Frontiers in Astrophysics

Particle Astrophysics:

Dark Matter 3: Indirect Detection

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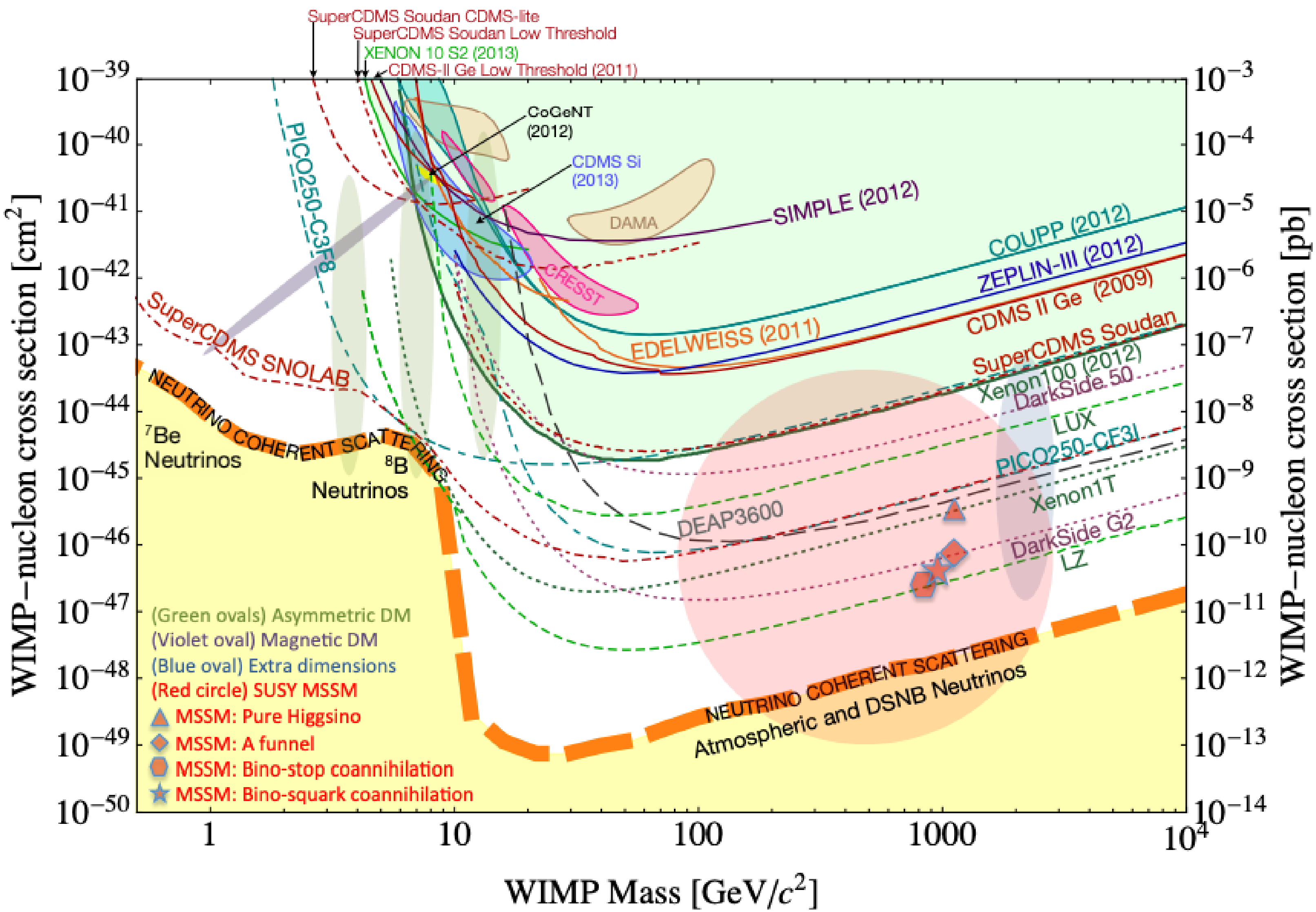
Credit to Pat Scott for many of the slides

Overview

- Results of direct detection experiments
  - Hints of non-zero results?
- Survey of indirect detection
  - Uncharged, Charged messengers
  - General theory, what we probe
  - Some experiments, results
- If time: Where do colliders fit in?

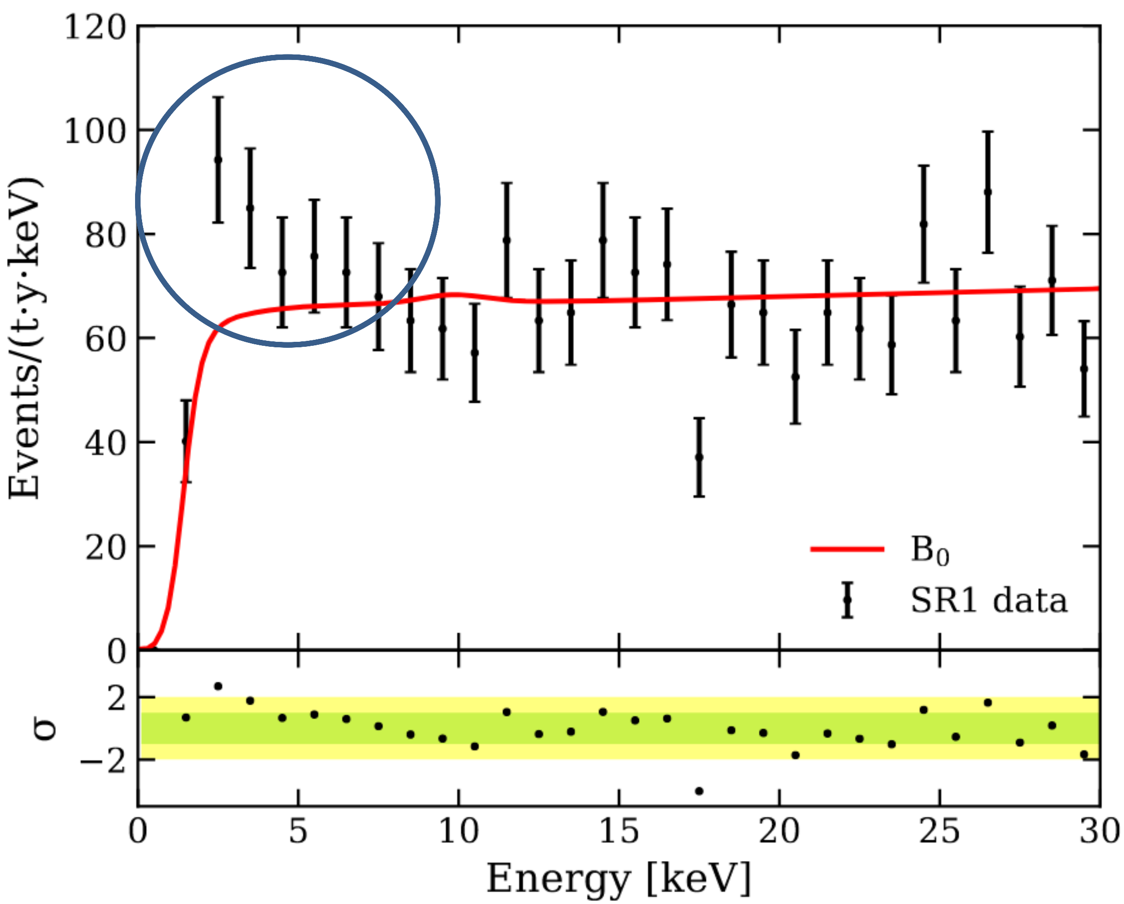
Part 1: Direct Detection Results
Hints of positive detections?



img: arXiv:1310.8327

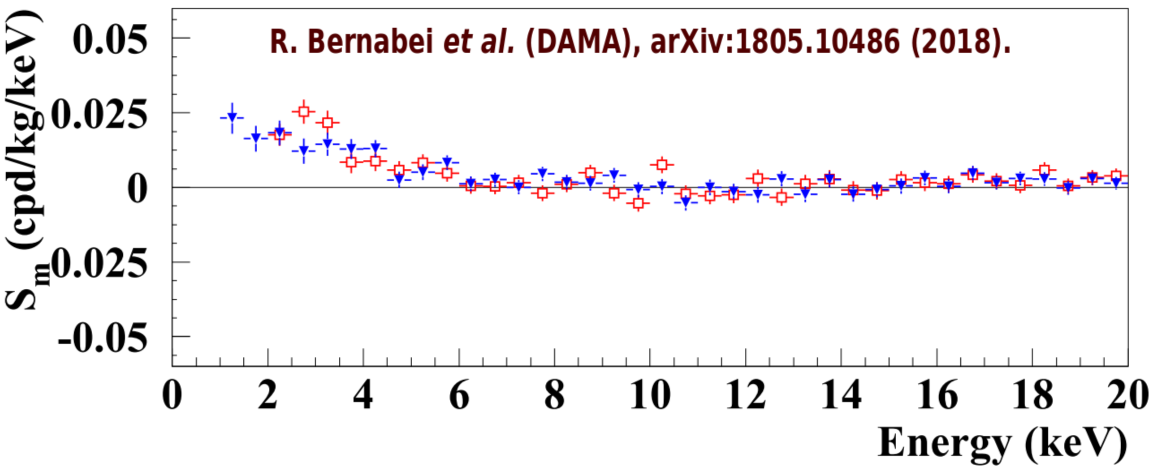
Observation of Excess Electronic Recoil Events in XENON1T

XENON1T, Phys. Rev. D **102**, 072004 (2020).

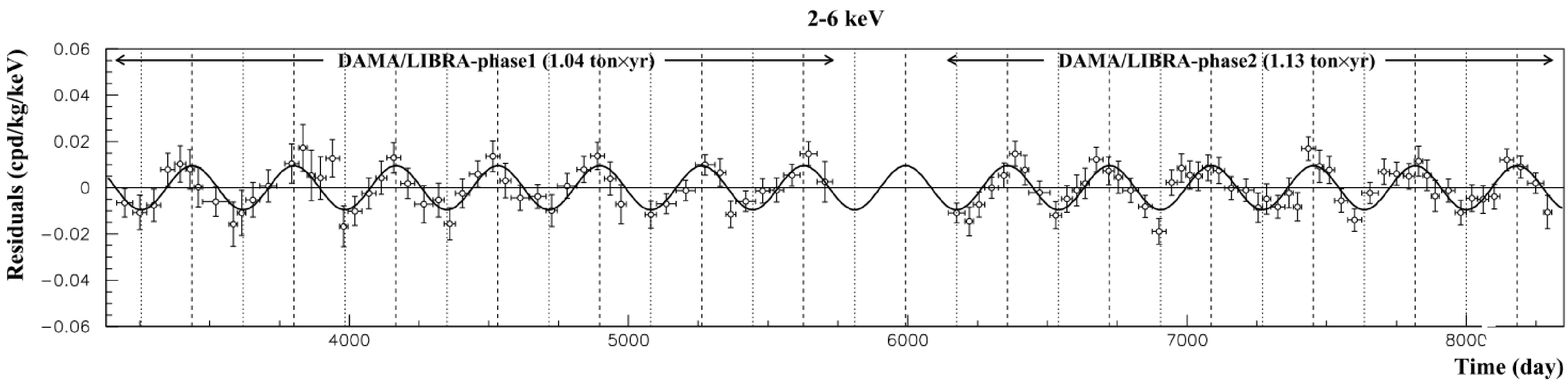


- 0.65 “tonne-years”
- Observe excess (over known background)
- Low-mass (MeV-GeV) WIMPs scattering on electrons?
- Most likely unaccounted for noise.. but interesting

