The Higgs Connection to SUSY & Dark Matter

Tim M.P. Tait
University of California, Irvine

Higgs Couplings 2016
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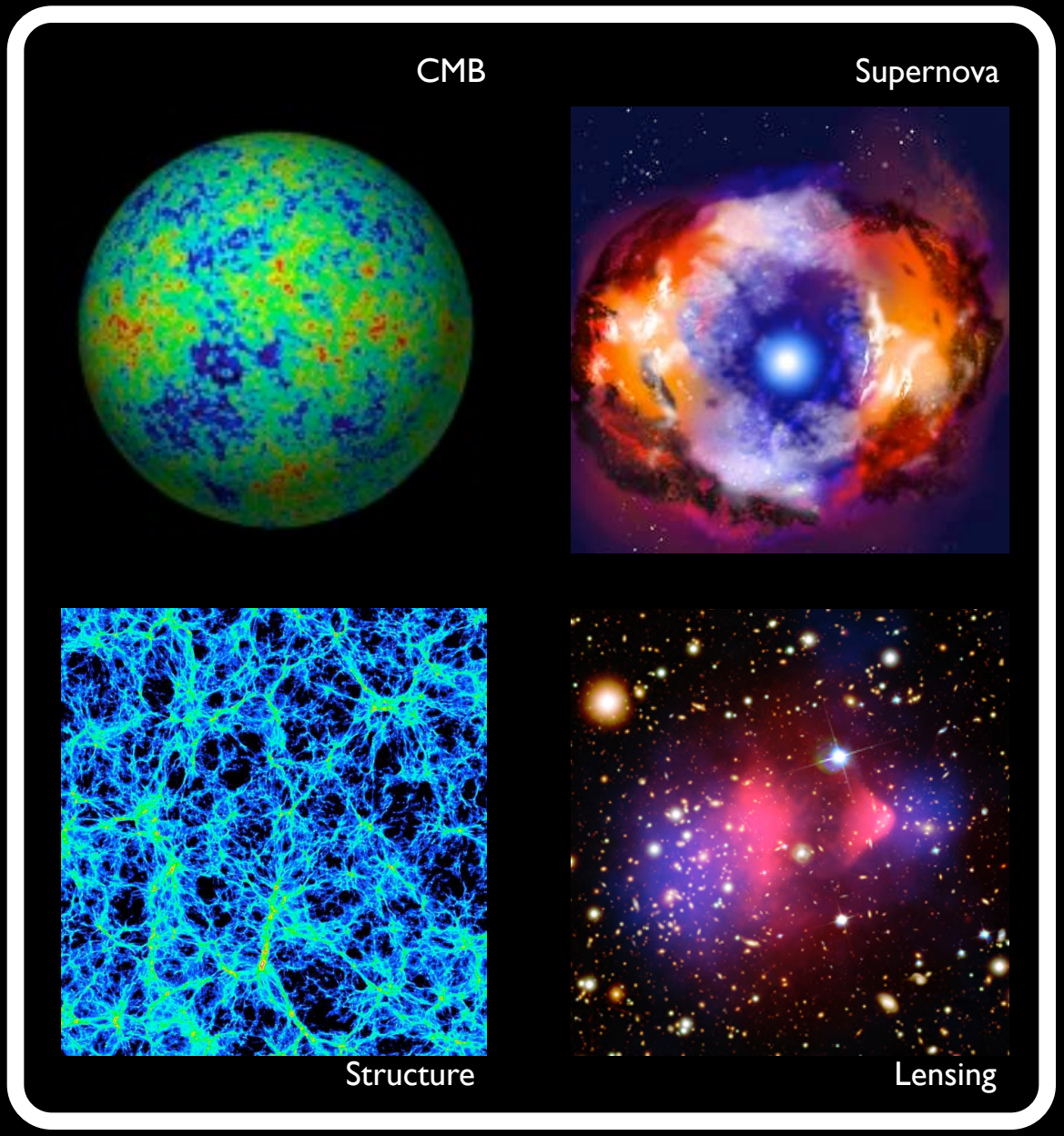
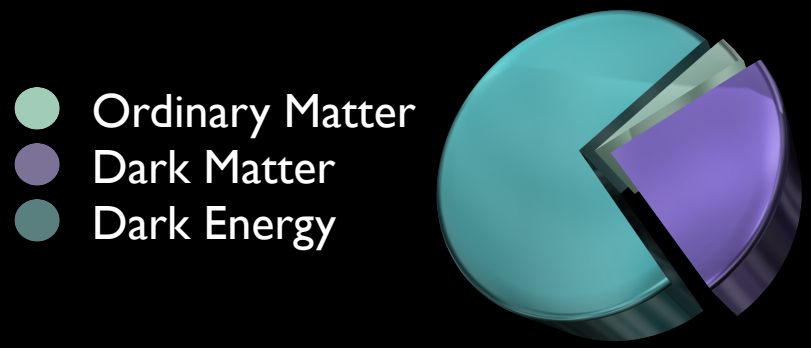
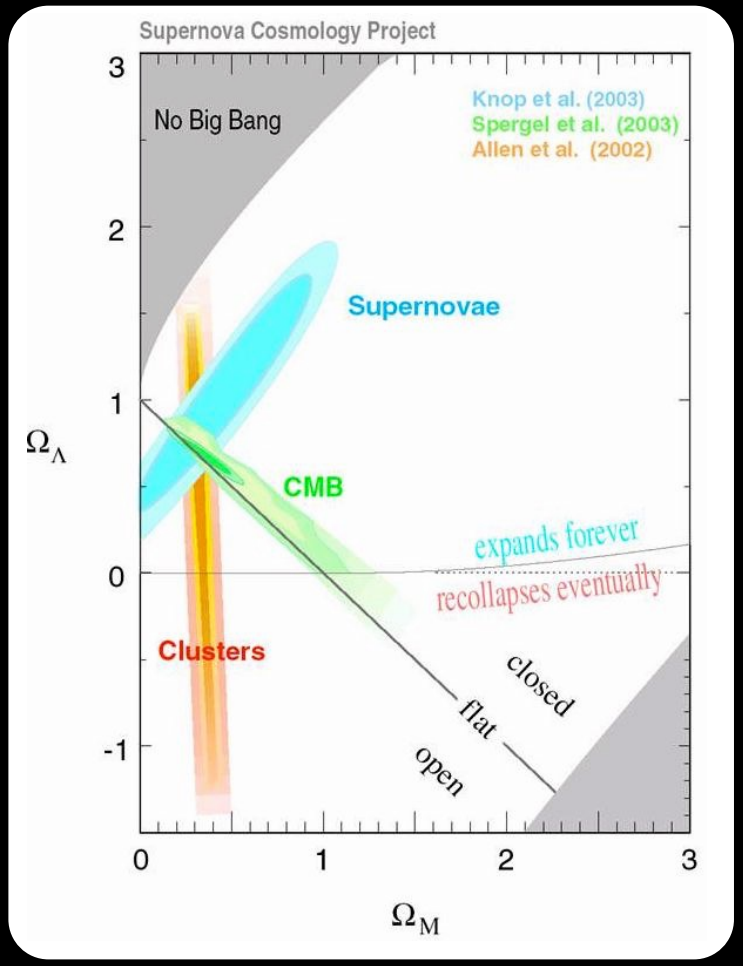
Outline

- A Higgs / Dark Matter Connection?
  - The WIMP Miracle
  - SUSY Dark Matter
- Generic Features
  - Interplay of LHC, Direct, and Indirect Searches
- The Higgs Portal
  - All kinds of constructions…
- Outlook

Dark Matter





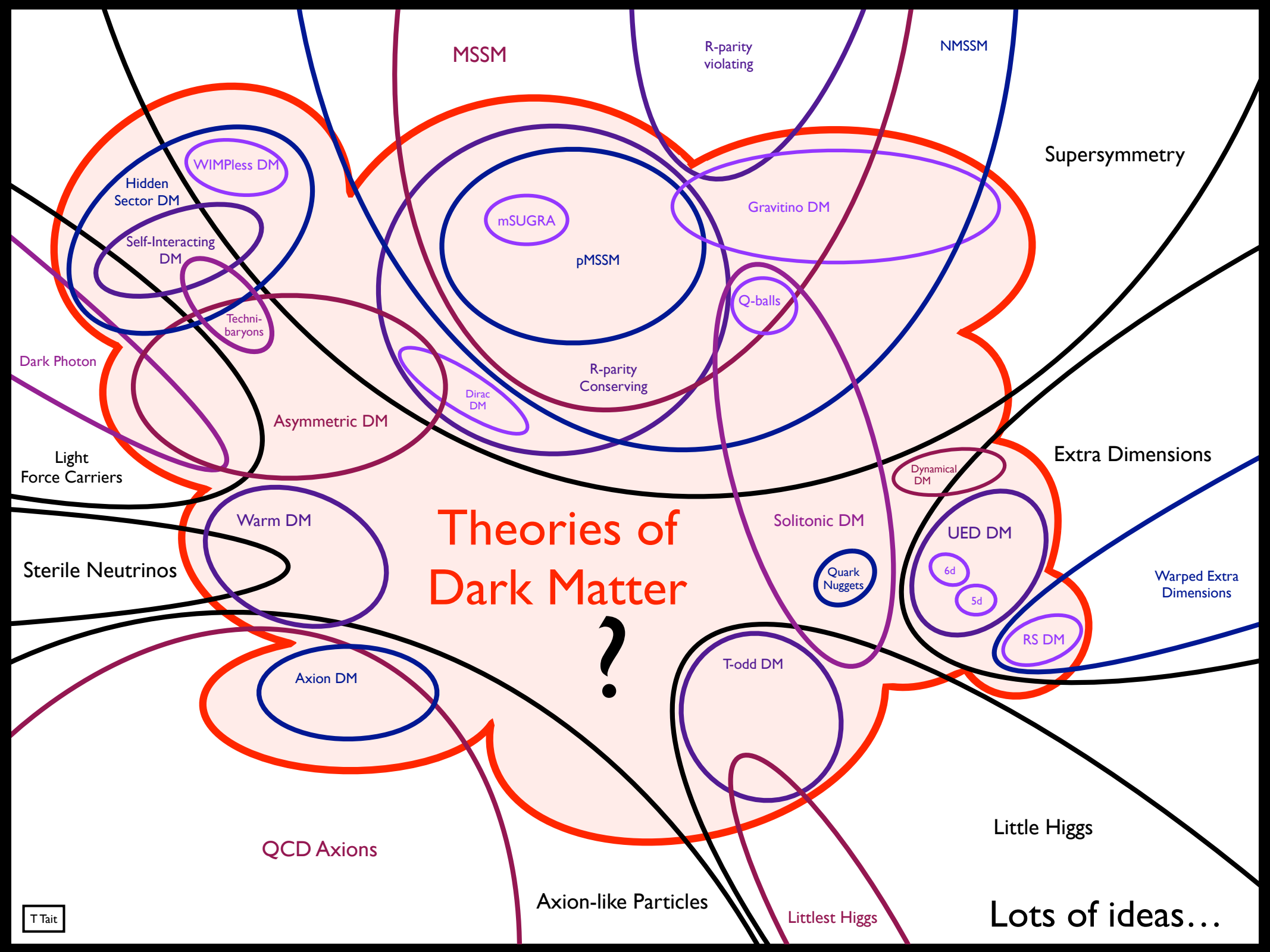


Evidence for dark matter is overwhelming…

So what is Dark Matter?


