Scrutinizing Possible Dark Matter Signatures with AMS-02, Fermi and Planck

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AMS Days @ CERN
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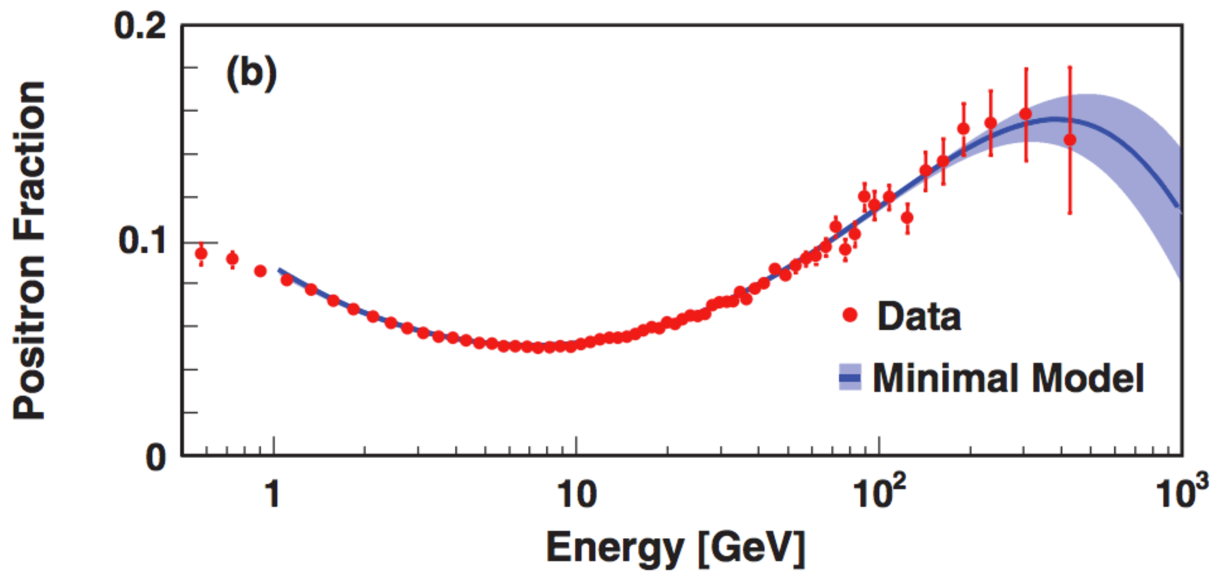
Outline

- From AMS-02 to Planck:
  - The annihilating dark matter hypothesis for the AMS-02 positron excess.
  - Planck polarization data sets powerful model-independent constraints.
- From Fermi to AMS-02:
  - Status of the GeV gamma-ray excess in the inner Galaxy.
  - AMS-02 measurements of positrons and antiprotons can probe its origin.
- (if time permits) “Dark sector” models and some of their implications - annihilation/decay cascades, semi-annihilation, boosted dark matter.

The AMS-02/PAMELA positron excess



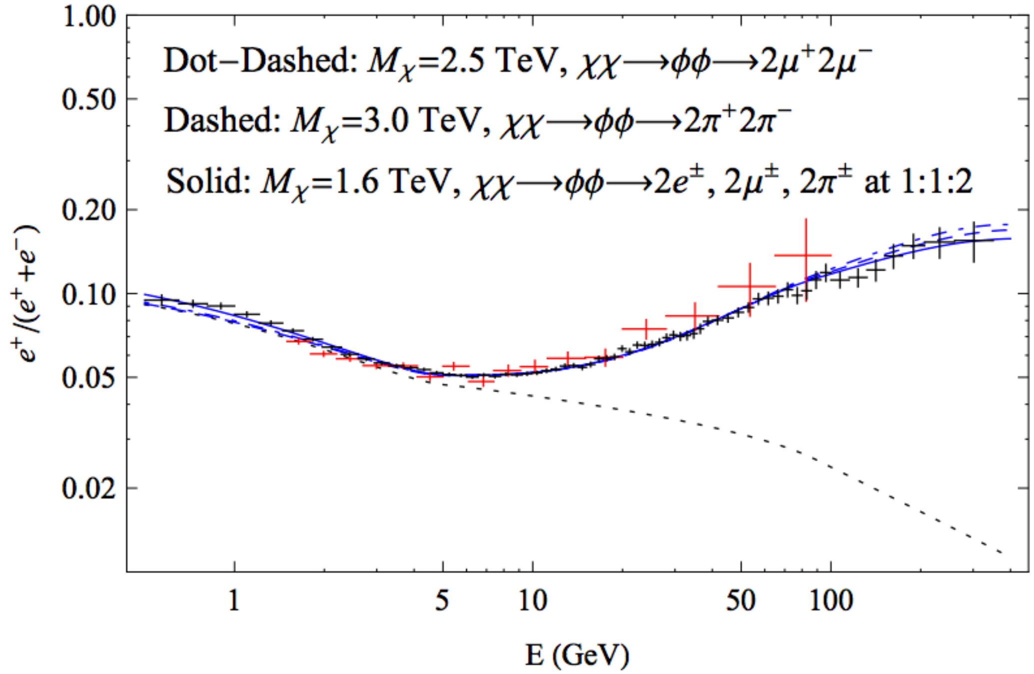
Accardo et al (AMS-02 Collaboration), PRL 113, 121101 (2014)

- Rise in positron fraction above 10 GeV observed by PAMELA experiment in 2008, confirmed to extend up to at least 500 GeV by AMS-02.

- Possible signal of DM annihilation, producing additional primary positrons. (Other possibilities: pulsars, supernova remnants, modified cosmic-ray production and/or propagation.)

DM models fitting AMS-02

- Some example models worked out in Cholis & Hooper 1304.1840.
- Typically require:
  - Heavy DM (~500 GeV or higher, TeV+ to also fit Fermi data)
  - Cross sections significantly higher than thermal value (2-3 orders of magnitude)
- There are significant constraints from gamma-rays, but depend on assumed DM density profile and annihilation channel.



Cross sections taken to be:

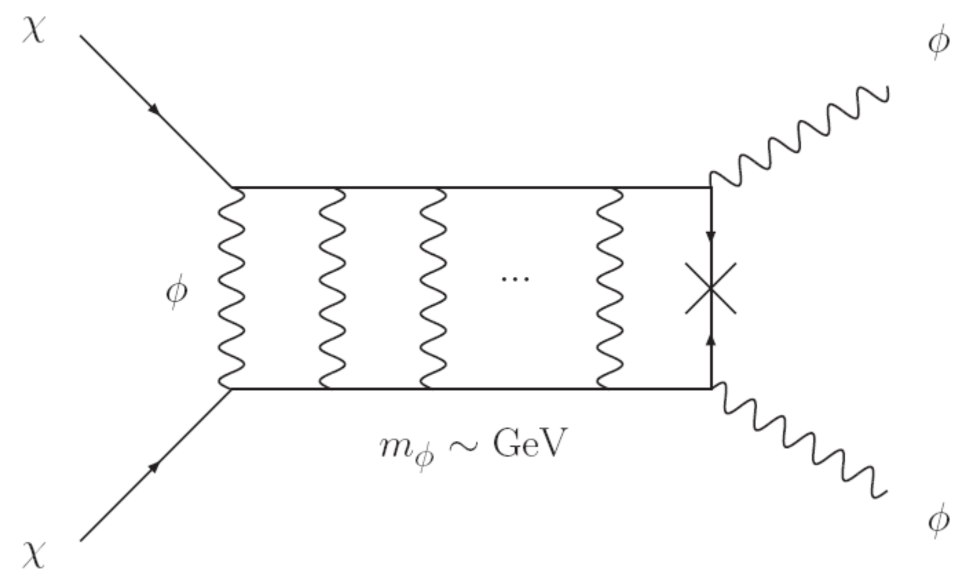
Model 1 $\langle\sigma v\rangle = 1.5\times10^{-23}\mathrm{cm}^3/\mathrm{s}$

Model 2 $\langle\sigma v\rangle = 2.3\times10^{-23}\mathrm{cm}^3/\mathrm{s}$

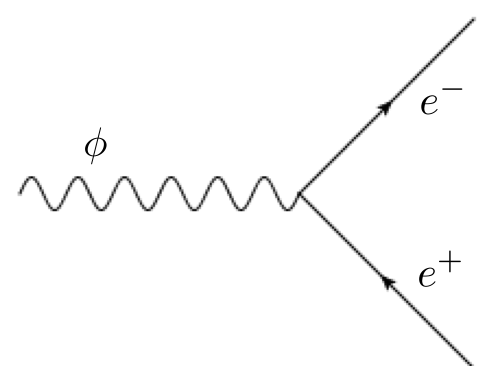
Model 3 $\langle\sigma v\rangle = 6.5\times10^{-24}\mathrm{cm}^3/\mathrm{s}$

“Dark force” models

- If DM couples to a new light particle (~100 MeV - GeV), which then decays to light known particles, three features naturally explained:
  - Short cascade → hard spectrum.
  - Decays to antiprotons kinematically forbidden.
  - Automatic Sommerfeld enhancement can boost rate by O(100) factor at low velocities.
- Proposed by Arkani-Hamed, Finkbeiner, TRS & Weiner, + (independently) Pospelov & Ritz, in 2008.
- New light particles (which also have other independent motivations) can be searched for directly.

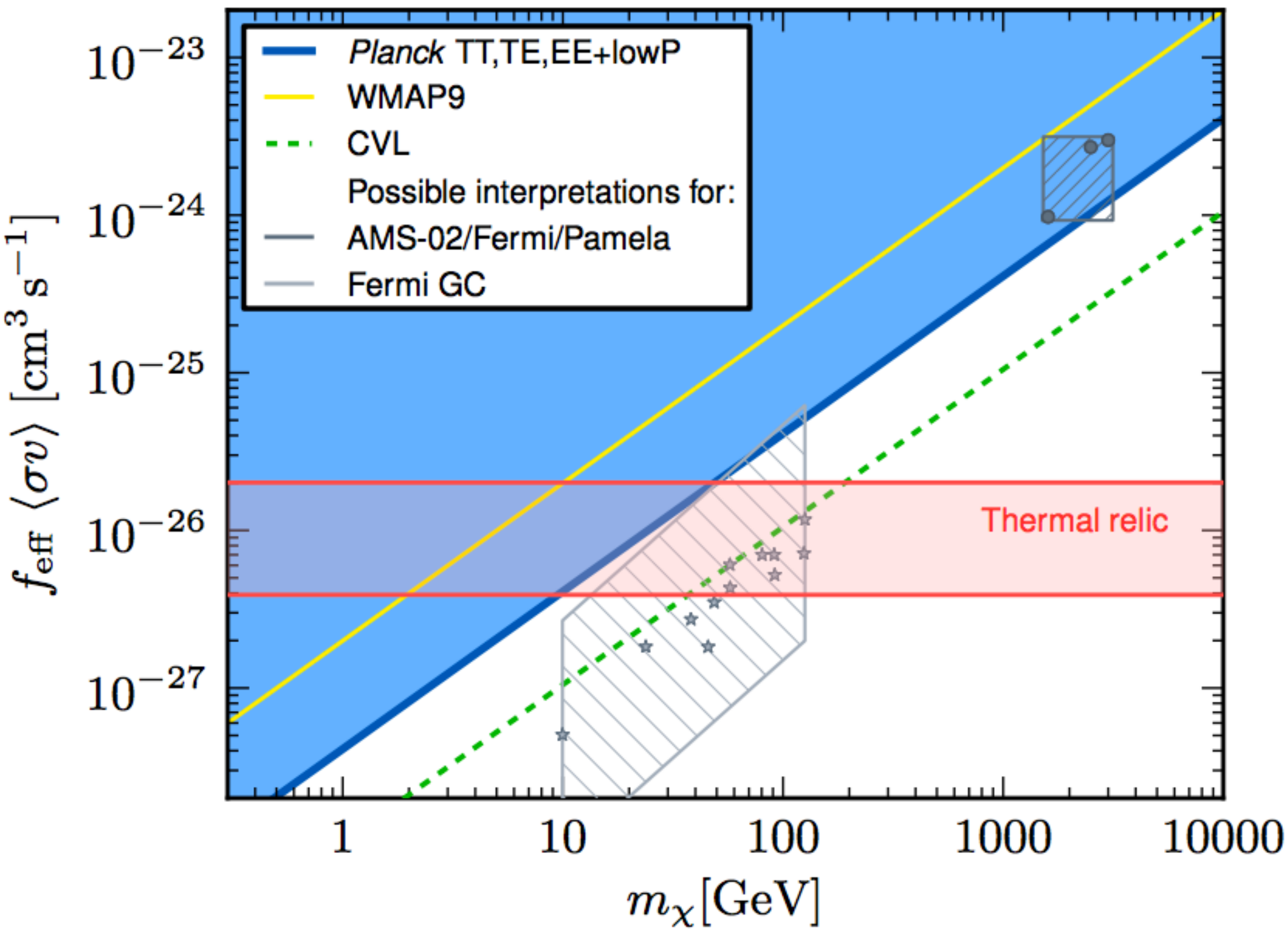


Sommerfeld-enhanced annihilation (above), followed by decay (below)



Bounds from Planck

- Early this year, Planck Collaboration released polarization results.
- 1502.01589 presented bounds on DM annihilation; consistent with sensitivity predictions from TRS et al, Galli et al 2009.
- Constraints are on $\langle\sigma v\rangle f_{eff}/m_{DM}$, where f_{eff} is a model-dependent efficiency factor.
- Tension with annihilating DM interpretation of AMS-02 positrons.



How general are these limits?
or, what determines f_{eff}?