DAMA-LIBRA

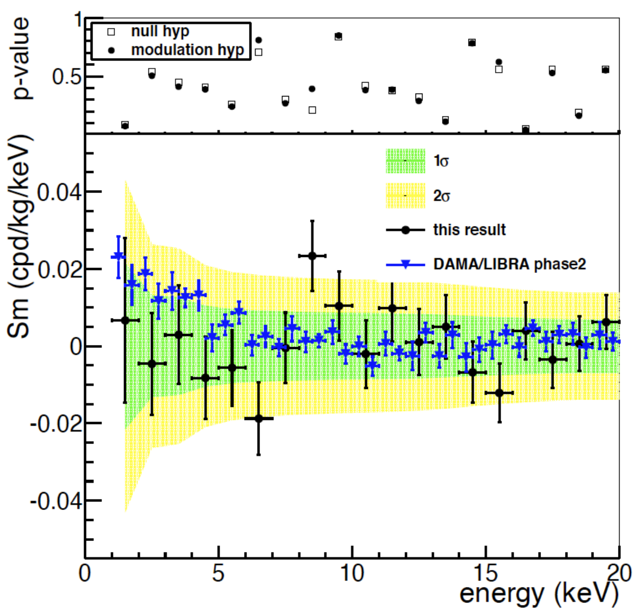


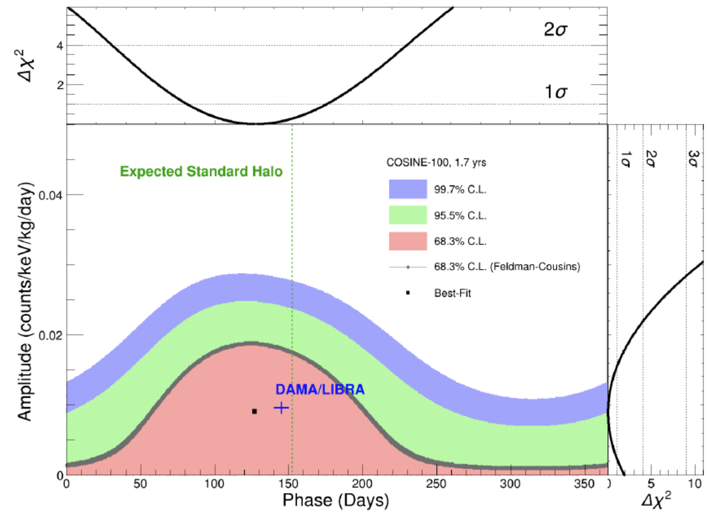
- NaI detector
- Low E, high noise: modulation
- Phase 1: 1.13 ton-year (blue)
- Phase 2: 1.33 ton-year (red)
- Low energy (1keV)
- 12 σ modulation (correct phase)



DAMA-LIBRA

ANAIS-112 and COSINE-100 have been built to test DAMA annual modulation directly. . . but need more exposure

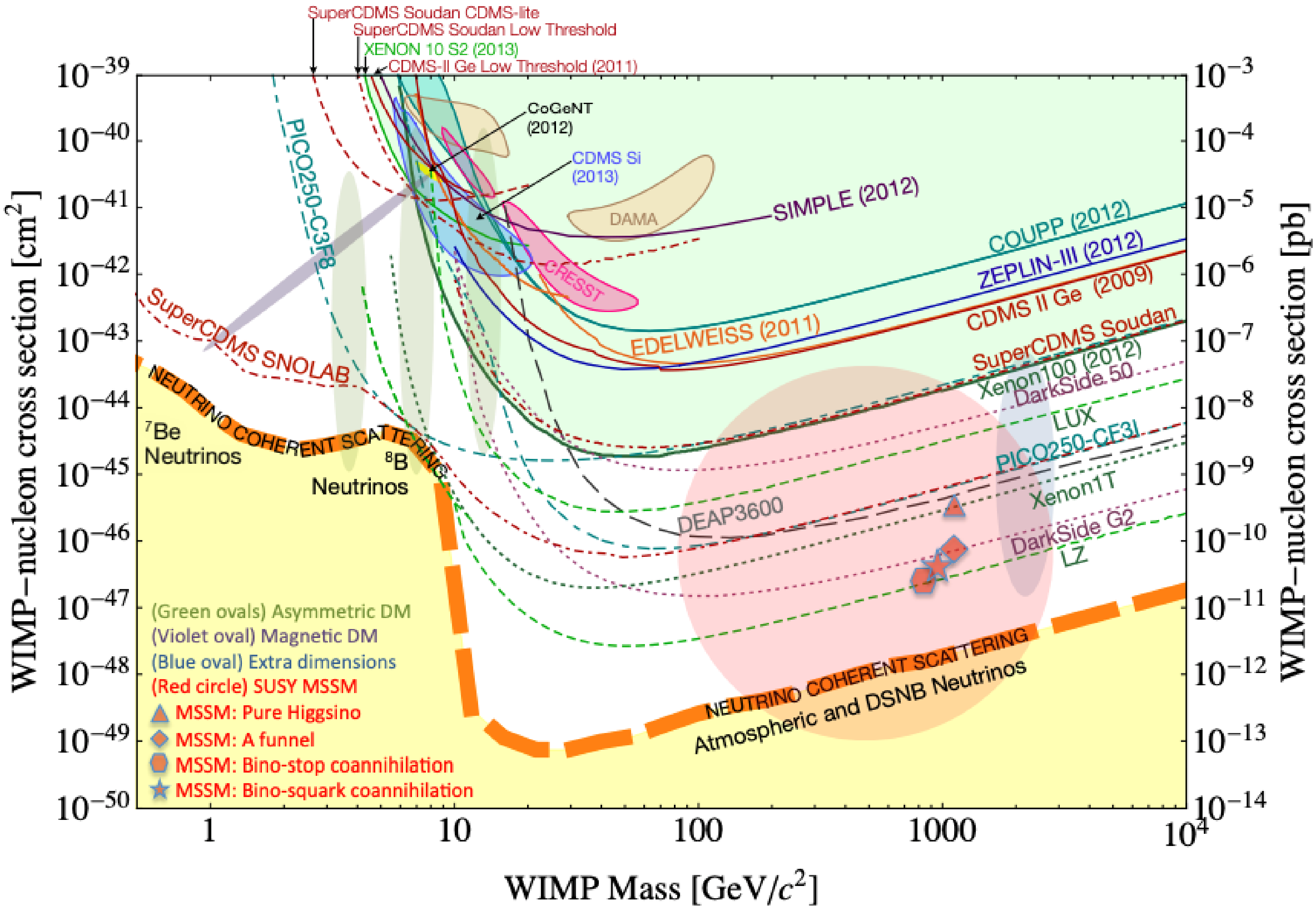




ANAIS, Phys. Rev. Lett. 2019
COSINE, Phys. Rev. Lett. 2019

- Very hard to reconcile with other experiments (XENON, COSINE, ANAIS)
- COSINE total rate excludes DAMA for most models
- SABRE – build NaI detector in southern hemisphere (Stawell)
- BUT unlikely to help (COSINE already excludes, and has head start)
- Still: not explained

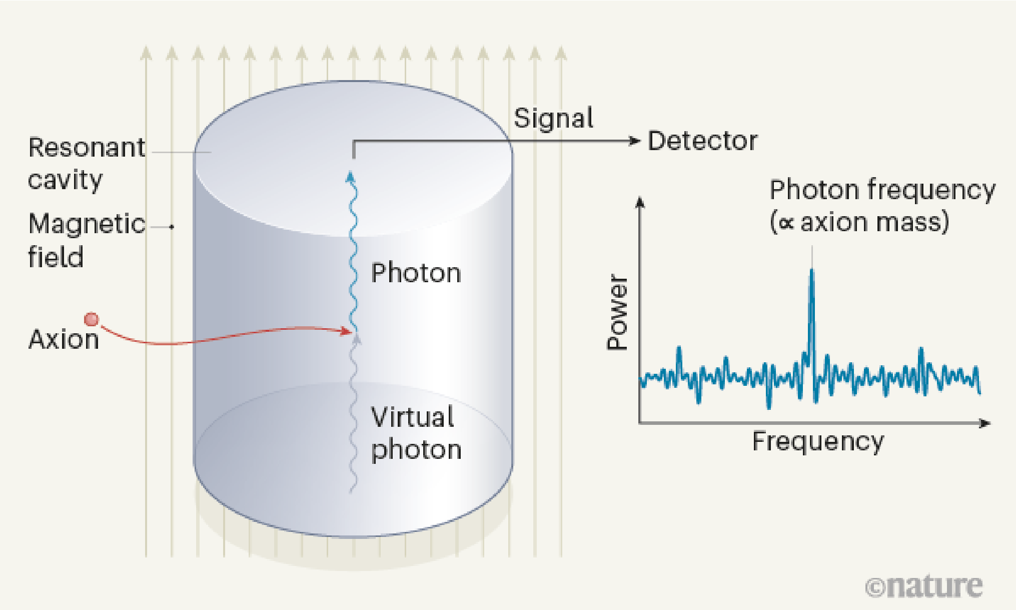
Future



img: arXiv:1310.8327

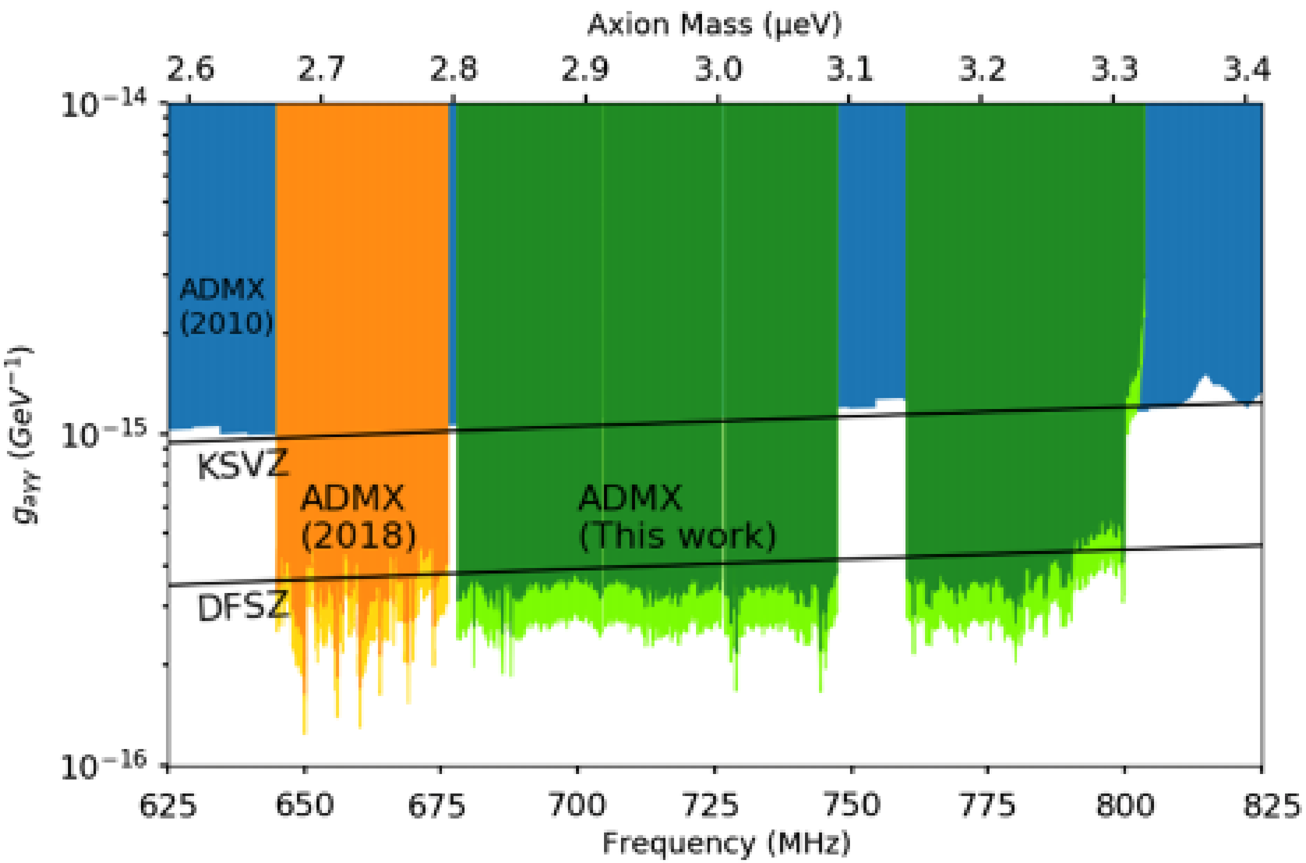
Bonus: Axions (reminder)

