Dark Matter Phenomenology and Indirect Detection

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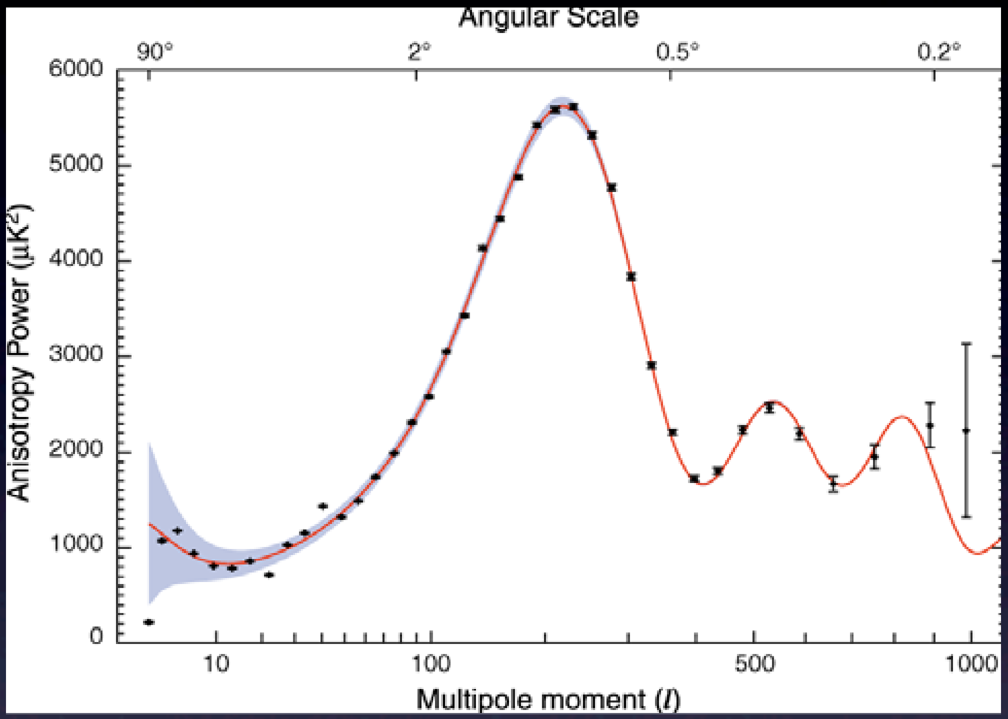
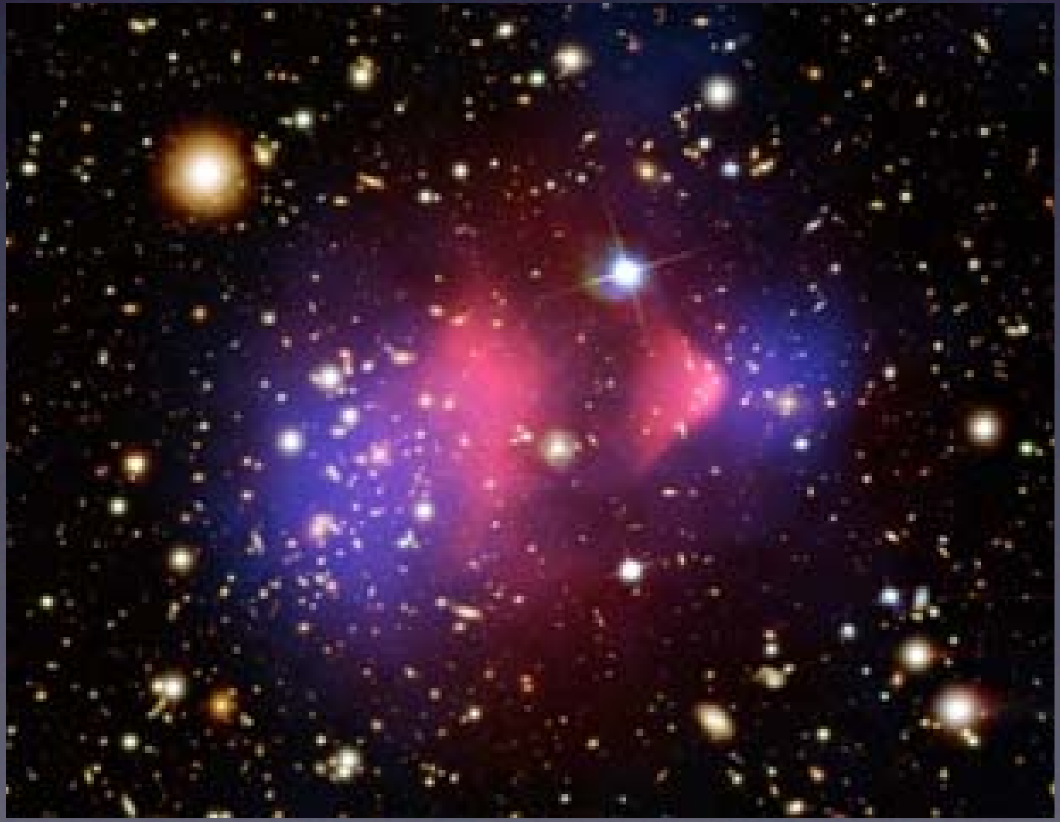
Outline

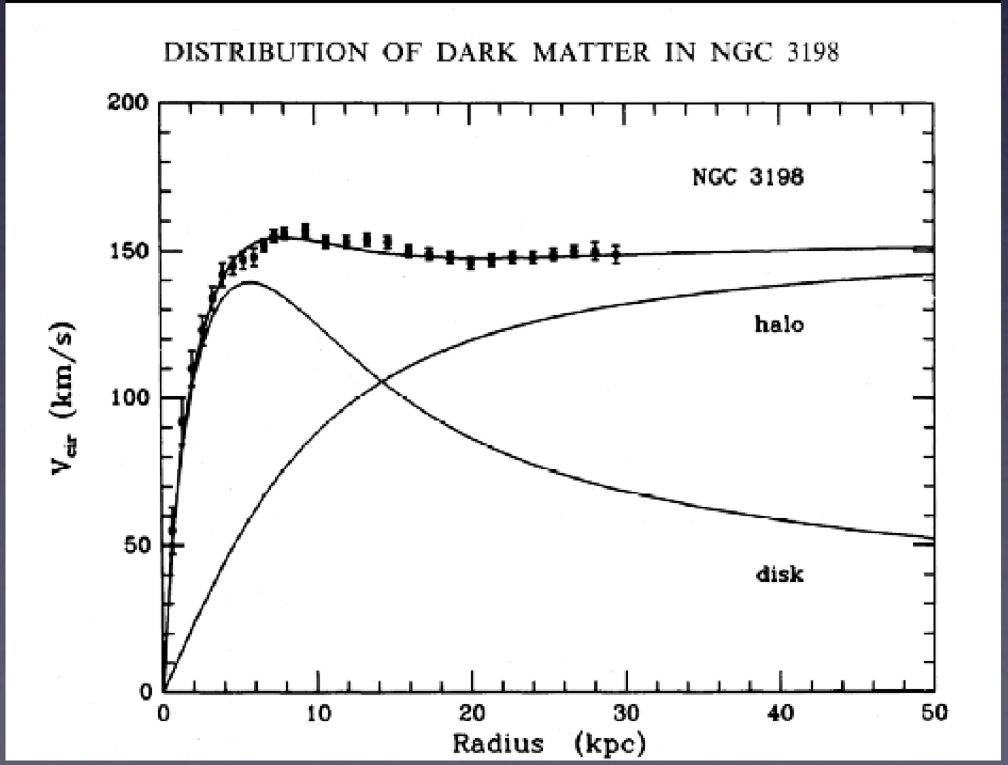
- Introduction
- Gamma rays:
  - Status of the 130 GeV line
  - The few-GeV excess in the inner Galaxy
  - Implications for DM interpretations
- Cosmic rays:
  - New favored parameter space for DM models explaining the positron excess, after AMS-02
  - Constraints on the DM interpretation

The search for dark matter

- Standard cosmological model: ~5/6 of the matter in the universe (~22% of the total energy budget) is non-baryonic "dark matter".
- Evidence from galactic rotation curves, cluster mass-to-light ratios, gravitational lensing, structure formation, cosmic microwave background...







DM as new physics

- One of the most powerful pieces of evidence for physics beyond the Standard Model, but currently only detected gravitationally: we would like to understand its interactions with the Standard Model.
- Most popular general candidate class is Weakly Interacting Massive Particles, WIMPs (axions are another widely-discussed well-motivated candidate, and there are many other ideas).
- If we keep naturalness as a motivation, we expect new physics at ~weak scale anyway.
- Stable WIMPs occur naturally in BSM models of weak-scale physics with some new symmetry.
- Classic example is SUSY with R-parity.

Why WIMPs?

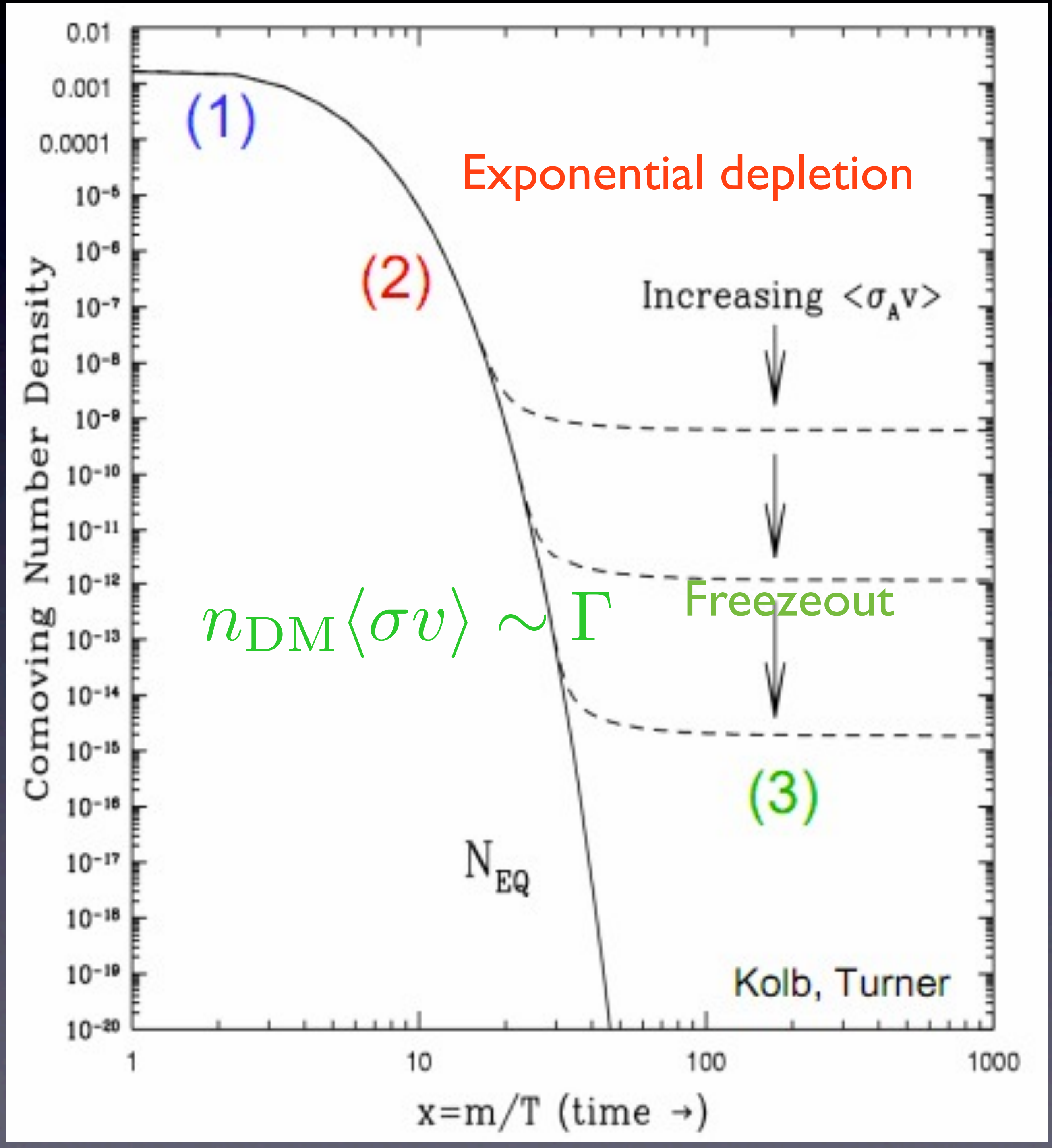
- In presence of new parity, can still have:

$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- When temperature drops below m_{DM}, exponential depletion due to:

$$\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM}$$
$$\chi\chi \not\leftarrow \mathrm{SM}\,\mathrm{SM} \quad (2)$$

- When annihilation timescale ~ universe's expansion timescale, depletion cuts off.



The WIMP "miracle"

- Present-day dark matter density set directly by annihilation rate at freezeout, in this scenario. The inferred annihilation rate is:

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

- This is the "thermal relic cross section" - naturally weak scale. Independent reason to consider weak scale!
- (Of course, there are other possibilities; dark matter could be nonthermally produced, or asymmetric in the same way as the baryonic sector, or something quite different like an axion.)

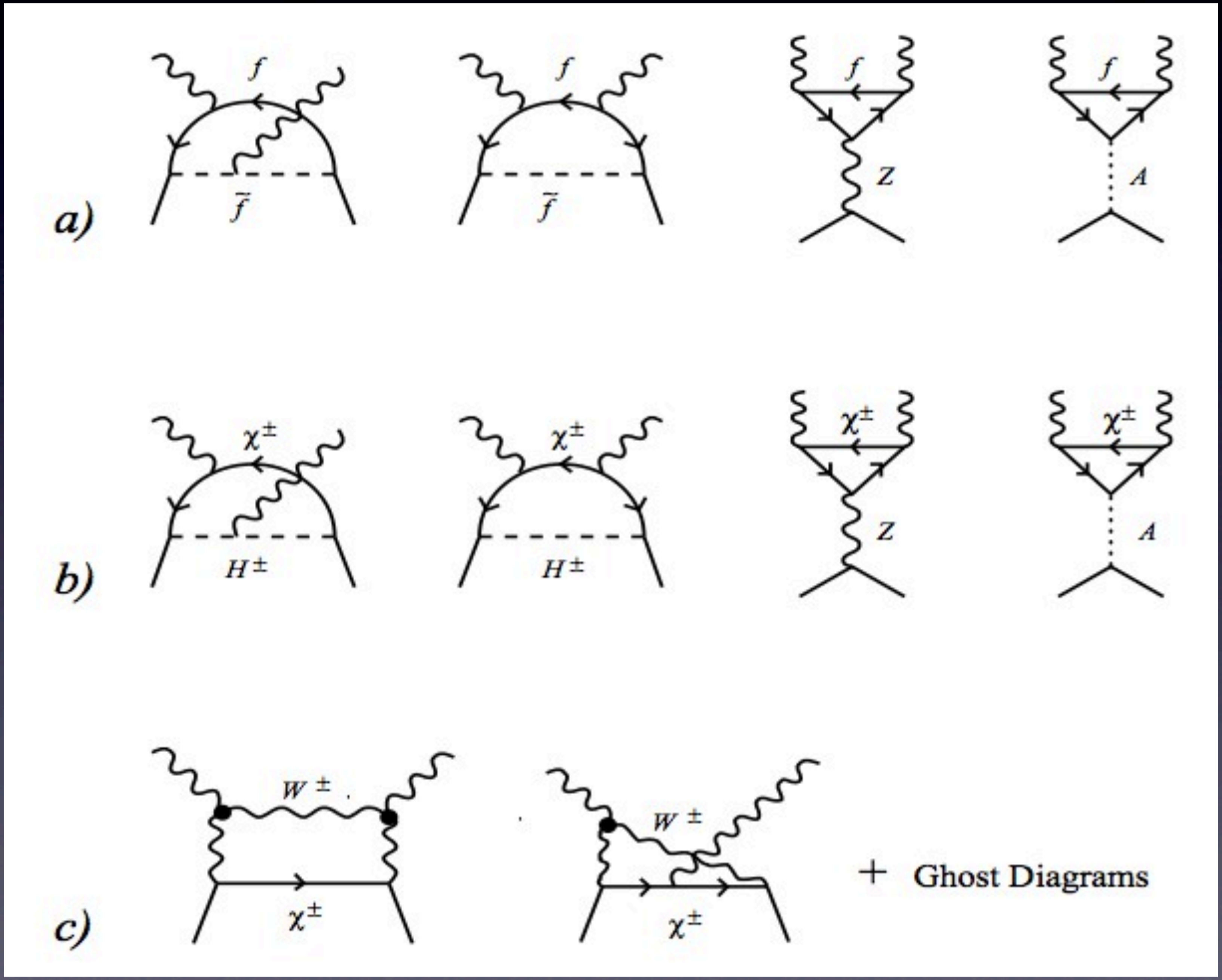
Annihilating dark matter

- If this picture is correct, DM should/could still be annihilating in the present day.
- Of course, annihilation is frozen out - but that just means it doesn't change the comoving DM density.
- Annihilation rate scales as density-squared, and there are regions where the density is much higher than the cosmic average (e.g. galaxies).
- Use telescopes to search for ~weak-scale particles produced by DM annihilation:
  - Charged particle cosmic rays (electrons, positrons, antiprotons, antideuterons, etc)
  - Gamma-rays
  - Neutrinos
  - More indirect effects: e.g. heating and ionization in the early universe, modifications to Big Bang nucleosynthesis, etc

GAMMA RAYS: THE FERMI LINE

Gamma-ray lines from DM

- Direct DM annihilation to two photons produces a spectral line at the DM mass.
- No known astrophysical counterparts, if DM is near weak scale: “smoking gun” signal.
- Signal expected to be small since annihilation must proceed through a loop, as DM is uncharged.

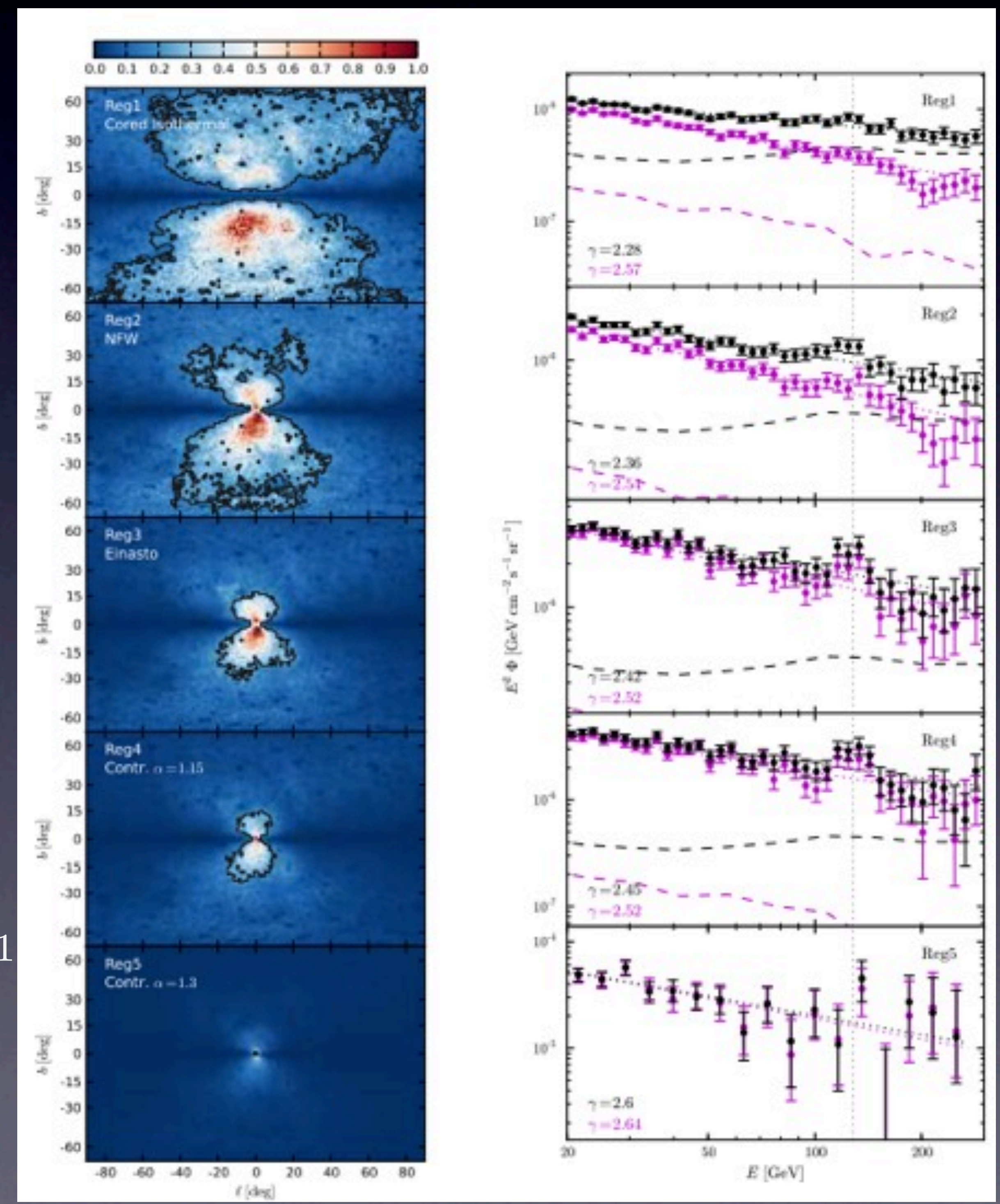


Jungman and Kamionkowski, hep-ph/9501365

A gamma-ray line at 130 (or 135) GeV?

