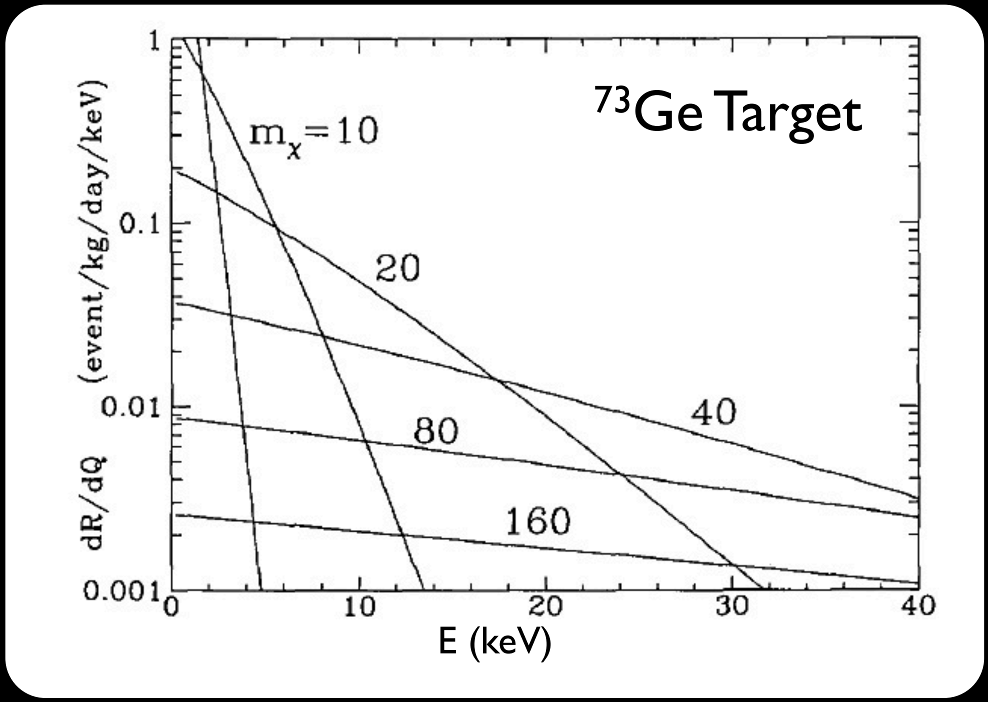
Tough Questions

If the dark matter particle is detected, what can we learn about its properties (e.g. spin)? Would we be able to learn whether it interacts with the SM through the Higgs portal?

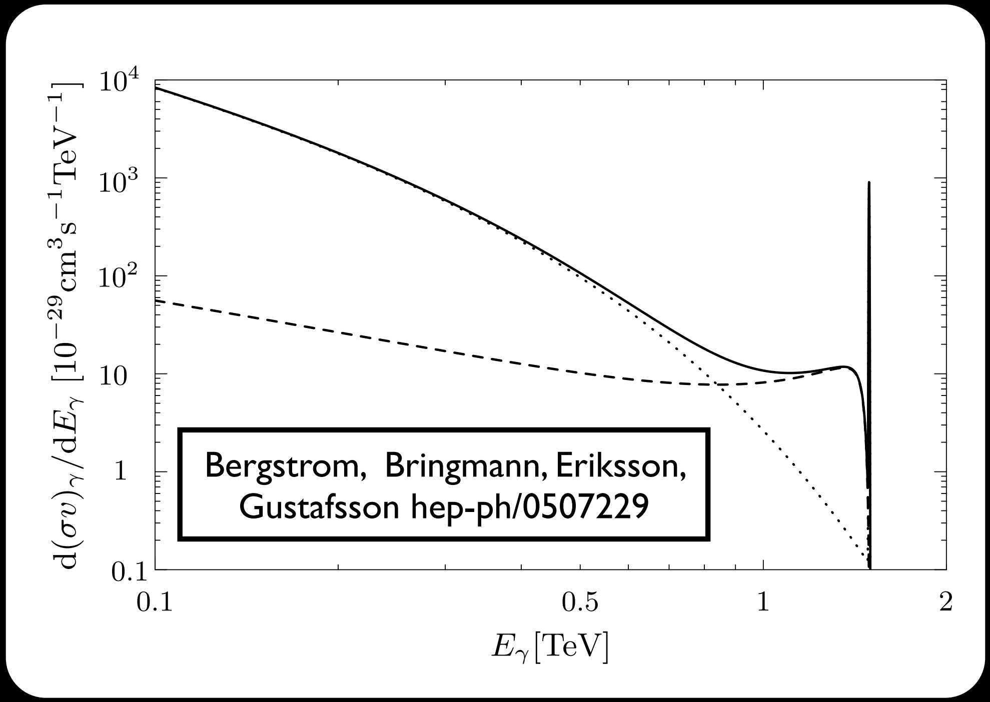
The answer to this question depends quite a bit on the actual scenario one has in mind. Let's look at some cases one can imagine, starting with the mass...

An Elastic Scattering Signal



The energy spectrum of the recoiling nucleus is characterized by the reduced mass of the system. For DM lighter than the target nucleus, there is an opportunity to infer the mass.

A Gamma-ray Line Signal



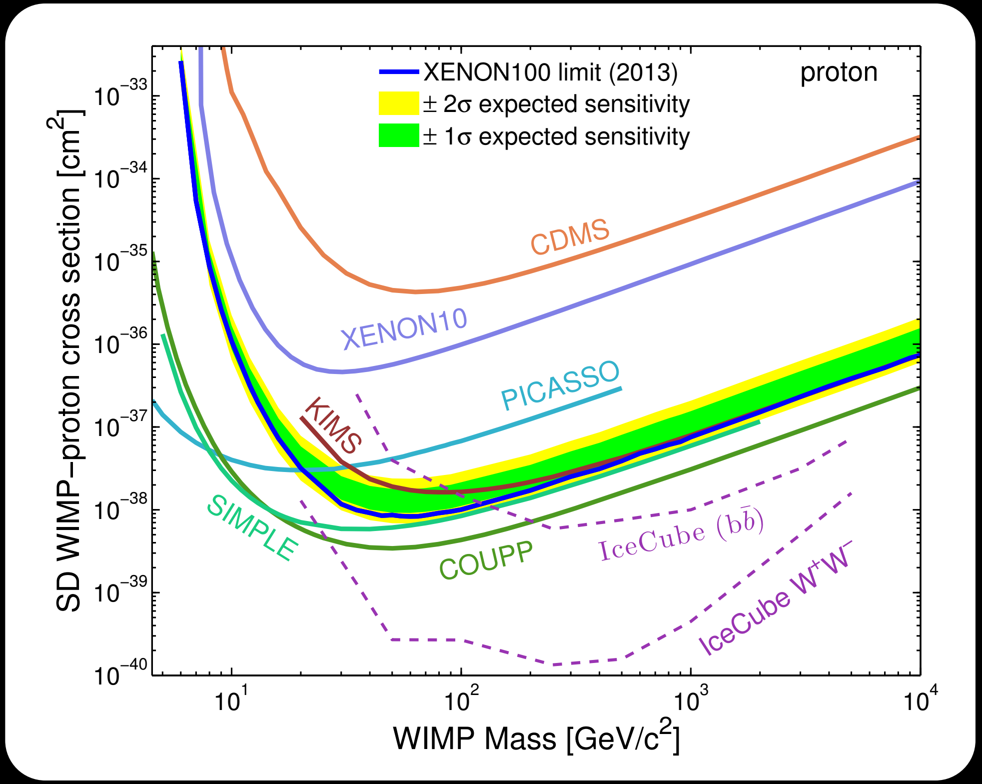
The energy of the gamma ray produced in a two-body final state is a simple function of the dark matter mass and the other particle mass. Typically, there is a γγ line whose energy is M_{DM}.

Colliders see dark matter as missing momentum, and thus only relativistically -- they are typically less sensitive to the mass than either of these cases can aim to be.

If the dark matter particle is detected, what can we learn about its properties (e.g. spin)? Would we be able to learn whether it interacts with the SM through the Higgs portal?

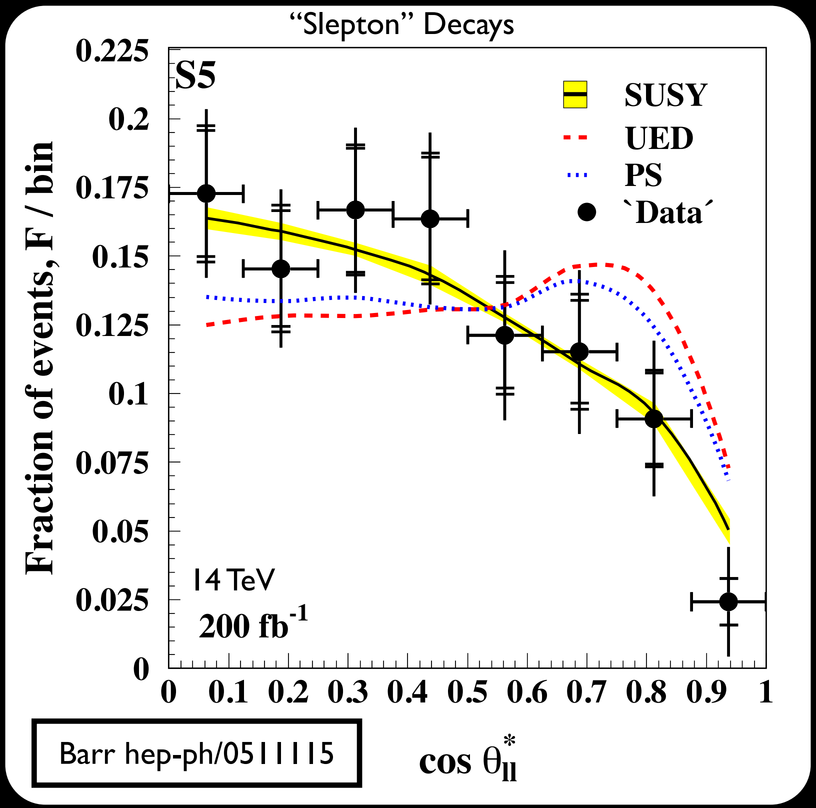
Another important quantity is the spin of the Dark Matter.

Spin-Dependent versus Spin-Independent Scattering



With coverage by enough targets, one can correlate experiments which see a signal and those which do not, to infer whether the dark matter has spin-dependent interactions. This would at least suggest the WIMP has a spin if there are positive signals in SD targets.

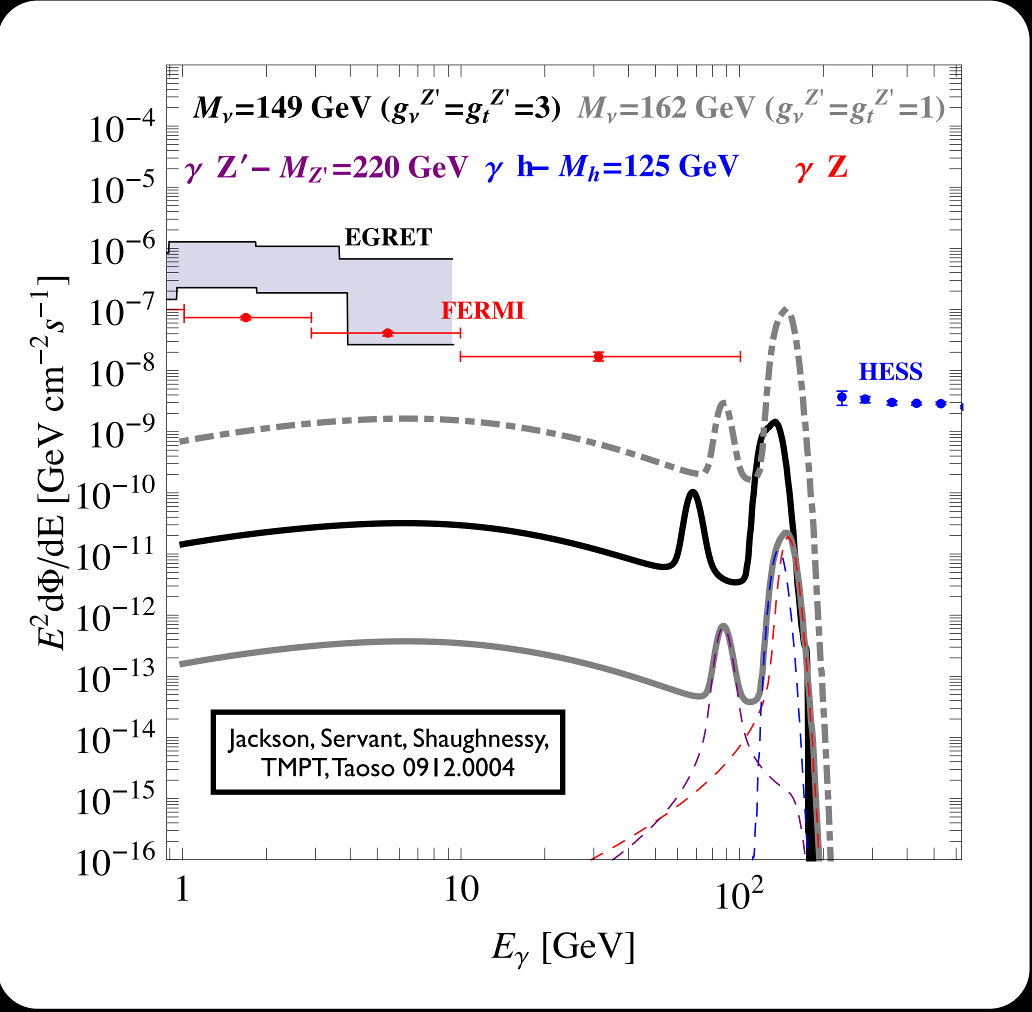
Distributions at Colliders



The spin of the DM itself is not generally directly accessible to colliders, but decay distributions of sibling particles into DM can distinguish between the space of possibilities.

