Dark Matter & Particle Physics

Nicole Bell
The University of Melbourne

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

THE UNIVERSITY OF MELBOURNE

Outline

- ❖Introduction
- ❖WIMPs, ADM, etc.
- ❖Indirect detection
- ❖Direct detection
- ❖Effective theories
  Collider DM production
- ❖Summary

Dark matter: the most concrete evidence there is new particle physics to be discovered.

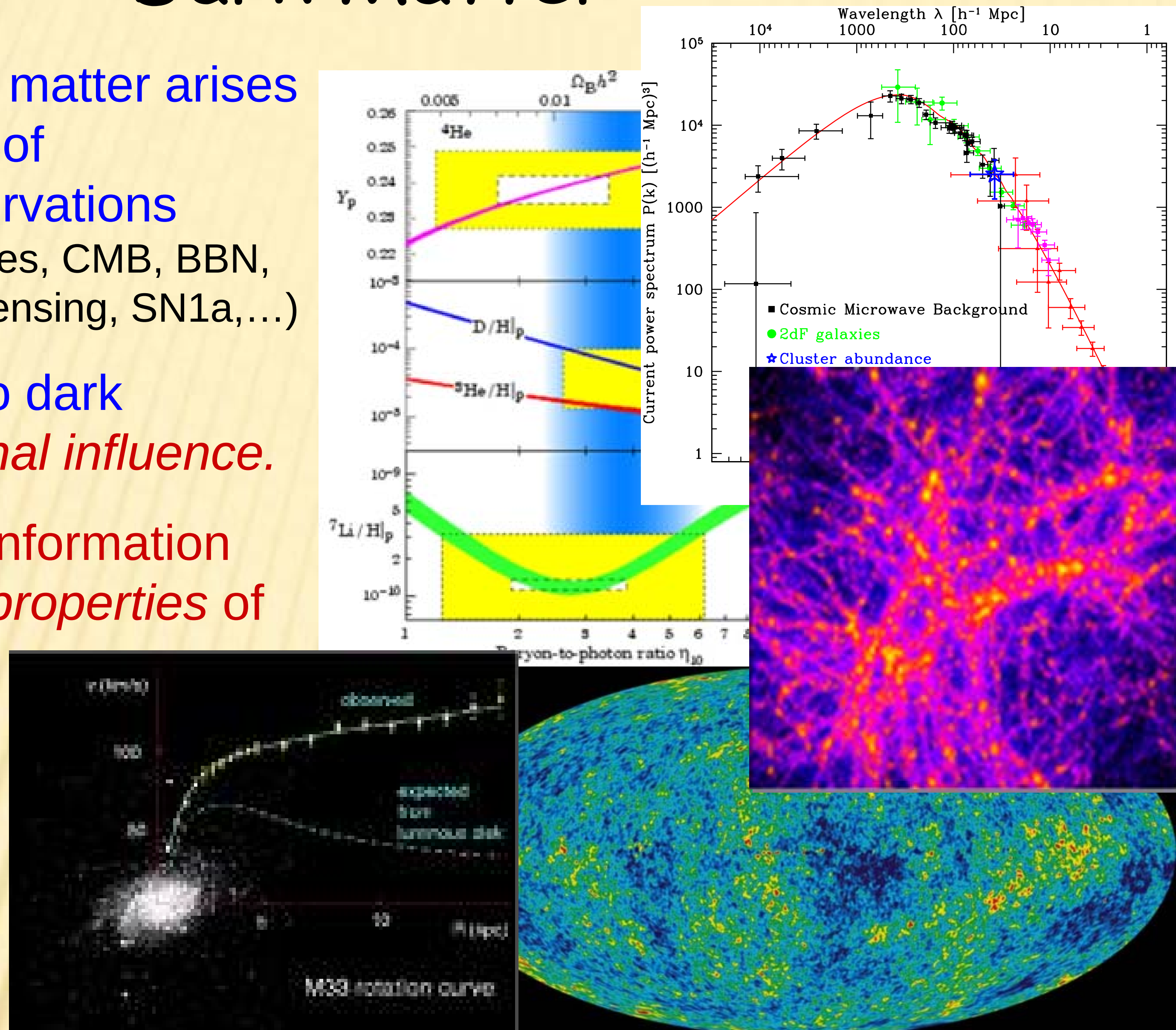
i.e. Very different to the various new physics motivated by theoretical prejudices such as naturalness, hierarchy, etc.

Dark Matter

- Evidence for dark matter arises from a wide range of astrophysical observations
(→galaxy rotation curves, CMB, BBN, large scale structure, lensing, SN1a,…)

- All are sensitive to dark matter's *gravitational influence.*

- As yet, very little information about the *particle properties* of dark matter.



No shortage of DM candidates…

Axions, WIMPS, Neutralinos, Gravitinos, Axinos, Sneutrinos, Kaluza-Klein particles, Heavy Fourth Generation Neutrinos, Mirror particles, superWIMPs, WIMPzillas, Sterile Neutrinos, Light Scalars, Q-Balls, Brane World Dark Matter, Primordial Black Holes, Asymmetric Dark Matter….

….or, perhaps most likely, something we haven't thought of yet….

DM candidates

- Thermal DM (i.e. a WIMP)
  → some theoretical motivation plus good chance of detection

- Asymmetric Dark Matter
  → Motivated by $\Omega_{DM} \approx 5\Omega_b$

- Axions
  → motivated by QCD strong CP

- DM with only gravitational interactions
  →Nightmare scenario!

Thermal Relic Dark Matter

(1) Assume dark matter initially in thermal equilib.

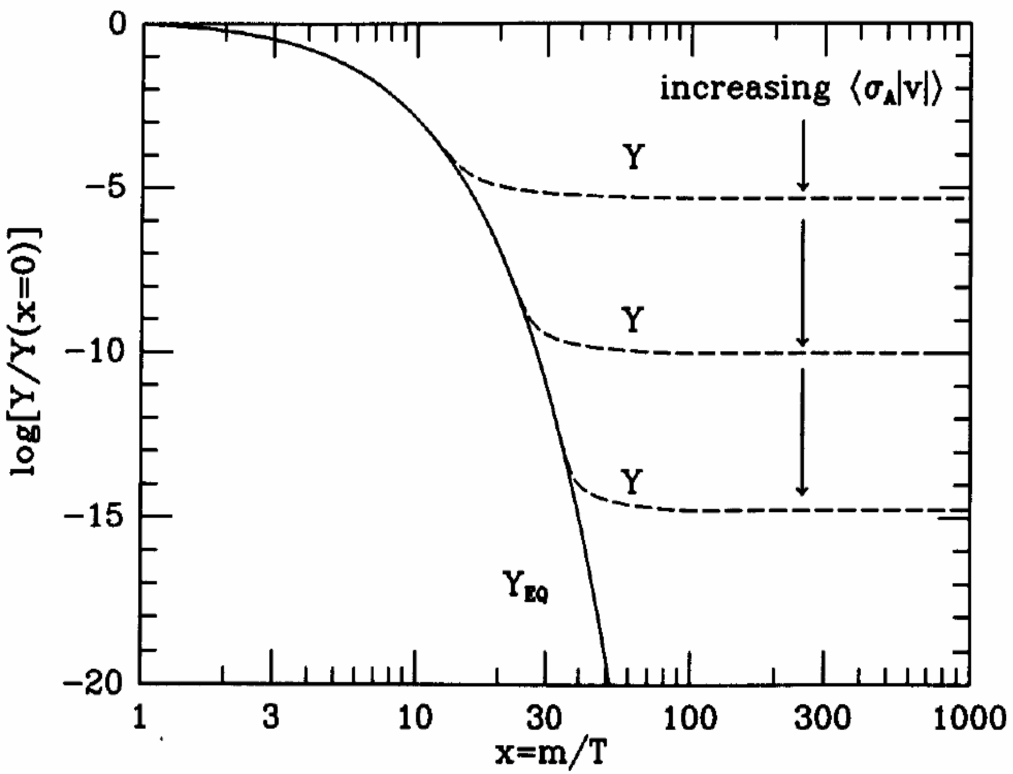
$$\chi\chi \leftrightarrow f\,\bar{f}$$

(2) Universe cools and the non-relativistic DM is Boltzmann suppressed:

$$N \sim (mT)^{3/2} e^{-m/T}$$

(3)"Freeze out" at m/T~20. Relic density fixed:

$$N = const. \propto \frac{1}{<\sigma v>}$$



→ Final dark matter abundance proportional to inverse of the annihilation cross section.

"WIMP Miracle"

- The thermal relic picture sets the "natural scale" for the dark matter annihilation cross section:
- $\Omega_{DM} \sim 0.2$ implies $\langle \sigma_A v \rangle \sim 2 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
- Suggests electroweak-scale parameters since:

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{(100\,\mathrm{GeV})^2} \sim 10^{-26}\ \mathrm{cm}^3 \mathrm{s}^{-1}$$

→ 1)A compelling argument, given we have other reason to expect new physics at the GeV-TeV scale.

→ 2) Realistic prospects of detection:
- annihilation signals (indirect detection)
- nuclear recoils (direct detection)
- monojets+missing ET (colliders)

"WIMPless Miracle" ?

❖ Actually, thermal freezeout does not single out the electroweak scale. The relic density simply sets

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

→ we can choose any m or g, provided we fix the ratio

Note: Partial wave unitarity bounds the cross section

$$(\sigma_J)_{\max} v_{\rm rel} \approx \frac{4\pi(2J+1)}{m_X^2 v_{\rm rel}}$$

→ rules out thermal relic DM for very large masses.

$$\langle \sigma v \rangle = \langle \sigma v \rangle_{thermal} \quad \Rightarrow \quad m_\chi < 300\,\mathrm{TeV}$$

Griest & Kamionkowski

Asymmetric Dark Matter

This is an idea connecting:
- Relic DM abundance
- Baryon-antibaryon asymmetry

$$\Omega_{DM} \approx 5\Omega_b$$

Assume DM density set by a matter anti-matter asymmetry of the same size as the baryon asym.

then $n_{DM} \approx n_b$ (assuming complete asymmetry)

and $m_{DM} \approx 5 m_b \approx 5\,\mathrm{GeV}$

Asymmetric Dark Matter

Requirements:

- A mechanism to simultaneously create B(visible) and B(dark), or to communicate the asymmetry from one sector to the other.
- A sufficiently large DM annihilation cross section to annihilate the symmetric part (to leave only DM particles and no antiparticles).

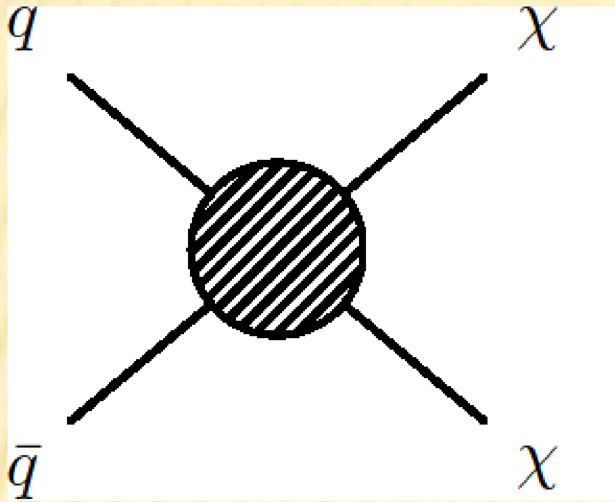
Implications:

- Light DM.
- No indirect detection (nothing to annihilate with)
- The physics that connects the dark and visible sectors may or may not be at an experimentally accessible energy scale.
- Large annihilation cross section means either sizeable couplings with SM particles, or else new light degrees of freedom.

