Higgs and dark matter

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Outline

- The Standard Model, naturalness, and scales
- Weakly coupled Higgs with no SUSY
- Higgs portal to dark matter
- Coleman-Weinberg radiative breaking in the dark sector
- CW dark sector + Higgs portal inducing EWSB:
    - Model with pseudoscalar DM
    - Model with vector boson DM
    - Model with fermion DM

Collaborators:
Wolfgang Altmannshofer, Bill Bardeen, Martin Bauer, Marcela Carena

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 $m_0^2(\mu)$

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

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

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

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

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

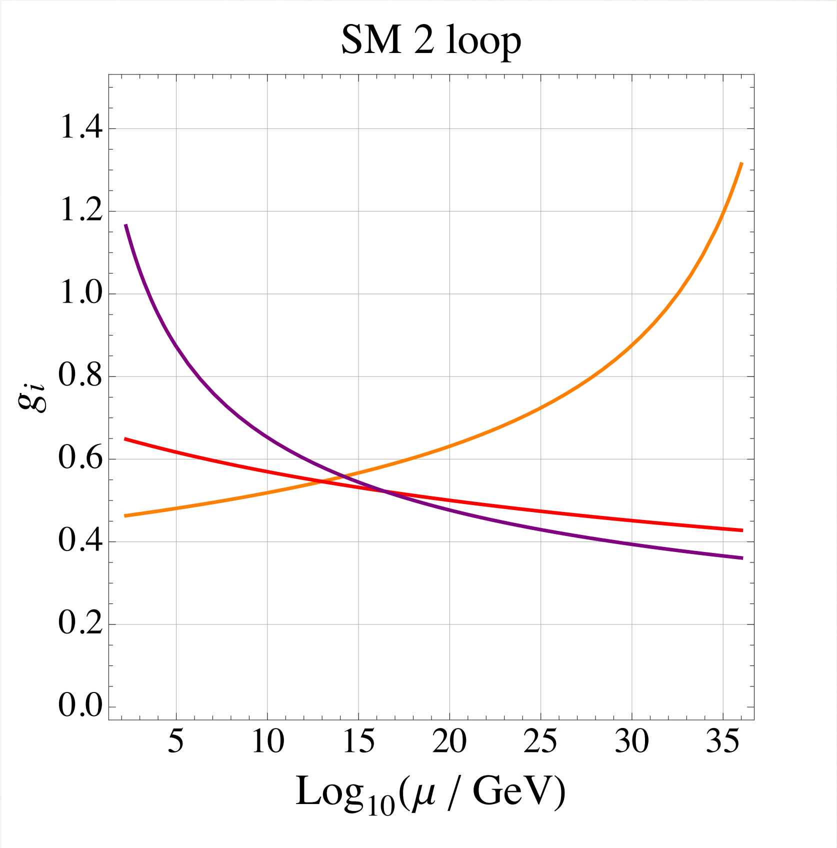
very small

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

SM beta functions: gauge couplings

one loop:

$$16\pi^2\beta_{g_1} = \frac{41}{10}g_1^3\,, \quad 16\pi^2\beta_{g_2} = -\frac{19}{6}g_2^3\,, \quad 16\pi^2\beta_{g_3} = -7g_3^3$$



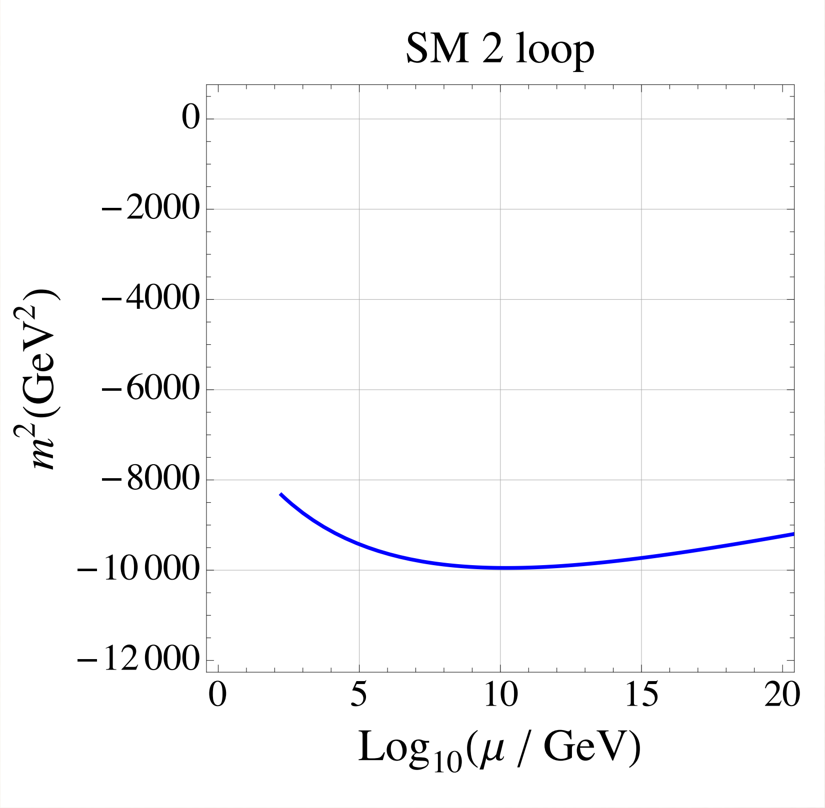
- The asymptotically-free couplings are (apparently) heading for UV Gaussian fixed points
- But the hypercharge (apparently) has a Landau pole at ~ 10^{36} GeV
- Often claimed to be an internal inconsistency/ incompleteness of the Standard Model
- However even semi-classically we would expect that scattering at super-Planckian energies sees all black holes before it sees this strong coupling

SM beta functions: Higgs mass parameter

one loop:

$$16\pi^2\beta_{m_0^2} = m_0^2\,(6\lambda + 6y_t^2 - \frac{9}{10}g_1^2 - \frac{9}{2}g_2^2)$$

- If you use dimensional regularization, the radiative corrections are multiplicative
- This is because of a symmetry: scale invariance
- The SM is scale invariant at tree level in the limit that $m_0^2 \to 0$
- Since dim-reg respects the scale invariance, the Higgs mass-squared parameter hardly runs at all



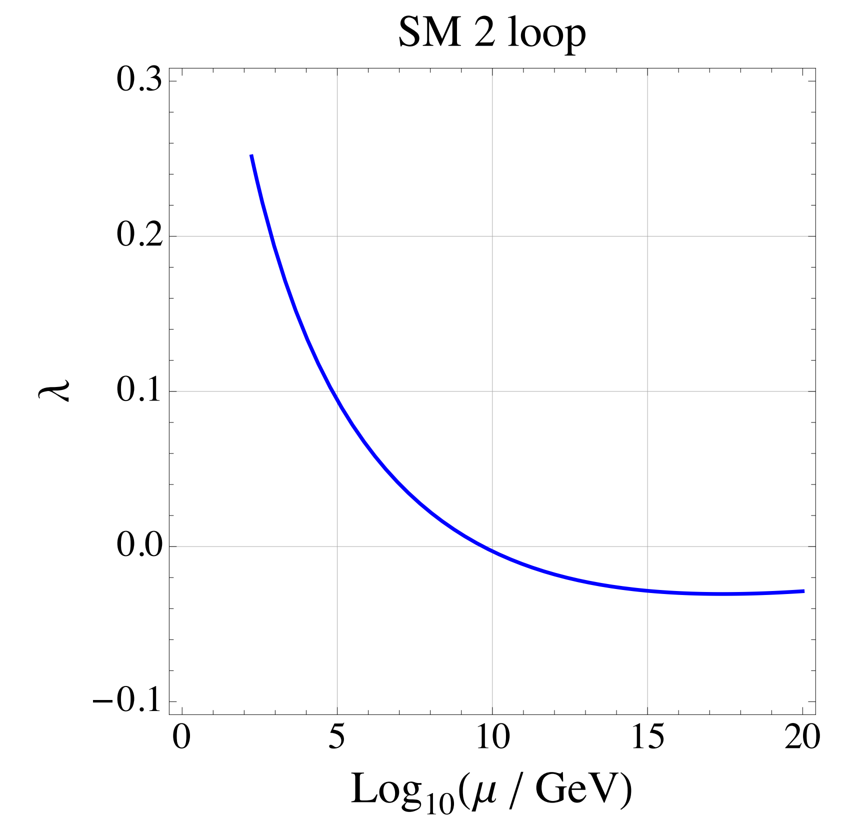
The most unnatural feature of the Higgs mass-squared parameter in the SM is not how it runs, but rather that it is tachyonic

