DARK MATTER

IN THE UNIVERSE

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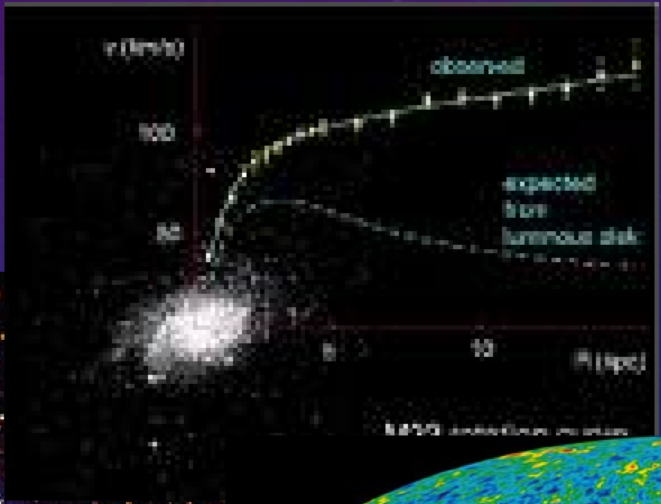
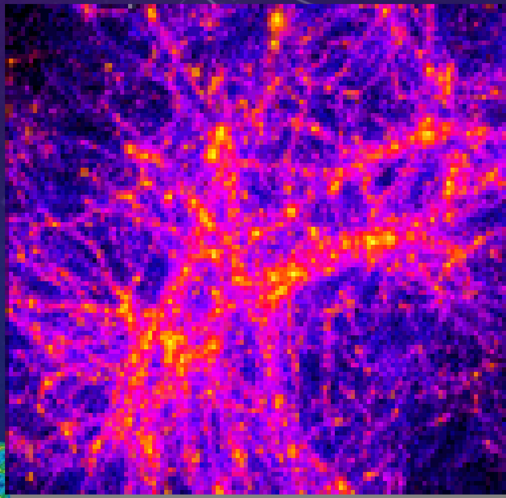
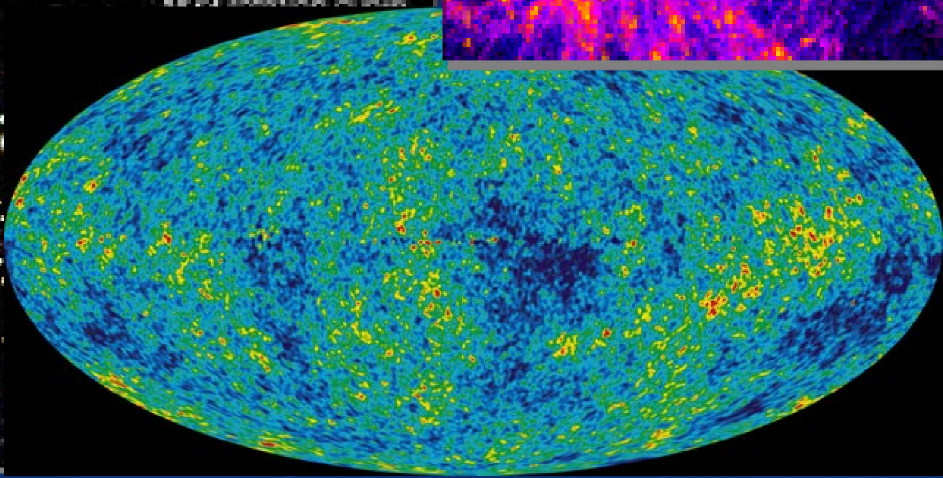
Outline

- Introduction
- WIMPs
- Indirect Detection
- Direct Detection
- Beyond WIMPs

Dark matter: compelling evidence there are new particles to be discovered







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….

Well-motivated DM candidates

- Thermal WIMPs (e.g. SUSY neutralinos)
  →well motivated theoretically & good detection prospects

- Axions
  → motivated by QCD strong CP

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

- Sterile neutrinos
  → new physics already required in neutrino sector

- DM with only gravitational interactions
  →Nightmare scenario!

Thermal Relic Dark Matter

(1) Dark matter initially in thermal equilib:

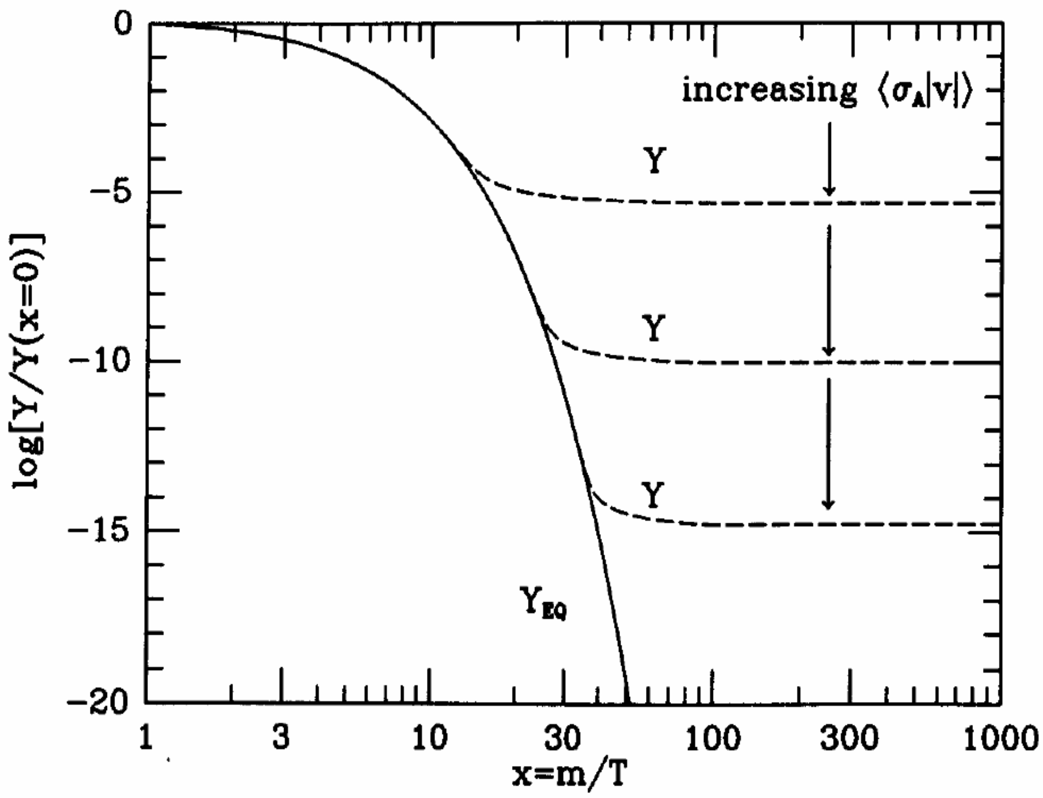
$$\chi\chi \leftrightarrow \bar{f}f$$

(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.

$$N = constant \propto \frac{1}{\langle \sigma v \rangle}$$



→ 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:

$$\Omega_{DM} \sim 0.2 \text{ implies } \langle \sigma v \rangle \sim 2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

- Suggests electroweak-scale parameters since:

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

→ 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

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

Feng & Kumar

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

Note: Partial wave unitarity bounds the cross section

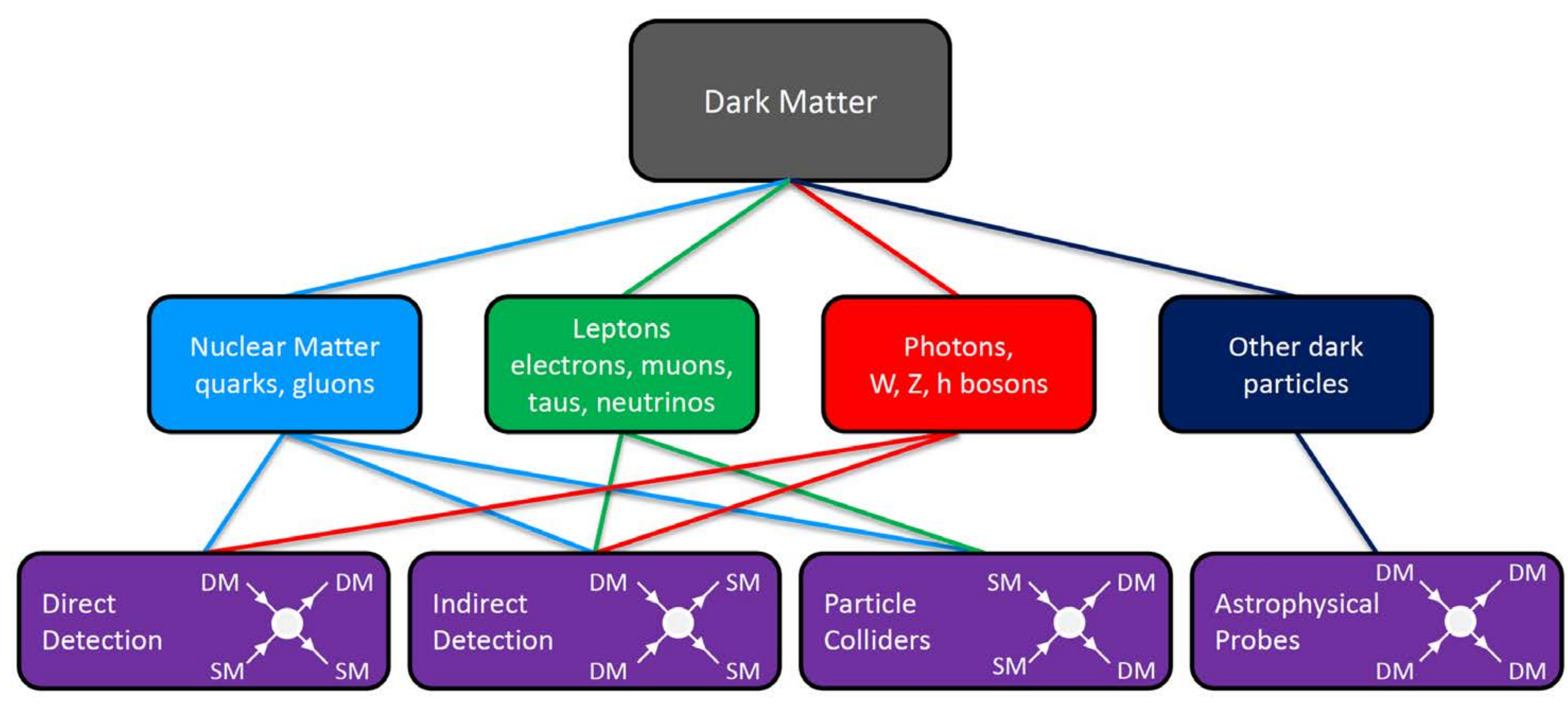
$$(\sigma_J)_{\max} v_{\text{rel}} \approx \frac{4\pi(2J+1)}{m_X^2 v_{\text{rel}}}$$

Griest & Kamionkowski

→ rules out thermal relic DM for very large masses.

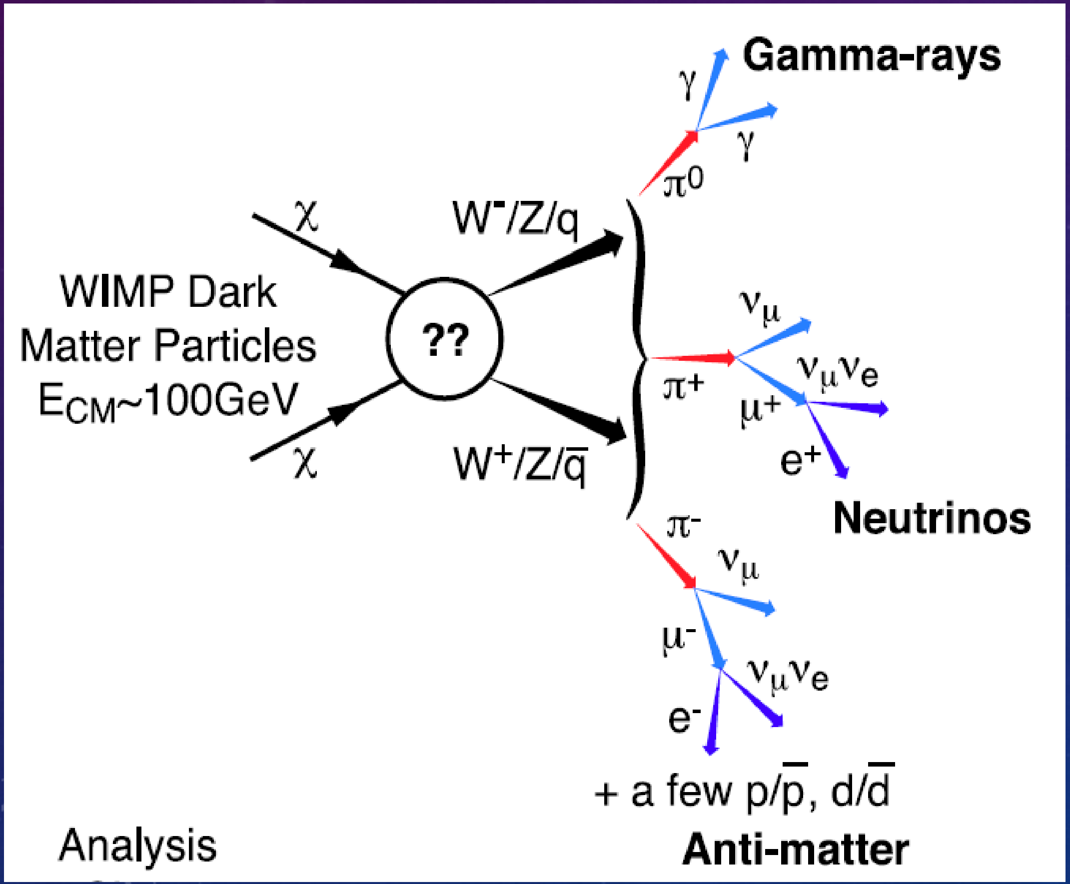
$$\langle \sigma v \rangle = \langle \sigma v \rangle_{thermal} \quad \Rightarrow \quad m_\chi < 300\ \text{TeV}$$

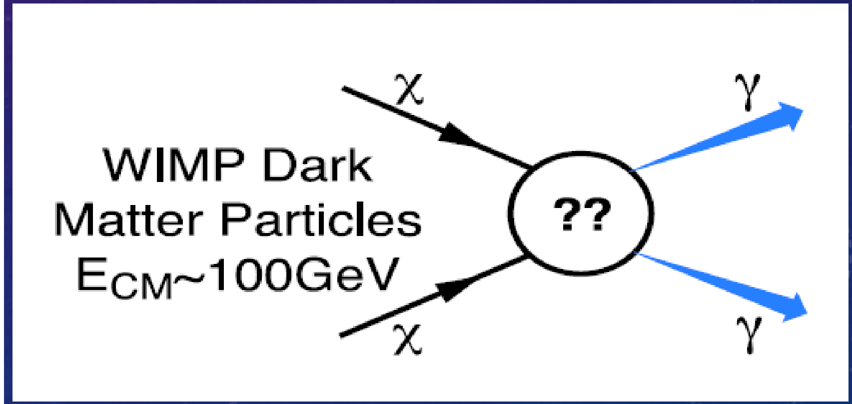
Complementary ways to probe (non-gravitational) DM interactions



Indirect detection

Search for DM annihilation (or decay) products from regions where DM density is high and (ideally) backgrounds are low:





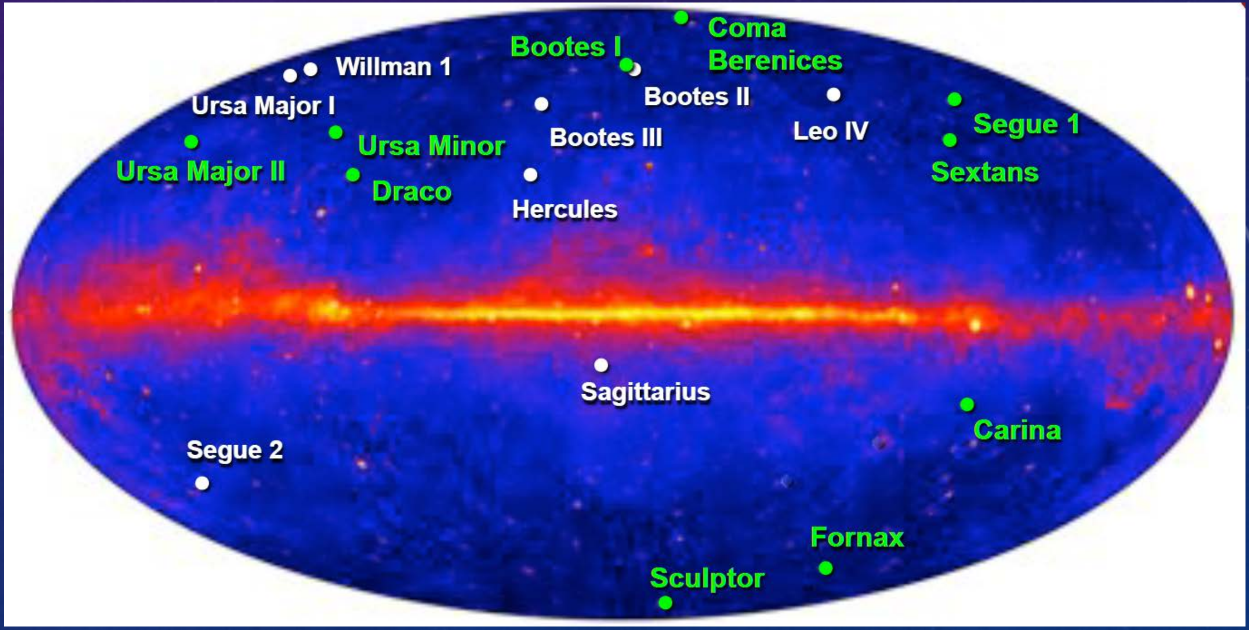
Indirect detection with MW dwarfs

Fermi Gamma-ray Space Telescope

Dwarf spheroidal galaxies

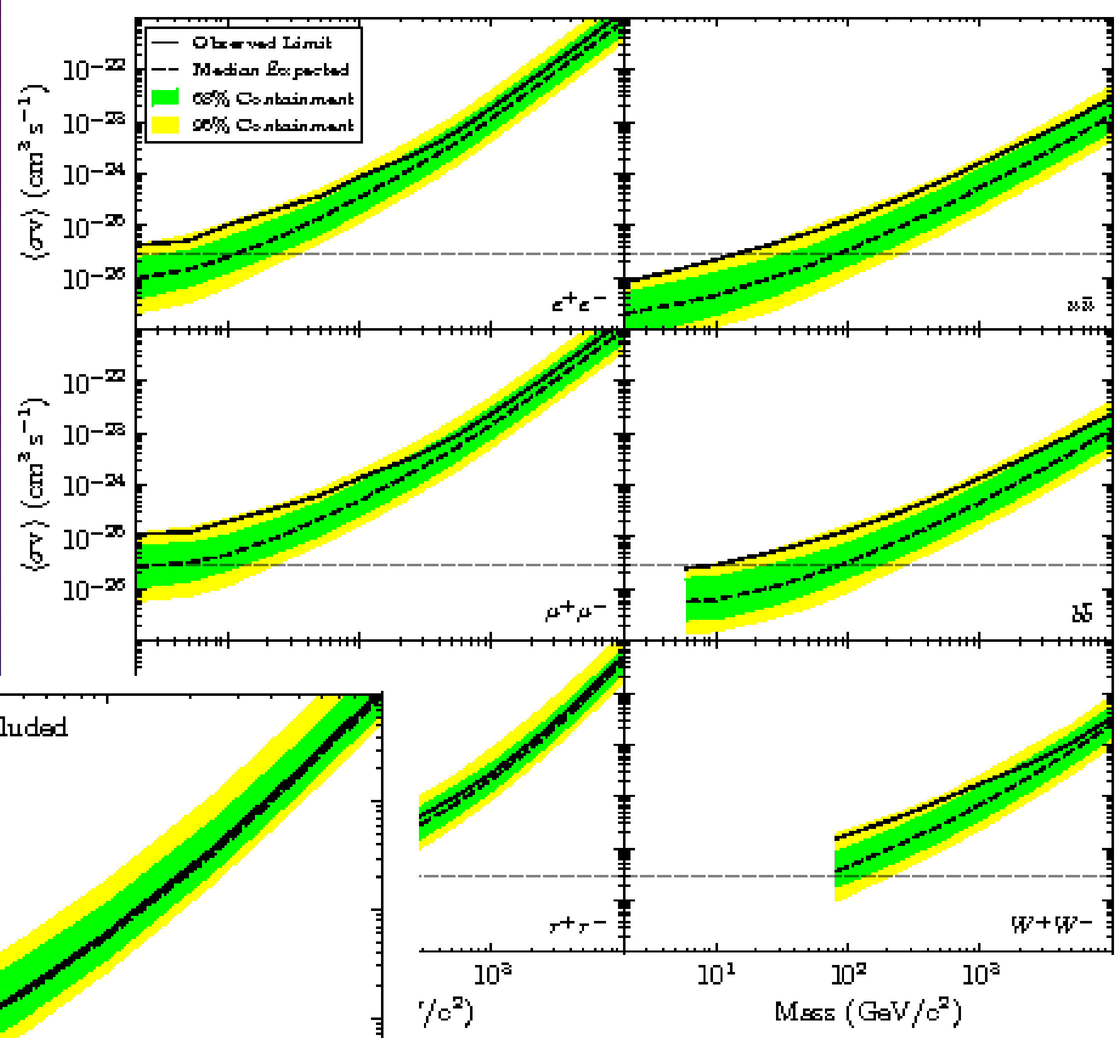
- ✔ dSphs are DM dominated systems (they have very high M/L ratios).
- ✔ Many dSphs are closer than 100 kpc to the Galactic Centre.
- ✔ Low background