“Cold Dark Matter: An Exploded View” by Cornelia Parker

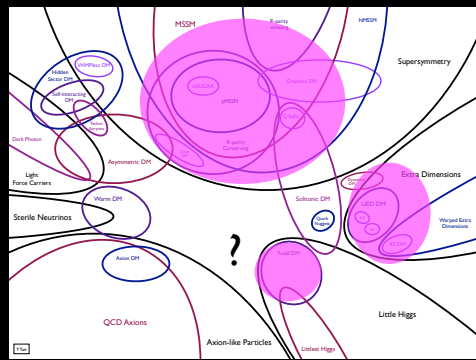
- As particle physicists, we want to know how dark matter fits into a particle description of Nature.
- What do we know about it?
  - Dark (neutral)
  - Massive (cold/non-relativistic)
  - Still around today (stable or with a lifetime of the order of the age of the Universe itself).
- Nothing in the Standard Model of particle physics fits the description.


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Dynamical DM
Warm DM
Theories of Dark Matter
?
Solitonic DM
UED DM
Quark Nuggets
6d
5d
Sterile Neutrinos
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
Lots of ideas…
T Tait

WIMPs

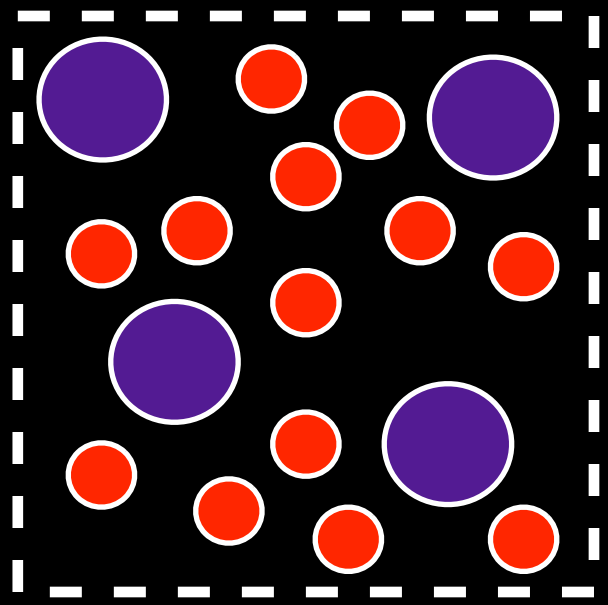
- One of the most attractive proposals for dark matter is that it is a Weakly Interacting Massive Particle.
  - WIMPs naturally can account for the amount of dark matter we observe in the Universe.
  - WIMPs automatically occur in many models of physics beyond the Standard Model:
    - Supersymmetric extensions with R-parity;
    - Extra-dimensional theories with KK-parity;
    - Natural theories of electroweak symmetry breaking with T-parity.

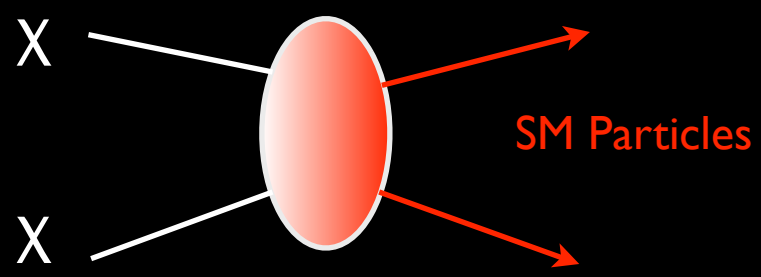
$80 CAD for 20 servings
Available in Blue Raspberry, Fruit Punch, and Grape flavors....



The WIMP Miracle

- One of the primary motivations for WIMPs is the "WIMP miracle", an attractive picture explaining the density of dark matter in the Universe today.
- The picture starts out with the WIMP in chemical equilibrium with the Standard Model plasma at early times.
- Equilibrium is maintained by scattering of WIMPs into SM particles, $\chi\chi$ -> SM.
- While in equilibrium at temperatures below its mass, the WIMP number density follows the Boltzmann distribution:

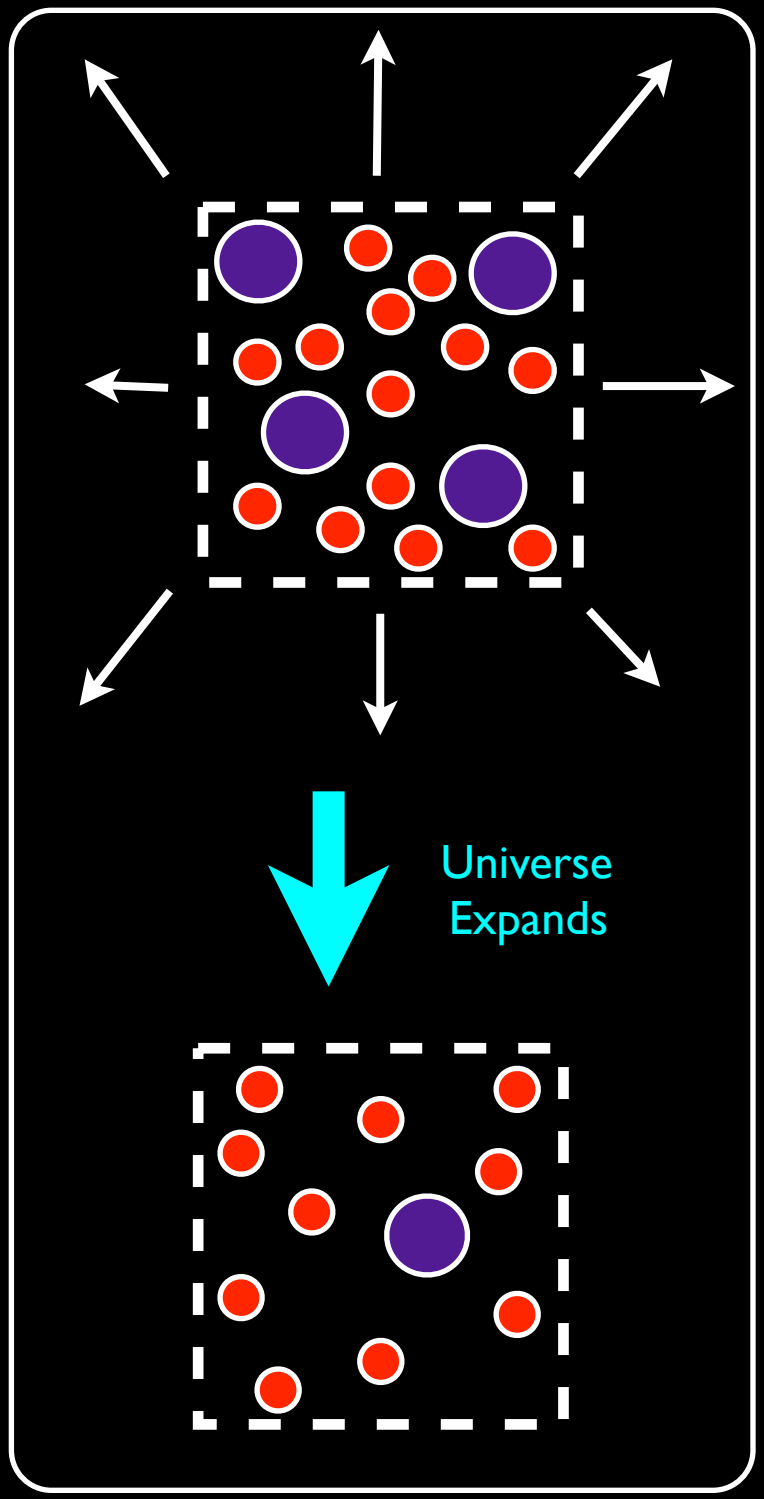




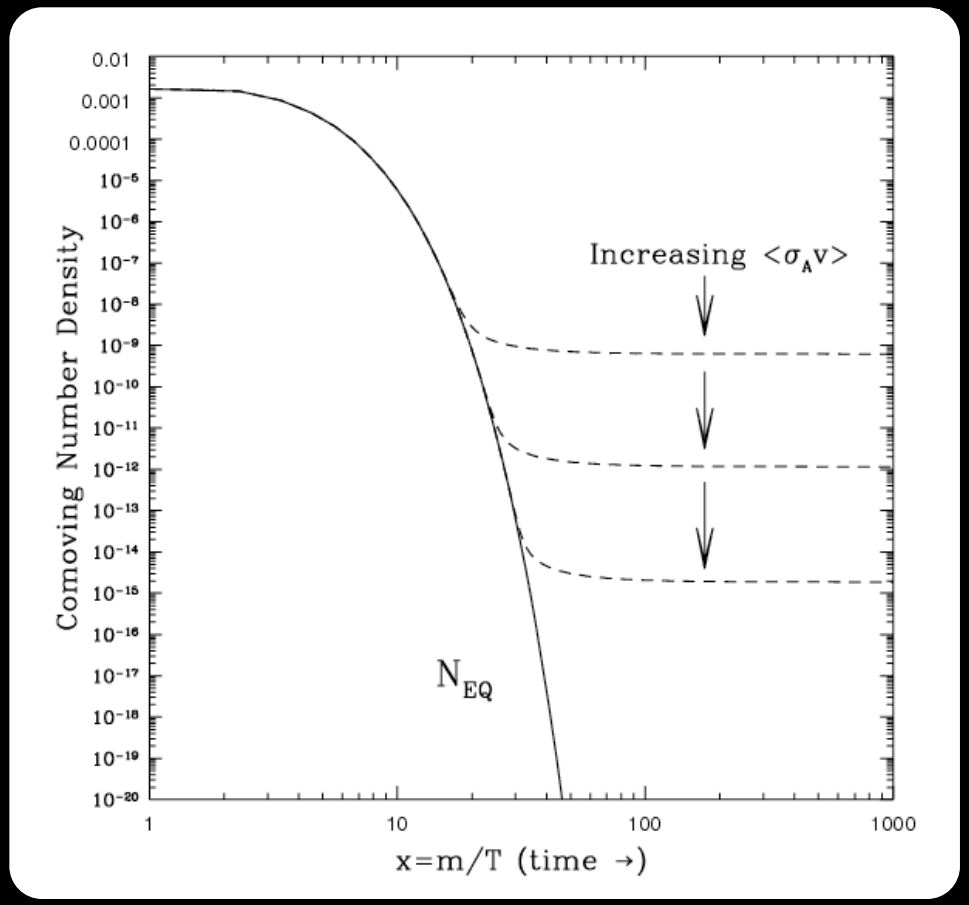
$$n_{eq} = g\left(\frac{mT}{2\pi}\right)^{3/2} \mathrm{Exp}\left[-m/T\right]$$

