Dark Matter Theory and (Indirect) Searches

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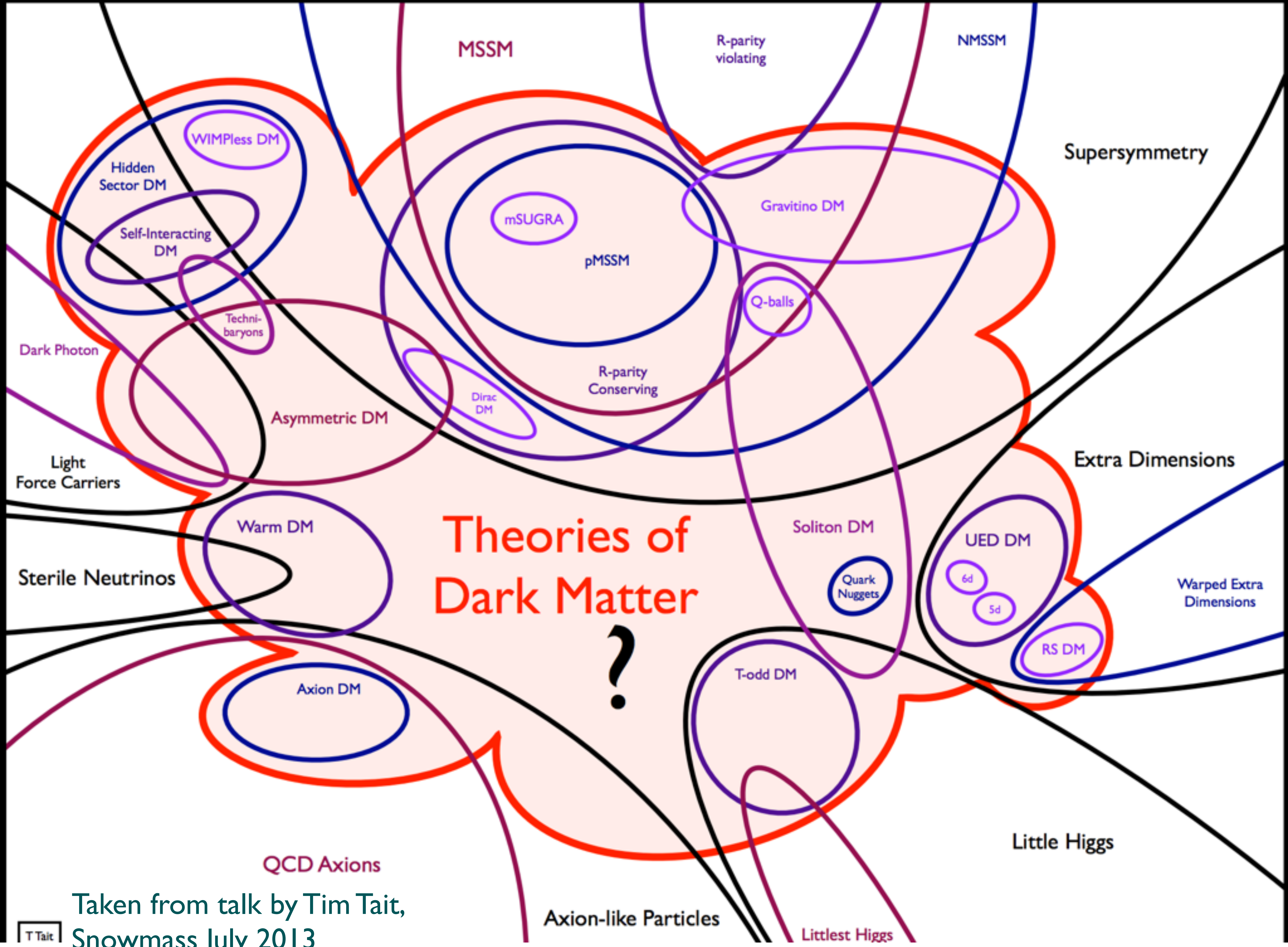
Pheno '15

University of Pittsburgh

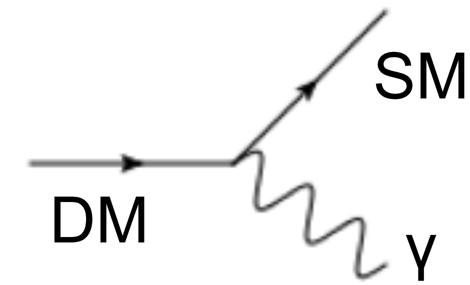
5 May 2015

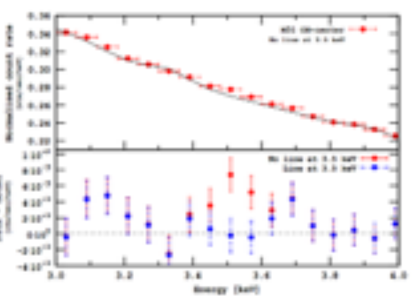


Taken from talk by Tim Tait, Snowmass July 2013

Outline

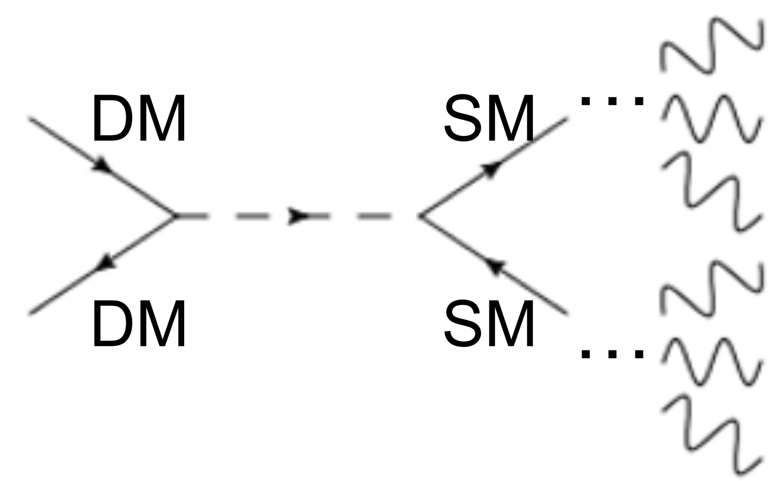
DM decay?

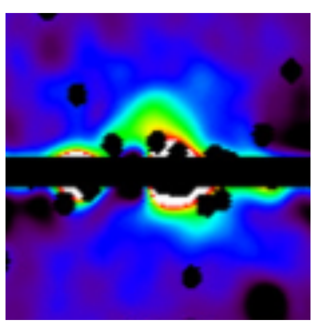




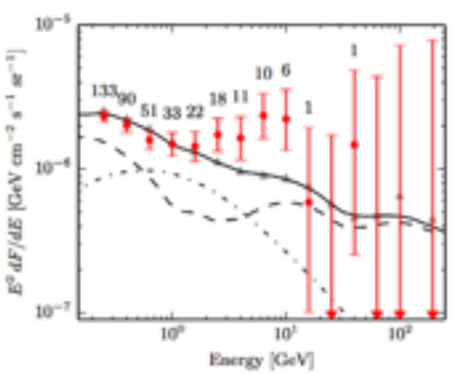
Status of the 3.5 keV line

DM annihilation?

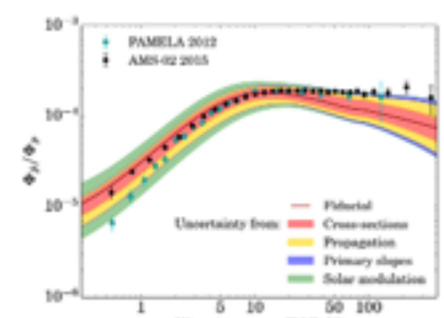


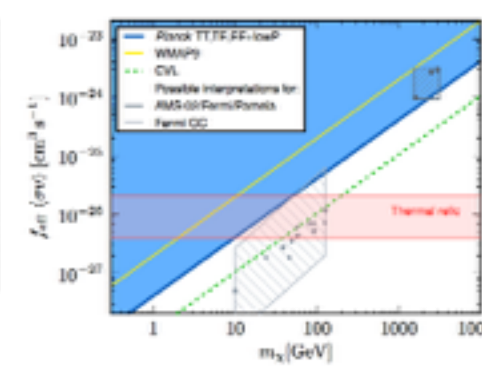


Status of the inner Galaxy GeV gamma-ray excess



The impact of new results from Fermi dwarf galaxy searches, AMS-02 and Planck

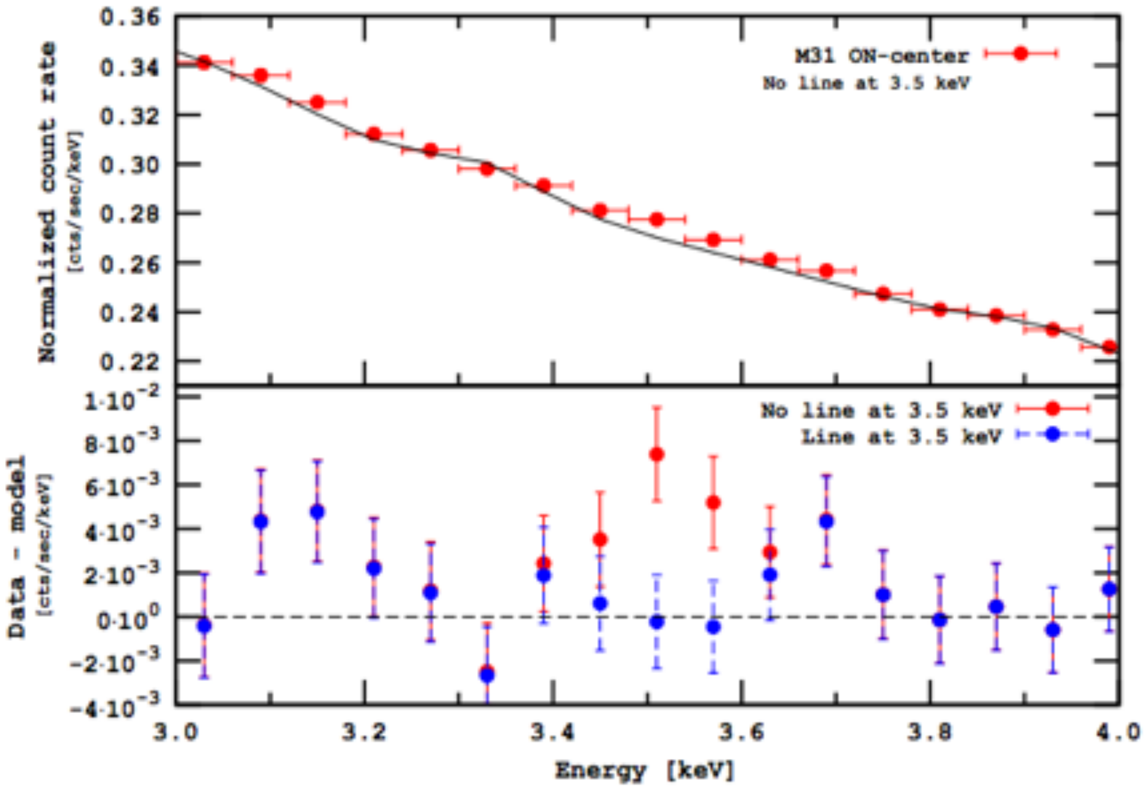




The 3.5 keV line

- 3.5 keV X-ray spectral line: initial discovery in XMM-Newton data by Bulbul et al (1402.2301) and Boyarsky et al (1402.4119), at ~4σ significance.

- Follow-up observational studies by:



Riemer-Sorenson (1405.7943, MW with Chandra data)
Jeltema & Profumo (1408.1699, MW)
Boyarsky et al (1408.2503, MW center)
Malyshev et al (1408.3531, dwarf spheroidal galaxies)
Anderson et al (1408.4115, stacked galaxies with Chandra and XMM-Newton)
Urban et al (1411.0050, Suzaku)

	XMM-Newton	Chandra	Suzaku
Milky Way center	✓	✗	
Andromeda galaxy	✓?		
Perseus cluster	✓	✓	✓
Coma, Virgo, Ophiuchus	✓	✗ Virgo only	✗
Stacked clusters	✓		
Stacked galaxies	✗	✗	
Milky Way dwarfs	✗		

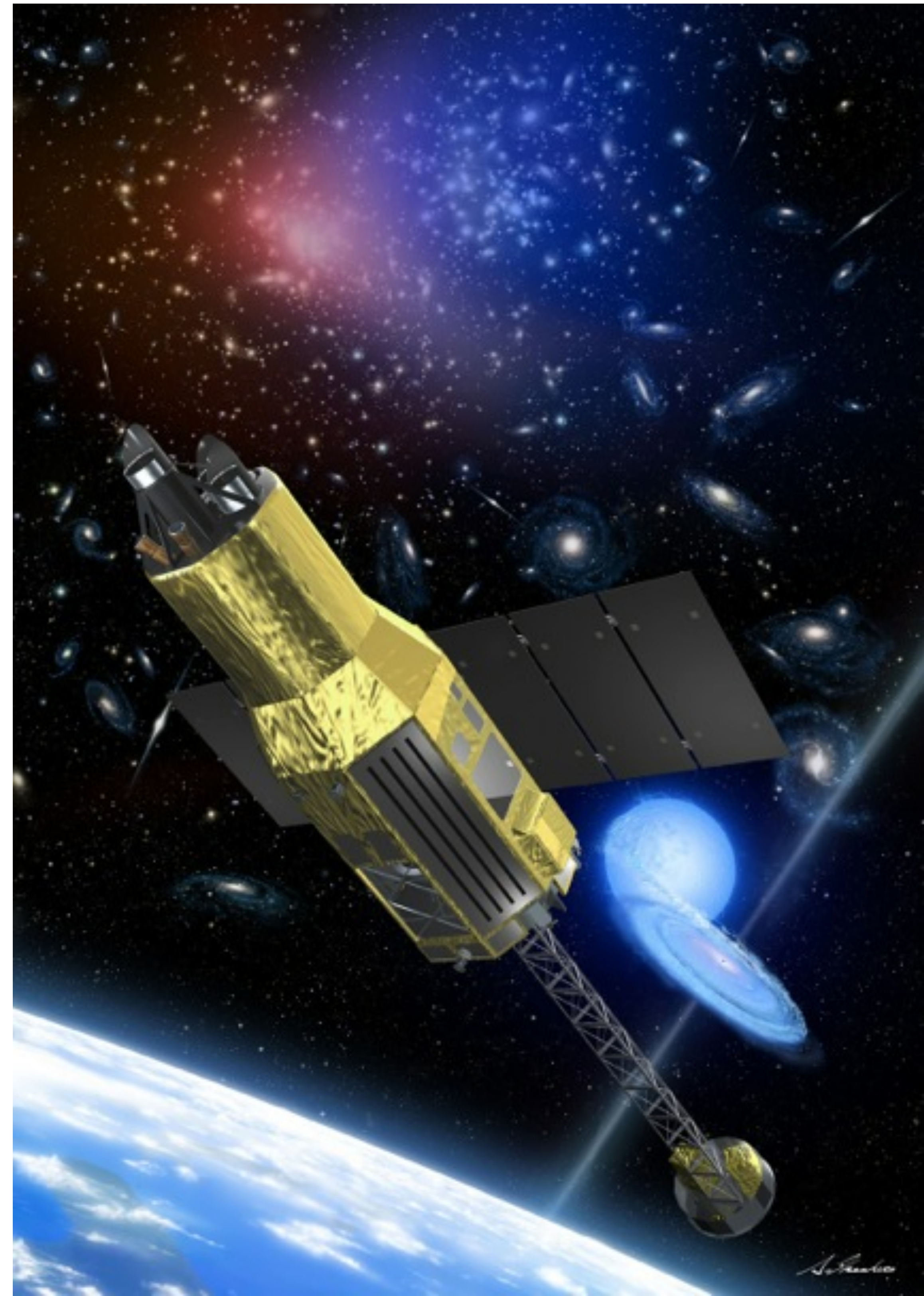
✓ Claimed detection
✗ No detection, upper limit

DM interpretations

- Simplest DM explanation is decaying sterile neutrino at a mass around 7 keV - long-standing DM candidate.
- However, simple DM decay models appear ruled out (at 12σ) by non-detection in dwarfs and stacked galaxies (1411.1758 also claims Perseus morphology is incompatible with DM decay).
- DM alternatives include exciting dark matter:
(Finkbeiner & Weiner 1402.6671, Cline & Frey 1410.7766)
    - DM has a metastable excited state 3.5 keV above the ground state.
    - This state is excited by DM-DM collisions, and subsequently decays producing a photon.
    - Rate of excitation scales as density^2 x velocity dependence - much less constrained than just DM density, seems to allow compatibility with data.
- Another possibility is conversion of an axion-like particle to an X-ray photon in the presence of magnetic fields (e.g. 1404.7741) - can lead to widely varying signals from different systems (e.g. 1410.1867).

Is it background?

- Ongoing controversy over possible contamination from potassium and chlorine plasma lines.
  (see e.g. 1408.1699, 1408.4388, 1409.4143, 1411.1759)
- There are two potassium lines close to 3.5 keV and their strength can depend sensitively on the plasma temperature.
- Astro-H experiment hopes to launch in 2016.
  - Soft X-ray Spectrometer System will cover energy range 0.3-12 keV with energy resolution ~7 eV.



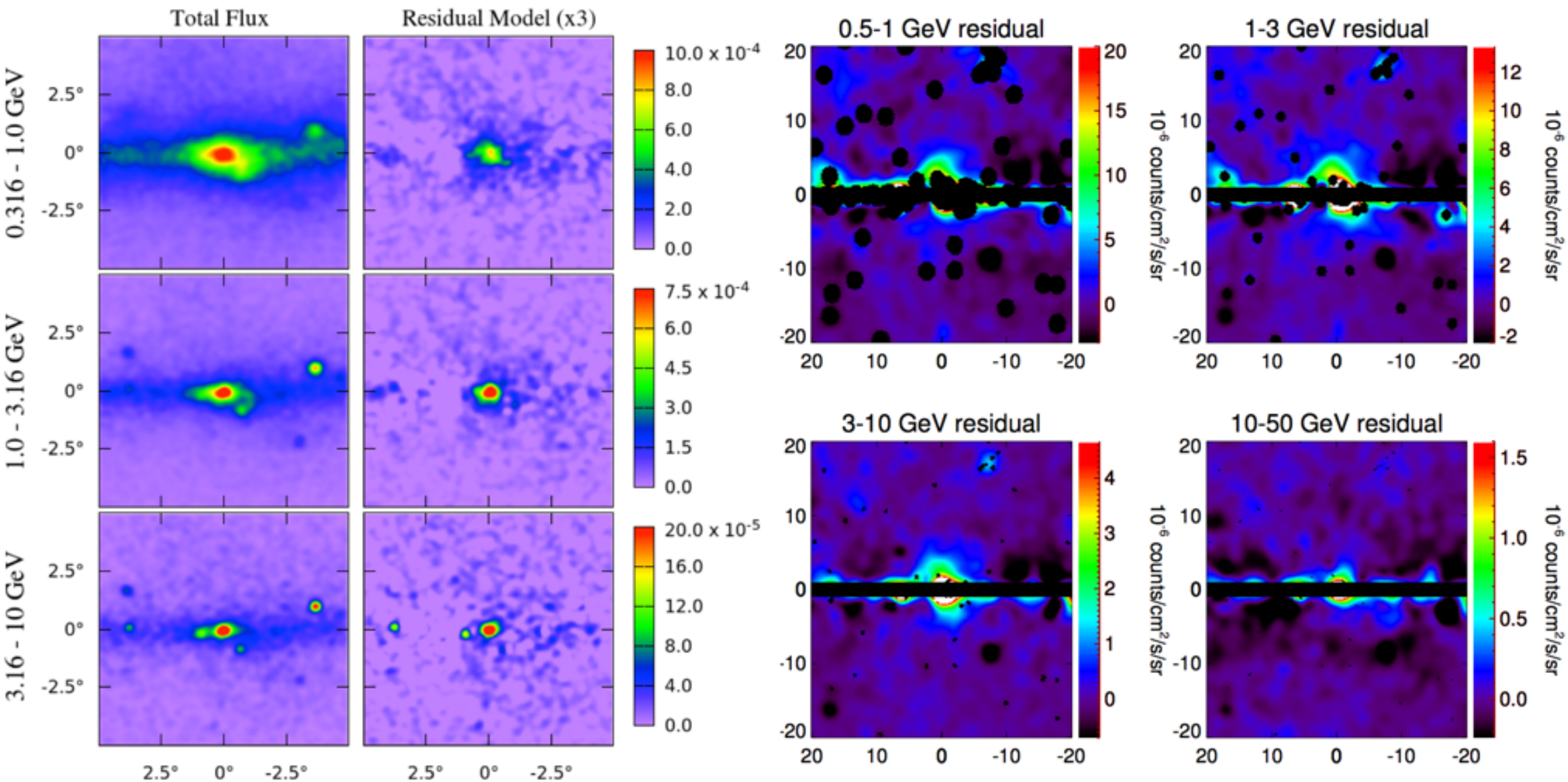
The Inner Galaxy GeV Gamma-Ray Excess

Summary

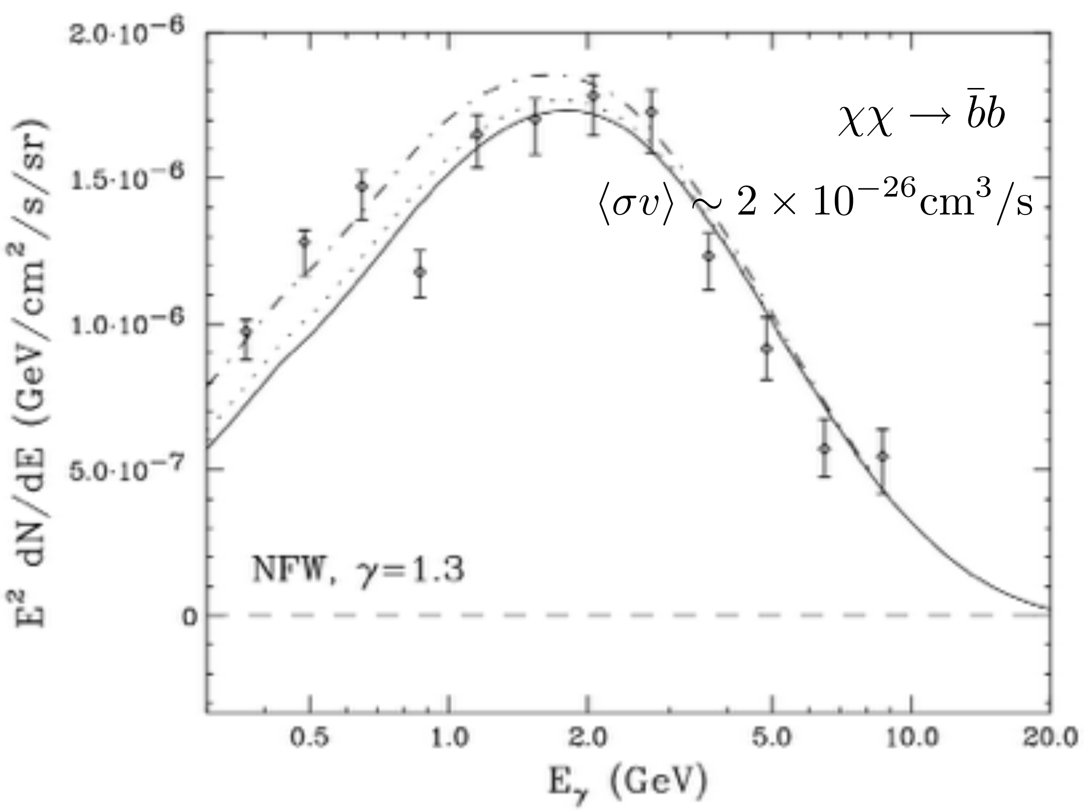
- Discovered in public data from the Fermi Gamma-Ray Space Telescope, first in the Galactic Center (Goodenough & Hooper 09) and later extending to higher latitudes (Hooper & TRS 13). Highly significant (test statistic, similar to $\Delta\chi^2$, is O(1000)) - not a statistical fluctuation.
- Spectral 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.
  - Small-r power-law slope of power/volume ~ $r^{-2.2-2.8}$ (corresponds to dark matter density profile with inner slope γ~1.1-1.4).
  - Appears centered on Sgr A*, the black hole at the center of the Milky Way.
  - Extends out to at least 10 degrees from the GC.