Detecting Dark Matter

production (collider searches)

→

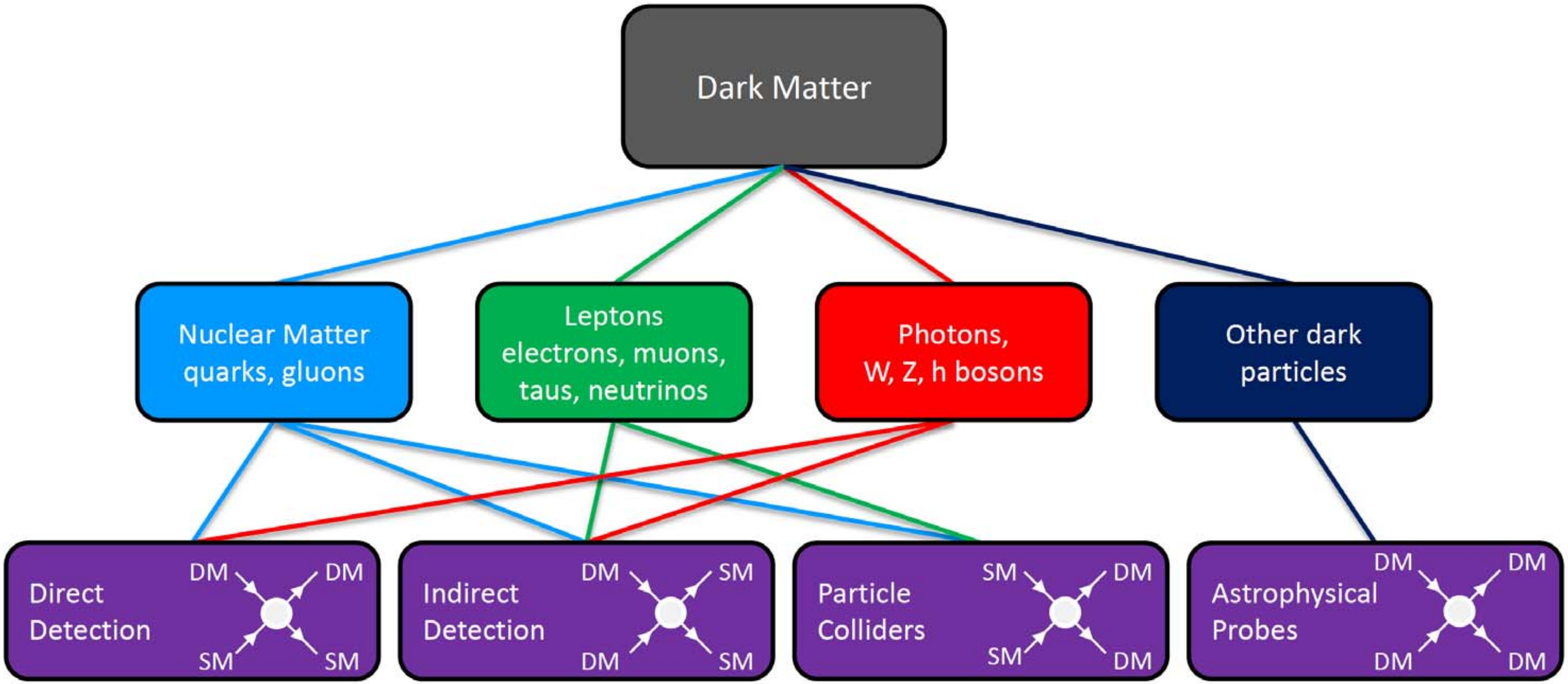


↓ scattering (direct detection)

←

annihilation (indirect detection)

Complementary ways to probe (non-gravitational) DM interactions



Dark Matter Self Interactions

❖ Dark matter should not strongly self interact.
- The Bullet Cluster
- Halo shapes (self interactions would makes galaxies too spherical)

❖ But some amount of self interaction is usually expected. This is ok, and maybe even helpful.
- Helps to alleviate the CDM problem of too much structure on small scales. However, there are other solutions to this problem, including warm dark matter, decaying dark matter, …

Indirect Detection

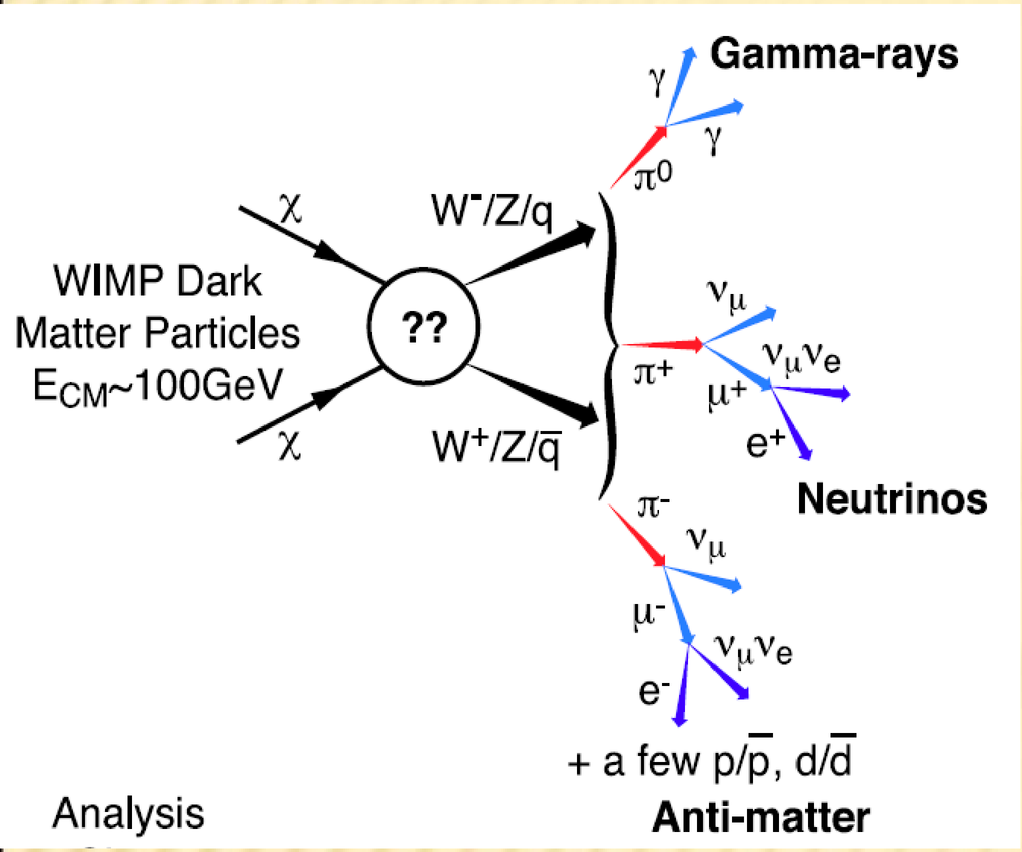
Search for fluxes of DM annihilation or decay products from regions where the DM density is high:

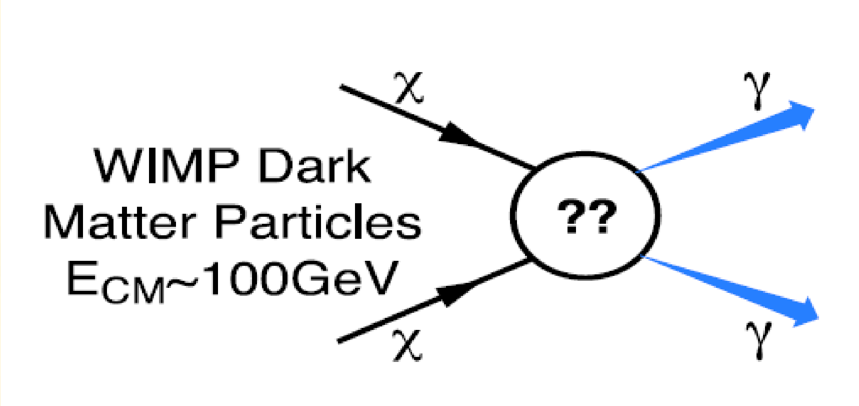
- Annihilation in our Galaxy or in nearby galaxies
→ Photons, antimatter, neutrinos

- Annihilations in galaxies throughout the Universe
→ cosmic diffuse fluxes of photons