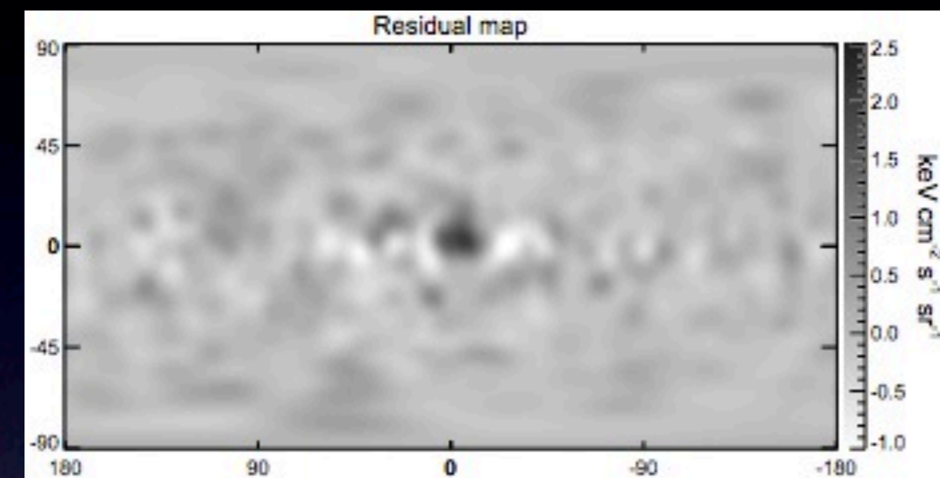
- Initial observation detailed in two papers: Weniger 1204.2797, see also Bringmann et al 1203.1312.
- Claimed result: detection of a gamma-ray line at 130 GeV, with a local significance of 4.6 σ, or 3.3 σ once the look-elsewhere effect is taken into account.
- If interpreted as a signal of DM annihilation to $\gamma\gamma$, if an Einasto density profile is assumed, the inferred best-fit cross section for annihilation is about 1/20 the thermal relic value:

$$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = \left(1.27 \pm 0.32^{+0.18}_{-0.28}\right) \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}$$



Instrumental systematics?

- Finkbeiner & Su map-based analysis shows that the line is only seen in the Galactic Center region, to a good approximation.
- Not seen along the Galactic plane (which has much higher statistics, in aggregate, than the center).
- Eliminates most obvious systematics - can't be a simple problem with the energy reconstruction algorithm.
- *Fermi* rocks in its orbit, no strong correlation between angle of incidence and origin on sky.
- More generally, Whiteson looked at a wide range of detector variables, checked consistency between background and peak distributions: no significant discrepancies.
- Nonetheless, there are several apparent systematics at 130-135 GeV: they do not seem to explain the signal but do reduce its significance.



Finkbeiner & Su 2012

Whiteson 1208.3677

TABLE I: Summary of consistency between background and peak distributions for each of the considered instrumental variables, expressed as the χ^2 per degree of freedom.

Variable	Single-line χ^2/dof	Double-line χ^2/dof
$\cos(\theta)$	8.9/5	10.7/5
Detector Azmith	4.4/7	7.9/7
Zenith Angle	4.3/7	10.2/7
Earth Azimuth	1.1/4	2.5/4
Mission Time	1.6/7	2.7/7
Conversion Type	0.0/1	0.0/1
Prob correct energy	6.8/7	12.1/7
Prob correct dir	2.7/7	6.0/7
Reco/Raw energy	11.9/6	11.4/6
First tracker hit	2.4/7	3.6/7
McIlwain *B*	11.9/7	11.9/7
McIlwain *L*	2.5/7	3.8/7
Distance from SA Anomaly	1.4/6	1.9/6
Geomagnetic Latitude	2.6/7	6.5/7

Systematics (II)

Talks by A. Albert, E. Charles, E. Bloom at Fermi Symposium Nov 2012:

- Reprocessing of data (correcting energy scale) + performing more careful modeling of energy resolution => significance of result lowered to 3.35σ local, from 4.01σ local (in a 4° by 4° region around the GC). Shifted preferred energy to 135 GeV.
- Dip in efficiency in flight data vs MC, just above 135 GeV, in cut efficiency.
- Bump at ~135 GeV in proton MC after initial cuts.

Apparent signals where none are expected:

- ~3σ line at 135 GeV in photons from the Earth's atmosphere at certain incidence angles (Finkbeiner, Su & Weniger 1209.4562; Hektor, Raidal & Tempel 1209.4548.)
- Apparent line at 135 GeV in photons ~5 degrees from the Sun (Whiteson 2013).

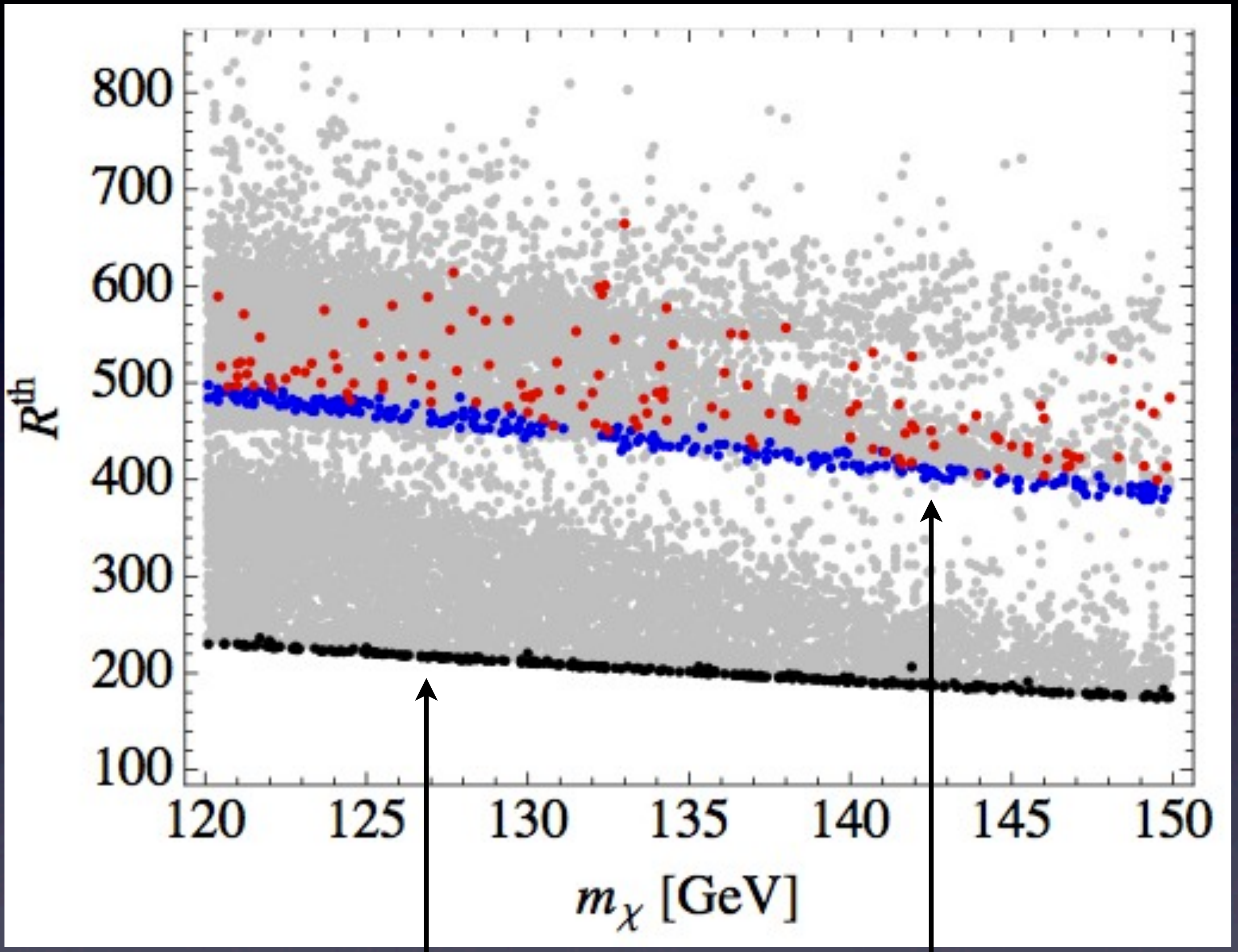
"The LAT Collaboration does not have a consistent interpretation of the GC 135 GeV feature originating from a systematic error at this time." Fermi Symposium, Nov 2012.

Dark matter?

- Annihilation signal is much larger than nominally expected. Depends on $\langle \sigma v \rangle_{\gamma\gamma} n_{\mathrm{DM}}^2$
- Case 1: line cross section >> than expected.
  - Search dwarf galaxies, clusters, extragalactic diffuse emission, etc, even where previously line searches seemed unlikely to yield meaningful results.
  - Tentative claims of detection of line signal in clusters (Hektor, Raidal & Tempel 1207.4466) and non-associated sources (Su & Finkbeiner 1207.7060).
- Case 2: DM density at GC >> than expected. Study the GC in multiwavelength.
  - Lower-energy continuum gamma rays produced in annihilation (Cohen, Lisanti, TRS & Wacker 1207.0800; Buchmuller & Garny 1206.7056), at tree level rather than loop level.
  - Radio from e^+e^- produced in annihilation (Laha et al 1208.5488)
  - No signals detected; places strong limits on e.g. MSSM dark matter.

MSSM neutralino DM?

- R^{th} = ratio of continuum cross section to line signal.
- Robust lower bound for admixed wino/higgsino DM with non-negligible annihilation cross section to γγ or γZ.
- Upper bounds of ~100 from supersaturation (not overproducing total GC photons) and ~10 from fit assuming power-law background.
- Test effect of relaxing assumptions on sfermion and Higgs masses: changes lower bound on R^{th} at sub-percent level, for wino/higgsino-like DM.
- Light sfermions allow annihilating bino DM, but cross sections are very small.
- Similar approach and conclusion in Buchmuller & Garny, 1206.7056.



Wino

Higgsino (blue: tanβ>5, red = tanβ<5)

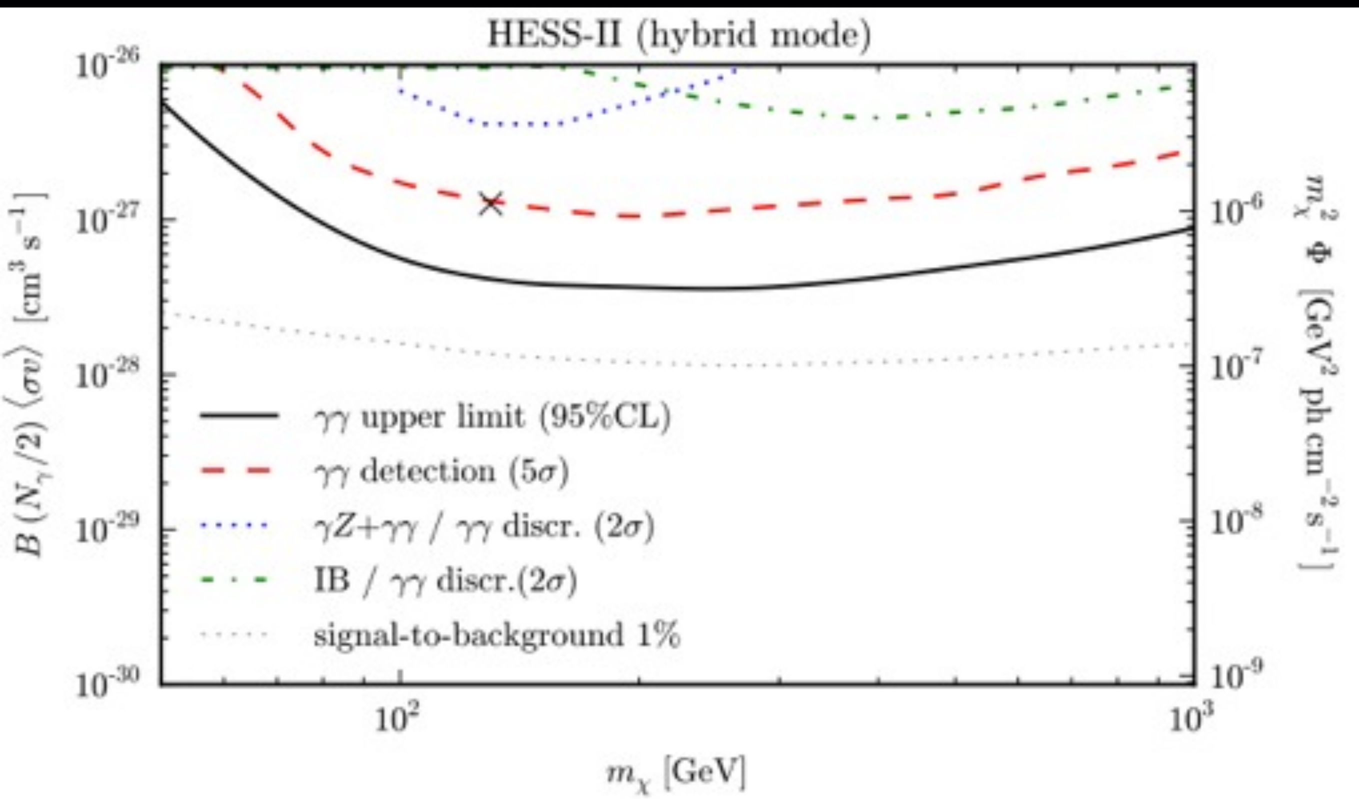
A bright line without continuum

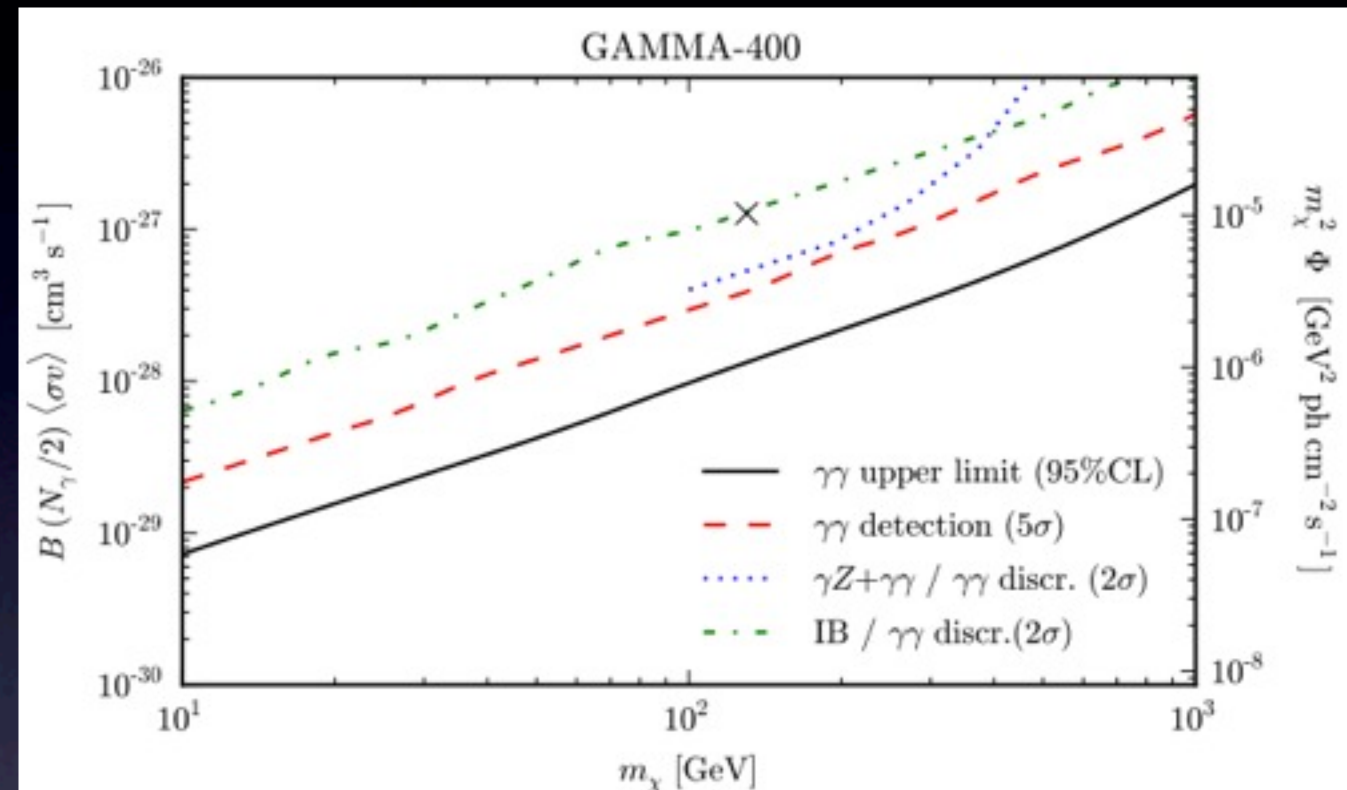
General ingredients include new light charged particles, resonances, large couplings, mass degeneracy in spectrum.

- Annihilation through loops of relatively light new charged particles (but heavier than the DM) + resonant annihilation (requiring mass degeneracy) and/or large couplings (e.g. Cline 1205.2688; Buckley & Hooper 1205.6811; Bai & Shelton 1208.4100).
- DM interacts with SM electroweak gauge bosons through high-dimension magnetic dipole or Rayleigh operators, with moderately strong coupling; continuum produced at same order as line (e.g. Weiner & Yavin 1209.1093; Cline, Frey & Moore 1208.2685).
- If tree level is velocity-suppressed, loop-level annihilation can dominate in the Galactic Center (e.g. Choi & Seto 1205.3276; Lee, Park & Park 1205.4675).
- Not a line: sharp feature from internal bremsstrahlung, or narrow box-like spectrum from annihilation into states that later decay - usually requires a mass degeneracy (e.g. Dudas et al 1205.1520; Buckley & Hooper1205.6811; Bai & Shelton 1208.4100; Fan & Reece 1209.1097; Shakya 1209.2427).

Apologies if I've failed to cite your idea/paper!

Upcoming tests





HESS-II:

- 50 hours of observation enough to rule out signature or confirm at 5σ (if systematics are under control)
- GC close to zenith from March 2013 onward, 230 hours per season possible in principle
- Results end of 2014?