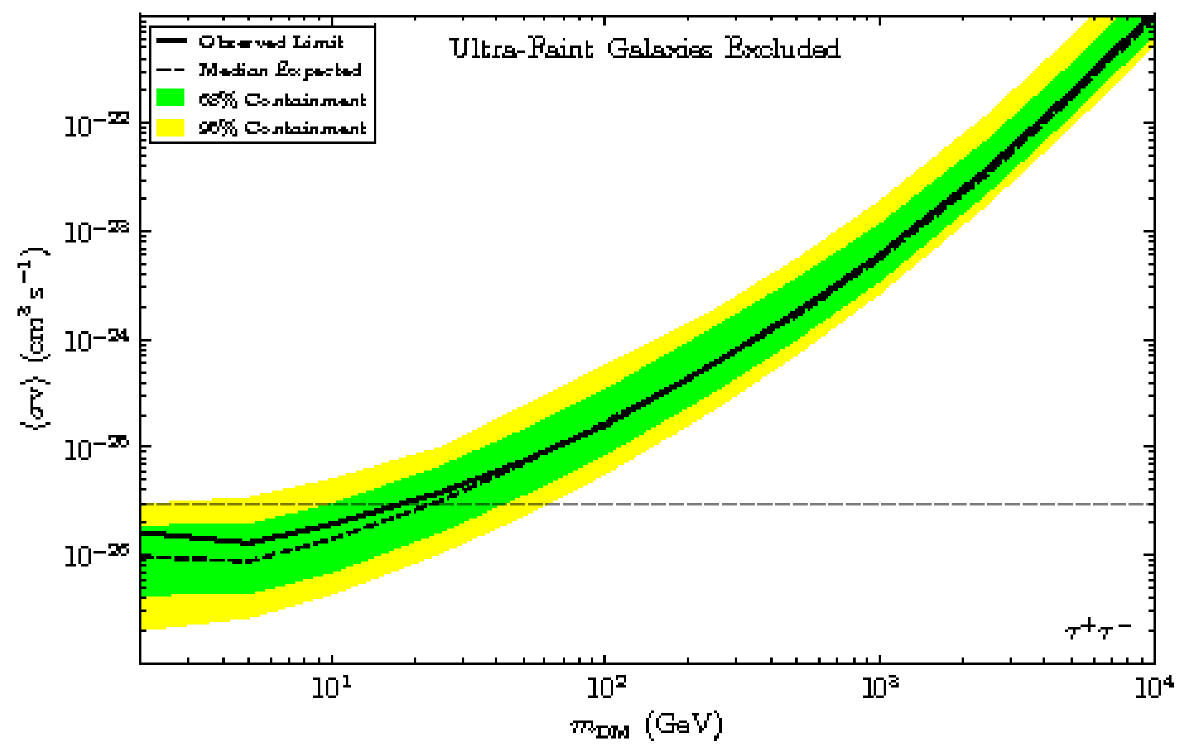
Negligible astrophysical backgrounds
→ robust limits



Fermi dwarf results

Fermi-LAT, Ackermann et al, arXiv:1310.0828,





Cluster limits

Galaxy clusters have large DM density and low background

- ➢ Good for indirect detection

Uncertainties:

- ➢ DM density profile
- ➢ Existence of sub-halos (clumpiness boost factor)
- ➢ Gamma emission induced by cosmic rays

Very strong limits! Rule out some proposed signals!

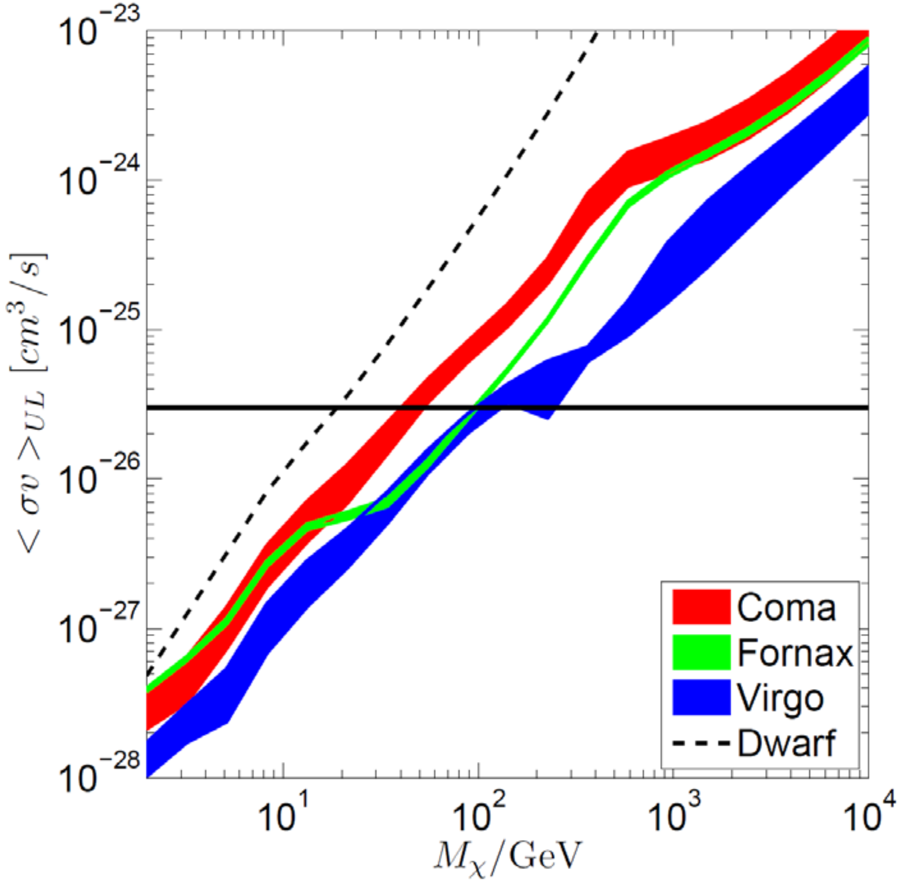


Figure 9. Upper limits for the DM annihilation cross-section in the $\tau^+\tau^-$ channel. Line styles are as in Fig. 6, but only the EXT results are shown. The black dashed line is the dwarf galaxy constraint. (Geringer-Sameth & Koushiappas 2011)

Han et al, arXiv:1207.6749

CMB limits on DM annihilation

- Recombination history of the universe could be modified if DM annihilations inject energy into the photon-baryon plasma.

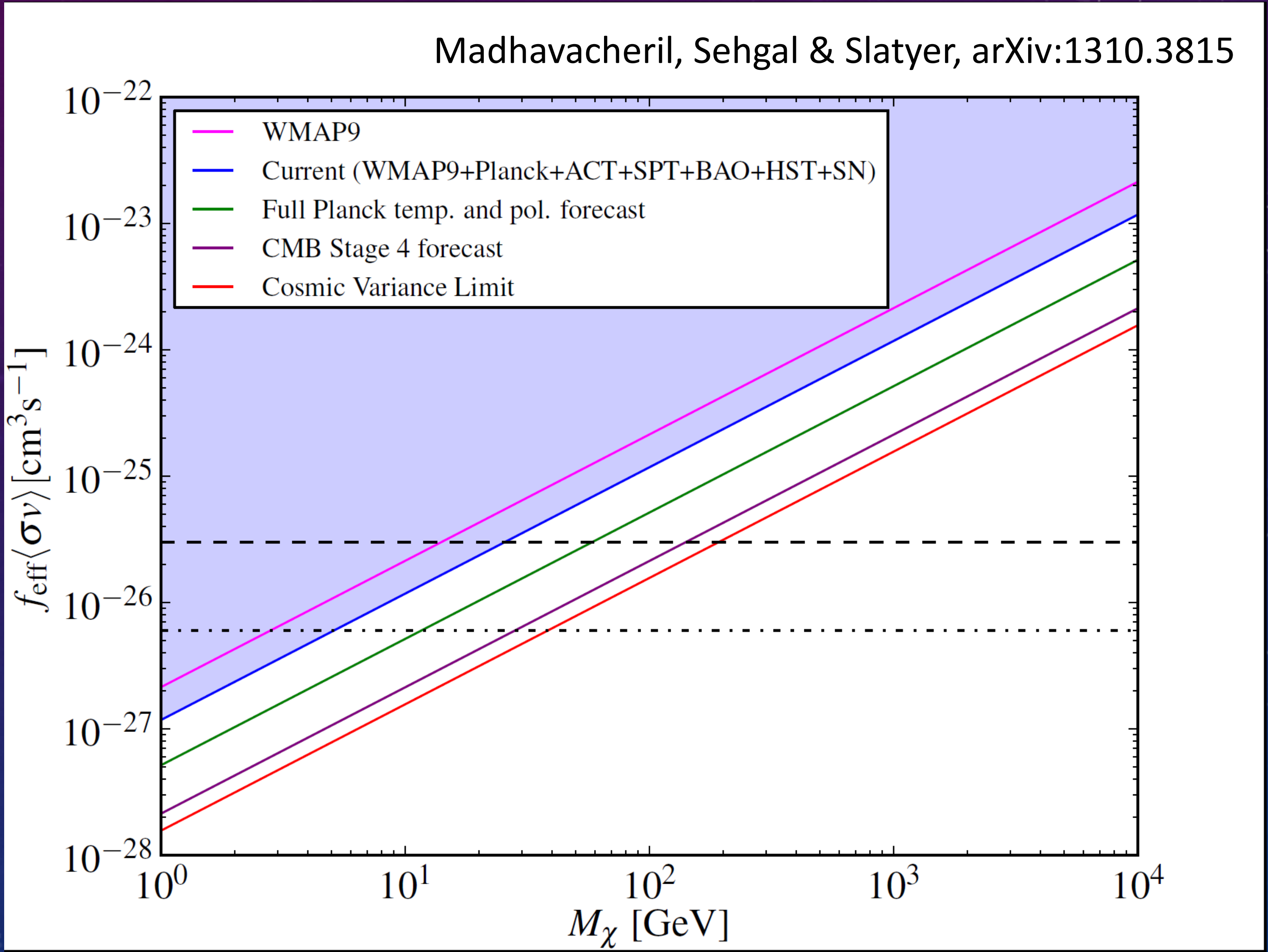
- Limits depend on:

→ the fraction of the DM energy absorbed by the plasma
  → typical value f=0.2 (larger for annihilation to electrons)

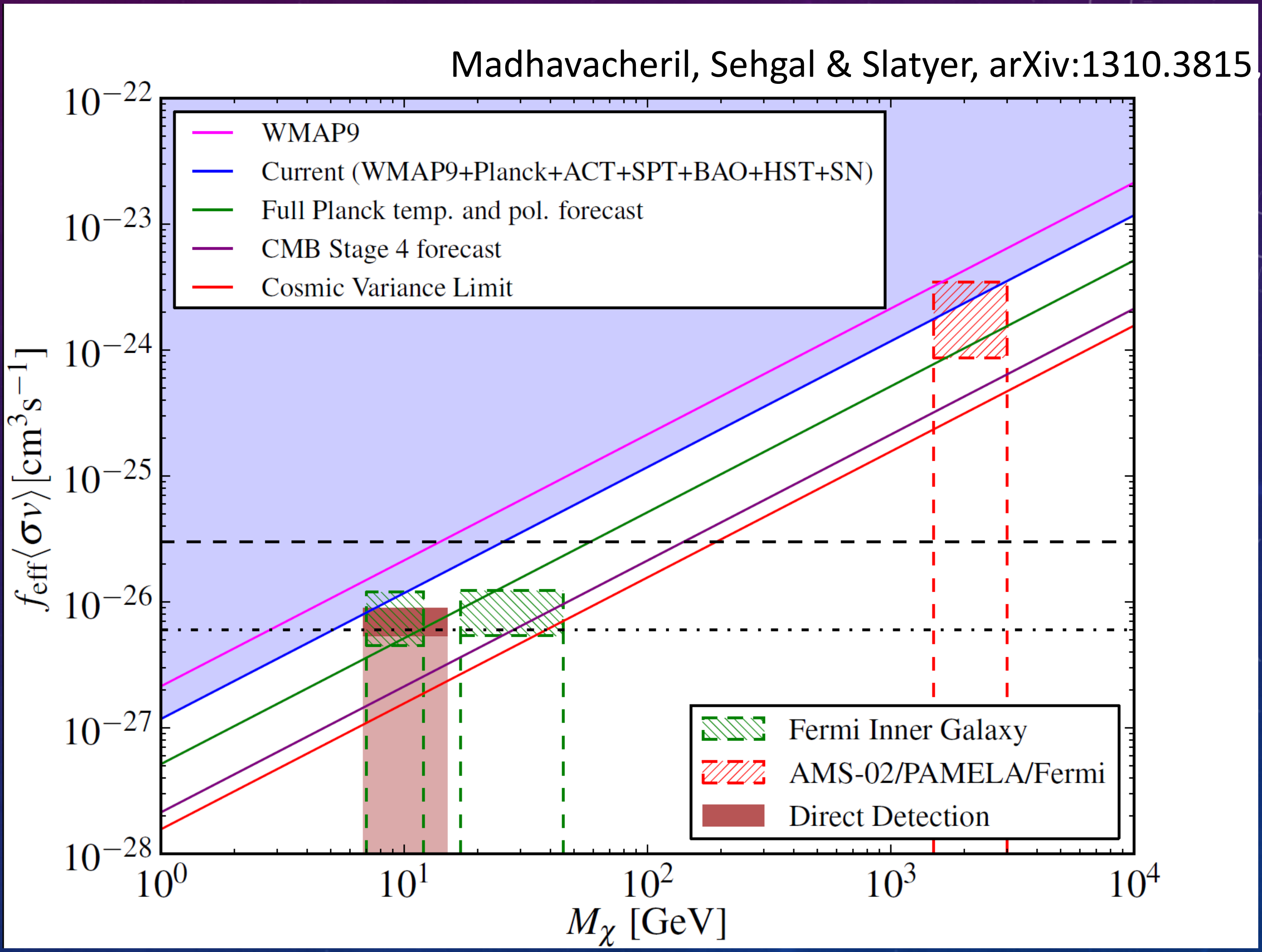
→ Velocity dependence of the cross section
  → If p-wave suppressed, annihilation rate is very small

- Currently exclude thermal relics with m <5 GeV

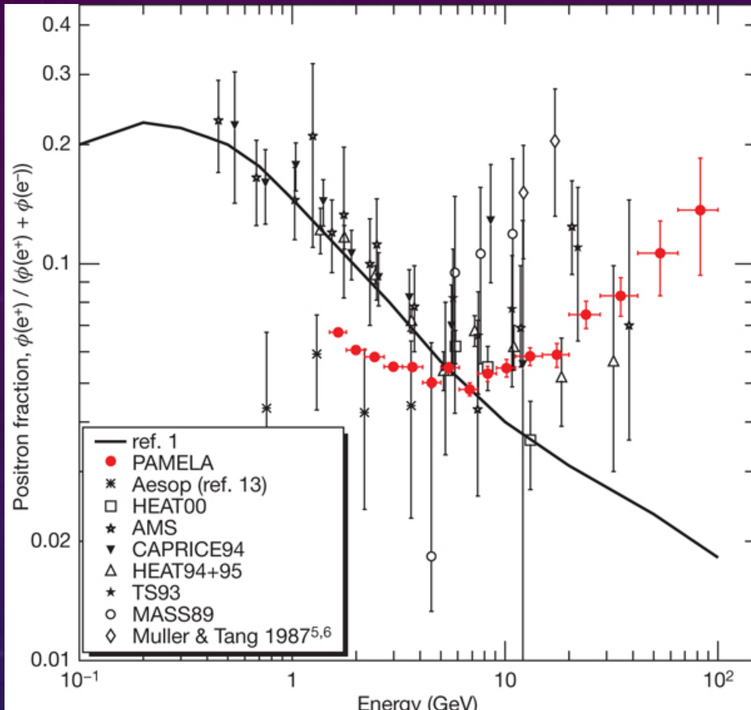
CMB limits on DM annihilation



CMB limits on DM annihilation



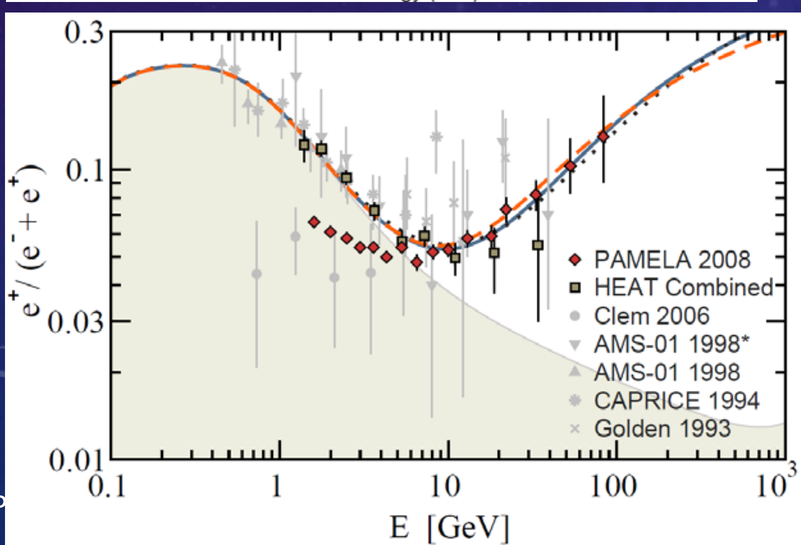
Indirect detection: positrons?



