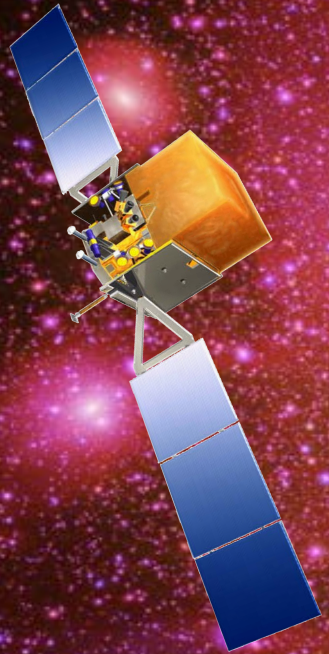
Search for Dark Matter with Gamma-rays: A Review



Aldo Morselli

INFN Roma Tor Vergata

28 May 2012

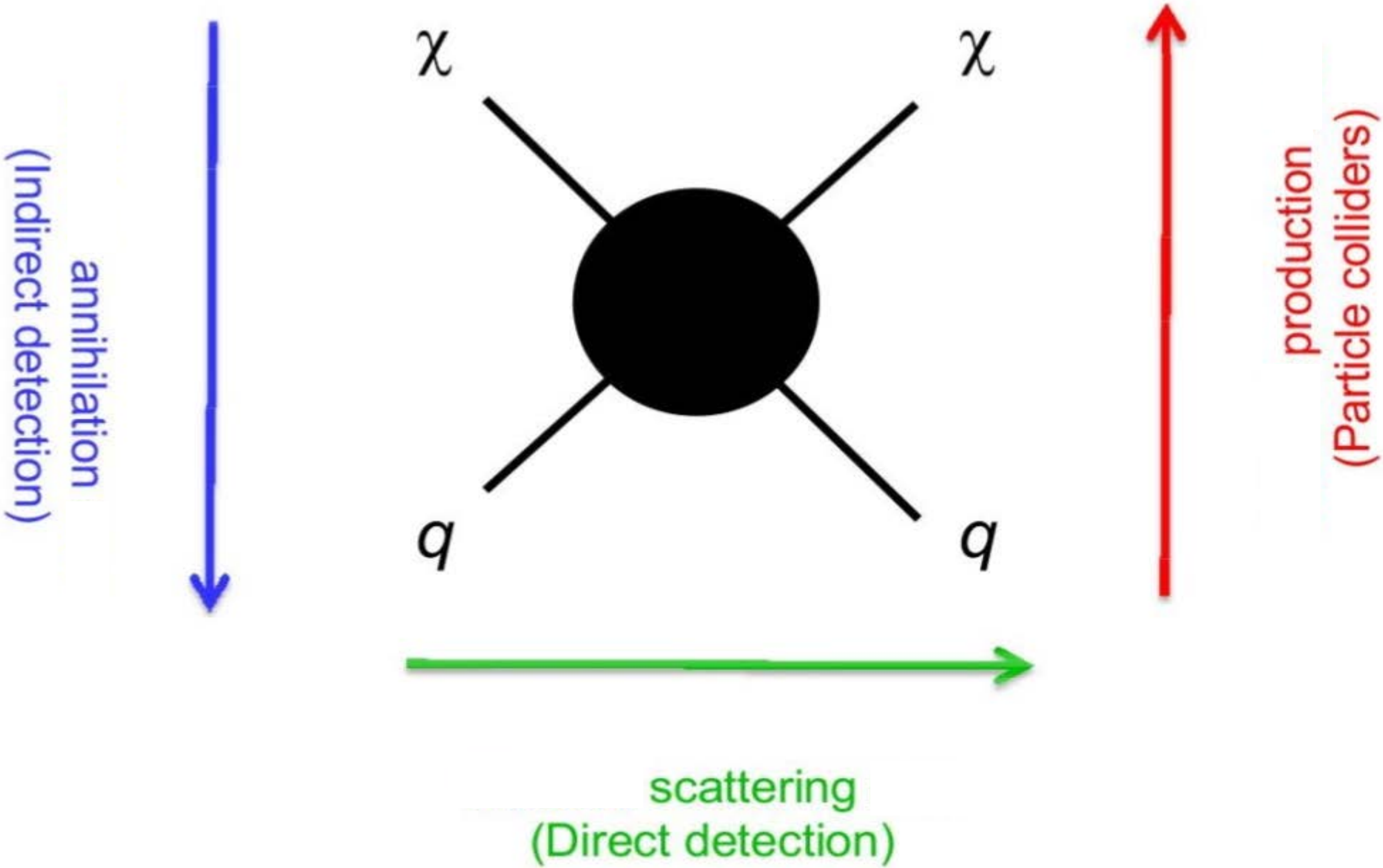
VULCANO WORKSHOP 2012

FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

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.


χ
χ
q
q
annihilation
(Indirect detection)
production
(Particle colliders)
scattering
(Direct detection)

They Play Together!

Direct Detection
Relic scattering RIGHT HERE at low energy. Push to larger target mass, lower backgrounds, directional sensitivity?

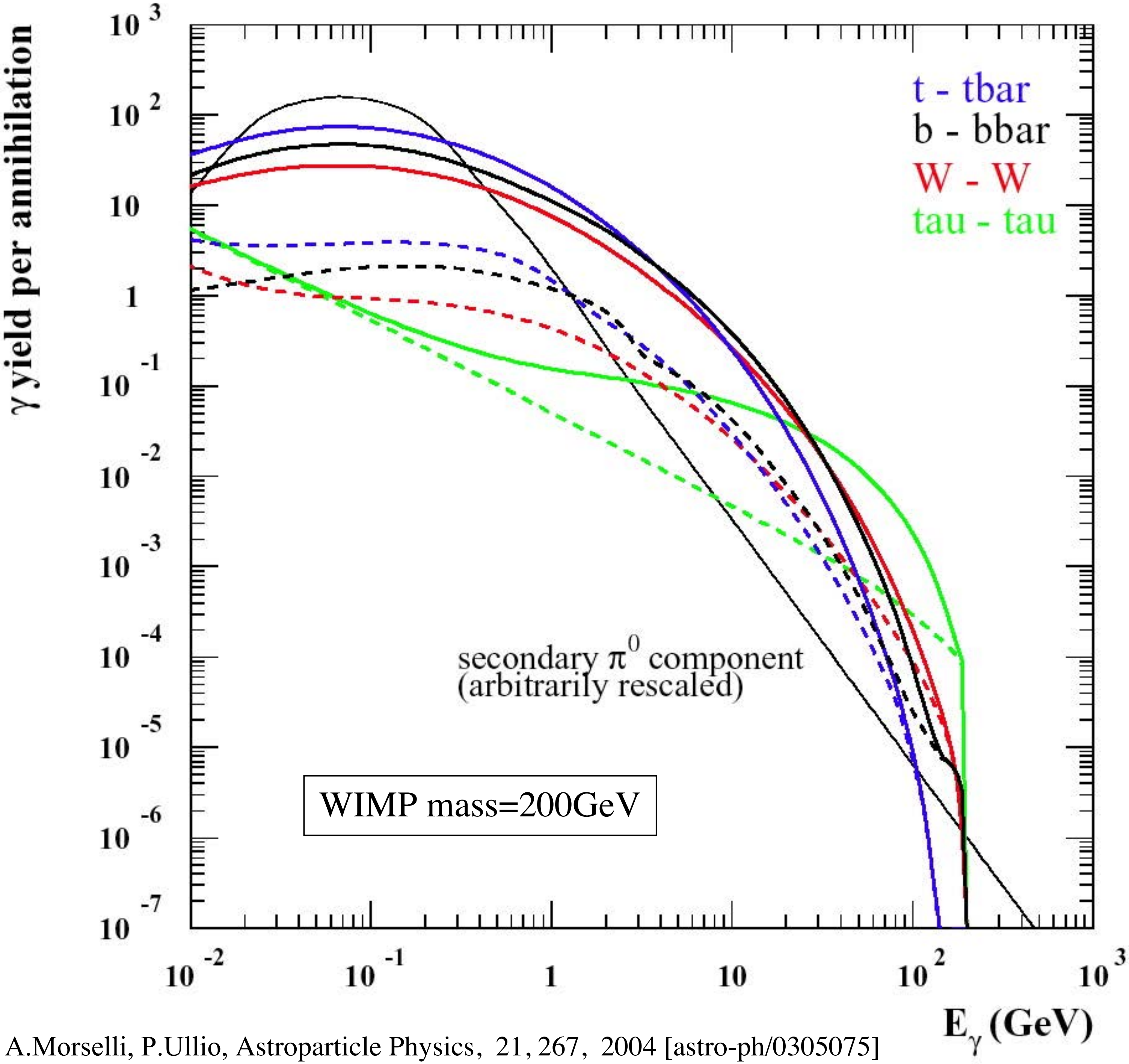
Accelerators
Direct production. Push to higher energy

Observations
Push toward finding and studying galactic halo objects and large scale structure.

Indirect Detection
Relic interactions (annihilations, decays) Understand the astrophysical backgrounds in signal-rich regions. Reveal the detailed astrophysical distribution of dark matter.

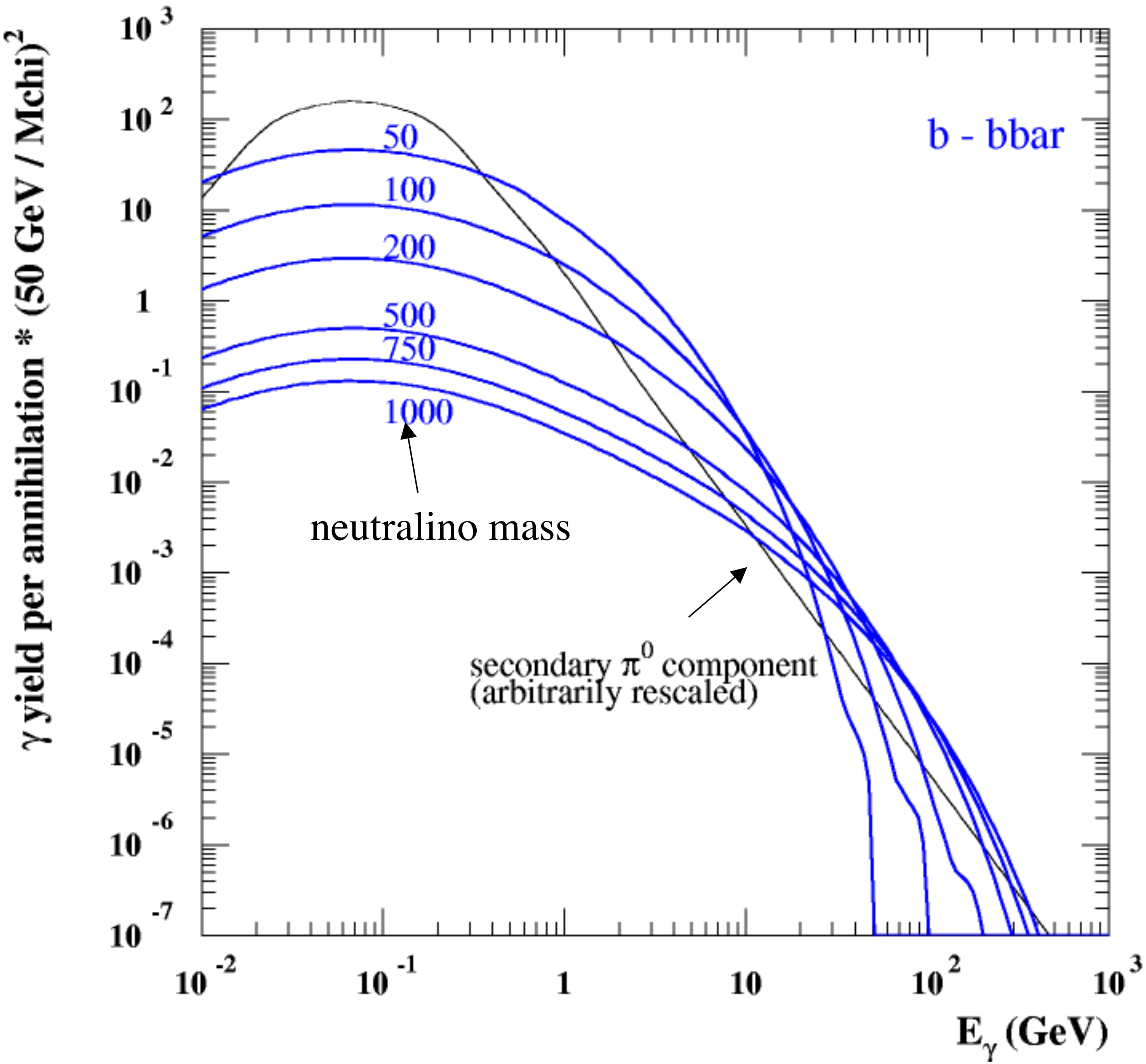
Simulations
Large scale structure formation. Push toward larger simulations, finer details.

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

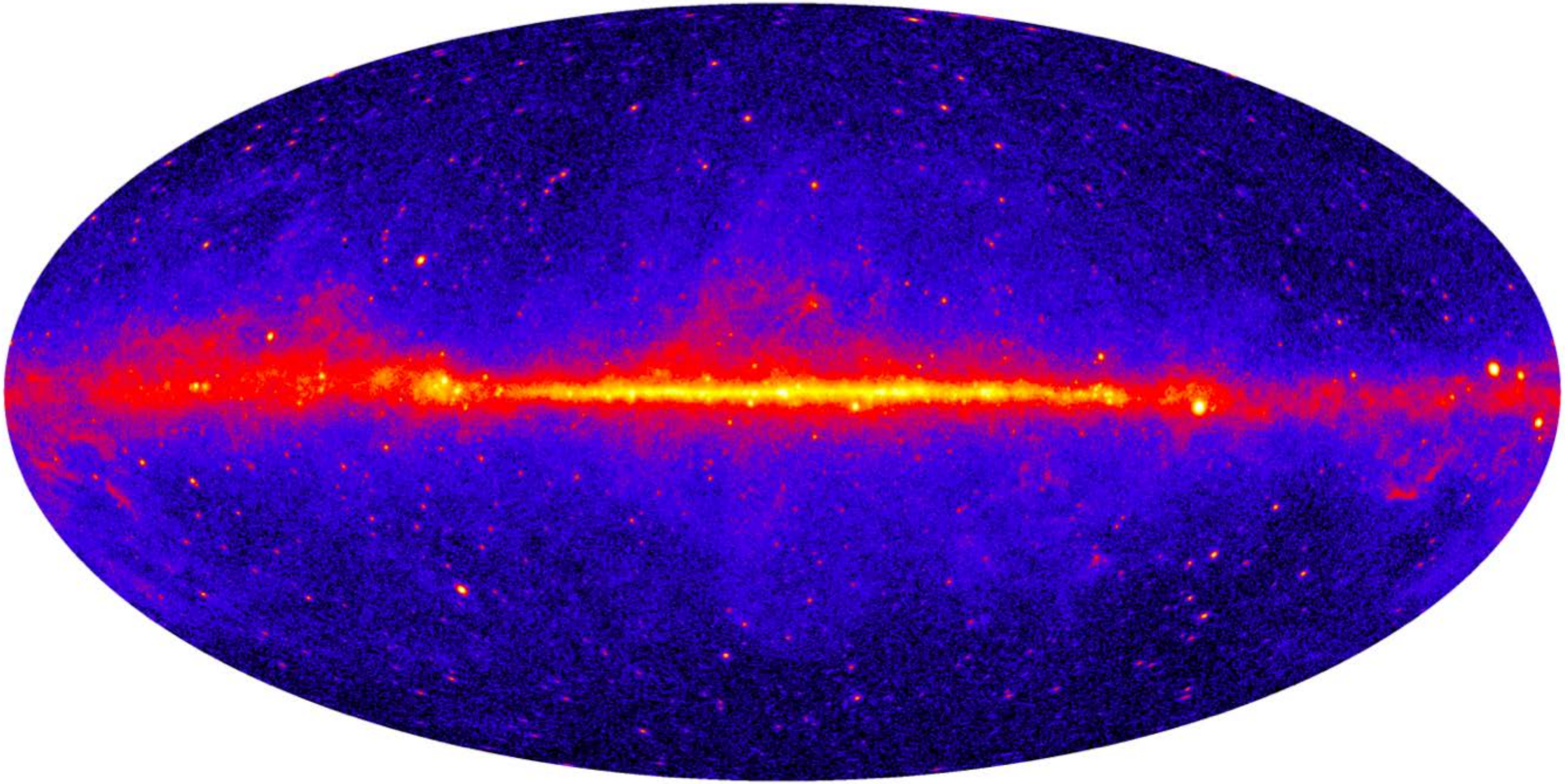


A.Cesarini, F.Fucito, A.Lionetto, A.Morselli, P.Ullio, Astroparticle Physics, 21, 267-285, 2004 [astro-ph/0305075]


Fermi
Gamma-ray
Space Telescope
11 June 2008

The Fermi LAT gamma-ray sky

3-year all-sky map, E > 1 GeV

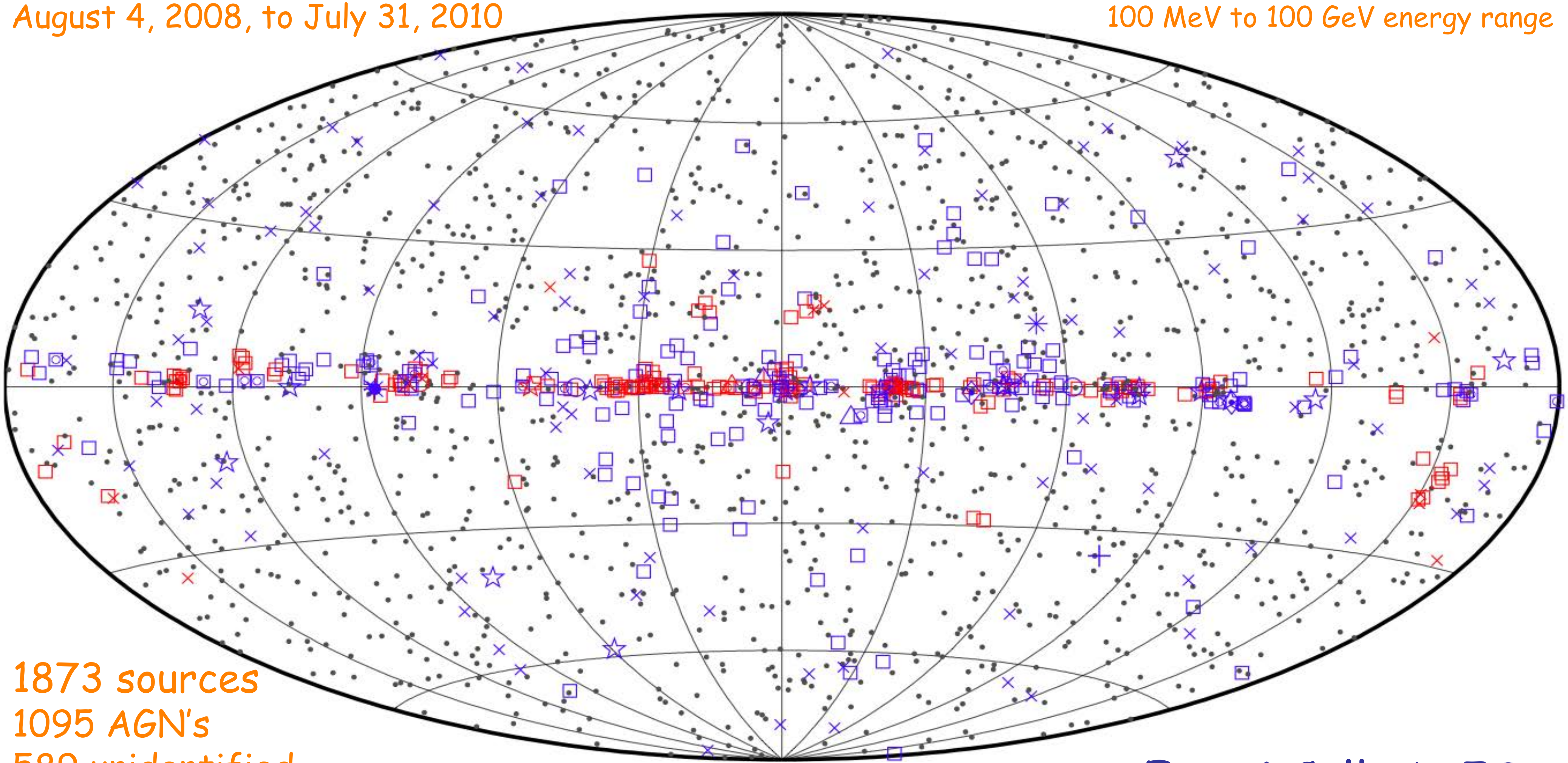


The Fermi LAT 2FGL Source Catalog

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

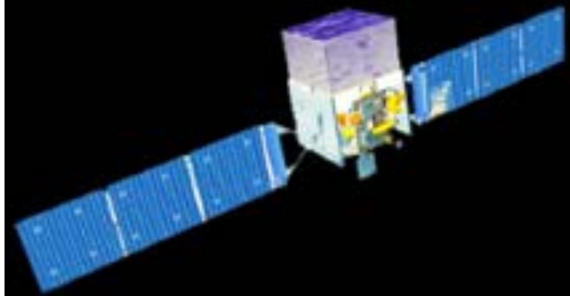


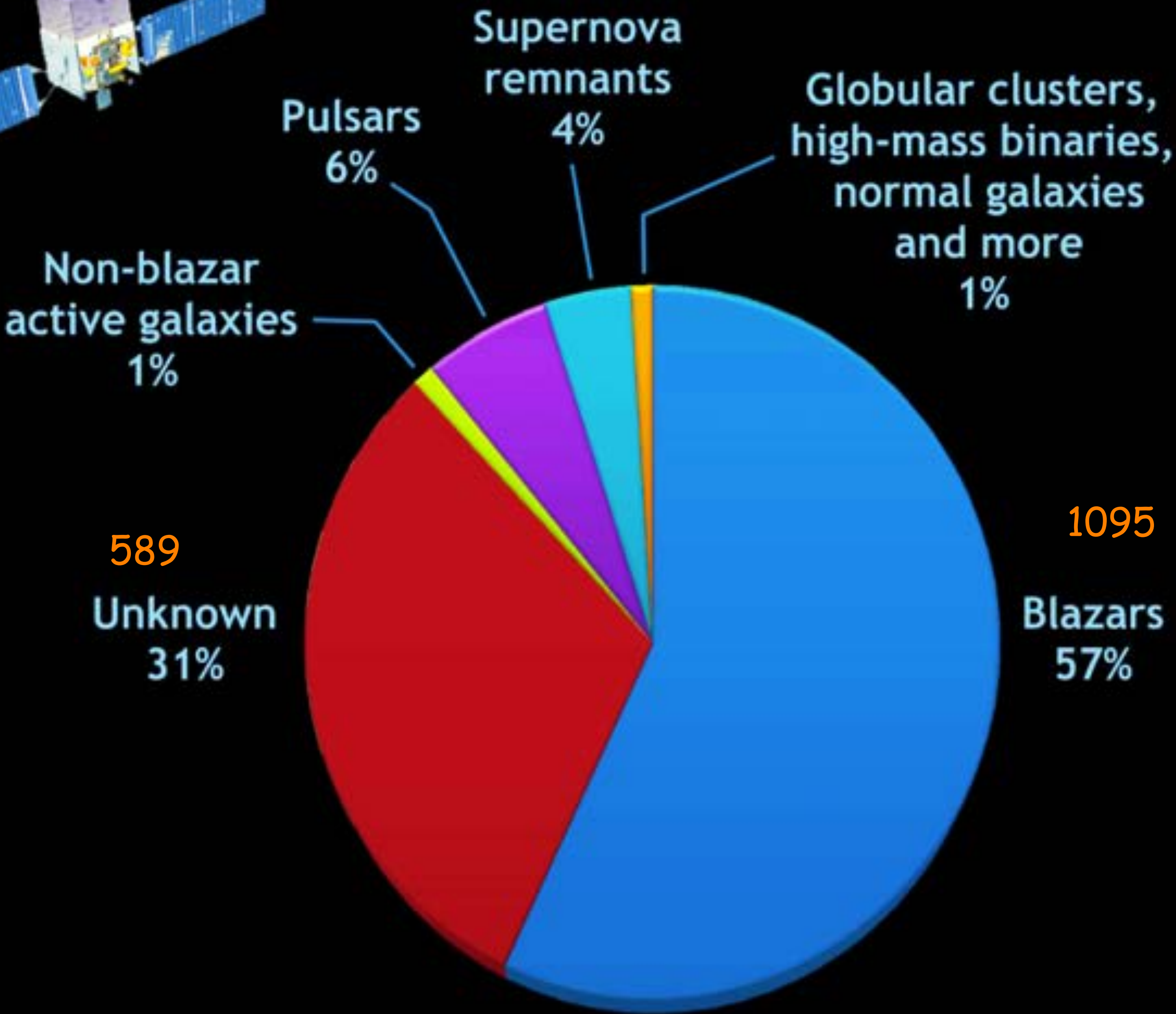
1873 sources
1095 AGN's
589 unidentified

□ No association	⊡ Possible association with SNR or PWN	
× AGN	☆ Pulsar	△ Globular cluster
✳ Starburst Gal	◇ PWN	⊠ HMB
+ Galaxy	○ SNR	✷ Nova

