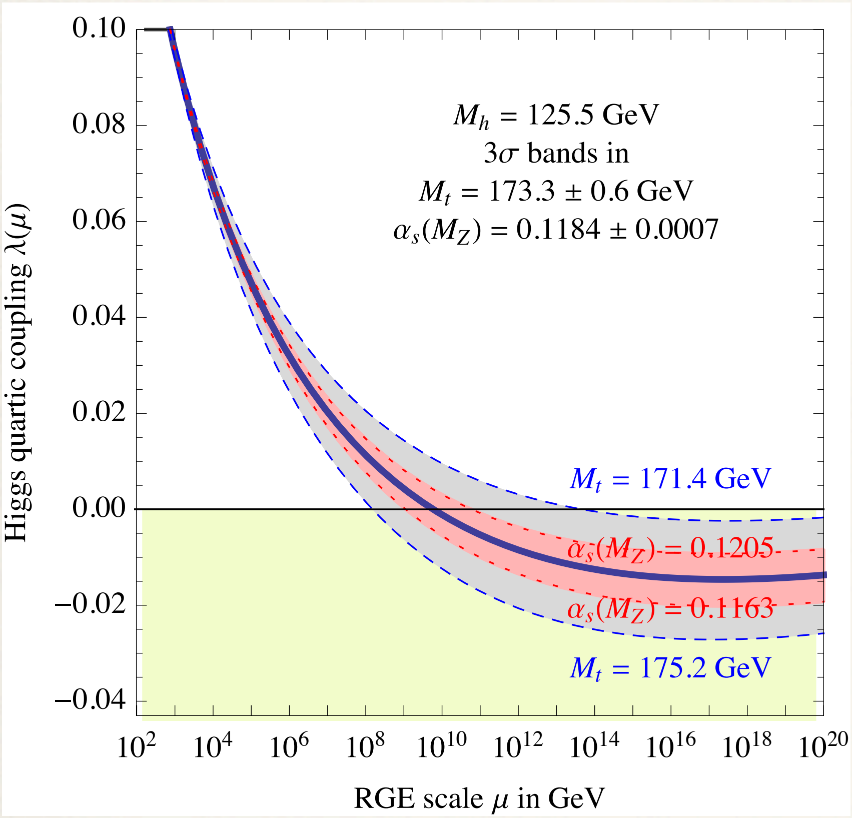
$$\mathbf{V}(\phi) = \mathbf{V_0}(\phi) + \mathbf{V_1}(\phi) + \mathbf{V_2}(\phi) + \ldots$$

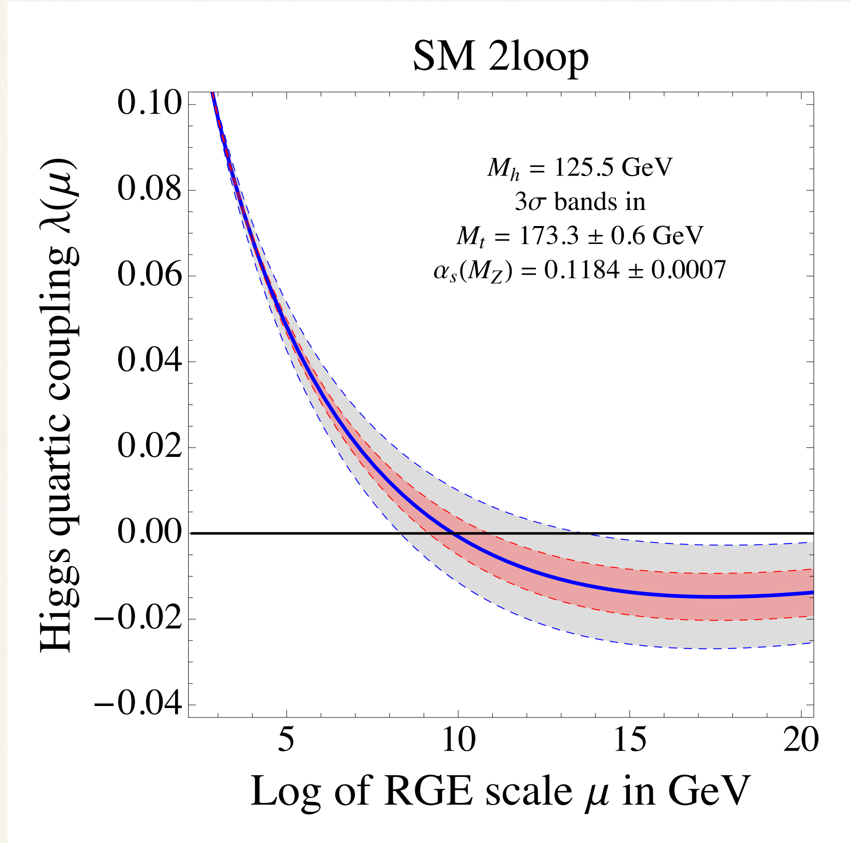
$$\mathbf{V_0}(\phi) = \frac{1}{2}\mathbf{m_0^2}\phi^2 + \frac{1}{8}\lambda\phi^4$$