Freeze-Out

- Expansion of the Universe eventually results in a loss of equilibrium.
- At the "freeze-out" temperature, the WIMPs are sufficiently diluted that they can no longer find each other to annihilate and they cease tracking the Boltzmann distribution.
- The temperature at which this occurs depends quite sensitively on $\sigma(\chi\chi \to SM)$: more strongly interacting WIMPs will stay in equilibrium longer, and thus end up with a smaller relic density than more weakly interacting WIMPs.



Relic Density



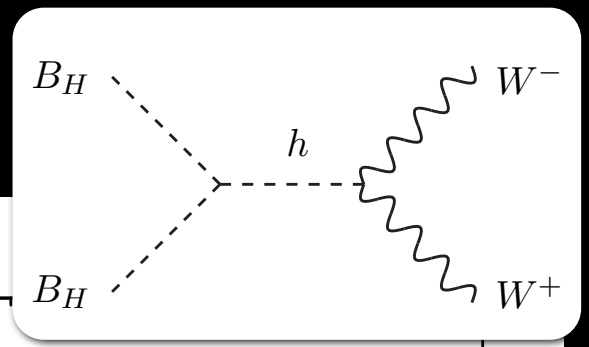
x=m/T increasing
is
T decreasing
is
time increasing

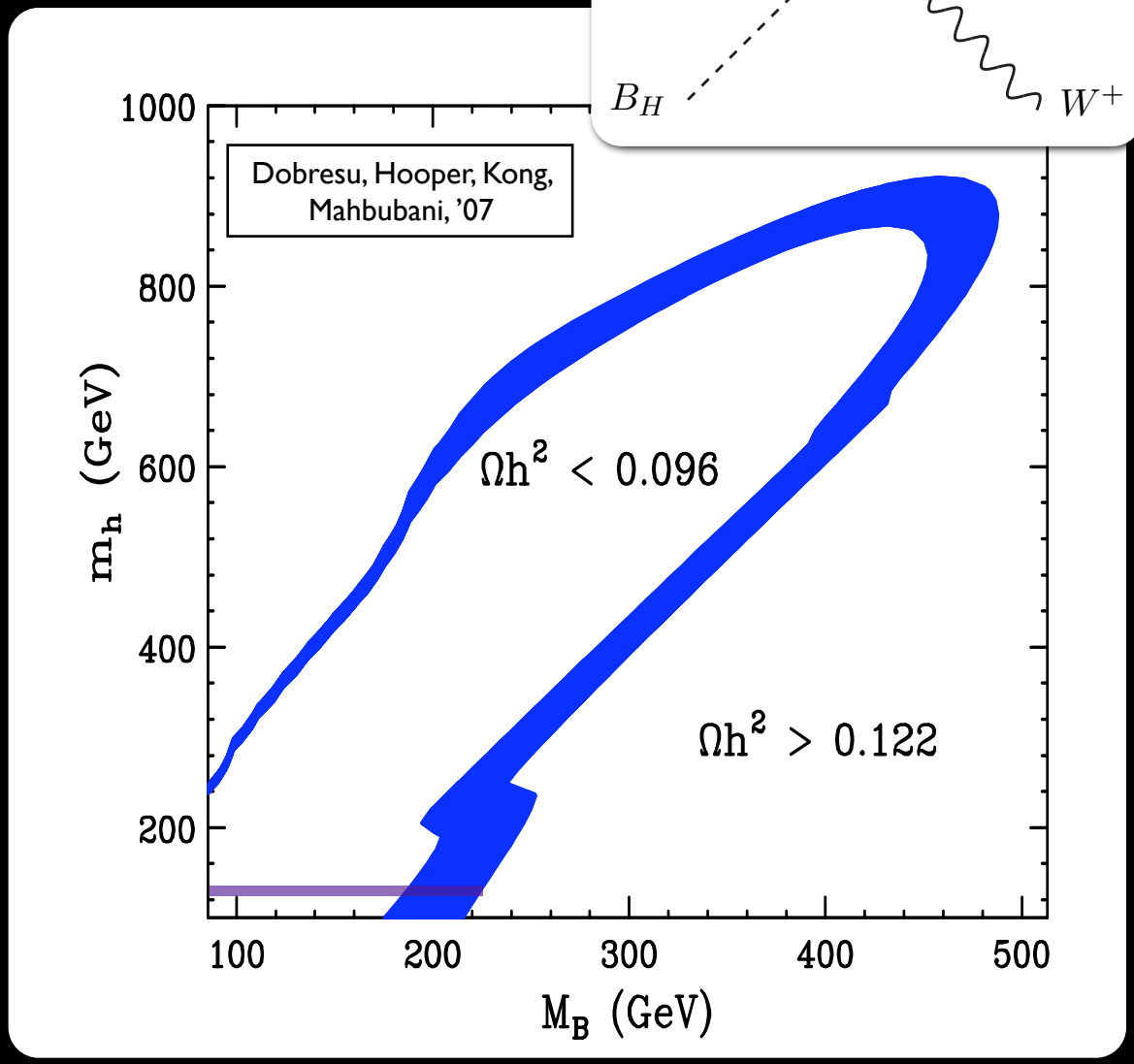
- The observed quantity of dark matter is suggestive of ~ an electroweak cross section for annihilation into SM particles: $<\sigma v> \sim 3 \times 10^{-26}$ cm^3/s, roughly independently of the mass of the dark matter.

- The Higgs VEV is where all of the information about the weak scale is encoded. If the WIMP miracle is not a red herring, the Higgs MUST be involved somehow…

The Power of Higgs

- For a scalar dark matter particle coupling to the Higgs, what we know about the Higgs already tells us a lot about dark matter.
- This specific plot is for the minimal 6-dimensional "chiral square" UED model.
- The measured Higgs mass essentially fixes the dark matter mass. When one takes into account the fact that UED also predicts colored particles nearby, minimal version of this model are simply ruled out.