PAMELA e+ excess,
Nature 458, 607-609

DM annihilation signal?

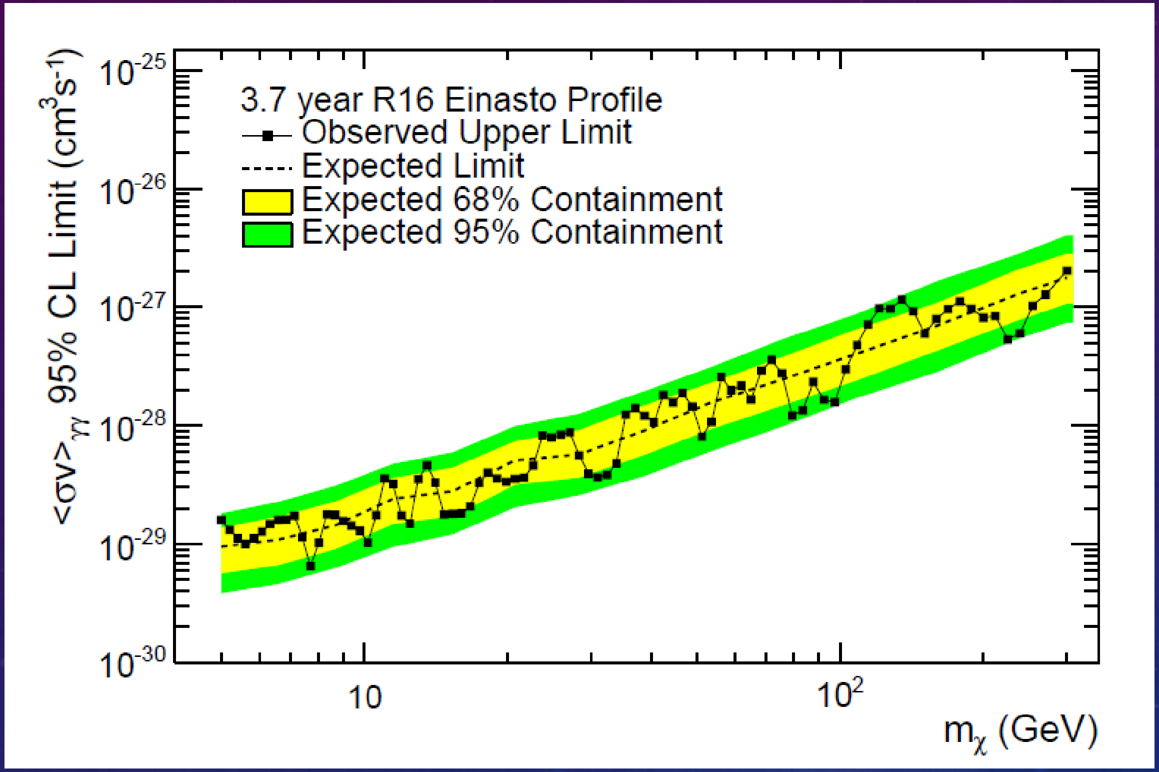
Or maybe pulsars?



Possible contribution from Geminga pulsar.
Yuksel, Kistler and Stanev, PRL 2009

Gamma ray lines – the smoking gun…

Fermi Gamma ray line search from 5 – 300 GeV

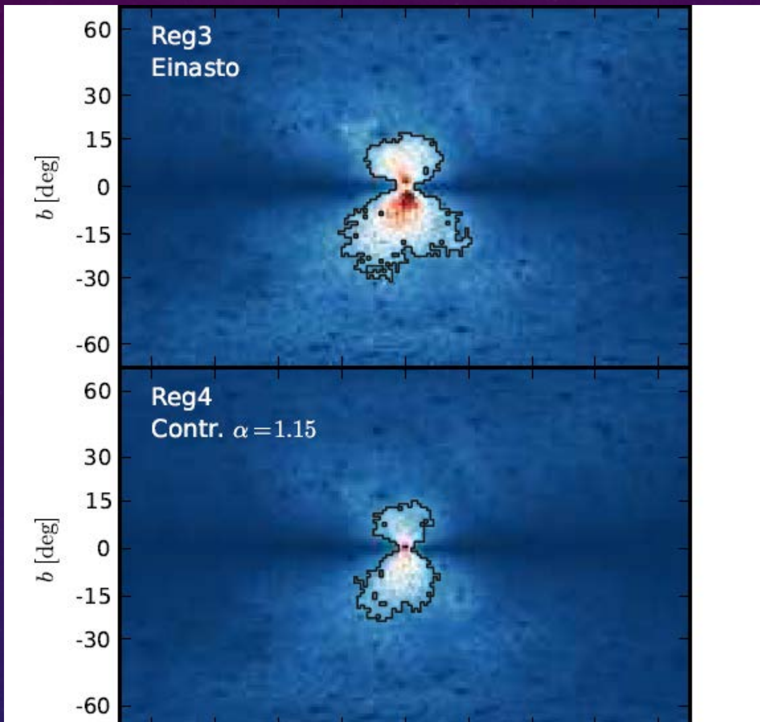


Fermi 1305.5597

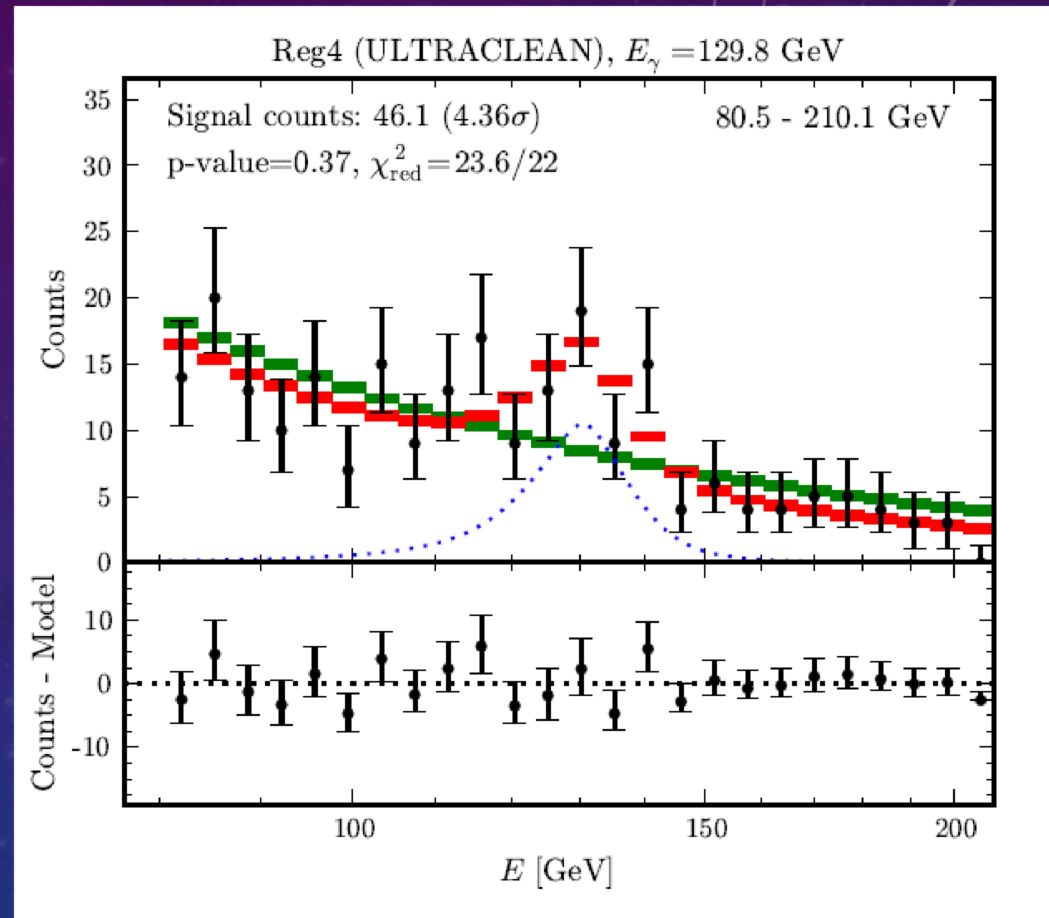
No globally significant line signal

Note: gamma ray lines should be loop suppressed, thus subdominant to continuum gammas.

Fermi gamma ray line at ~ 130 GeV?



Weniger 1204.2797, and several other groups.



A surprise! Remember, gamma ray lines are loop suppressed.

Official Fermi-LAT analysis with more data found a lower significance.

Galactic center emission – dark matter?

Extended source of 1-3 GeV gamma ray emission at the Galactic centre is seen in Fermi-LAT data. (Hooper et al. + other groups.)

Spatial distribution consistent with DM distribution

Can be fit by annihilation to

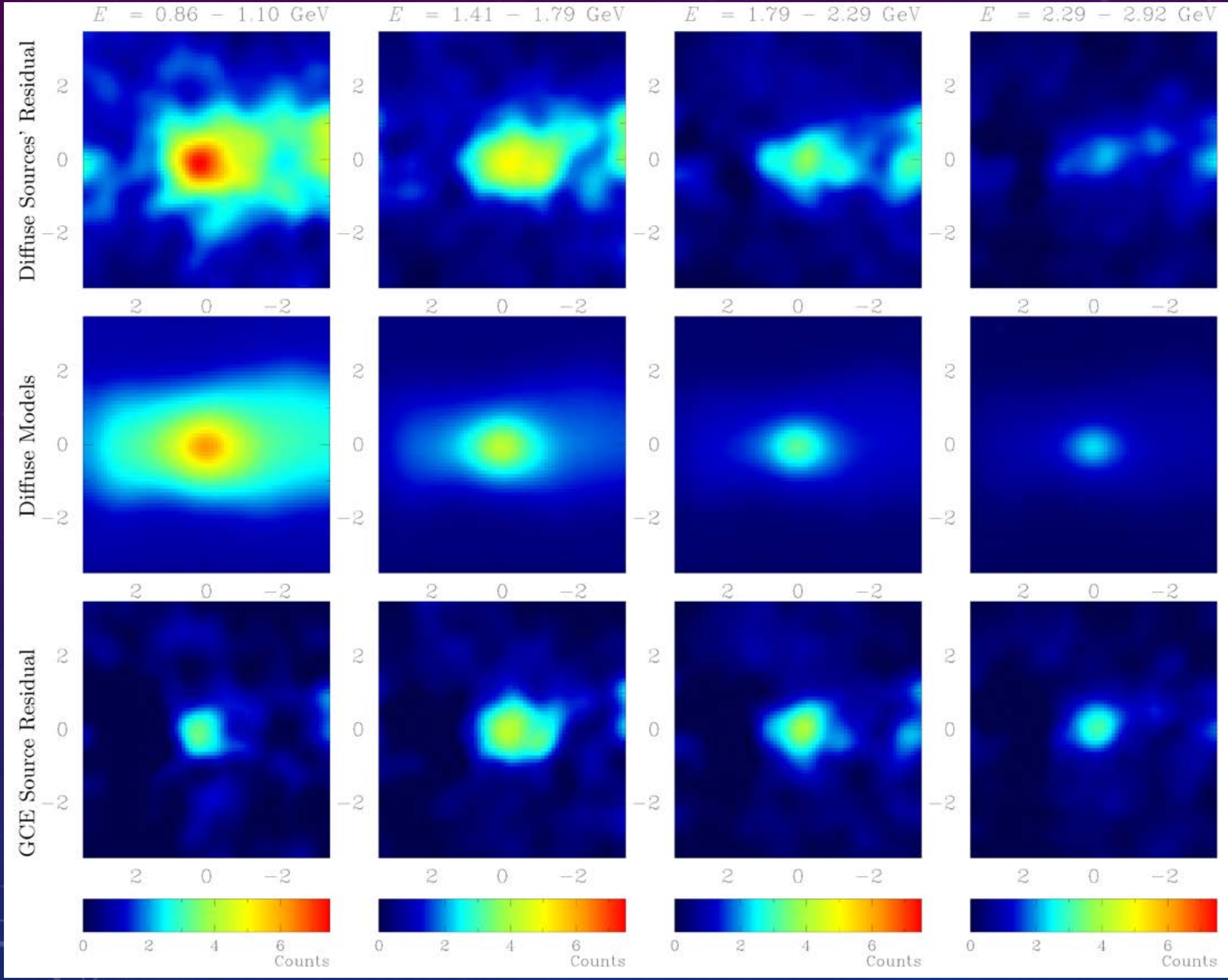
- bbar with 40 GeV DM mass
- tau+tau- with 10 GeV DM mass

with a cross section roughly consistent with a thermal relic.

BUT, unresolved point sources (e.g. millisecond pulsars) can mimic this signal.

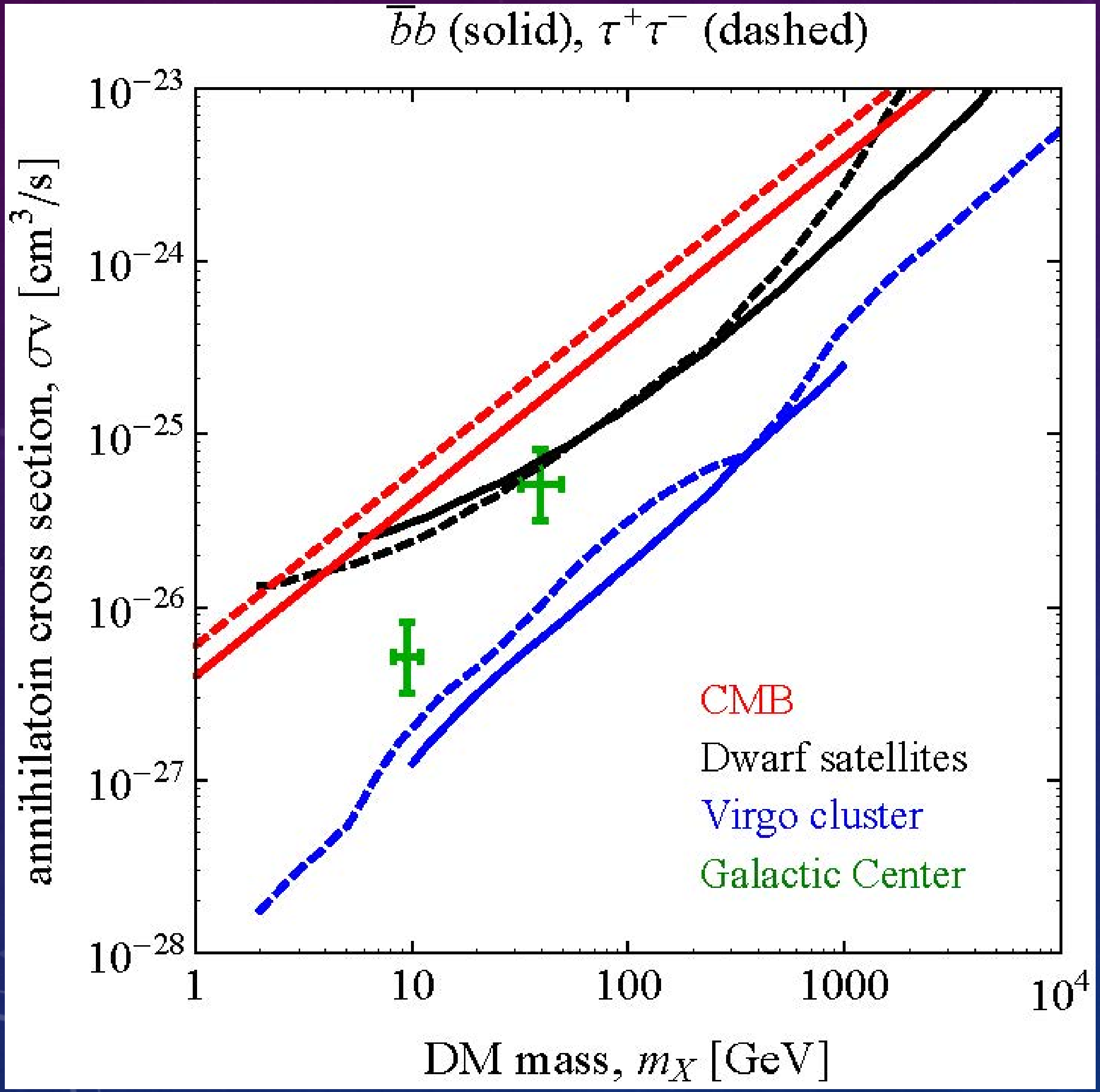
And, at these low DM masses, in tension with indirect detection limits from clusters.

Galactic center emission – dark matter?



