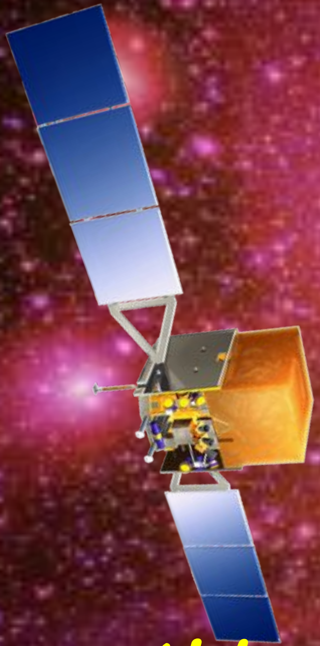
Search for Dark Matter in the sky with the Fermi Large Area Telescope



Aldo Morselli
INFN Roma Tor Vergata
on behalf of the Fermi-Lat Collaboration

LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE
Results and Perspectives in Particle Physics

La Thuile ***25 Feb 2013***

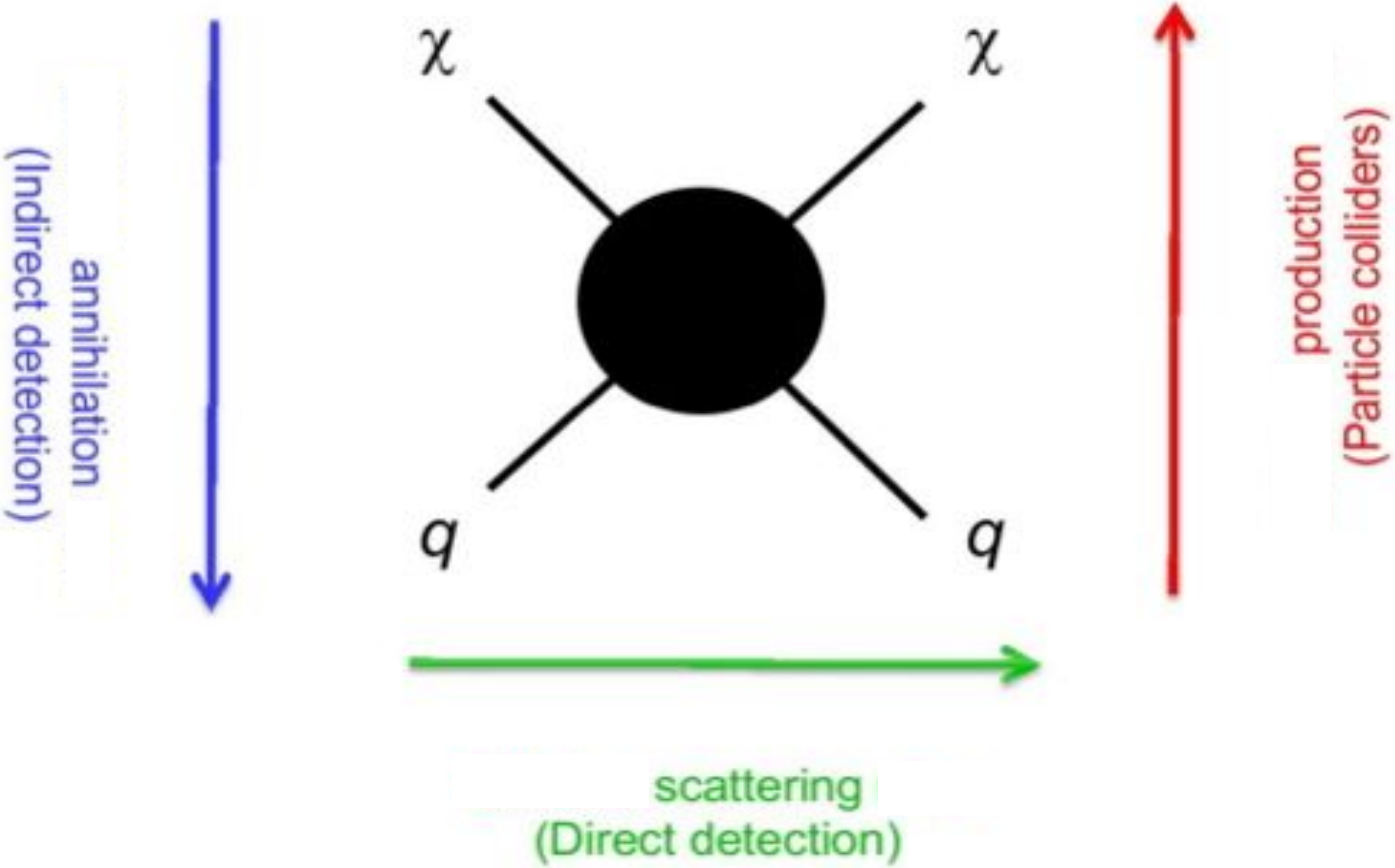
Past decades saw precision studies of 5 % of our Universe -> Discovery of the Standard Model

The LHC is delivering data

We are just at the beginning of exploring 95 % of the Universe.

Exciting prospects

R.-D. Heuer, CERN General Director 36th International Conference on High Energy Physics ICHEP2012, Closing Talk

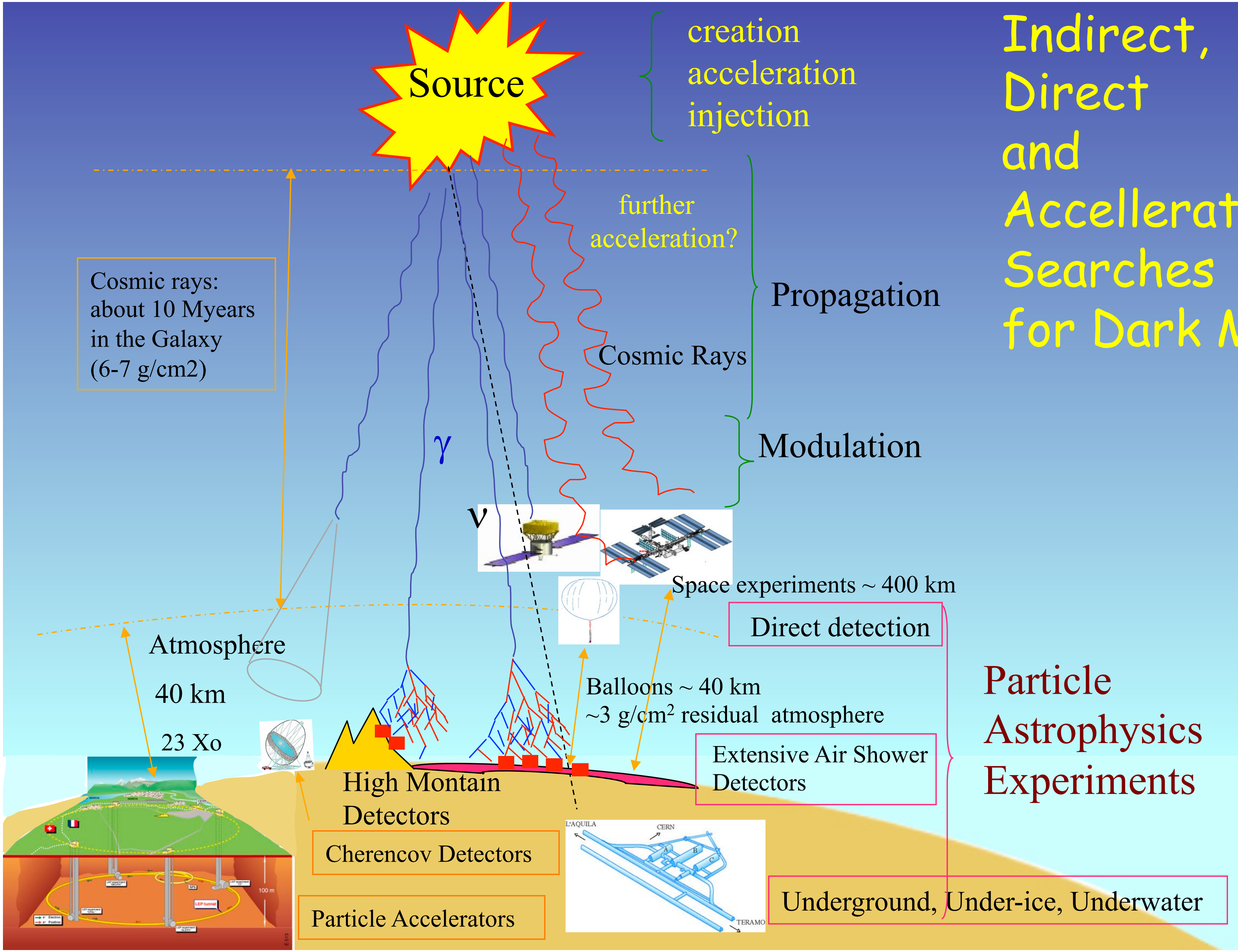


annihilation
(Indirect detection)

production
(Particle colliders)

scattering
(Direct detection)

Indirect, Direct and Accellerator Searches for Dark Matter



Source

creation
acceleration
injection

further
acceleration?

Propagation

Cosmic Rays

Modulation

Cosmic rays:
about 10 Myears
in the Galaxy
(6-7 g/cm2)

γ

ν

Space experiments ~ 400 km

Direct detection

Atmosphere

40 km

23 Xo

Balloons ~ 40 km
~3 g/cm^2 residual atmosphere

Extensive Air Shower
Detectors

High Montain
Detectors

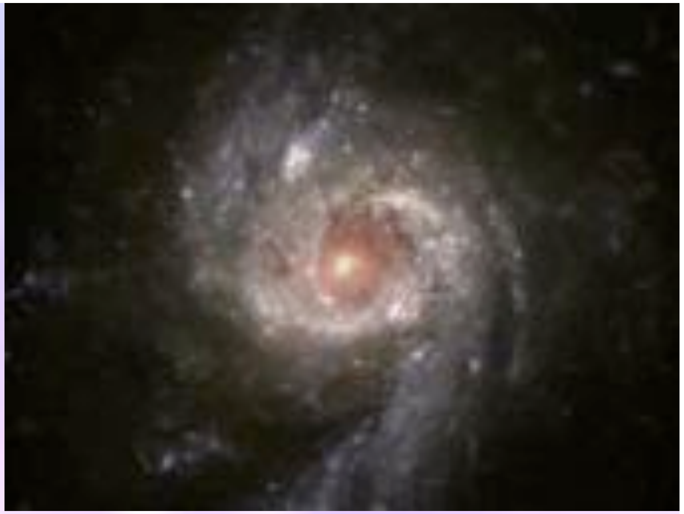
Cherencov Detectors

Particle Accelerators

Underground, Under-ice, Underwater

Particle
Astrophysics
Experiments

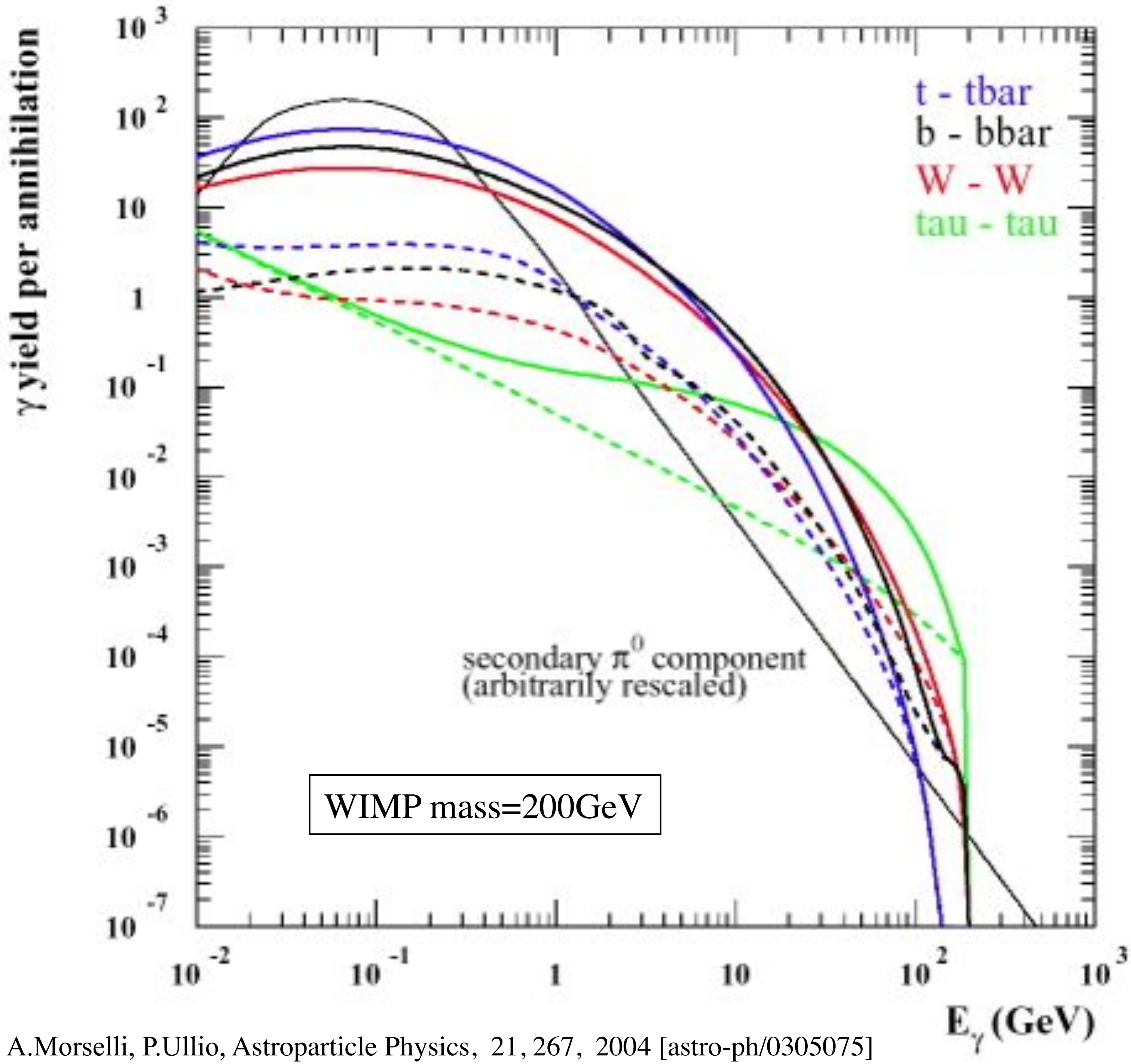
Neutralino WIMPs



Assume χ present in the galactic halo

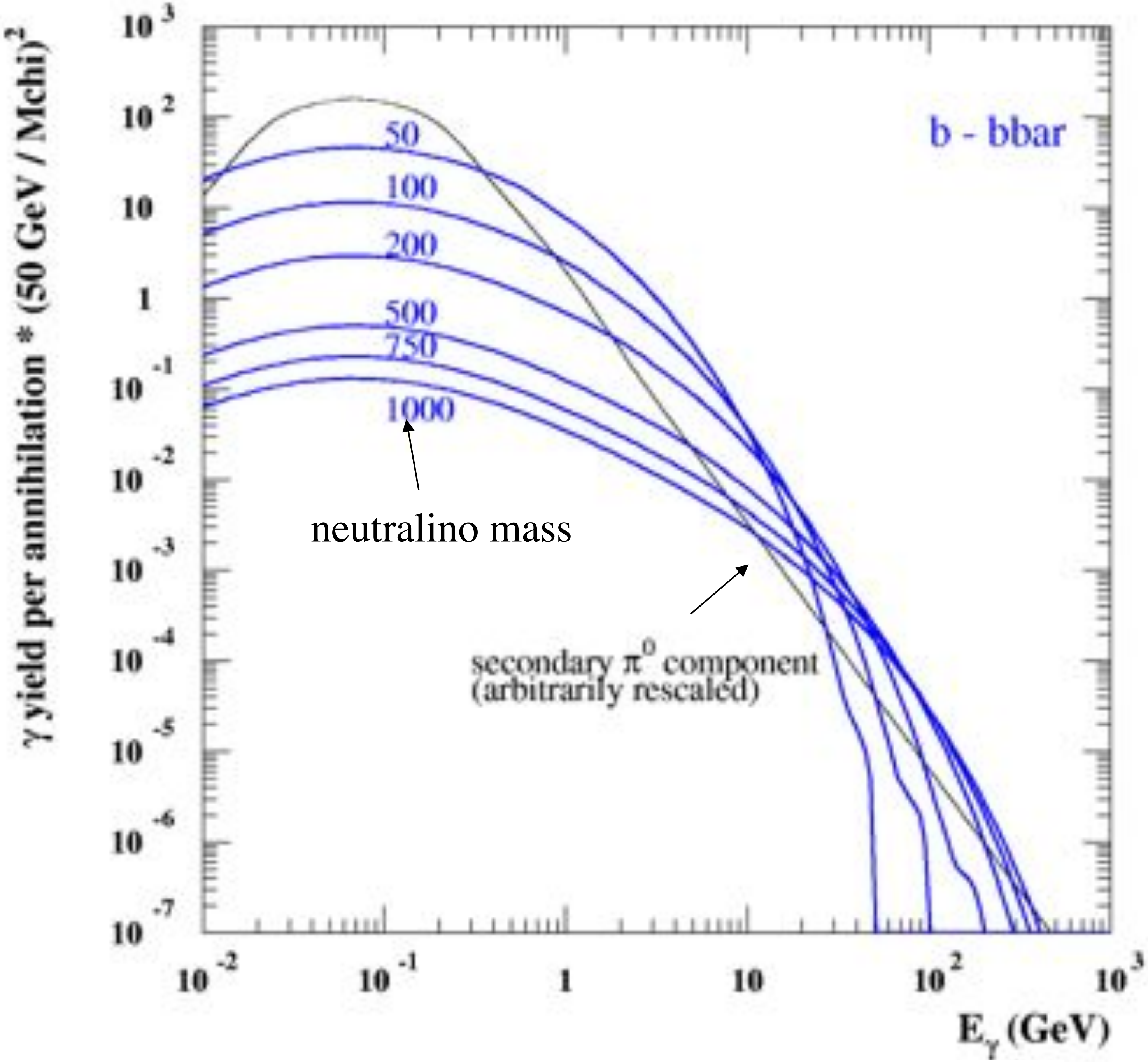
- χ is its own antiparticle **=>** can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through p + p **-->** anti p + X)
- So, any extra contribution from exotic sources ($\chi\ \chi$ annihilation) is an interesting signature
- ie: $\chi\ \chi$ --> anti p + X
- Produced from (e. g.) $\chi\ \chi$ **-->** q / g / gauge boson / Higgs boson and subsequent decay and/ or hadronisation.

Differential yield for each annihilation channel



A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267, 2004 [astro-ph/0305075]

Differential yield for b bar



A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267-285, 2004 [astro-ph/0305075]

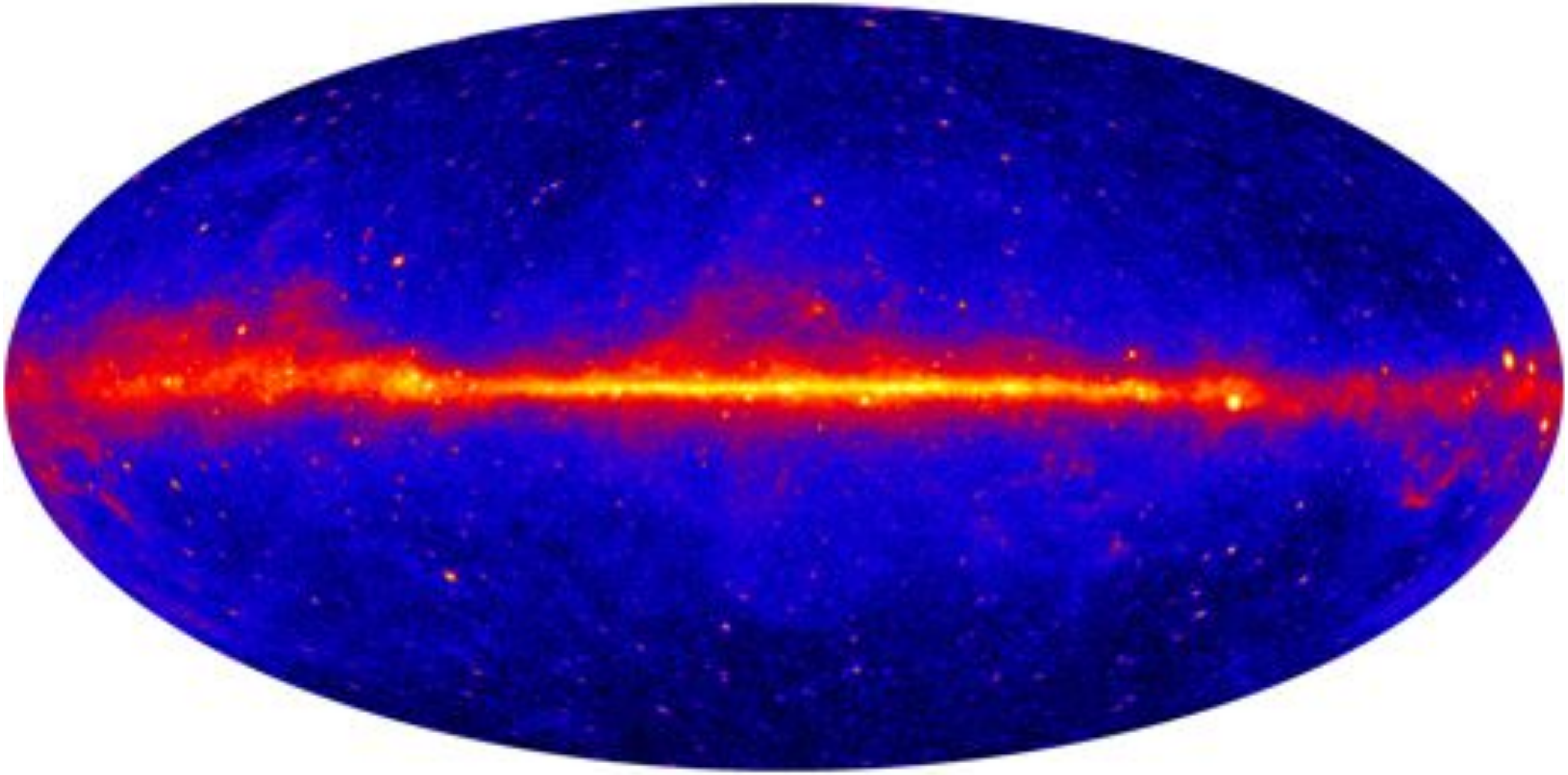
Fermi
Gamma-ray
Space Telescope

Happy 4th Birthday Fermi !!

11 June 2008

Fermi LAT Gamma-ray Sky

4 year all sky map (E > 1 GeV)

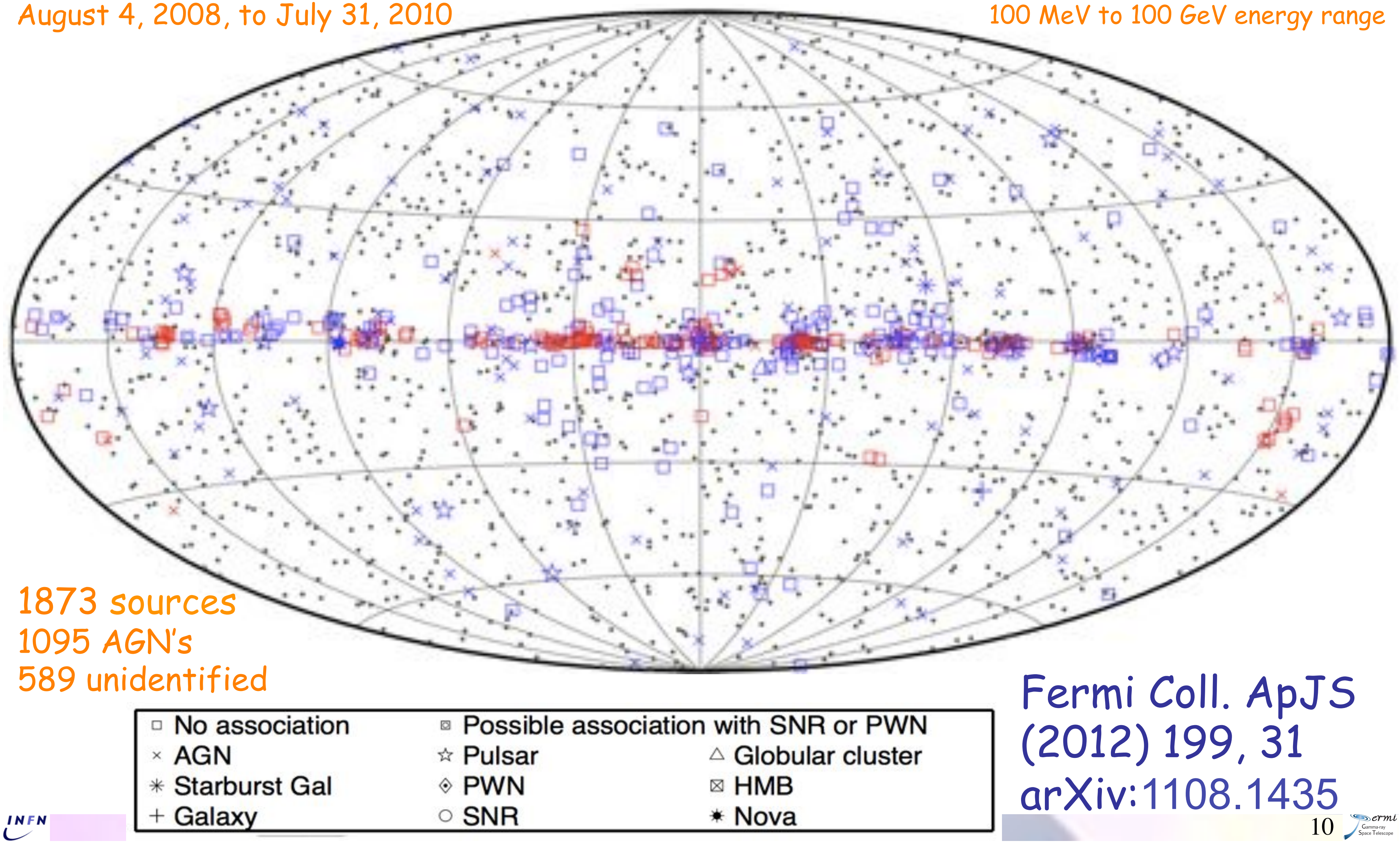


The Fermi LAT 2FGL Source Catalog

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/2yr_catalog/

August 4, 2008, to July 31, 2010

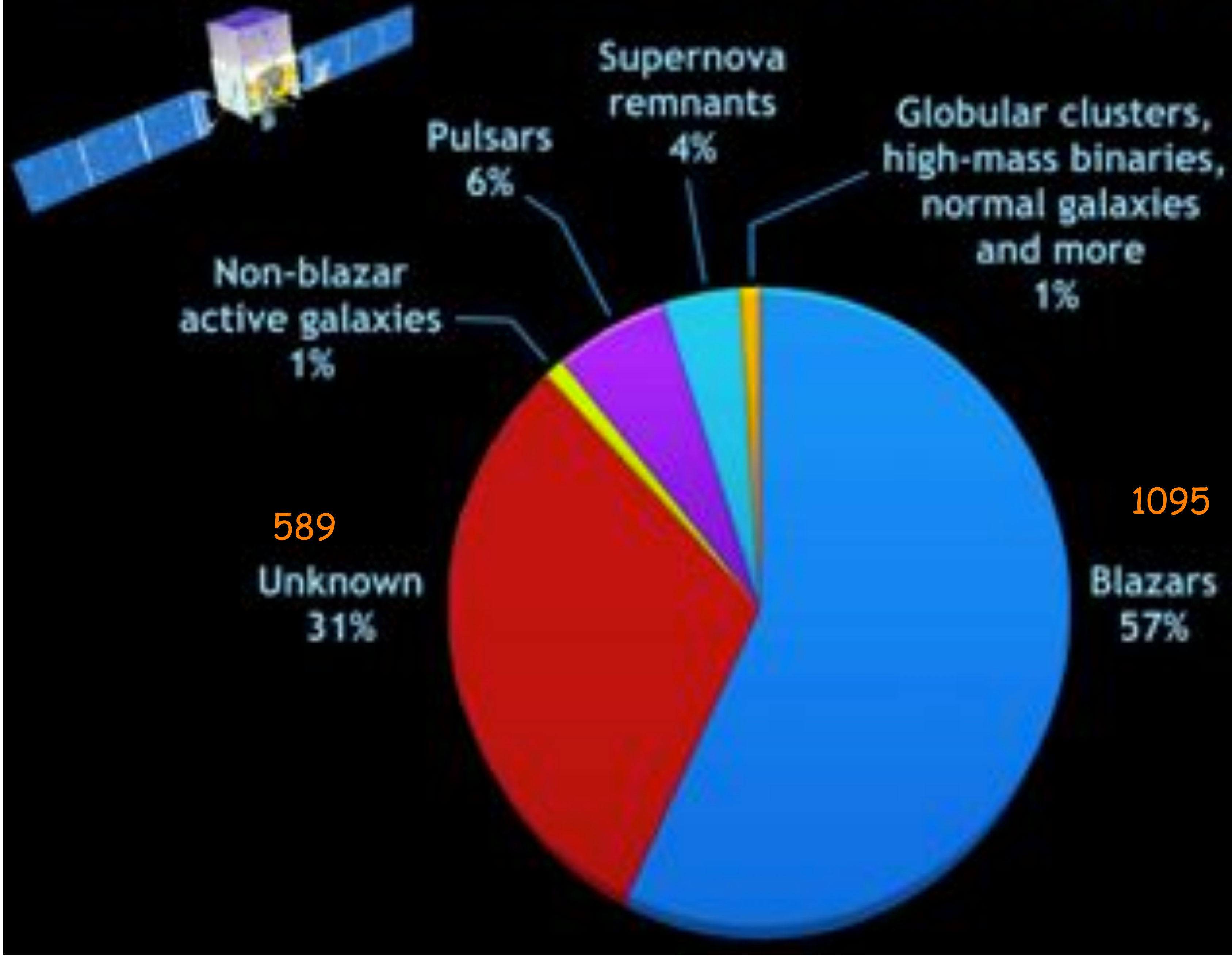
100 MeV to 100 GeV energy range



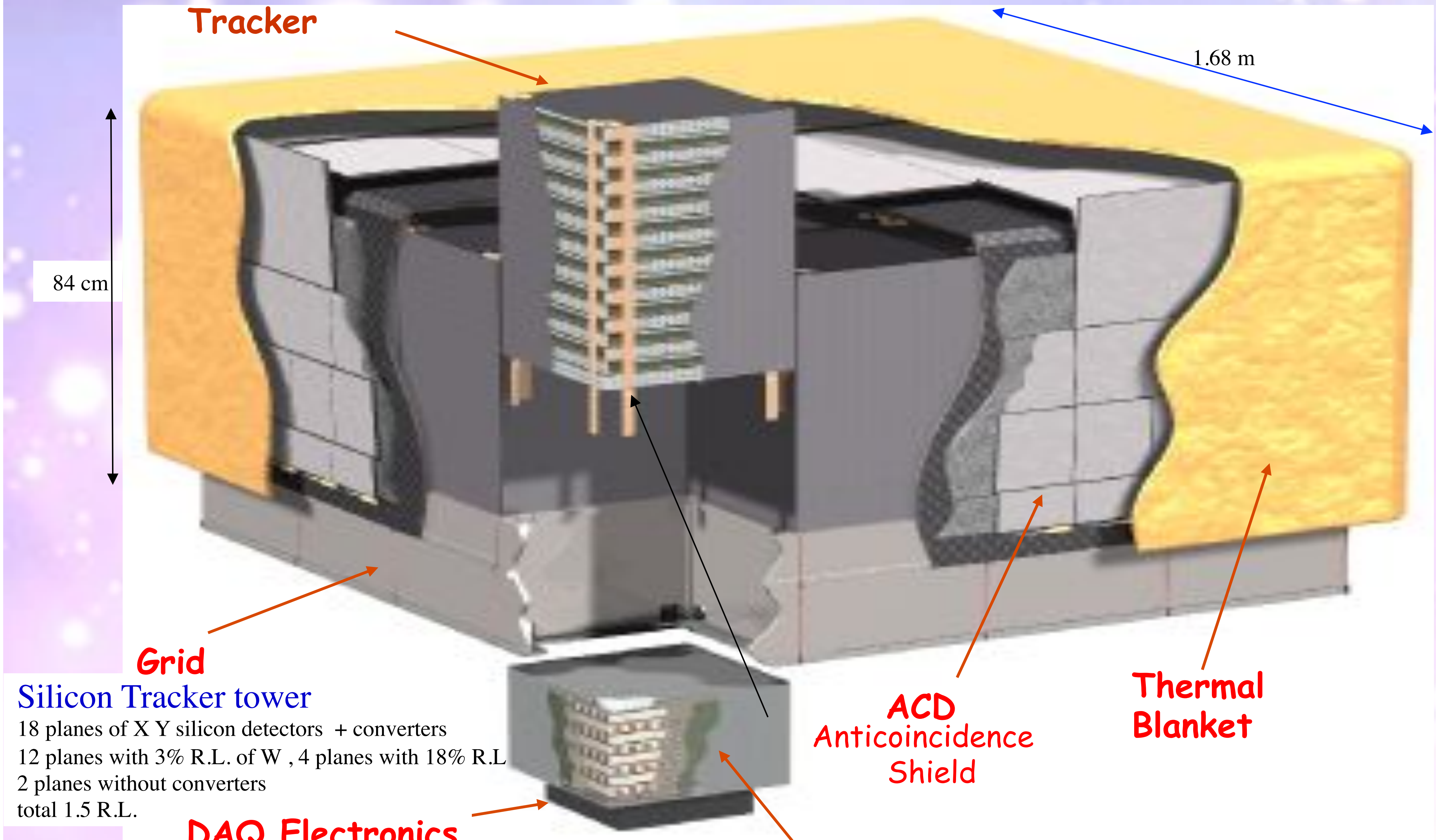
1873 sources
1095 AGN's
589 unidentified

Fermi Coll. ApJS (2012) 199, 31
arXiv:1108.1435

What has Fermi found: The LAT two-year catalog



Fermi Gamma-Ray Large Area Space Telescope



Tracker

Grid

ACD
Anticoincidence
Shield

Thermal
Blanket

DAQ Electronics

Calorimeter (8.6 Rad.Length)

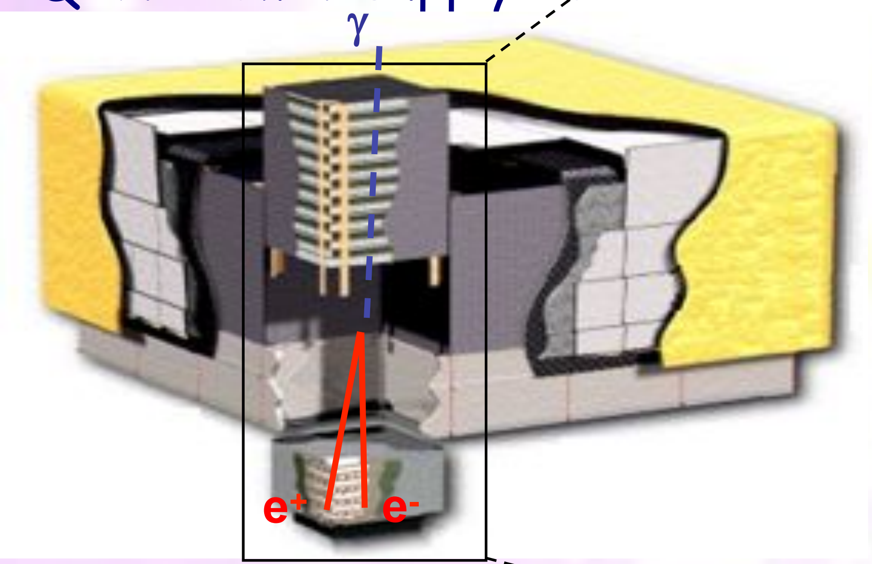
Silicon Tracker tower

18 planes of X Y silicon detectors + converters
12 planes with 3% R.L. of W , 4 planes with 18% R.L
2 planes without converters
total 1.5 R.L.

