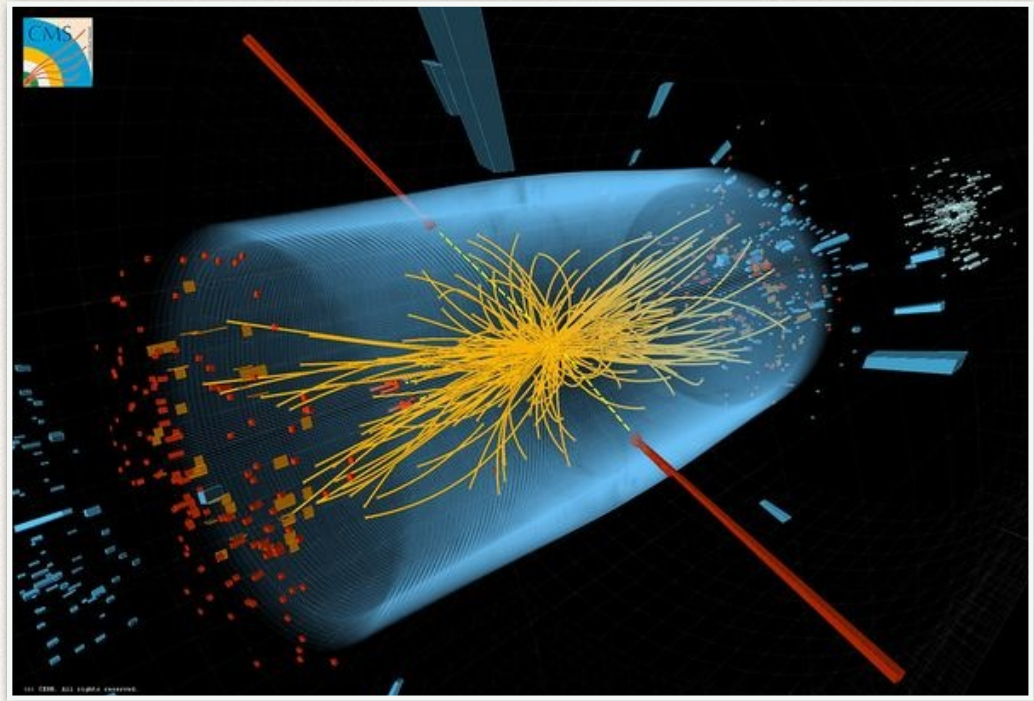
Connecting the Dots: The Path from the Higgs Boson to the Dark Sector

Chris Jackson

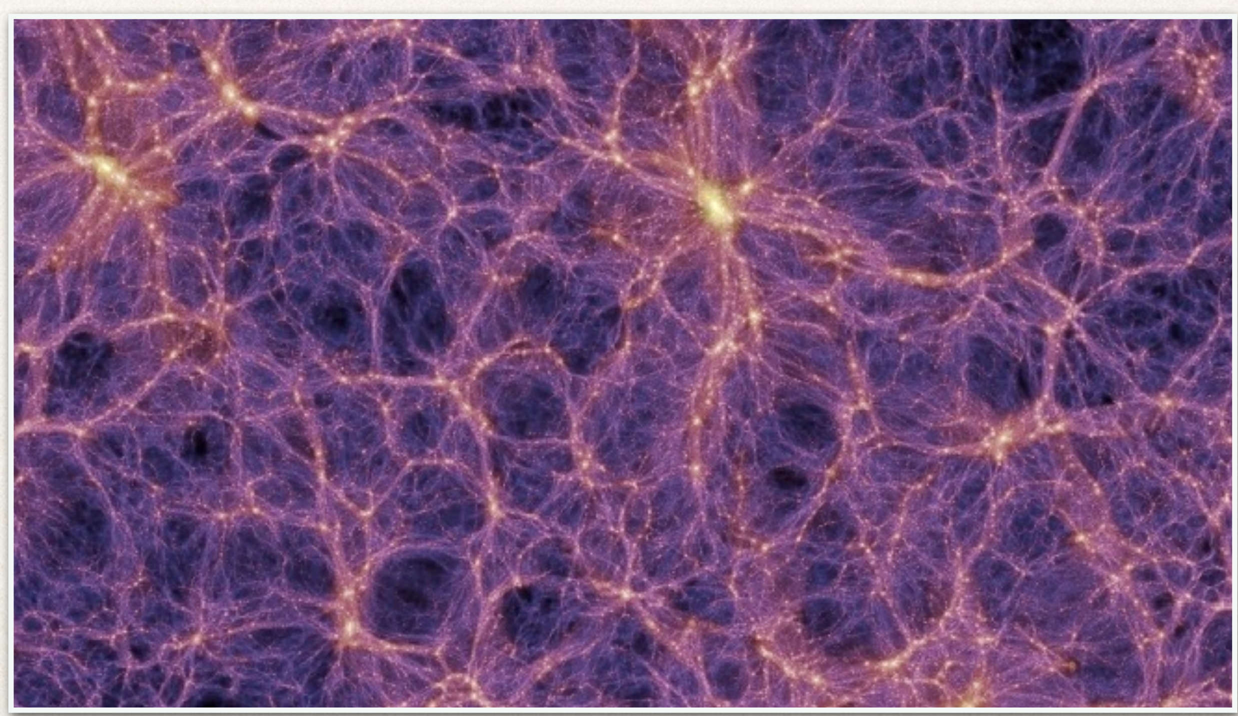
University of Texas at Arlington

UNIVERSITY OF TEXAS ARLINGTON

- Question: why should astrophysicists care about the Higgs boson?



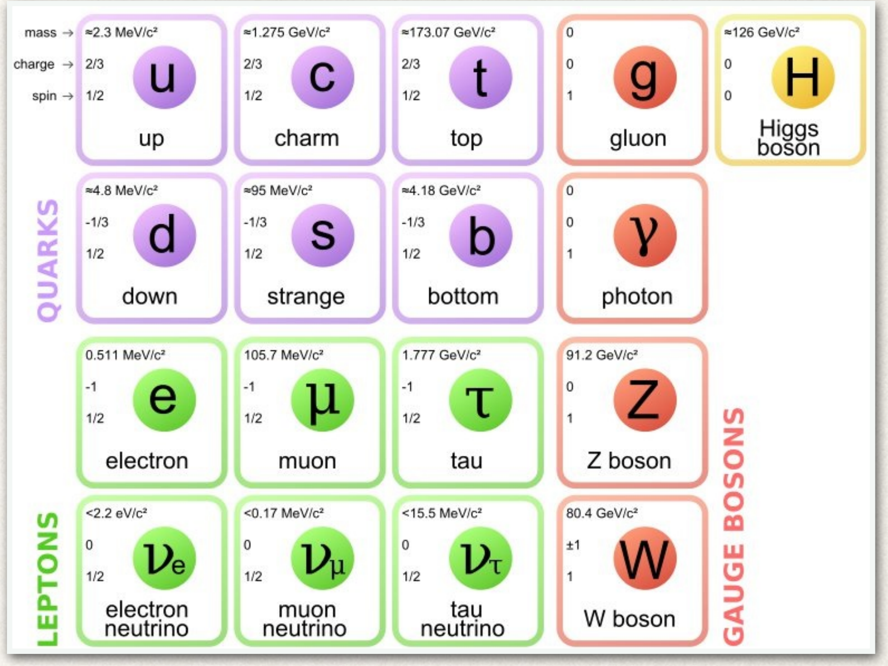
- Answer: because there may be an *intimate connection* between the Higgs and the "dark sector" (i.e., dark matter & dark energy) of our Universe!