- Low-mass (<< eV), high number:
  Axion condensate (classical axion field)
- May be cold dark matter
- Nice candidate: solve two problems (strong CP + dark matter)
- Axion-photon conversion: detection channel



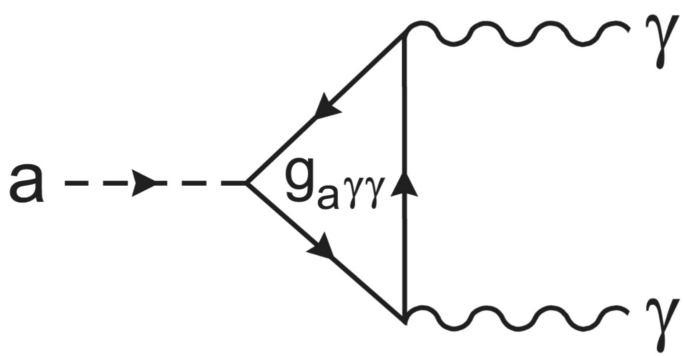
ADMX

Bonus: Axions Constraints

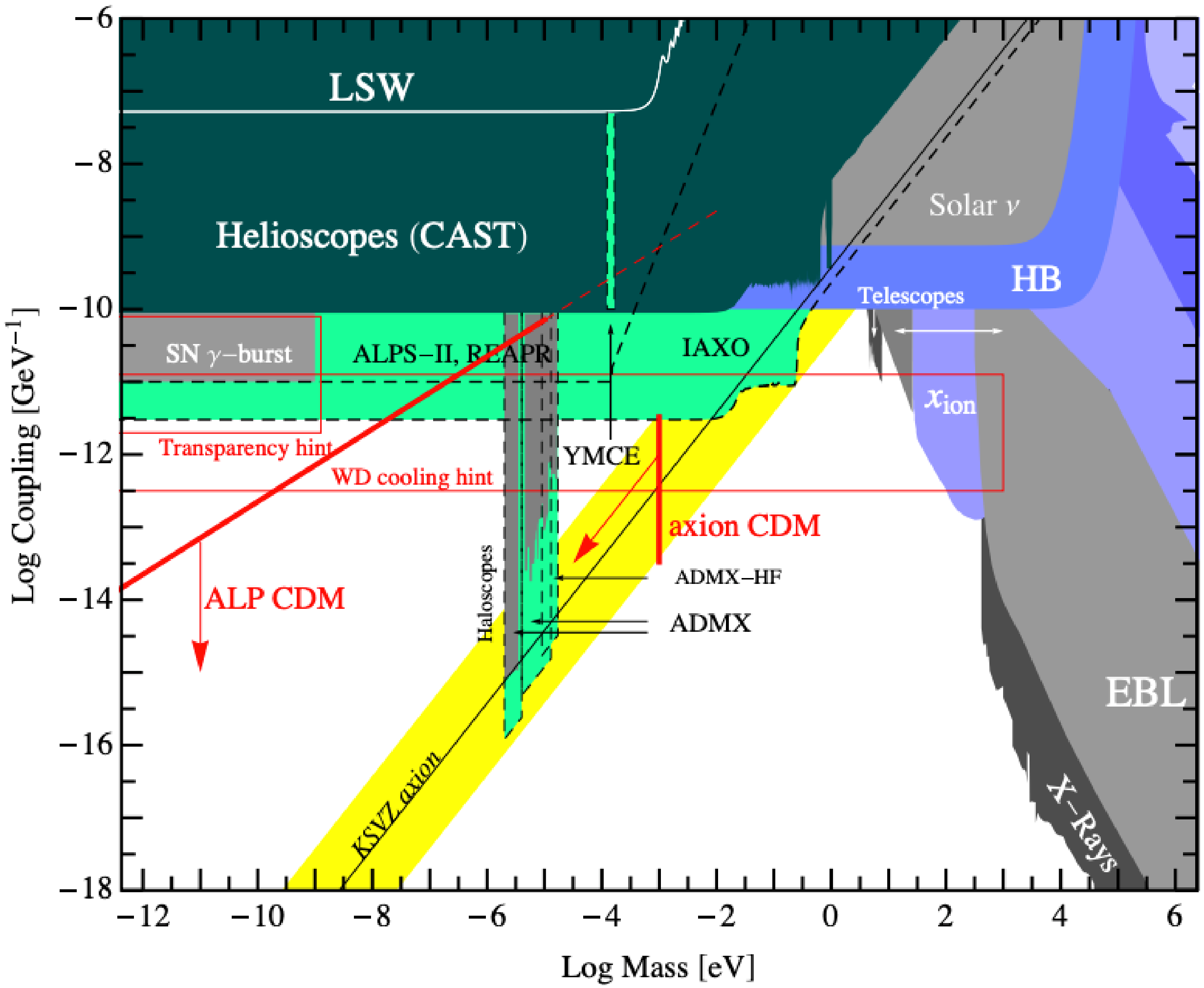


ADMX, Phys. Rev. Lett. **124**, 101303 (2020).

- Very narrow mass range
- Other experiments less sensitive, but cover wider range



Bonus: Axions Constraints



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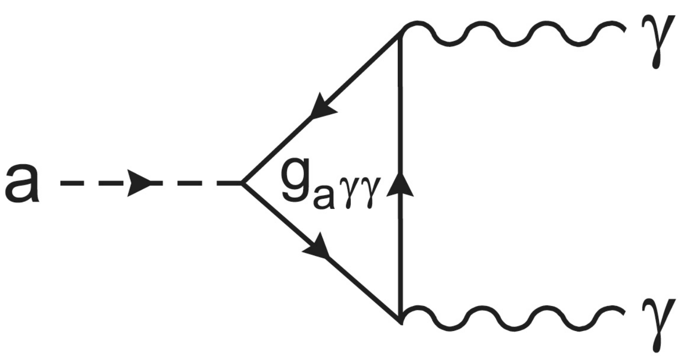
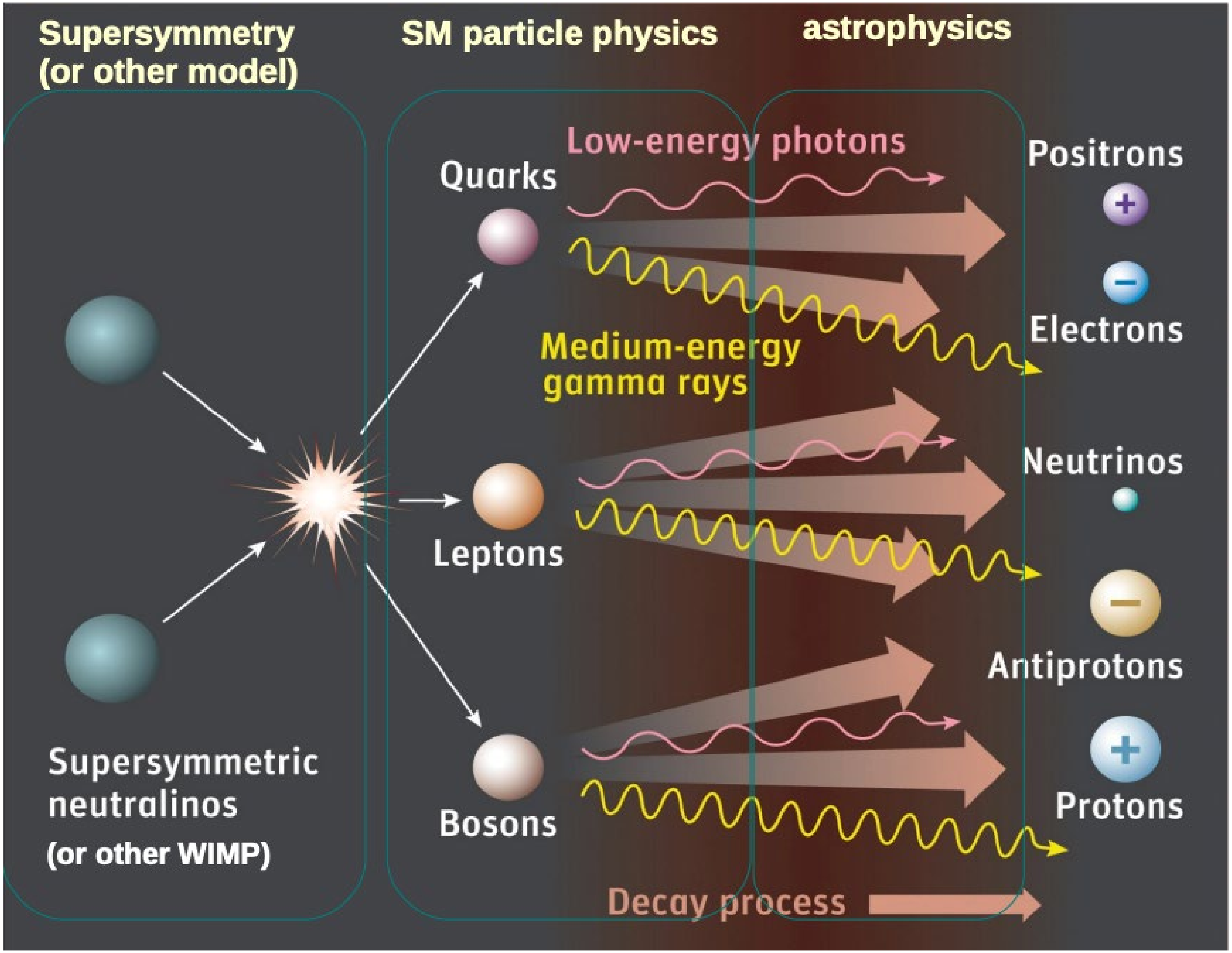


Review: A. Ringwald, Dark Universe 1, 116 (2012)

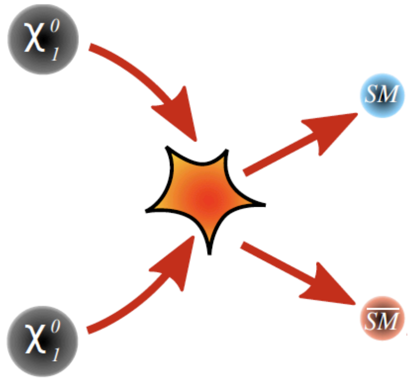
Part 2: Indirect Detection



What is indirect detection?

Looking for Standard Model particles produced by dark matter annihilation or decay.