$$\mathbf{V_1}(\phi) = \frac{1}{64\pi^2}\Big[-12\mathbf{m_t^4}(\log\left(\frac{\mathbf{m_t^2}}{\mu^2} - \frac{3}{2}\right) + 6\mathbf{m_W^4}(\log\left(\frac{\mathbf{m_W^2}}{\mu^2} - \frac{5}{6}\right) + 3\mathbf{m_Z^4}(\log\left(\frac{\mathbf{m_Z^2}}{\mu^2} - \frac{5}{6}\right)$$
$$+\mathbf{m_h^4}(\log\left(\frac{\mathbf{m_h^2}}{\mu^2} - \frac{3}{2}\right) + 3\mathbf{m_\chi^4}(\log\left(\frac{\mathbf{m_\chi^2}}{\mu^2} - \frac{3}{2}\right)\Big]$$

SM Higgs quartic self-coupling

SM 3-loop running with 2-loop matching





A. Strumia, Moriond EW 2013

W. Altmannshofer, M. Carena, JL

SM Higgs vacuum instability

- For large field values we can just scale out ϕ^4 and write the RG improved effective potential in terms of a $\lambda_{\mathbf{eff}}$

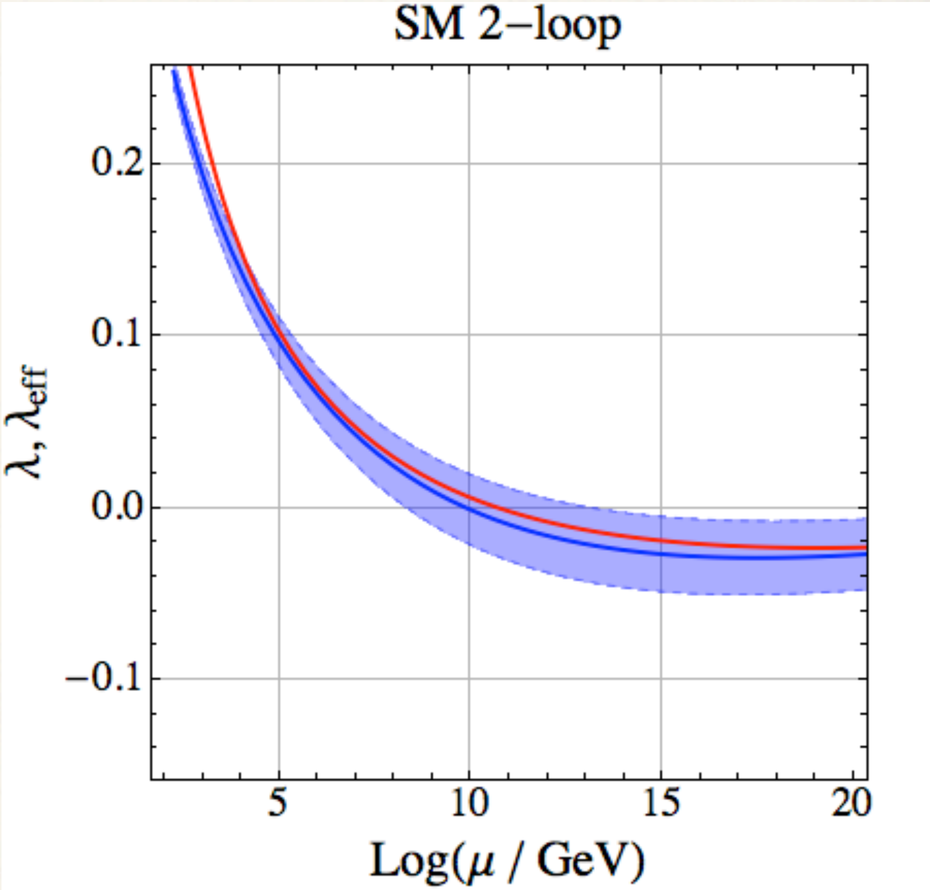
$$\mathbf{V}(\phi) = \mathbf{V_0}(\phi) + \mathbf{V_1}(\phi) \simeq \lambda_{\mathbf{eff}}\, \phi^{\mathbf{4}}$$