If the dark matter particle is detected, what can we learn about its properties (e.g. spin)? Would we be able to learn whether it interacts with the SM through the Higgs portal?

(More) Gamma Ray Lines

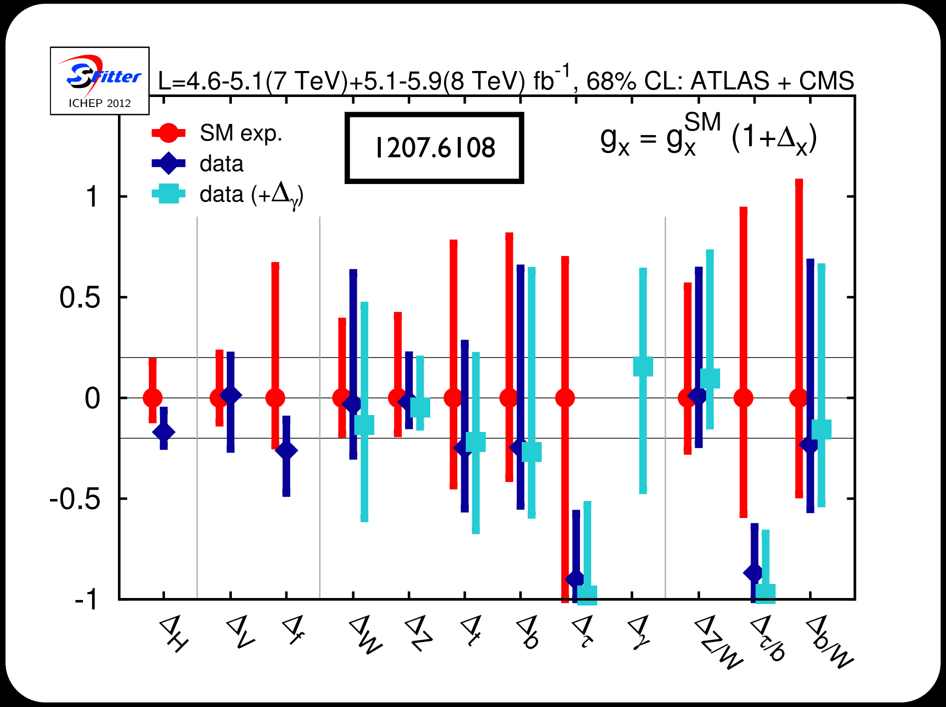


If one observes multiple lines, one may infer the mass of the dark matter and also additional particles in γ+X channels. The presence of a bright γh line (which is net Spin S = 1) would be suggestive of dark matter which is a Dirac fermion or vector particle based on conservation of angular momentum and Fermi statistics.

Spin is challenging for any detection technique, and an accurate measurement by any one technique requires us to "get lucky" in a particular way. Since evidence may be circumstantial, combinations of different probes can be particularly powerful here.

If the dark matter particle is detected, what can we learn about its properties (e.g. spin)? Would we be able to learn whether it interacts with the SM through the Higgs portal?

We saw discussion of determination of couplings to various particles during the presentations. Coupling to the Higgs is particularly challenging.

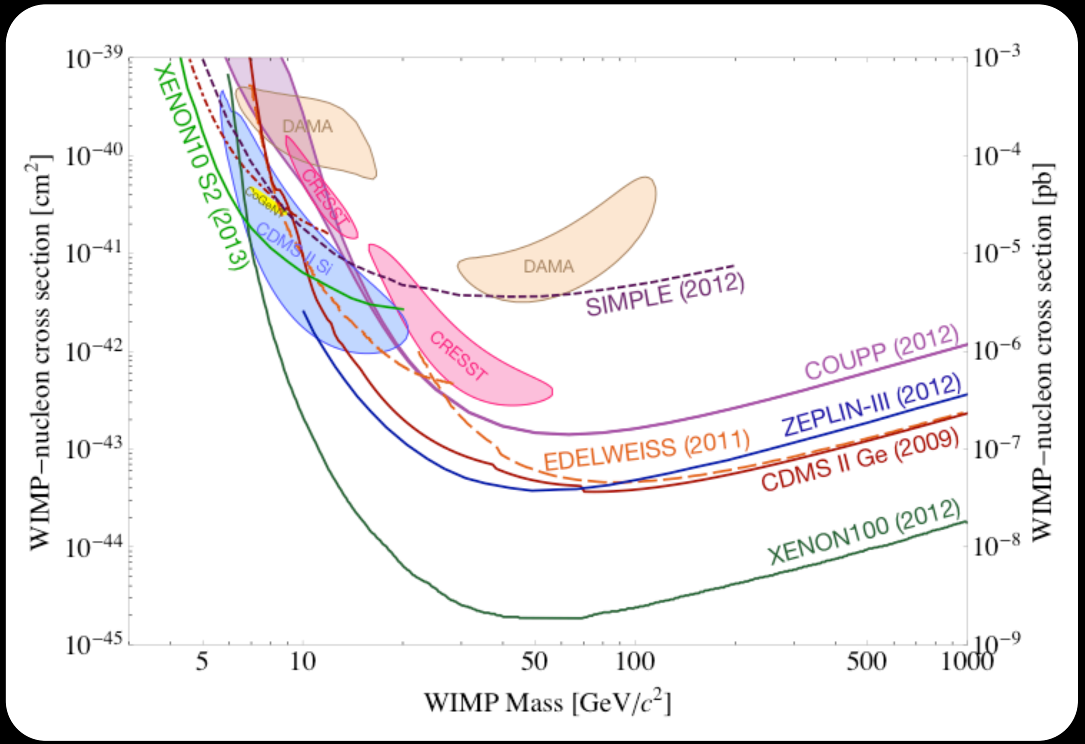


The most obvious way to infer DM coupling to the Higgs would be to see the Higgs decaying into DM. This will only be possible if the DM mass is less than M_h / 2.

For heavier DM, things are much less straight-forward at colliders.

Direct Detection can be suggestive. If the Higgs is the dominant mediator of (SI) scattering, one expects that the cross sections with protons and neutrons will be equal, which tells one how to scale from one target to another.

Knowing the Higgs mass suggests regime of cross section ~ 10^{-45} cm2 [but note this also assumes the DM-Higgs coupling is O(1)].



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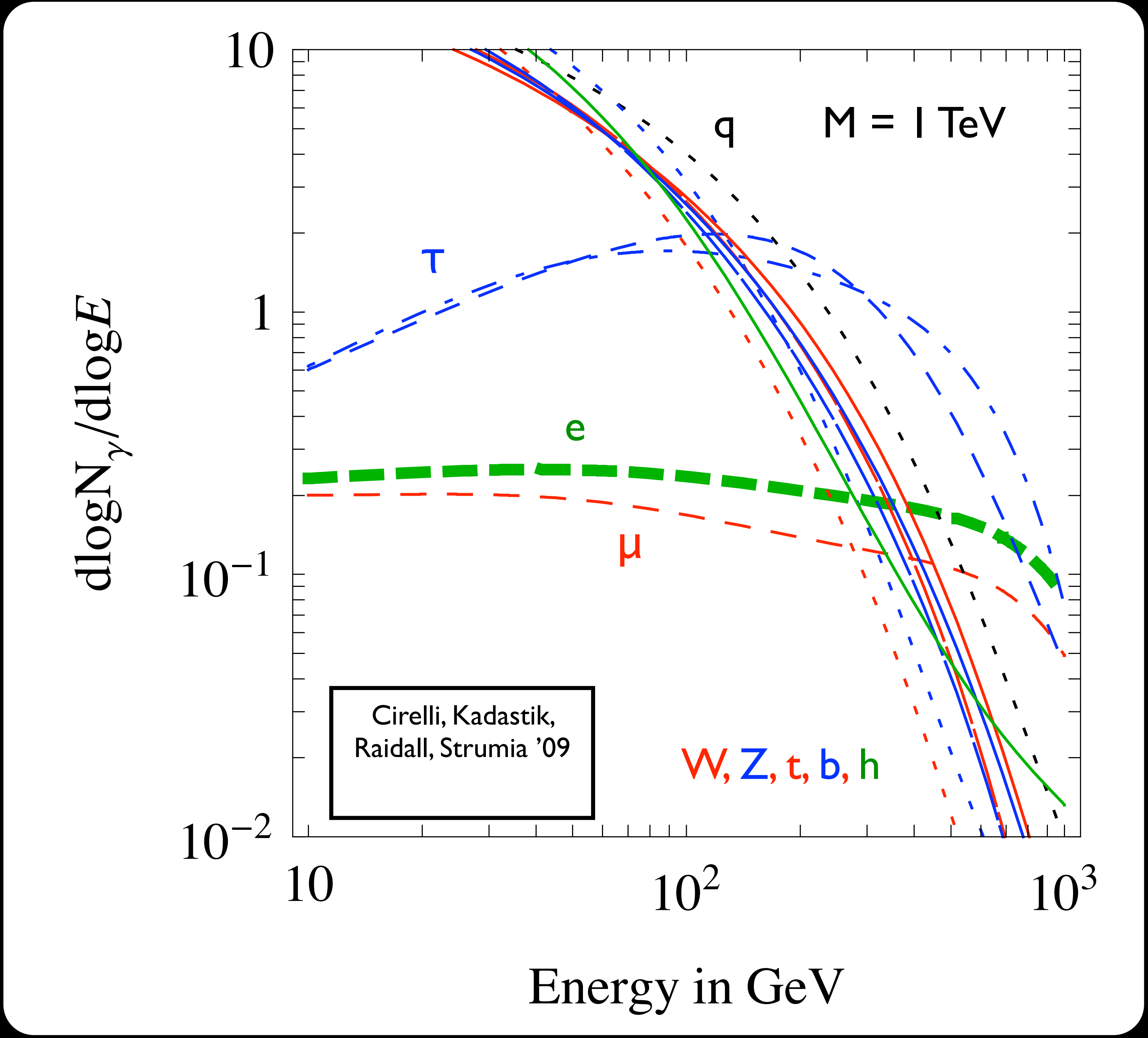
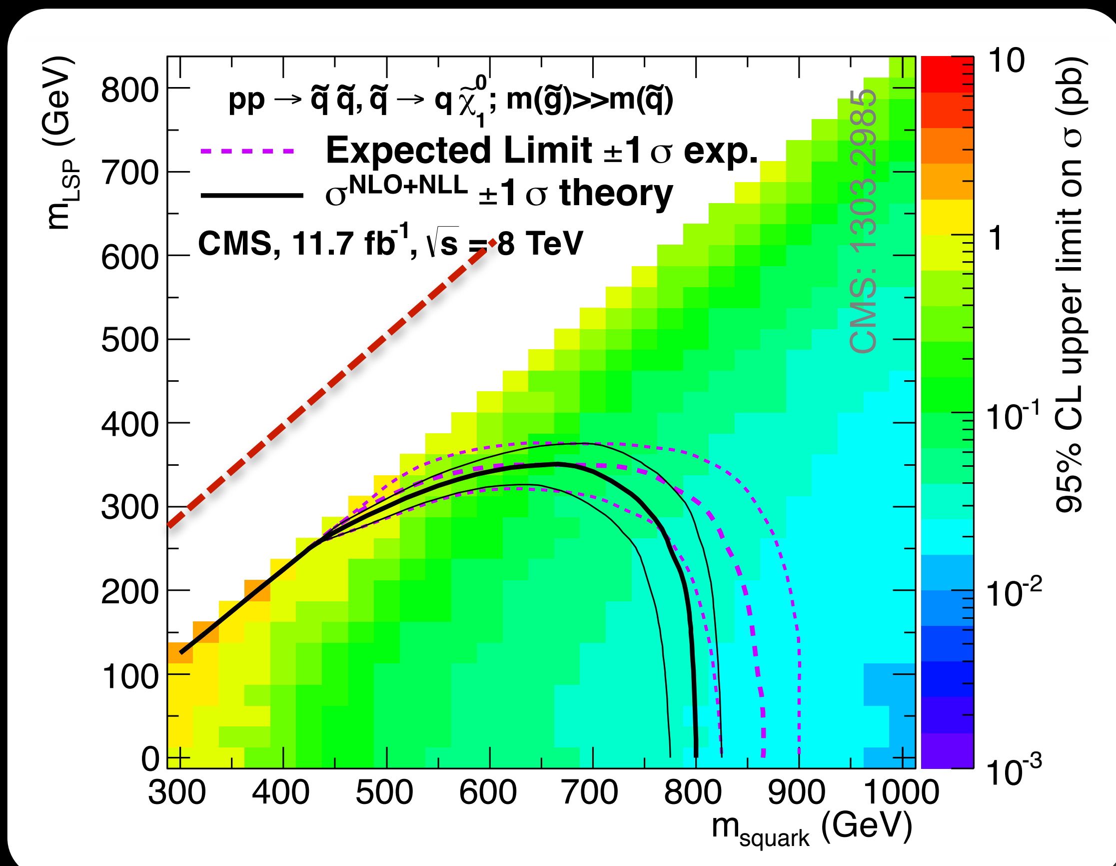
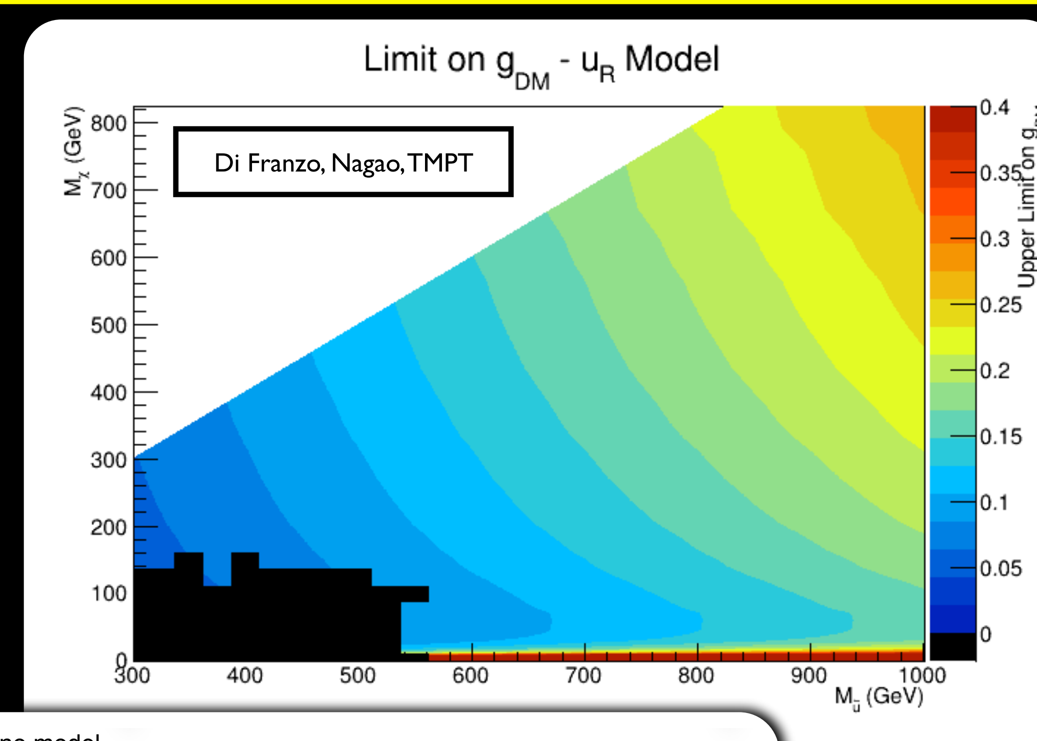
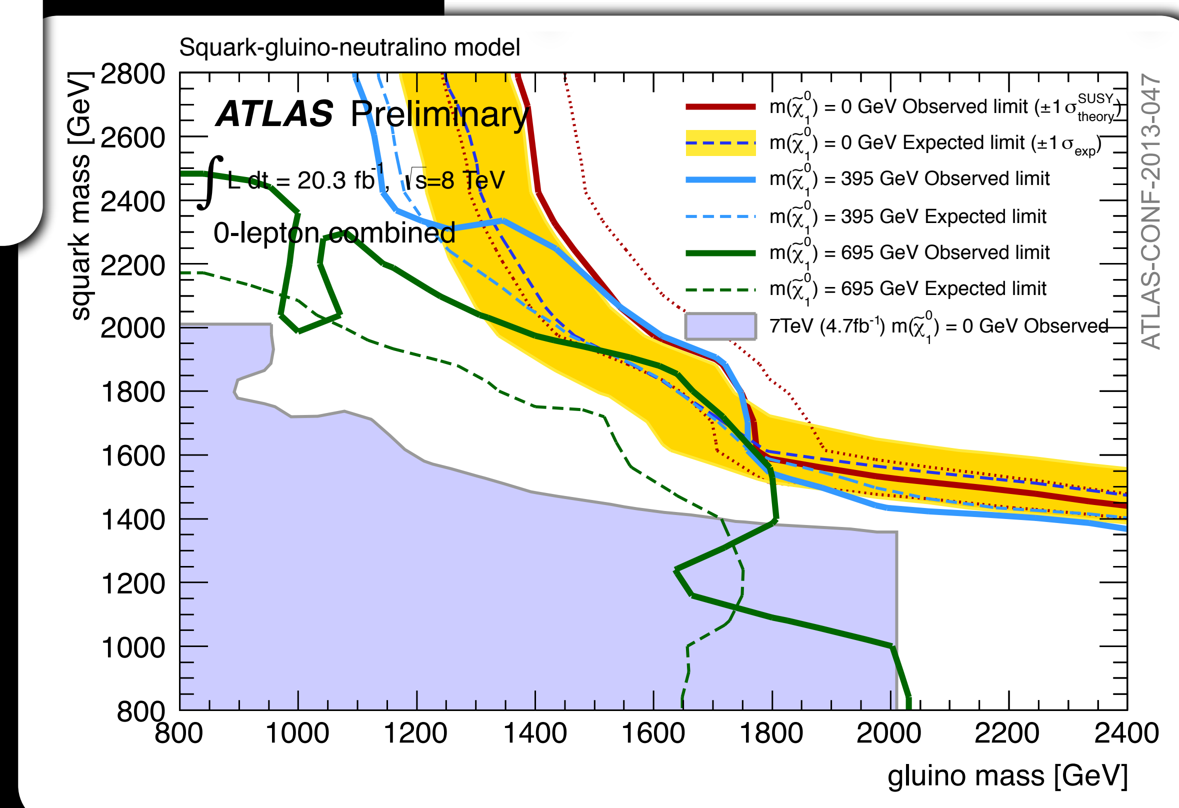
The spectrum of (e.g.) gamma rays and neutrinos from annihilations can be difficult to read, but evidence of heavier particles in the right proportions would be suggestive of the Higgs as a mediator.