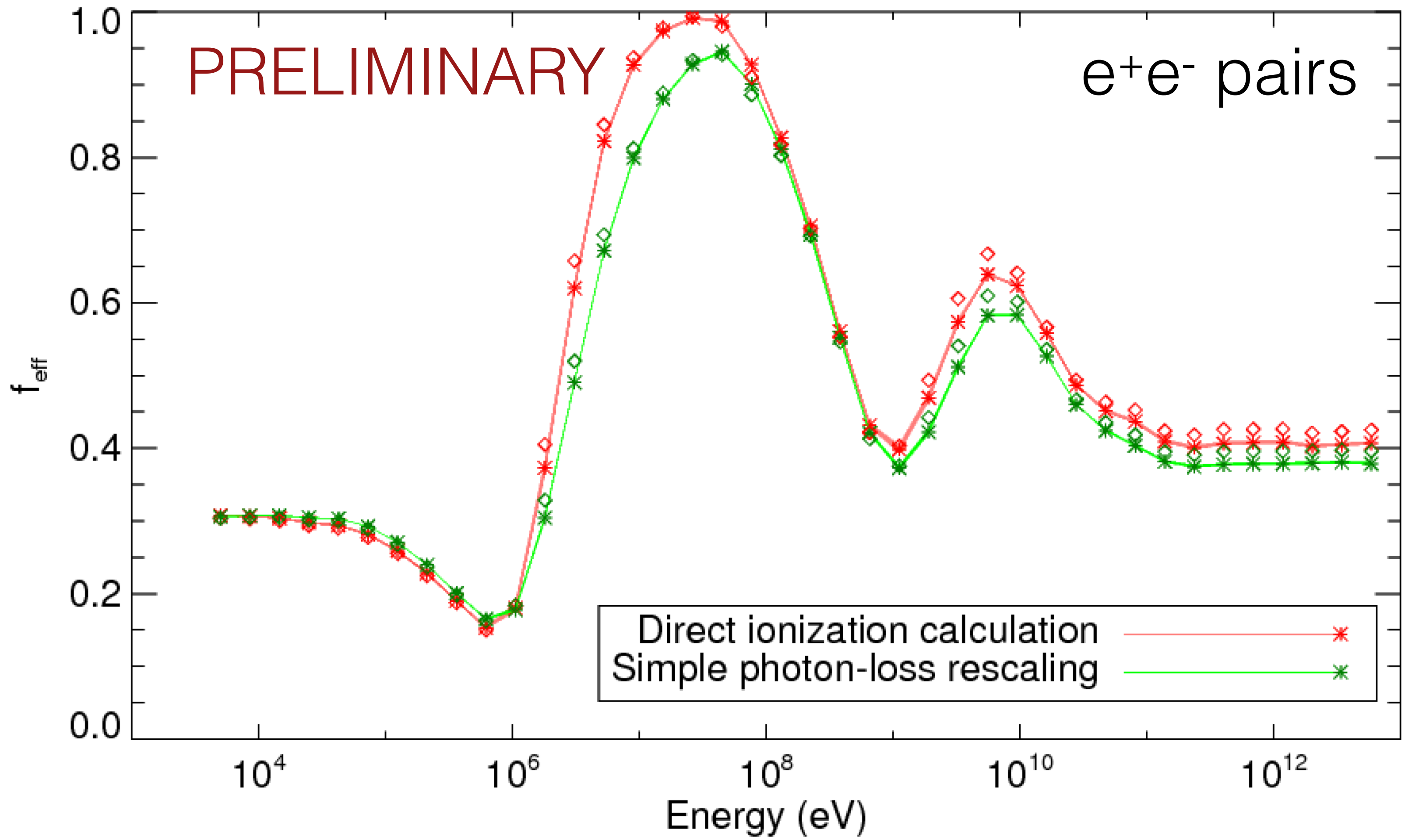
Understanding the CMB bounds

DM annihilation → photons, electrons, positrons → ionization → scale-dependent perturbation to CMB anisotropies

Adams, Sarkar & Sciama 1998; Chen & Kamionkowski 2003; Finkbeiner & Padmanabhan 2005

- The bound for annihilating DM depends on essentially one number: excess ionization at z~600 (Galli, Lin, TRS & Finkbeiner ’11, + work in preparation).
- Parameterized by efficiency parameter f_{eff}: first computed in TRS, Padmanabhan & Finkbeiner ’09, significant updates to calculation described in Galli, TRS, Valdes & Iocco ’13.
- f_{eff}, and hence the constraint on a given (s-wave annihilating) DM model, depends on:
  - PRIMARILY, how much power goes into photons/electrons/positrons vs neutrinos and other channels.
  - SECONDARILY, the spectrum of photons/electrons/positrons produced (but most variation is for particles below the GeV scale).
- There is a lower bound on both of these for any model explaining the positron fraction.

The efficiency factor



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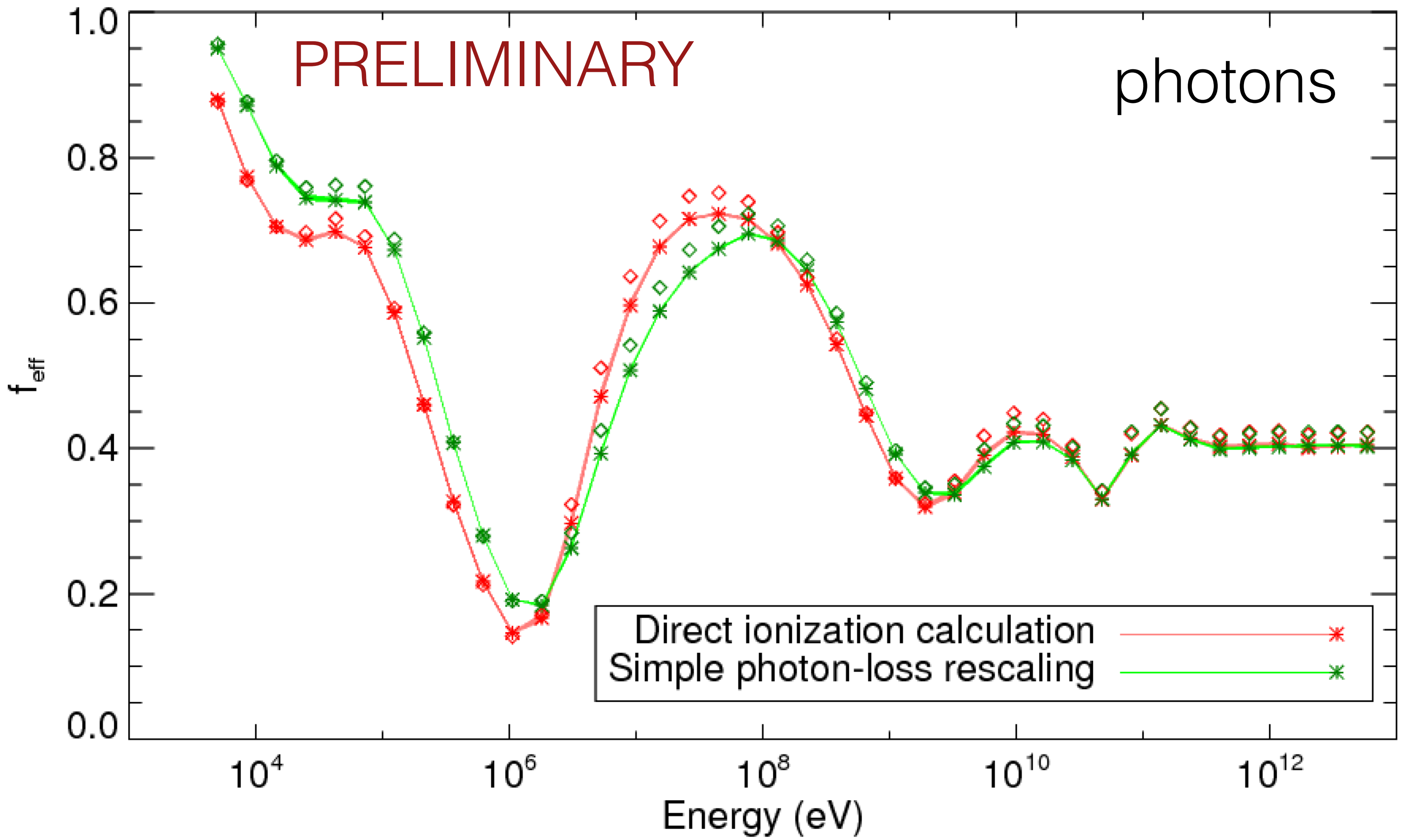
f_{eff} parameterizes detectability for a given DM model (mass and annihilation channel/s). Can be computed for photons and e^+e^- pairs at all energies (TRS, to appear), and integrated over the actual spectrum produced by a specific model.

The efficiency factor (cont.)



Electron/positron pairs and photons behave similarly at high injection energies (f_{eff} ~ 0.4), f_{eff} rises to 0.7-1 around 10-100 MeV, can fall as low as ~0.15 around 1 MeV. Rises steeply again for low-energy photons (but not at-rest electrons/positrons).

Example of applying the CMB bounds

- A recent model: Boudaud et al 1410.3799 identified a favored model: 0.5-1 TeV DM annihilating through a light mediator into 75% taus and 25% electrons, with a cross section of 7.4 x 10^{-24} cm^3/s at a mass of 600 GeV.

(Note: these authors assumed a local density of 0.3 GeV/cm^3; taking a higher but still commonly used value of 0.4 GeV/cm^3 would lower the cross section by a factor of nearly 2.)

- At this mass scale we can estimate (preliminary) f_{eff} ~ 0.4 for electrons, and f_{eff} ~ 0.14-0.15 for the tau component (due to losses to neutrinos). This yields an overall f_{eff} ~ 0.21, and consequently:

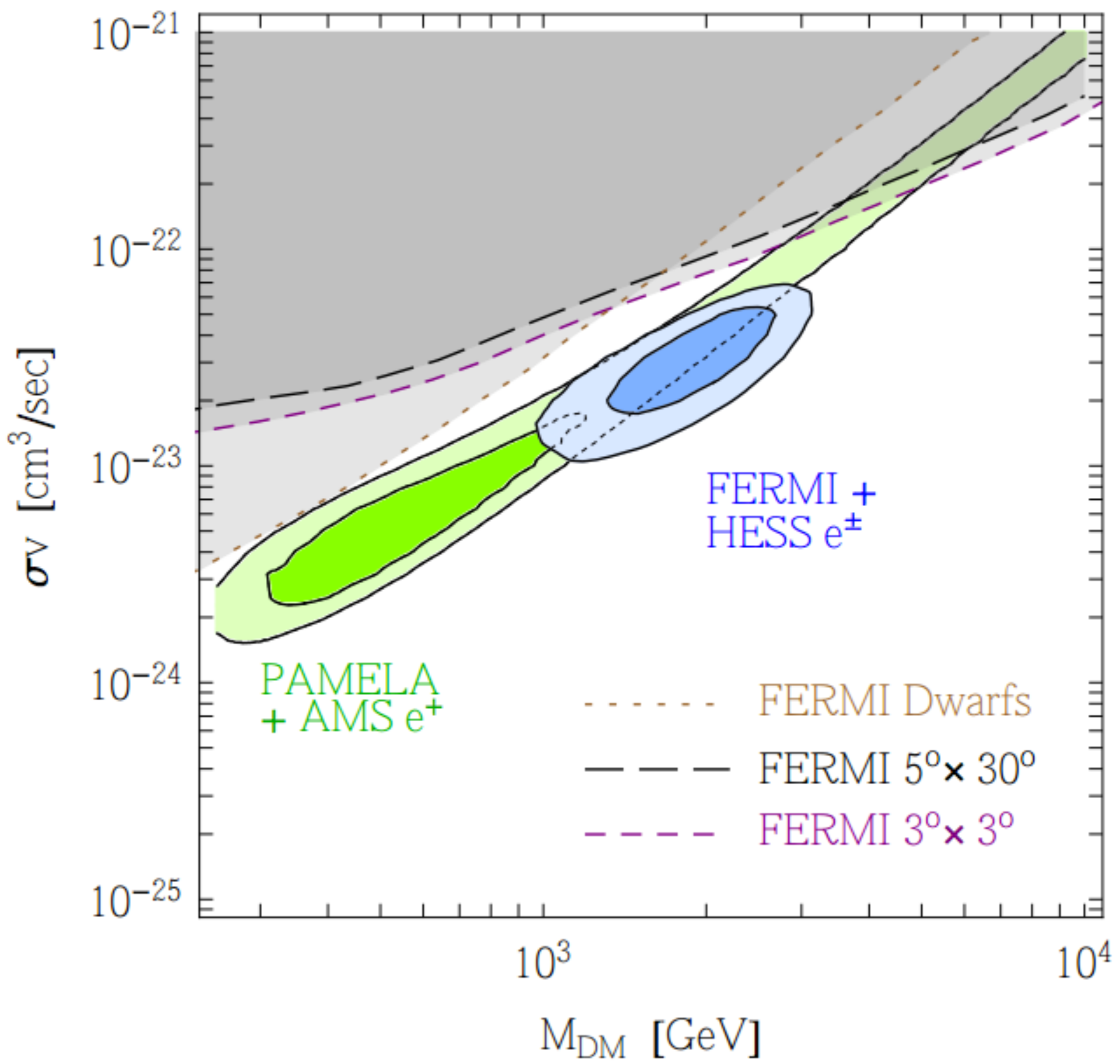
$$f_{\rm eff} \langle \sigma v \rangle \approx 1.6 \times 10^{-24} {\rm cm}^3/{\rm s}$$

- In contrast, the bound from Planck at 600 GeV constrains this number to satisfy

$$f_{\rm eff} \langle \sigma v \rangle \lesssim 2.5 \times 10^{-25} {\rm cm}^3/{\rm s}$$

A second example

- Cirelli et al 0809.2409: updated 2013 to include AMS-02 data.
- This plot shows 2μ annihilation channel, + bounds from gamma rays (assuming a cored isothermal DM density profile).
- Can calculate f_{eff} as a function of DM mass, translate CMB bounds to cross section limits.
- Rules out 5σ region for AMS-02 by a factor of 2.