SM beta functions: Higgs self coupling

one loop:

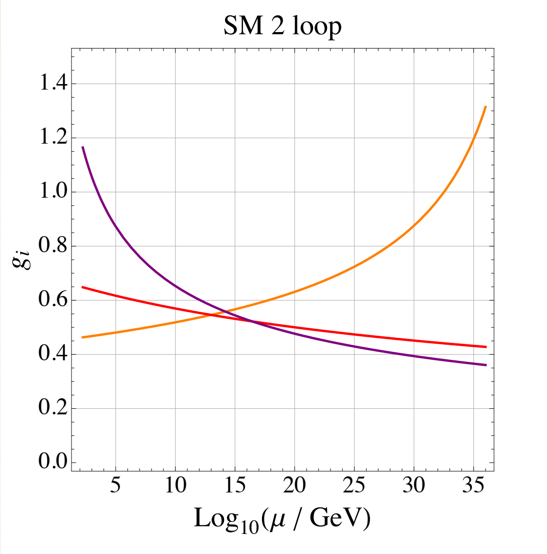
$$16\pi^2\beta_\lambda = 12\lambda^2 + 12\lambda y_t^2 - 12 y_t^4 - \lambda(\frac{9}{5}g_1^2 + 9g_2^2) + \frac{27}{100}g_1^4 + \frac{9}{10}g_1^2 g_2^2 + \frac{9}{4}g_2^4$$

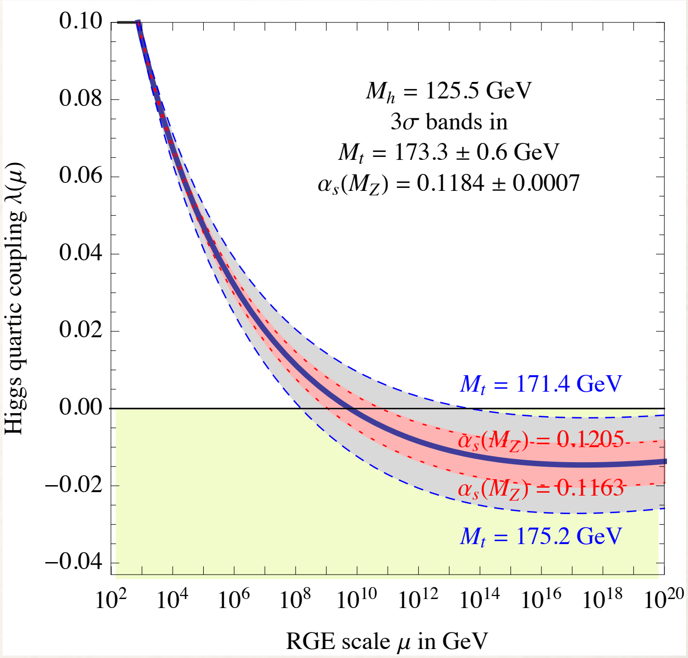
- In the absence of other couplings, would eventually have a Landau pole
- But it has additive radiative corrections, including a negative one from the top yukawa
- If the Higgs boson is light enough and the top quark is heavy enough, then the top Yukawa wins
- So for very large Higgs field values, apparently about 10^{10} GeV, there is an instability because the self coupling goes negative



“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?
- We already discounted the hypercharge Landau pole
- There is of course the gauge coupling unification story, usually taken as a hint of weak scale SUSY
- There is also the apparent Higgs instability, possibily related to a UV scale that is 10^{10} GeV or higher



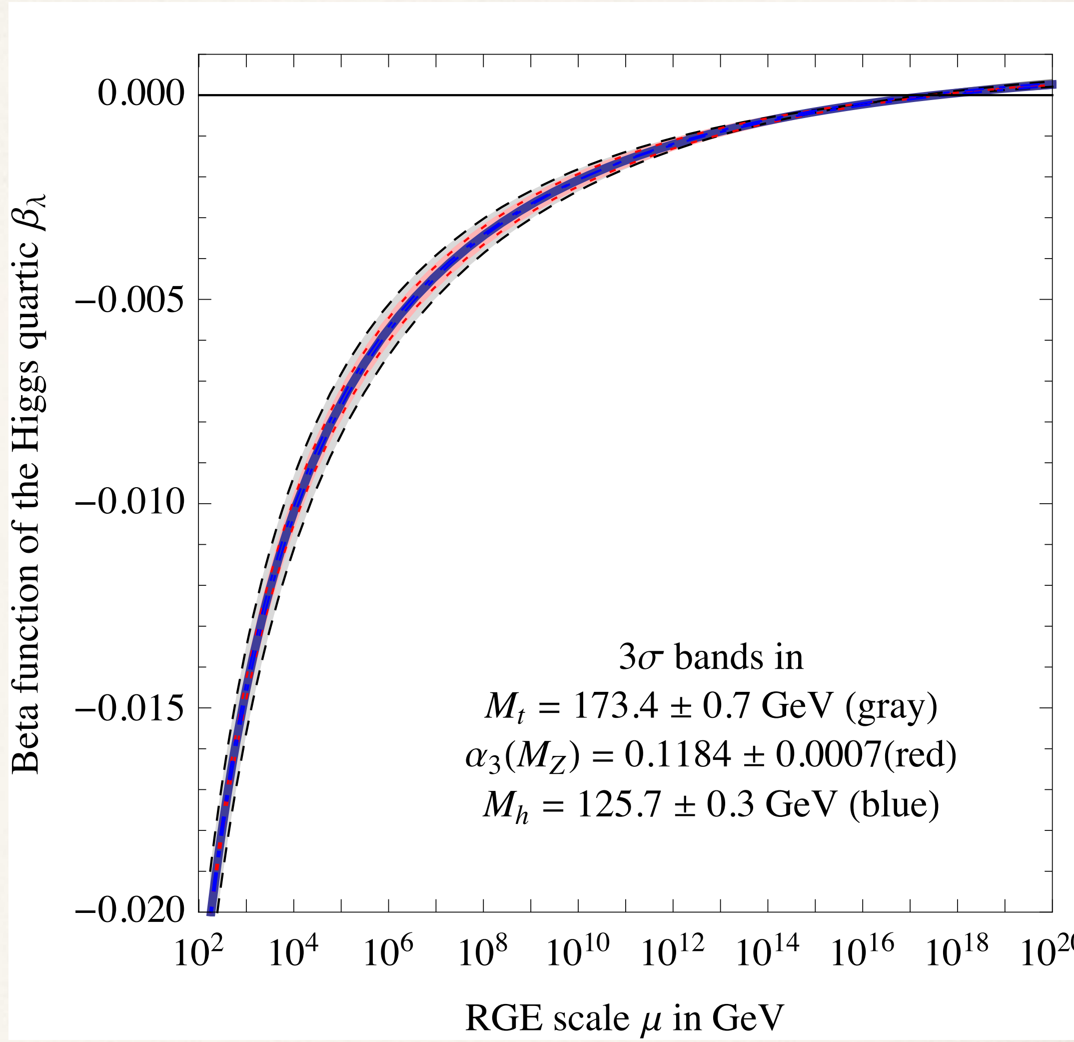


SM 3-loop running with 2-loop matching

A. Strumia, Moriond EW 2013

“Deriving” the Planck scale from 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?



