Fermi

Gamma-ray Space Telescope

Observations with the Fermi Large Area Telescope

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INFN-Pisa
On behalf of the Fermi Mission Team

Electron-Nucleus Scattering XI
Marciana Marina, 21-25/6/2010

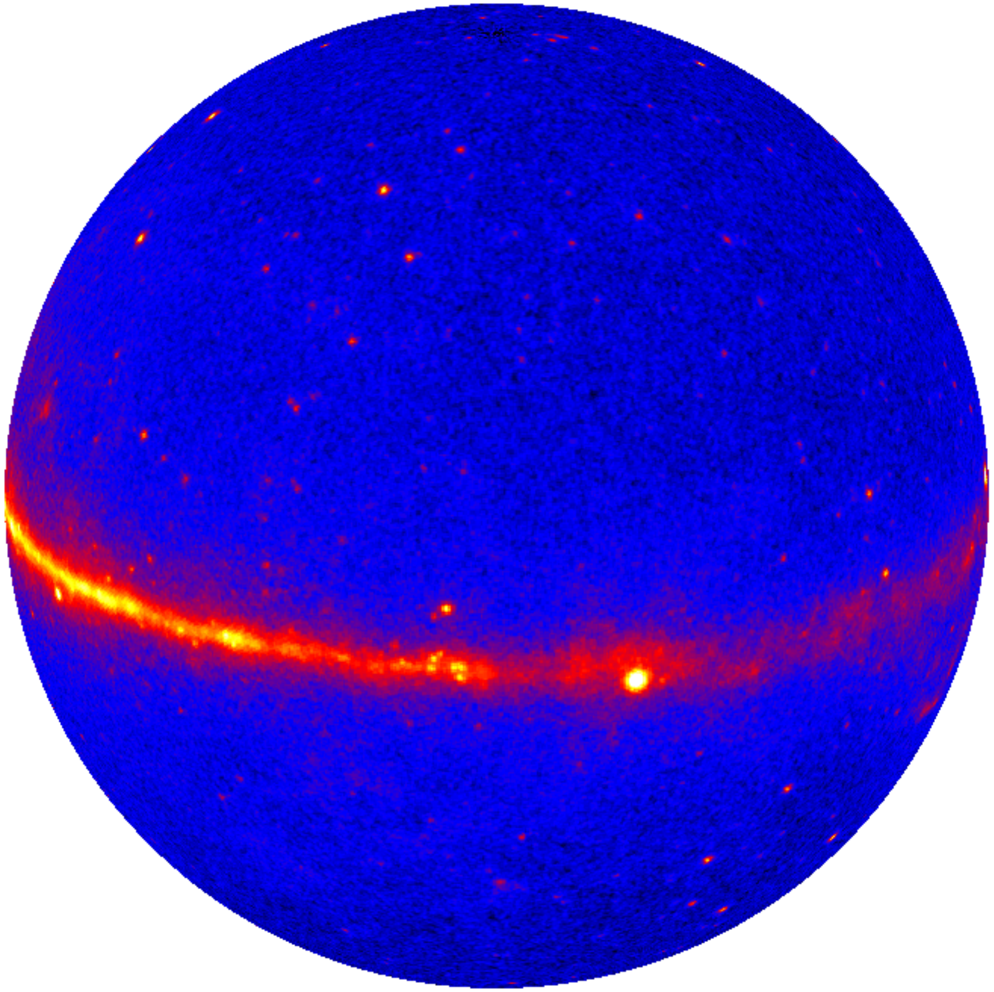
Talk Outline

The Fermi γ-ray observatory

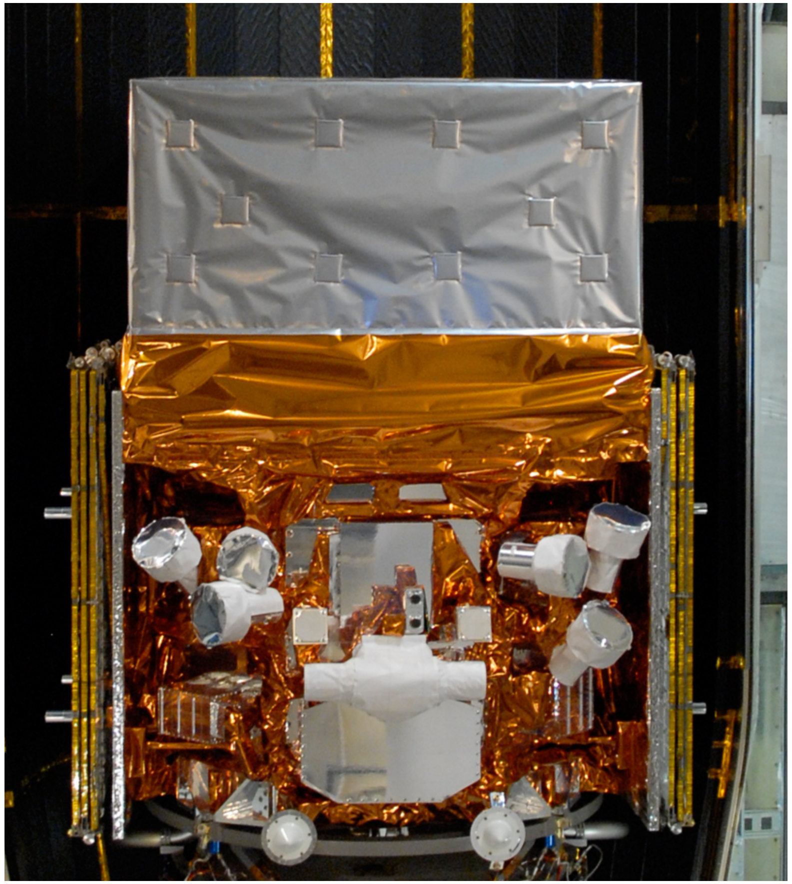
CR – γ-ray connection

CR Electrons with the LAT

Interpretations and constraints on Dark Matter

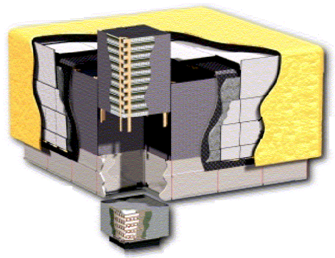