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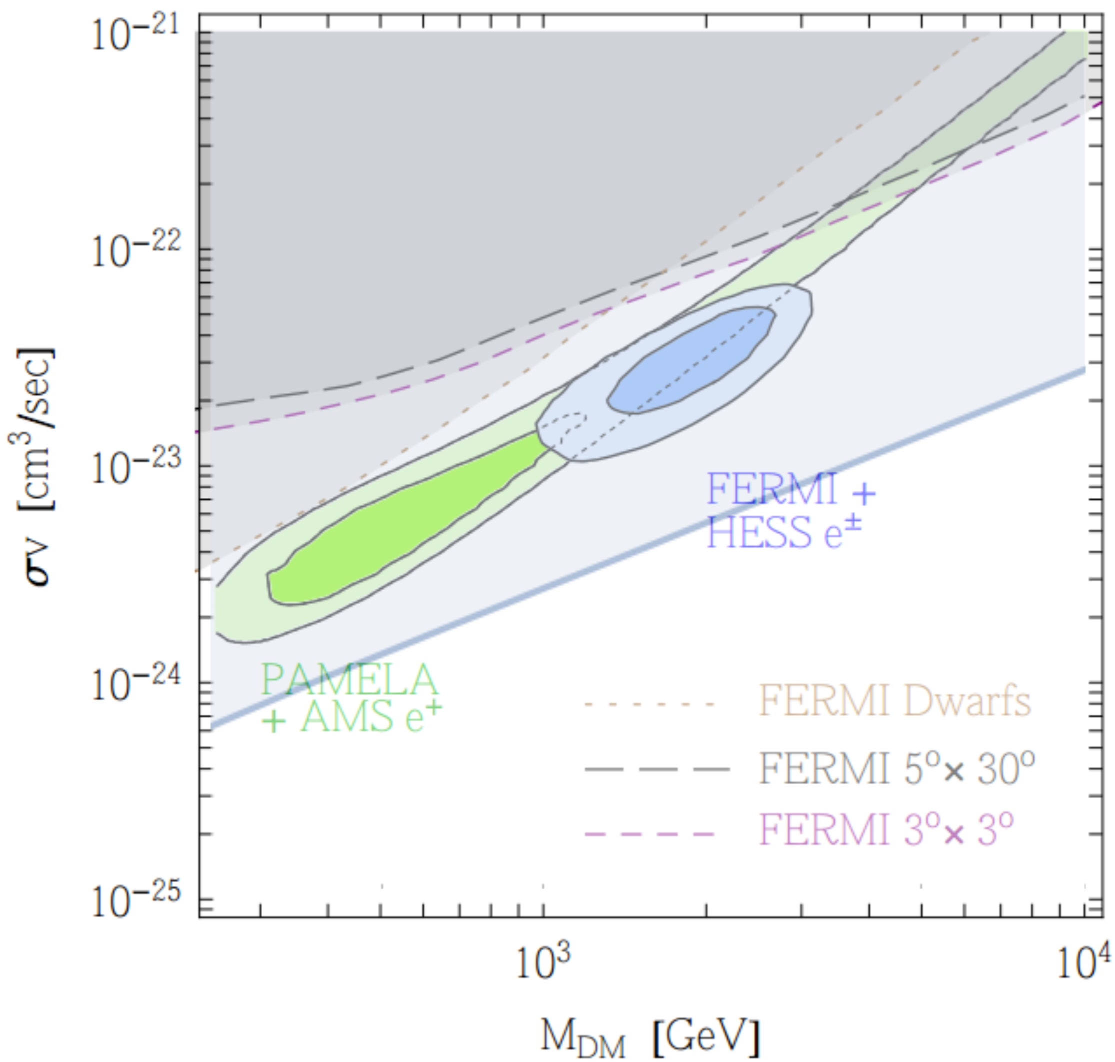


Constraints from the CMB

- The annihilating DM explanation for the positron fraction rise appears to be in fairly model-independent tension with Planck limits.
- Constraints are alleviated if:
  - The local DM density is higher than 0.4 GeV/cm^3, or there is a large substructure contribution - e.g. double disk dark matter (see talk by L. Randall yesterday).
  - A smaller cross section is required to fit the signal for other reasons, e.g. attributing some of the rise in the positron fraction to non-DM sources or propagation.
- Constraints do not apply to:
  - Decaying DM (slower scaling with density reduces high-redshift signal)
  - DM with velocity-suppressed annihilation, e.g. p-wave (however, would require a non-thermal history)
- Constraints are <u>stronger</u> for Sommerfeld-enhanced DM annihilation, as typical velocity at z~600 is typically << velocity of halo DM (~10^{-8} c vs 10^{-3} c).

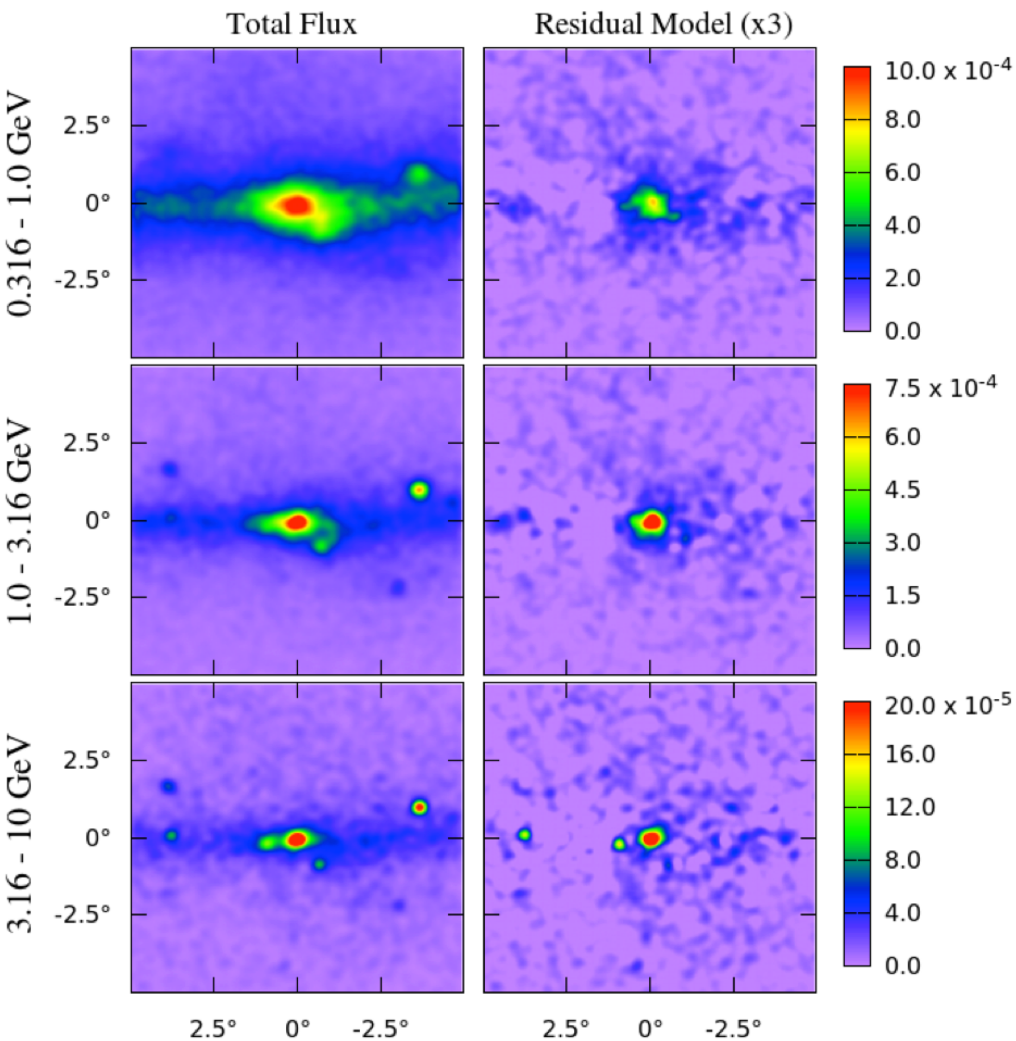
The GeV gamma-ray excess

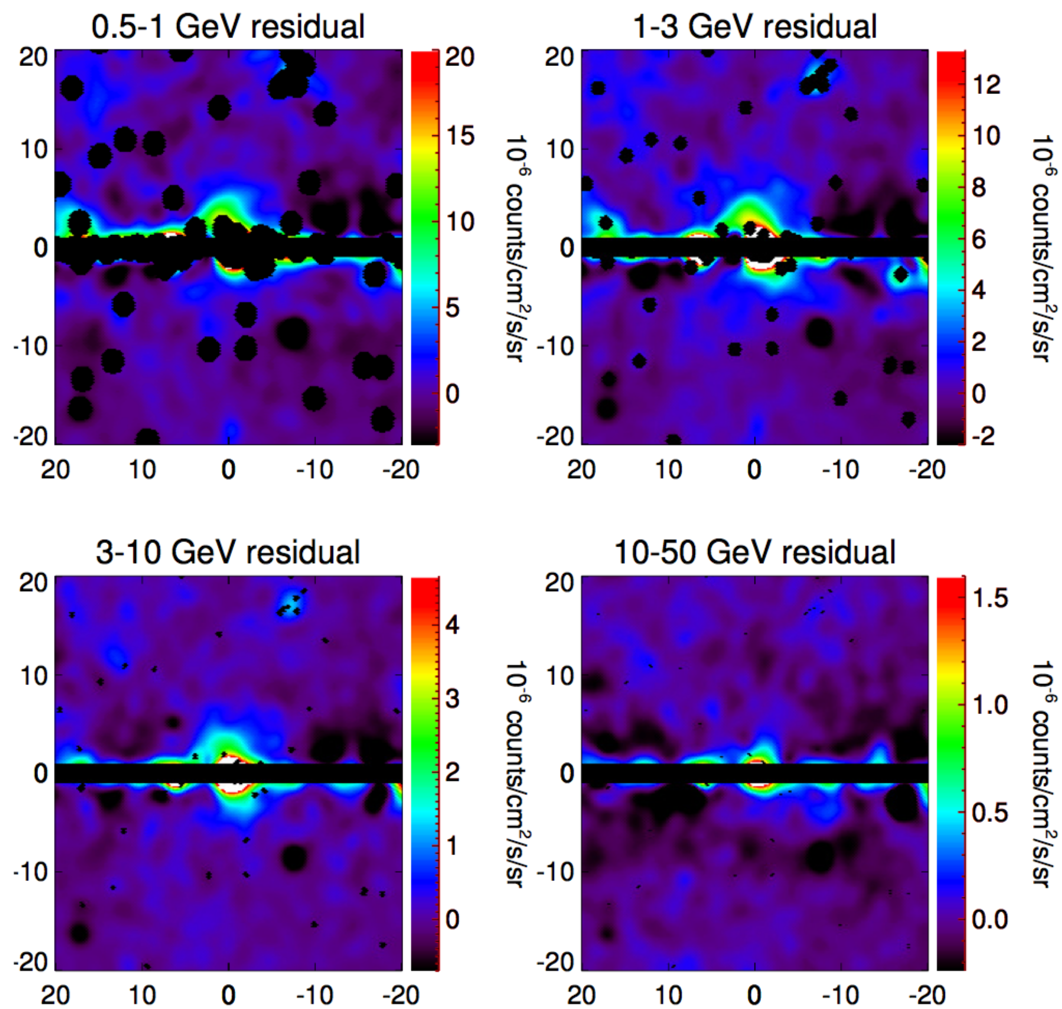
What we know

- Discovered in public data from the Fermi Gamma-Ray Space Telescope, first in the Galactic Center (Goodenough & Hooper 09) and later extending to higher latitudes (Hooper & TRS 13).
- Spectral properties:
  - Rises at energies below 1 GeV, peaks around ~2 GeV (in $E^2 dN/dE$, power per logarithmic interval), falls off above ~5 GeV.
  - Best-fit DM annihilation models have a ~thermal relic cross section.
- Spatial properties:
  - Generally consistent with spherical symmetry around the Galactic Center (some hints of extension along an axis NOT the Galactic plane).
  - Small-r power-law slope of power/volume ~ $r^{-2.5}$ (corresponds to NFW profile with inner slope γ~1.1-1.4).
  - Appears centered on Sgr A*.
  - Extends out to at least 10 degrees from the GC.

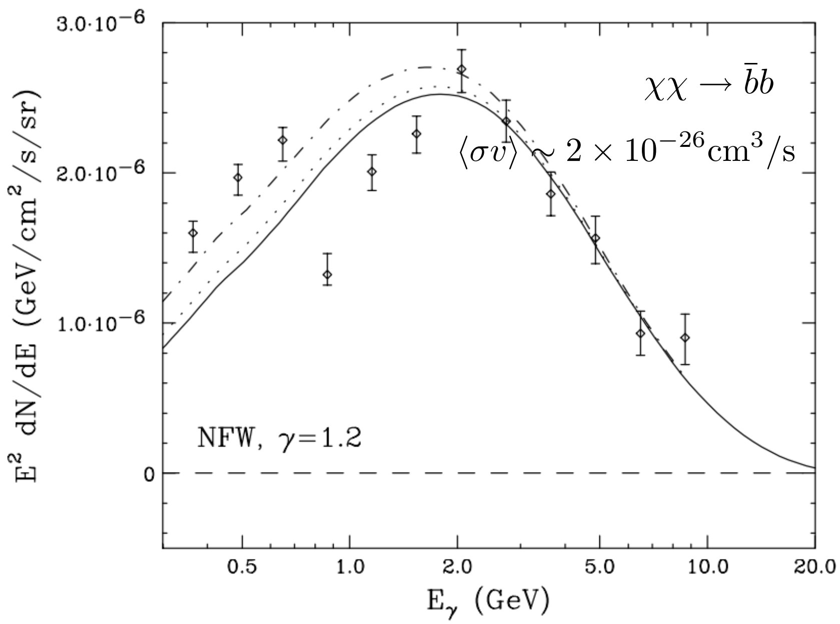
Spatial morphology

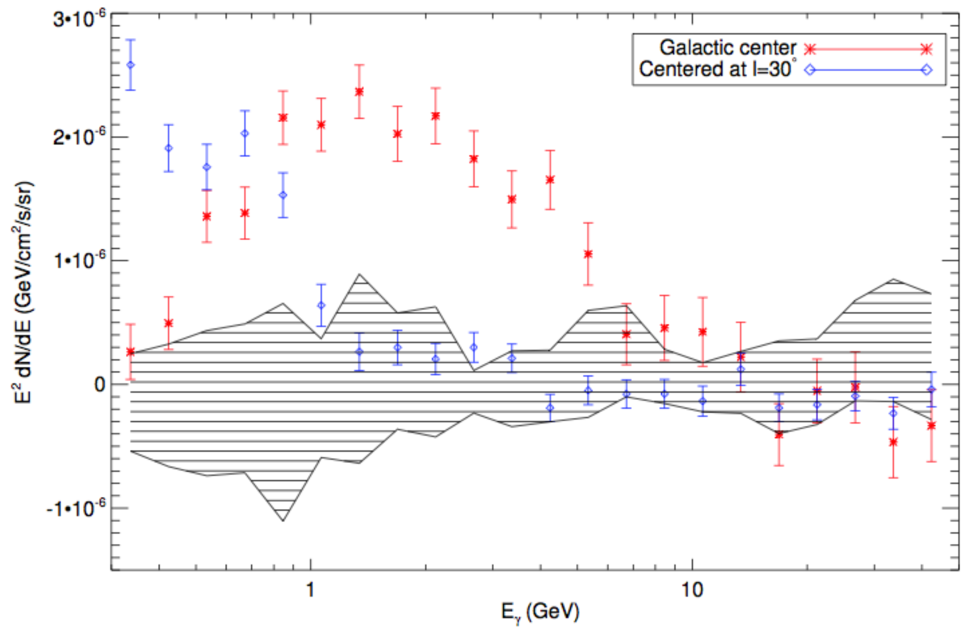
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd & TRS ’14