D. Buttazzo et al, arXiv:1307.3536

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

A general effective field theory argument:

- Renormalizable QFTs are just stand-ins for effective field theories that flow down from some fancy UV completion associated to (at least one) actual UV scale

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

- The SM at lab energies is an approximation to some effective theory with a bunch of higher dimension operators suppressed by powers of UV scales
- 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

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 single 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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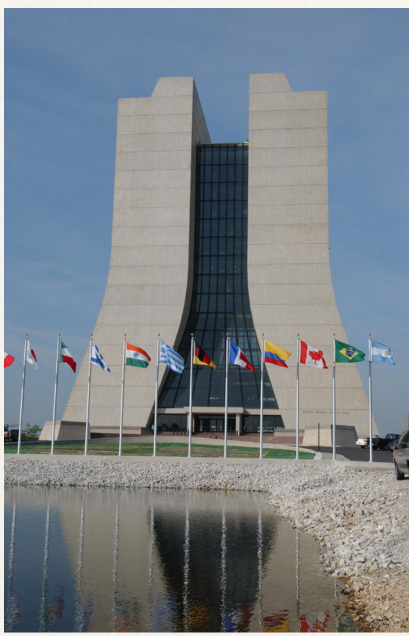
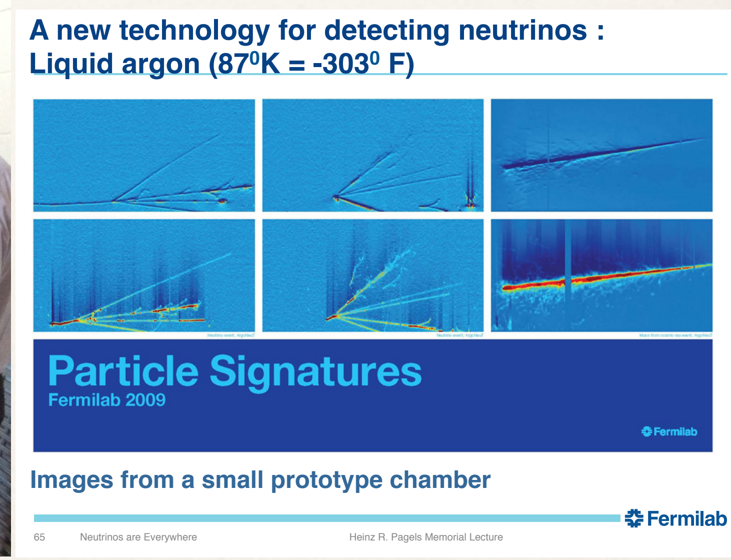




The Standard Model is not all there is (right?)

An almost-as-general argument:

- **Gravity exists!**
- It seems to have a built-in scale, (reduced) $M_{Planck} \sim 10^{18}$ GeV
- There should be a highly nontrivial UV completion of the SM that includes quantum gravity
- Candidates include string theory, where there are a whole bunch of superheavy states that couple to the Higgs
- Another reasonable candidate is asymptotic safety, where there is a highly nontrivial UV fixed point

This is also a good argument

- It is, however, speculative
- The gravity effects that we know how to compute are soft, i.e. suppressed by powers of M_{Planck} in the denominator
- To get a Higgs naturalness+hierarchy problem, you need to show that the Higgs mass squared parameter gets additive corrections proportional to powers of M_{Planck} in the numerator
- This can/will happen in string theory, because of explicit heavy particle states
- Gia Dvali has argued that this is true independently of string theory, because the existence of macroscopic black holes implies the existence of microscopic black holes that act like single particle states

Dvali and Gomez

- Marques, Schmaltz, Skiba have argued that any nontrivial UV completion, even without gravity or heavy particle states, creates a fine tuning problem

Marques Tavares, Schmaltz, Skiba

- Dubovsky et al argue that quantum gravity may get around this

Dubovsky, Gorbenko, Mirbabayi

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

Other arguments:

- **Dark matter exists!** (more on this in a moment)
- Dark energy exists! (but if just a cosmological constant, what does this imply?)
- 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? How do you explain away the triumphant discovery of BICEP2? (umm…dust)

Higgs and dark matter?

what if there is no SUSY at the weak scale?

- In that case I would assert that the best-motivated new particles at or around the weak scale are some kind of WIMP dark matter
- The simplest mediator between the dark and visible sectors is the Higgs itself, though a direct Higgs portal coupling to, e.g. a dark scalar
- In such a picture we can try to improve on the SM by deriving the electroweak scale from the dark scale

The weak scale from the dark scale

Assumptions for the rest of this talk:

- Dark matter is WIMPs at or around the electroweak scale
- The electroweak scale is generated from a **Higgs portal** interaction with the dark sector
- Nothing else (except possibly neutrinos) is relevant for the Higgs sector up to ~ the Planck scale
- Whatever is happening at ~ the Planck scale doesn't spoil this picture

Coleman-Weinberg dark matter

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

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

- I will 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
- The Higgs mass-squared parameter stays zero under radiative corrections provided that the dark sector has no explicit mass parameters
- The latter requirement can be satisfied if **the scale of the dark sector is generated radiatively by the Coleman-Weinberg mechanism**
- Thus we will assume that the dark sector is classically scale invariant and weakly coupled

Higgs portal to Coleman-Weinberg dark matter

There are then three simple choices for your dark matter candidate:

- The pseudoscalar part of your complex portal scalar

  Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal and Spethmann

- A chiral fermion that gets mass from a Yukawa coupling to your complex portal scalar

  Altmannshofer, Bardeen, Bauer, Carena and JL

- A gauge boson that gets mass by eating a Goldstone from your complex portal scalar

  Hambye and Strumia

review of Coleman-(E.)Weinberg radiative breaking mechanism

Let's review how this can work for a very simple theory: a single SU(2) doublet complex scalar with a classically scale invariant potential

$$\mathcal{L} = |(\partial_\mu - i\frac{g_X}{2}\sigma^a A^a_\mu)\Sigma|^2 - \frac{\lambda_\Sigma}{2}|\Sigma|^4 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\Sigma = \begin{pmatrix} a^\pm \\ \frac{1}{\sqrt{2}}(s+ia) \end{pmatrix}$$

$$V(h) = V_0(h) + V_1(h) + V_2(h) + \ldots$$

Effective potential to one loop order:

$$V_0(s,\mu) = \frac{1}{8}\lambda_\Sigma^{(1)}(t)\left[\xi_s^{(1)}(t)\right]^4 s^4$$

$$16\pi^2\, V_1(s,\mu) = \frac{6}{4}m^4_{WX}(s,t)\left(\log\frac{m^2_{WX}(s,t)}{\mu^2} - \frac{5}{6}\right) + \frac{3}{4}m^4_{ZX}(s,t)\left(\log\frac{m^2_{ZX}(s,t}{\mu^2} - \frac{5}{6}\right) + \frac{1}{4}m^4_\Sigma(s,t)\left(\log\frac{m^2_\Sigma(s,t)}{\mu^2} - \frac{3}{2}\right) + \frac{3}{4}m^4_\chi(s,t)\left(\log\frac{m^2_\chi(s,t)}{\mu^2} - \frac{3}{2}\right)$$