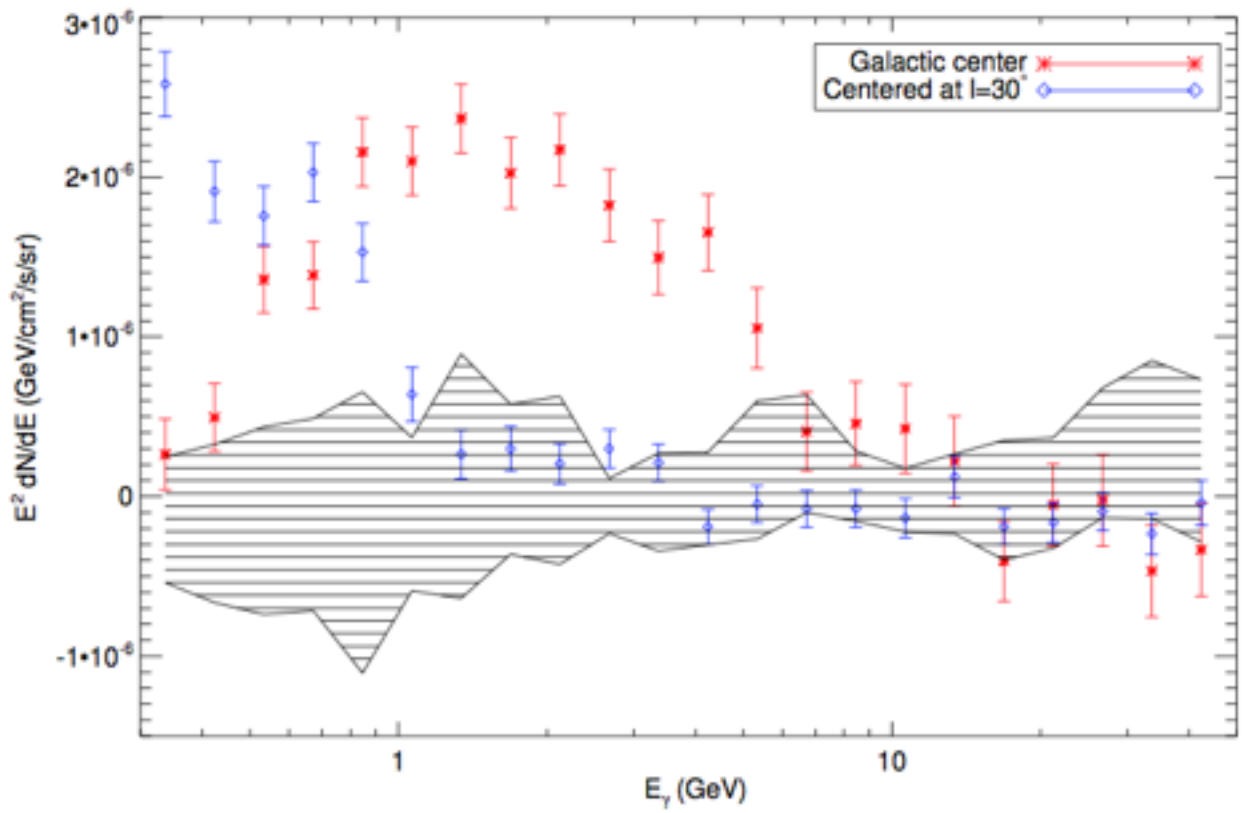
Spatial morphology

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

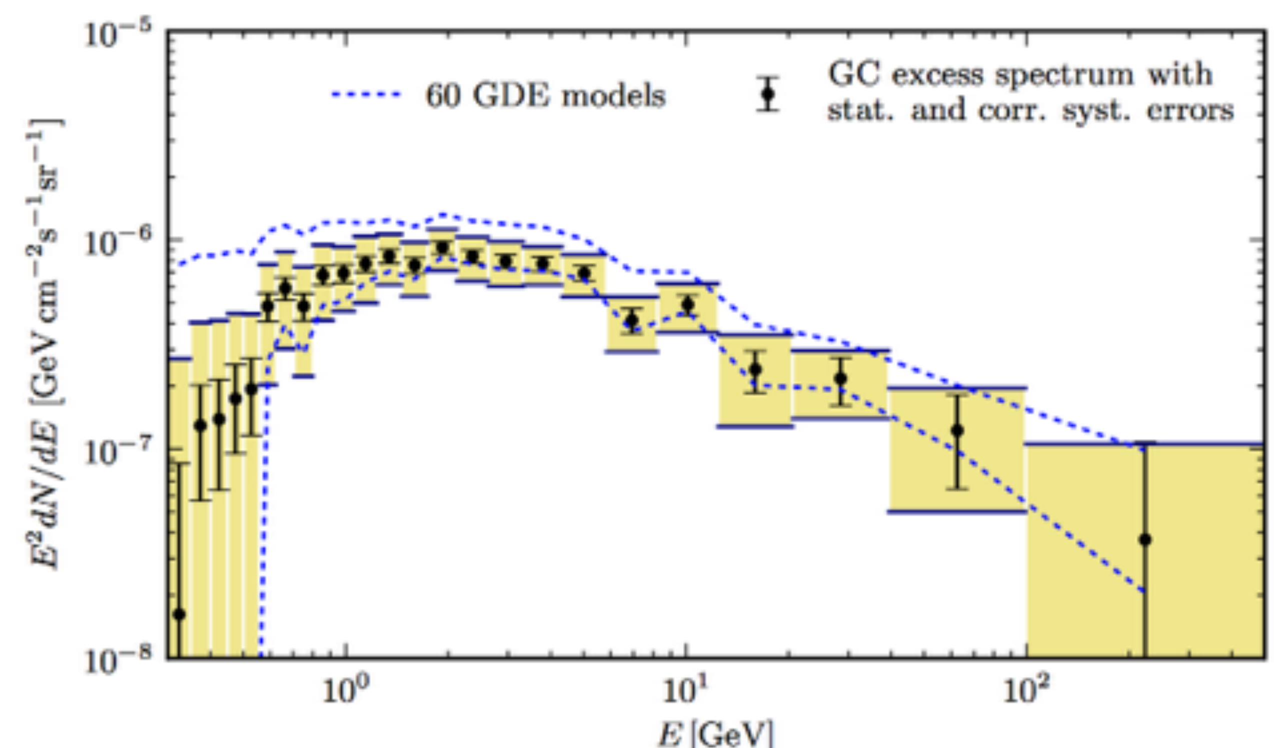


Spectral properties



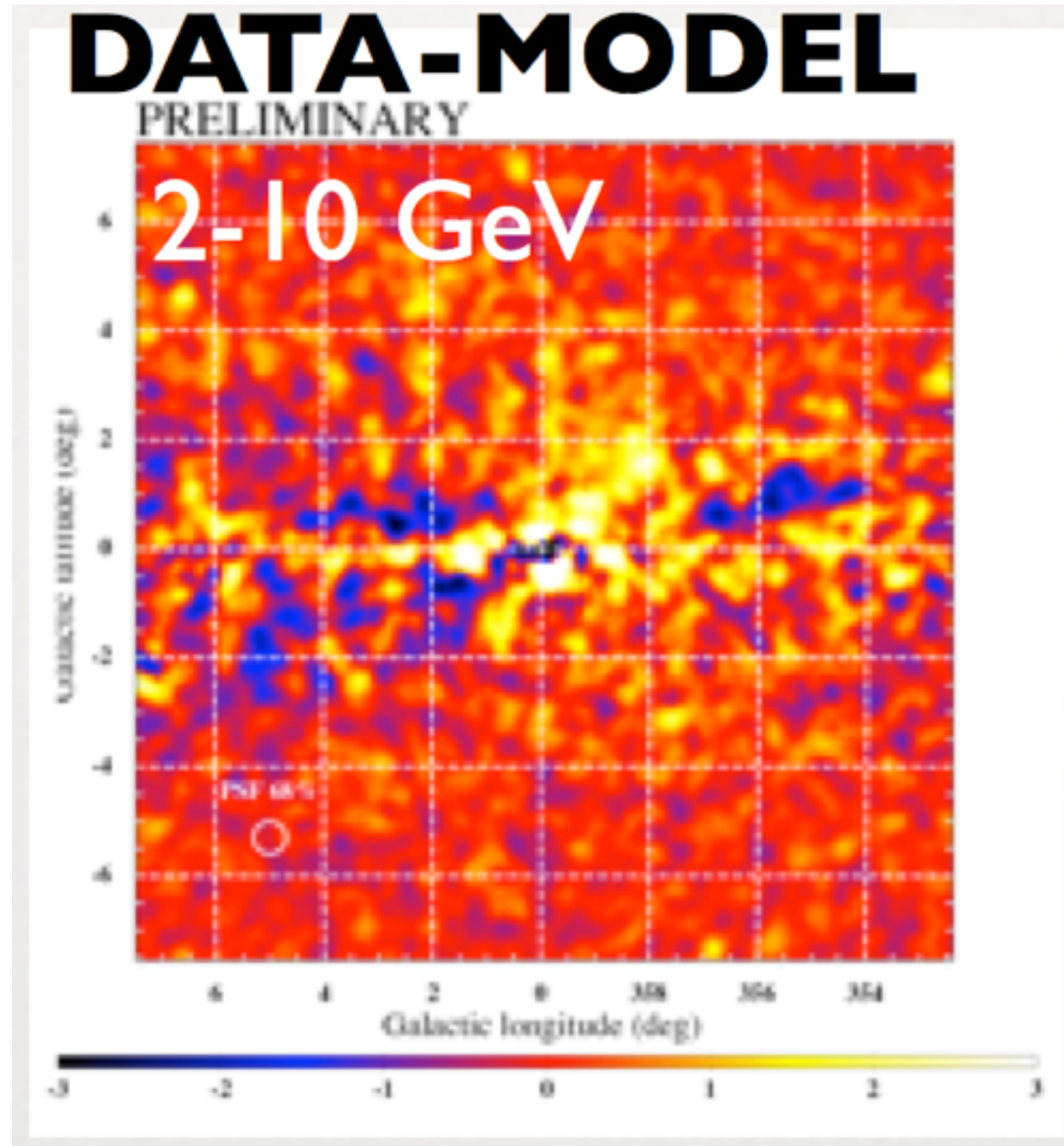


- Top: Daylan et al ’14. Left: Galactic Center spectrum. Right: Inner Galaxy spectrum (cross-hatched band and blue points indicate spectra if same analysis applied to other sky regions).
- Bottom: Calore, Cholis & Weniger ’14.

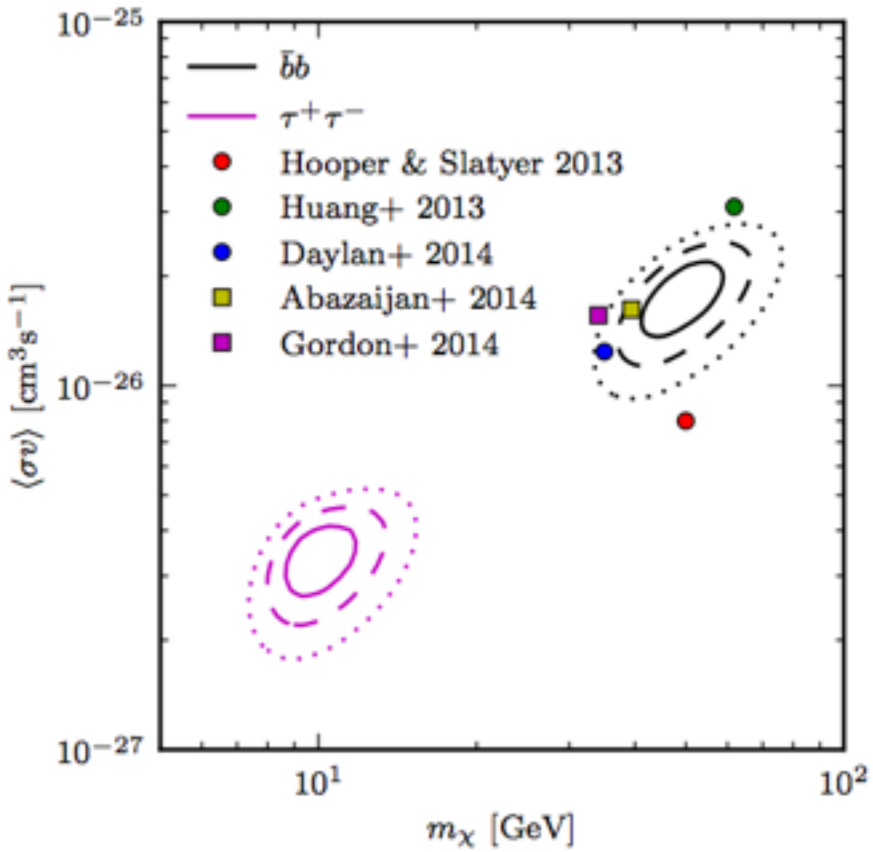


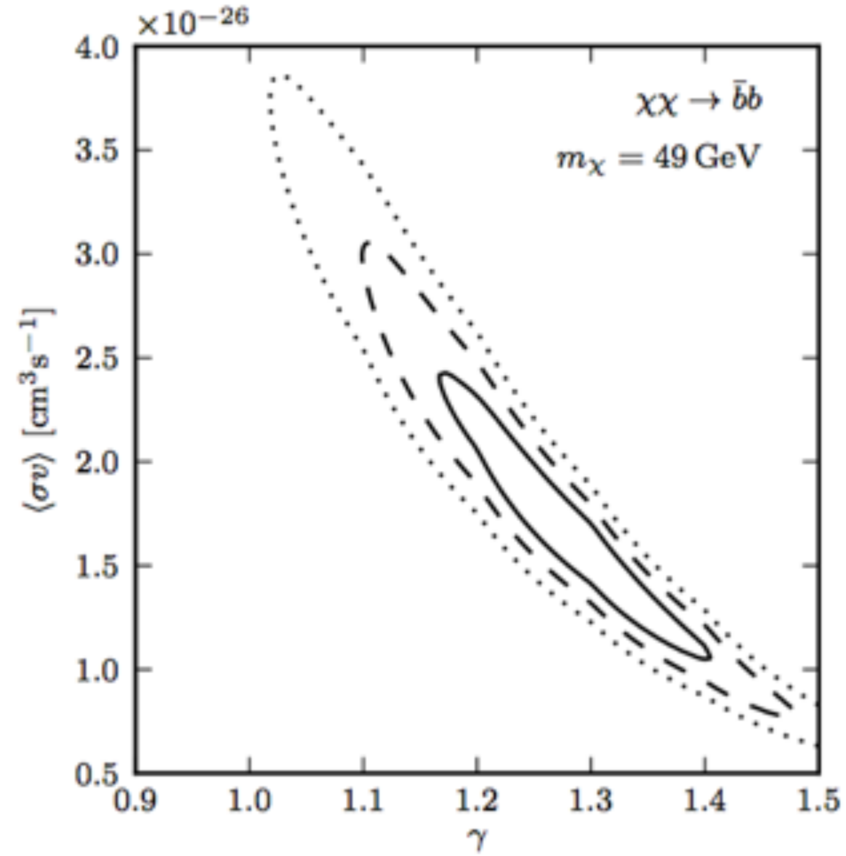
What does the Fermi Collaboration say?

- 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





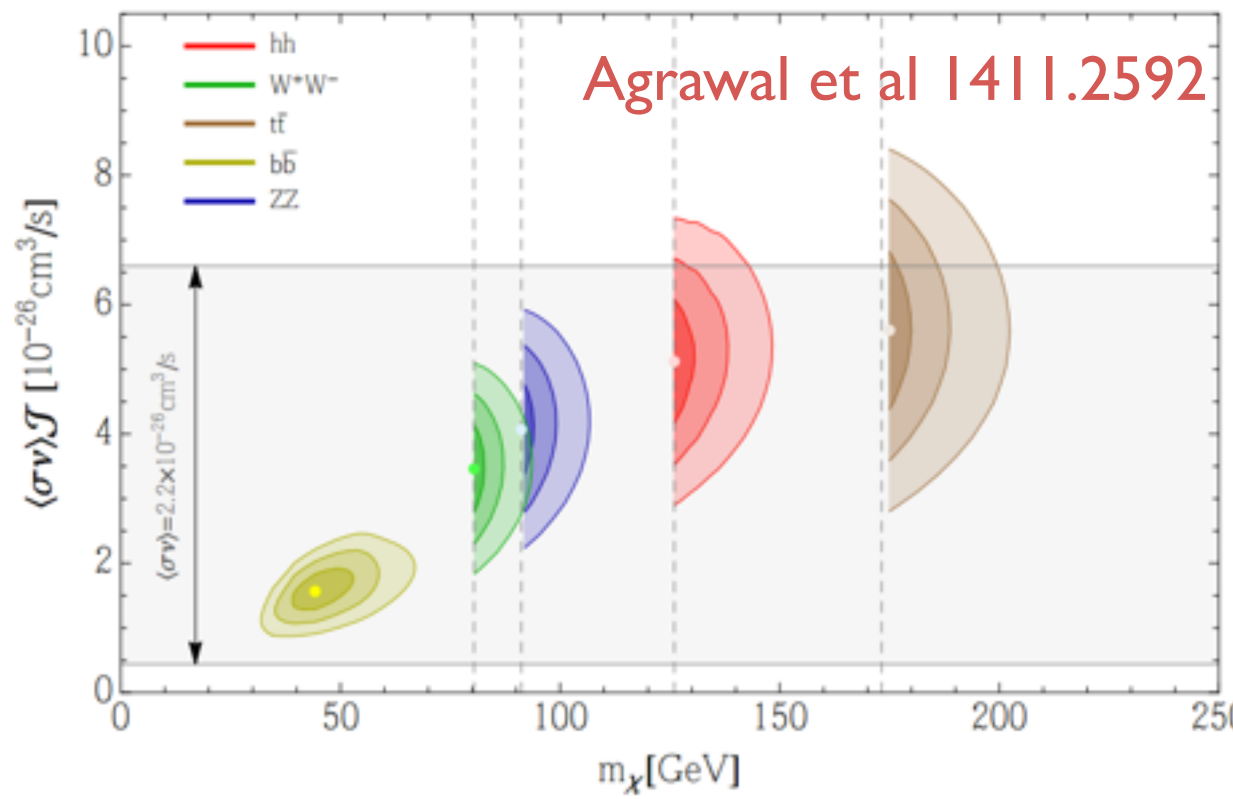
- Preference for DM below the 100 GeV scale, best fits come from annihilation to quarks.
- These results taken from Calore, Cholis & Weniger '14 (CCW), include a first estimate of systematic uncertainties.
- Consistent results from several independent groups.

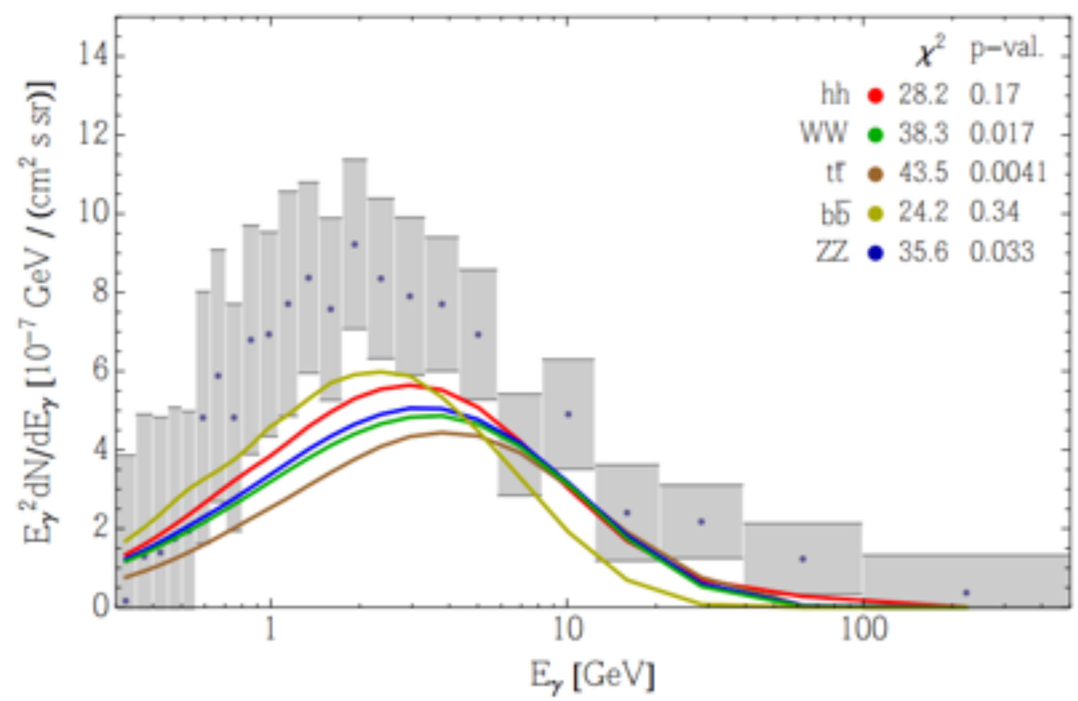
A higher mass scale?

- Heavier DM annihilating to hh can also provide a good fit to CCW results (1411.2592; Calore et al 1411.4647).

- Preferred DM mass is right at the threshold, as peak is slightly too high-energy.

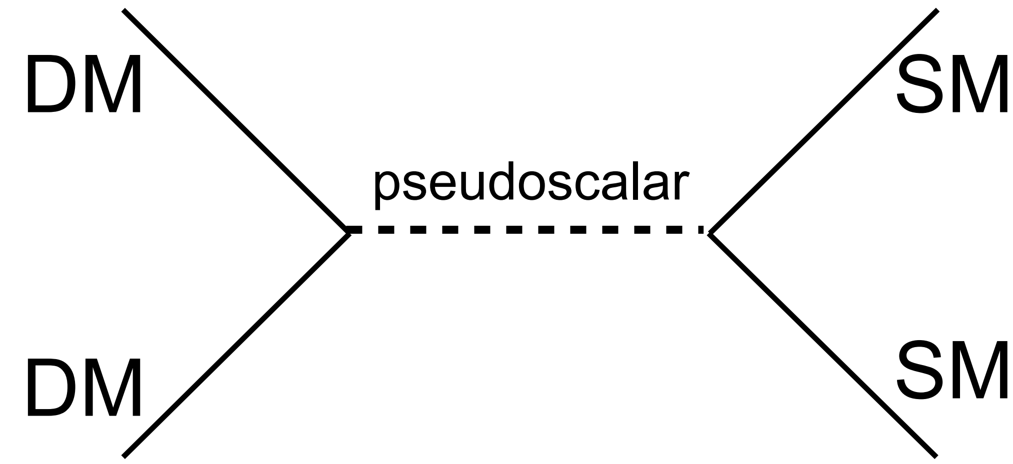
- Annihilation to W's, Z's and tops provides a worse fit.

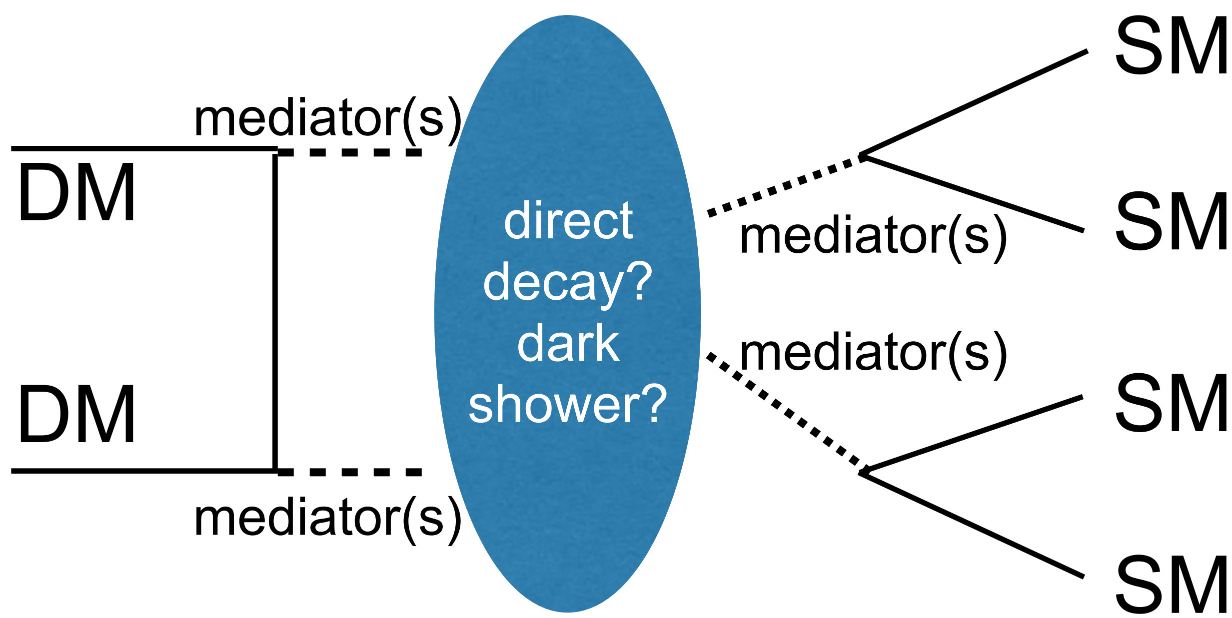




Dark matter phenomenology

- DM interpretations must evade constraints from direct detection and colliders
- Two frequent classes of models:
  - s-wave annihilation through a pseudoscalar (e.g. 1401.6458, 1404.3716).
  - 2→4(+) models - DM annihilates to some invisible particle which subsequently decays to SM particles (e.g. 1404.5257, 1405.0272, 1405.5204, 1410.3818).
- SUSY implementations: difficult in the MSSM, can be done in the NMSSM (e.g. 1406.6372, 1409.1573).





Dark matter or astrophysics?

Dark matter

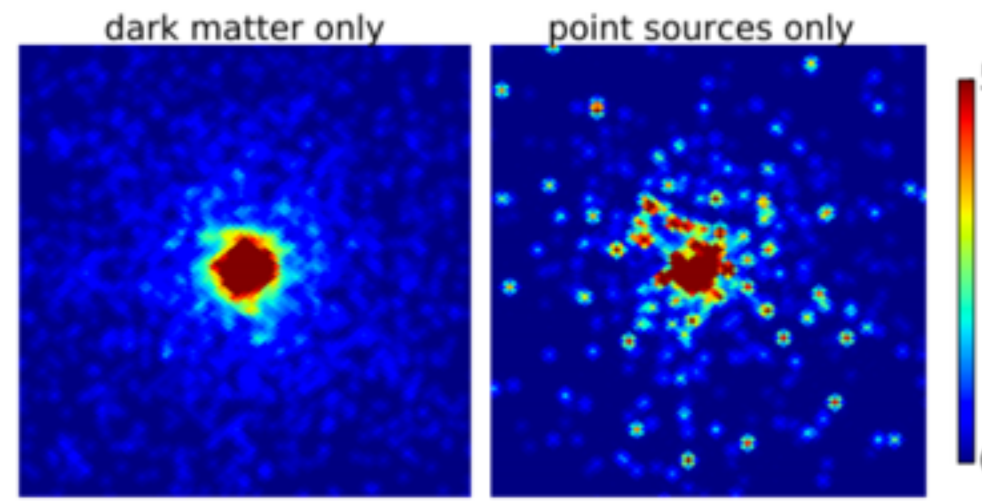
- Naturally explains:
  - The invariance of the spectrum with position.
  - The ~spherical morphology of the signal.
  - The profile: steeply peaked at the Galactic Center but extending out to (at least) 10 degrees.
- Required annihilation cross section lines up with long-standing predictions for the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

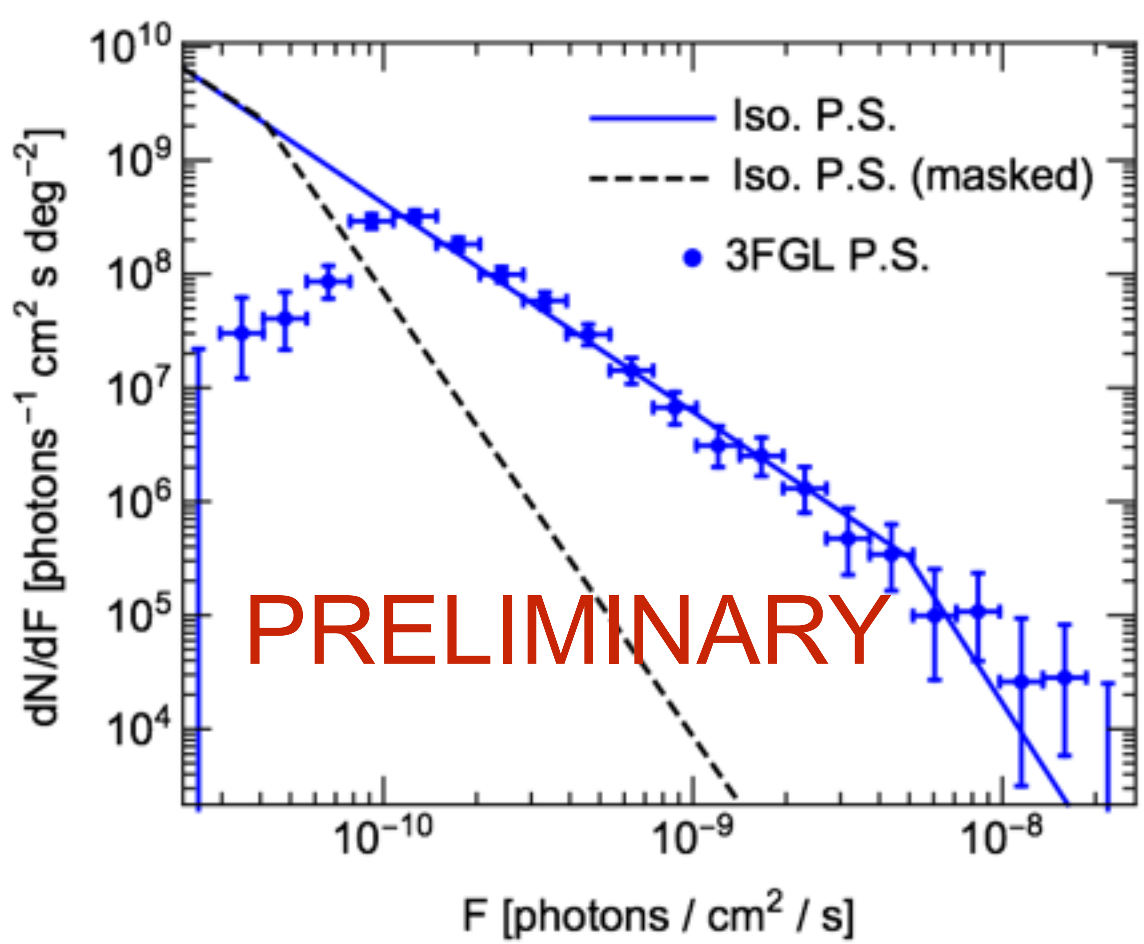
Alternatives

- 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.
  - Sphericity unexpected; required luminosity function different than inferred elsewhere in the Galaxy.
- TRANSIENT OUTFLOWS:
  - Known to occur in the Galactic Center - but challenges in matching morphology + spectrum.