“Particle physics is dead they say…”

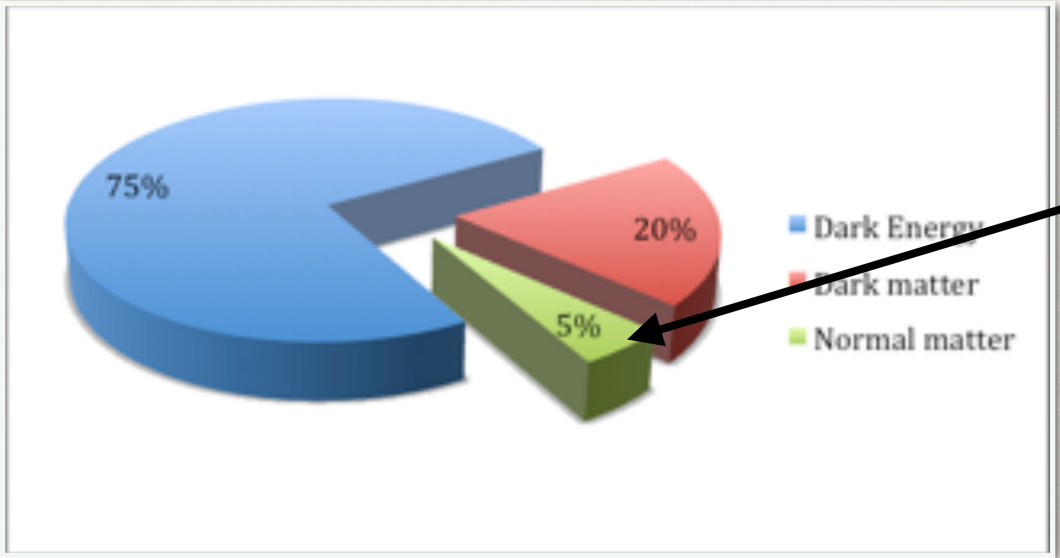
- Pete Townsend of The Who

- Discovery of the Higgs boson completes the (minimal) content of particles in the “Standard Model”



- HOWEVER: despite claims in the “popular press”, it does not signal the END of particle physics!

- It’s only the beginning of a new era!

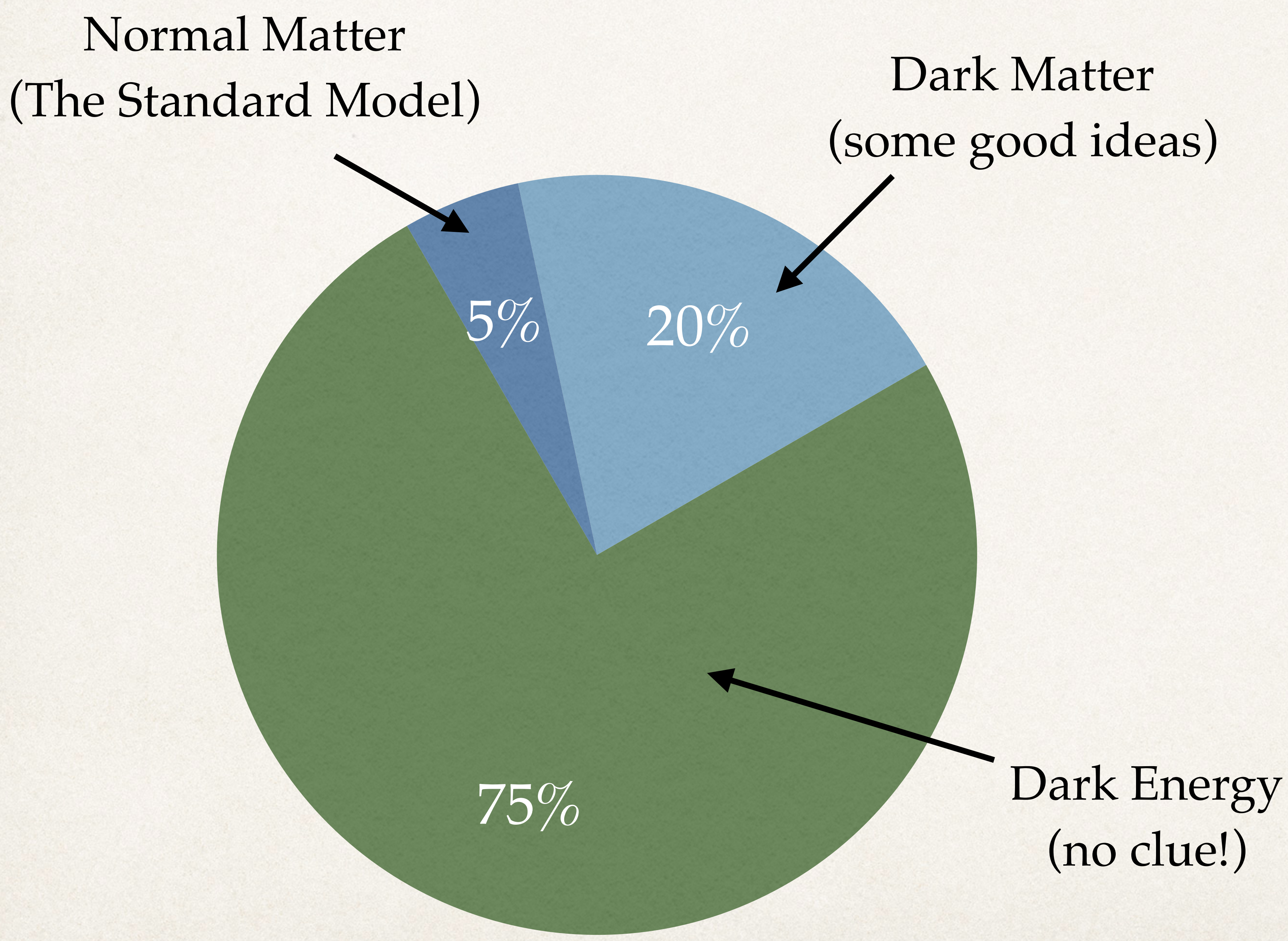


The stuff we “understand”… but, what about:

- neutrino masses?
- hierarchy in the couplings of fermions to the Higgs boson?
- the “ad hoc-ness” of the Higgs mechanism?
- gravity???

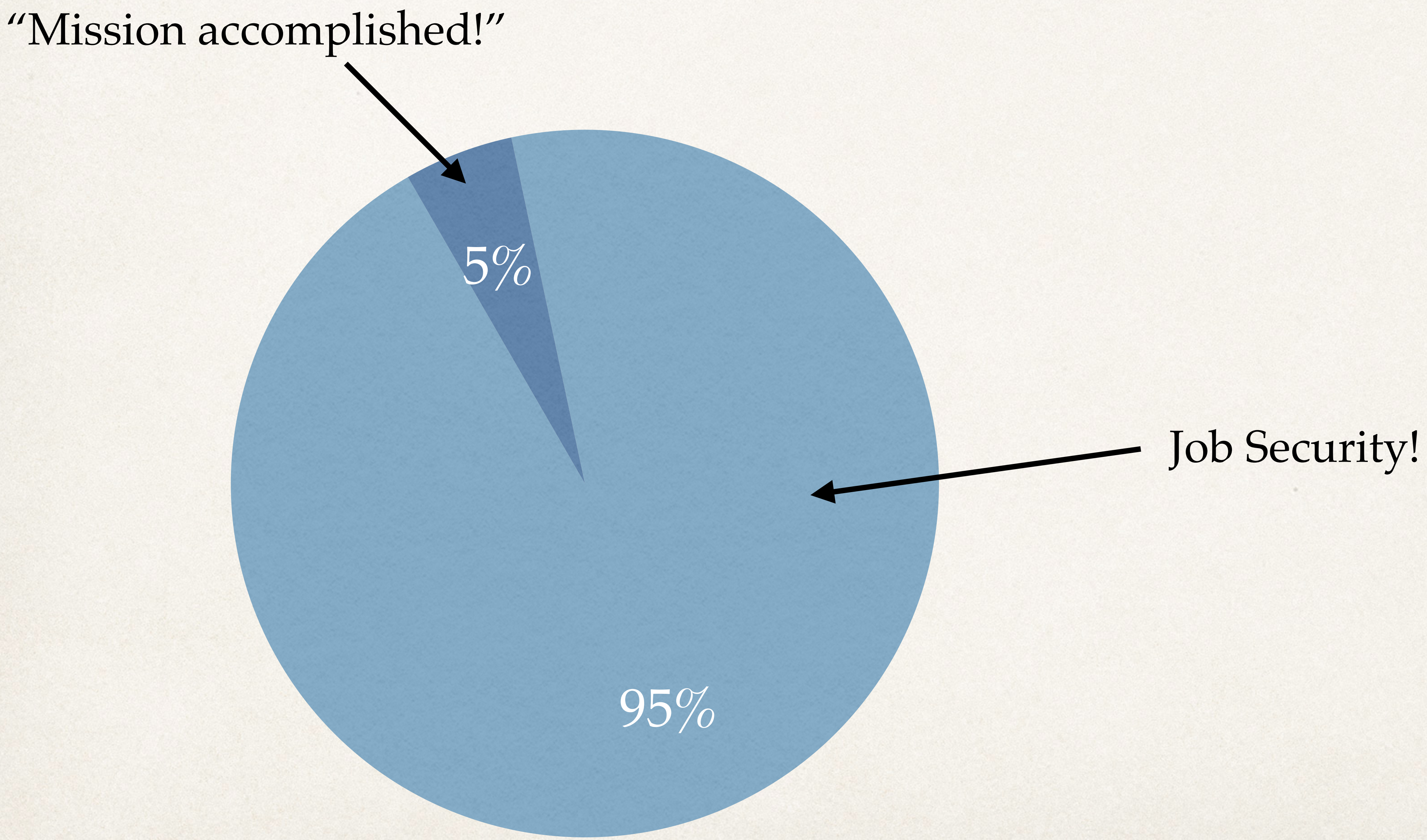
"… long live particle physics!!!"