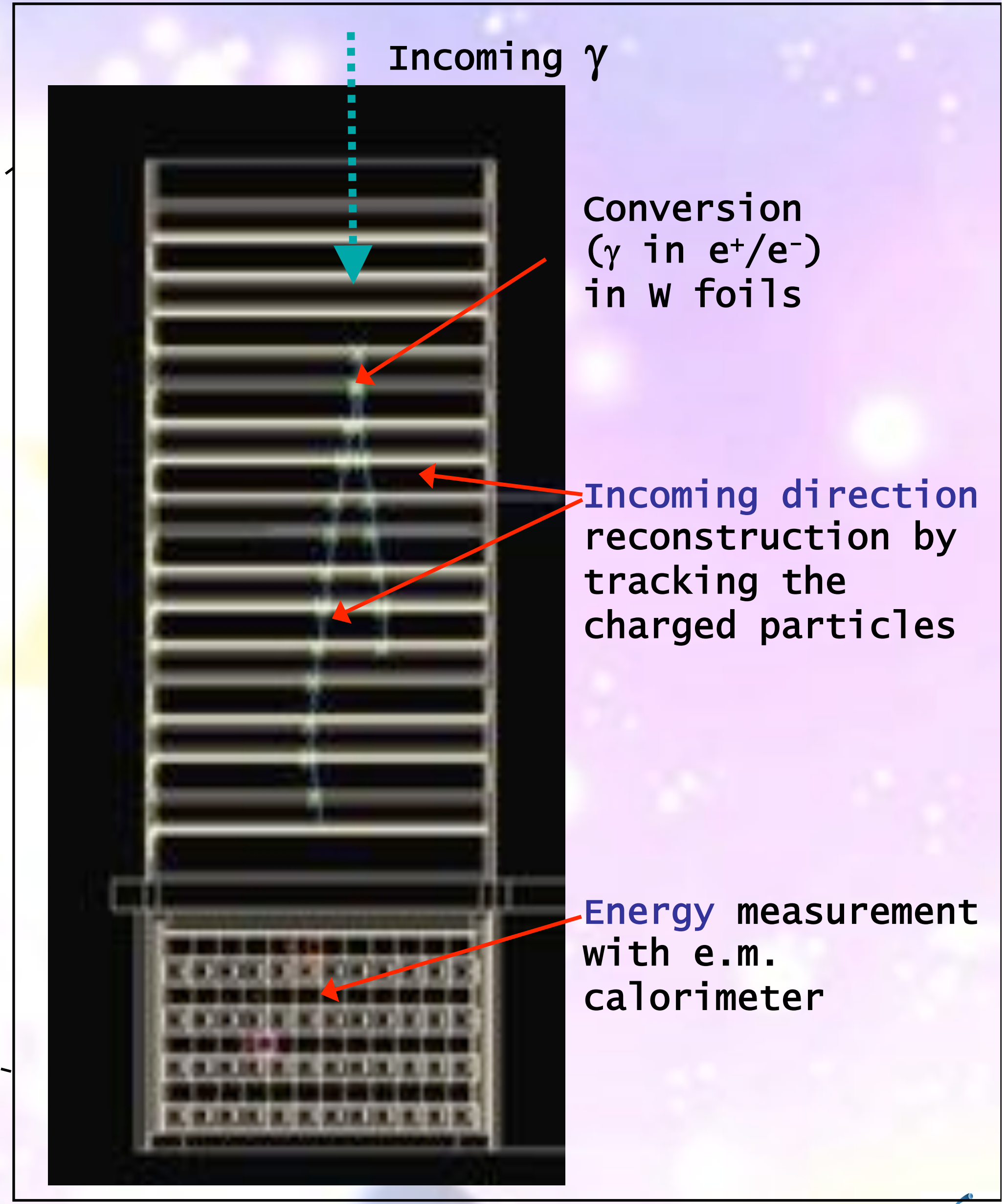
How Fermi LAT detects gamma rays

4 x 4 array of identical towers with:

- Precision Si-strip tracker (TKR)
  - With W converter foils
- Hodoscopic CsI calorimeter (CAL)
- DAQ and Power supply box



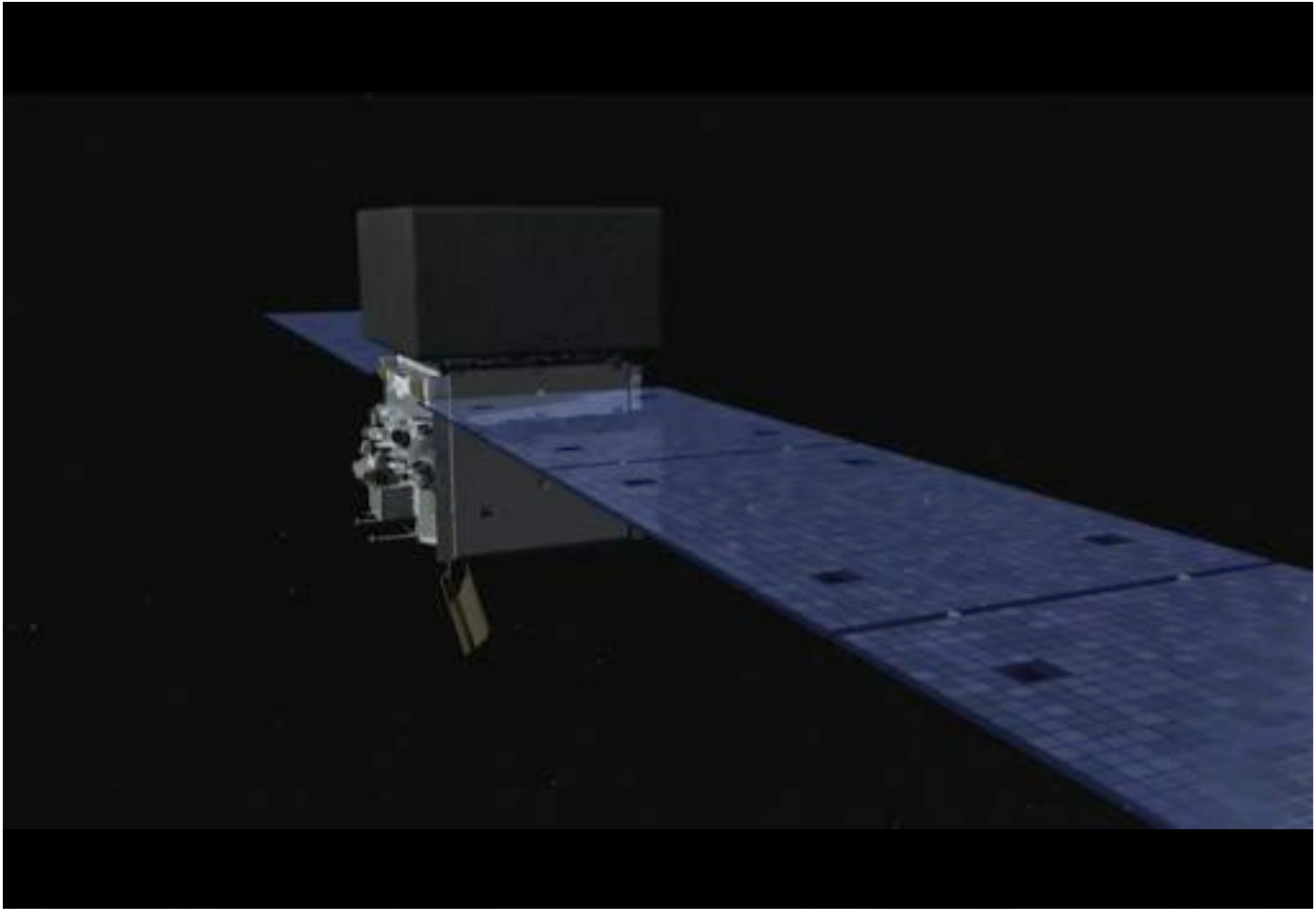
An anticoincidence detector around the telescope distinguishes gamma-rays from charged particles



Conversion (γ in e^+/e^-) in W foils

Incoming direction reconstruction by tracking the charged particles

Energy measurement with e.m. calorimeter



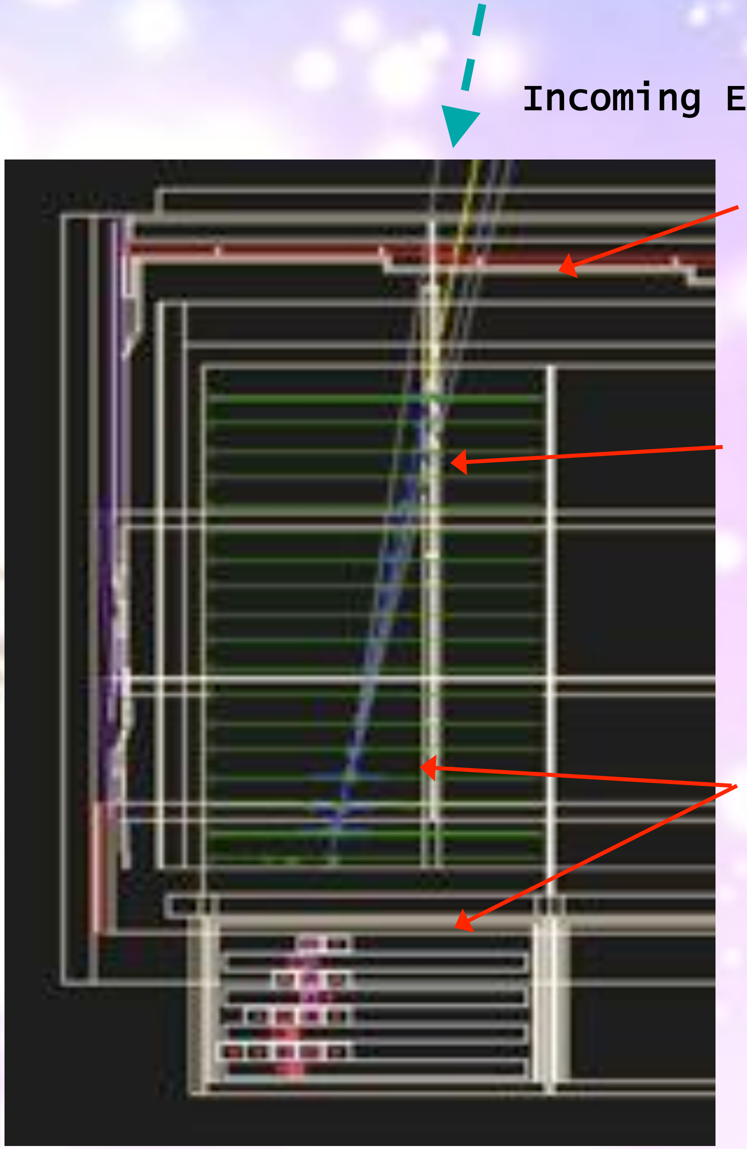
How Fermi LAT detects electrons

Trigger and downlink

- LAT triggers on (almost) every particle that crosses the LAT
  - ~ 2.2 kHz trigger rate
- On board processing removes many charged particles events
  - But keeps events with more that 20 GeV of deposited energy in the CAL
  - ~ 400 Hz downlink rate
- Only ~1 Hz are good γ-rays

Electron identification

- The challenge is identifying the good electrons among the proton background
  - Rejection power of 10^3 - 10^4 required
  - Can not separate electrons from positrons



Incoming Electron

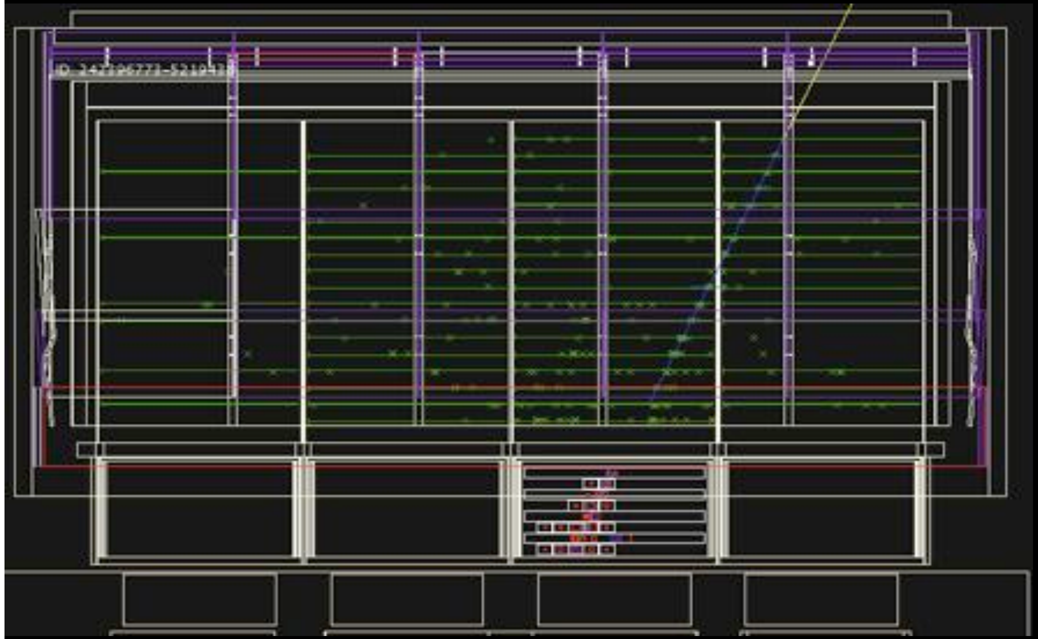
ACD identifies charged particle

Main track pointing to the hit ACD tile

Same tracking and energy reconstruction algorithms used for γ-rays

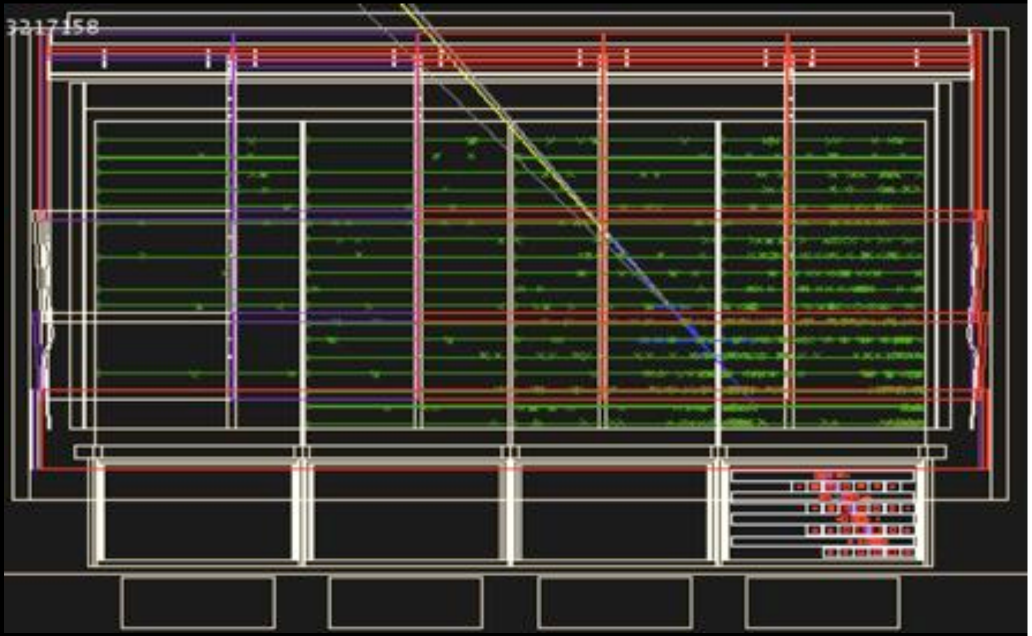
Event topology

A candidate electron
(recon energy 844 GeV)



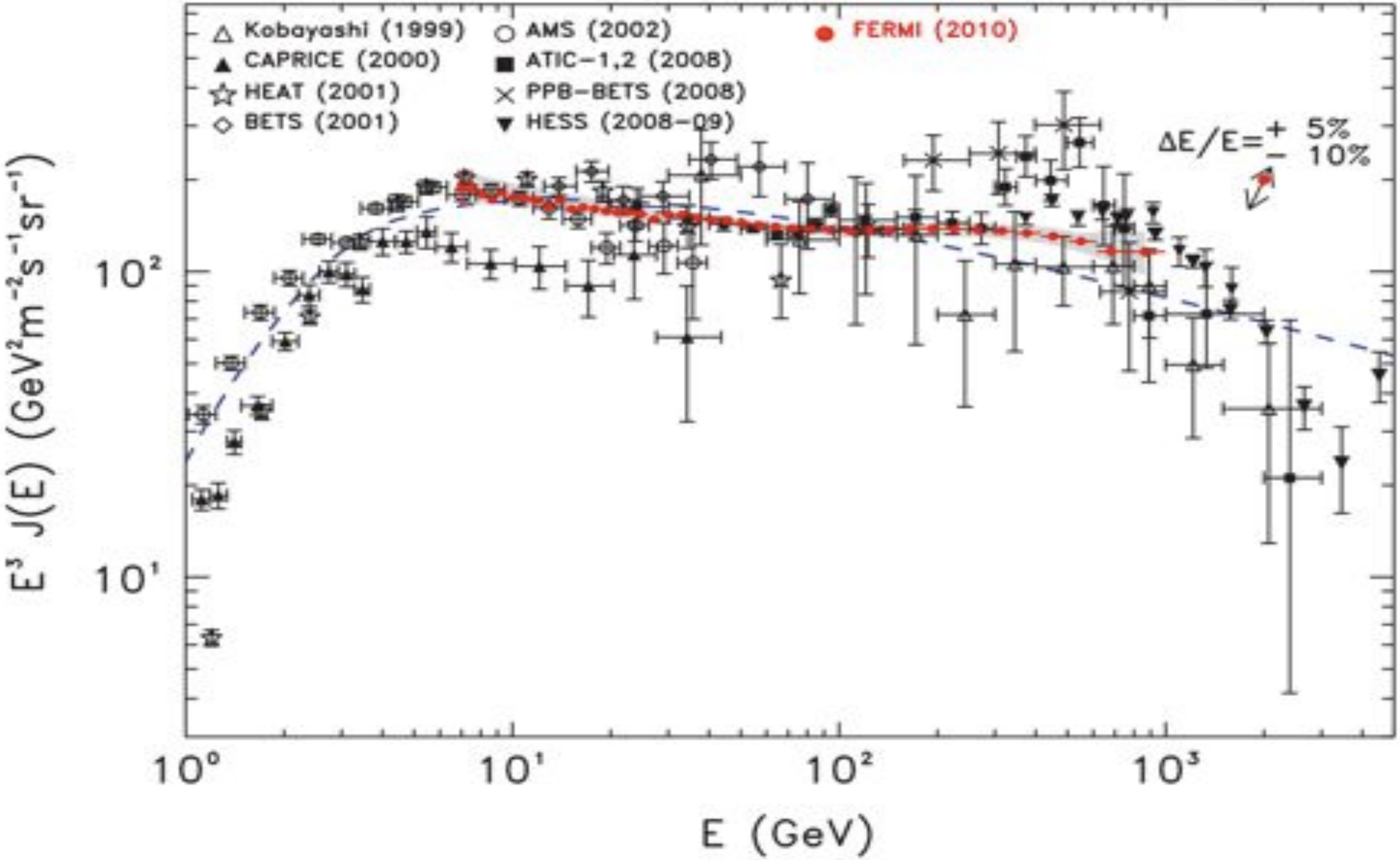
- TKR: clean main track with extra-clusters very close to the track
- CAL: clean EM shower profile, not fully contained
- ACD: few hits in conjunction with the track

A candidate hadron
(raw energy > 800 GeV)



- TKR: small number of extra clusters around main track
- CAL: large and asymmetric shower profile
- ACD: large energy deposit per tile

Fermi Electron + Positron spectrum

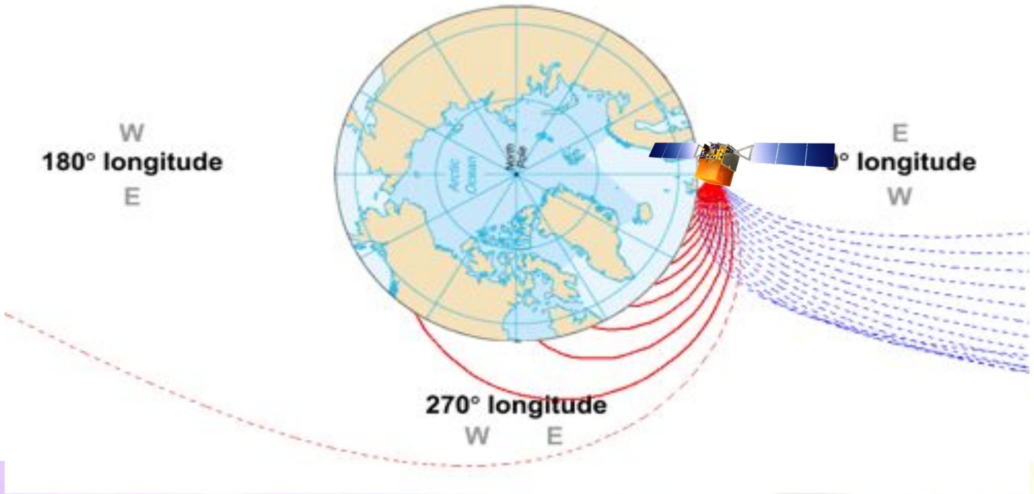


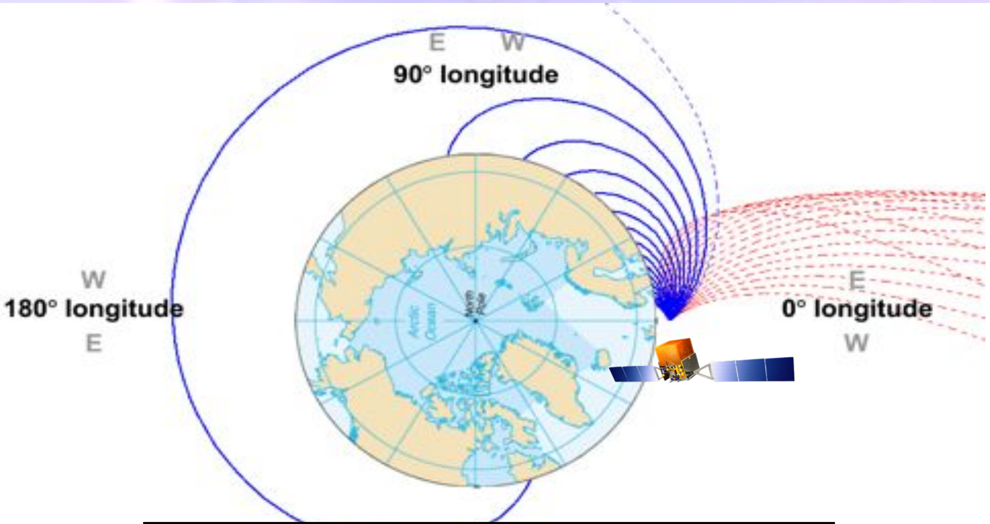
Extended Energy Range (7 GeV – 1 TeV) One year statistics (8M evts)

Fermi LAT Coll. Physical Review D, 82 092004 (2010) [arXiv:1008.3999]

Geomagnetic field + Earth shadow = directions from which only electrons or only positrons are allowed

events arriving from West:
e^+ allowed, e^- blocked

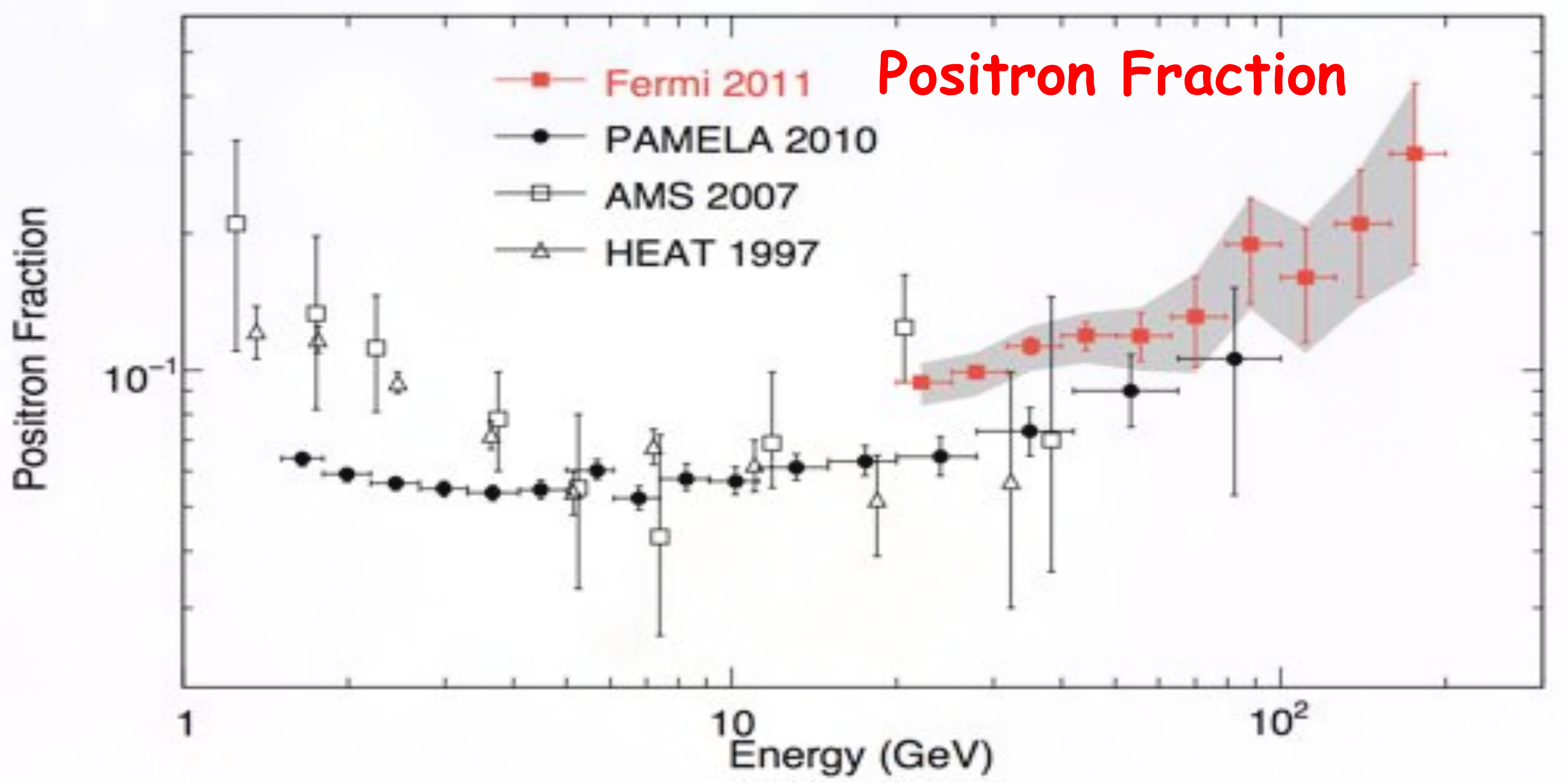




events arriving from East:
e^- allowed, e^+ blocked

- For some directions, e^- or e^+ forbidden
- Pure e^+ region looking West and pure e^- region looking East
- Regions vary with particle energy and spacecraft position
- To determine regions, use code by Don Smart and Peggy Shea (numerically traces trajectory in geomagnetic field)
- Using International Geomagnetic Reference Field for the 2010 epoch

Positron Fraction



The Fermi-LAT has measured the cosmic-ray positron and electron spectra separately, between 20 and 130 GeV, using the Earth's magnetic field as a charge discriminator

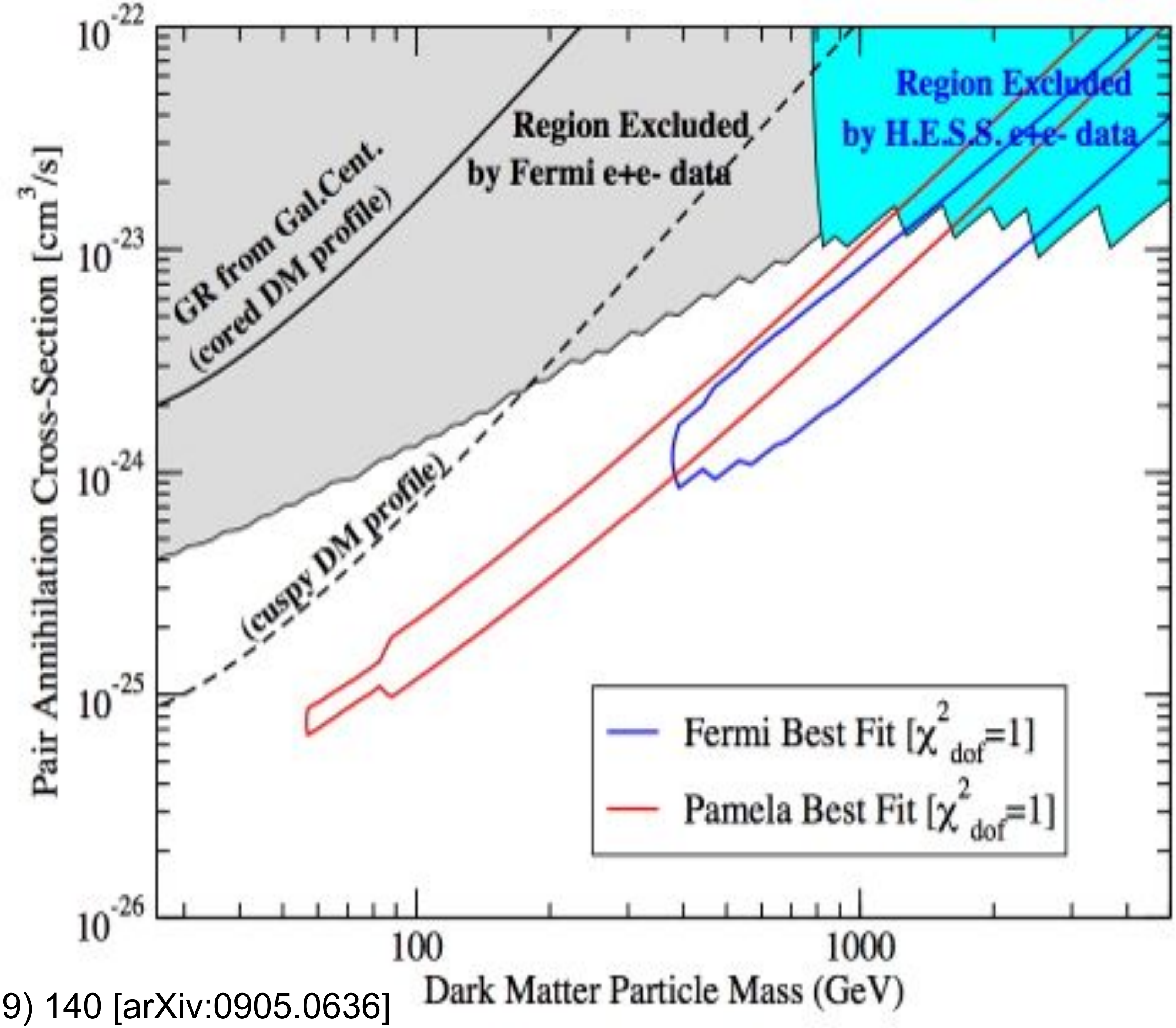
- **Two independent methods of background subtraction produce consistent results**
- **The observed positron fraction is consistent with the one measured by PAMELA**

Differences between different experiments below few GeV's probably due to charge-sign-dependent modulation but still under study

Fermi Coll., PRL, 108 (2012) 011103 arXiv:1109.0521

Lepto-philic Models

here we assume a democratic dark matter pair-annihilation branching ratio into each charged lepton species: 1/3 into e+e-, 1/3 into μ+ μ- and 1/3 into τ+ τ- Here too antiprotons are not produced in dark matter pair annihilation.