Where next in the inner Galaxy?

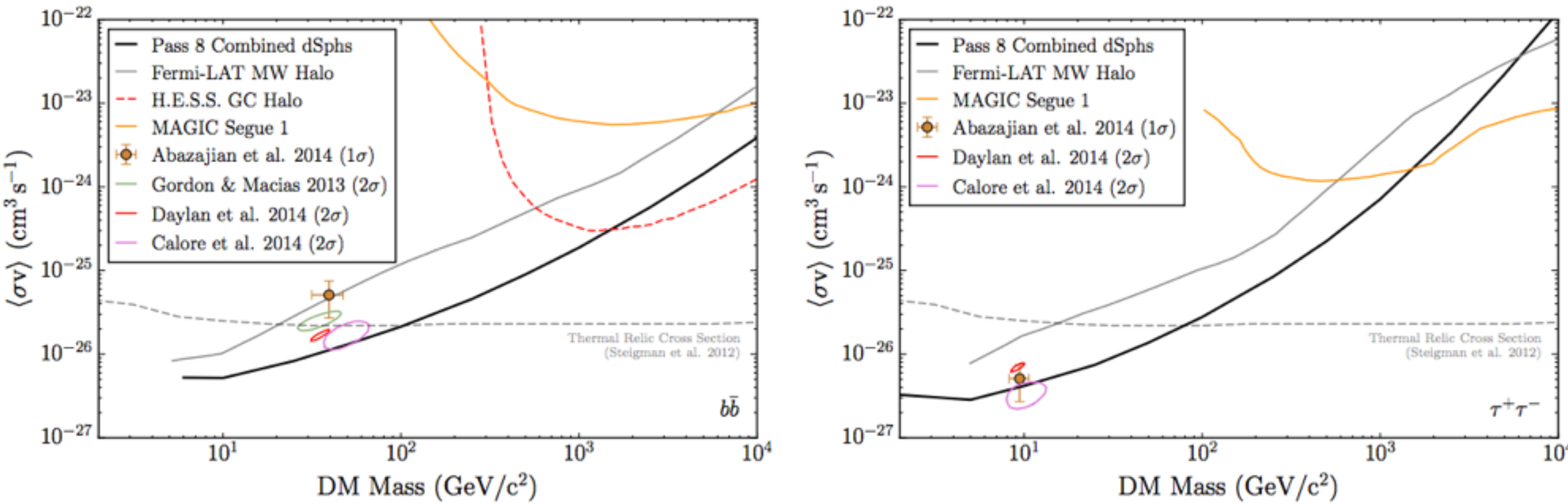
- One idea: can we disentangle diffuse emission from unresolved sources using photon statistics? (Lee, Lisanti & Safdi 1412.6099)
- Basic idea: point sources = more very bright and very faint pixels.
- Initial tests at high latitude are promising.
- But new data may also play a role…





New results from DES and Fermi

Dwarf galaxies



- Dwarf satellites of the Milky Way: DM-dominated systems, provide a clean test of DM-annihilation hypothesis (gamma-ray spectrum should be identical to that found in GC / inner Galaxy, if it comes from annihilation photons).

- Fermi Collaboration study of stacked dwarfs (1503.02641) → most sensitive current constraint on sub-TeV DM annihilating through hadronic channels and to tau's, reaching thermal relic cross section for DM masses below ~100 GeV (or ~50-60 GeV when systematic uncertainties on DM content are included).

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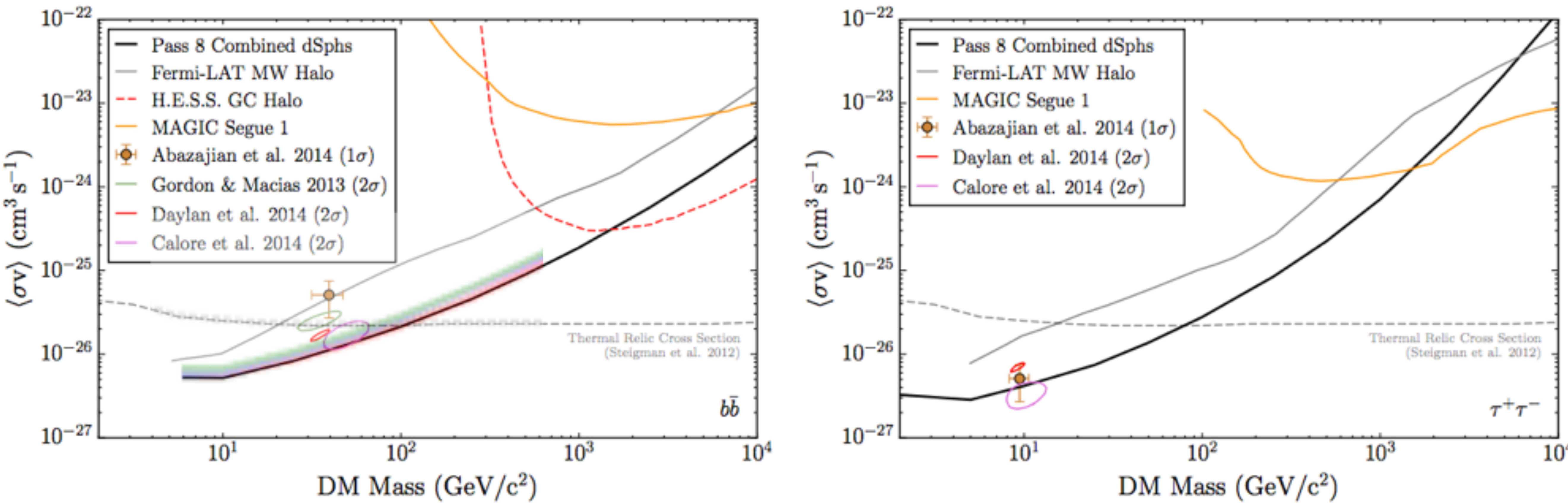

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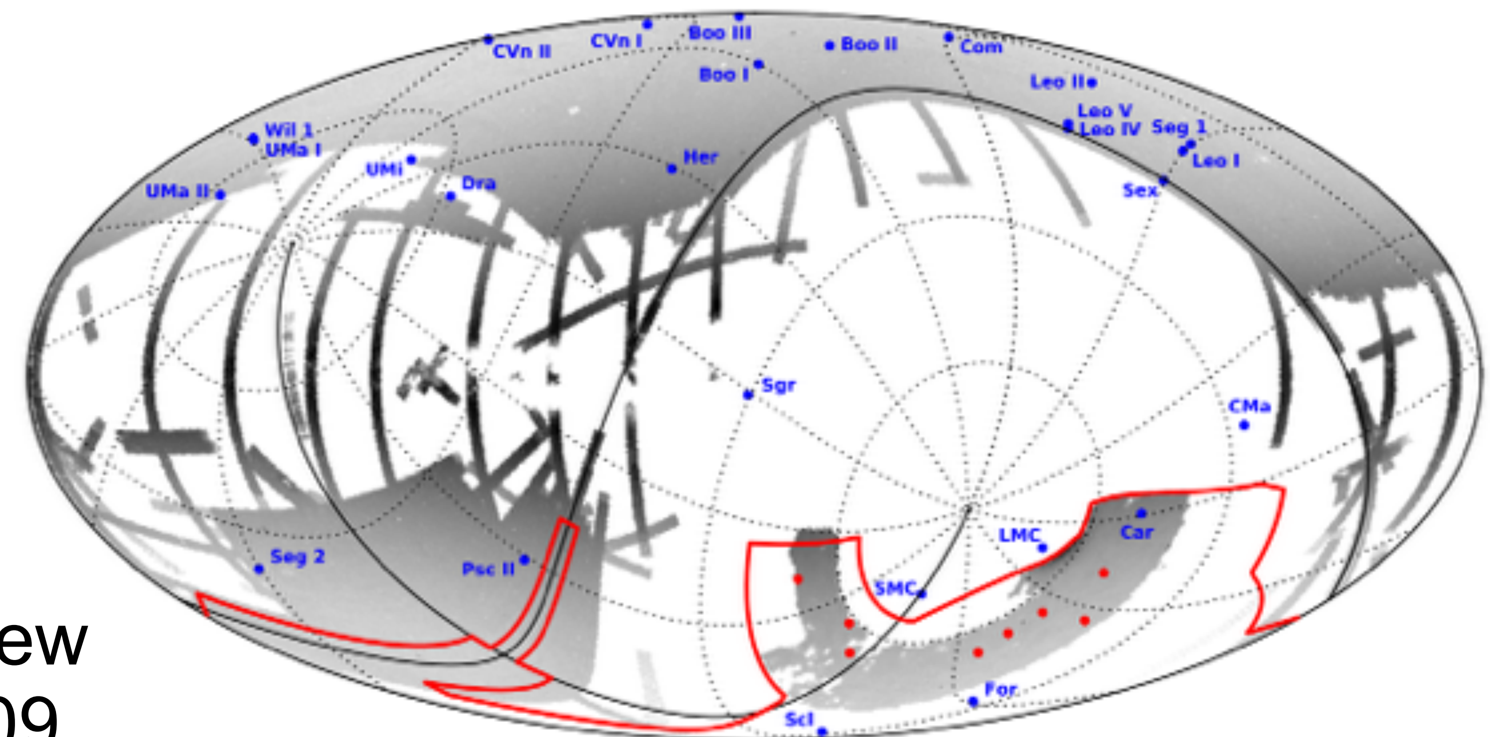
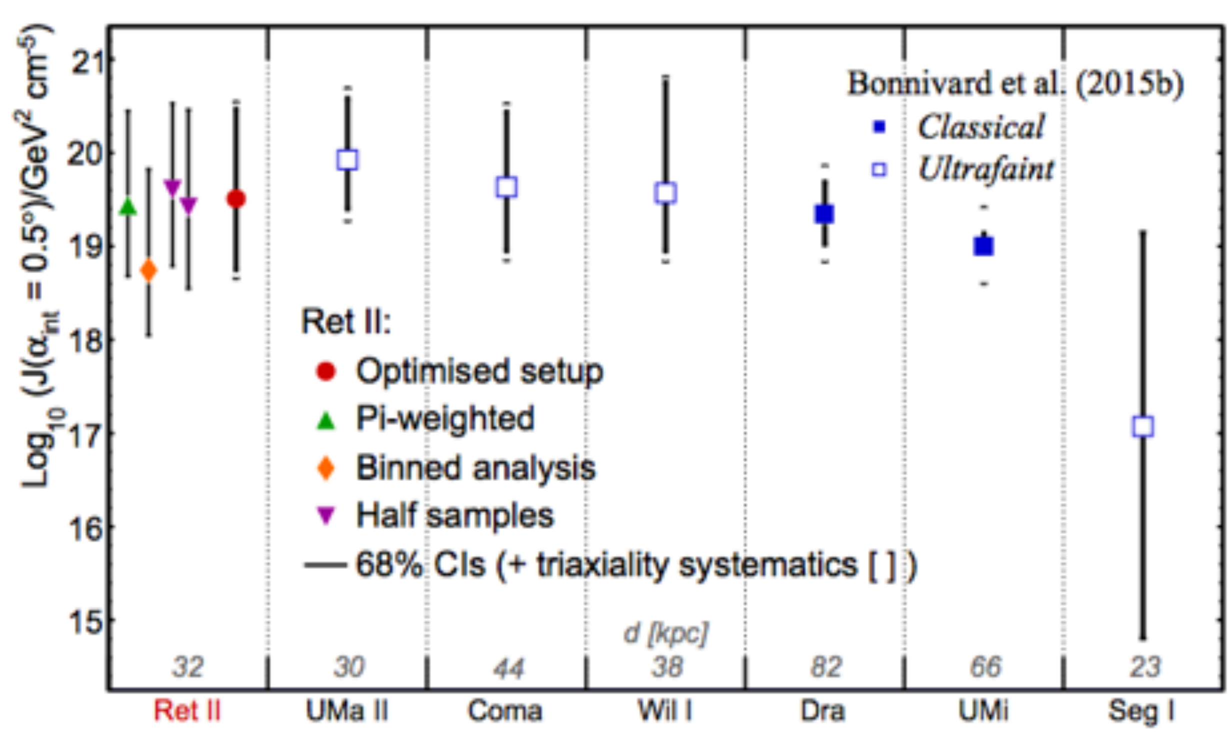
DES discovers new dwarf galaxies

- Discovery of 8-9 new dwarf candidates in DES data in March (1503.02079, 1503.02584).
- More recently, kinematic studies were made of the DM content of “Reticulum II”, the closest of the new dwarfs (Bonnivard et al 1504.03309, Simon et al 1504.02889).
- Want to estimate “J-factor”, figure of merit for DM annihilation.
- Results are consistent within the (large) error bars, but Simon et al prefer a somewhat smaller value.





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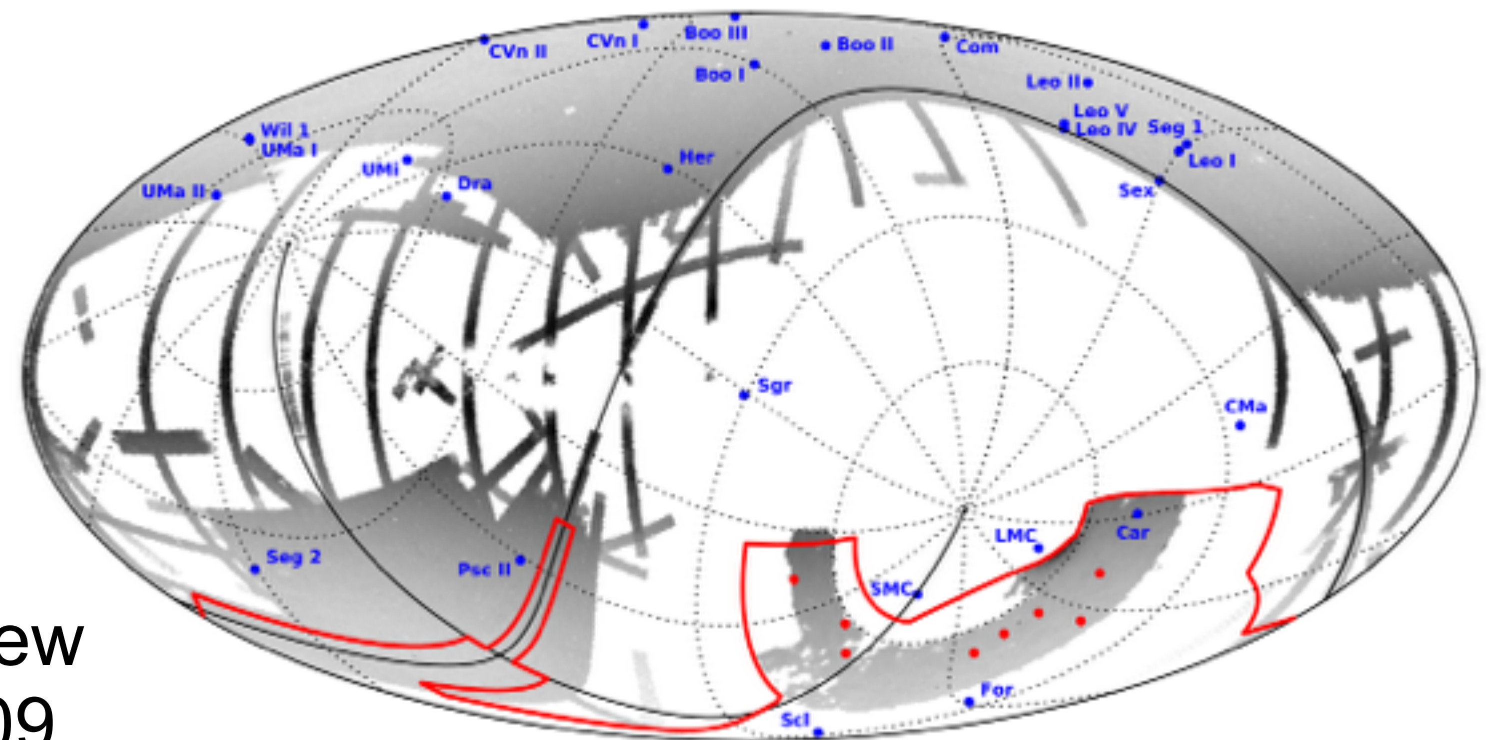
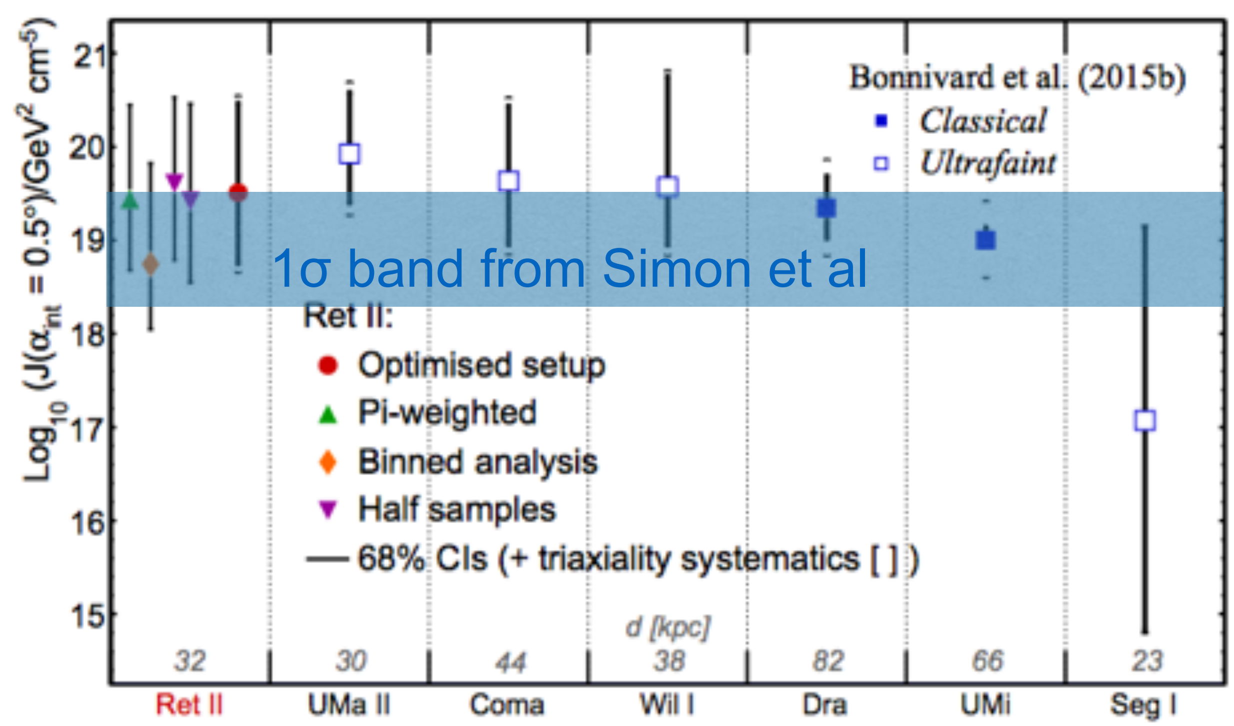
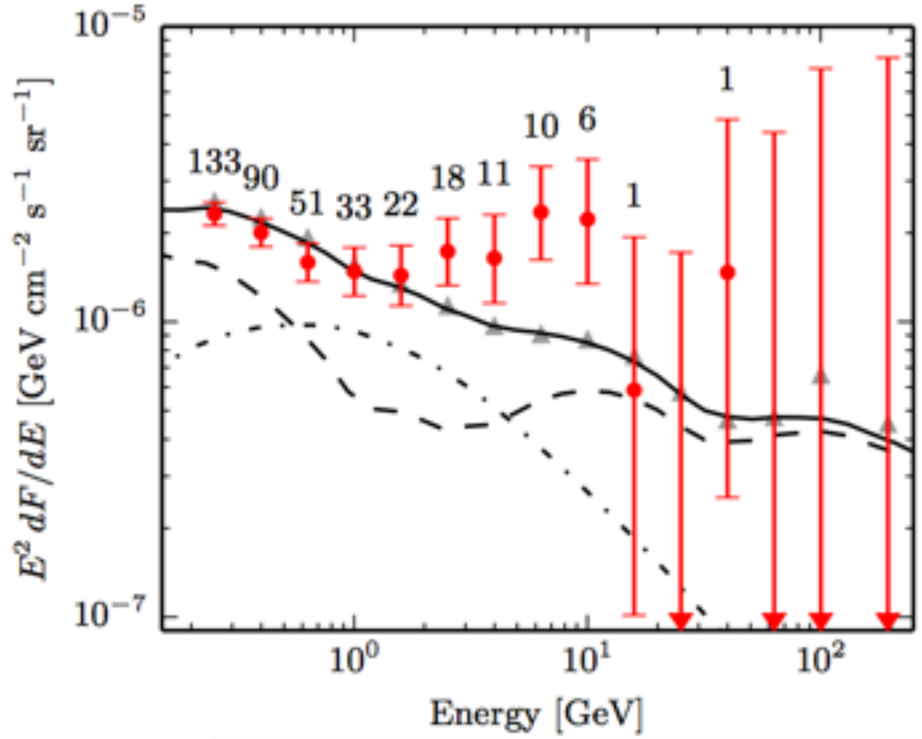


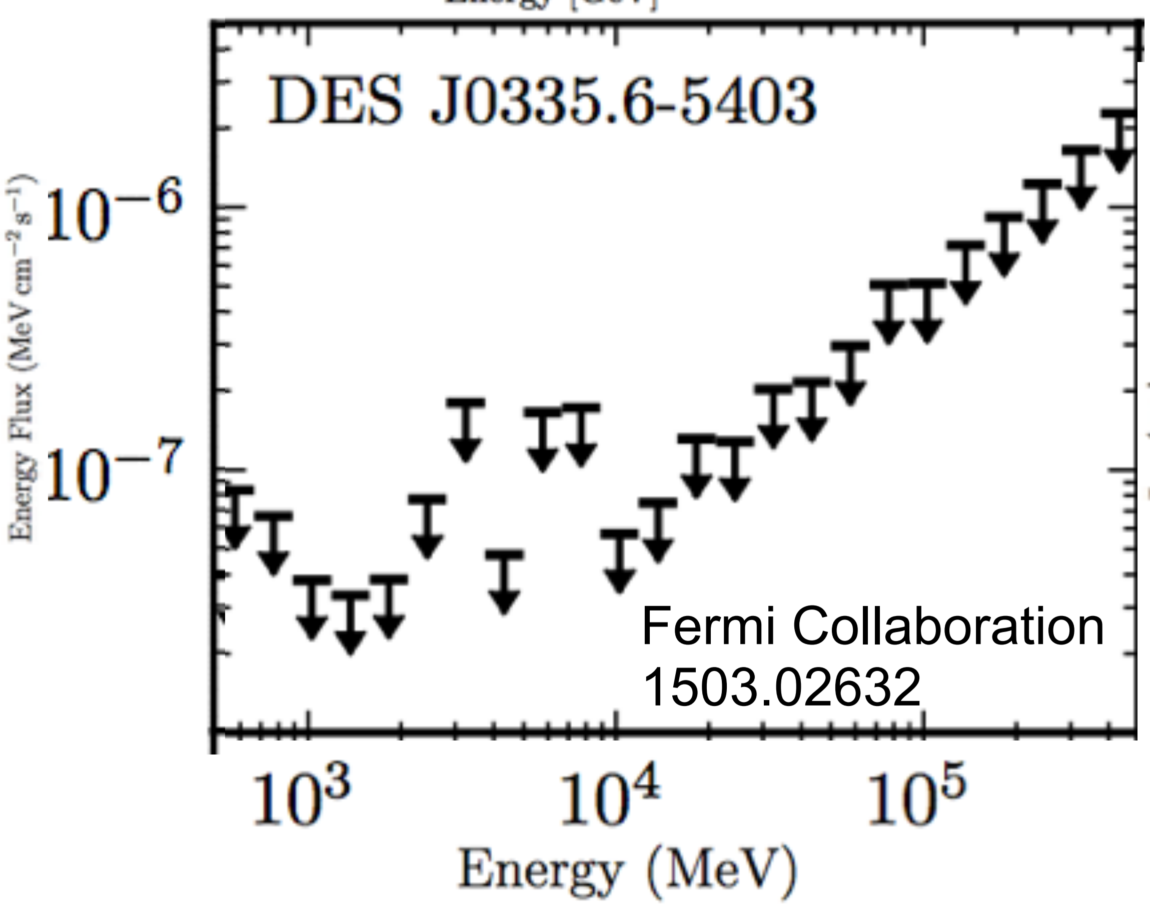


Reticulum II

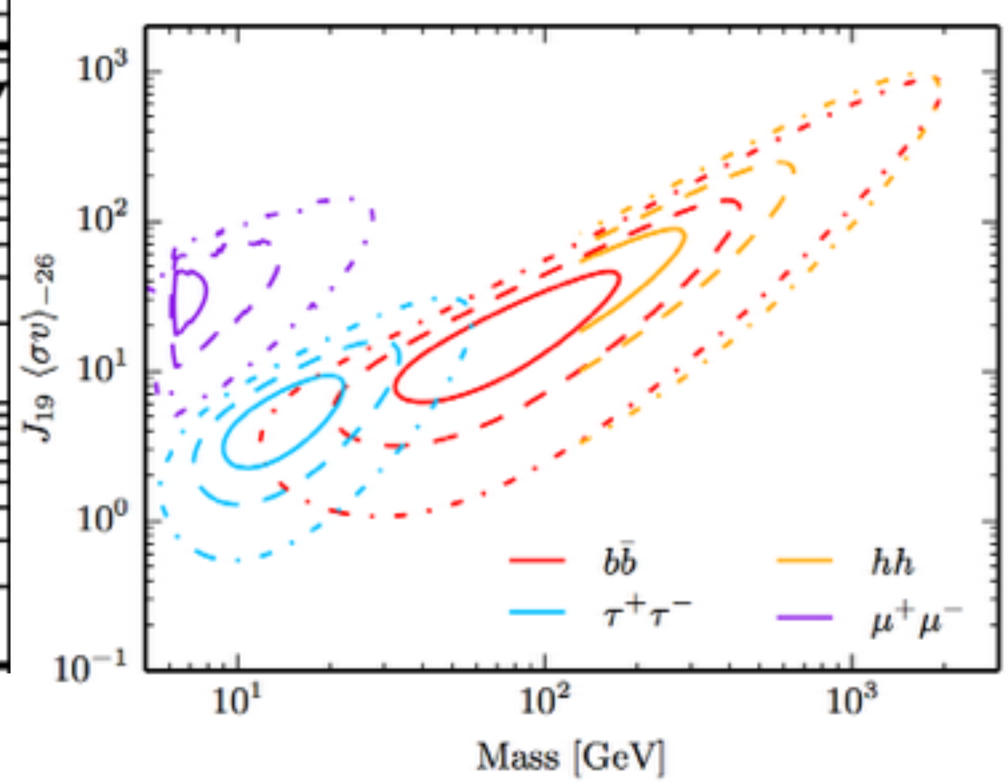
Geringer-Sameth et al 1503.02320



- A gamma-ray excess is seen, in the 2-10 GeV energy range - significance debated.
  - Geringer-Sameth et al: 2.3-3.7σ (depending on background modeling; including trials factor for DM mass).
  - Hooper & Linden (1503.06209): 3.2σ (holding DM spectrum fixed at GCE best-fit)
  - Fermi Collaboration: 1.5σ locally, 0.3σ after trials factor for multiple DM masses and channels.