- Pete Townsend of The Who



"… long live particle physics!!!"

- Pete Townsend of The Who



The Standard Model at a Glance

- The Standard Model (SM) is an (effective) gauge quantum field theory based on the group structure $SU(3)_C \times SU(2)_L \times U(1)_Y$

- The Lagrangian consists of several key components:

  - Kinetic terms for the gauge fields (photons, W's, Z's and gluons):

$$\mathcal{L}_{KE} = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

  - Interactions between "matter fields" (leptons and quarks) and gauge fields:

$$\mathcal{L}_I = i\bar{U}\left(\partial_\mu - ig_s G^a_\mu T^a\right)\gamma^\mu U + i\bar{D}\left(\partial_\mu - ig_s G^a_\mu T^a\right)\gamma^\mu D + \sum_\psi \bar{\psi}\gamma^\mu\left(i\partial_\mu - g'\frac{1}{2}Y_W B_\mu - g\frac{1}{2}\tau^a W^a_\mu\right)\psi$$

- These two equations describe (extremely precisely!) the physics all around us.

- BUT… "where's the mass?!?" Gauge-invariance FORBIDS us from writing down EXPLICIT mass terms

The Higgs Mechanism

- To correct for this deficiency, we can introduce a complex scalar field which is a doublet under the SM $SU(2)_L$ gauge group.

$$\mathcal{L}_H = \left[\left(\partial_\mu - igW_\mu^a\tau^a - ig'Y_\phi B_\mu\right)\phi\right]^2 + \mu^2\phi^\dagger\phi - \lambda\left(\phi^\dagger\phi\right)^2$$

- The "weird" sign choice for the μ^2 term results in a non-zero vacuum expectation value (vev or v) for ϕ

- To interpret the theory correctly, we should shift ϕ by its vev and expand about this "true" minimum. For example, in a particularly nice gauge choice, the shift looks like:

$$\phi(x) = \frac{1}{\sqrt{2}} e^{i\frac{\chi(x)}{v}} \left(v + H(x)\right)$$

where χ are massless (Goldstone) bosons and H is a physical scalar field (Higgs boson). The result are quadratic terms in the gauge fields which "look like" mass terms. For example, the mass of the W boson looks like:

$$M_W = g\,v$$

Fermion masses and Higgs Interactions

- To give masses to the fermions of the SM, we write down "Yukawa interactions" between the scalar field and the fermions:

$$\mathcal{L}_Y = \bar{U}_L \lambda_u U_R \phi^0 - \bar{D}_L \lambda_u U_R \phi^- + \bar{U}_L \lambda_d D_R \phi^+ + \bar{D}_L \lambda_d D_R \phi^0 + h.c.$$

- After SSB, we find quadratic terms in the fermion fields which can be interpreted as mass terms:

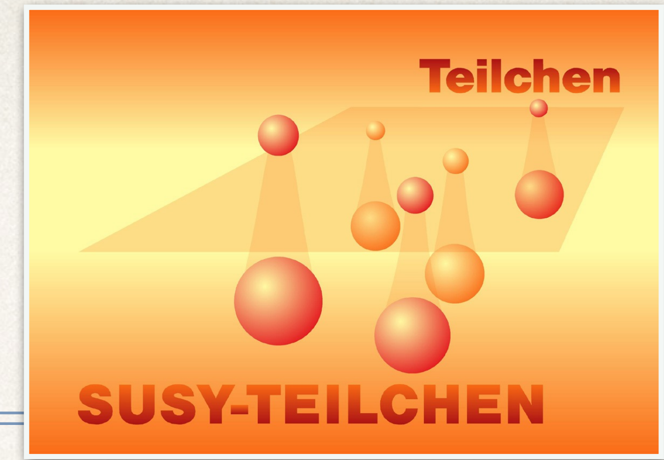
$$m_u = \lambda_u v$$

- In addition to mass terms for gauge/fermion fields, the Higgs mechanism results in interactions between the gauge (fermion) field and the physical "Higgs boson". These interactions are proportional to the combination of gauge (Yukawa) coupling times the Higgs vev… i.e., to the mass!

- Therefore, in the interaction terms, we can exchange the combination of "coupling × vev" for mass. We say that the Higgs boson "couples to mass." In other words, the Higgs couples most strongly to the most massive particles.

- This feature motivates the way we look for the Higgs at colliders (as Joe has already shown you :)

No dark matter?(!?)

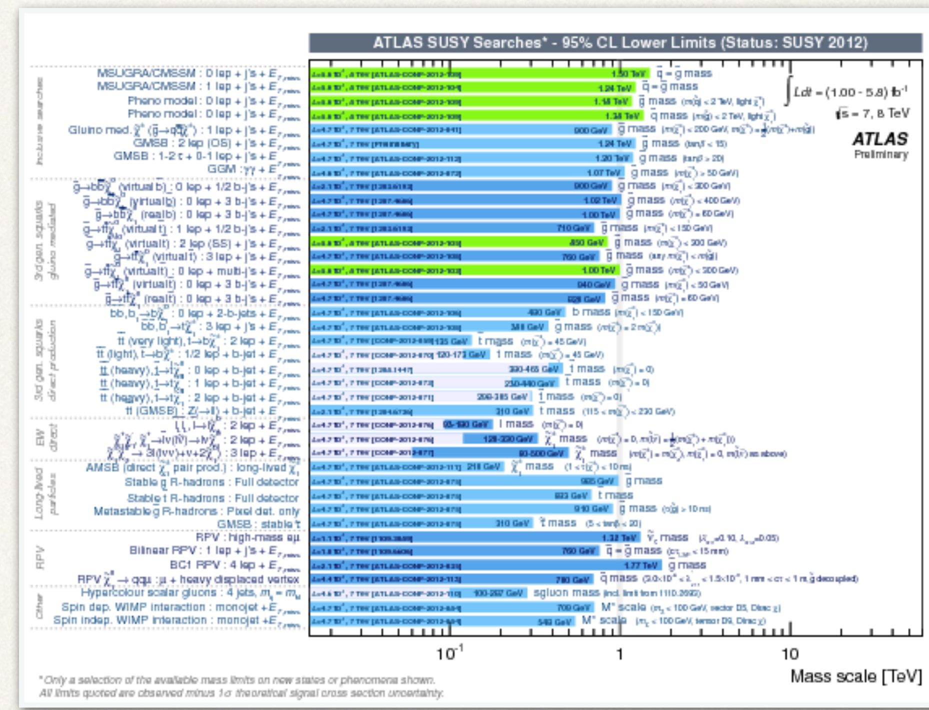


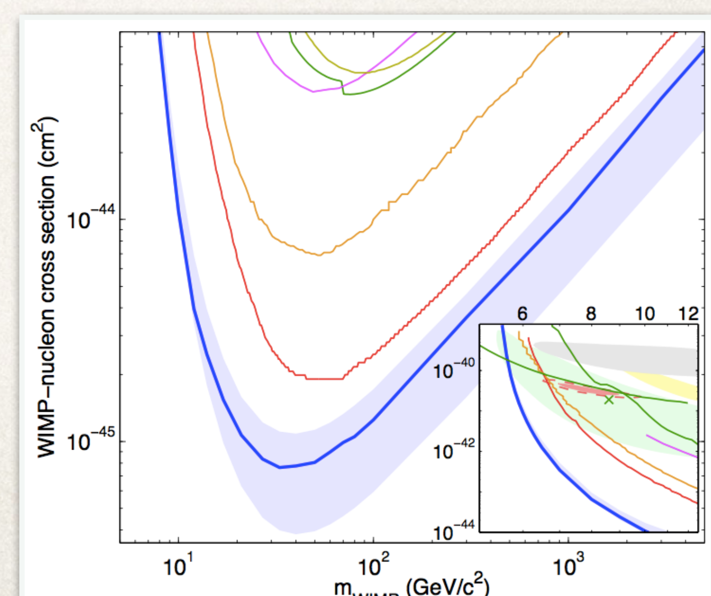
- One of the major deficiencies of the Standard Model is the lack of a good candidate for (cold) dark matter.