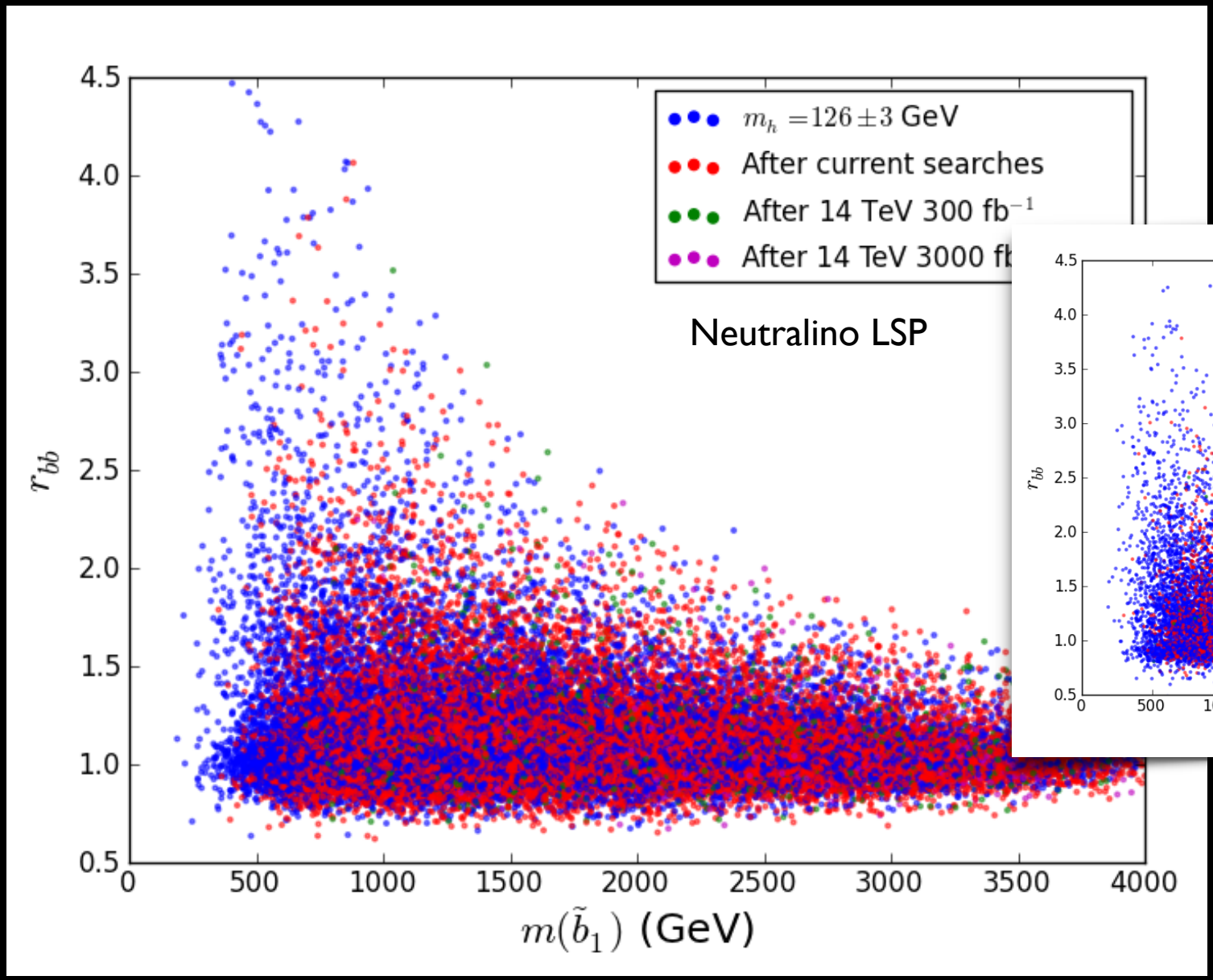


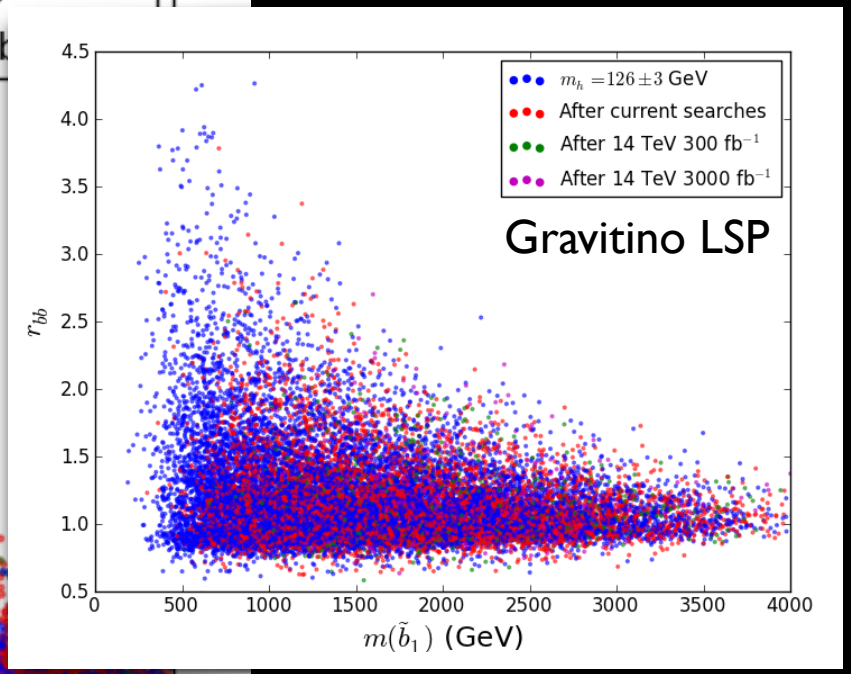
SUSY

SUSY

- As long as the primary reason for SUSY is to solve the hierarchy problem, it is very closely tied to the Higgs.
  - The EWSB scale is fixed by the SUSY-breaking scale.
  - (But don't forget the mu-problem…)
- The MSSM in particular must realize the Higgs quartic interaction as D-terms from the electroweak sector. This means that the Higgs mass is calculable, unlike in the SM where it is a free parameter.
  - The mass and properties of the Higgs give indirect information about the rest of the MSSM parameters.
  - At the same time, SUSY relates important couplings involved in (e.g.) neutralino and stop mixing to the Higgs couplings to SM particles.

pMSSM & Higgs

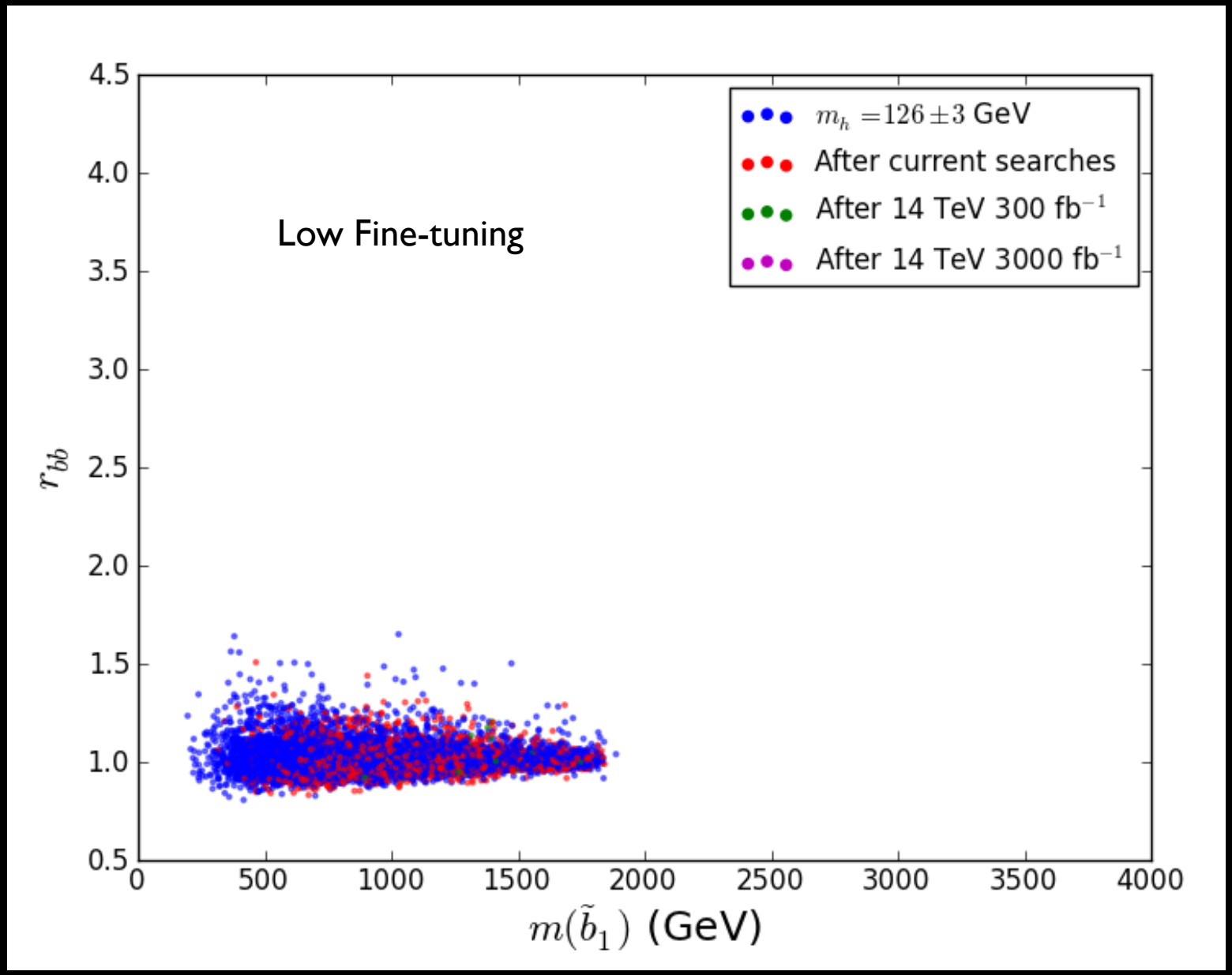




Cahill-Rowley, Hewett, Ismail, Rizzo 1407.7021

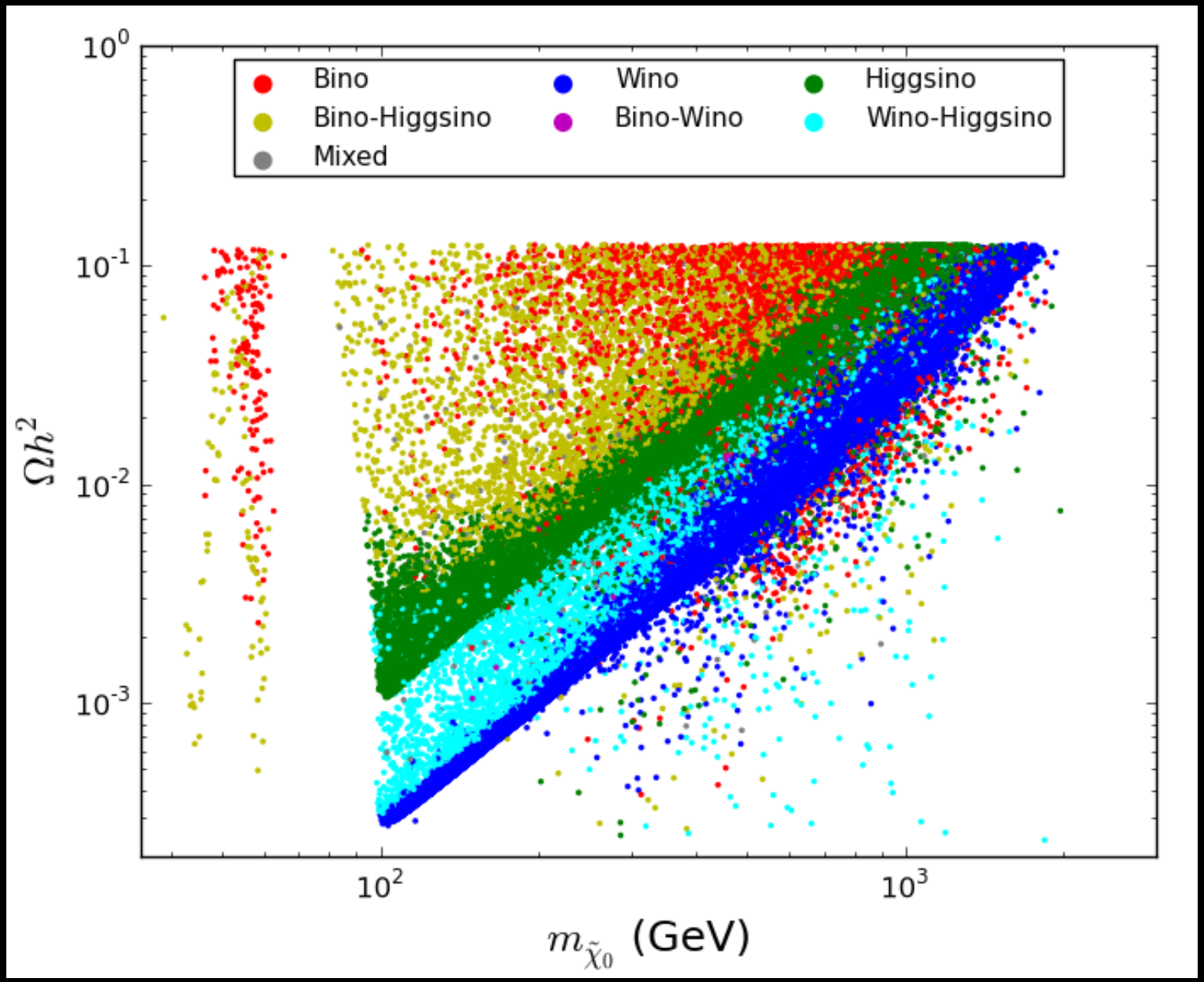
Deviation in the Higgs coupling to bottom quarks