Astrp Phys.32 (2009) 140 [arXiv:0905.0636]

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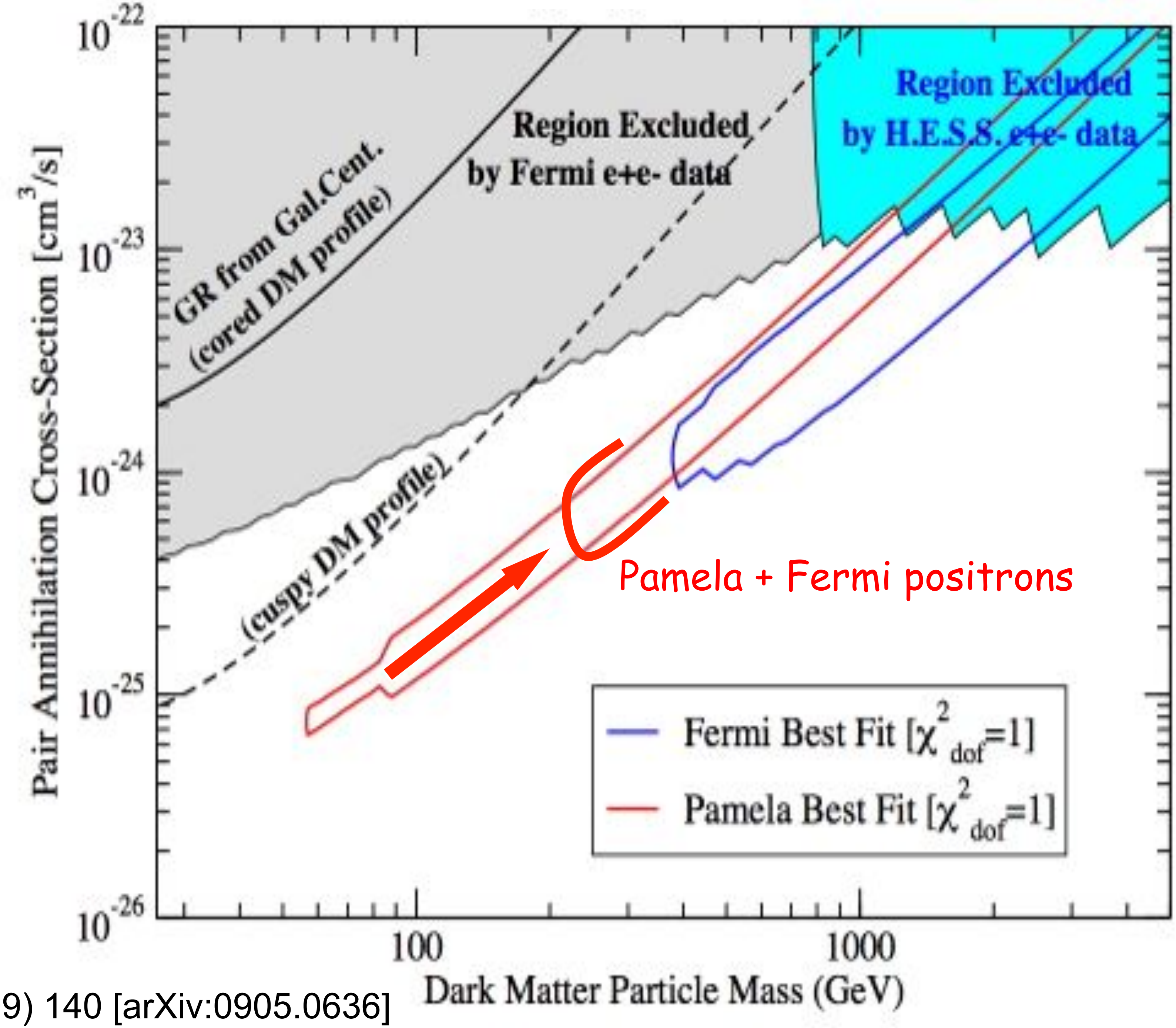


Pamela + Fermi positrons

update of

Astrp Phys.32 (2009) 140 [arXiv:0905.0636]

Pulsars

1. On purely energetic grounds they work (relatively large efficiency)

2. On the basis of the spectrum, it is not clear
    1. The spectra of PWN show relatively flat spectra of pairs at Low energies but we do not understand what it is
    2. The general spectra (acceleration at the termination shock) are too steep

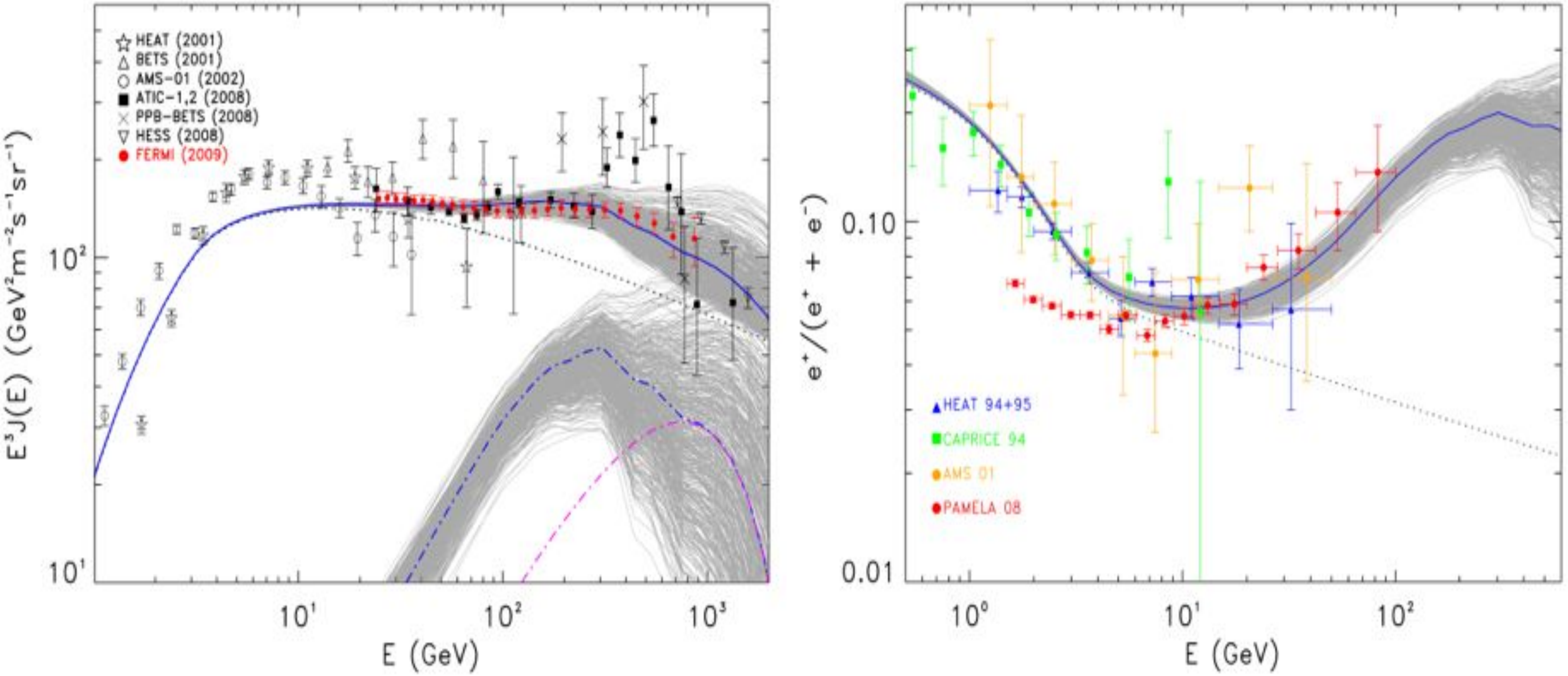
The biggest problem is that of escape of particles from the pulsar

1. Even if acceleration works, pairs have to survive losses
2. And in order to escape they have to cross other two shocks

New Fermi data on pulsars will help to constrain the pulsar models

What if we randomly vary the pulsar parameters relevant for e+e- production?

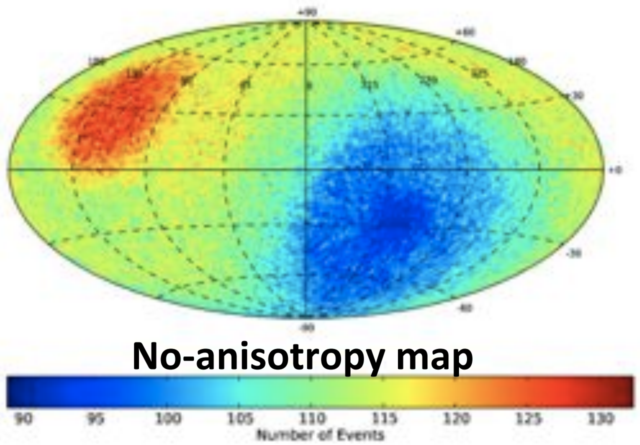
(*injection spectrum, e+e- production efficiency, PWN "trapping" time*)



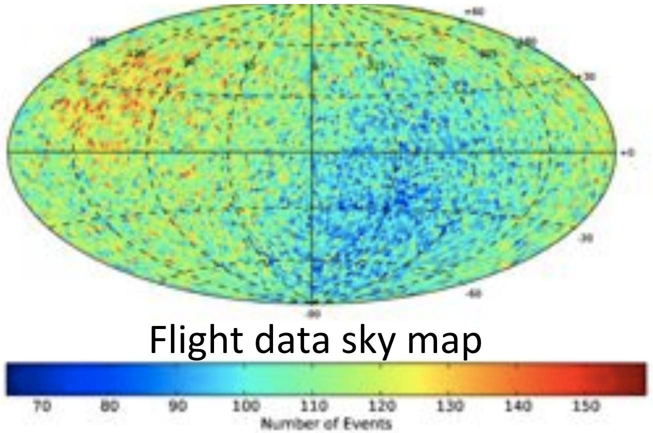
Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results.

D.Grasso et al. Astropart. Phys. 32 (2009), pp.140 [arXiv:0905.0636]

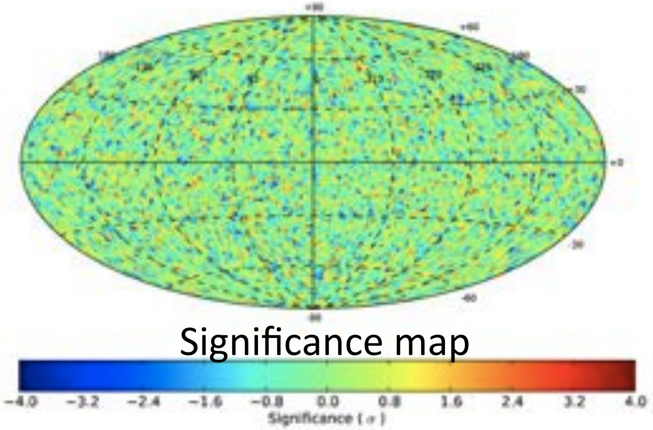
Cosmic Ray Electrons Anisotropy



No-anisotropy map



Flight data sky map

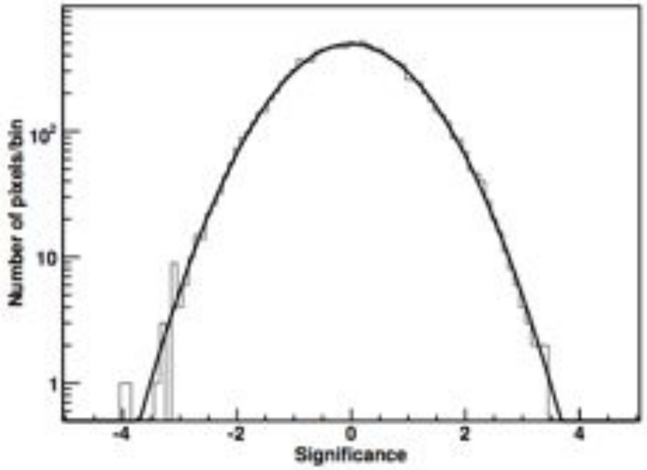


Significance map

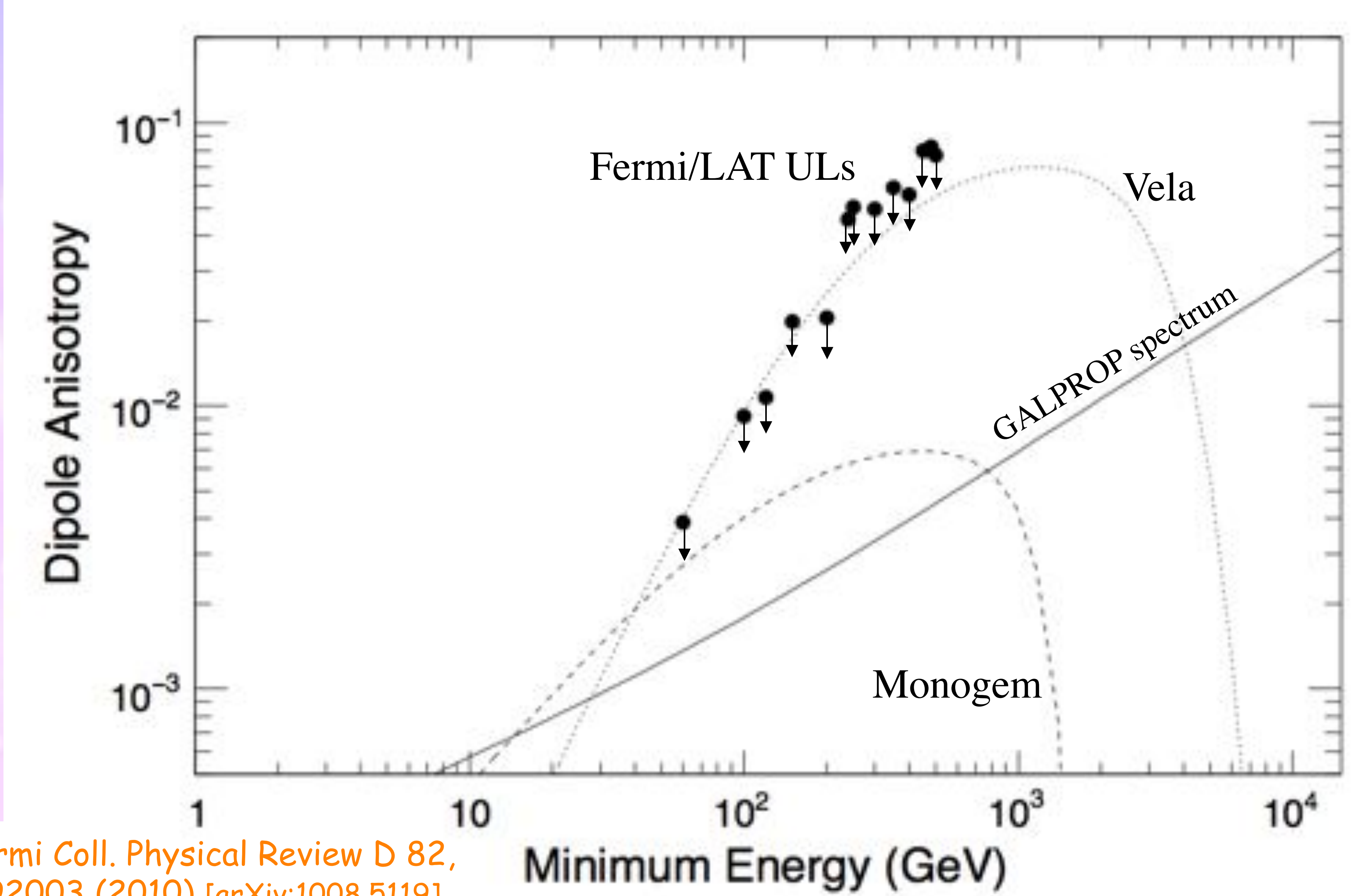
the levels of anisotropy expected for Geminga-like and Monogem-like sources (i.e. sources with similar distances and ages) seem to be higher than the scale of anisotropies excluded by the results However, it is worth to point out that the model results are affected by large uncertainties related to the choice of the free parameters

Distribution of significance, fitted by a Gaussian →

Fermi Coll. Physical Review D 82, 092003 (2010) [arXiv:1008.5119]

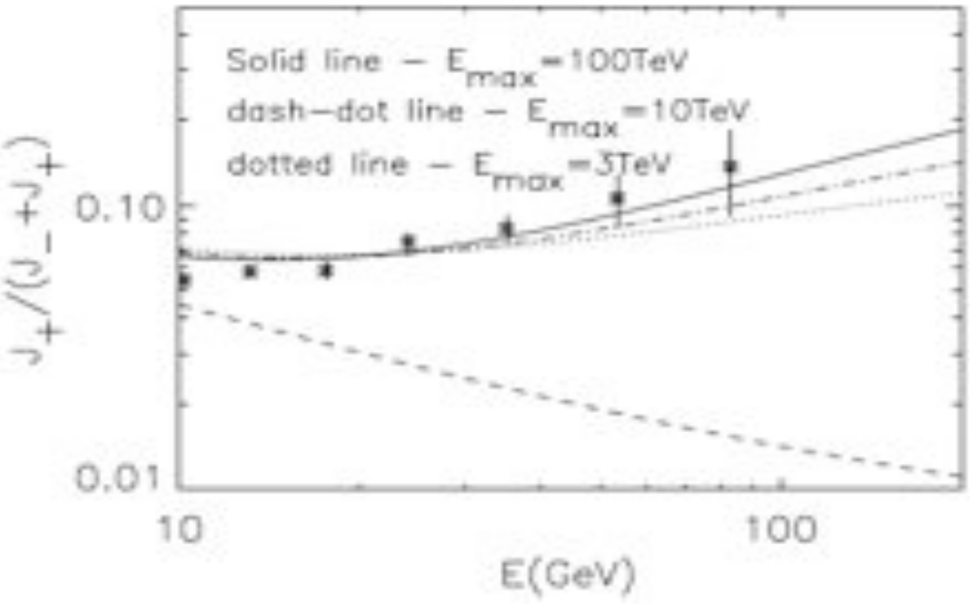


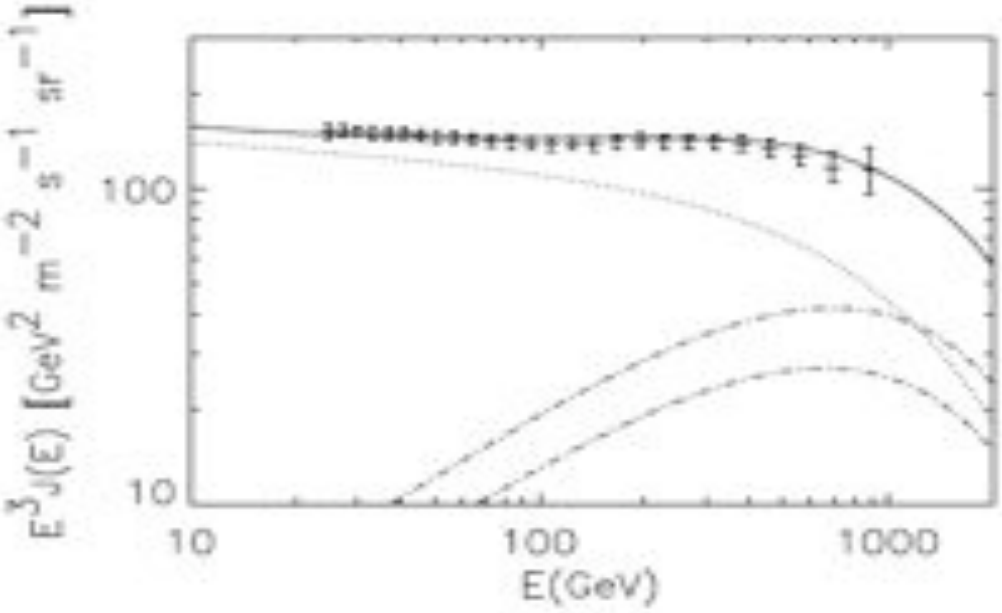
electron + positron expected anisotropy in the directions of Monogem and Vela



Fermi Coll. Physical Review D 82, 092003 (2010) [arXiv:1008.5119]

other Astrophysical solution



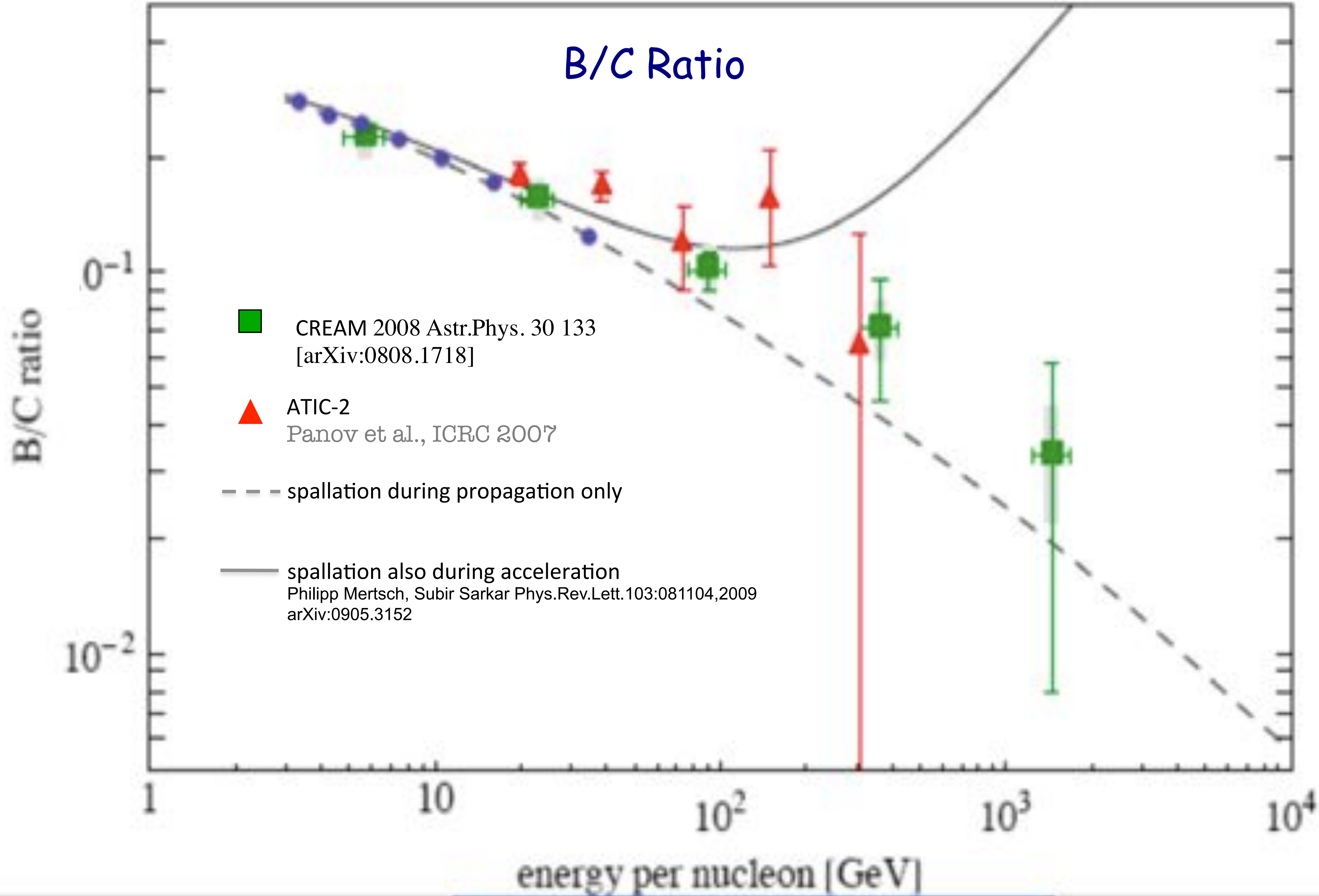


- Positrons created as secondary products of hadronic interactions inside the sources
- Secondary production takes place in the same region where cosmic rays are being accelerated

-> Therefore secondary positron have a very flat spectrum, which is responsible, after propagation in the Galaxy, for the observed positron excess

Blasi, arXiv:0903.2794

B/C Ratio



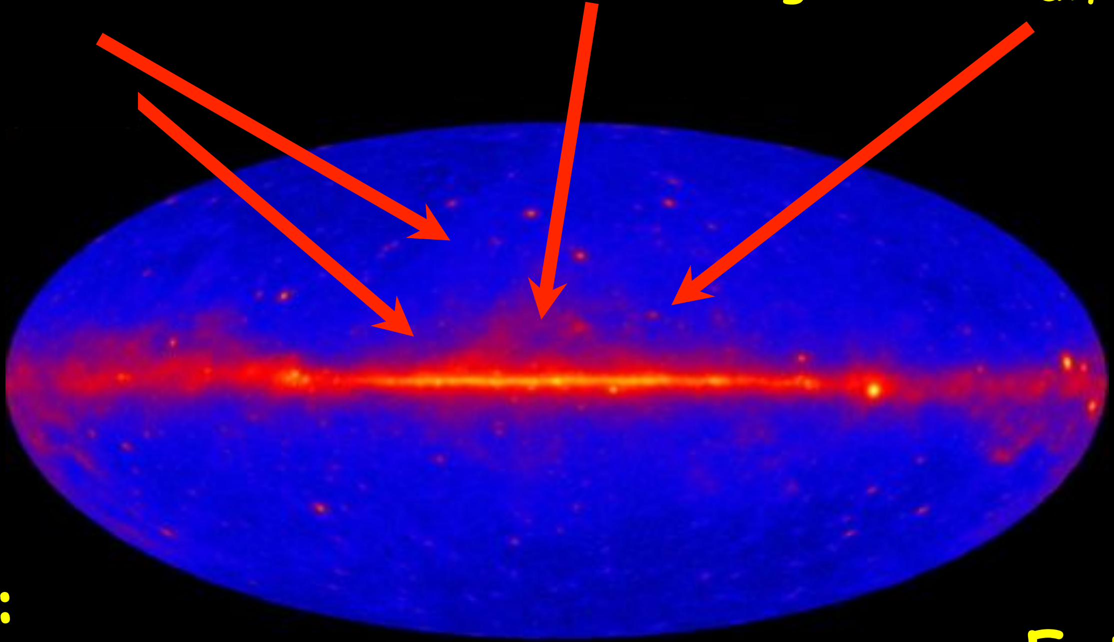
🟩 CREAM 2008 Astr.Phys. 30 133
[arXiv:0808.1718]

▲ ATIC-2
Panov et al., ICRC 2007

- - - spallation during propagation only

— spallation also during acceleration
Philipp Mertsch, Subir Sarkar Phys.Rev.Lett.103:081104,2009
arXiv:0905.3152

Search Strategies



Satellites:

Low background and good source id, but low statistics

Galactic center:

Good statistics but source confusion/diffuse background

Milky Way halo:

Large statistics but diffuse background

And electrons!

and Anisotropies

Spectral lines:

No astrophysical uncertainties, good source id, but low statistics

Galaxy clusters:

Low background but low statistics

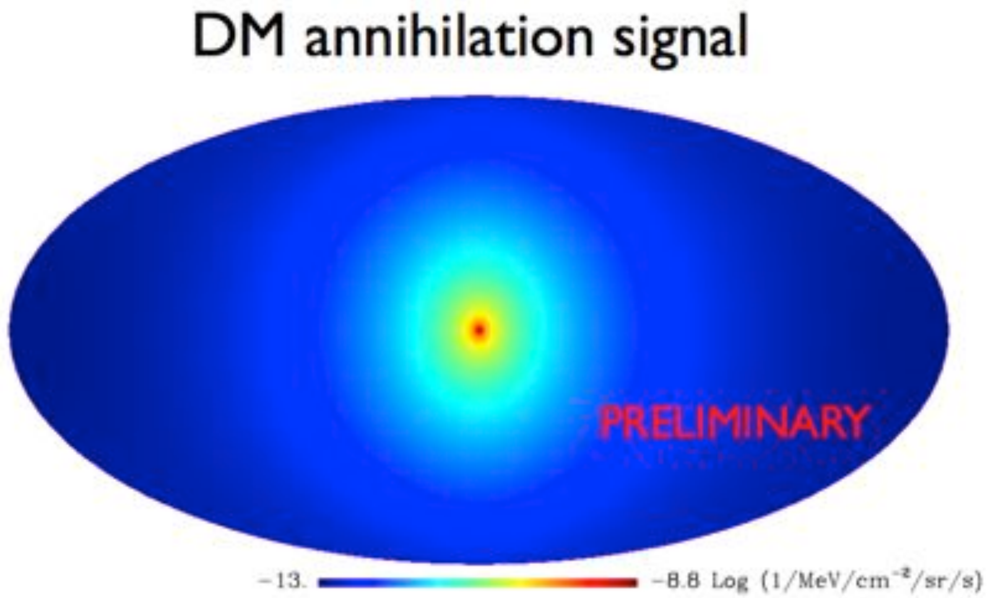
Extra-galactic:

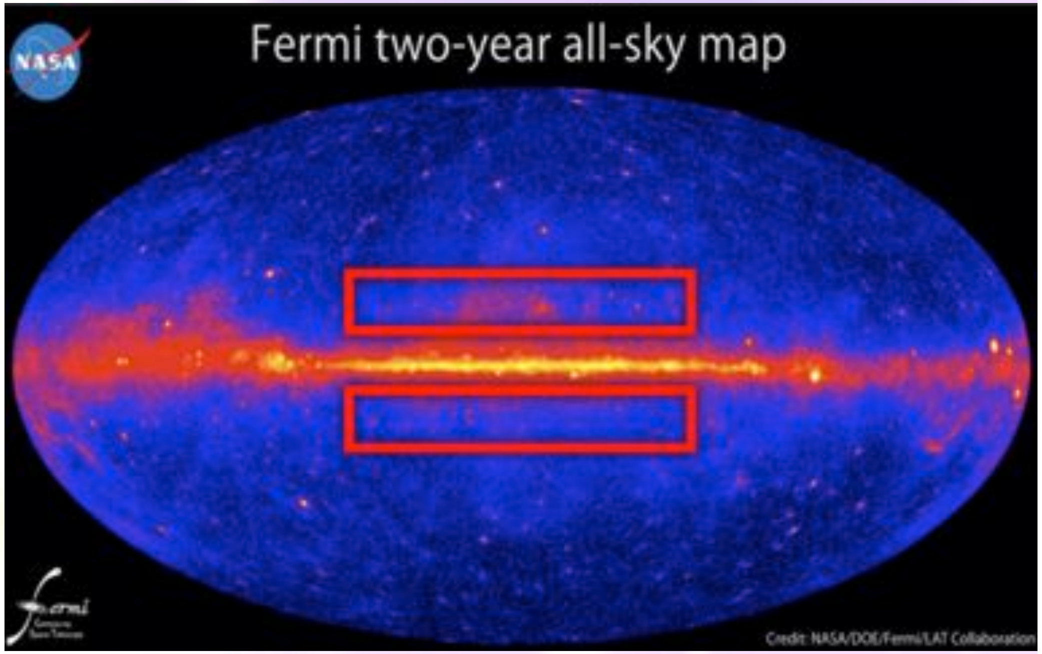
Large statistics, but astrophysics,galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

Constraints from the Milky Way halo

testing the LAT diffuse data for a contribution from a Milky Way DM annihilation/decay signal


DM annihilation signal

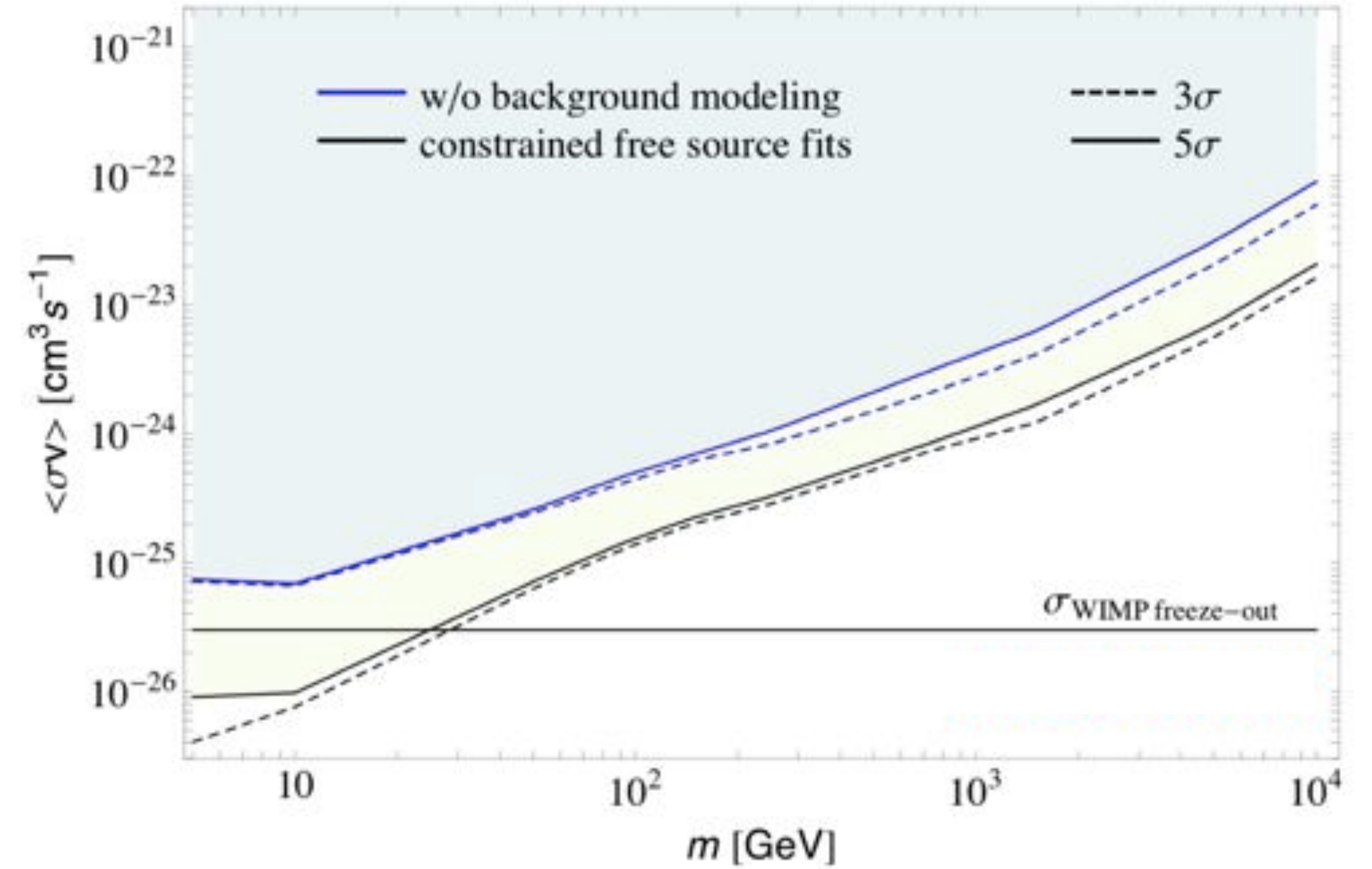

Fermi two-year all-sky map

2 years of data 1-100 GeV energy range

ROI: 5° <|b|<15° and |l|<80°, chosen to:

- minimize DM profile uncertainty (highest in the Galactic Center region)
- limit astrophysical uncertainty by masking out the Galactic plane and cutting-out high- latitude emission from the Fermi lobes and Loop I

Constraints from the Milky Way halo



- Blue = "no-background limits"
- Black = limits obtained by marginalization over the CR source distribution, diffusive halo height and electron injection index, gas to dust ratio, and in which CR sources are held to zero in the inner 3 kpc
- Limits with NFW density profile (not shown) are only slightly stronger

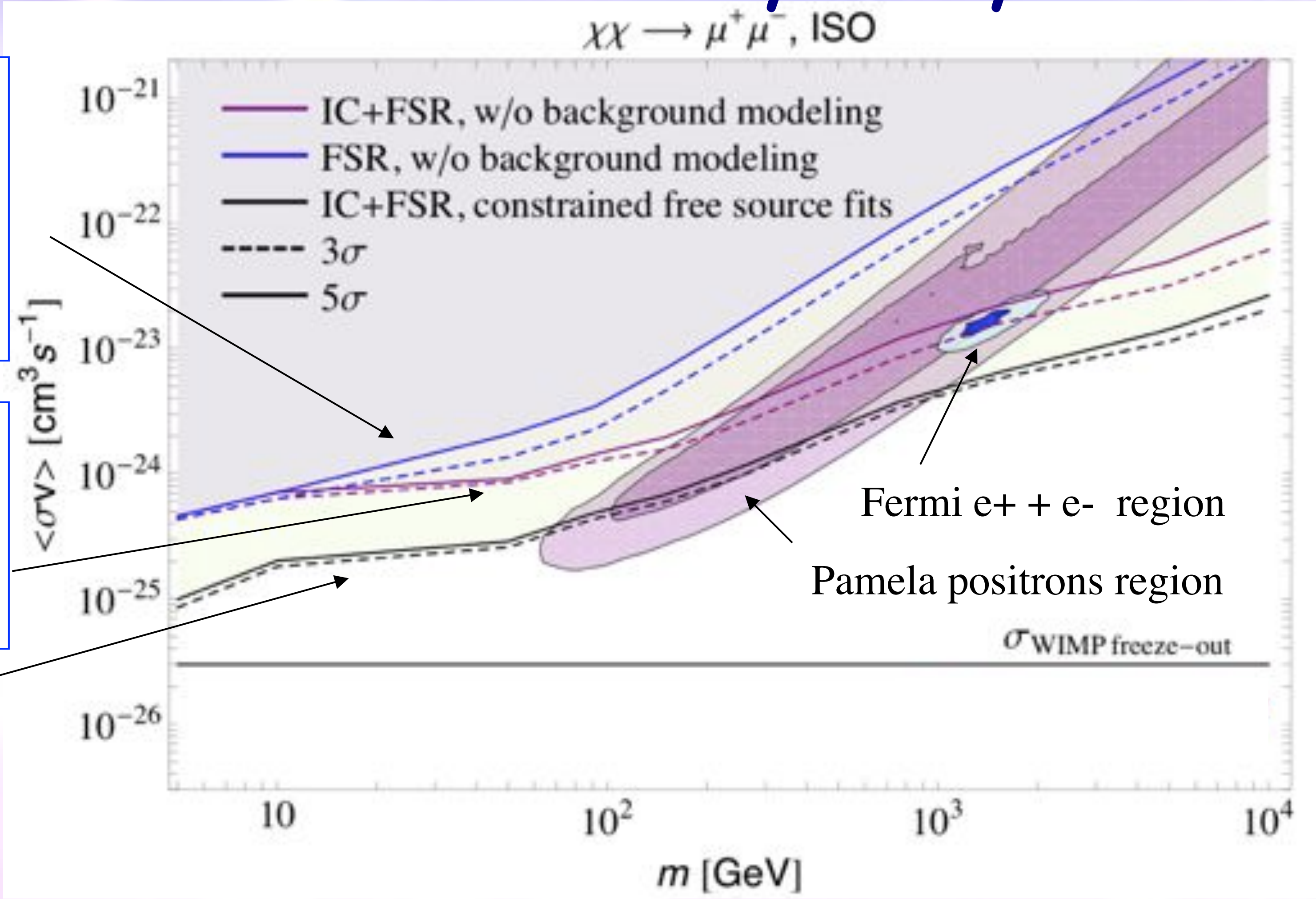
Fermi Coll.ApJ 761 (2012) 91 [arXiv:1205.6474]

Constraints from the Milky Way halo

only photons produced by muons (no electrons) to set "no-background limits"

"no-background limits" including FSR +IC from dark matter

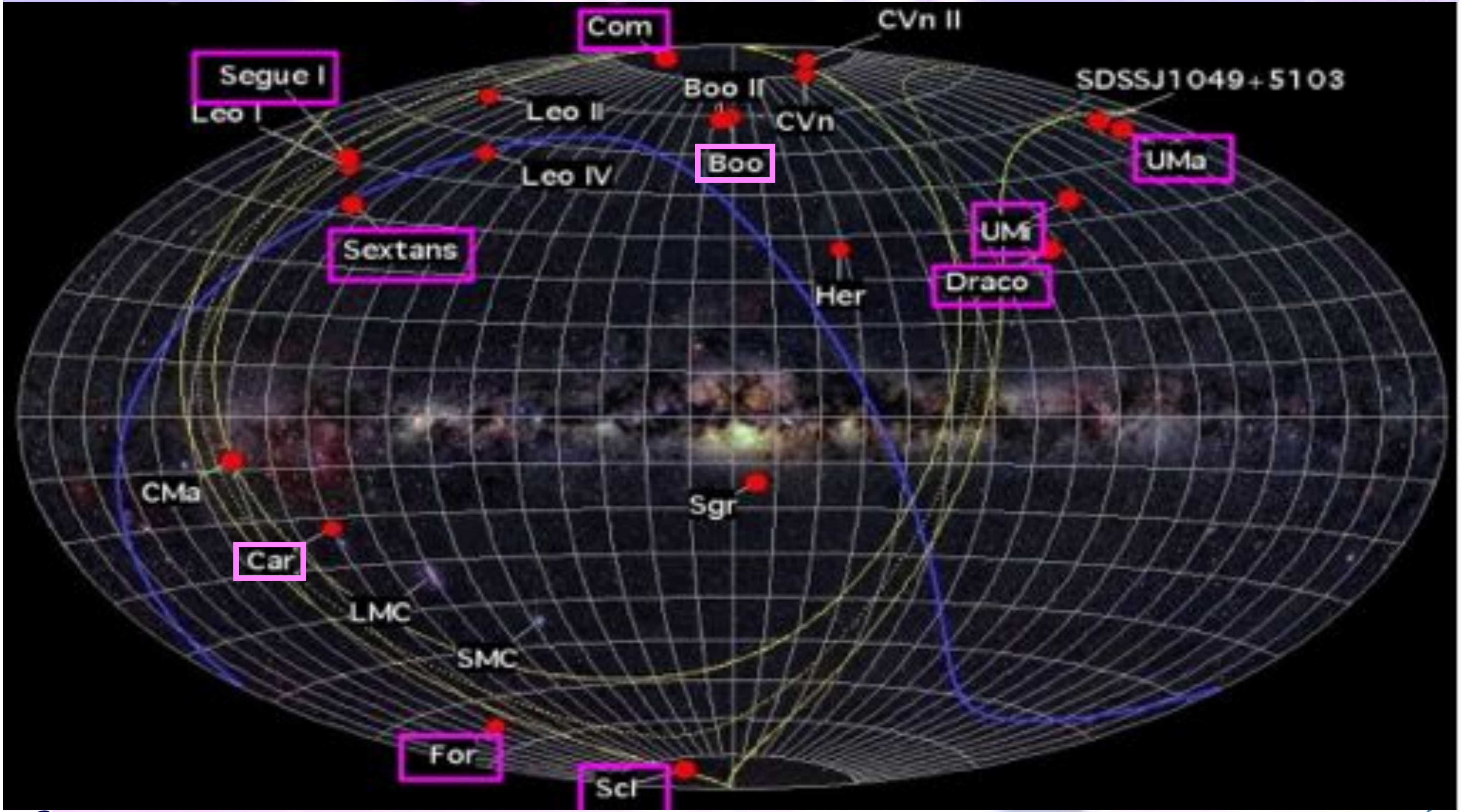
limits from profile likelihood and CR sources set to zero in the inner 3 kpc



DM interpretation of PAMELA/Fermi CR anomalies disfavored

Fermi Coll.ApJ 761 (2012) 91 [arXiv:1205.6474]

Dwarf spheroidal galaxies (dSph) : promising targets for DM detection

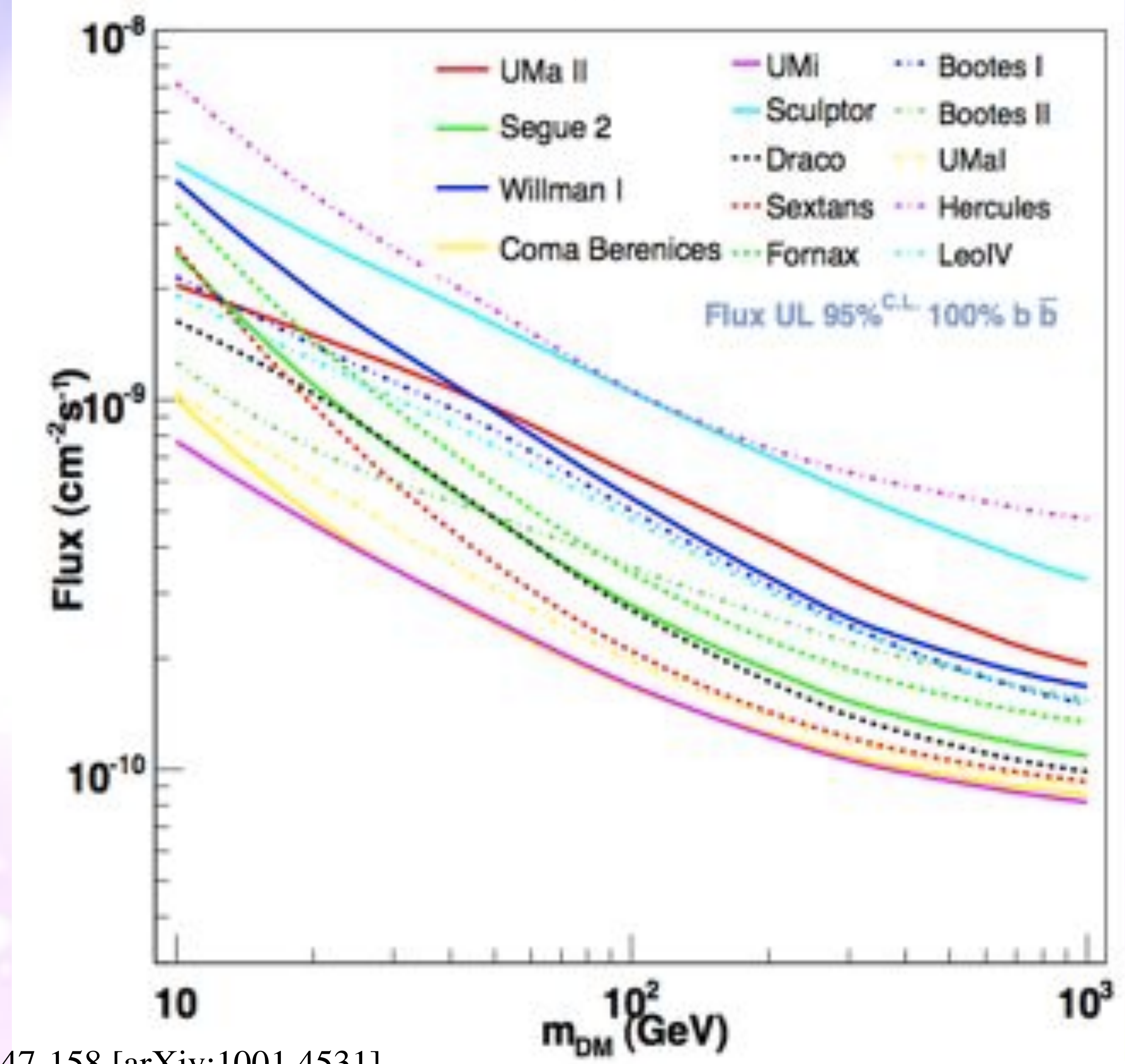


Dwarf Spheroidal Galaxies upper-limits

No detection by Fermi with 11 months of data. 95% flux upper limits are placed for several possible annihilation final states.

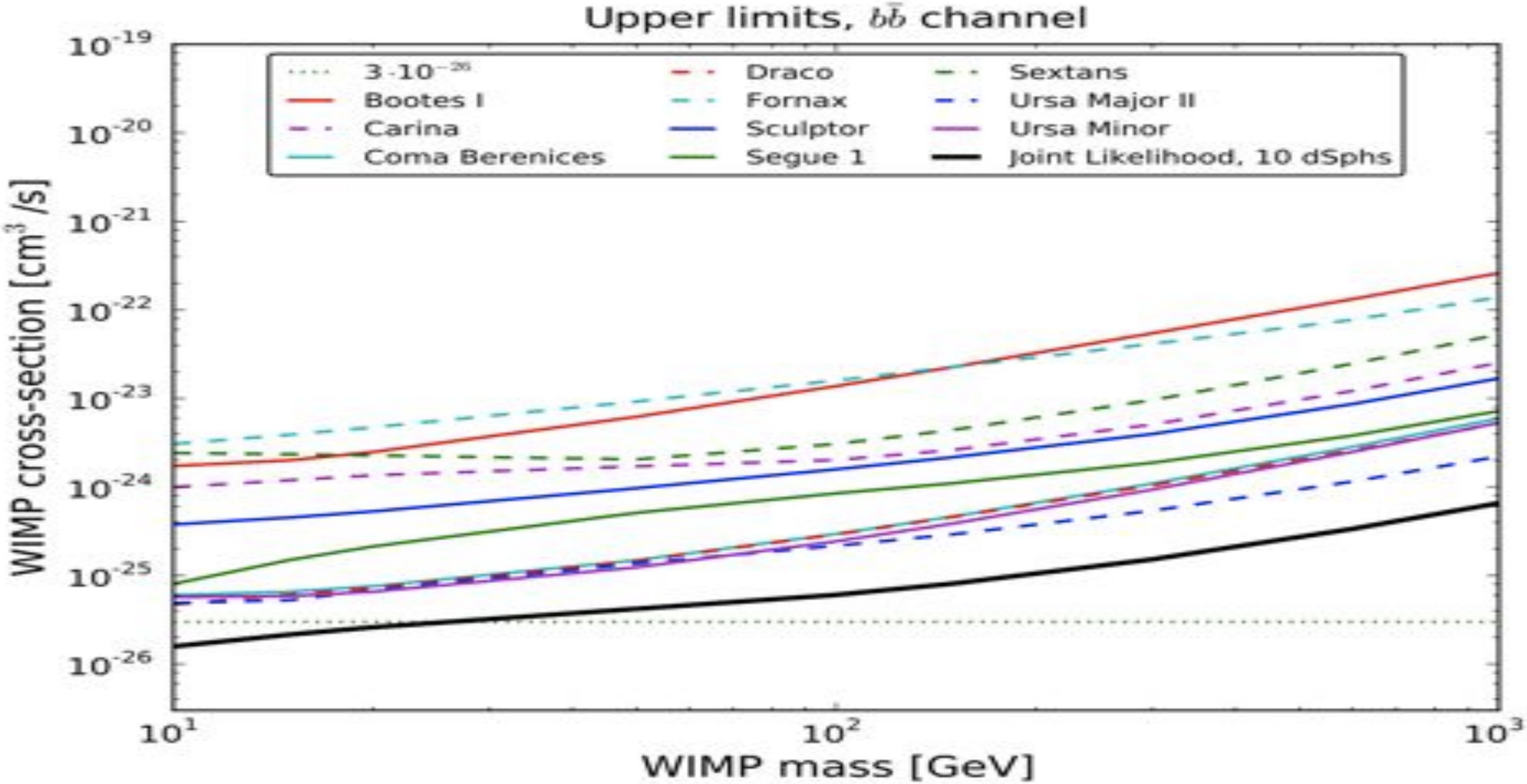
- Flux upper limits are combined with the DM density inferred by the stellar data[(*)]for a subset of 8 dSph (based on quality of stellar data) to extract constraints on < σ v> vs WIMP mass for specific DM models

(*) stellar data from the Keck observatory (by Martinez, Bullock, Kaplinghat)



Fermi Coll. ApJ 712 (2010) 147-158 [arXiv:1001.4531]

Dwarf Spheroidal Galaxies combined analysis

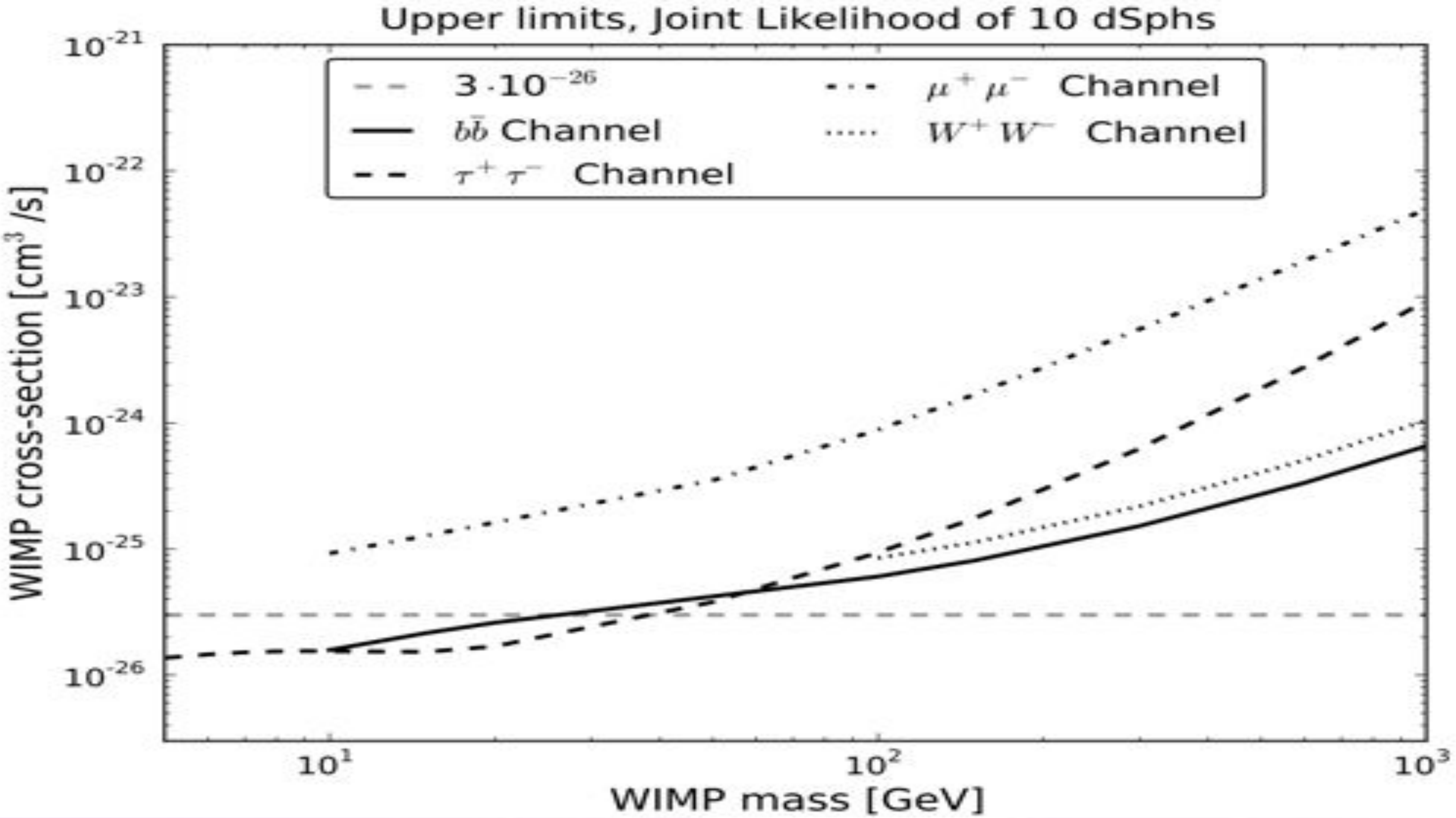


robust constraints including J-factor uncertainties from the stellar data statistical analysis

NFW. For cored dark matter profile, the J-factors for most of the dSphs would either increase or not change much

Fermi Lat Coll., PRL 107, 241302 (2011) [arXiv:1108.3546]

Dwarf Spheroidal Galaxies combined analysis



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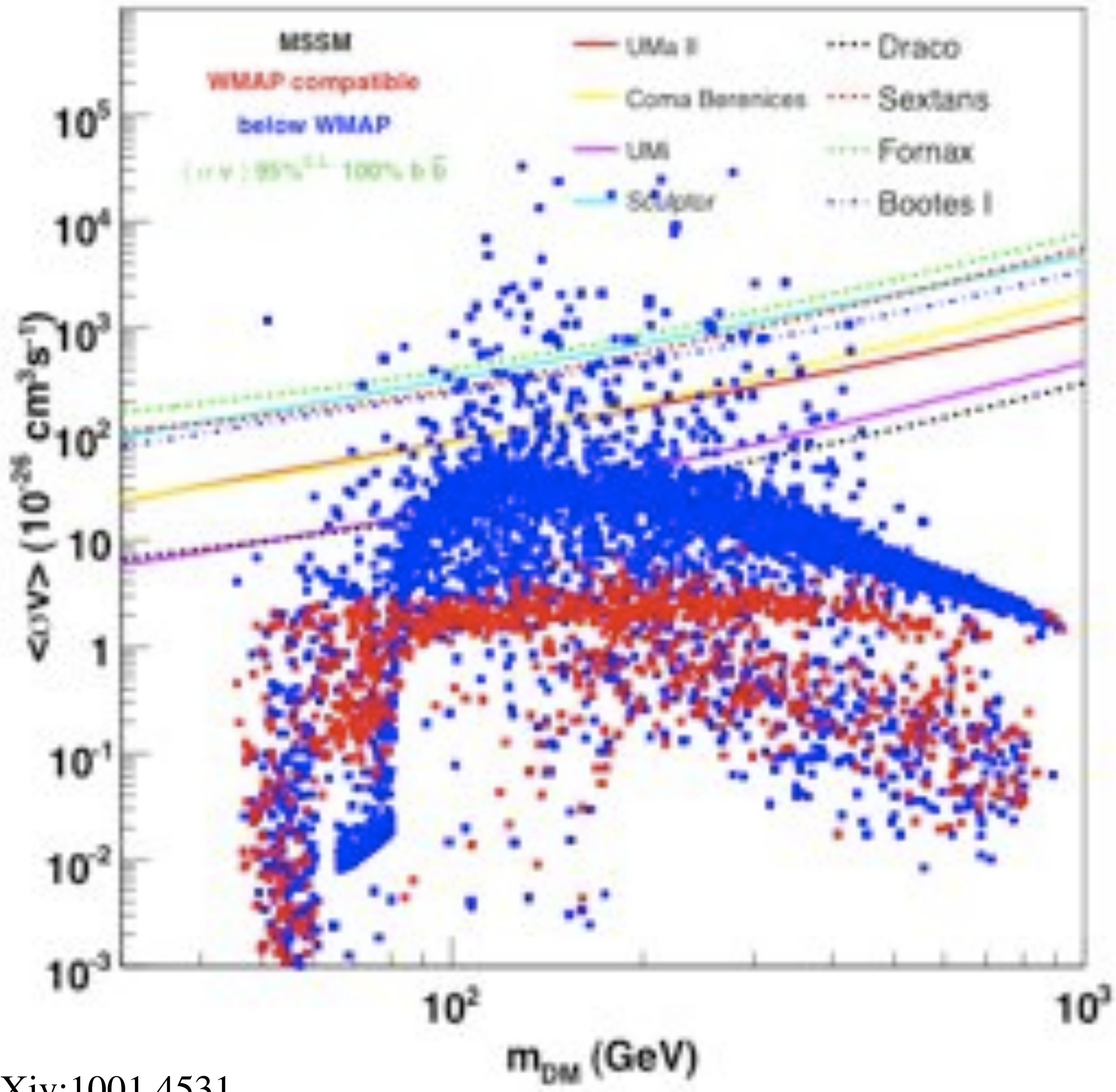
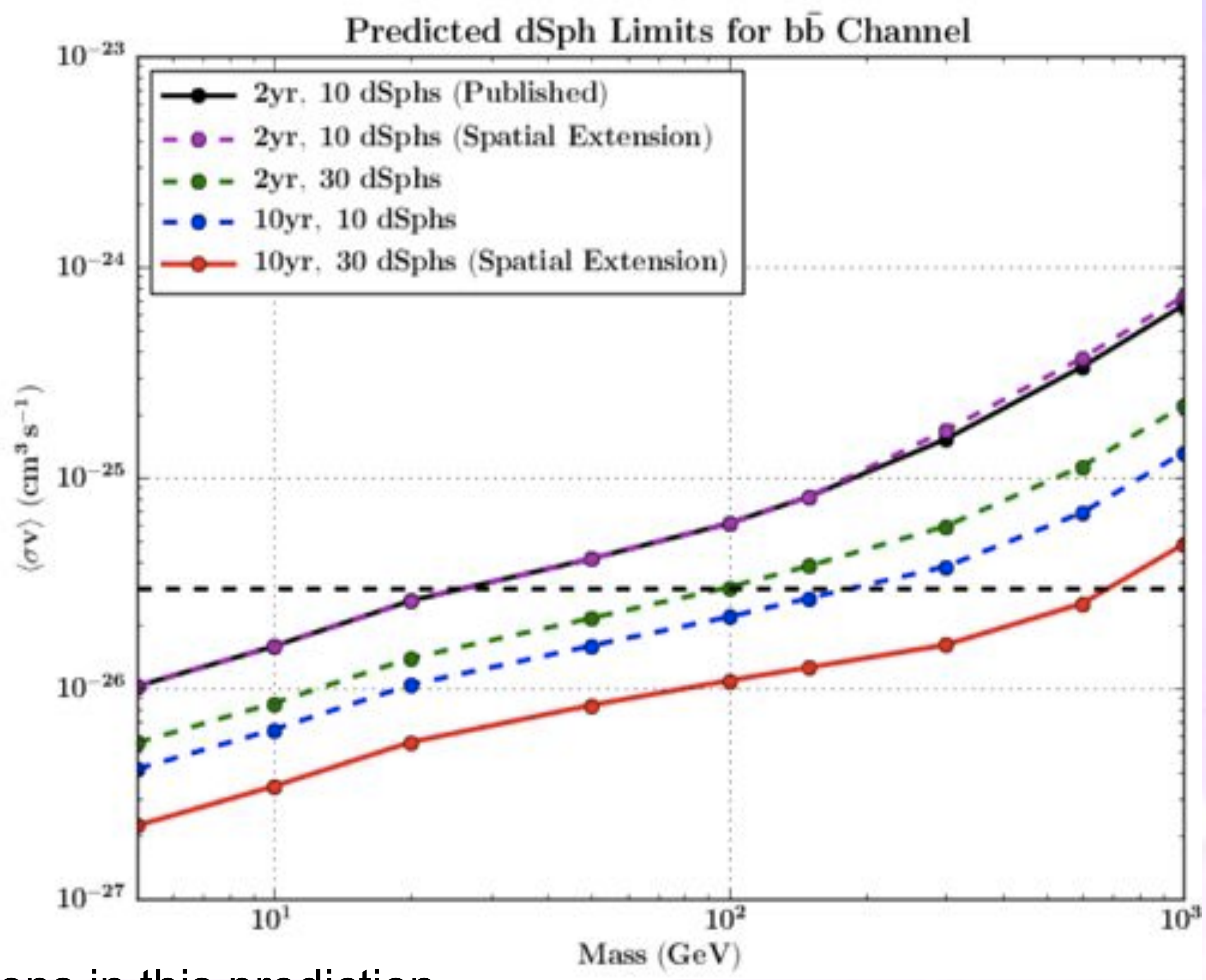


Fermi Coll. ApJ 712 (2010) 147-158 arXiv:1001.4531

DM limit improvement estimate in 10 years with the composite likelihood approach (2008- 2018)

- 10 years of data instead of 2(5x)
- 30 dSphs (3x) (supposing that the new optical surveys will find new dSph)
- -10% from spatial extension (source extension increases the signal region at high energy E > 10 GeV, M > 200 GeV)

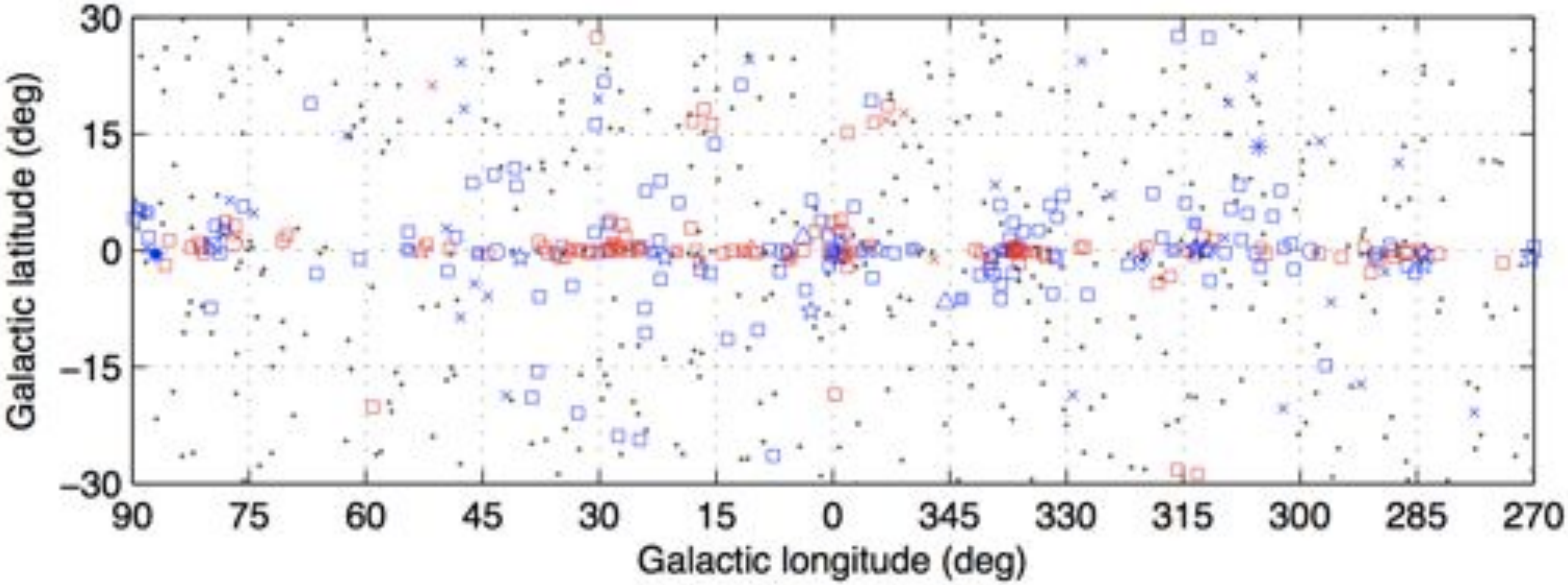


- There are many assumptions in this prediction
- Doesn’t deal with a possible detections.