- To account for DM, we have to go "beyond the SM." Many examples of this:
supersymmetry, extra-dimensional models, etc.

- <u>One problem</u>: we haven't seen ANY SIGNS that these ideas are correct

- In fact, they're becoming highly-constrained both at collider experiments and DM direct-detection experiments





The Higgs Portal

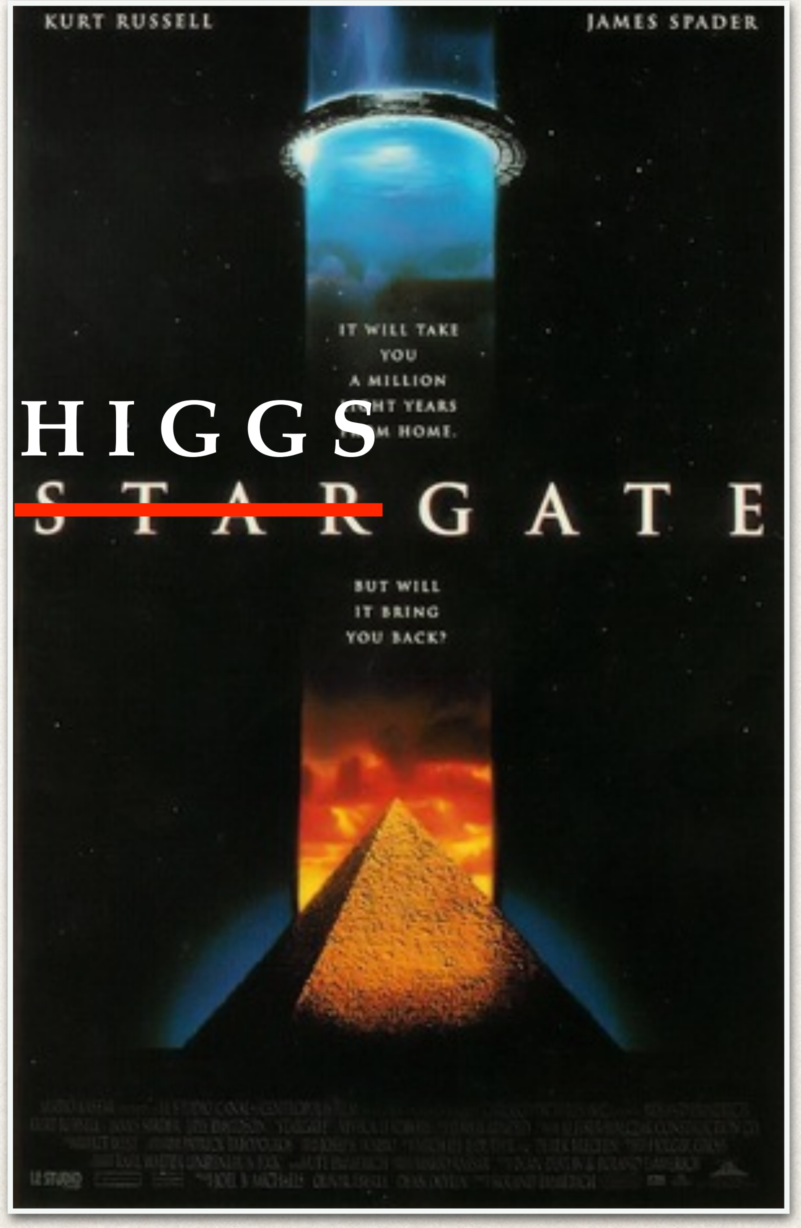
B. Patt & F. Wilzcek, ‘06

- One interesting alternative to the SUSY DM paradigm (that is “neither grotesque nor unnatural”) is the so-called “Higgs portal”

- With one exception, all terms in the SM Lagrangian are renormalizable. In other words, the interactions and kinetic terms are represented by operators of mass dimension 4. This means they have dimensionless couplings (highly-desirable).

- The one exception is the Higgs field mass term ($\phi^\dagger\phi$) which is mass dimension 2… and, thus, requires a mass-dimension 2 coupling.

- Viewed from another perspective, the $\phi^\dagger\phi$ operator can be used to build RENORMALIZABLE interactions with fields which are singlets under the SM gauge group (i.e., “dark particles”)



- The simplest example of this is given by adding a single real scalar field to the SM with Lagrangian:

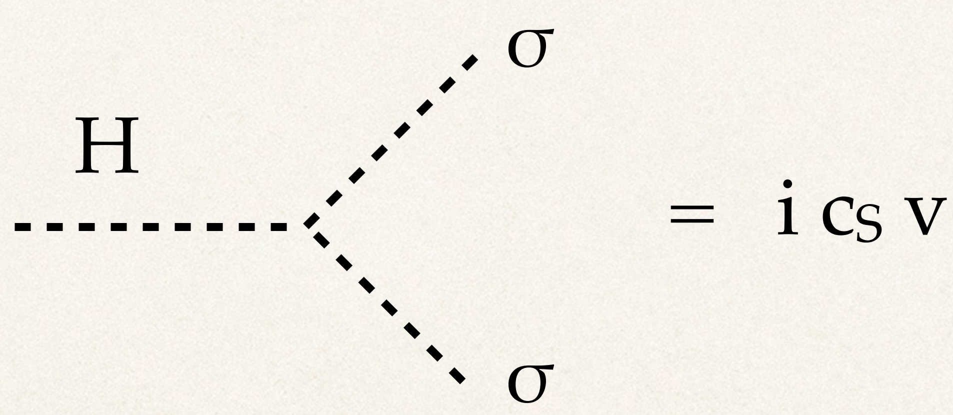
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{c_S}{2}\phi^\dagger\phi\,\sigma^2 - \frac{\lambda_\sigma}{4!}\sigma^4$$

where we have imposed a discrete Z_2 symmetry to keep σ stable (this can be achieved naturally in more sophisticated models).

- Once the SM Higgs field (ϕ) acquires its vet, the physical mass of the σ field will be:

$$m_\sigma^2 \to m_\sigma^2 + \frac{c_S v^2}{2}$$

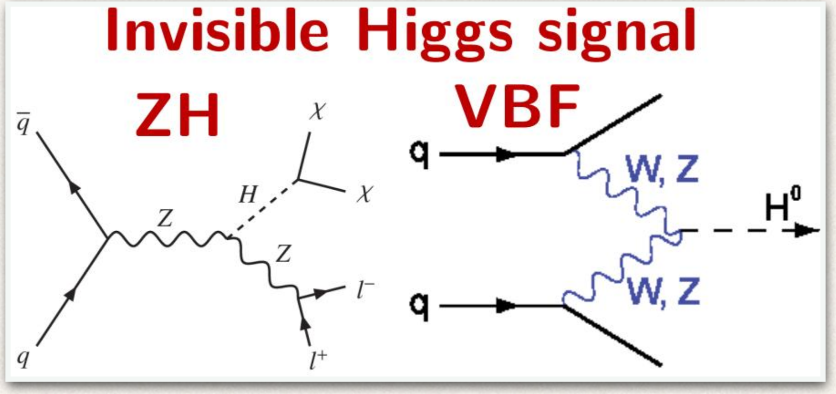
- From the "link" term in the Lagrangian, we will also acquire an interaction term between one physical Higgs boson and two σ fields:



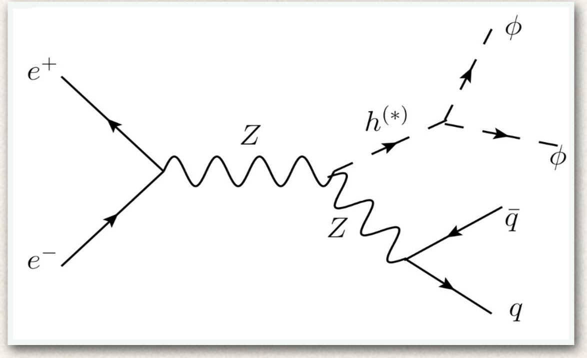
- The interaction will allow us to look for dark matter in association with Higgs bosons!