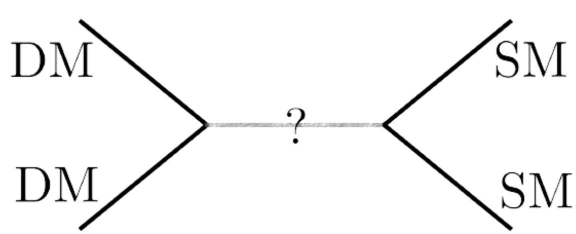
- neutrinos – IceCube, Super-K, KM3NET
- gamma-rays – Fermi-LAT, HESS, CTA
- X-rays – XMM-NEWTON, Chandra, NuStar
- anti-protons – PAMELA, AMS-02, CALET
- anti-deuterons – AMS-02, GAPS
- e^+e^- – PAMELA, Fermi, AMS-02, CALET
  $\rightarrow$ secondary radiation: inverse Compton, synchrotron, bremsstrahlung
- secondary impacts on the CMB, reionisation
- 'indirect direct detection' $\rightarrow$ impacts on solar and stellar structure

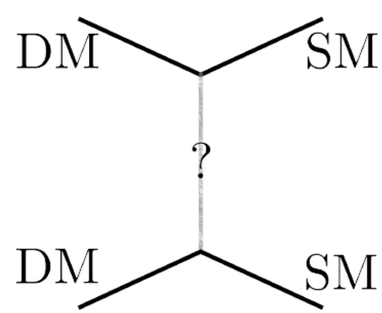


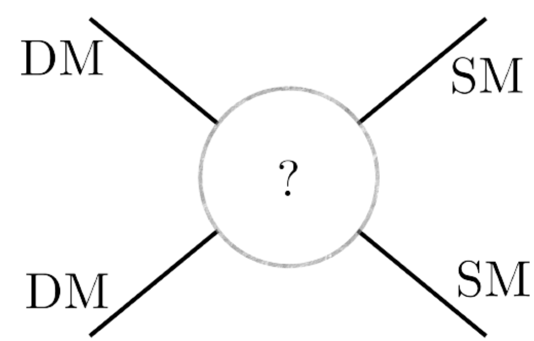
Neutral messengers
Charged messengers
Other messengers

What we can probe

- Direct detection
  - Probes DM-SM scattering cross section
    - (Typically DM-nucleus)
- Indirect detection
  - Typically directly probes annihilation cross-section
  - cf thermal production (project 3)



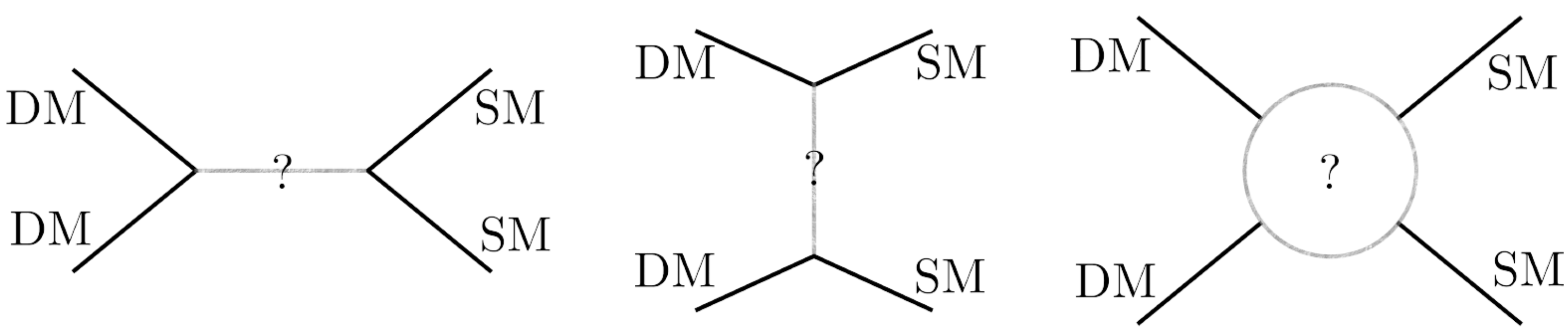




What we can probe

Indirect detection probes:

- DM mass m_χ
- annihilation cross-section $\langle \sigma v \rangle$ + branching fractions to different SM final states
  $\longrightarrow$ mediator mass + mediator couplings to DM and SM
- decay width Γ_χ + branching fractions to different SM final states
  $\longrightarrow$ DM couplings to SM
- scattering cross-section with nuclei
  (neutrinos + stellar 'indirect direct detection' only)
  $\longrightarrow$ mediator mass + mediator couplings to DM and SM



Neutral fluxes and propagation

Gamma rays, X rays and neutrinos are nice because they travel straight

$\Longrightarrow$ they point straight back to their sources

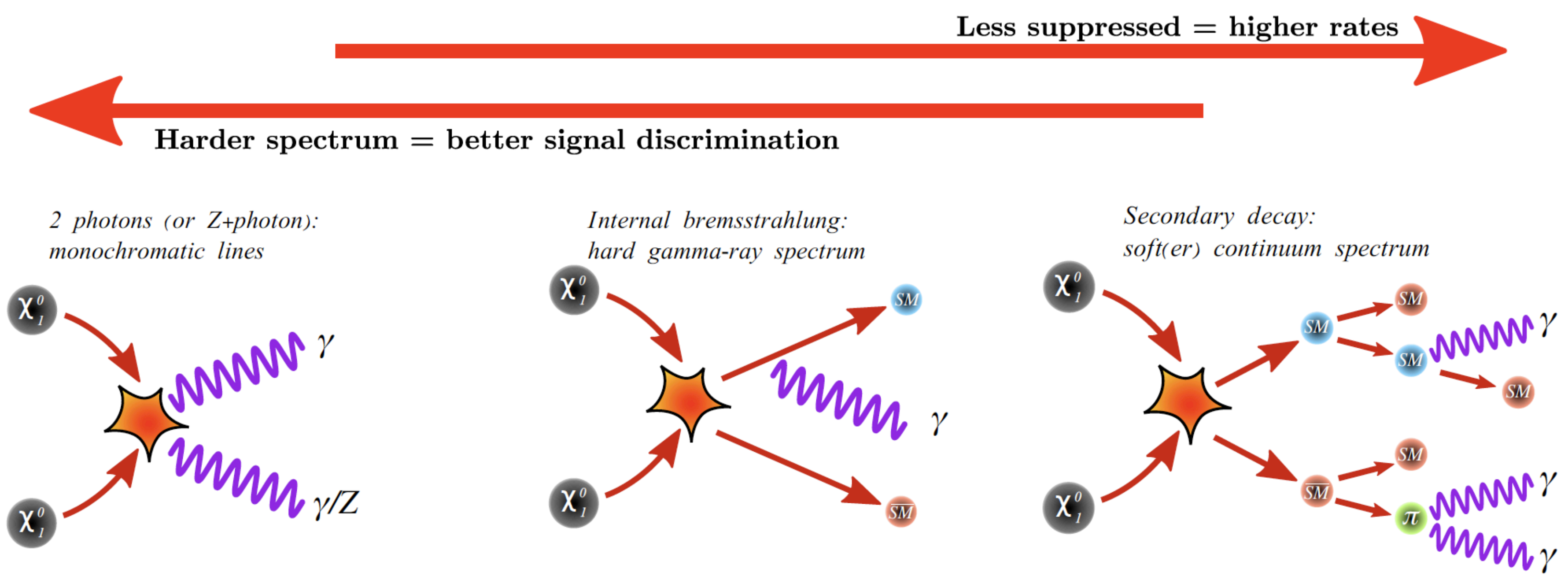
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1+BF}{8\pi m_\chi^2}\sum_f \frac{\mathrm{d}N_f^\gamma}{\mathrm{d}E}\sigma_f v \int_{\mathrm{l.o.s.}} \rho_\chi^2(l)\mathrm{d}l. \qquad (1)$$

Φ	$= \gamma, \nu$ flux	$\mathrm{d}N^\gamma/\mathrm{d}E$	= annihilation spectrum
$\frac{\mathrm{d}\Phi}{\mathrm{d}E\mathrm{d}\Omega}$	= differential flux per	$\sigma_f v$	= annihlation cross-section
	= unit energy and solid angle	$\mathrm{l.o.s.}$	= line of sight
BF	= boost factor (substructure)	ρ	= DM density
f	= final state	l	= line parameter along l.o.s.

J factor is the 'astrophysical bit' integrated over some solid angle $\Delta\Omega$

$$J \equiv \int_{\Delta\Omega}\int_{\mathrm{l.o.s.}} \rho_\chi^2(l)\mathrm{d}l$$

Gamma-ray spectra



- 3 main gamma-ray channels:
  - monochromatic lines
  - internal bremsstrahlung (FSR + VIB)
  - continuum from secondary decay

(Final-state brem.; Virtual Internal brem.)

Monochromatic (100% 'hard') ~ GeV ; Hard (peaked high energy) ; soft

Gamma-ray spectra: Observation Targets

Look for targets with:

- Lots of DM
- Few other astrophysical processes that produce gamma rays

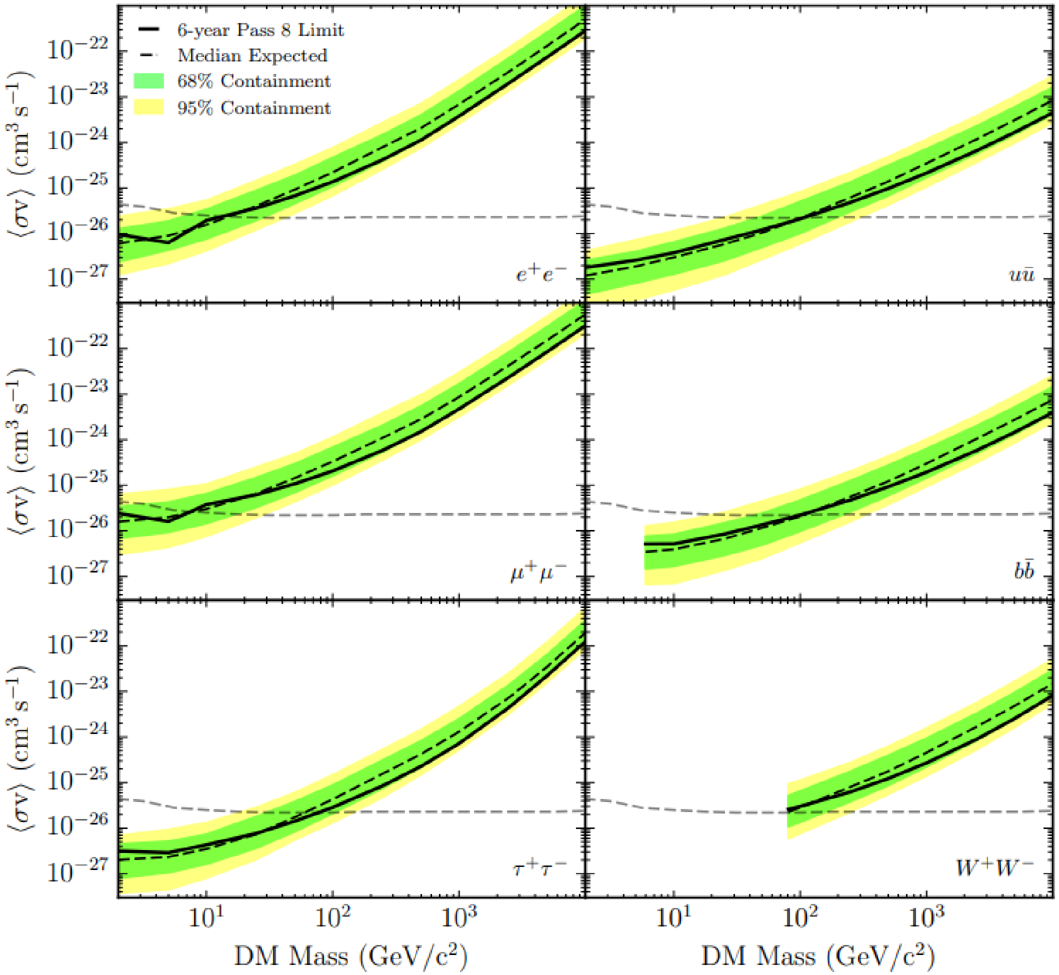
- $\Phi \propto$ annihilation rate $\propto \rho_{\rm DM}^2$

Likely targets:

- dwarf galaxies - low statistics, low BG
- Galactic centre - large signal, large BG
- Galactic halo - moderate signal, moderate BG
- clusters/extragalactic diffuse - large modelling uncertainties, low signal, low BG
- dark clumps - low statistics, low BG

Outside Galaxy (harder) [bracketing the last two items]

Gamma Rays: Dwarf Galaxies



Fermi-LAT arXiv:1503.02641

Phys. Rev. Lett. **115**, 231301 (2015)