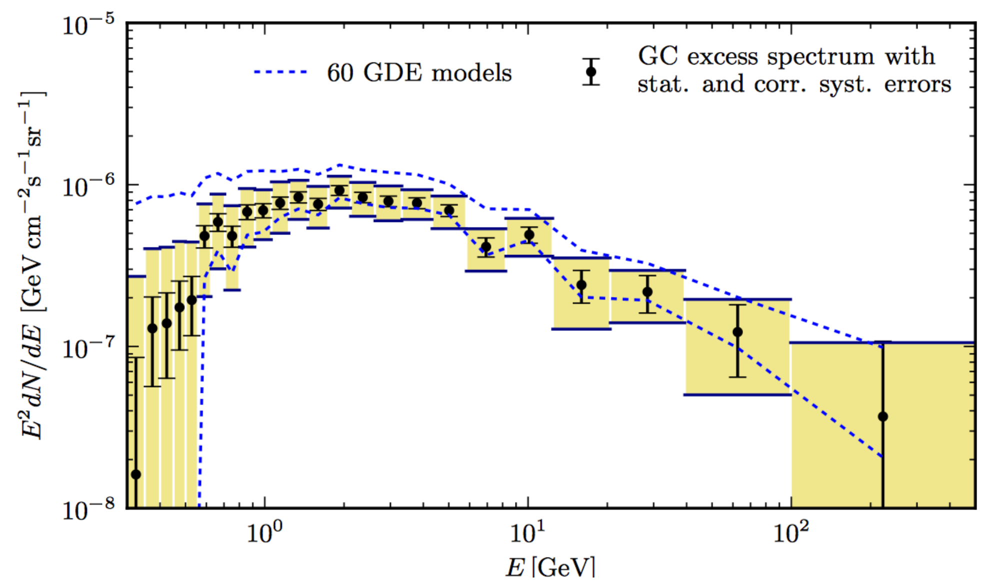


Spectral properties





- Top: Daylan et al ’14. Left: Galactic Center spectrum. Right: Inner Galaxy spectrum (cross-hatched band and blue points indicate spectra if same analysis applied to other sky regions).
- Bottom: Calore, Cholis & Weniger ’14.



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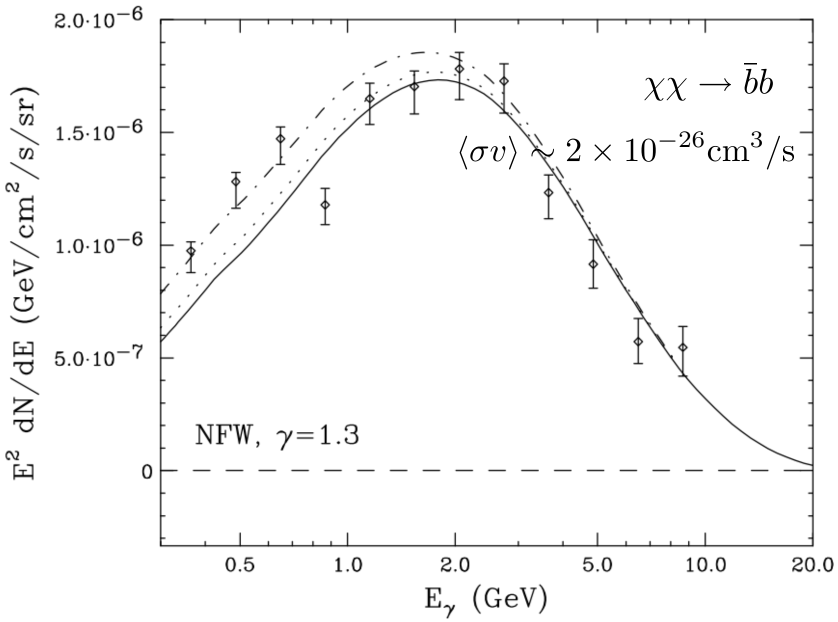

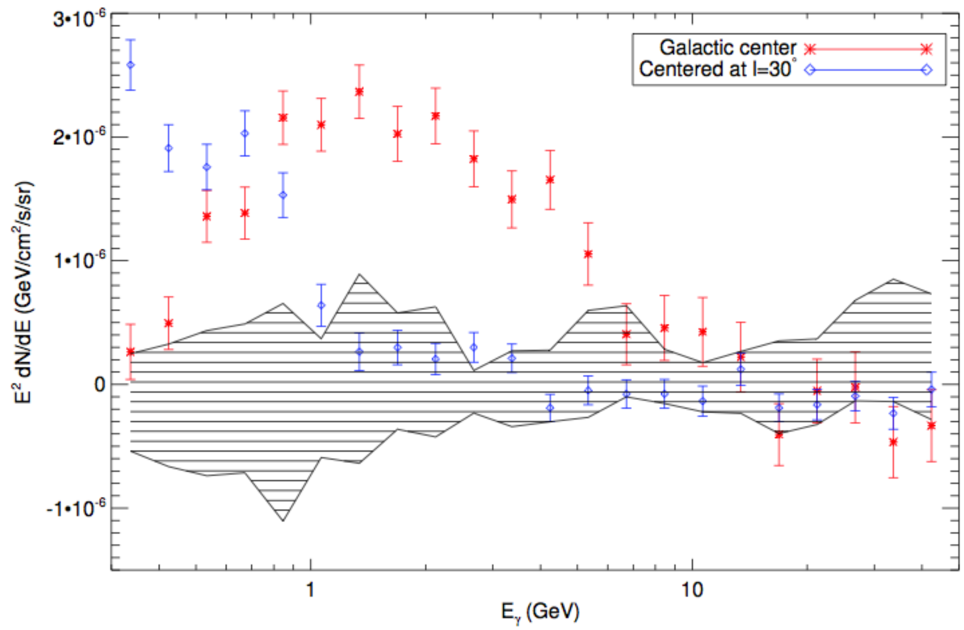

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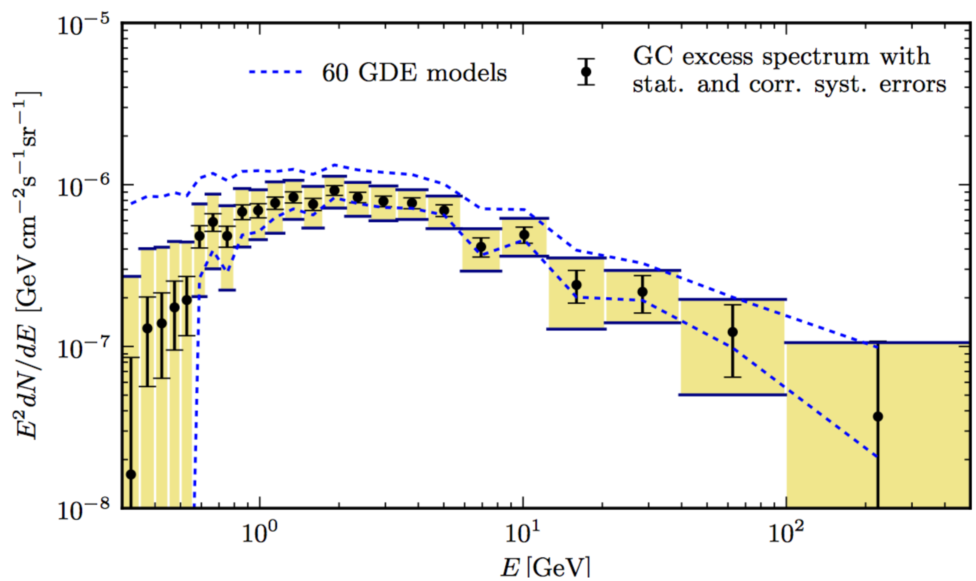
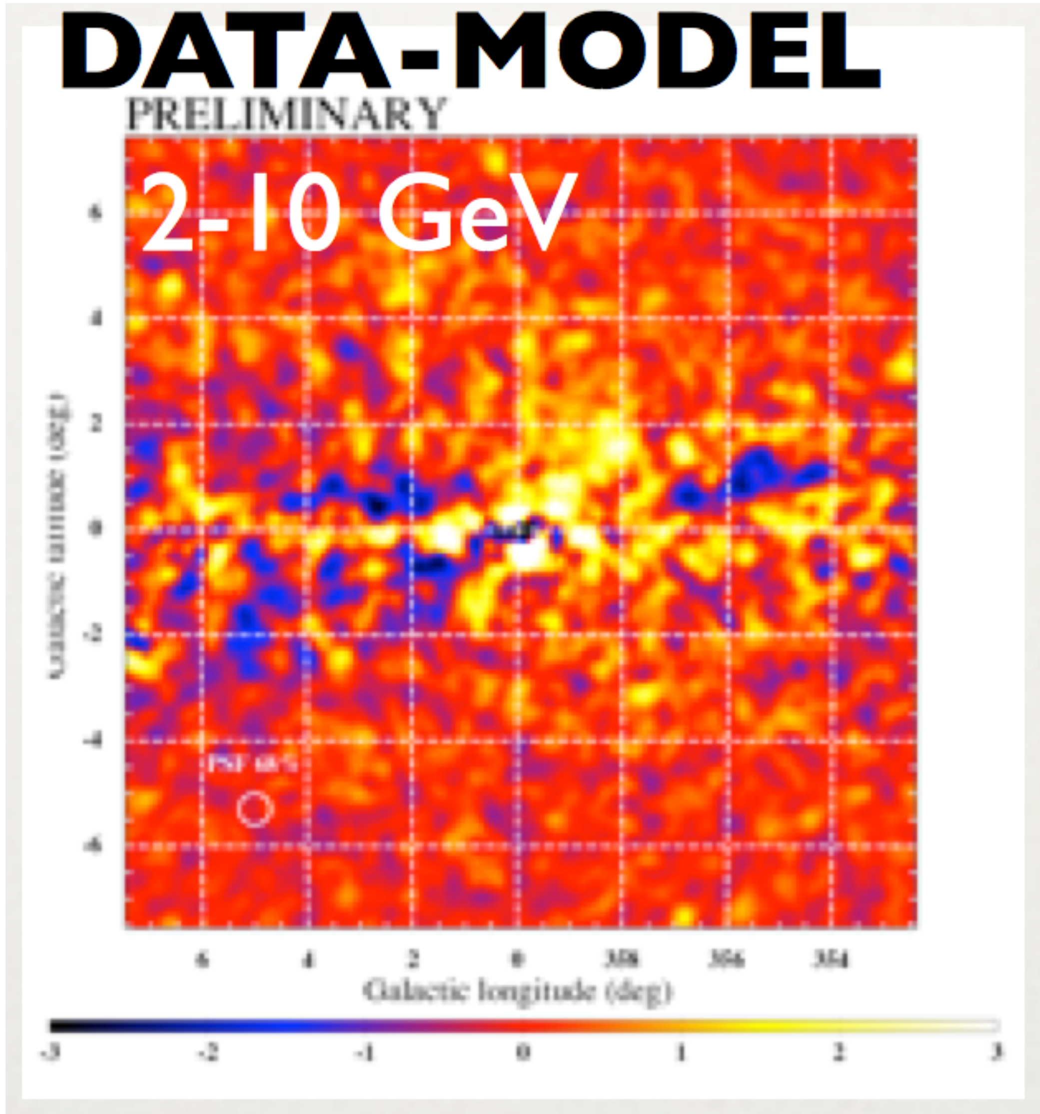
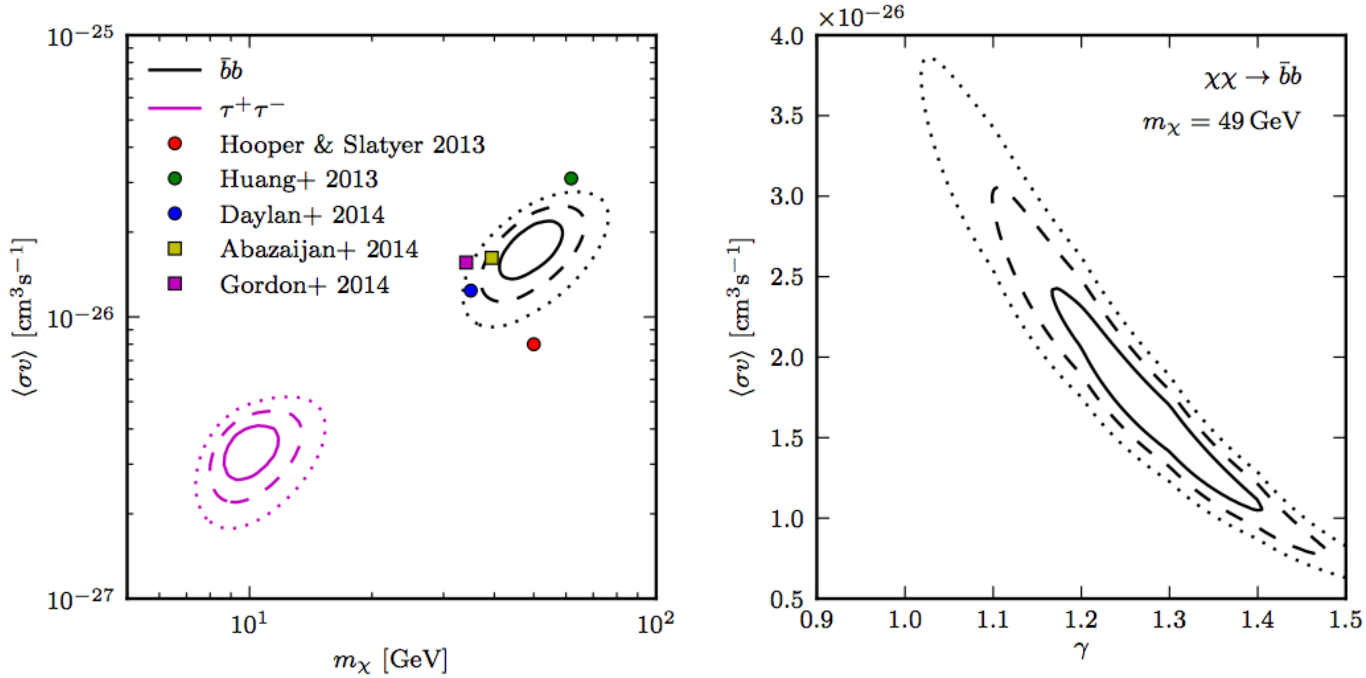


What does the Fermi Collaboration say?