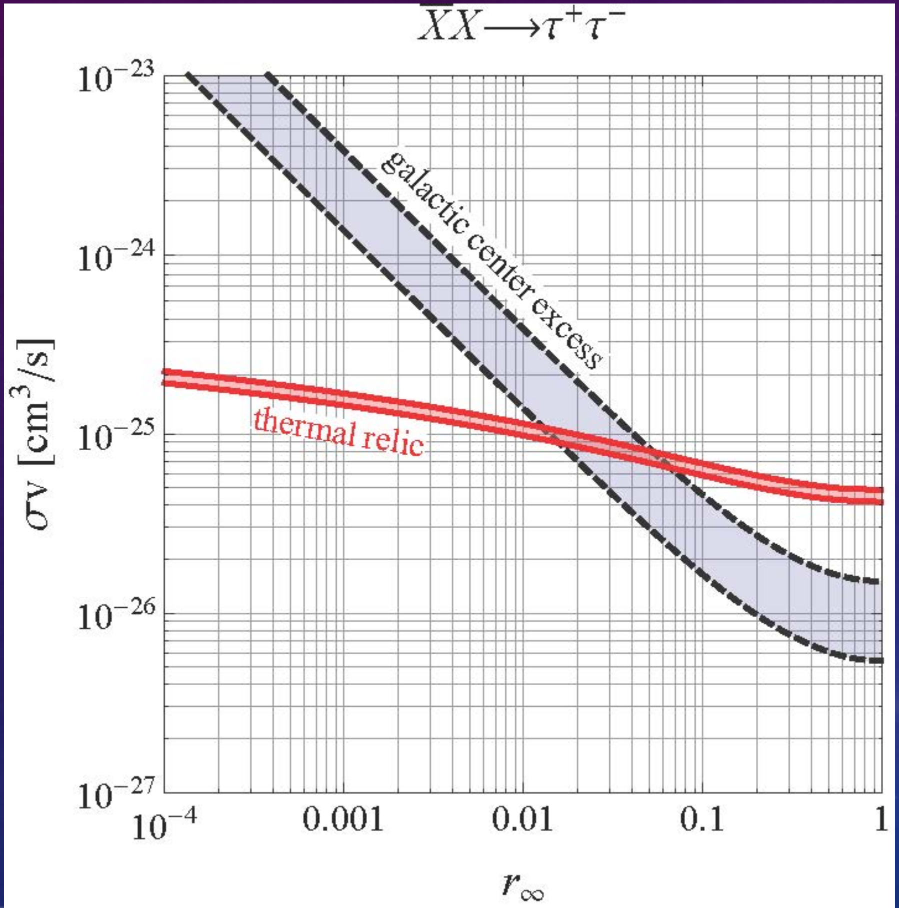
Abazajian et al, arXiv:1402.4090

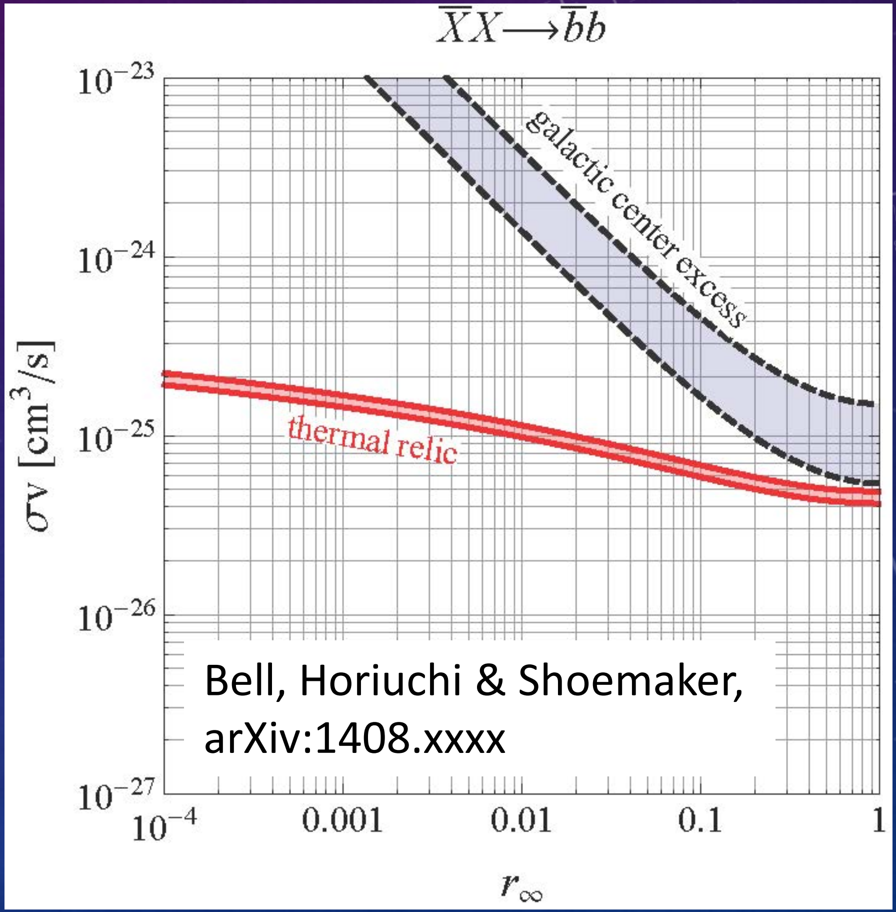
Comparing limits



Bell, Horiuchi & Shoemaker, arXiv:1408.xxxx

Interpreting the GC emission in an asymmetric DM model

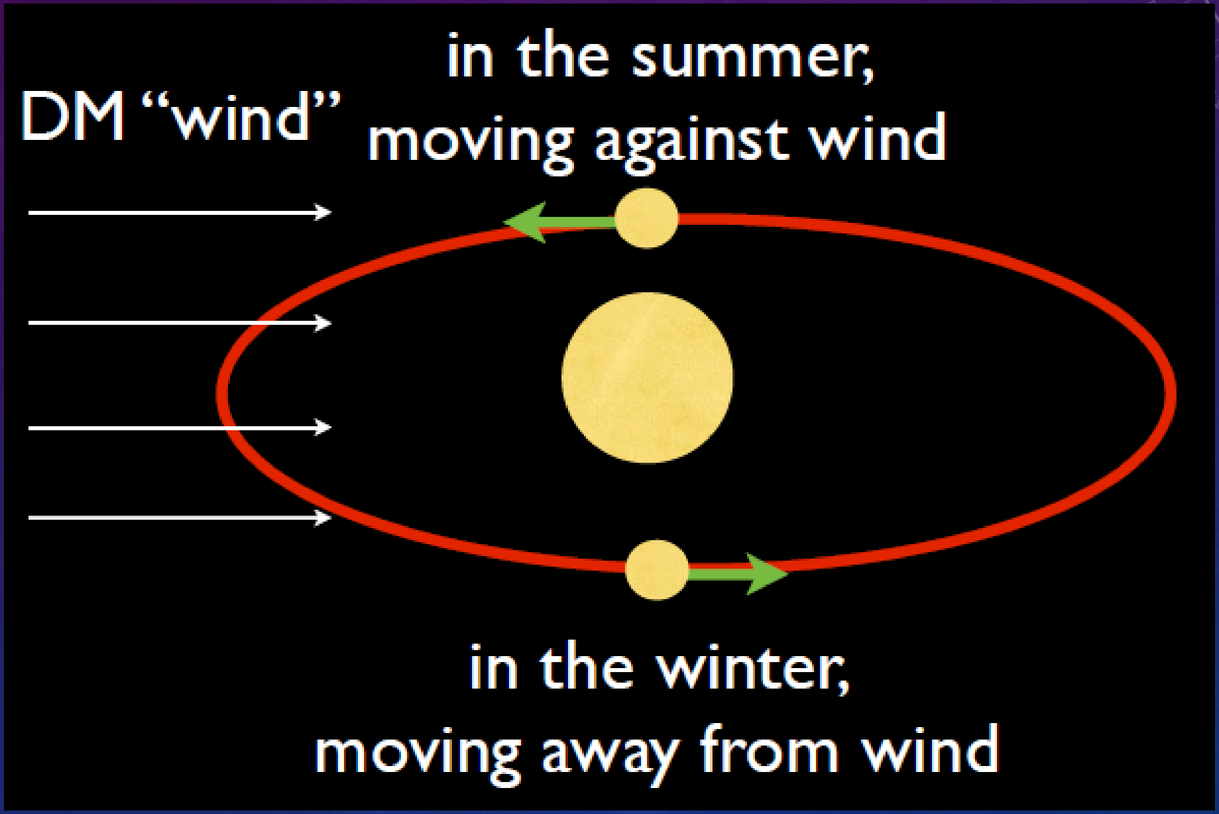




Bell, Horiuchi & Shoemaker, arXiv:1408.xxxx

ADM → tau+tau- channel consistent with thermal freezeout

Direct Detection



Spin-independent vs Spin-dependent

Spin independent - DM interacts coherently with whole nucleus
- A^2 enhancement of cross section

Spin dependent - DM couples to spin of nucleus

(a)Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI

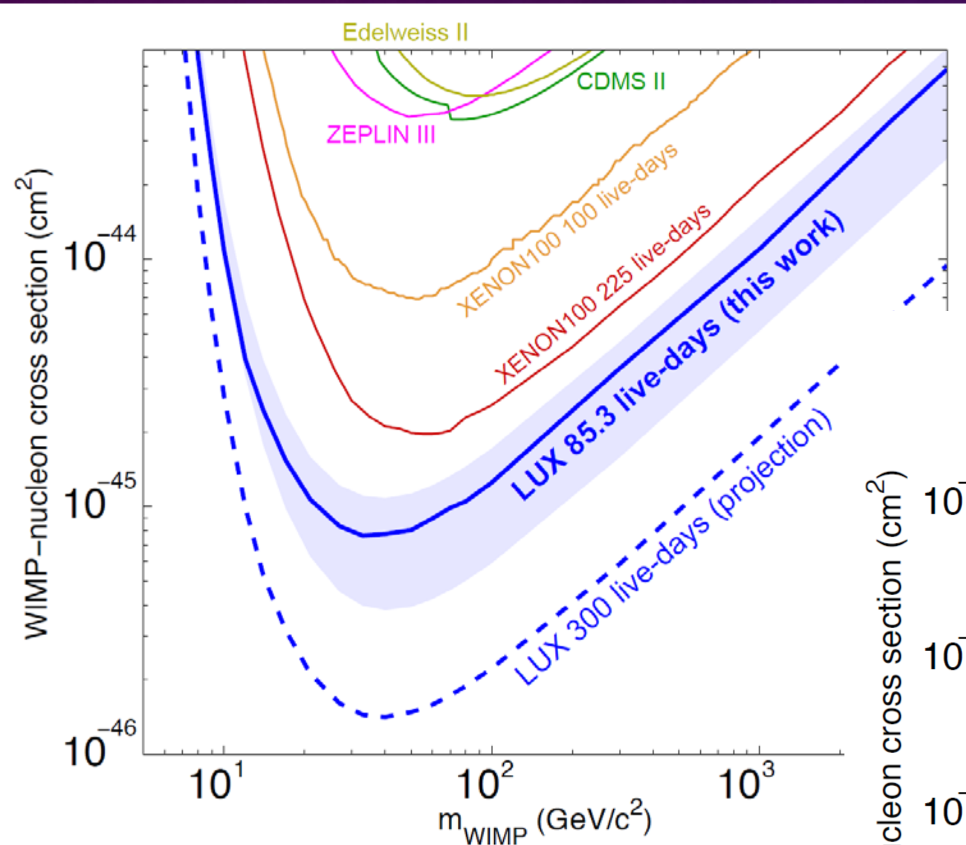
(b)Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	6	SI
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C5	$\frac{\alpha_s}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI

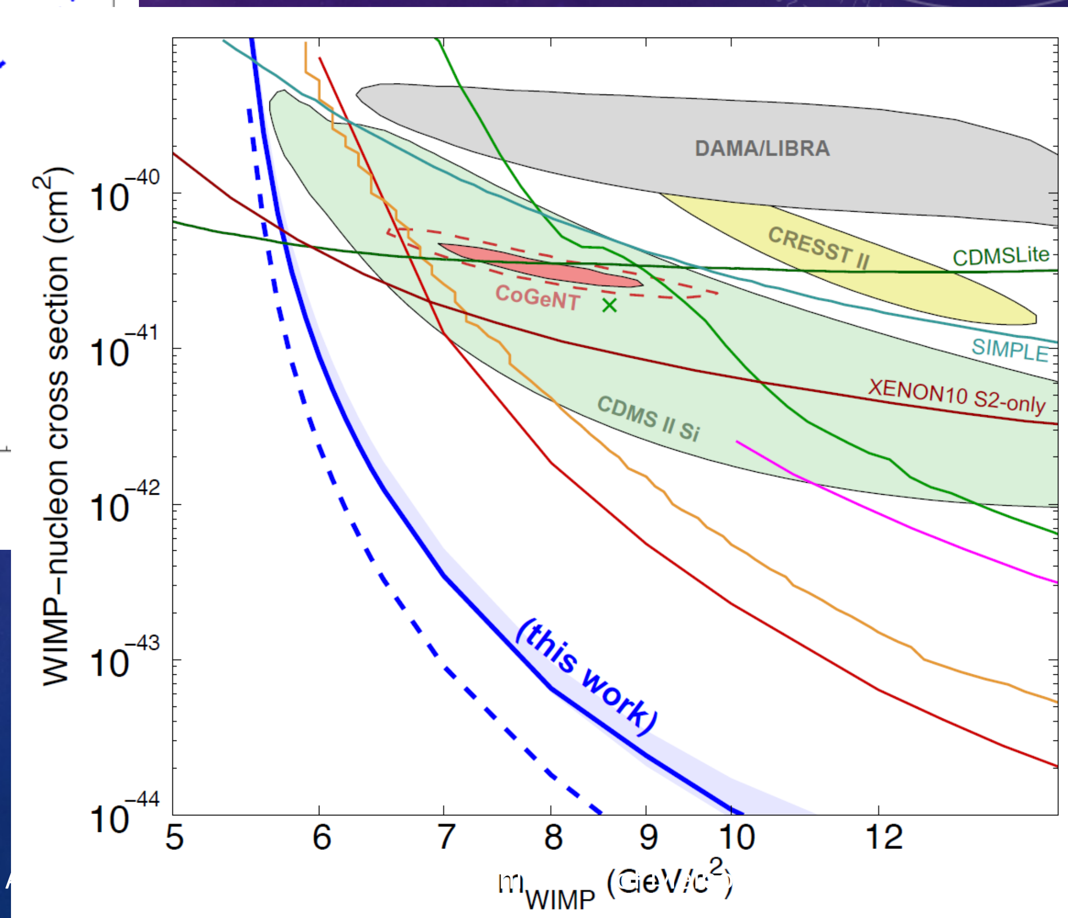
Further operators, not shown, have a velocity suppressed WIMP-nucleon cross section

Direct Detection Results

Spin-independent WIMP-nucleon scattering

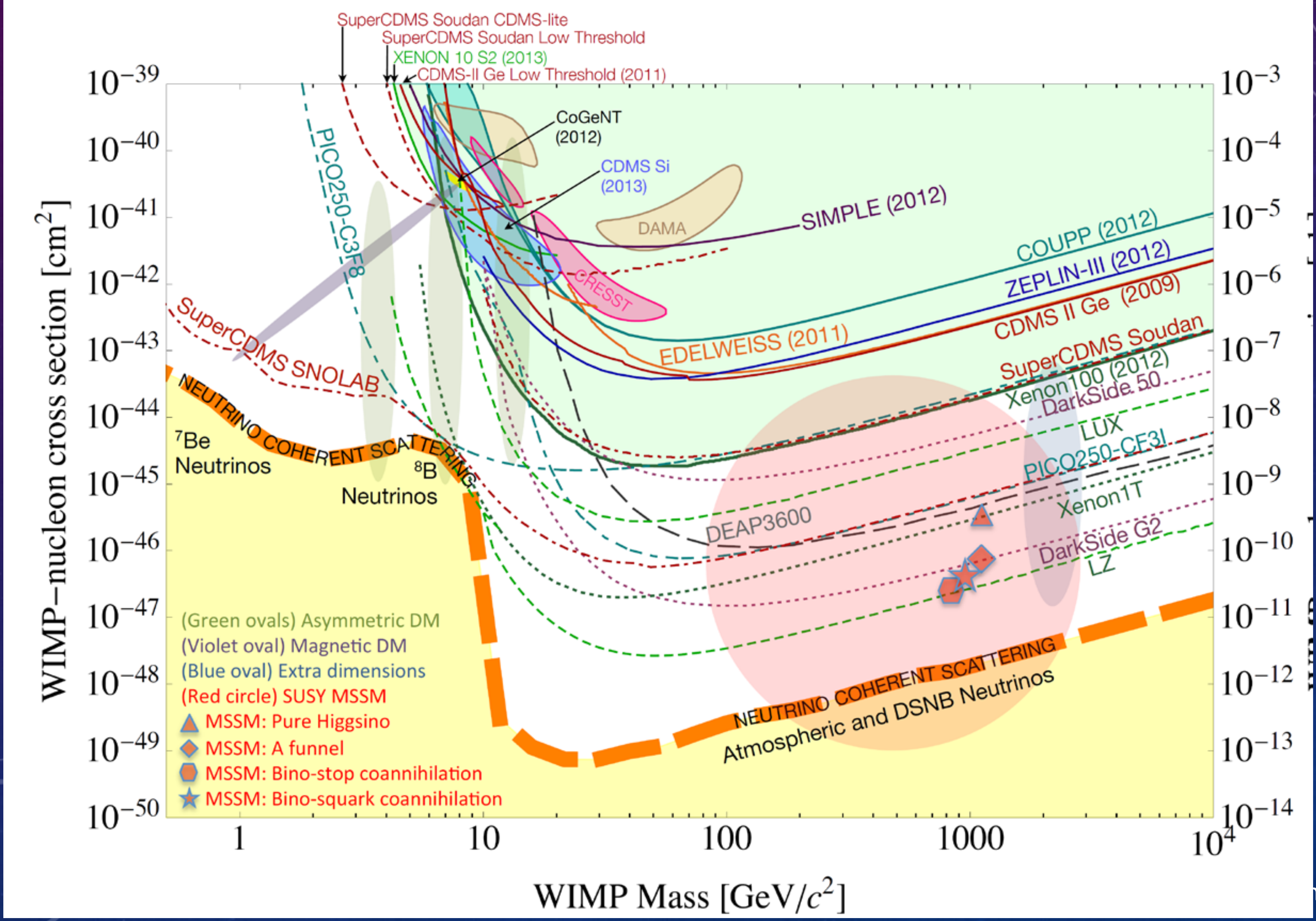


LUX, arXiv:1405.5906



Future: “neutrino floor” is irreducible background

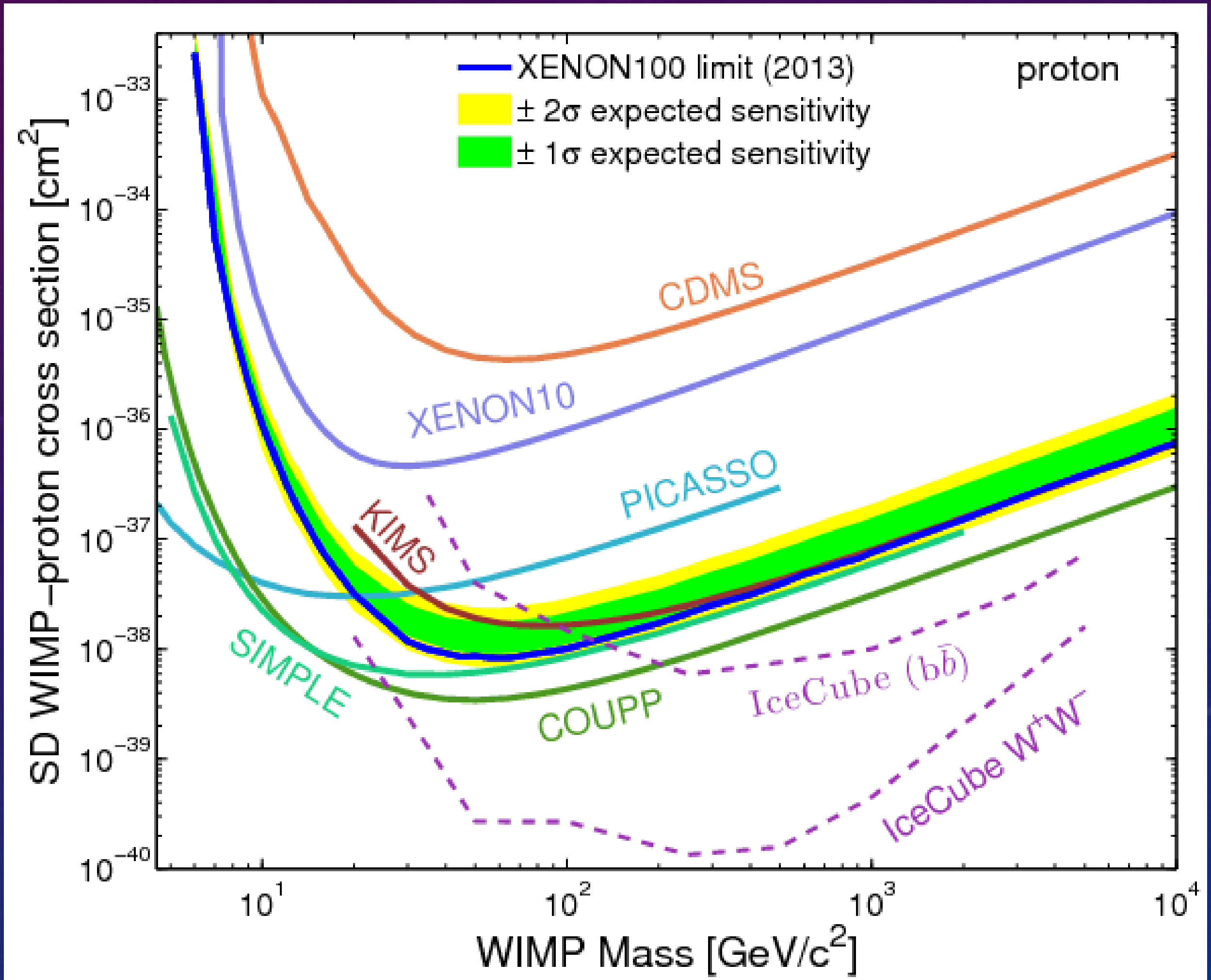
Coherent neutrino-nucleus scattering of solar/atmospheric neutrinos!