GAMMA-400: Bergstrom et al 1207.6773

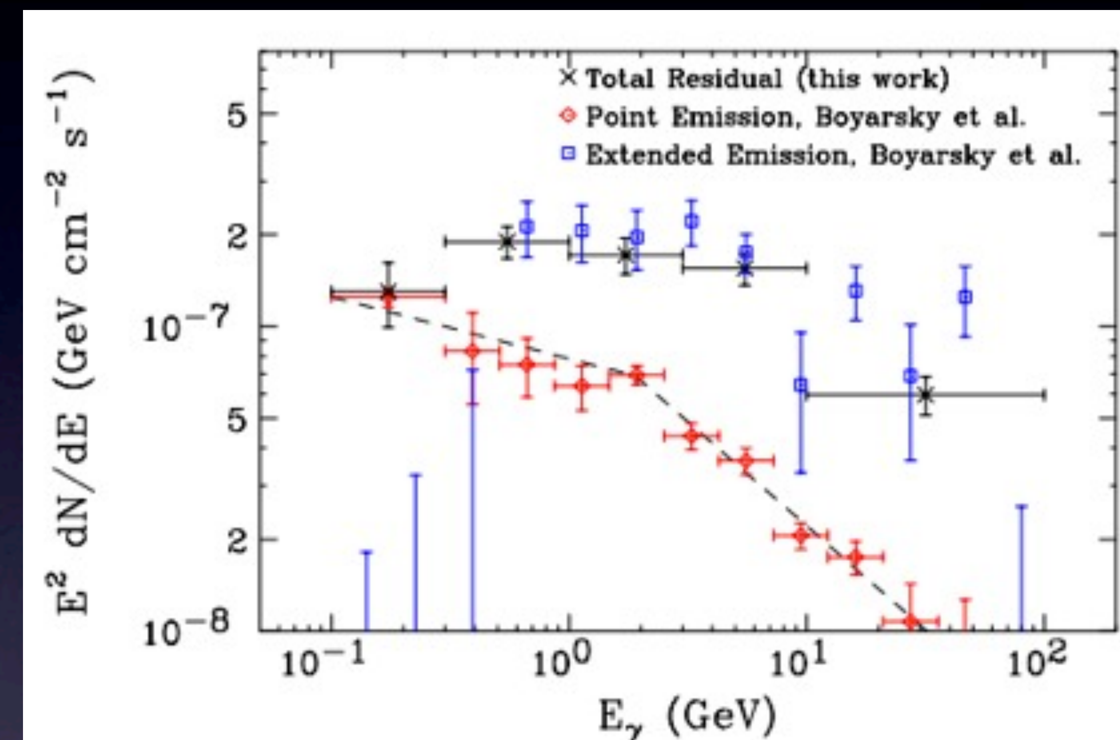
- 5 years of survey mode (5σ detection would require ~10 months)
- Allows discrimination of line vs box spectrum, detection of γZ down to 20% branching ratio.
- Launch in 2018?

(taken from C. Weniger's talk, Light Dark Matter Workshop, April 2013)

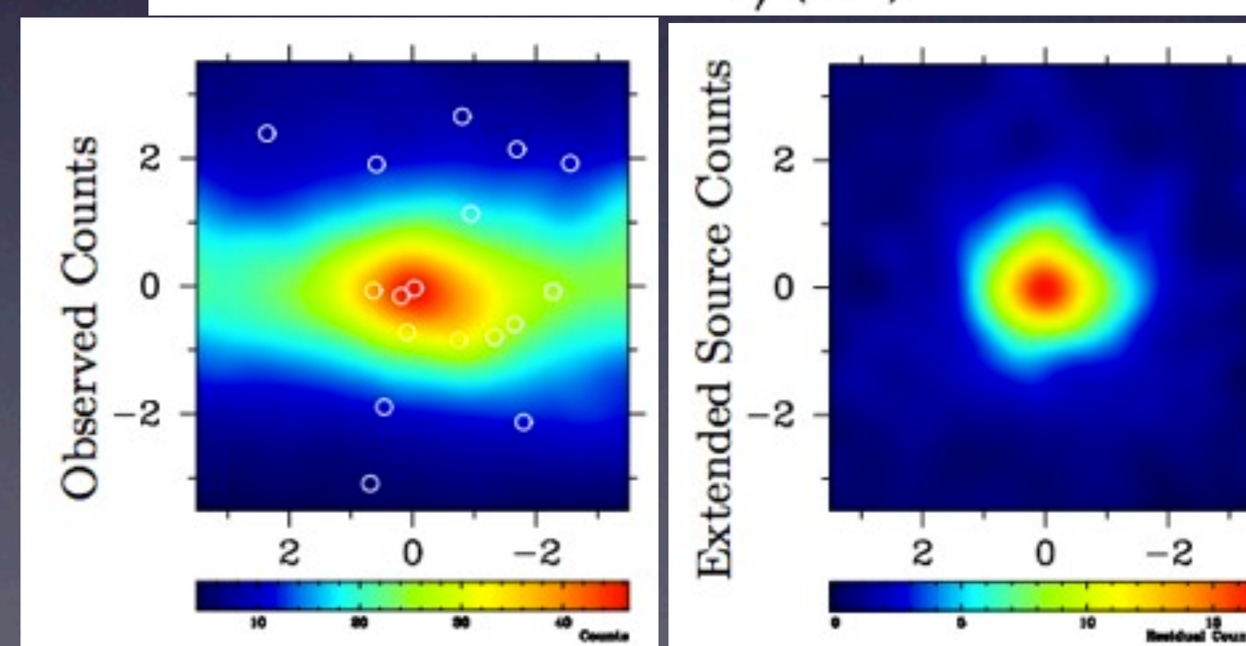
THE GEV EXCESS

The Galactic Center GeV excess

Hooper & Linden 2011



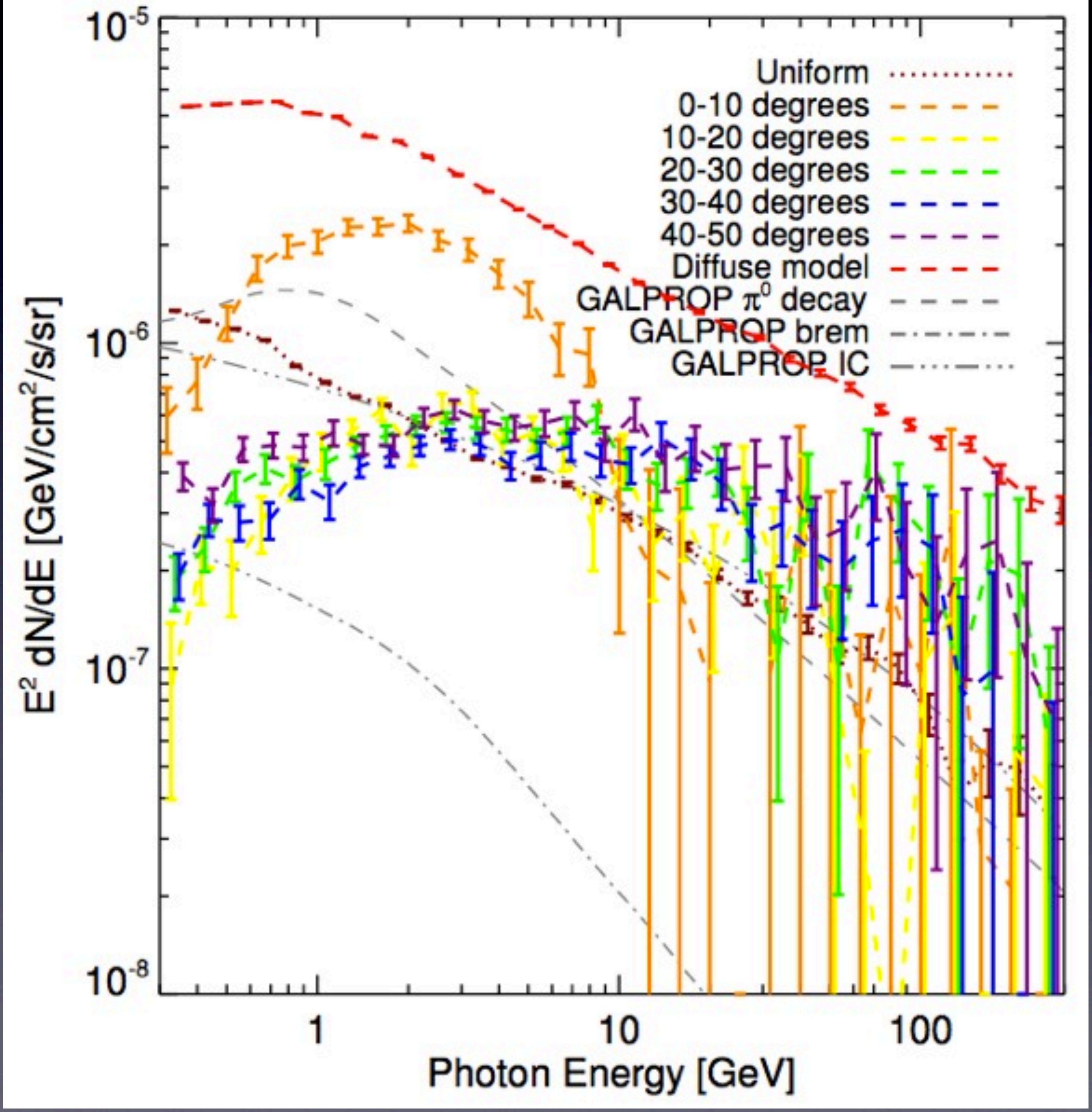
- Claims of a spectral feature in Fermi public data:
  - Peaking at a few GeV,
  - Localized around the Galactic Center.
- First identified by Goodenough and Hooper in 2009-10: not then clearly separable from emission associated with the bright point source at the GC.
- Subsequent studies (Hooper & Linden; Boyarsky, Malyshev & Ruchayskiy; Abazajian & Kaplinghat) found strong evidence for extended (non-point-like) emission, with spherical morphology.
- Abazajian & Kaplinghat find a best-fit volume emissivity profile of $r^{-2.4}$ (assuming spherical symmetry). For a dark matter scenario, this corresponds to an inner slope of γ=1.2. (γ was varied from 0.9 to 1.4 in increments of 0.1.)
- Fits are consistent with 10 GeV - 1 TeV DM annihilating to b quarks, and also 10-30 GeV DM annihilating to tau leptons.



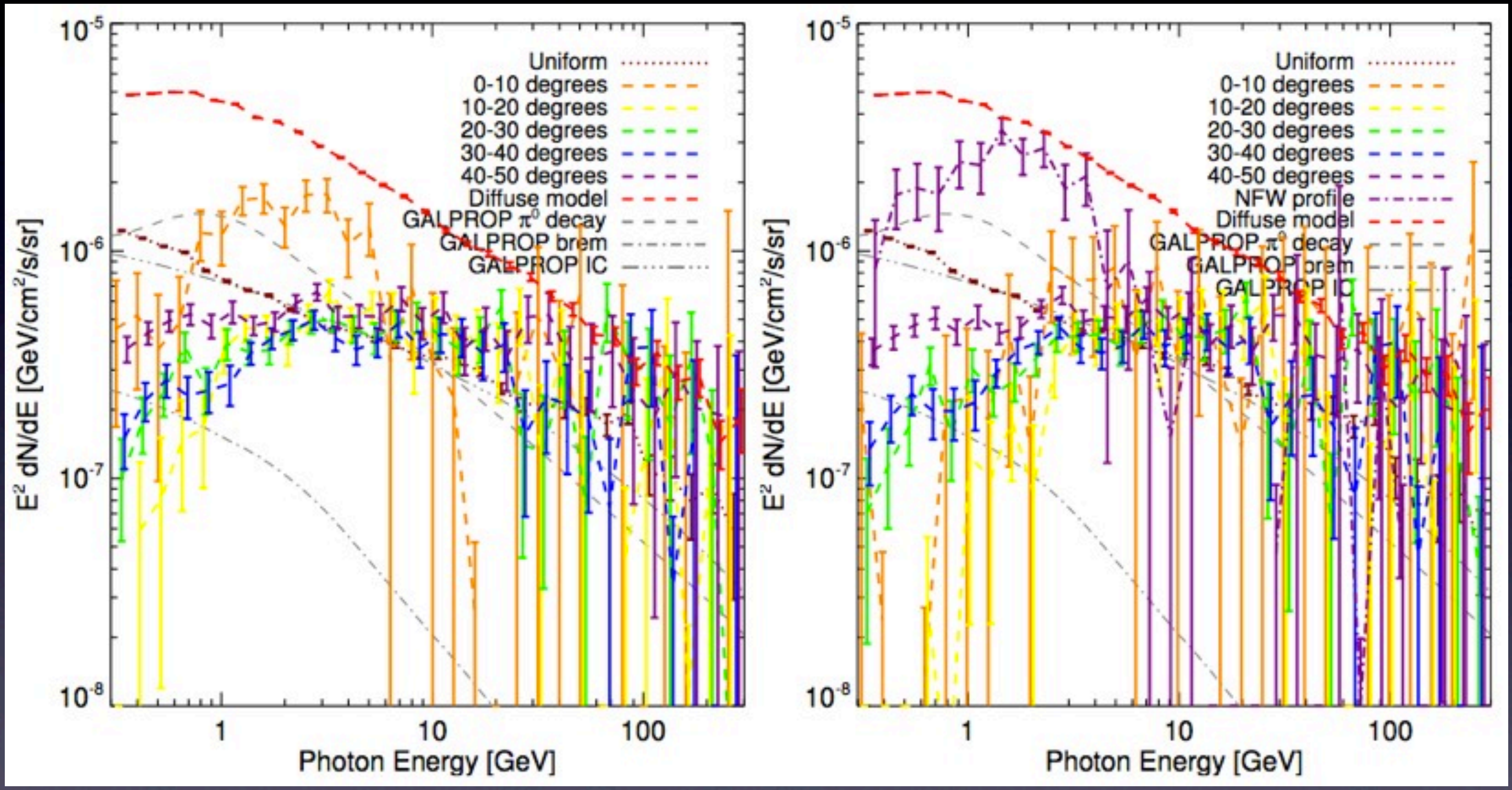
Abazajian & Kaplinghat 2012

An inner Galaxy counterpart

- Study aiming to measure latitude variation in the Fermi Bubbles (multi-kpc gamma-ray structure centered on the GC) found pronounced few-GeV bump at low latitudes. (Hooper and TRS, 1302.6589)
- Systematics at these larger Galactocentric radii should be very different than in the Galactic Center.
- The result is stable to different foreground models and the degree of masking of the Galactic plane.



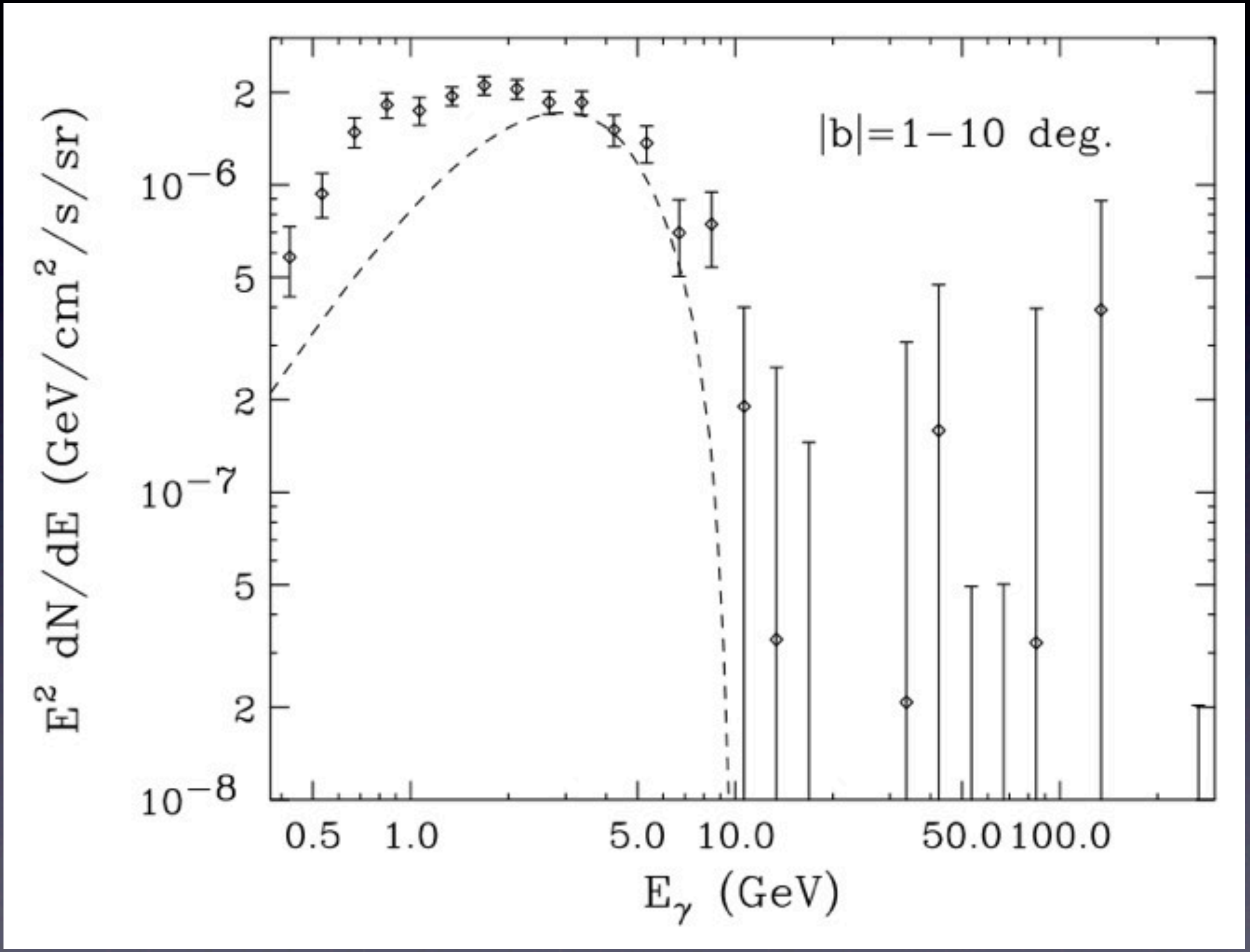
A dark matter template



- Is the signal confined to the region of the Bubbles, or could it be a spherically symmetric signal?
- To avoid structures in the north (e.g. Loop 1), fit in the southern sky only. Mask the area where b > -5° to minimize disk emission.
- Add a template corresponding to a (projected, squared) NFW profile, inner slope of 1.2.
- Left panel: bubble templates only, right panel: NFW profile included.

A consistent signal?

- Assume high-latitude emission is inverse Compton scattering (ICS) - gives a fairly flat spectrum.
- Take the high-latitude electron spectrum, assume the same spectrum at low latitudes, compute photon spectrum from ICS.
- In each band, normalize ICS spectrum to fit high-energy data, subtract it and look at the residual bubble-correlated emission.



Dashed line = 10 GeV DM annihilating to taus, chosen to fit GC excess (no free normalization), extrapolated outward with squared modified NFW profile with inner slope $r^{-1.2}$.