pMSSM & Higgs



Cahill-Rowley, Hewett, Ismail, Rizzo 1407.7021

pMSSM: Higgs & DM

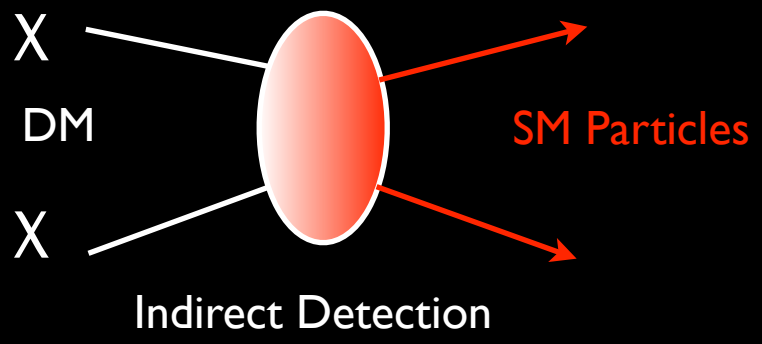


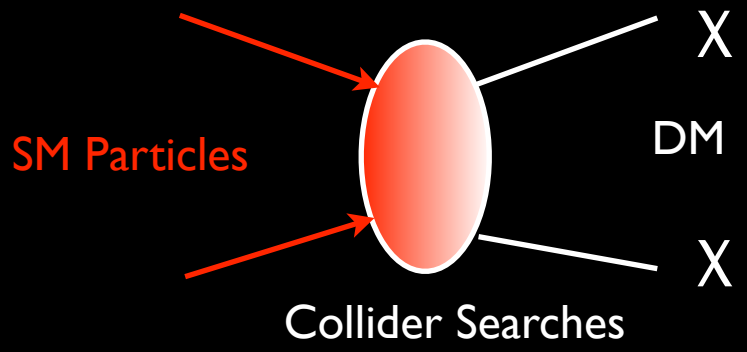
The neutralino Higgs couplings control (with soft masses M1 and M2) the LSP composition.

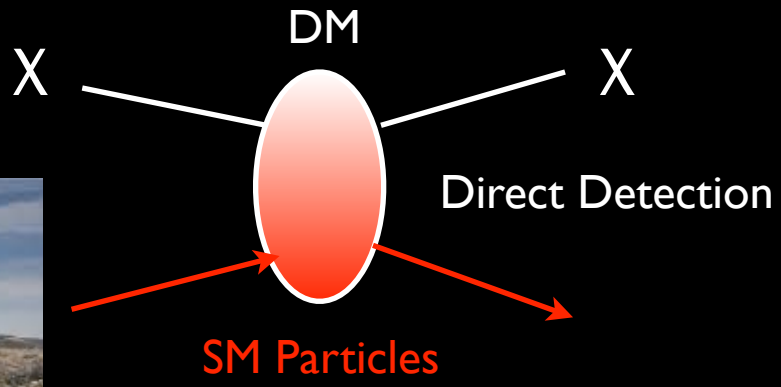
Cahill-Rowley, Cotta, Drlica-Wagner, Funk, Hewett, Ismail, Rizzo, Wood 1305.6921

Generic Features for DM

Particle Probes of DM





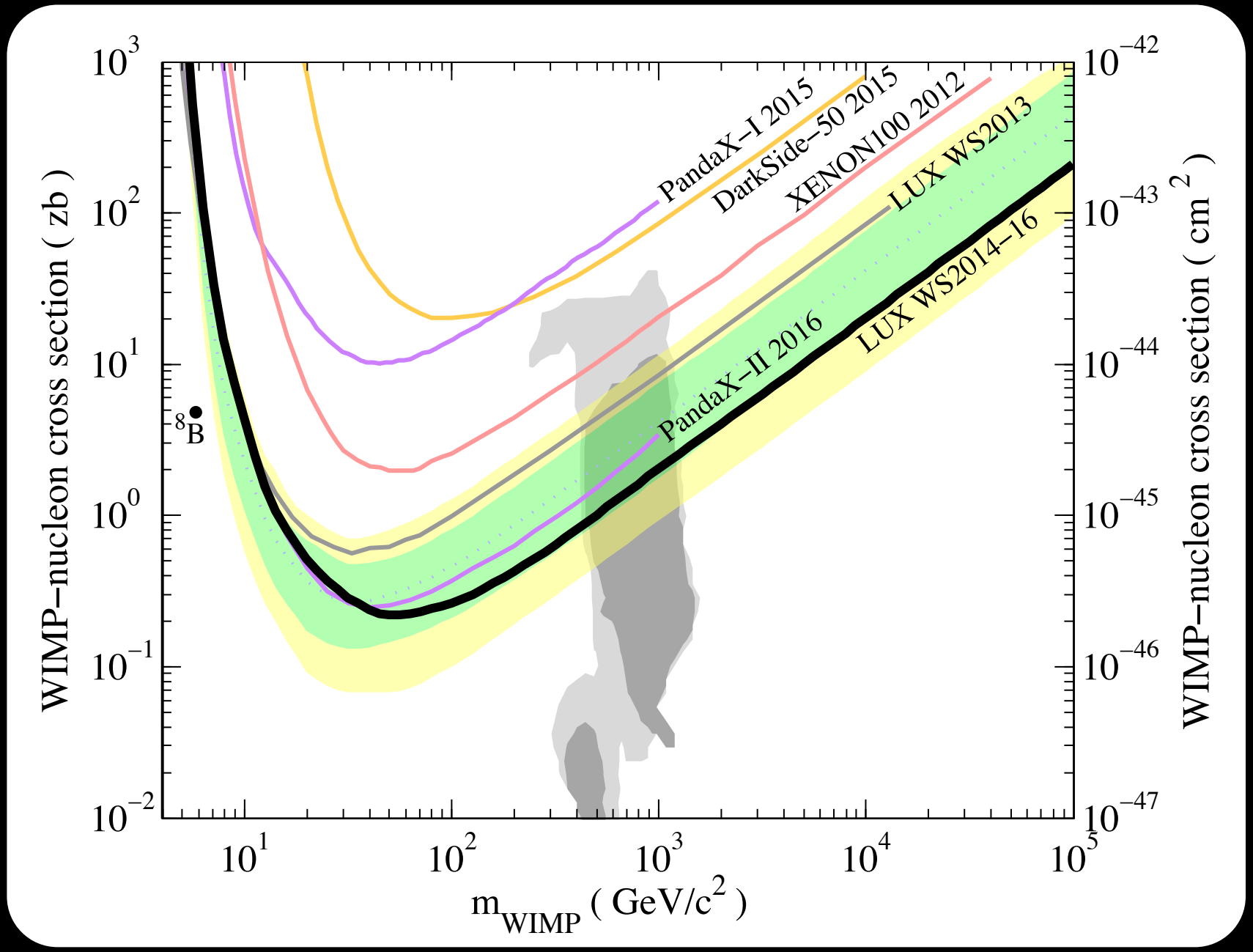


- The common feature of particle searches for dark matter is that all of them are determined by how it interacts with the Standard Model.

Higgs Portal Probes

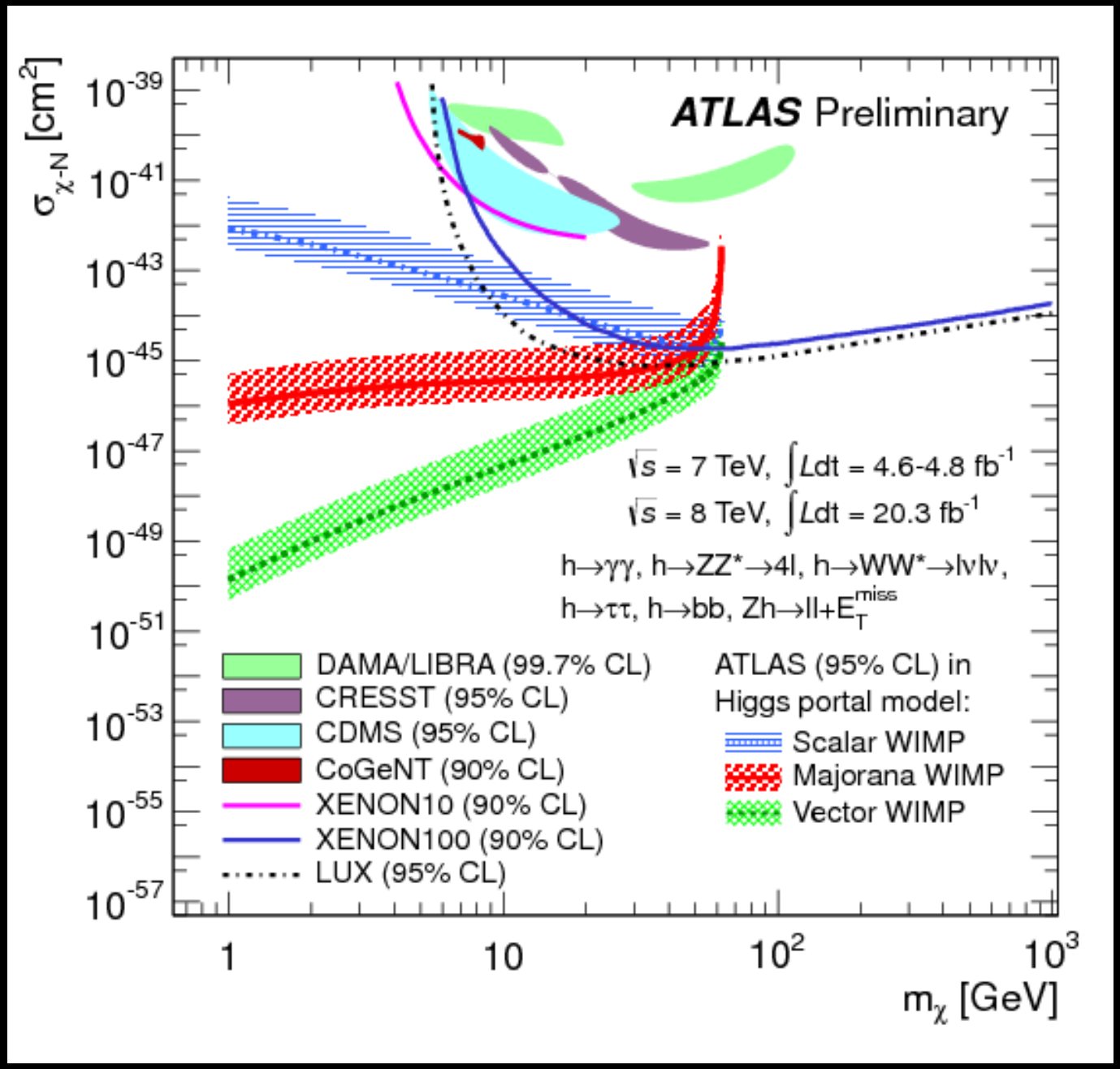
- If the dark matter communicates largely through the Higgs portal, there are systematic things we can expect:
  - If the dark matter is light enough that the Higgs can decay into it, there will be strong constraints from the direct searches for invisible decay modes. We already know the invisible BR is less than about 30%!
  - There are also important constraints on this case from the total width of the Higgs.
  - When the dark matter is too heavy, on-shell Higgs processes become ineffective. Off-shell production is still important, but is less easily associated with the Higgs itself and tends to look more like generic MET searches.
- Direct detection is generically an effective means to search for Higgs portal dark matter, because the large coupling to gluons implies a large coupling to nucleons.