Billard et al 1307.5458

Cushman et al 1310.8327

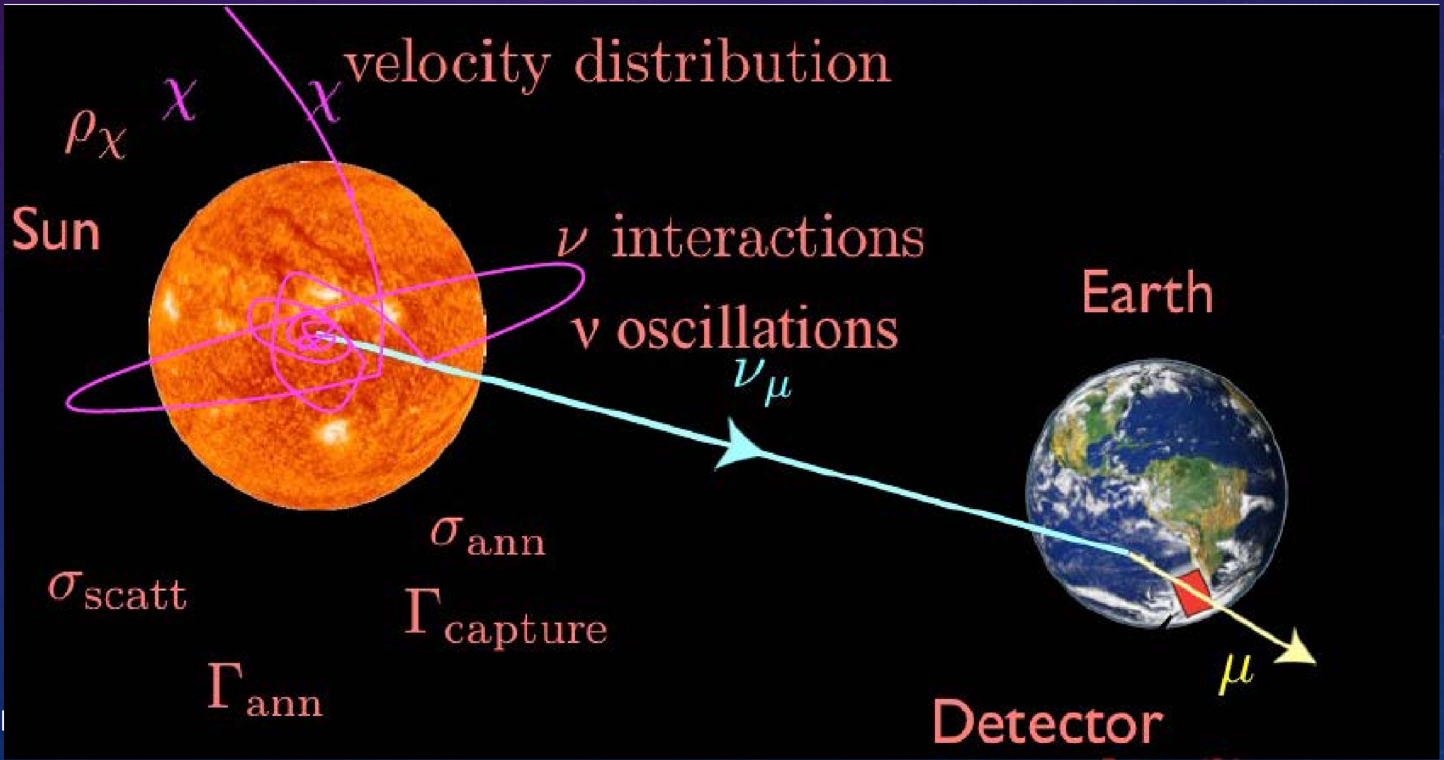
Spin-dependent WIMP-nucleon scattering



Xenon100
1301.6620

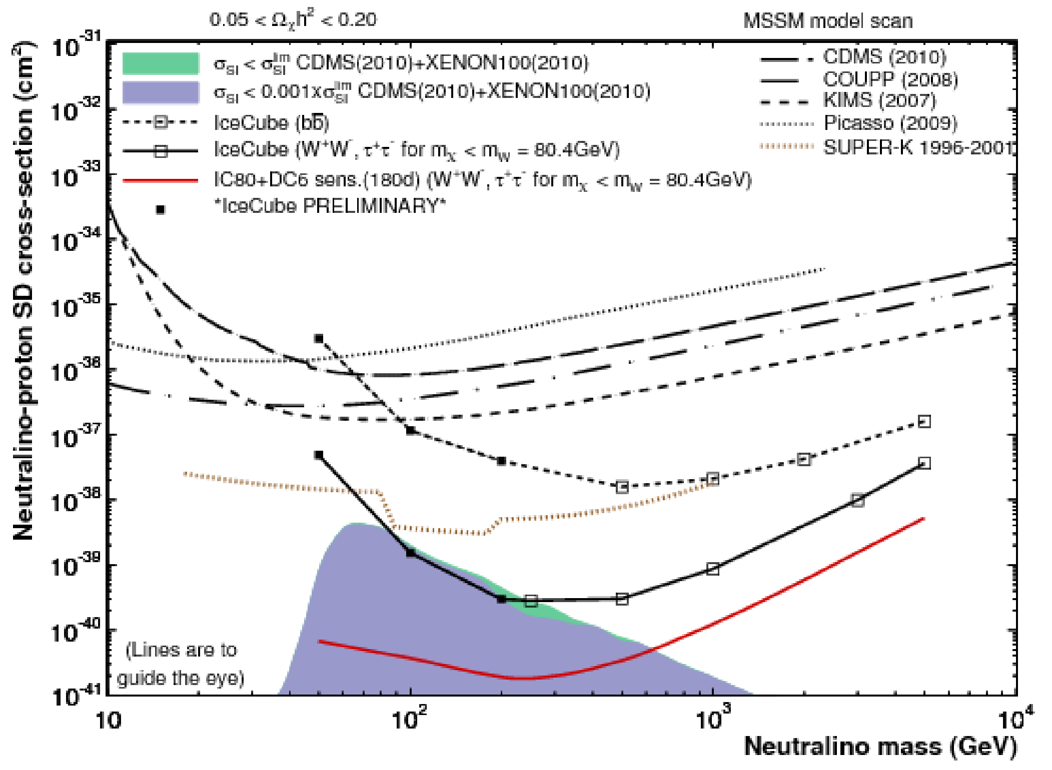
Solar WIMPS

- Dark matter accumulates and annihilates in the centre of Sun
- Only neutrinos escape the Sun → IceCube, SuperK
- Capture determined by WIMP-nucleon scattering cross section.
  → capture rate = annihilation rate (in equilibrium)
- Hence probes the same quantity as direct detection experiments
  → Competitive limits for spin-dependent cross sections



Spin-dependent WIMP-nucleon scattering

IceCube solar WIMP limits more sensitive than nuclear recoil experiments.

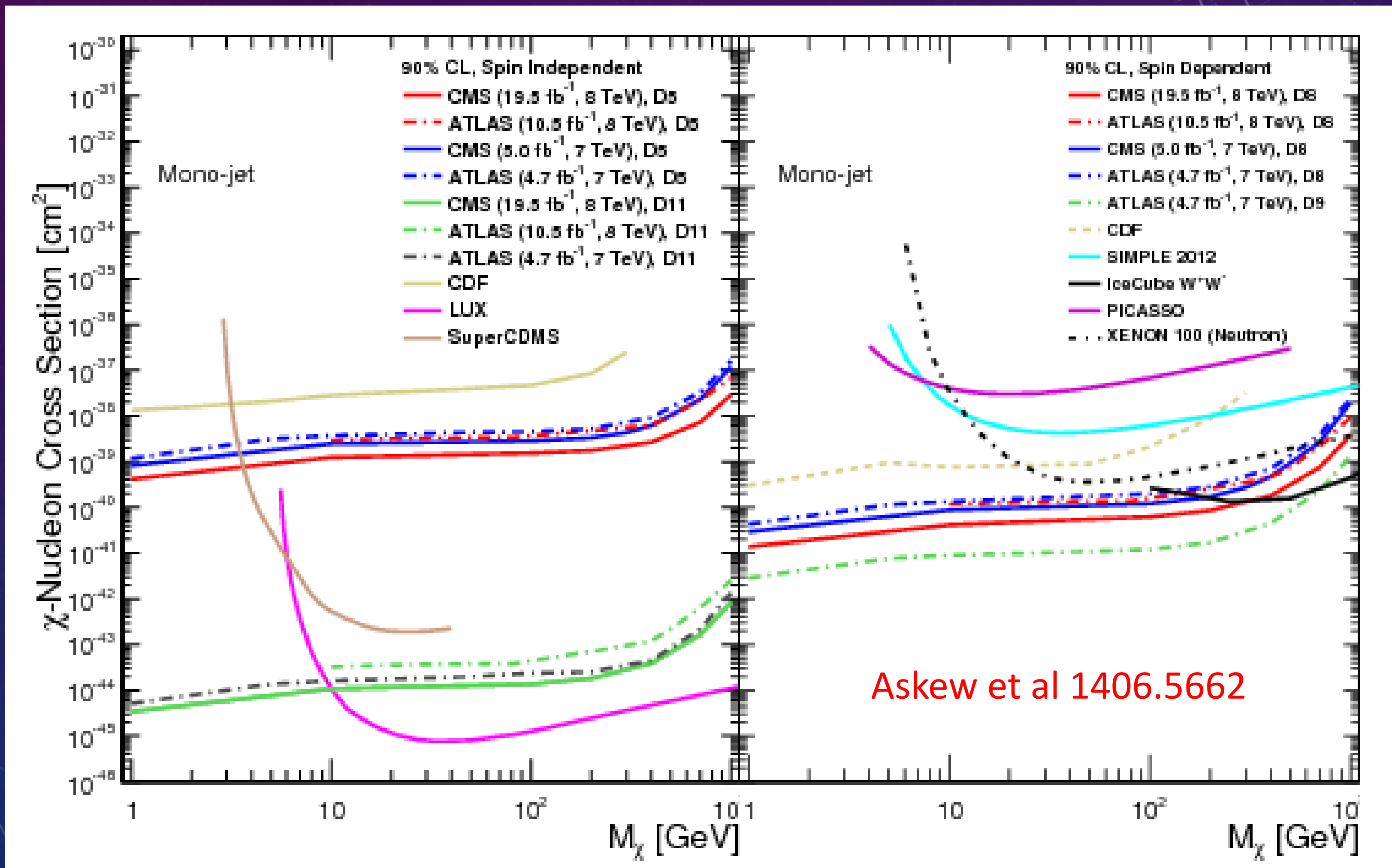


Complementary: Collider, nuclear recoil, and solar wimp searches rely on very different assumptions.

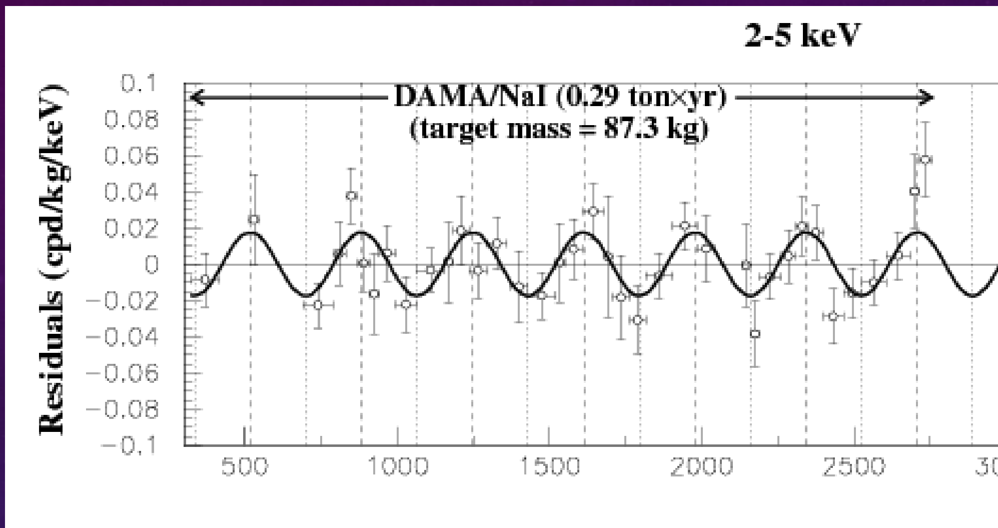
LHC vs direct detection

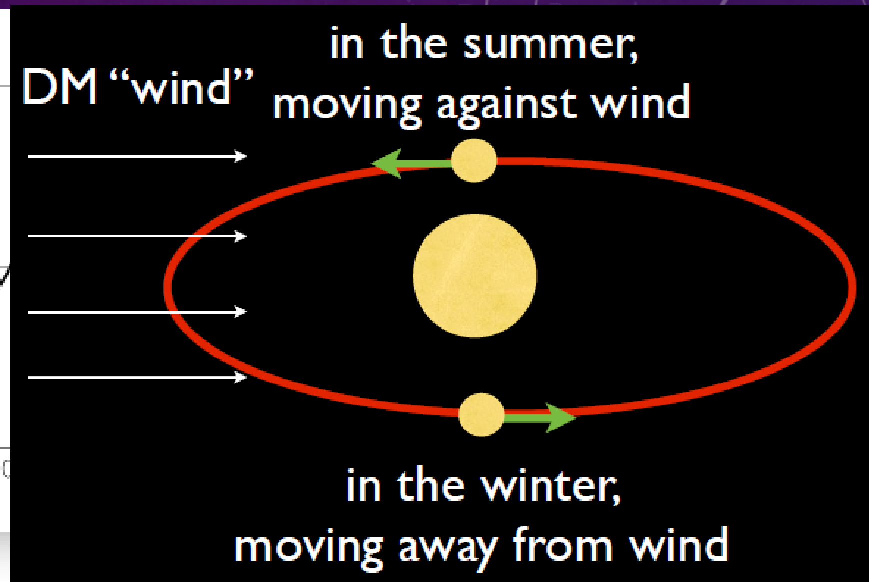
Spin-independent

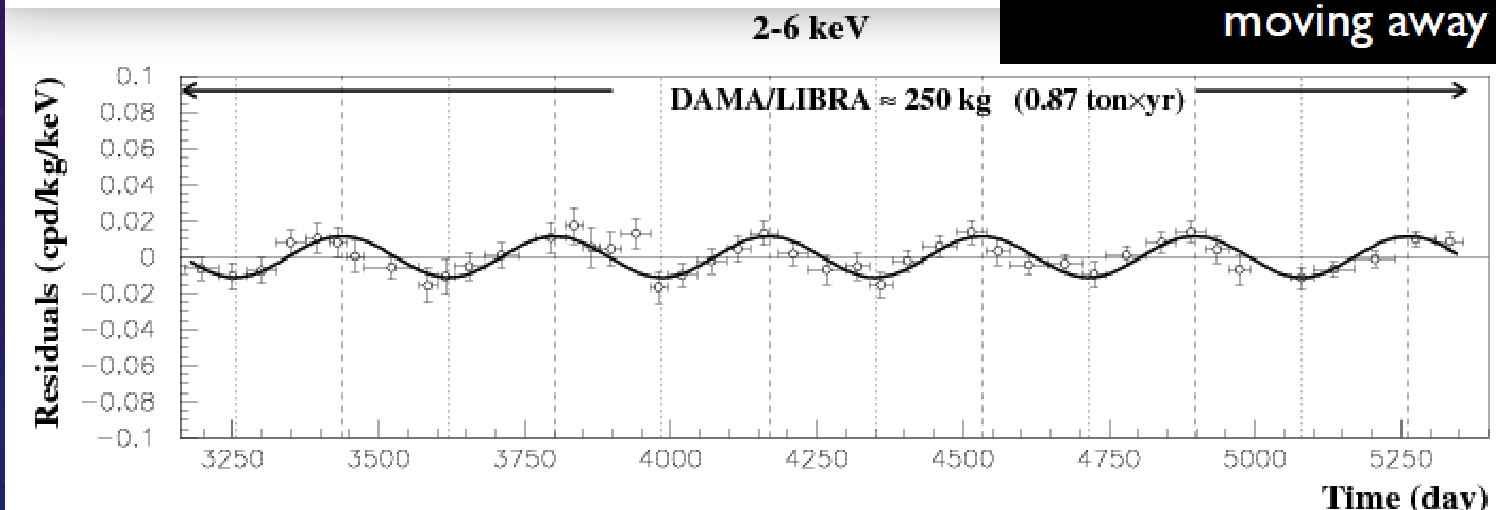
Spin-dependent



DAMA/LIBRA annual modulation







Now 8.9 σ confidence level

Is the DAMA signal really DM ?

Something is modulated

There is strong motivation to check the systematics with an experiment in the southern hemisphere.

→ True DM signal should have the same modulation phase.
→ The phase of a background modulation could be expected to change with location (sessional variation of atmosphere, etc).

→ Various proposed southern hemisphere experiments :
- South pole (DMIce)
- Chile-Argentina (ANDES)
- Australia

DM in Australia!

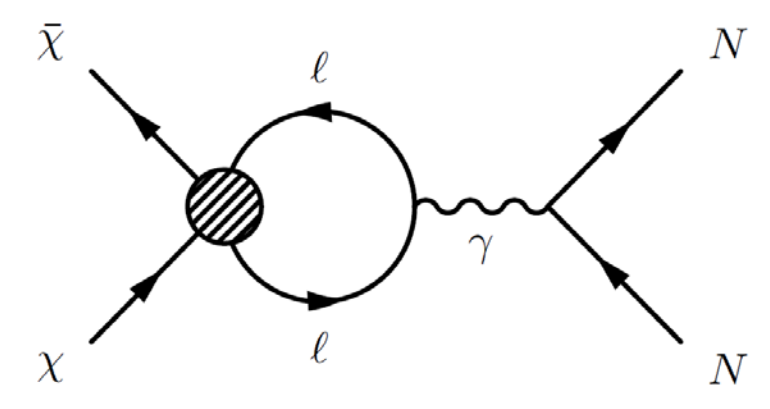
Mine identified in Stawell (near Melbourne)

Studies to assess suitability of the site are underway. (E. Barberio et al.)