Fermi Collaboration 1503.02632

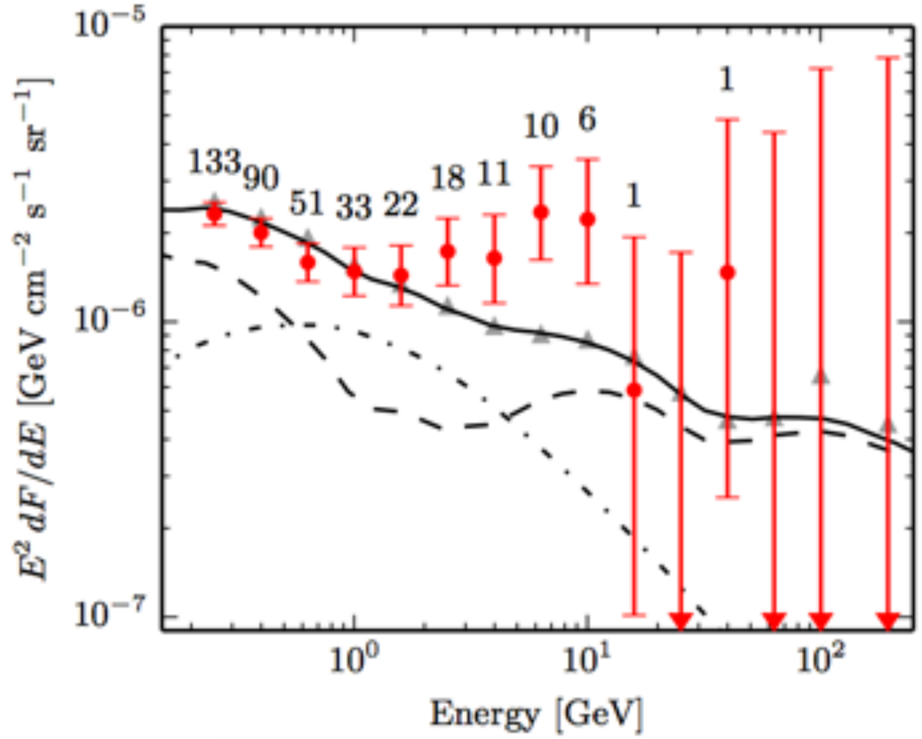


If we take a J-factor of $10^{19.5}$ GeV^2/cm^5 as found by 1504.03309*, favored region compatible with inner Galaxy excess.

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

Reticulum II

Geringer-Sameth et al 1503.02320



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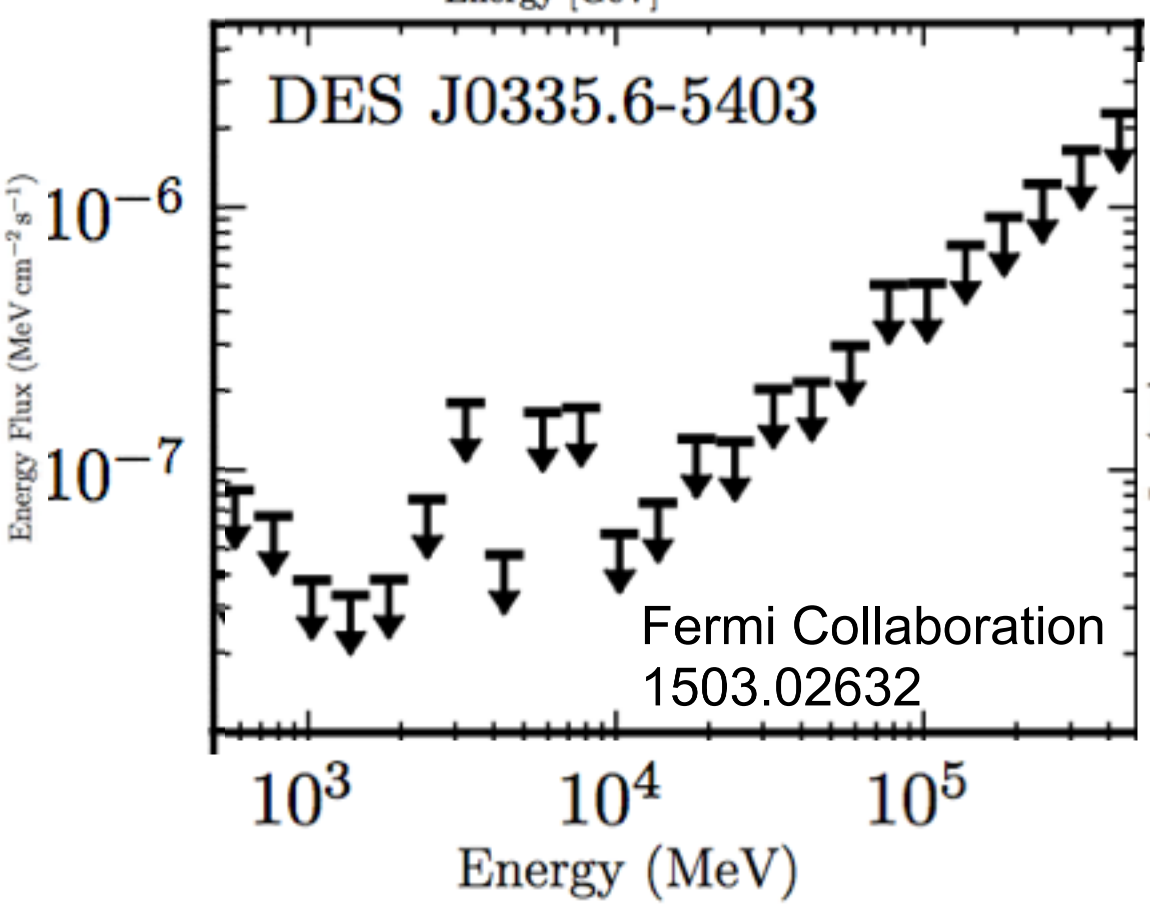
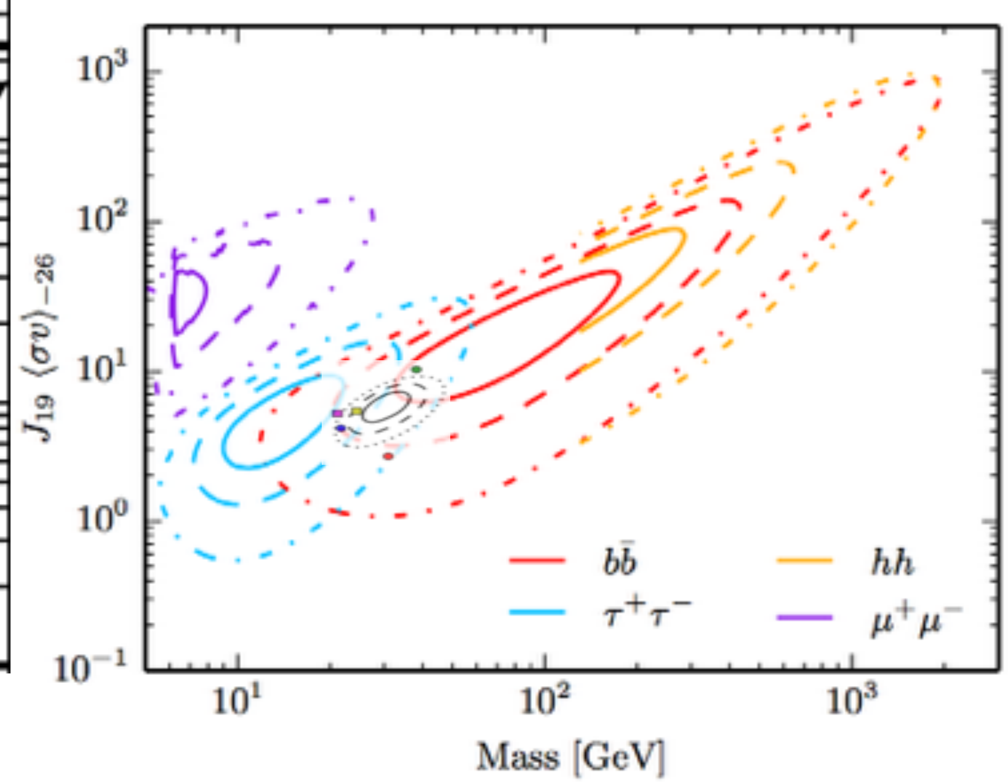


Fermi Collaboration 1503.02632



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New results from AMS-02 and Planck

AMS-02 cosmic ray data

- Presented last month at "AMS Days @ CERN" workshop
- Protons, helium, lithium show consistent hardening of spectrum above ~ 200 GV rigidity - point to new CR source or propagation effects?
- Antiproton/proton ratio flattens to a constant at high energies

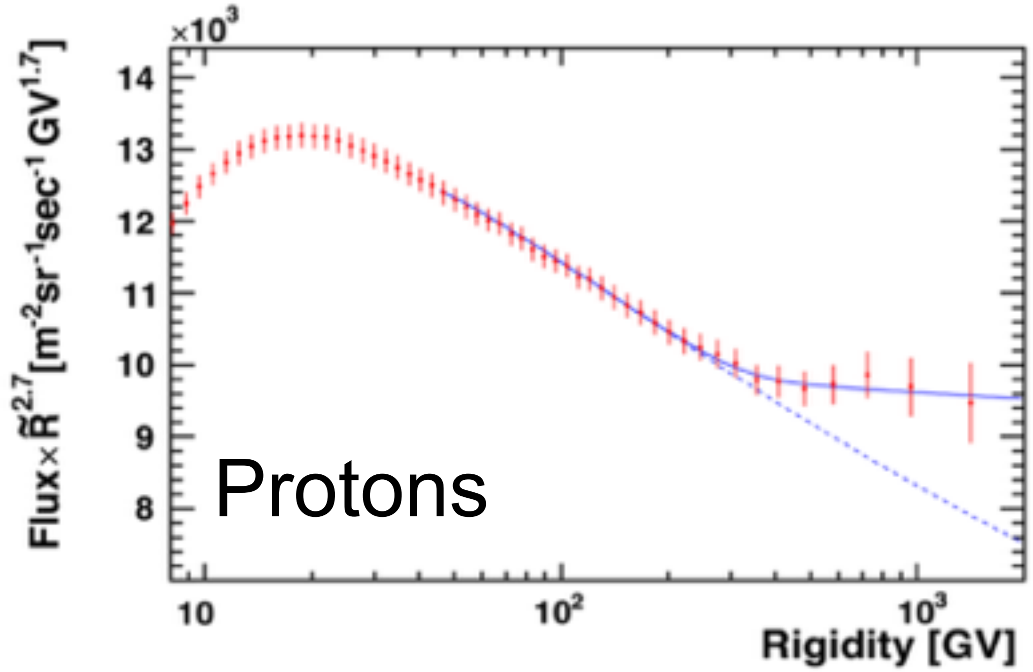
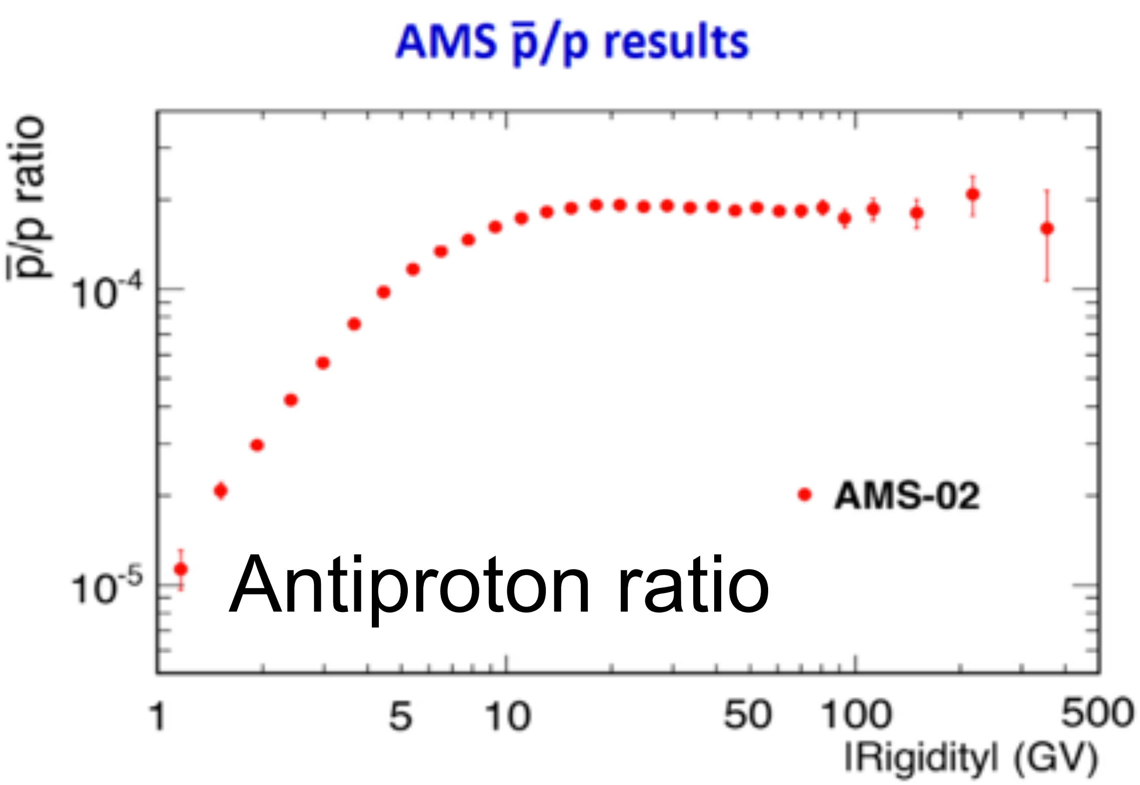
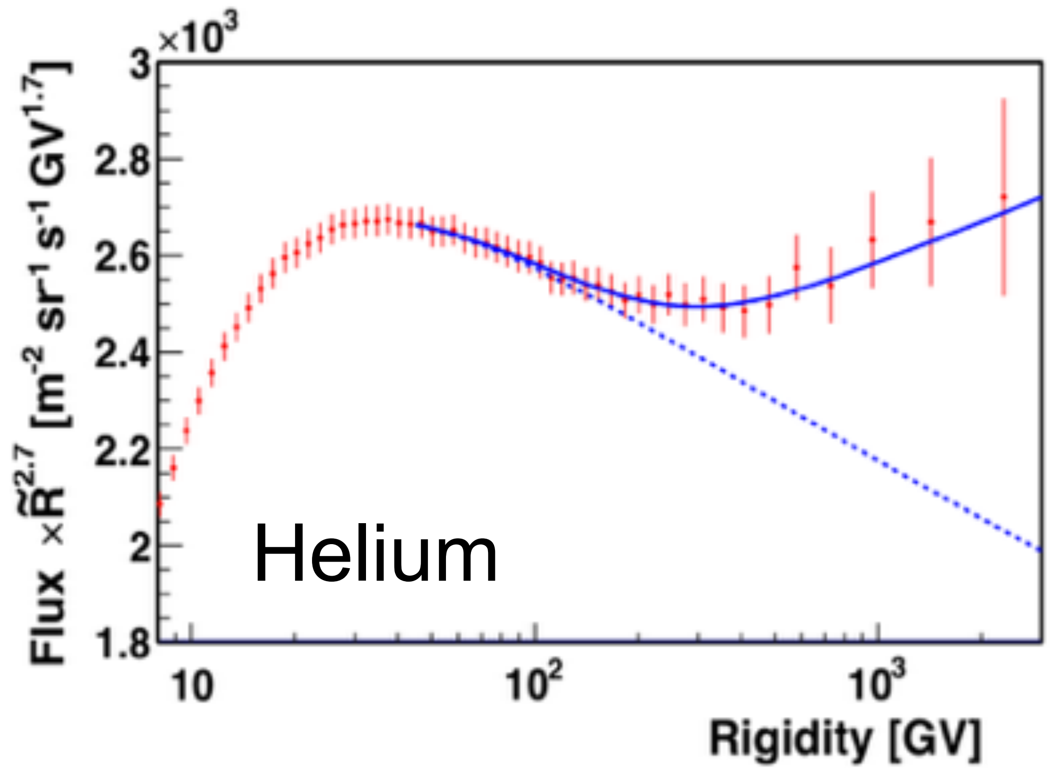


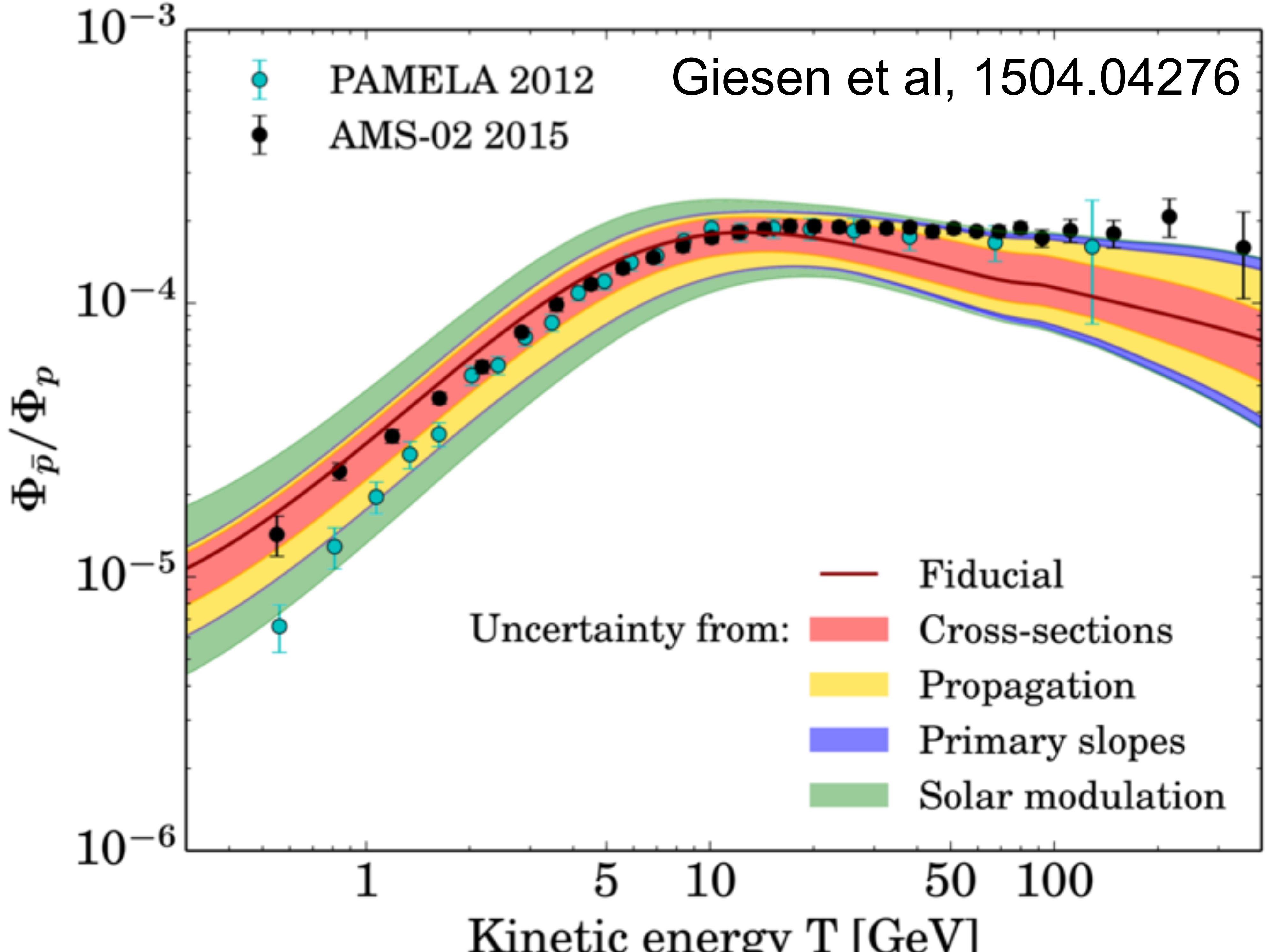
Figure 2: Measured proton fluxes as a function of rigidity.



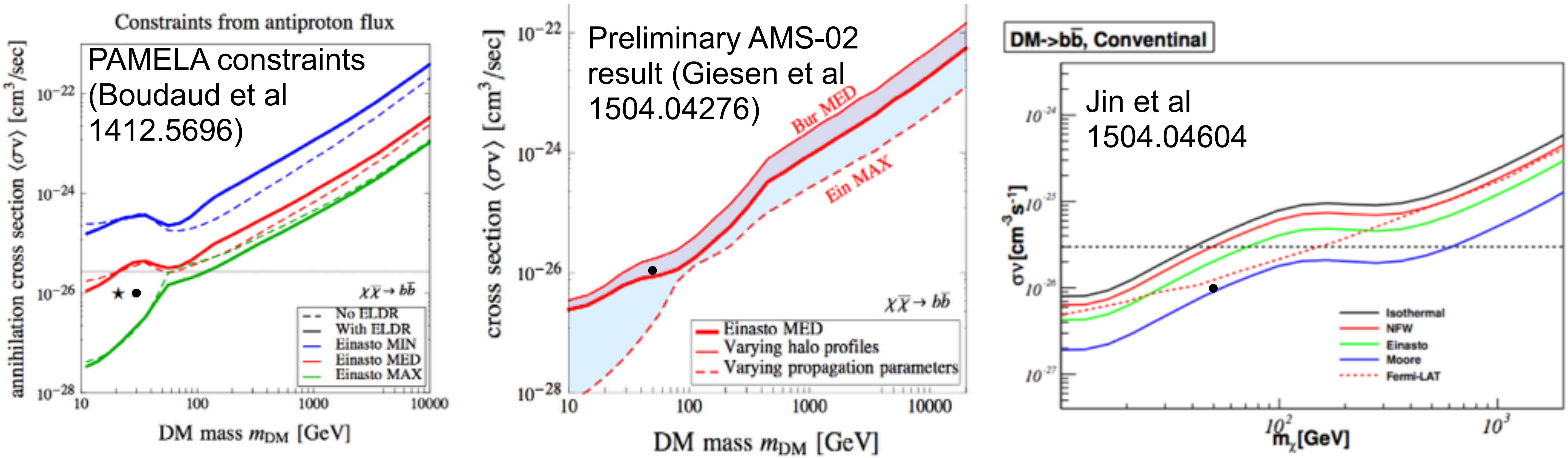


Do AMS-02 antiprotons need a new DM component?

- Flattening not expected from secondary production - should fall with energy
- But within uncertainties, existing models can ~fit the data

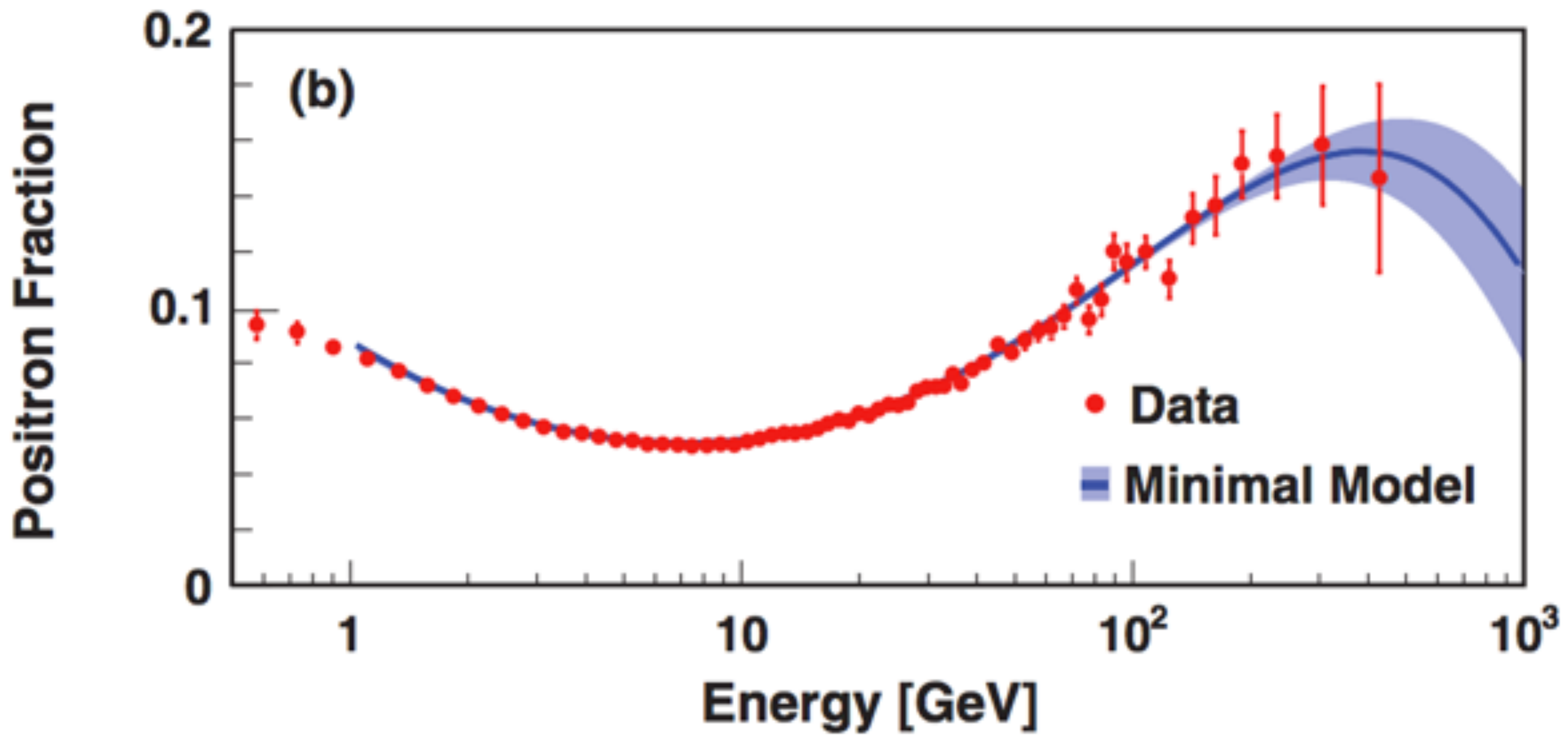


Constraining light dark matter



- Precision measurements give the hope of setting competitive constraints on DM annihilating into hadronic channels.
- Large systematic uncertainties due to complex propagation effects (e.g. solar modulation, energy loss from tertiary particles, diffusive reacceleration). Incorporating all AMS-02 data may help constrain propagation models.
- Current estimates constrain thermal relic DM annihilating to b quarks below (very roughly) ~30-200 GeV, depending on DM density profile and propagation model.