Direct Detection

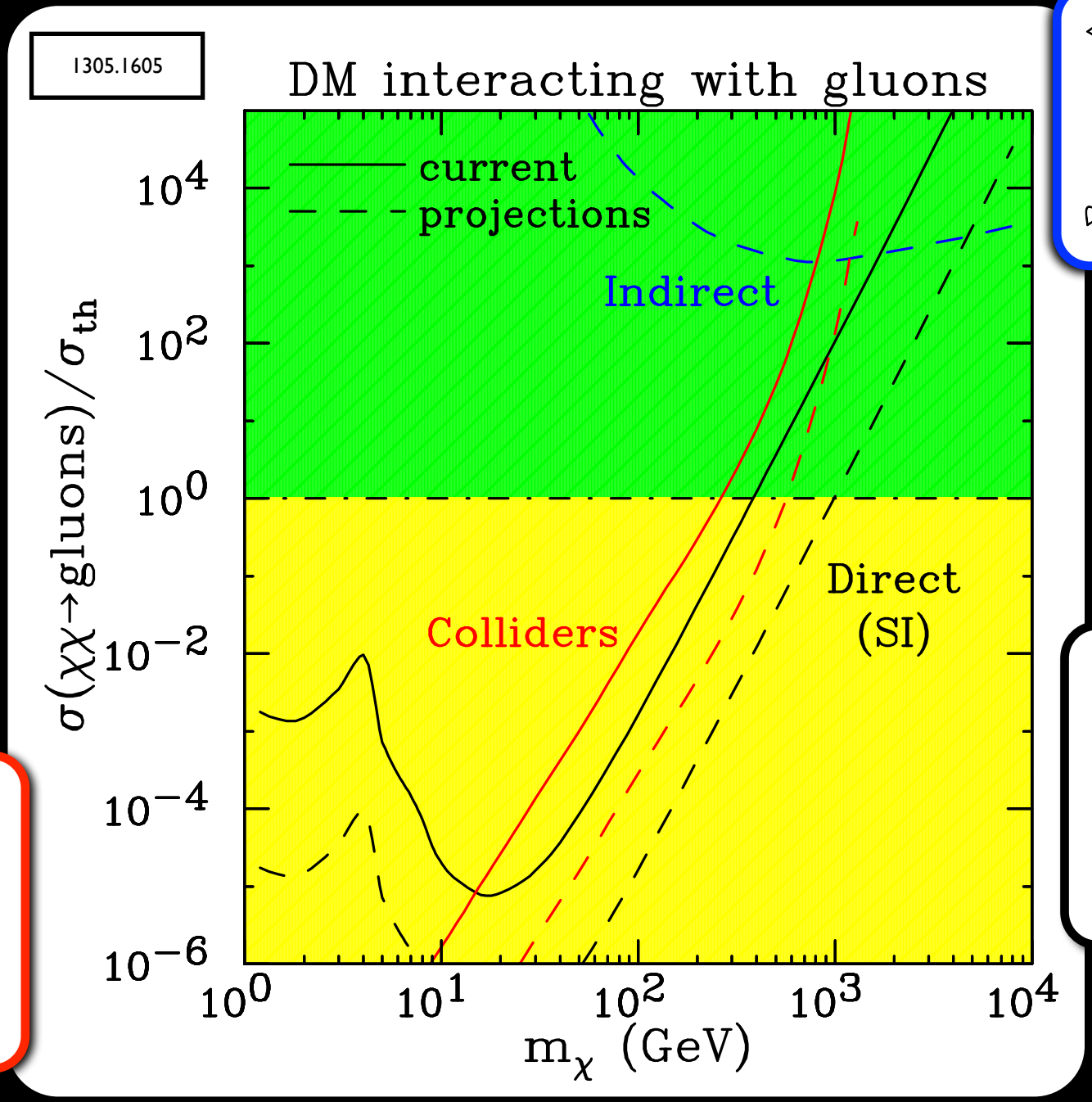


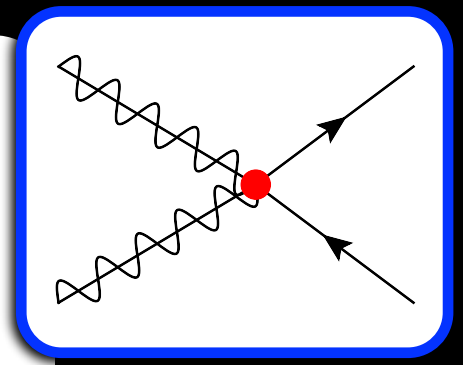
LUX 1608.07648

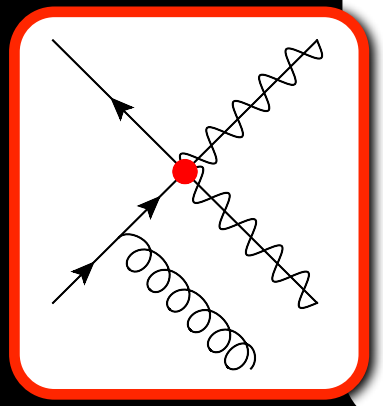
Invisible Higgs Width

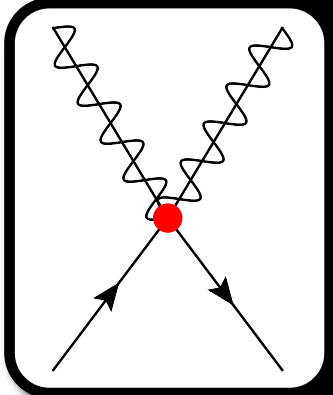


MET Search Trends





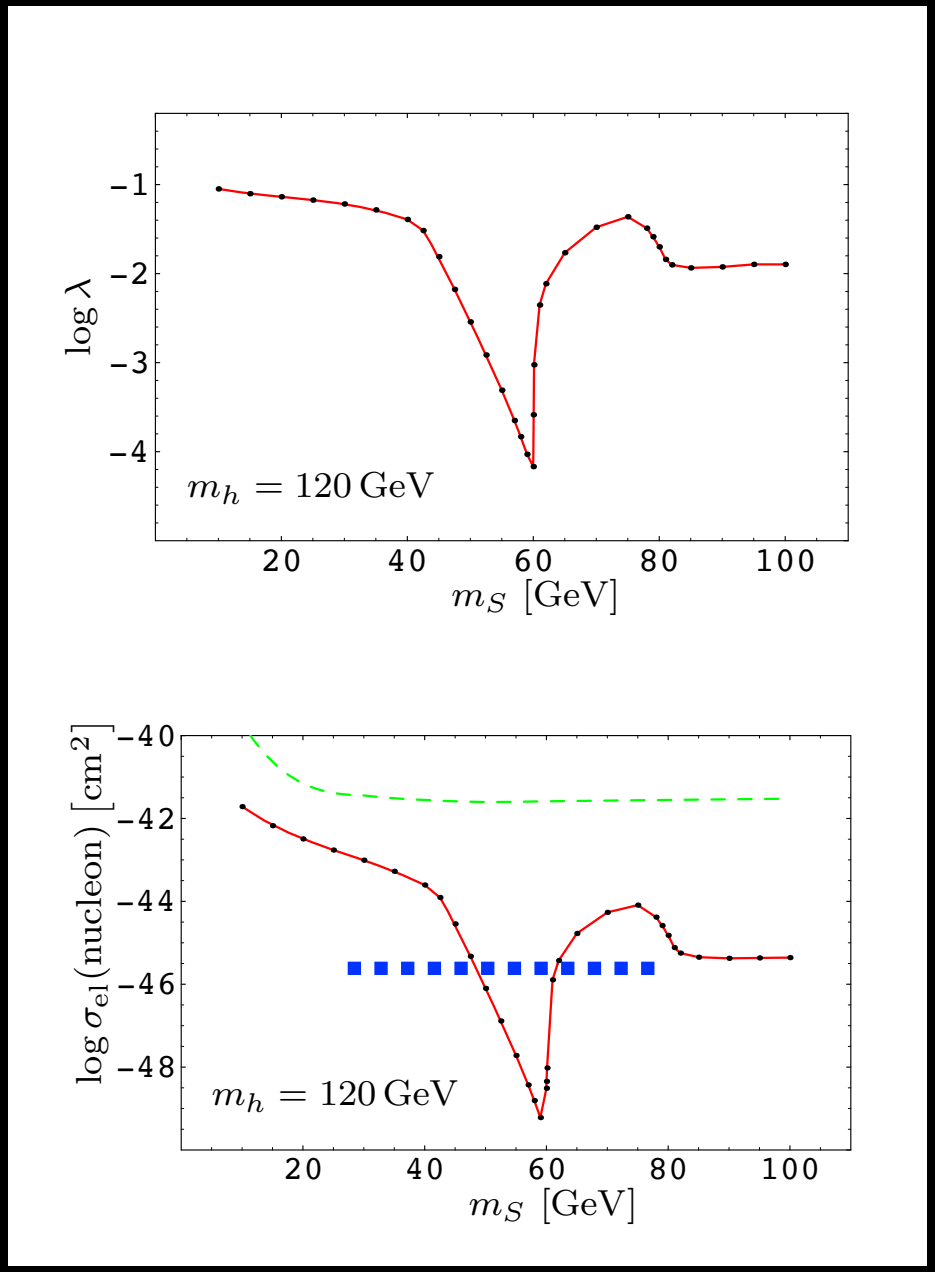




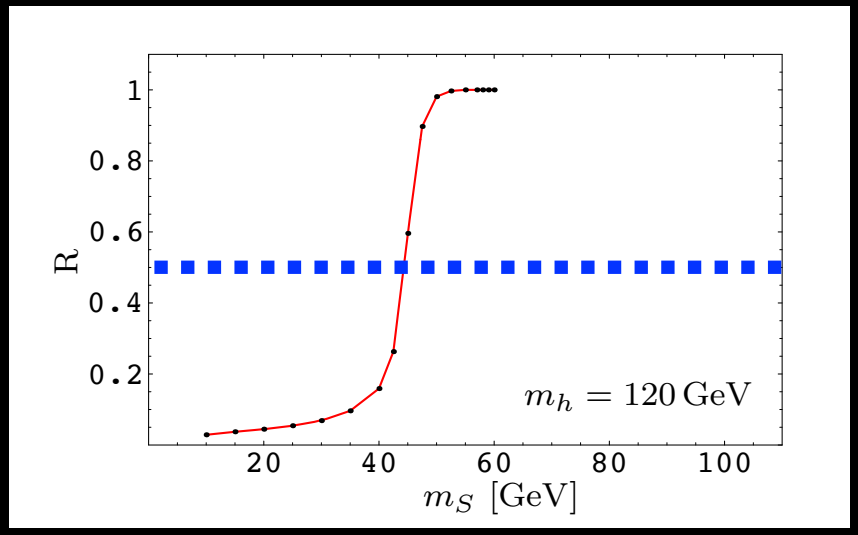
Higgs Portal

Scalar Dark Matter

- If the dark matter is a scalar, there is a simple renormalizable portal to the SM through a quartic interaction.
- If the scalar is an EW singlet, this single coupling represents its sole renormalizable way of reaching the Standard Model.
- For a thermal relic, direct detection excludes everything except for the narrow window around the Higgs funnel.



$R=\Gamma/\Gamma_{SM}$



Burgess, Pospelov, ter Veldhuis hep-ph/0011335

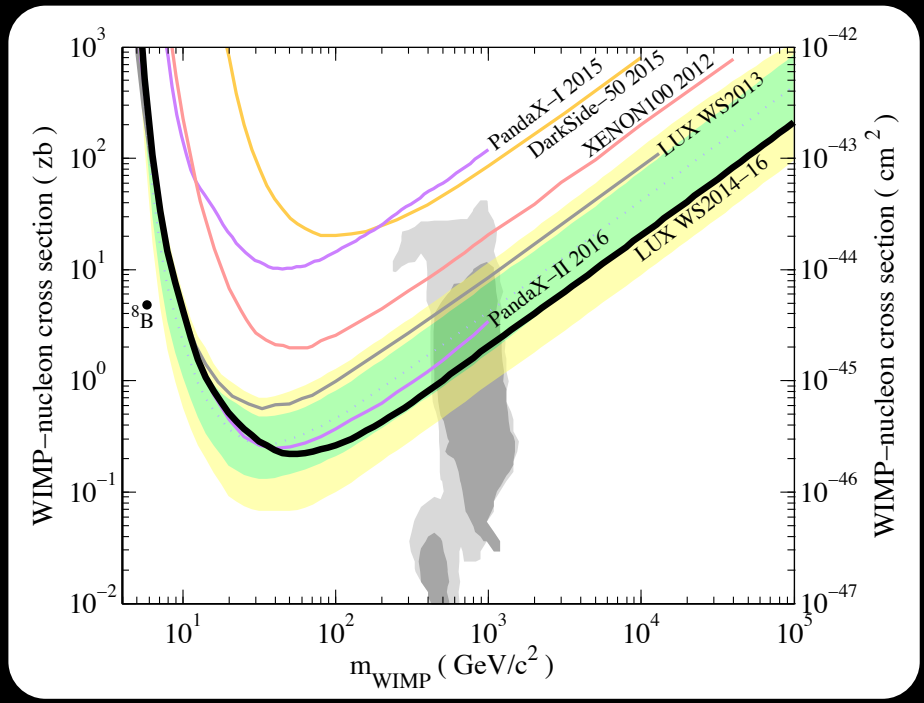
Fermion Dark Matter

- If the dark matter is a fermion, renormalizable interactions require that a coupling to the Higgs is chiral, consisting of two different SU(2) representations:

$$\underset{(2,1/2)}{H}\,\underset{(n,Y)}{\psi_1}\,\underset{(n+1,Y-1/2)}{\psi_2}$$