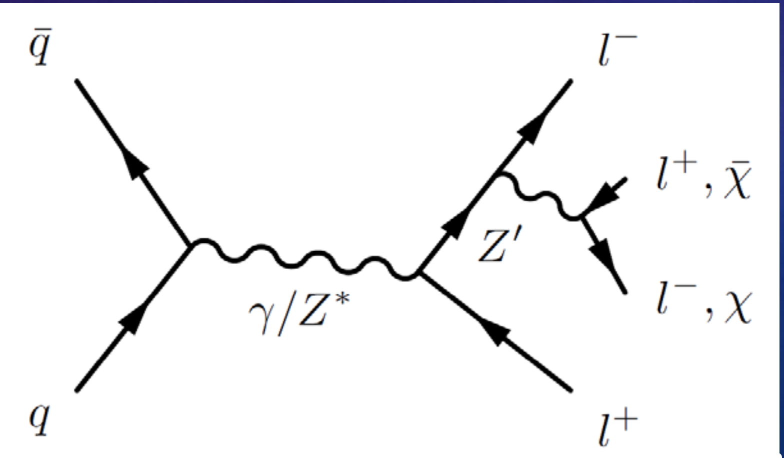
Beyond WIMPs

Leptophilic WIMP?

- Suppose DM couples only to leptons (at tree level)
- Usual direct detection and mono-jet bounds not applicable.
- Even so, this scenario is strongly constrained



Direct detection loop-suppressed, yet still yields strong limits



Collider production via Drell-Yan process

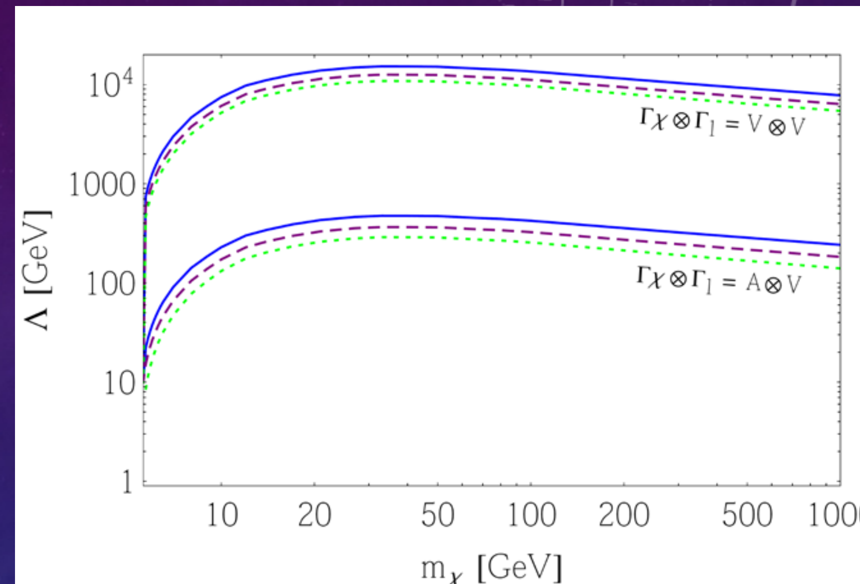
Bell et al 1407.4566.
See also: Kopp 0907.3159
Altmannshofer 1406.1269

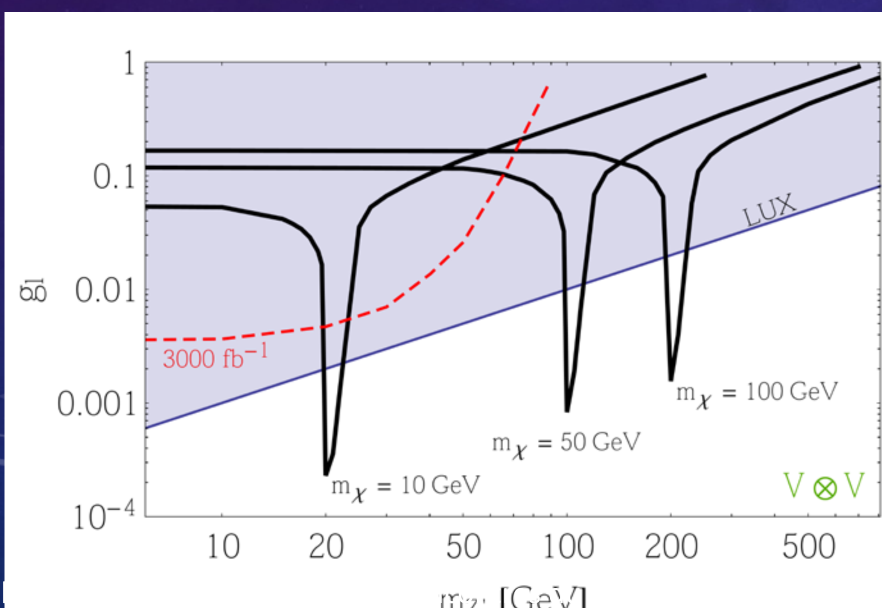
Leptophilic WIMP

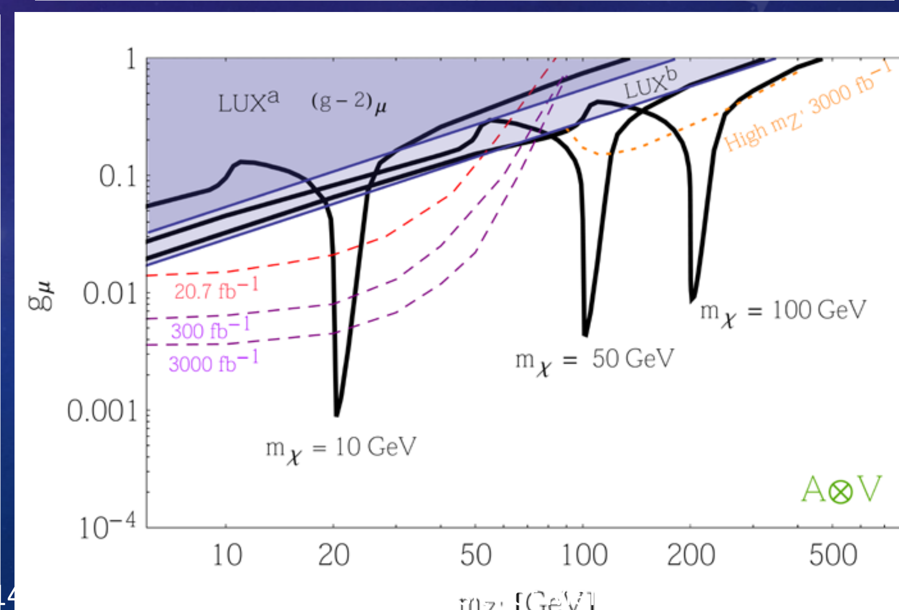
Direct detection still requires the new-physics scale to be high

→ some tension with relic density requirement

Bell et al 1407.4566.

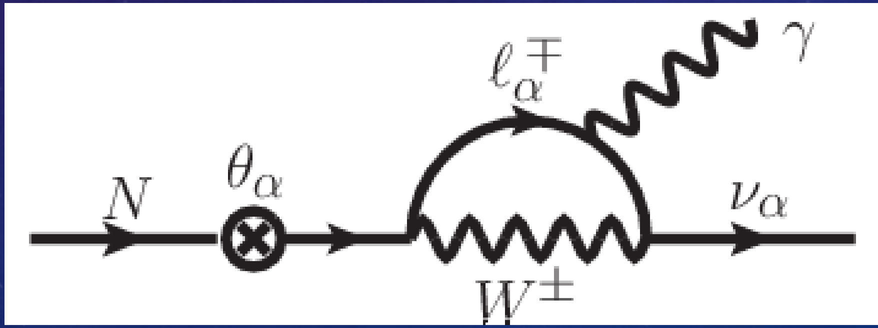






Sterile neutrino dark matter

- keV sterile neutrinos → good candidate for warm DM
- Produced in early universe via active-sterile oscillations
- Exclusion principle prevents arbitrary high density
  → dense galaxies set lower limit on mass (Tremaine–Gunn bound)
- Unstable. Decays produce x-ray line.

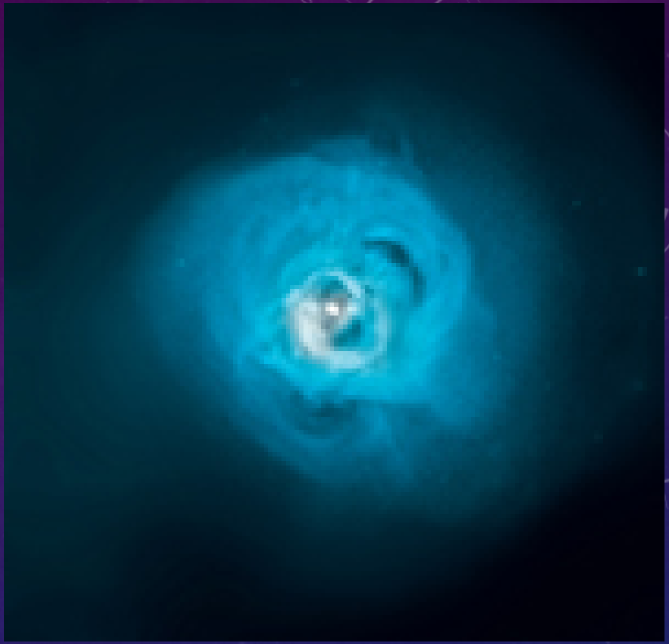


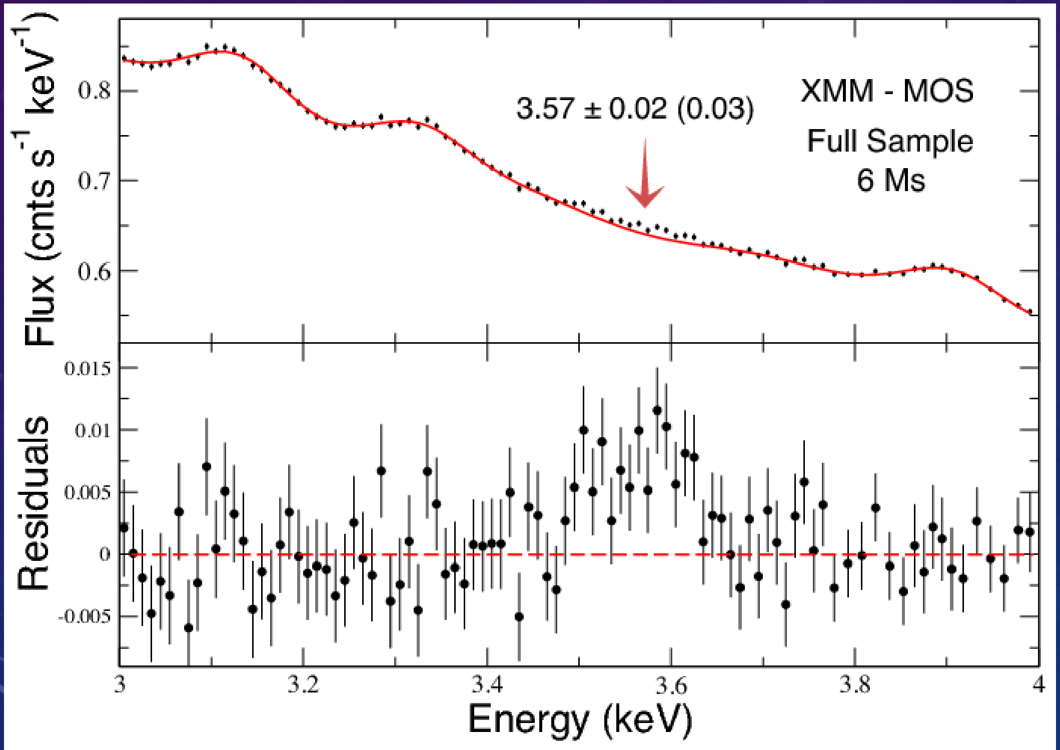
Possible signal in Perseus and other galaxy clusters.

E = 3.57 ± 0.02 keV

$\Rightarrow$ m = 7.1 keV

Bulbul et al 1402.2301, ApJ

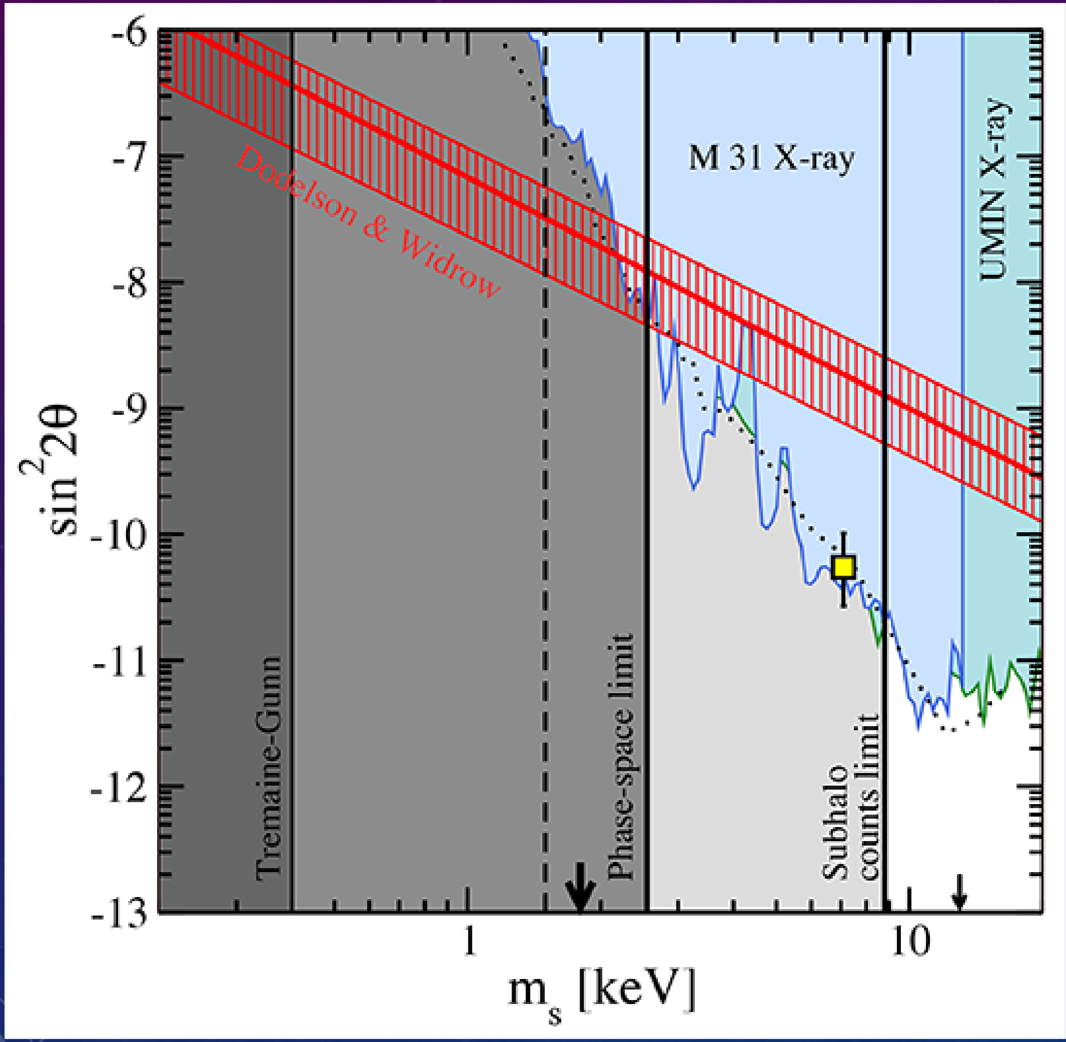




Caution:

many nearby atomic transition lines

Sterile neutrino DM parameter space



Horiuchi et al
1311.0282

Asymmetric dark matter

Two birds with one stone: (i) Relic DM abundance
(ii) baryon-antibaryon asymmetry

❖ Motivation: $\Omega_{DM} \approx 5\Omega_b$

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

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

and $m_{DM} \approx 5m_b \approx 5$ GeV (prediction for DM mass)

❖ ADM replaces $\Omega_{DM} \approx \Omega_b$ puzzle, with a $m_{DM} \approx m_b$ puzzle

Asymmetric dark matter

Requirements:

- Mechanism to simultaneously create B(visible) and B(dark) asymmetries, or create an asymmetry in one sector and communicate it to the other.
- Sufficiently large DM annihilation cross section to annihilate the symmetric part (to leave only particles and no antiparticles).

Implications:

- Light DM.
- Suppressed indirect detection (nothing to annihilate with)
- Large annihilation cross section means either sizeable couplings with SM particles, or else new light degrees of freedom.

ADM annihilation cross section

WIMPs – relic density set by annihilation cross section

ADM – relic density set by asymmetry, *provided annihilation cross section is big enough to remove the symmetric part*
→ still need a WIMP-like cross section!