The AMS-02/PAMELA positron excess

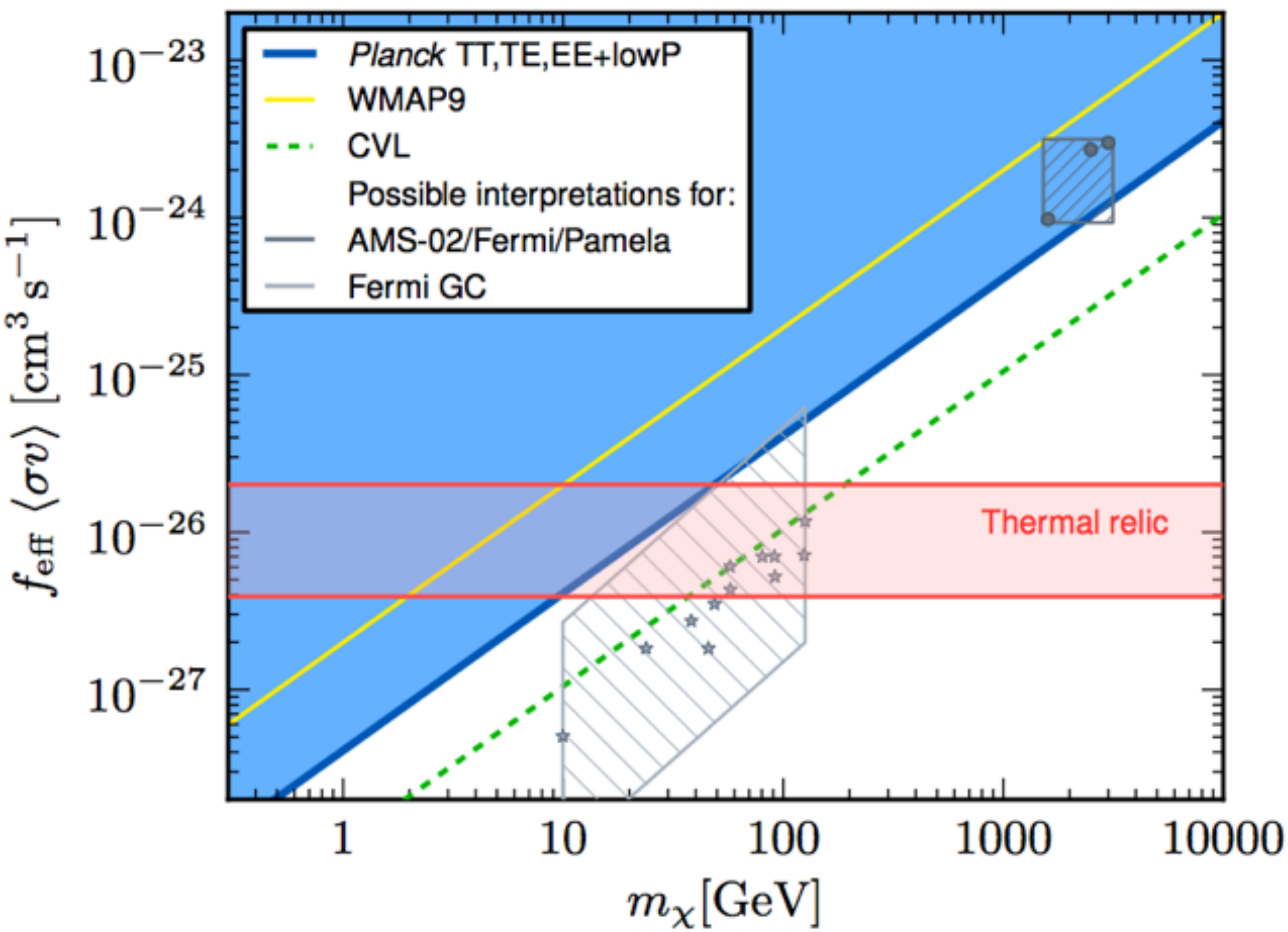


Accardo et al (AMS-02 Collaboration), PRL 113, 121101 (2014)

- 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.)

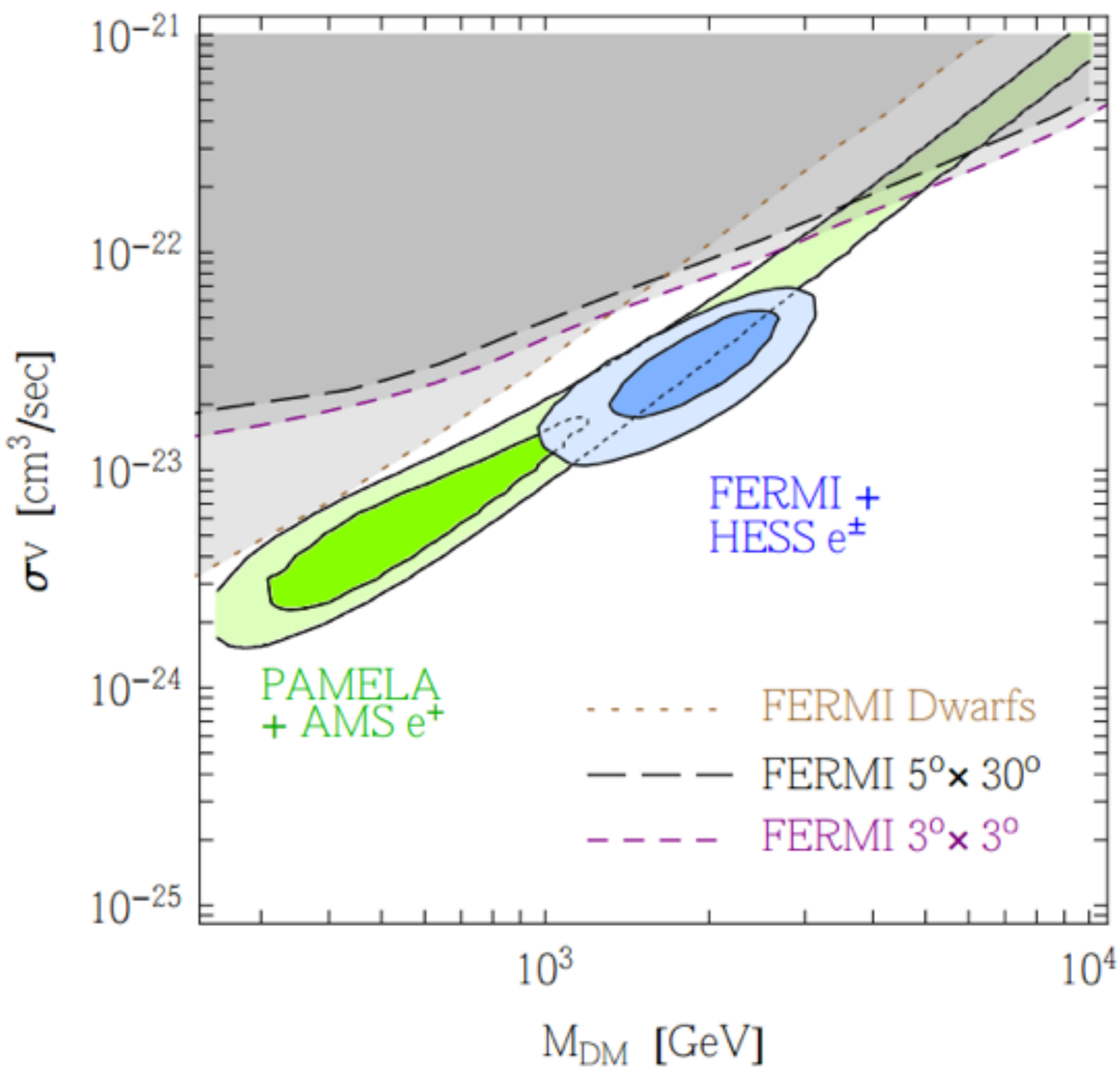
Bounds from Planck

- Early this year, Planck Collaboration released polarization results. See plenary talk by S. Galli.
- Ade et al 1502.01589 presented bounds on DM annihilation parameter, $\langle \sigma v \rangle f_{eff}/m_{DM}$, where f_{eff} is a model-dependent efficiency factor.
- Tension with annihilating DM interpretation of AMS-02 positrons.



An example application

- 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 and channel (TRS, to appear), translate CMB bounds to cross section limits.
- Rules out 5σ region for AMS-02 by a factor of 2.



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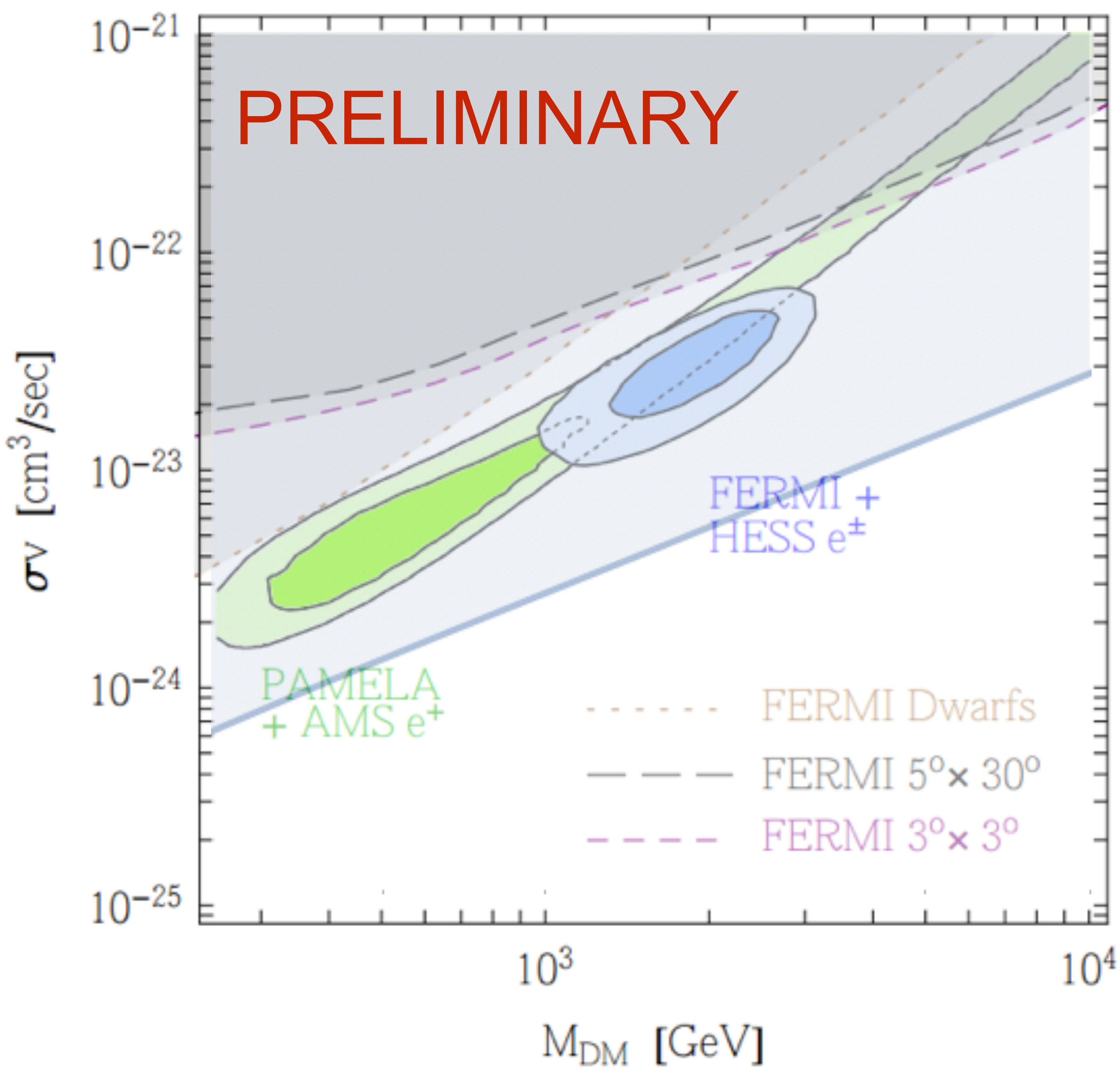


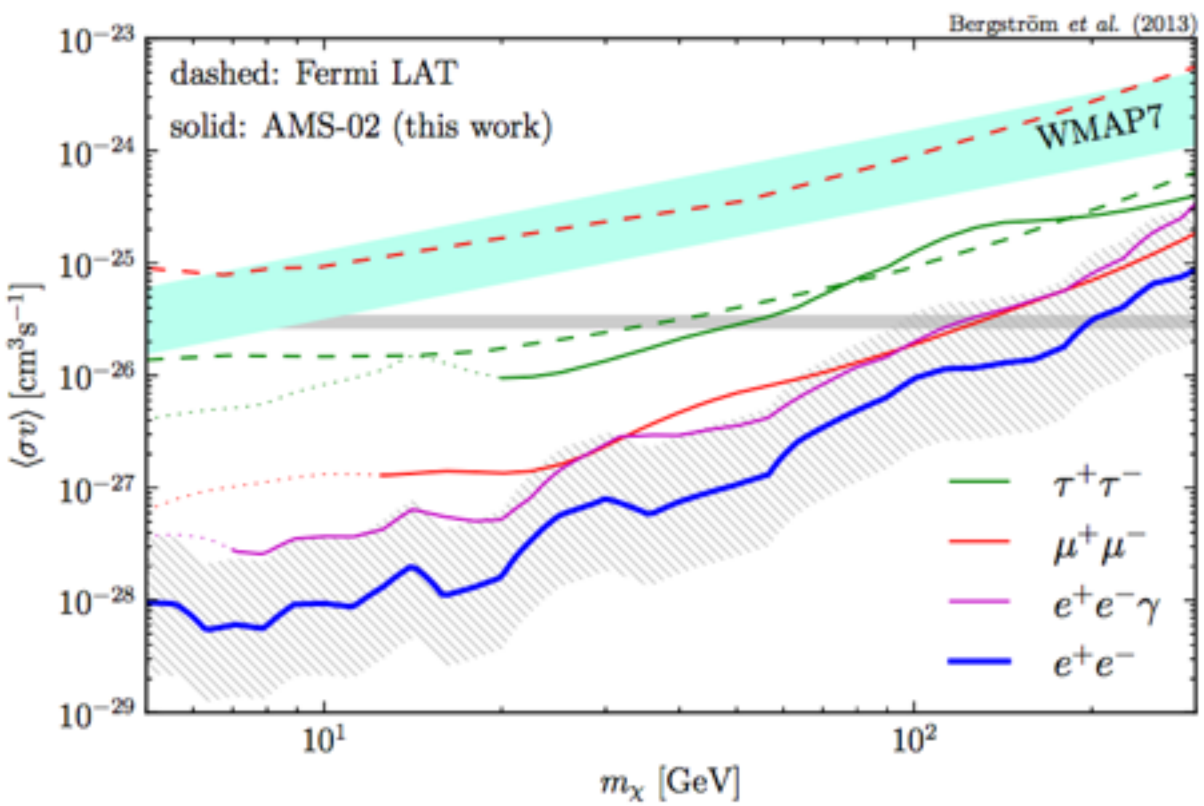
Outlook

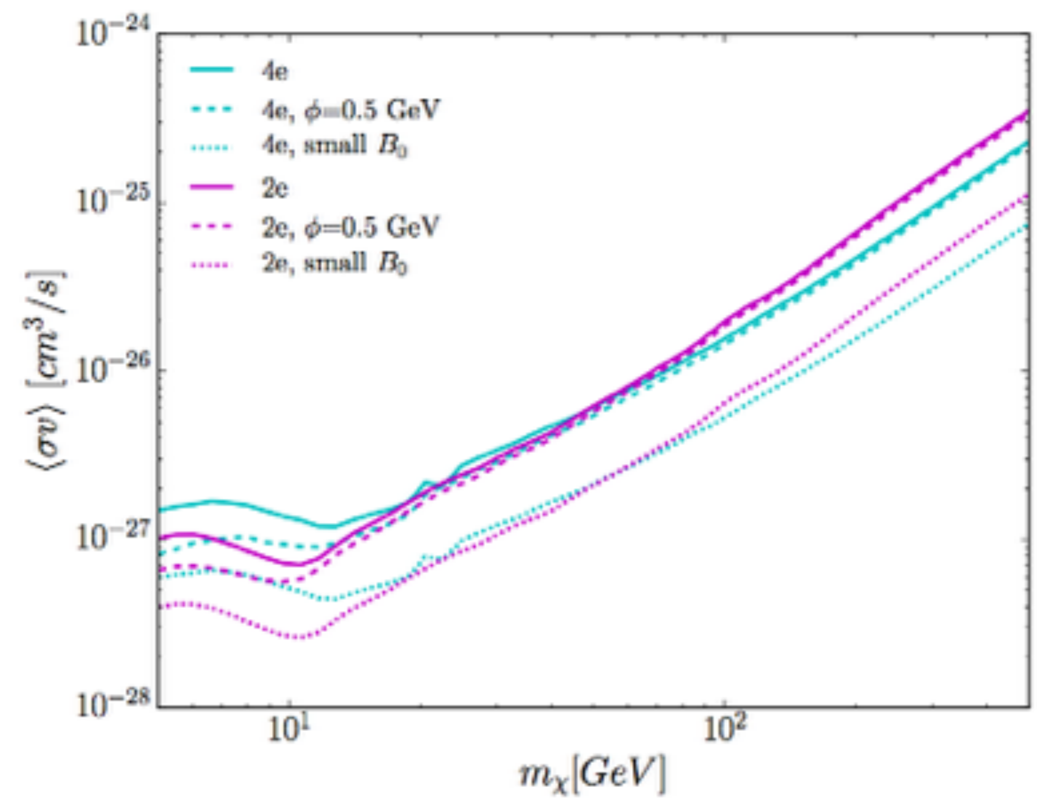
- Astrophysical/cosmological datasets are rich, rapidly evolving, and hold several candidate dark matter signals - might be the first non-gravitational hints of dark matter physics.
- BUT astrophysical backgrounds are complex; any detection will require confirmation in multiple channels. Complementary searches can provide either confirmation or constraints.

	3.5 keV X-ray line	GeV gamma-ray excess
Where?	Multiple experiments, multiple target systems	Only Fermi data, GC + inner Galaxy (perhaps a hint in Reticulum II?)
DM explanation?	Exciting DM, ALP conversion - simplest decaying-DM models in strong tension with other limits	Thermal-relic annihilating DM explains properties well
Non-DM explanation?	Contamination from plasma lines	Pulsars, transient outflows
Where next?	Astro-H observations	Further dwarf studies? Improved analyses of GC / inner Galaxy? Direct detection / LHC?

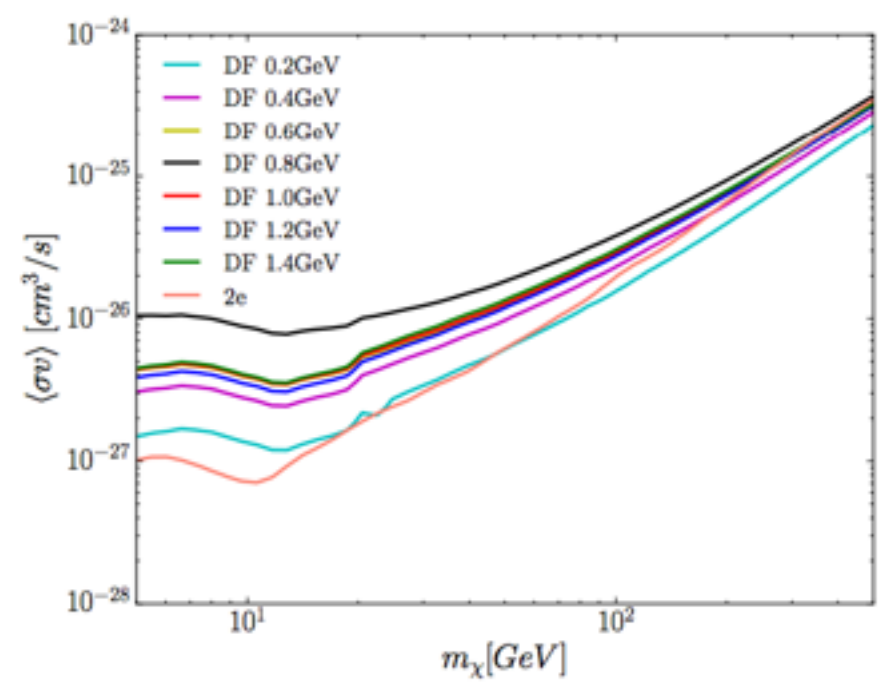
BONUS SLIDES

Leptonic final states



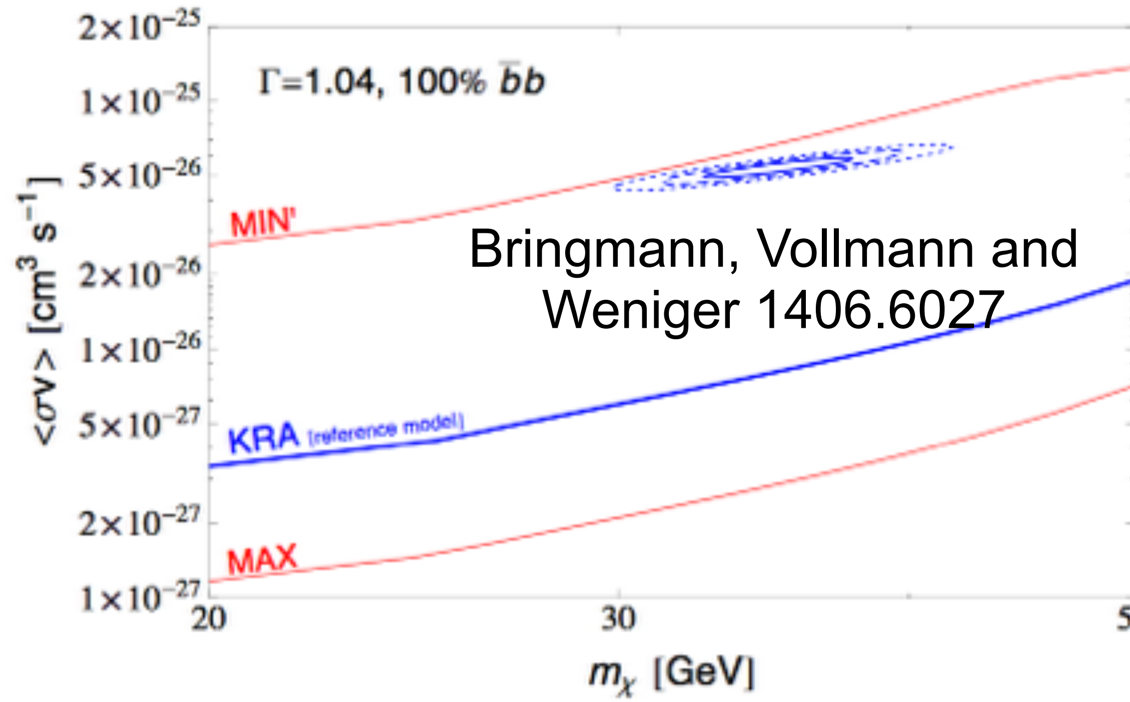


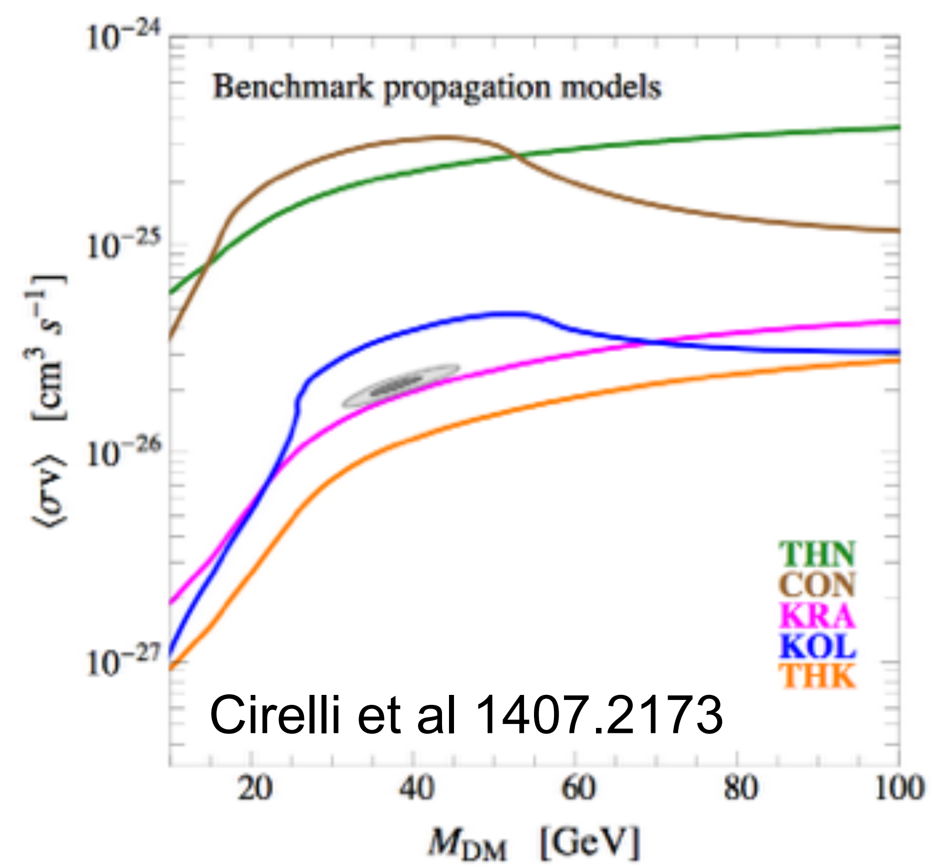
- Bergstrom et al 1306.3983: AMS-02 positron fraction yields strong bounds on the cross section for relatively light DM annihilating to channels that produce hard positrons.
- Liu et al 1412.1485: test constraints for annihilation through dark photons as well as 2e. These authors include systematic uncertainties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



Cosmic ray antiprotons

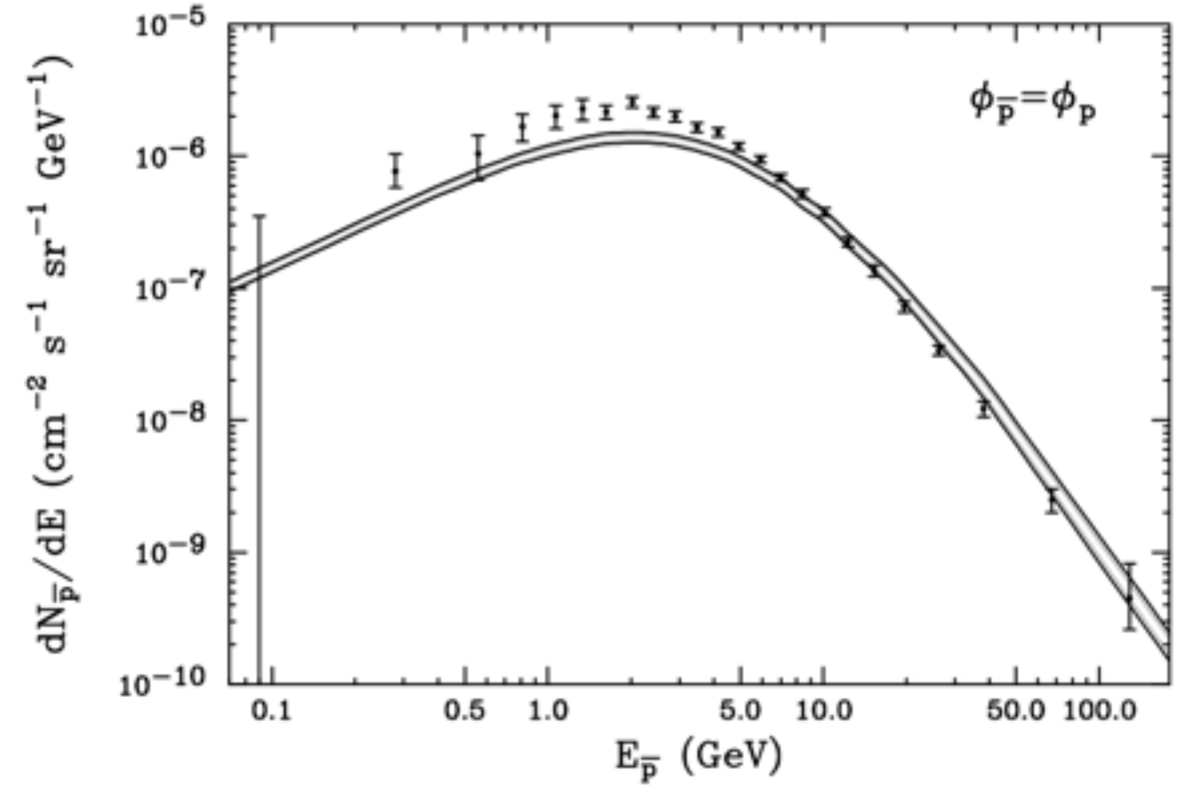
- DM annihilation could produce a flux of antiprotons.
- Usual uncertainties on DM distribution are mitigated since we are testing an actual signal! (not just setting limits)
- Some claimed tension between PAMELA data and the DM interpretation of the excess, but depends on the cosmic-ray propagation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