- Talk presented by Simona Murgia at Fermi Symposium 20-24 October.
- “We find an enhancement approximately centered on the Galactic center with a spectrum that peaks in the GeV range, that persists across the models we have employed”
- “Peaked profiles with long tails (NFW, NFW contracted) yield the most significant improvements in the data- model agreement”



The DM interpretation



- Preference for DM below the 100 GeV scale, best fits come from annihilation to quarks.

- These results taken from Calore, Cholis & Weniger '14, include a first estimate of systematic uncertainties. (Left panel: scanning DM mass at best-fit morphology; right panel: scanning slope of profile at fixed DM mass.)

- Consistent results from several independent groups.

Dark matter or astrophysics?

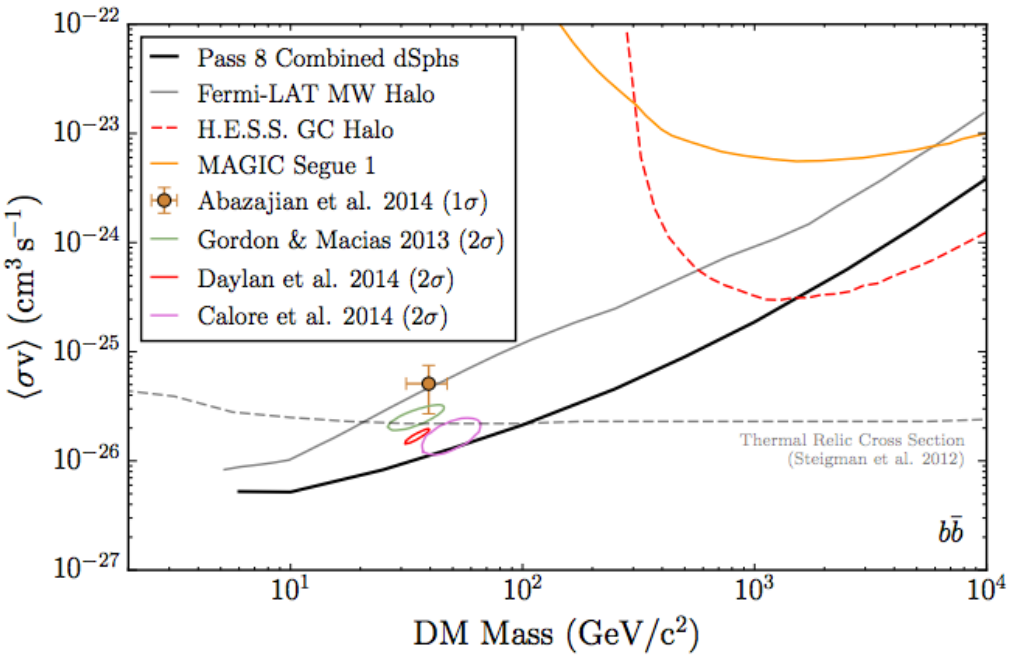
Dark matter

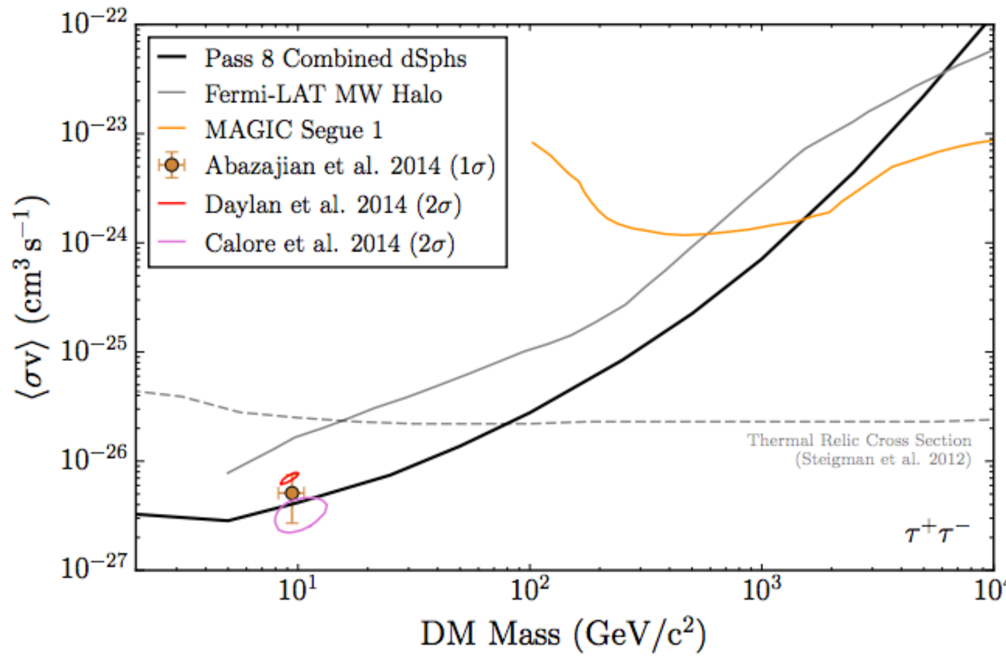
- Naturally explains:
  - The invariance of the spectrum with position.
  - The ~spherical morphology of the signal.
  - The profile: steeply peaked at the Galactic Center but extending out to (at least) 10 degrees.
- Required annihilation cross section lines up with long-standing predictions from the simple “thermal relic” scenario.
- Spectrum can be easily produced by annihilation of light DM.
- BUT: no detection yet in other channels - is DM excluded? (short answer: no, but is constrained)

Alternatives

- MILLISECOND PULSARS:
  - Spectrum of observed MSPs matches excess well at energies > 1 GeV.
  - MSPs originate from binary systems, can naturally explain steep slope of profile.
  - BUT: several studies suggest such a population would need to have unexpected spatial/luminosity properties.
- TRANSIENT OUTFLOWS:
  - Known to occur in the Galactic Center - but challenges in matching morphology + spectrum.

Dwarf galaxies





- Fermi study of stacked dwarfs with Pass 8 (1503.02641) can constrain nominal cross section for some channels.
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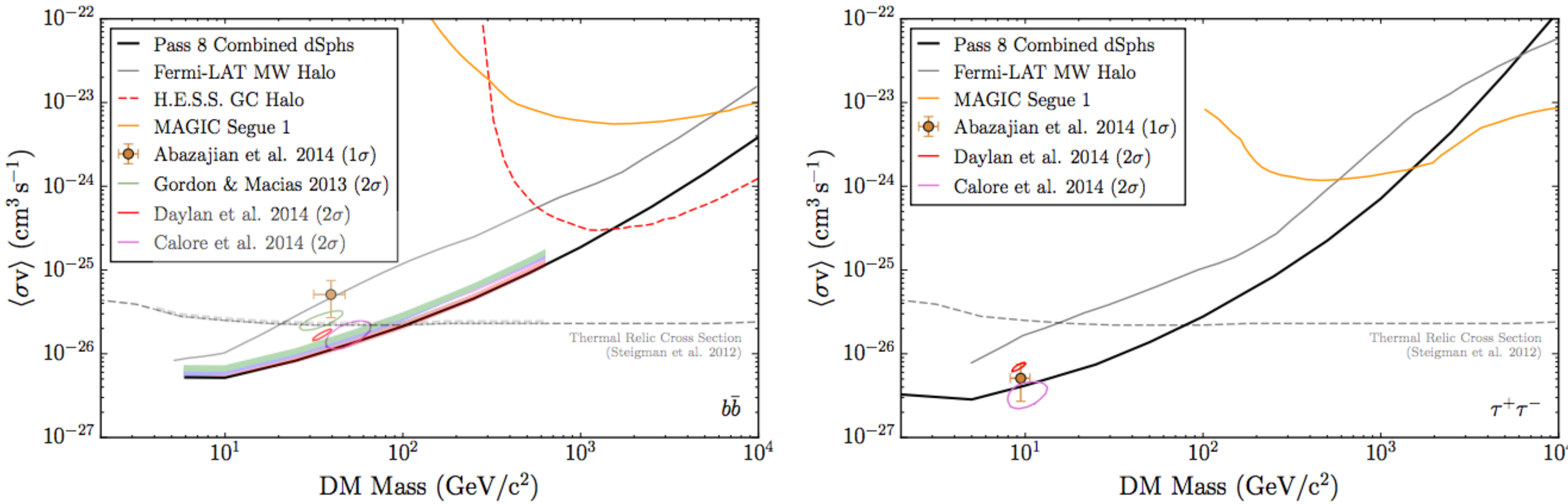
- Hope for a possible detection!

Dwarf galaxies



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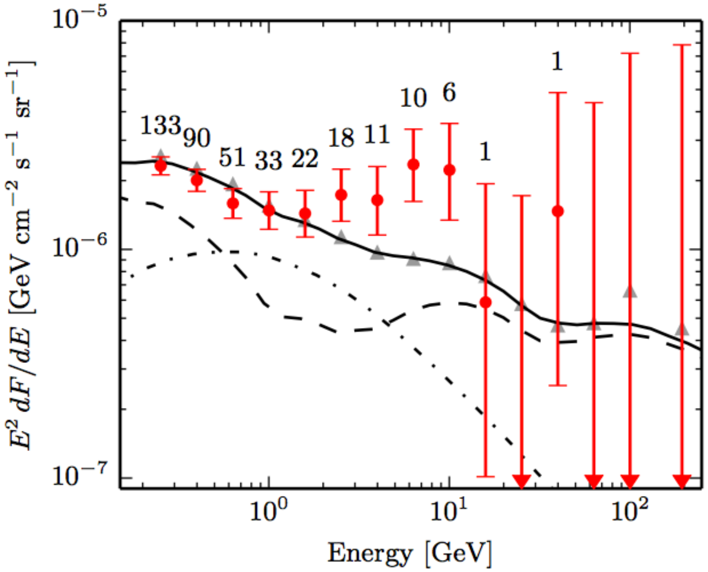
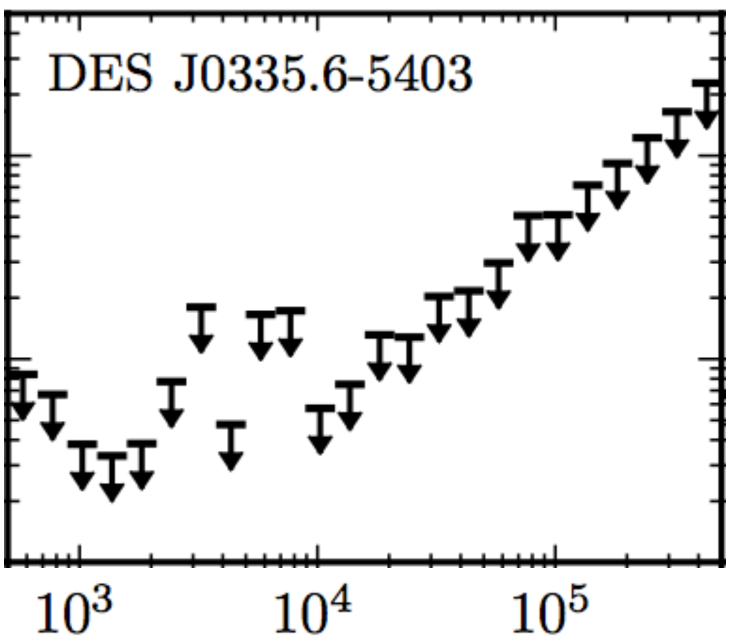
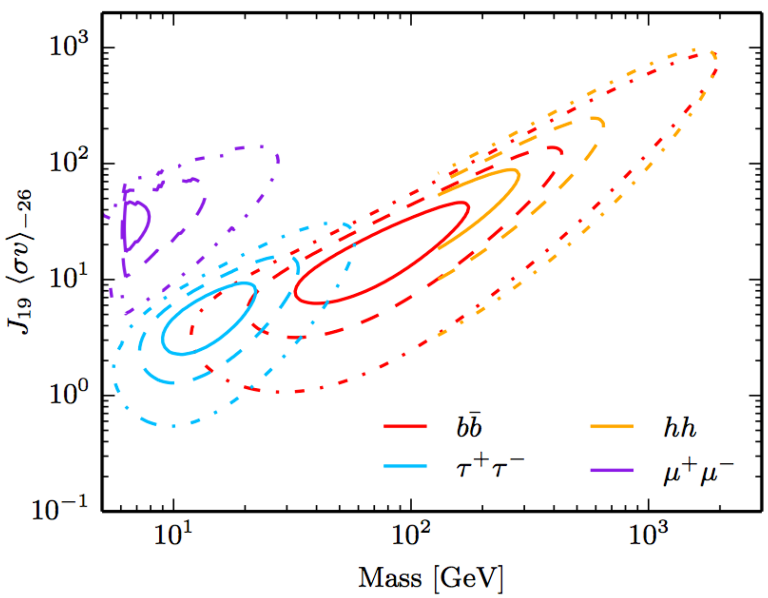
Reticulum II



- Geringer-Sameth et al (1503.02320, upper left) claim 2.3-3.7σ (depending on background modeling) excess from newly discovered dwarf candidate Reticulum II, in ~2-10 GeV range. Lower right: DM fits. (Similar results found by Hooper & Linden, 1503.06209 - they claim 3.2σ.)

- Fermi Collaboration paper (1503.02632, lower left) finds local ~1.5σ excess there, in same energy range, negligible after trials factor.





If we take a J-factor of $10^{19.5}$ GeV^2/cm^5 as found by 1504.03309*, favored region compatible with inner Galaxy excess.