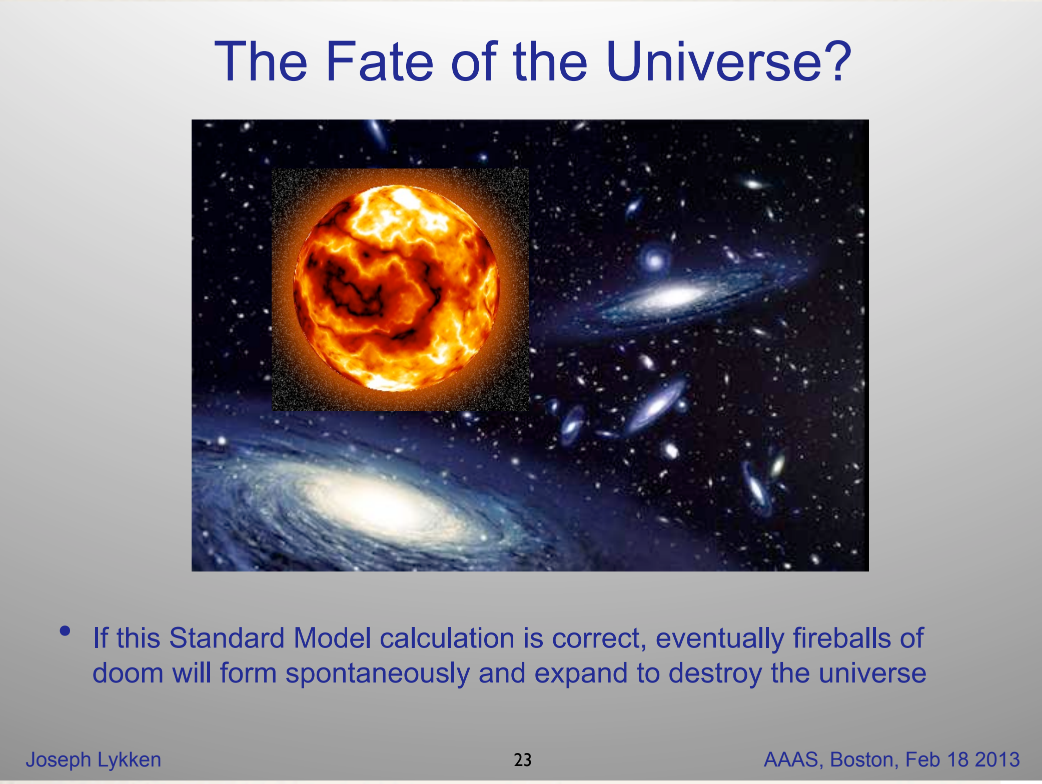
J. Casas, J. Espinosa, M. Quiros, hep-ph/9409458

- Then $\lambda_{\mathbf{eff}} < \mathbf{0}$ at large field values implies that the SM EWSB vacuum is unstable

- This possibility has been studied since the 1970s, but now we can finally put in the correct numbers

D. Politzer, S. Wolfram, Phys. Lett. 82B, 1979





the press didn't hear about this possibility until last month...

NPR (blog)

Subatomic calculations indicate finite lifespan for universe
Reuters - Feb 18, 2013
"If you use all the physics that we know now and you do what you think straightforward calculation, it's bad news," Joseph **Lykken**, ...