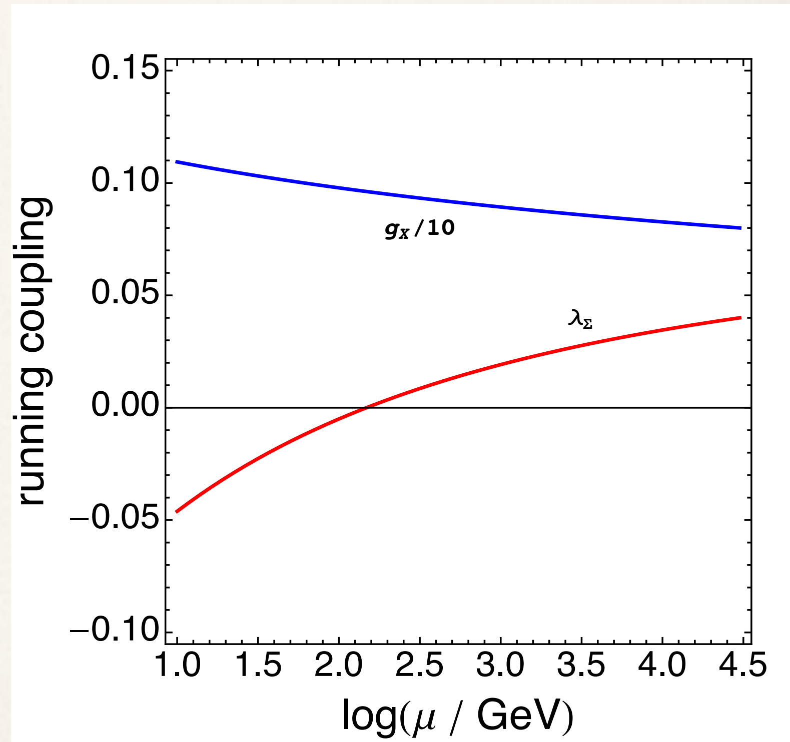
review of Coleman-(E.)Weinberg radiative breaking mechanism

You can check that this satisfies the one-loop RG equation:

$$\mu \frac{\partial}{\partial \mu} V_1(s, \mu) + \beta^{(1)}_{\lambda_\Sigma} \frac{d}{d\lambda_\Sigma} V_0 - \gamma^{(1)}_s s \frac{d}{ds} V_0 = 0$$

to be concrete, let's impose some UV boundary conditions:

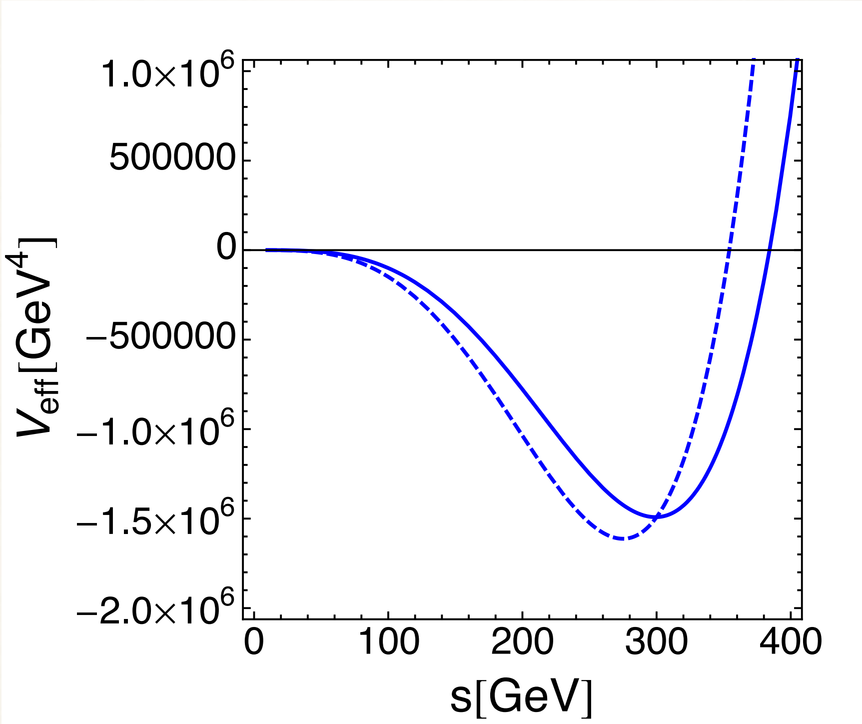
$$\mu_0 = 30 \text{ TeV}$$
$$g_{X0} = 0.8$$
$$\lambda_{\Sigma 0} = 0.04$$



Everything is weakly coupled. As we run down to the IR, the scalar self-coupling goes to zero at some scale O(100) GeV. What happens?

review of Coleman-(E.)Weinberg radiative breaking mechanism

- The one loop effective potential has a minimum at <s> = 300 GeV
- This comes from interplay between the tree level quartic coupling and the logs in the Coleman-Weinberg one loop contribution
- You can see what is happening by expanding the logs around $s/\mu = 1$, with $\mu =< s >= 300 \text{ GeV}$



$$V_0 = 0.00082s^4$$

$$V_1 = -0.0014s^4 + 0.000000004s^6$$

Of course for the actual Standard Model this isn't happening, but it could be happening in a weakly coupled dark sector

Higgs portal with pseudoscalar dark matter

Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal and Spethmann,
+ earlier works

Choose the most general classically scale invariant potential:

$$V_0 = \frac{1}{2}\lambda|H|^4 + \lambda_{\Sigma H}|H|^2|\Sigma|^2 + V_\Sigma(\Sigma) \ +\frac{1}{2}\lambda'_{\Sigma H}|H|^2\left[\Sigma^2 + h.c.\right]$$

$$V_\Sigma = \lambda_\Sigma|\Sigma|^4 + \frac{1}{2}\lambda'_\Sigma\left[\Sigma^4 + h.c.\right] + \frac{1}{2}\lambda''_\Sigma|\Sigma|^2\left[\Sigma^2 + h.c.\right]$$