The Fermi observatory



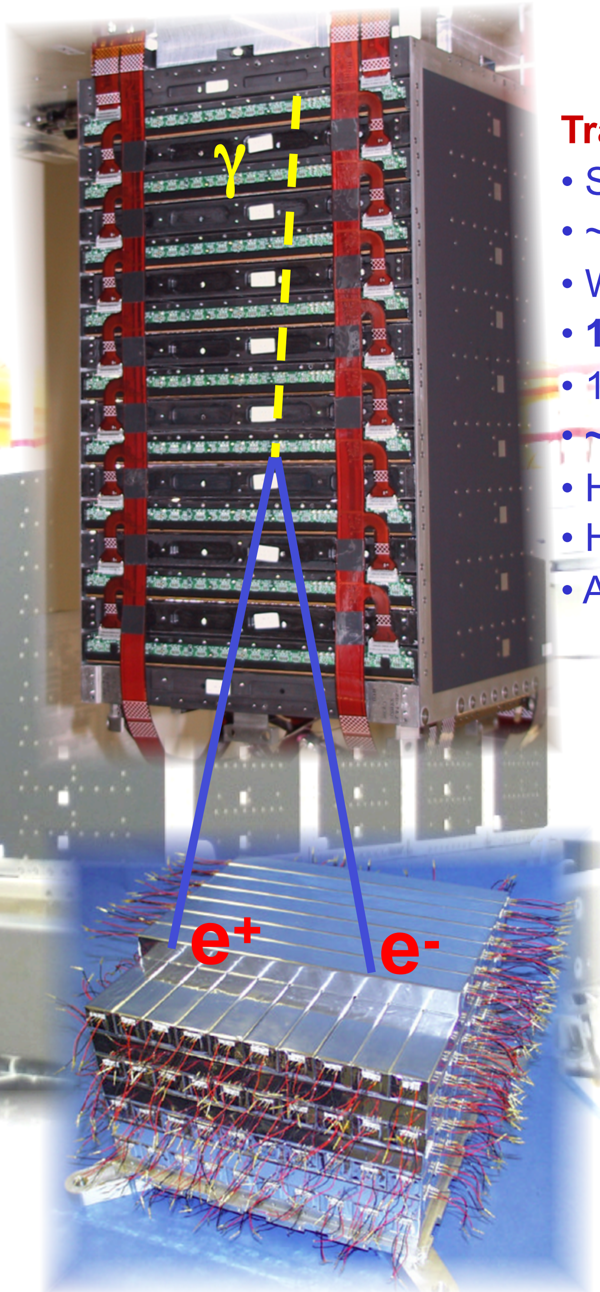
- Satellite gamma-ray telescope
  - Large Area Telescope (LAT)
    - 20 MeV – > 300 GeV
  - Gamma Burst Monitor (GBM)
    - 8 KeV – 40 MeV
- Key features
  - Huge field of view (30' full sky any 3 hrs)
  - Huge energy range
- Milestones
  - 11 jun 2008: launch
  - 04 aug 2008: science ops start
  - 13 aug 2009: γ data go public
  - 18 feb 2010: 100B triggers
  - 11 jun 2010: 2^{nd} year
    - 99.1% uptime from launch
    - 99.99% from October 2009