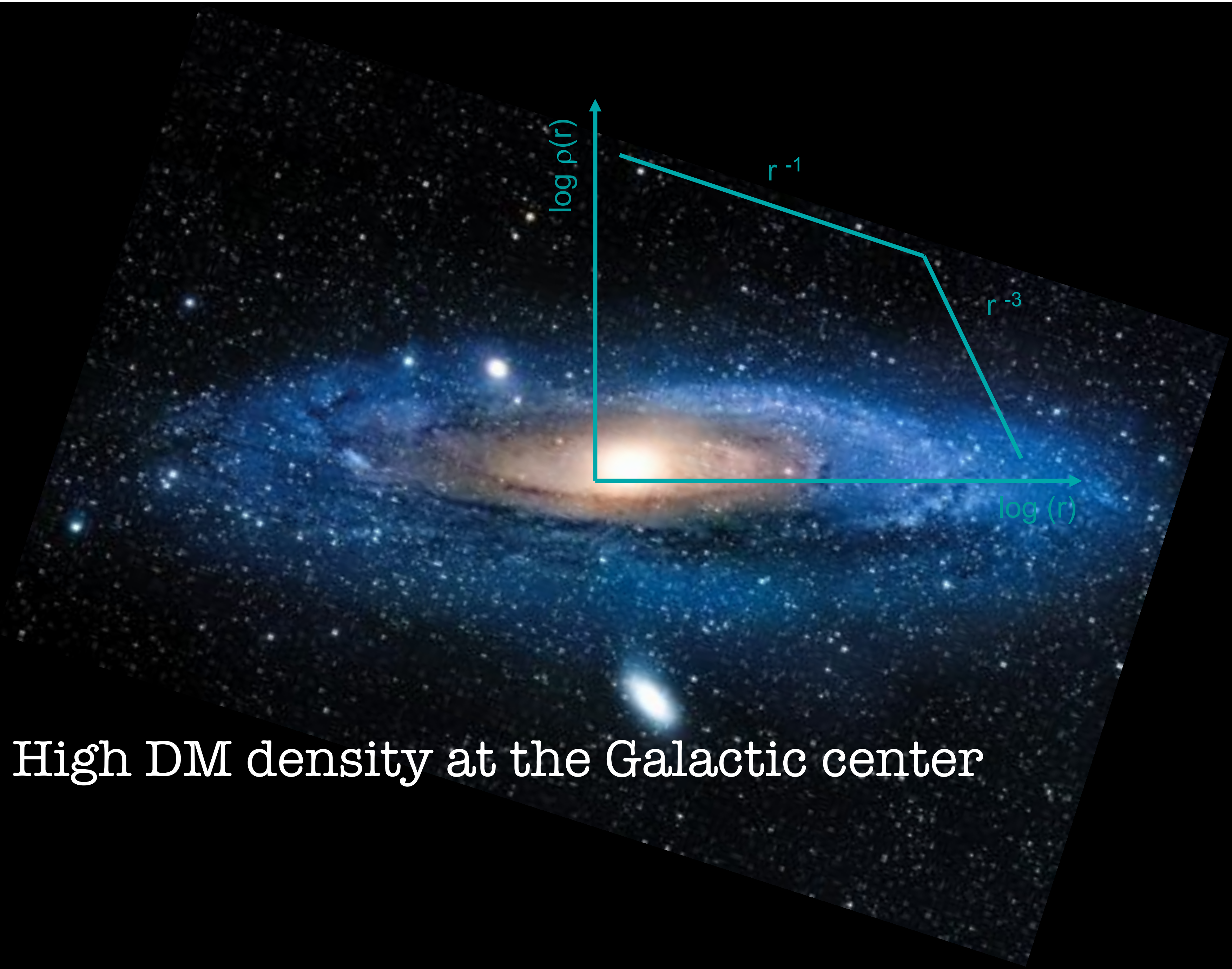
The Fermi LAT 2FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range



Fermi Coll. ApJS (2012) 199, 31
arXiv:1108.1435



High DM density at the Galactic center

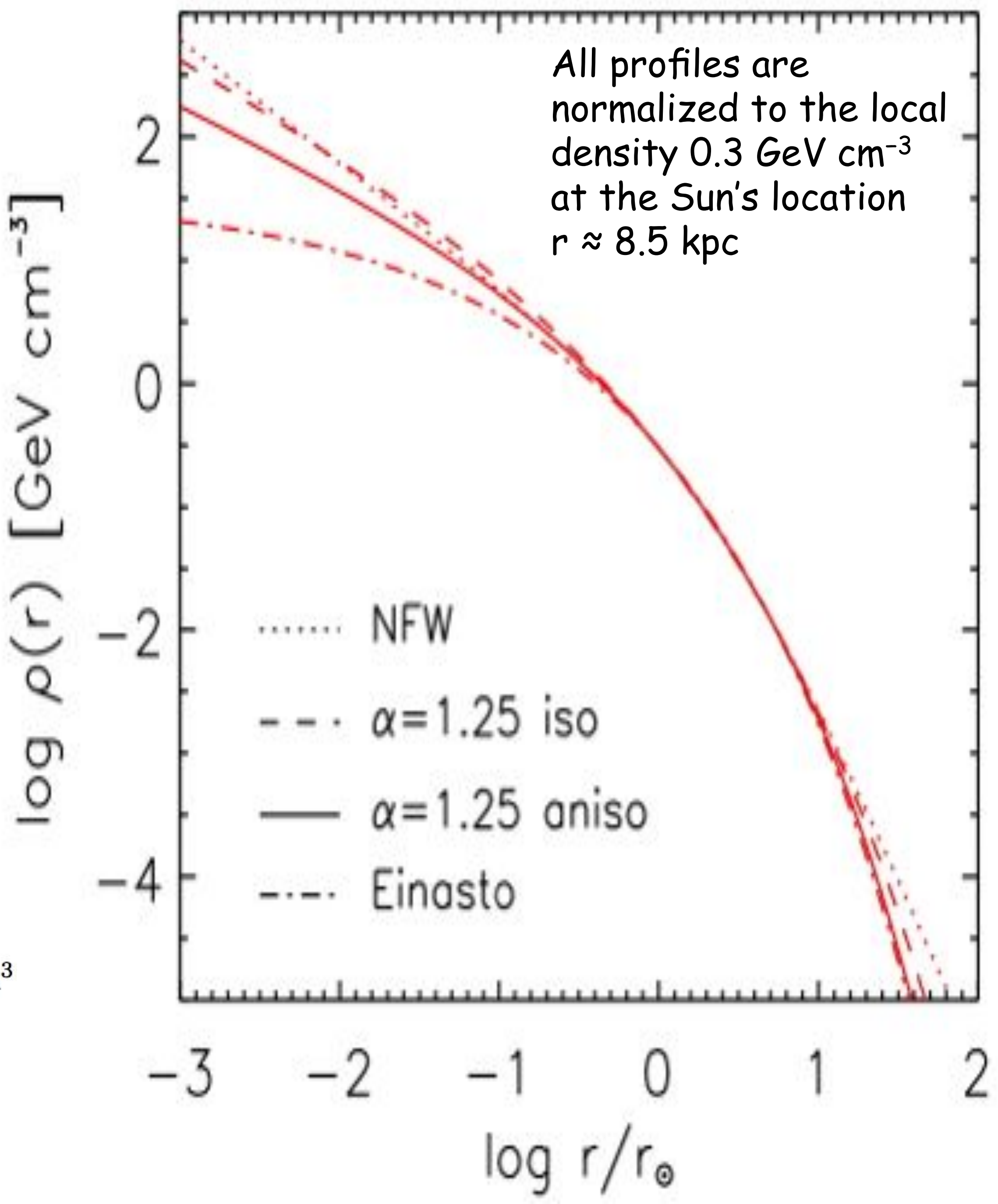
Milky Way Dark Matter Profiles

$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1+(r_\odot/r_s)^\alpha}{1+(r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

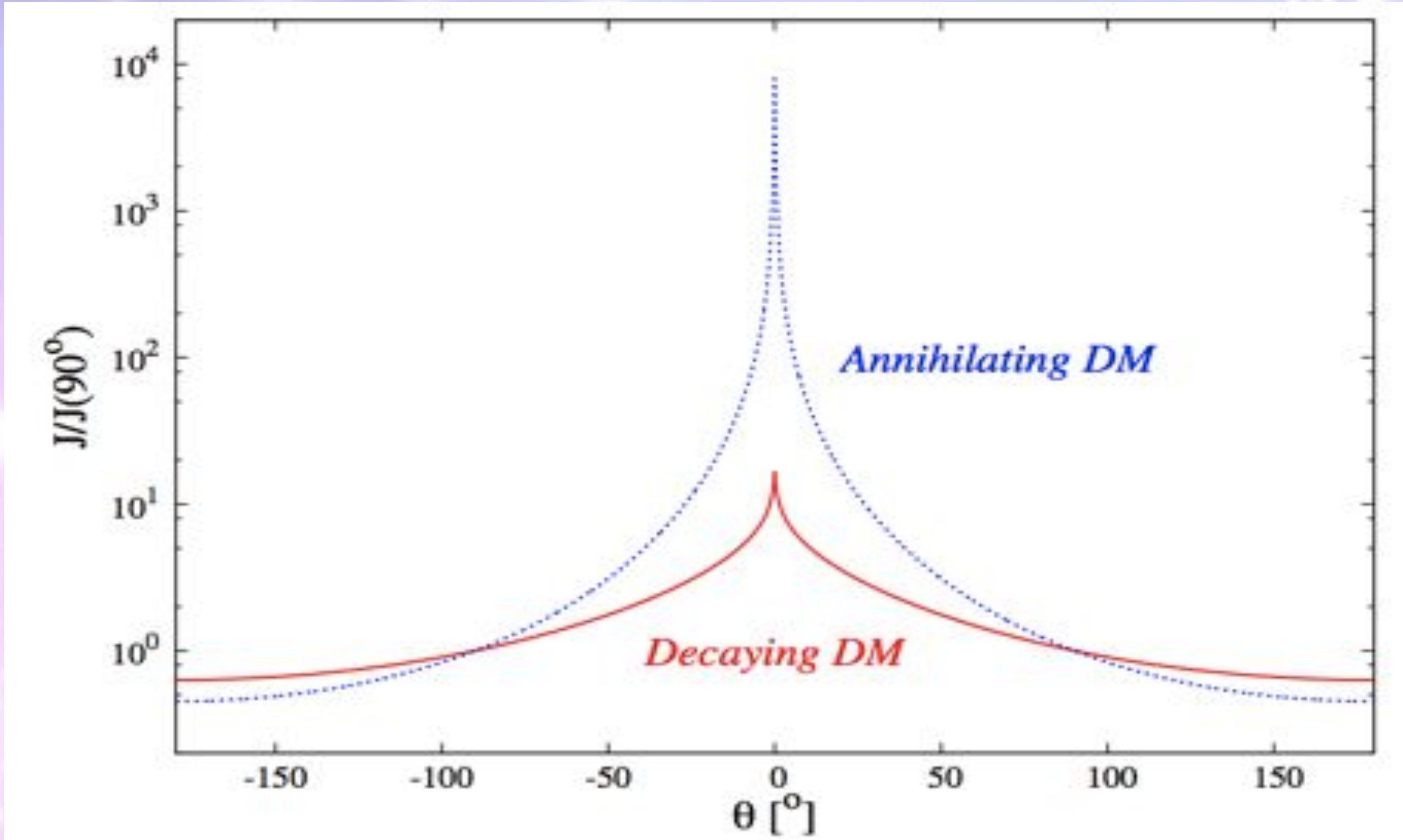
Einasto | $\alpha = 0.17$ $r_s = 20\,\mathrm{kpc}$ $\rho_s = 0.06\,\mathrm{GeV/cm^3}$

A.Lapi et al. arXiv:0912.1766



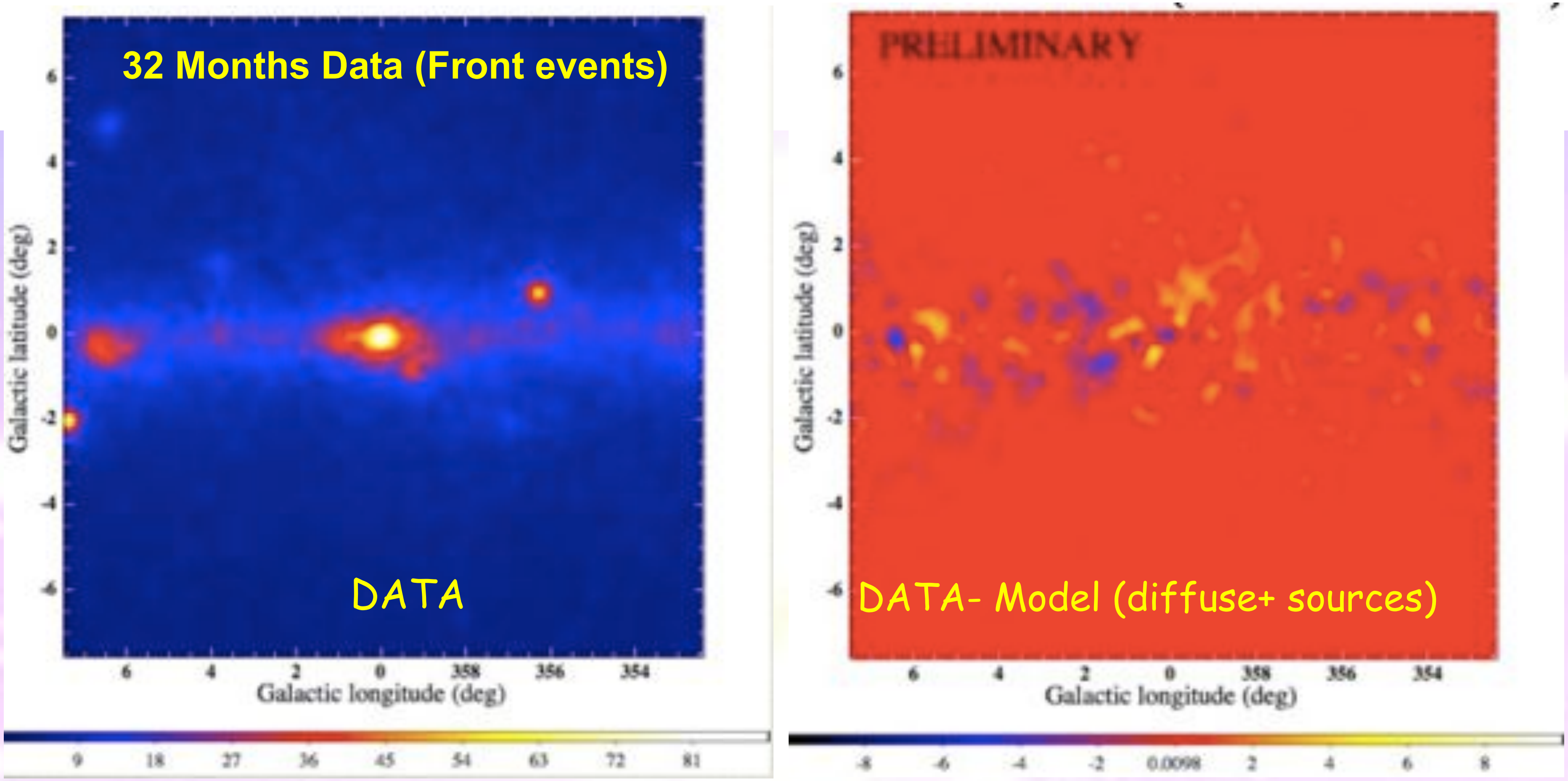
All profiles are normalized to the local density 0.3 GeV cm^{-3} at the Sun's location r ≈ 8.5 kpc

Different spatial behaviour for decaying or annihilating dark matter



The angular profile of the gamma-ray signal is shown, as function of the angle θ to the centre of the galaxy for a Navarro-Frenk-White (NFW) halo distribution for decaying DM, solid (red) line, compared to the case of self-annihilating DM, dashed (blue) line

Residual Emission for 15 * 15 degrees around the Galactic center

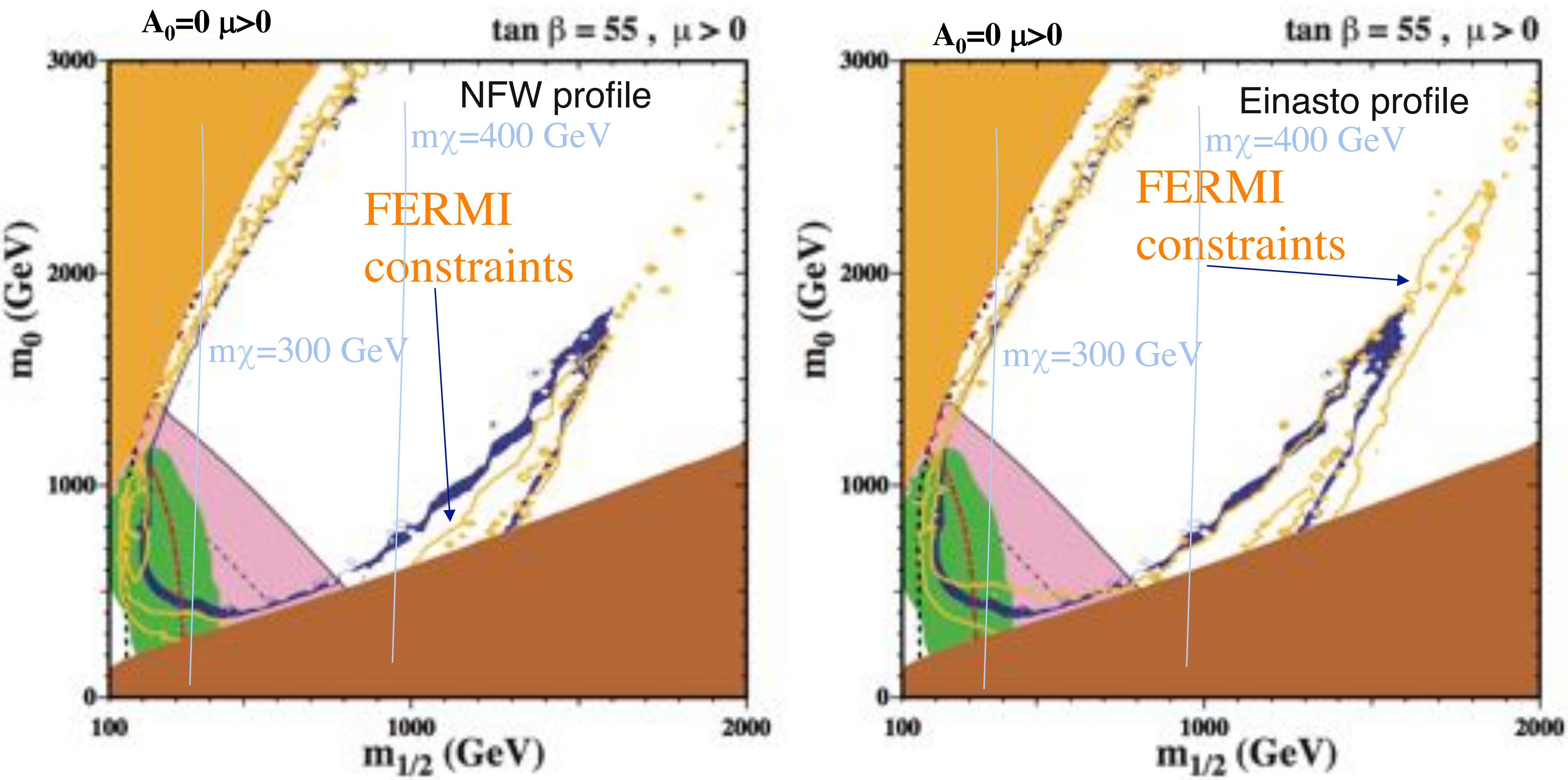


Diffuse emission and point sources account for most of the emission observed in the region.

Low-level residuals remain, the interpretation of these is work in-progress

Papers are forthcoming and will include dark matter results.

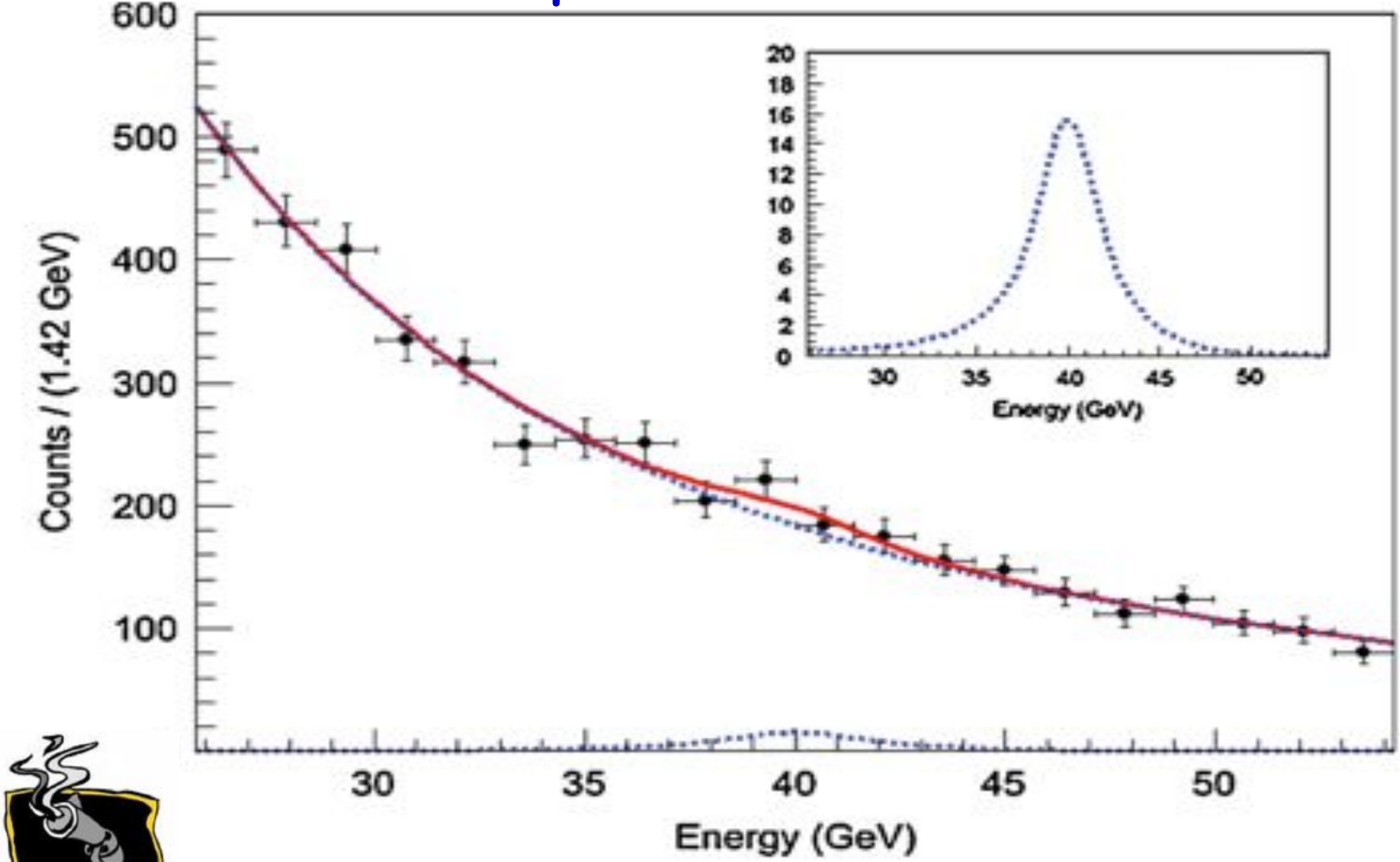
Galactic-Centre Gamma Rays in CMSSM Dark Matter Scenarios



The constraints due to the absences of charginos and the Higgs boson at LEP are also shown, as black dashed and red dot-dashed lines, respectively. Regions excluded by the requirements of electroweak symmetry breaking and a neutral LSP are shaded dark pink and brown, respectively. The green region is excluded by b → sγ, and the pink region is favoured by the supersymmetric interpretation of the discrepancy between the Standard Model calculation and the experimental measurement of $g_\mu - 2$ within 1 and 2 standard deviations (dashed and solid lines, respectively)

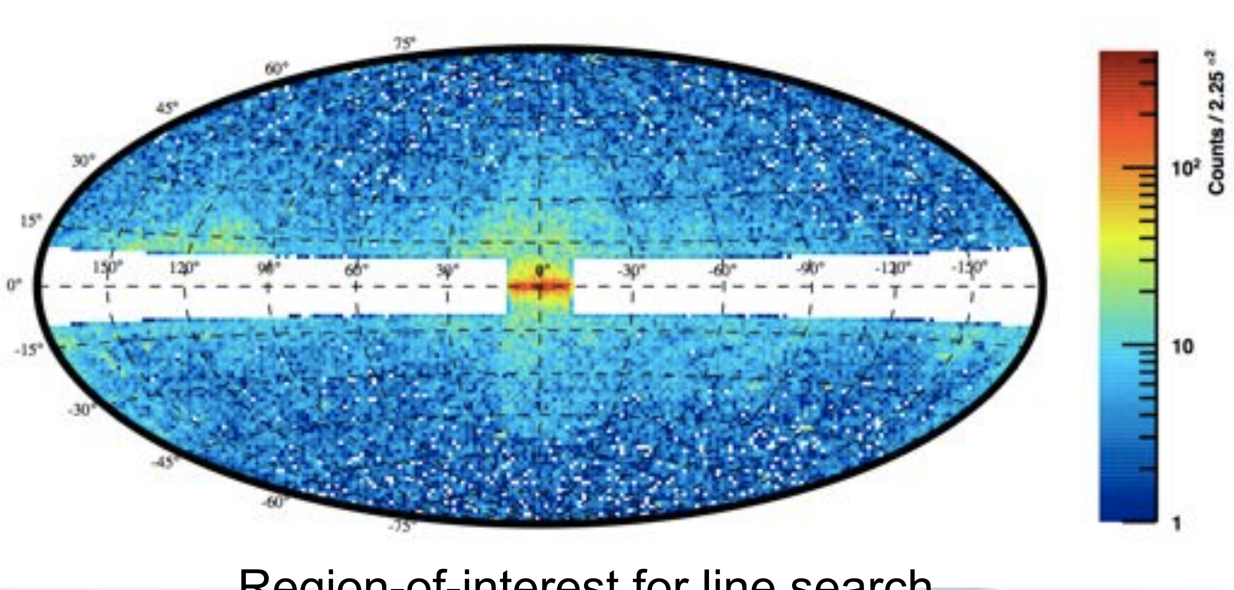
Ellis et al., arXiv:1106.0768

Wimp lines search



Search for Spectral Gamma Lines

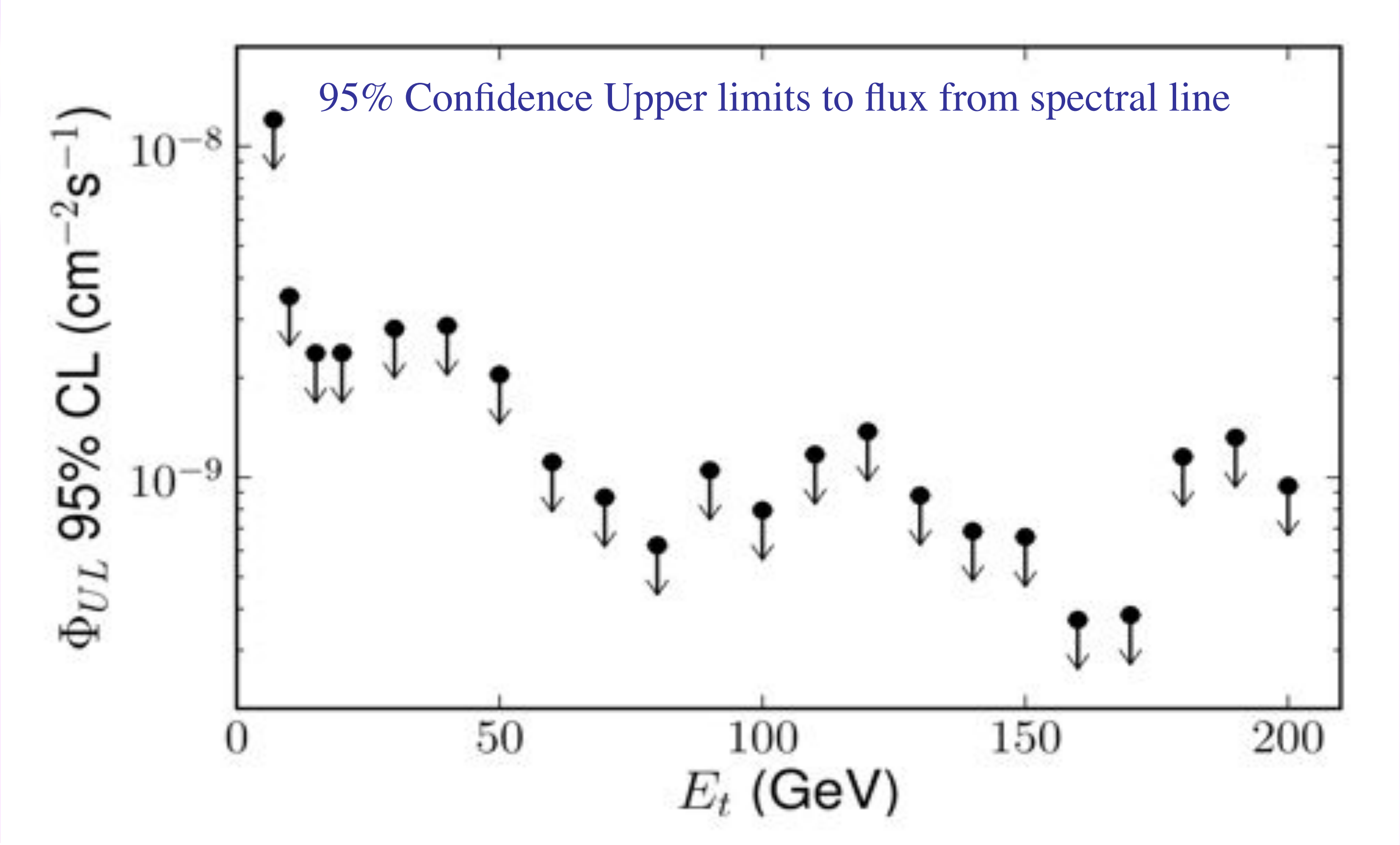
- Smoking gun signal of dark matter
- Search for lines in the first 23 months of Fermi data (7-200 GeV en.range)
- Search region |b|>10° plus a 20°x 20° square centered at the galactic center
- For the region within 1°of the GC, no point source removal was done as this would have removed the GC
- For the remaining part of the ROI, point sources were masked from the analysis using a circle of radius 0.2 deg
- The data selection includes additional cuts to remove residual charged particle contamination.



Region-of-interest for line search

Fermi LAT 23 Month Line search results
Flux Upper Limits, 7 GeV - 200 GeV

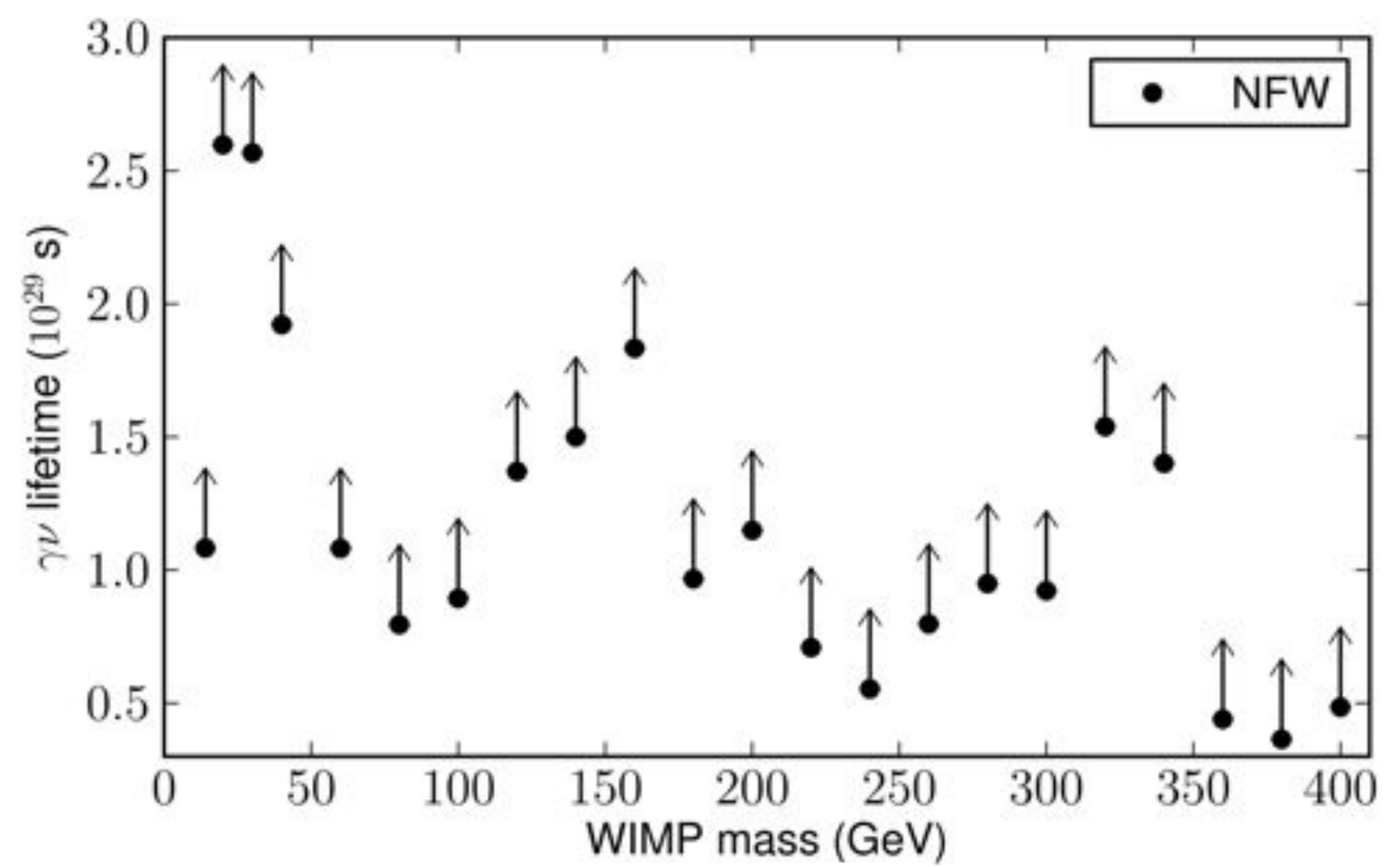
- 23 % systematic uncertainty for E < 130 GeV and 30% for E > 130 GeV
- **7 and 10 GeV bins use a modified event selection to reduce the systematic uncertainty associated with public IRFs**.
- For E > 12 GeV no indication of a spectral structure systematic effect is seen.