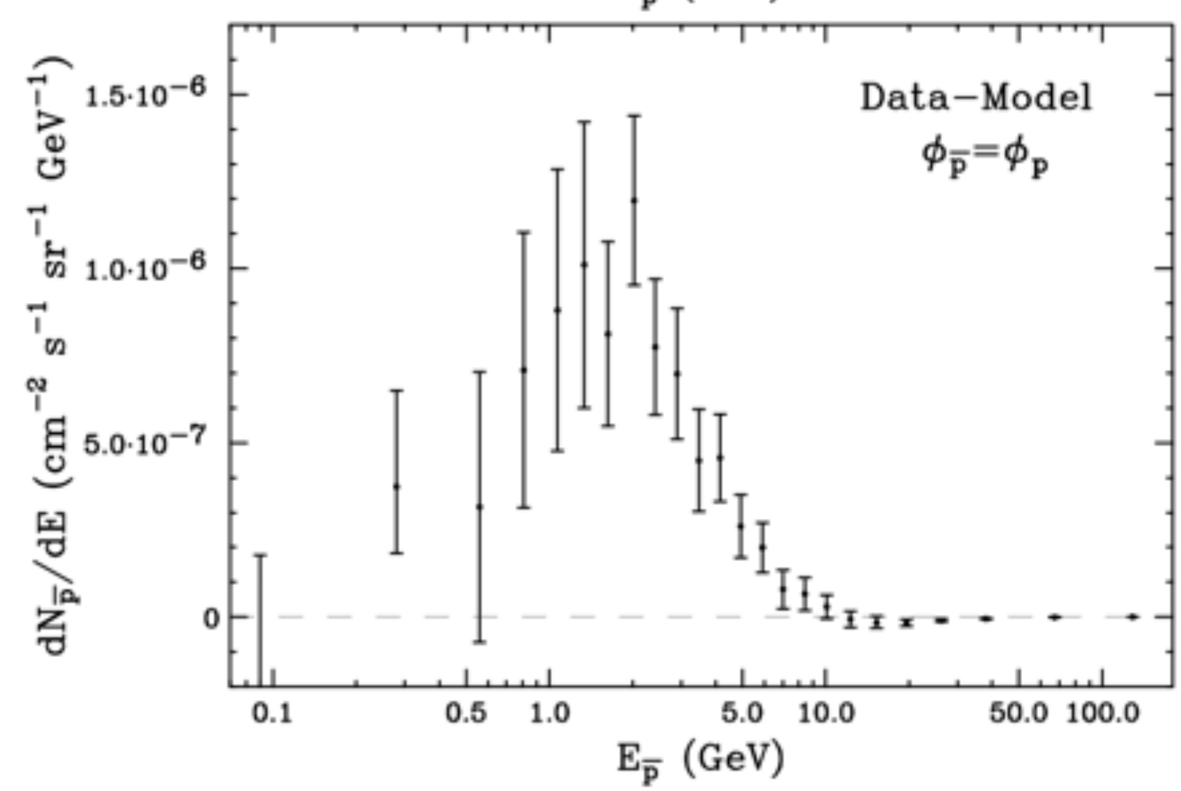


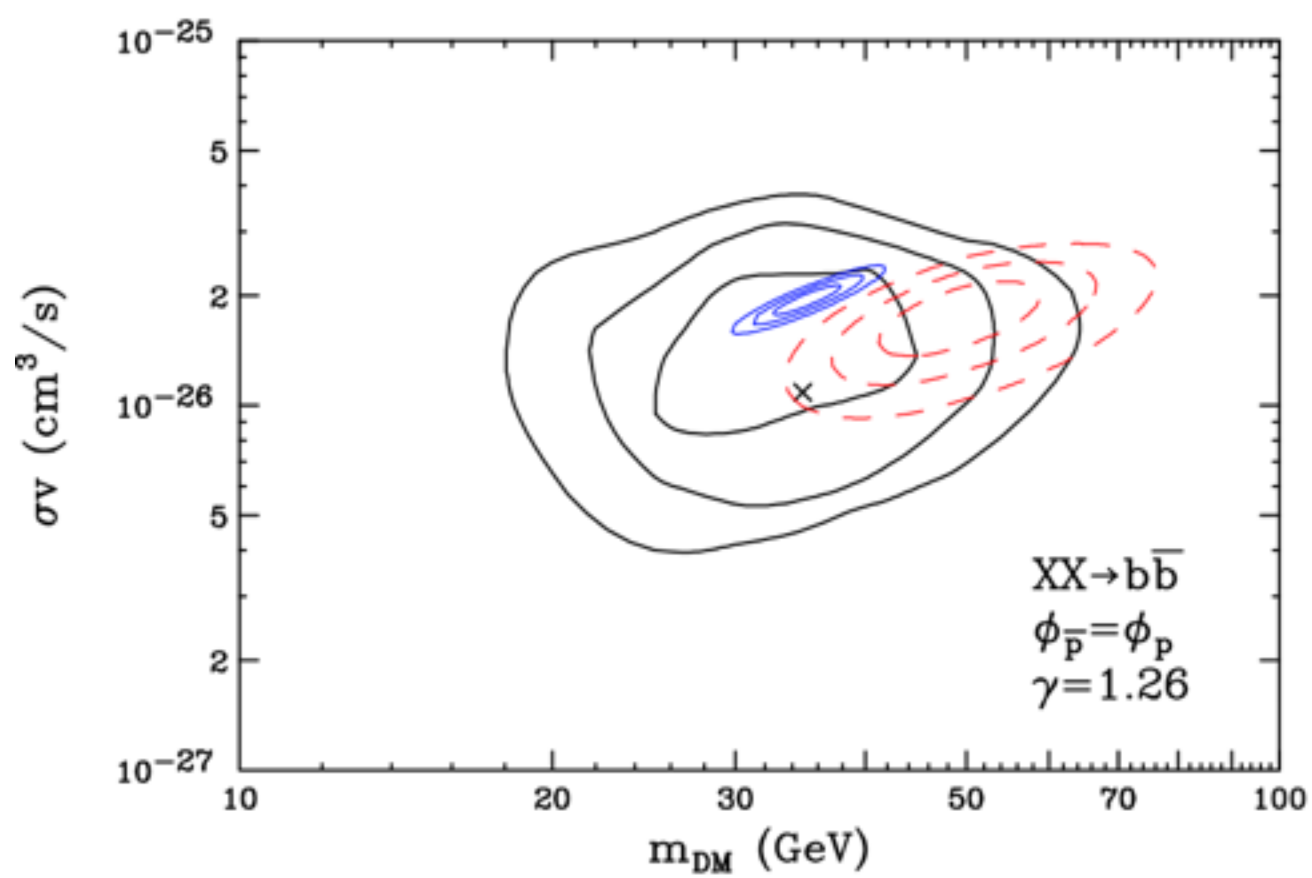


Antiprotons (cont.)

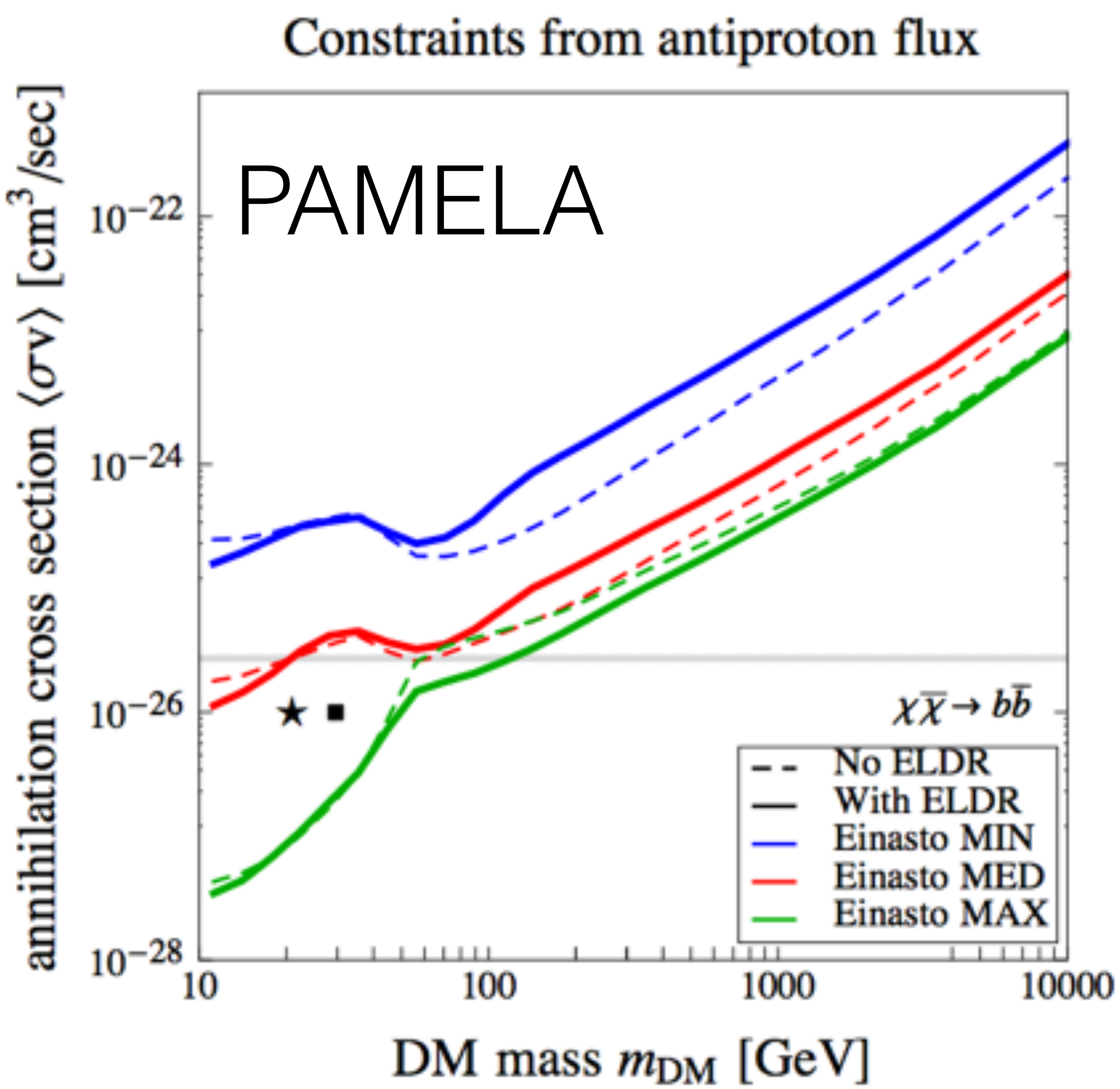
- Hooper, Linden & Mertsch 1410.1527: claim a consistent low-energy <u>excess</u> in PAMELA antiprotons.
- But may be background mismodeling.

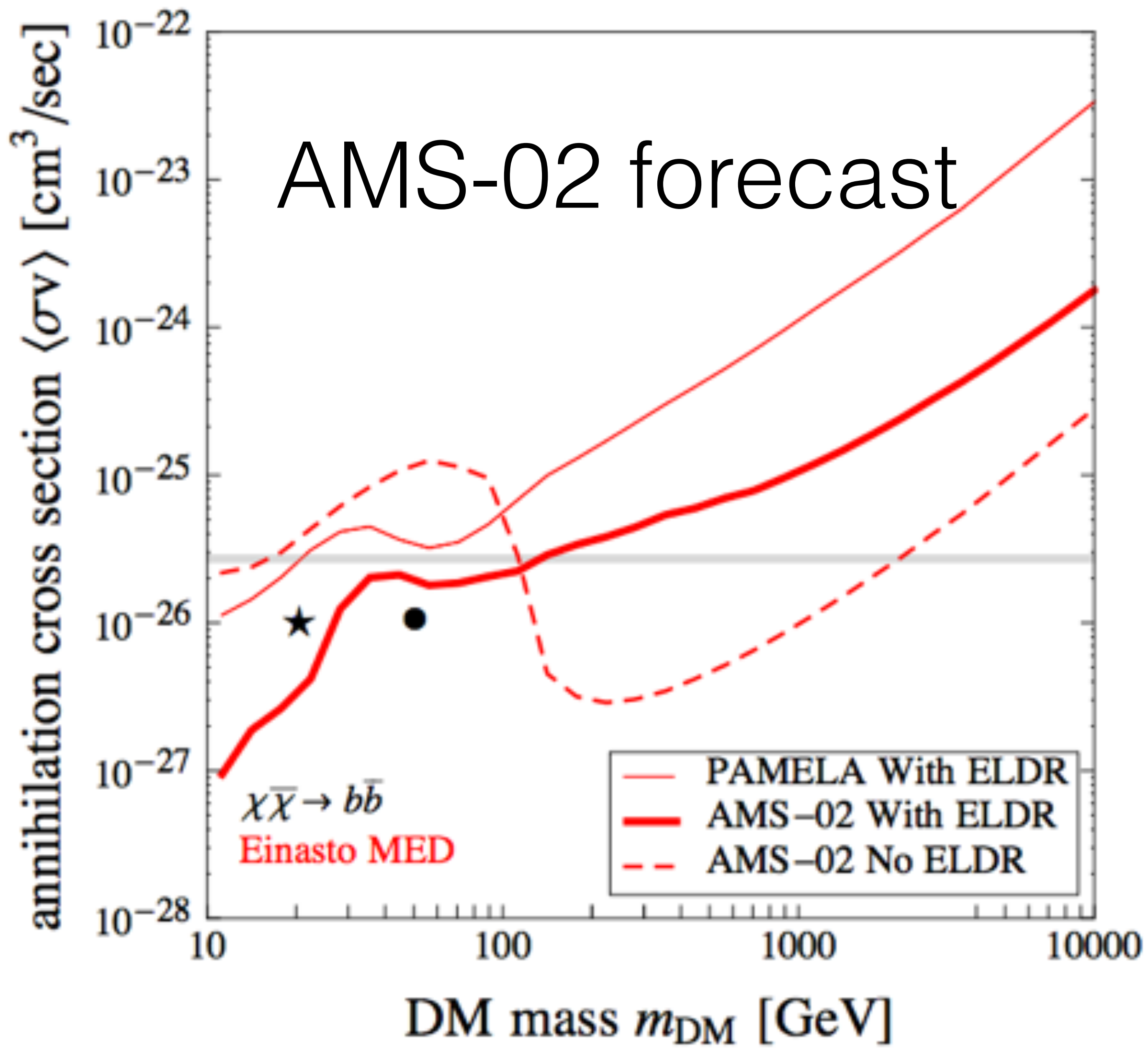






Antiprotons (cont.)

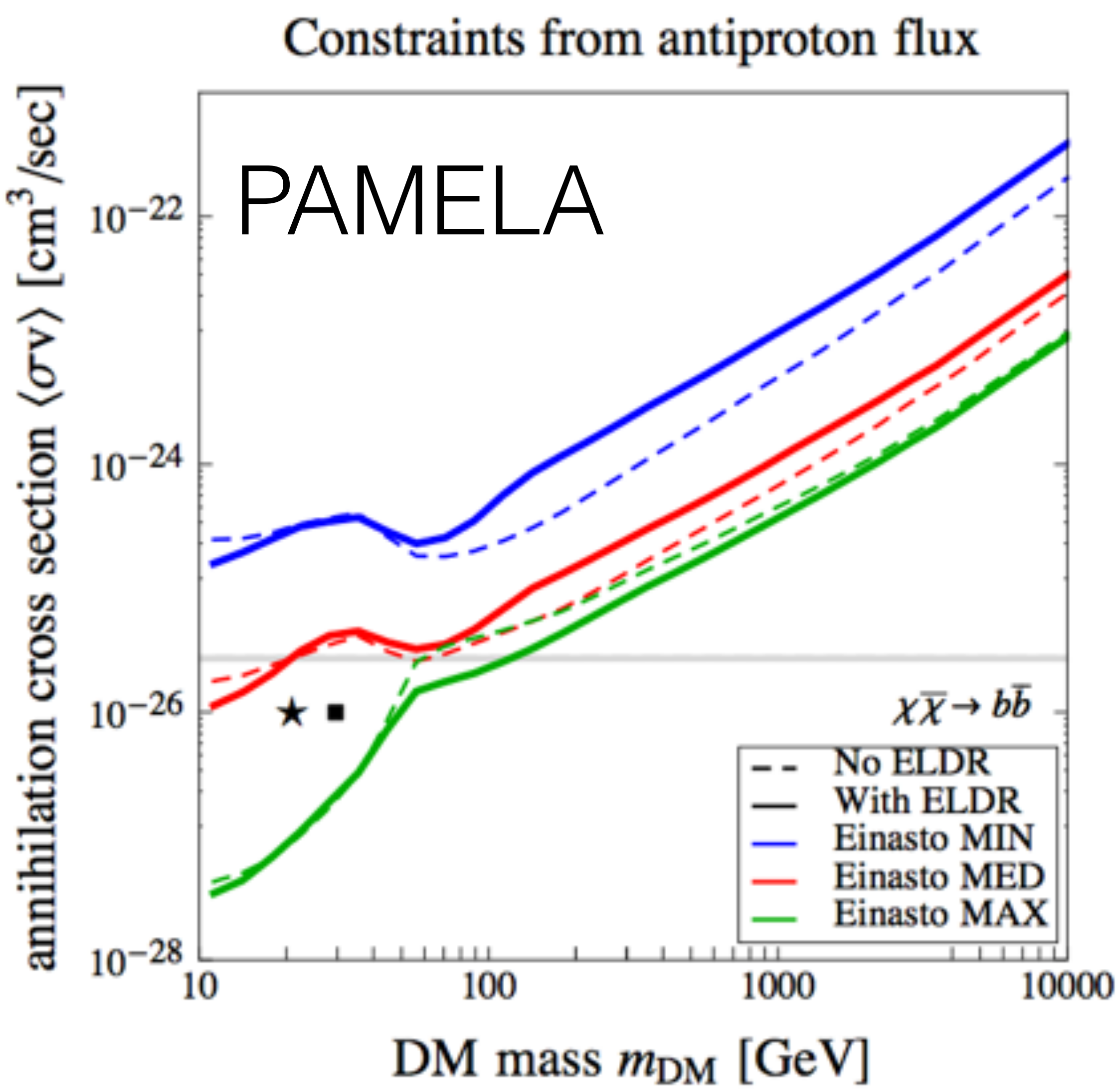


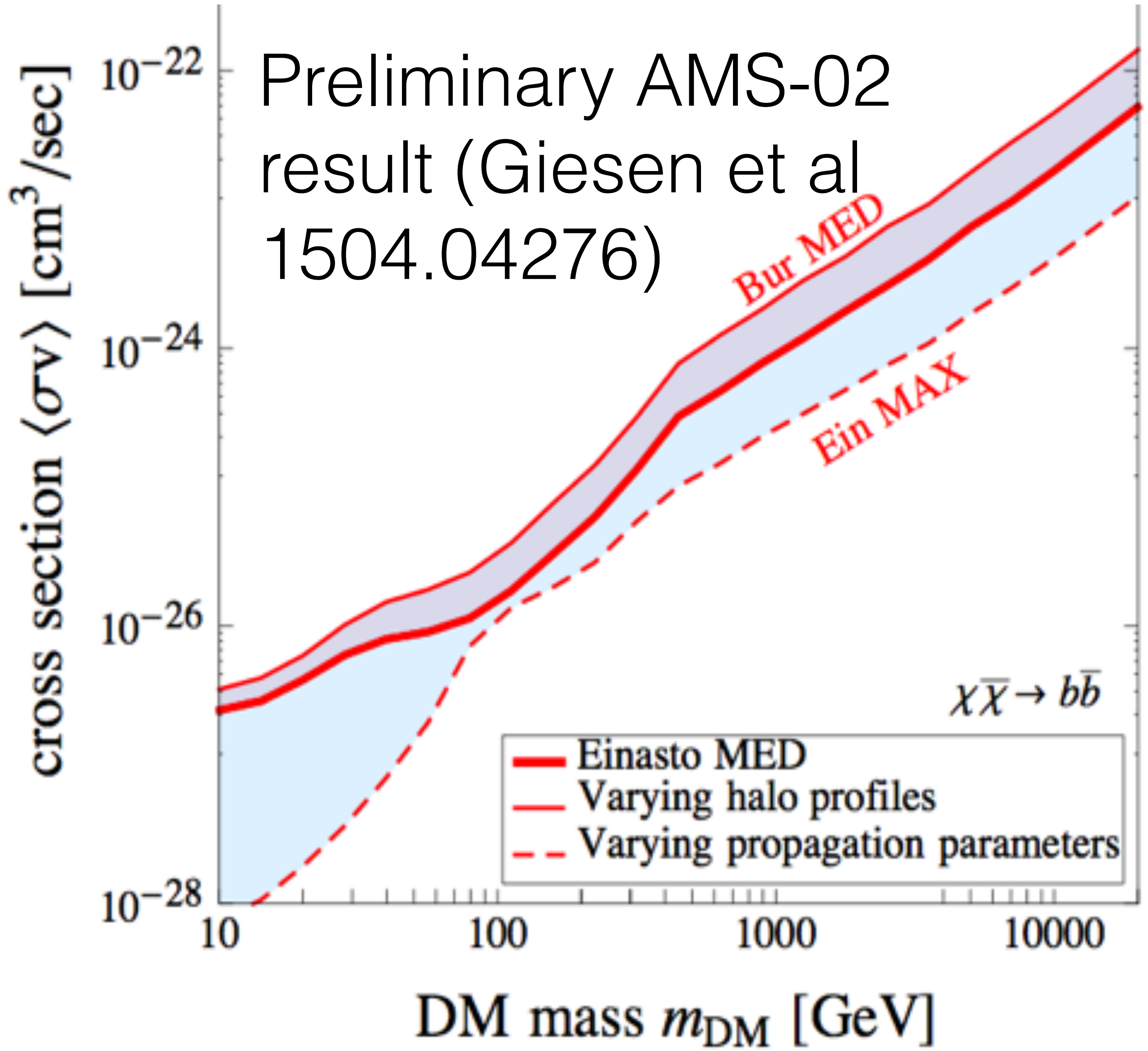


- Boudaud et al 1412.5696: important to take into account energy losses from tertiaries and diffusive reaccelerating (neglecting these effects can cause a false preference for a DM signal). Their different modeling does not pick up the claimed low-energy excess.

- 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.

Antiprotons (cont.)





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CMB bounds

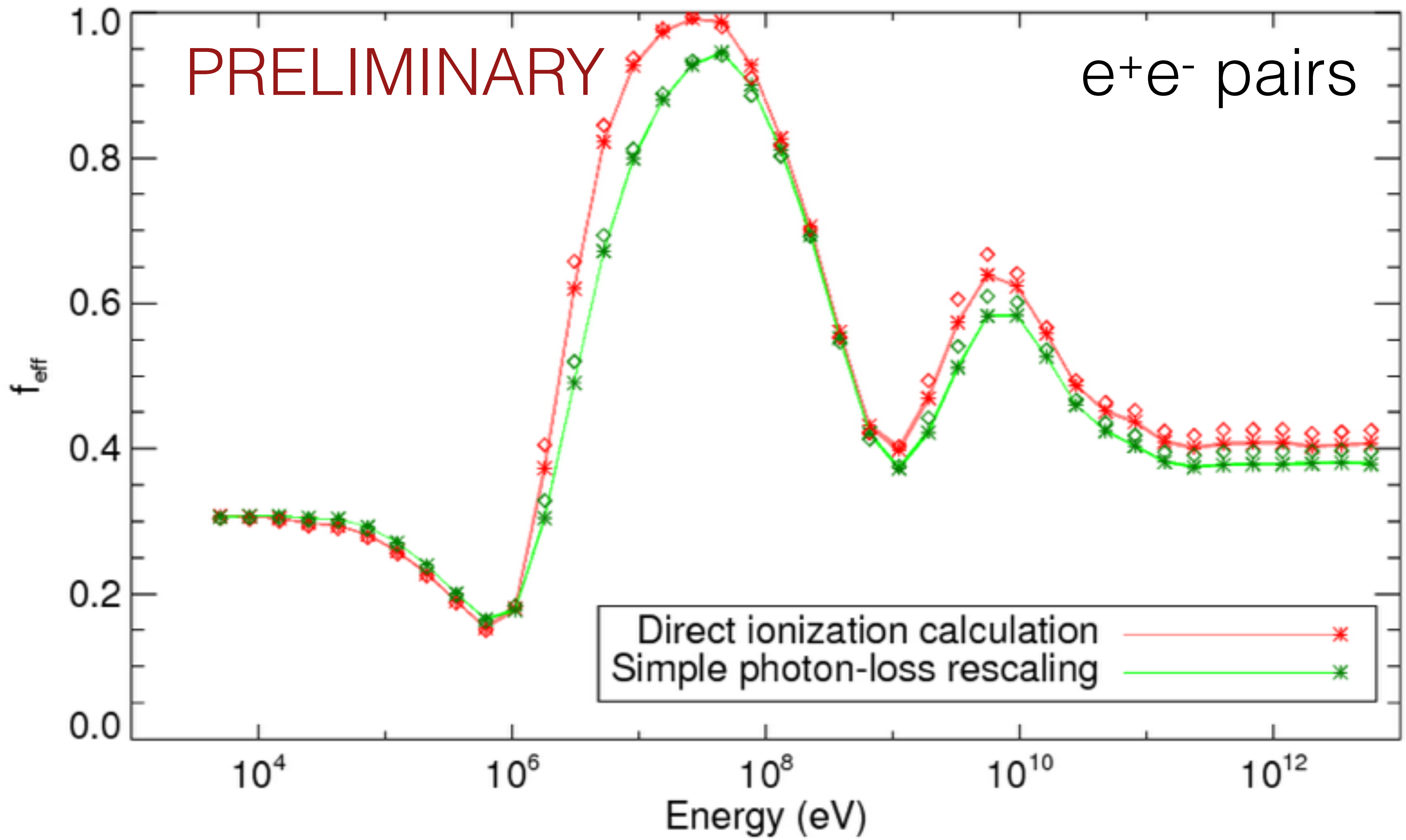
Understanding the CMB bounds

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.