Overview of the Large Area Telescope



LAT:
- modular - 4x4 array
- 3ton – 650watts

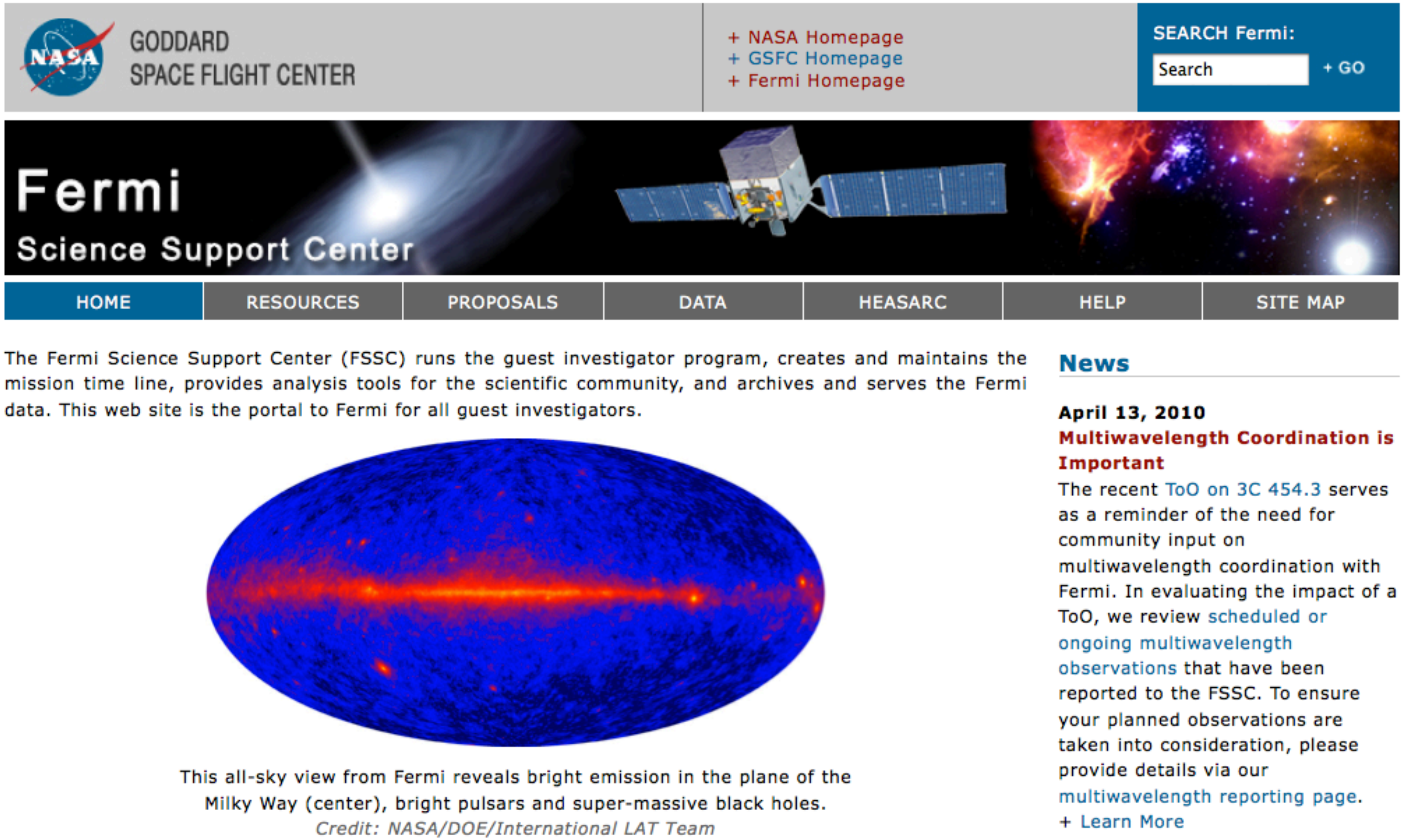
Anti-Coincidence (ACD):
- Segmented (89 tiles + 8 ribbons)
- Self-veto @ high energy limited
- **0.9997 detection efficiency**



Tracker/Converter (TKR):
- Si-strip detectors
- ~80 m^2 of silicon (total)
- W conversion foils
- **1.5 X0 on-axis**
- 18XY planes
- **~10^6 digital elx chans**
- Highly granular
- High precision tracking
- Average plane PHA

Calorimeter (CAL):
- 1536 CsI(Tl) crystals
- **8.6 X0 on-axis**
- large elx dynamic range (2MeV-60GeV per xtal)
- **Hodoscopic (8x12)**
- Shower profile recon
- leakage correction
- EM vs HAD separation

Fermi Science Support Center



GODDARD SPACE FLIGHT CENTER

+ NASA Homepage
+ GSFC Homepage
+ Fermi Homepage

SEARCH Fermi:

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Fermi

Science Support Center

HOME | RESOURCES | PROPOSALS | DATA | HEASARC | HELP | SITE MAP

The Fermi Science Support Center (FSSC) runs the guest investigator program, creates and maintains the mission time line, provides analysis tools for the scientific community, and archives and serves the Fermi data. This web site is the portal to Fermi for all guest investigators.

This all-sky view from Fermi reveals bright emission in the plane of the Milky Way (center), bright pulsars and super-massive black holes.