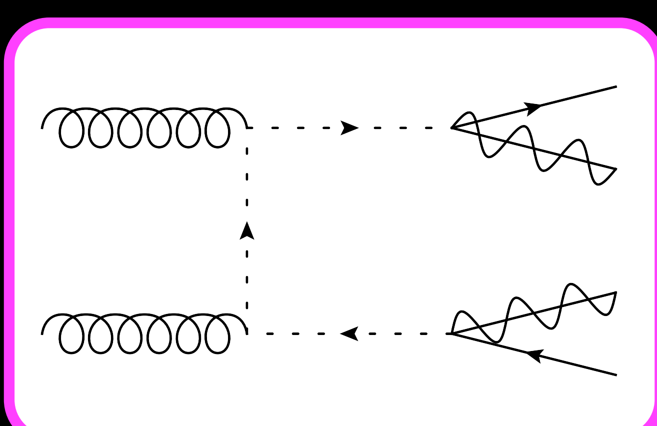


It has turned out that missing transverse energy is a very effective signature for discovery at the LHC. So, have we ruled out WIMP dark matter with mass below 500 GeV?









No.

Lian-Tao Wang

Question: It has turned out that missing transverse energy is a very effective signature for discovery at the LHC. So, have we ruled out WIMP dark matter with mass below 500 GeV? (CF4) Answer: No. (Tim Tait)

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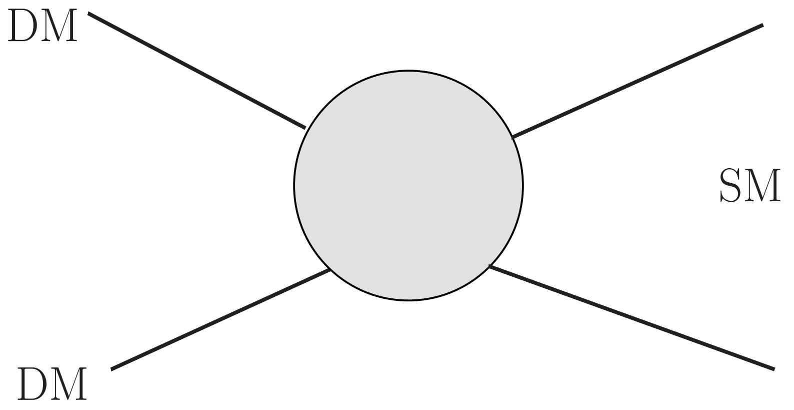
I will address: What is the reach for WIMPs at colliders?

WIMP

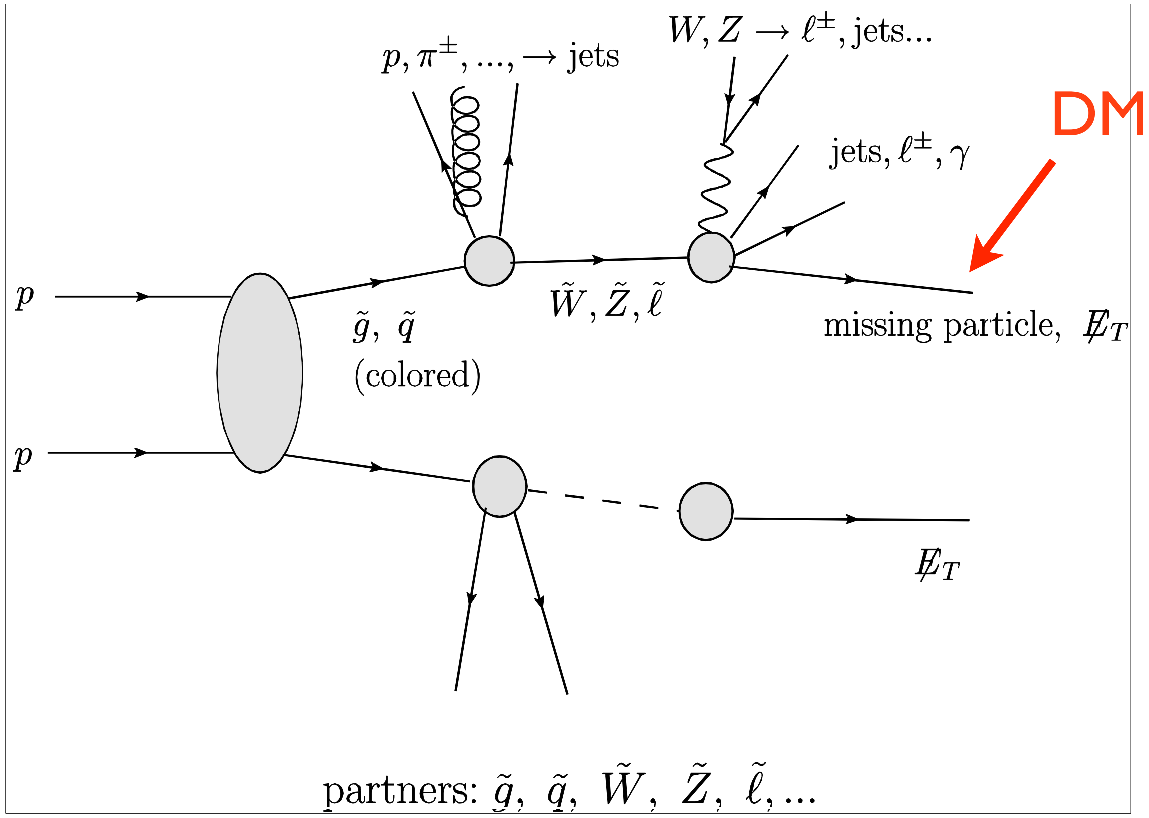
$$m_{\mathrm{WIMP}} \leq 2\ \mathrm{TeV}\left(\frac{g_{\mathrm{eff}}^2}{0.3}\right)$$



g^2_{eff}: coupling between WIMP and SM

- Much of the parameter space can be probed at high energy colliders.

“standard” story.



- WIMP is part of a complete model at weak scale.
- It's produced as part of the NP signal, shows up as missing energy.
  - Dominated by colored NP particle production: eg. gluino.
- The reach is correlated with the rest of the particle spectrum.
  - Can have blind spots/regions especially at pp collider.

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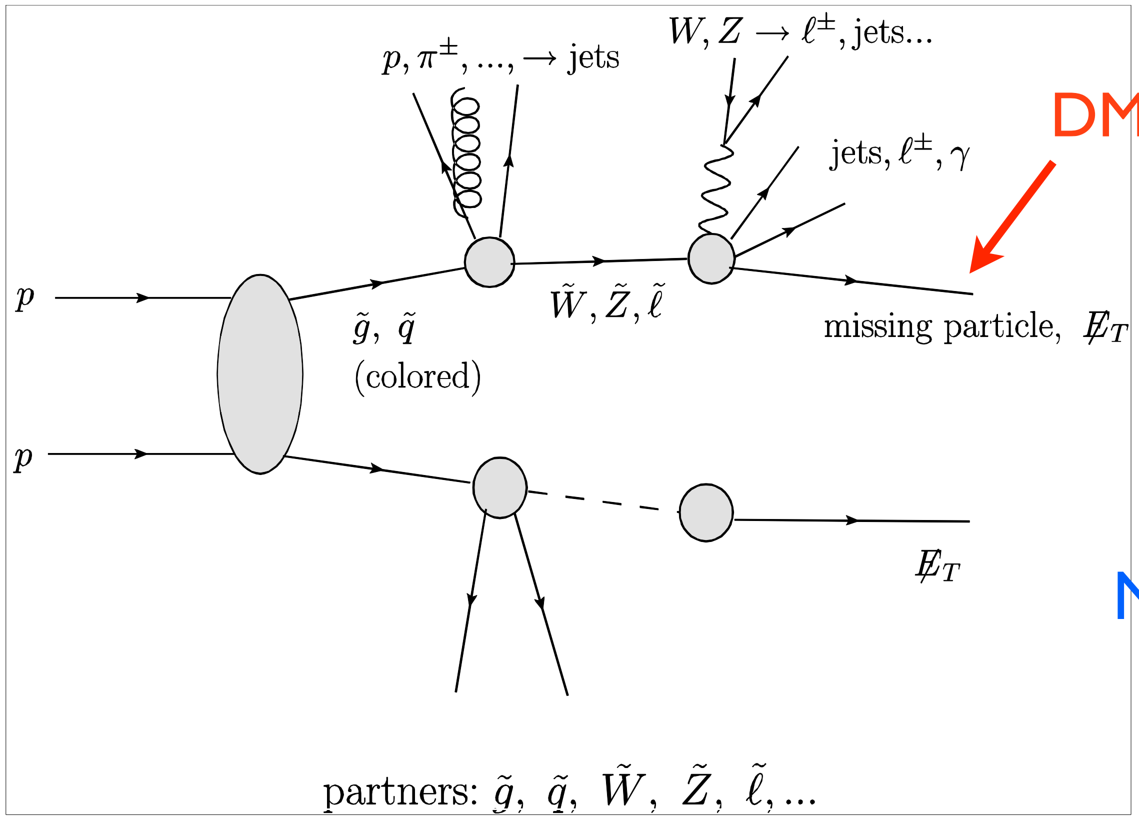
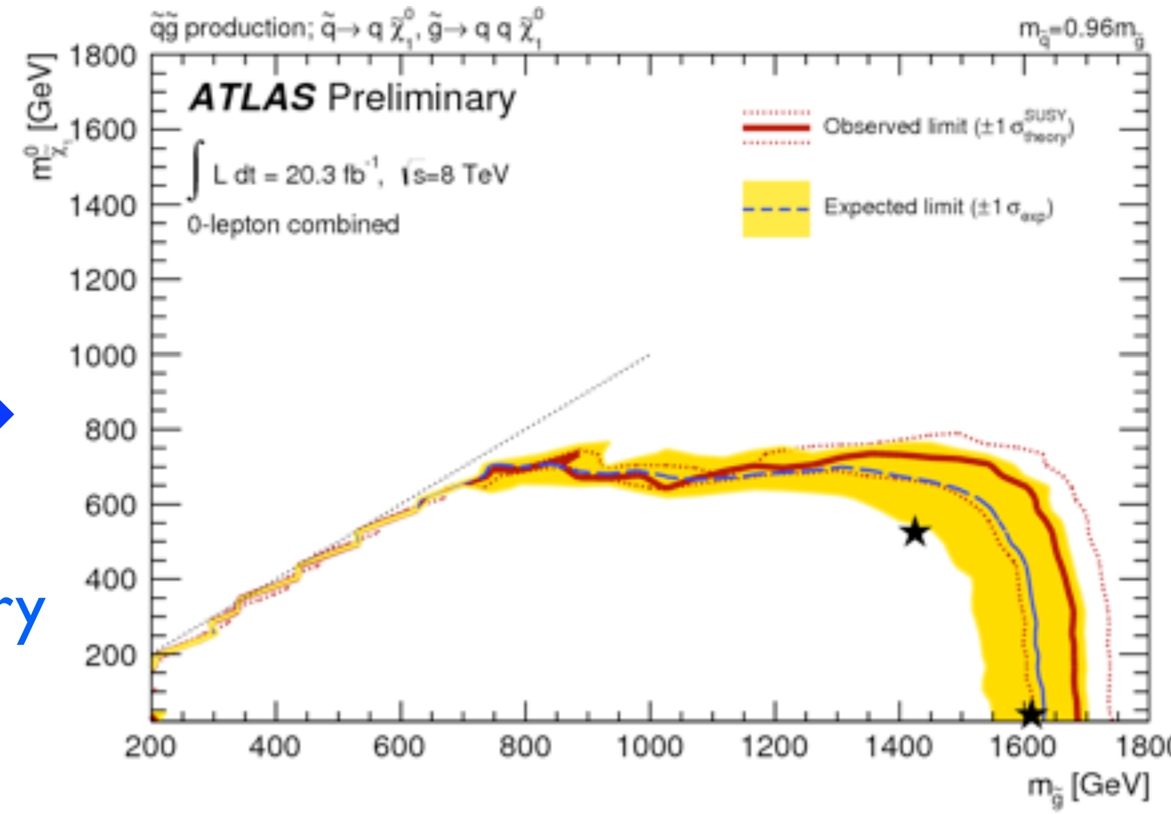