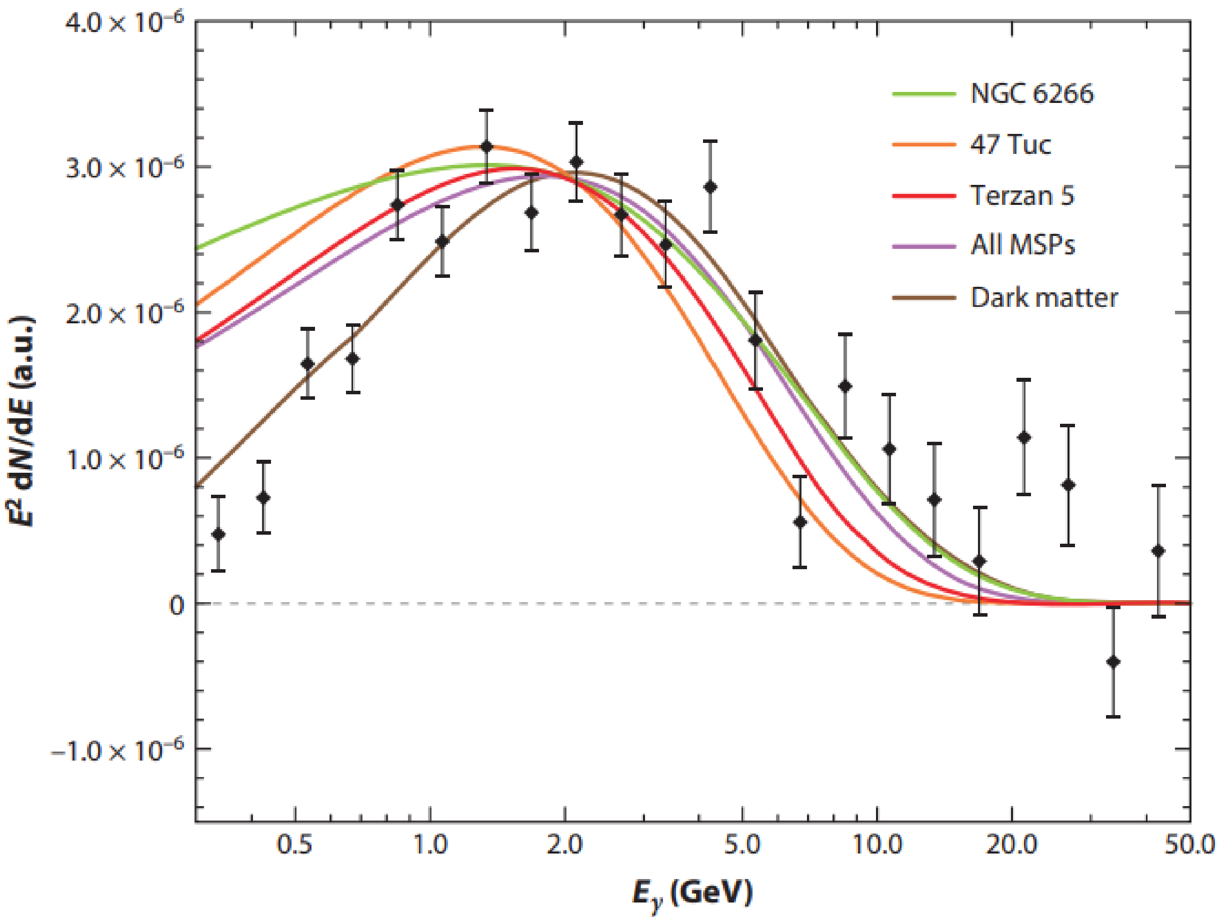
- Pass 8 event reconstruction
- 6 years of data
- 15 dwarfs

Gold standard for indirect detection.

Excludes canonical thermal cross-section up to $m_\chi \sim 100$ GeV.

Note model dependence though!

Galactic Centre Excess



- Excess of GeV gamma rays observed from GC
- (Excess = >expected)
- May be DM signal..
- Likely actually from pulsars
- DM Below 10 GeV excluded

img: Annual Review of Nuclear and Particle Science **70**, 455 (2020)

Galactic Centre Excess

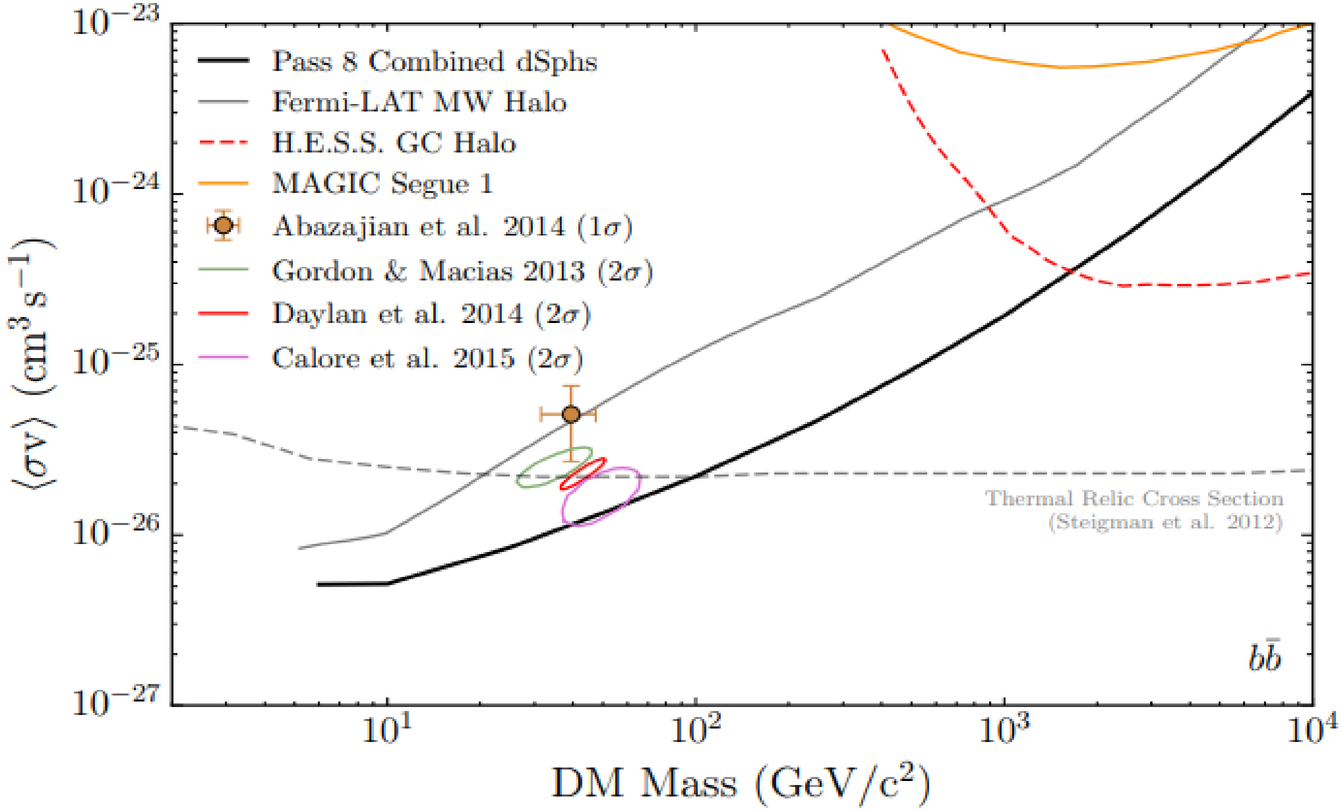
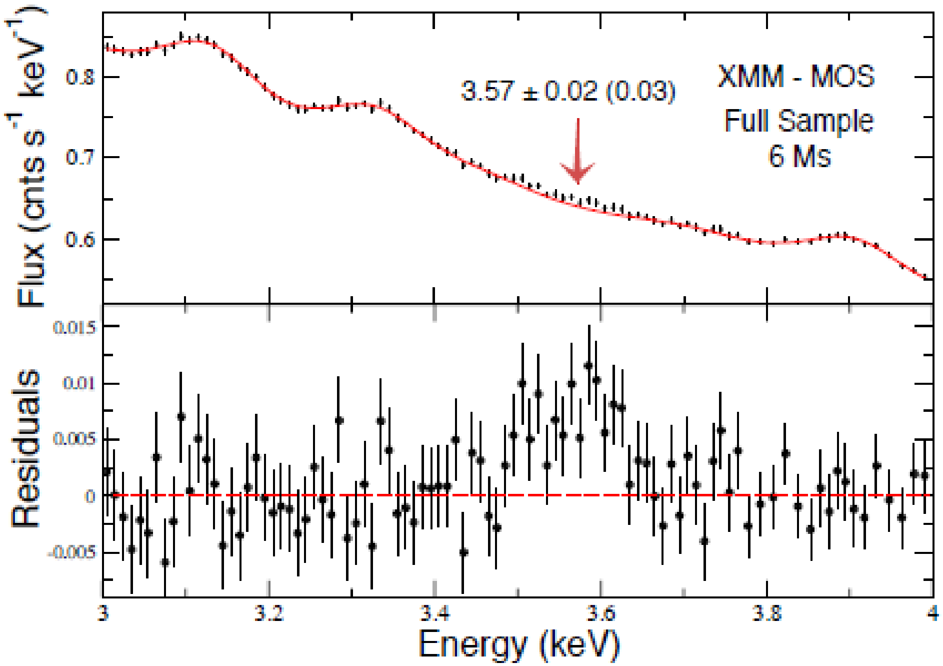


FIG. 2. Comparison of constraints on the DM annihilation cross section for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels from this work with previously published constraints from LAT analysis of the Milky Way halo (3σ limit) [34], 112 hours of observations of the Galactic Center with H.E.S.S. [35], and 157.9 hours of observations of Segue 1 with MAGIC [36]. Pure annihilation channel limits for the Galactic Center H.E.S.S. observations are taken from Abazajian and Harding [37] and assume an Einasto Milky Way density profile with $\rho_\odot = 0.389\,\mathrm{GeV\,cm^{-3}}$. Closed contours and the marker with error bars show the best-fit cross section and mass from several interpretations of the Galactic center excess [16–19].

Fermi LAT: Phys. Rev. Lett. **115**, 231301 (2015)

X-rays:
Sterile Neutrinos

A 3.5 keV line from sterile ν decay?



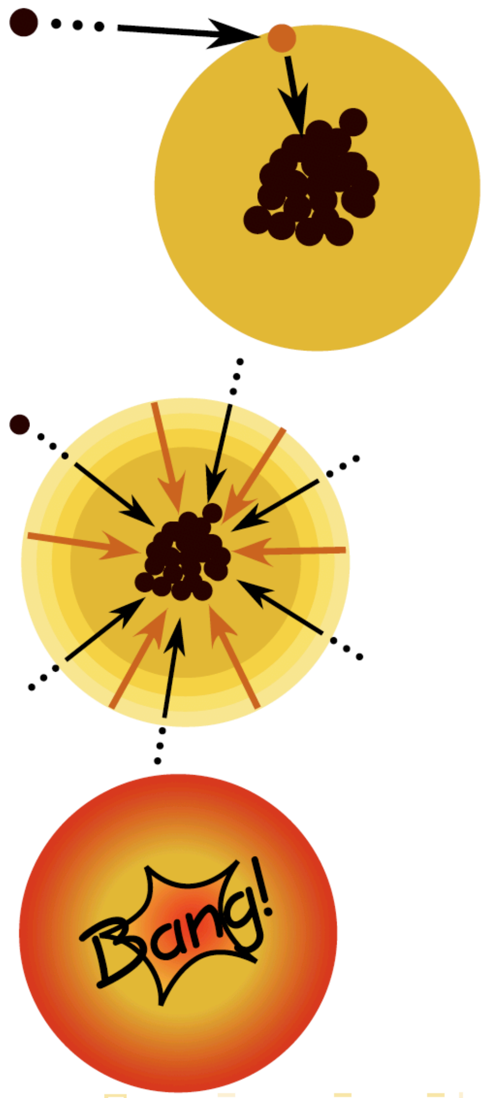
Bulbul et al *ApJ* 2014

- Blip seen in XMM-Newton observations of clusters
- Inclusion of *all* nuclear lines in background radiative transfer modelling very important (and generally not done correctly)
- Not replicated in dwarf galaxy observations