If Higgs Boson Calculations Are Right, A Catastrophic 'Bubble ...
NPR (blog) - Feb 19, 2013

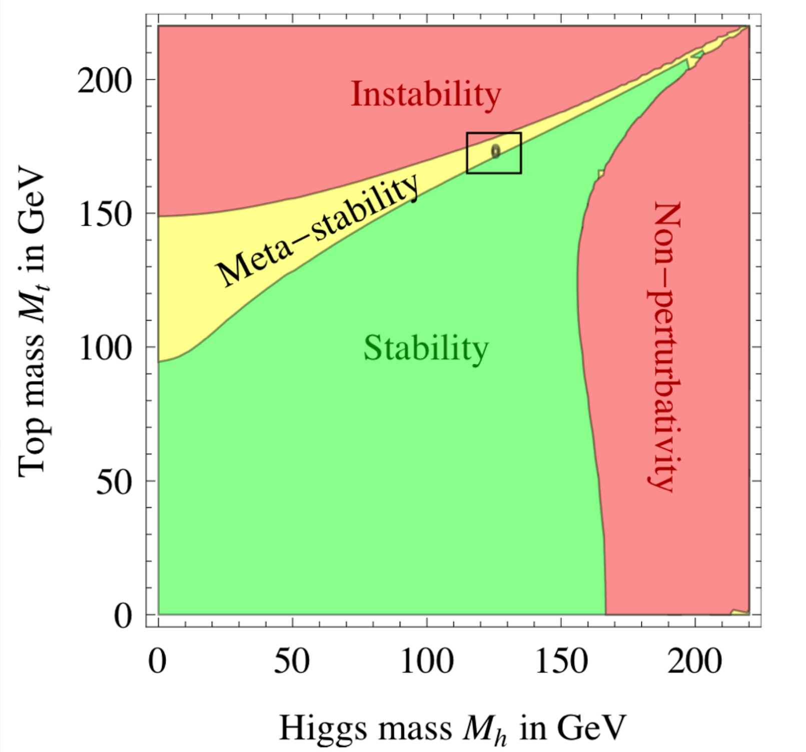
Higgs boson find may spell doom for universe
Fox News - Feb 19, 2013

Cosmos may be 'inherently unstable'
Highly Cited - BBC News - Feb 19, 2013

Ars Technica | Voice of A... | BBC News | NBCNews.... | The Atlanti... | UPI.com (b... | Daily Aztec

all 61 news sources »

why do we live on the ragged edge of doom?



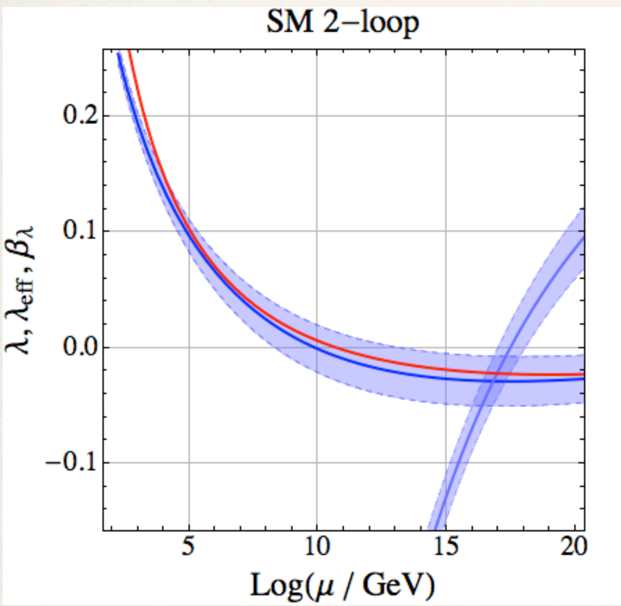
A. Strumia, Moriond EW 2013

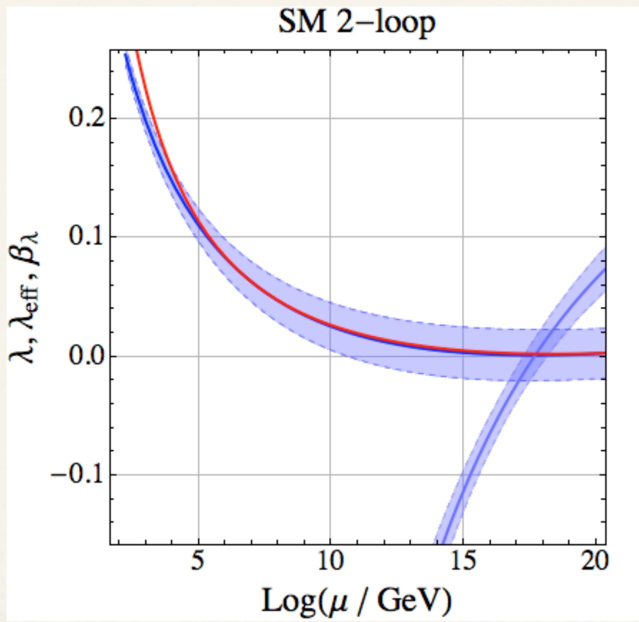
- if you believe in SUSY, then this is just a coincidence
- but dismissing striking features of the data as coincidence has historically not been a winning strategy...