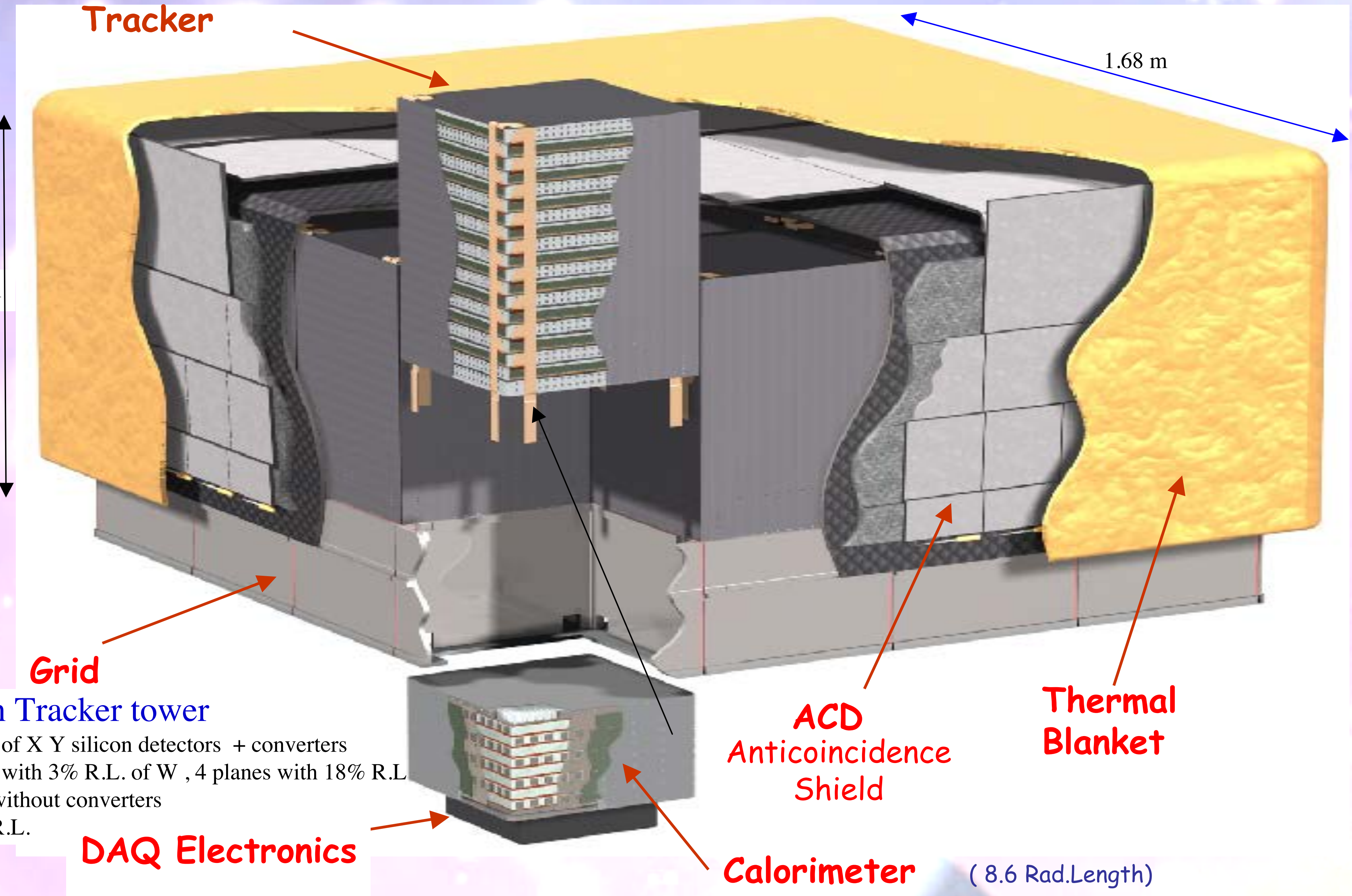
Fermi Coll. ApJS (2012) 199, 31
arXiv:1108.1435

What has Fermi found: The LAT two-year catalog





Fermi Gamma-Ray Large Area Space Telescope



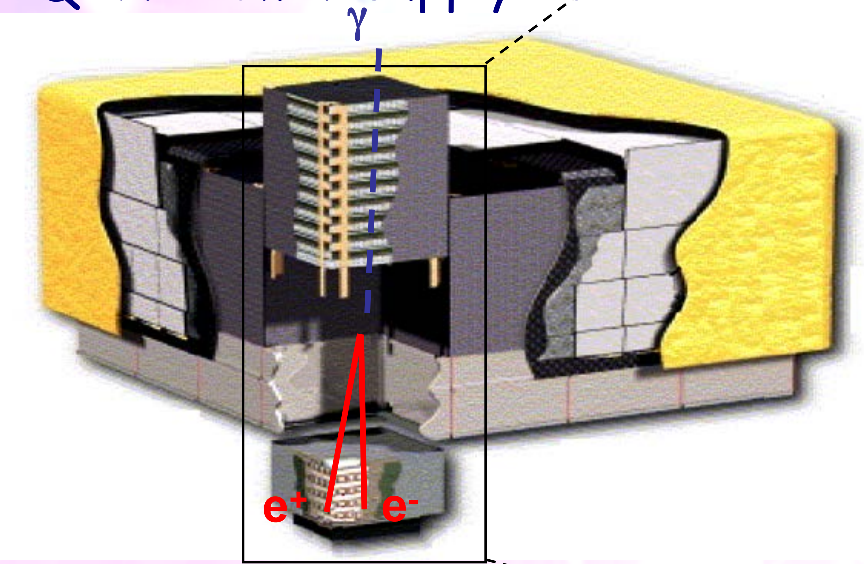
Silicon Tracker tower

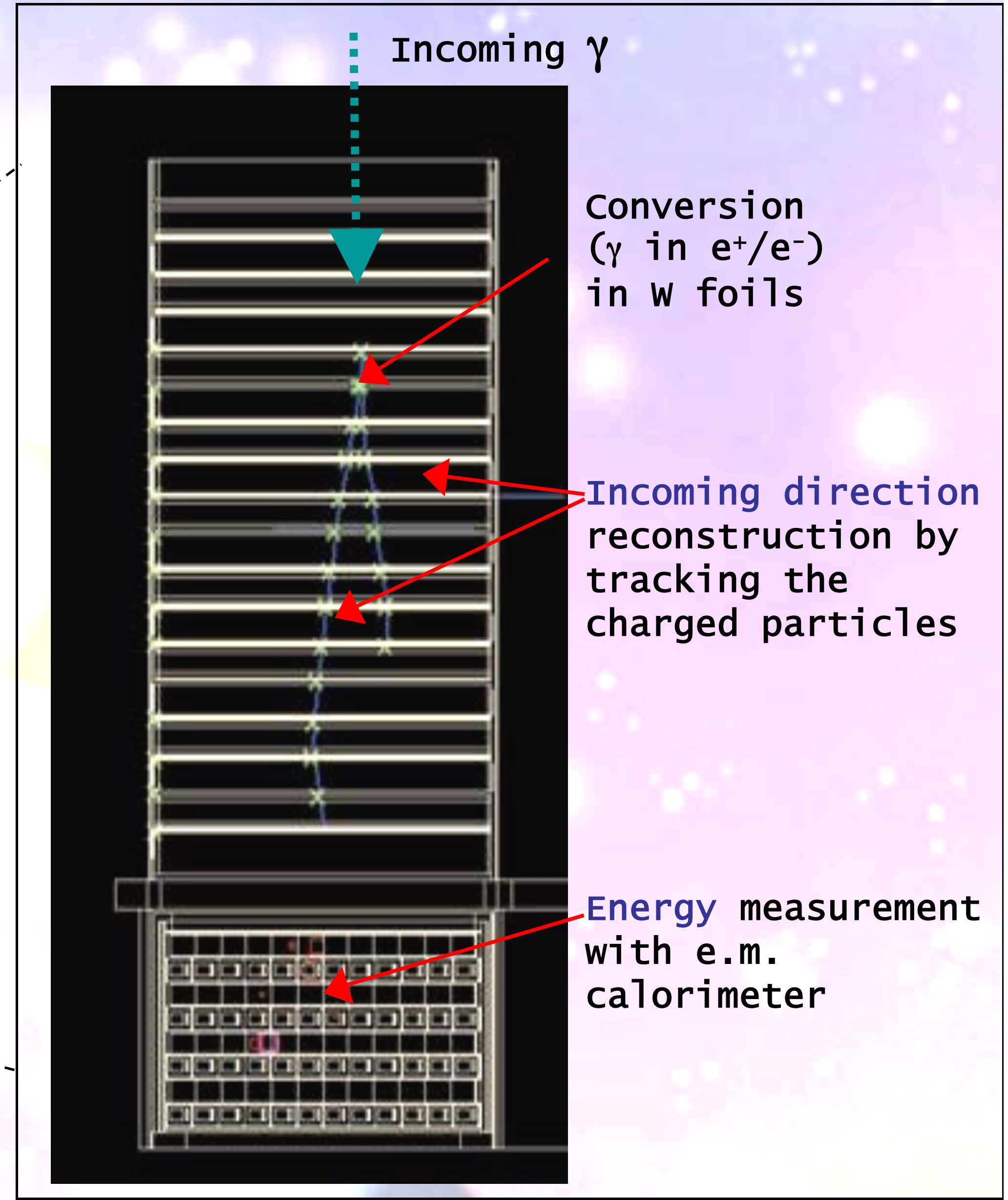
18 planes of X Y silicon detectors + converters
12 planes with 3% R.L. of W , 4 planes with 18% R.L
2 planes without converters
total 1.5 R.L.

How Fermi LAT detects gamma rays

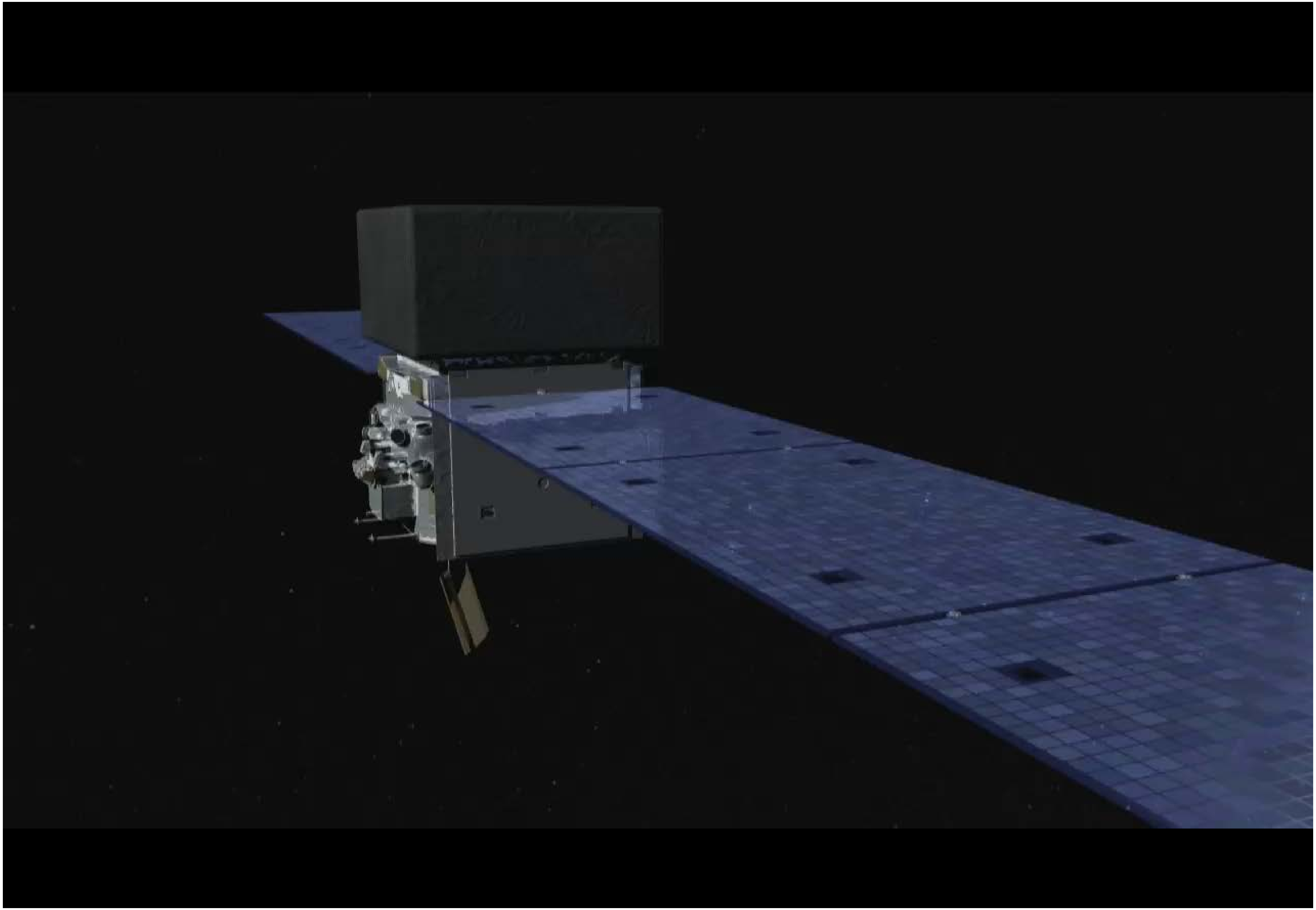
4 x 4 array of identical towers with:

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

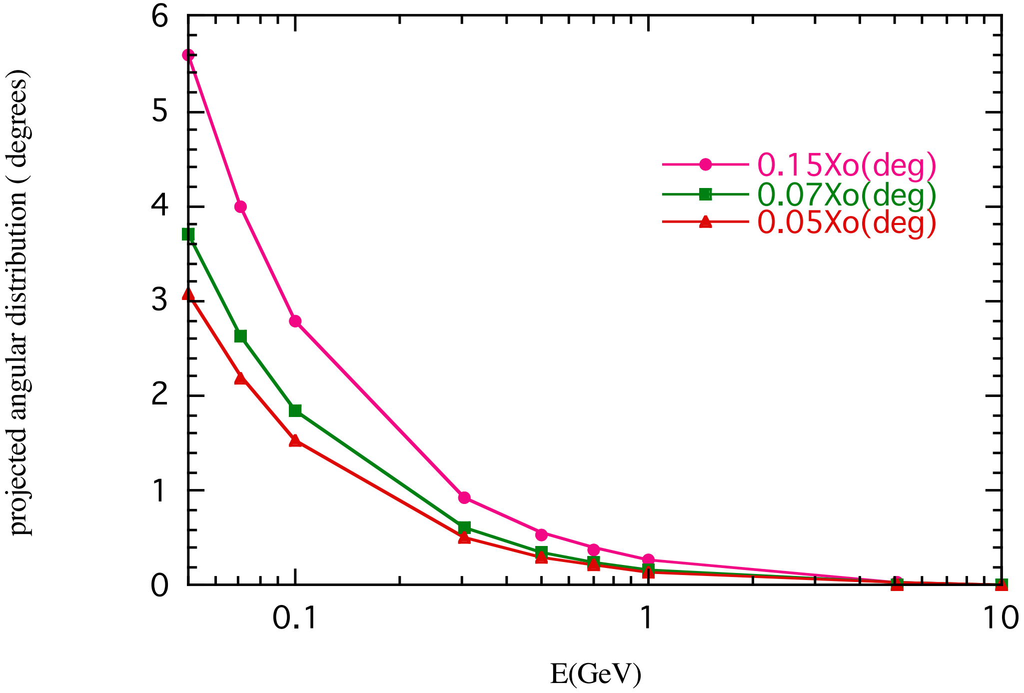


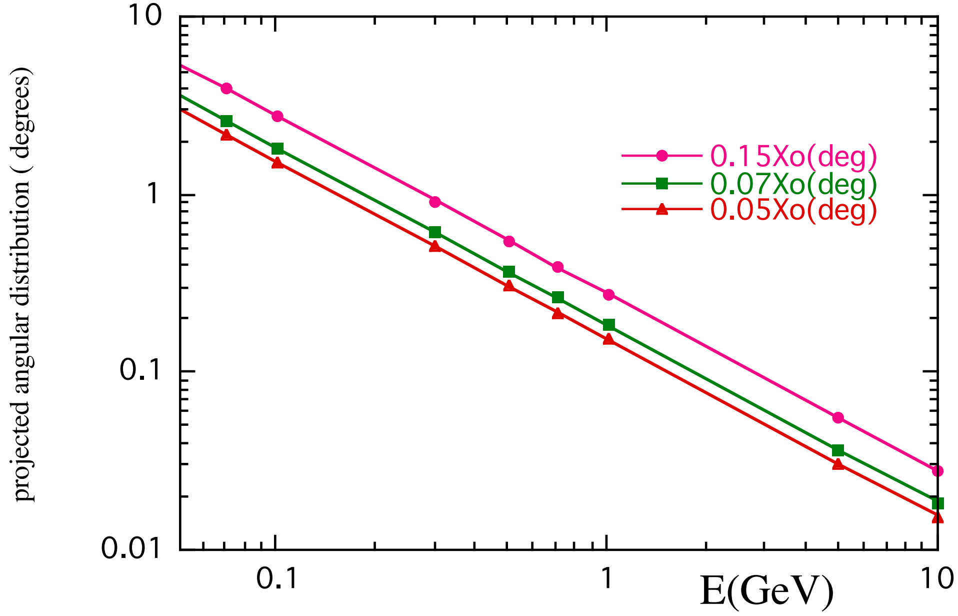


An anticoincidence detector around the telescope distinguishes gamma-rays from charged particles



Multiple Scattering

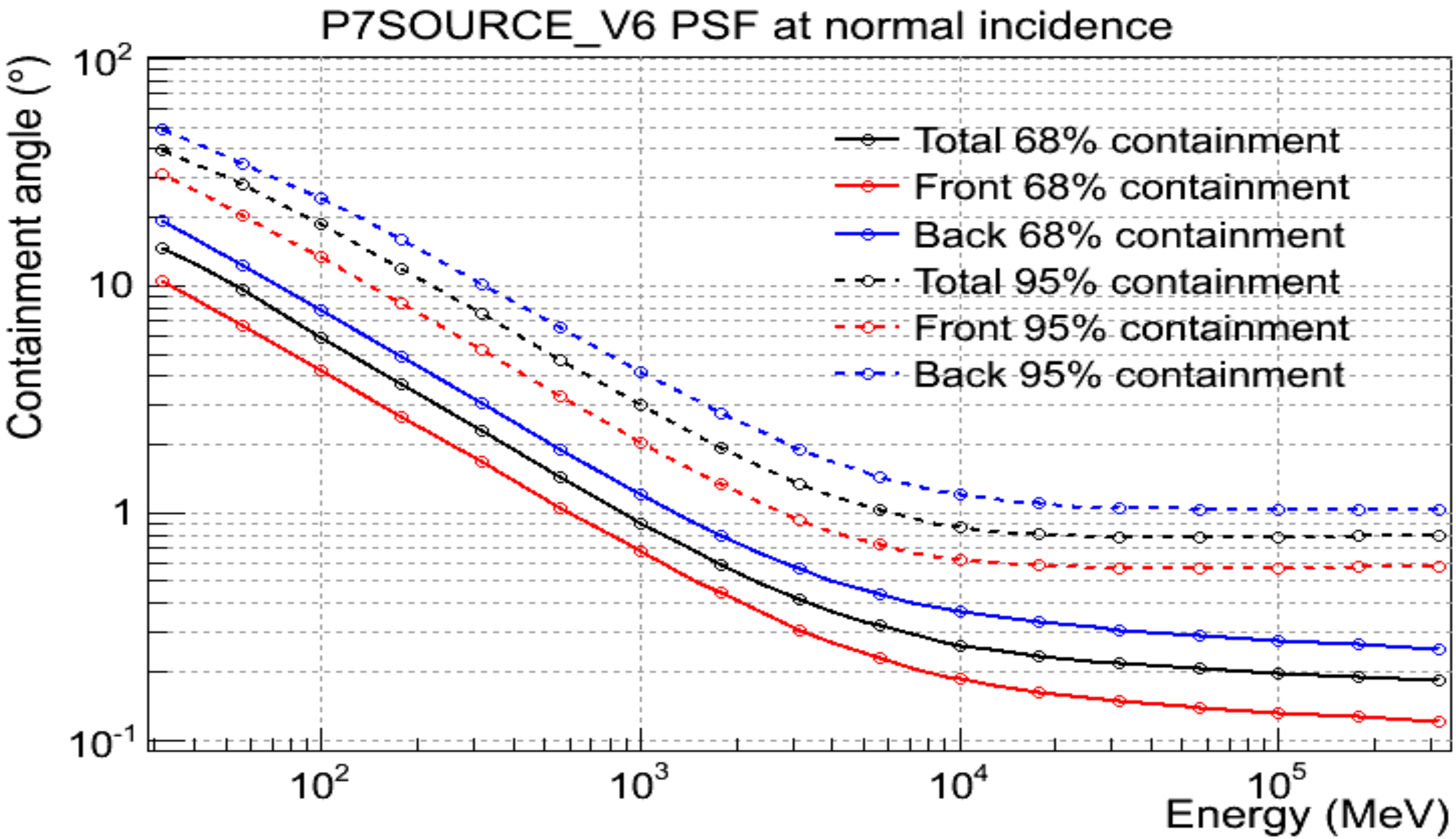




$$\theta_0 = \theta^{rms}_{plane} = \frac{1}{\sqrt{2}}\theta^{rms}_{space}$$

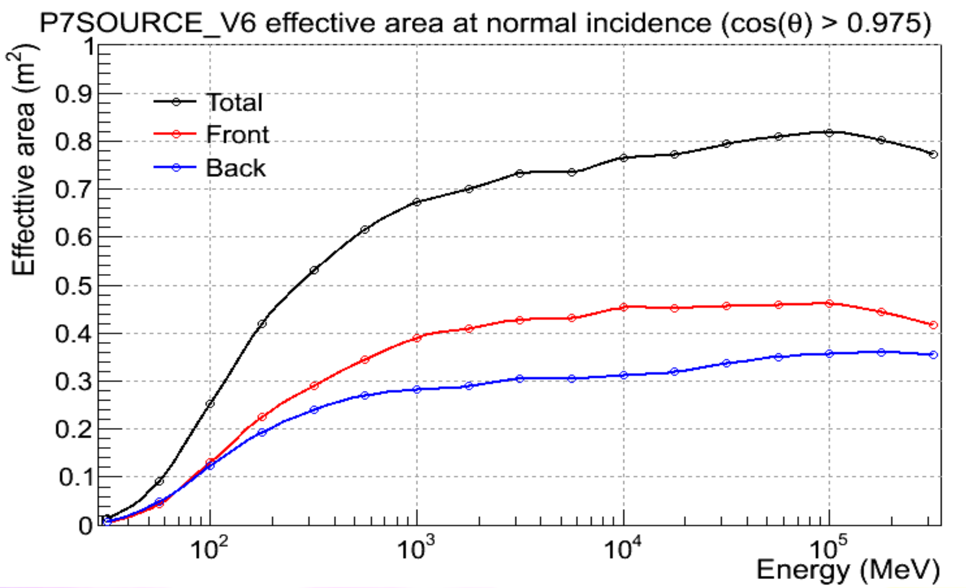
$$\theta_0 = \frac{13.6 MeV}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

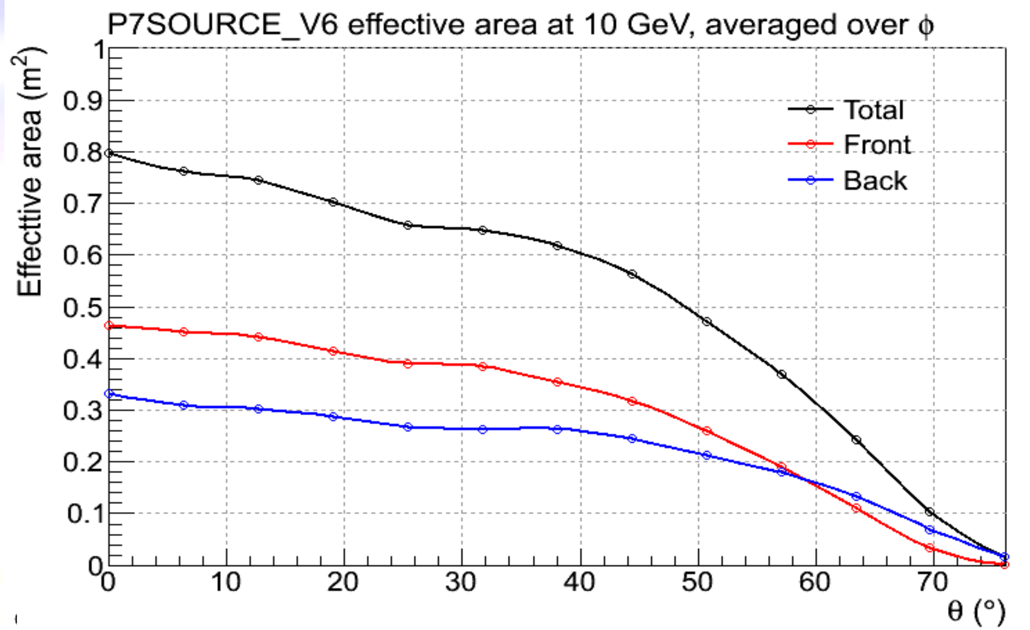
Fermi Instrument Response Function

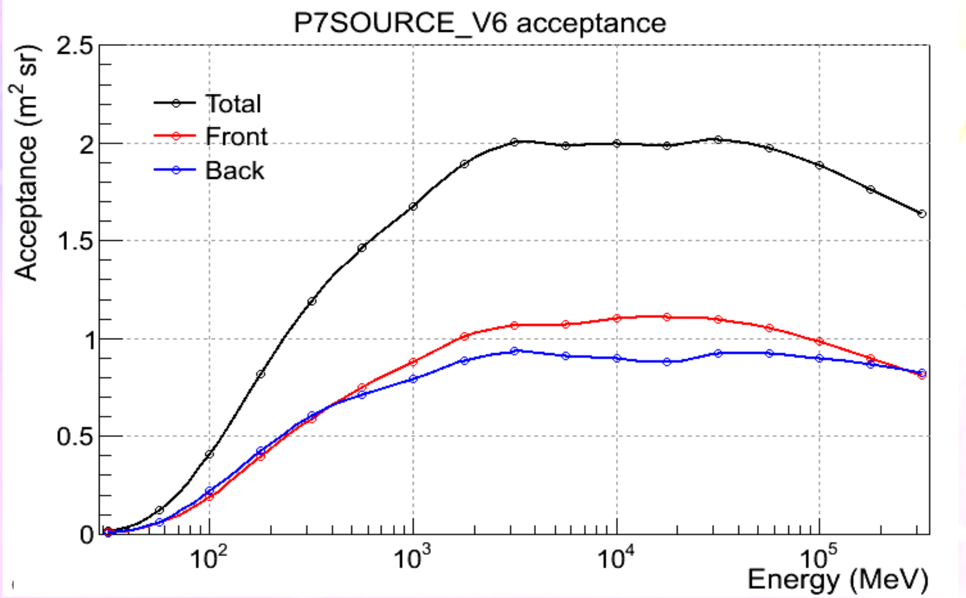


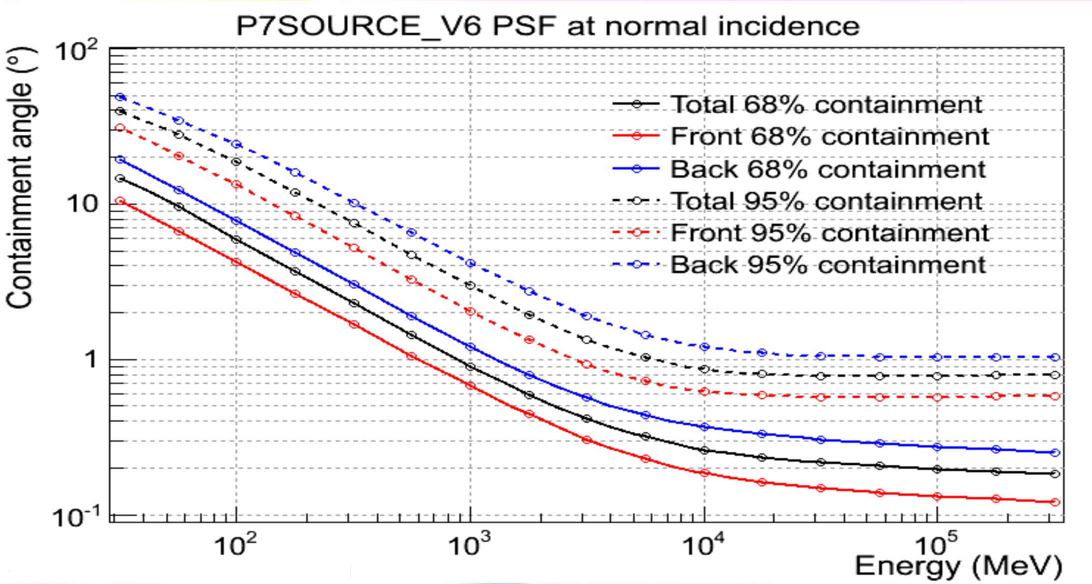
http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Fermi Instrument Response Function