- Annihilation in Sun/Earth
→ Neutrinos only

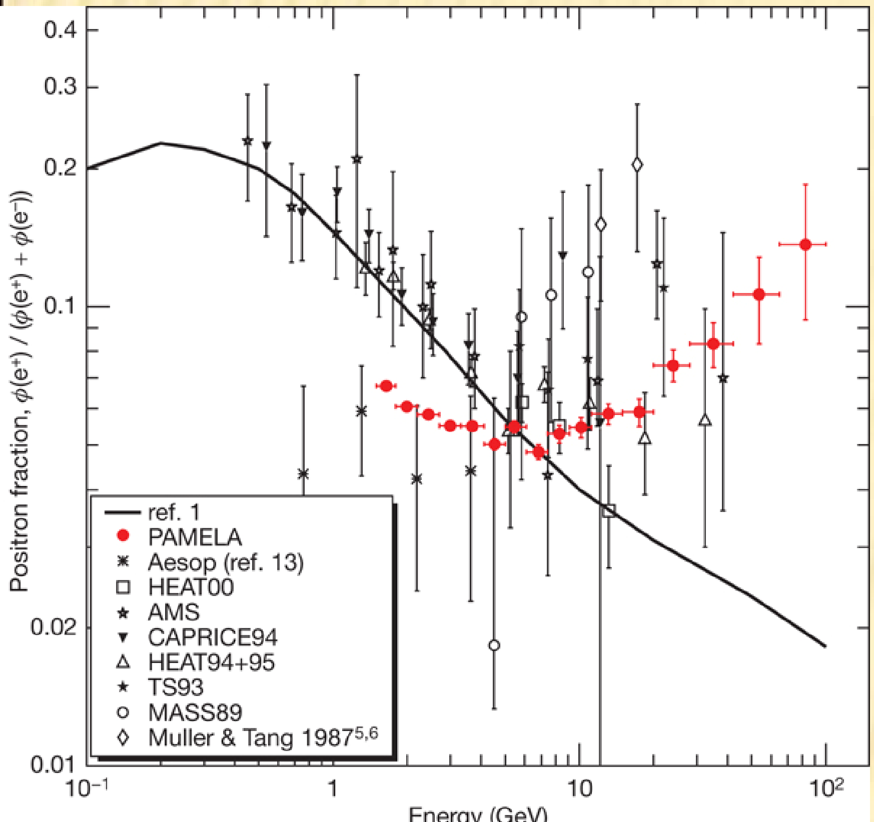
Indirect detection of DM annihilation

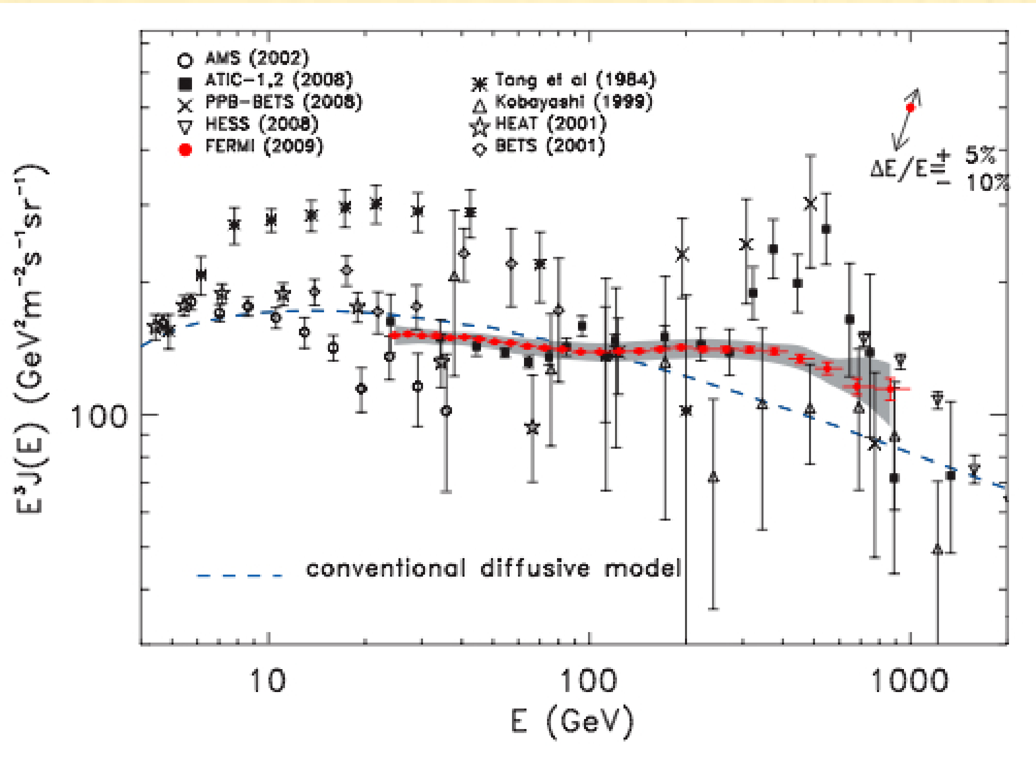




Annihilation to Antimatter

Positrons



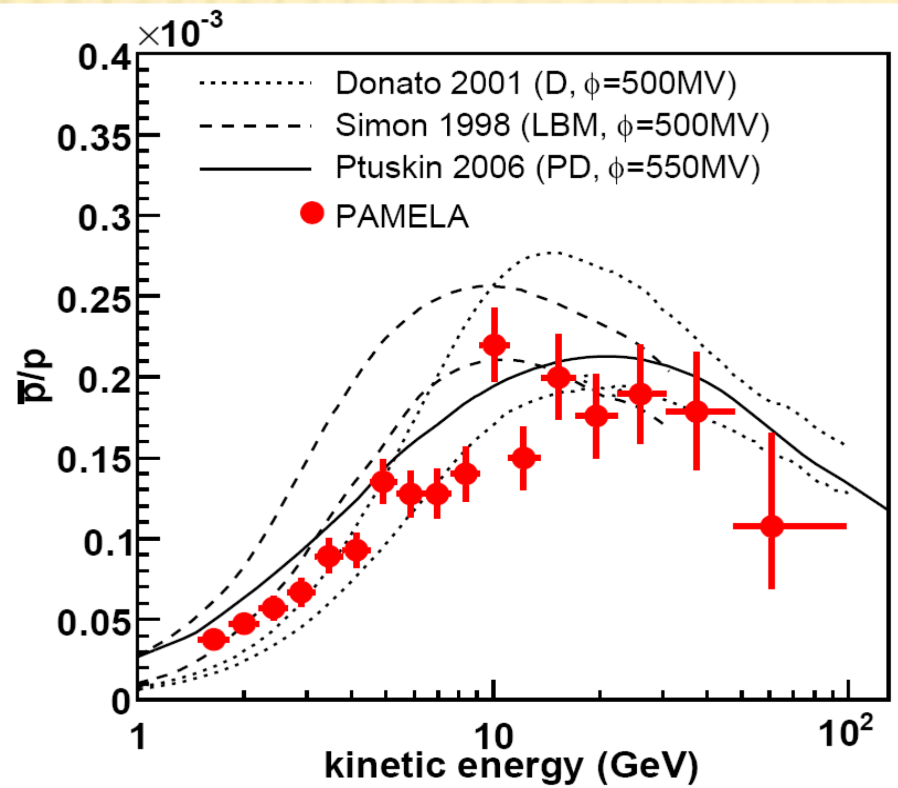


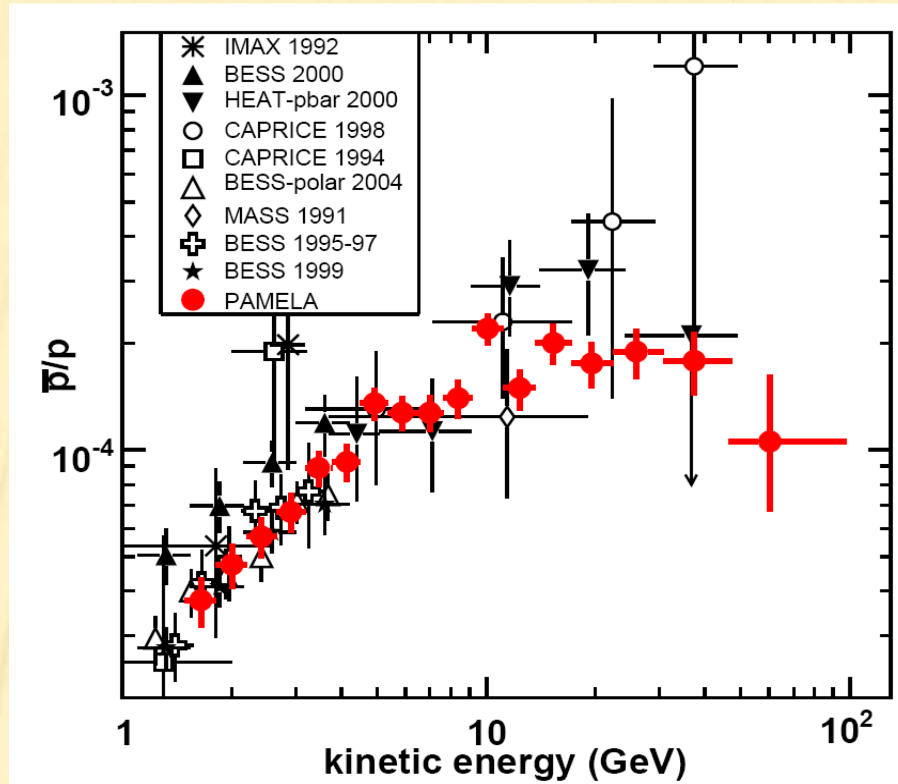
PAMELA e+
Nature 458, 607-609

Fermi e^++e^- excess
Phys. Rev. Lett. 102, 181101

Annihilation to Antimatter

Antiprotons

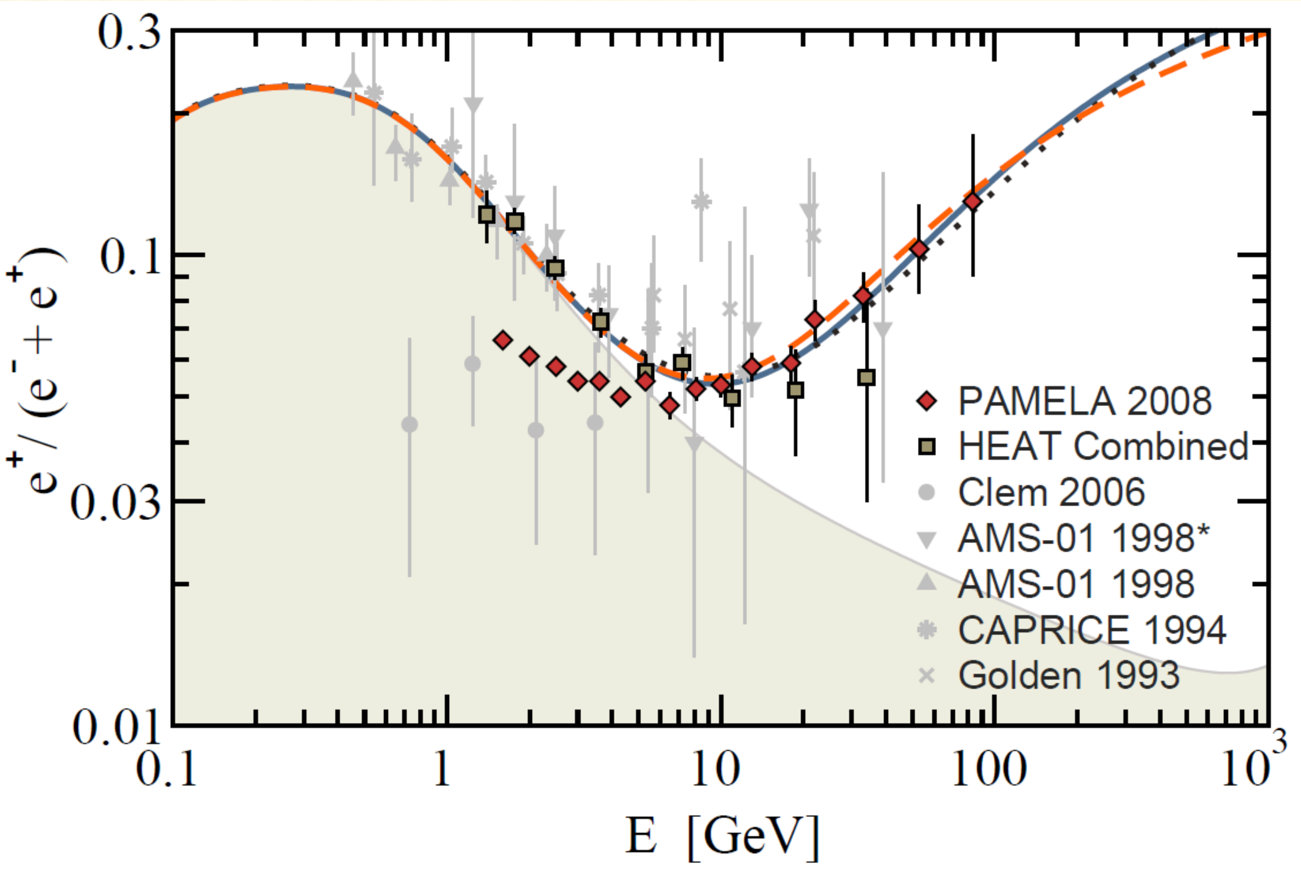




Antiproton data consistent with theory expectation (for secondary production of antiprotons via cosmic ray propagation in the Galaxy).

Pulsars?