*Note however that this value has a 1-order-of-magnitude error bar.

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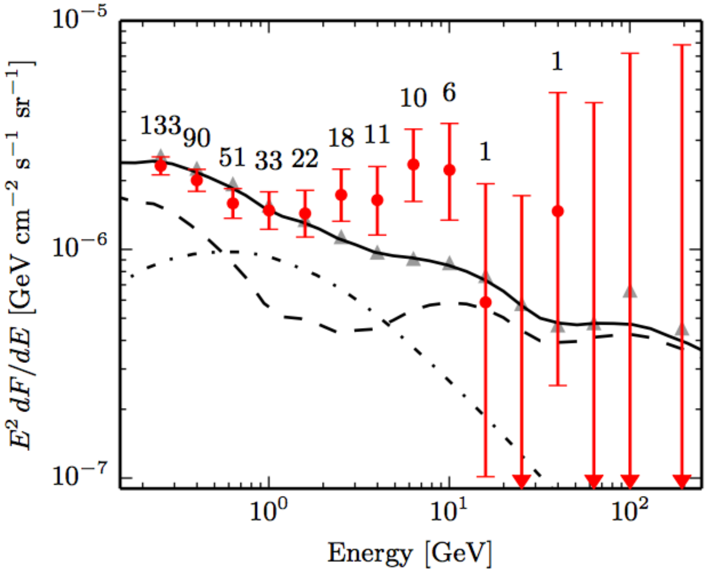

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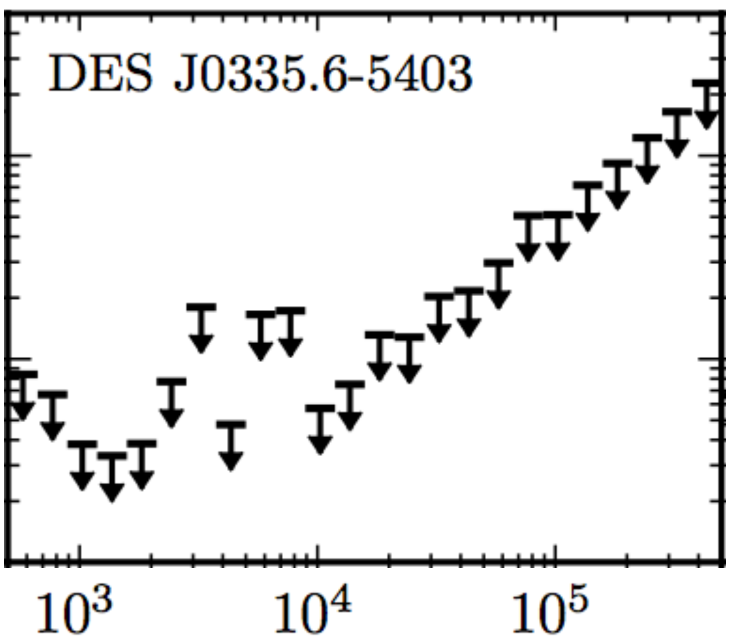

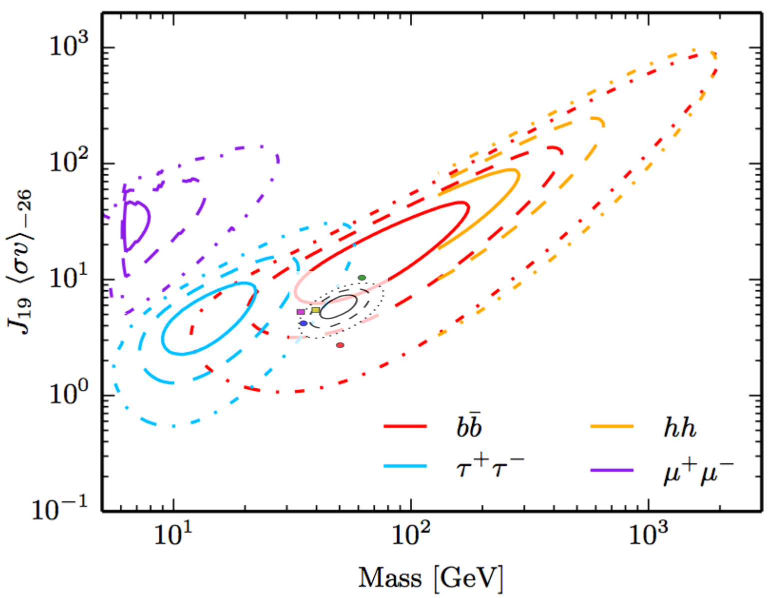

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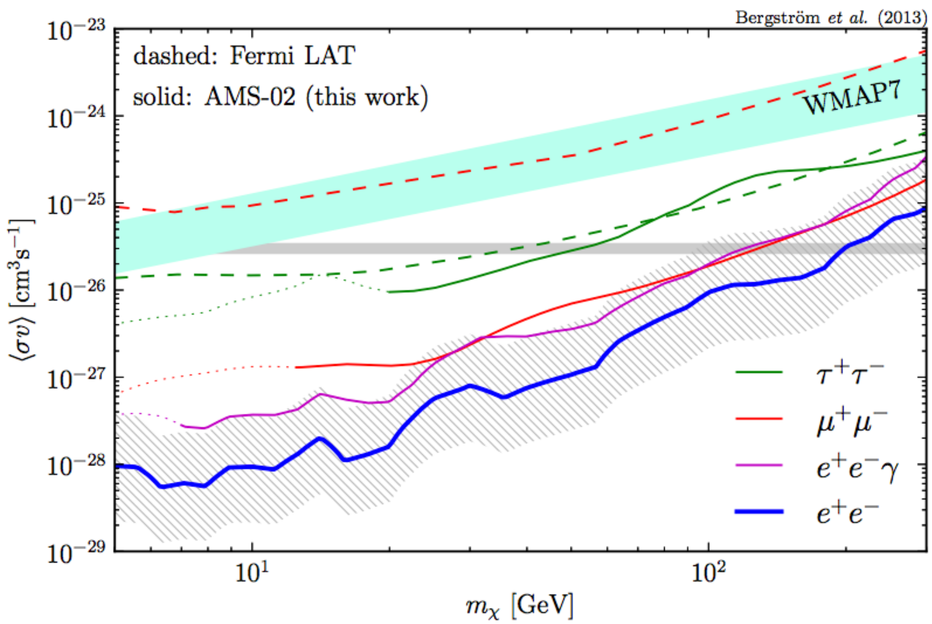
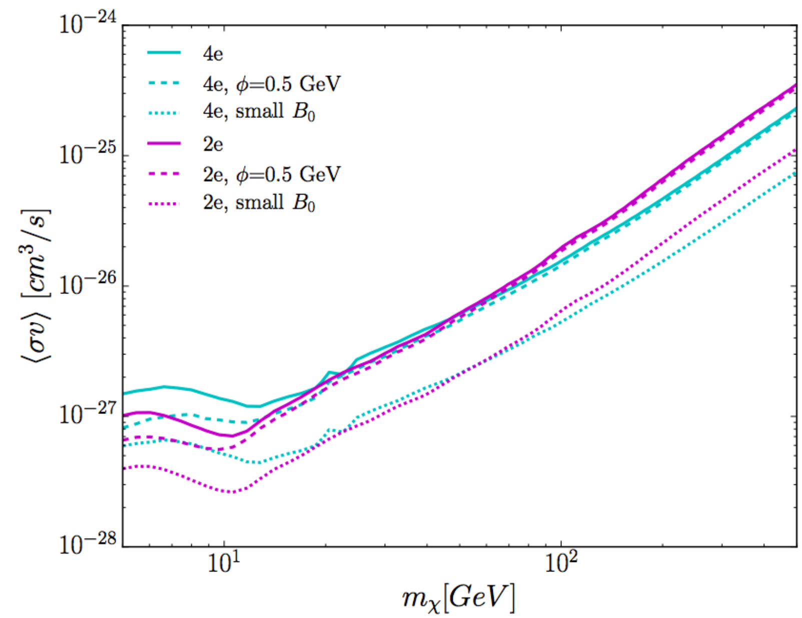
What can AMS-02 tell us?

- Stringent limits from AMS-02 on annihilation to leptonic final states

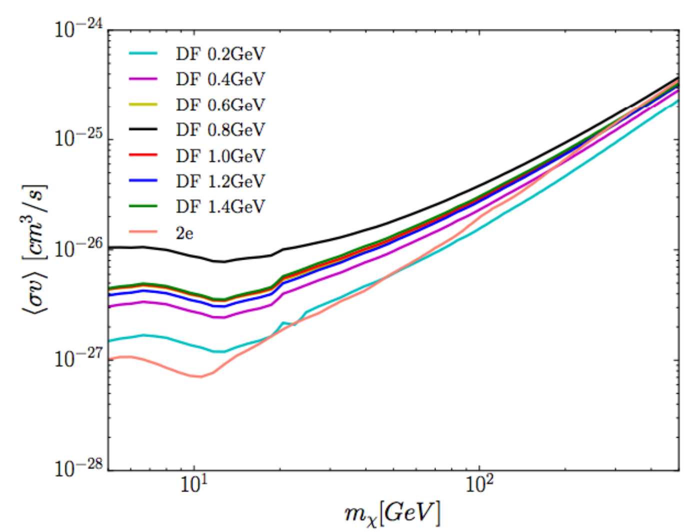
- Antiproton measurements from PAMELA already have sensitivity to hadronic scenarios - but large uncertainties on propagation

Leptonic final states



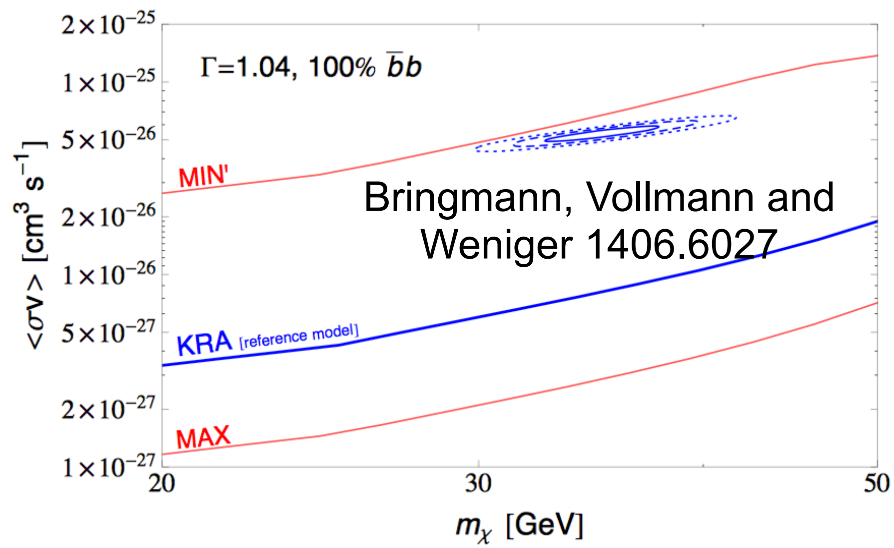


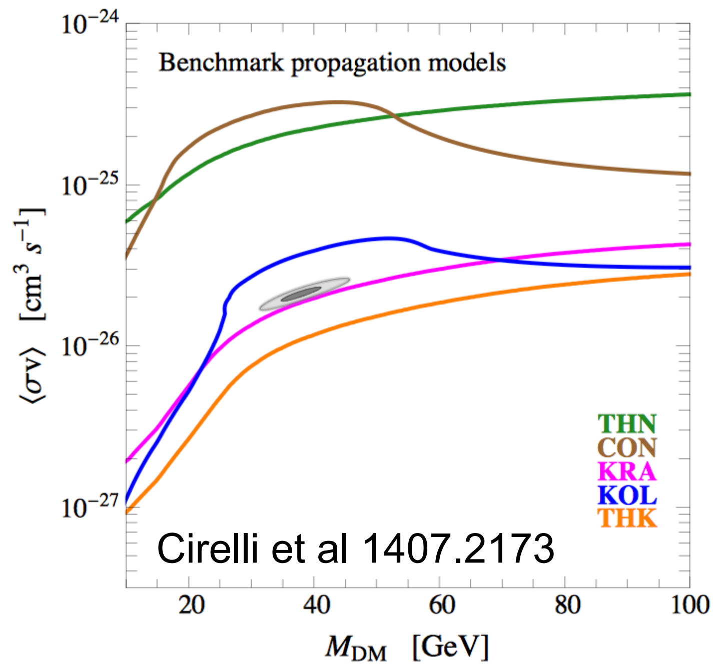
- Bergstrom et al 1306.3983: AMS-02 positron fraction yields strong bounds on the cross section for relatively light DM annihilating to channels that produce hard positrons.
- Liu et al 1412.1485: test constraints for annihilation through dark photons as well as 2e. These authors include systematic uncertainties from solar modulation & magnetic fields, and find somewhat weaker constraints (also plot 3 sigma exclusions rather than 90% CL).



Cosmic ray antiprotons

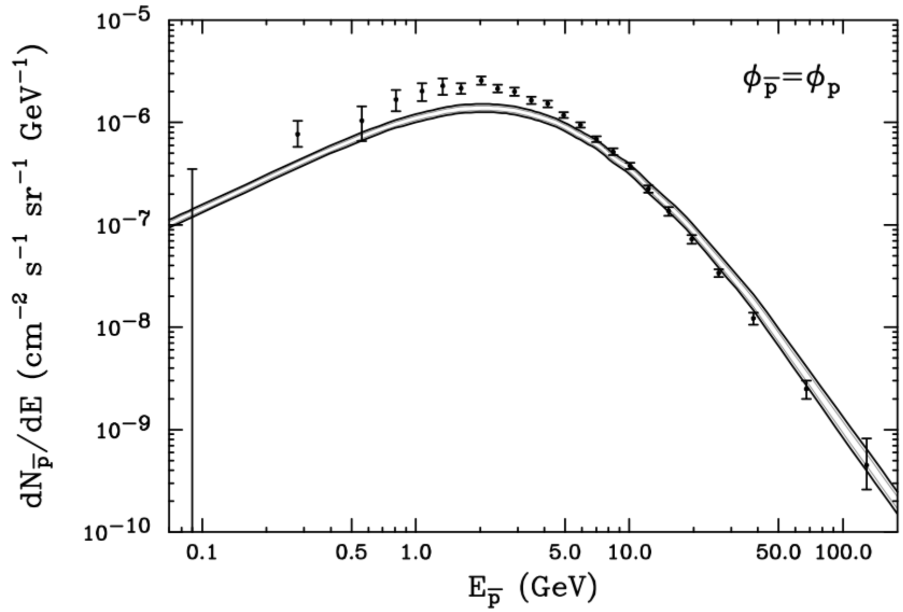
- DM annihilation could produce a flux of antiprotons.
- Usual uncertainties on DM distribution are mitigated since we are testing an actual signal! (not just setting limits)
- Some claimed tension between PAMELA data and the DM interpretation of the excess, but depends on the cosmic-ray propagation model and the statistical treatment.