special high scale boundary conditions?

- Instead of an instability, perhaps the SM extrapolation is telling us that there are special boundary conditions at some high scale
- For example, perhaps the SM emerges from a UV completion somewhere between 10^{10} and 10^{17} GeV with $\lambda = \mathbf{0}$, or perhaps with $\lambda = \mathbf{0}$ and $\beta_\lambda = \mathbf{0}$

$\mathbf{M_t = 171\ GeV}$





What does this mean?

A hint about Planckian fixed points?

M. Shaposhnikov, C. Wetterich, arXiv:0912.0208

radiative EWSB?

- Having (perhaps) convinced you that the Higgs mass-squared parameter is natural in the SM, the remaining mystery is why it is negative
- Going back to Coleman and Weinberg, one possibility is that EWSB is generated radiatively
- Thus the UV boundary condition could be $\mathbf{m_0^2 = 0}$, or $\mathbf{m_0^2 > 0}$

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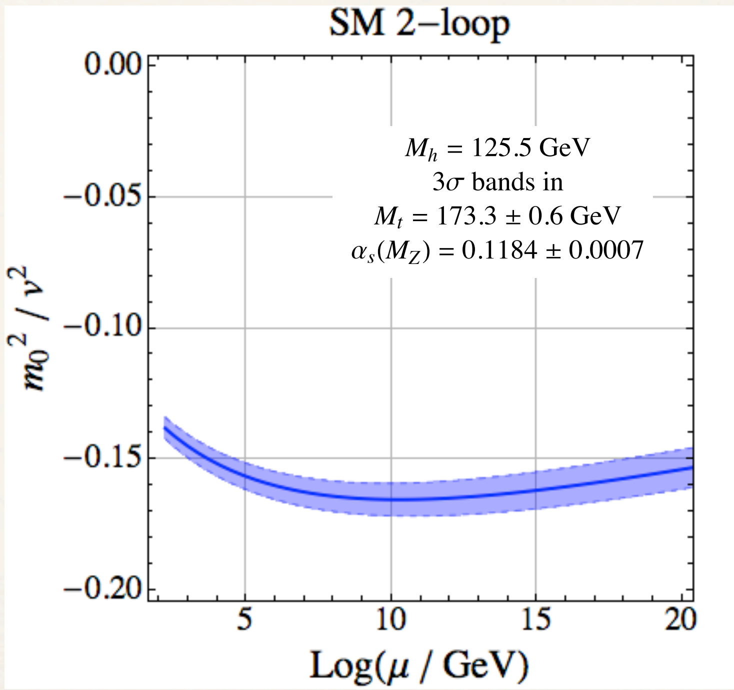


But this doesn't work for the pure SM

classical conformality

- Nevertheless, it is interesting to think about simple non-SUSY extensions of the SM in which one assumes $\mathbf{m_0^2 = 0}$ as a UV boundary condition. Meissner and Nicolai call such models "classically conformal"

K. Meissner and H. Nicolai, hep-th/0612165 et seq.

- One could also require as a UV boundary condition that the SM Higgs potential vanishes entirely, i.e. $\mathbf{m_0 = 0, \quad \lambda_0 = 0}$ This might arise if the UV theory (strings?) results in a shift symmetry on the degrees of freedom that become the Higgs

A. Hebecker, A. Knochel, T. Weigand, arXiv:1204.2551

SM + a complex singlet scalar

- The simplest addition to the SM that has interesting consequences for the Higgs sector is a single complex SM-singlet scalar, with a direct dimension four coupling to the Higgs (a Higgs portal coupling)

$$\mathbf{V_0(H, S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- We assume weak couplings, with no Landau poles occurring before we get to the UV scale where we impose boundary conditions like $\mathbf{m_0^2 = 0}$