http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

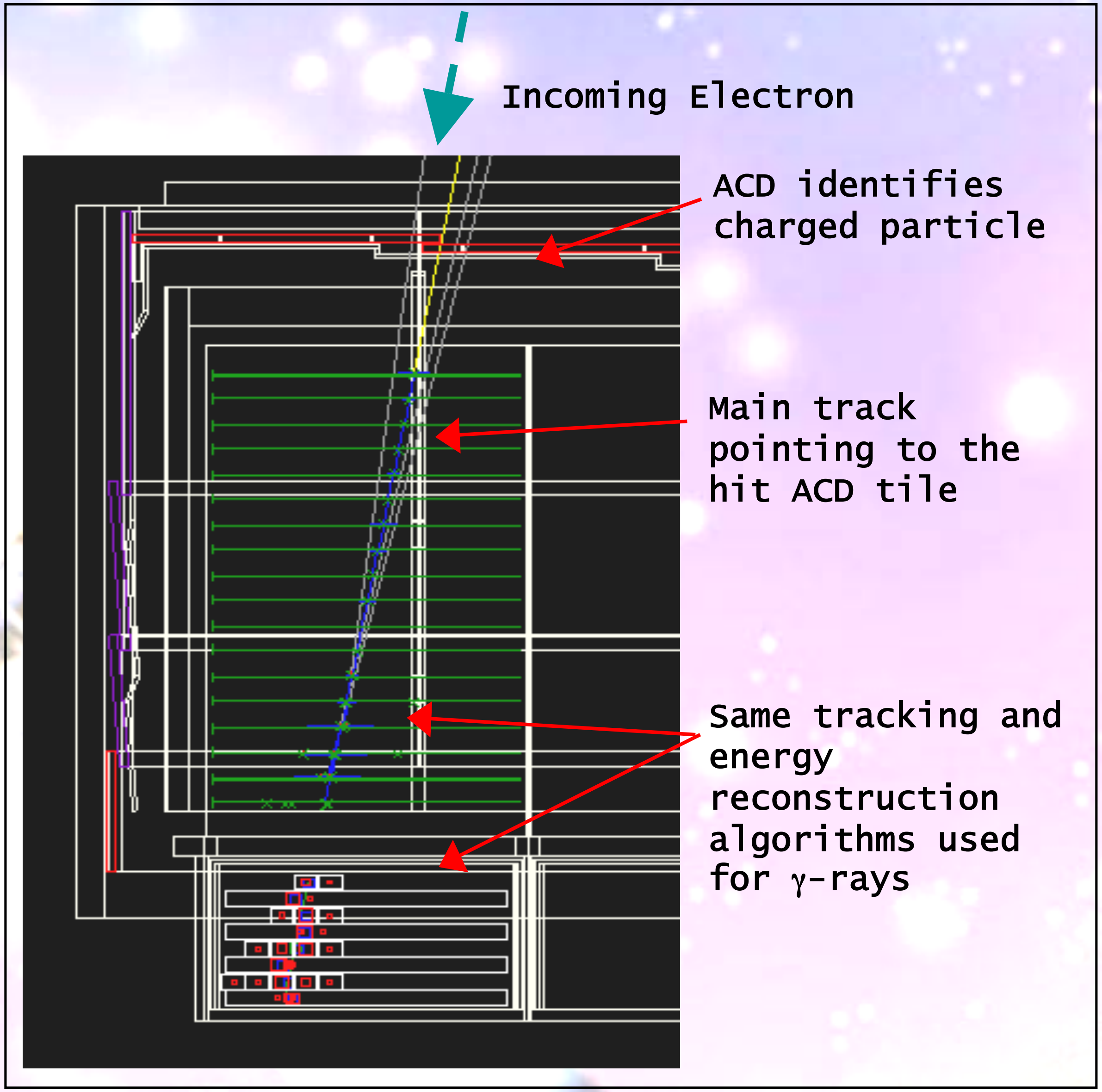
How Fermi LAT detects electrons

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

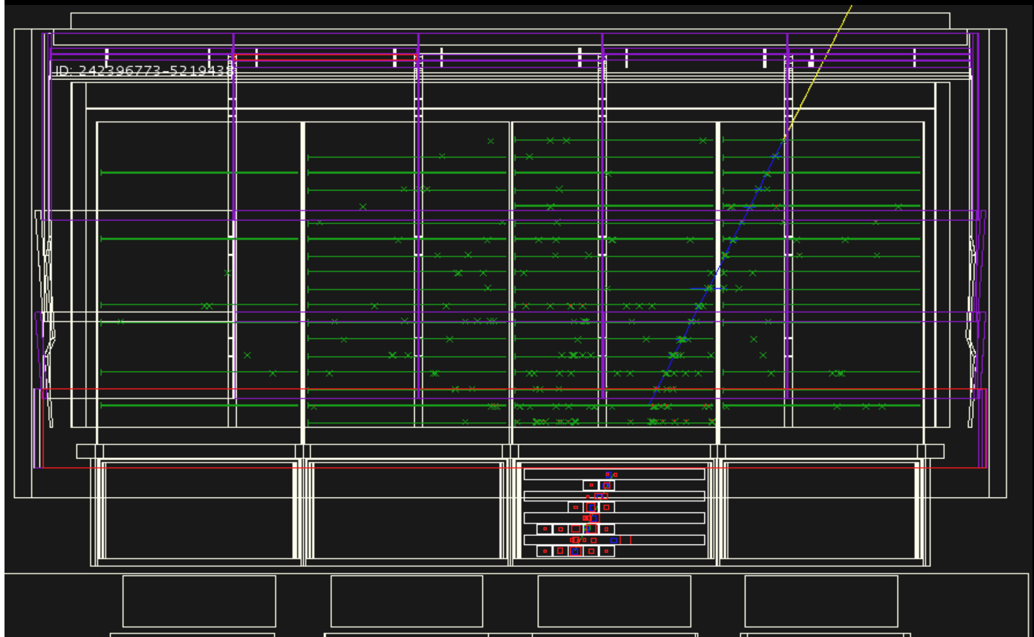
Electron identification

- 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

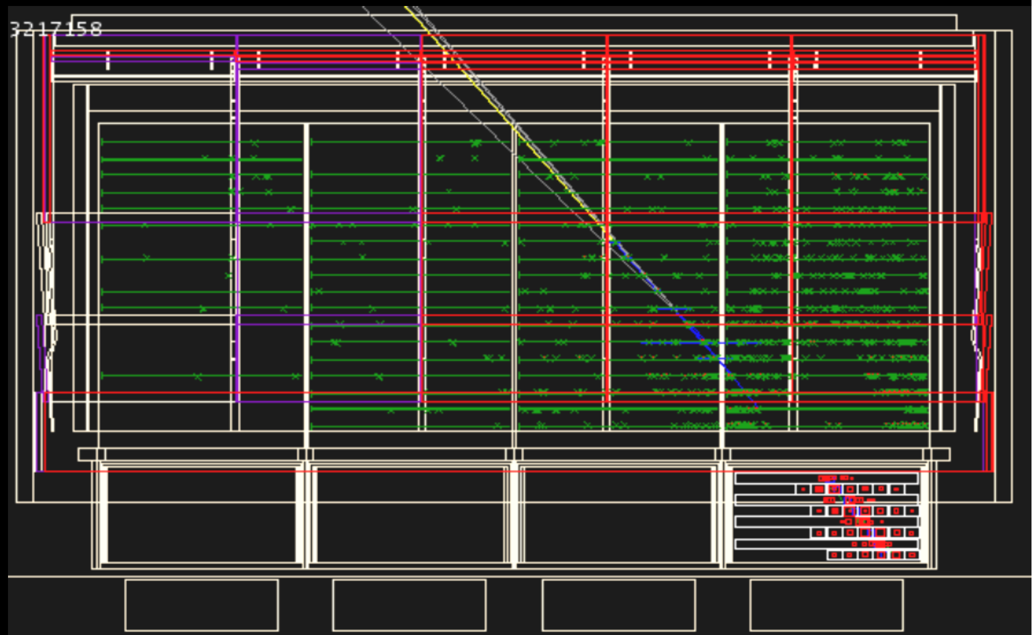


Event topology

A candidate electron
(recon energy 844 GeV)



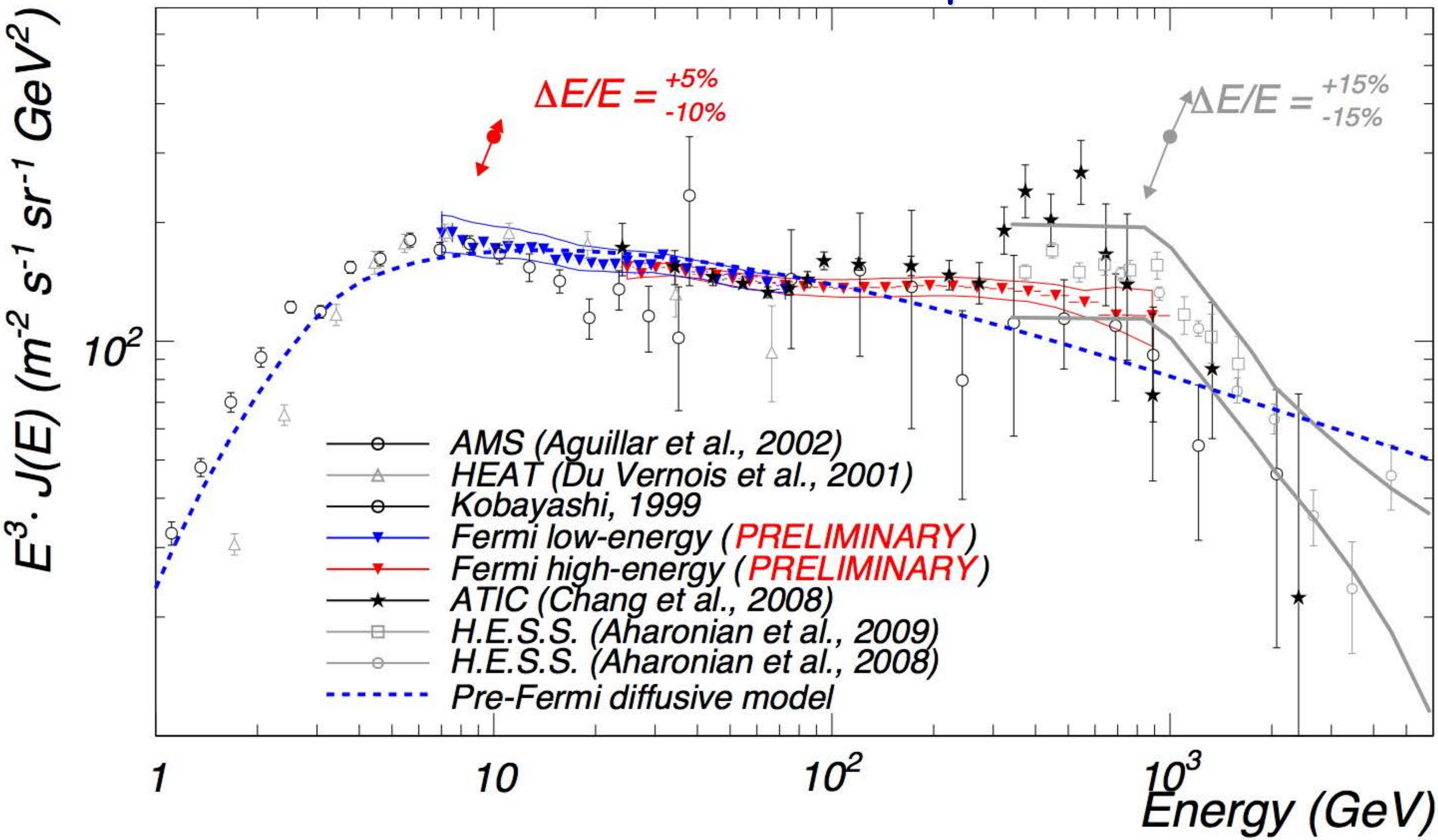
A candidate hadron
(raw energy > 800 GeV)



- 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

- 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

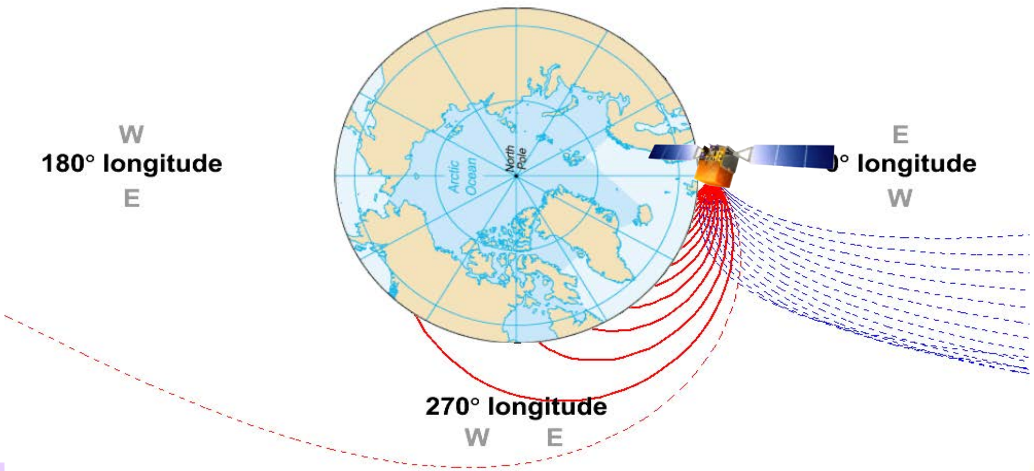


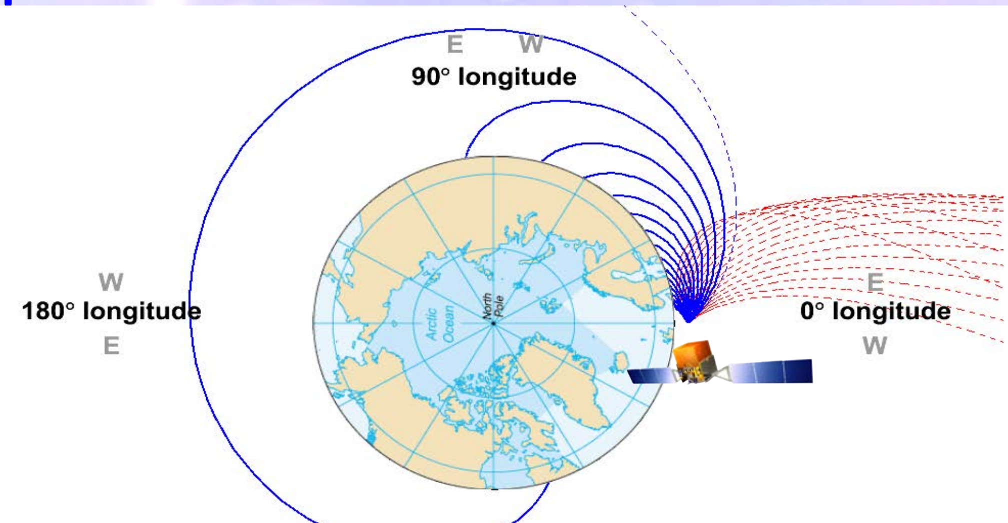
Extended Energy Range (7 GeV – 1 TeV) One year statistics (8M evts)

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

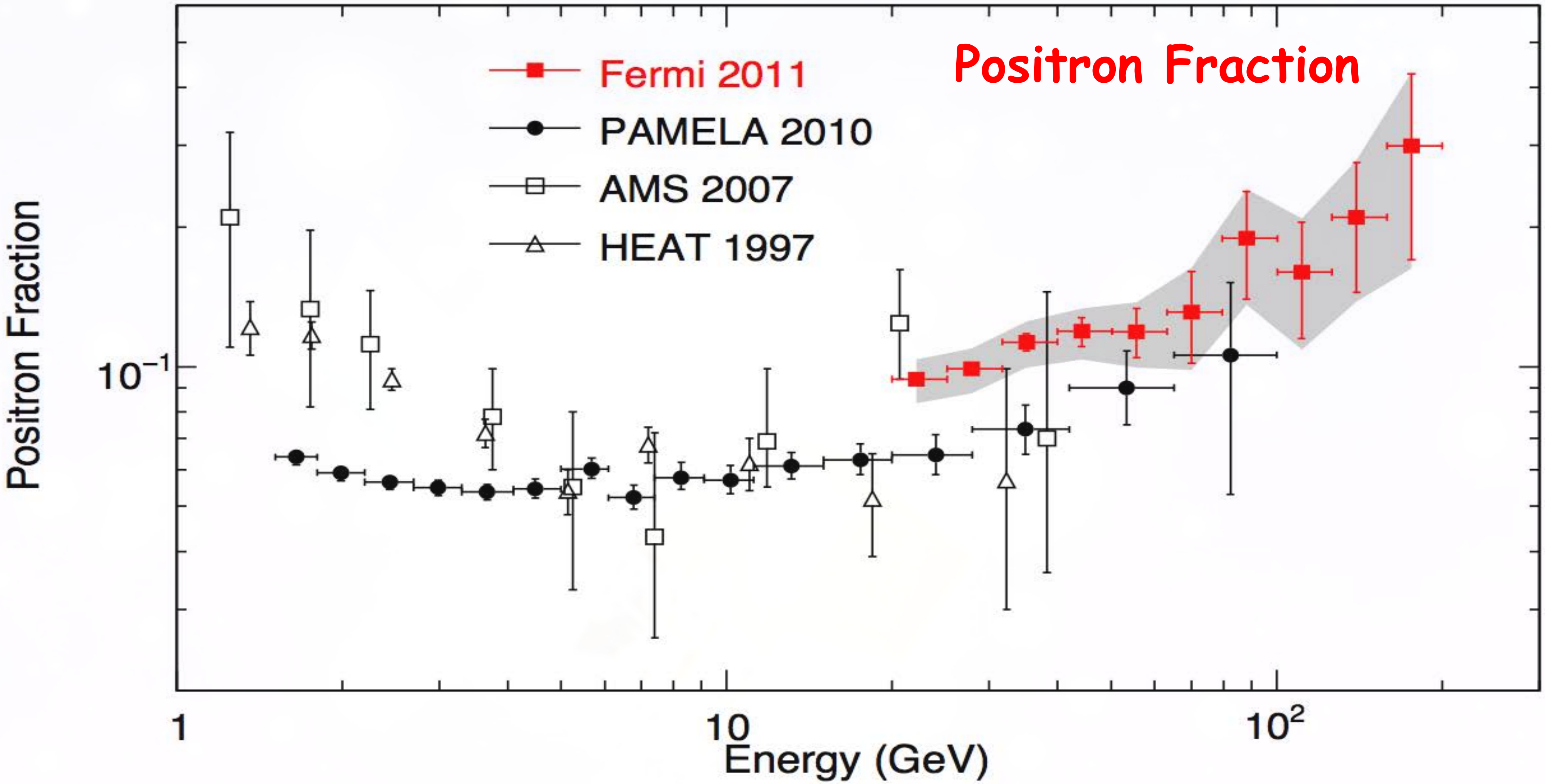
events arriving from West: e^+ allowed, e^- blocked





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



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

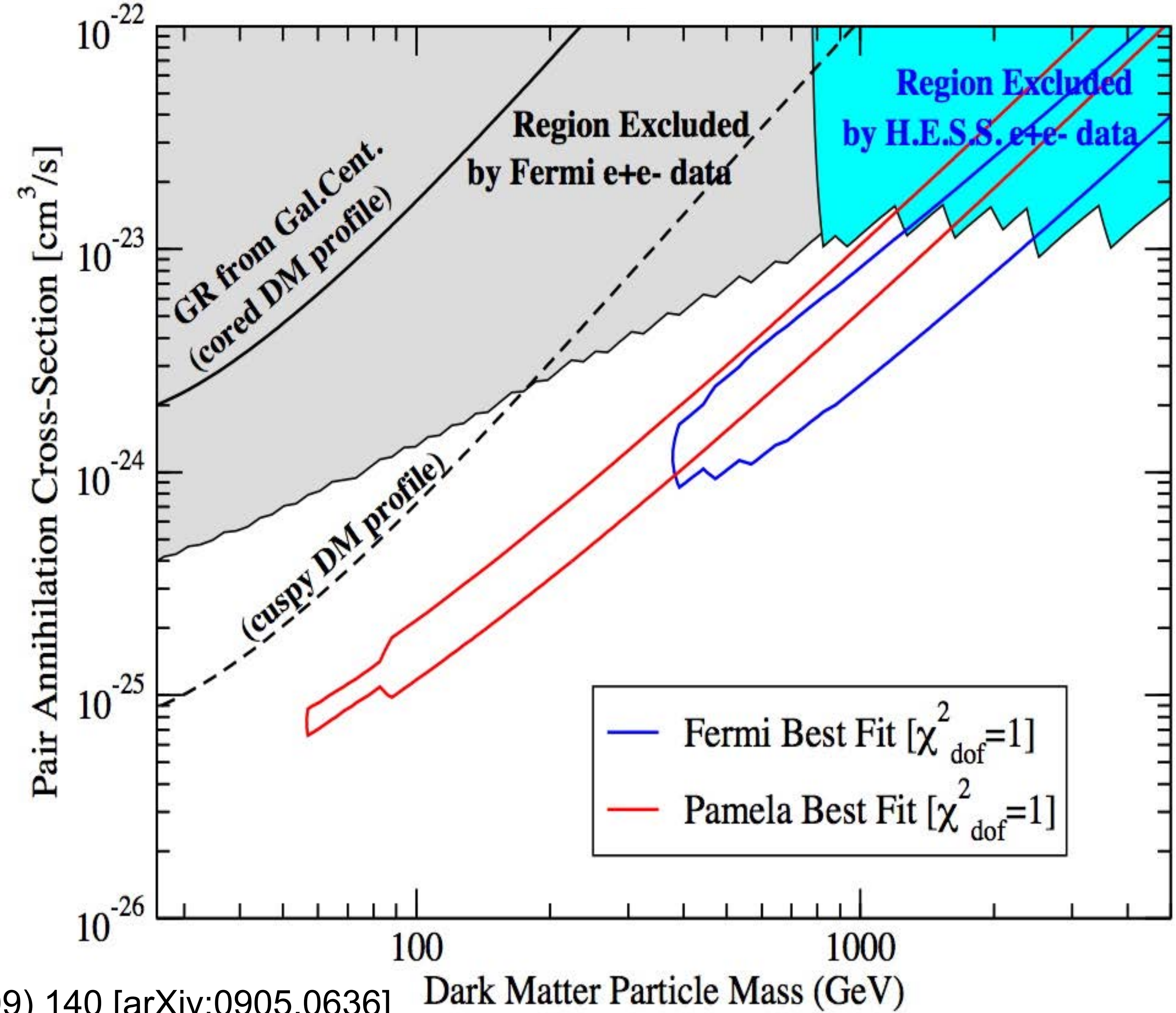
- **Two independent methods of background subtraction produce consistent results**
- **The observed positron fraction is consistent with the one measured by PAMELA**

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 $\mu+\ \mu-$ and 1/3 into $\tau+\tau-$ Here too antiprotons are not produced in dark matter pair annihilation.