Credit: NASA/DOE/International LAT Team

News

April 13, 2010

Multiwavelength Coordination is Important

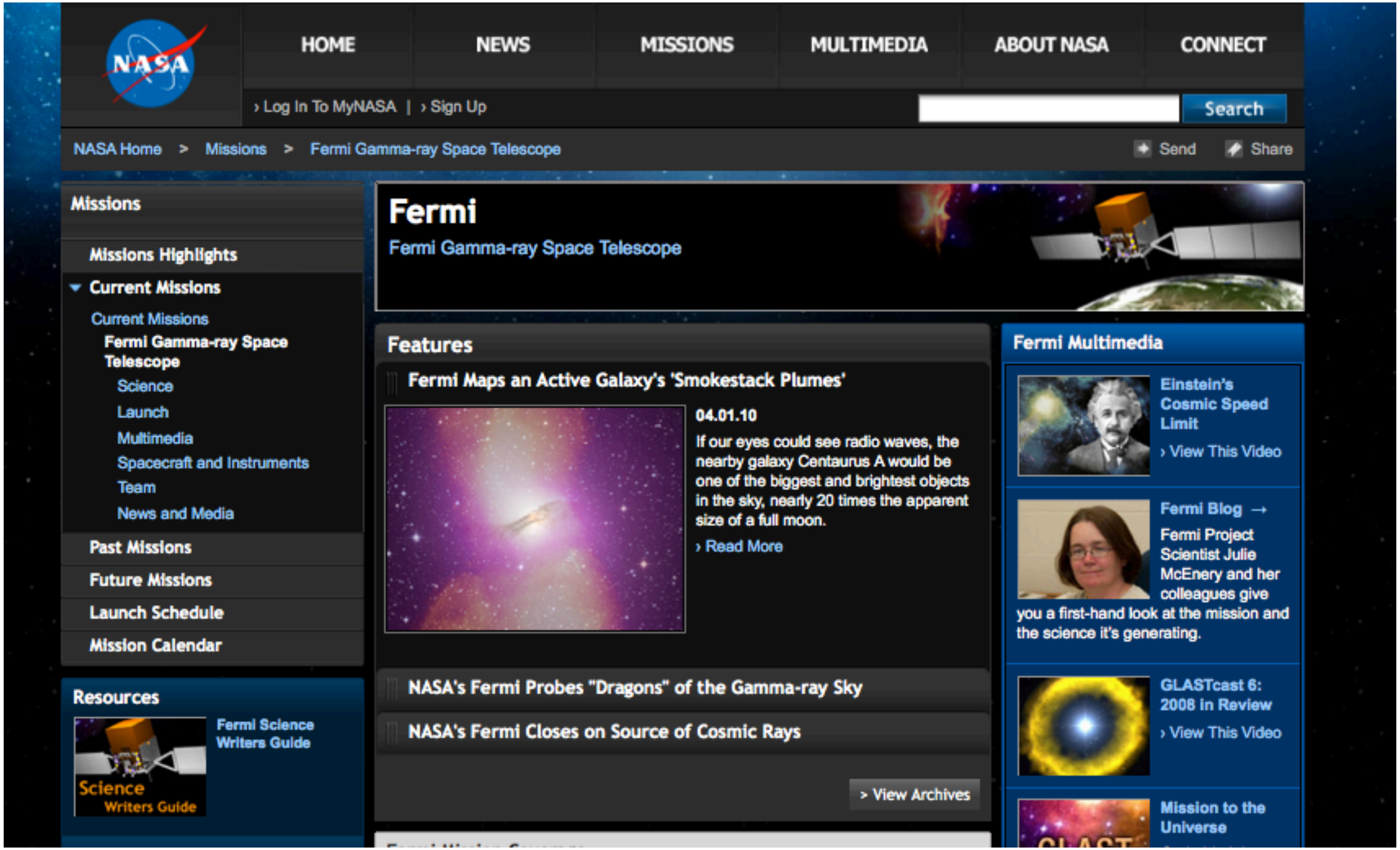
The recent ToO on 3C 454.3 serves as a reminder of the need for community input on multiwavelength coordination with Fermi. In evaluating the impact of a ToO, we review scheduled or ongoing multiwavelength observations that have been reported to the FSSC. To ensure your planned observations are taken into consideration, please provide details via our multiwavelength reporting page.