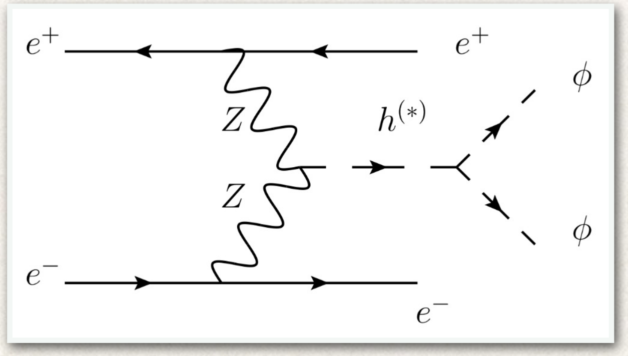
Looking through the Higgs portal for dark matter

- Searches for "invisible decays" of the Higgs are currently being conducted at the LHC (stick around for Darien's talk next):



- We will also be able to study these decay modes at a linear e+-e- linear collider (a "Higgs factory"):

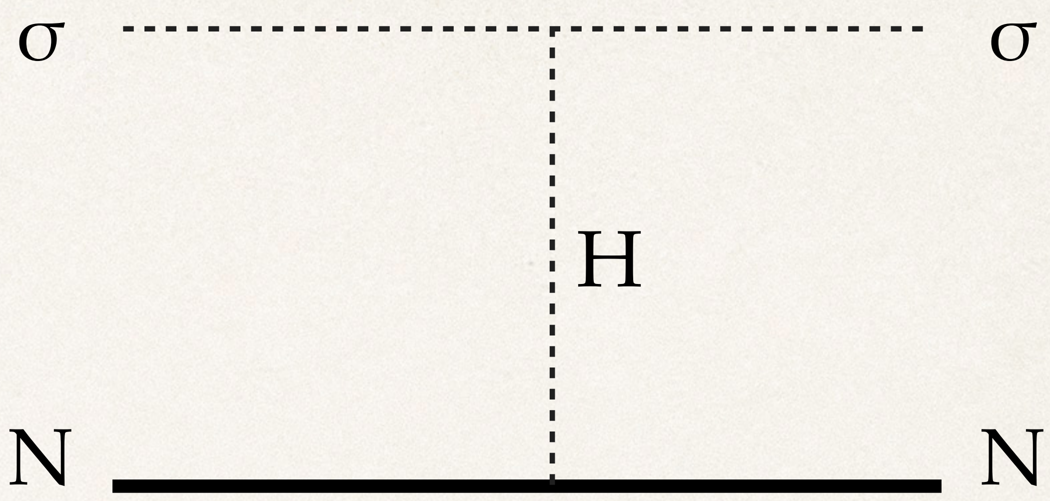


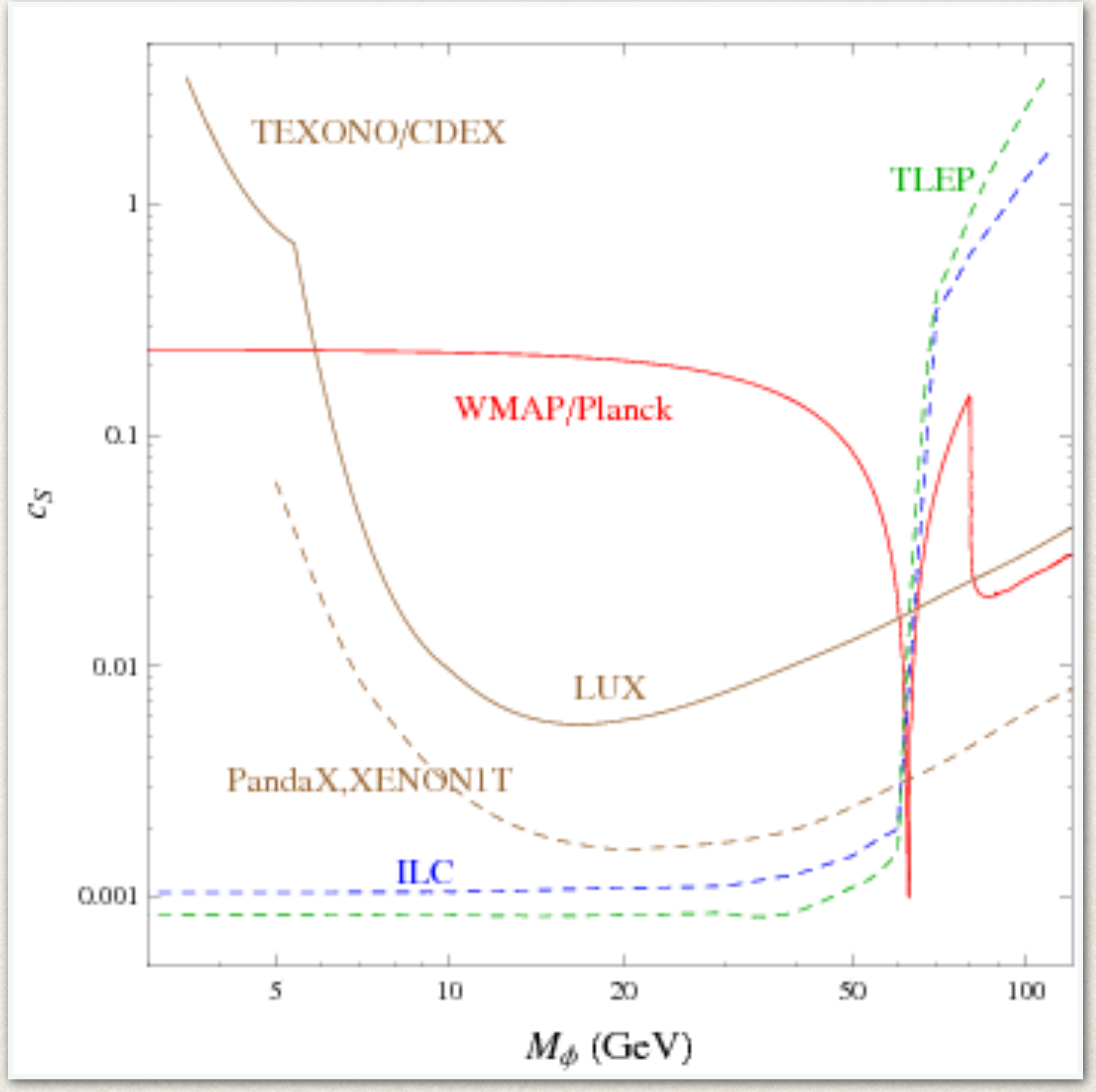


- Note: the more precisely we measure the decays of the Higgs into SM particles, the more constrained the invisible decay modes become.

- We can also look for this type of dark matter via direct detection here on Earth (through Higgs exchange):

Large Underground Xenon (LUX) detector





- A recent study by Chacko et al. (arXiv:1311.3306) shows the searches at a linear collider and direct detection experiments are very complimentary to each other.

Higgs in Space!