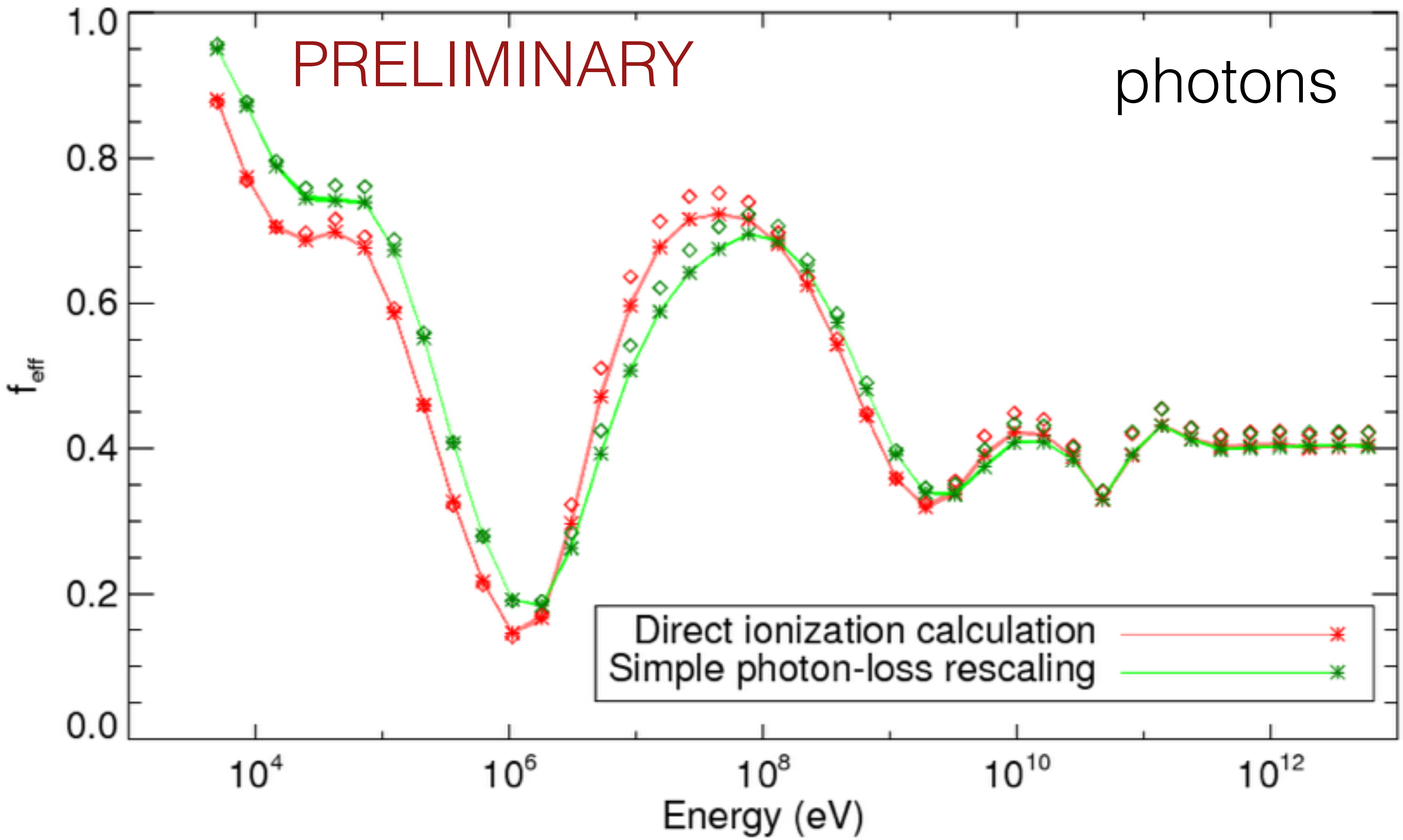
The efficiency factor



to

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:

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

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

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

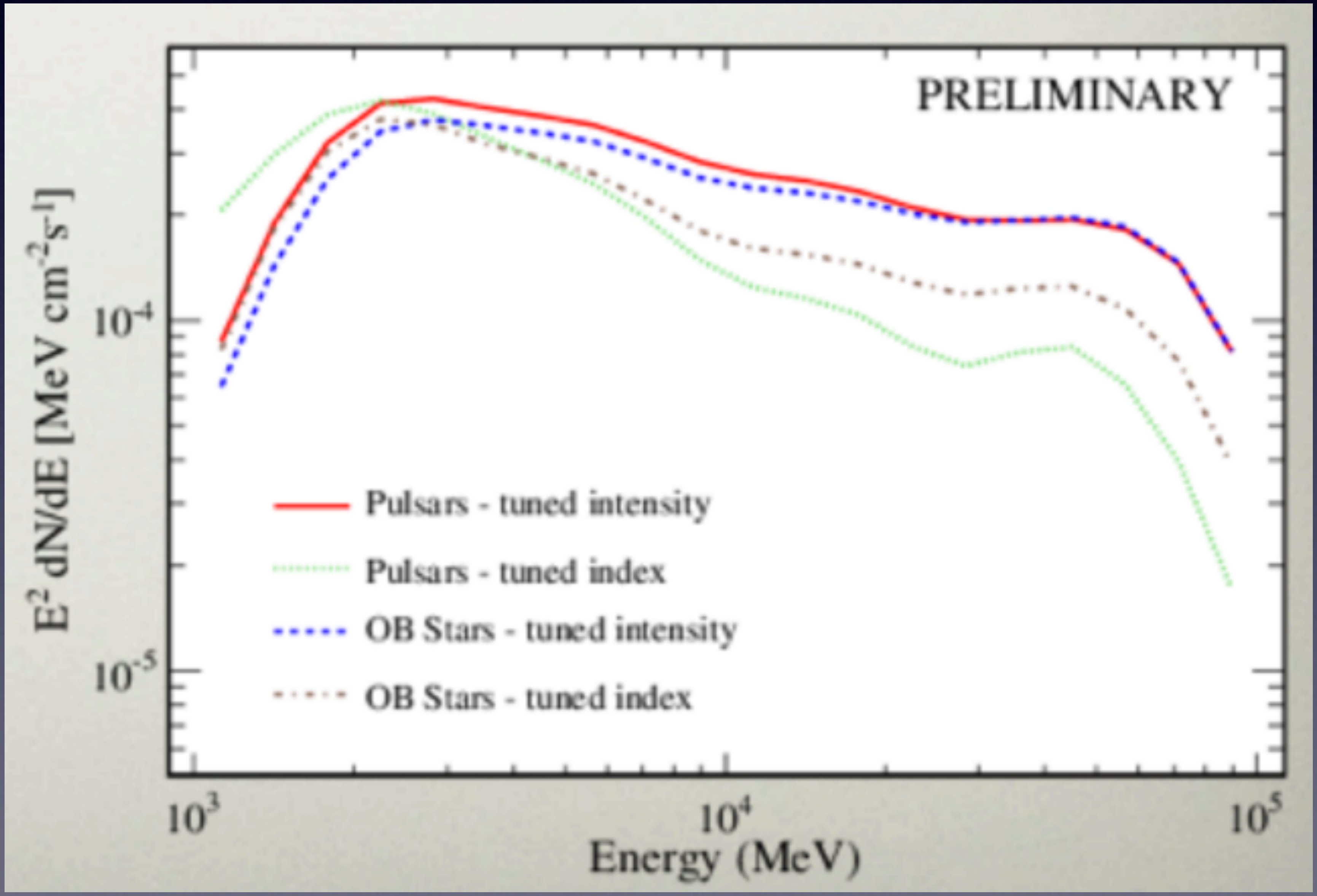
Constraints from the CMB

- 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 excess

The spectrum from the Fermi Collaboration

- Two sets of source distributions ("pulsars" and "OB stars"). "Tuned index" models allow spectral indices of background to vary (rather than just intensity), provide better agreement with data.
- Spectrum of excess seems broadly consistent with other results (lower at ~1 GeV); tuned-intensity models lead to higher "signal" tails at large E, but are known to generically undersubtract data at high energies.



Talk presented by Simona Murgia at Fermi Symposium

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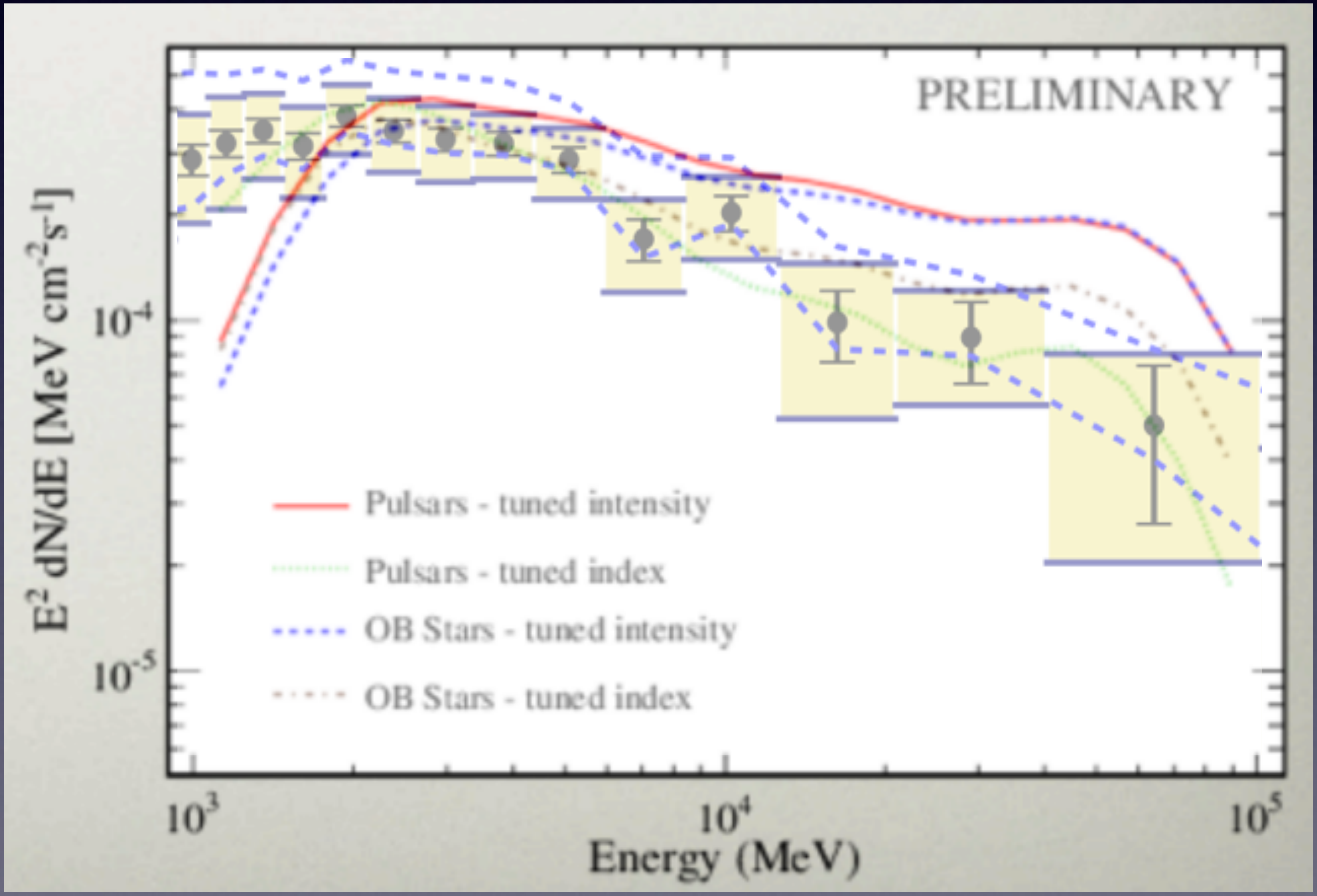
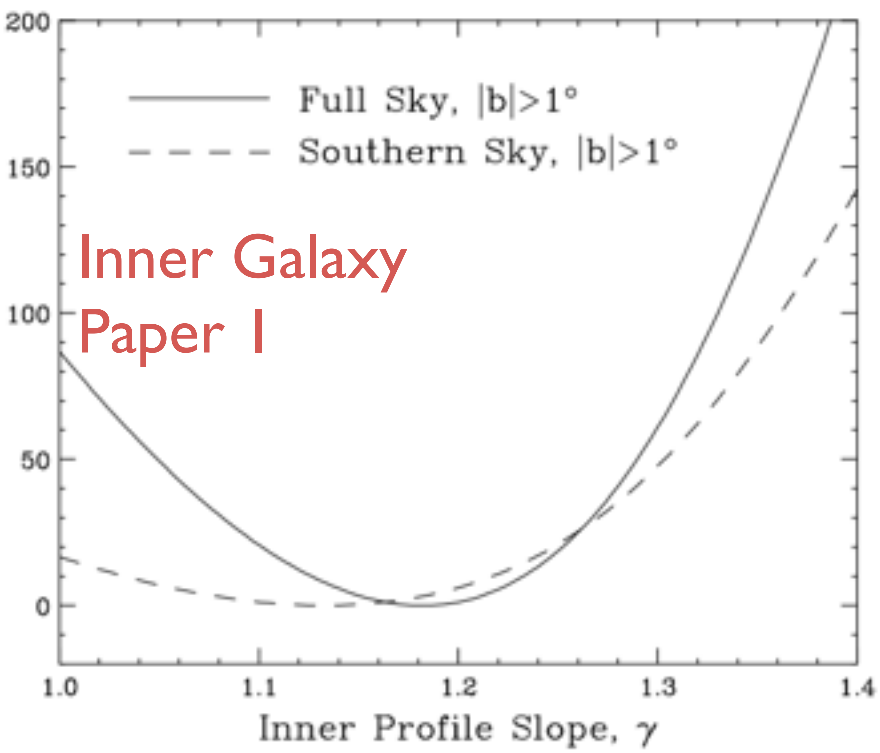
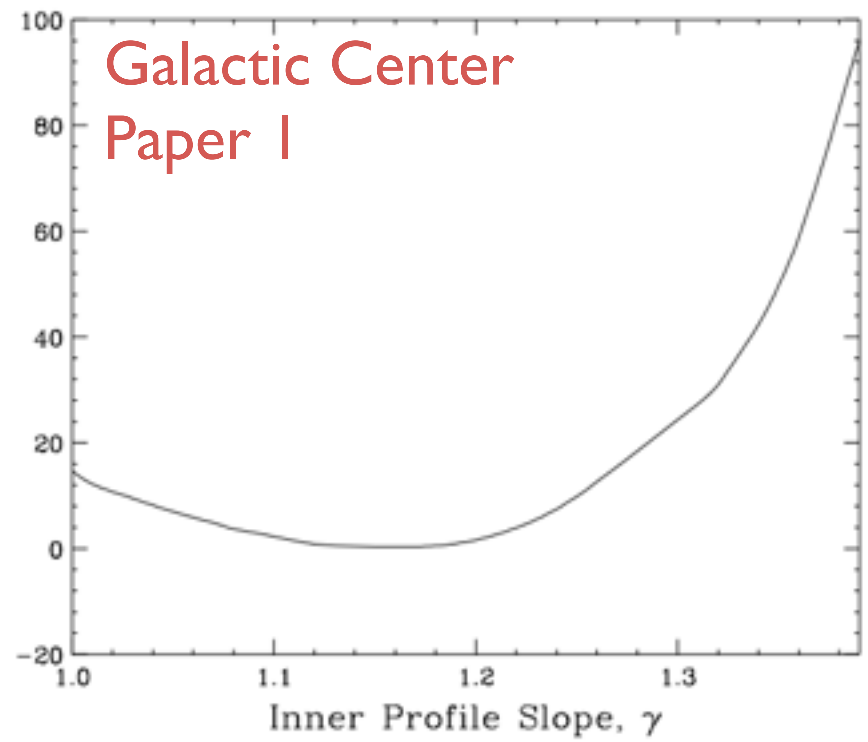
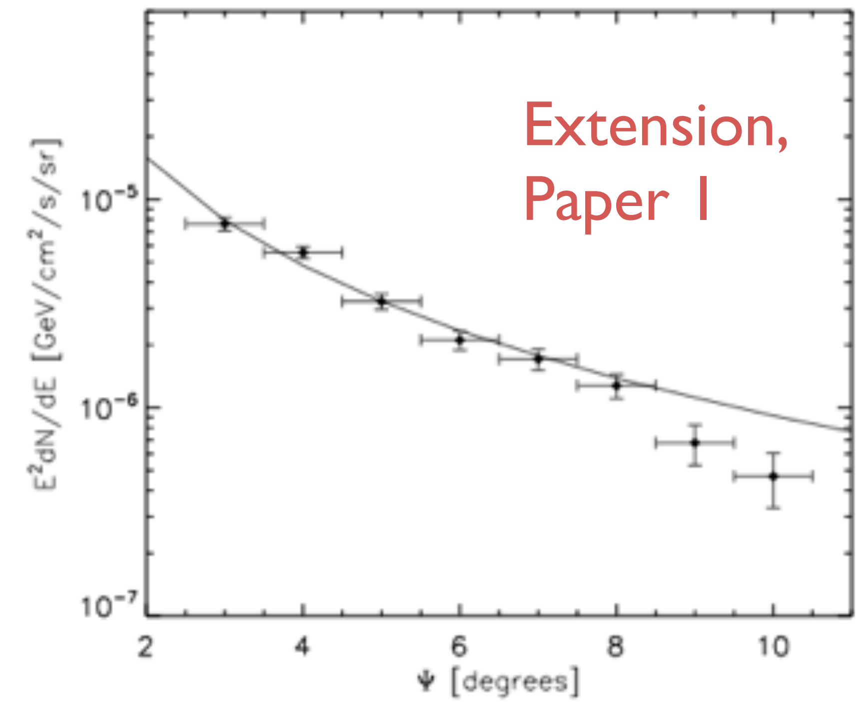


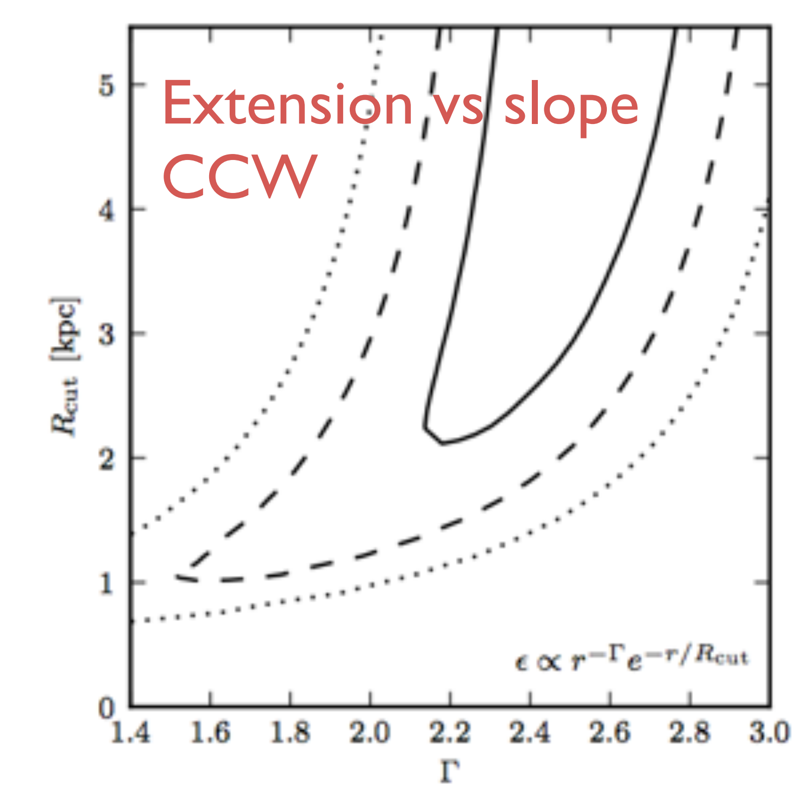
Talk presented by Simona Murgia at Fermi Symposium

Slope and extension





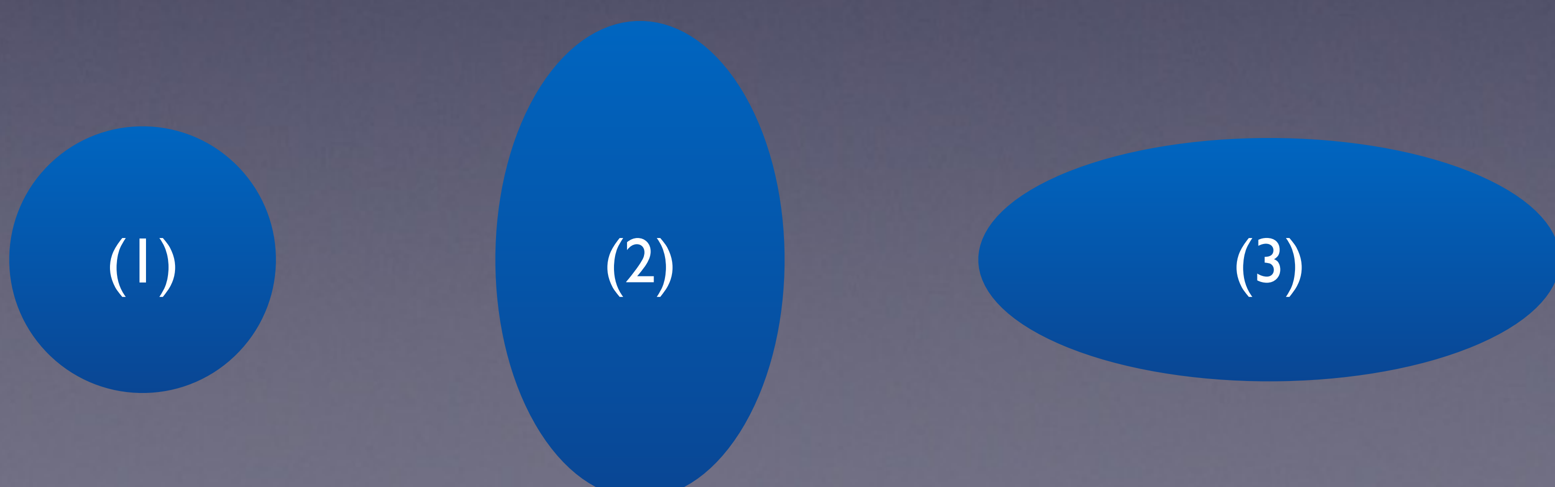


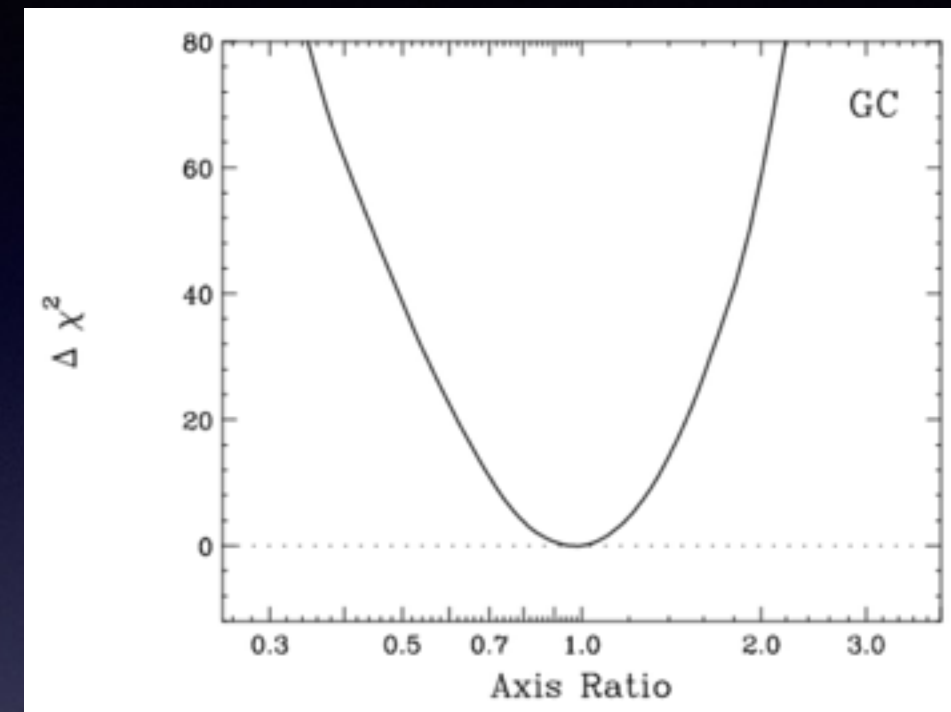


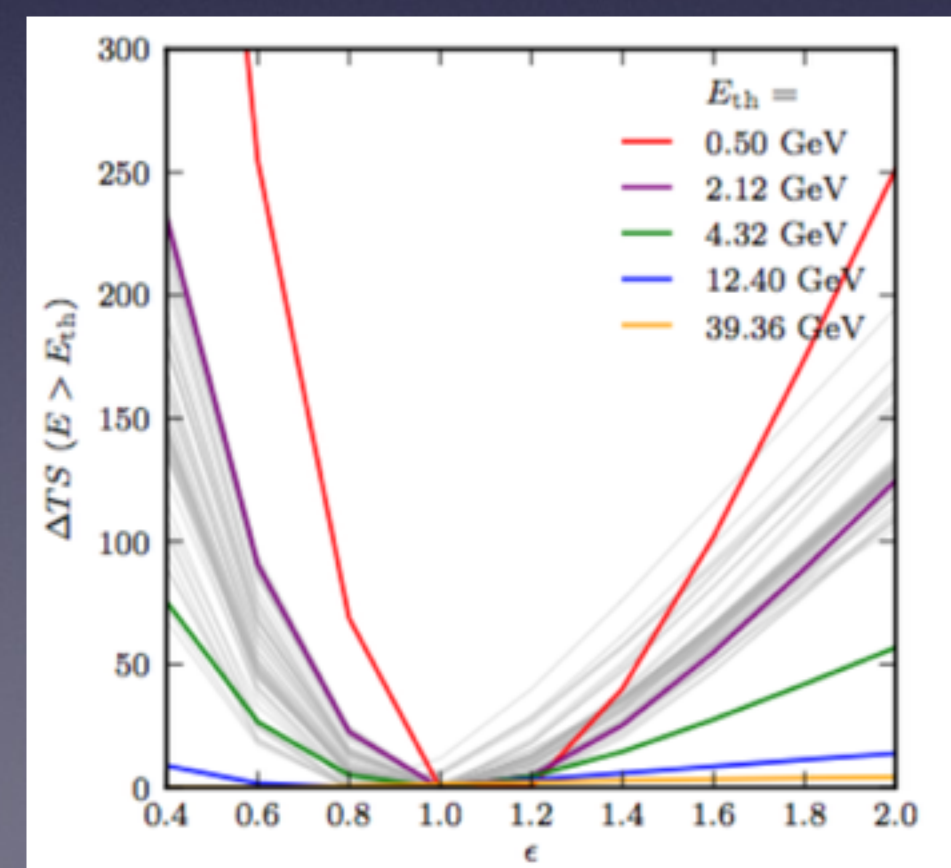
- Preferred power-law slope for power per unit volume (i.e. 2γ for annihilation from an NFW profile): ~2.2-2.4 (Galactic Center, Paper I), ~2.2-2.6 (Inner Galaxy, Paper I), ~2.2-2.8 (CCW, syst. errors included)
- Extends to ~10 degrees / 1.5 kpc.