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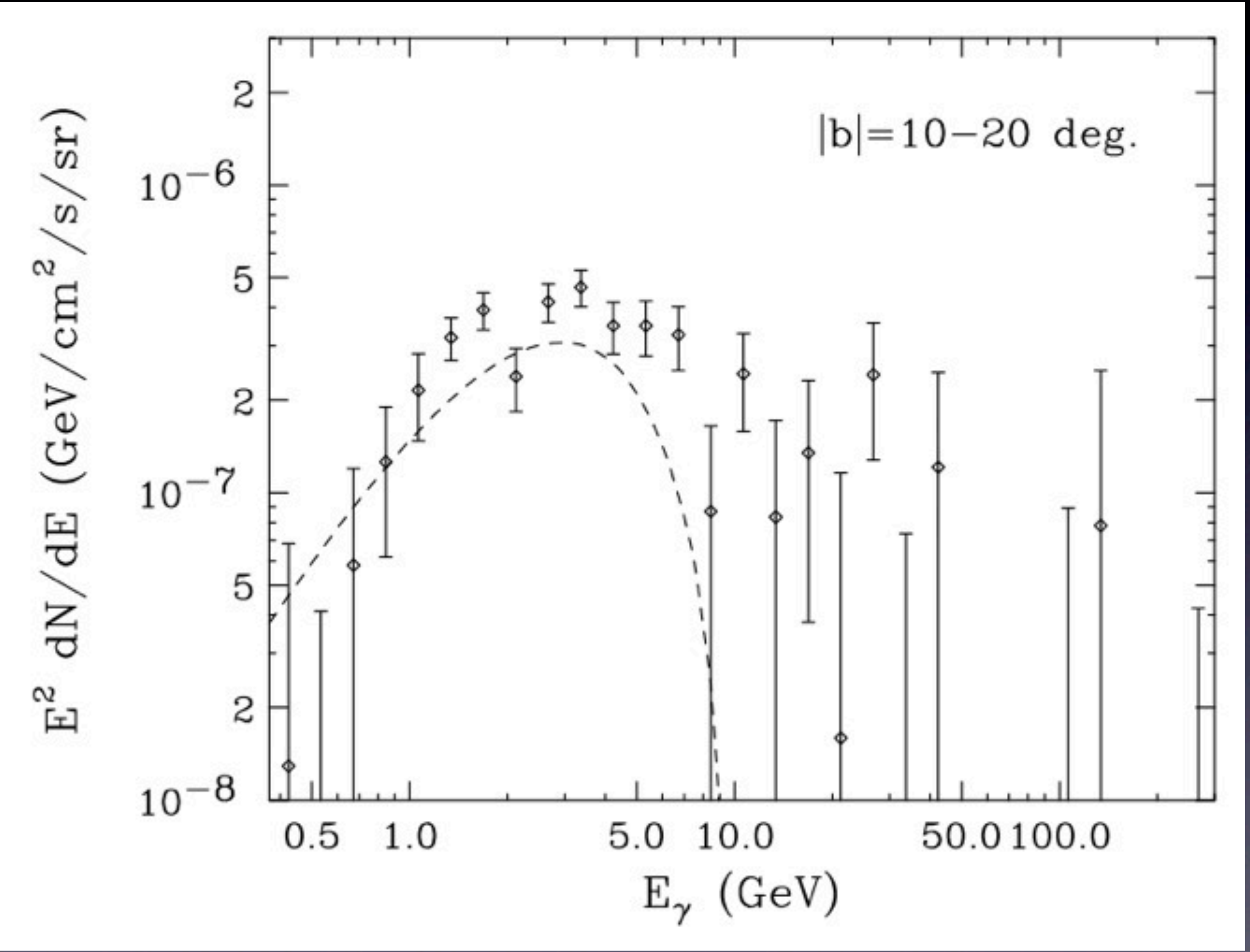

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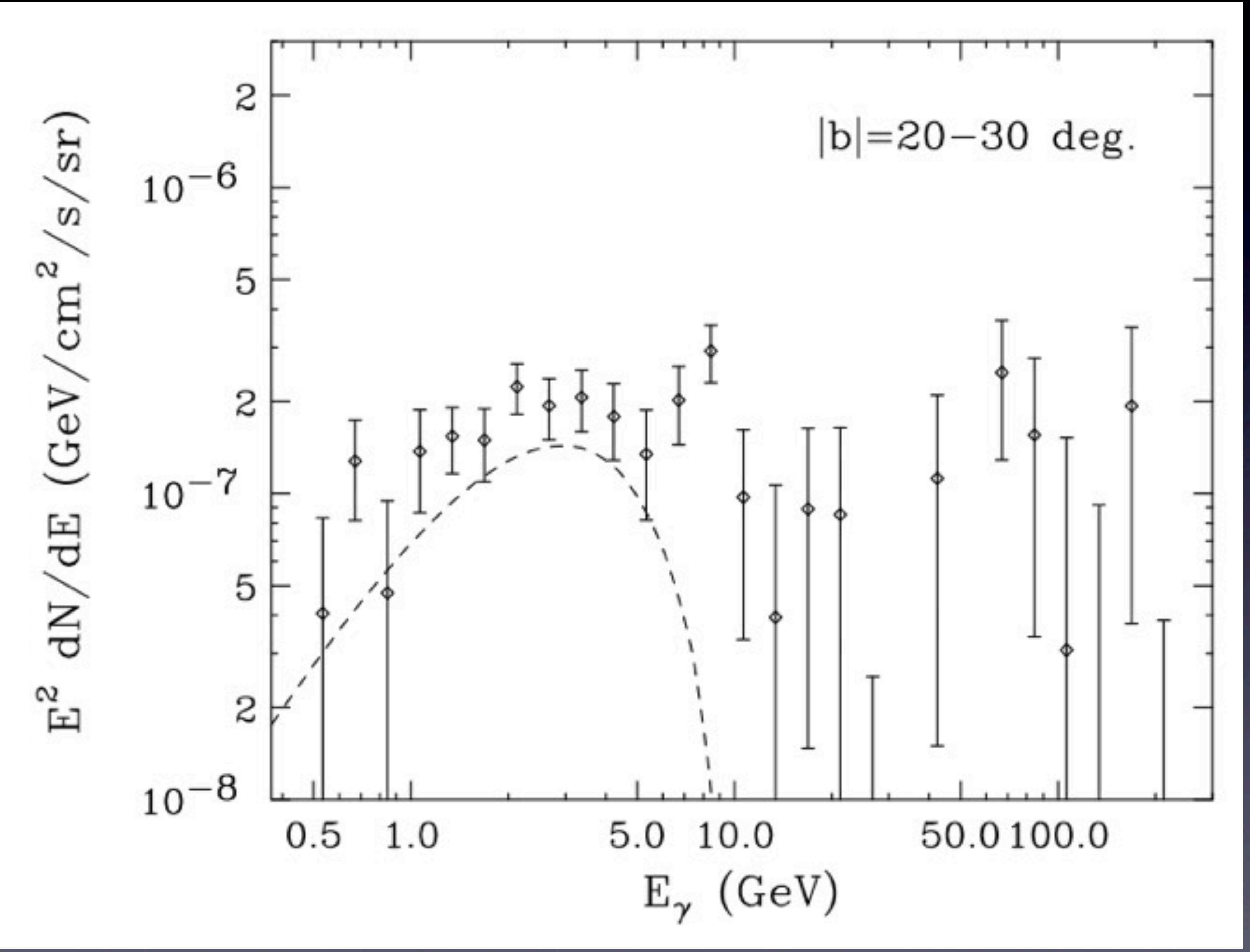

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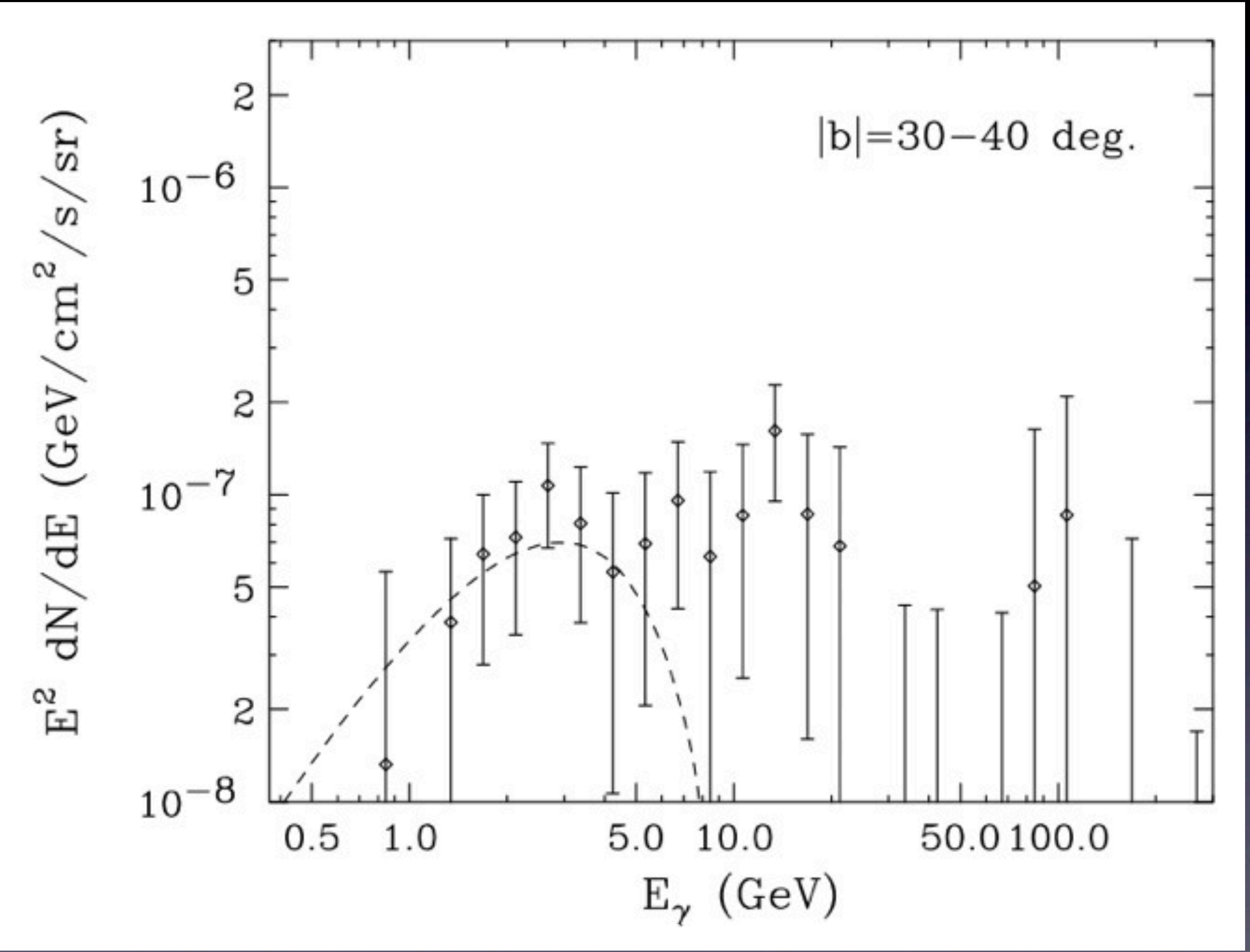

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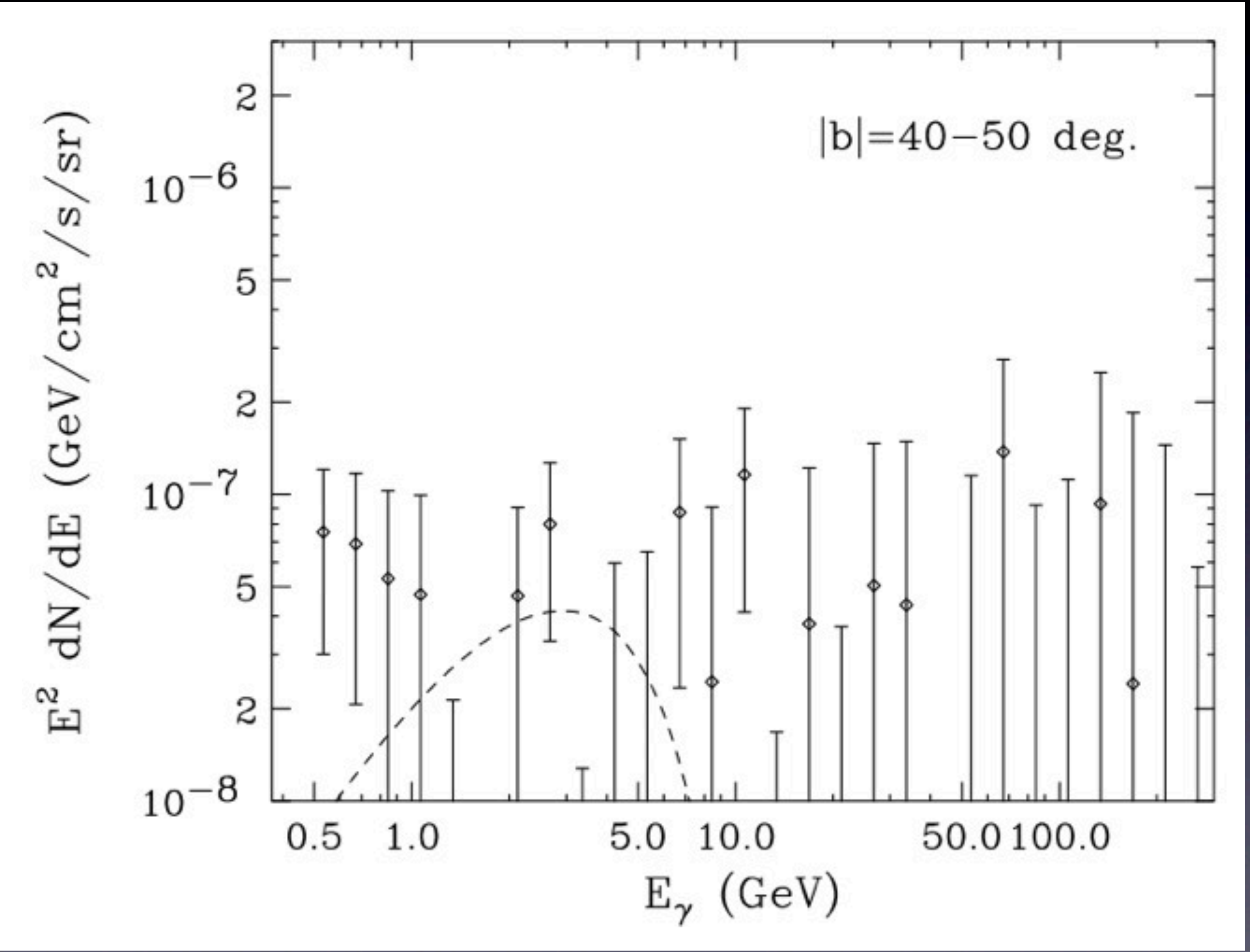

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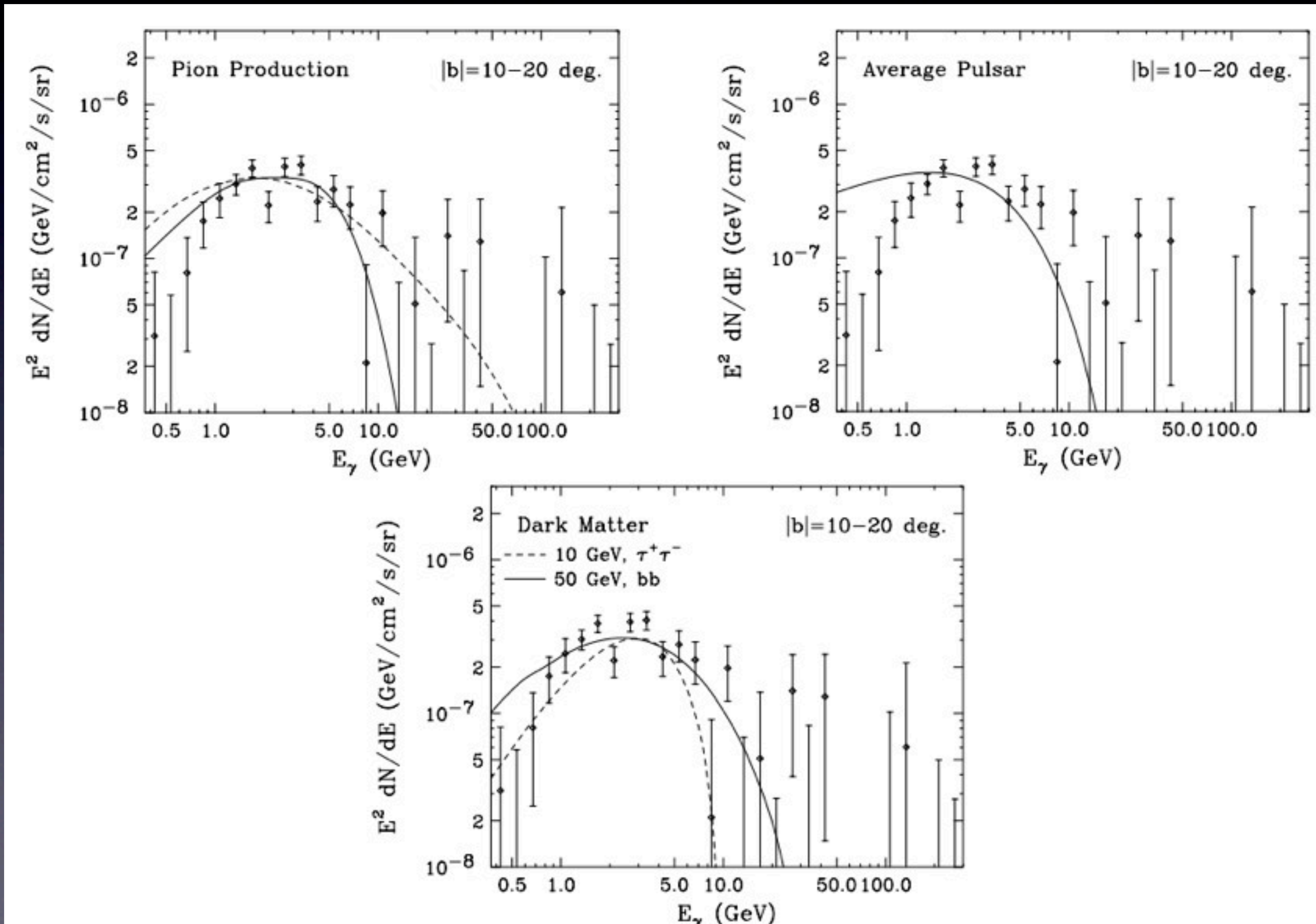
Spectral comparisons



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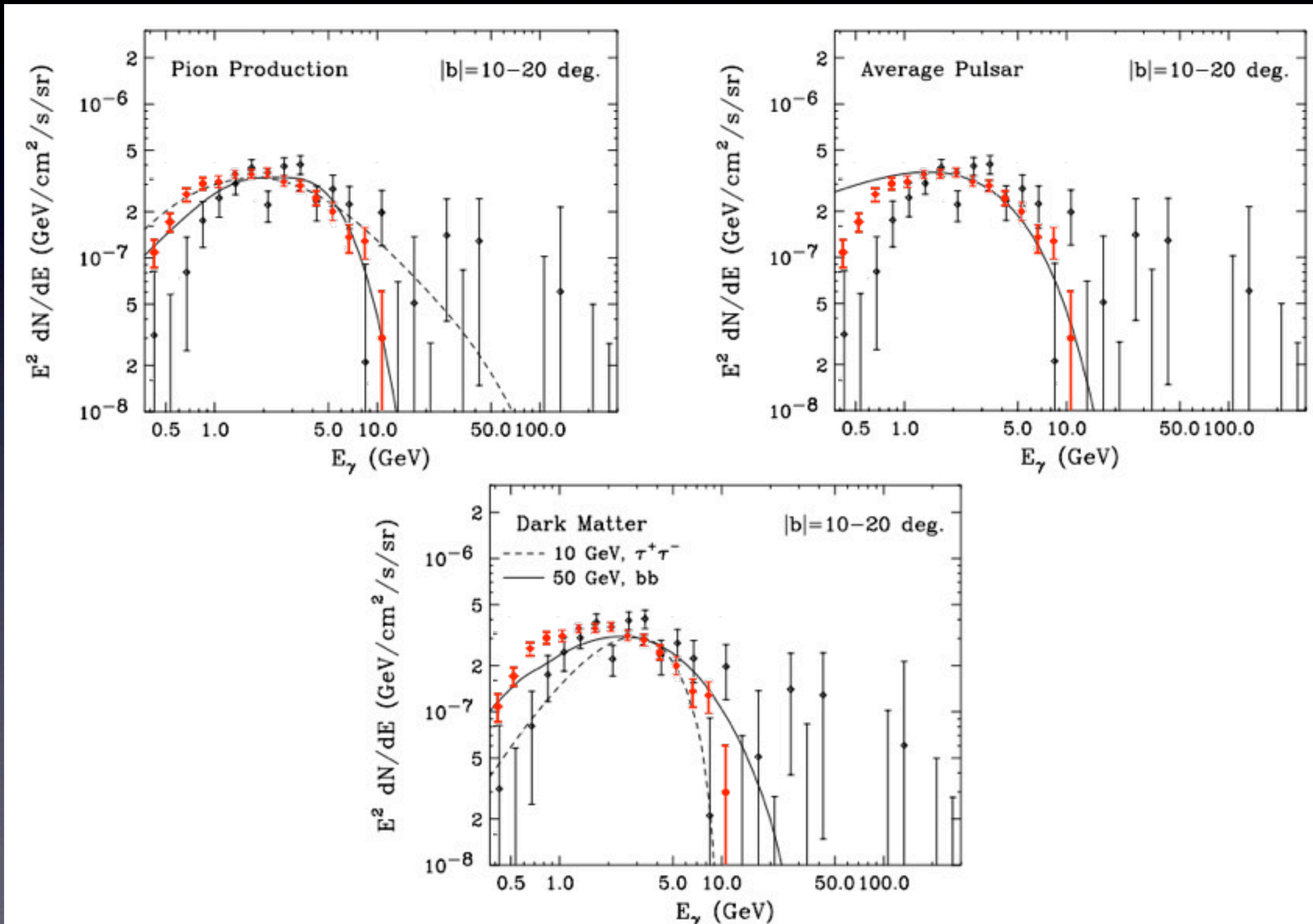


Questions

- Could it be a systematic effect?
  - We extract the spectrum of the whole-sky diffuse emission, and see no particular structure at these energies - likely not an effective area issue.
  - Angular resolution should not matter at these scales.
- Spectral variation not captured in the diffuse model?
  - Cosmic ray spectra responsible for the foreground diffuse emission vary as a function of Galactic location.
  - Could modify the extracted spectrum, although absorbing the bump entirely seems to require a peculiar CR spectrum.
- Millisecond pulsars? (work in progress)
  - Spectrum would need to be skewed by oversubtraction of diffuse-correlated emission below 1 GeV.
  - Would require large population of low-luminosity pulsars, not expected from pulsar population models, and requiring a peculiar shape to the pulsar luminosity function.