Possible contribution from Geminga pulsar to positron fraction:



Yuksel, Kistler and Stanev, PRL 2009

Verdict on the positron excess

❖Probably not dark matter. However, it motivated people to think more deeply about possible DM scenarios.

e.g. SUSY neutralinos did not provide a good fit to PAMELA/Fermi.
- Difficult to have large enough cross section (> than thermal relic)
- Difficult to have enough e+, without too many photons, antiprotons

❖ Models with light mediators were investigated.
Heavy mediators (contact interactions) give annihilation cross sections:

$$\langle \sigma v \rangle \propto v^n, \qquad n = 0,2,...$$

Light mediators: the cross section becomes Coulomb-like, with

$$\langle \sigma v \rangle \propto v^{-1}$$

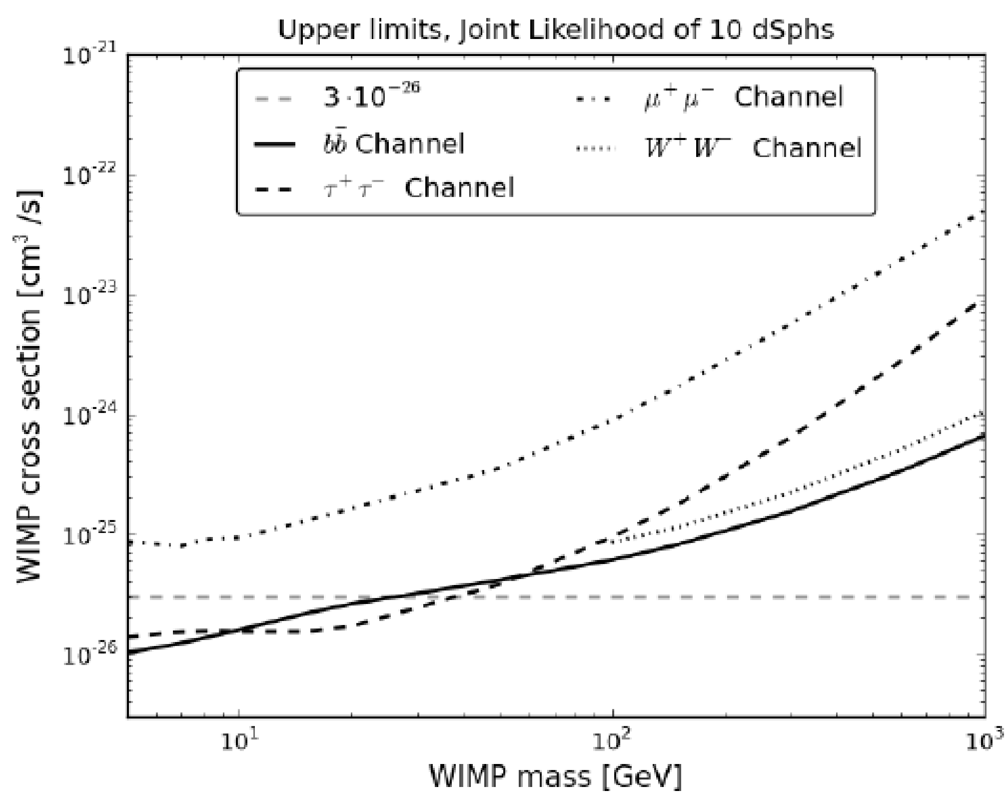
resulting in "Sommerfeld enhancement" to the cross section at low velocities.

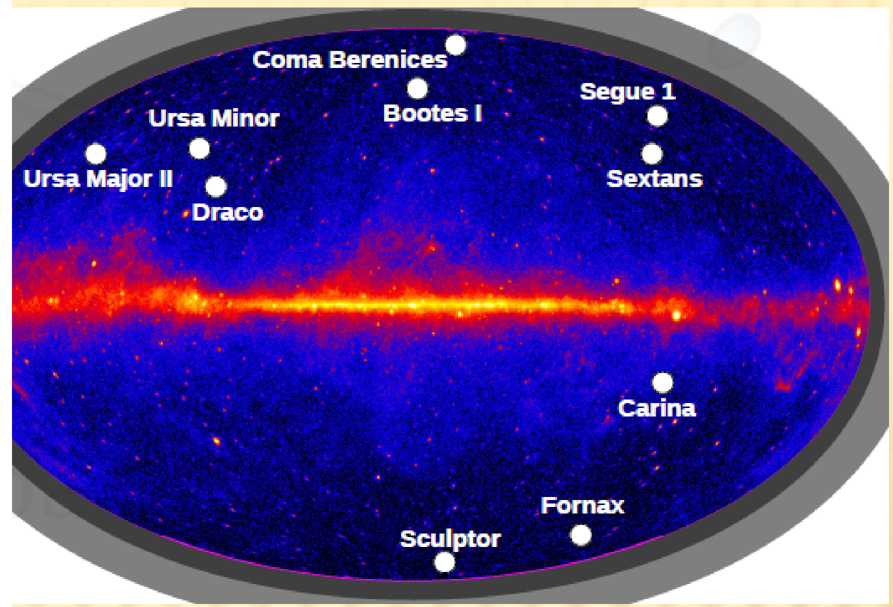
Annihilation - gamma rays
Limits from Fermi-LAT

Fermi Gamma-ray Space Telescope

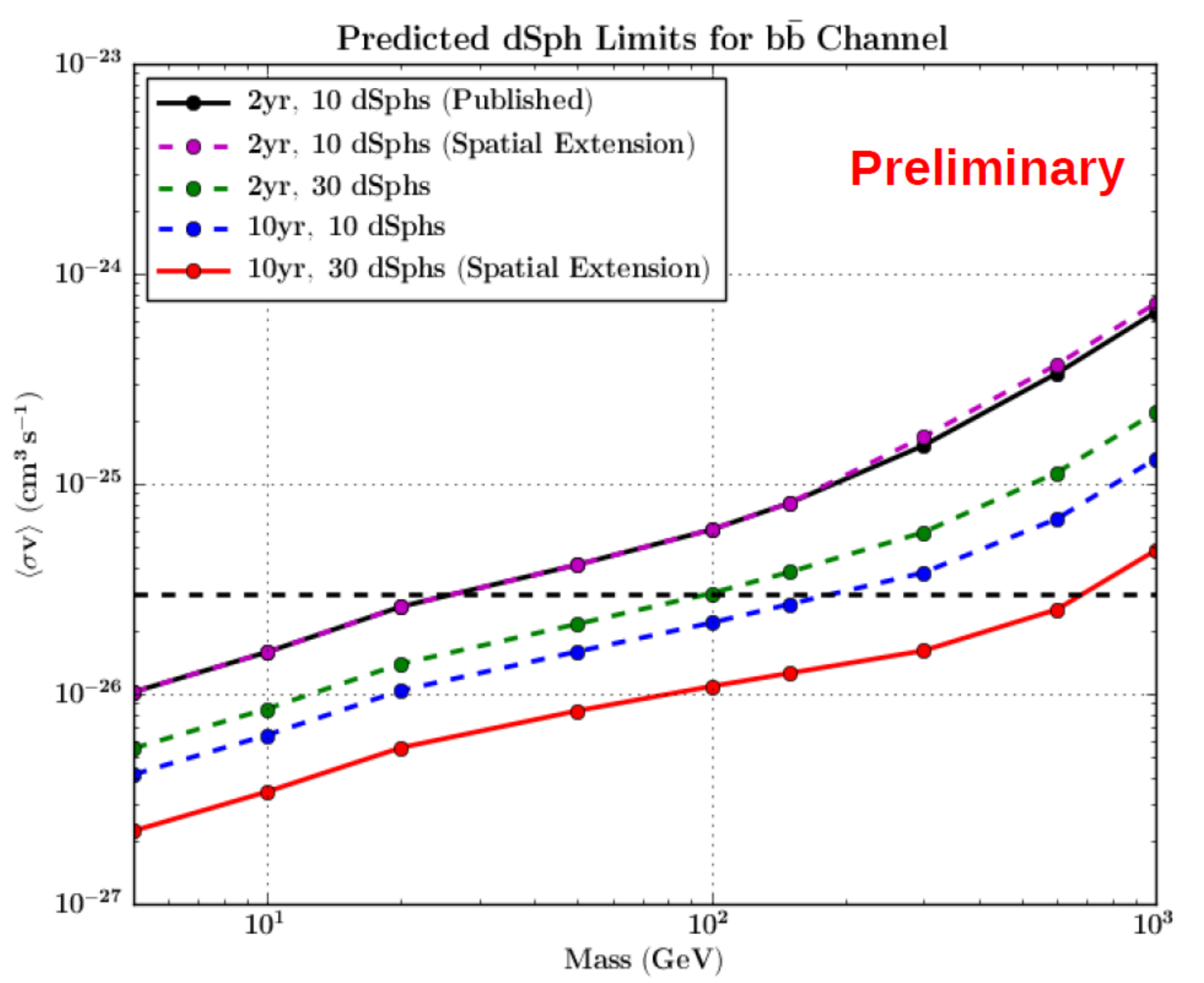
Dwarf spheroidal galaxies

- ✔ dSphs are DM dominated systems (they have very high M/L ratios).
- ✔ Many dSphs are closer than 100 kpc to the Galactic Centre.
- ✔ Low background