Based on:

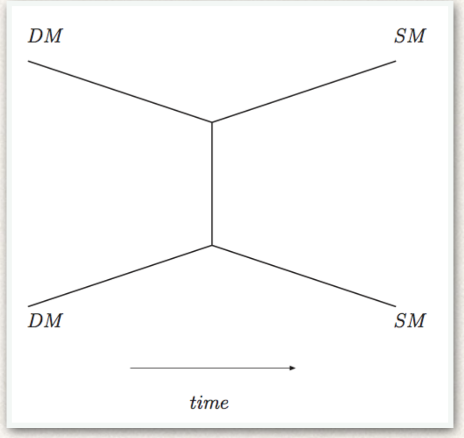
CJ, G. Servant, G. Shaughnessy, T. Tait and M. Taoso

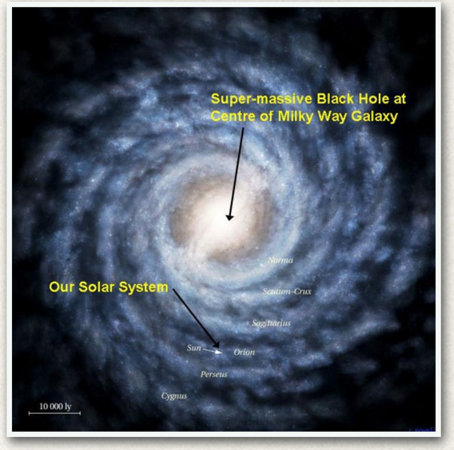
JCAP 1004 (2010) 004, arXiv:0912.0004

JCAP 1307 (2013) 006, arXiv:1303.4717

Indirect Detection of Dark Matter

- "Indirect detection" experiments look for signs of dark matter from its annihilation into SM particles

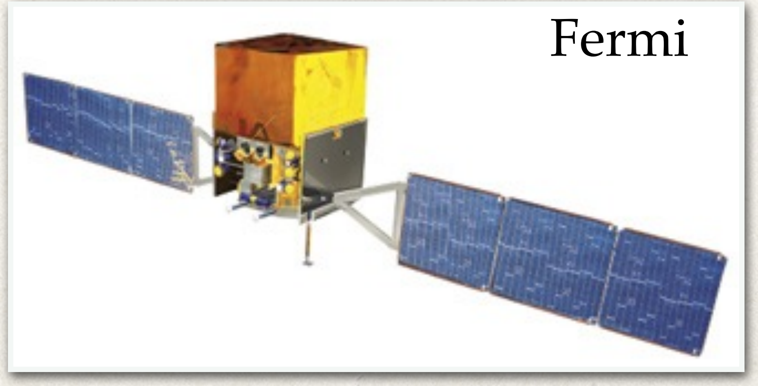


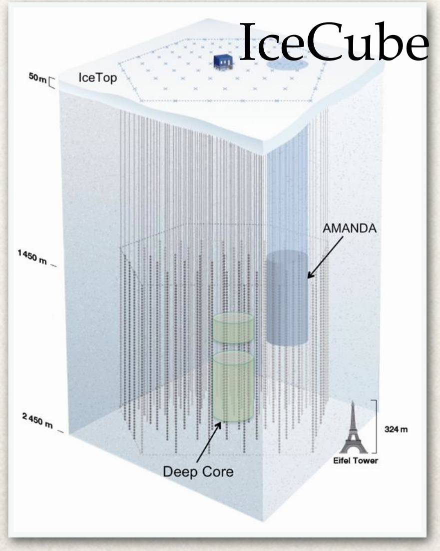


- Greater probability for these annihilations to take place (and for us to observe them) in places where we expect dark matter to "clump"

- Decay products include electrons/positrons, neutrinos and photons. Charged particles must come from "local" sources, while neutral particles can travel great distances w/o deflection and/or energy loss.

- Experiments/observatories come in all shapes and sizes:



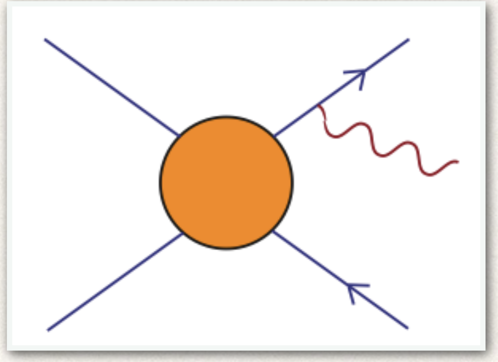


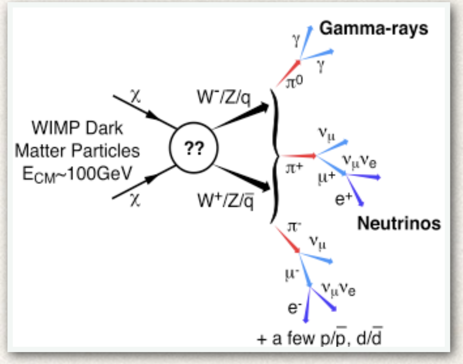
Seeing the light from Dark Matter

- Dark matter is dark… i.e., it doesn't interact with light. Dark matter annihilations can, however, produce photons. Wait, what?!?

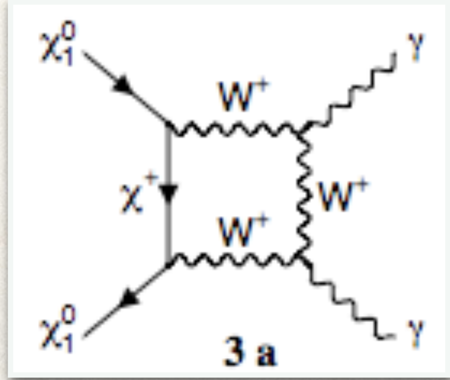
- Dark matter doesn't interact DIRECTLY with photons, but it can interact INDIRECTLY. In fact, dark matter annihilations can produce photons (gamma rays) in several ways.

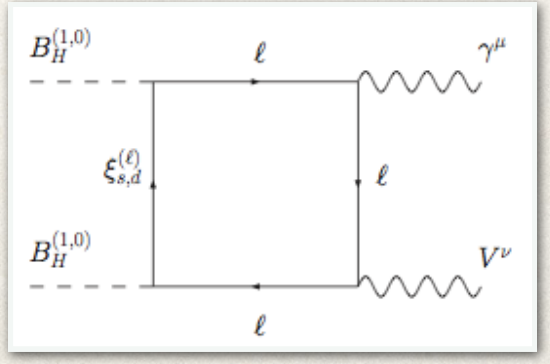
- Annihilation into SM particles which then radiate and/or hadronize or decay into gamma rays





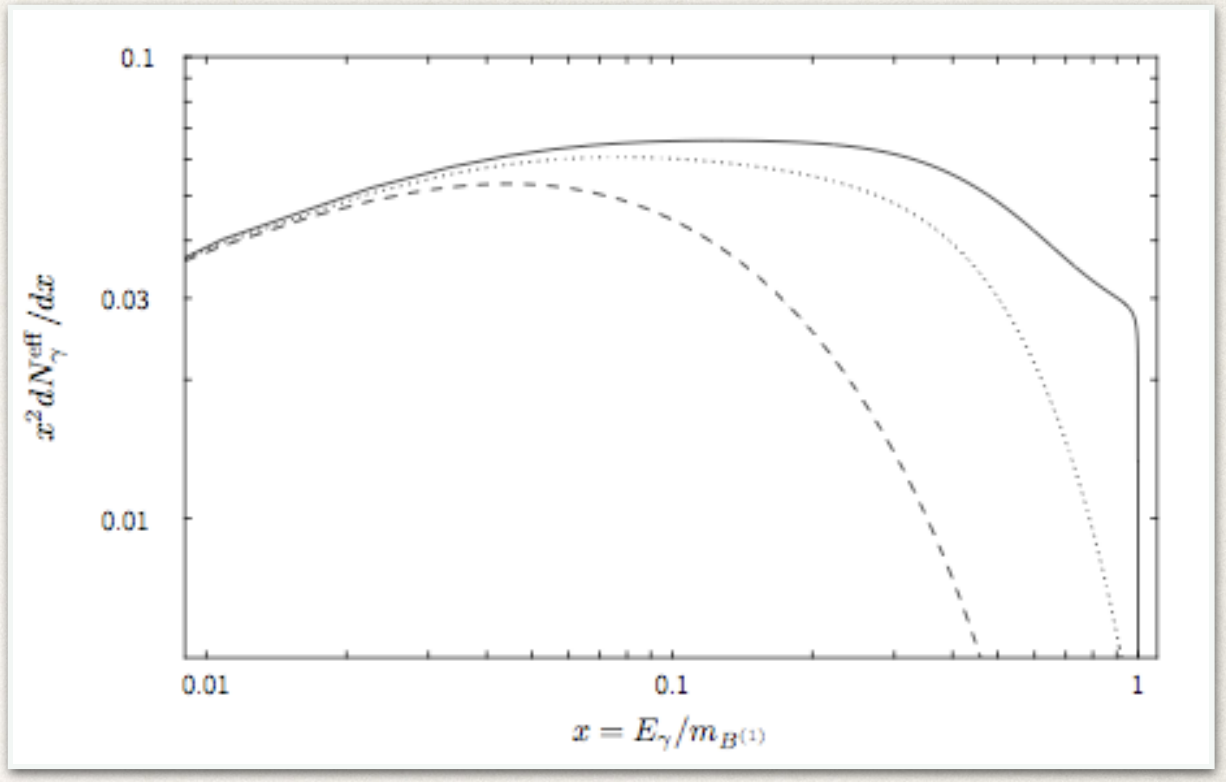
- Annihilate through loops of "virtual particles"





- What does the gamma ray spectrum look like from DM annihilations?