No discovery yet



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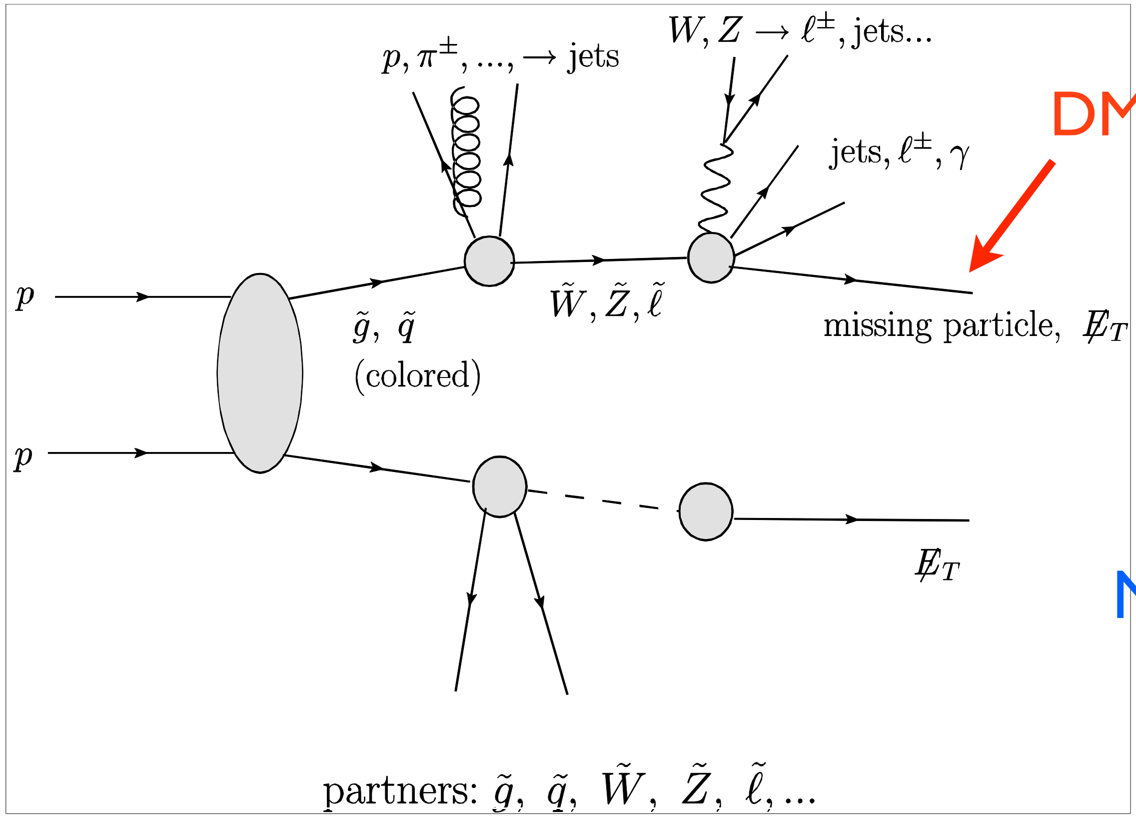

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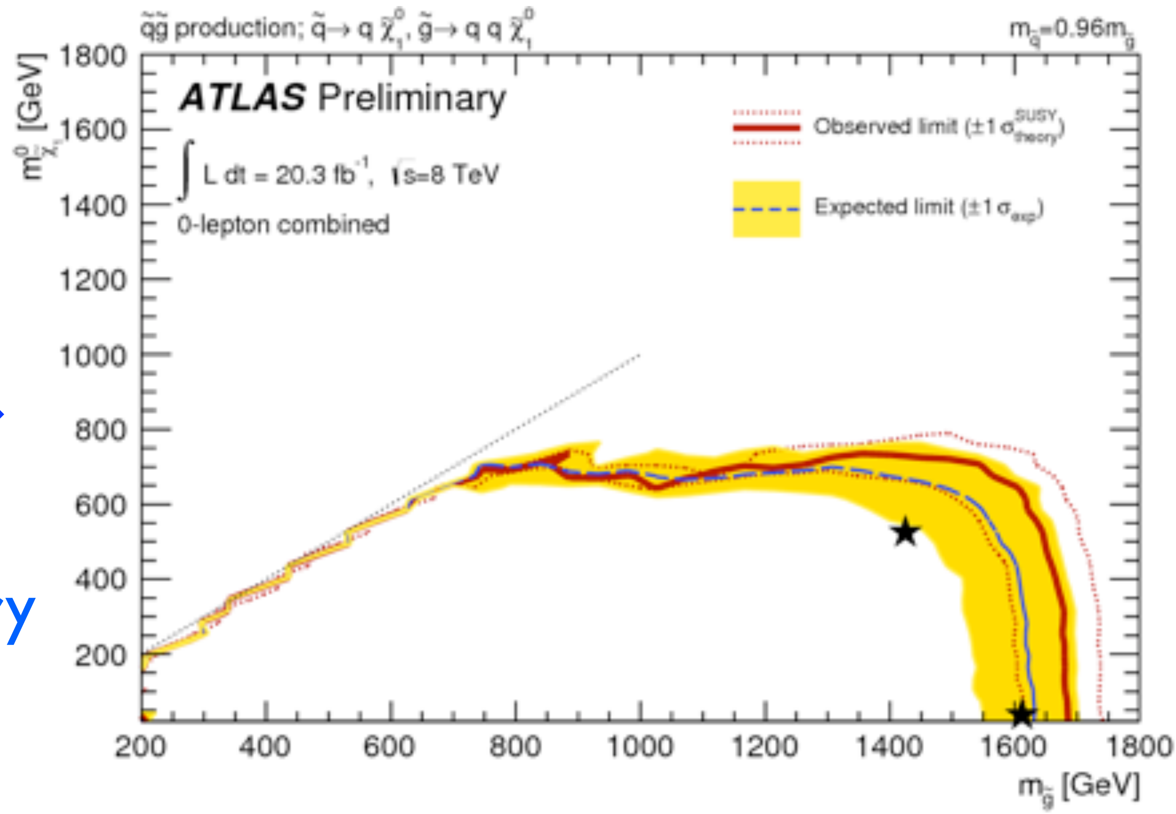
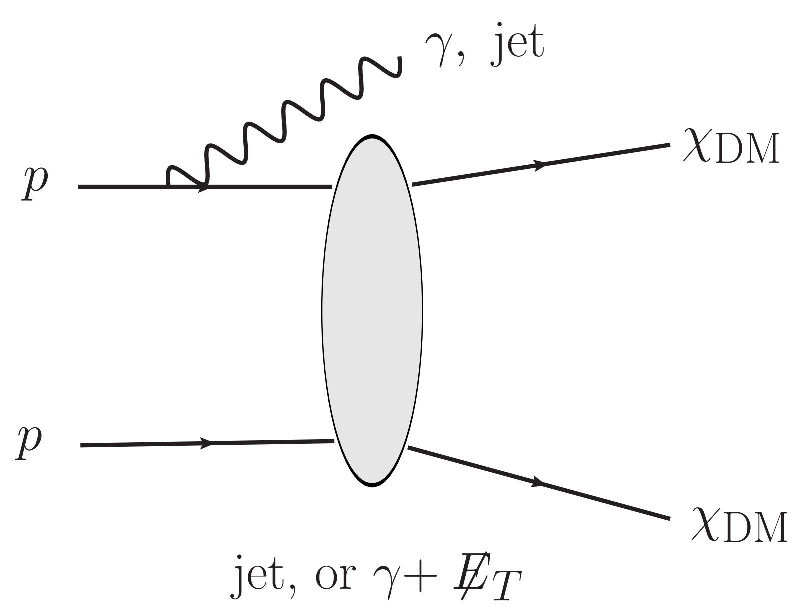


Of course, still plausible, will keep looking.
Higher energy ⇒ higher reach

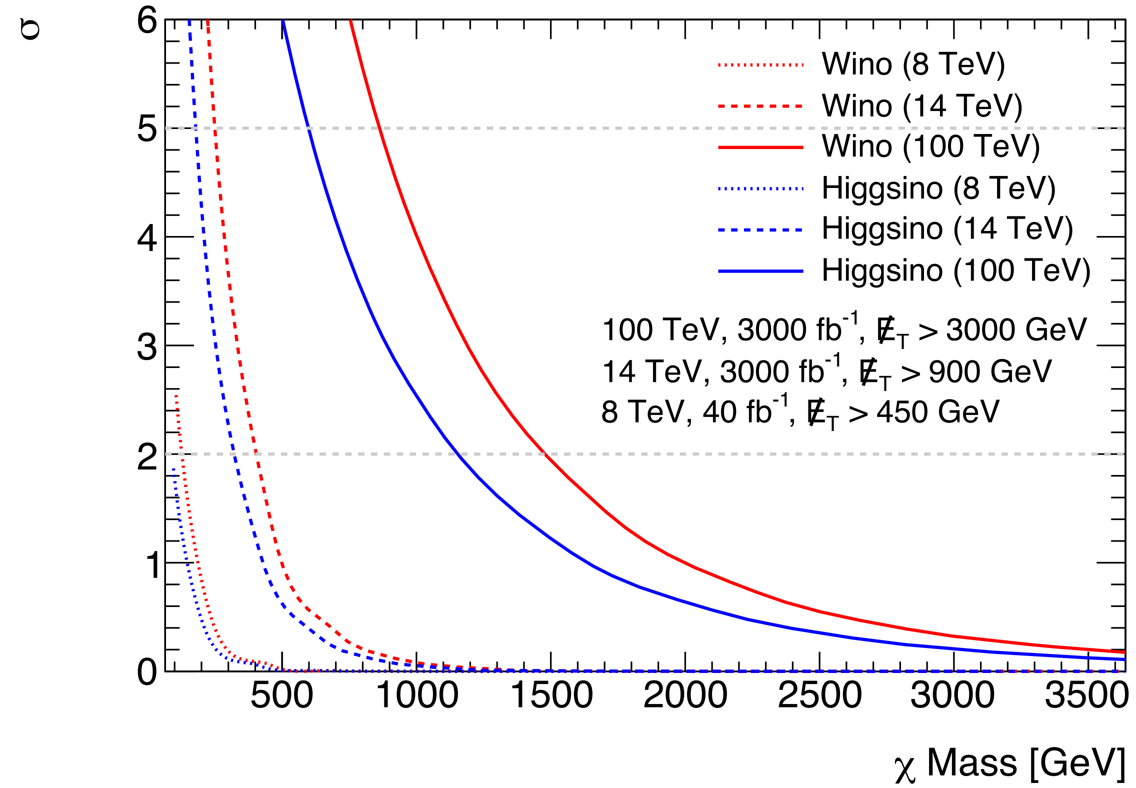
Lepton collider ⇒ cover possible blind spots

Back to basics.



mono: jet, γ, Z, b, ...

mono: jet+γ



Reach for SUSY WIMPs at pp colliders

- VLHC can cover most of the WIMP parameter space.
- High energy lepton collider can give clean signal up to $M_{WIMP} \lesssim 0.5 \times E_{CM}$
- Can probe sterile neutrino scenarios as well. Pospelov, 1103.3261, Friedland, Graesser, Shoemaker, Vecchi, 1111.5331

Questions about:
DM spin/mass, higgs portal, origin of stability

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I will elaborate on:
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What can collider measurements say about these?