Sphericity

- Test: which provides a better fit to the data? (1) Circular template, (2) template stretched perpendicular to the Galactic plane, (3) template stretched along the Galactic plane?
- (3) would be a strong hint at an astrophysical origin. But data seem to prefer (1), disfavoring a stretch by a factor of more than 1.2.
- Top - paper I, bottom - CCW.

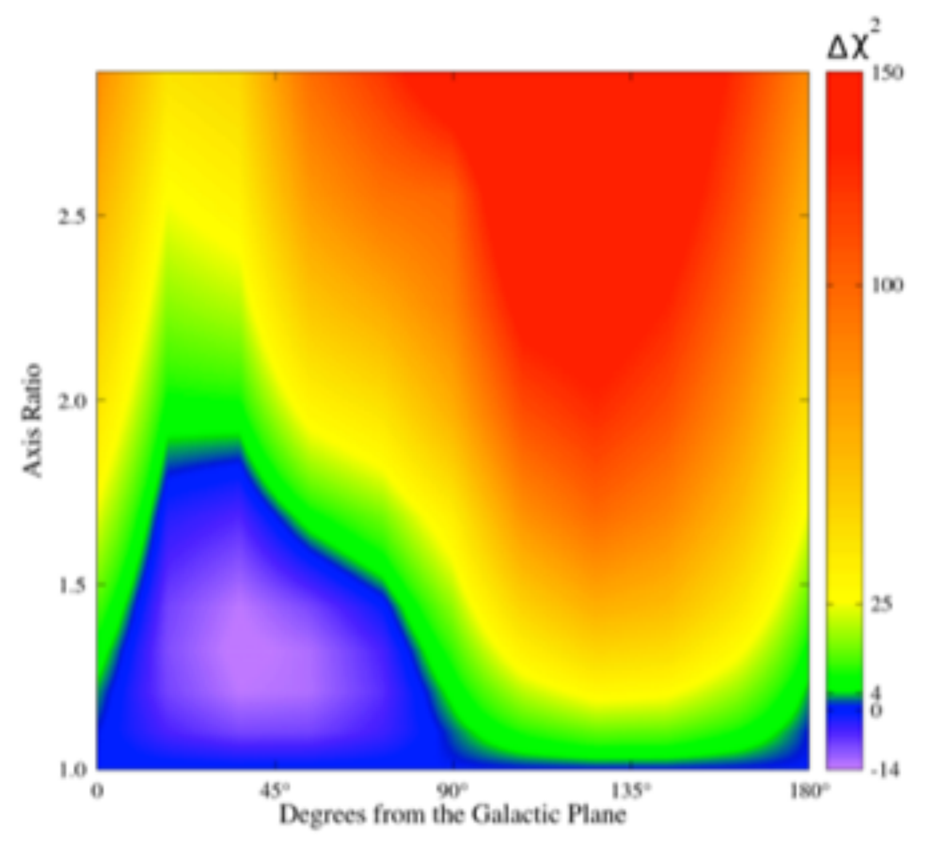


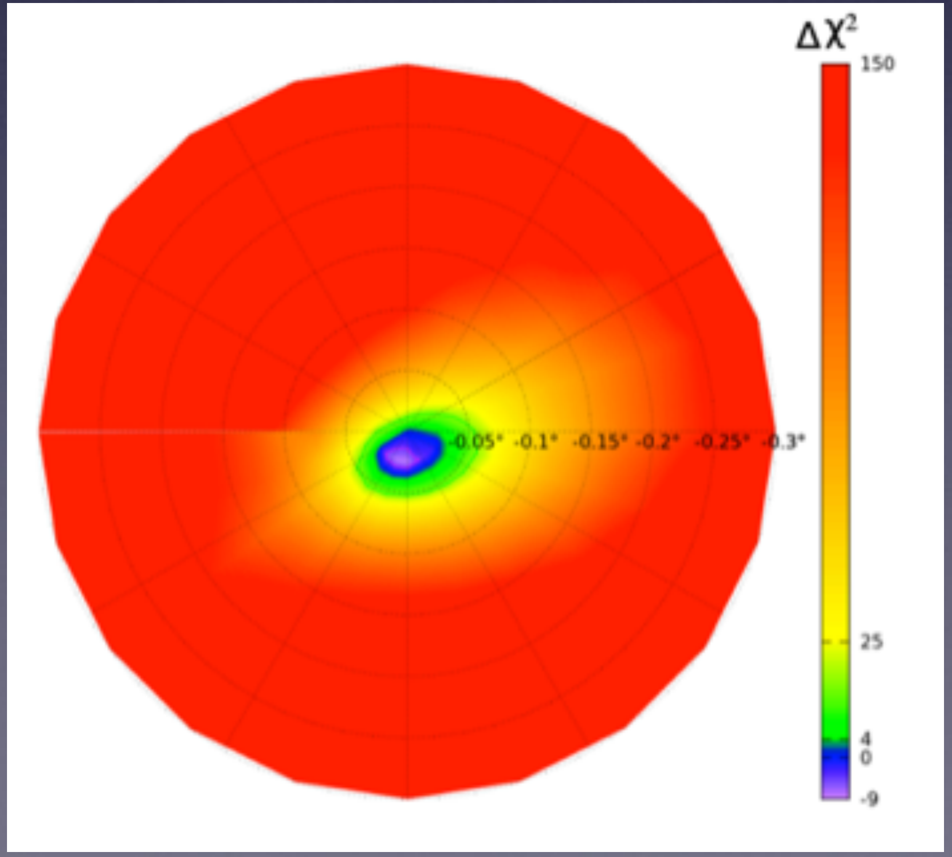




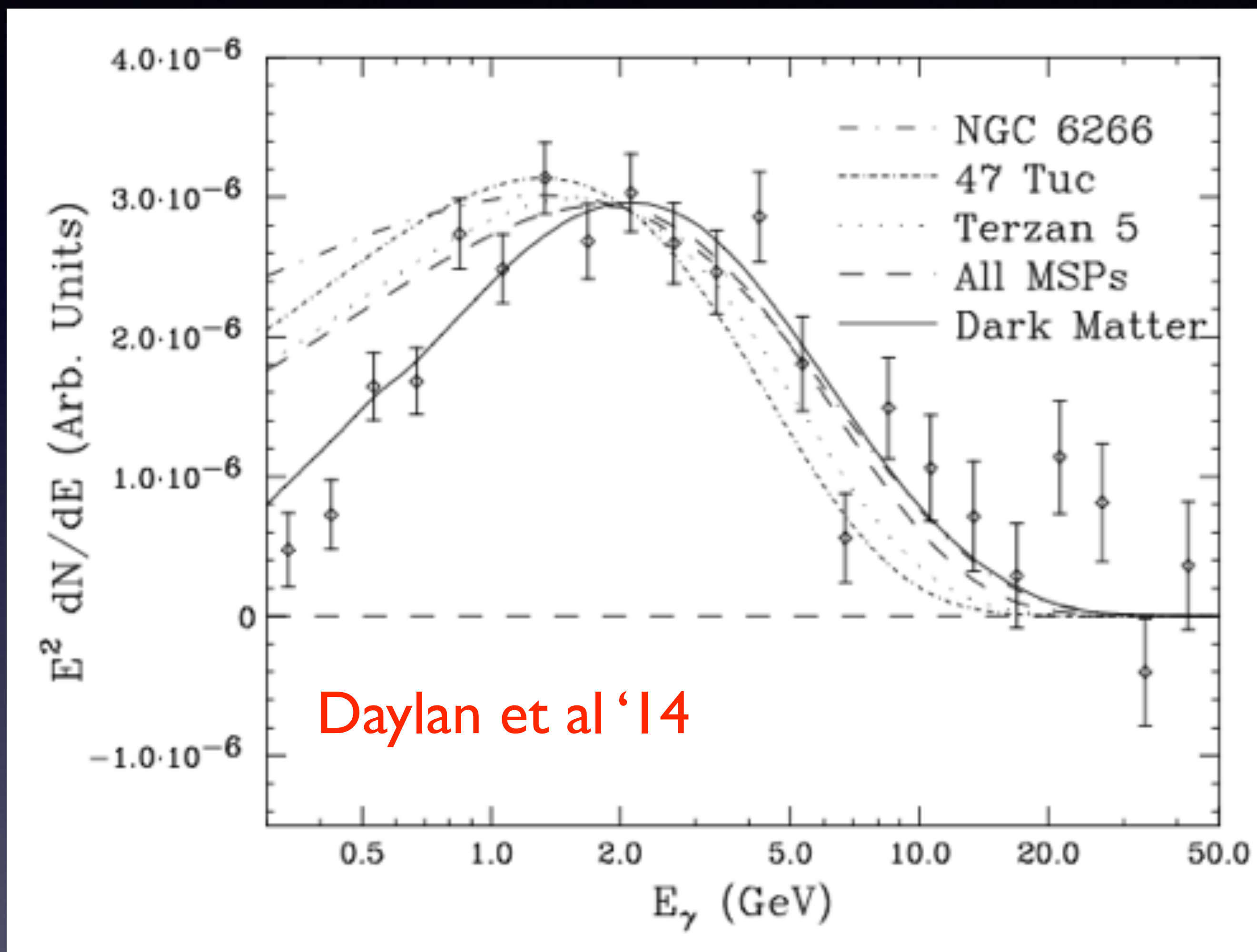
Orientation & centering

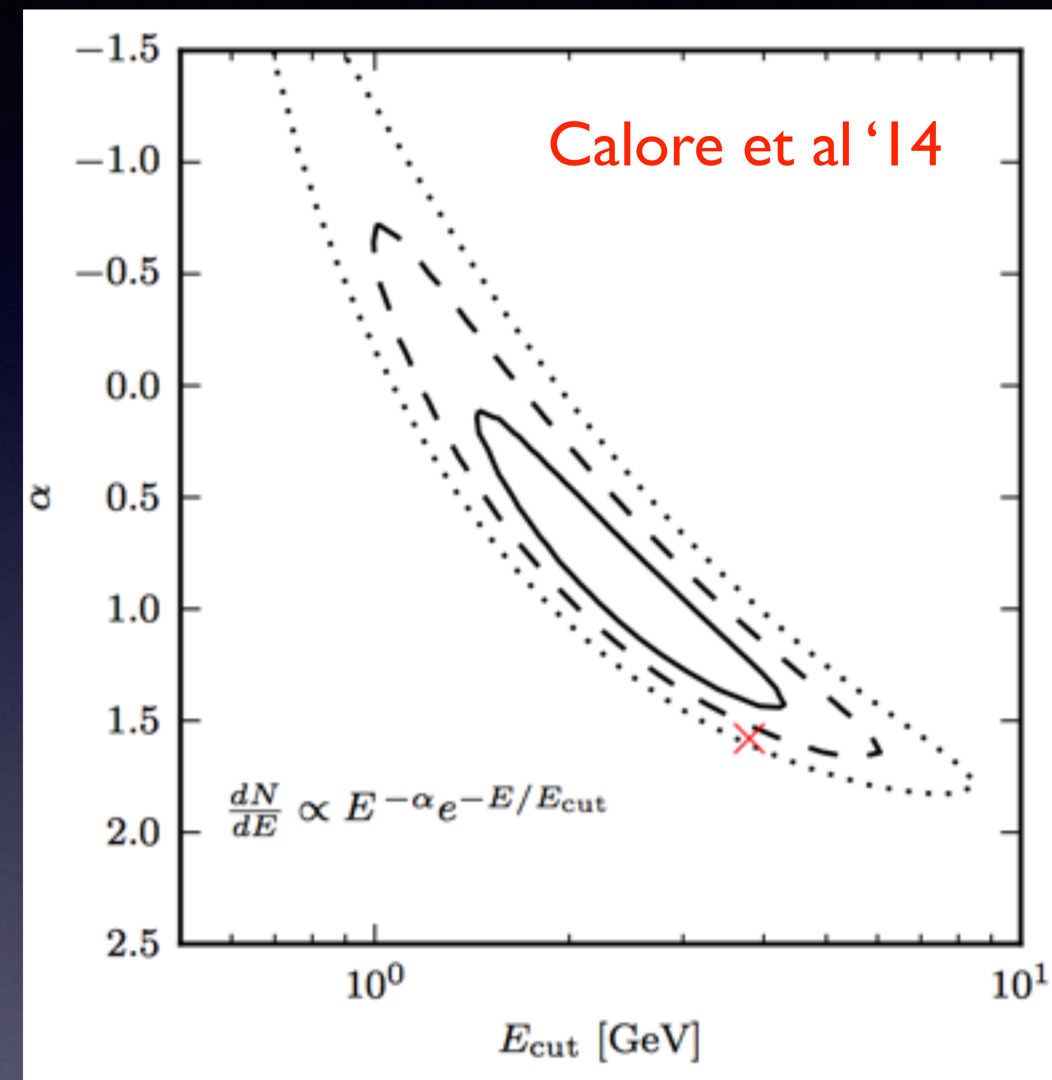
- More spatial tests (from paper I):
  - Stretch signal template along arbitrary angles to the Galactic plane.
  - Move template so it is not centered on Galactic Center.
- Results: shift more than 0.05 degrees from the GC is disfavored at 95% confidence (from GC analysis - inner Galaxy analysis less sensitive). Mild preference for stretch factor of 1.3-1.4 at an angle ~35 degrees from the Galactic Plane, but not significant.





The pulsar spectrum

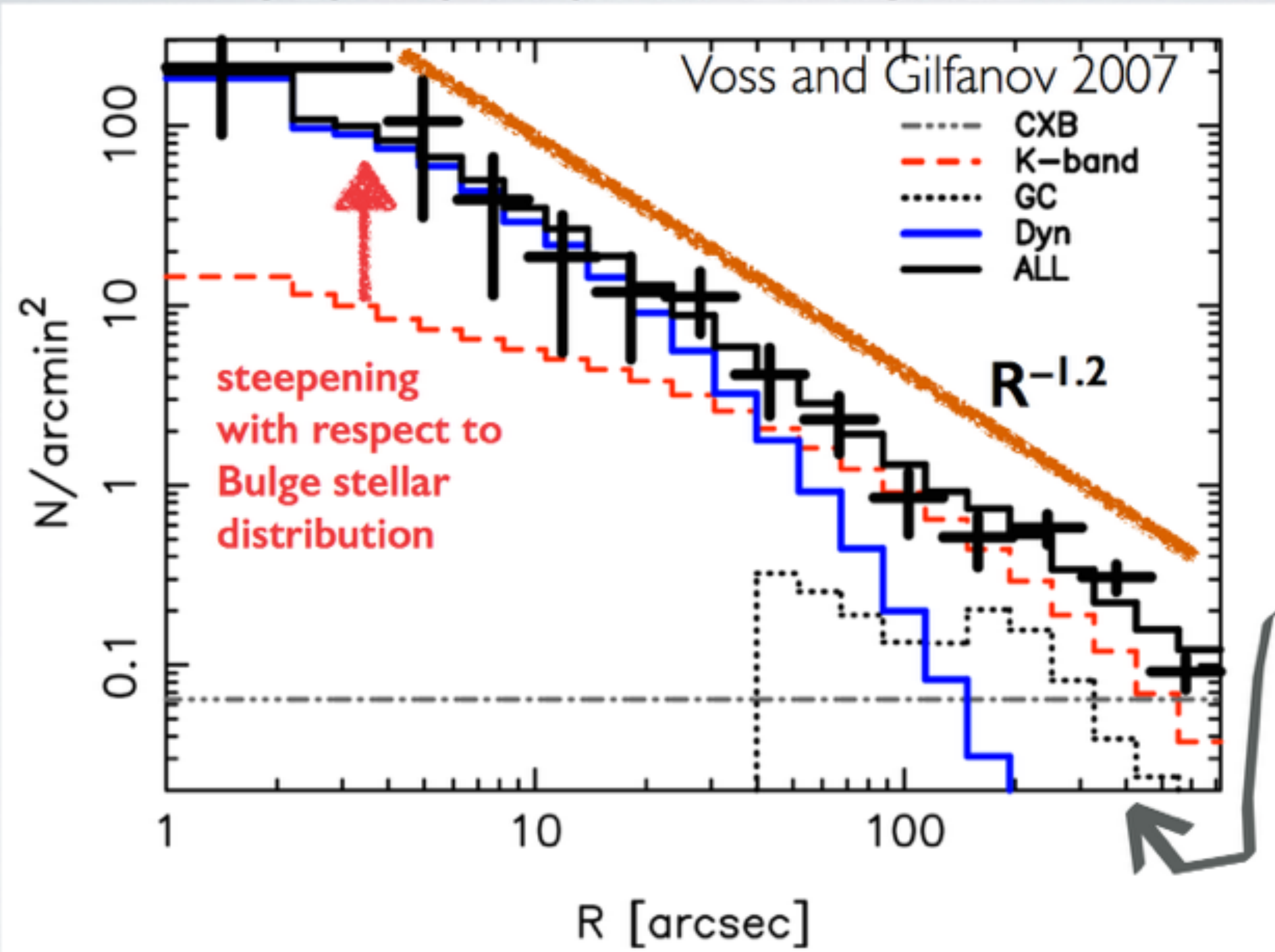




- Millisecond pulsars (MSPs) have an (observed) spectral cutoff at approximately the correct energy (~5-10 GeV).
- Low-energy spectrum of MSPs seems somewhat softer than signal (marginally compatible given CCW estimates on systematic uncertainties).
- Abundance estimates seem to predict fewer MSPs than required (e.g. 1305.0830, 1407.5625).

Why Could it be MSPs?

DEGENERACY WITH MILLI-SECOND PULSARS IN SPATIAL PROFILE



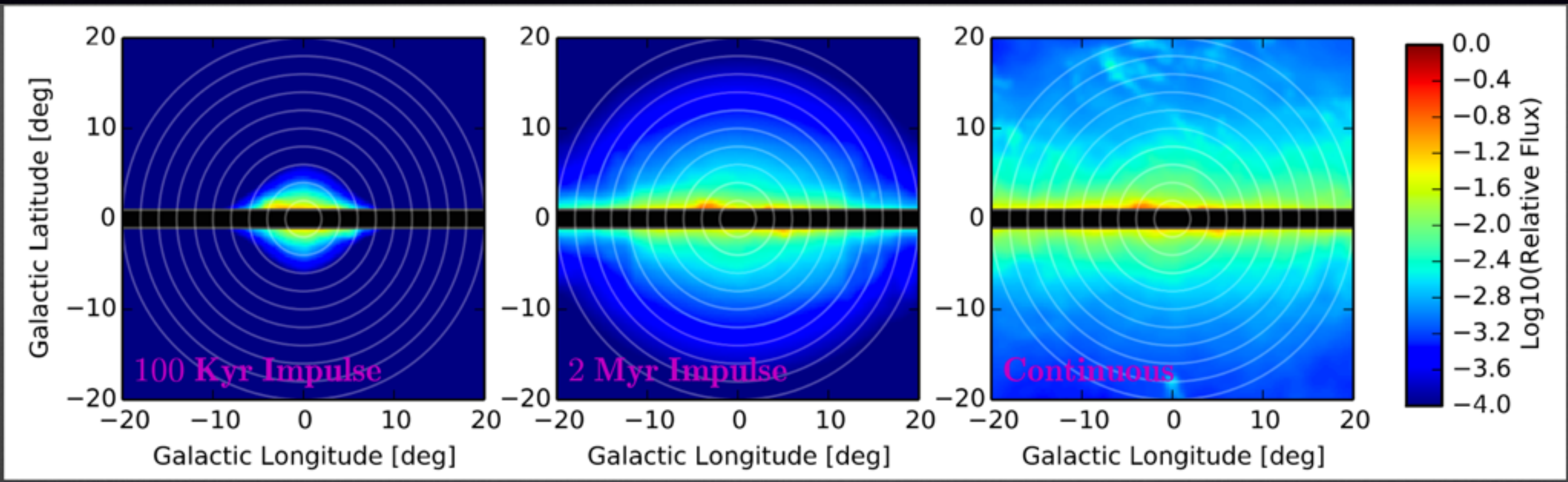
We make the reasonable assumption that Low-Mass X-ray Binaries have the same spatial distribution as MSPs

400” towards M31 center = 1.5 kpc distance from center = 10 degrees towards MW center

Orange line is same as best-fit excess template ($R^{-1.2}$ in projection implies $r^{-2.2}$ de-projected)!

Slide from Manoj Kaplinghat

Hadronic outbursts



- Carlson & Profumo '14 proposed that an outflow of energetic protons from the Galactic Center could explain the excess.
- Transient event could perhaps give a sharp spectral feature and roughly spherical profile - however, best-fit to spectrum with a broken power law for the proton spectrum requires the index below the break to be -0.7 and above the break to be 17.35.
- Broken power laws common in astrophysics, but not such sharp breaks.

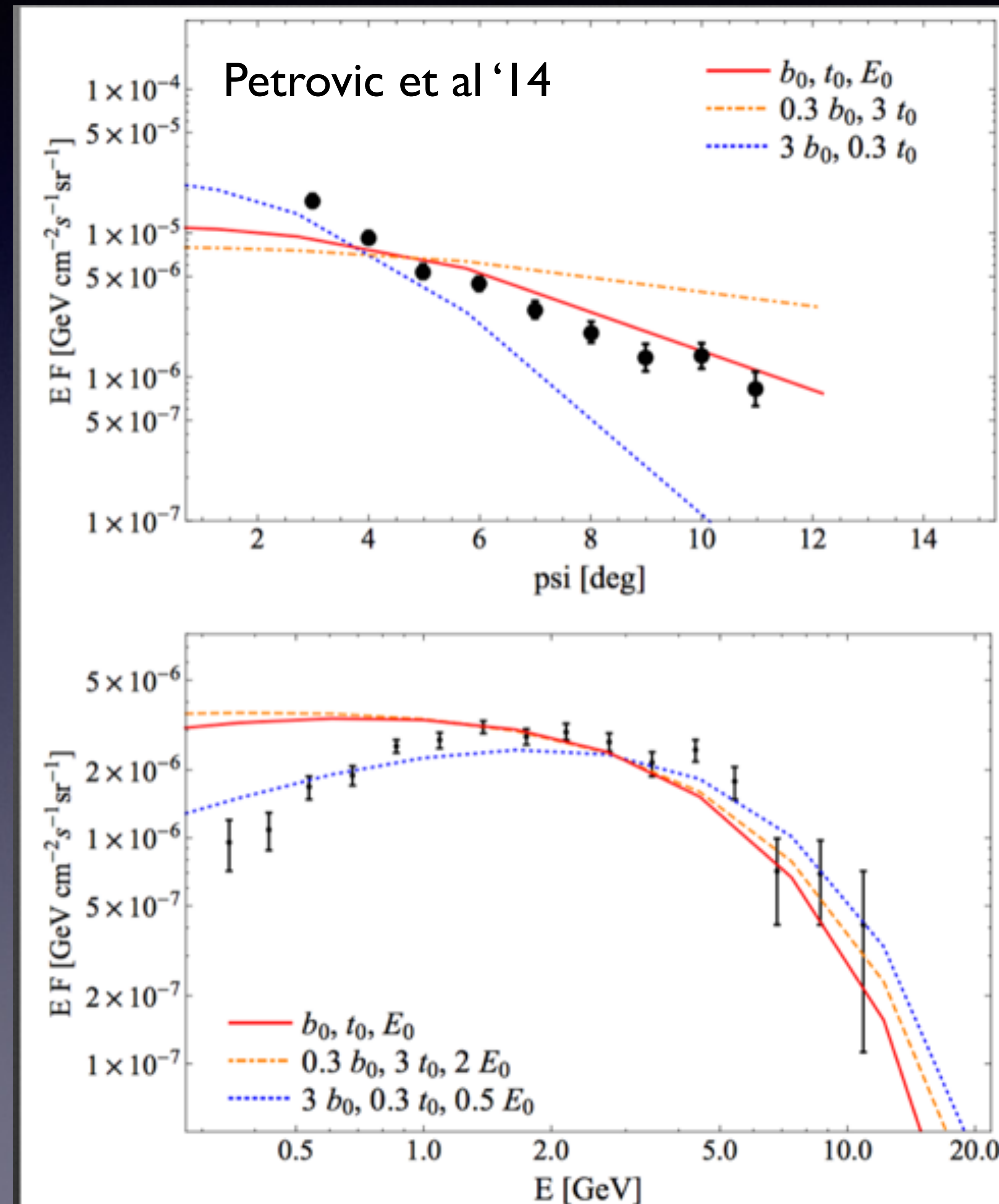
Current Models Don’t Fit

- Thanks to Eric Carlson and Stefano Profumo for providing us with the Galprop output files.
- We have run these models through our code (similar to what we do with the dark matter fits). The models pick up the following TS values:
  - 0.5 kyr: TS = 33
  - 2.5 kyr: TS = 43
  - 19 kyr: TS = 14 (with arbitrary spectrum: TS = 26.6)
  - 100 kyr: TS = 0.0 (with arbitrary spectrum: TS = 0.28)
  - 2 Myr: TS = 0.0, (with arbitrary spectrum: TS = 0.0)
  - 7.5 Myr Continuous: TS = 0.0 (with arbitrary spectrum: TS = 0.0)
  - **Linear Combination of All Hadronic Outburst Models TS = 51**
  - Dark Matter Template (Daylan et al. 2014): TS = 315

Slide taken from talk by Tim Linden, Cosmo-14

Leptonic outbursts

- CR electrons can produce gamma rays from ICS (or bremsstrahlung, but this would give gas-correlated emission)
- Electron cooling => difficult to produce the same hard spectrum over several degrees of sky.



Model-building challenges

- Direct detection is very sensitive in this mass range, why haven't we seen it?
  - Annihilation may be resonant
  - Direct detection may be dominantly spin-dependent or otherwise suppressed (although in many models, upcoming direct detection experiments have sensitivity anyway)
  - Annihilation may be 2->4 and the intermediate particles may have small couplings to the SM
- What about bounds from colliders?
  - Sensitivity is reduced in the presence of light mediators, which may be needed to raise the cross section to thermal relic values
  - Nonetheless, substantial classes of simplified models can be ruled out.
- There are existence proofs of UV-complete models that satisfy all constraints.

Effective field theory…

(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
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
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
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(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
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

Study couplings to hadronic states only

Alves et al
1403.5027

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D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
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
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

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C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

ruled out by DD

Study couplings to hadronic states only

Alves et al 1403.5027

Effective field theory…

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D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

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C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

ruled out by DD

cannot fit signal

Study couplings to hadronic states only

Alves et al
1403.5027

Effective field theory…

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Name	Operator	Dimension	SI/SD
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

ruled out by DD

cannot fit signal

ruled out by LHC

Study couplings to hadronic states only

Alves et al 1403.5027

… and beyond

Berlin et al 1404.0022 (simplified models)

Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach?	
					Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Varying the background model (CCW)

- What CCW varied:
  - Size of the diffusion zone (height, radius)
  - Cosmic ray source distributions
  - Diffusion coefficient at reference rigidity
  - Alfven speed
  - Gradient of convection velocity
  - Brightness of optical/infrared emission
  - Magnitude and profile of Galactic magnetic field
- Assumptions they did not vary:
  - CR diffusion is homogeneous + isotropic
  - CR re-acceleration is homogeneous
  - CR convection does not depend on Galactocentric radius
  - CR source distribution has radial symmetry (not accounting for spiral arms)
  - Steady state solution for CRs (no transient phenomena)
  - Same spatial distribution for hadronic and leptonic CR sources