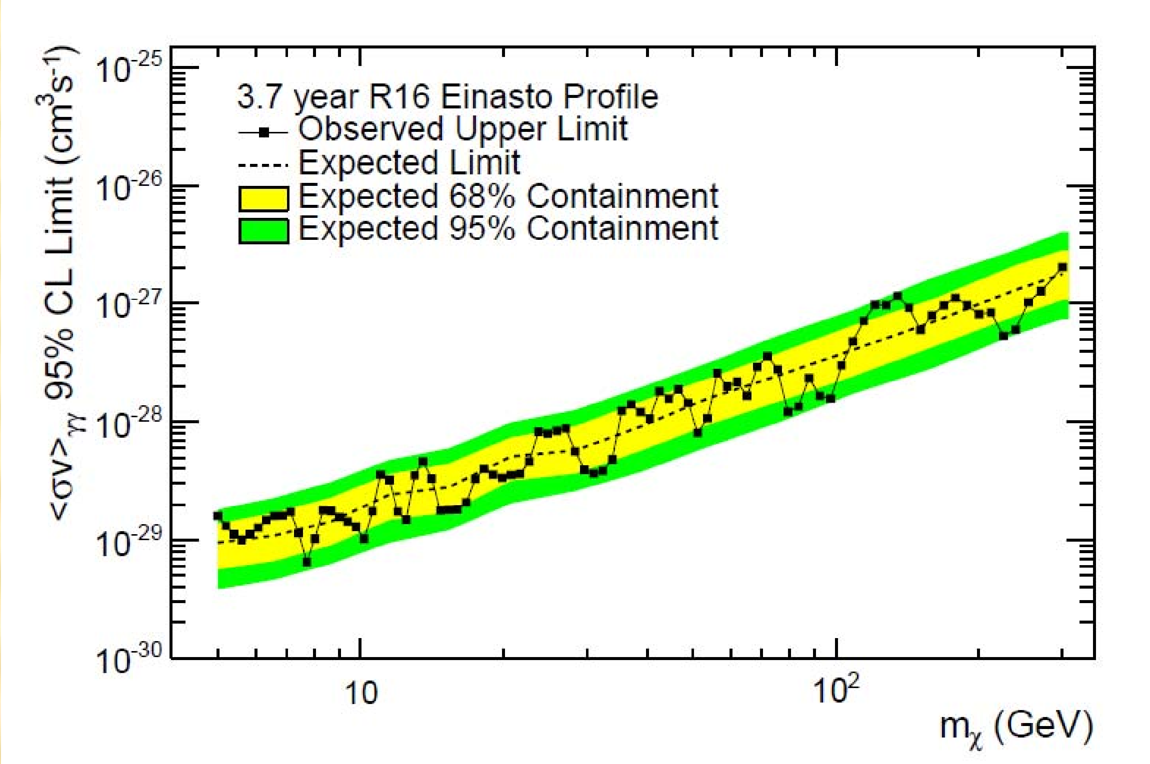


Future Fermi sensitivity



Gamma ray lines – the smoking gun…

❖ Fermi Gamma ray line search from 5 – 300 GeV

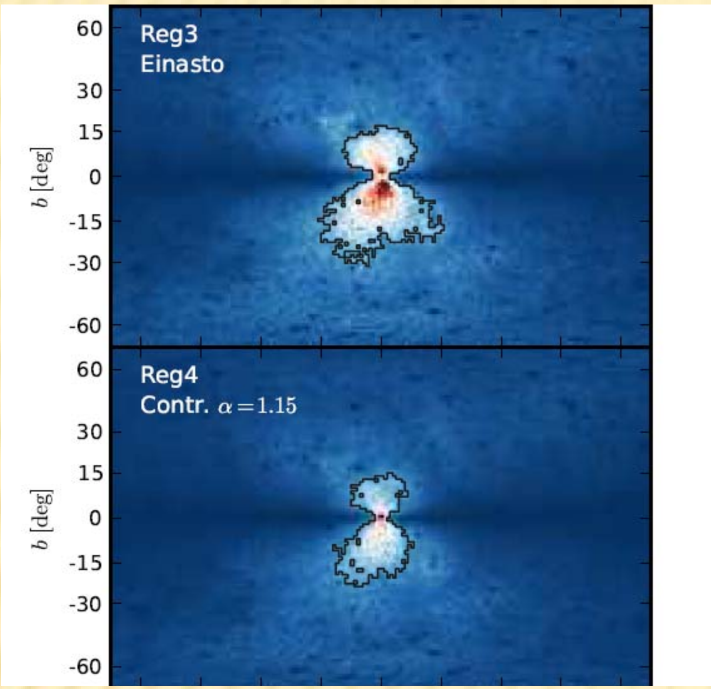


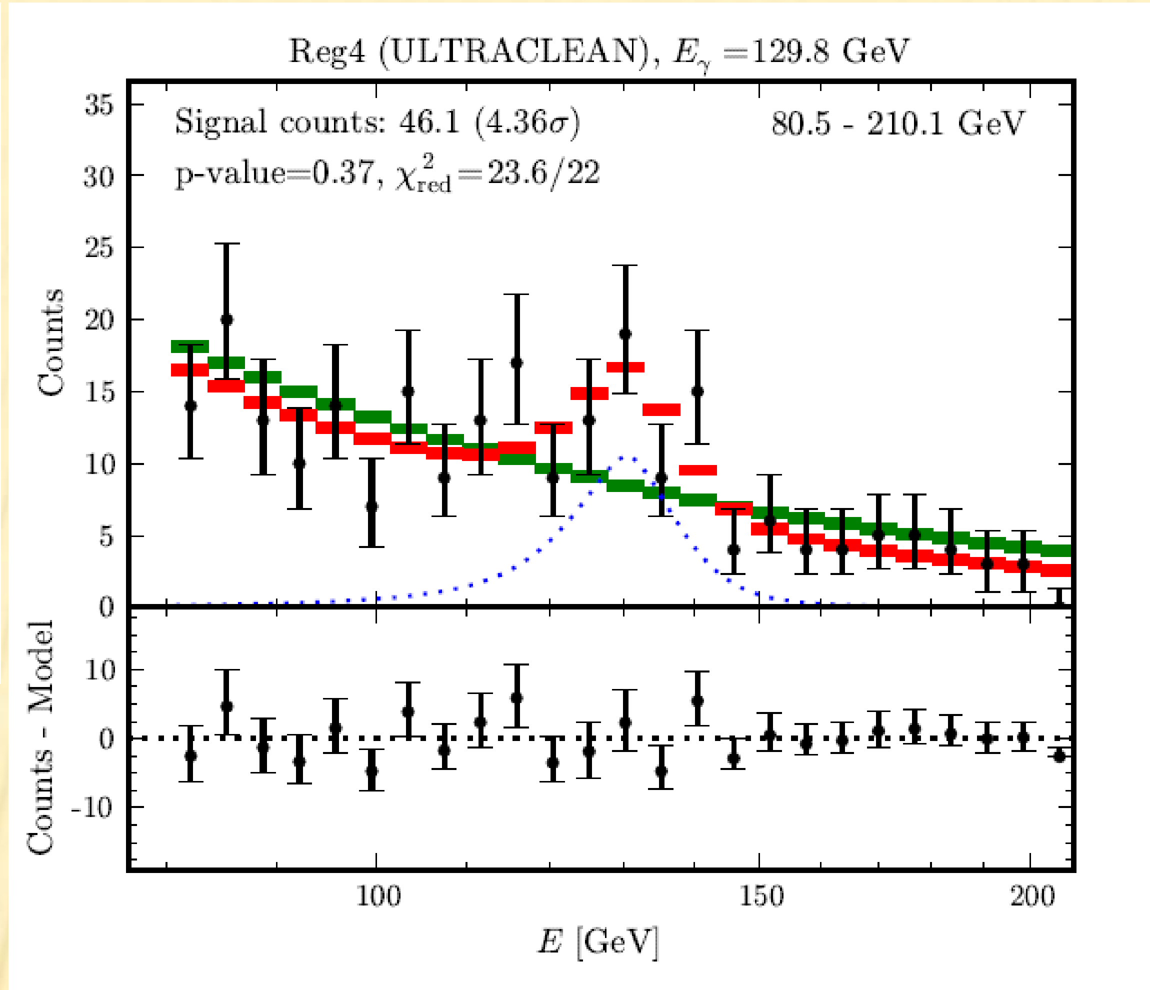
Fermi 1305.5597

No globally significant line signal

→ Translates to cross section limits an order of magnitude or more weaker than expected for a thermal relic WIMP.

Fermi gamma ray line at ~ 130 GeV?

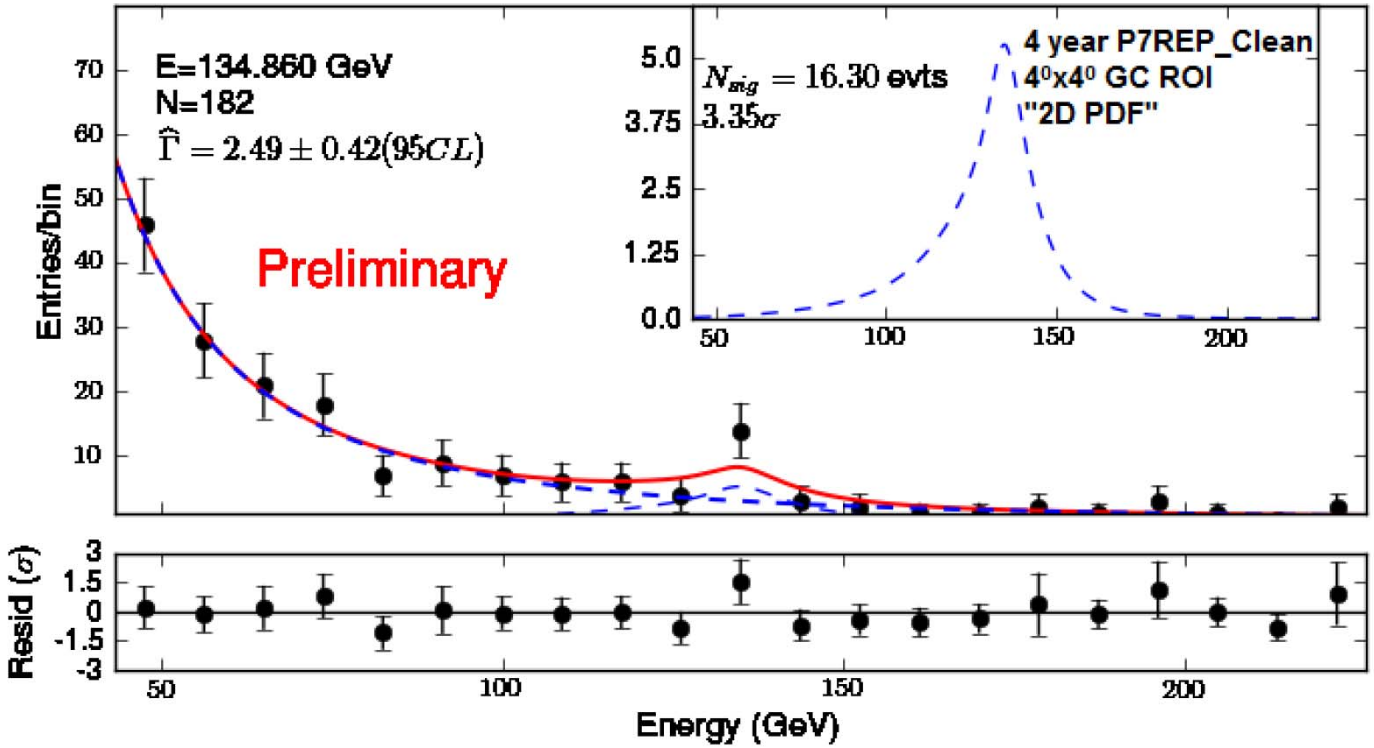




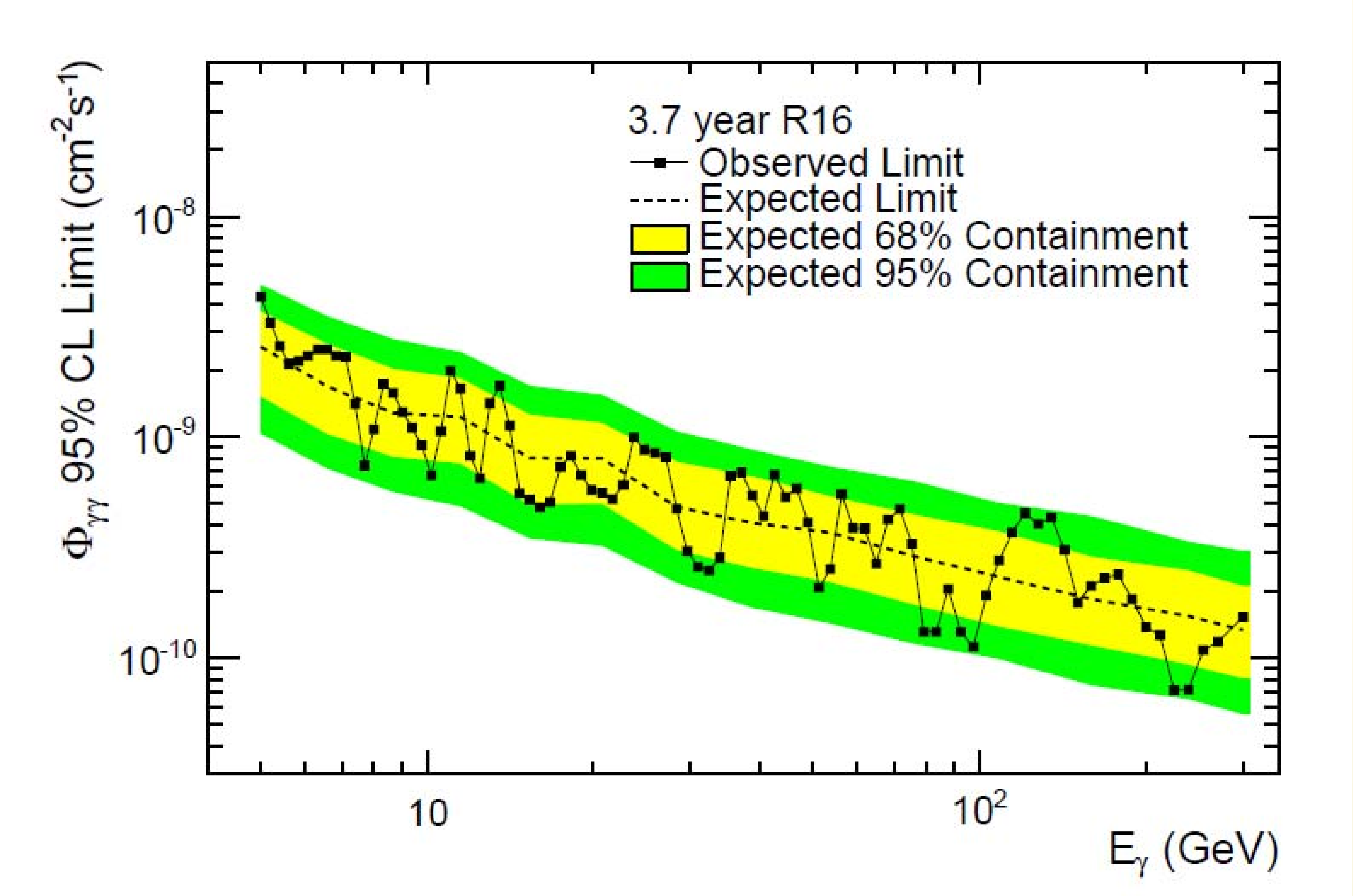
Weniger 1204.2797, and several other groups.

A surprise, because gamma ray lines should be loop suppressed, and thus subdominant to annihilation processes producing continuum gammas.