The measurement of these properties can give evidence for whether DM has single or multiple components.
1) Could find two or more different DM particles.
2) Could find out DM particle produced at the collider can not account for the full relic abundance.

Measurements at colliders

- DM coupling. Qualitatively, if DM
  - found in SUSY decay chain, can infer couplings from decay products.
  - found in mono-jet: couples to quark and/or gluon
  - found in mono-jet+photon: couples to quark/anti-quark
  - found in mono-b: evidence for Higgs portal
  - found in VBF only: couples to gauge bosons

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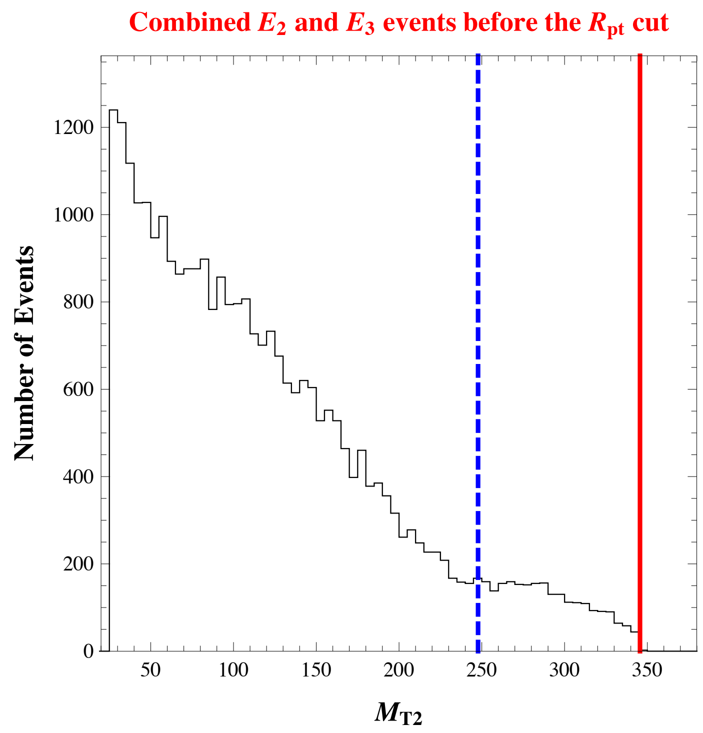
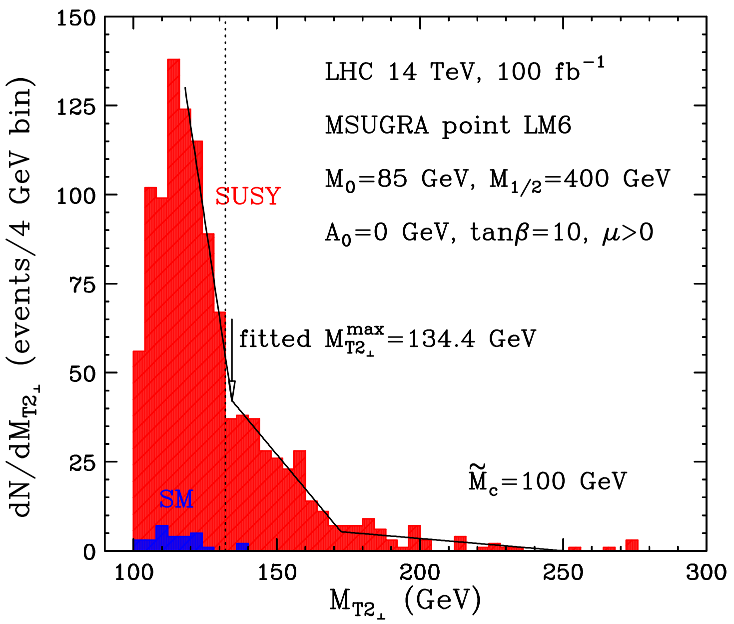
  - found in VBF only: couples to gauge bosons
- what symmetry ⇒Stability?
  - for example: Z_2 vs Z_3
  - Different Kin. distributions.



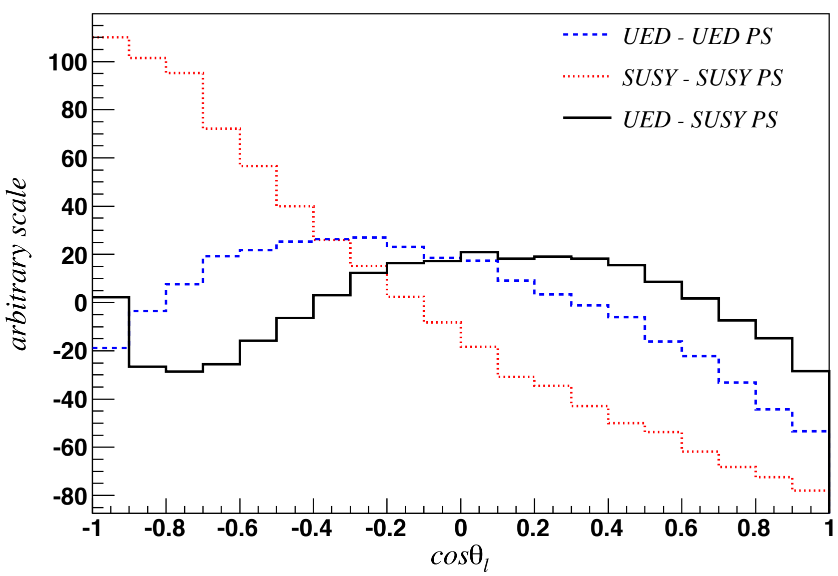
Agashe, Kim, Walker, Zhu, 1012.4460

More measurements at pp collider

- Only measures sum of DM momenta.
- Mass.
  - Inferred from kinematical distribution.
- Spin.
  - Similar story.
- Difficult, need
  - well separated signal sample
  - accurately identify decay topology
  - accurately measure kin. distribution
  - Very high statistics.



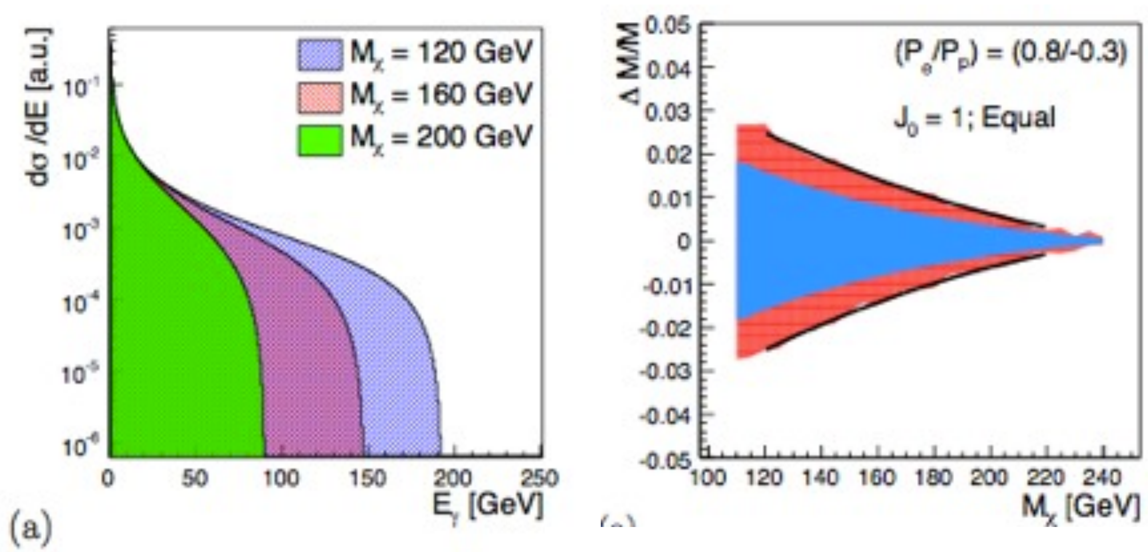
Konar, Kong, Matchev, Park, 0910.3679



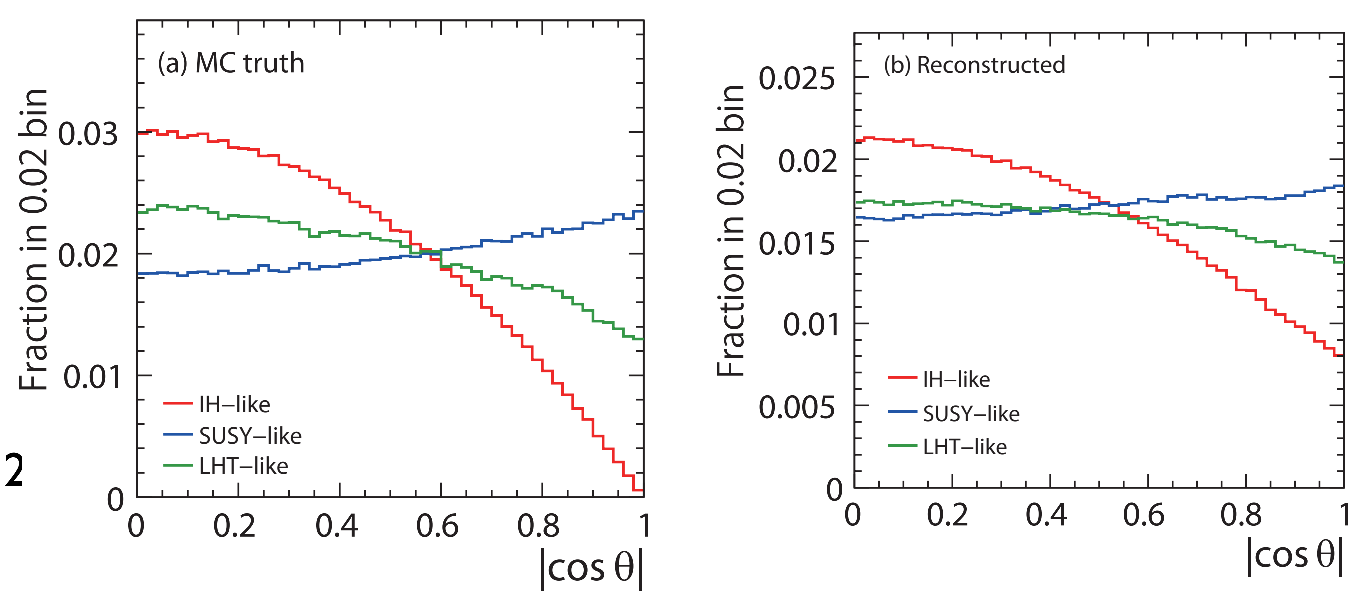
Cheng, Han, 1008.0405

High energy lepton collider

- provides a much cleaner environment to do these measurements.
- much easier to reconstruct kinematics.
- measurement as a function of E_{CM}