+ Learn More

Public data and extensive support for science Analysis Tools

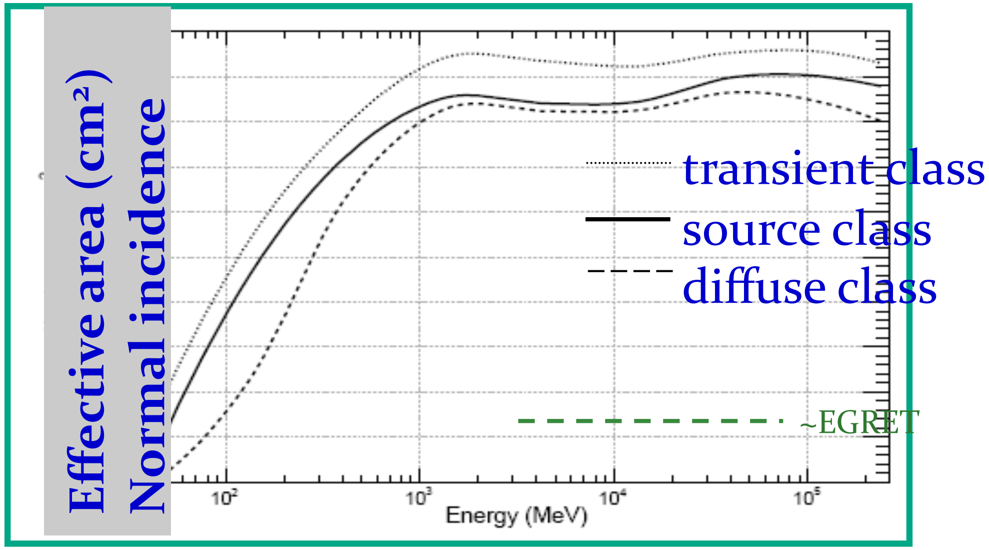
http://fermi.gsfc.nasa.gov/ssc/

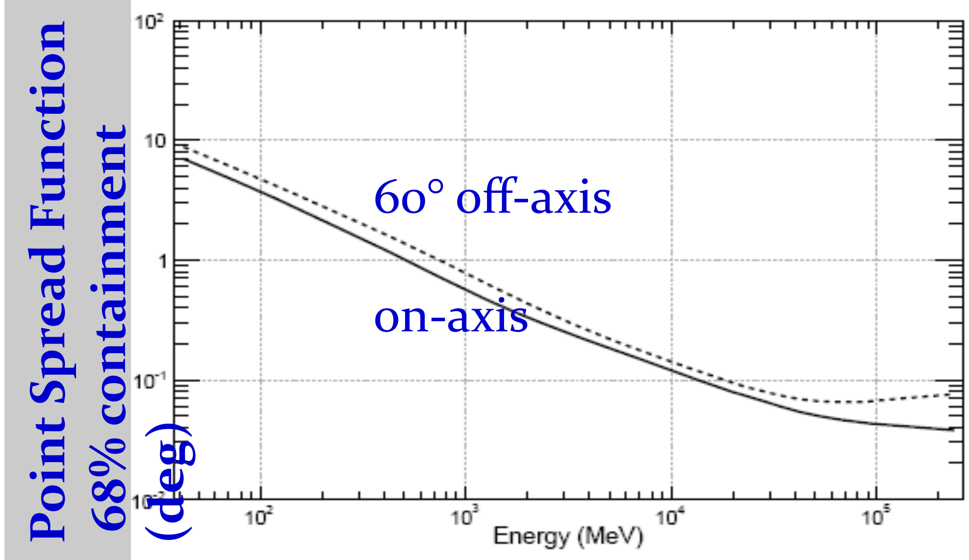
Fermi Public Portal

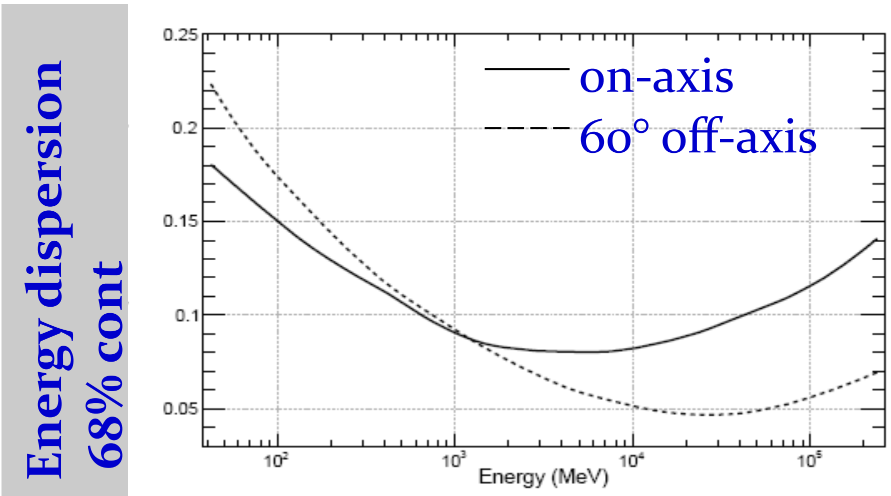


Large and professional outreach effort
http://www.nasa.gov/mission_pages/GLAST/main/index.html

Fermi-LAT Performances for photons







The Large Area Telescope on the Fermi Gamma-ray Space Telescope
Atwood, W. B. et al. 2009, ApJ, 697, 1071

These are pre-launch estimates

Instrument performance updated after launch and distributed (arXiv.0907.0626)

On-going efforts to improve it (see examples later)

Fermi-LAT scientific highlights

- ❑ **Gamma-ray sky catalog**
  - – >1400 sources > 100 MeV
  - – Known classes plus UNID
- ❑ **Pulsar catalog**
  - – >60 γ-ray PSR, ~20 γ-ray only
- ❑ **Active Galactic Nuclei**
  - – TeV cosmic accelerators
- ❑ **Gamma-ray Bursts**
  - – Cosmological probes
  - – Fundamental physics (LIV)
- ❑ **Diffuse emission**
  - – Galactic model
  - – EGB
- ❑ **Cosmic Rays Electrons**
- ❑ **Indirect Dark Matter Searches**

Science, 325 (2009)