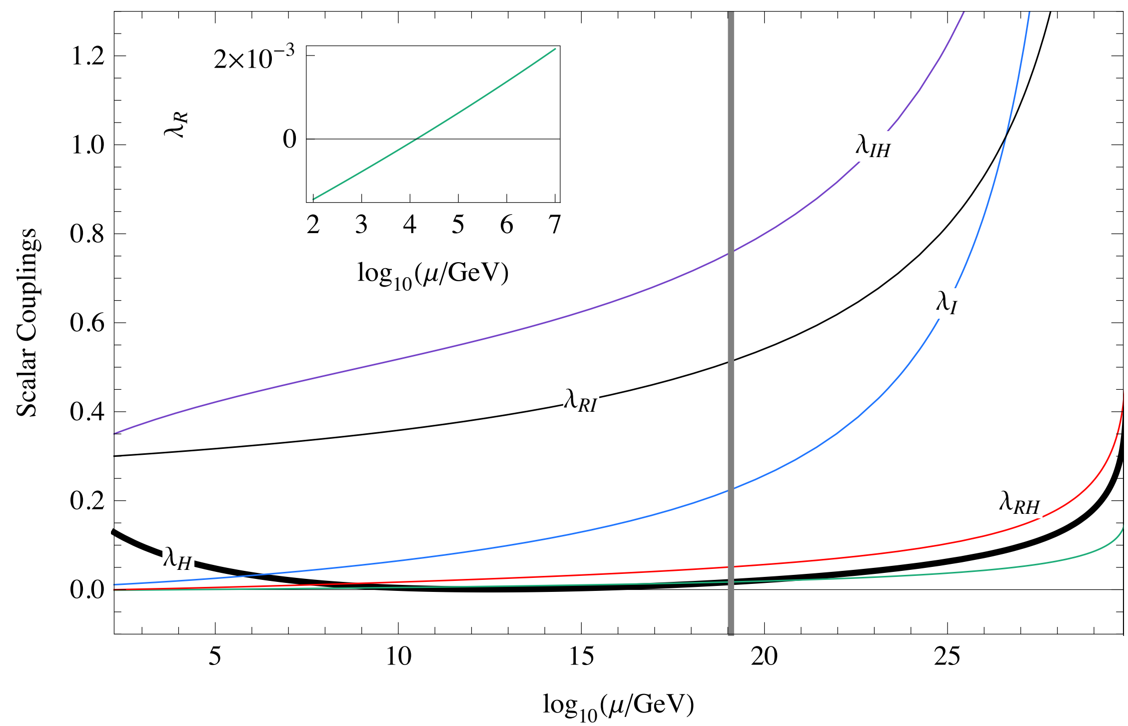
- For suitable choices of couplings, you get a Coleman-Weinberg radiatively induced vev for Σ
- Dark sector has no gauge bosons or fermions
- There a conserved Z_2 (essentially just CP), so the massive dark pseudoscalar is stable
- So you have a stable heavy WIMP and another heavy scalar that mixes with the Higgs through the portal coupling

Higgs portal with pseudoscalar dark matter

Gabrielli, Heikinheimo, Kannike, Racioppi, Raidal and Spethmann

- Rewrite the scalar couplings in terms of the real and imaginary parts of Σ
- The Coleman-Weinberg radiative breaking is the fact that λ_R goes negative near the electroweak scale
- All the scalar couplings have Landau poles, but they can be way above the Planck scale
- And the Higgs vacuum instability can go away

$$V = \frac{1}{4}\lambda_H \phi^4 + \frac{1}{4}\lambda_I s_I^4 + \frac{1}{4}\lambda_{RI} s_I^2 s_R^2 + \frac{1}{4}\lambda_R s_R^4 + \frac{1}{4}\lambda_{IH}\phi^2 s_I^2 + \frac{1}{4}\lambda_{RH}\phi^2 s_R^2,$$



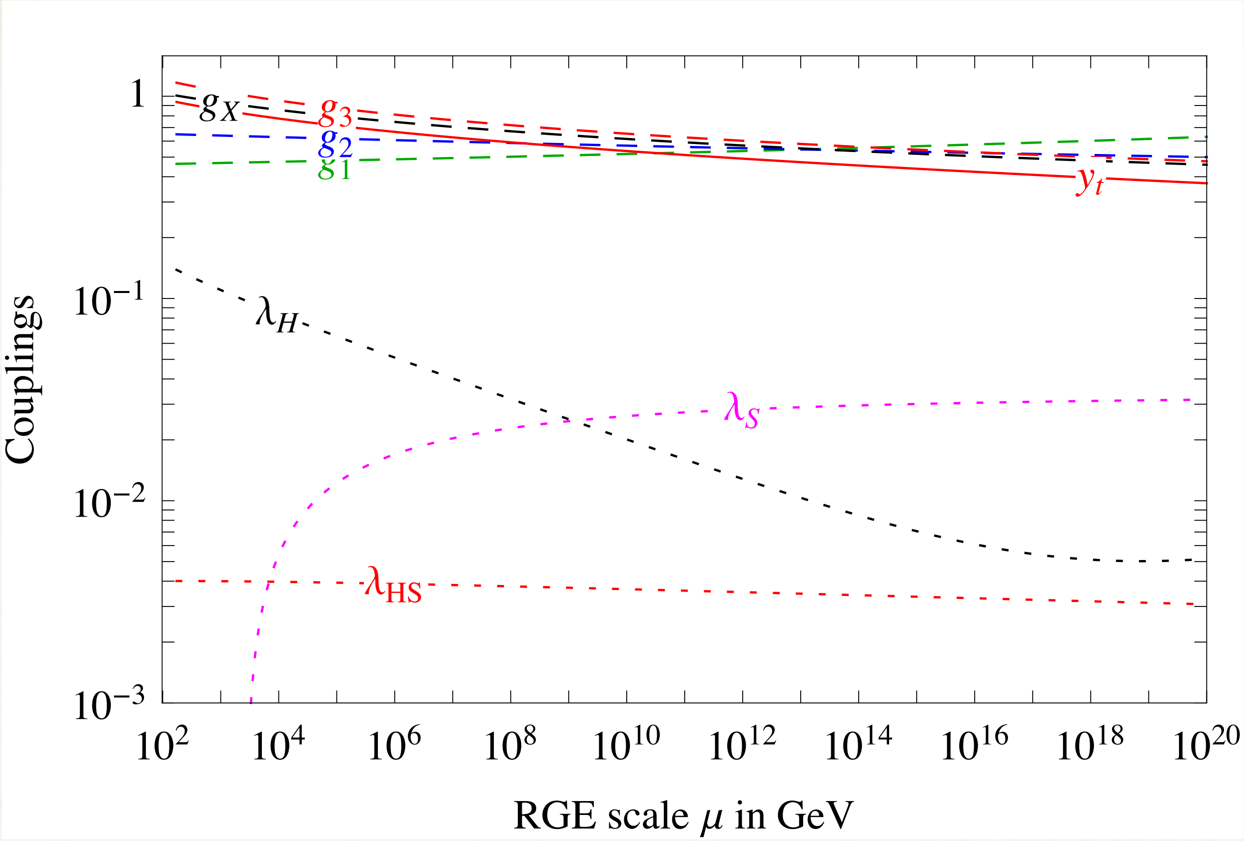
Minimal Coleman-Weinberg dark matter

- 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 the simple Coleman-Weinberg example that I showed you: 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



The UV running is reasonable

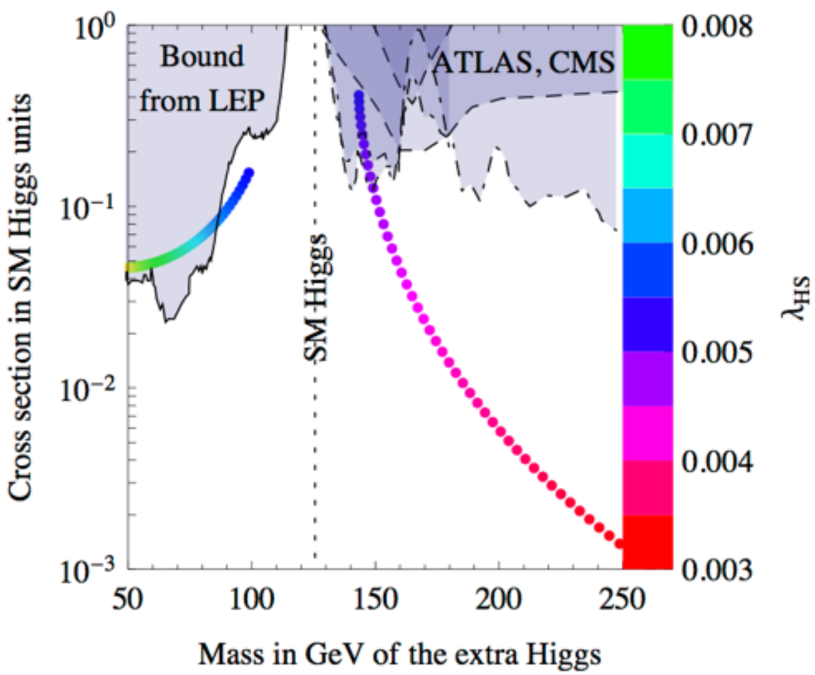
T. Hambye and A. Strumia, arXiv:1306.2329