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

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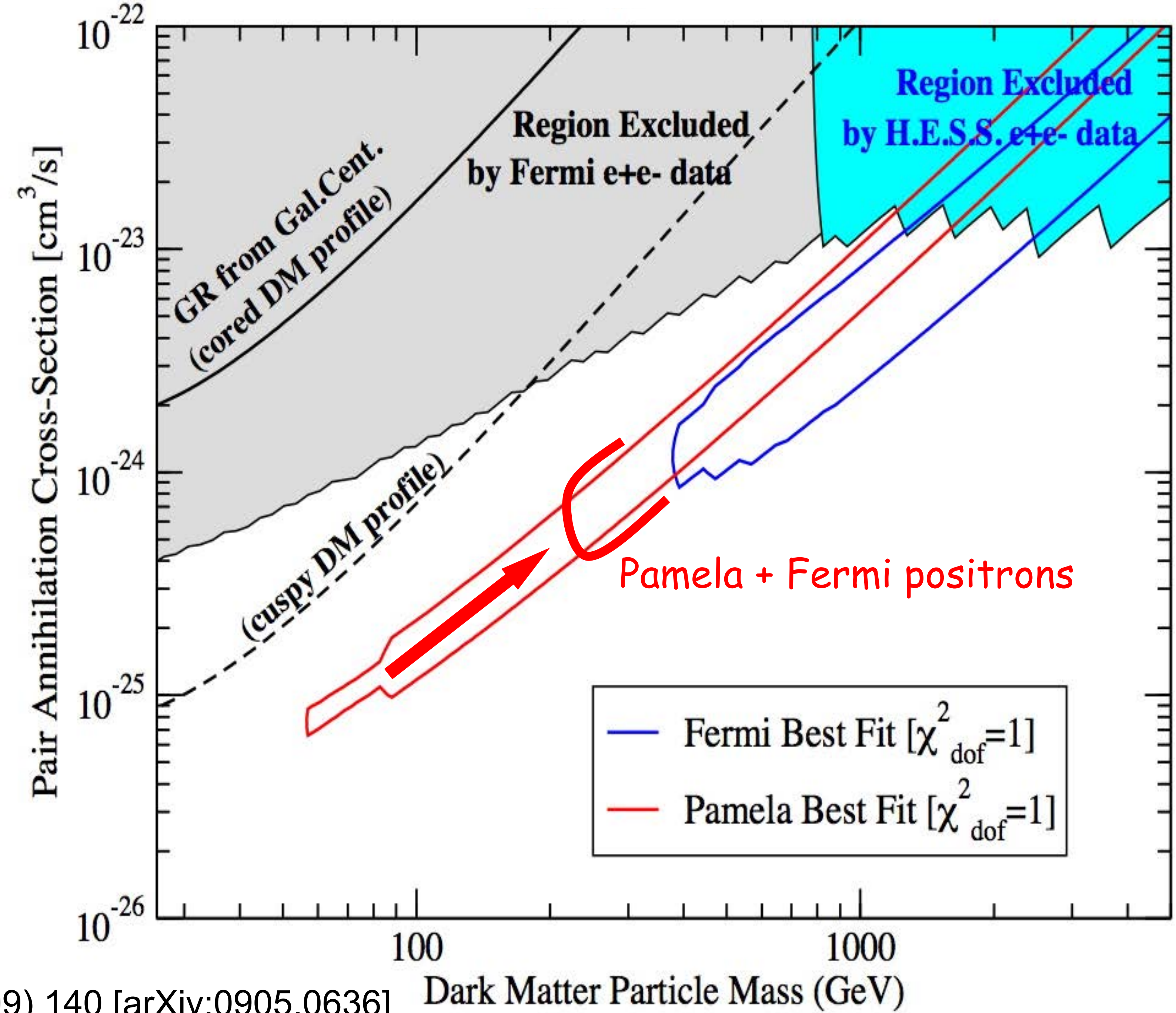
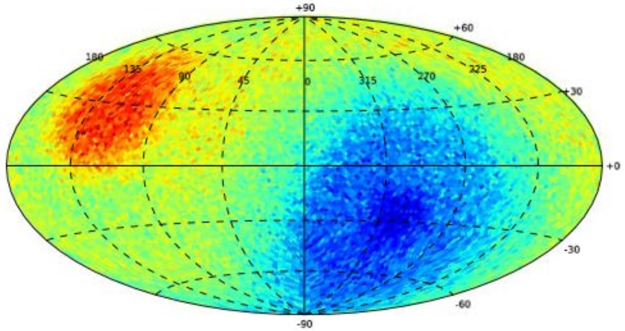
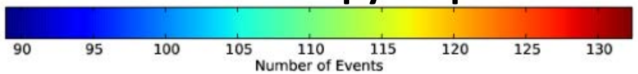


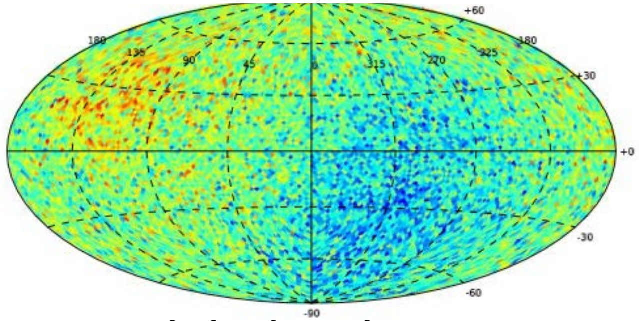
Astrp Phys.32 (2009) 140 [arXiv:0905.0636]

Cosmic Ray Electrons Anisotropy

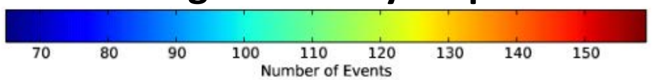


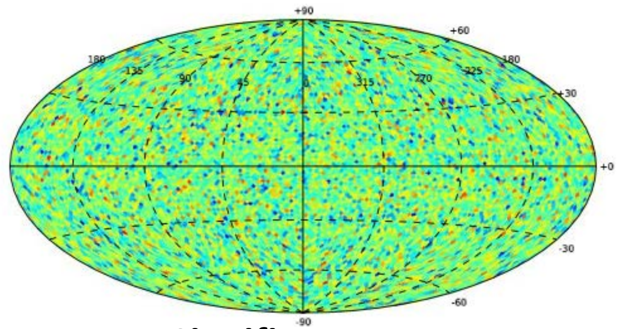
No-anisotropy map



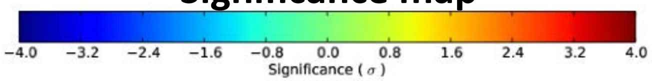


Flight data sky map



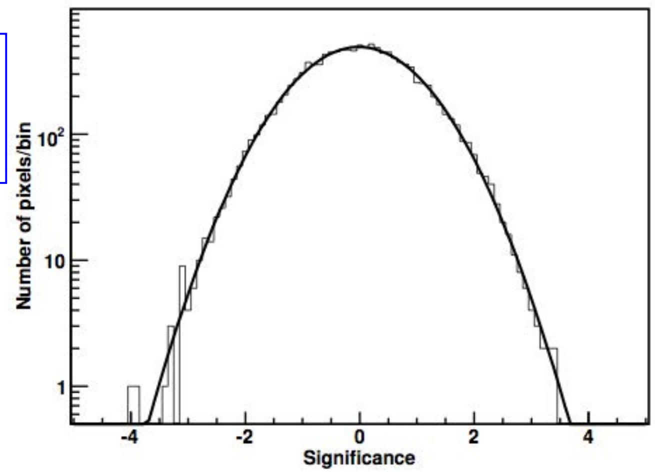


Significance map



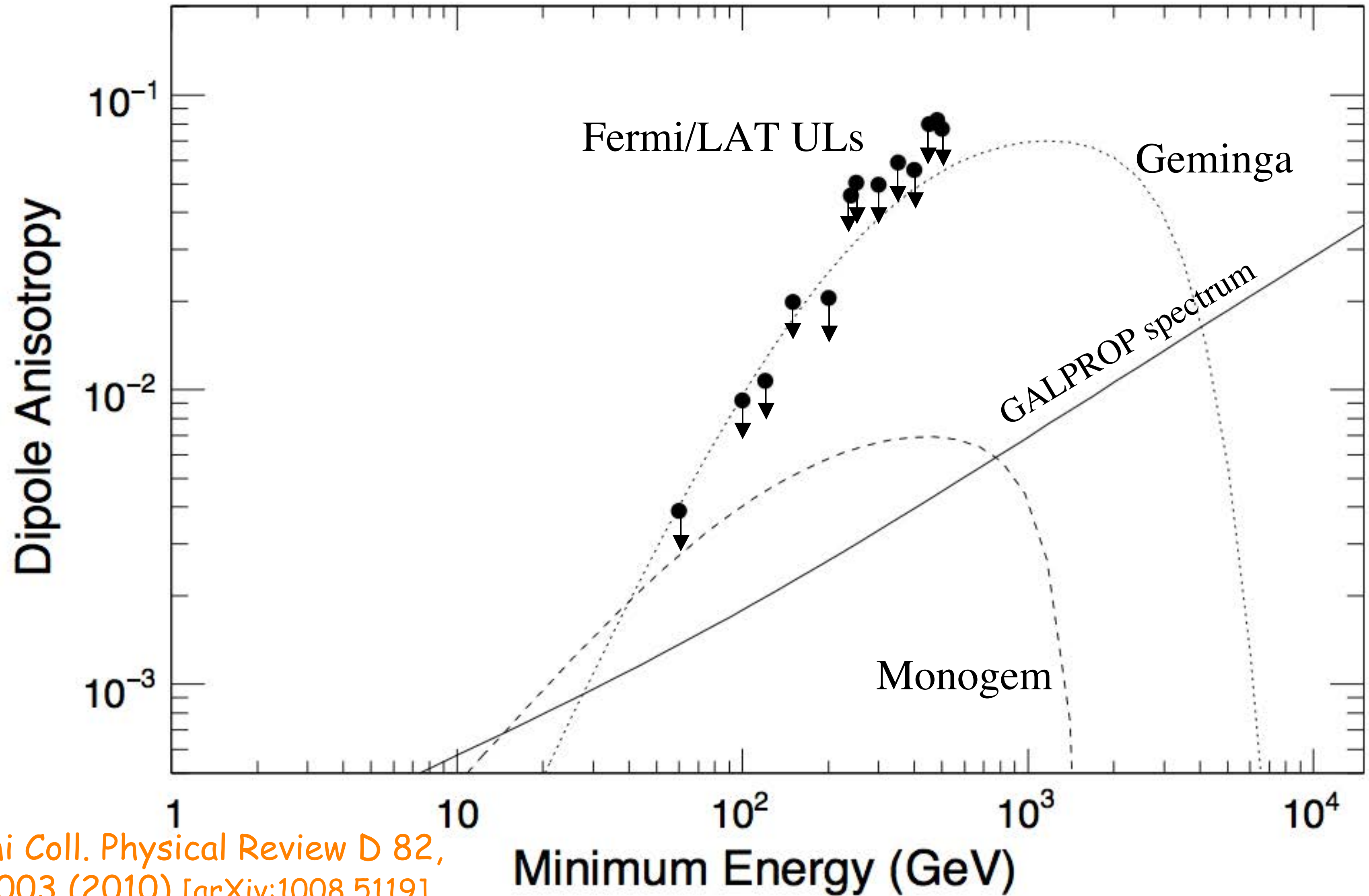
<u>the levels of anisotropy expected for Geminga-like and Monogem-like sources</u> (i.e. sources with similar distances and ages) <u>seem to be higher than the scale of anisotropies excluded by the results</u>
However, it is worth to point out that the model results are affected by large uncertainties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



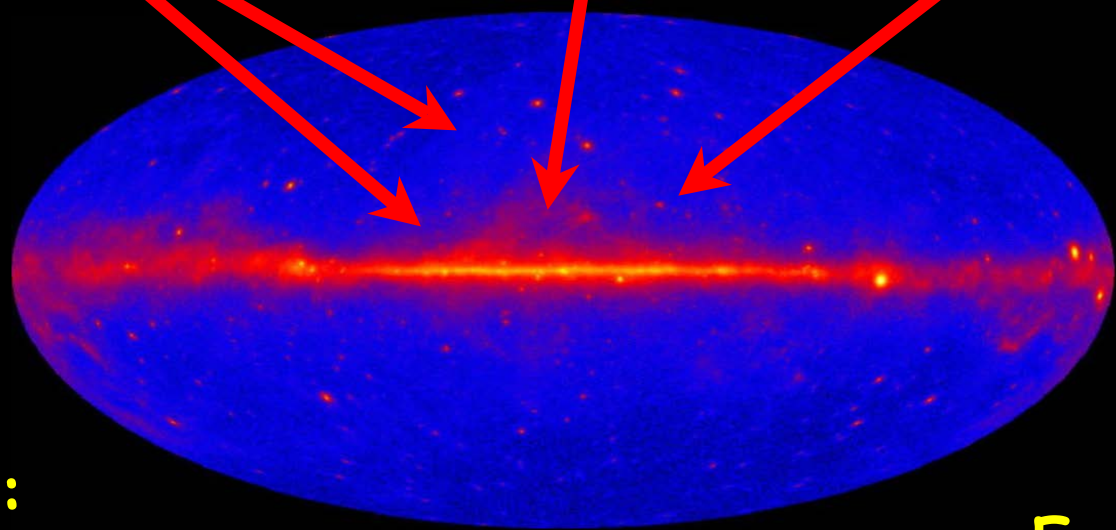
Fermi Coll. Physical Review D 82, 092003 (2010) [arXiv:1008.5119]

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

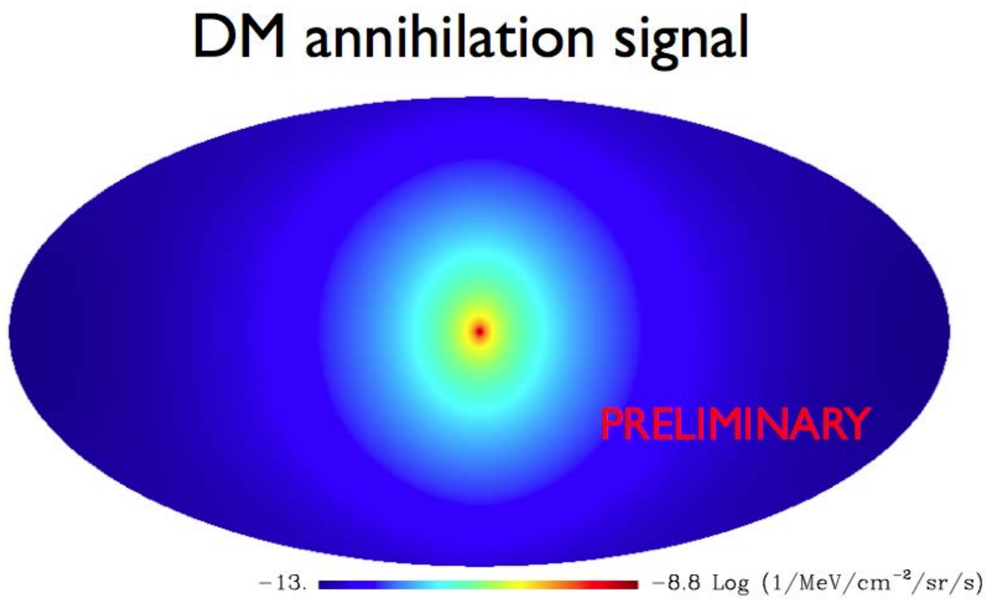
Galaxy clusters:
Low background but low statistics

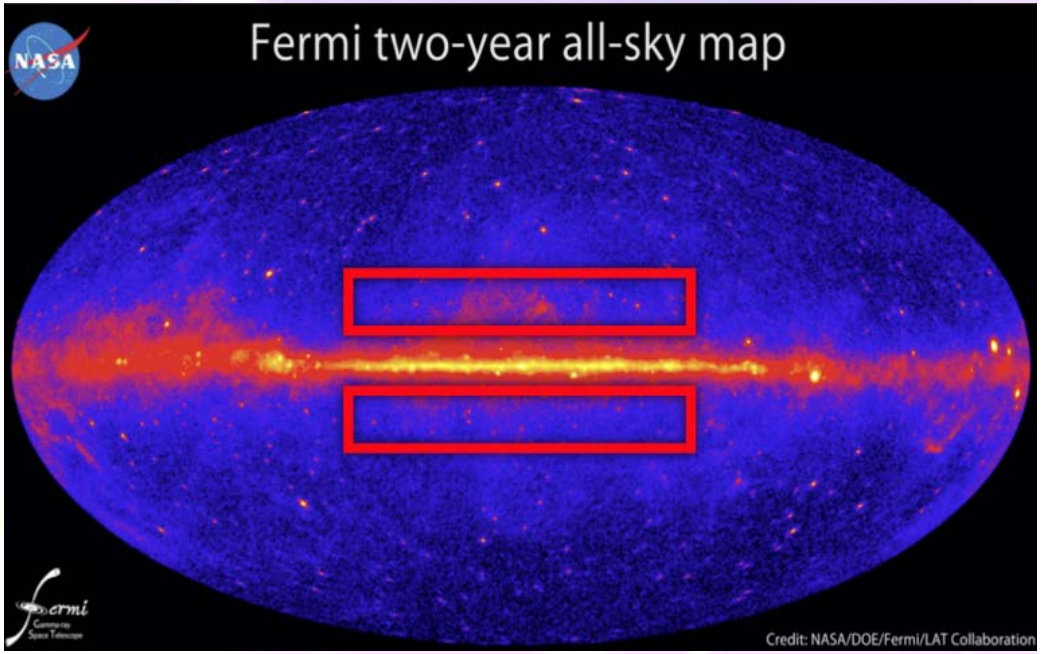
Extra-galactic:
Large statistics, but astrophysics,galactic diffuse background

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



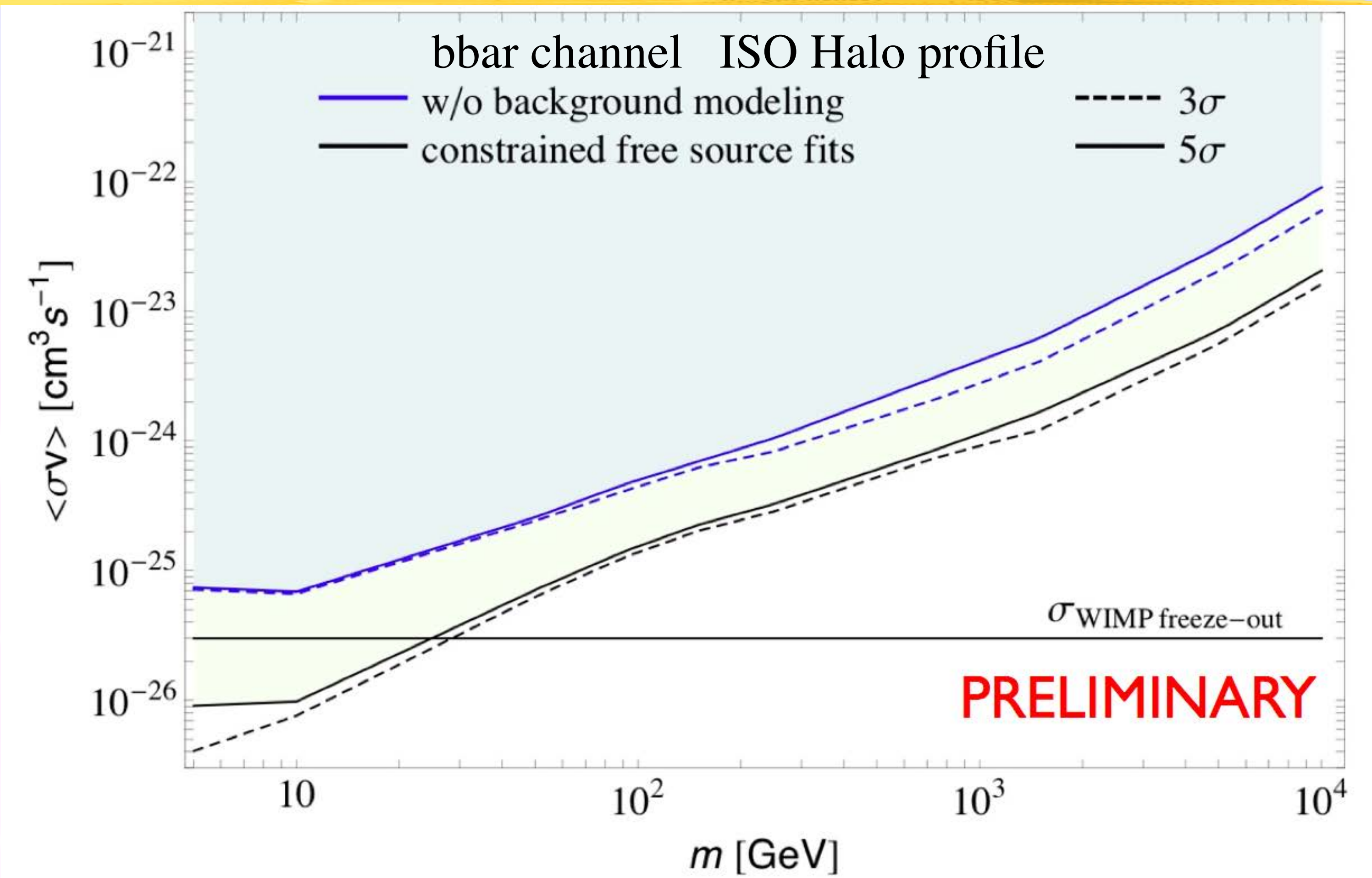


2 years of data   1-100 GeV energy range

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



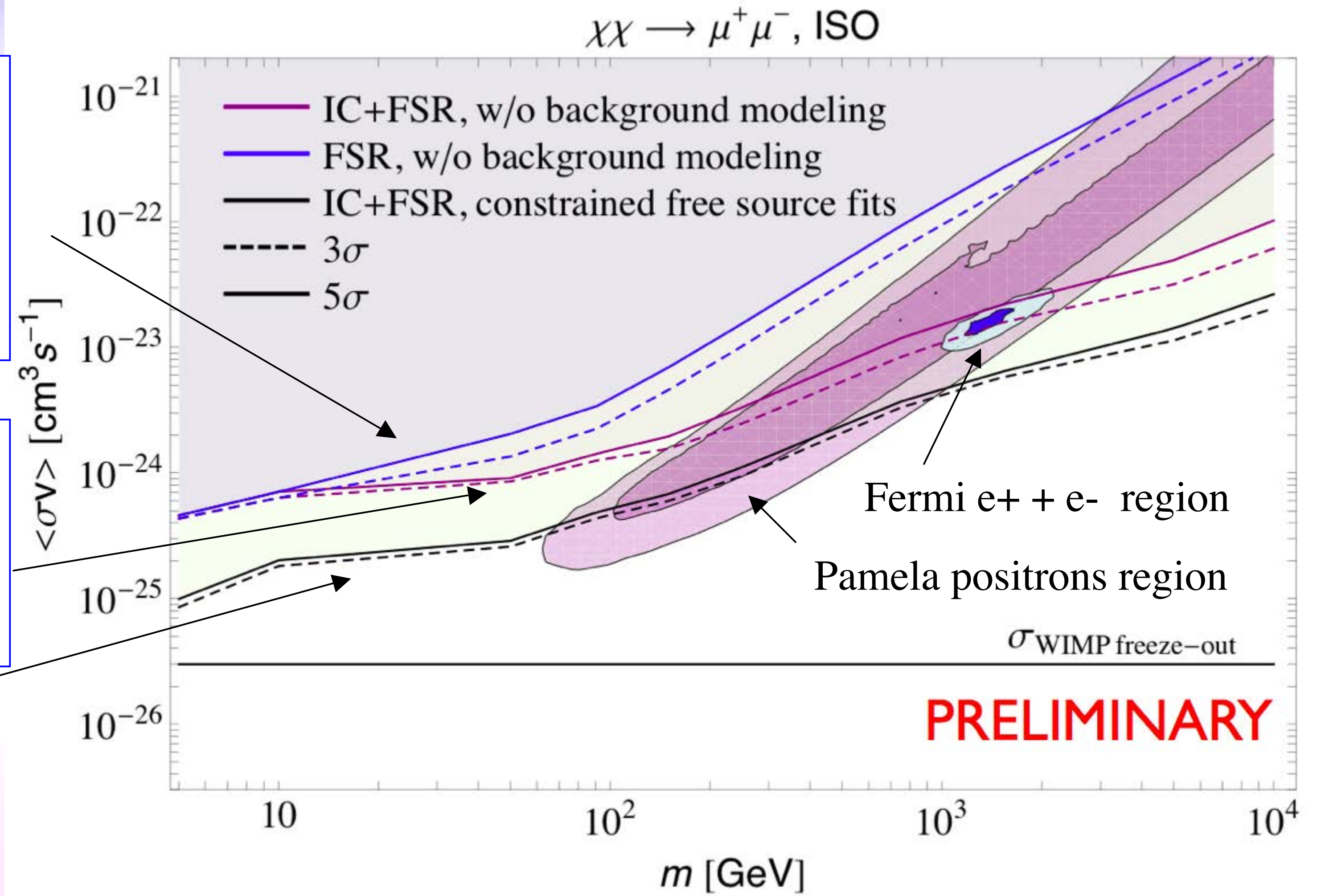
- Blue = "no-background limits"
- Black = limits obtained by marginalization over the CR source distribution, diffusive halo height and electron injection index, gas to dust ratio, and in which CR sources are held to zero in the inner 3 kpc
- Limits with NFW density profile (not shown) are only slightly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

Constraints from the Milky Way halo

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

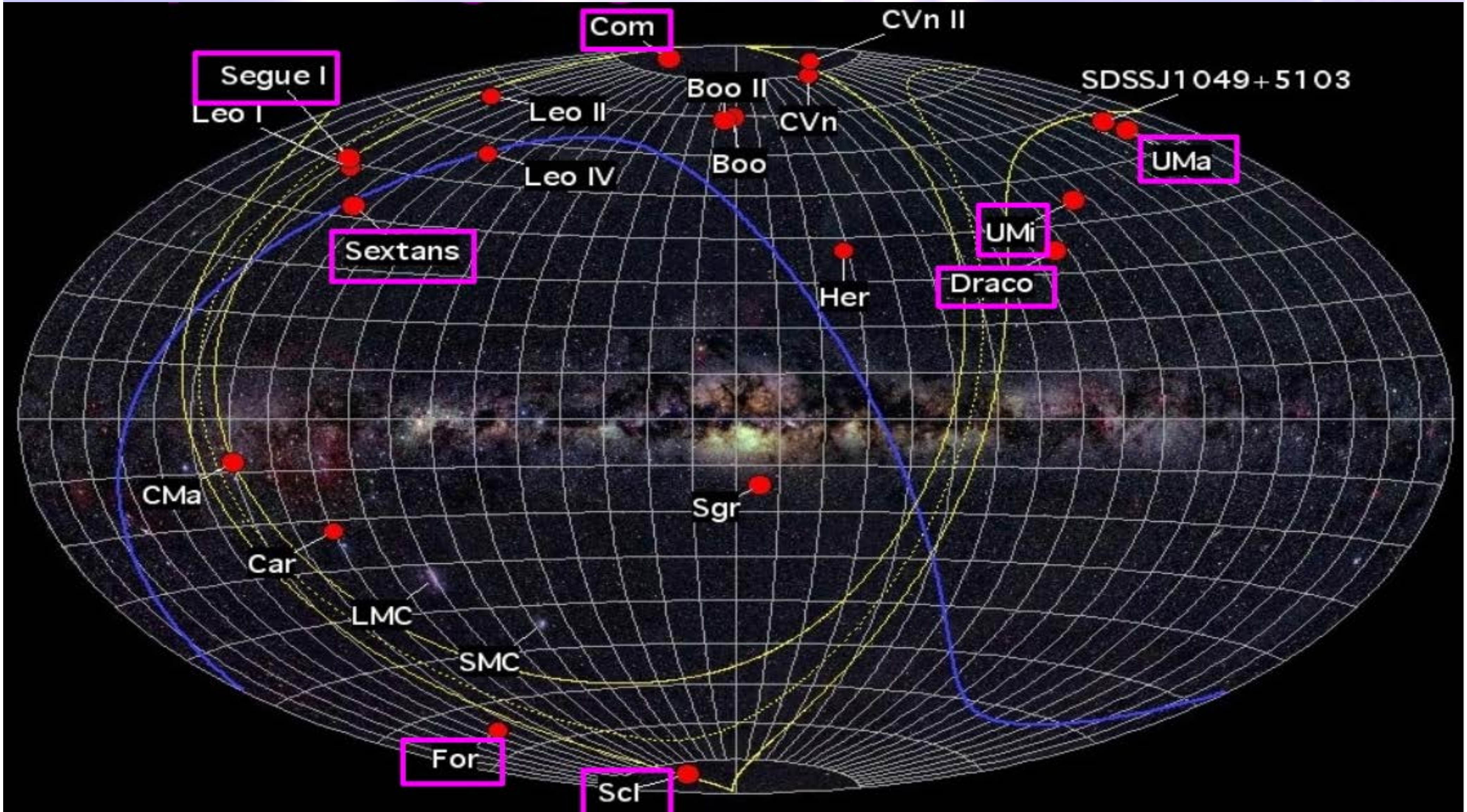
"no-background limits" including FSR+IC from dark matter

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



DM interpretation of PAMELA/Fermi CR anomalies disfavored

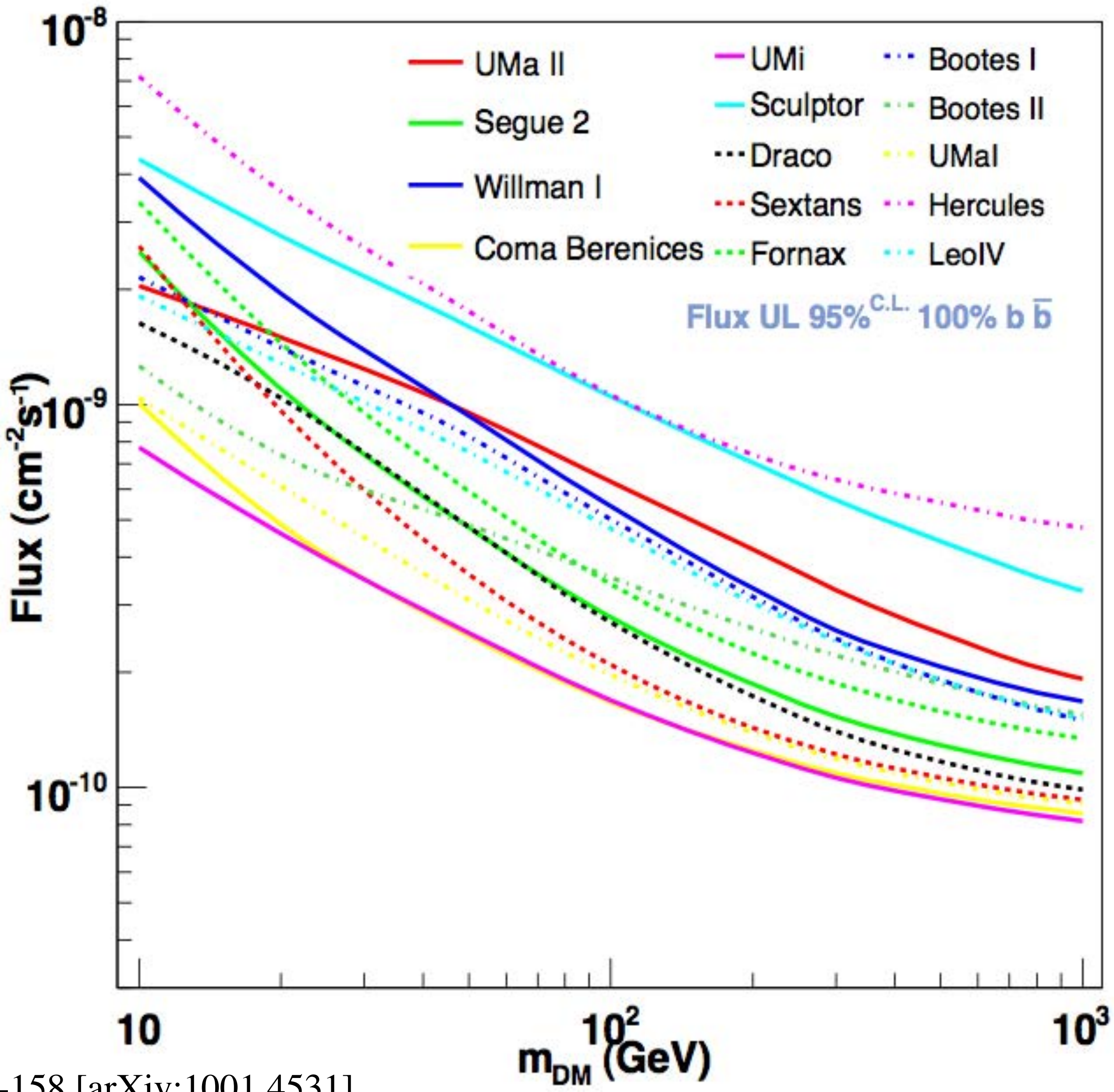
Dwarf spheroidal galaxies (dSph) : promising targets for DM detection



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.