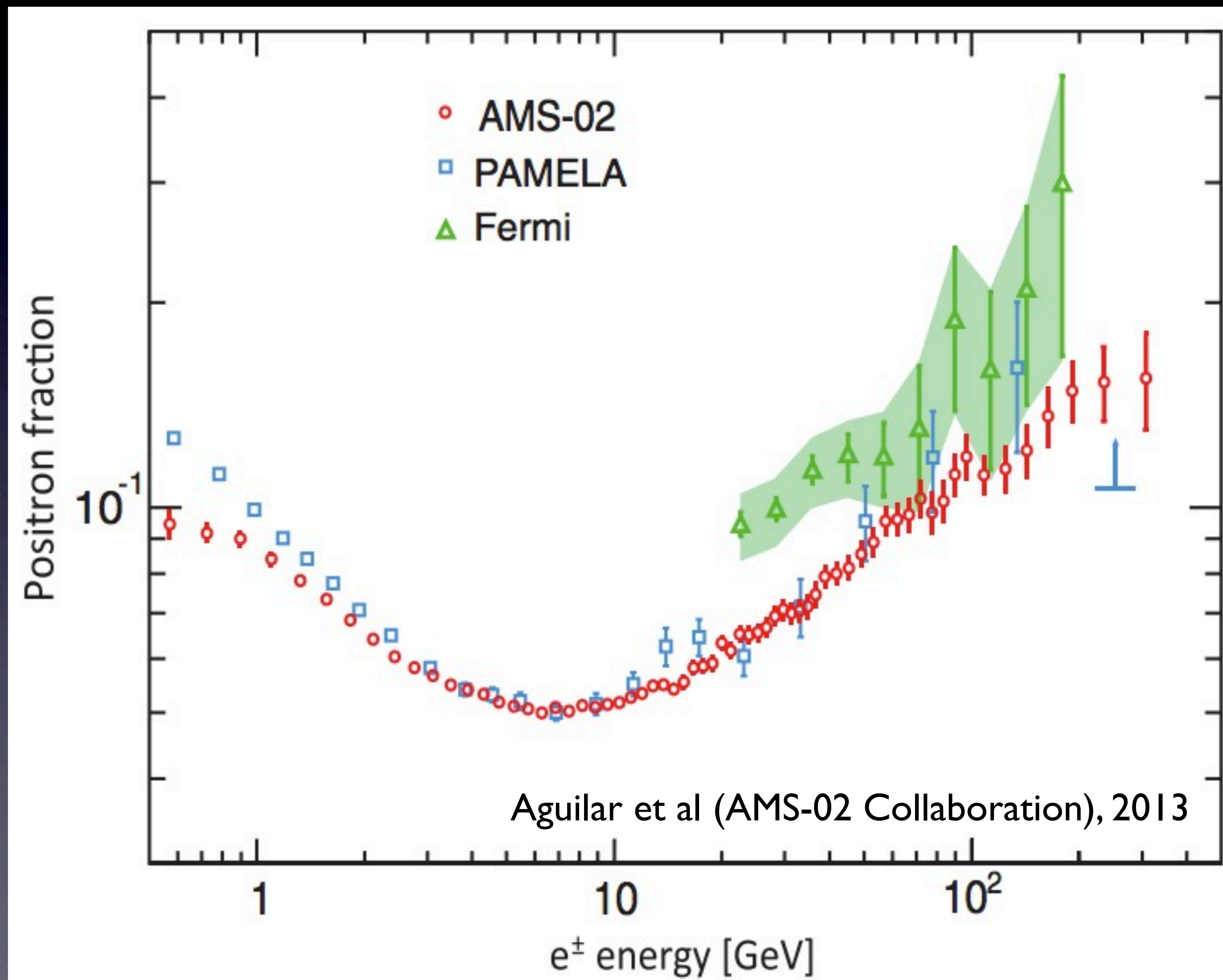
Dark matter?

- The 10 GeV cutoff scale is suggestive of several anomalies / possible signals in direct detection experiments.
- If we interpret the GC signal as originating from ~10 GeV DM, favors leptonic annihilation channels (as opposed to quarks) to get a sufficiently hard spectrum.
- One example consistent scenario uses ~10 GeV DM coupled to an O(GeV) vector (Hooper, Weiner & Xue 1206.2929), to generate large direct-detection cross section, leptonic decay modes, and correct relic density.
- Cross section currently consistent with all other indirect detection constraints; factor of a few below limits from dwarf galaxies, cosmic microwave background.

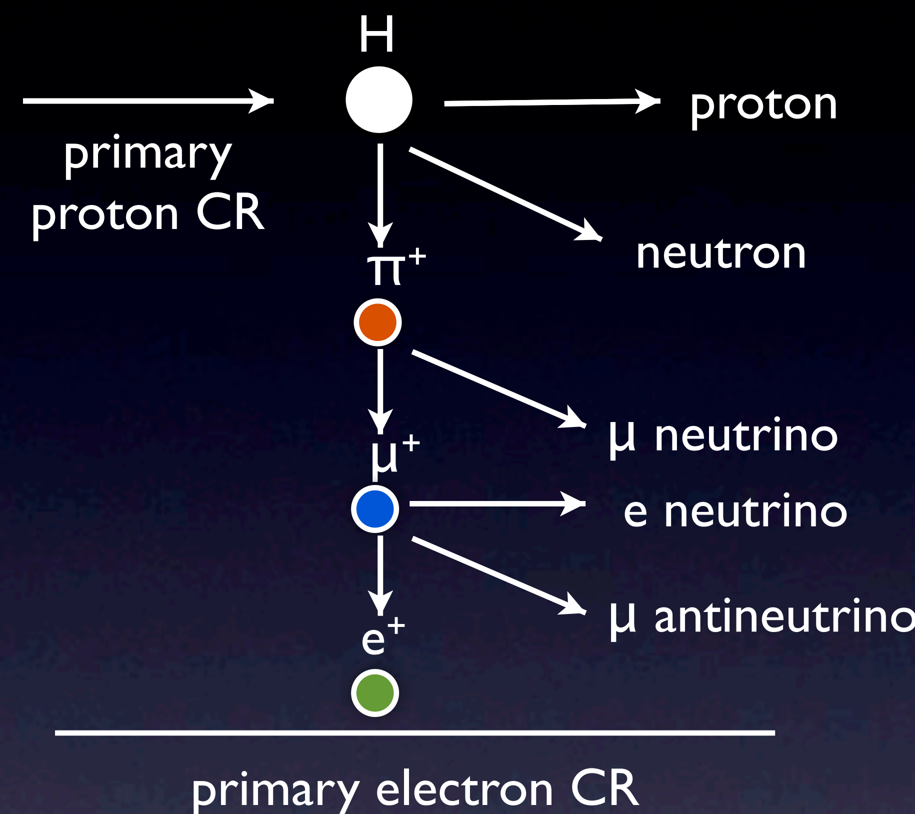
POSITRON FRACTION MEASUREMENTS

PAMELA, Fermi, AMS-02

- Measurement of the $e^+/(e^+ + e^-)$ ratio ("positron fraction") as a function of energy.
- Data below 10 GeV affected by "solar modulation" effect; above 10 GeV, sharp rise is observed.



Cosmic ray positrons



Secondary particles = spectrally softer than primaries. Ratio of antimatter/ matter from supernova shocks should fall at high energies.

But dark matter is charge-neutral - in most models, DM annihilation produces particles, antiparticles equally.

Rise in the antimatter fraction at weak-scale energies = potential WIMP annihilation signal.

PAMELA experiment designed to measure this and other CR spectra, succeeded by AMS-02.

Fermi Gamma-Ray Space Telescope: designed to observe gamma rays, but can measure the total electron + positron spectrum; positron fraction analysis uses the Earth's magnetic field to perform charge discrimination.

DM and the positron excess

- Three problems arise with conventional DM interpretation:
  - Signal is too large by a factor of ~100 relative to expected thermal relic cross section.
  - Signal is too hard, rising too quickly with energy - typical e^+ spectra from DM annihilation are produced by a lengthy cascade, and are softer than observed.
  - No corresponding excess is observed in antiprotons; would generally expect both p^+ and e^+ to be produced by WIMP annihilation.
- All three can be evaded by the addition of a new GeV-scale force carrier coupled to dark matter (Arkani-Hamed, Finkbeiner, TRS & Weiner 2008; Pospelov & Ritz 2008).
- There are other possibilities; e.g. nonthermally produced or decaying dark matter can evade the first issue, leptophilic DM the other two (to some degree - electroweak final state radiation still gives hadronic contributions).

A new dark force

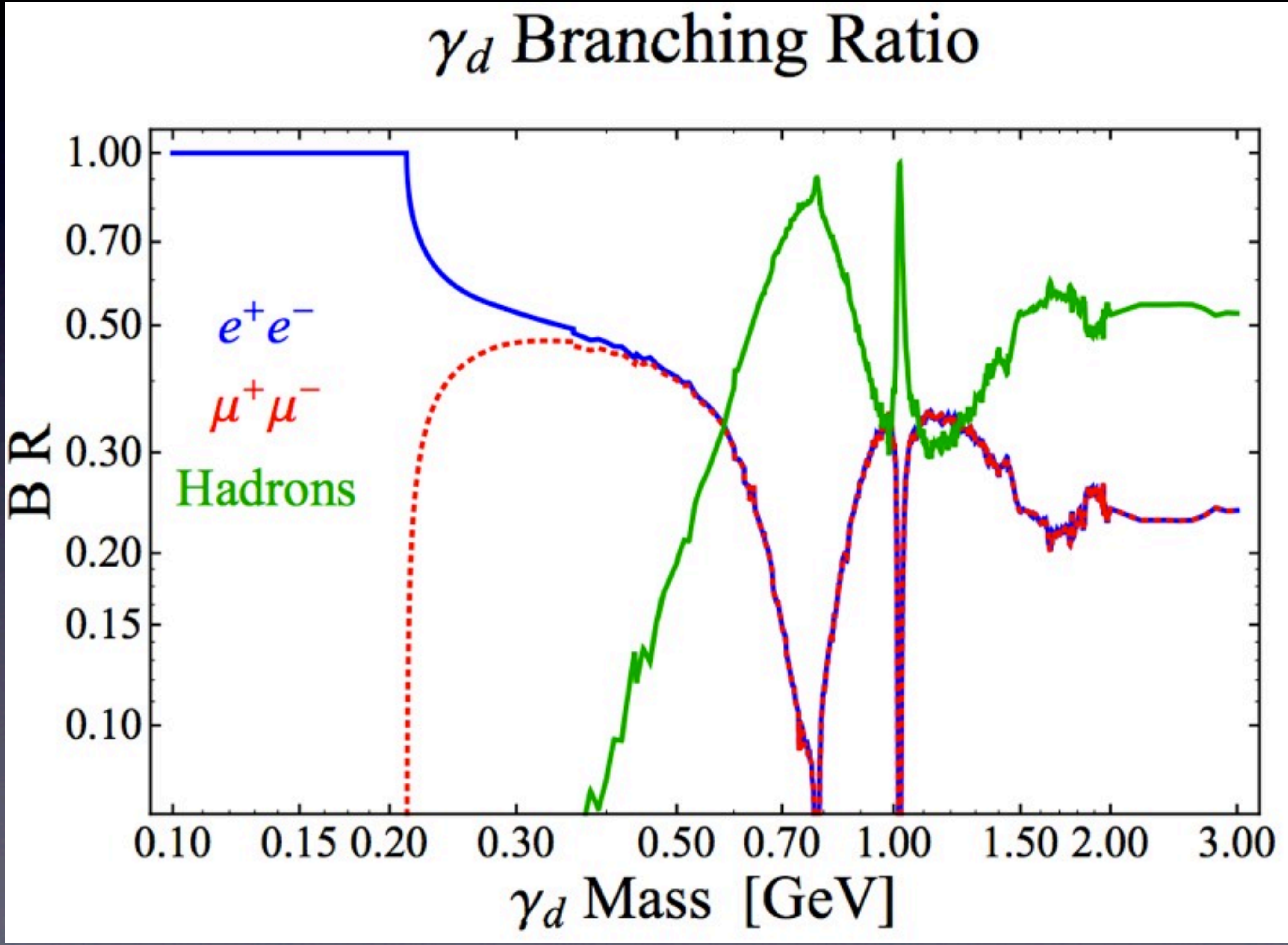
- Suppose we couple the DM to a new vector A' which mixes with the photon.
- Dominant annihilation channel is now:

  $\chi\chi \to A'A'$ followed by $A' \to e^+e^-, \mu^+\mu^- \pi^+\pi^-, \ldots$
- The decay channels of the A' depend on its mass.
- The annihilation rate does not depend on the mixing with the SM, only the χ-A' coupling.
- If the A' is around 100 MeV - 1 GeV in mass then:
  - The relatively short decay chain yields a hard spectrum.
  - The A' cannot decay to proton-antiproton pairs due to its low mass.
  - The long-range (~fm) interaction enhances the annihilation rate at non-relativistic velocities.

Decays of a dark photon

Falkowski et al 1002.2952

In simplest case, decays are leptonically dominated below ~500 MeV; mixture of leptons and charged pions up to 1 GeV; then additional contributions from ρ, kaons, taus.



Implications of AMS-02

- First reaction: exactly as expected! PAMELA is confirmed! But...
- Hint of flattening at high energy favors softer spectra (multi-particle final states, charged pions, taus) => heavier force carrier masses, or more complex dark sector.
- Possible tension with Fermi e^+e^- measurement if astrophysical background for electrons is a single power law and the new component is half e^+/half e^-.
- Possible asymmetry goes in the direction of $n(e^-) > n(e^+)$, up to a factor of 2 (Masina & Sannino 1304.2800).
- However, above statements depend on assumptions about the e^- background (and hence on cosmic-ray propagation).
- No hint of anisotropy, but not expected given sensitivity of constraints (cannot currently rule out even a single nearby pulsar as the source).

Post-AMS analysis

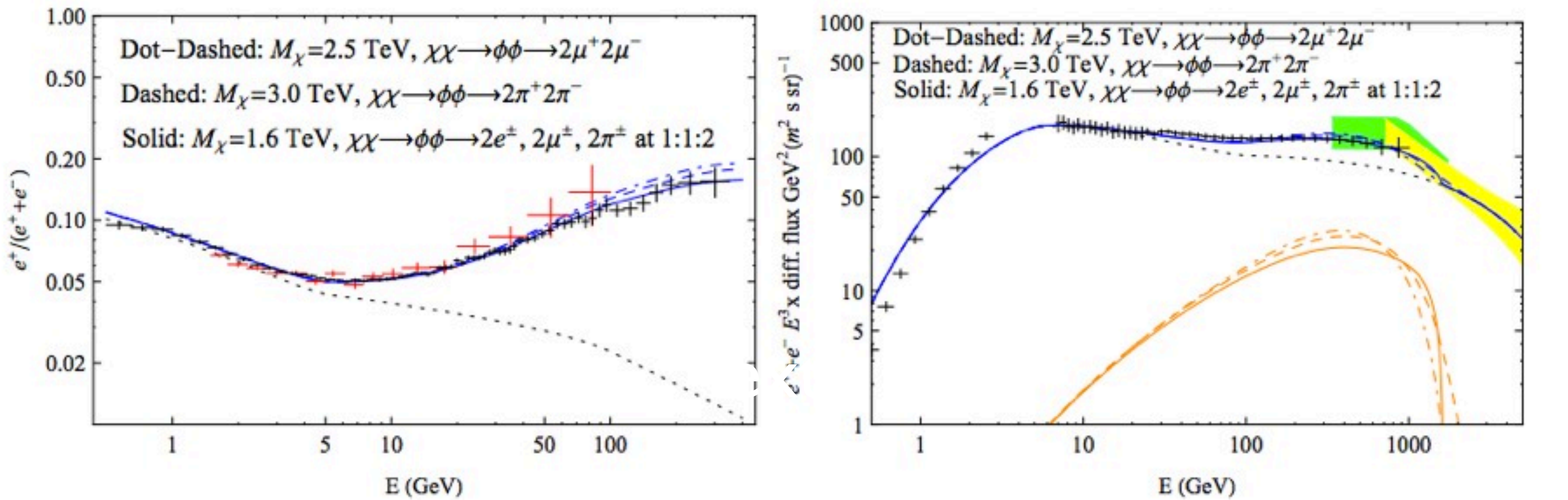


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections are the same as given in the caption of Fig. 5. With this cosmic ray background, the dark matter models shown can simultaneously accommodate the measurements of the cosmic ray positron fraction and the overall leptonic spectrum.

Cholis & Hooper 1304.1840

- Direct annihilation to e^+e^-, $\mu^+\mu^-$ can no longer accommodate the data (Yuan et al 1304.1482, Cholis & Hooper 1304.1840).
- Direct annihilation to $\tau^+\tau^-$ (1304.1482) or to an intermediate state decaying to muons and charged pions (1304.1840) can provide a good fit.
- The first possibility appears in conflict with gamma-ray limits from dwarf galaxies (1304.1482).

Gamma-ray constraints

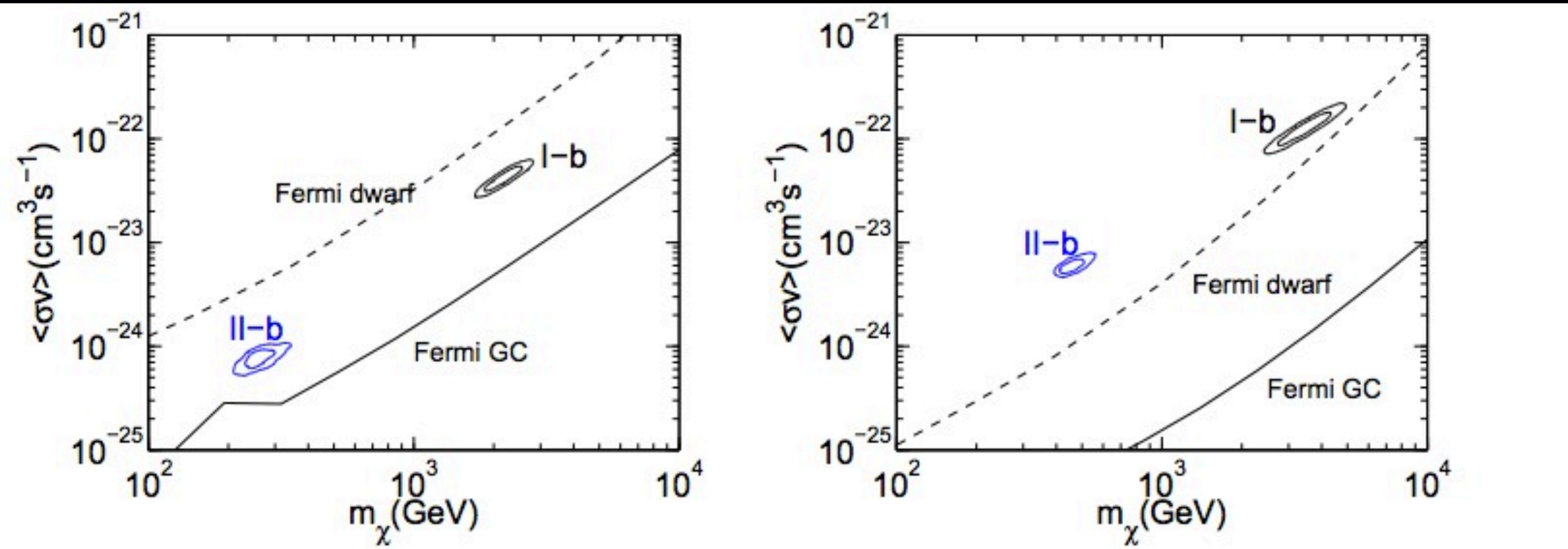


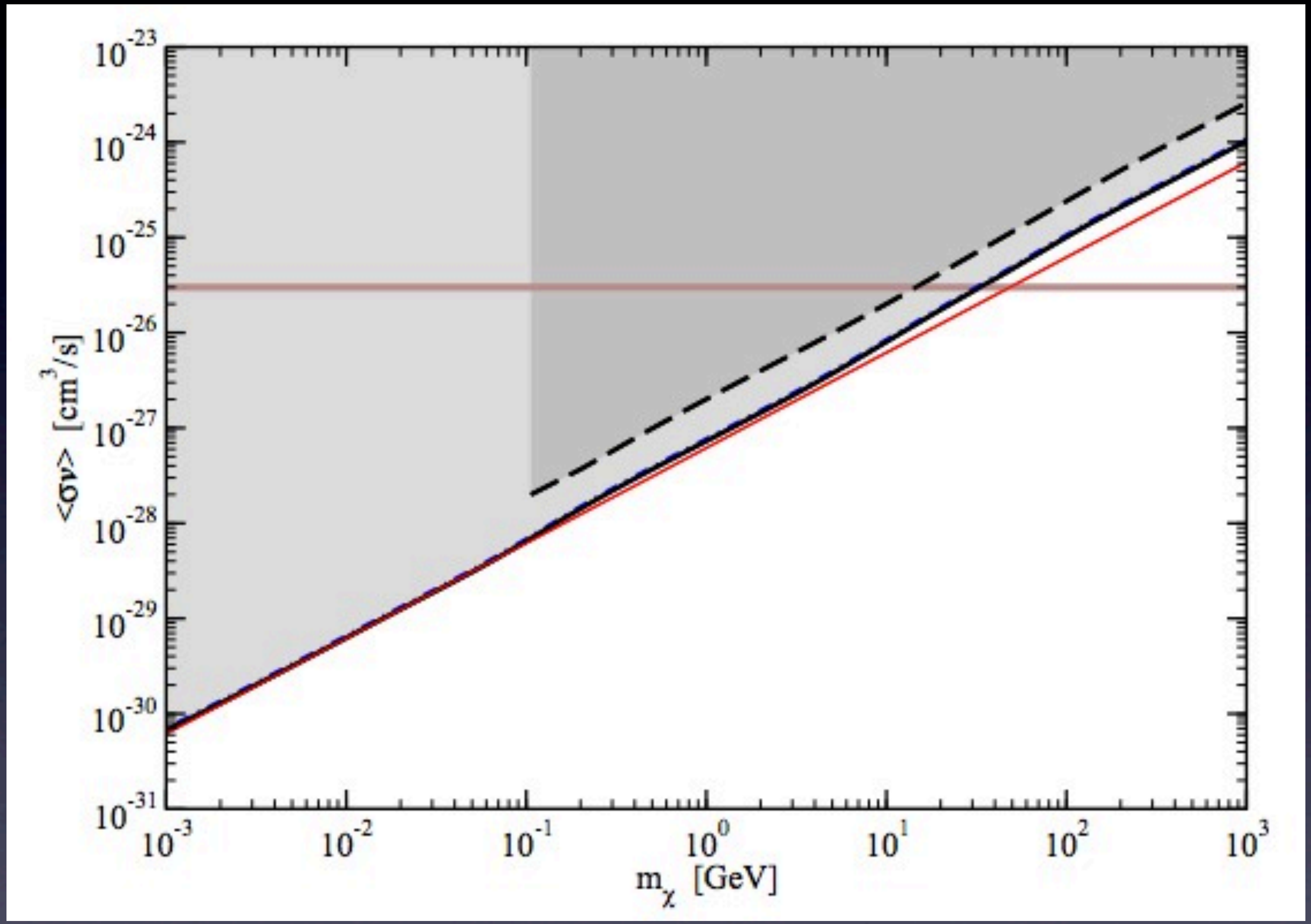
FIG. 10: 1σ and 2σ confidence regions on the DM mass and cross section plane, for the fits I-b and II-b respectively. The left panel is for $\mu^+\mu^-$ channel, and the right panel is for $\tau^+\tau^-$ channel. The solid lines show the 95% upper limit of Fermi γ-ray observations of the Galactic center (with normalization of the local density corrected) [59] and dwarf galaxies [60].