Fermi-LAT Team Line Search at 135 GeV



- 4.01σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 3.7 year reprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- **3.35σ (local) 2D fit at 135 GeV with 3.7 year reprocessed data**
  - **Look in 4°x4°GC ROI, Use 2D PDF (P_E in data)**
  - **<2σ global significance after trials factor**

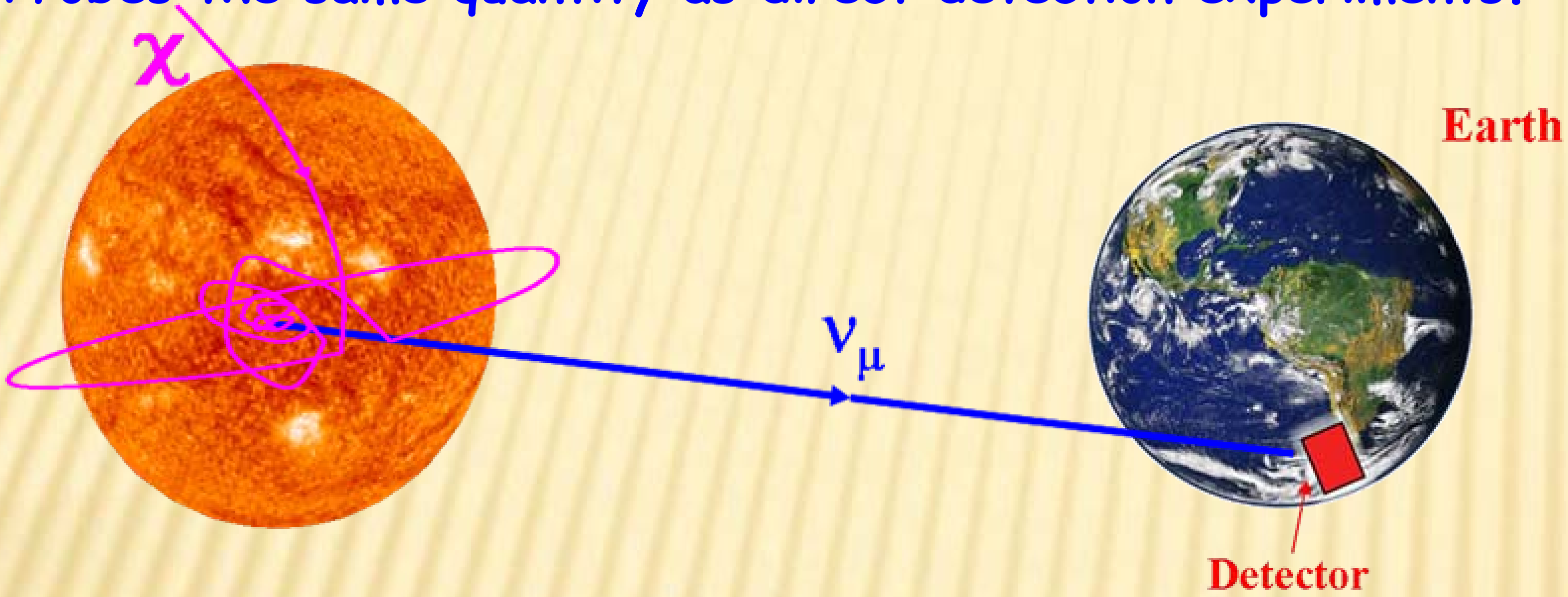


Fermi 1305.5597

Solar WIMPS

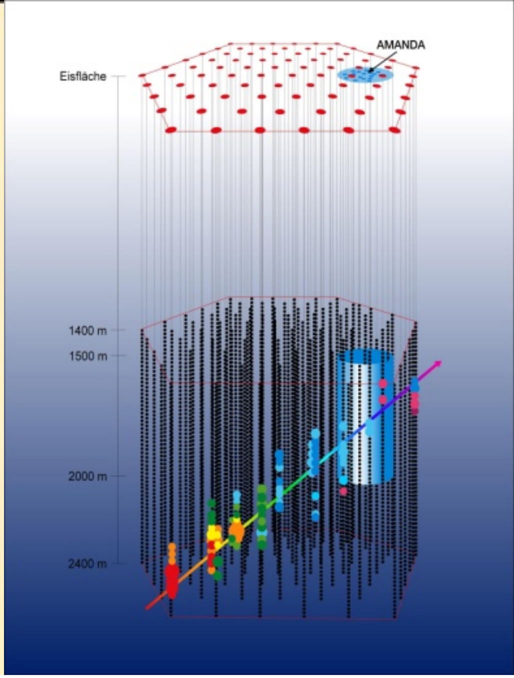
- Dark matter accumulates in the centre of Sun (and Earth)
- Neutrinos are the only annihilation products able to escape
- High energy neutrinos detected by IceCube, SuperK.
- Capture rate and (if in equilibrium) the annihilation rate controlled by WIMP-nucleon scattering cross section
- Competitive limits for spin-dependent cross sections

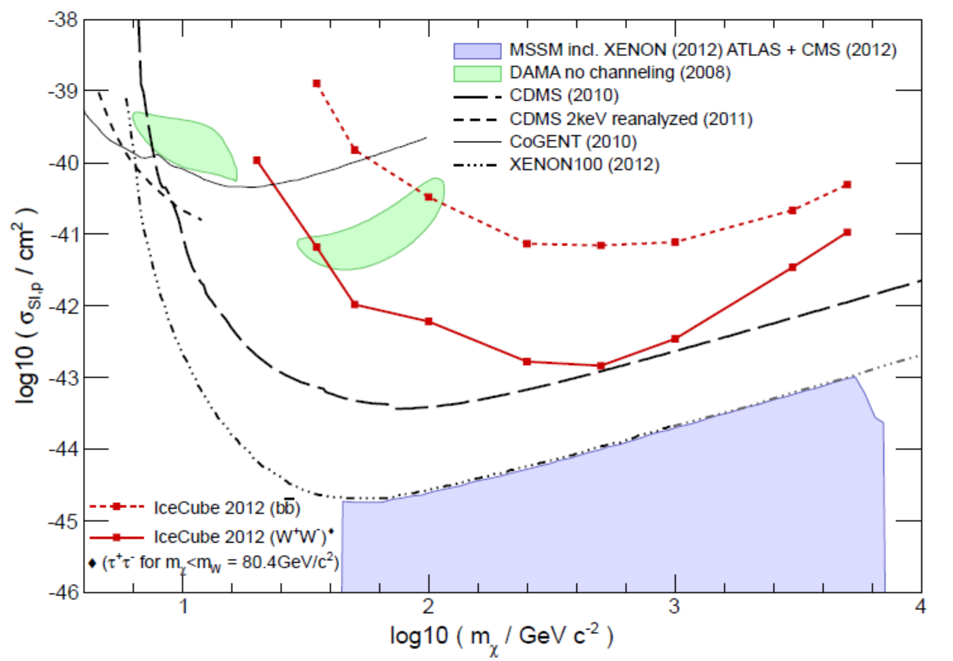
Probes the same quantity as direct detection experiments.

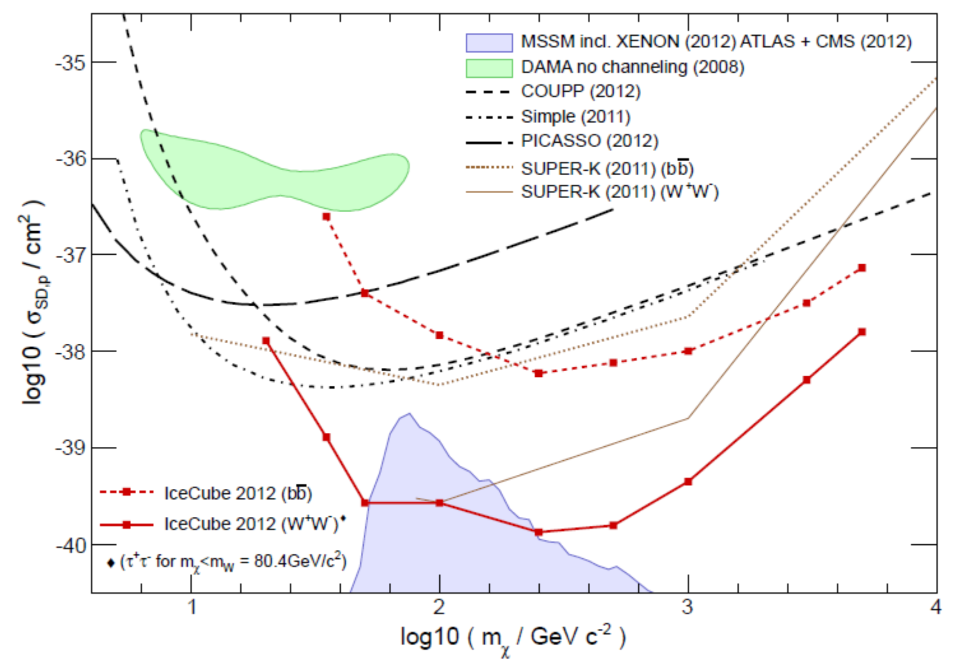


Solar WIMP limits

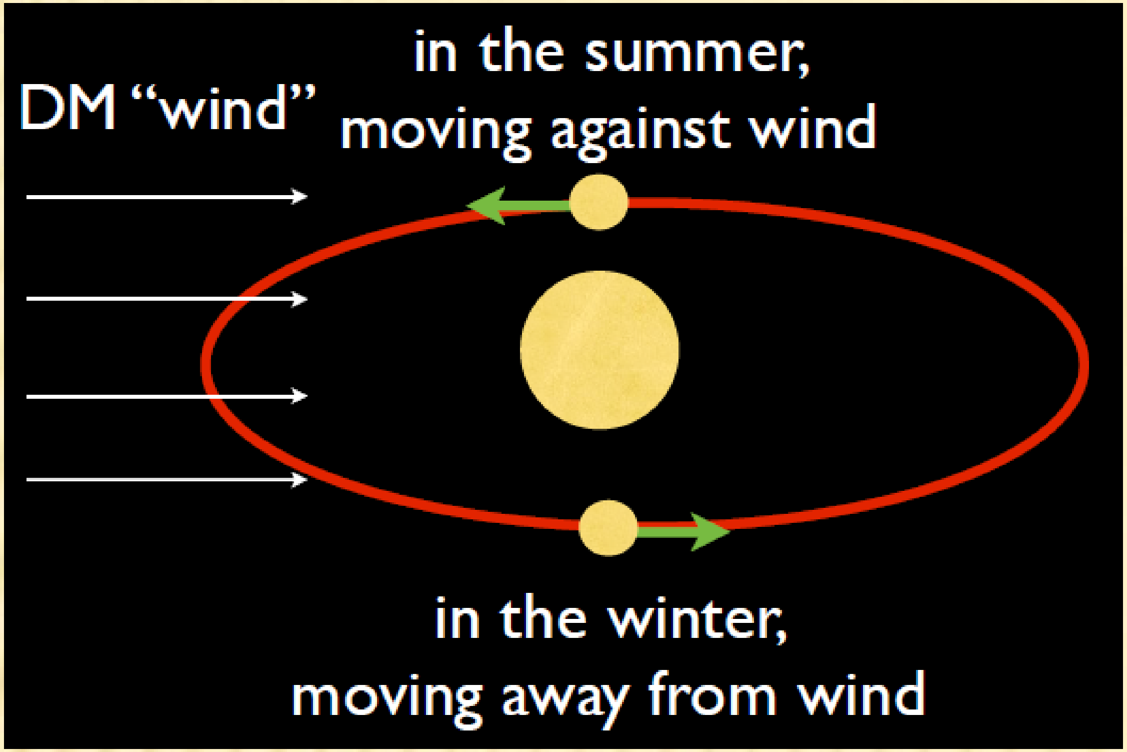
- limits depend on the assumed annihilation spectrum
- Solar limits are stronger than direct detection for spin-dep. interactions