Bartels, Berggrens, List, 1206.6639

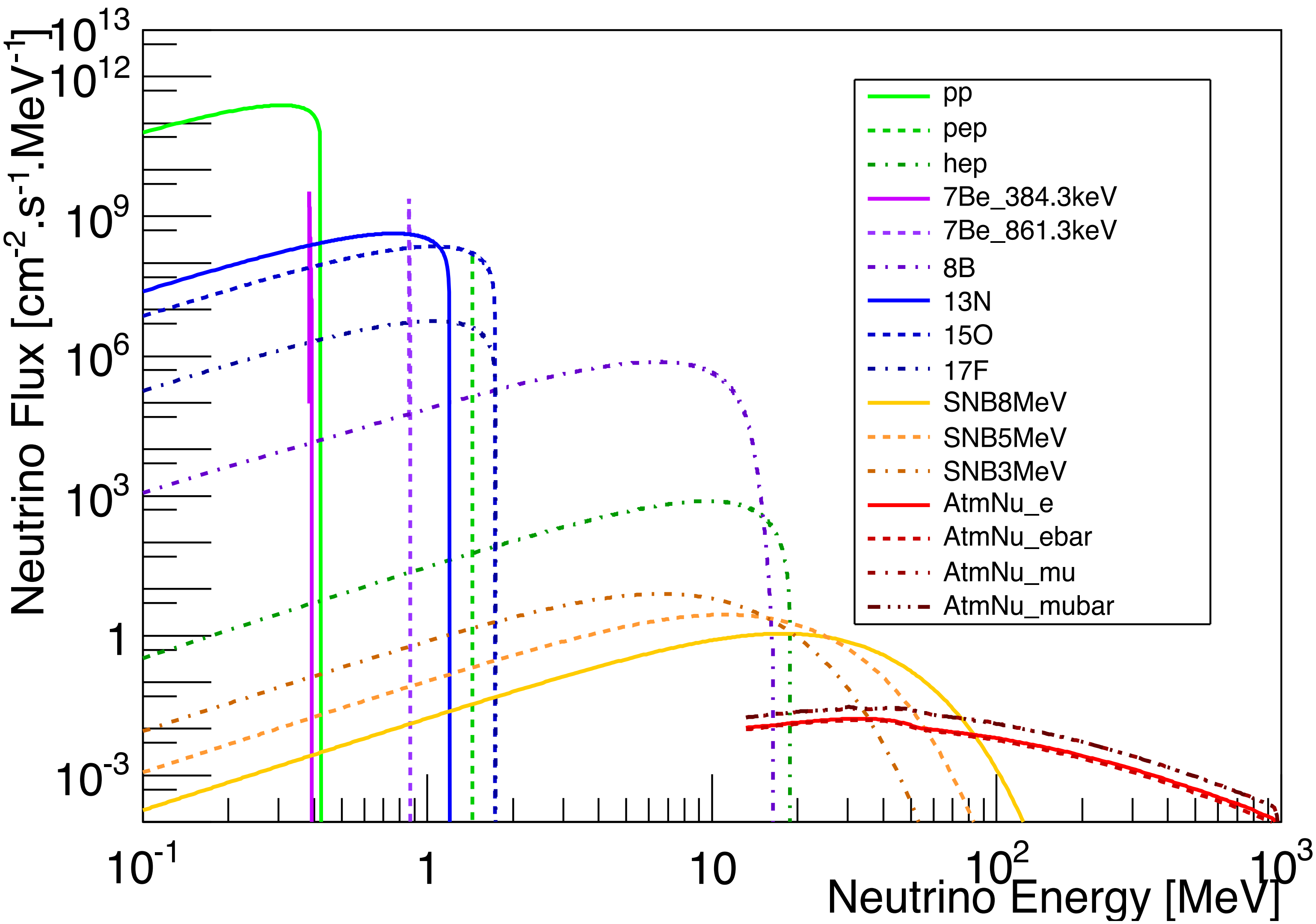


Asano et al, 1106.1932

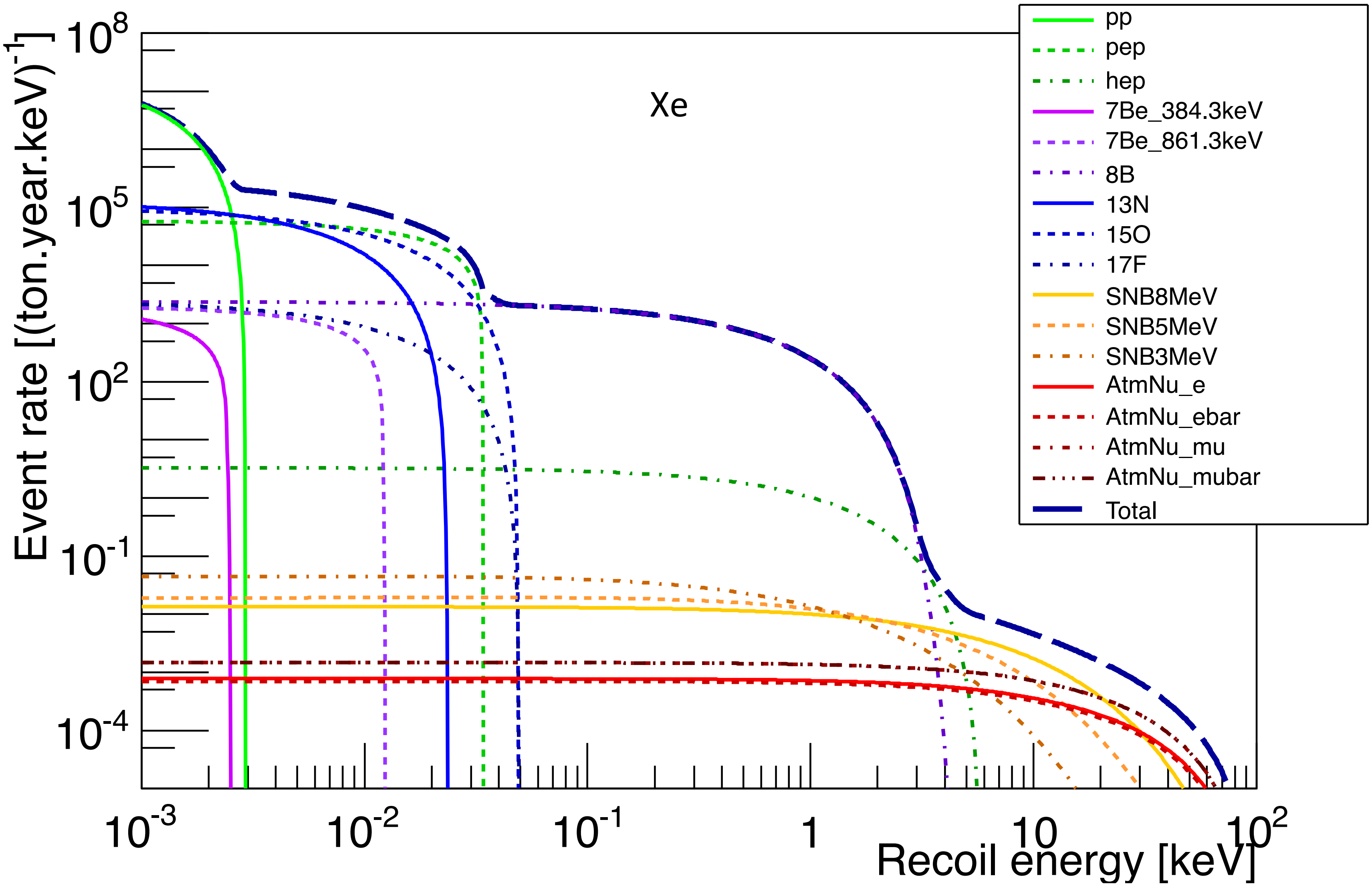
CF3. For direct detection, when is the right time to move from small projects toward larger ones?

Any new project should either be testing a putative WIMP signal, or have substantially better (~order of magnitude) sensitivity to WIMP-nucleon cross-section in some mass range. With high-mass WIMP sensitivities continuing to improve rapidly from one year to the next, it simply isn't possible to stay competitive without scaling up in target mass. The programmatic move from smaller to larger projects in the US is already part of DOE and NSF strategy, starting with the selection of a subset of so-called “Second Generation” dark matter detectors, and looking forward to worldwide collaboration on a few large scale “Third Generation” installations. On the other hand, if a putative WIMP signal is seen (such as the current indications at 8.6 GeV), then it can make sense to test the signal with several approaches, involving multiple targets and technologies. In this case there is less emphasis on scaling to a few large projects, and more emphasis on multiple, smaller experiments to test the signal.

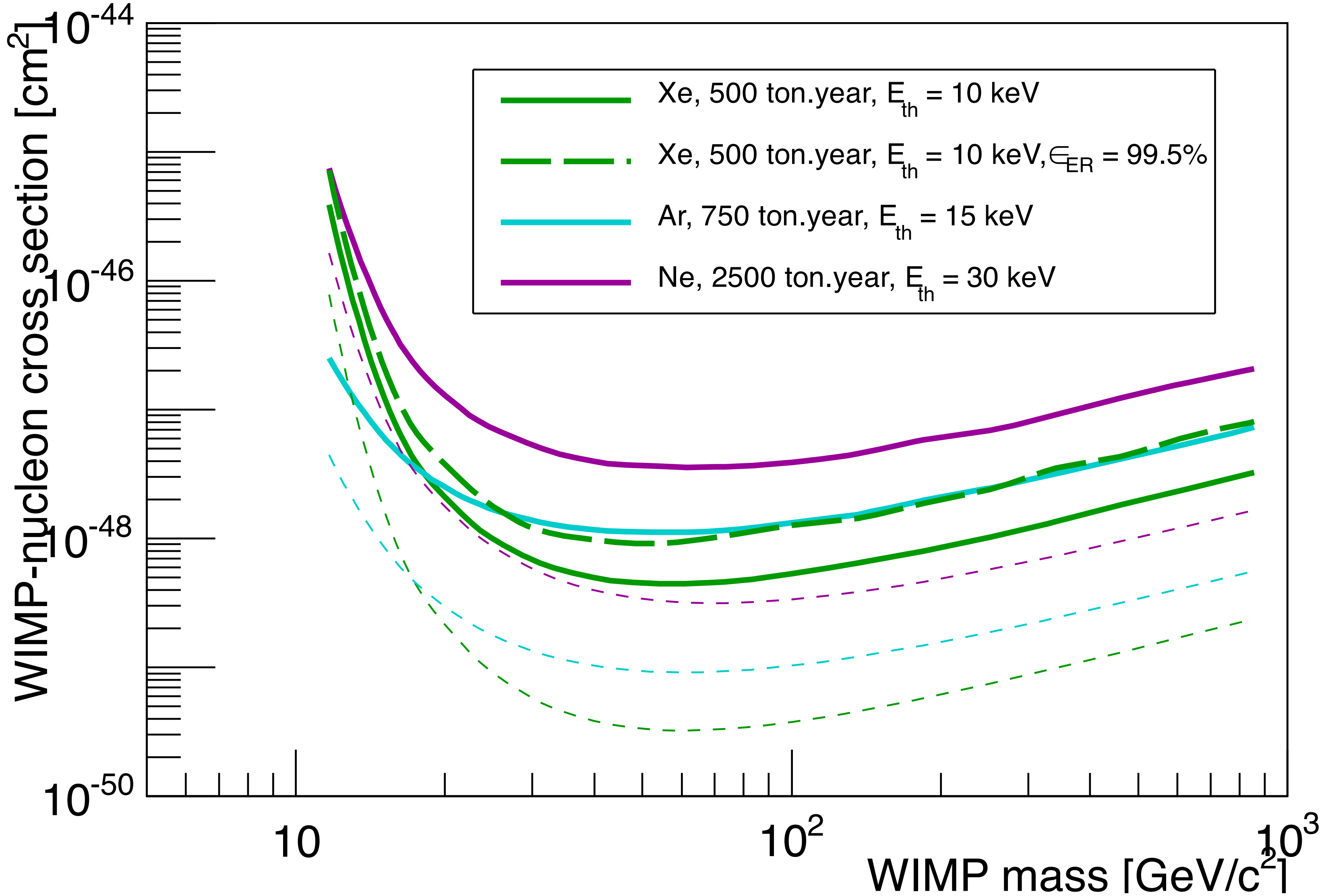
Solar and atmospheric neutrino fluxes



Coherent neutrino-nucleus scattering events
(Billard, Strigari, and Figeroa-Feliciano, arXiv:1307.5458)



WIMP sensitivity limits, given coherent neutrino scattering background (Billard, Strigari, and Figeroa-Feliciano, arXiv:1307.5458)



CF4. Dark matter direct detection will reach the neutrino background at some stage. Although this background is not formally irreducible, is it realistic to think that one could go beyond this? What experiments would make this possible in a cost-effective way?

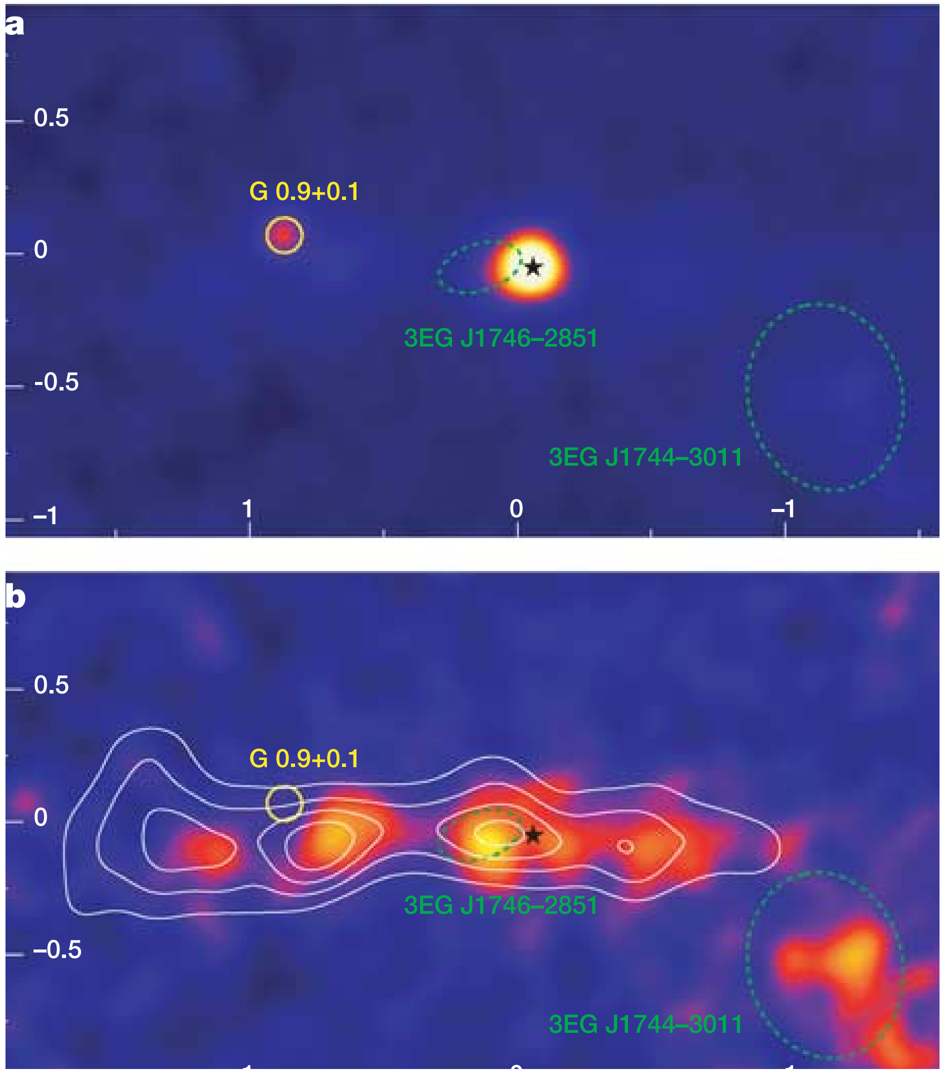
Achieving sensitivities below the neutrino floor will require extremely large detectors capable of disentangling the small energy dependence of neutrino and WIMP-induced signal. In this case, maintaining stable operation to be sensitive to annual modulation can provide an additional constraint. Better understanding of solar and atmospheric neutrino physics can narrow down the neutrino spectrum normalization and aid in background subtraction. Detectors with directional capability and head-tail discrimination can also push beyond the neutrino floor, provided they are very large, of mass 10 tons and above.