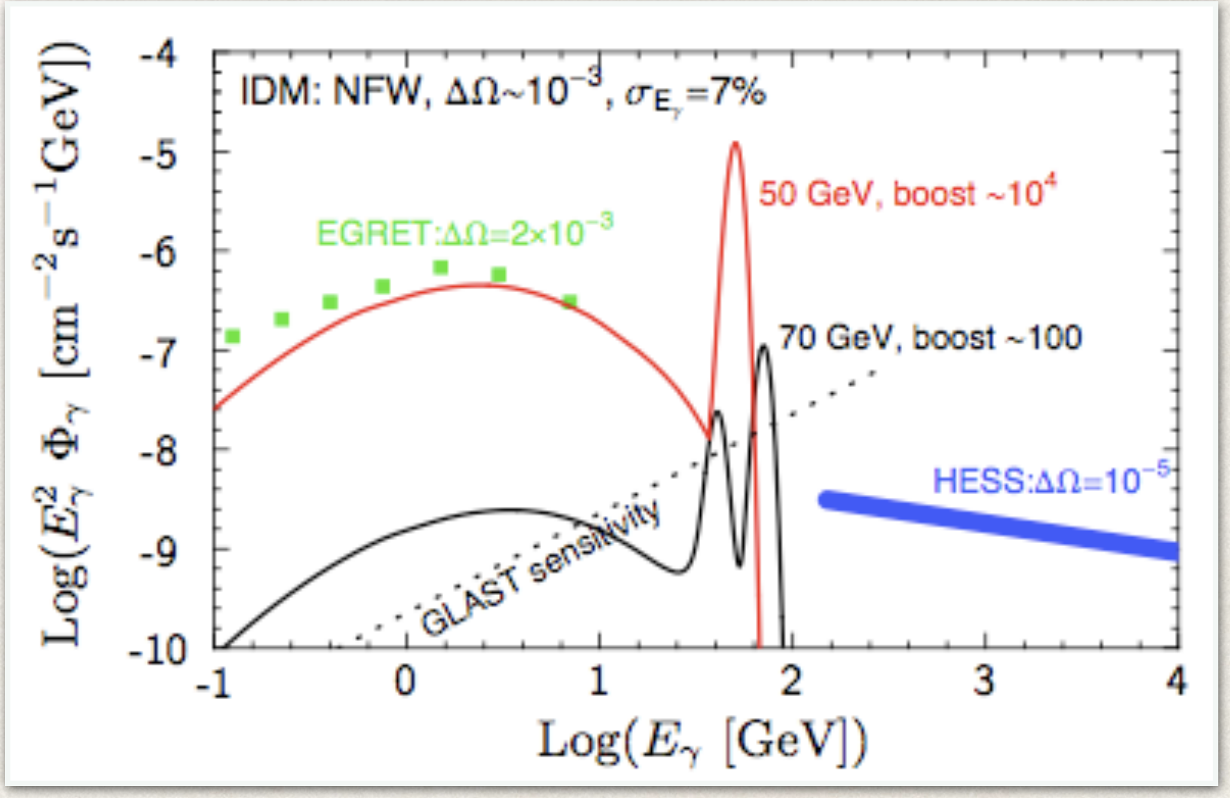
- The annihilations into SM particles which then radiate or decay into gammas produces a rather featureless continuous spectrum (cutoff at the DM mass)



- The loop-induced annihilations produce ɣ + X final states (where identity of X depends on the spin of the DM particle).

- Because the DM particles are non-relativistic, the photons are (nearly) mono-energetic. The position of the line(s) depends on the mass of X:

$$E_\gamma = m_{DM}\left(1 - \frac{m_X^2}{4m_{DM}^2}\right)$$



- Many models are capable of producing multiple lines

Higgs in Space!

- "WIMP Miracle": Electroweak-scale masses (100's of GeV) and couplings can naturally account for the observed abundance of dark matter

- Another "miracle" that involves EW-scale masses and couplings is the process of electroweak symmetry breaking in the SM. The "remnant" of this process is the "Higgs boson."

- Coincidence that these two "miracles" occur for the same ranges of masses and couplings? Could dark matter and EWSB dynamics be related?

- If so, we might expect WIMPs to have enhanced couplings to the heaviest SM particles (W's, Z's and/or top quarks) much like the Higgs boson itself

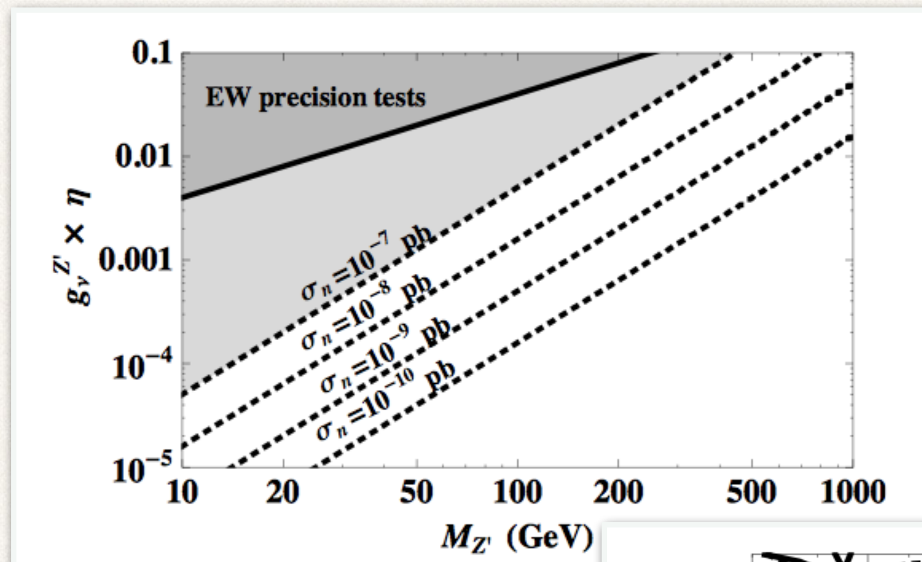
- In this case, dark matter annihilations into γ+X final statess might be producing Higgs bosons… in space!!!

- We have considered several scenarios where WIMPs have sizable (albeit indirect) couplings to top quarks.

- The simplest example is one where the WIMP candidate is a Dirac fermion (ν) which couples to the SM via the "vector portal":

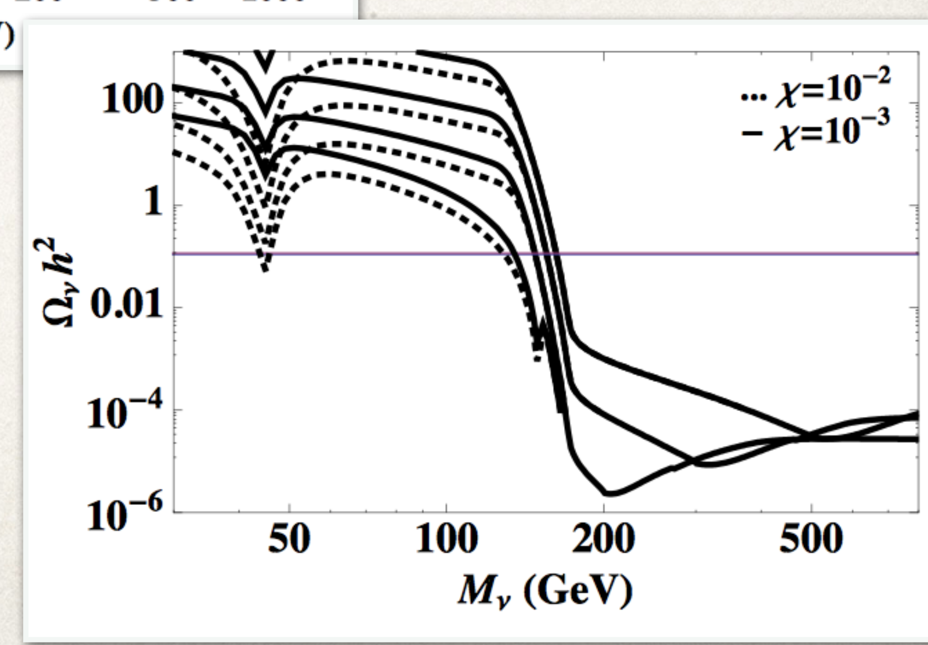
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\chi}{2} F'_{\mu\nu} F_Y^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + M_{Z'}^2 Z'_\mu Z'^\mu + i\bar{\nu}\gamma^\mu \left(\partial_\mu - i g_\nu^{Z'} Z'_\nu\right) \nu + M_\nu \bar{\nu}\nu + g_t^{Z'} \bar{t}\gamma^\mu P_R Z'_\mu t$$

(if you're interested, see our second paper for a more realistic UV-completed model)



- Free parameters:
  - masses (Z′ and WIMP)
  - couplings of Z′ to ν and top

- Considering constraints from direct detection experiments and relic abundance of DM, we find O(1) couplings are allowed and preferred WIMP mass is ≈ m_{top}.