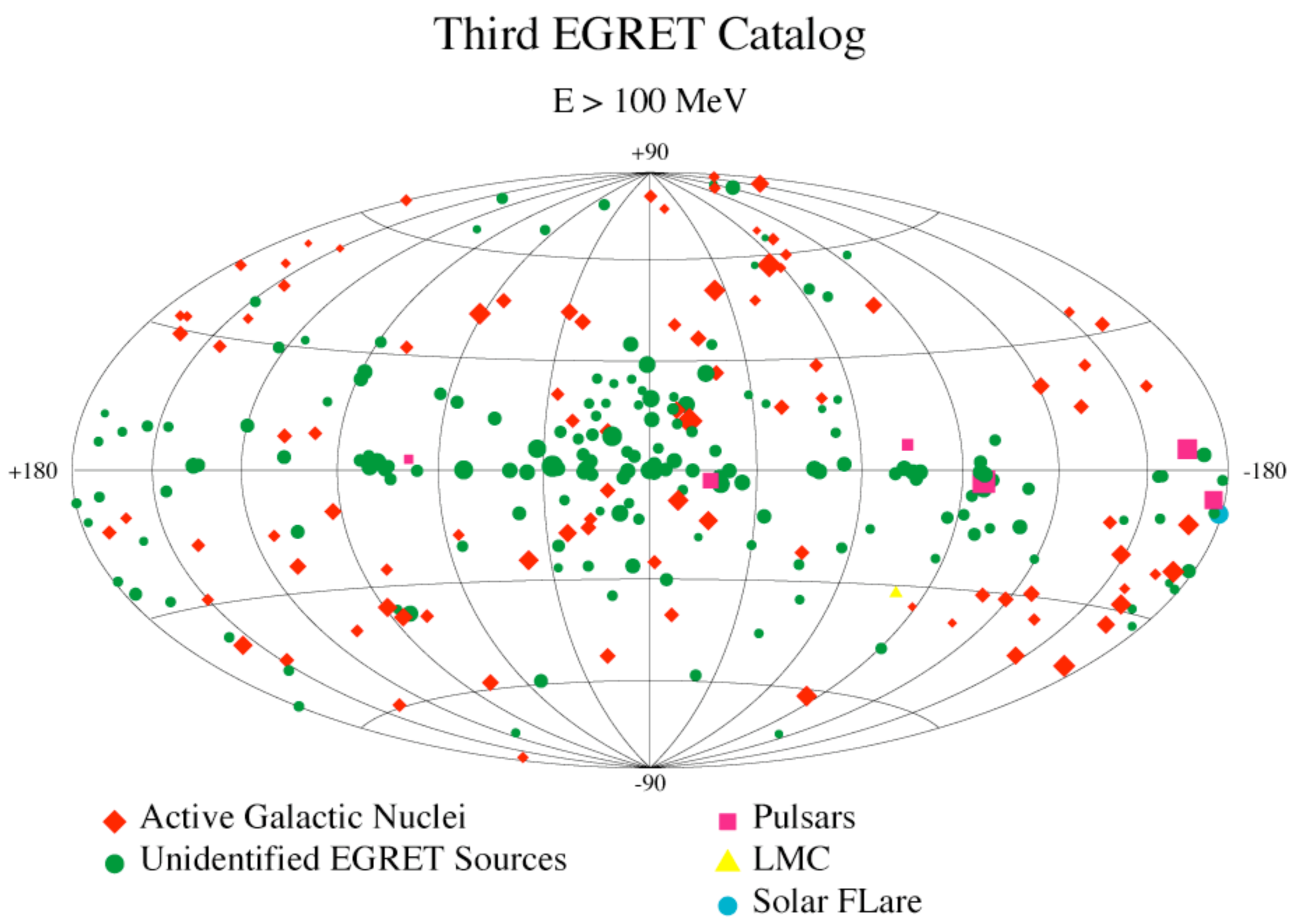
Nature, 462 (2009)

87 refereed papers

86 Atels / 25 GCN circulars

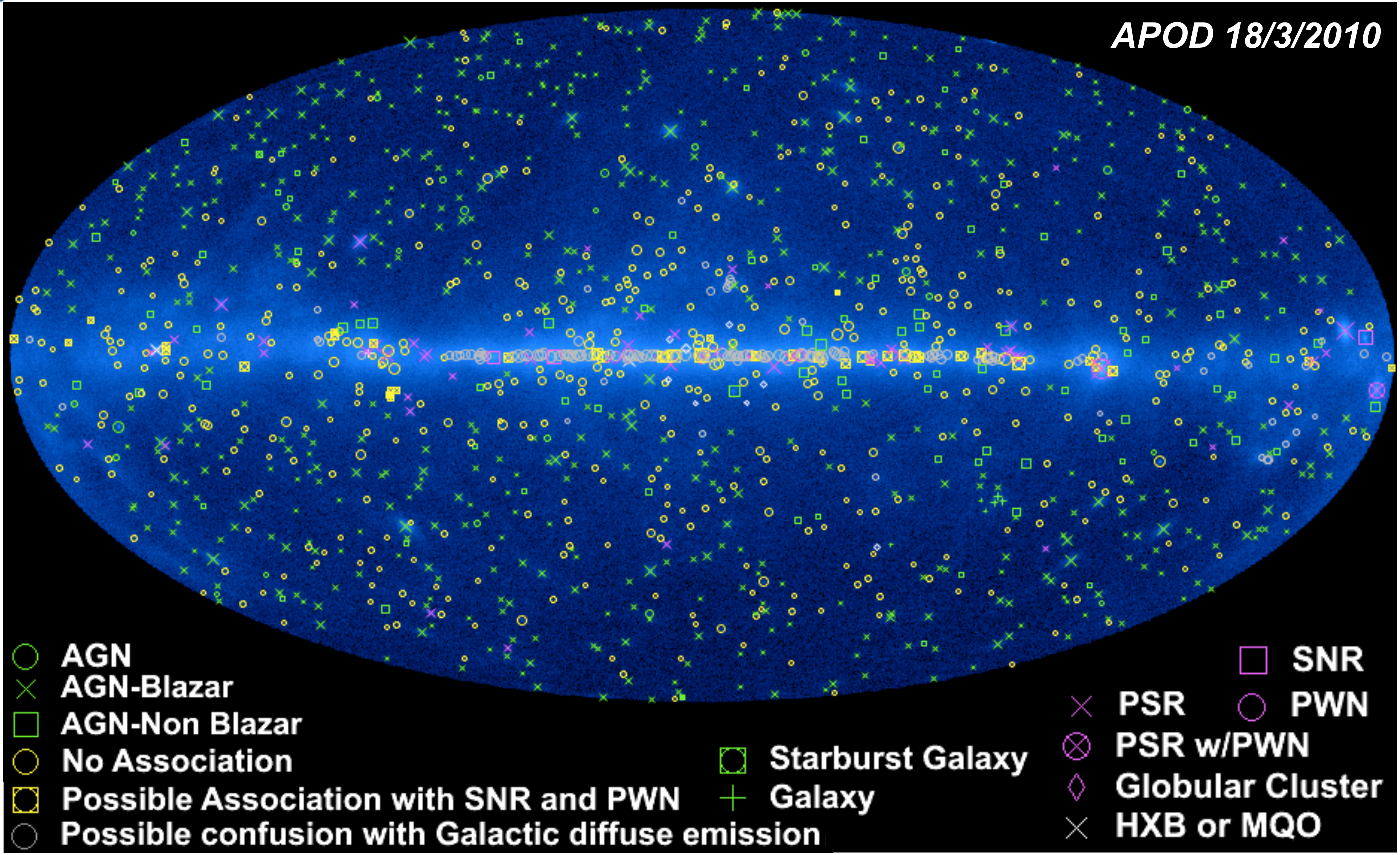
https://www-glast.stanford.edu/cgi-bin/pubpub