- The complex scalar in general carries its own charge, Z_2 or U(1), which may or may not be spontaneously and/or explicitly broken

SM + a complex singlet scalar

$$\mathbf{V_0(H, S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- There are many families of scenarios, depending for example on
  - Does the singlet scalar get a vev?
  - Is the mass scale of the singlet very roughly the same as the Higgs, or is it hierarchically larger?
- The generic effect of the Higgs portal coupling is to increase the Higgs vacuum stability, since at 1-loop it makes a positive contribution to β_λ

$$\beta_\lambda = \beta_\lambda^{\mathbf{SM}} + \mathbf{2\lambda_{sh}^2}$$

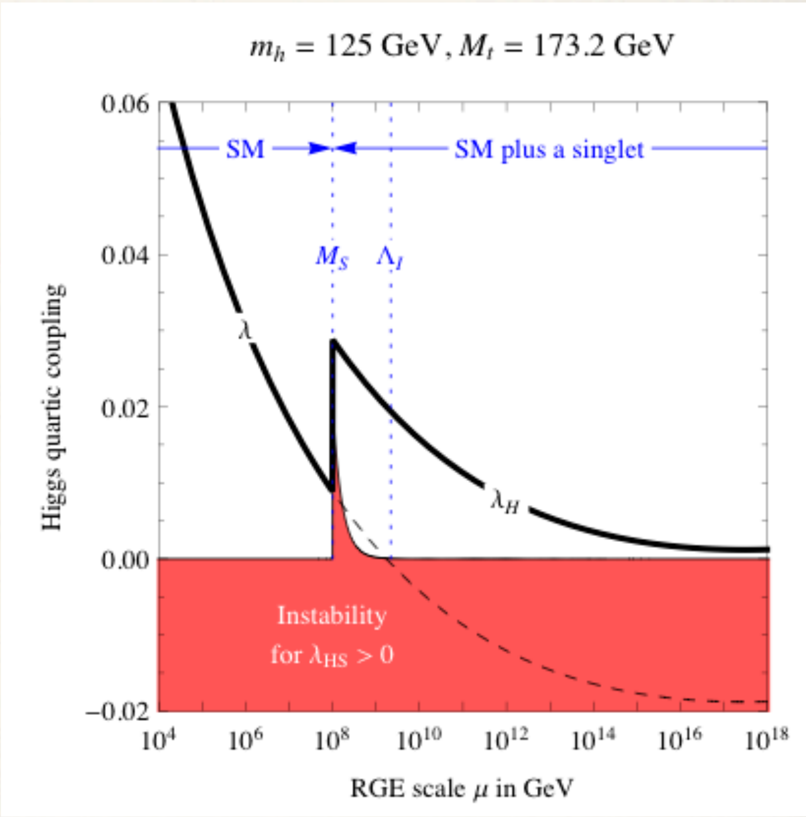
SM + a complex singlet scalar

$$V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4$$

- If the mass scale of the singlet is hierarchically larger than the Higgs, then there is a new heavy threshold scale associated with it

- Of course this is a case where you re-introduce fine-tuning problems, and you can't argue them away...

- So I will from here on assume that the singlet scale is not much more than a TeV



J. Elias-Miro, J. Espinosa, G. Giudice, H-M Lee, A. Strumia, arXiv:1203.0237

SM + a complex scalar with vev

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- If the singlet gets a vev, this spontaneously breaks the Z_2 or U(1) symmetry under which it is charged.
- Thus we have a heavy scalar that mixes with the Higgs, so we get interesting LHC phenomenology:
    - some suppression of the signal strengths of the 125 GeV Higgs
    - a heavy Higgs with SM-like decays
    - a heavy Higgs that decays to two on-shell 125 GeV Higgses

C. Englert, T. Plehn, D. Zerwas, P. Zerwas, arXiv:1106.3097

SM + a complex scalar with vev

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- Even better, if $\lambda_{\mathbf{sh}} < \mathbf{0}$ the vev of the singlet can generate the negative mass-square that we need for EWSB
- Thus we can attempt a scenario in which $\mathbf{m_0 = 0,\ m_s = 0}$ is our UV boundary condition, we generate the U(1) breaking radiatively a la Coleman-Weinberg, which then causes EWSB
- Thus in this simple extension of the SM *all mass scales are generated via dimensional transmutation*. Much more elegant than the SM!