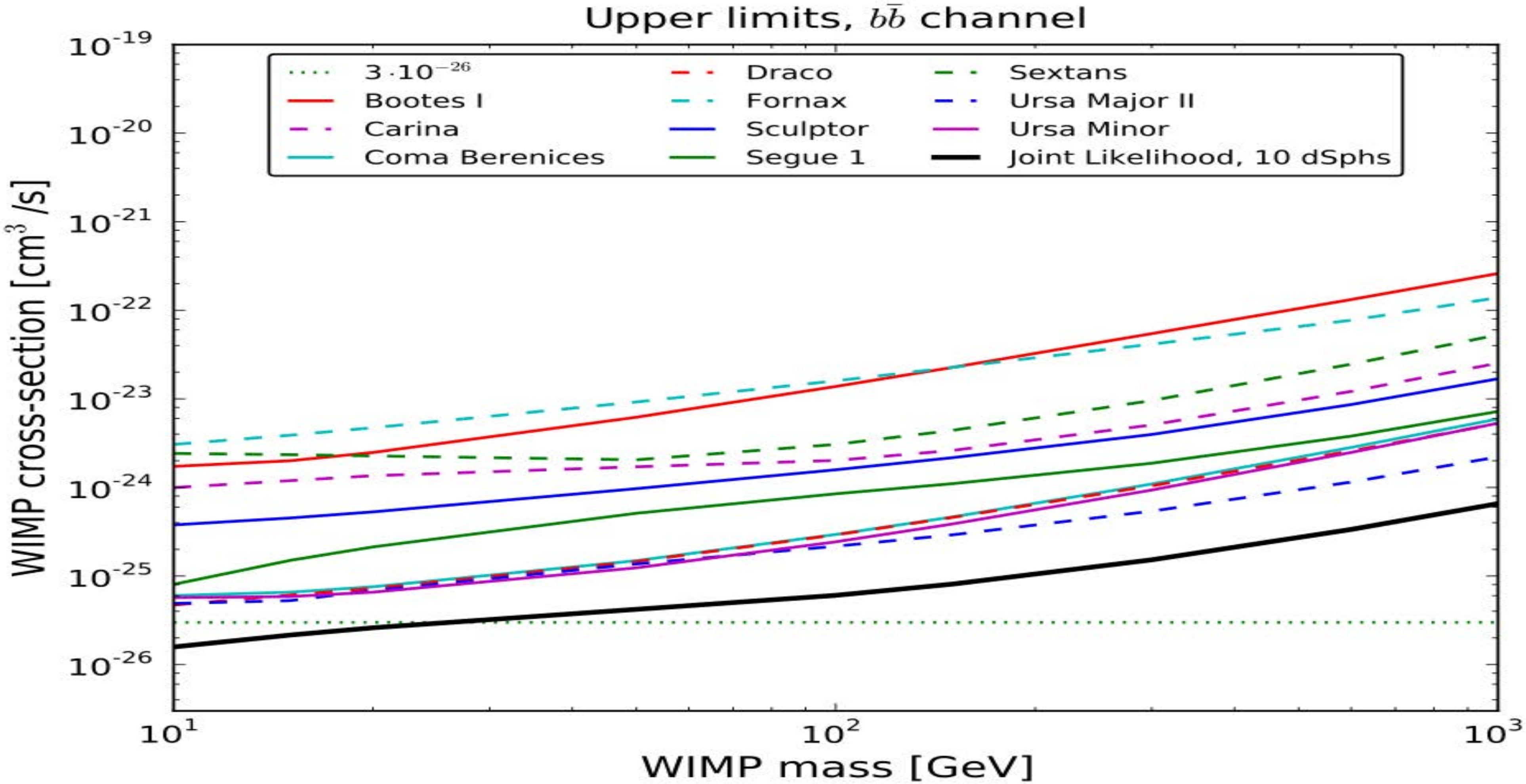
- Flux upper limits are combined with the DM density inferred by the stellar data(*) for a subset of 8 dSph (based on quality of stellar data) on quality of stellar data) to extract constraints on < σv> vs WIMP mass for specific DM models



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

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

Dwarf Spheroidal Galaxies upper-limits Update

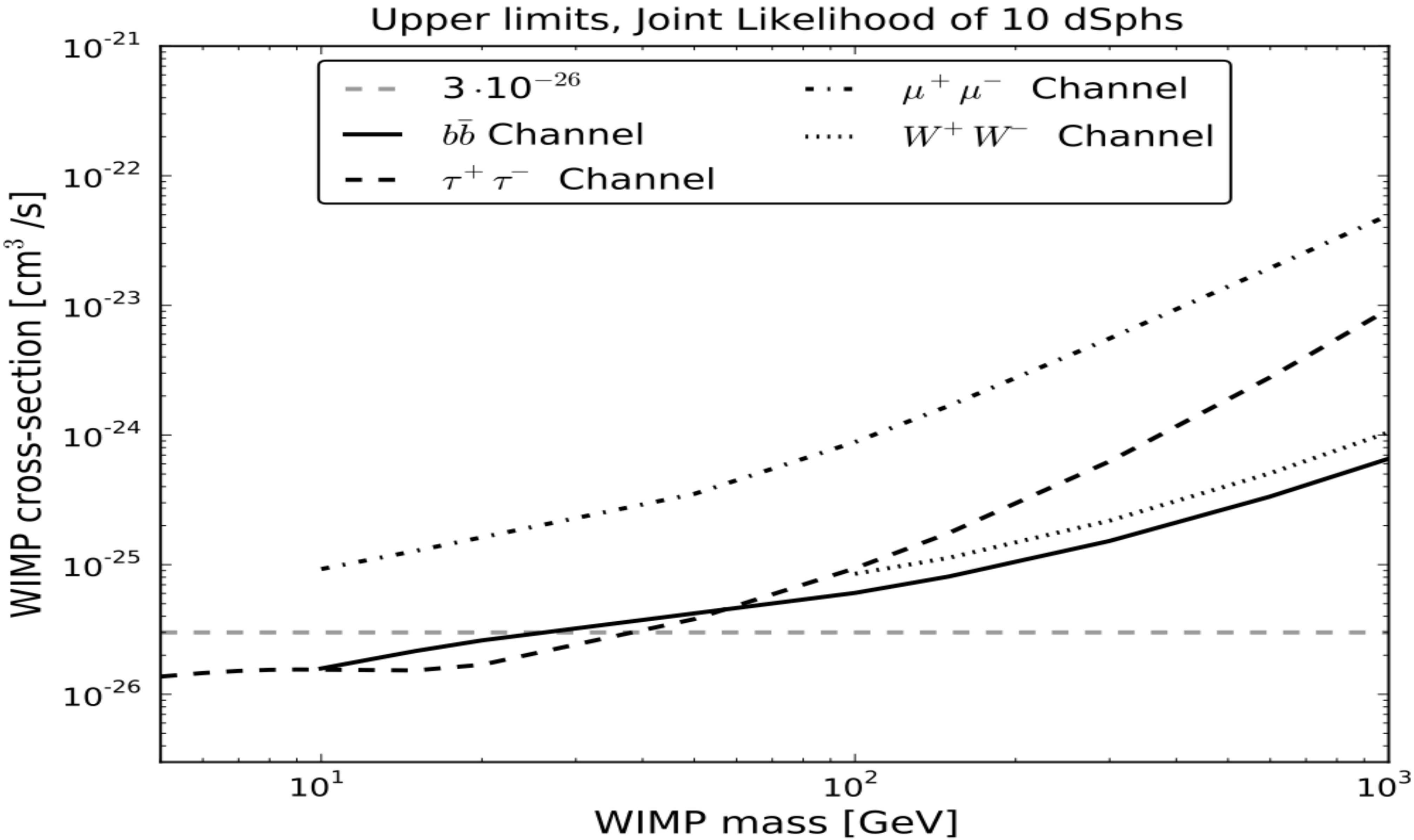


robust constraints including J-factor uncertainties

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 upper-limits Update

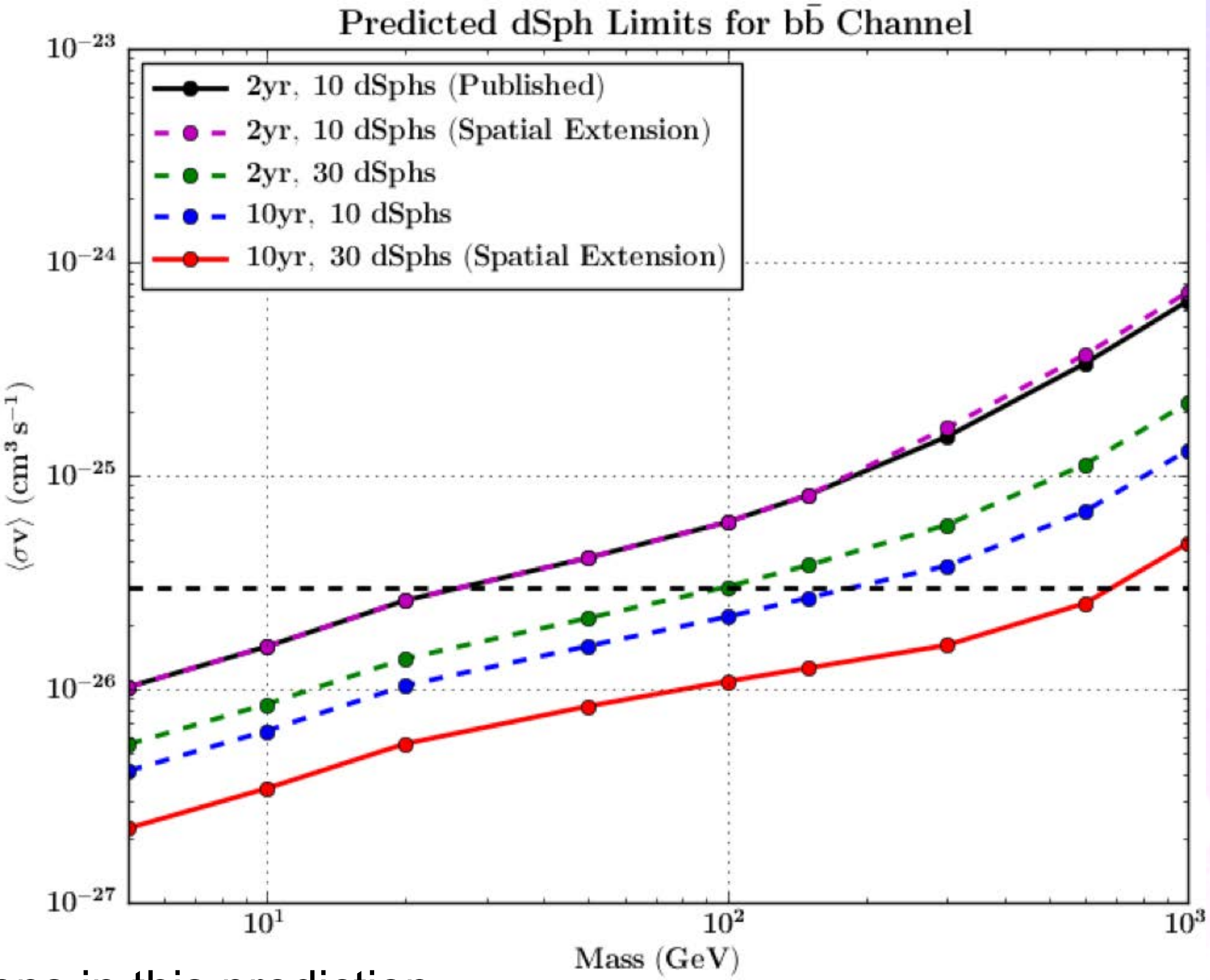


robust constraints including J-factor uncertainties

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

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

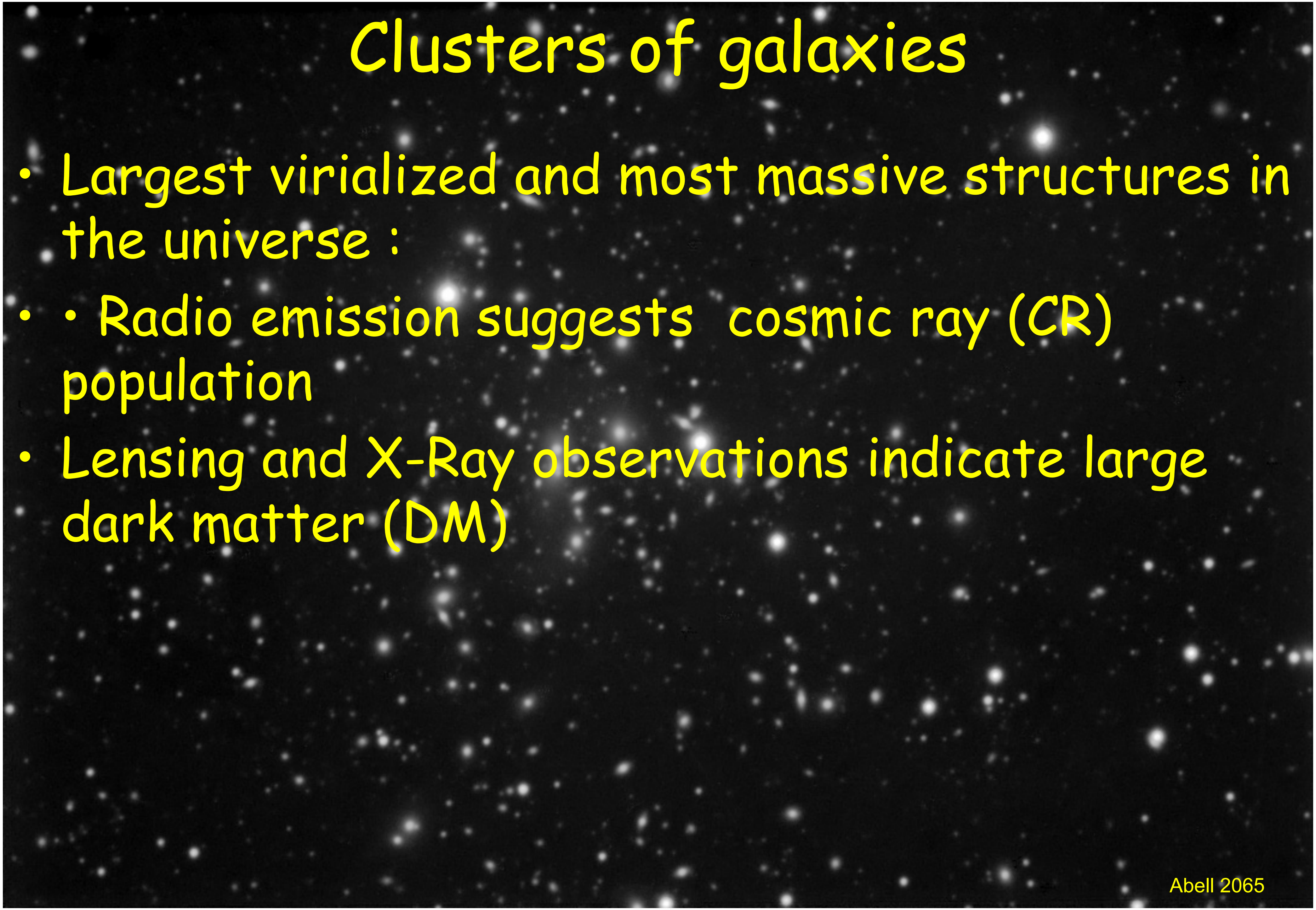
- 10 years of data instead of 2(5x)
- 30 dSphs (3x) (supposing that the new optical surveys will find new dSph)
- -10% from spatial extension (source extension increases the signal region at high energy E > 10 GeV, M > 200 GeV)



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

Clusters of galaxies

- Largest virialized and most massive structures in the universe :
- • Radio emission suggests cosmic ray (CR) population
- Lensing and X-Ray observations indicate large dark matter (DM)

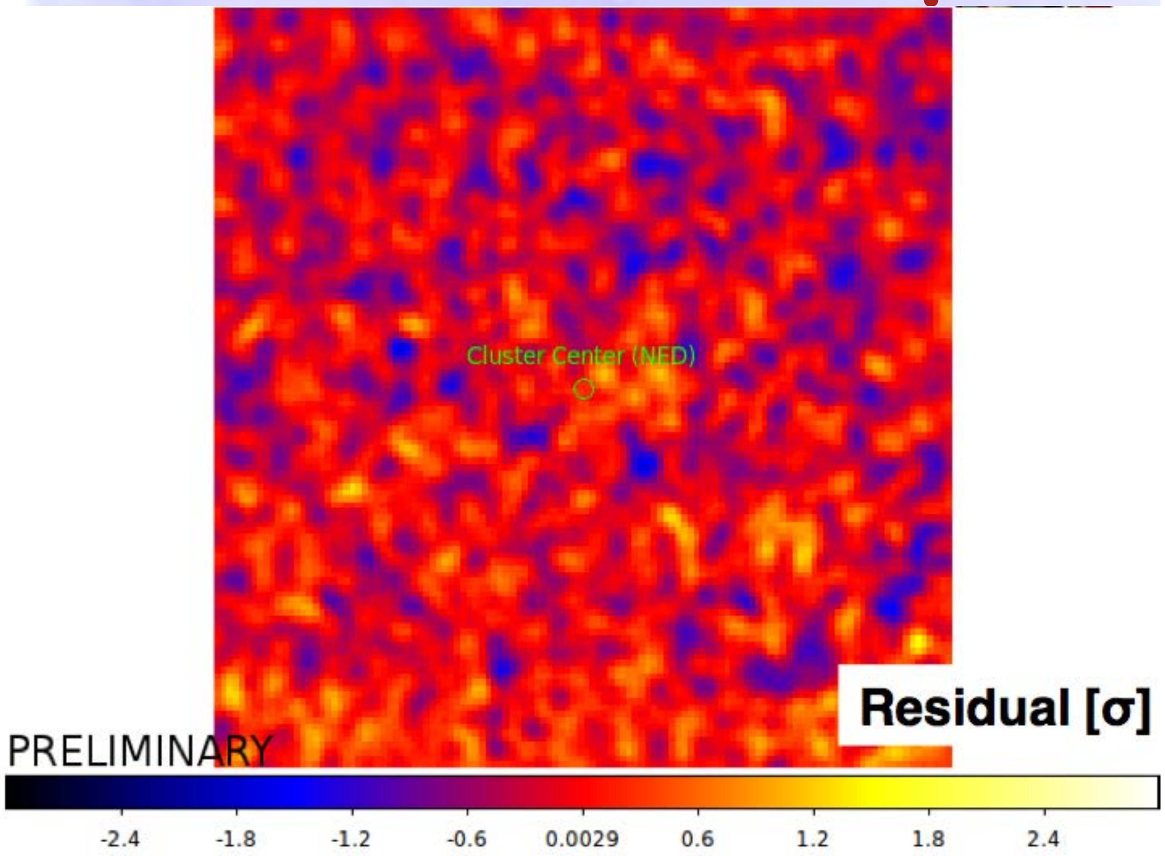


6 Clusters Stacked Residual Map

- 24 Months of LAT **P6V11 Diffuse** data (P7V6 analysis ongoing)
- Binned analysis, **10 deg ROI**

20 Energy Bins from 200 MeV to100 GeV

- Clusters modeled as **point sources**
- **No significant excess in stacked residual map!**

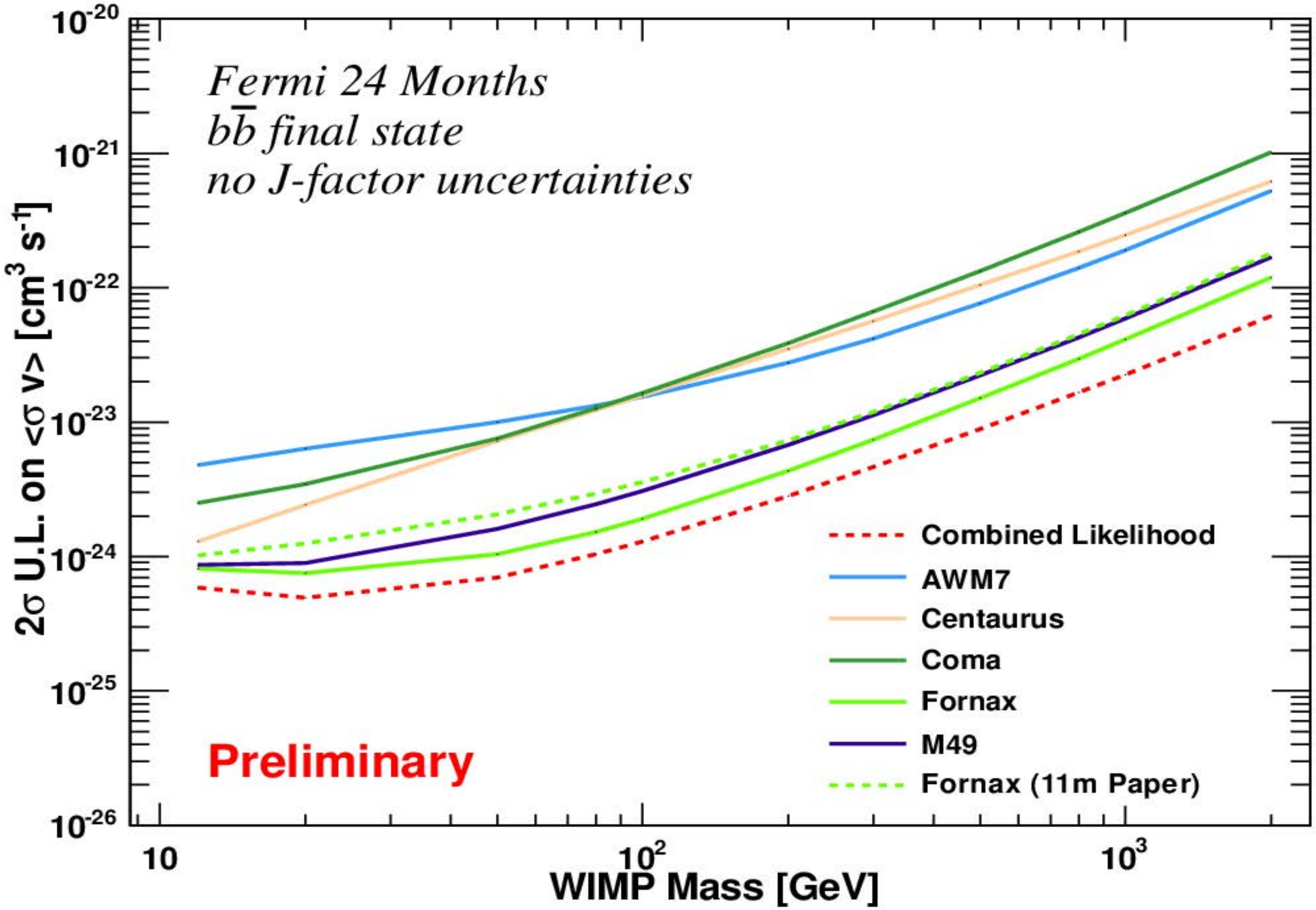


And from outside the collaboration: • Using 3y P7V6 data and 8 clusters (together and singularly) authors ofJCAP01(2012)042 don't find signal above 3σ.