Direct Detection



Direct Detection

Differential rate for wimp scattering:

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\min}}^{v_{\max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}$$

where: Mw = DM mass
vmin ← detection energy threshold
vmax ← galactic escape velocity

Ball park numbers:

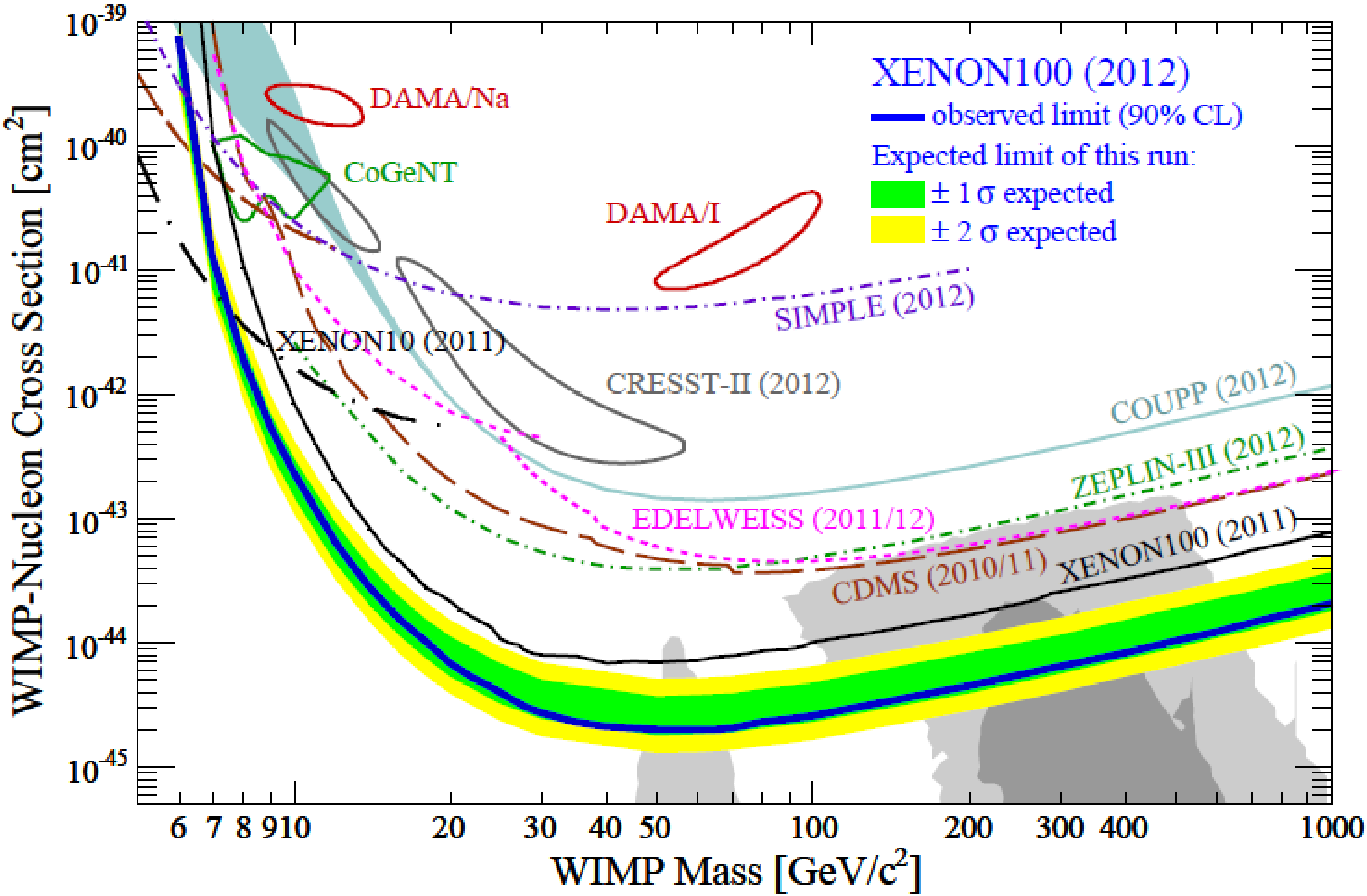
$$R \sim 0.13\ \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}}\right]$$

$$E_R = \frac{p^2}{2m_N} = \frac{m_{\rm r}^2 v^2}{m_N}(1-\cos\theta) \sim 30\ \text{keV}$$

Some backgrounds:

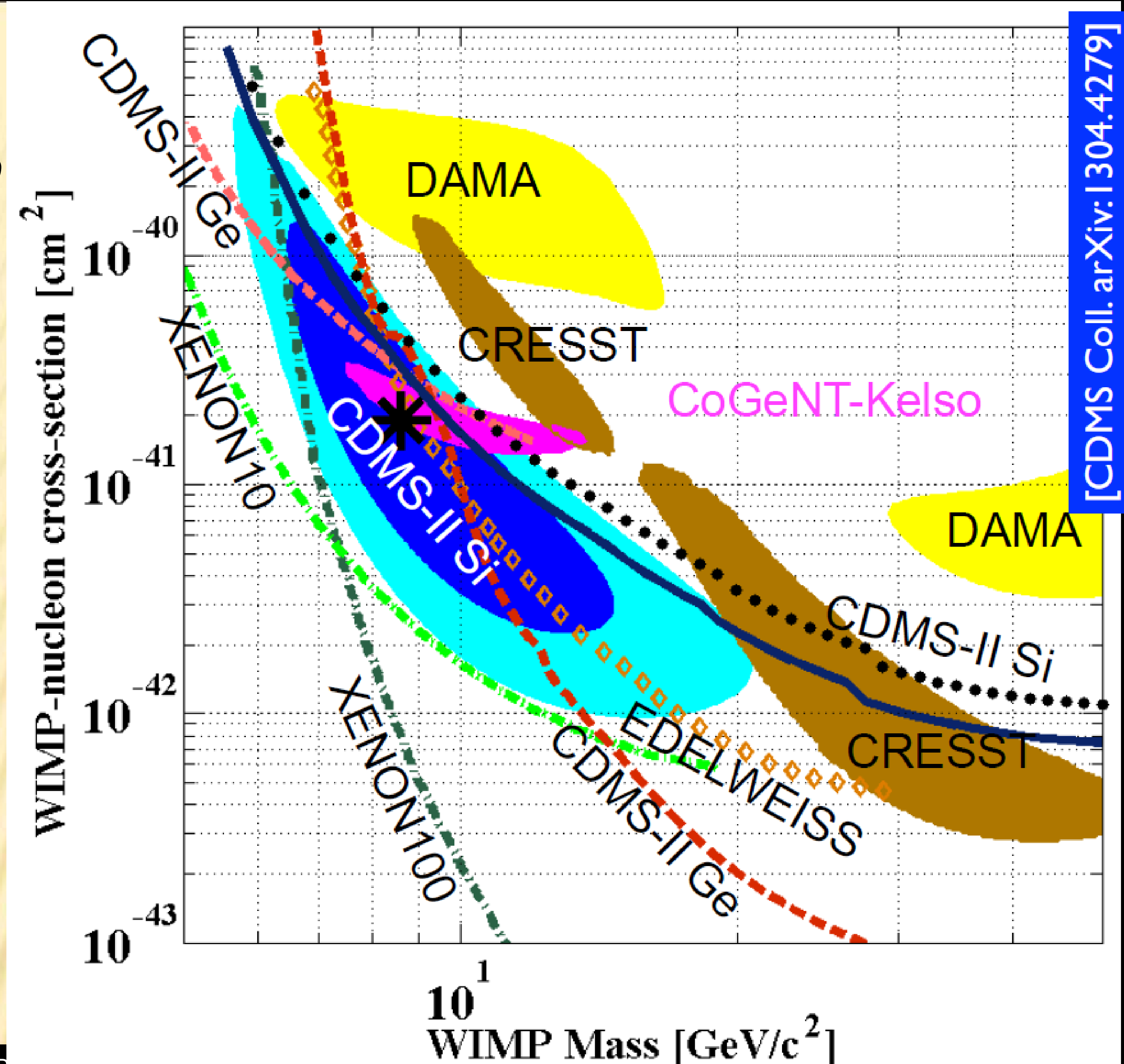
- Neutrons produced by cosmic ray muon interaction
- Neutrons from radioactivity of detector
- Neutrinos! At cross sections of order 10^{-48} cm^2 and below, solar and atmospheric neutrinos become an irreducible background!

Signals and limits



CDMS(Si)

arXiv:1304.4279



Xenon and Isospin

$$\sigma_{SI} = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

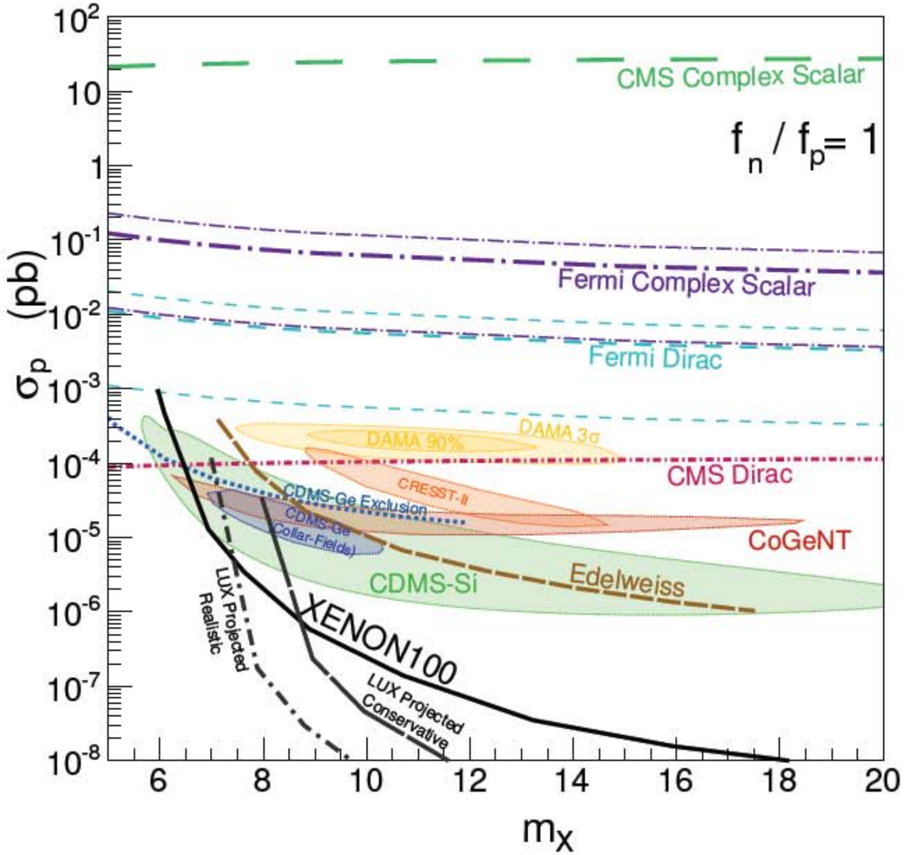
f_p and f_n parameterize the strength of the DM coupling to protons and neutrons.