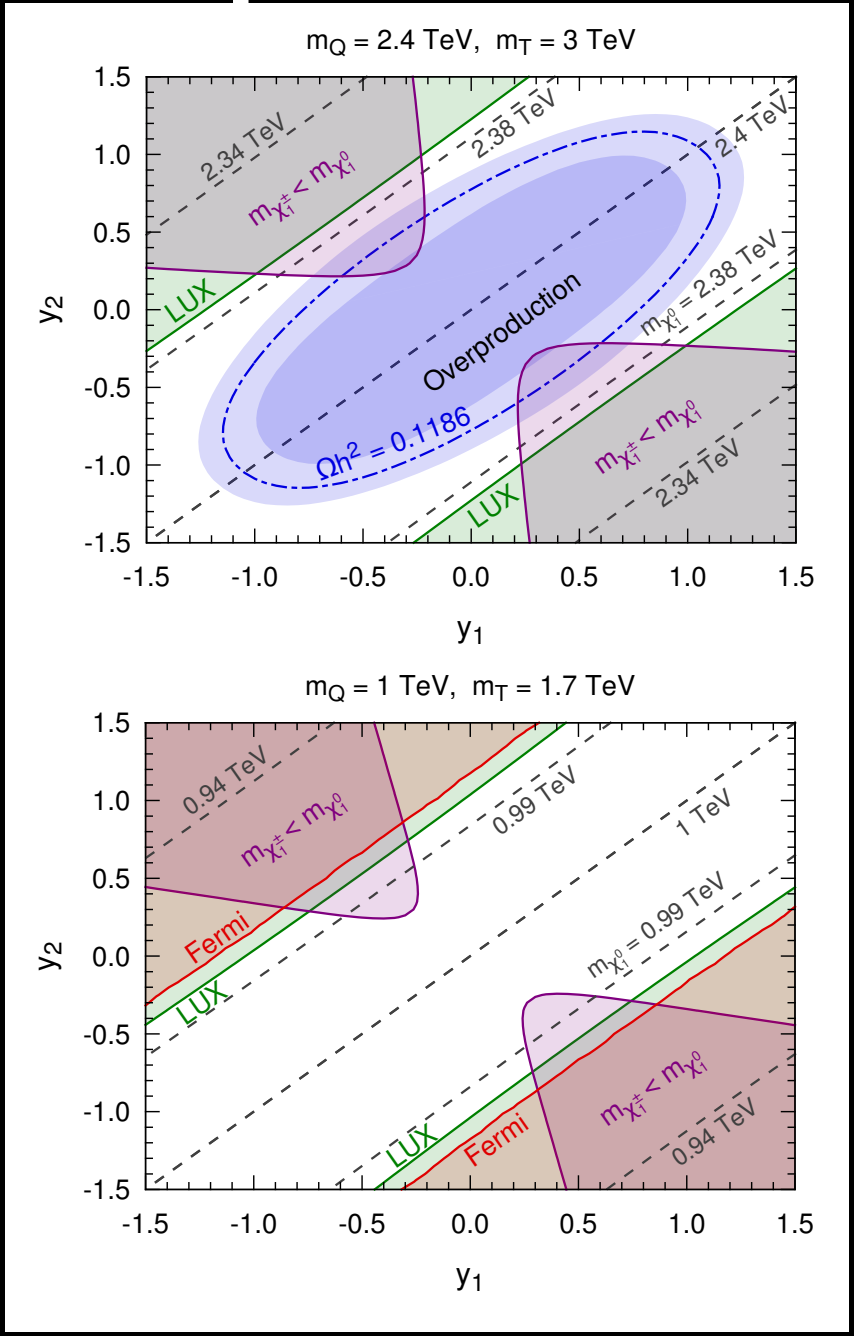
σ_{SI} for full strength Z coupling

- This looks a lot like a SM neutrino with a Dirac mass. As a result, the dark matter, like the SM neutrino, has a large vector coupling to the Z boson. Essig 0710.1668
  - Direct detection rules this out up to extremely large DM masses!
- Viable constructions need to control the vector couplings. The simplest thing is to introduce Majorana masses.



Triplet-Quadruplet

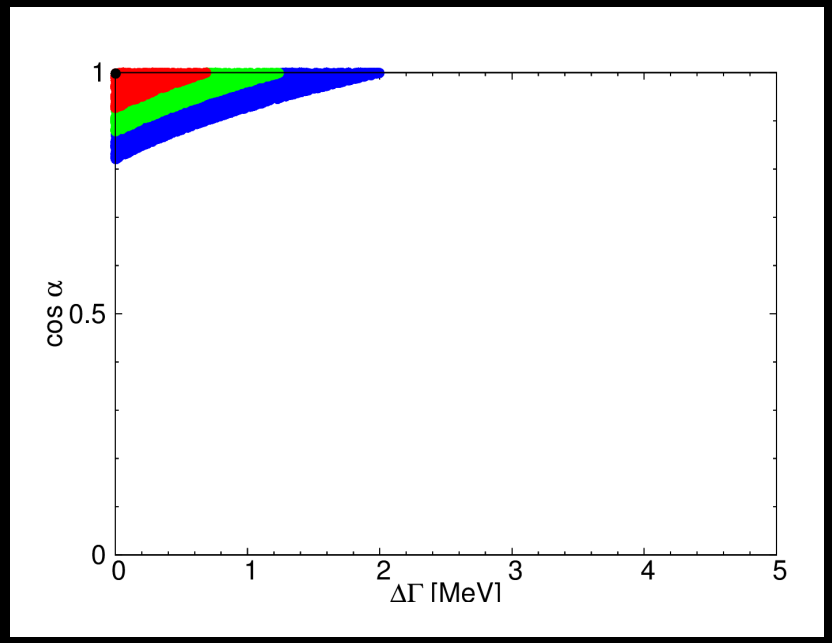
- Many constructions are possible:
  - Doublet-Singlet Cohen, Kearny, Pierce 1109.2604
  - Doublet-Triplet Dedes, Karamitros 1403.7744
  - Triplet-Quadruplet TMPT, ZH Yu 1601.01354
- The first two have particle content which look like MSSM neutralinos/charginos.
  - But note that their couplings are not fixed by SUSY, leading to a wider range of spectra and properties!
- Triplet-Quadruplet has a richer spectrum including doubly charged fermion states.
- The preferred masses are pretty high for direct searches.
- The best hope is probably a very precise H->γγ measurement with high luminosity.