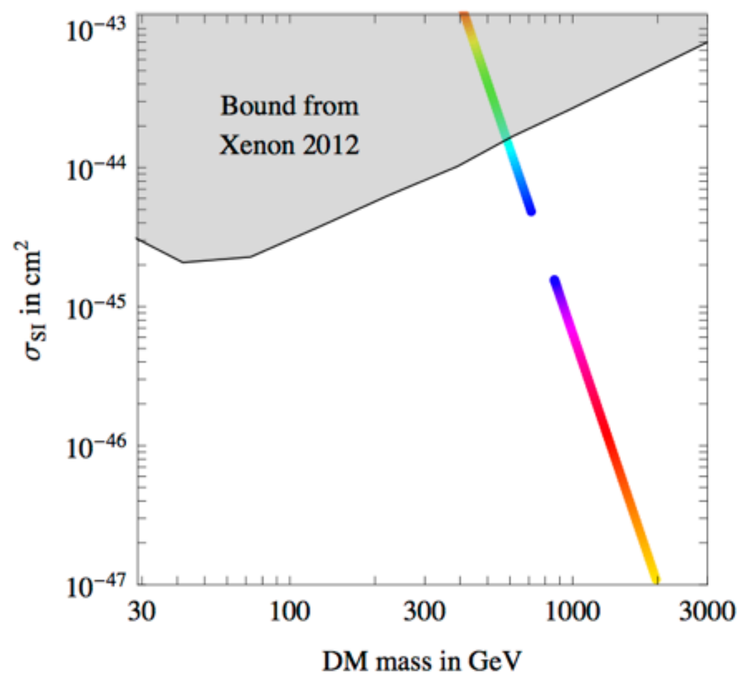
Experimental implications

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, 2013 IFT workshop

Coleman-Weinberg dark matter with fermions

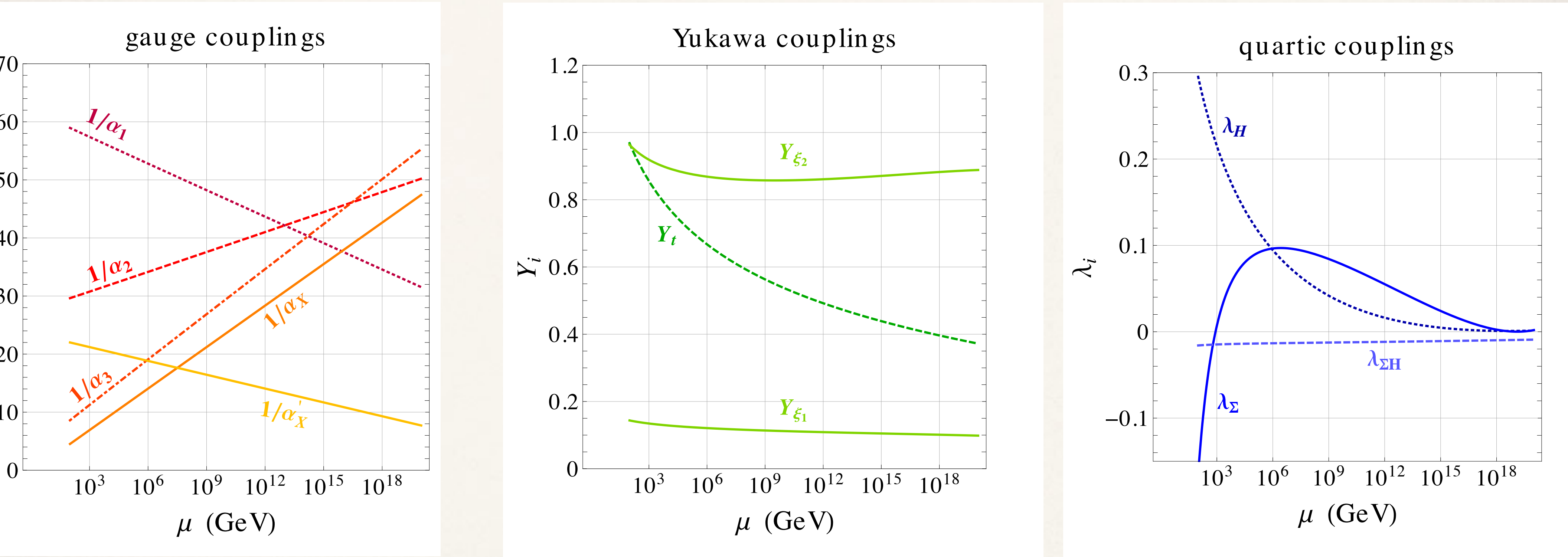
W. Altmannshofer, W. Bardeen, M Bauer, M. Carena, JL

- Dark matter doesn't have to be heavy gauge bosons, or scalars, it could be fermions
- Dark sector has Yukawa couplings, gauge couplings, and one scalar self-coupling, but no explicit mass parameters
- 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

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h + v + iG^0) \end{pmatrix} , \quad \Sigma = \begin{pmatrix} a^+ \\ \frac{1}{\sqrt{2}}(s + w + ia) \end{pmatrix}$$

$$m_{\gamma'} = 0 \, , \quad m_{W'} = \frac{w}{2} g_X \, , \quad m_{Z'} = \frac{w}{2}\sqrt{g_X^2 + {g'_X}^2} \, .$$

The UV running in these kinds of models is even more interesting than for Hambye and Strumia:



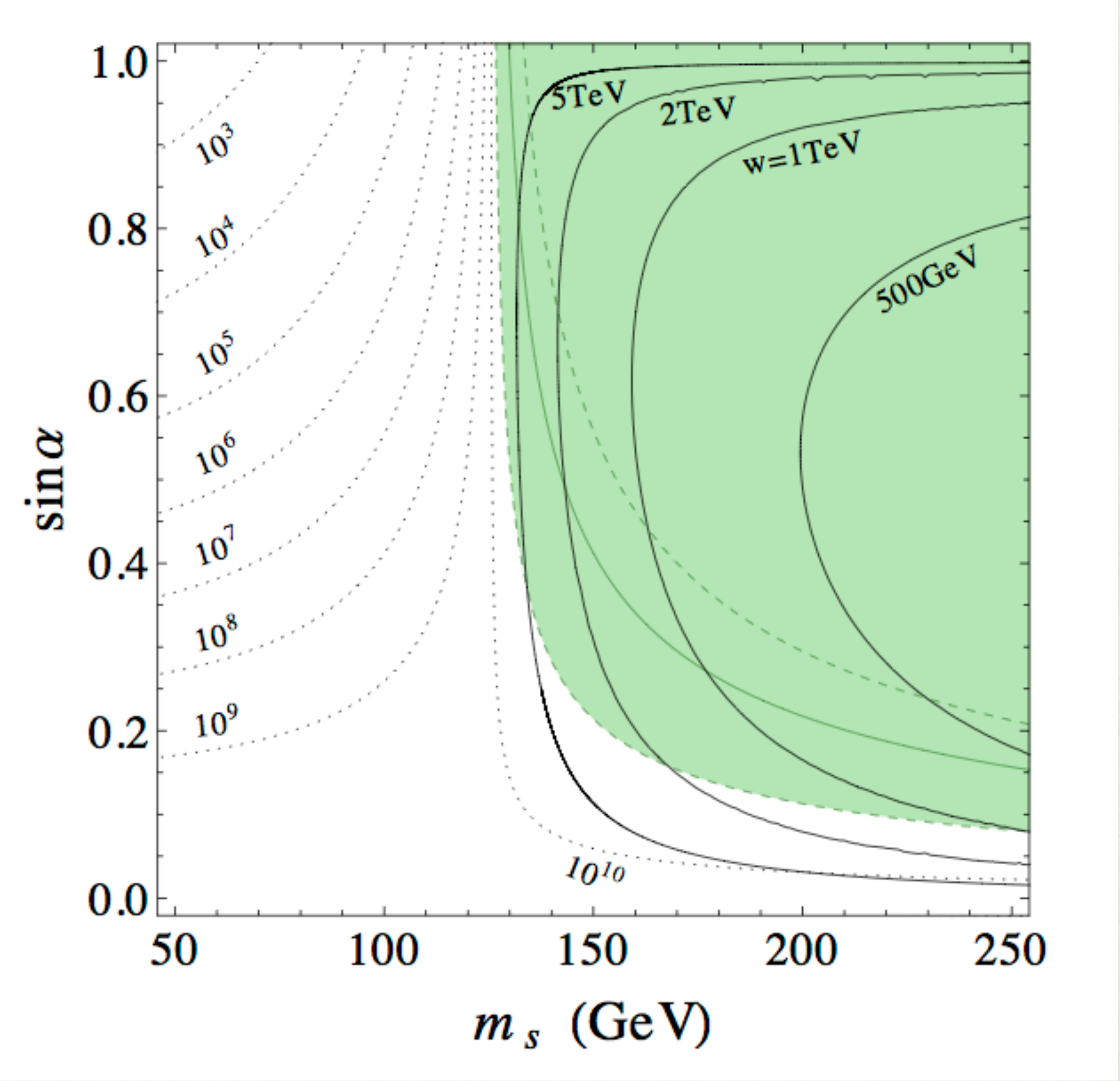
Stabilizing the Higgs vacuum

- The Higgs and the dark scalar mix through the portal coupling:

$$\begin{pmatrix} h \\ s \end{pmatrix} \to \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} , \quad \sin 2\alpha = \frac{2\sqrt{\lambda_H |\lambda_{\Sigma H}|} v^2}{m_s^2 - m_h^2}$$

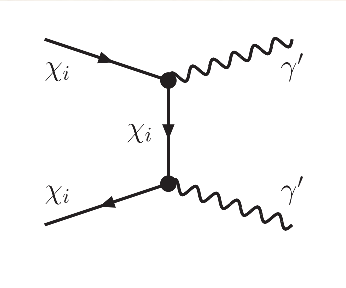
- This works in the direction of stabilizing the Higgs vacuum

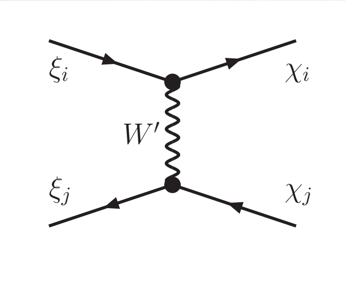
$$m_h^2 \simeq v^2 \left(\lambda_H - \frac{2\lambda_{\Sigma H}^2}{\beta_{\lambda_\Sigma} - 2|\lambda_{\Sigma H}|} \right)$$

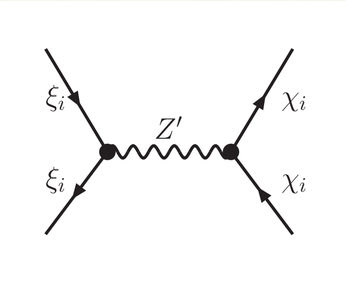


fermion dark matter thermal relic abundance

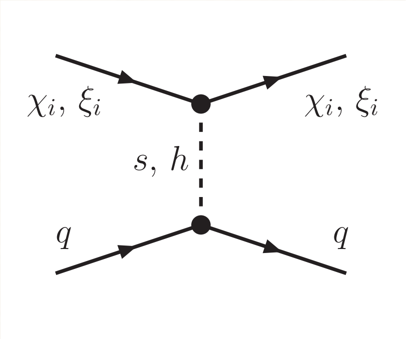
- Generically this kind of model has two different stable fermion dark matter components: one neutral and one dark-charged
- Since the dark-charged one annihilates efficiently to dark photons (which then redshift away), it is a subdominant but still interesting fraction (e.g. 5%) of the total