$f_p \neq f_n$ isospin violating

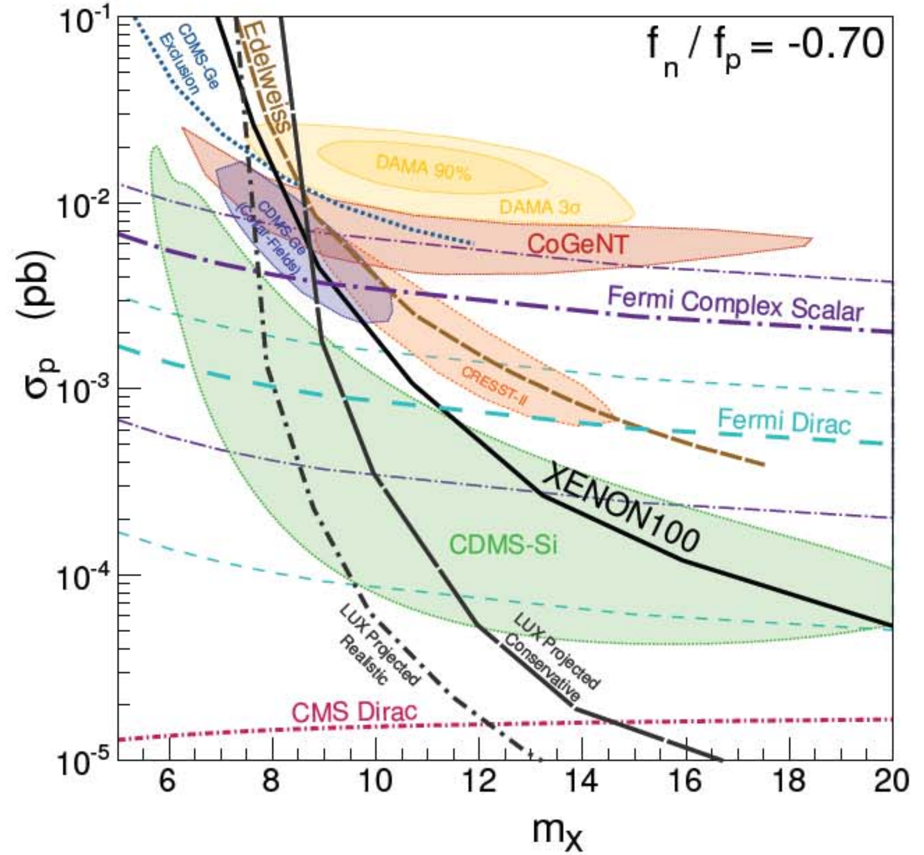
Isospin violation may help reconcile the XENON null results with the signals seen in CoGENT/CDMS(SI).

Need to choose f_p & f_n such that σ (Xe) ≈ 0.
Note: complete cancellation impossible as detectors contain multiple Xe isotopes.

Isospin conserving



Isospin violating



Feng et al, 1306.2315

Effective operators

Collider and direct detection bounds typically use EFT operators:

$$L_{Eff} = G_\chi \ \bar{\chi}\Gamma_\chi\chi \ \bar{q}\Gamma_q q$$

$$\Gamma_{\chi,q} \in \{1, \gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}.$$

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Advantages:
- Generic description
- Valid for direct detection where momentum transfer is very small

Disadvantages:
-EFT description can break down at colliders where q^2 is large.

Direct detection:

$Q^2 \sim (30 \text{ MeV})^2$

EFT description should be valid, unless extremely light particles

$$\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$$

Colliders:

$Q^2 \sim (p_T)^2$

EFT description breaks down, at least for some parameters.

$$\sigma(pp \to \bar{\chi}\chi + X) \sim \frac{g_q^2 g_\chi^2}{(q^2 - M^2)^2 + \Gamma^2/4} E^2$$

When the mediator mass is small, colliders are at a disadvantage wrt direct detection, unless the mediator can be produced on shell (and the width is narrow).

EFT and collider bounds

❖EFT bounds can over-estimate constraints on a given model

e.g. Models with light mediators (except where $M_{mediator} > 2M_{DM}$, allowing the resonance where the mediator is produced on shell.)

❖EFT bounds can under-estimate constraints on a given model

e.g. If DM-SM interaction mediated by a new coloured particle, the EFT mono-jet bounds are often too conservative.

Also note: in many UV complete theories, there exists other dark sector particles at energy scales accessible to the LHC. Either particles with SM quantum numbers, or a Z′ gauge boson, see arXiv:1003.1912

Dark matter at the LHC

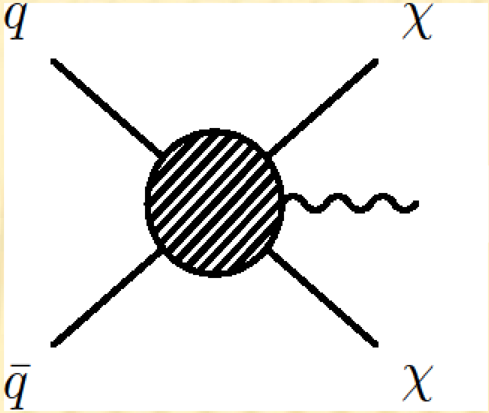
❖The dominant DM production process at the LHC may be:

$$\bar{q}q \to \chi\chi$$

But this process is invisible to the detectors (DM stable, weakly interacting)

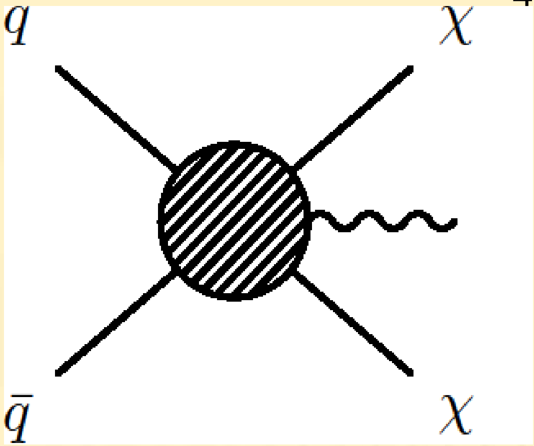
❖We need a visible particle in the final state, to recoil against some missing transverse energy,

e.g. $\bar{q}q \to \chi\chi + \text{gauge boson}$



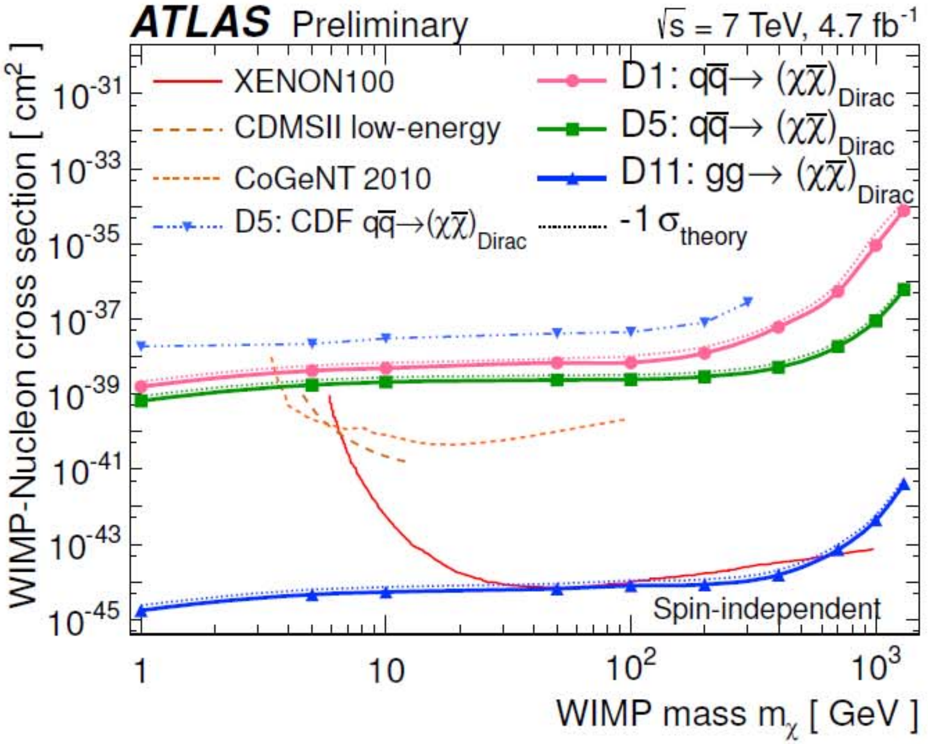
Dark matter visible as high pT state + missing ET

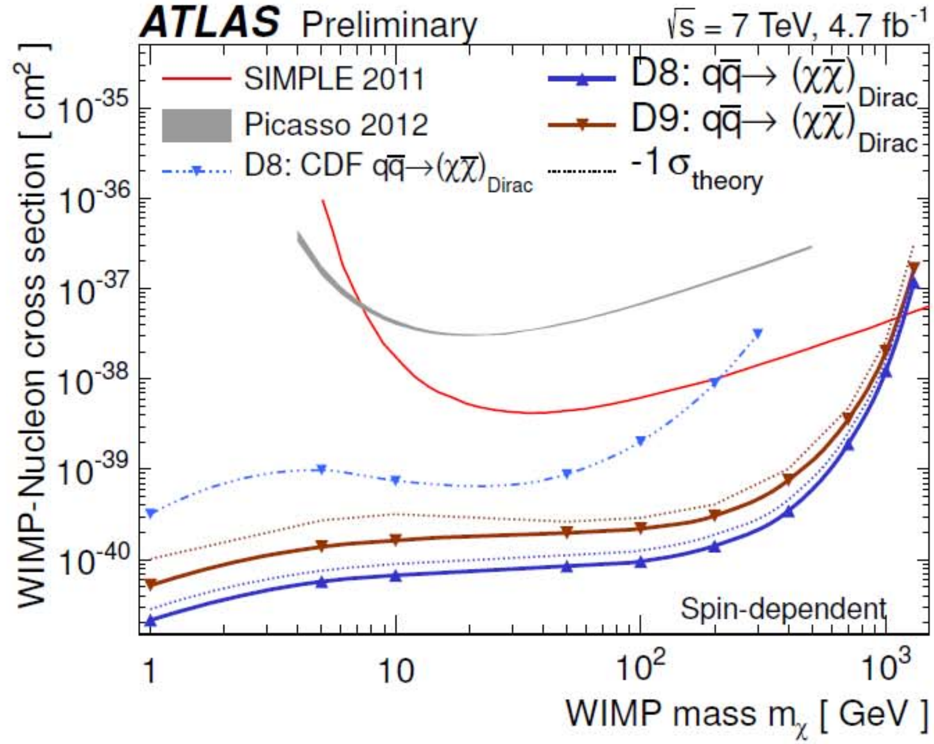
Dark matter at the LHC



- mono-jet (gluon)
  - high cross section & large backgrounds
- mono-photon
  - complementary to (but less constraining than) monojets
- mono-Z and mono-W
  - complementary to monojets;
  - cleaner signal
  - mono-W also has ability to distinguish different couplings to u and d type quarks

ATLAS mono-jet limits





ATLAS-CONF-2012-084

DM and missing E_T at colliders

If we see a MET signal that can be attributed to a new weakly interacting particle, we won't know if it is really the dark matter without other information.

❖We will know it is stable on a timescale of order nanoseconds (long enough to escape the detector). DM must be stable on a timescale of order 10 Gyr.

❖We won't know what contribution (if any) it makes to the relic density without, at least, measuring its couplings to all SM particles.

❖Cross correlating signals from direct and/or indirect detection will be important. E.g. Do we see a gamma ray line at the same energy as the DM mass inferred at the collider?

Conclusions / Outlook

- WIMPS…is this idea compelling, or are we searching under the lamp post? ADM…is the similarity of the dark and visible matter densities an important clue, or just a red herring?

- Indirect detection…various signals observed, but so far probably not dark matter.

- Direct detection…some exciting signals, some possible inconsistencies; no consensus yet whether we are really observing dark matter.

- Colliders…stay tuned to LHC monojet searches (and other exotics searches)

- EFT…useful, but limited in validity. Need more collider analyses of UV complete models