Yuan et al 1304.1482

- Stringent constraints on these scenarios from Fermi studies of dwarf galaxies in gamma rays (uncertainly due to DM density profile is only ~20%). Not very sensitive to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, as these do not decay producing gammas.
- Galactic Center constraints are nominally stronger but far more dependent on the DM profile (here NFW is assumed).
- This assumes annihilation - decaying DM would evade these bounds.

CMB constraints

- DM annihilation producing e^+e^- will modify the ionization history of the universe during the cosmic dark ages (z~10-1000).
- This changes the power spectrum of CMB anisotropies: sensitively probed by WMAP, ACT, SPT and now Planck.
- Independent of DM structure formation, relies only on power in e^+e^- and cosmological average DM density - very clean probe of claimed annihilation xsec.
- Tension at the factor-of-2 level with AMS best-fit cross-section - seem to require O(1-2) local "boost factor" from higher local DM density or substructure.
- Planck limits (with polarization) should be about a factor of 3 stronger than these.



Lopez-Honorez et al 1303.5094

- Electron channel:

$$\langle \sigma v \rangle \lesssim 30 \left(\frac{1\mathrm{TeV}}{m_\chi} \right) \times 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

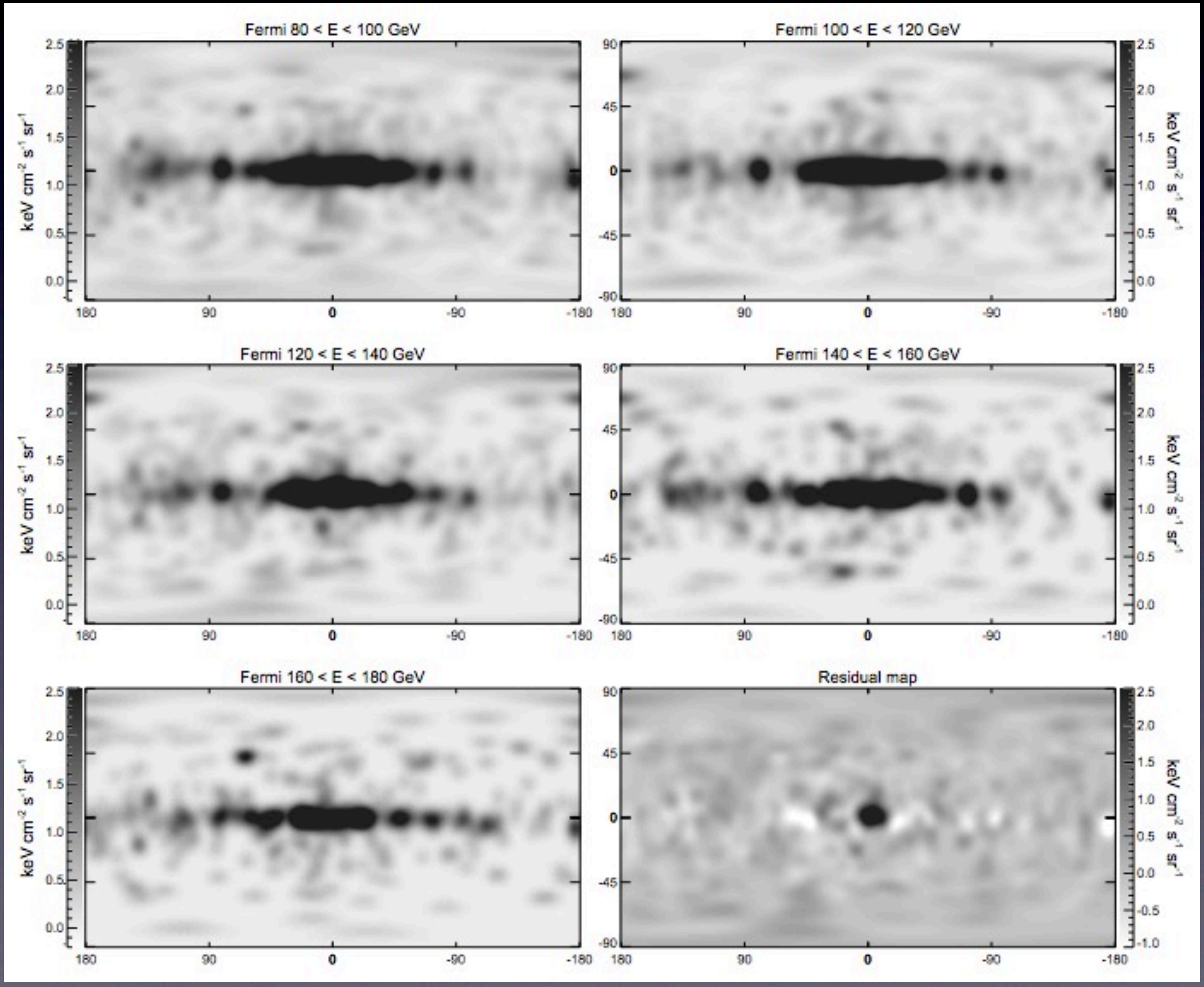
Conclusions

- Indirect detection is currently a data-rich field: new results from Fermi, AMS-02, Planck.
- Several signals that might be hints of DM annihilation/decay. I focused here on:
  - The possible spectral line in 135 GeV photons (Galactic Center)
  - The spectral feature in few-GeV photons (inner Galaxy)
  - The rising positron fraction recently confirmed by AMS-02
- Critical to understand astrophysical backgrounds, detector systematics - and possible tests in multiwavelength observations, direct detection, colliders, precision constraints.
- If interpreted as DM signals, they have surprising features which motivate models that go beyond the simplest WIMP paradigm.

BONUS SLIDES

Sideband analysis

- Finkbeiner and Su 1206.1616: map-based analysis, find excess localized in GC, best-fit centered at l=-1.5 (see also Tempel, Raidal and Hektor 1205.1045).
- Significance accordingly higher than Weniger result, Finkbeiner and Su find 3.7σ after trials factor.



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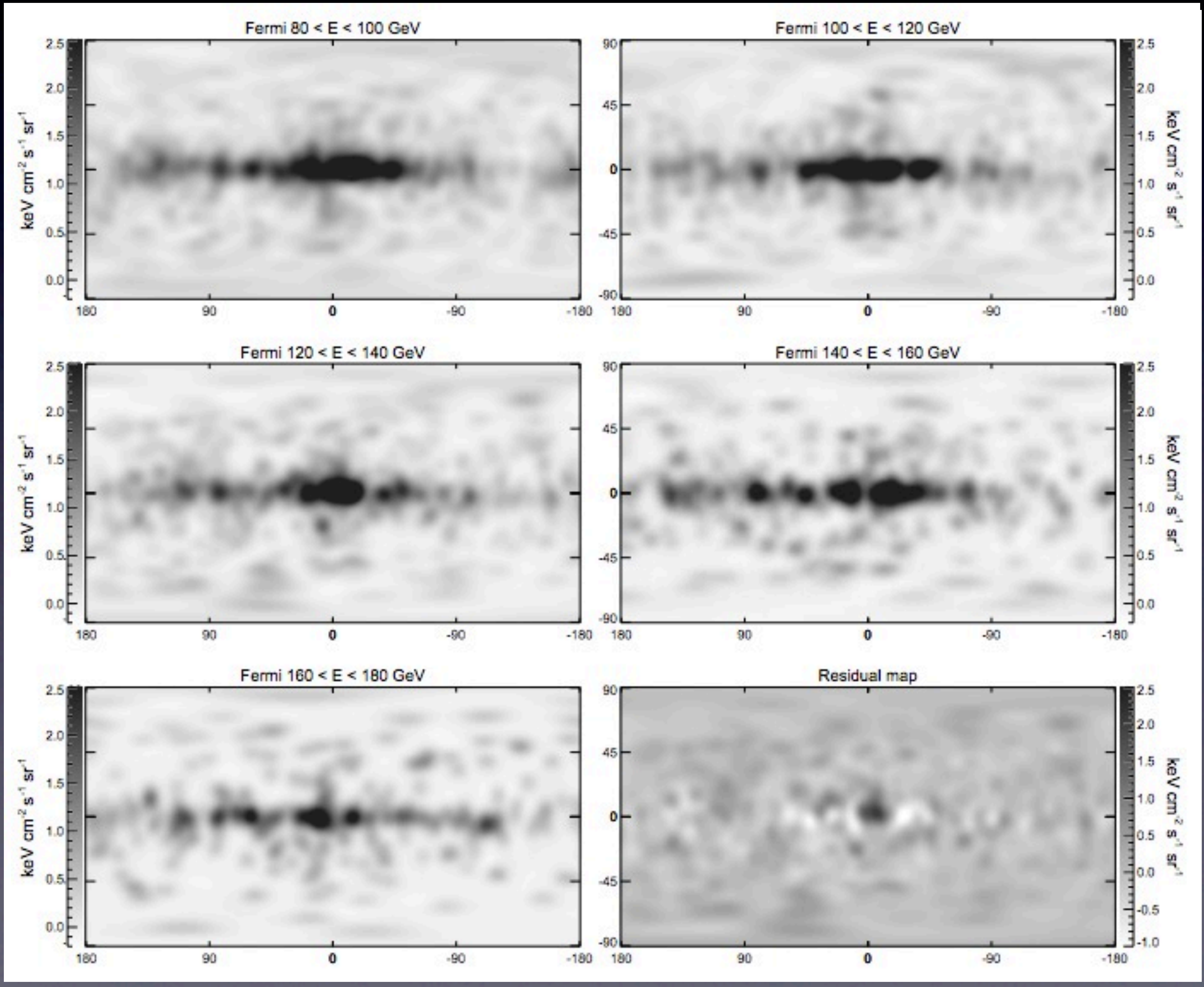
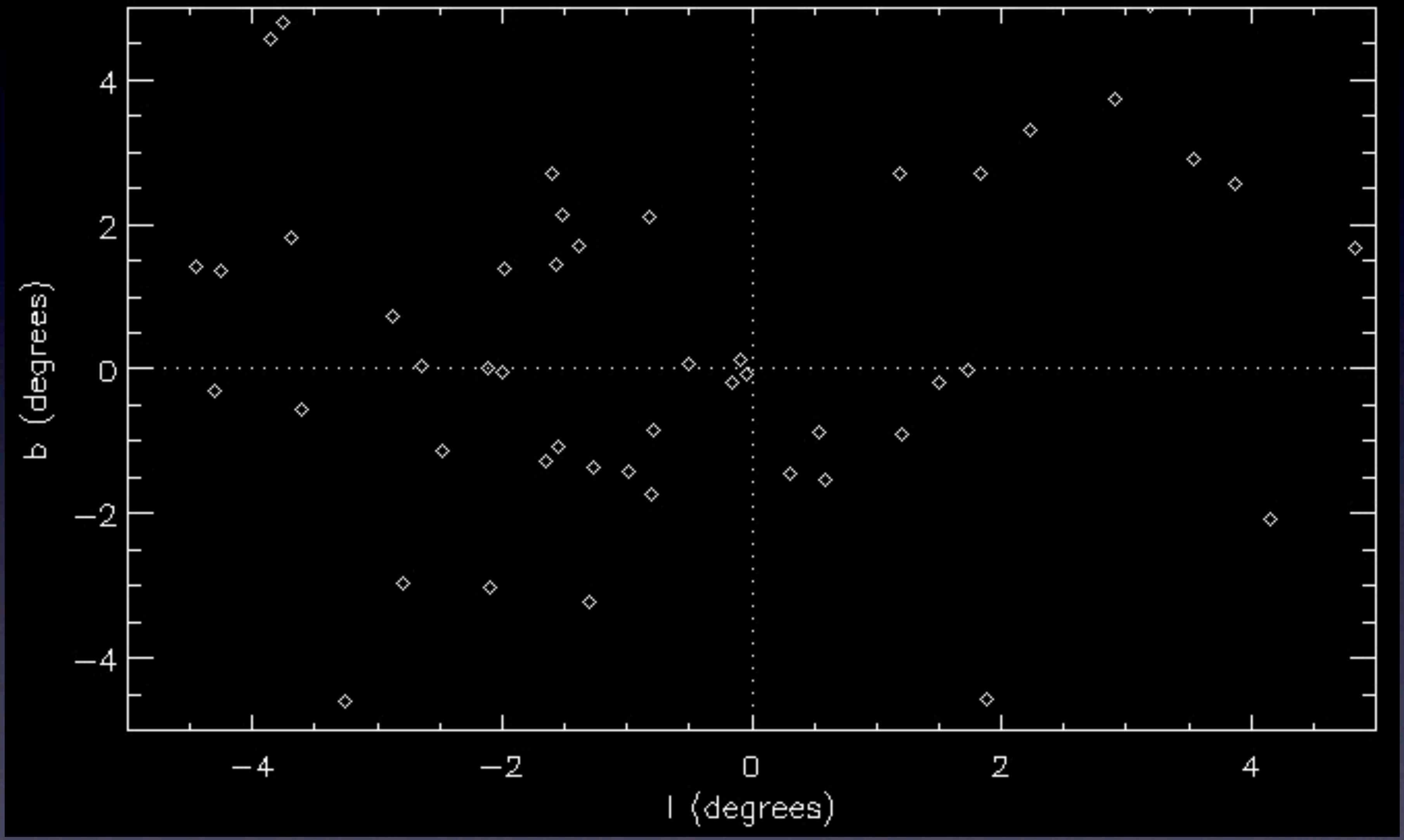


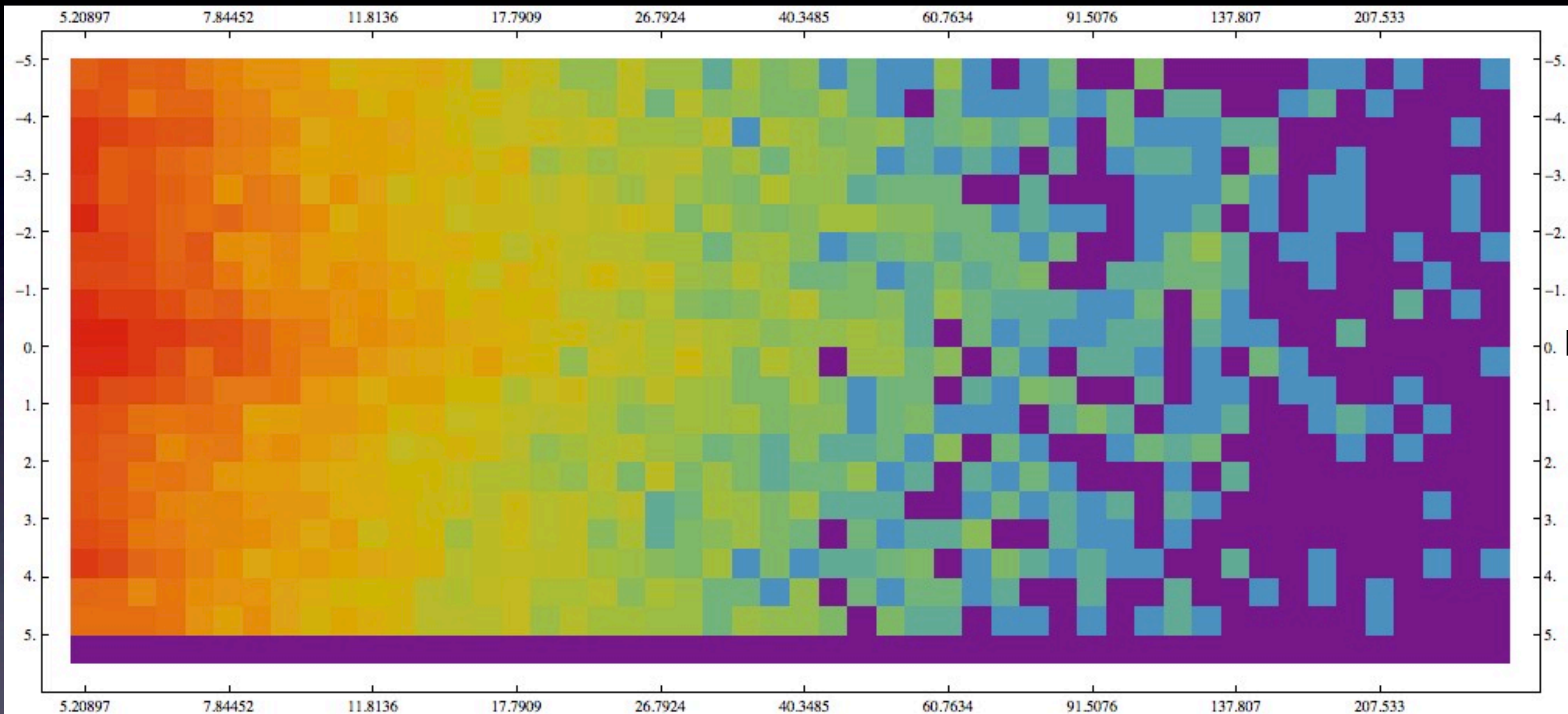
Spatial distribution (I)



SOURCE class photons between 120-140 GeV.

- Recent study by Carlson, Linden, Profumo & Weniger (1304.5524): can rule out the possibility that 1 (2, 4) or fewer point-like sources produce the data at 99% (95%, 90%) confidence level.