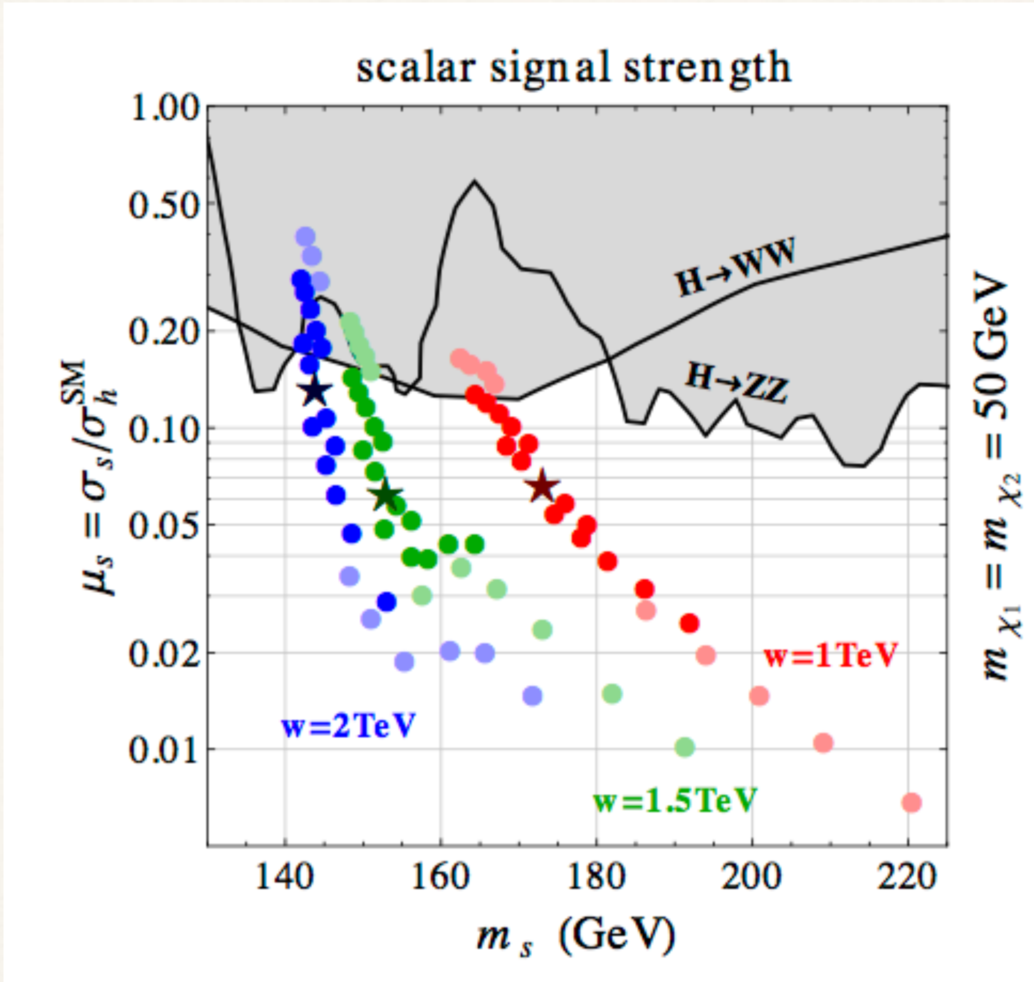




DM direct detection is via mixing of the dark scalar with the Higgs boson

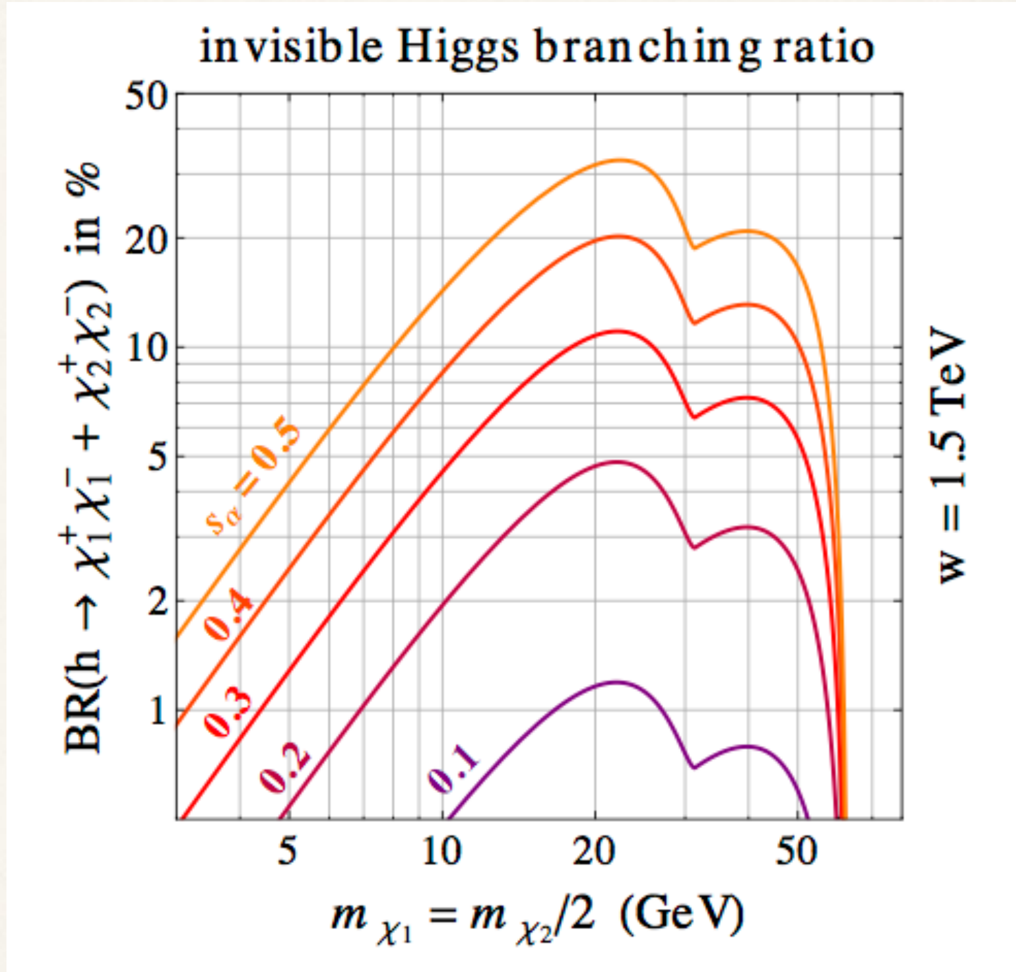


Finding the dark scalar at the LHC



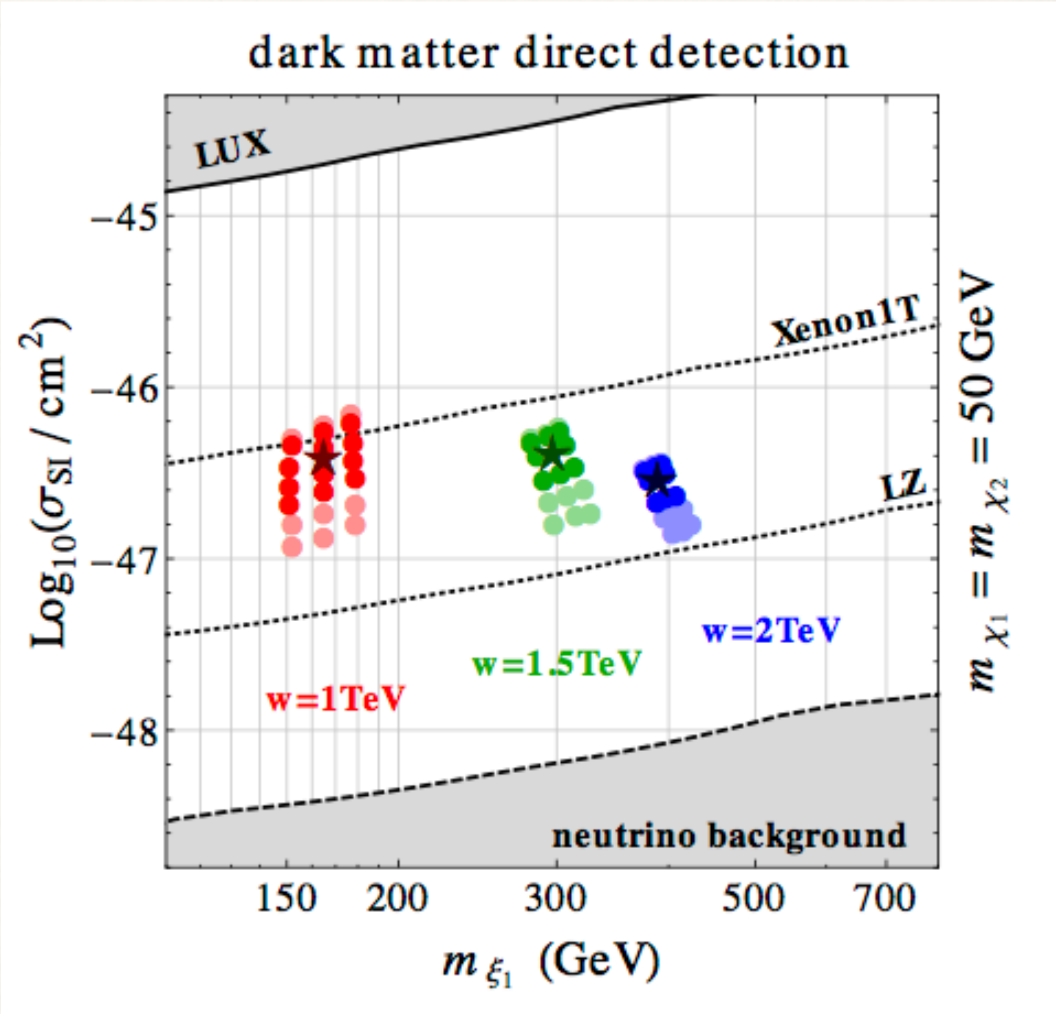
Higgs invisible width

- Since the Higgs boson mixes with the dark scalar, it can have an invisible decay to a pair of dark fermions
- These fermions are the subdominant dark matter component, i.e. the dark-charged fermions



dark matter detection

- Direct detection of the dominant dark-neutral fermions will come from LZ or XENON Nton
- The dark-charged fermions cannot be seen in direct detection, but could have observable effects on galactic/local structure



Summary

- Maybe there will be SUSY at the LHC, or maybe not
- We do not understand the naturalness problem, so should be open minded
- Maybe the electroweak scale is generated from the dark sector
- Discoveries from the LHC and direct dark matter detection could clarify this picture!!!