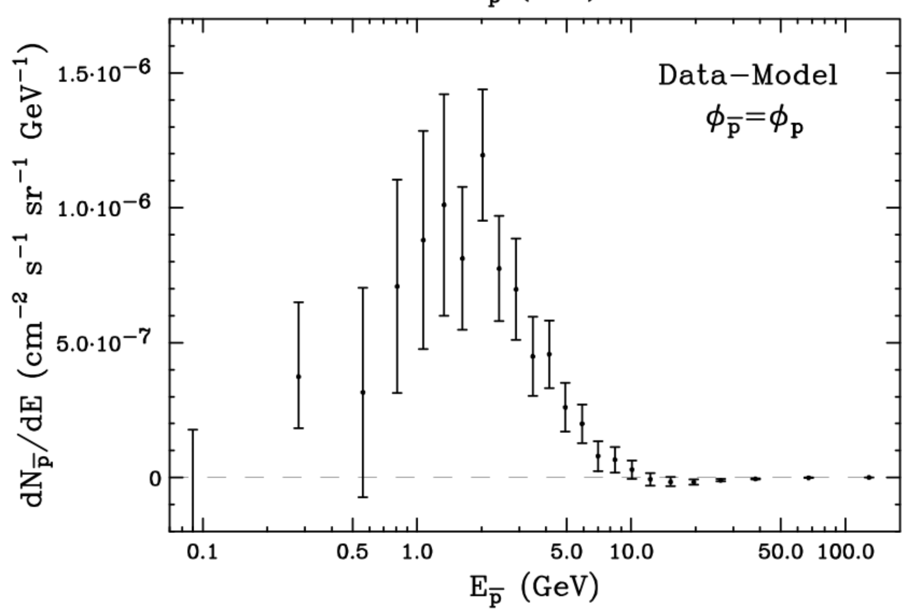


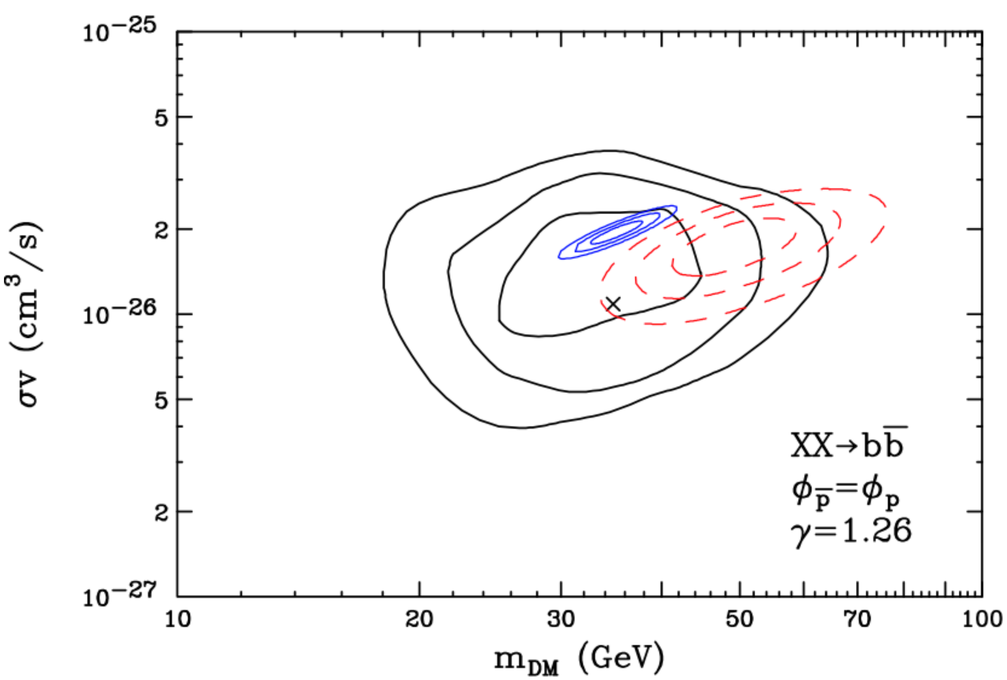


Antiprotons (cont.)

- Hooper, Linden & Mertsch 1410.1527: claim a consistent low-energy <u>excess</u> in PAMELA antiprotons.
- But may be background mismodeling.







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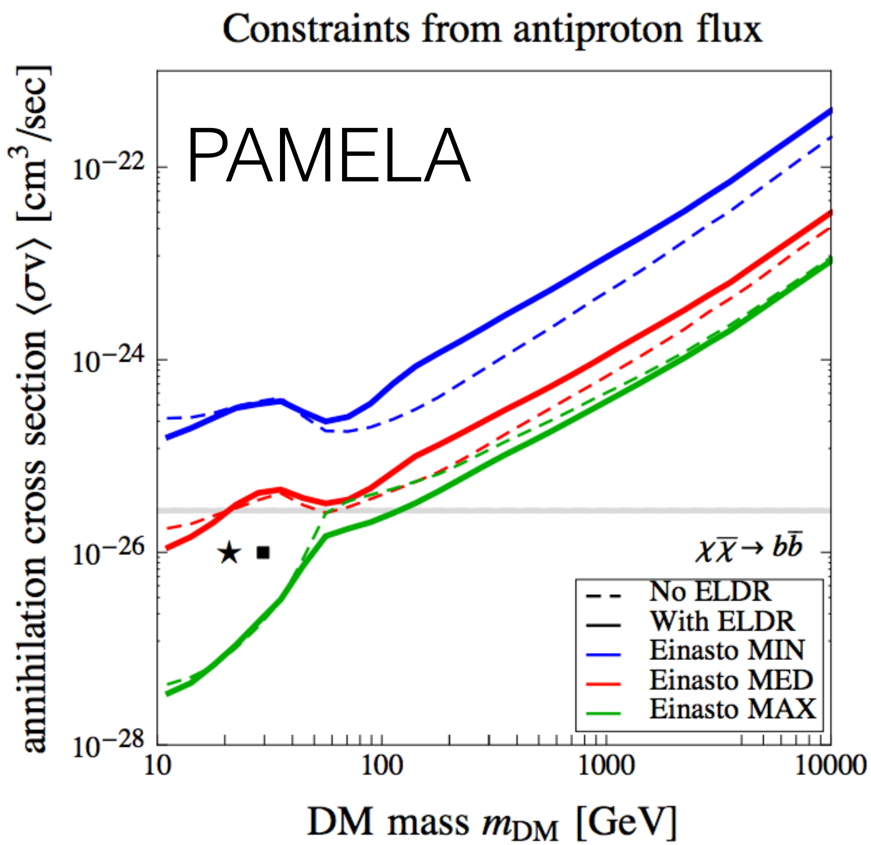

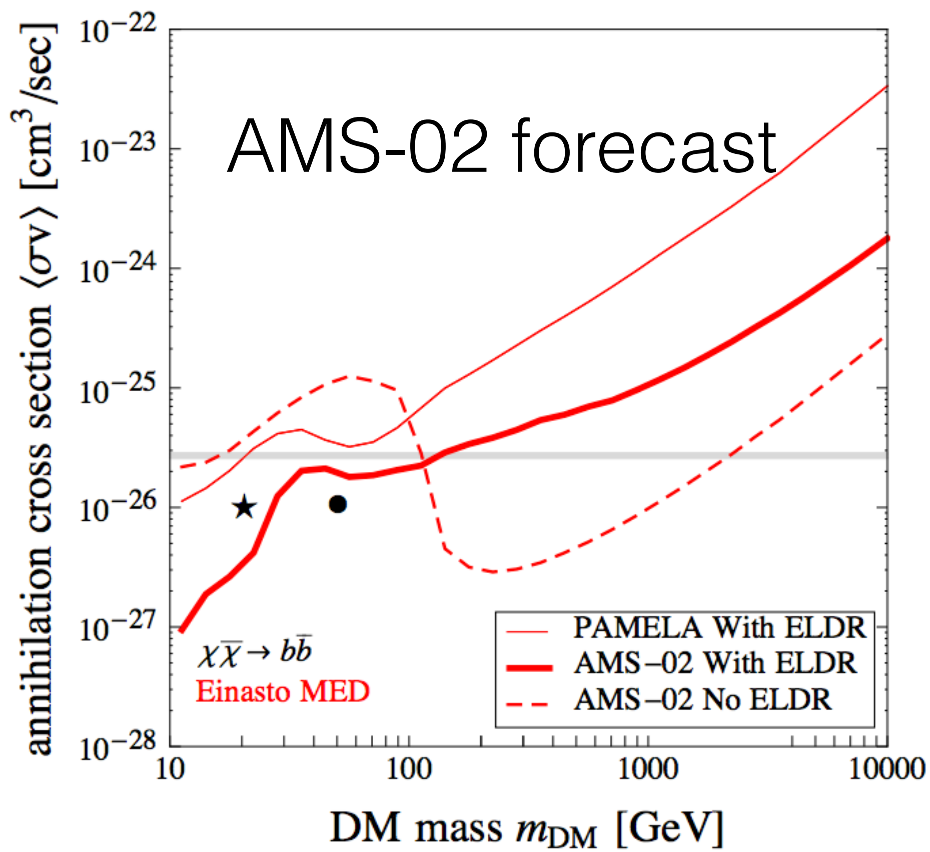

- Boudaud et al 1412.5696: important to take into account energy losses from tertiaries and diffusive reaccelerating (neglecting these effects can cause a false preference for a DM signal). Their different modeling does not pick up the claimed low-energy excess.
- Predict that AMS-02 will have sensitivity to thermal relic DM below ~150 GeV for MED propagation model - initial results based on preliminary AMS-02 data posted on arXiv today.

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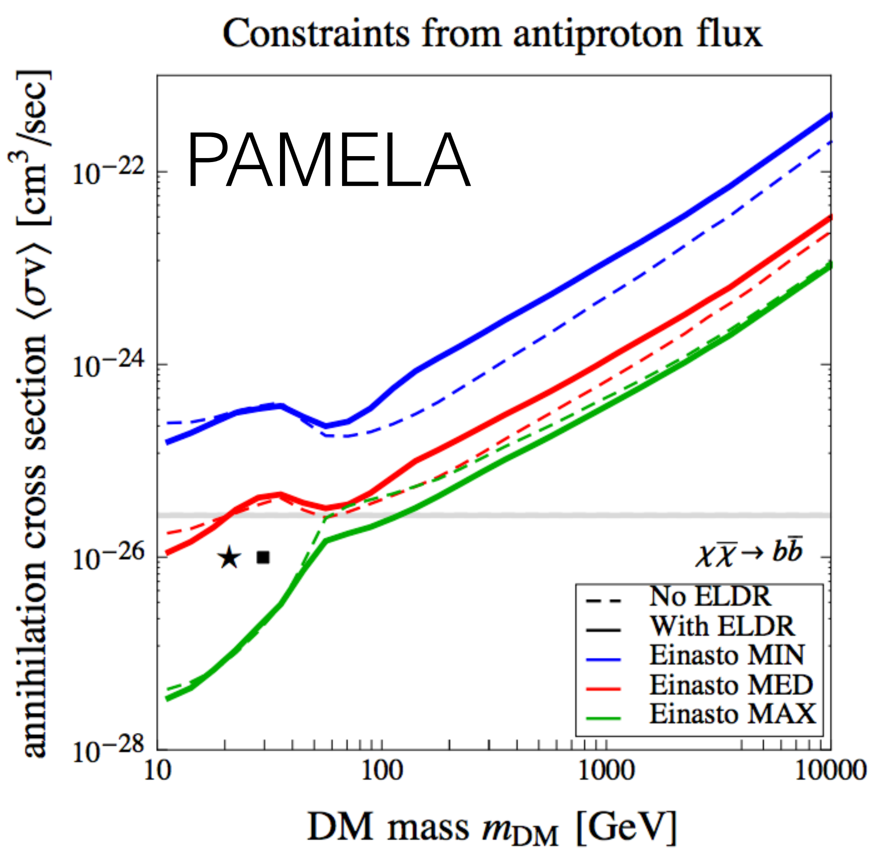