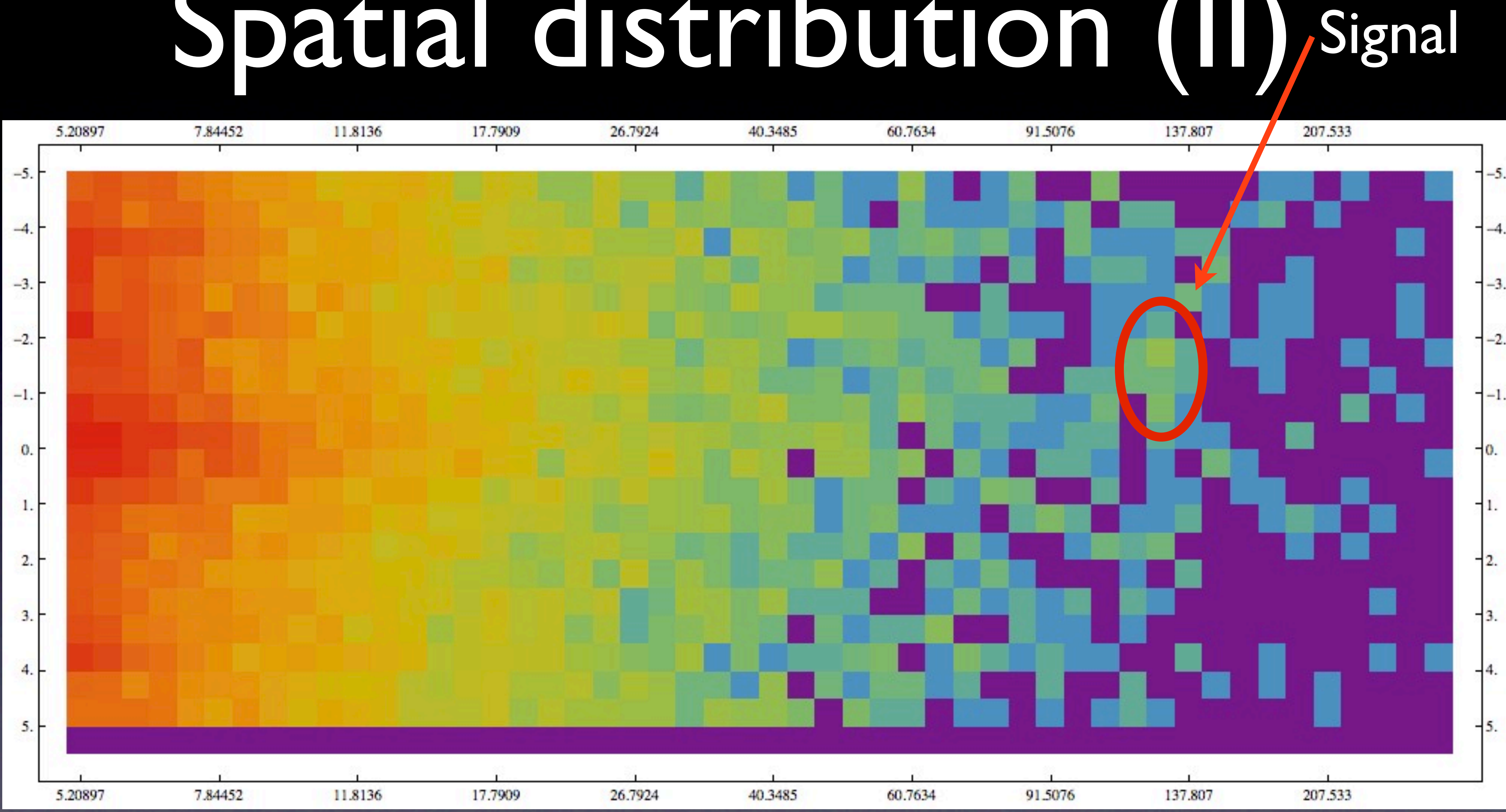
Spatial distribution (II)



Energy (GeV)

- Histogram of counts with |b| < 5°, by energy and galactic longitude.

Spatial distribution (II)



Energy (GeV)

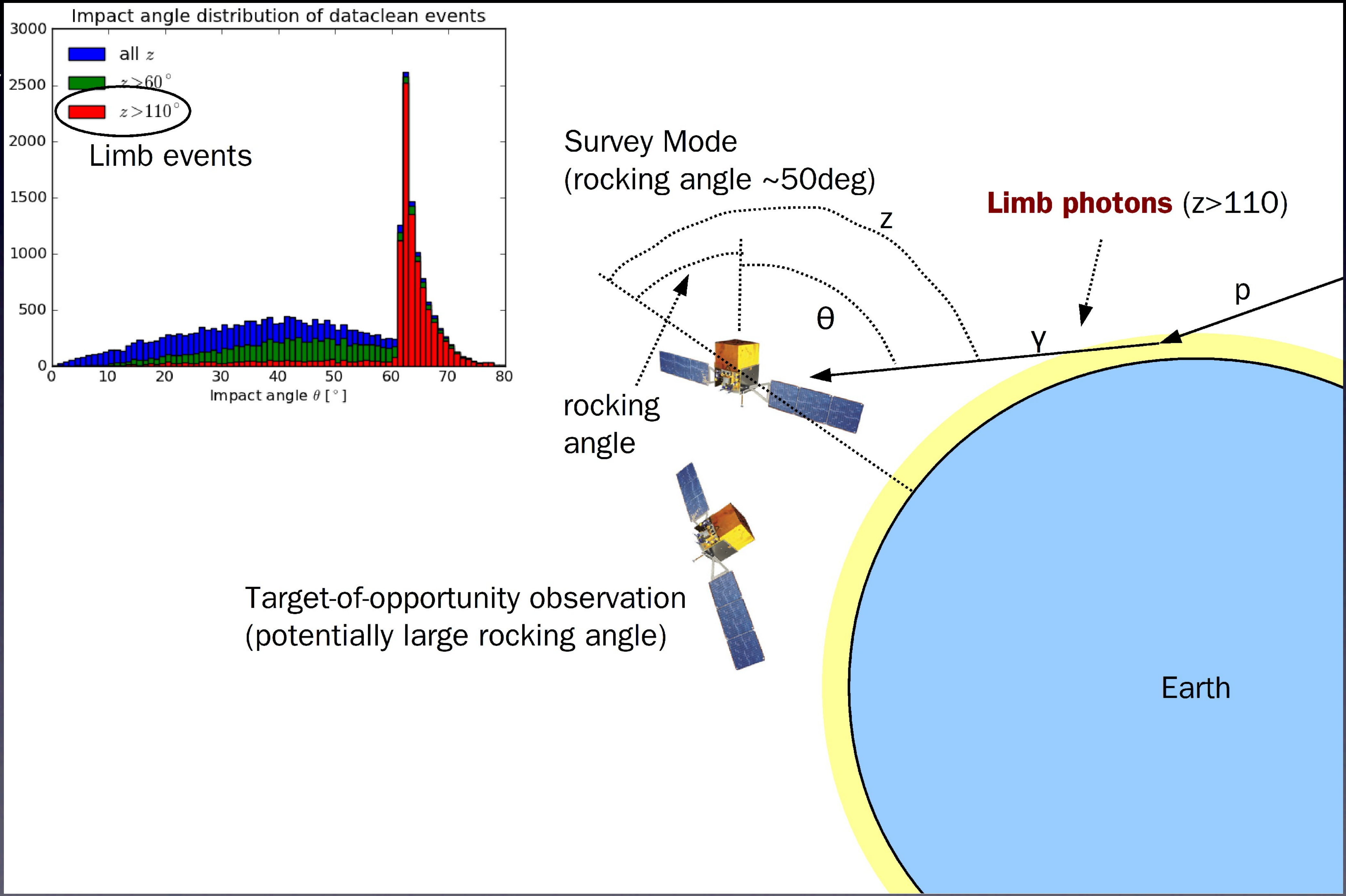
- Histogram of counts with |b| < 5°, by energy and galactic longitude.

Is the signal off-center?

- Definitely a preference for negative l; however, the background also seems to be skewed to negative l.
- Studies by Chang et al 1207.1621 and Rao & Whiteson, 1210.4934, indicate that the excess is statistically consistent with being centered on the GC.
- If it *were* to be offset, Guedes et al 1208.4844 found that the DM cusp might be displaced from the GC by several hundred parsecs, albeit without much contrast between the cusp and the GC.

Limb photons

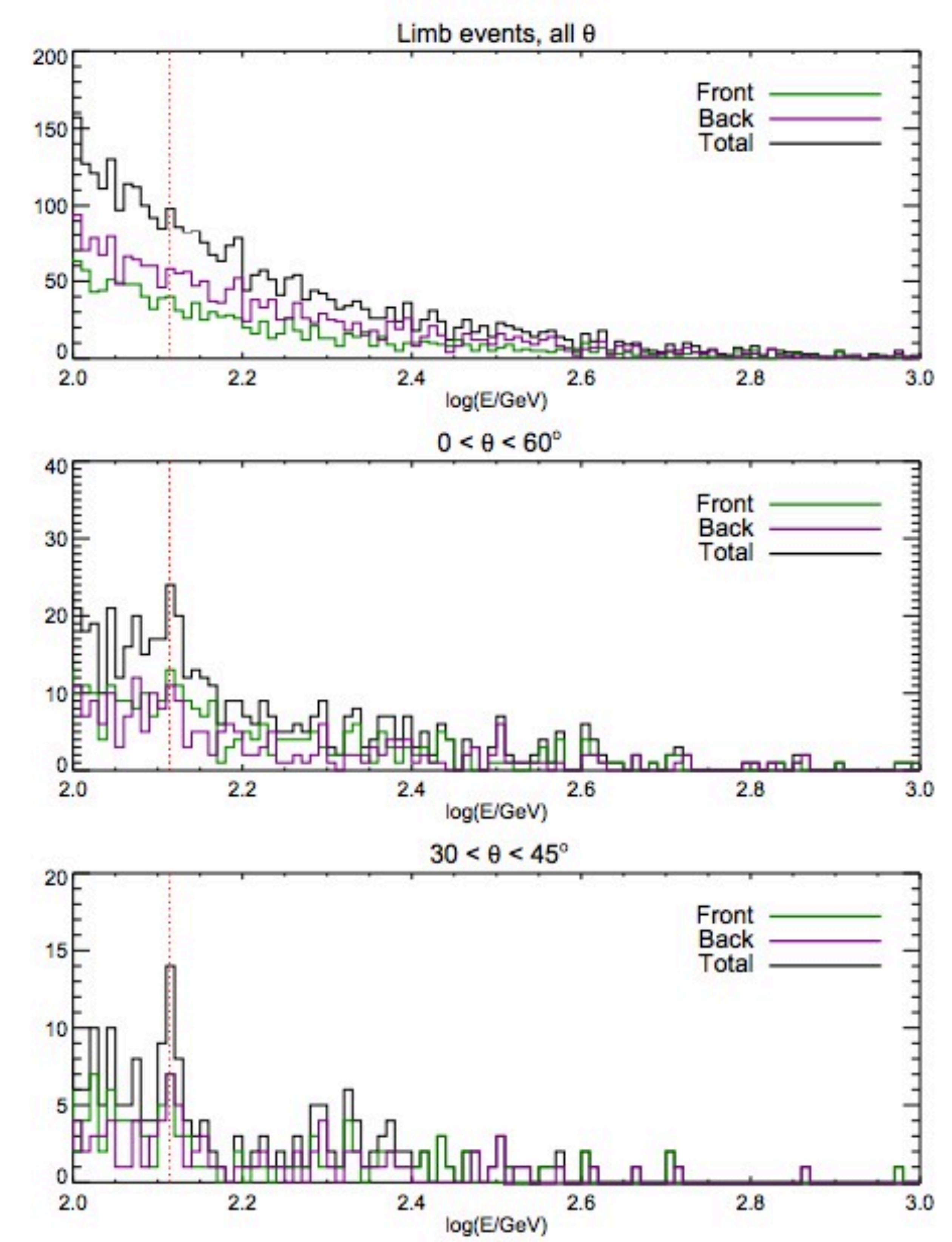
- "Earth limb" or "albedo" photons, produced by CRs striking the Earth's atmosphere, provide a control sample.
- No signal expected, large statistics.



Reproduced from talk by Christoph Weniger @ IDM 2012.

However...

- Limb photons in aggregate show no signal. But limb photons with low impact angles, in particular $30° < \theta < 45°$, do show a bump at 130 GeV (above 3σ).
- Studied by Finkbeiner, Su & Weniger 1209.4562; Hektor, Raidal & Tempel 1209.4548.
- Removing this angular range does not substantially effect the GC line.
- In non-limb events in this incidence angle range, the line is not detected.
- Both groups conclude this is probably a statistical fluctuation, but would like further limb data.



Finkbeiner, Su & Weniger 1209.4562

Continuum vs line

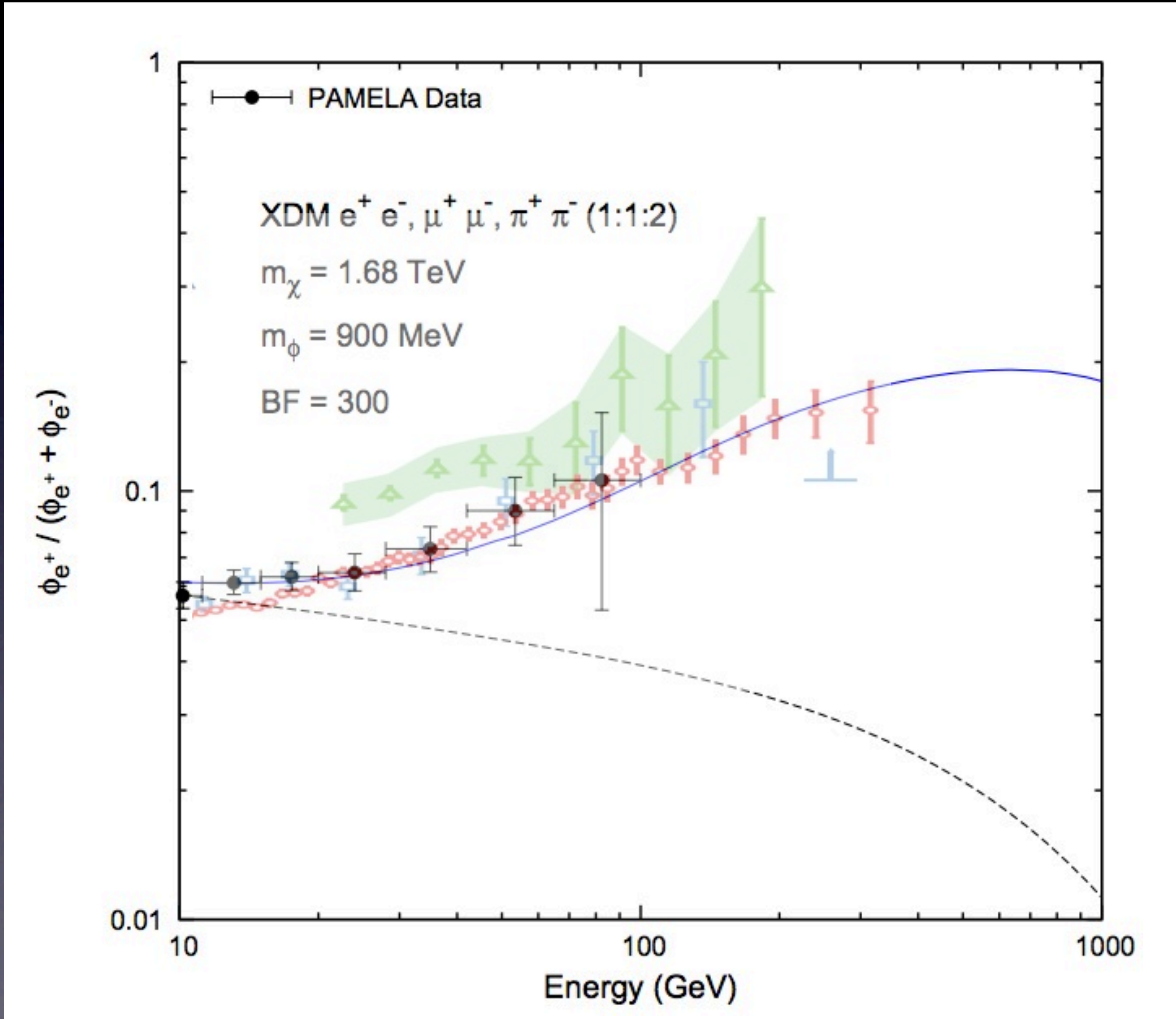
- As well as the line signal there will generally be other annihilation channels. In the context of a particular DM model, can look for photons from these other channels.
- Compare exactly the same region of the sky: cancel out uncertainties on the DM density profile (and ignore channels requiring modeling of charged-particle propagation).
- Most conservative constraint: supersaturation. Require only that the number of photons observed by Fermi (in some energy range) is at *least* as large as the number of photons predicted for the continuum.
- Compare the quantity:

Dependent on energy range chosen

$$R^{\rm th} \equiv \frac{\sigma_{\rm ann}}{2\sigma_{\gamma\gamma} + \sigma_{\gamma Z}} \quad \text{to} \quad R^{\rm ob} \equiv \frac{1}{n^{\gamma}_{\rm ann}} \frac{N_{\rm ann}}{N_{\gamma\gamma} + N_{\gamma Z}}$$

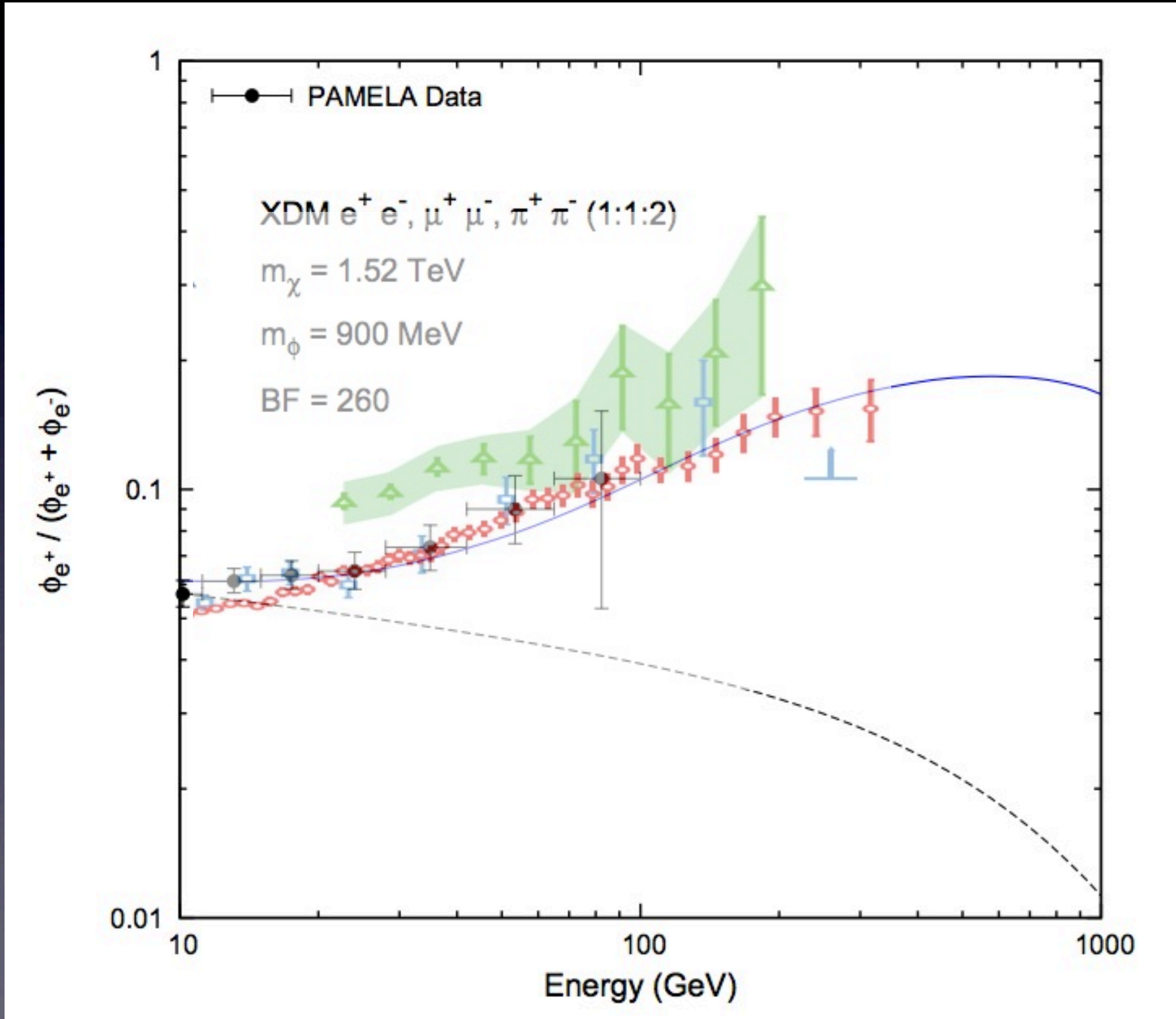
- Can also compute a constraint based on the spectral shape, since the observed spectrum is very power-law-like.