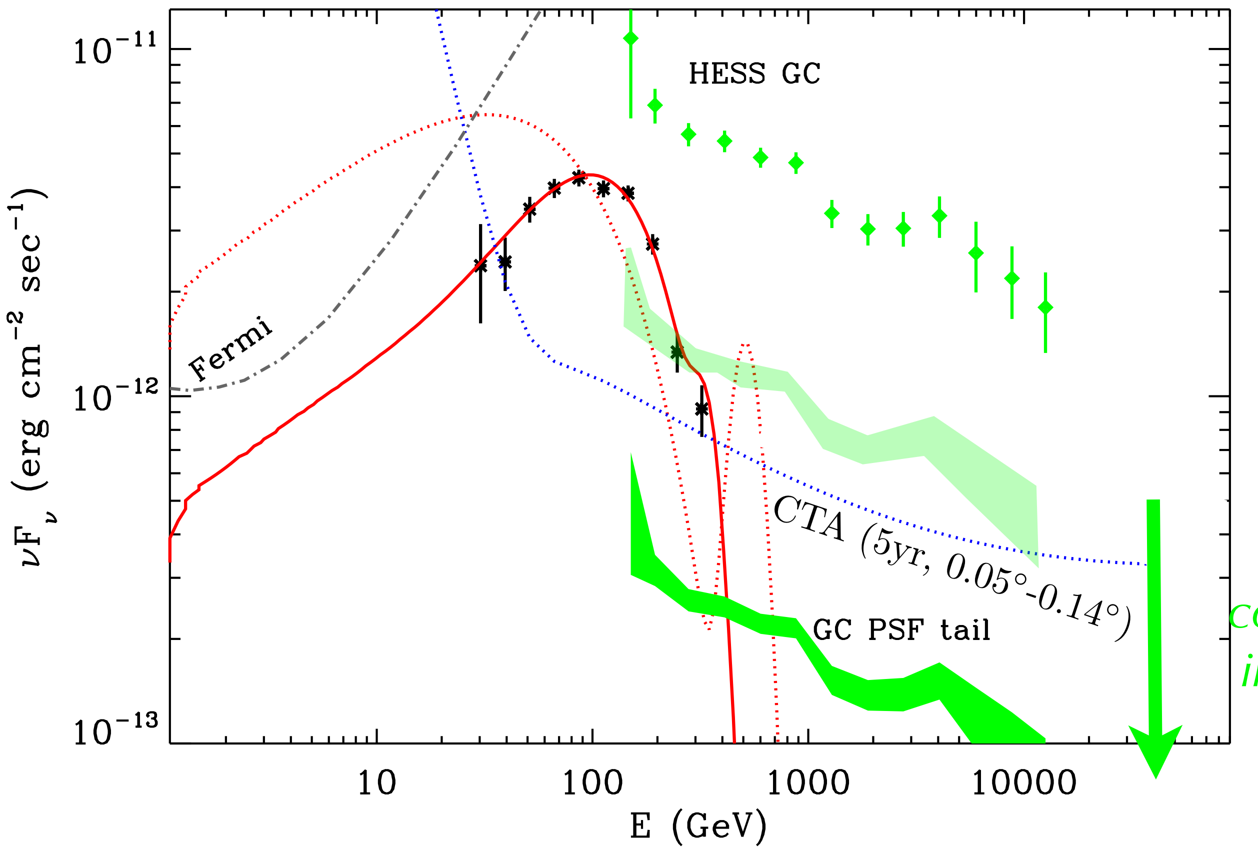
CF5. To what level should we continue to search directly for WIMP dark matter in the absence of a convincing signal? Is there a technique, or a motivation, to search beyond the neutrino floor? Is there a natural stopping point for direct DM searches?

The neutrino floor may be a natural stopping point if the cost of detectors with masses in the tens of tons is prohibitively high or if a path to comparable size directional detector technology cannot be demonstrated. However, from the theory side, there are compelling models that predict a variety of dark matter masses with small cross-sections, motivating continued exploration of WIMP cross-sections beyond the neutrino floor, across a wide range of WIMP masses.

Tough Question C12

``Given large and unknown astrophysics uncertainties (for example, when observing the galactic center), what is the strategy to make progress in a project such as CTA which is in new territory as far as backgrounds go? How can we believe the limit projections until we have a better indication for backgrounds and how far does Fermi data go in terms of suggesting them? What would it take to convince ourselves we have a discovery of dark matter?''





Dwarf galaxies have almost no known astrophysical backgrounds, for backgrounds the GC is worst case. HESS provides the best data on the GC (below, with point source at Sgr A* subtracted). Better angular resolution can reduce the background from the tail of the PSF function, which dominates over other sources in the plane

Tough Question CF12

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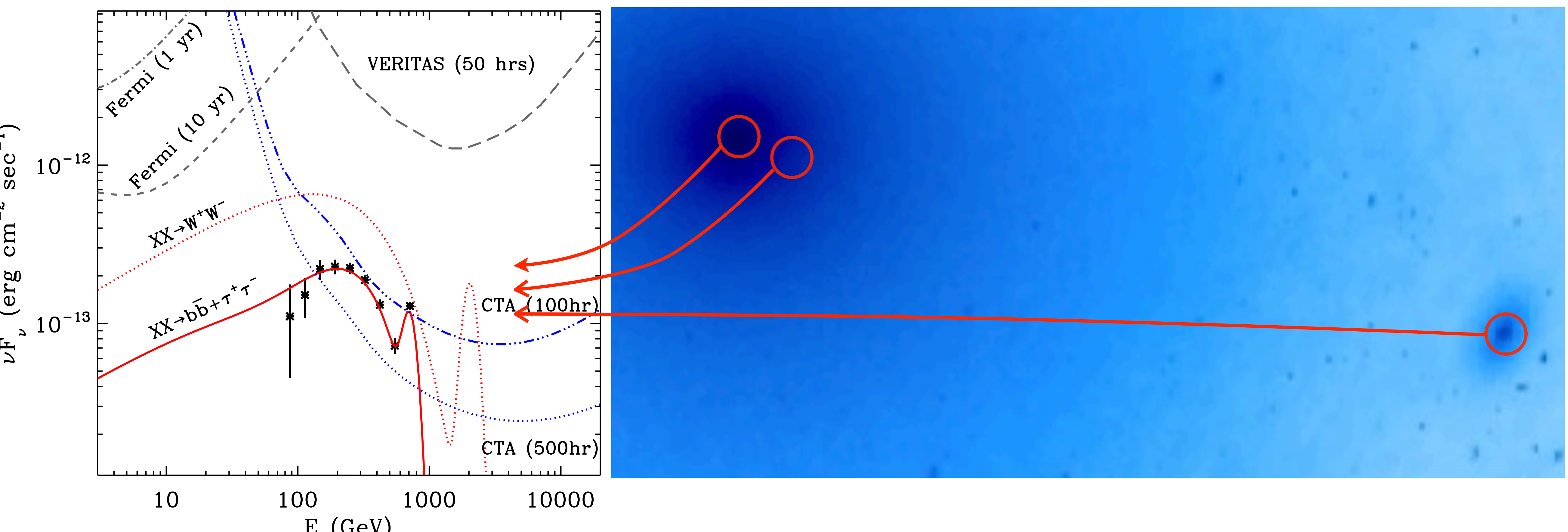
Backgrounds get lower at higher energies, but even at 1-3 GeV with no background subtraction get a limit within $1^\circ \sim 1 \times 10^{-7} \mathrm{cm}^{-2}\, \mathrm{s}^{-1} \Rightarrow \langle \sigma v \rangle = 1.6 \times 10^{-25}\ \mathrm{cm}^{3} \mathrm{s}^{-1}$

(Tim Linden, SLAC CF meeting)

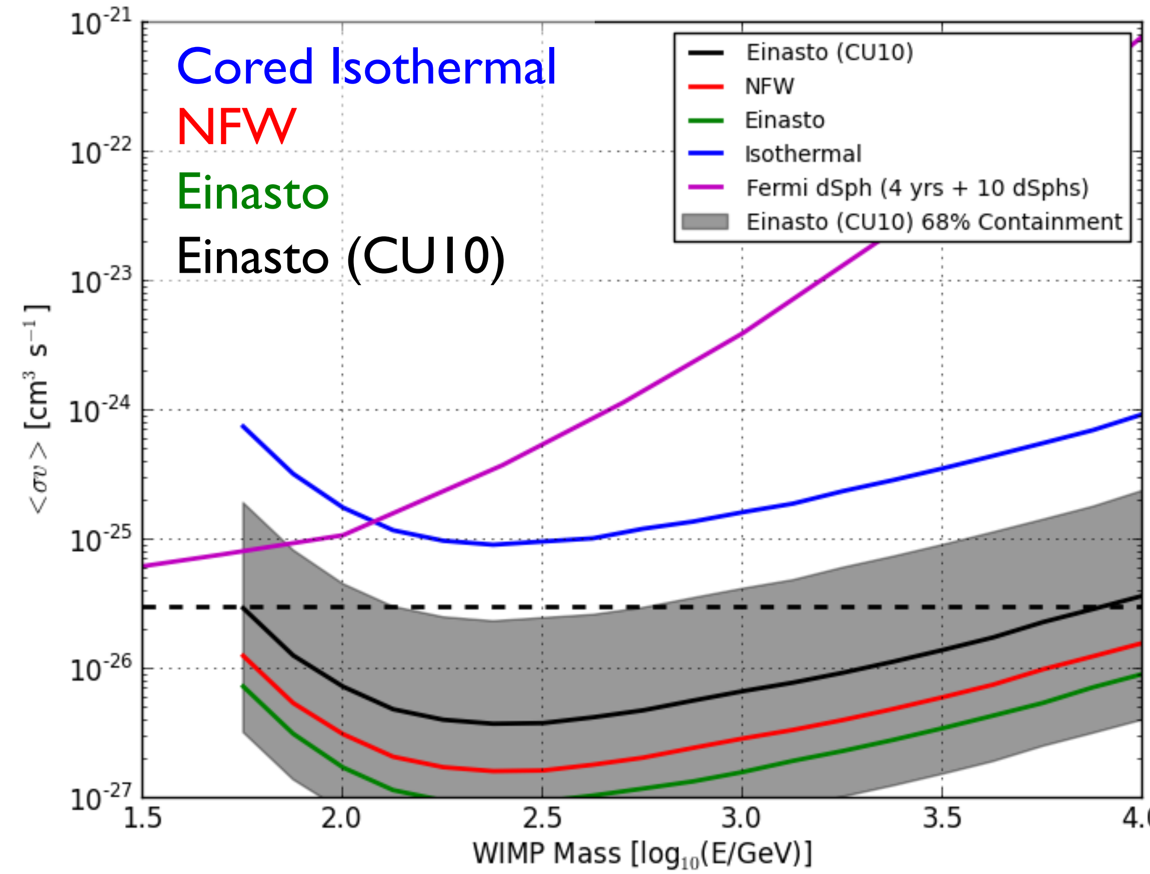


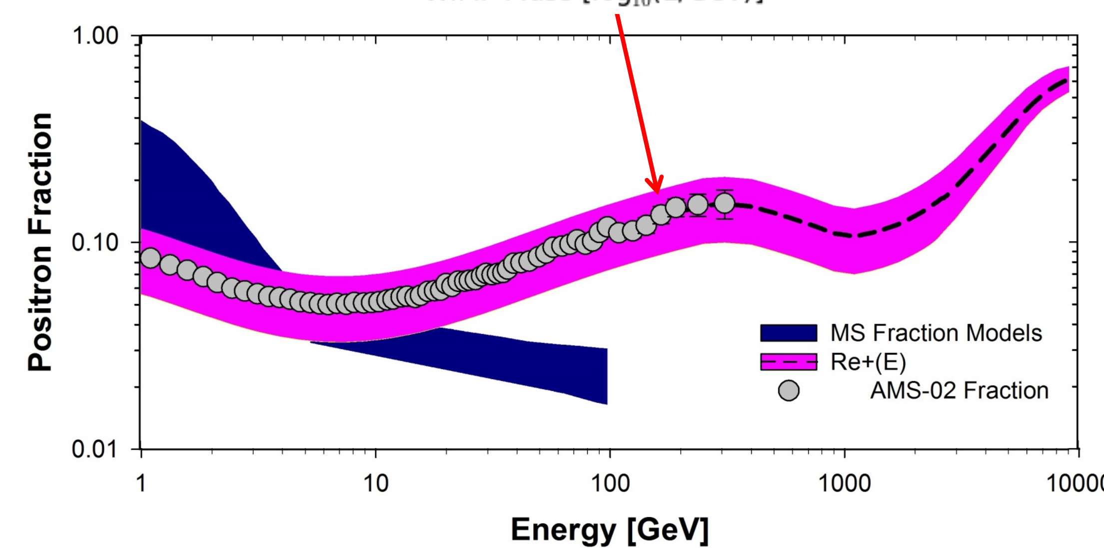
Unlike other astrophysical sources, would see a universal hard spectrum (typically harder by ~$E^{0.5}$) with a sharp cutoff. The spectral shape would be universal: the same throughout the GC halo, in halos of Dwarf galaxies, with no variability.

Tough Question CF11

``Can dark matter be convincingly discovered by indirect searches given astrophysical and propagation model uncertainties? Do indirect searches only serve a corroborating role?''