- Annihilations proceed via an s-channel Z′ and a closed loop of top quarks

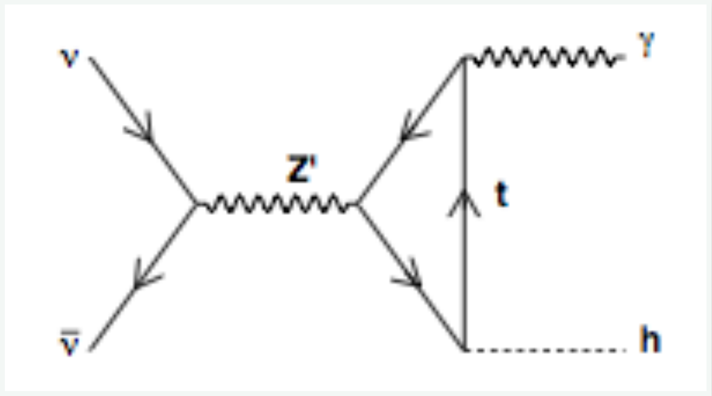
- No ɣɣ line! (Landau-Yang Theorem)

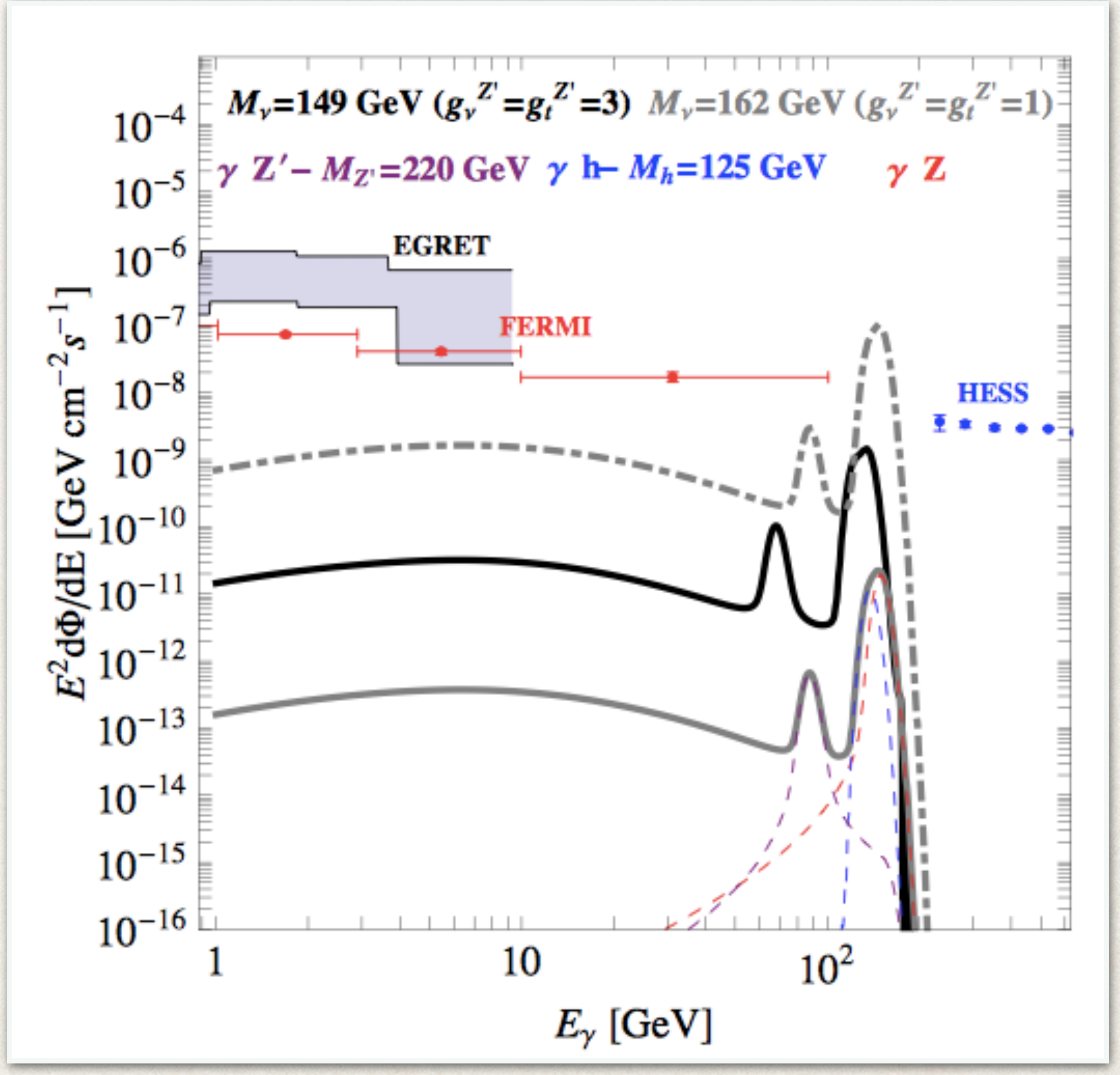
- Possible lines include ɣZ, ɣH and ɣZ′

- Source = Galactic center (different curves correspond to different models for the DM density profile)

- Unfortunately, since the Higgs and Z boson masses are so close, the first two lines merge into one "bump" once detector resolutions are accounted for.

- However, for the right couplings and mass, the line from the ɣZ′ final state is clearly observable

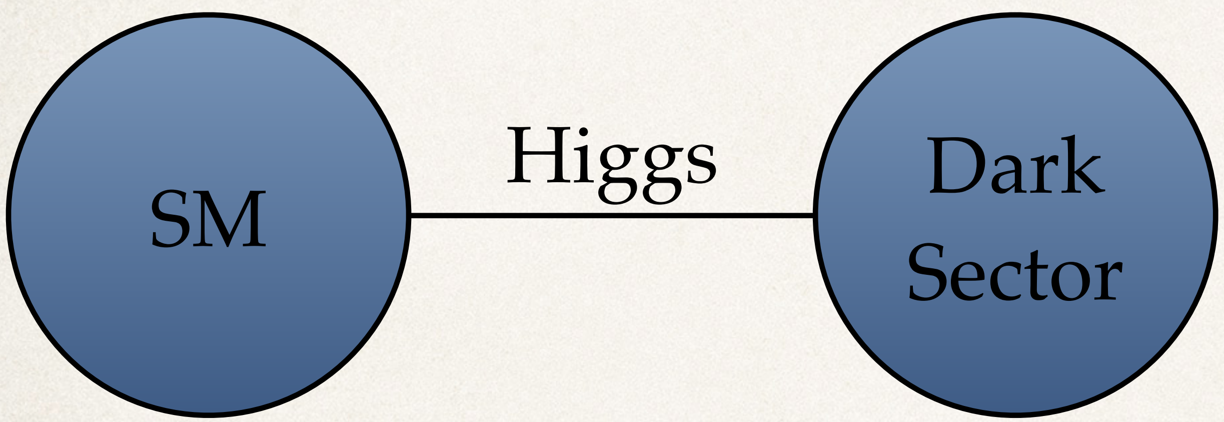




Summary

- The discovery of the Higgs DOES NOT mean that particle physics is “done”.

- The Higgs sector of the SM provides a natural “portal” to a possible “dark sector”



- These types of scenarios can show up in collider experiments (as “invisible decays” of the Higgs) and/or tested at direct detection experiments.

- If there is a connection between the dynamics of EWSB and DM, signals of the Higgs may be observable in “indirect” searches for dark matter .