TMPT, ZH Yu 1601.01354

Higgs Mixing

- Another strategy is to take the dark matter as a SM singlet, coupled to a scalar which is also a singlet.
- Then the scalar mixes with the Higgs, stealing a small amount of its coupling to the SM.
- In the simplest models, one can parameterize the effect on Higgs physics in terms of the mixing angle between the scalars, and the impact on the total Higgs width. Cheung, Ko, Lee, Tseng 1507.06158
- For dark matter observables, it is often important to include both the mostly-singlet and mostly-Higgs mediators because of important interference effects in the scattering cross section. Baek, Ko, Park[2], Yu 1506.06556



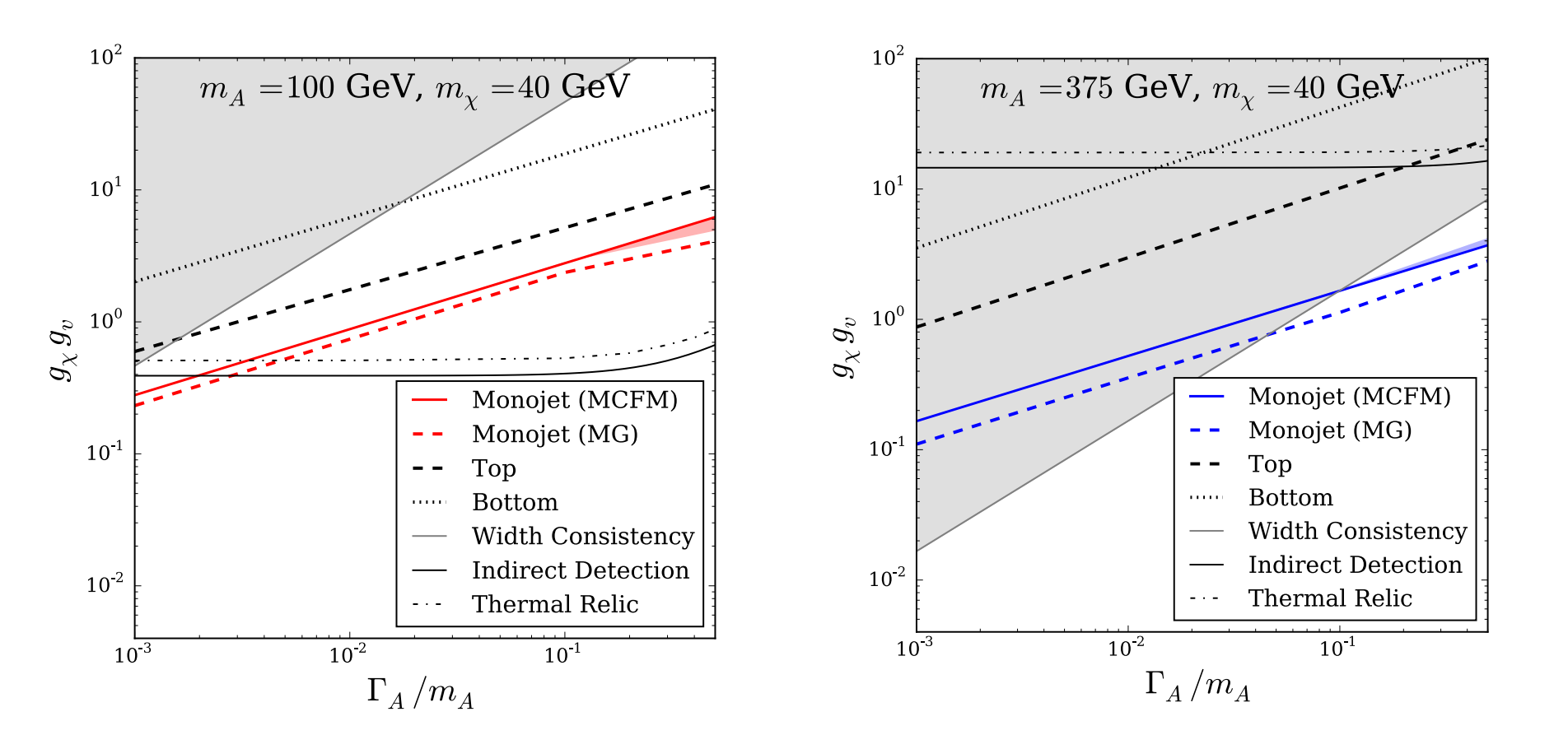
Cheung, Ko, Lee, Tseng 1507.06158

Higgs Mixing

- If the mediator scalar field is complex, one can also realize a pseudo-scalar mediator scenario, which is relatively free from direct bounds, but can be bounded by indirect detection.

- Depending on parameters, bounds can be dominated by deviations in the Higgs properties, by mono-jet searches, and/or by the Fermi LAT bounds from dwarf galaxies.

Buckley, Feld, Goncalves 1410.06497



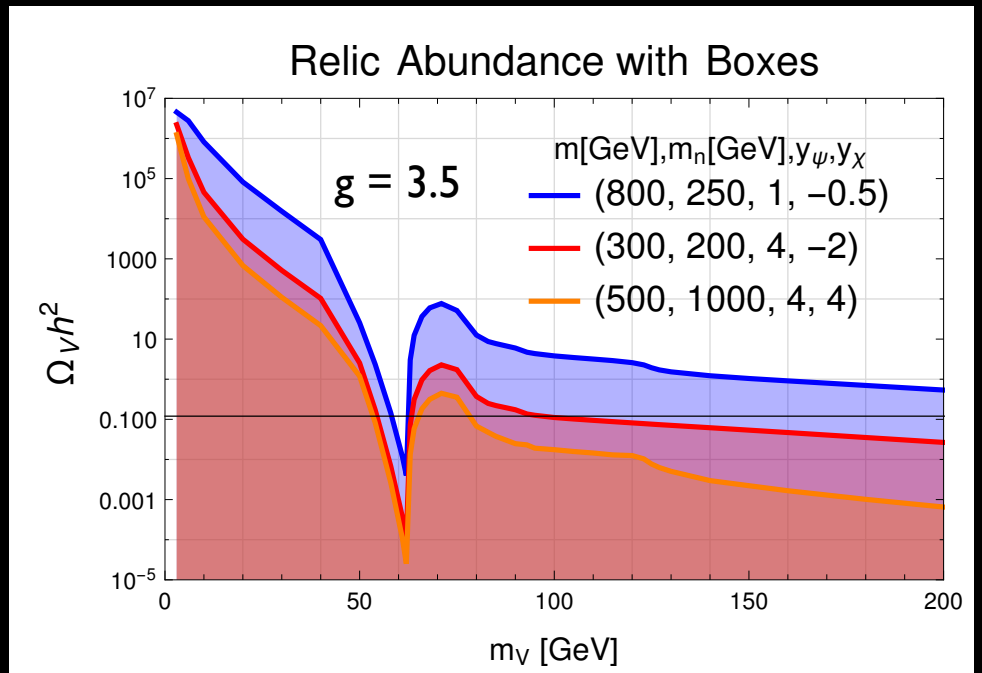
Vector Dark Matter

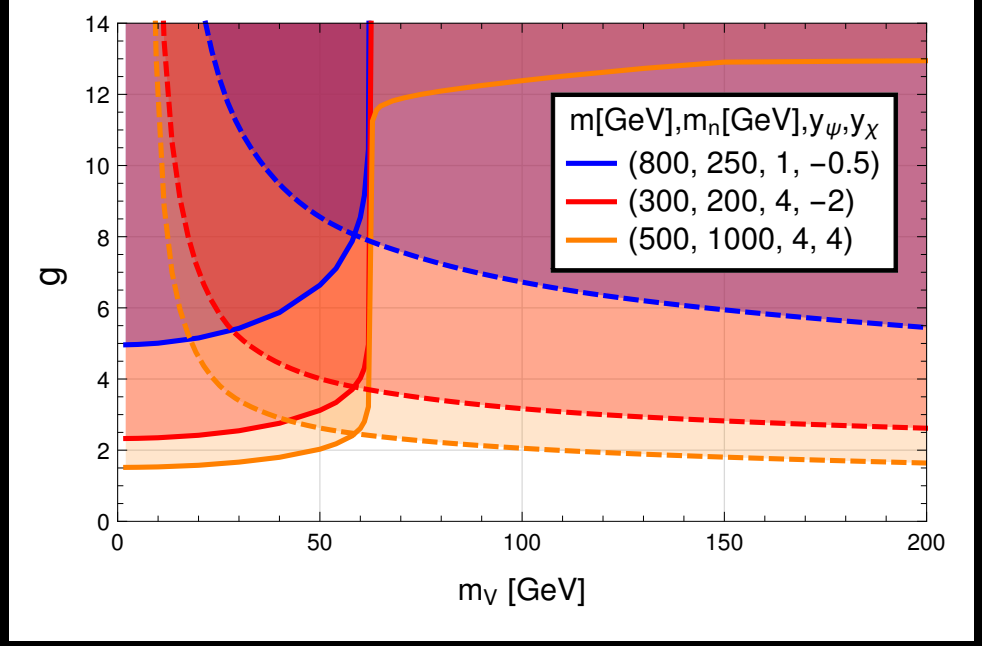
- Vector dark matter can couple to the Higgs via its mixing with another scalar mediator.
  - Systematically, this looks much like the fermion dark matter case already discussed.

Baek, Ko, Park, Senaha 1212.2131

- There is also the possibility of a radiative portal, where the coupling is induced at one loop.
  - Relatively strong couplings are needed to have a thermal relic.
  - Higgs constraints play an important complementary role to the direct detection ones.

DiFranzo, Fox, TMPT 1512.06853
DiFranzo, Mohlabeng 1610.7606





Outlook

- Taken all together, what have we learned?
  - Among the best motivated and favorite ideas for dark matter are WIMPs, which through the WIMP miracle suggest a connection to the weak scale.
  - This connection could be built in to the model's DNA, such as for the MSSM addressing the hierarchy problem.
  - It could also be "just the way Nature works", when the dark matter representation(s) combined with renormalizability dictate communication through the Higgs.
  - In all cases, there is an interesting mix of information from direct searches, indirect searches, and from colliders.
  - In many cases, the properties of the Higgs boson are defining what we know. This is anticipated to be the case in the future!