Neutrinos

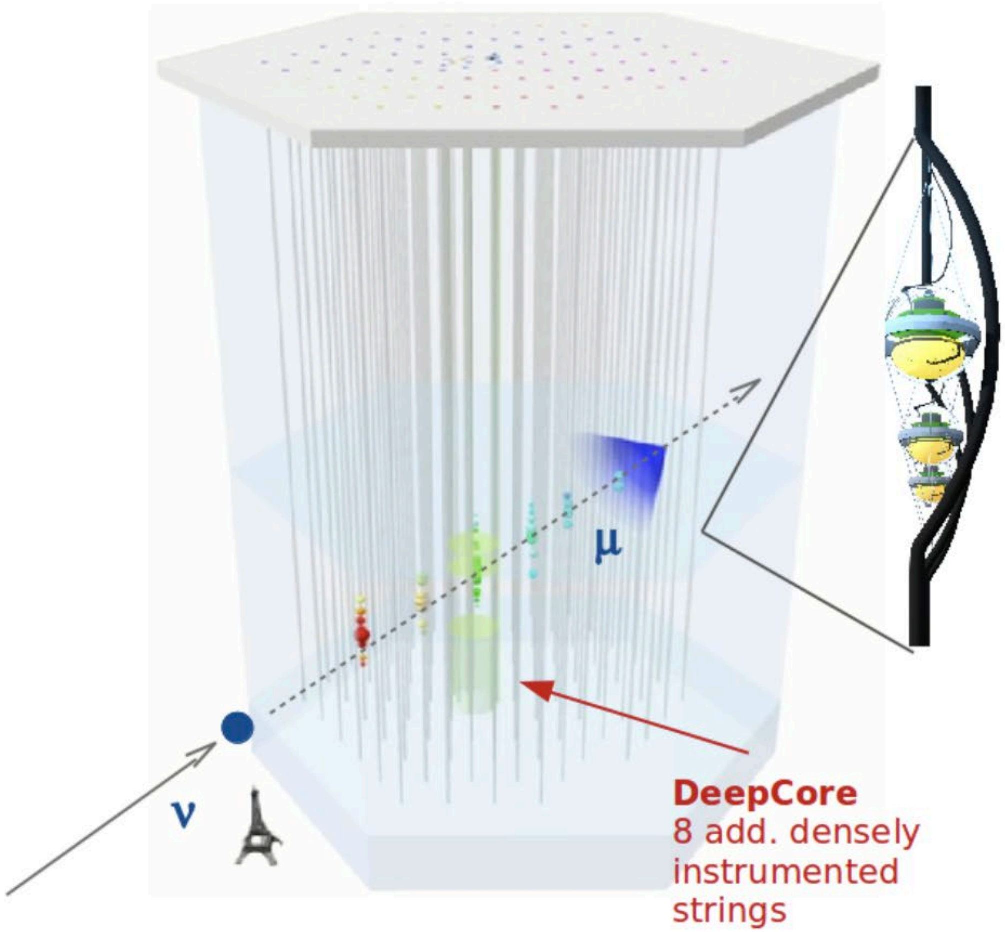
The cartoon version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in **IceCube**, ANTARES, etc



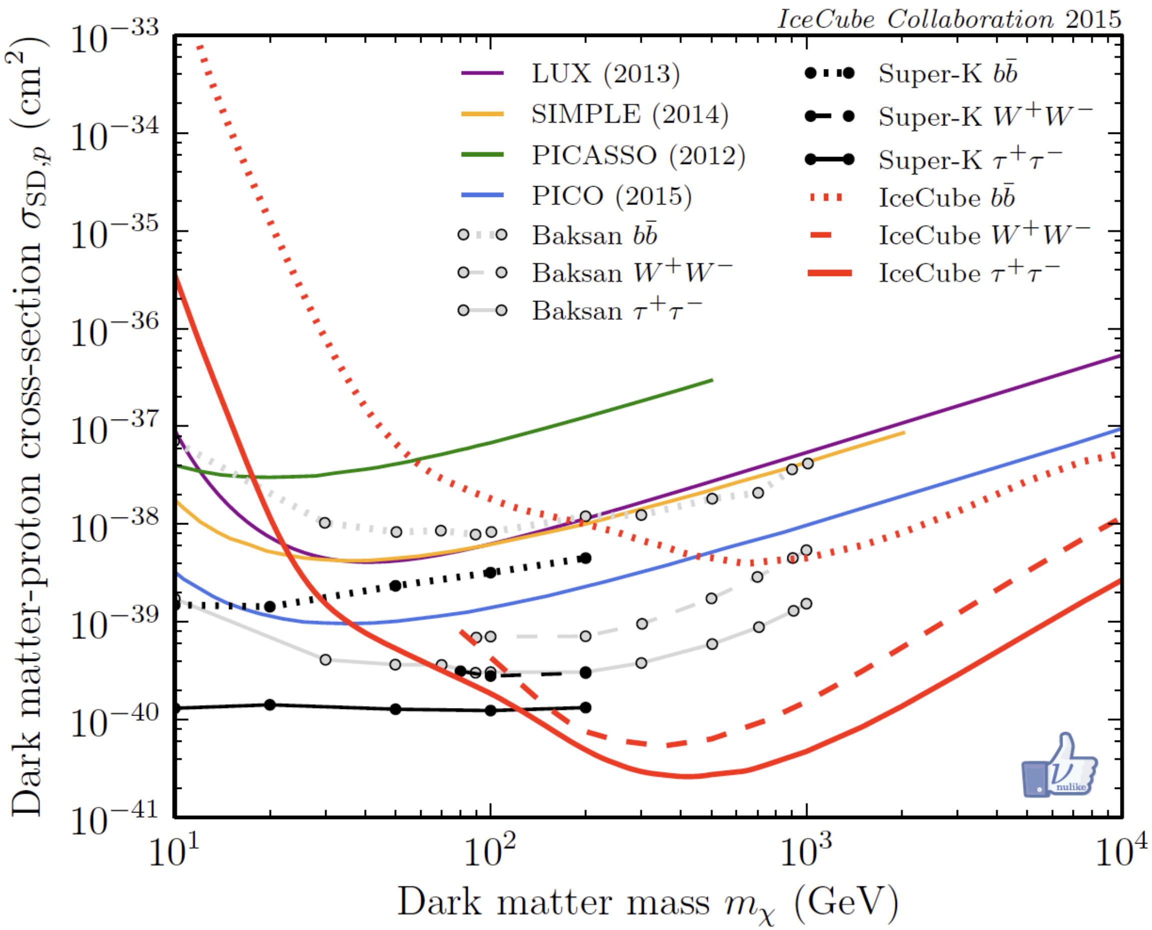
IceCube Neutrino Observatory

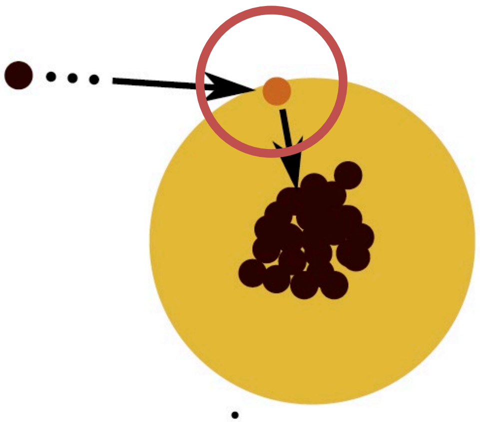
- 86 strings
- 1.5–2.5 km deep in Antarctic ice sheet
- $\sim$125 m spacing between strings
- $\sim$70 m in DeepCore ($10\times$ higher optical detector density)
- 1 km^3 instrumented volume (1 Gton)



- Directional: Path of propagating Cherenkov sites (from single μ)

Neutrinos – IceCube, Super-K et al





Sun: mostly H

⇒ spin-dependent dominates

⇒ Competitive w/ direct det.

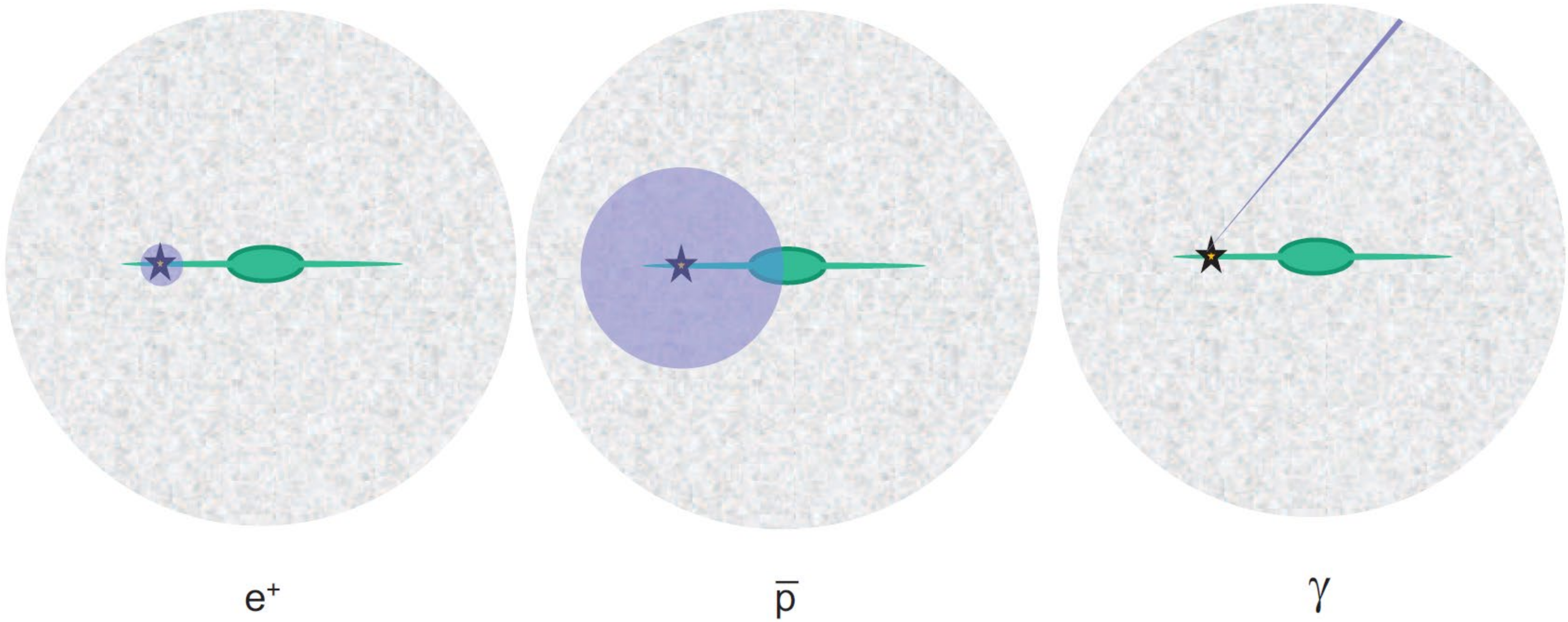
IceCube Collaboration, P. Scott, Savage & Edsjö, JCAP 2016

`nulike`: model-independent unbinned limit calculator for generic BSM models

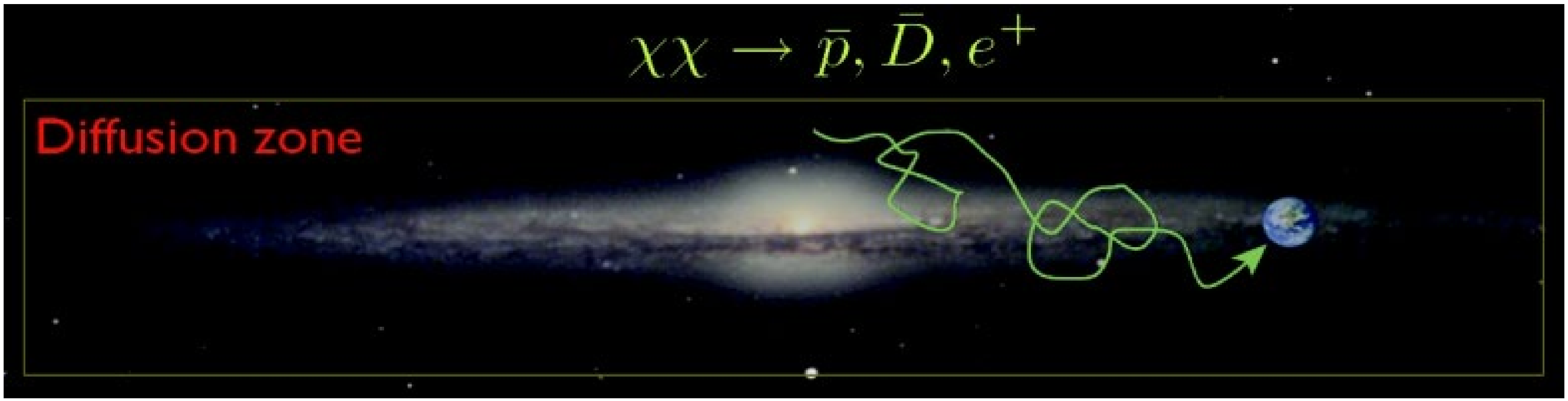
https://nulike.hepforge.org

Charged Messengers

- More complex: do not follow straight path
- Probe finite volume around detector
  - Get deflected