• Authors of arXiv:1201.1003v1, using 3 years of P7V6 data and assuming no CR emission, they obtain a detection of DM in Virgo at 4.4σ (2.1 σ when optimal CR model is included

Fermi LAT Clusters Combined Upper Limits on <σv>

(from P6V11 analysis, currently working on P7V6)

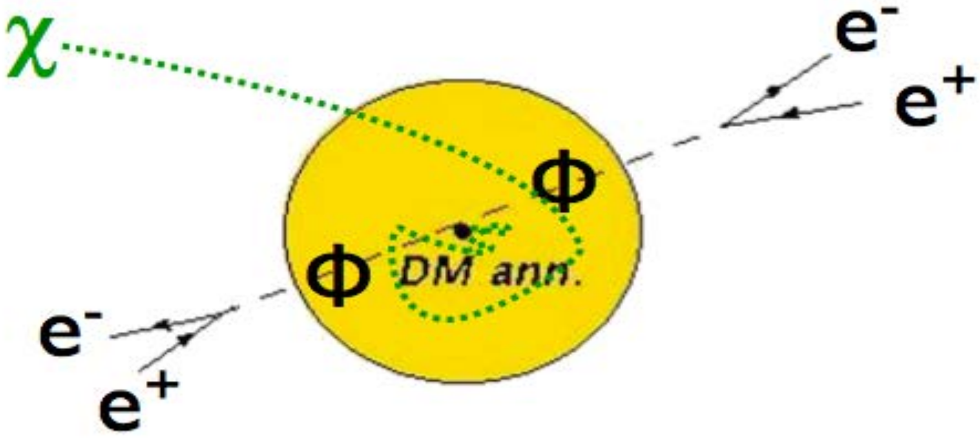


- Combined DM Limits ~ **factor 2 better than individual** ones
- S/N tests indicates **several more within reach** of Fermi-LAT

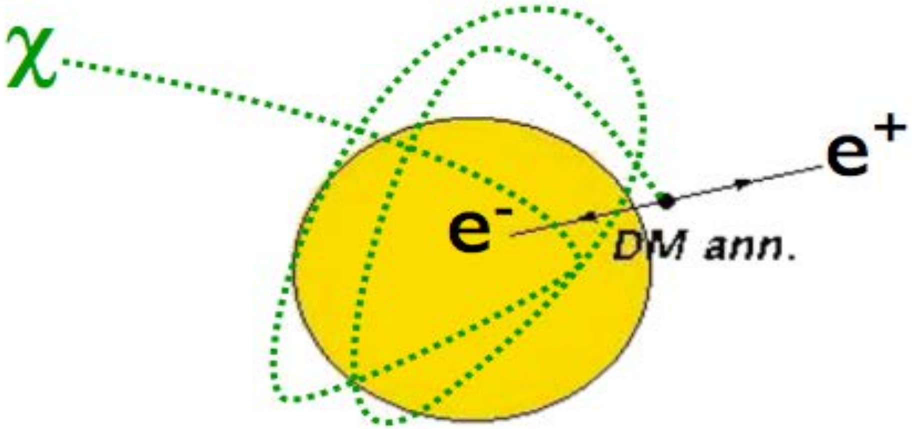
CREs from DM annihilation

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

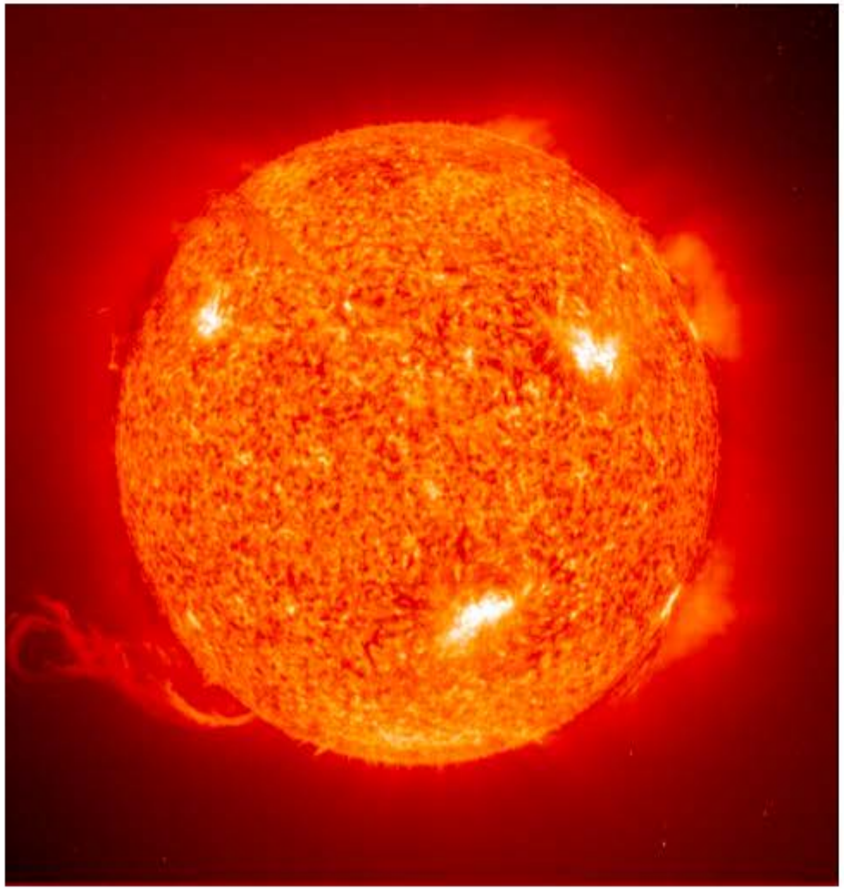


- iDM scenario: Inelastic dark matter (iDM) captured by the Sun remains on large orbits, then annihilates directly to CREs outside the surface of the Sun



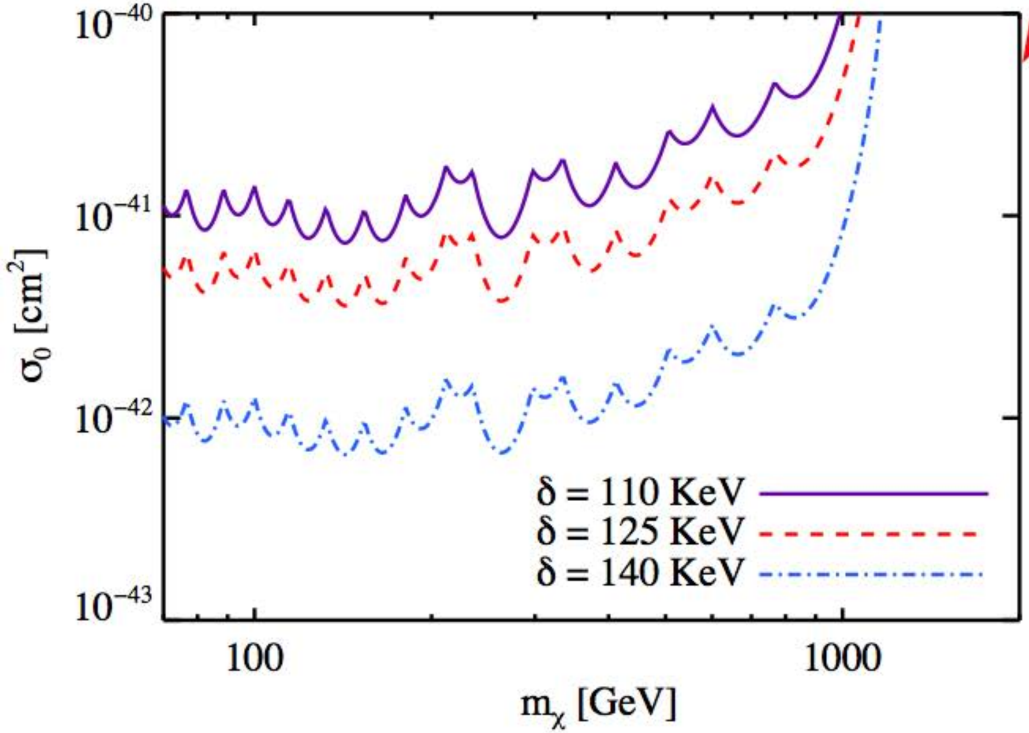
Data selection and analysis

- ~10^6 CRE events (E > 60 GeV), from 1st year of operation
- analysis performed in ecliptic coordinates, in reference frame centered on the Sun
- search for a flux excess correlated with Sun's direction yielded no significant detection, flux upper limits placed

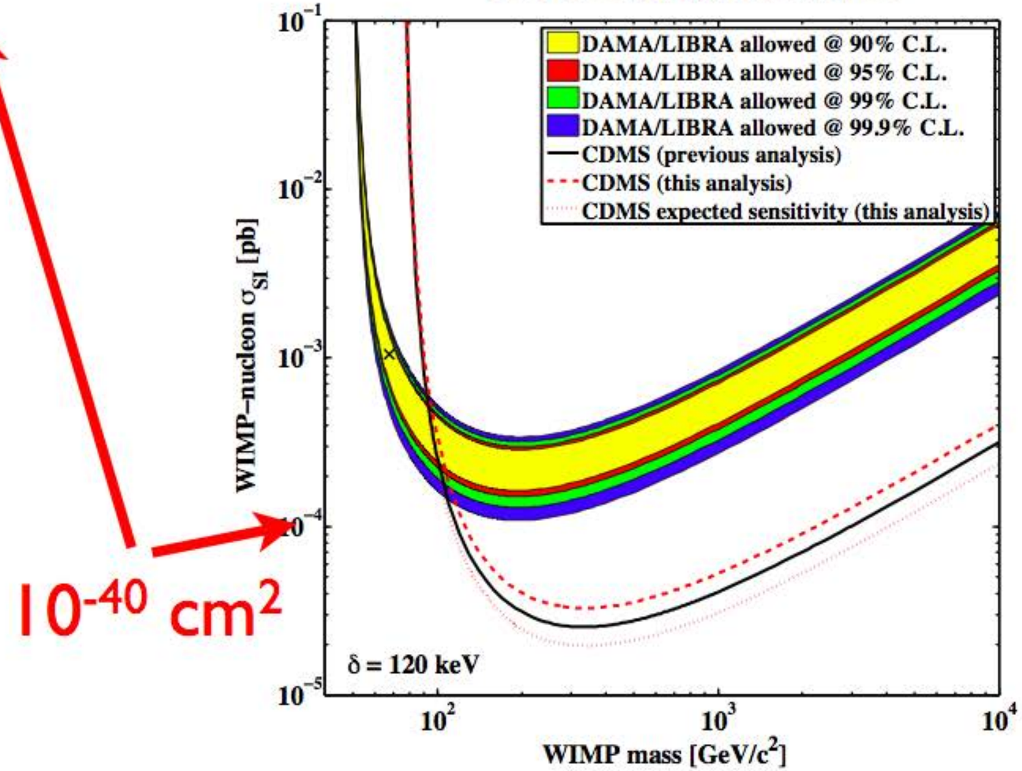


Limits on inelastic scattering cross-section

Parameter space above curves excluded at 95% CL for CRE final state



DAMA/LIBRA allowed regions and CDMS exclusion curves

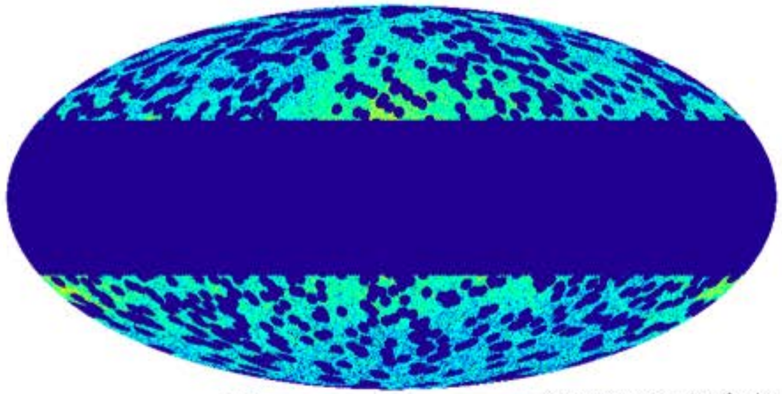


solar CRE constraints exclude by ~ 1-2 orders of magnitude all of the parameter space compatible with an inelastic DM explanation of DAMA/LIBRA and CDMS for DM masses greater than ~ 70 GeV, assuming DM annihilates to CREs

CDMS Collaboration (2011)

Anisotropy constraints on dark matter

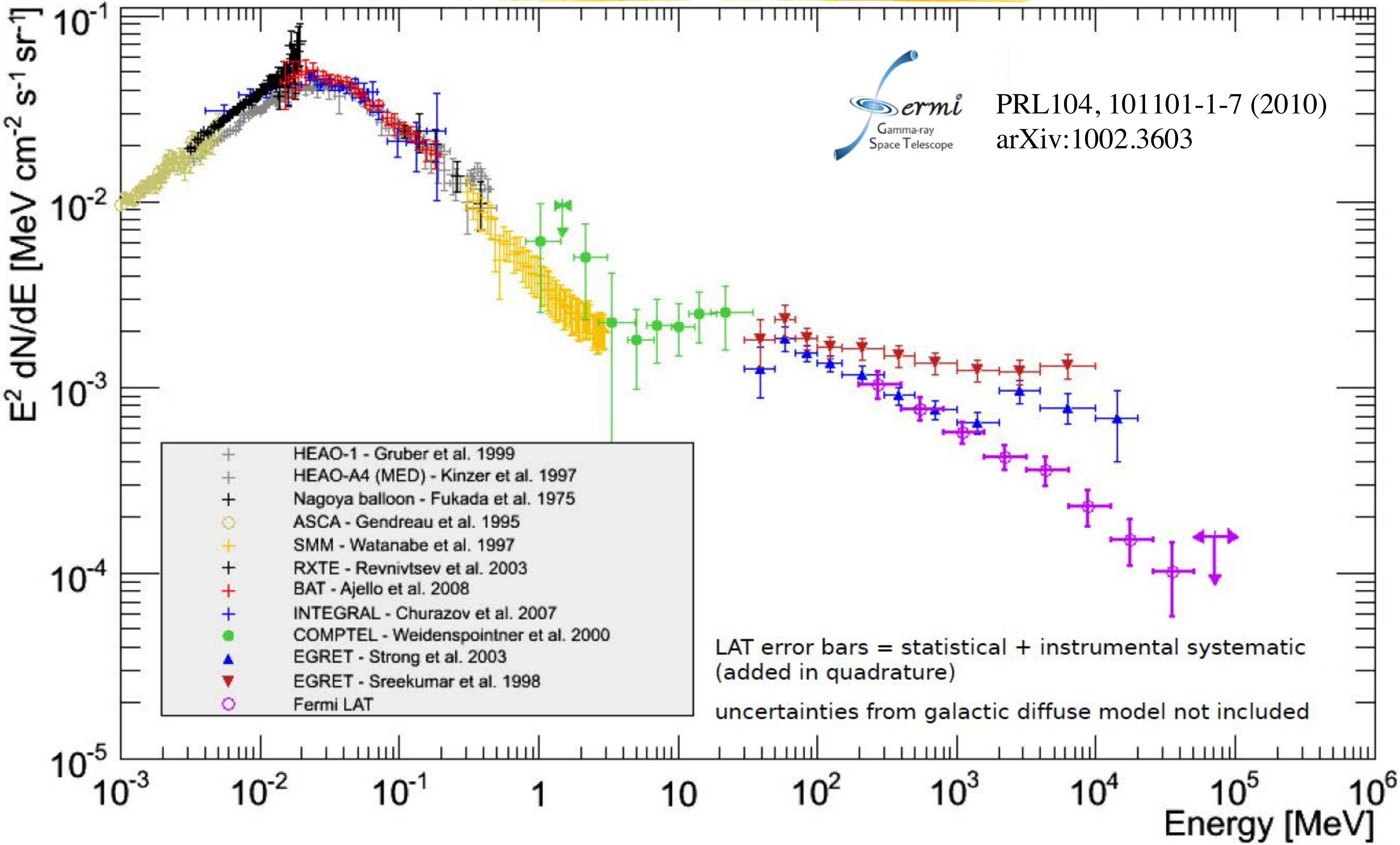
- angular power spectrum analysis of the large-scale isotropic gamma-ray background (IGRB) yielded a significant (>3σ) detection of angular power up to 10 GeV, lower significance power measured at 10-50 GeV
- measured (dimensionless) fluctuation angular power consistent with a constant value in four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



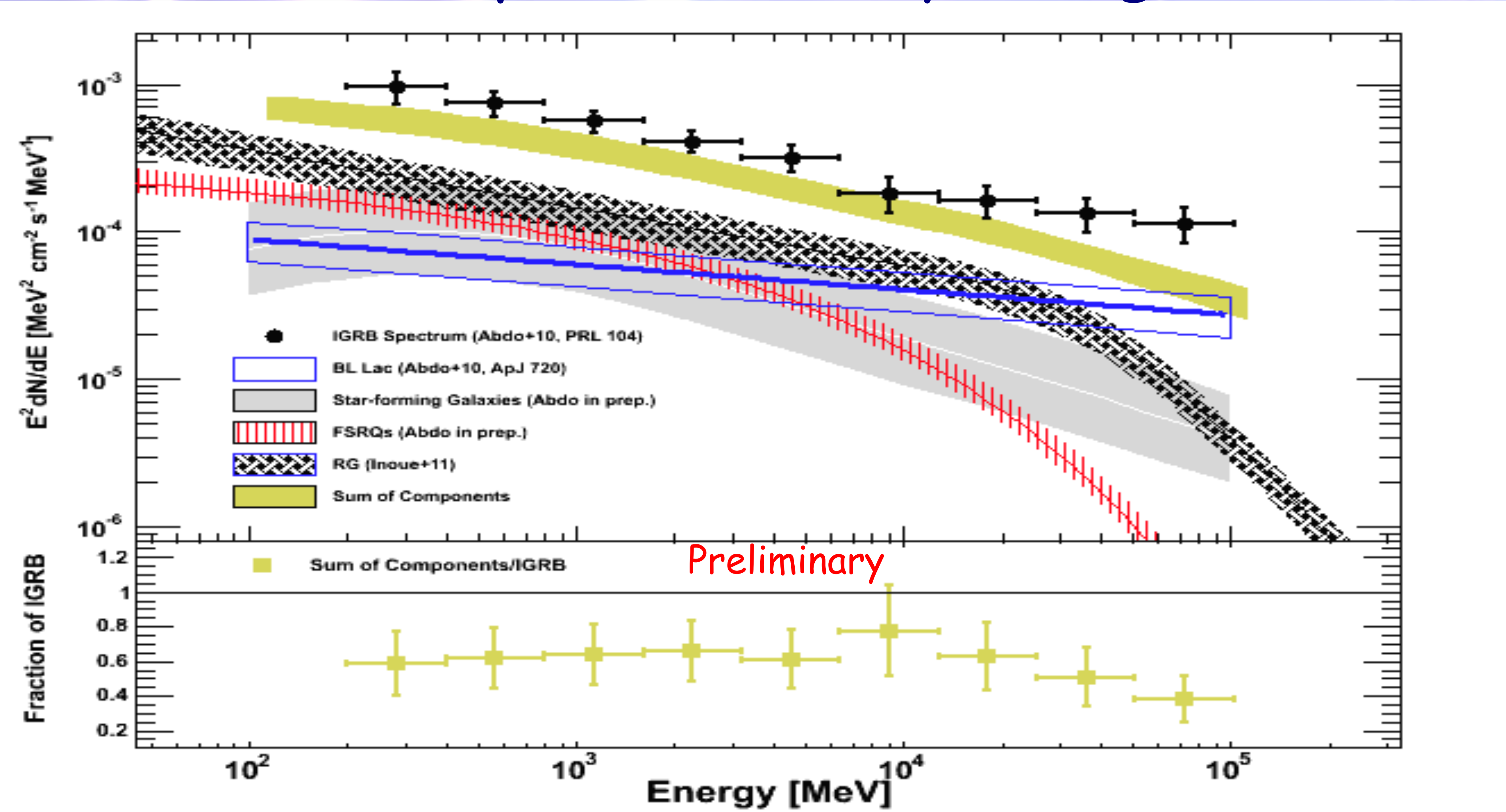
Constraints from best-fit constant fluctuation angular power (l ≳ 150) measured in the data and foreground-cleaned data

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%

SED of the isotropic diffuse emission (1 keV–100 GeV)



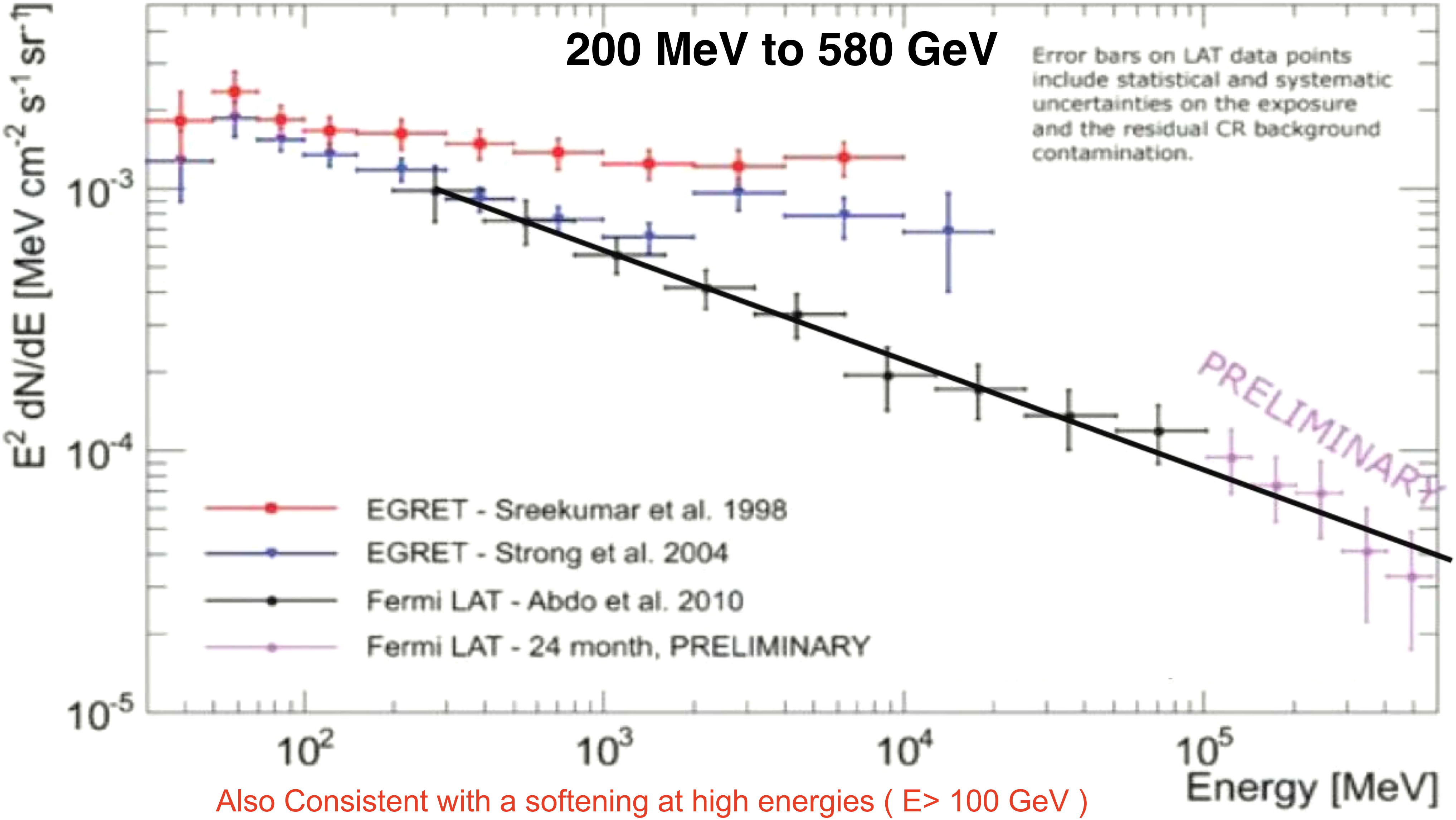
the Isotropic Gamma-ray Background (IGRB)



- Total contribution from FSRQ + BL Lac + Radio galaxies + Star-forming galaxies: ~ 50%- 80%
- 25% foreground modeling uncertainty not included in EGB error bands.

The remaining contribution could be due to more unresolved point sources populations or different diffuse process (as cosmological DM annihilation).