S. Iso and Y. Orikasa, arXiv:1210.2848
C. Englert, J. Jaeckel, V. Khoze, M. Spannowsky arXiv:1301.4224

SM + a complex scalar with vev

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- Let the U(1) be a gauged $U(1)_{B\text{-}L}$, so there is also a B-L gauge boson that will eat the Goldstone mode when the extra complex scalar gets a vev
- At some high scale assume a UV boundary condition $\mathbf{m_0 = 0,\ m_s = 0,\ \lambda = 0}$
- So we have classical conformality and no SM Higgs potential at the UV starting point
- If there is some small kinetic mixing of the B-L gauge boson and hypercharge already at the UV starting point, we can assume $\mathbf{\lambda_{sh} = 0}$ in our UV boundary condition, since we can generate a small negative value radiatively

S. Iso and Y. Orikasa, arXiv:1210.2848
C. Englert, J. Jaeckel, V. Khoze, M. Spannowsky arXiv:1301.4224

SM + a complex scalar with vev

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- A small $\lambda_{\mathbf{sh}}$ is just enough to stabilize the EWSB vacuum
- The new particles are, e.g. a 4 TeV Z' of the broken B-L, and an extra 400 GeV heavy scalar
- As an extra bonus, can also use the B-L breaking scalar vev to generate Majorana masses for right-handed neutrinos

SM + a complex scalar with unbroken Z_2

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- Another interesting case is when the extra scalar does not get a vev and carries an unbroken Z_2 charge
- Then the extra scalar could be WIMP dark matter, or could decay into something lighter that is the WIMP dark matter
- So this is the scenario of a dark sector with a Higgs portal...

S. Kanemura, S. Matsumoto, T. Nabeshima, N. Okada, arXiv:1005.5651
A. Djouadi, O. Lebedev, Y. Mambrini, J. Quevillon, arXiv:1112.3299

SM + a complex scalar with unbroken Z_2

- For reasonable values of the Higgs portal coupling and O(100) GeV WIMP mass, can get the “correct” WMAP relic density
- Can we also impose interesting UV boundary conditions on such a model?

A. Djouadi, O. Lebedev, Y. Mambrini, J. Quevillon, arXiv:1112.3299

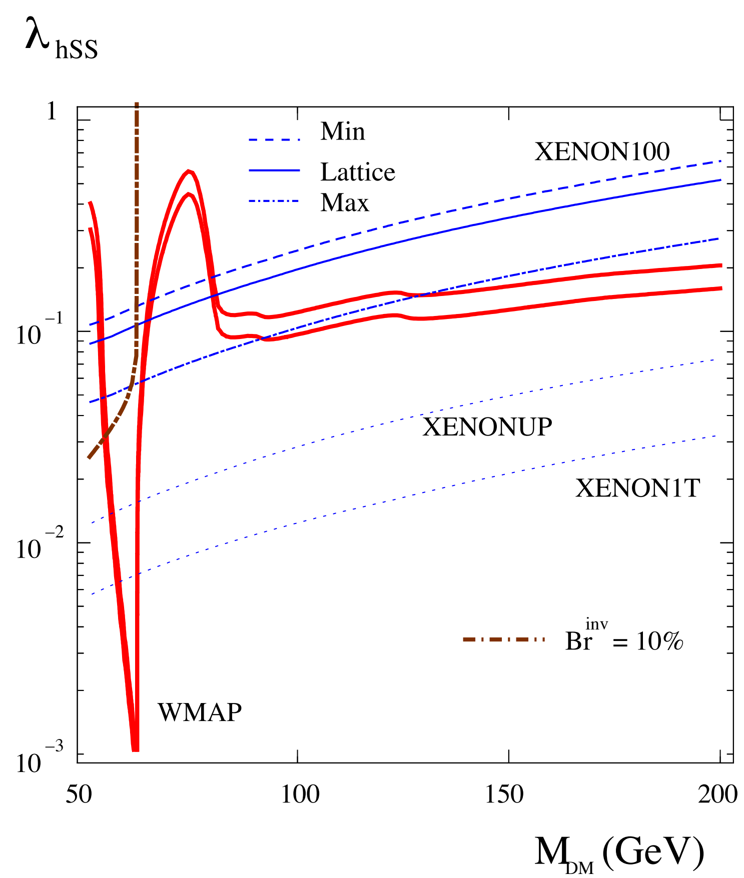


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\mathrm{BR}^{\mathrm{inv}} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