Fermi Lat Coll., PRD 86, (2012) 022002 arXiv:1205.2739

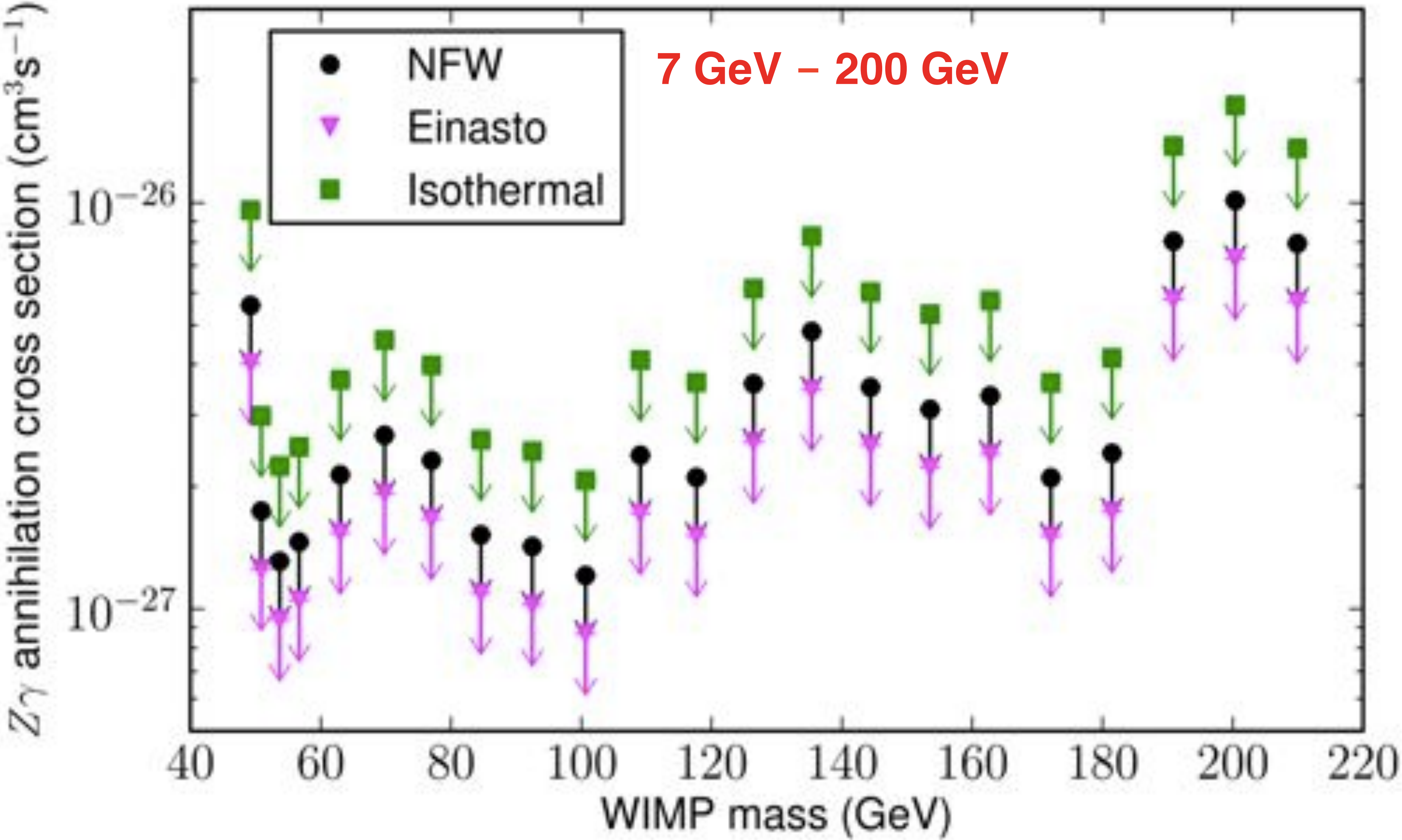
Decay lifetime lower limits

- Limits similar for all 3 DM density profiles due to linear dependence of flux on ρ
- Disfavors lifetimes smaller than 10^{29} s



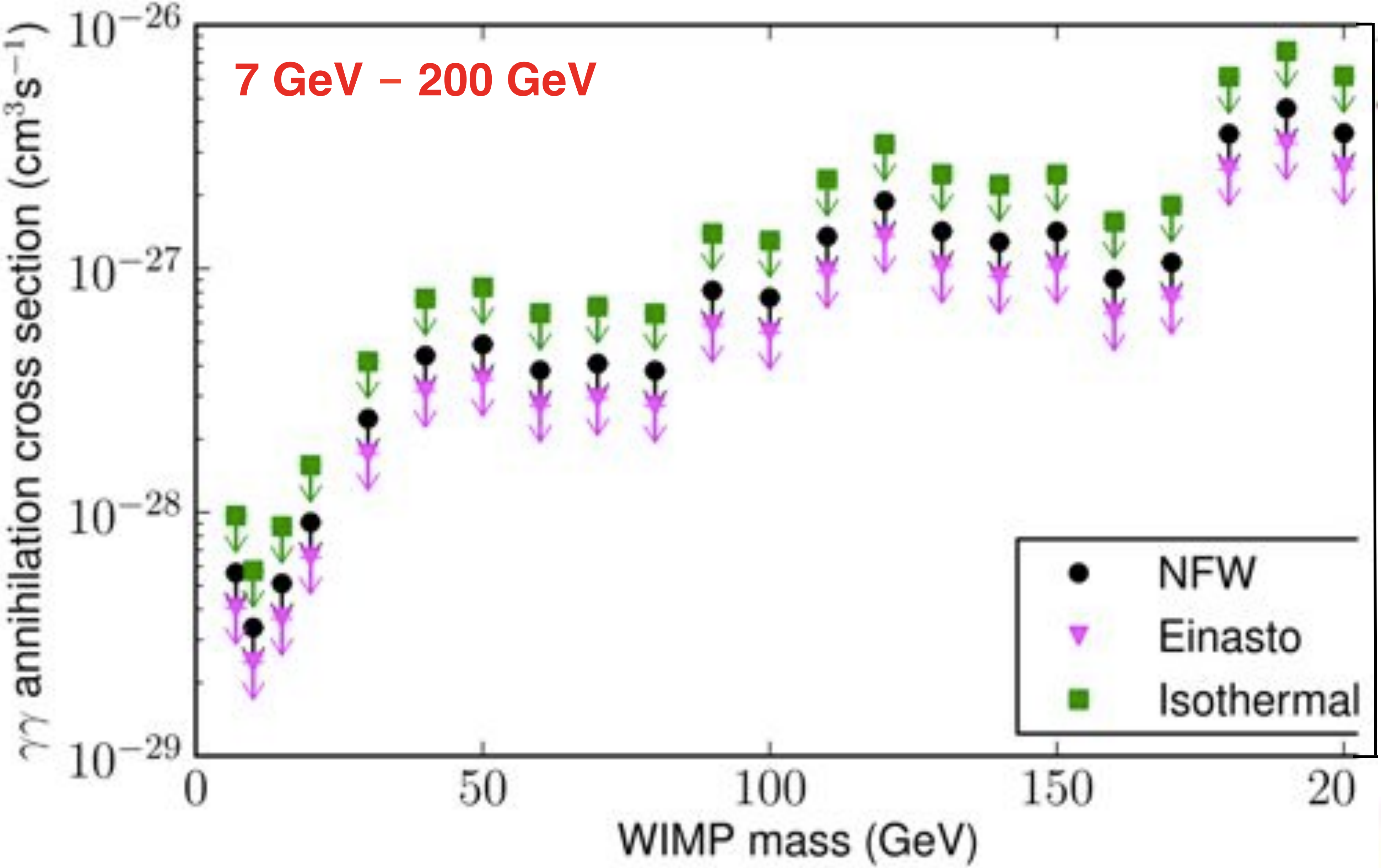
Fermi Lat Coll., PRD 86, (2012) 022002 arXiv:1205.2739

Fermi LAT 23 Month Zγ-Cross-section limits



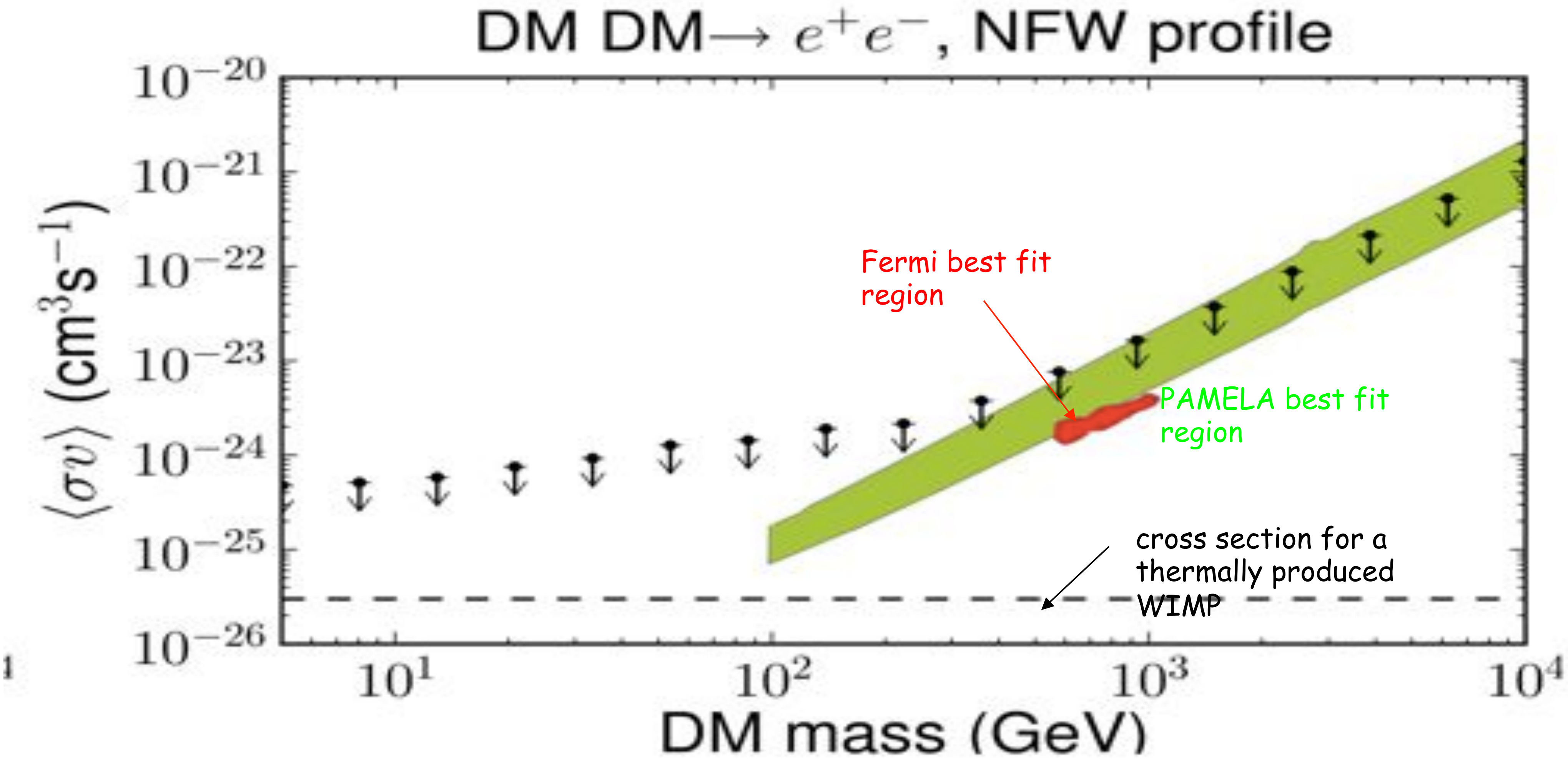
Fermi Lat Coll., PRD 86, (2012) 022002 arXiv:1205.2739

Fermi LAT 23 Month $\gamma\gamma$-Cross-section limits



Fermi Lat Coll., PRD 86, (2012) 022002 arXiv:1205.2739

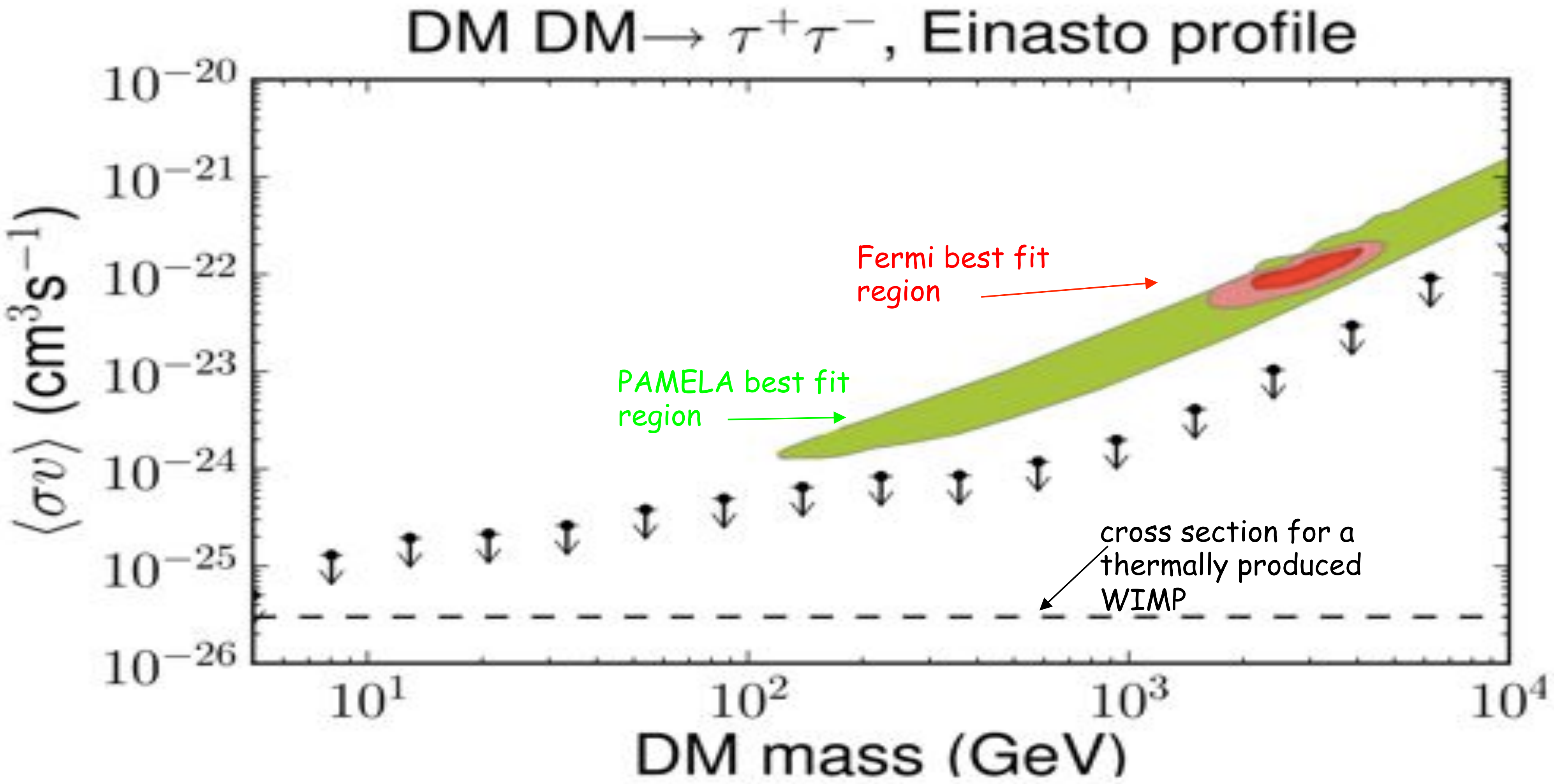
Cross section upper limits for dark matter annihilation



No photons from astrophysical background sources have been included, making these limits very conservative.

Fermi Lat Coll., PRD D 86, (2012) 022002 [arXiv:1205.2739]

Cross section upper limits for dark matter annihilation



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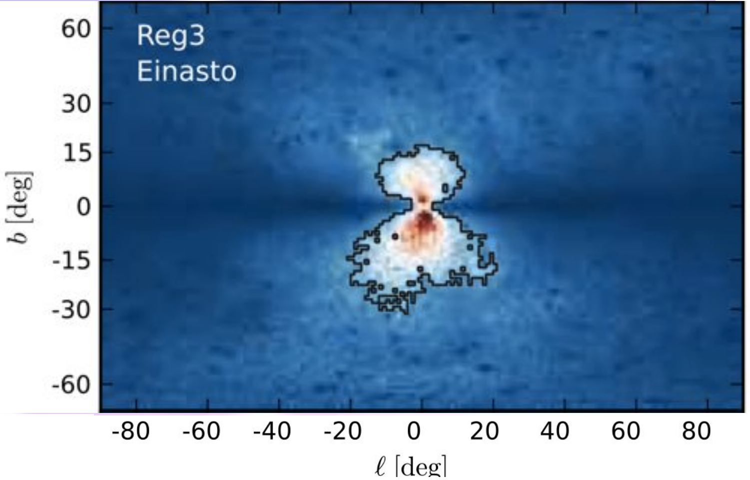
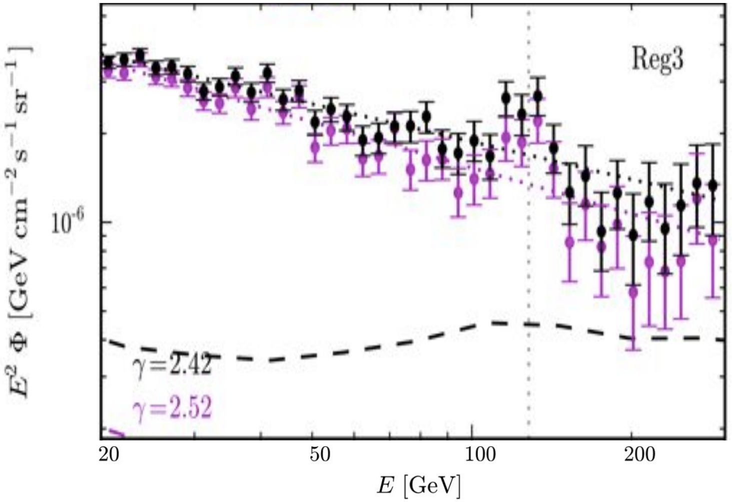
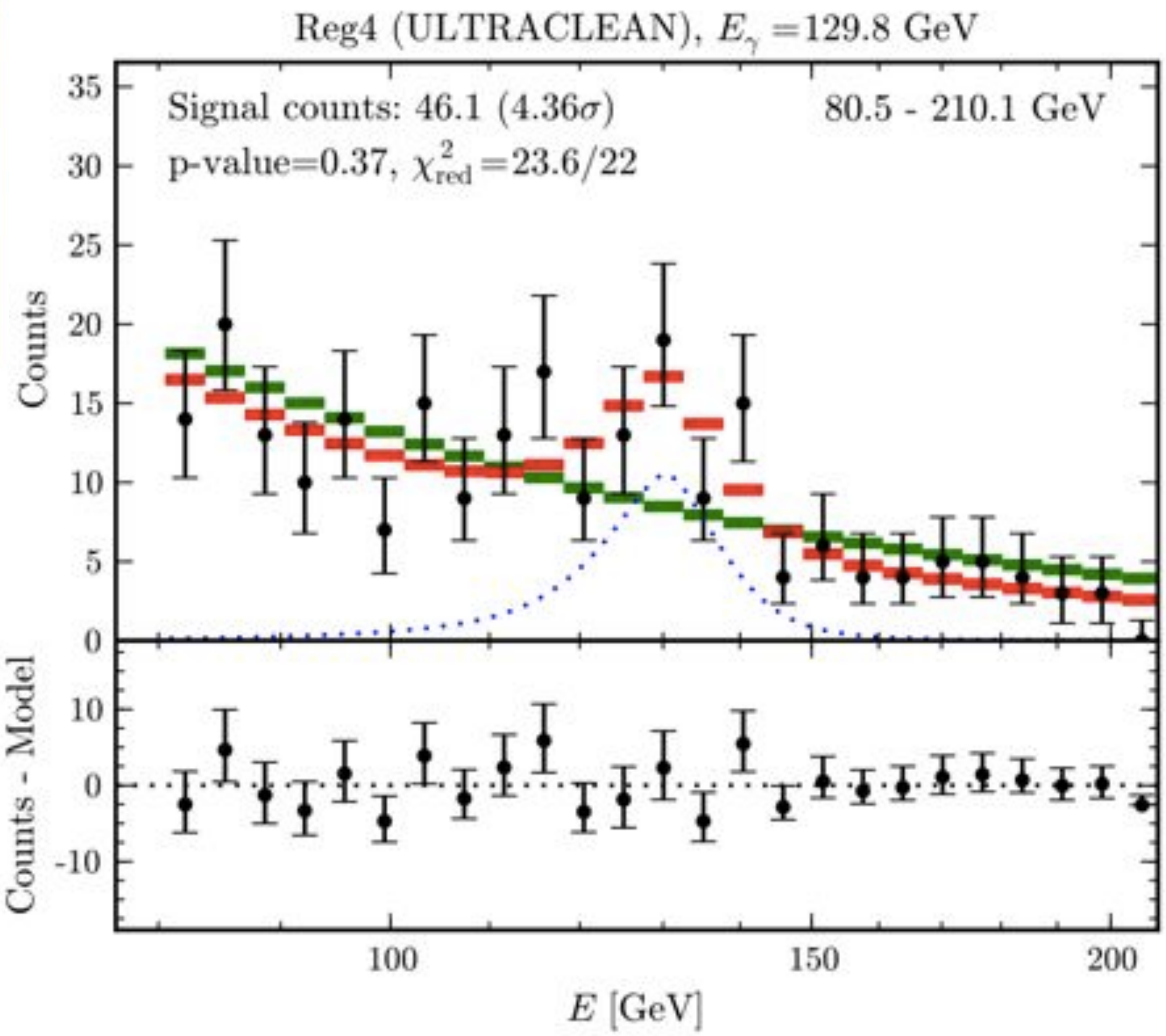
Fermi Lat Coll., PRD 86, (2012) 022002 arXiv:1205.2739

A line at ~ 130 GeV ?







Weniger arXiv:1204.2797

A line at ~ 130 GeV ?

see also

Tempel et al. arXiv:1205.1045

Kyae & Park arXiv:1205.4151

Dudas Mambrini et al. arXiv:1205.1520

Boyarsky et al. arXiv:1205.4700

Lee et al. arXiv:1205.4700

Acharya, Kane et al. arXiv:1205.5789

Buckley, Hooper arXiv:1205.6811

Su, Finkbeiner arXiv:1206.1616

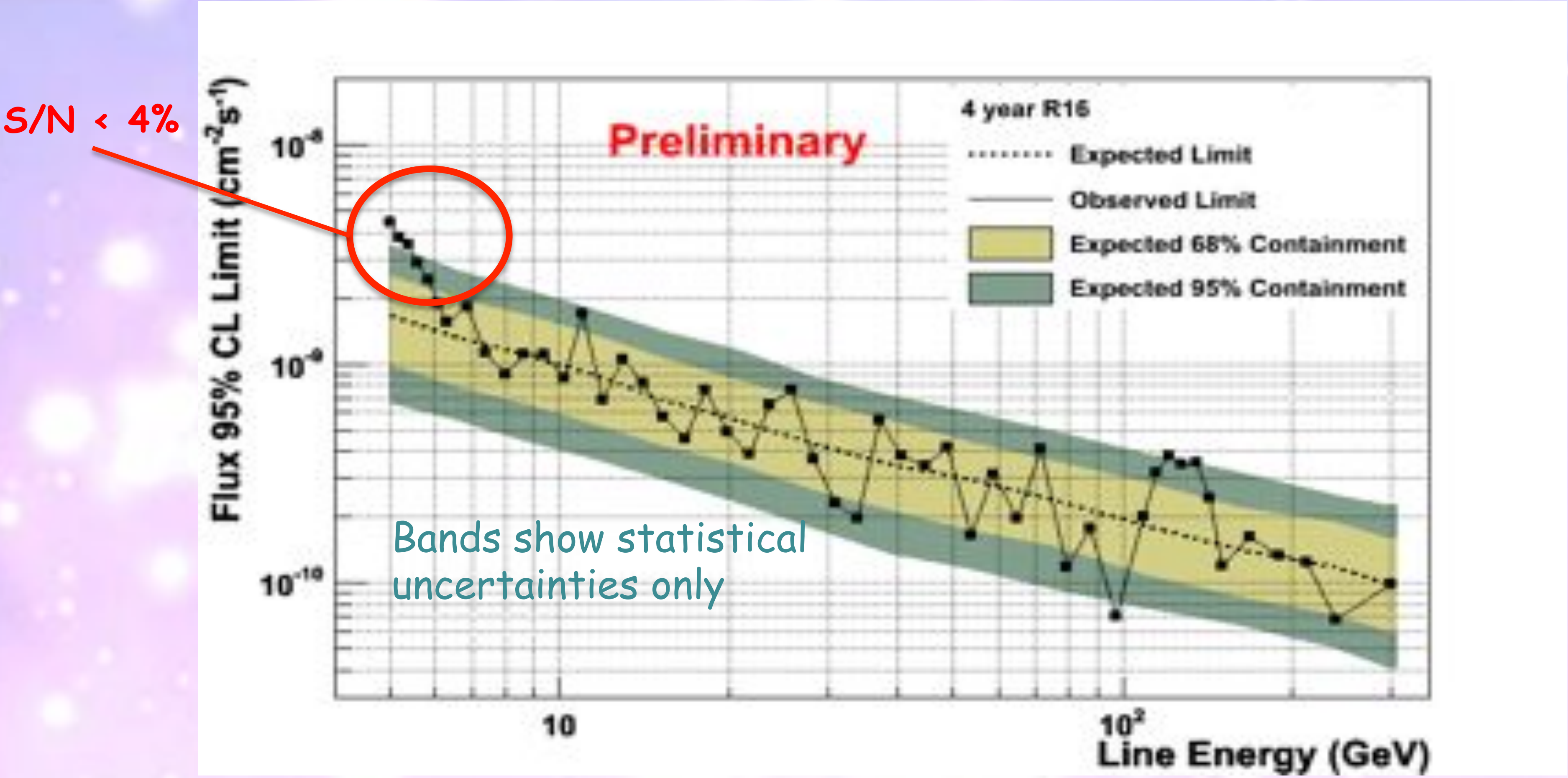
Chu,Hambye et al. arXiv:1206.2279

Finkbeiner, Su, Weniger arXiv:1209.4562

……..

Fermi-LAT analysis is in progress

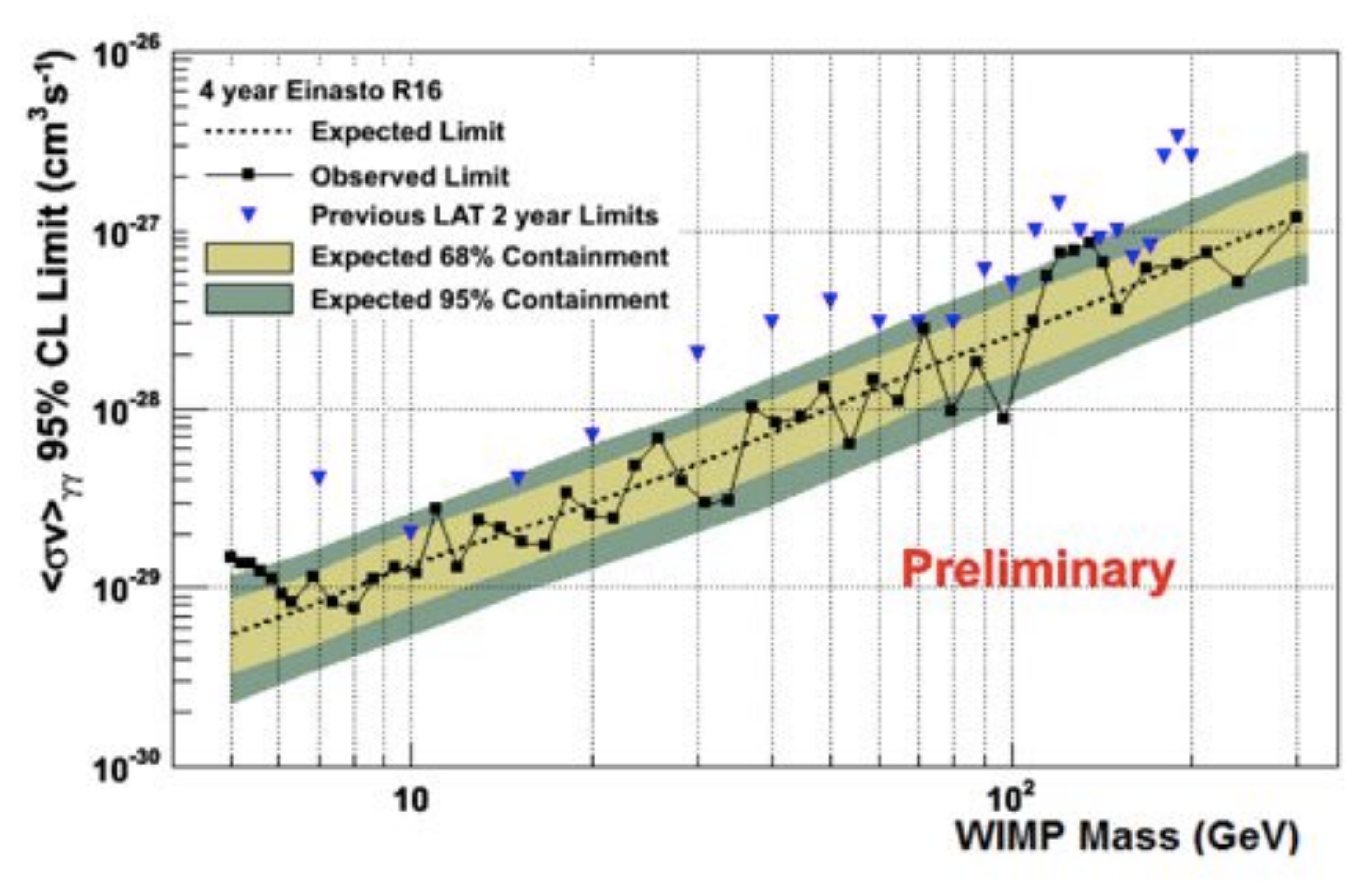
Fermi-LAT Line Search Flux Upper Limits



Bands show statistical uncertainties only

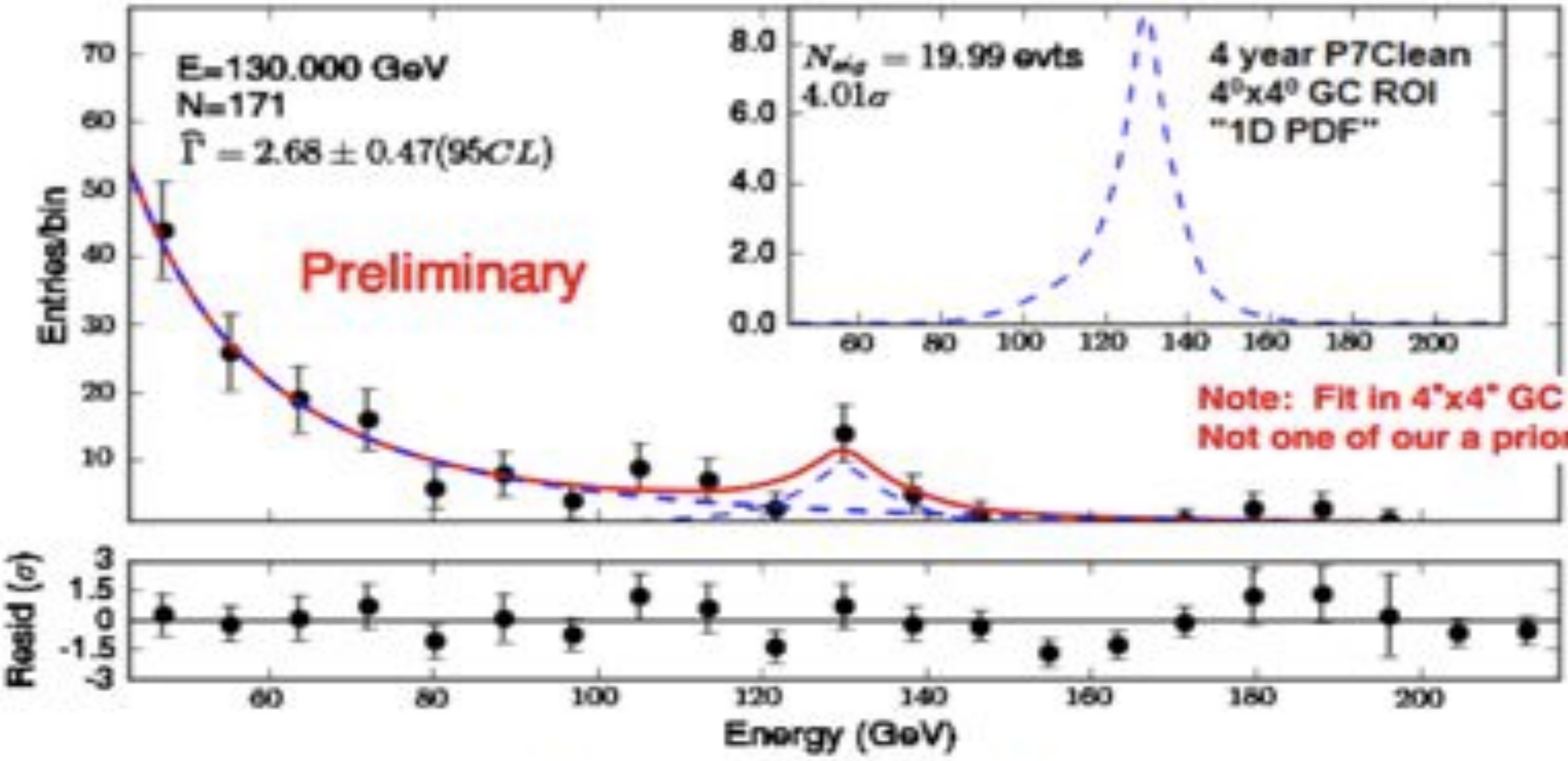
- Most of the limits fall within the expected bands.
- Near 135 GeV the limits are near the upper edge of the bands.
- The huge statistics at low energies mean small uncertainties in the collecting area can produce statistical significant spectral features.