The EGRET Gamma-ray Sky

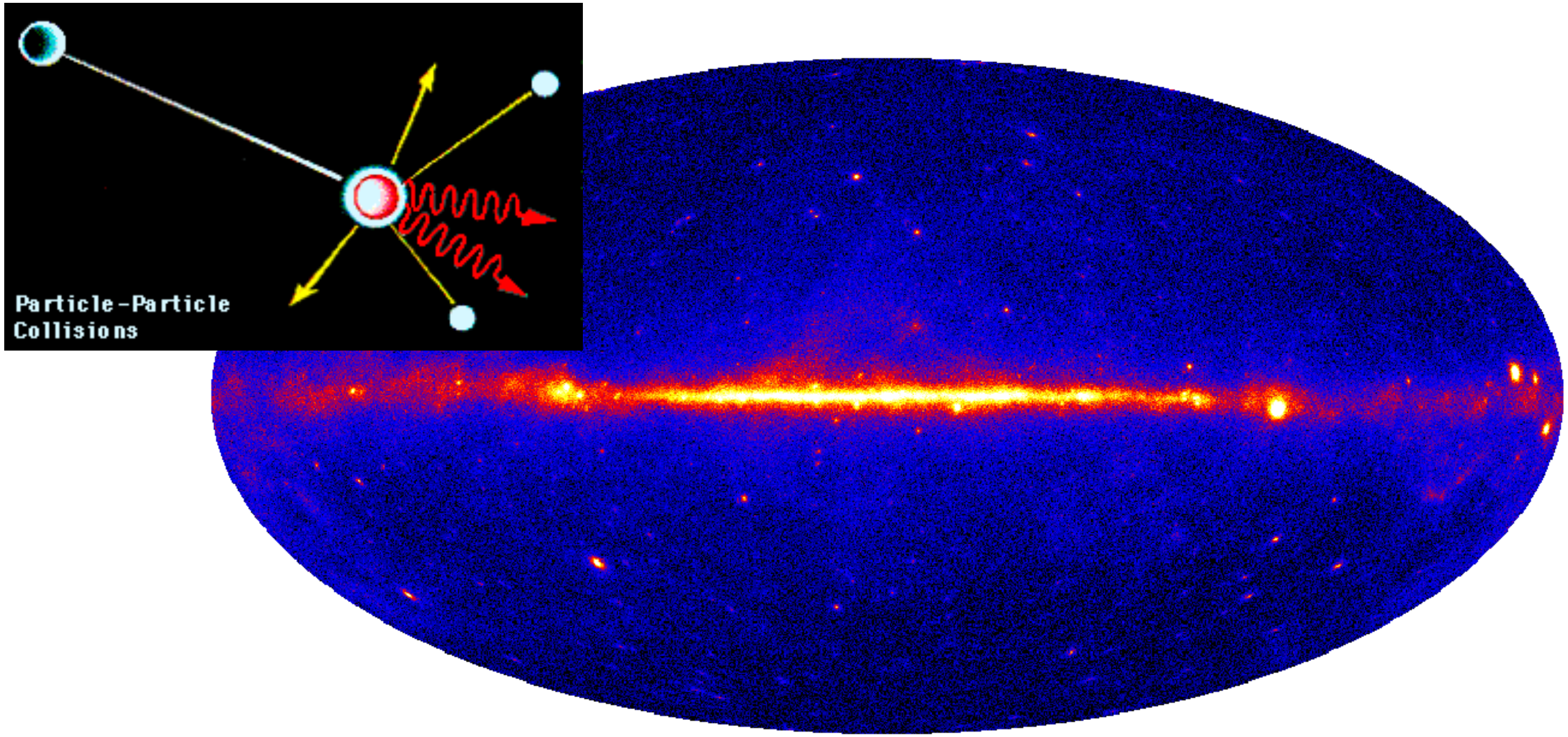


271 sources, ~200 real (see EGR catalog, Casandjian & Grenier 2008)