generating the electroweak scale from the dark matter scale

- Assume that the dark sector gets its O(100) GeV mass scale from somewhere
- Can we generate the EW scale radiatively from the DM scale?
- Try to impose the UV boundary conditions $\mathbf{m_0 = 0}, \quad \boldsymbol{\lambda_0 = 0}$, i.e. vanishing of the SM Higgs potential at the high scale

generating the electroweak scale from the dark matter scale

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

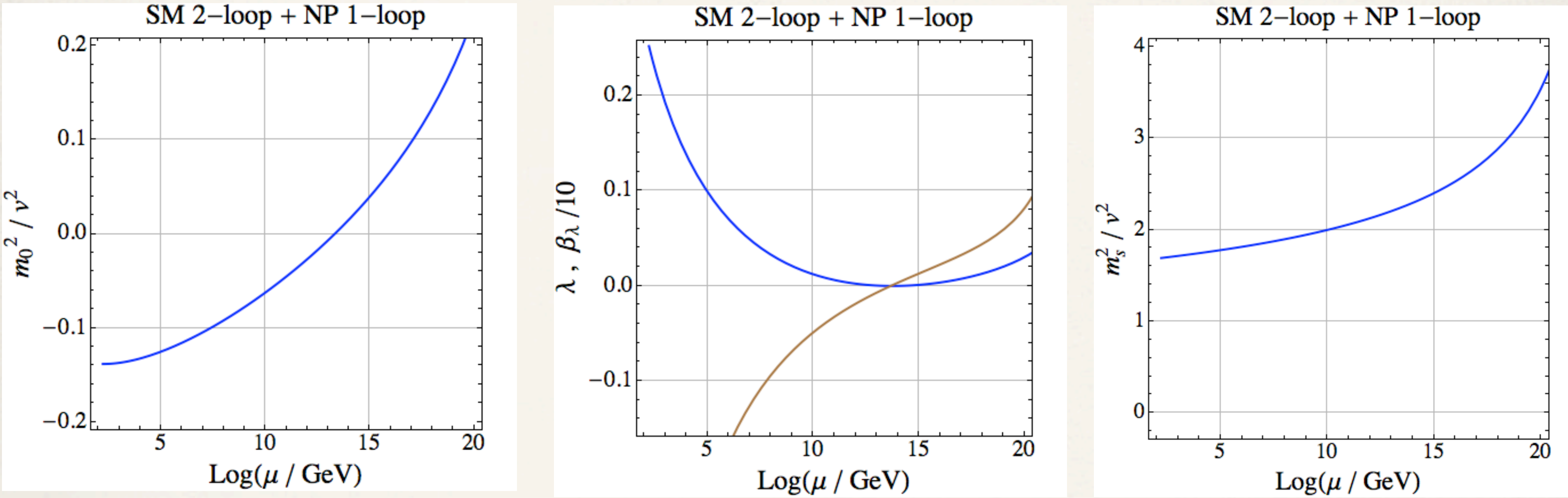
- Example: $\mathbf{m_s(v) = 320\ GeV,\ \lambda_{sh}(M_t) = 0.2,\ \lambda_s(M_t) = 0.3}$
- This is not ruled out by XENON and has more-or-less the correct relic abundance
- Do we get correct radiative EWSB?

W. Altmannshofer, M. Carena, JL

$$V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4$$

$$m_s(v) = 320\ \mathrm{GeV},\ \lambda_{sh}(M_t) = 0.2,\ \lambda_s(M_t) = 0.3$$

W. Altmannshofer, M. Carena, JL



- So at a UV starting point of about 10^{13} GeV we have $m_0 = 0,\ \lambda_0 = 0,\ \beta_\lambda = 0$
- *No Higgs potential is input*, but we get radiative EWSB from an input dark matter scale of about 360 GeV!

Summary

- There is no SUSY
- There is no naturalness problem
- There is no input Higgs potential: EWSB is generated radiatively
- All masses come from dimensional transmutation and whatever is going on in the dark sector
- There will be discoveries from the LHC and direct dark matter detection confirming this picture