Charged Messengers



- **Solve complex diffusion eq. to find expected flux**

$$\frac{\partial N}{\partial t} = \underbrace{q}_{\text{sources}} + \underbrace{\vec{\nabla} \cdot (\hat{K}_{xx} \vec{\nabla} N - \vec{V}_c N)}_{\text{spatial diffusion \& convection}} + \underbrace{\frac{\partial}{\partial p} p^2 K_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} N}_{\text{momentum diffusion}}$$

$$- \underbrace{\frac{\partial}{\partial p} \left[\frac{\partial p}{\partial t} N - \frac{p}{3} \left(\vec{\nabla} \vec{V}_c \right) N \right]}_{\text{energy losses}} - \underbrace{\frac{1}{\tau_s} N}_{\text{spallation}} - \underbrace{\frac{1}{\tau_r} N}_{\text{radioactive decay}}$$

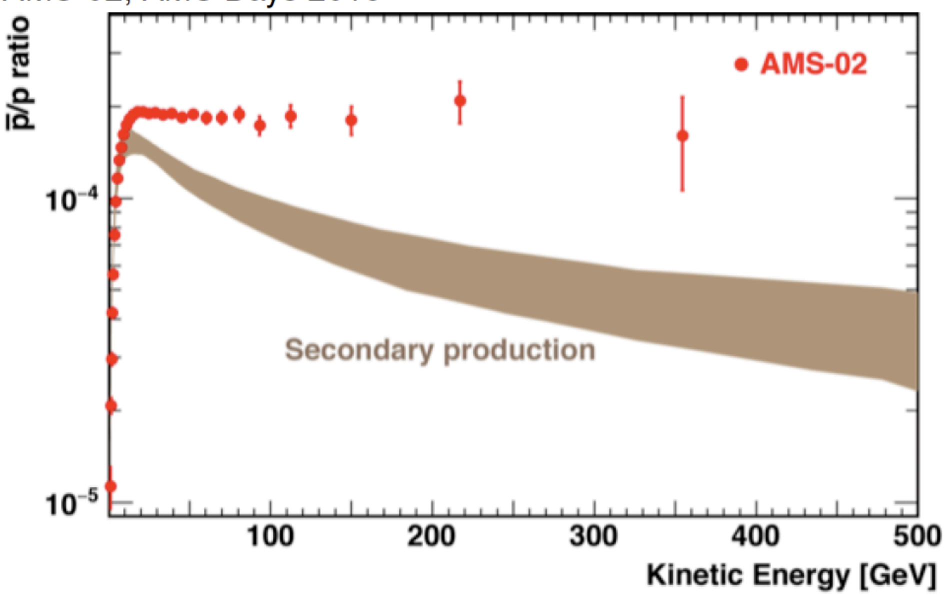
img: Carlos de los Heros, ISAPP Summer School “The Dark Side of the Universe” (2011)

Anti-protons – AMS-02
Alpha Magnetic Spectrometer ($e^+, \bar{p}$)

- **On the ISS**

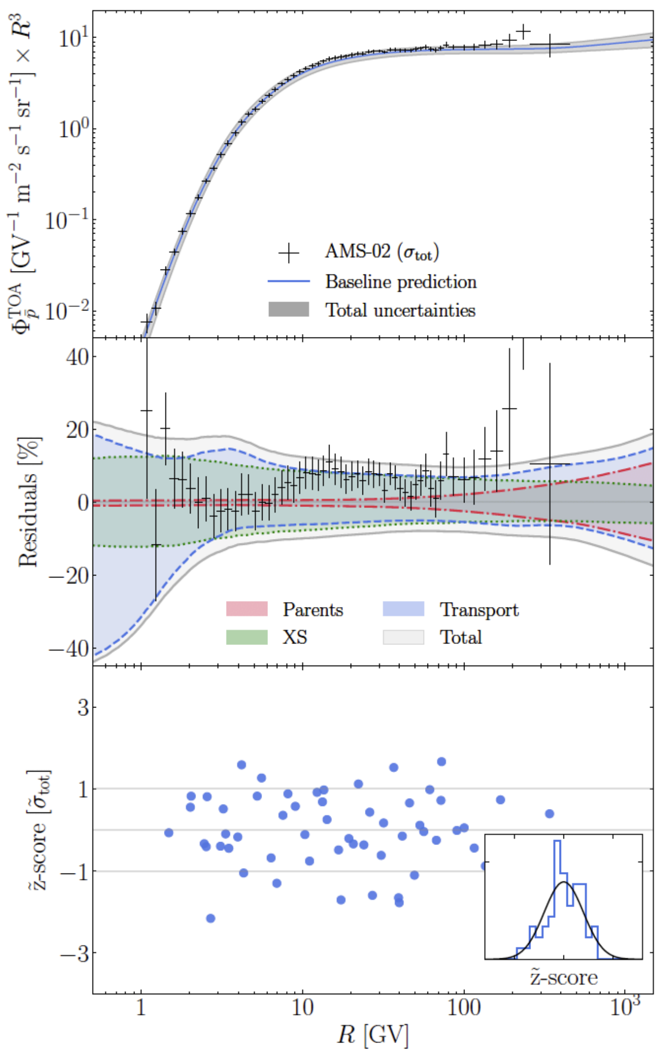
AMS-02 *claims* to have seen something DM-like in $\bar{p}$ . . .

AMS-02, AMS Days 2015



Improved fit of cosmic ray diffusion using AMS boron to carbon ratio (B/C) suggests otherwise. →

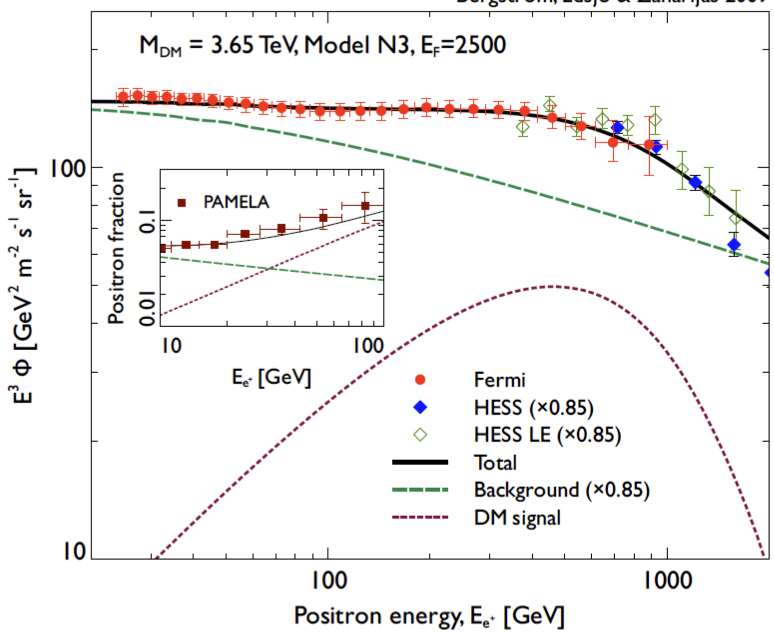
Boudaud et al, arXiv:1906.07119



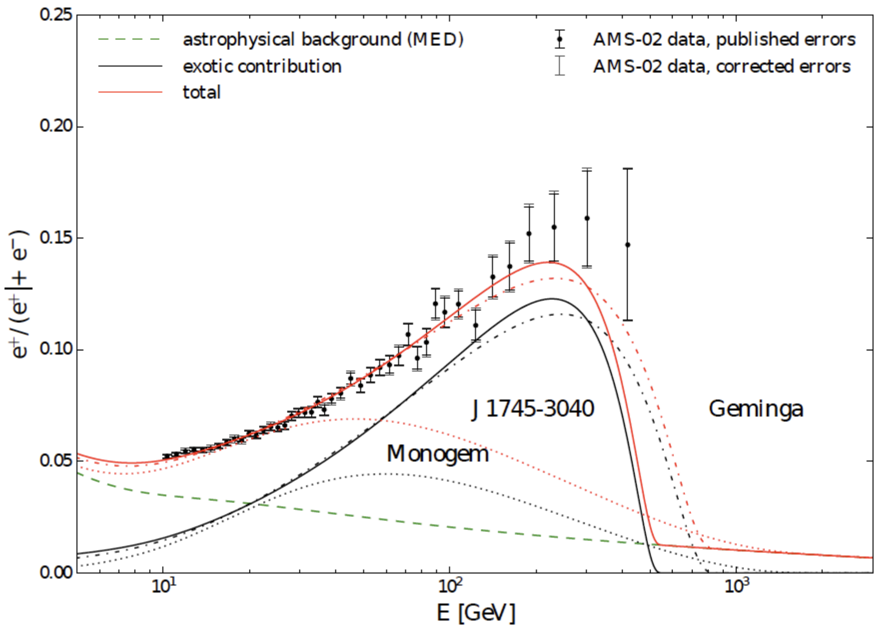
Positrons – PAMELA, AMS-02

- Excess over expected background (secondary) positron ratio observed
- First seen by PAMELA, confirmed by *Fermi* then AMS-02. Still unexplained.
- Could be evidence of dark matter, could be caused by pulsars

Bergström, Edsjö & Zaharijas 2009



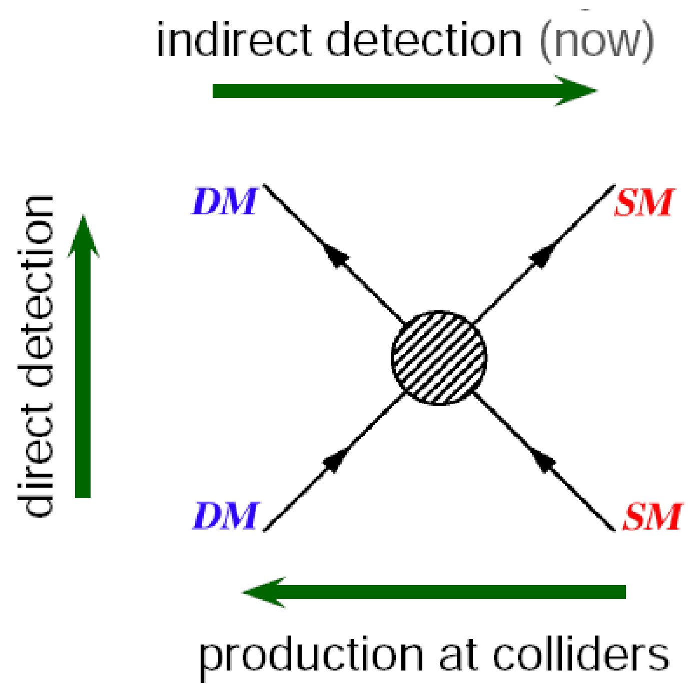
Boudaud et al *A&A* 2015



Other probes

- CMB: Impact of DM-SM energy injection
  - Distort CMB power spectra
- Stellar evolution: depends on models
  - DM Collides with stars
  - DM gravitationally bound inside stars
  - Cooling, energy exchange