Fractional asymmetry: $$r \equiv \frac{n(\bar{\chi})}{n(\chi)}$$

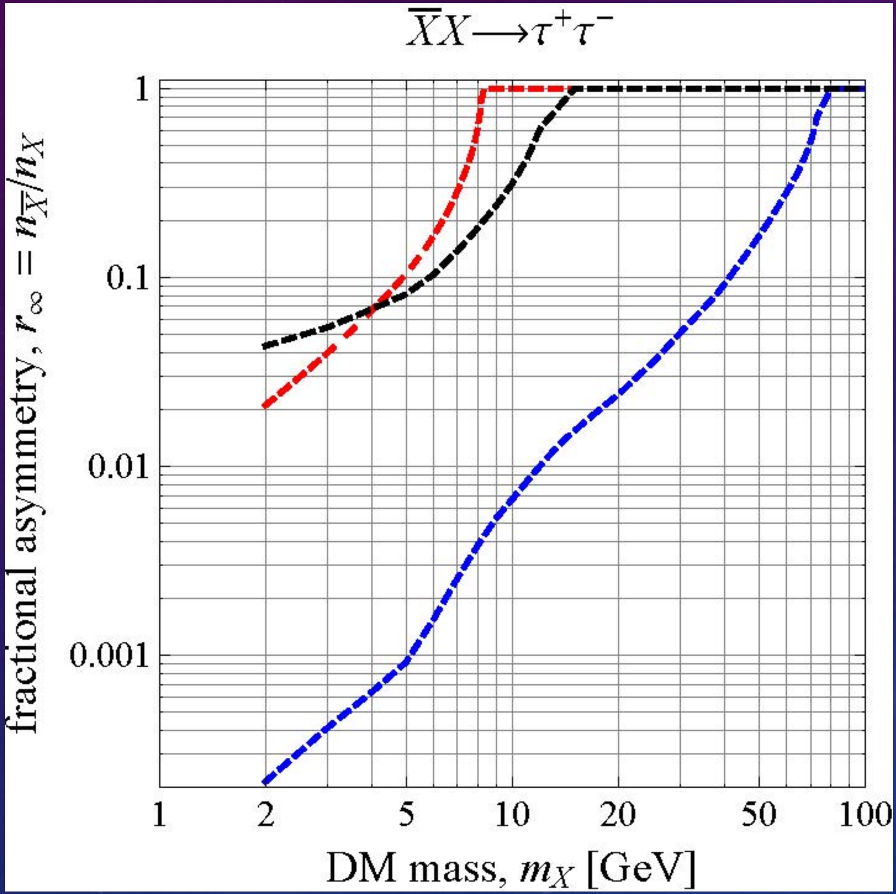
$$r_\infty \approx \exp\left[-2\left(\frac{\sigma_0}{\sigma_{0,\mathrm{WIMP}}}\right)\left(\frac{1-r_\infty}{1+r_\infty}\right)\right] \xrightarrow{r_\infty \ll 1} \exp\left[-2\sigma_0/\sigma_{0,\mathrm{WIMP}}\right]$$

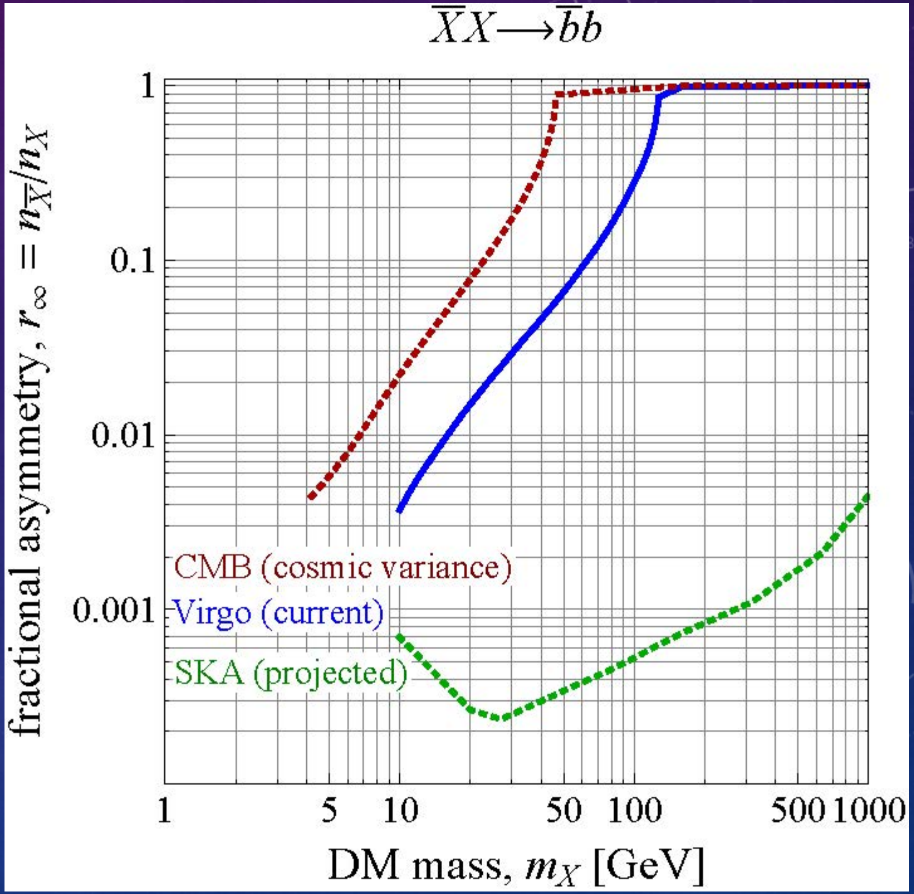
For $r_\infty < 0.1$, require: $$\sigma_0 \gtrsim 1.4\,\sigma_{0,\mathrm{WIMP}}$$

Graesser et al., arXiv:1103.2771

ADM – indirect detection limits

Bell, Horiuchi & Shoemaker, arXiv:1408.xxxx,





Current limits

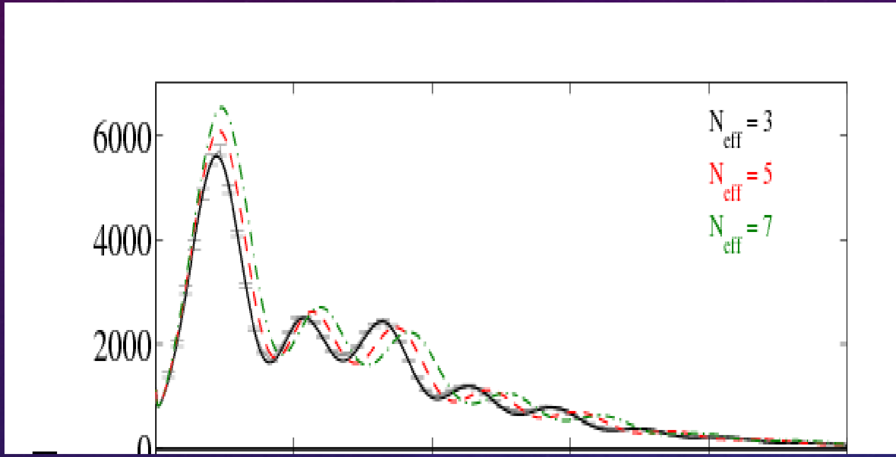
Future limits

Dark Radiation

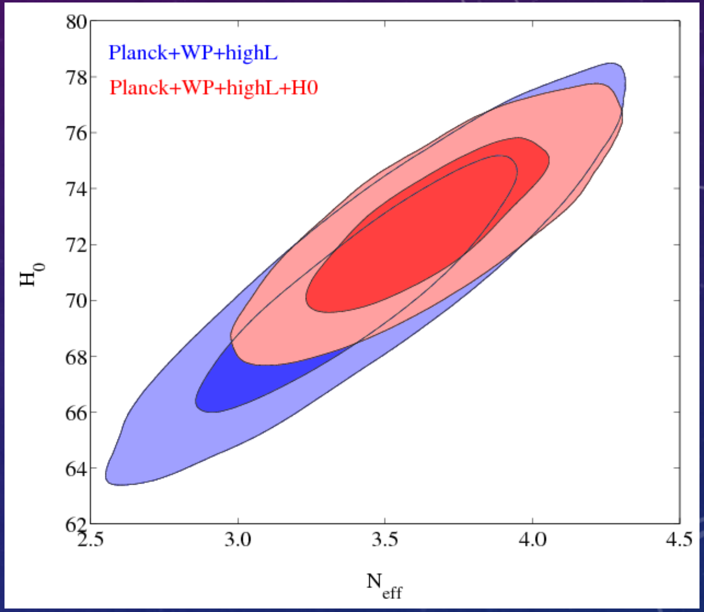
- Dark radiation = relativistic dark particles. E.g. dark photons,dark neutrinos, or similar.
- Needed in some models (e.g. many asymmetric DM models)
- This radiation need not have the same temperature as ordinary radiation.
- e.g. models with "dark atoms" have hydrogen-like states formed from two oppositely charged particles interacting via a massless $U(1)_D$ gauge boson.

The dark sector may have a particle spectrum as rich as the visible sector

- Dark Radiation leaves imprint in CMB (usually discussed in term of "effective number of neutrinos")
- CMB accommodates extra radiation:



Archidiacono et al, 1307.0637



- Can be more complicated: dark matter-dark radiation coupling leads to "dark acoustic oscillations"

Cyr-Rancine and Sigurdson

Dark Matter Self Interactions

❖ Dark matter should not strongly self interact.

- The Bullet Cluster
- Halo shapes (self interactions make galaxies too spherical)

❖ But some amount of self interaction is usually expected.

This is ok, and maybe even be desired:

→ 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, …

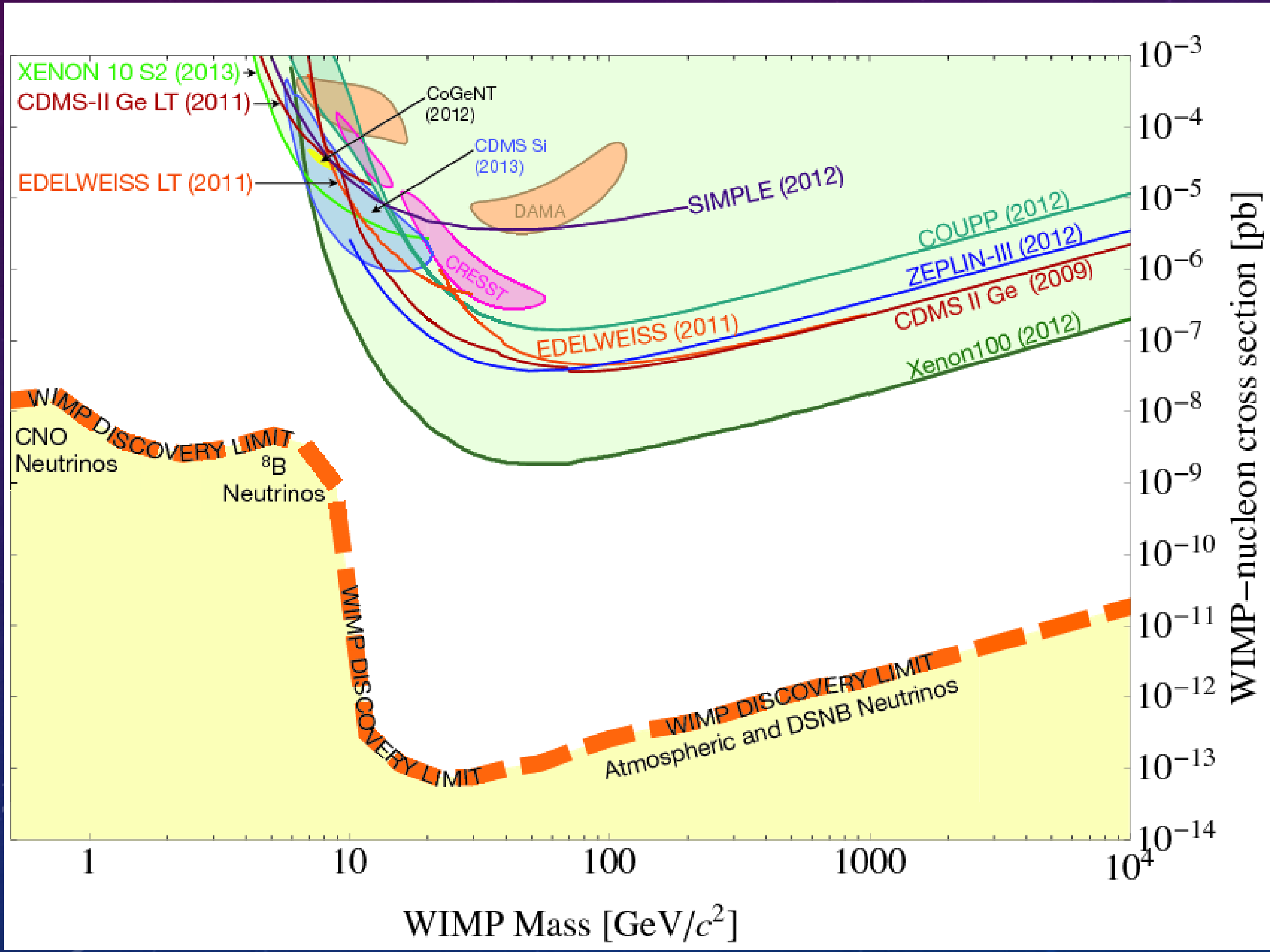
Outlook

- WIMP...is this idea compelling, or are we searching under the lamp post?
- If DM is a conventional WIMP, discovery should be close!
- ADM…is the similarity of the dark and visible matter densities an important clue, or just a red herring?
- Direct detection, indirect detection, colliders, solar WIMP searches, cosmological probe...all have good sensitivity and provide complementary information.
- We should remember that many dark-sector models have a rich spectrum of new particles. Indeed, DM may be multi-component.

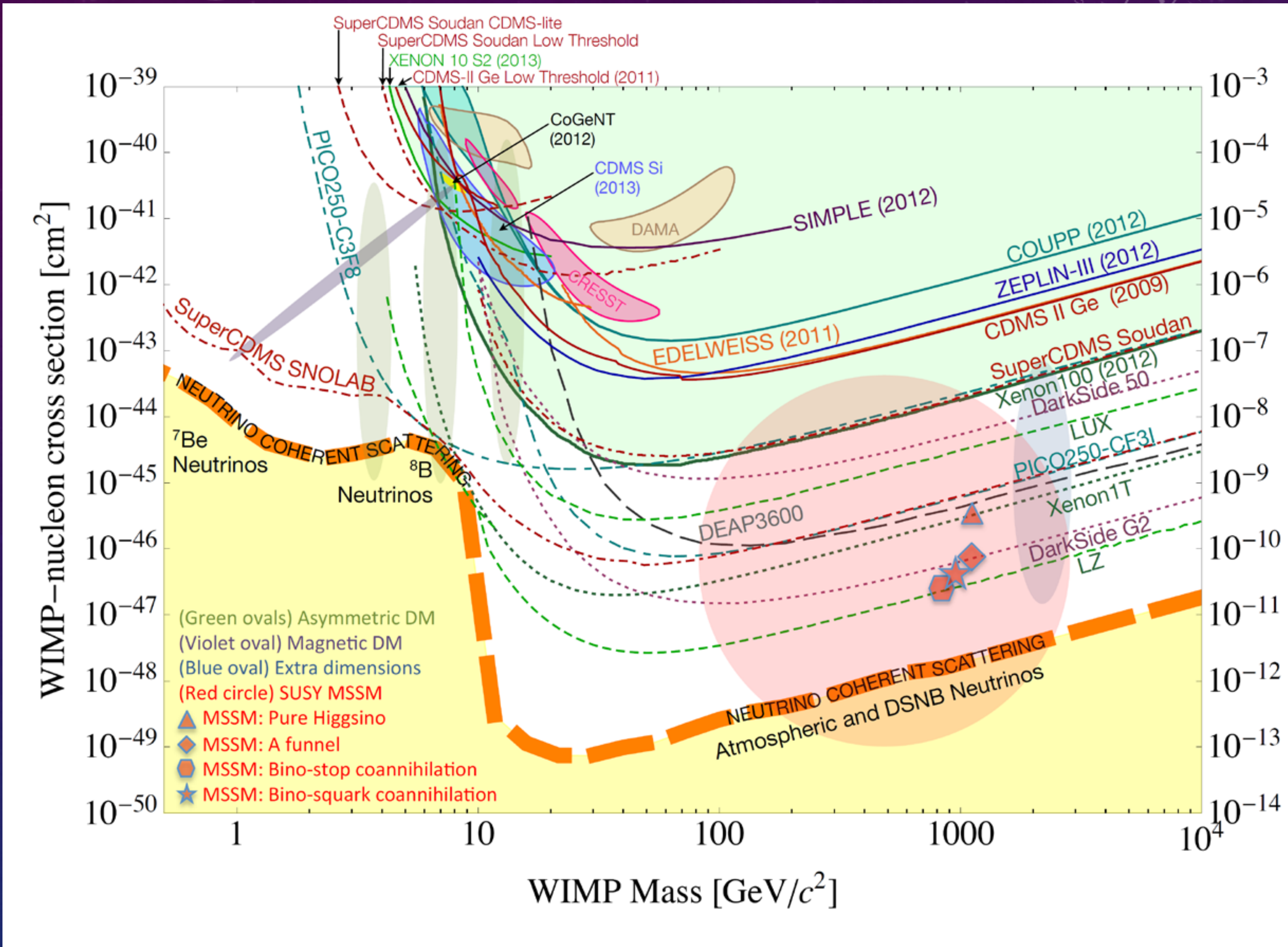
Extra slides

Future: “neutrino floor” is irreducible background

Coherent neutrino-nucleus scattering of solar/atmospheric neutrinos!



Billard et al
arXiv:1307.5458



Cushman et al arXiv:1310.8327

Linking dark matter and baryogensis

Connect (i) Relic DM abundance
(ii) baryon-antibaryon asymmetry

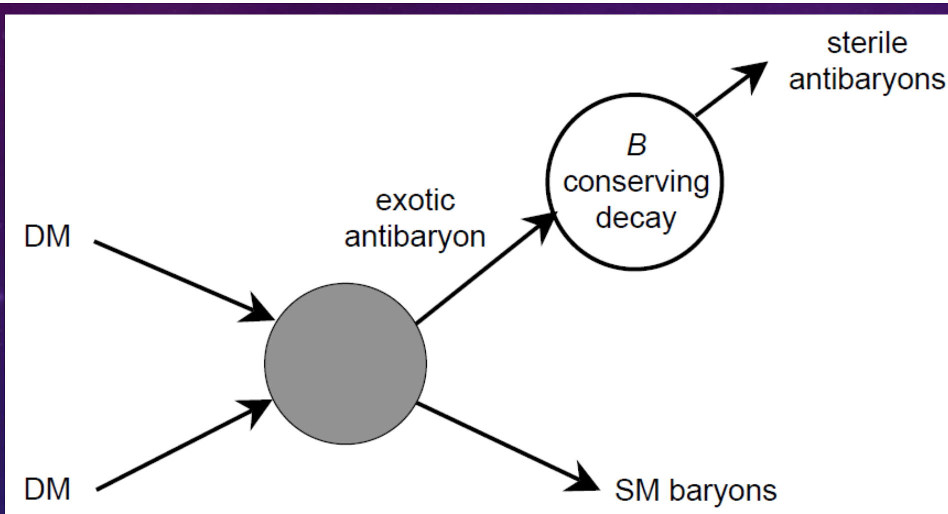
Various ideas: Asymmetric dark matter, WIMPy baryogensis, Baryomorphosis, DM assimilation, ……

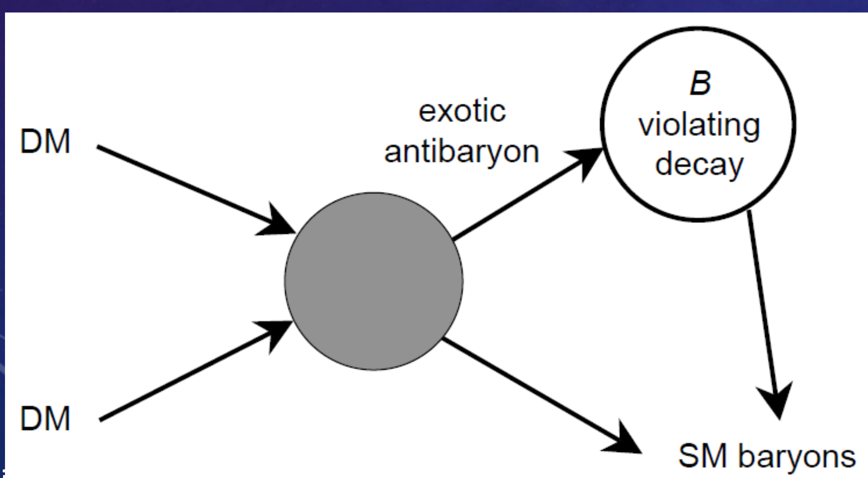
	Asymmetric dark matter	WIMPy baryogenesis
WIMP miracle	✘	✓
Explain $\Omega_{DM} \approx \Omega_b$	✓	✘