Update on the Isotropic Gamma-ray Background (IGRB)

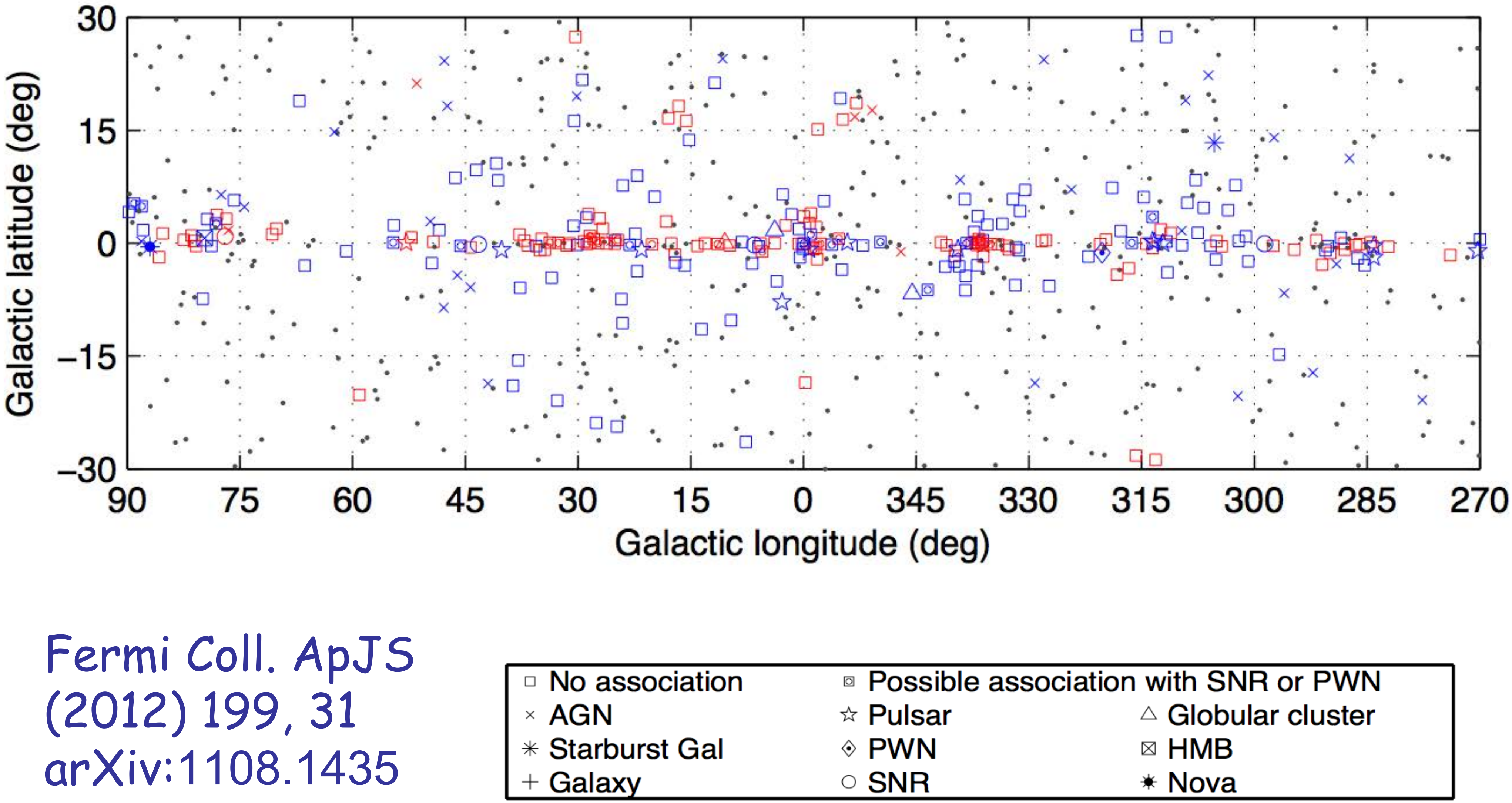


Also Consistent with a softening at high energies (E> 100 GeV)

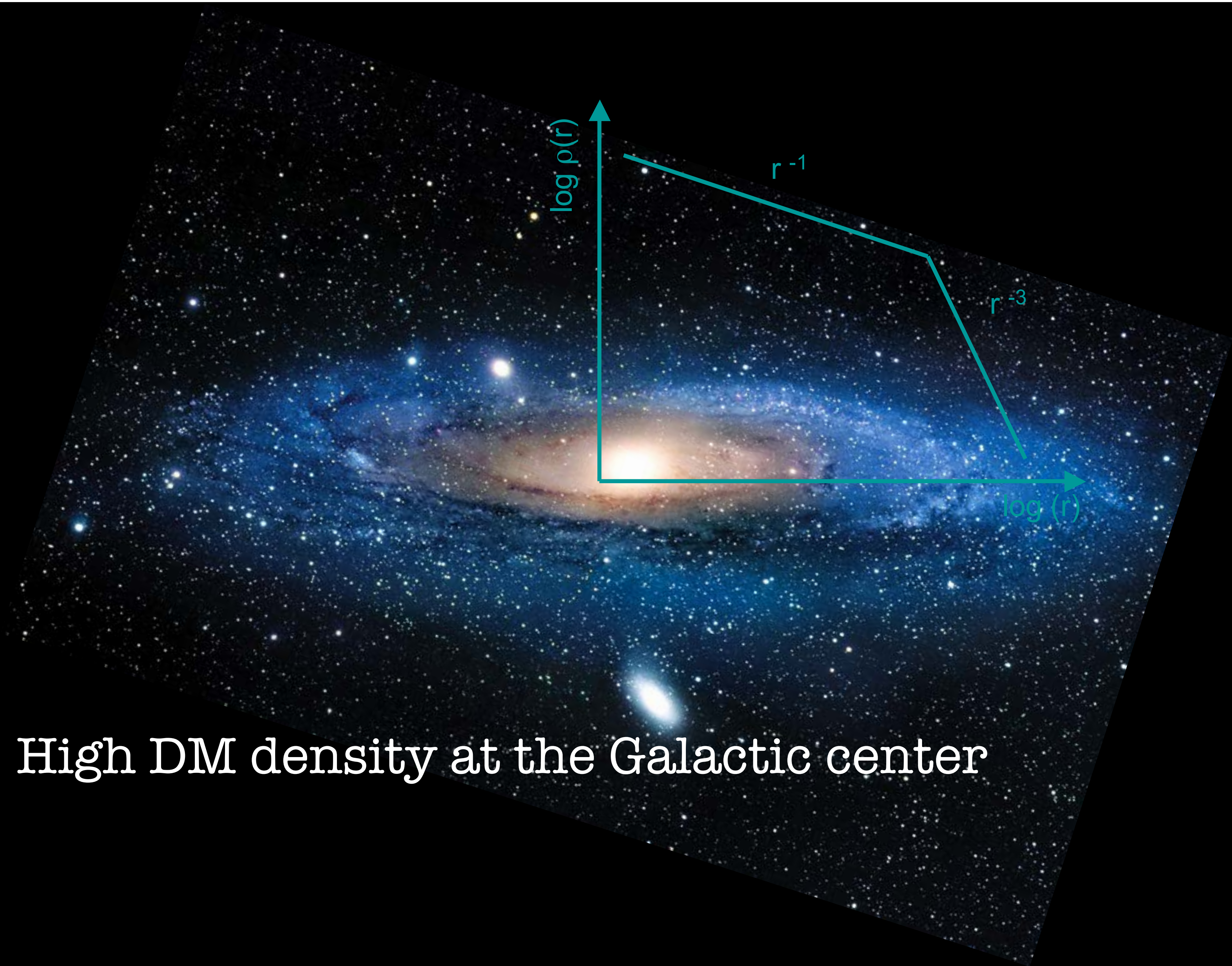
The Fermi LAT 2FGL Inner Galactic Region

August 4, 2008, to July 31, 2010

100 MeV to 100 GeV energy range



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



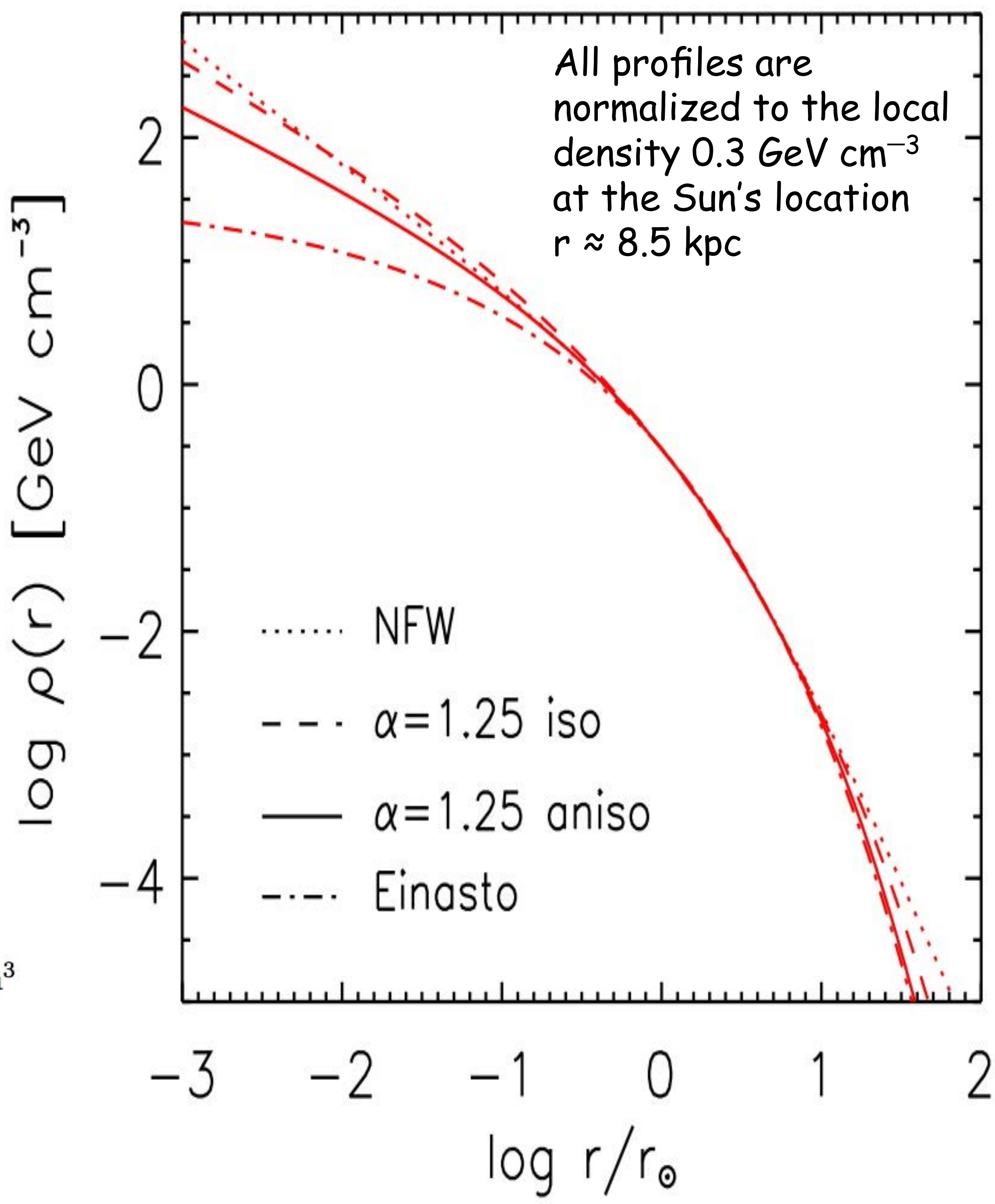
High DM density at the Galactic center

Milky Way Dark Matter Profiles

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

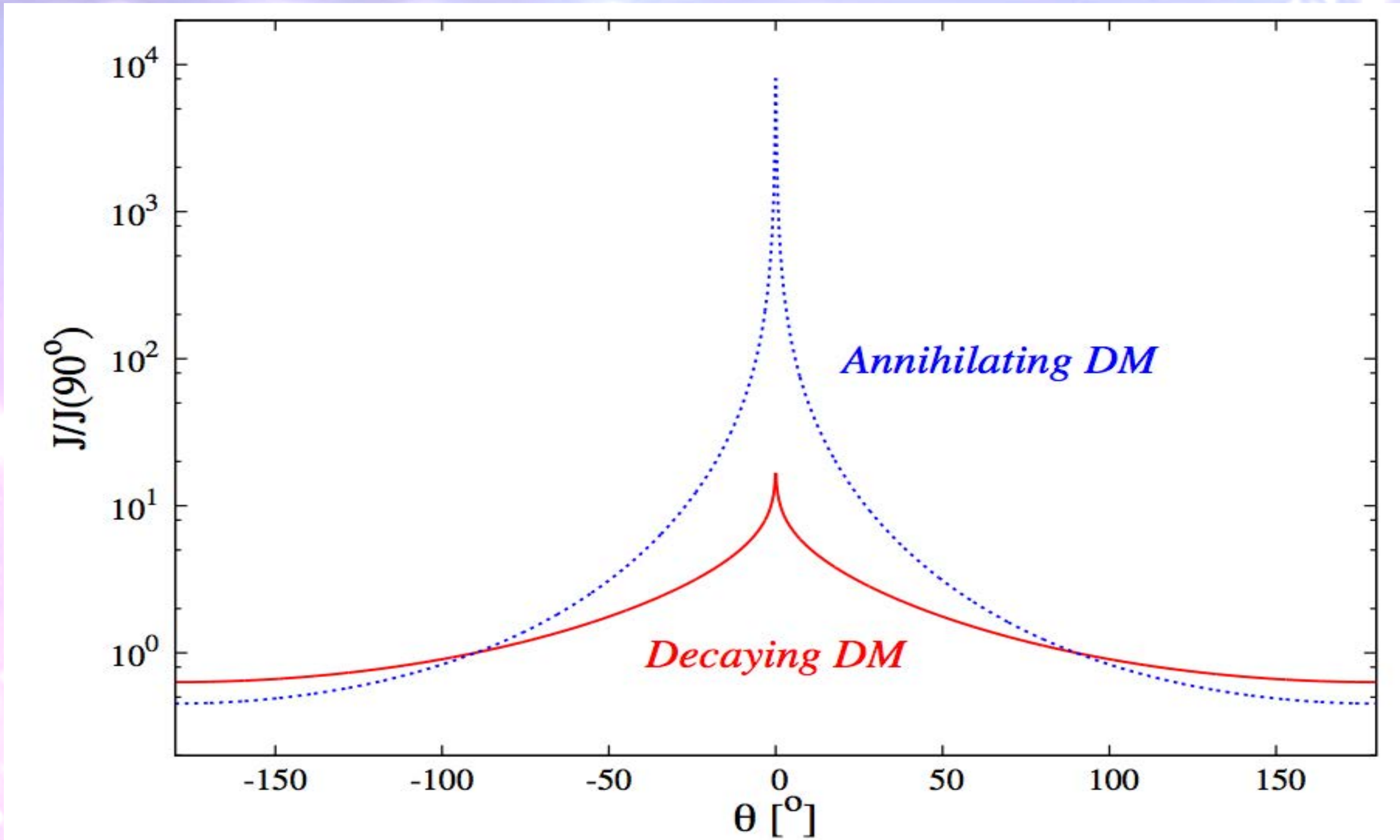
Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

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



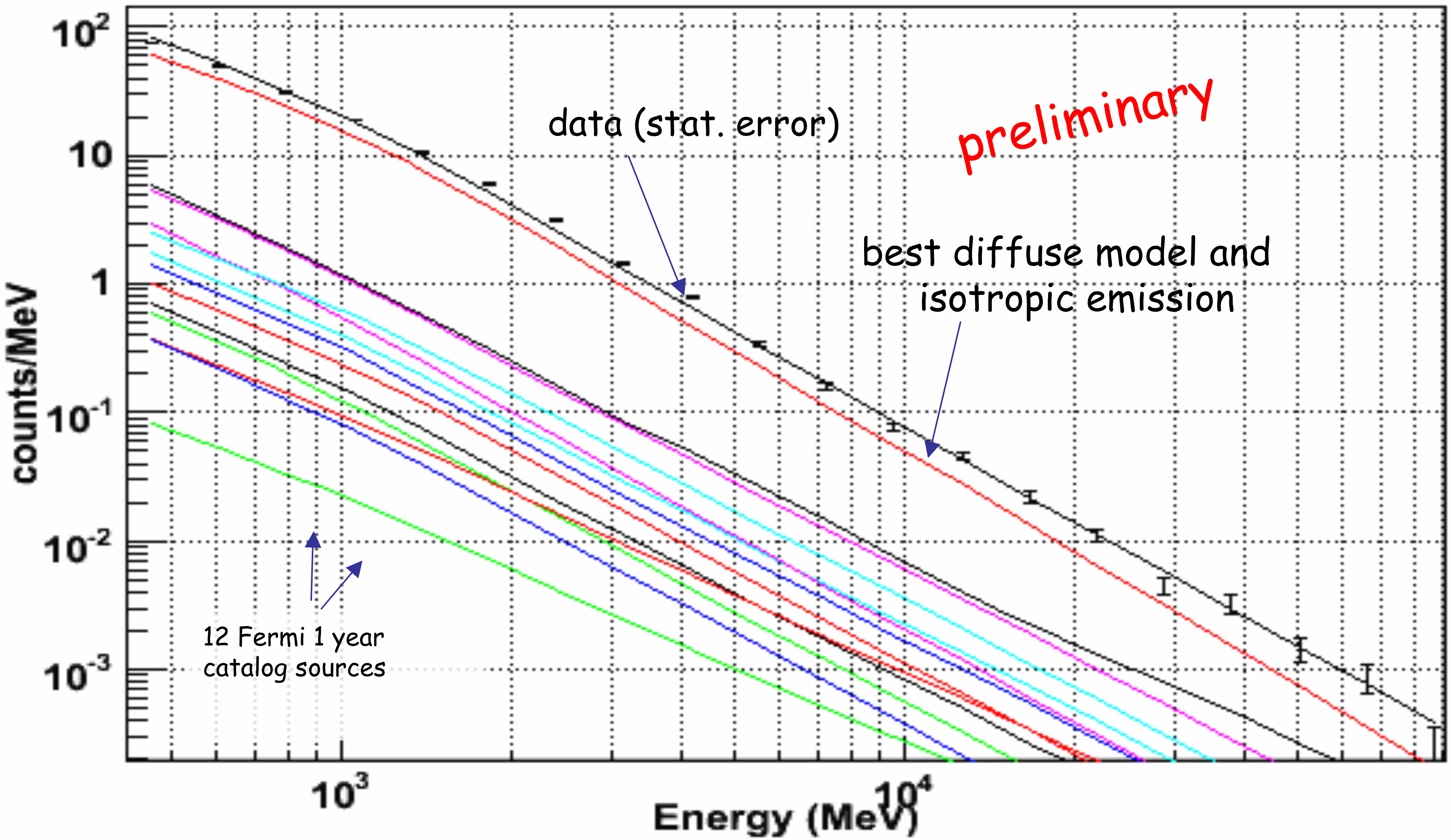
A.Lapi et al. arXiv:0912.1766

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

Spectrum (E> 400 MeV, 7°x7° region centered on the Galactic Center analyzed with binned likelihood analysis)



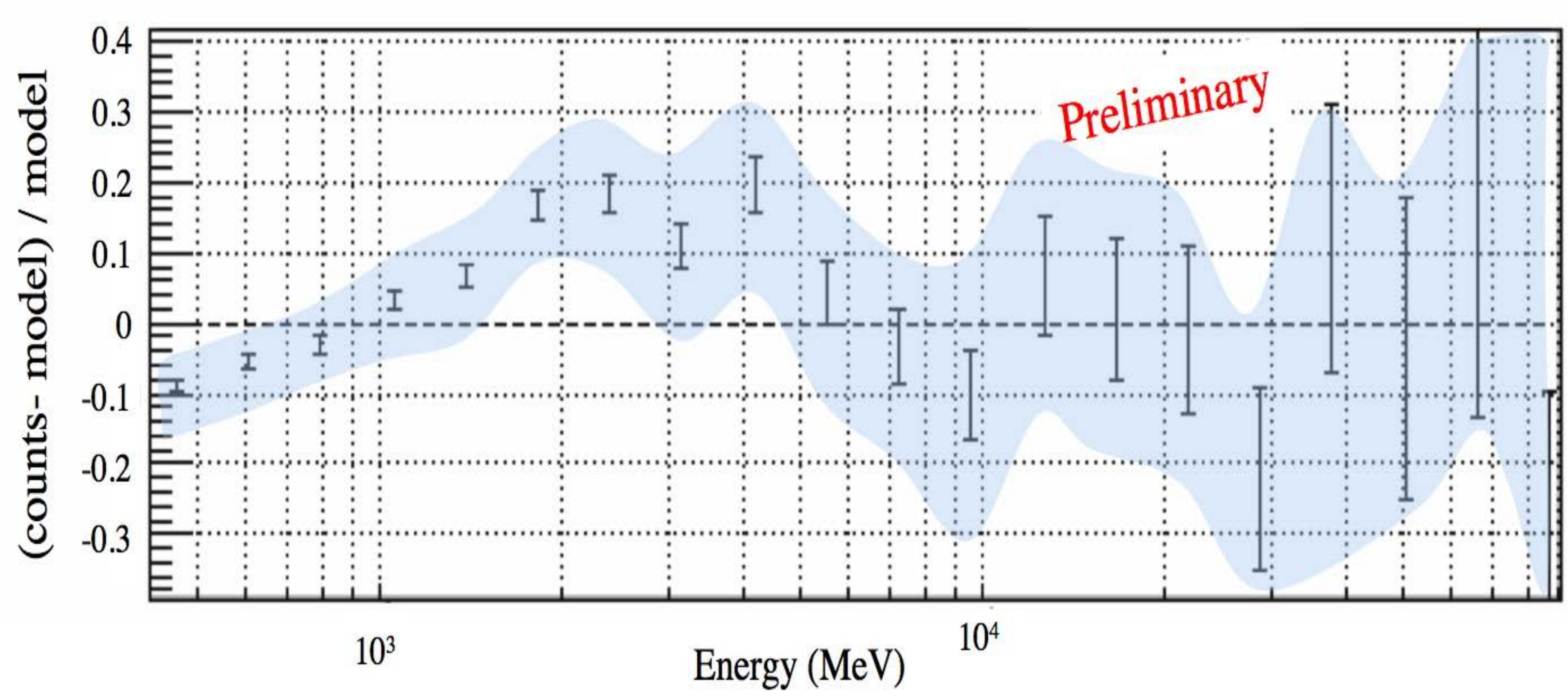
Fermi Coll. NIM A630 (2011) 147 [arXiv:0912.3828]

GC Residuals

7°x7° region centered on the Galactic Center

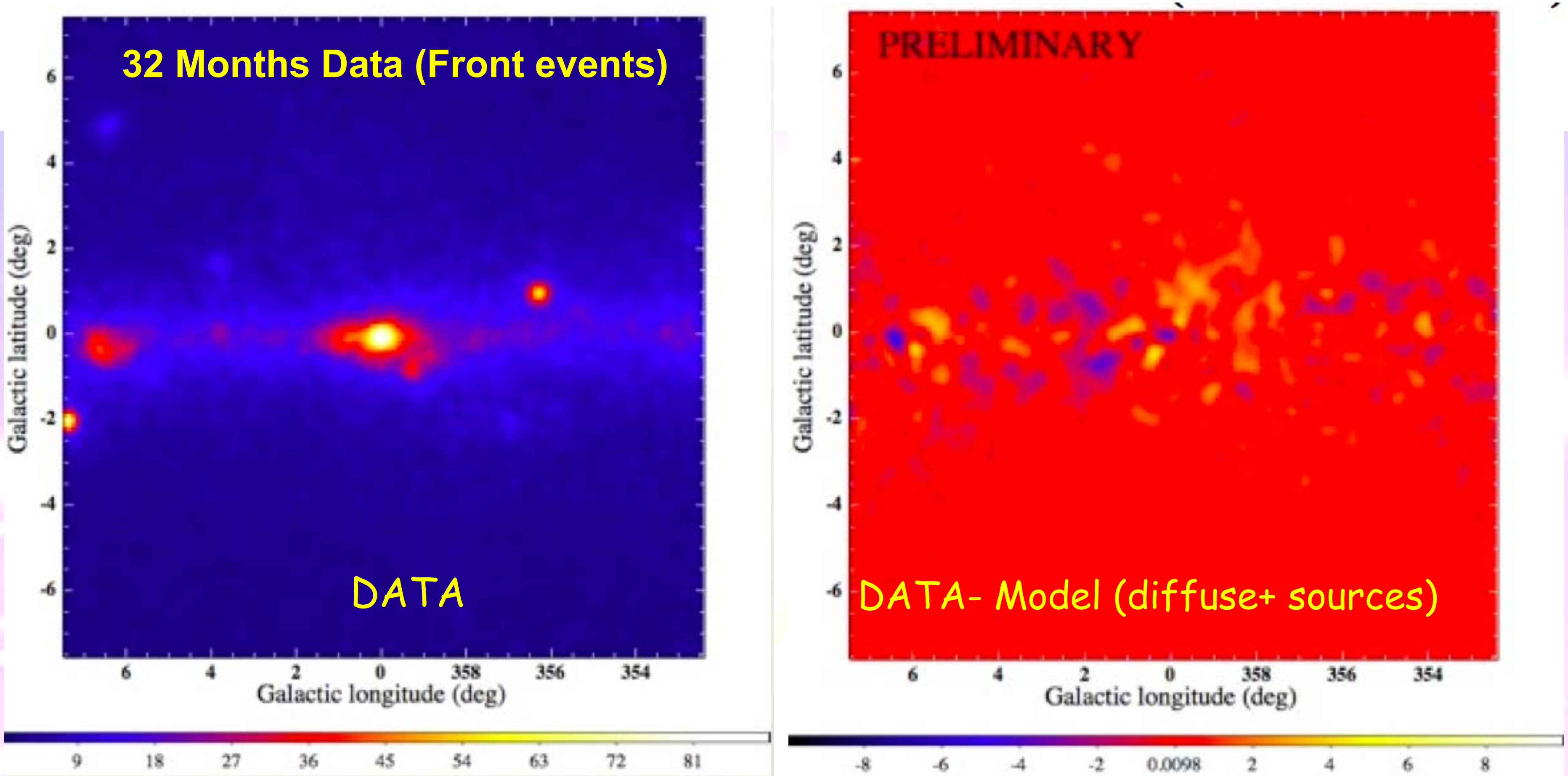
11 months of data, E >400 MeV, front-converting events analyzed with binned likelihood analysis)

- The systematic uncertainty of the effective area (blue area) of the LAT is ~10% at 100 MeV, decreasing to 5% at 560 MeV and increasing to 20% at 10 GeV



Fermi Coll. NIM A630 (2011) 147 [arXiv:0912.3828]

Residual Emission for 15 * 15 degrees around the Galactic center

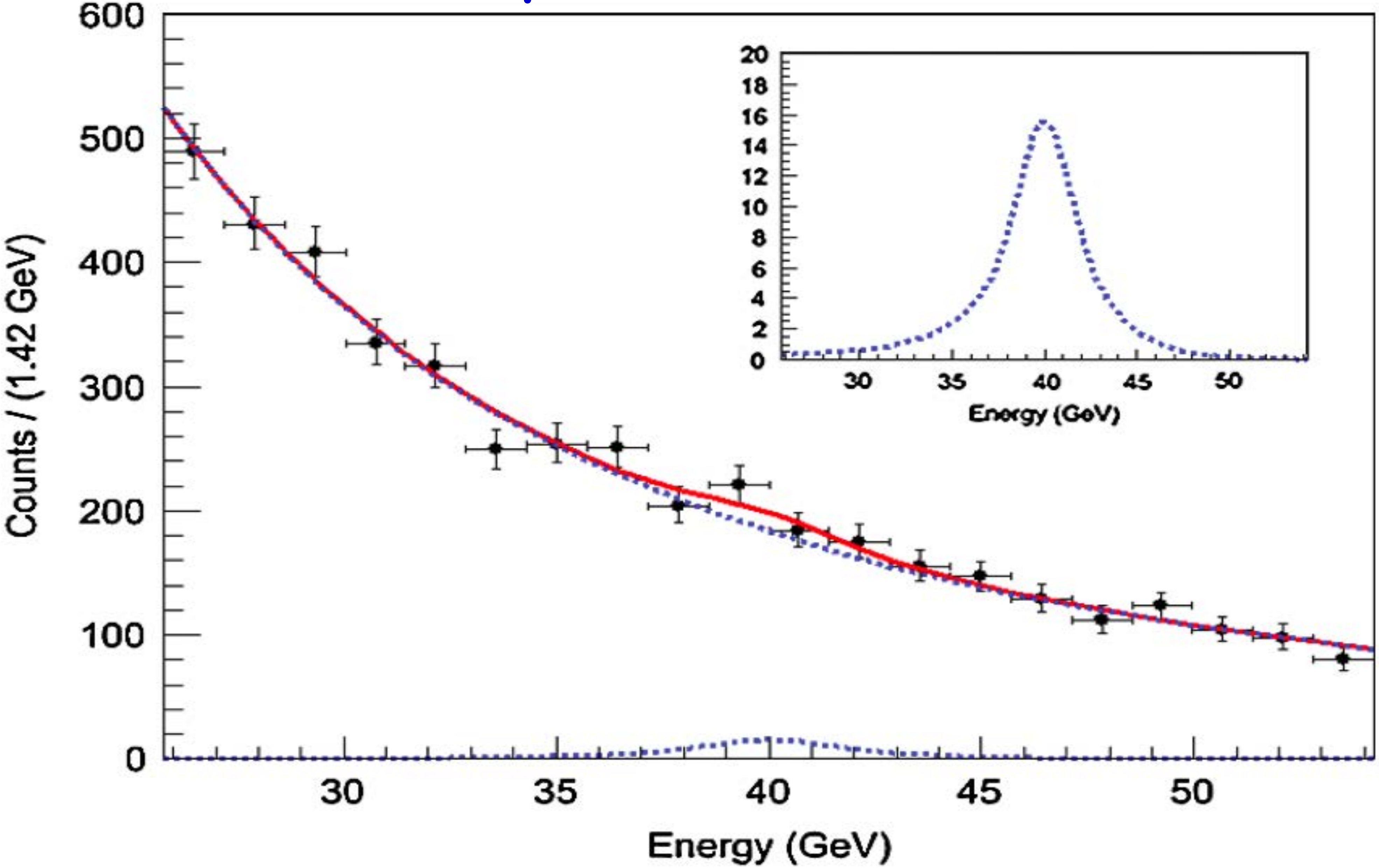


Diffuse emission and point sources account for most of the emission observed in the region.