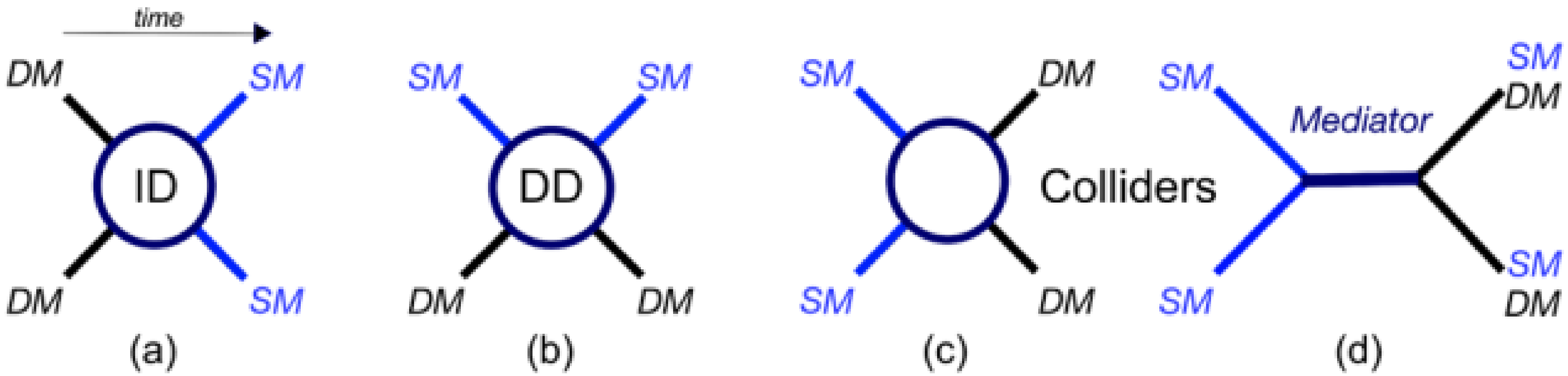
Bonus: What about colliders?



- Discussed direct + indirect detection
- Where do colliders come in?

img: [https://www.mpi-hd.mpg.de]

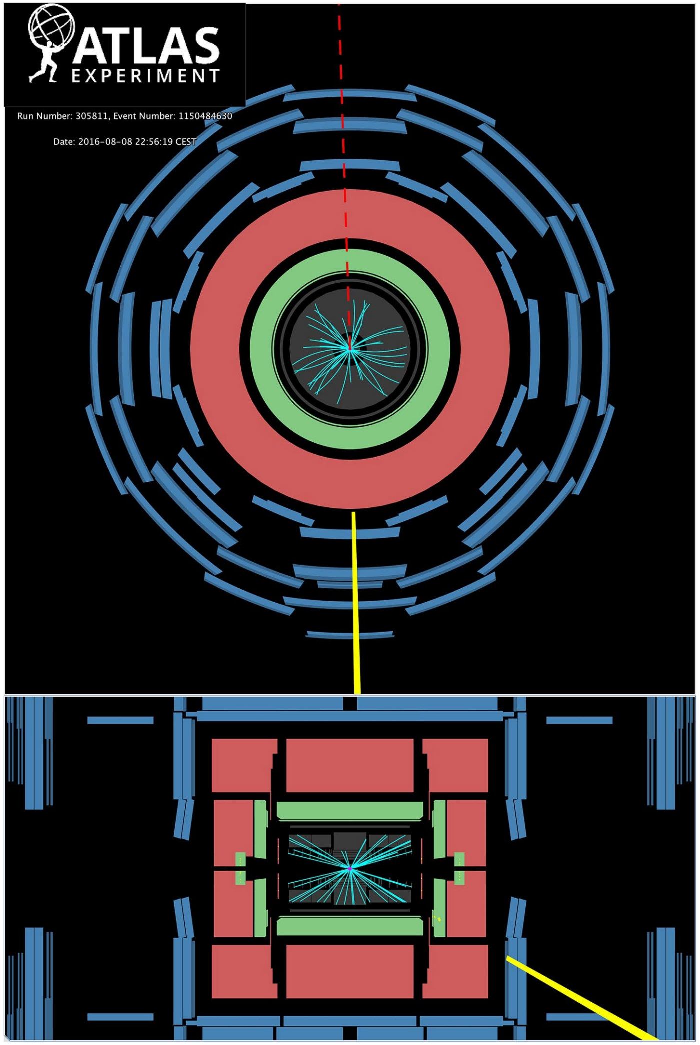
Bonus: Production in Colliders



- Existence of “dark interactions”
- Dark particles produced in high-energy collisions
- Final states, or intermediate

img: ATLAS/CERN: https://atlas.cern/updates/feature/dark-matter

Bonus: Production in Colliders

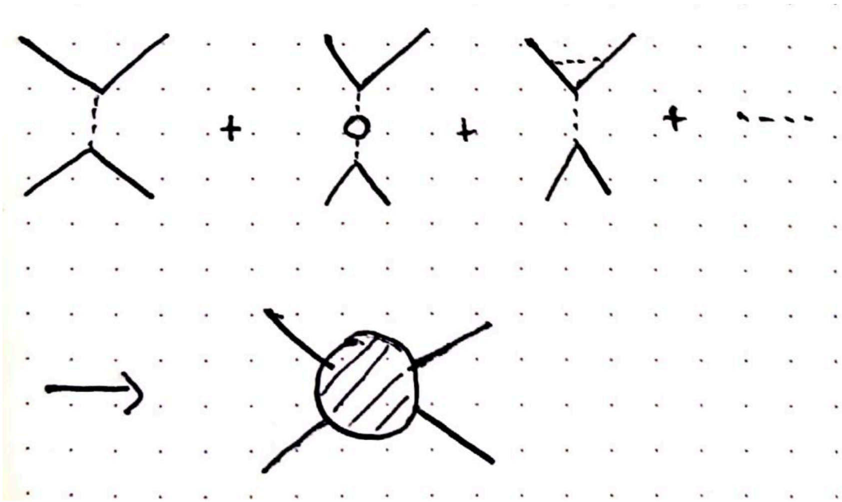


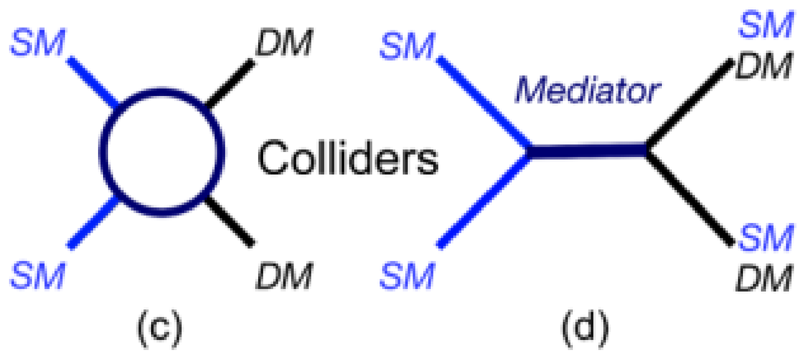
Production:

- Dark particles produced in high-energy collisions (final states)
- Can't be directly detected: look for "missing" energy/ momentum

img: ATLAS/CERN: https://atlas.cern/updates/feature/dark-matter

Bonus: Virtual Dark-Sector Particles





Also:

- Existence of “dark sector” – modify Feynman diagrams (even if not present in final state)
- Leads to deviation from Standard Model prediction
- (Not just colliders: any high-precision measurements)
- Look for resonances (mediator mass)

img: ATLAS/CERN: https://atlas.cern/updates/feature/dark-matter

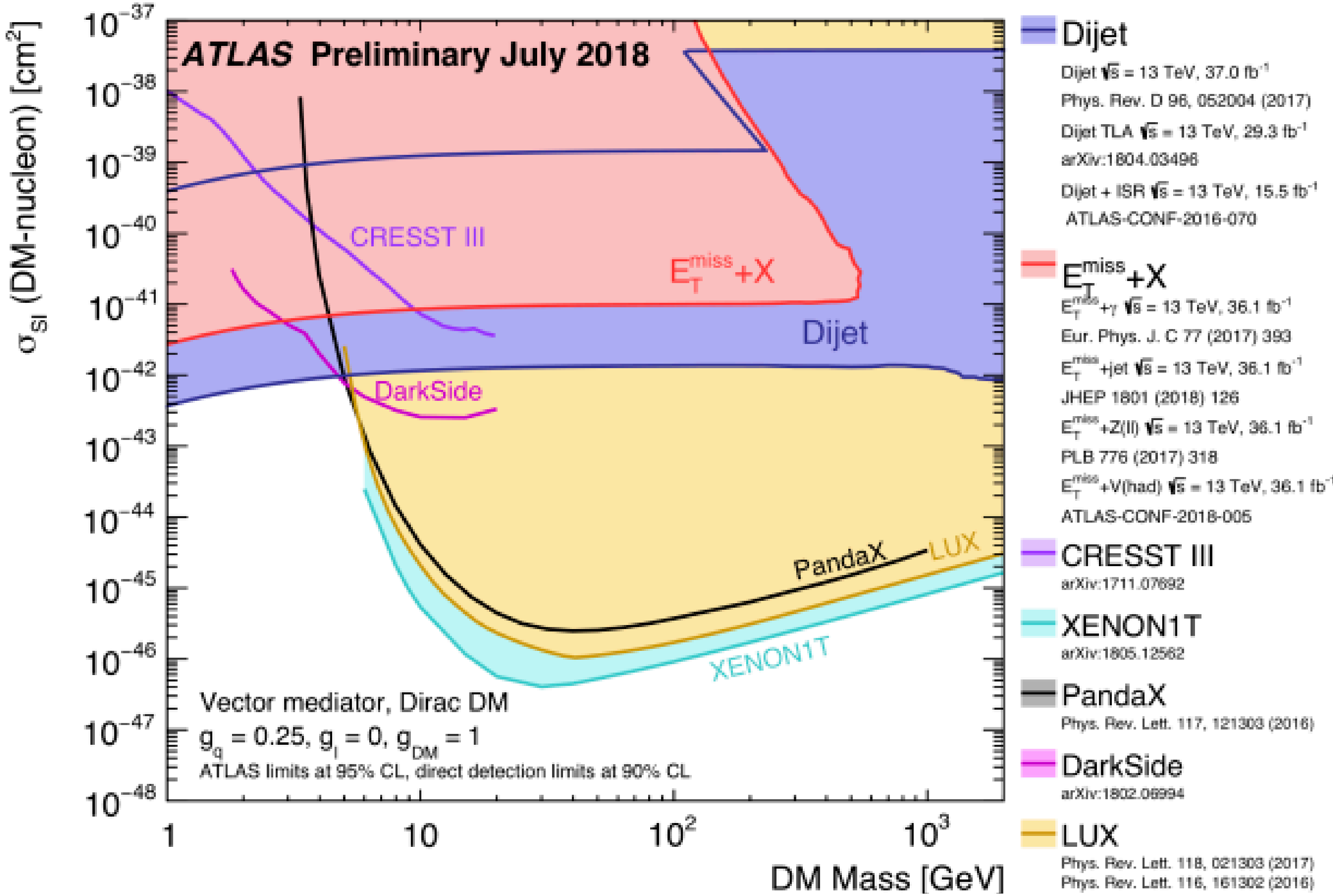
Bonus: Collider/Precision Constraints

- Unlike other methods, do not depend at all on galactic DM density
- Not searching for galactic DM
- Positive detection: new particles, not necessarily DM
- But: can constrain properties of candidate models

If your DM model assumes:

- Coupling to SM, new force carriers, etc
- Subject to LHC (+other) constraints
- Very model-dependent
- weak couplings: only sometimes significant

Bonus: Collider/Precision Constraints



ATLAS: JHEP 05, 142 (2019) [arXiv:1903.01400]

Summary

Indirect detection is now a mature field: ν, γ, charged cosmic rays, CMB + stars

There are anomalies:

- Positron excess persists
- Claimed anti-proton excess seems a bit of a beat up
- Galactic Centre gamma-ray excess probably exists
- Dark matter explanations looking increasingly unlikely vs pulsars

Looking Forward:

- Need to combine direct, indirect results