Pre-AMS benchmarks



Finkbeiner, Goodenough, TRS & Weiner 2010

Pre-AMS benchmarks



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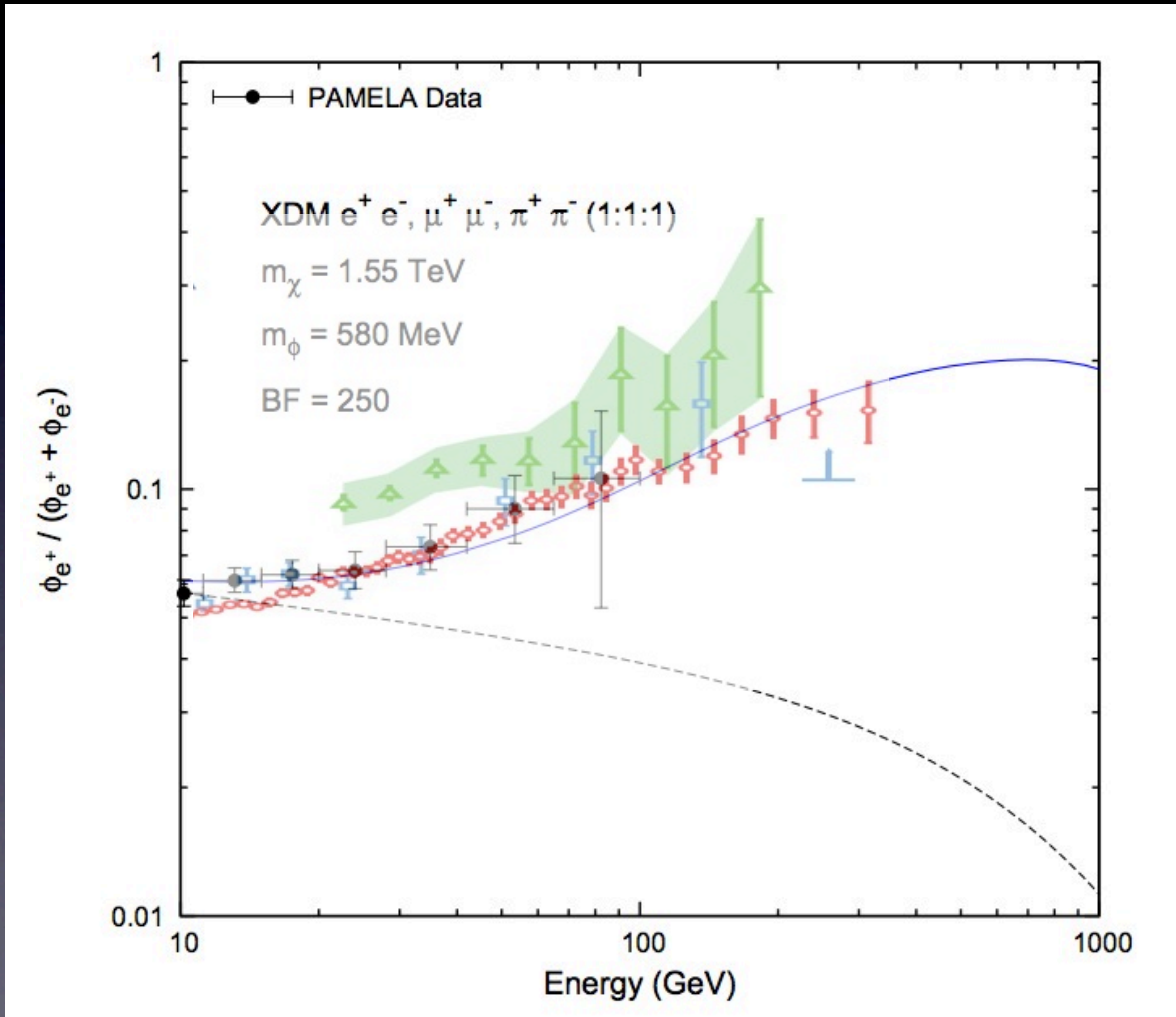

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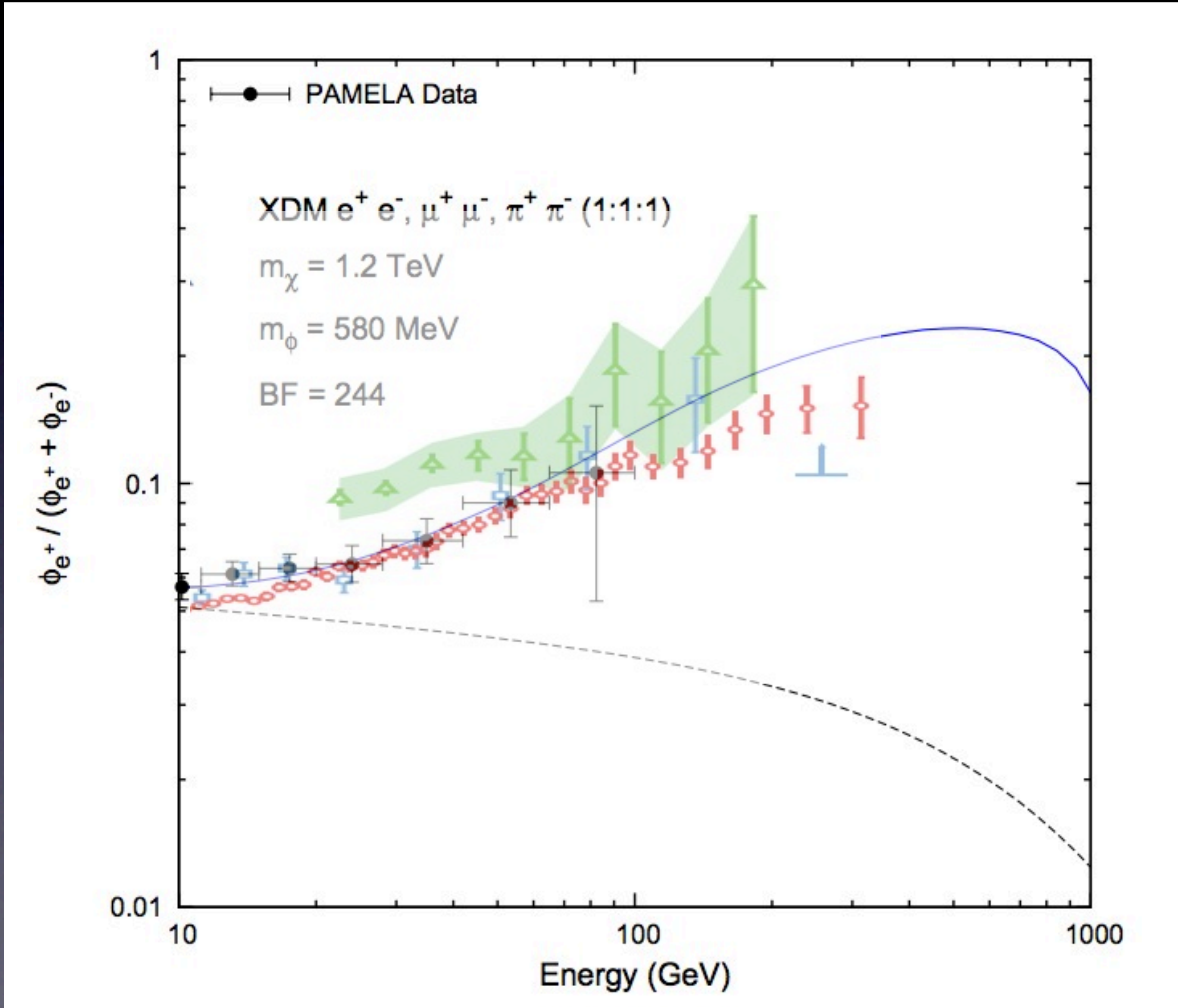

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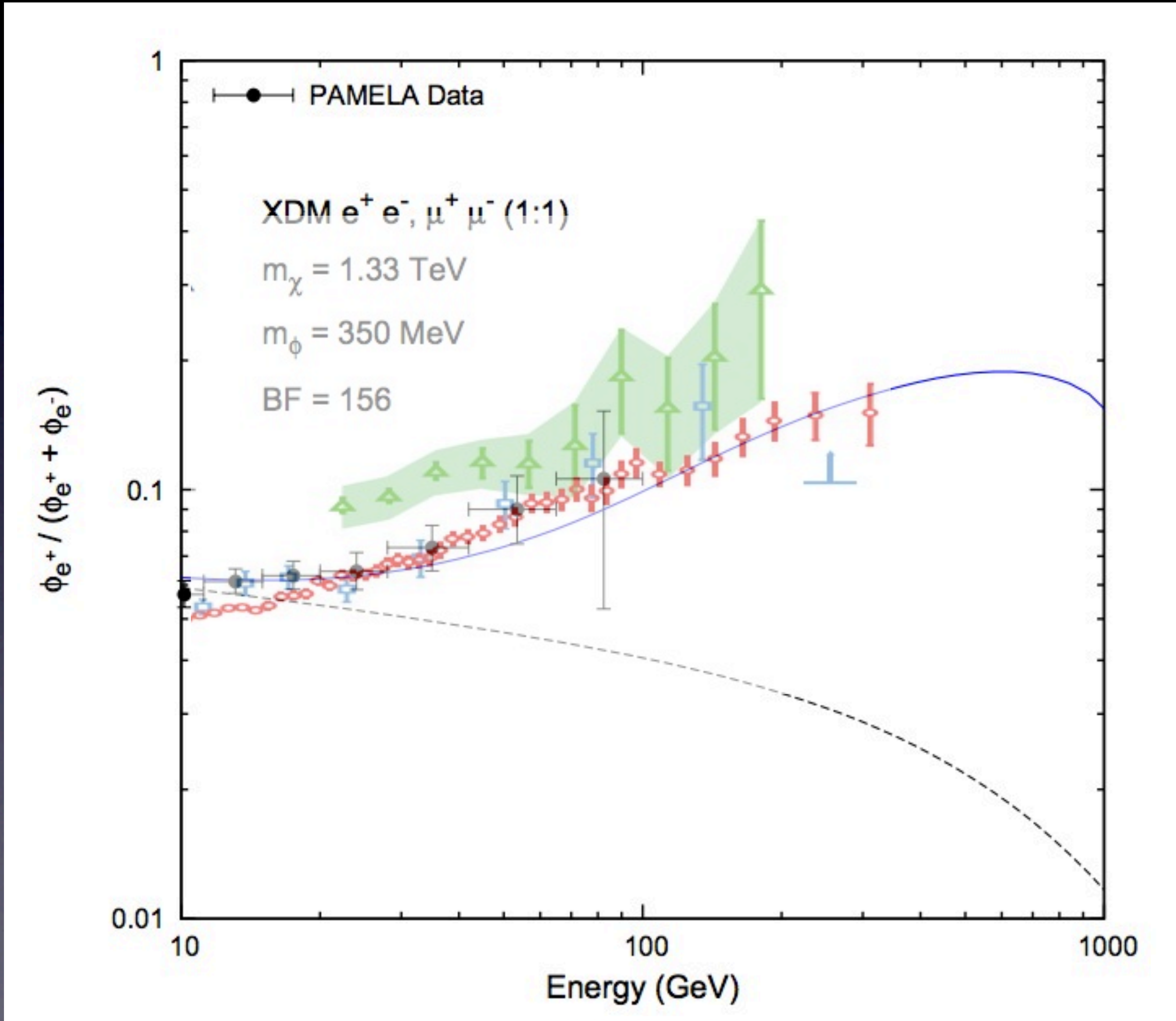
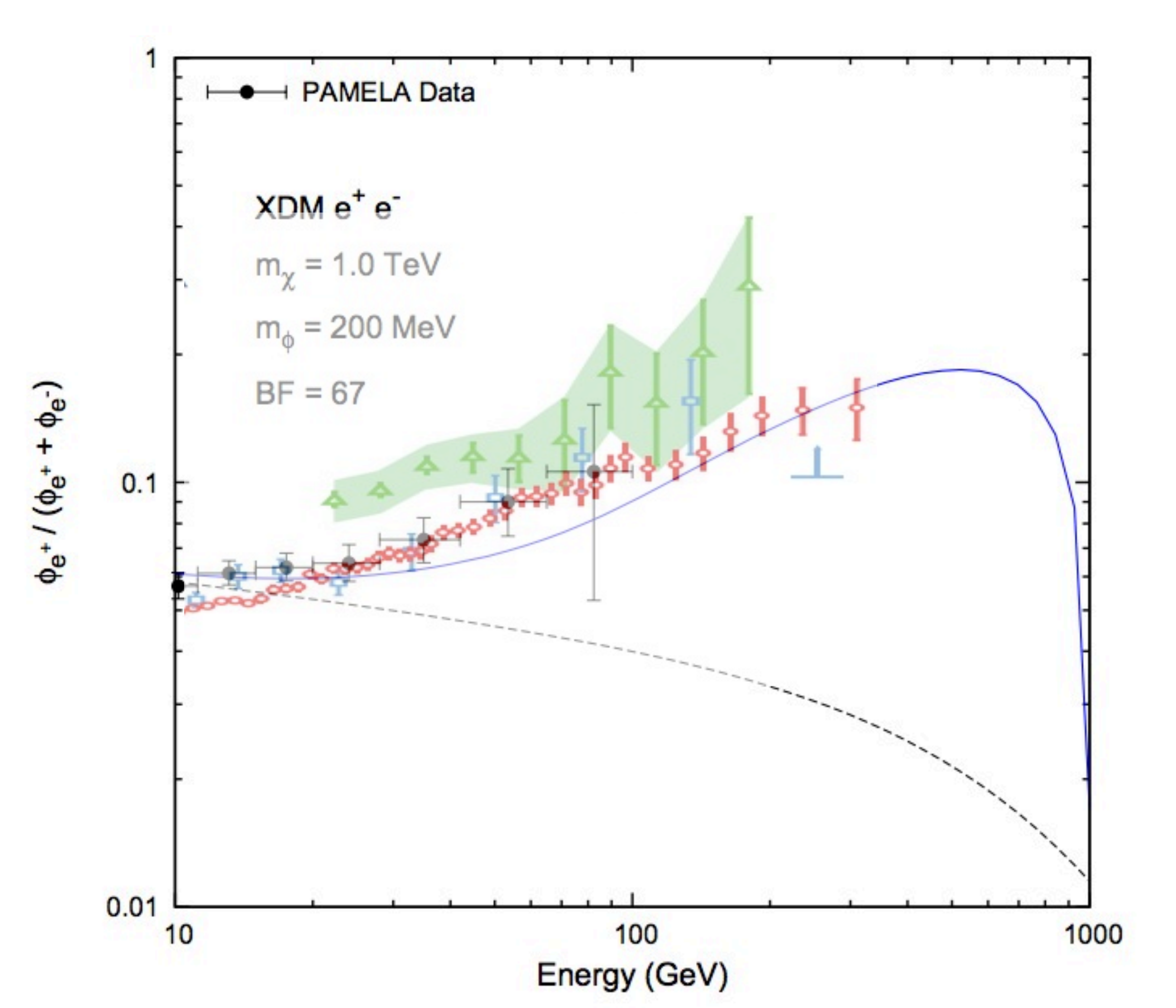
Pre-AMS benchmarks



Finkbeiner, Goodenough, TRS & Weiner 2010

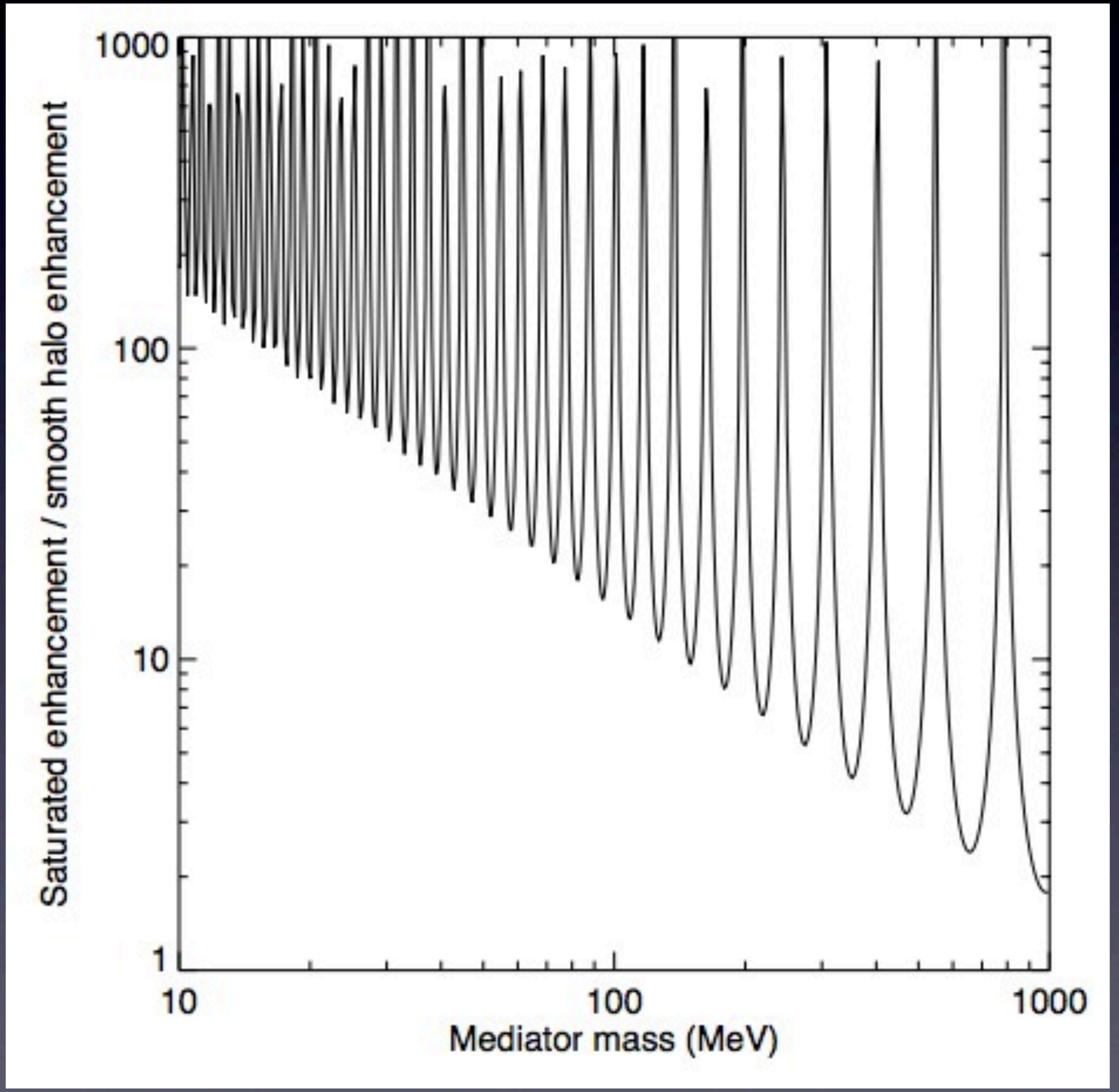
Pre-AMS benchmarks



Finkbeiner, Goodenough, TRS & Weiner 2010

Interpreting the CMB limits

- Latest CMB constraints (using 2011 ACT and SPT data) in tension with the best-fit cross sections given by Cholis & Hooper 1304.1840.
- Tension at the factor-of-2 level - seem to require O(1-2) local "boost factor" from higher local DM density or substructure.
- Exclusion can be much stronger for models where the cross section is greater at low velocities ($v \sim 10^{-8}$ relevant for CMB constraints, compared to $v \sim 10^{-3}$ for the local halo). Holds true for $v_{local} \sim 10^{-3} < m_{A'}/m_X$.
- Favors heavier force carrier masses.
- Alternative viable scenario: the local signal is dominated by DM substructure, where typical velocities are much smaller.



TRS, Toro & Weiner 1107.3546

Substructure

- DM halos built up hierarchically: lots of smaller clumps of dark matter.
- These bound clumps are <u>cold</u>:
  - Low internal velocities
  - High densities
  - Can contribute non-negligibly to local $<\rho^2>$, could be a factor of a few higher than the main halo
- For $m_{A'}$ < GeV, enhancement may be "saturated" (maximum value) in small subhalos, and during the CMB epoch, but NOT in the Milky Way smooth halo.
- If this gap is large, substructure signal can be >> main halo. Then behaves like large velocity-independent annihilation rate (since enhancement is always saturated).
- Need to account for the signal from small-scale structure in dwarf galaxies, extragalactic diffuse gamma rays, etc, but...
- Reopens viable parameter space at low mediator masses (below ~100 MeV), if sufficient substructure is present.