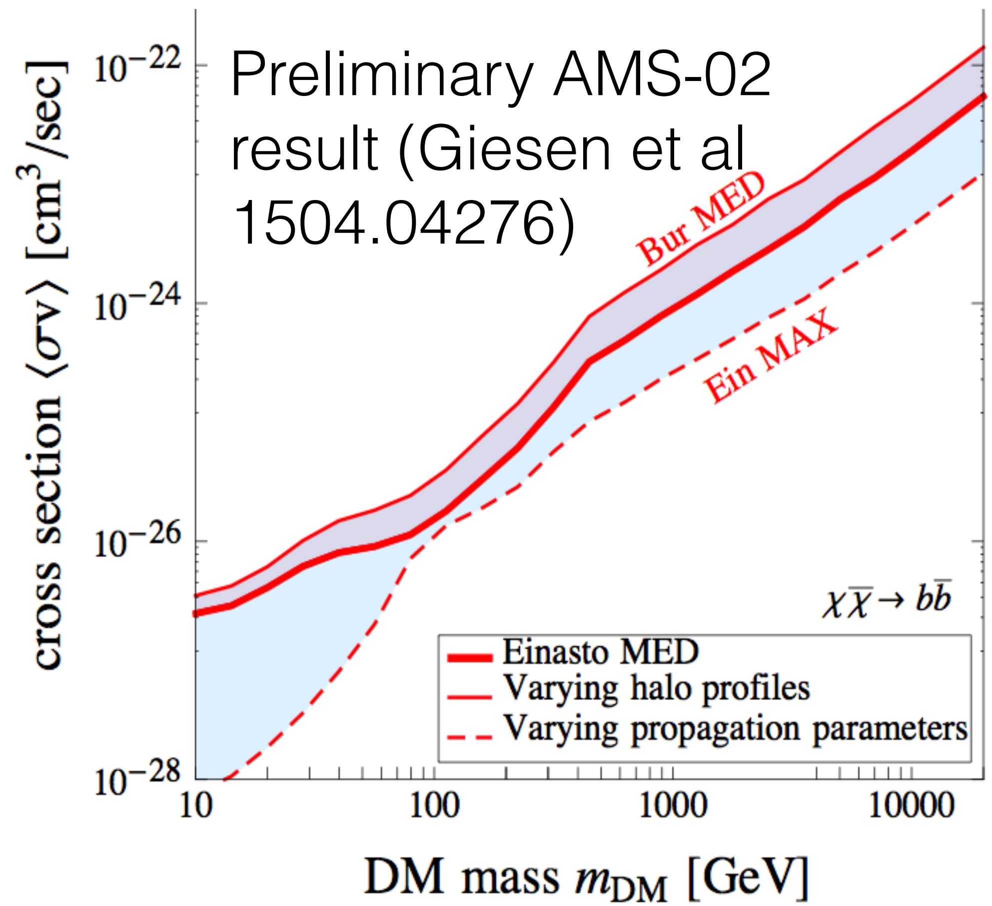

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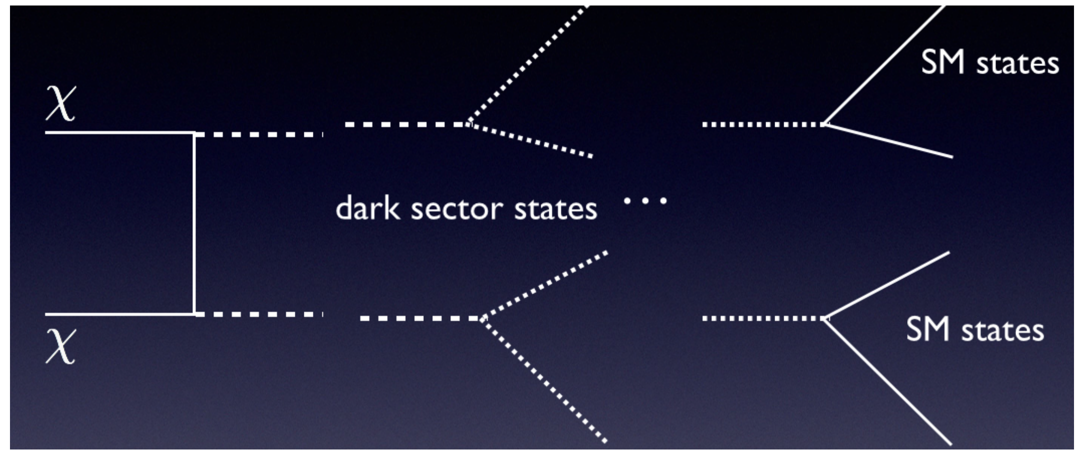
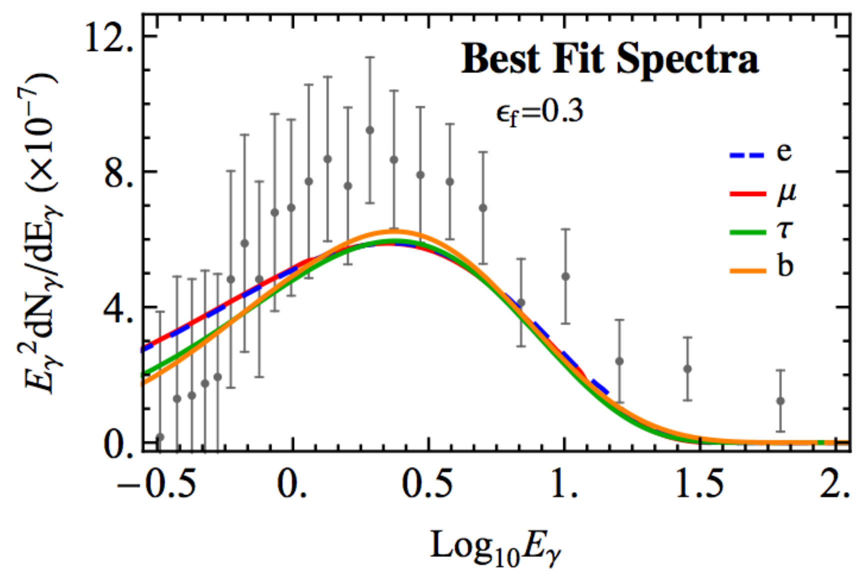
Indirect detection & dark sectors

Annihilation through a dark sector

- As in “dark force” models, dark matter could be embedded in a complex “dark sector” containing other states.



- DM annihilation/decay within dark sector can match relic density while suppressing direct/collider signatures.
- Potential novel signatures in indirect detection from dark sector physics - many examples, just a few shown here. (See also talk by L. Randall.)
- For GeV excess:
    - Direct annihilation favors hadronic channels.
    - Dark sector cascades can broaden more sharply peaked spectra to match the data better, + allow somewhat higher DM masses (e.g. Elor, Rodd & TRS ’15).
    - Essentially indistinguishable in photon spectrum - distinguishable in other channels? e.g. few antiprotons in leptonic/photon-dominated channels



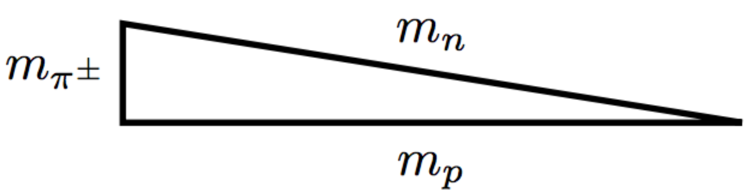
Multi-Component vs. Single Sector

Slides contributed by Jesse Thaler

Well-known that there might be multiple dark matter species
Less well-known that single dark matter sector can have many mass scales

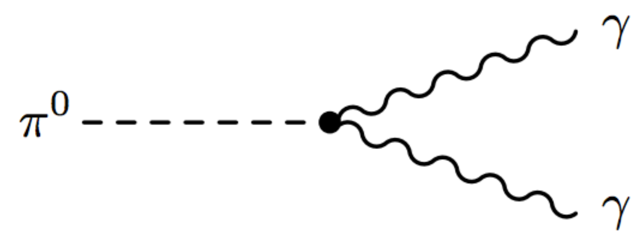
E.g.: Scaled-up QCD without weak interactions

Proton, neutron, charged pion mutually stable



(triangle inequality)

Neutral pion still decays to photons



Diverse gamma ray spectrum from multiple processes

Annihilation: $\pi^+\pi^- \to \pi^0\pi^0 \quad p\bar{p} \to \pi^0\pi^0 \quad n\bar{n} \to \pi^0\pi^0$

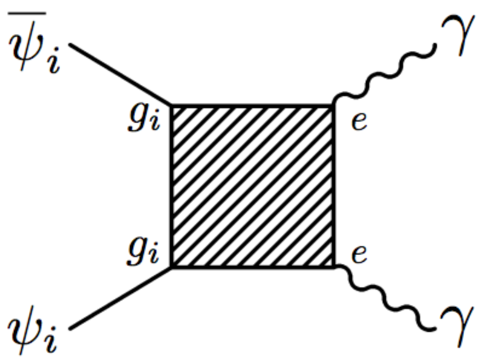
Semi-annihilation: $\pi^+ n \to p\,\pi^0 \quad \pi^- p \to n\,\pi^0 \quad p\,\bar{n} \to \pi^+\pi^0$

[D'Eramo, Thaler, 1003.5912; see also Hambye, 0811.0172, Hambye, Tytgat, 0907.1007]

Cosmic Ray Spectra from Semi-Annihilation

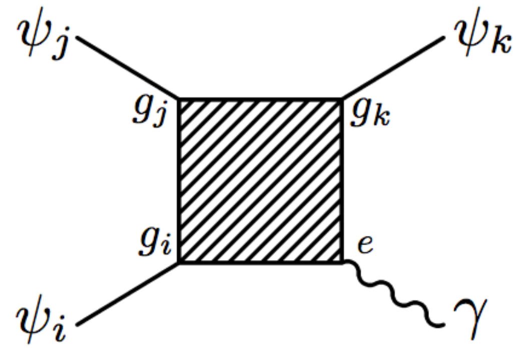
Equal mass DM states:

Annihilation line



$E_\gamma = m_{DM}$

Semi-annihilation line



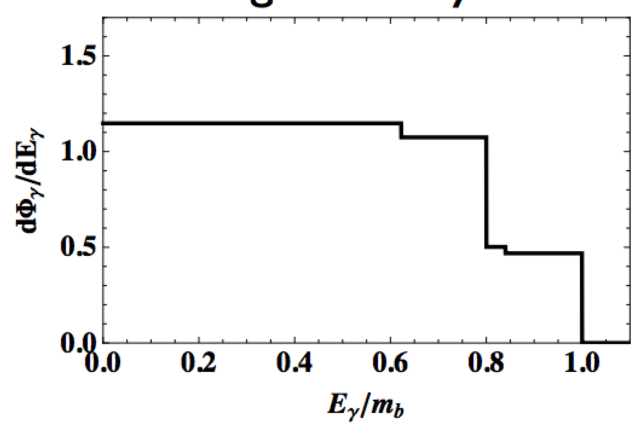
$E_\gamma = (3/4)\, m_{DM}$

Unequal mass DM states:

$$\chi_1\, \chi_2 \to \chi_3\, \varphi$$
$$\hookrightarrow \gamma\gamma$$

+ permutations

Stacked gamma ray "boxes"



Slides contributed by Jesse Thaler

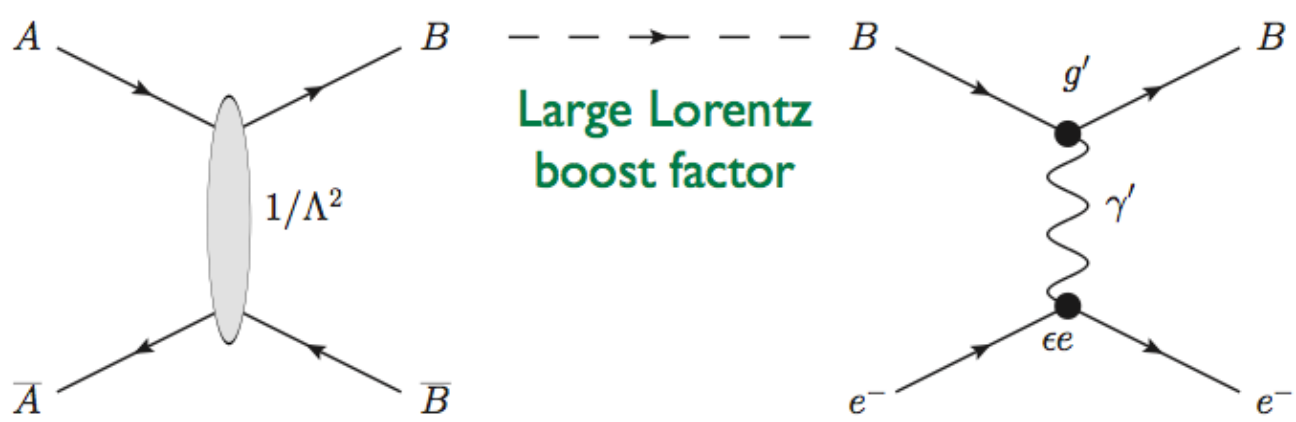
[D'Eramo, Thaler, 1003.5912; D'Eramo, McCullough, Thaler, 1210.7817]

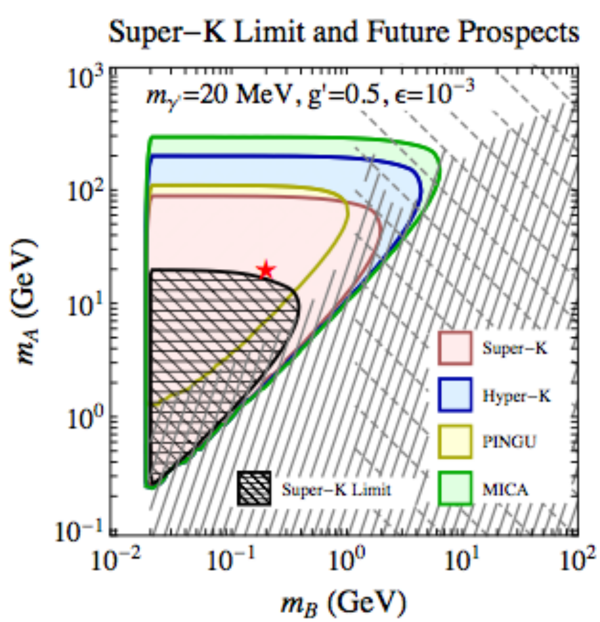
Dark Matter itself as "Cosmic Ray"

Slides contributed by Jesse Thaler

Heavy DM annihilates to light DM in Galactic Center (or Sun)

Light DM detected (in)directly via scattering on Earth





Boosted Dark Matter

Similar signals to neutrinos
Super-K already places limits (black region)
Needs dedicated analysis to "point" at GC (red region)
Additional signals possible from sun
Complementary to standard direct/indirect searches

[Agashe, Cui, Necib, Thaler, 1405.7370; see also Huang, Zhao, 1312.0011, Berger, Cui, Zhao, 1410.2246; Kong, Mohlabeng, Park, 1411.6632; Cherry, Frandsen, Shoemaker, 1501.03166; Kopp, Liu, Wang, 1503.02669]

Conclusions

- Planck CMB polarization measurements appear to exclude annihilating DM as primary source for AMS-02 positron excess.
  - Constraints especially strong for Sommerfeld-enhanced models.
  - Can be evaded in the presence of a large boost factor from DM density (e.g. from a dark disk), or suppression of annihilation at high redshift.
- AMS-02 e^+e^- and antiproton measurements can probe DM explanations for the GeV gamma-ray excess in the inner Galaxy.
  - e^+e^- measurements place powerful constraints on leptonic scenarios.
  - Antiproton measurements could potentially detect or rule out a counterpart signal, in hadronic DM annihilation scenarios - but currently limited by propagation/modulation uncertainties.