Fermi-LAT Line Search <σv> upper limits (Einasto)



- **Most of the limits fall within the expected bands.**
- **Near 135 GeV the limits are near the upper edge of the bands.**
- **The huge statistics at low energies mean small uncertainties in the collecting area can produce statistical significant spectral features.**

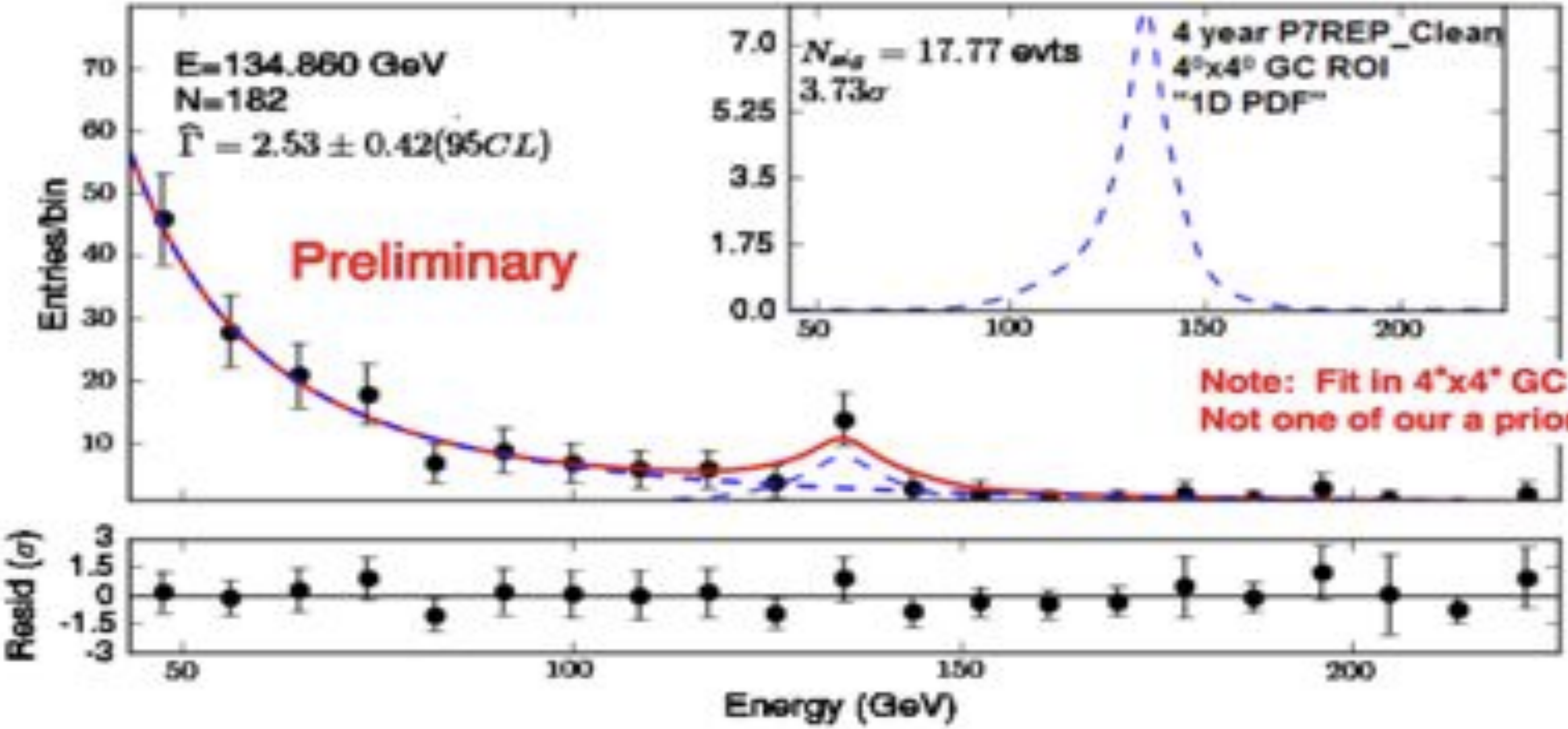
Fermi-LAT feature near 135 GeV



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
- Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)

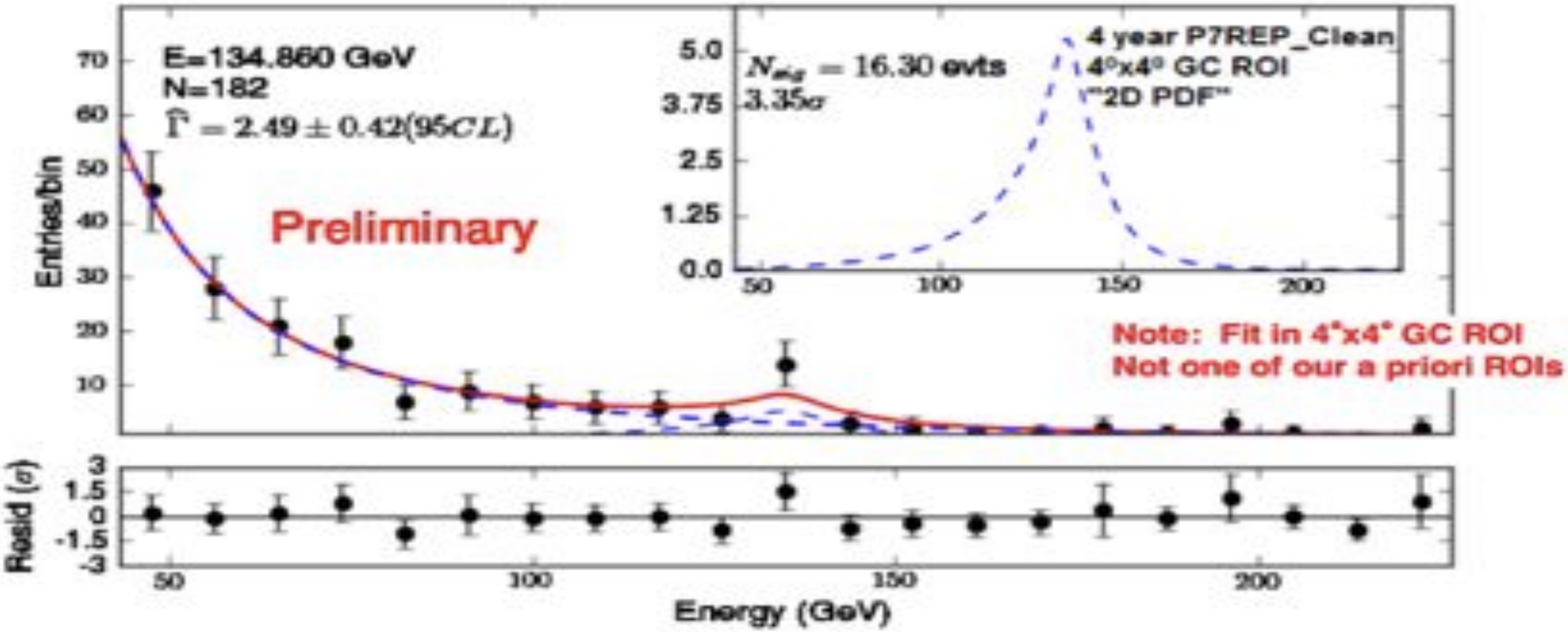
Fermi-LAT feature near 135 GeV



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

- 4.01σ (local) 1D fit at 130 GeV with 4 year unprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)

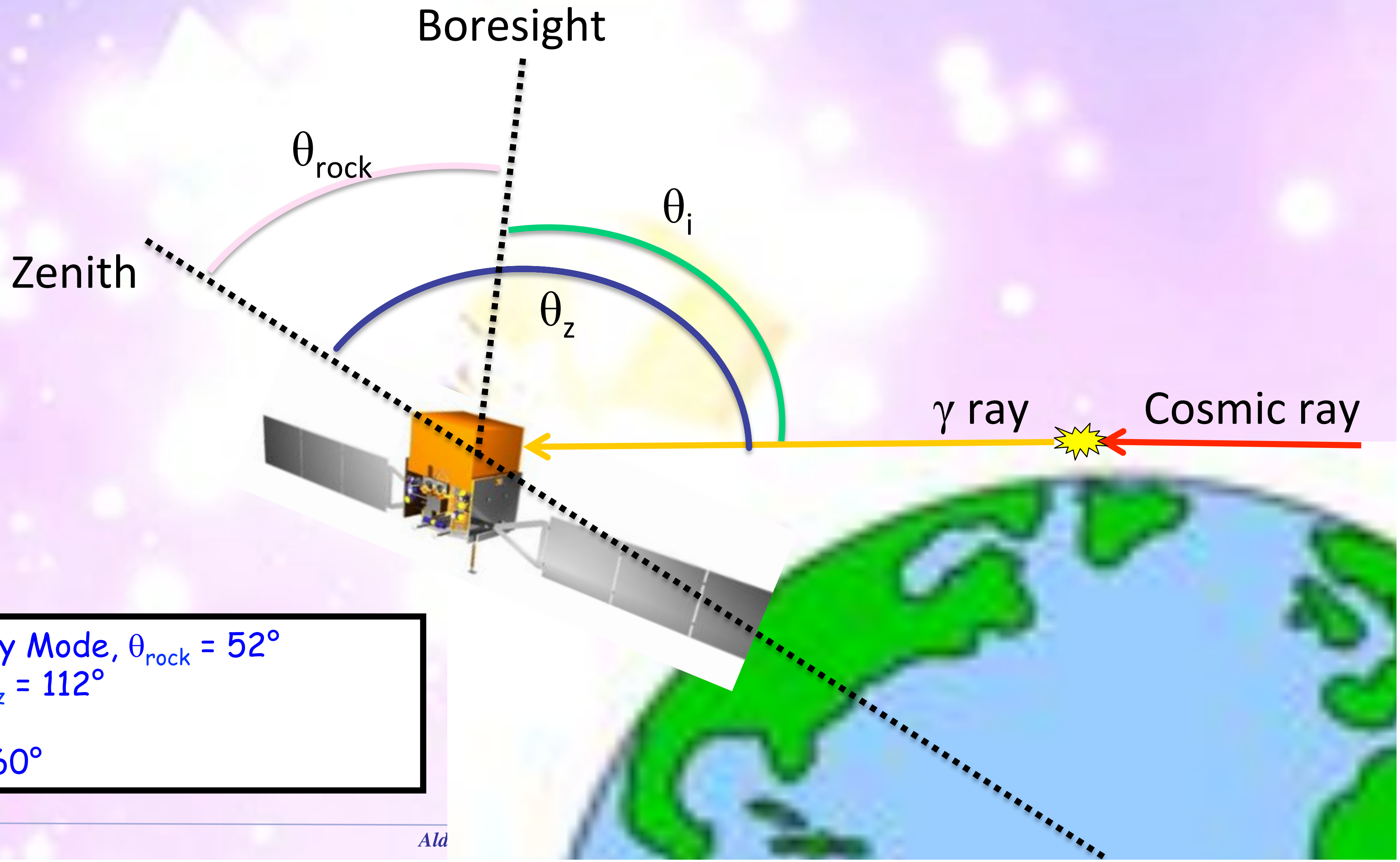
Fermi-LAT feature near 135 GeV



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4°GC ROI, Use 1D PDF (no use of P_E)
- **3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data**
  - **Look in 4°x4°GC ROI, Use 2D PDF (P_E in data)**
  - **<2σ global significance after trials factor**

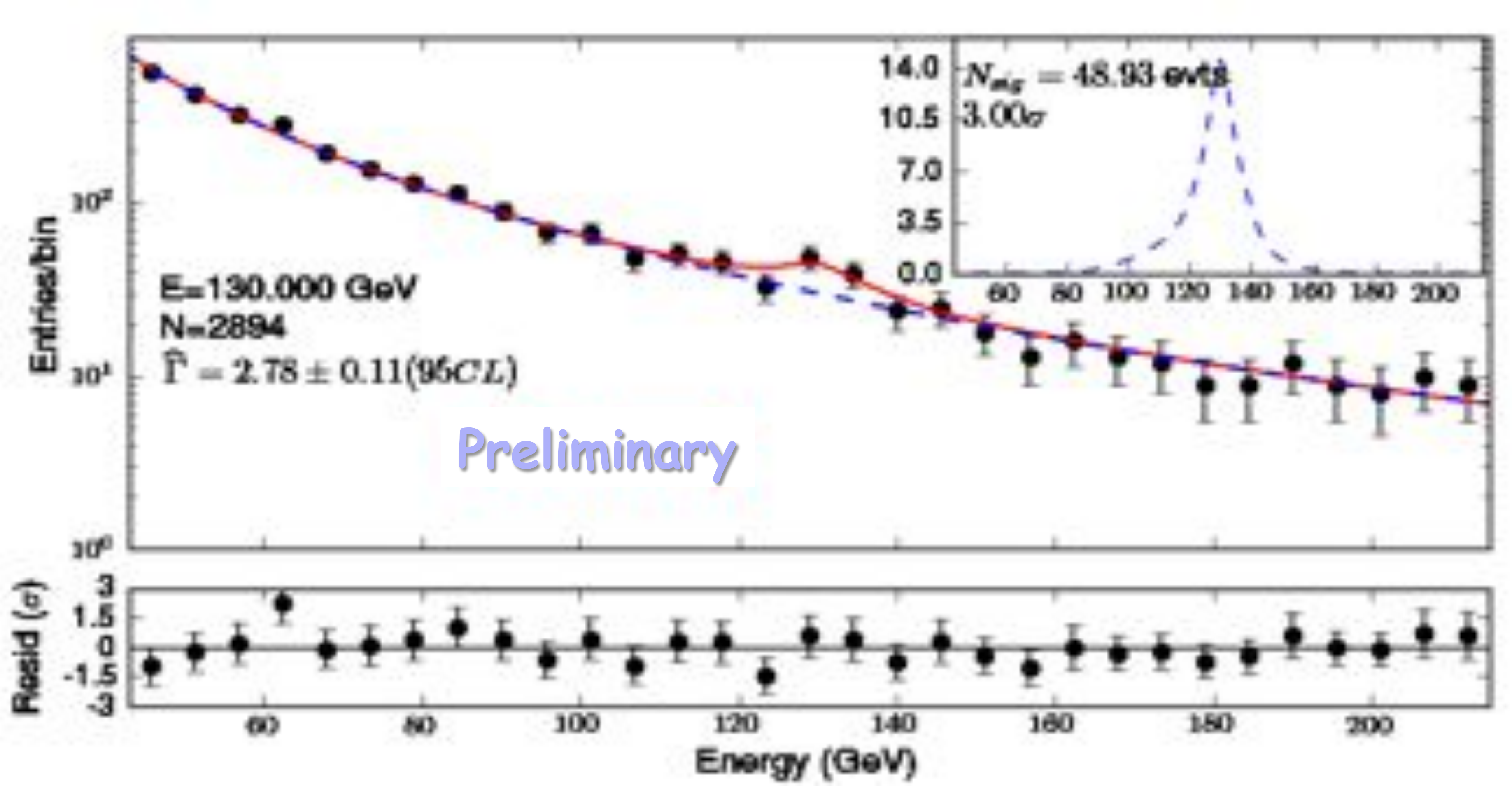
The Earth Limb as a Control Sample



Sky Survey Mode, θ_{rock} = 52°
Limb at θ_{rz} = 112°

Limb: $\theta_i > 60°$

Fitting the Earth Limb



The fit to Earth Limb data results in a 3.0σ signal, with a fractional residual (i.e., S/N) of ~18%.

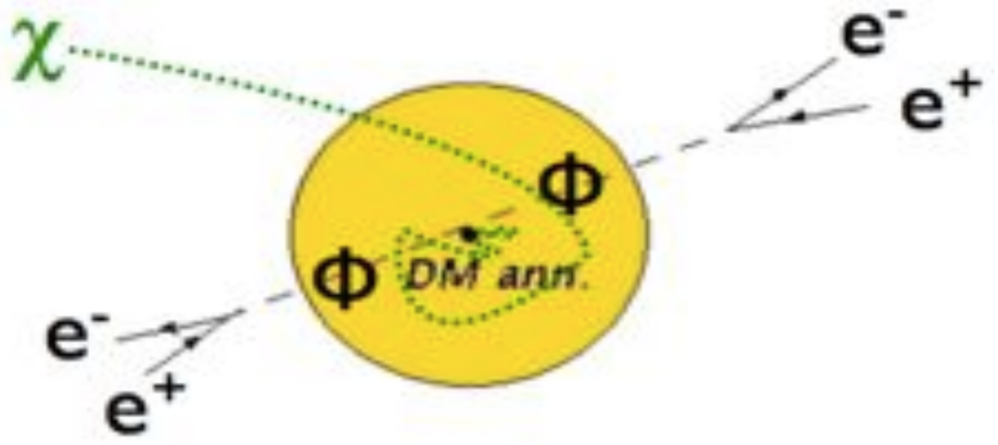
130 GeV Line Summary

- Spectral feature at 130 GeV near the Galactic center is a potentially interesting hint of Dark Matter annihilation
  - Fractional residual up to 60% in 4°x4° box around GC
  - Not caused by background contamination
- A similar spectral feature is seen in the Earth Limb and is likely attributable to dips in efficiency at energies just above and below 130 GeV
  - The Earth Limb instrumental features are not enough to explain all of the feature near the GC, however when accounted for they reduce the significance of the GC feature by up to 30%-50% depending on the ROI under consideration.
- Data have been reprocessed with updated CAL calibrations
  - Signal significance somewhat lower (~3.5σ local)
    - No longer globally significant (< 2σ global)

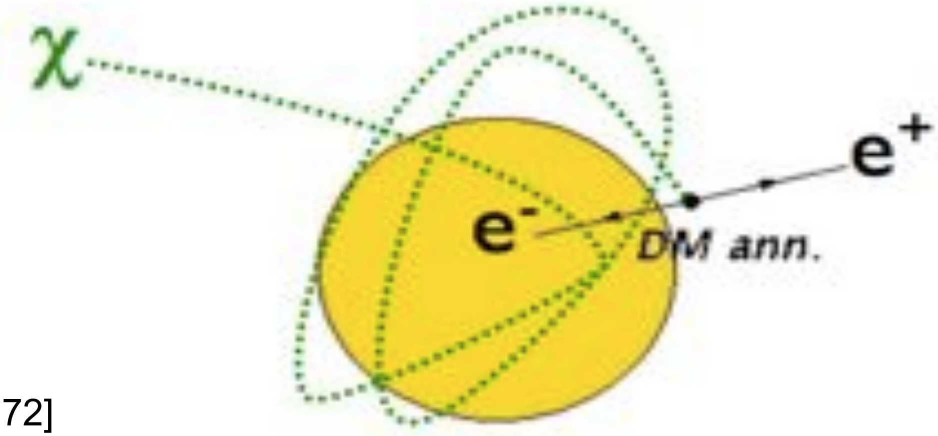
CREs from DM annihilation

Schuster et al. (2010) discuss 2 scenarios in which dark matter annihilation leads to cosmic-ray electron and positron (CRE) fluxes from the Sun:

- intermediate state scenario: Dark matter annihilates in the center of the Sun into an intermediate state Φ which then decays to CREs outside the surface of the Sun

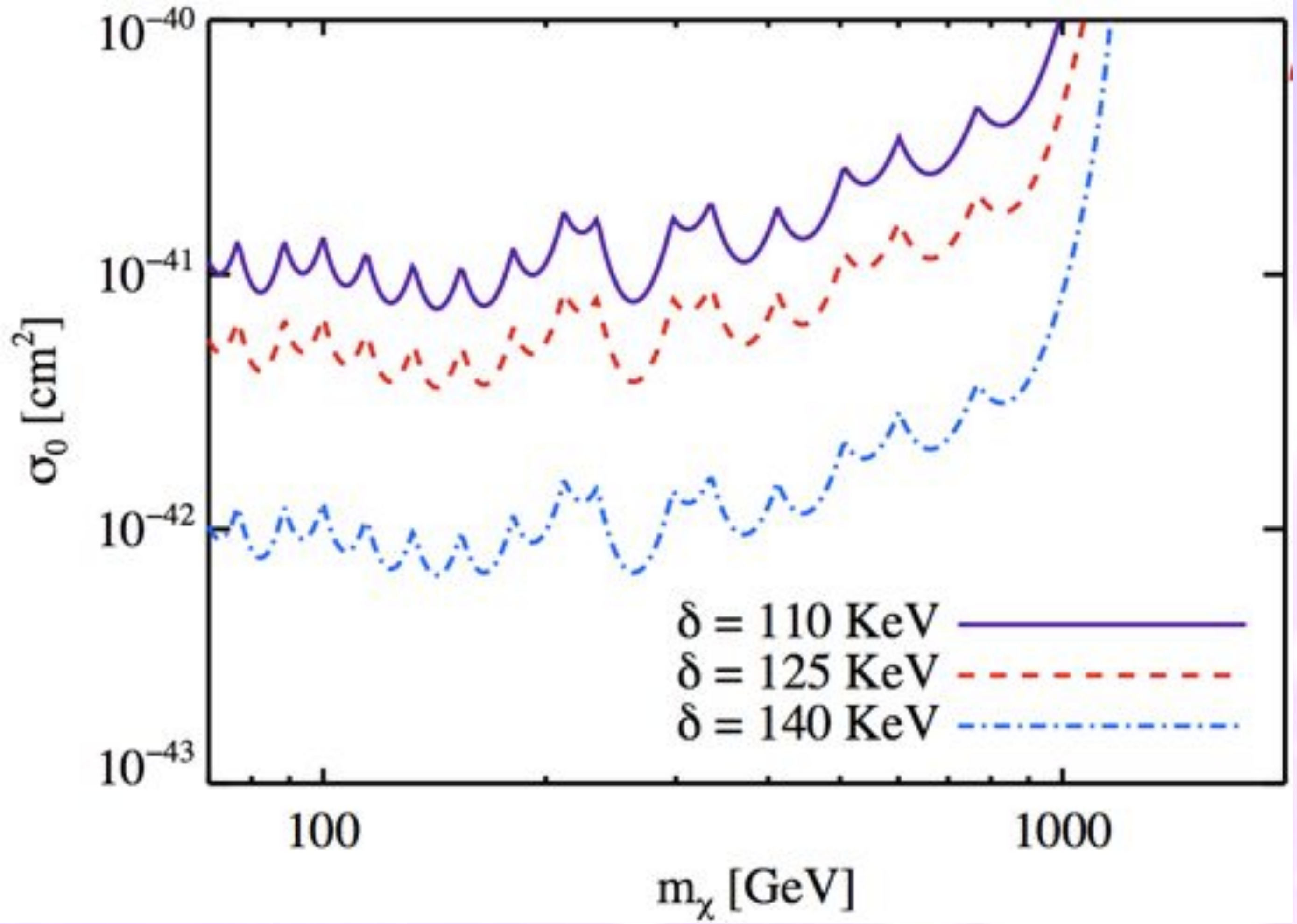


- iDM scenario: Inelastic dark matter (iDM) captured by the Sun remains on large orbits, then annihilates directly to CREs outside the surface of the Sun



Fermi Lat Coll., PRD 84, 032007 (2011) [arXiv:1107.4272]

Limits on inelastic scattering cross-section with electrons from the Sun

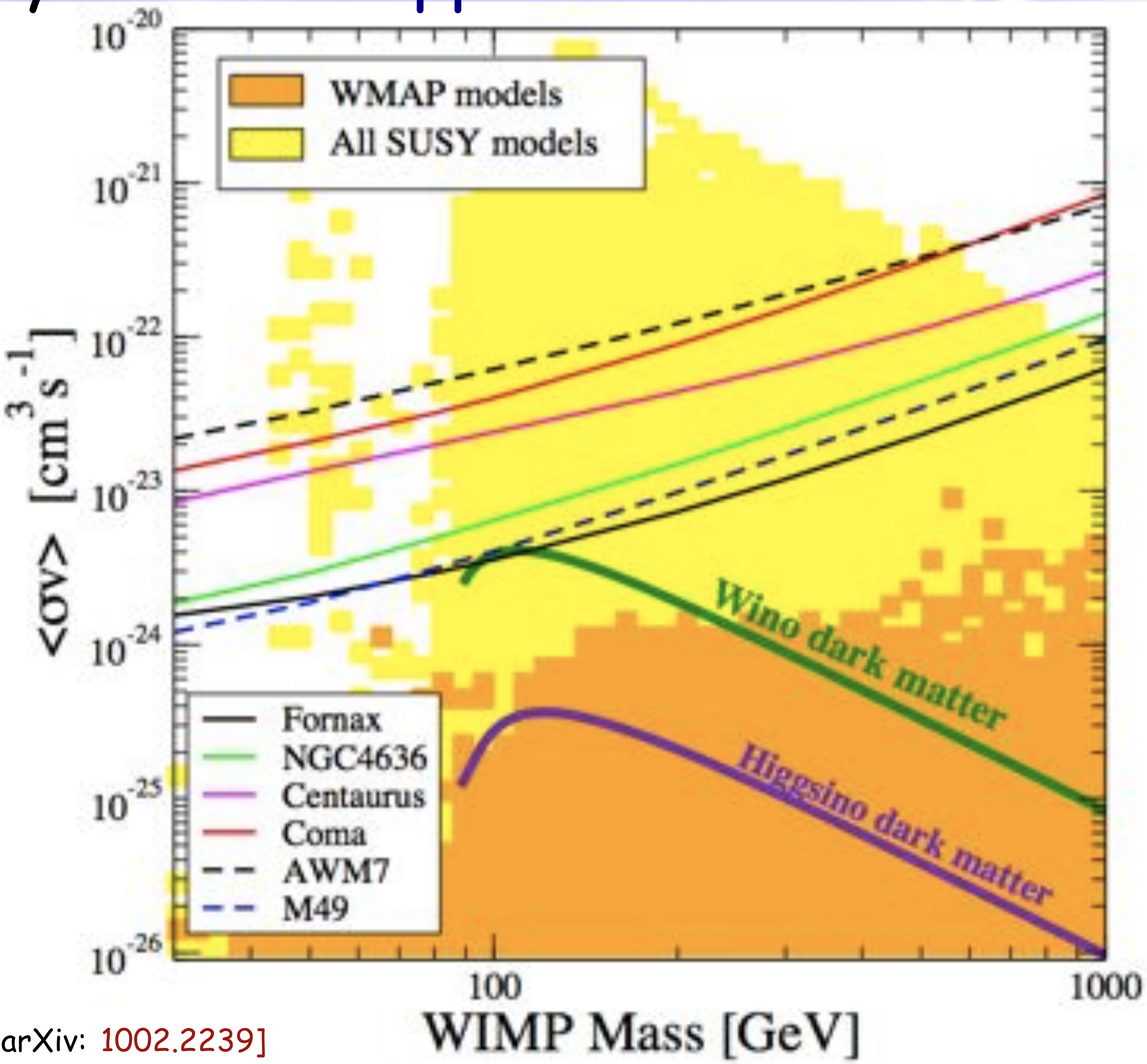


Fermi Coll.Phys. Rev. D 84, 032007 (2011) [arXiv:1107.4272]

There is a class of models that has garnered interest recently in light of claims that iDM could naturally explain such observations as the 511 keV line observed by INTEGRAL/SPI and the apparently inconsistent results of DAMA/LIBRA and CDMS if the DM scattered inelastically and thereby transitioned to an excited state with a slightly heavier mass. The bounds we derive exclude the relevant cross sections by 1–2 orders of magnitude -> the parameter space of models preferred by DAMA/LIBRA can be ruled out for m >70 GeV for annihilation to e+e-

Galaxy Clusters upper-limits

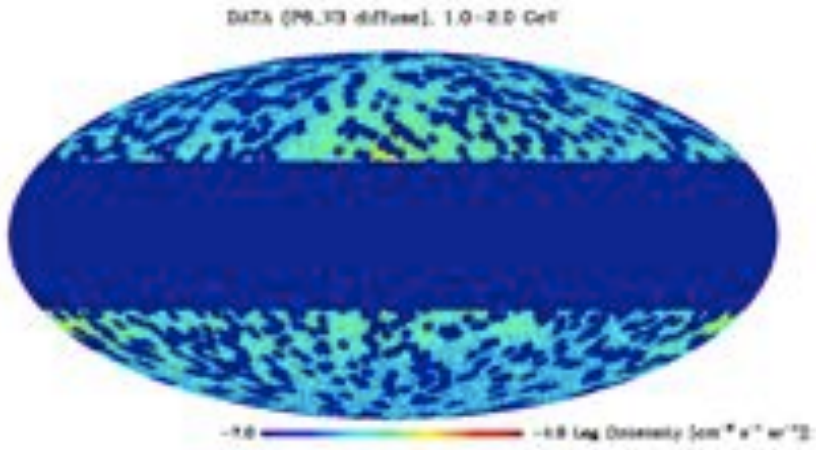
- Constraints for a b-bbar final state are weaker than or comparable to (depending on the assumption on substructures) the ones obtained with dSph



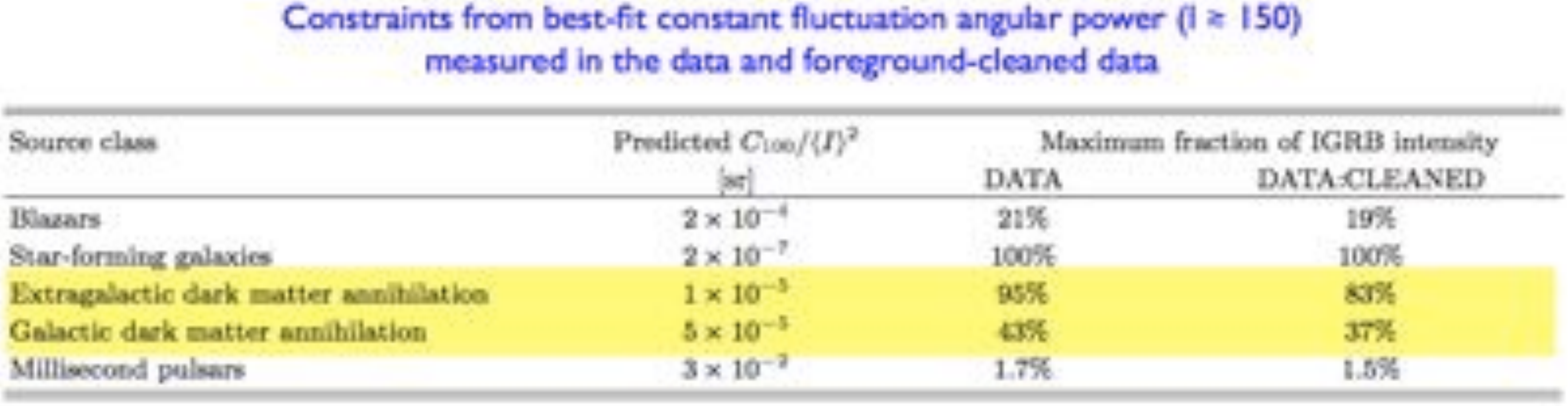
Fermi Coll. JCAP 05, 025 (2010) [arXiv: 1002.2239]

Anisotropy constraints on dark matter

- angular power spectrum analysis of the large-scale isotropic gamma-ray background (IGRB) yielded a significant (>3σ) detection of angular power up to 10 GeV, lower significance power measured at 10-50 GeV
- measured (dimensionless) fluctuation angular power consistent with a constant value in four energy bins spanning 1-50 GeV
- fluctuation angular power measurement constrains fractional contribution of individual source classes, including DM, to the IGRB intensity



Maximum fractional contribution of various source populations



Constraints from best-fit constant fluctuation angular power (l ≥ 150)
measured in the data and foreground-cleaned data

Source class	Predicted $C_{100}/\langle I\rangle^2$ [sr]	Maximum fraction of IGRB intensity DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-5}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%

Fermi Lat Coll., PRD 85, 083007 (2012) [arXiv:1202.2856]

Not only Dark Matter

Origin of Cosmic Rays

Cosmic rays are particles (mostly protons) accelerated to relativistic speeds.

Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking.

When accelerated protons encounter interstellar material they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons.

The identification of pion-decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering.