ADM: Many papers! See reviews by Petraki and Volkas 1305.4939 and Zurek 1308.0388.
WIMPy baryogenesis: Cui, Randall and Shuve, 1112.2704; Bernal et al., 1210.0094, Bernal et al., 1307.6878; Kumar & Stengel, 1309.1145
Baryomorphosis: McDonald 1009.3227 Dark matter assimilation: D'Eramo et al., 1111.5615

WIMPy baryogensis

Require WIMP annihilation satisfy the Sakharov conditions
→ a baryon asymmetry can be generated from DM annihilations





DM annihilation creates asymmetry in exotic antibaryons, then sequestered in sterile sector

Asymmetry in exotic antibaryons, which decay to SM baryons

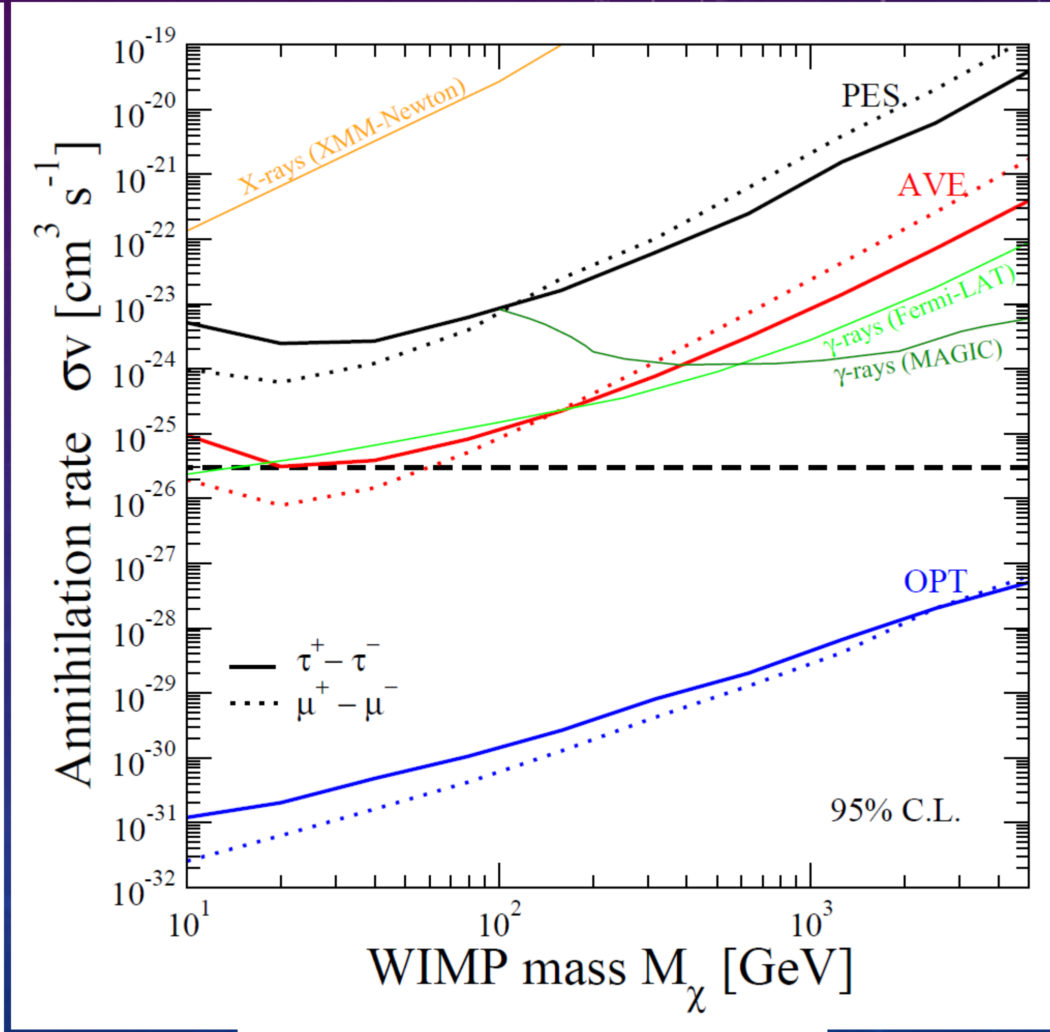
Cui, Randall and Shuve, 1112.2704

dSph radio limits

Most annihilation channels produce e- and e+

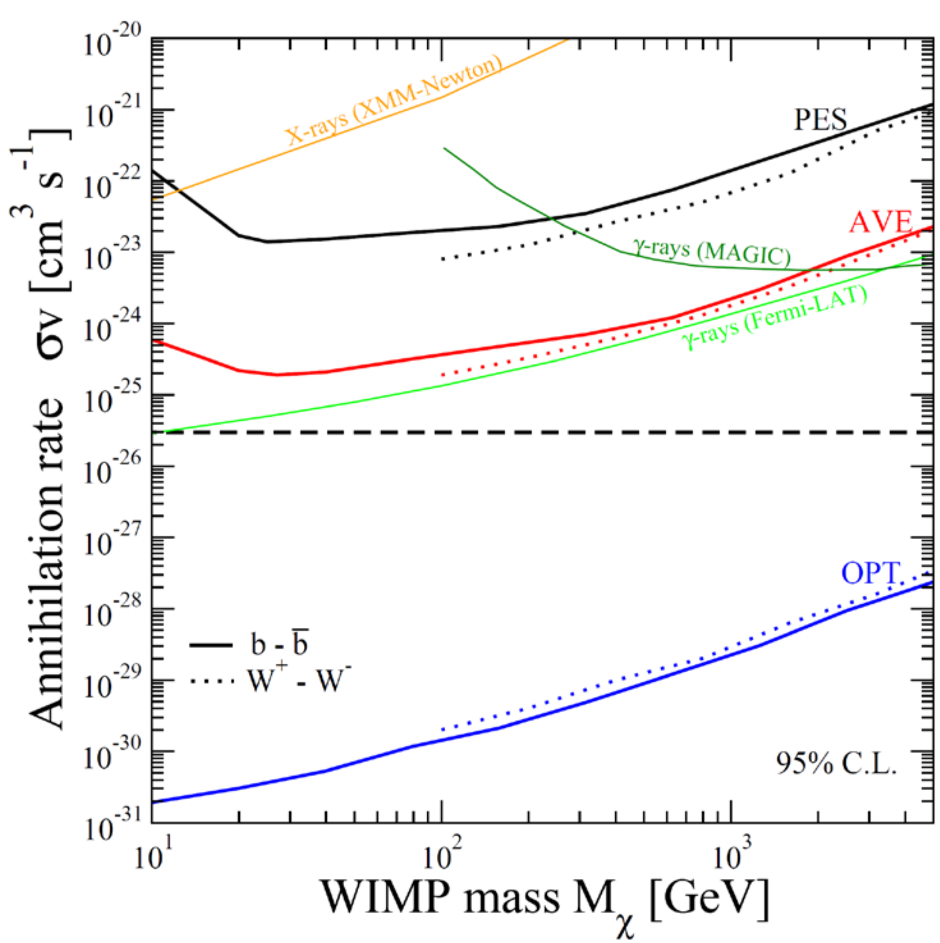
e+, e- loose energy (multiple processes) as they propagate

- Includes synchrotron radiation, at radio wavelengths
- Rates depend upon diffusion assumptions, especially magnetic field strengths

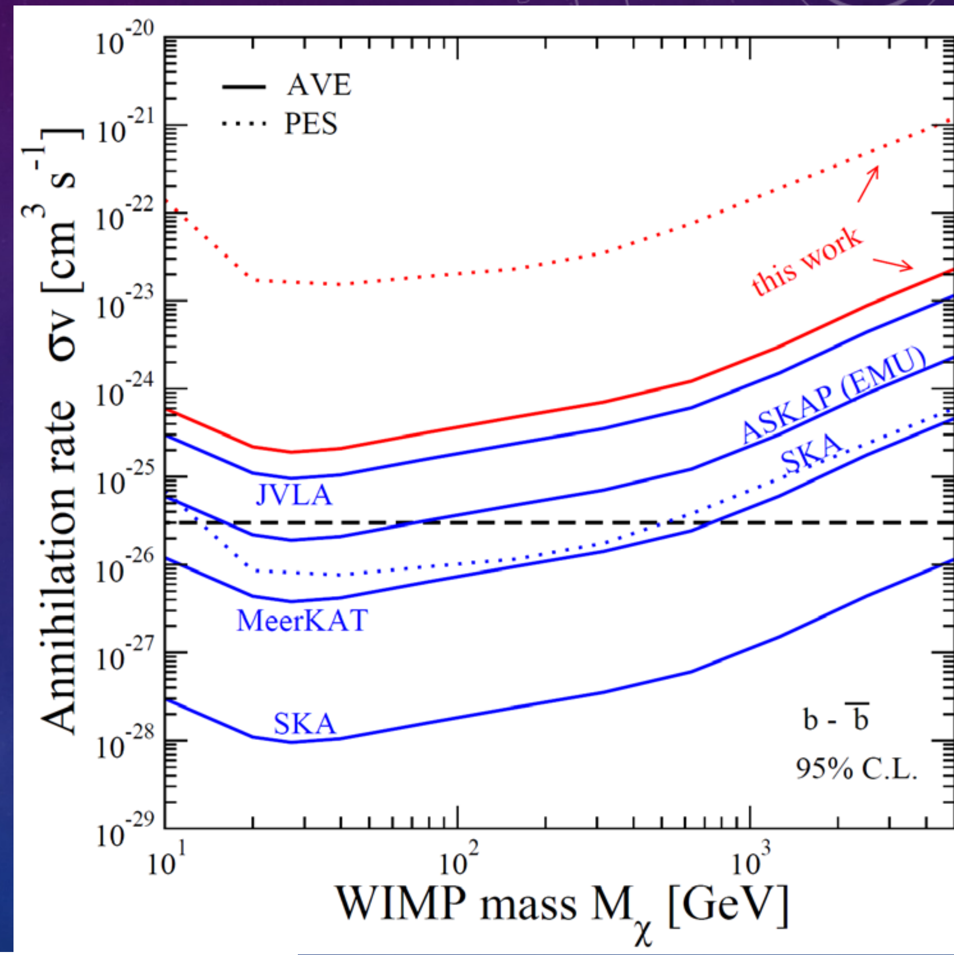


Regis et al, arXiv:1407.4948

current



future



Regis et al, arXiv:1407.4948

Effective operators for DM interactions

Model-independent description of DM interactions with SM particles:

$$L_{Eff} = \frac{1}{\Lambda_{\text{eff}}^2} \bar{\chi}\Gamma_\chi \chi \; \bar{q}\Gamma_q q$$

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

Advantages:

- model-independent description

Disadvantages:

- breaks down if q^2 is large or mediators light

Name	Operator	Coefficient	DD
D1	$[\bar{\chi}\chi][\bar{f}f]$	$m_f\Lambda^{-3}$	SI
D2	$[\bar{\chi}\gamma^5\chi][\bar{f}f]$	$im_f\Lambda^{-3}$	–
D3	$[\bar{\chi}\chi][\bar{f}\gamma^5 f]$	$im_f\Lambda^{-3}$	–
D4	$[\bar{\chi}\gamma^5\chi][\bar{f}\gamma^5 f]$	$m_f\Lambda^{-3}$	–
D5	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	SI
D6	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu f]$	Λ^{-2}	–
D7	$[\bar{\chi}\gamma^\mu\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	–
D8	$[\bar{\chi}\gamma^\mu\gamma^5\chi][\bar{f}\gamma_\mu\gamma^5 f]$	Λ^{-2}	SD
D9	$[\bar{\chi}\sigma^{\mu\nu}\chi][\bar{f}\sigma_{\mu\nu} f]$	Λ^{-2}	SD
D10	$[\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi][\bar{f}\sigma_{\mu\nu} f]$	$i\Lambda^{-2}$	–
D11	$[\bar{\chi}\chi][G_{\mu\nu}G^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	SI
D12	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}G^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D13	$[\bar{\chi}\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$i\alpha_S\Lambda^{-3}$	–
D14	$[\bar{\chi}\gamma^5\chi][G_{\mu\nu}\tilde{G}^{\mu\nu}]$	$\alpha_S\Lambda^{-3}$	–

Strong bounds on EFT operators!

Bounds on EFT operators are becoming quite constraining!

❖ Relic density
→upper limit on Λ_{eff} (to prevent over-closure)

❖ Direct detection, collider, and indirect detection
→ lower limits on Λ_{eff} (no signals)

For many operators, these limits are approaching!

If the EFT description is relevant for DM, we should see a signal soon!

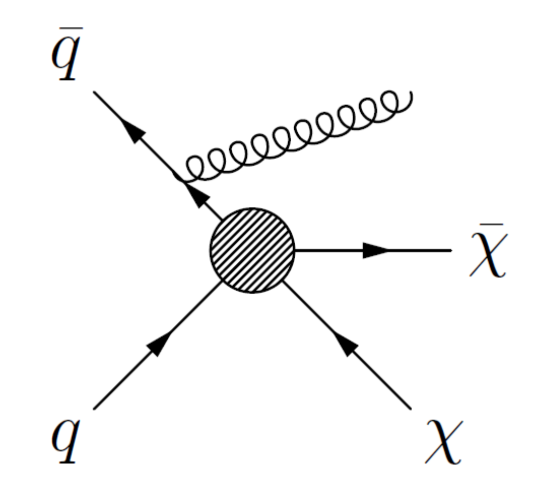
Dark Matter at the LHC

- The dominant DM production process is invisible (DM stable, weakly interacting) : $\bar{q}q \rightarrow \chi\chi$
- Need visible particles in the final state, to recoil against missing transverse energy

$$\bar{q}q \rightarrow \chi\chi + \text{single SM particle}$$

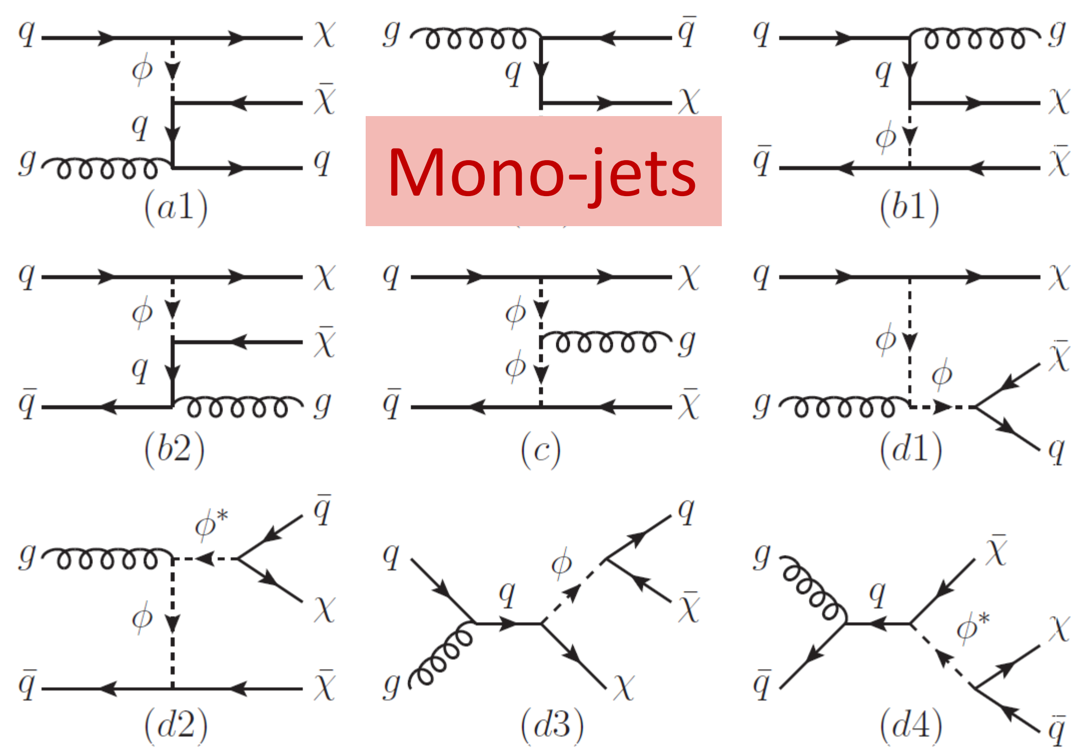
Mono-X process in which DM is visible as a high pT state + missing ET

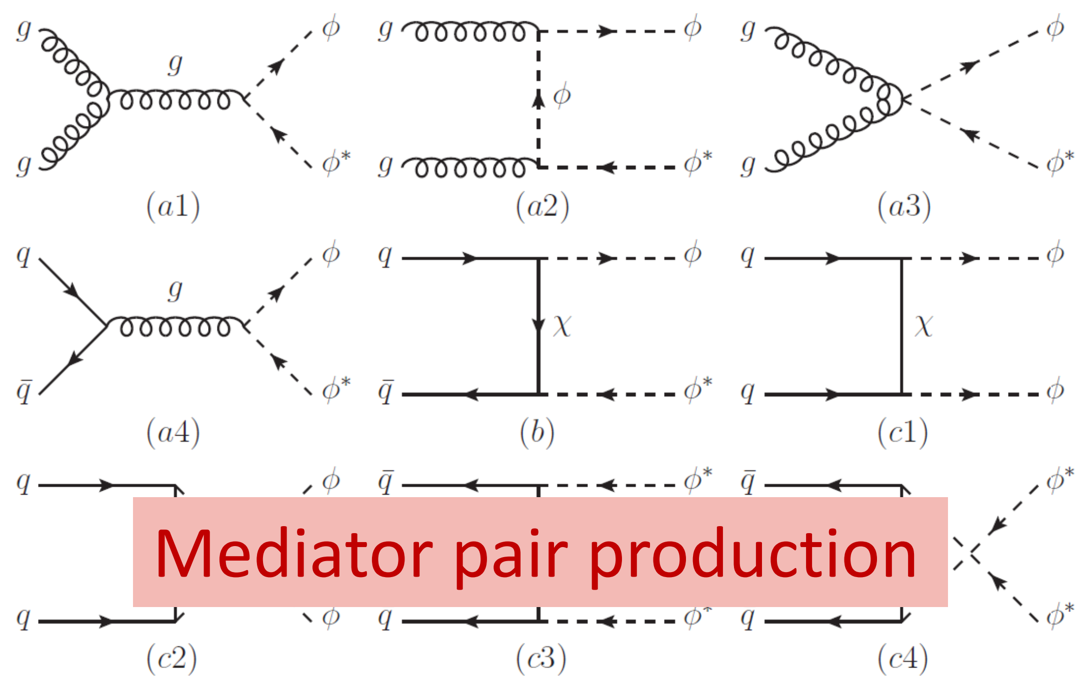
→ Mono-jet, mono-photon, mono-Z, mono-W, mono-Higgs



Beyond an EFT:

t-channel scalar mediator





H.An et al, 1308.0592

See also:
Chang et al. , 1307.8120
Bai & Berger, 1308.0612
DiFranzo et al., 1308.2679