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

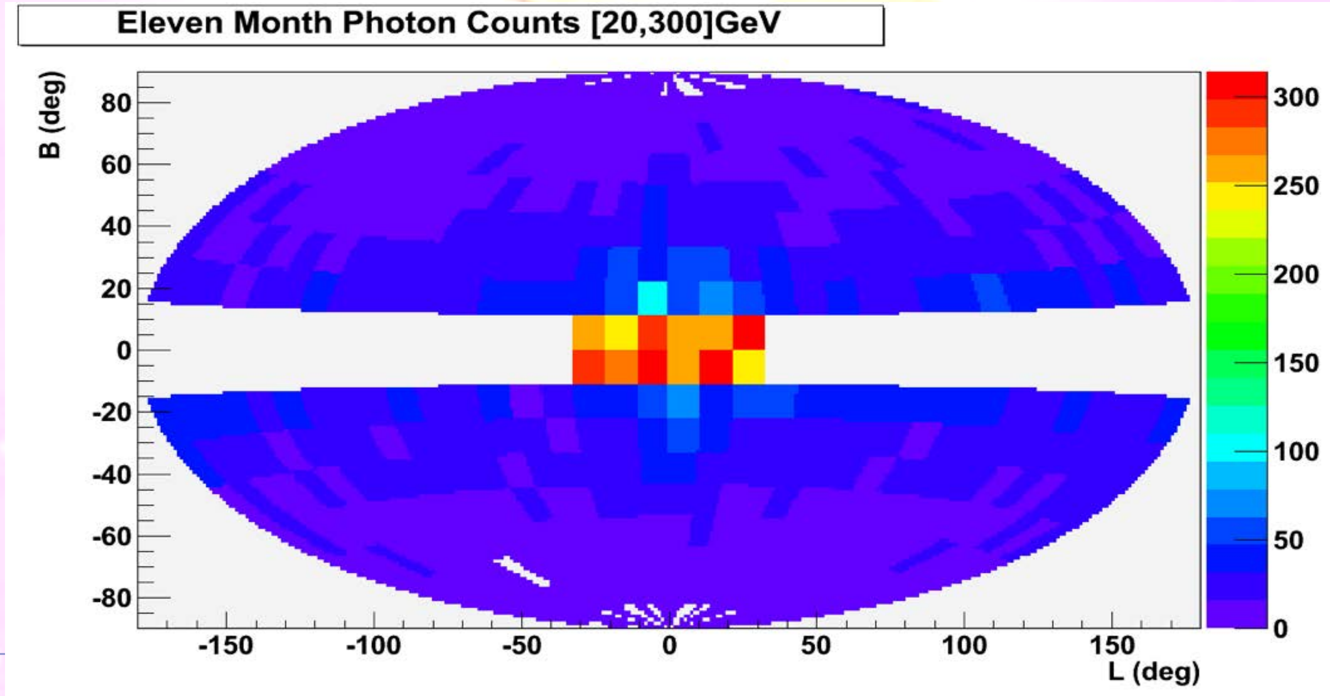
Papers are forthcoming and will include dark matter results.

Wimp lines search



Search for Spectral Gamma Lines

- Smoking gun signal of dark matter
- Search for lines in the first 11 months of Fermi data (30-200 GeV en.range)
- Search region |b|>10° and 30° around 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.

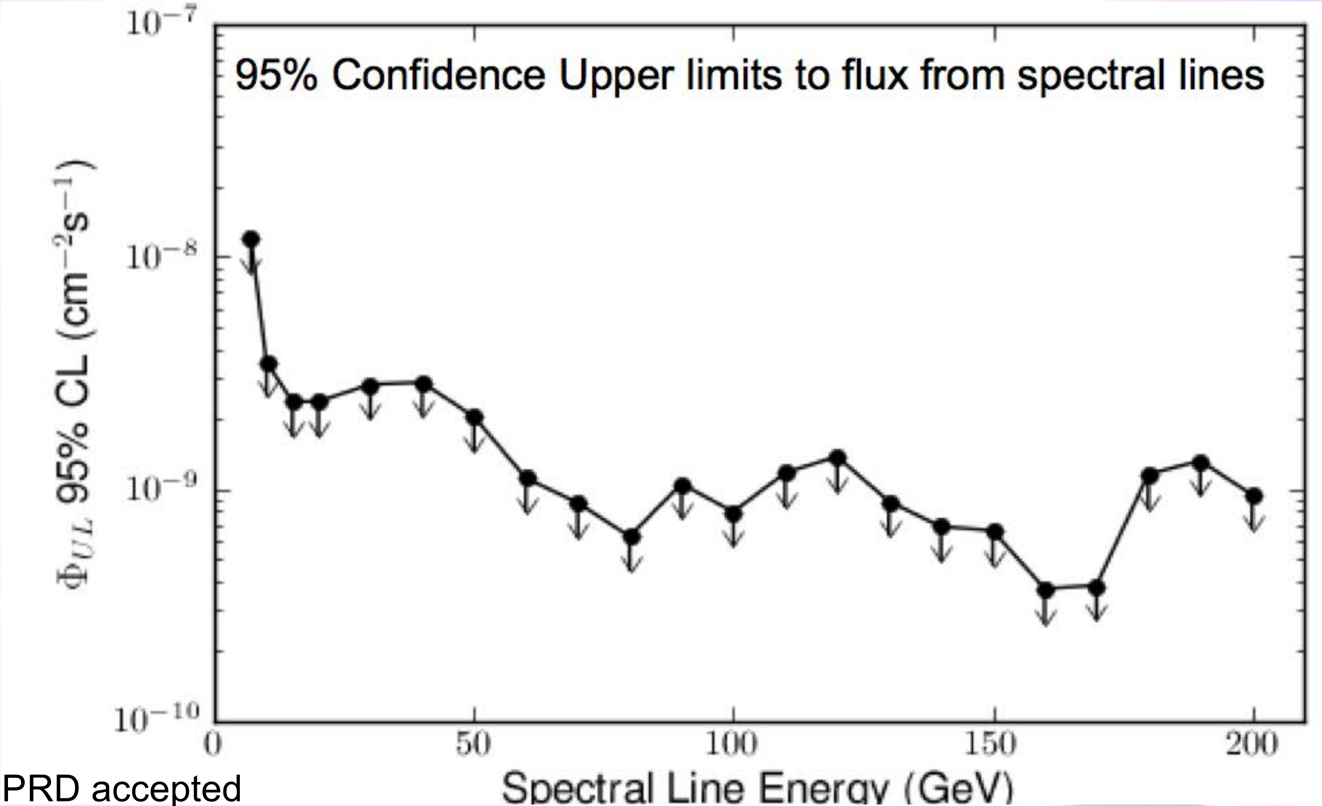


Fermi LAT 23 Month Line search results Flux Upper Limits, 7 GeV – 200 GeV

- ± 20 % overall scale systematic error (+20 % systematic for UL).

Additional systematic on spectral structures with LAT resolution for E < 13.2 GeV of s/bg ~ 1%.

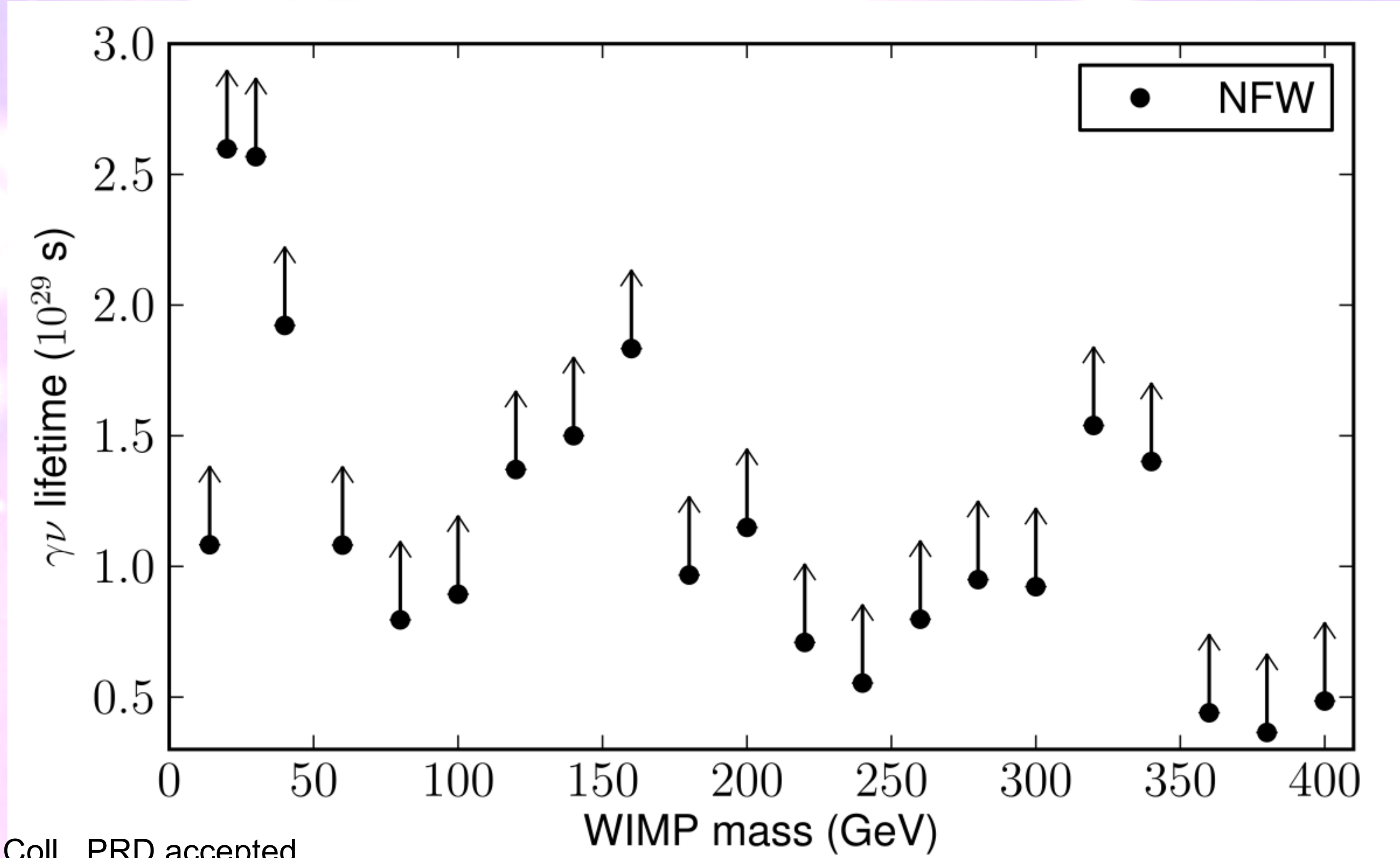
- **7 and 10 GeV bins use a modified event selection to reduce the systematic uncertainty associated with public IRFs**.
- For E > 12 GeV no indication of a spectral structure systematic effect is seen.



Fermi Lat Coll., PRD accepted
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

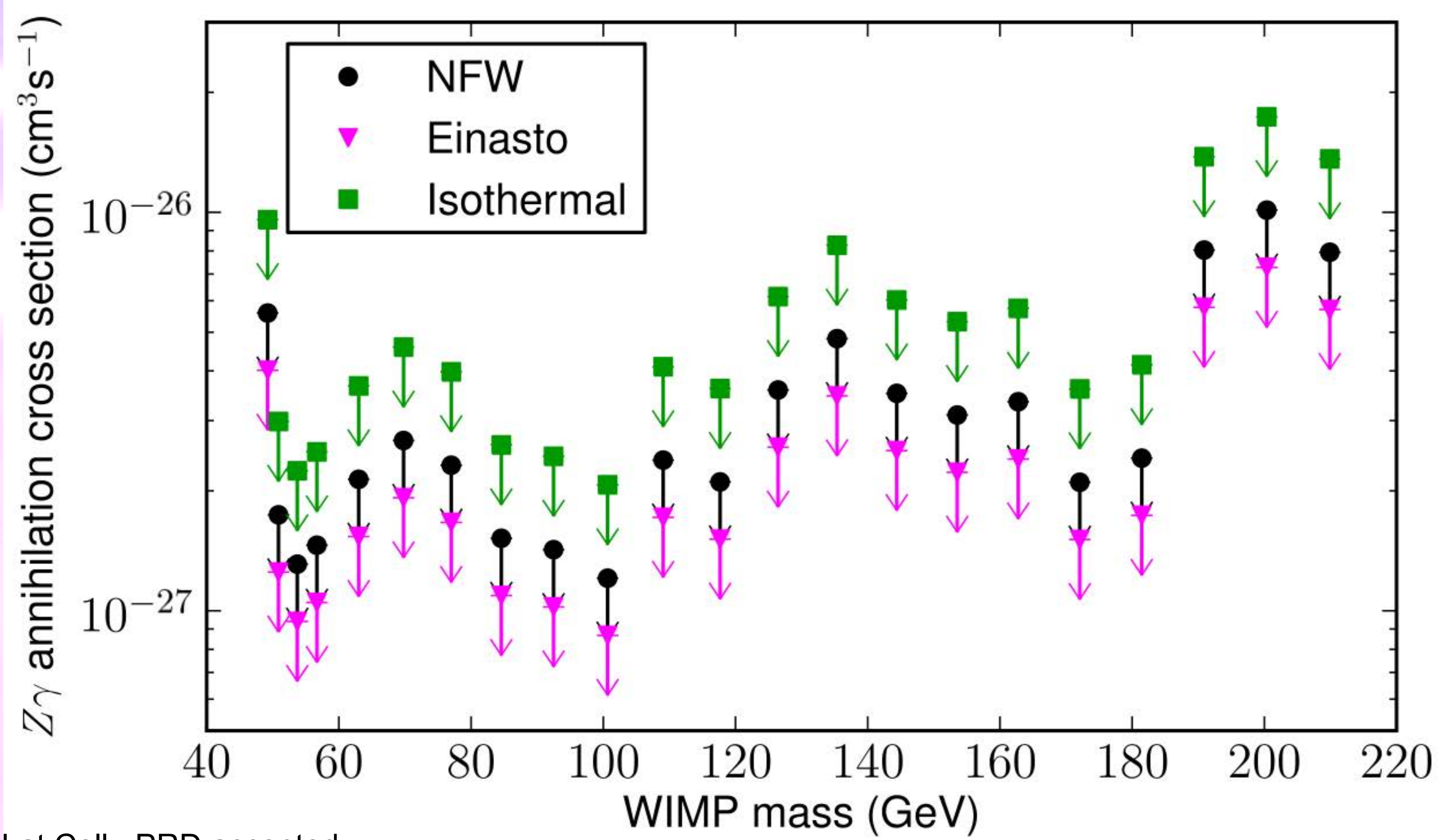


Fermi Lat Coll., PRD accepted
arXiv:1205.2739

Fermi LAT 23 Month Zγ-Cross-section limits 7 GeV – 200 GeV

- ± 20 % overall scale systematic error (+20 % systematic for UL).

Additional systematic on spectral structures with LAT resolution for E<13.2 GeV of s/bg ~ 1%.



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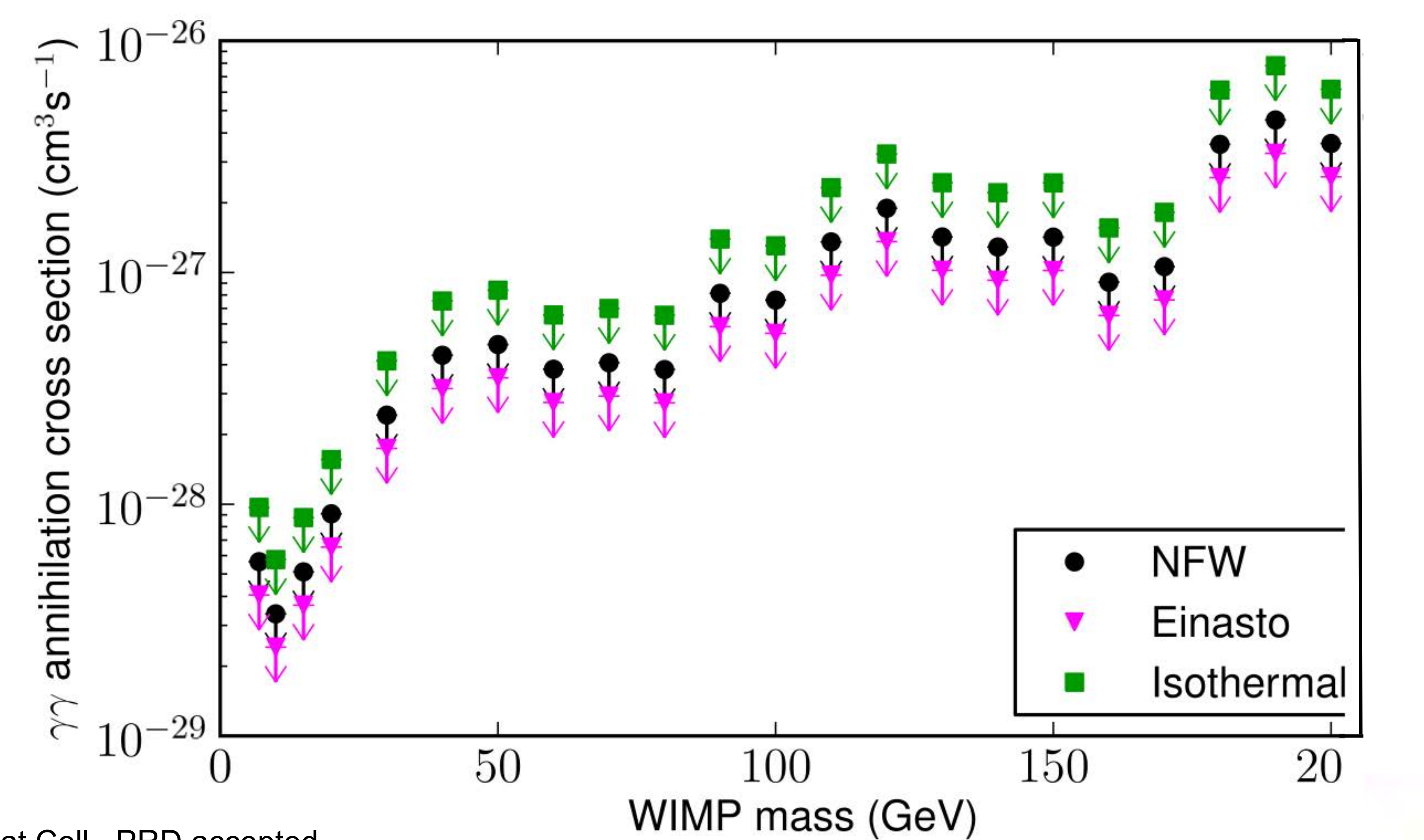
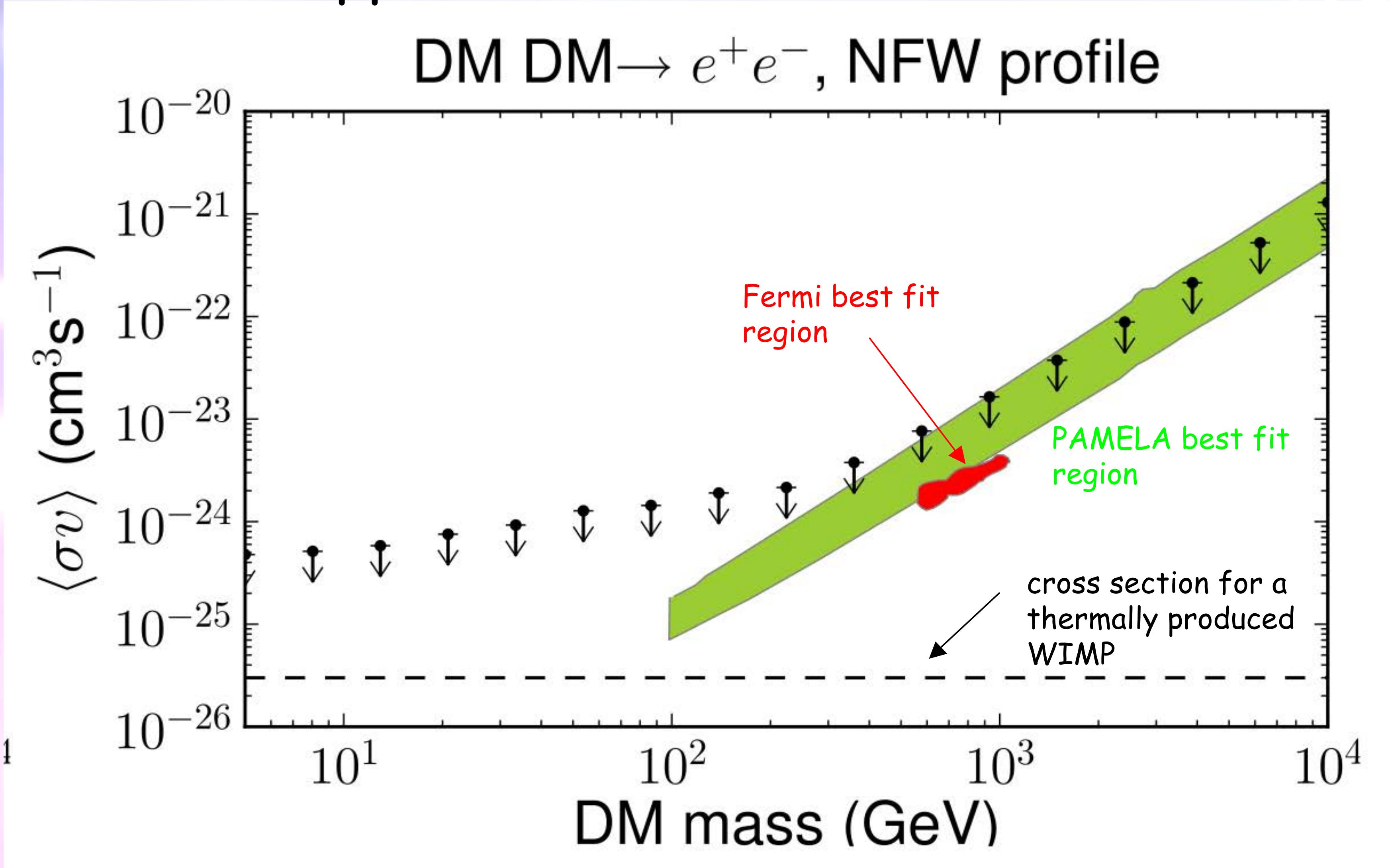


Fermi Lat Coll., PRD accepted
arXiv:1205.2739

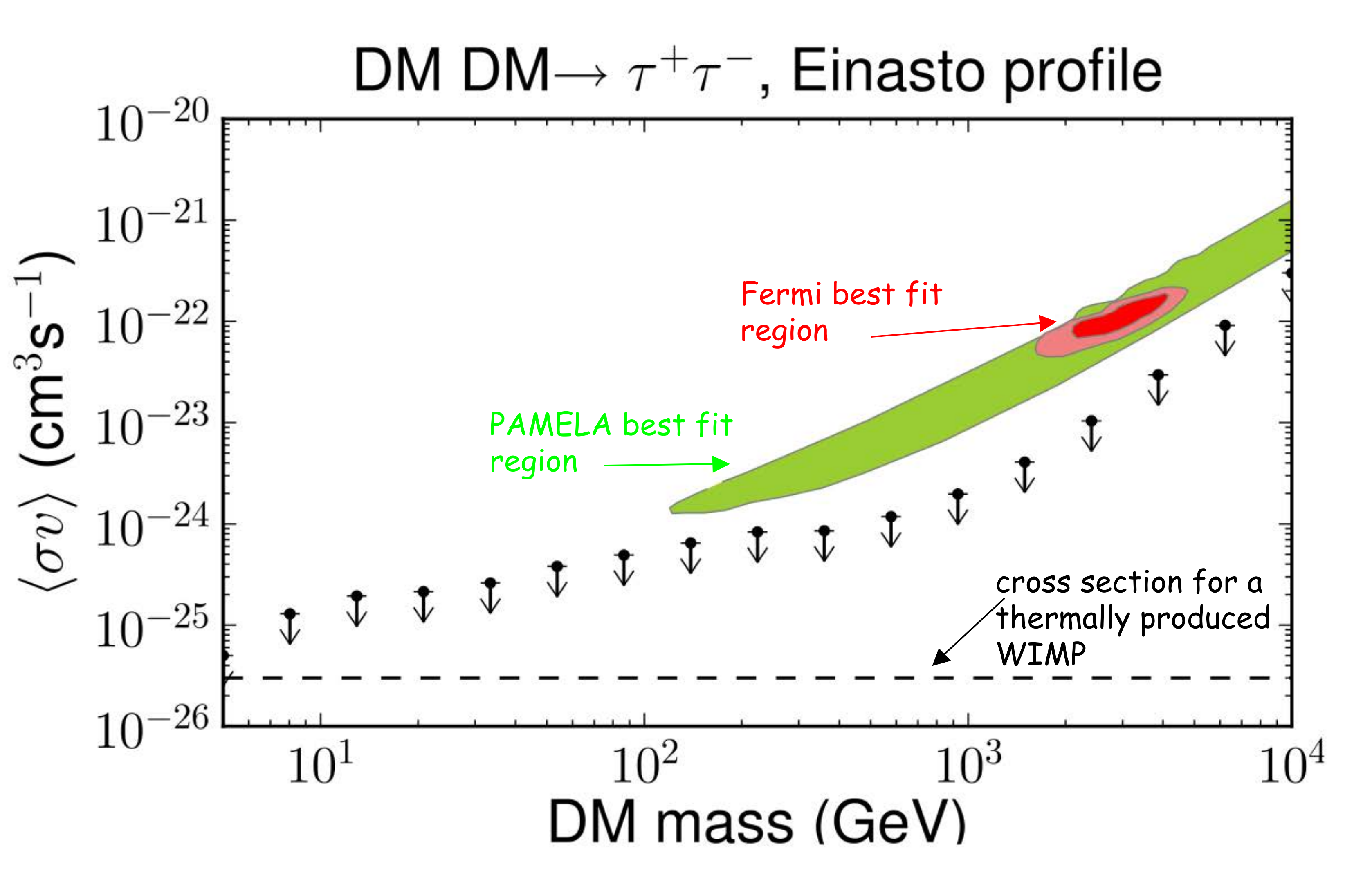
Cross section upper limits for dark matter annihilation



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

Fermi Lat Coll., PRD accepted
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 accepted
arXiv:1205.2739

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

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**

The longer we look, the more surprises we will see

thank you !


Come to
the dark side.
We have cookies...
Come to
the dark side.
We have cookies...
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