The π^0-decay bump

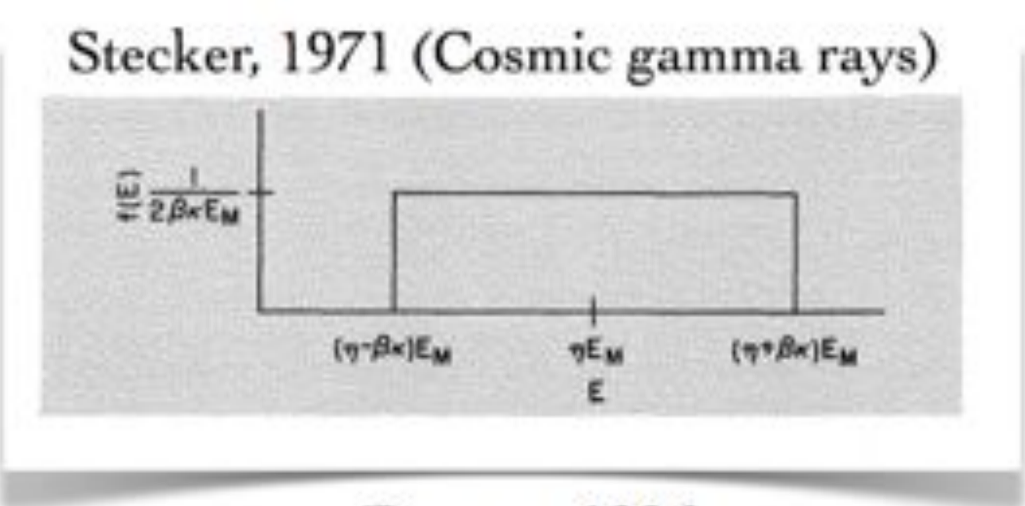
- Neutral pion-decay: in the rest-frame of the pion, the two γ rays have 67.5 MeV each (i.e. a line)

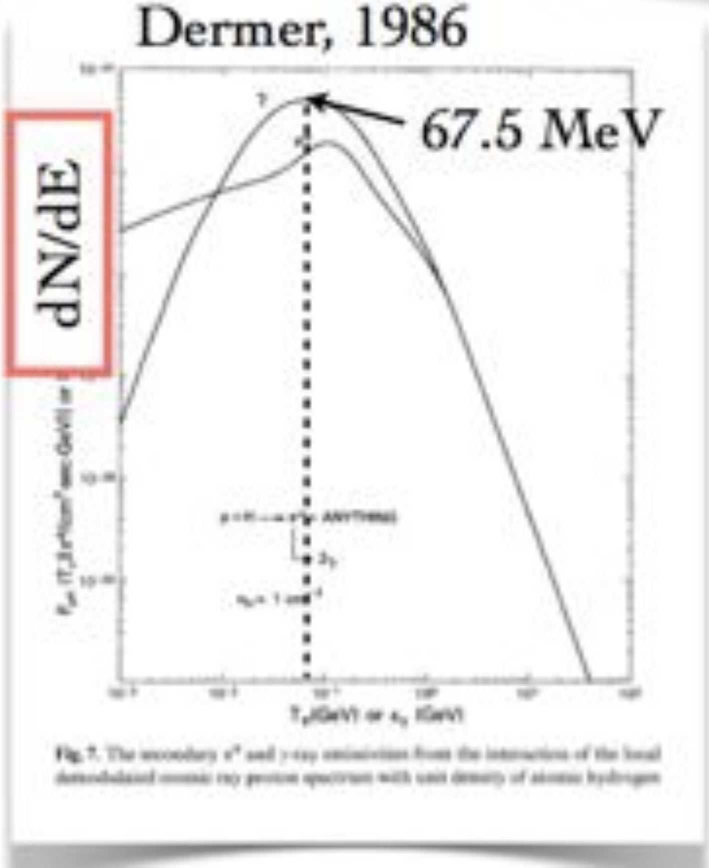
Stecker, 1971 (Cosmic gamma rays)

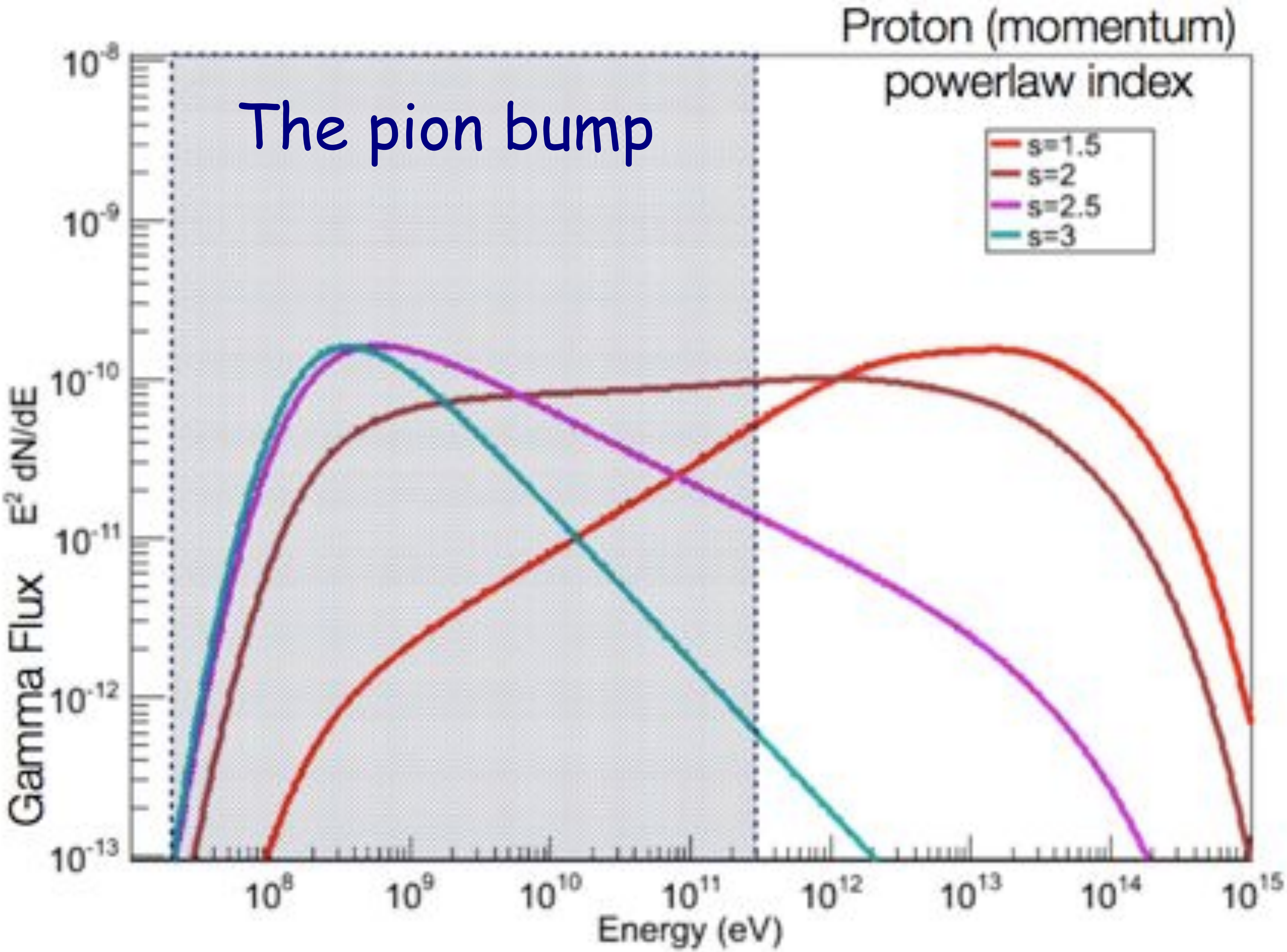
- Transforming into the lab-frame smears the line but keeps it symmetric about 67.5 MeV (in dN/dE)

Dermer, 1986

- Transforming to E2 dN/dE and drop in pion-production cross section destroys symmetry and generates the "bump"



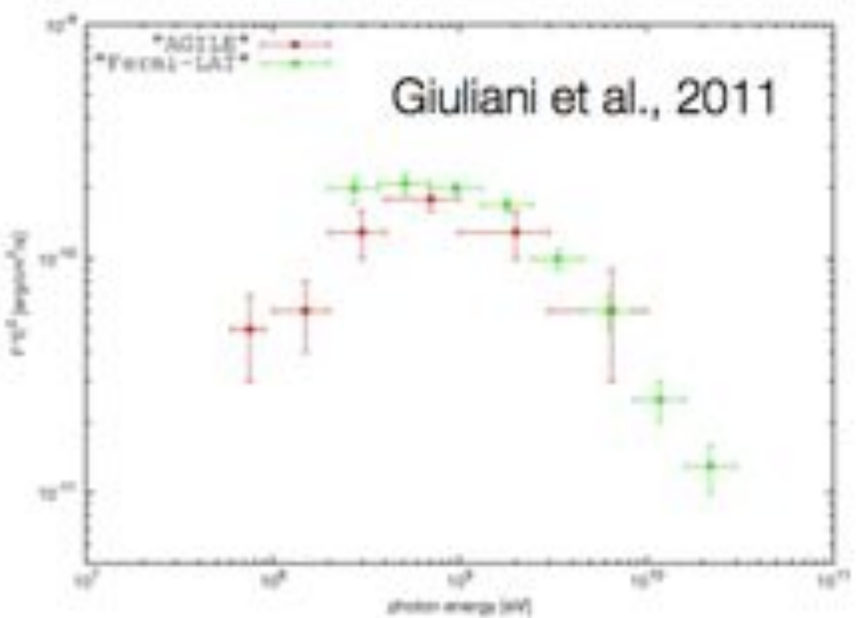


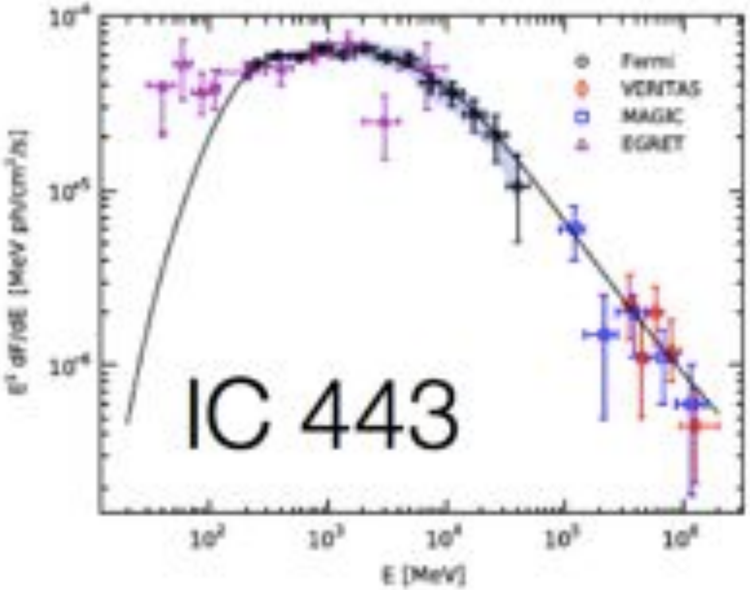


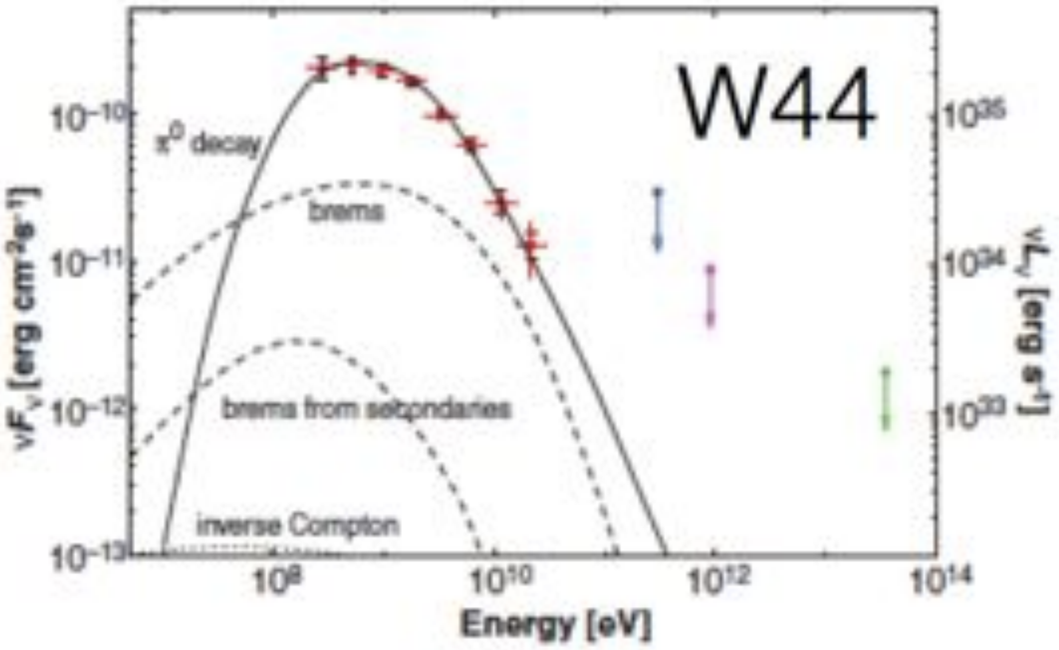
Smoking gun feature for accelerated protons

Earlier observations

- Seen with EGRET in the Galactic diffuse
- AGILE detection of “bump” in W44 (Giuliani et al., 2011)
- Previous Fermi-LAT analyses started at 200 MeV (rapidly changing effective area)



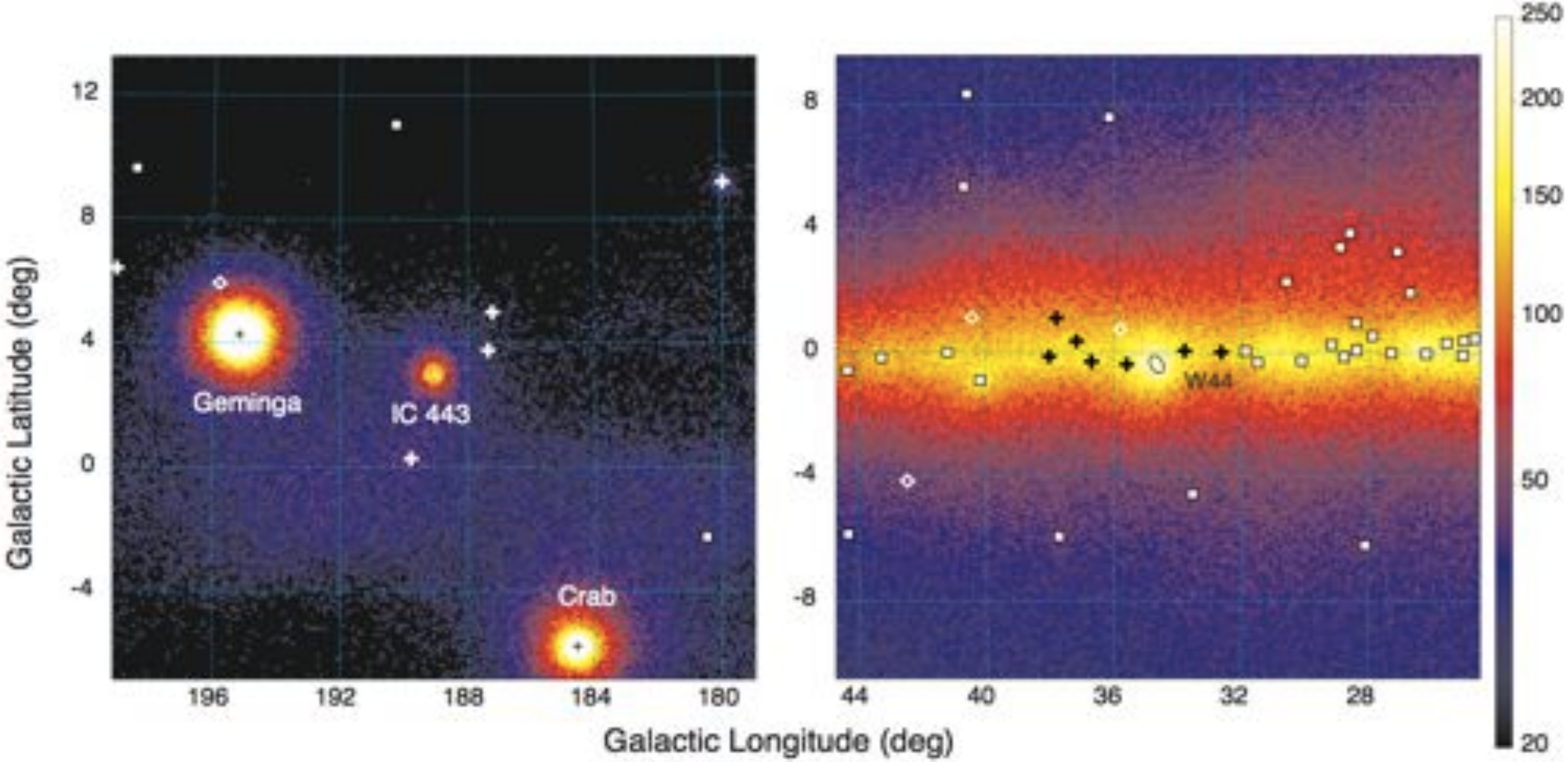




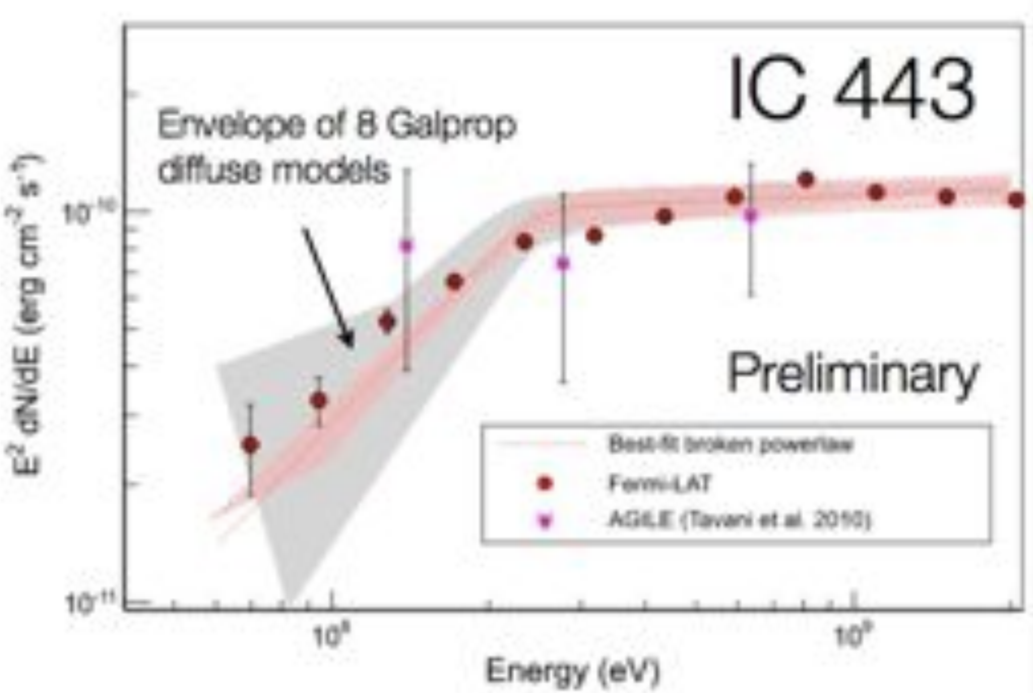
New Fermi Large Area Telescope analysis:

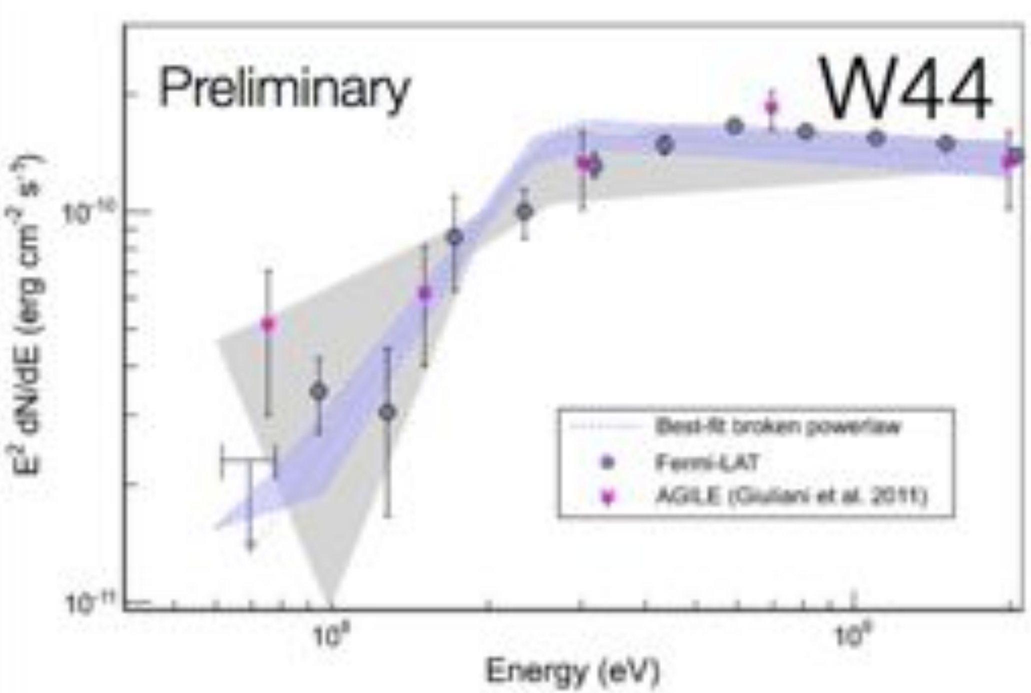
Time range: 2008 August, 4th to 2012 July 16^{th}

Gamma-ray count maps of the 20° × 20° fields around **IC 443** and **W44** in the energy range 60 MeV to 2 GeV



Energy spectra down to 60 MeV

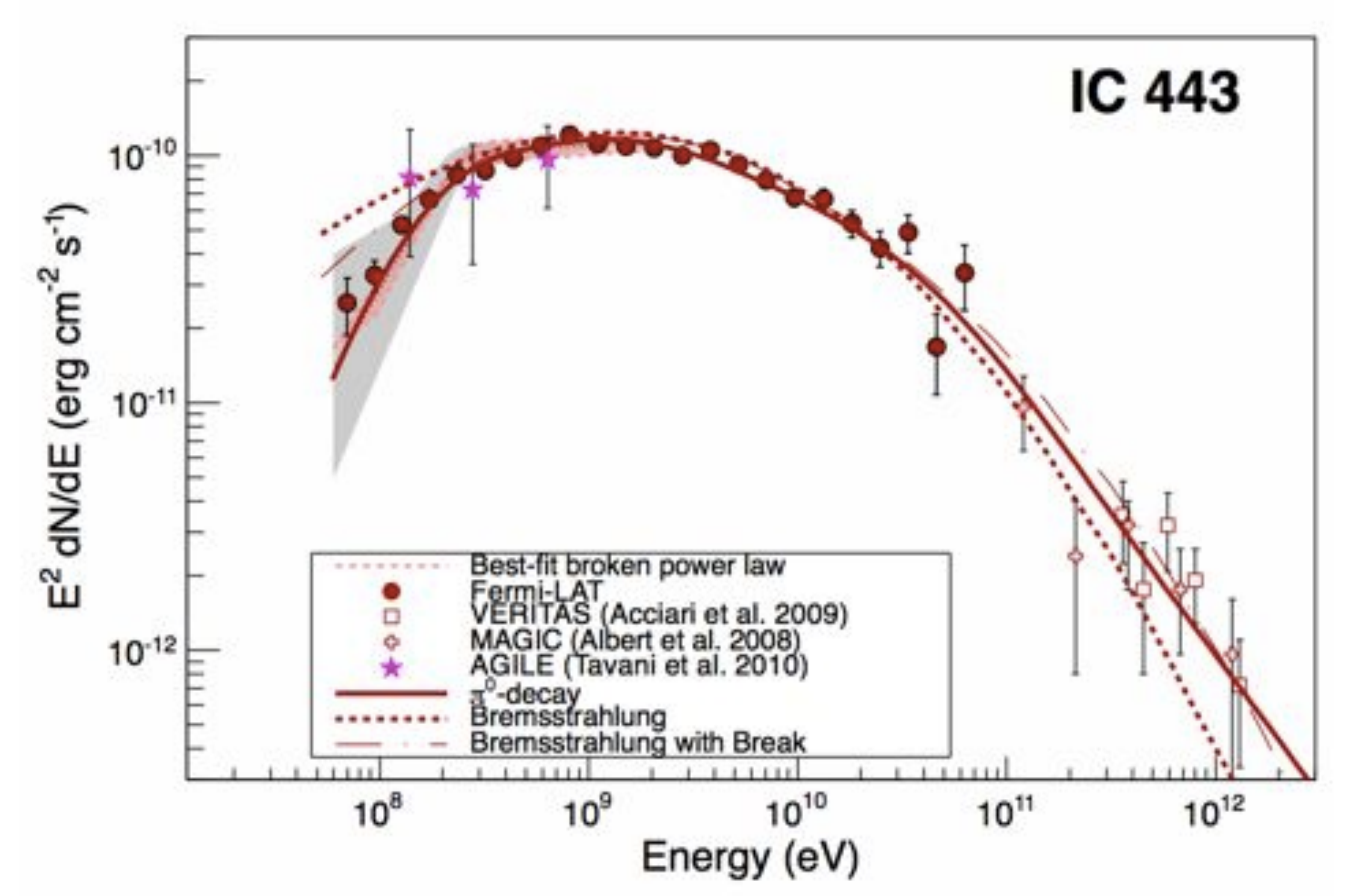




- Clear indication of a low-energy “turnover”
- Gray systematic error band estimated from 8 Galprop models of diffuse emission

Detection of the Characteristic Pion-decay Signature in Supernova Remnants

Direct evidence that cosmic-ray protons are accelerated in SNR



Science 339, (2013) 807 [arXiv:1302.3307] 15 Feb. 2013

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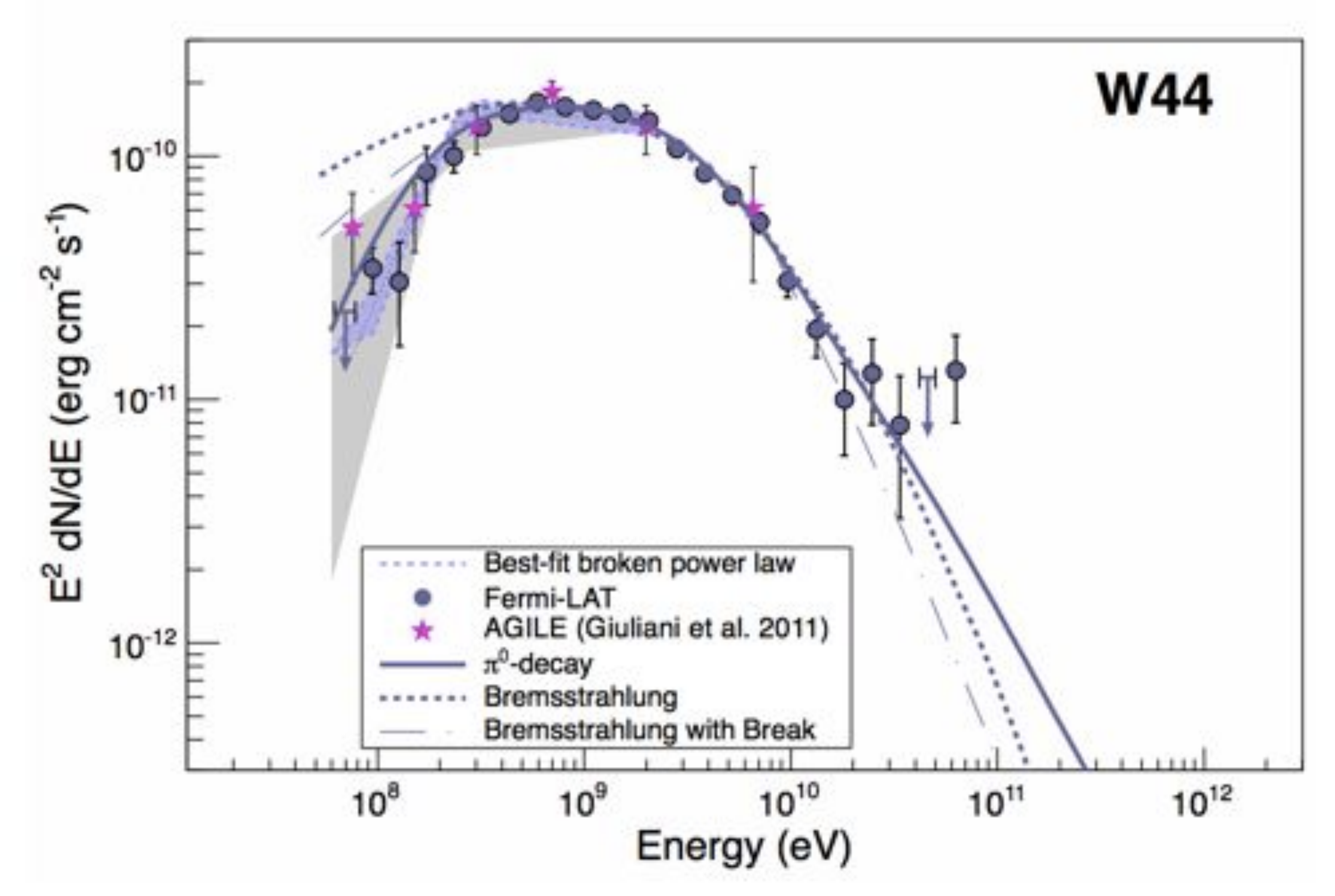
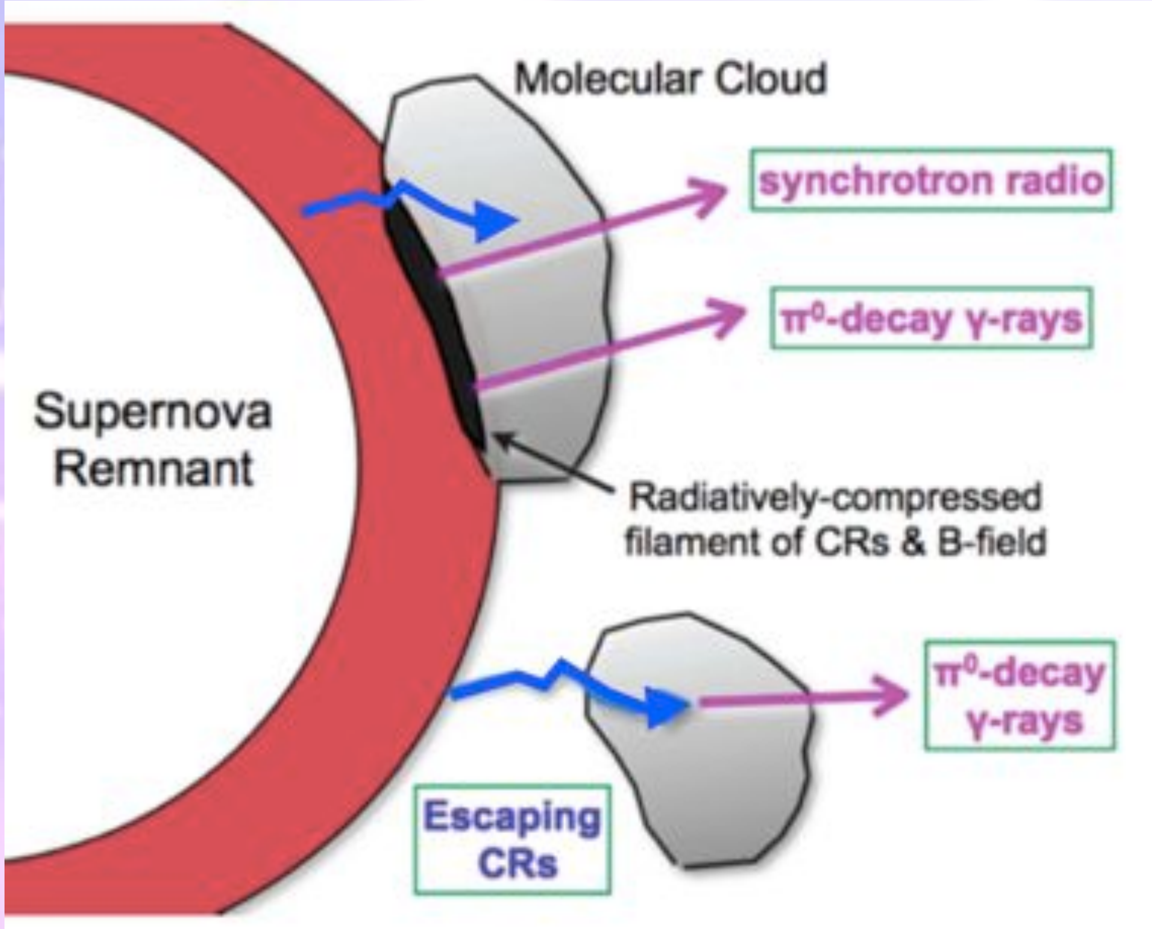


Science 339, (2013) 807 [arXiv:1302.3307] 15 Feb. 2013

Emission mechanism



- Emission site: probably downstream of shock (upstream expect harder spectrum) i.e. inside the SNR
- **Crushed cloud**: CRs and MC simultaneously compressed. Reacceleration of the “sea” of CRs.
- **Passive cloud**: CRs escape and interact with cloud. Fresh acceleration of CRs.

Summary and Conclusions

- The Fermi-LAT has made great progress toward constraining/ identifying the nature of DM
  - Many independent search strategies (dSphs, clusters, MW halo, etc.)
  - Best LAT constraints (dwarf stacking) are already beginning to reach some interesting areas of parameter space
- Fermi-LAT DM sensitivity is anticipated to improve

-Improved understanding of astrophysical backgrounds

-Increased exposure (sensitivity gain linear in time at high energies)

-Improvements in analysis and understanding of detector response

- Constraints provided by the Fermi-LAT are highly complementary to direct and accelerator searches

Future Surprises (...like CR Origin)

We are just beginning...

- Exposure continues to increase
  - Fainter sources become detectable
  - Increasingly detailed studies of bright sources
  - Catalogs become deeper and more detailed
- Time domain studies enter longer regimes
- Solar cycle beginning to warm up
- Plus, efforts continue to further improve performance and enhance analysis, particularly at low and high energies

Exciting progress on Pass8, expected to be the ultimate IRF version.

The longer we look, the more surprises we will see

Thank you for the attention !!