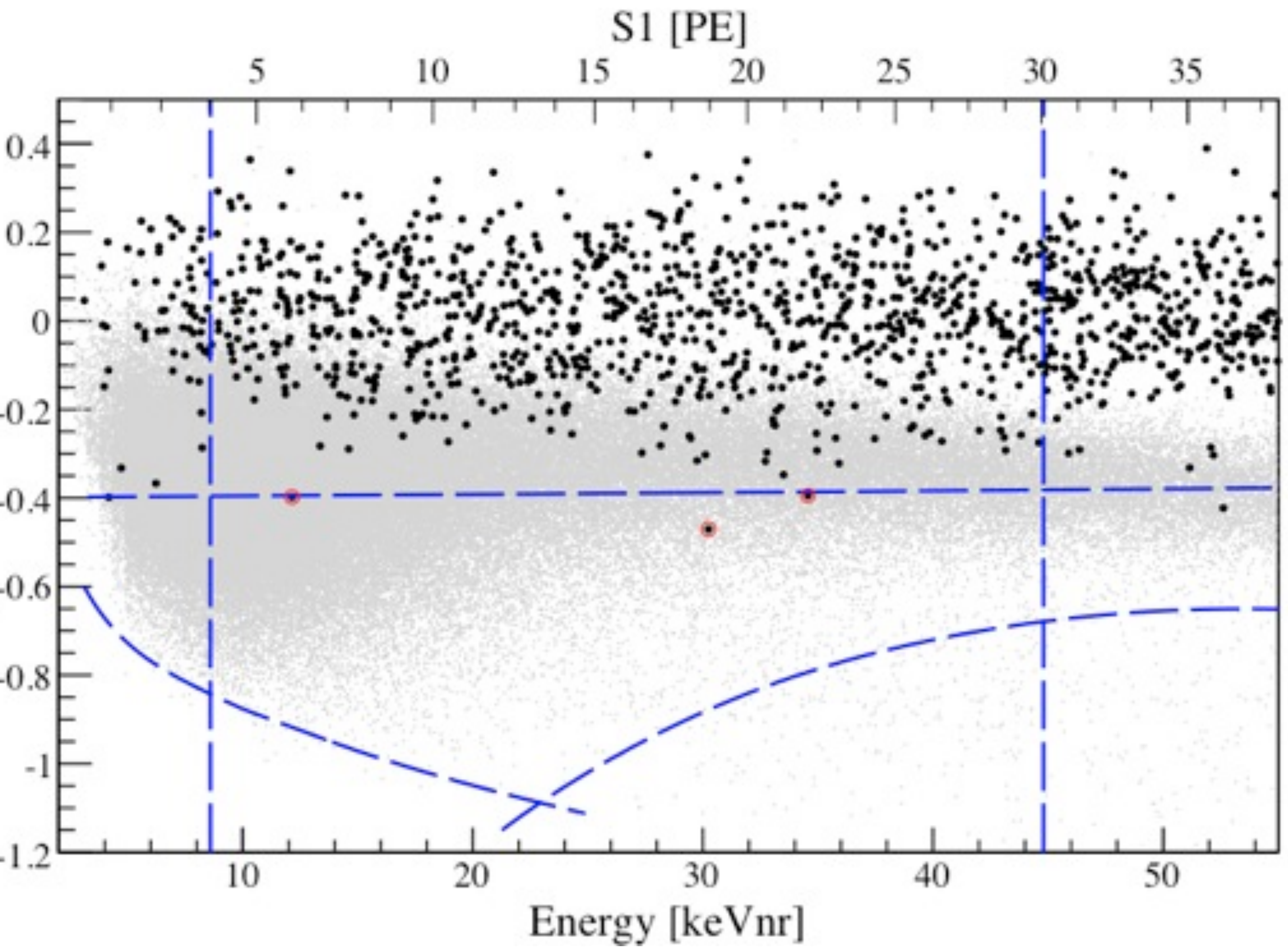
- Neutrinos from DM annihilation in the sun would be a smoking gun signature.
- An annihilation line in the gamma-ray spectrum would also provide a smoking gun signature (if detected at high significance!)
- The primary astrophysical uncertainties come for gamma-ray production come from uncertainties in the halo model. But even with uncertainties, the limits still reach the natural decoupling cross section.
- Extracting a DM signal from positron measurements does depend on backgrounds from secondaries produced in cosmic ray propagation, or astrophysical sources such as pulsars. The measured positron excess is orders of magnitude above the generic expectations for WIMP annihilation. However, a spectral feature (with a sharp cutoff) would be a strong indication of a signal.

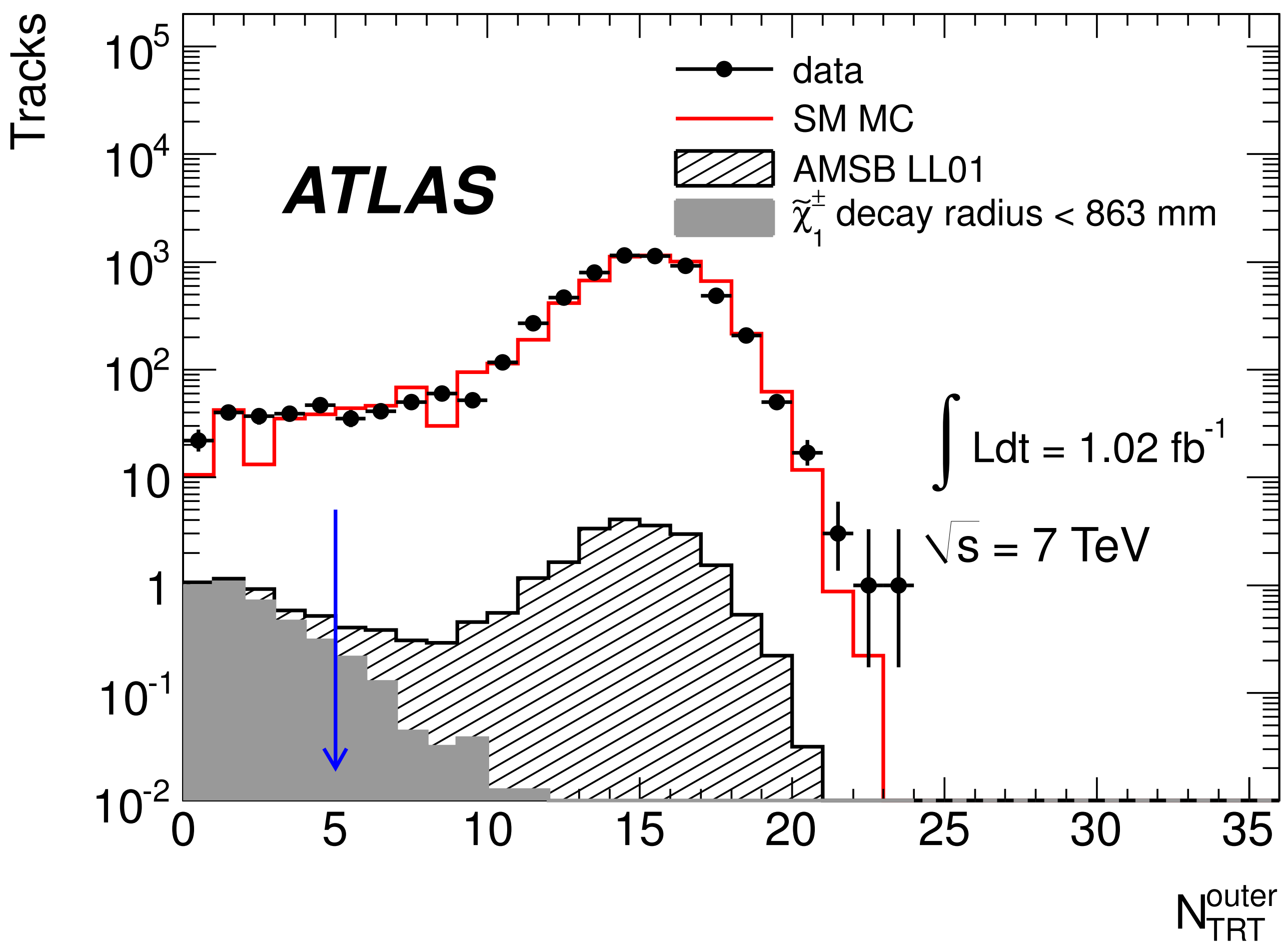




(Cowsik, Burch and Madziwa-Nussinov, arXiv:1305.1242)

Background?





- Upper limits are straightforward, but demonstrating that there is a signal and not a misidentified background is hard - this is true for DD, ID and Colliders.

Tough Question CF21: How do we discover that there is more than one type of dark matter particle?

In the **near term**, it would take two convincing detections of dark matter that do not agree with each other. For example, direct detection of a 20 GeV WIMP (with many events) and unambiguous signature of a 800 GeV WIMP in indirect gamma-ray searches and perhaps also at upgraded LHC.

In the **long term**, one could have scenarios like the following.
- Direct searches and LHC find a 60 GeV neutralino.
- Further LHC+ILC studies reveal it only contributes about half of the relic density.
- In time, axion detectors make a discovery consistent with axions being the other half of dark matter.
- Cosmological simulations and observations progress sufficiently that they ascertain dark matter is cold and non-interacting.
- This scenario would extend our understanding of the universe back to nano-seconds.

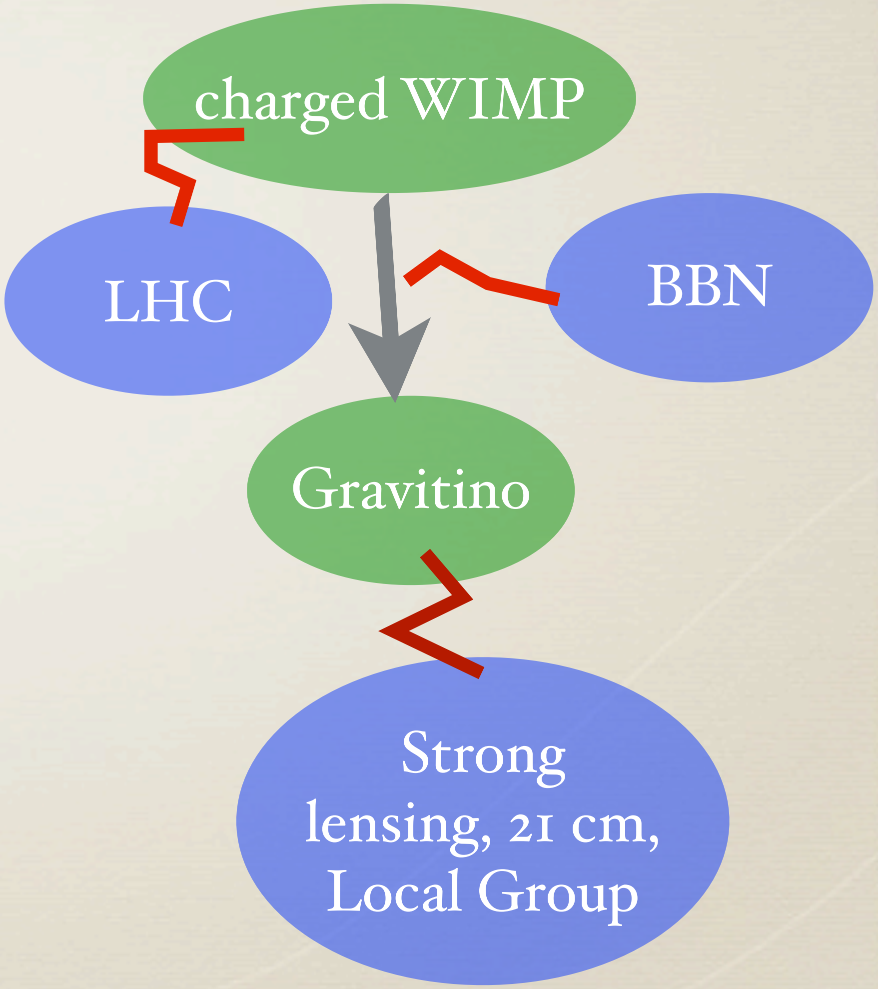
Tough Question CF23: If dark matter has no SM interactions stronger than gravitational, are there any prospects for discovering its particle nature?

A concrete model may help with this discussion. Consider a Gravitino with weak-scale mass (say in MSUGRA) that can naturally inherit the NLSP (WIMP) abundance (i.e., the SuperWIMP scenario).

Gravitinos could behave effectively as warm dark matter and have observable effect on galaxies.

The decay of NLSP to Gravitino affects BBN.

NLSP could be produced and, if charged, trapped at the LHC.



Tough Questions

CF1) What criteria could be used to prioritize activities across the Cosmic Frontier? The size of the communities? The connection to other key questions in particle physics and astrophysics? The variety of possible funding sources?

CF2) What are the needs for underground space for low-background direct searches, and are they met in current planning?

CF3) For direct detection, when is the right time to move from small projects toward larger ones?

CF4) Dark matter direct detection will reach the neutrino background at some stage. Although this background is not formally irreducible, is it realistic to think that one could go beyond this? How can one accomplish this cost-effectively?

CF5) Is there a natural stopping point for direct DM searches? Is there a technique or motivation to go beyond the neutrino floor?

CF6) Suppose direct experiments using one target are significantly more sensitive to σ_{SI}. Is there a rationale for supporting non-leading targets?

CF7) How important is it to carry out direct searches with different nuclei versus having multiple same-material detectors as cross checks?

CF8+CF9) How does one convincingly demonstrate that the low mass WIMP detection efficiency is well-understood? How can the conflicting results at low WIMP mass be resolved? What is the next step?

CF10) What can we learn about dark matter from direct detection? How important is directional technology?

CF11) Can dark matter be convincingly discovered by indirect searches given astrophysical and propagation uncertainties?

CF12) How does one demonstrate that the backgrounds to indirect searches are under control?

CF13+14)What are the target ranges for axion searches and how are they motivated? What systematics affect interpretation of axion searches?

CF15) What are the most promising techniques to extend searches for non-WIMP dark matter?

CF16) Can astrophysics reveal specific properties of dark matter particles, e.g. self-interactions or primordial velocities?

CF17) Is CDM in good agreement with structure at all scales? Can baryonic astrophysics rectify any discrepancies?

CF18) What would it take to convince ourselves of a discovery of one, more than one, all of, or a fake signal of dark matter?

CF19+20) What is the full set of measurements one is likely to make of dark matter from cosmic frontier probes alone?

CF21) How do we discover that there is more than one type of dark matter particle?

CF22) Would inputs from particle physics (such as the mass) help with indirect searches? What accuracy is needed?

CF23) What are the constraints on theories in which dark matter has no SM interactions stronger than gravitational? In such case, are there prospects for discovering its particle nature?

CF24) It has turned out that missing transverse energy is a very effective signature for discovery at the LHC. So, have we ruled out WIMP dark matter with mass below 500 GeV?