1FGL Catalog Associations/Identifications

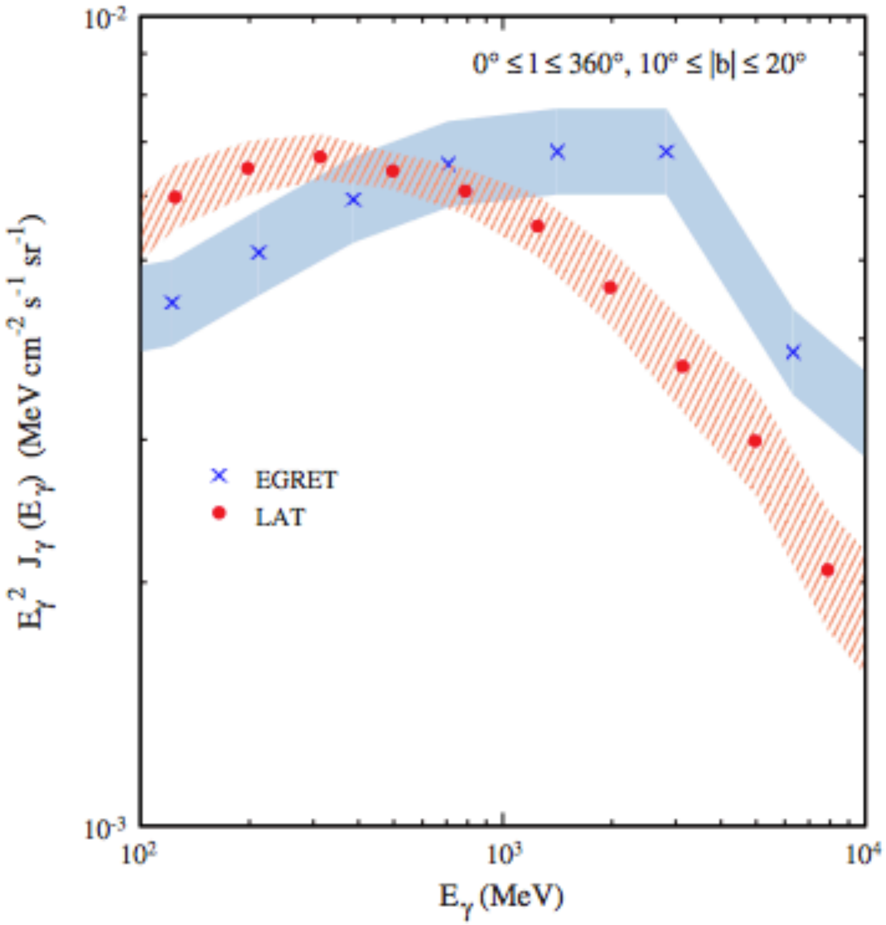


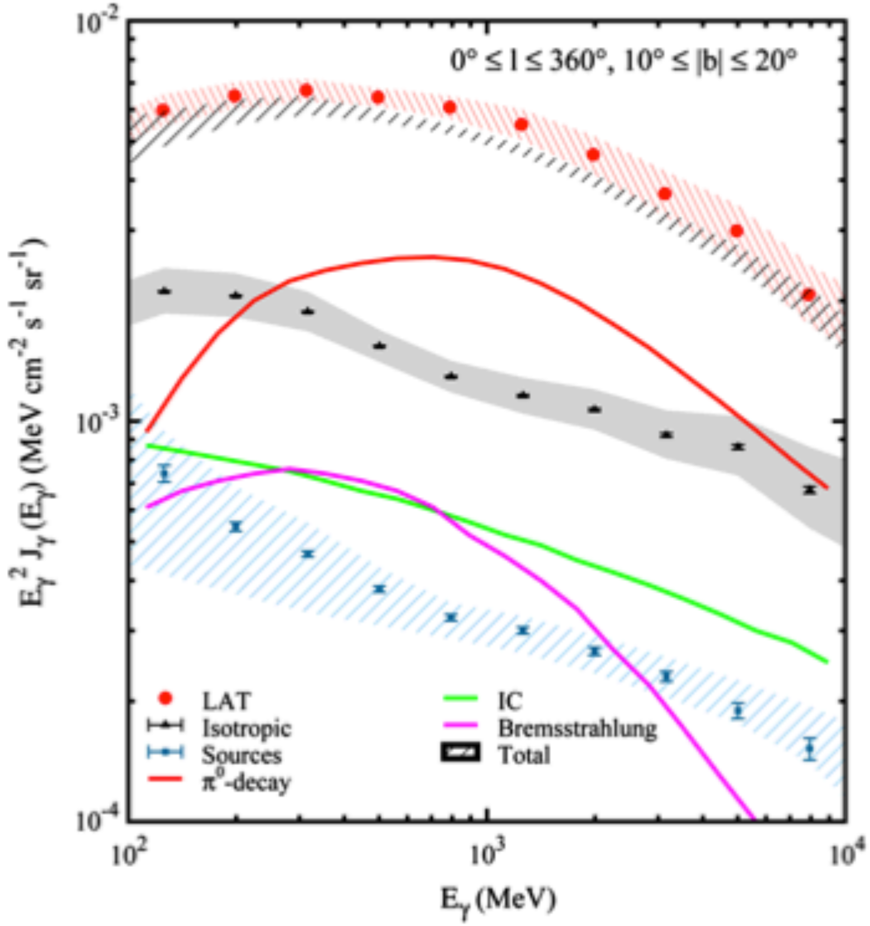
Cosmic Rays – Gamma-rays connection



- Galactic gamma rays trace cosmic-ray proton interactions (cosmic-ray acceleration sites & propagation)
- Observations of nearby galaxies provide an outside view
- Primary targets: galactic plane, starburst galaxies, LMC, SNR
- Direct CR observations

Fermi Large Area Telescope Measurements of the Diffuse Gamma-Ray Emission at Intermediate Galactic Latitudes

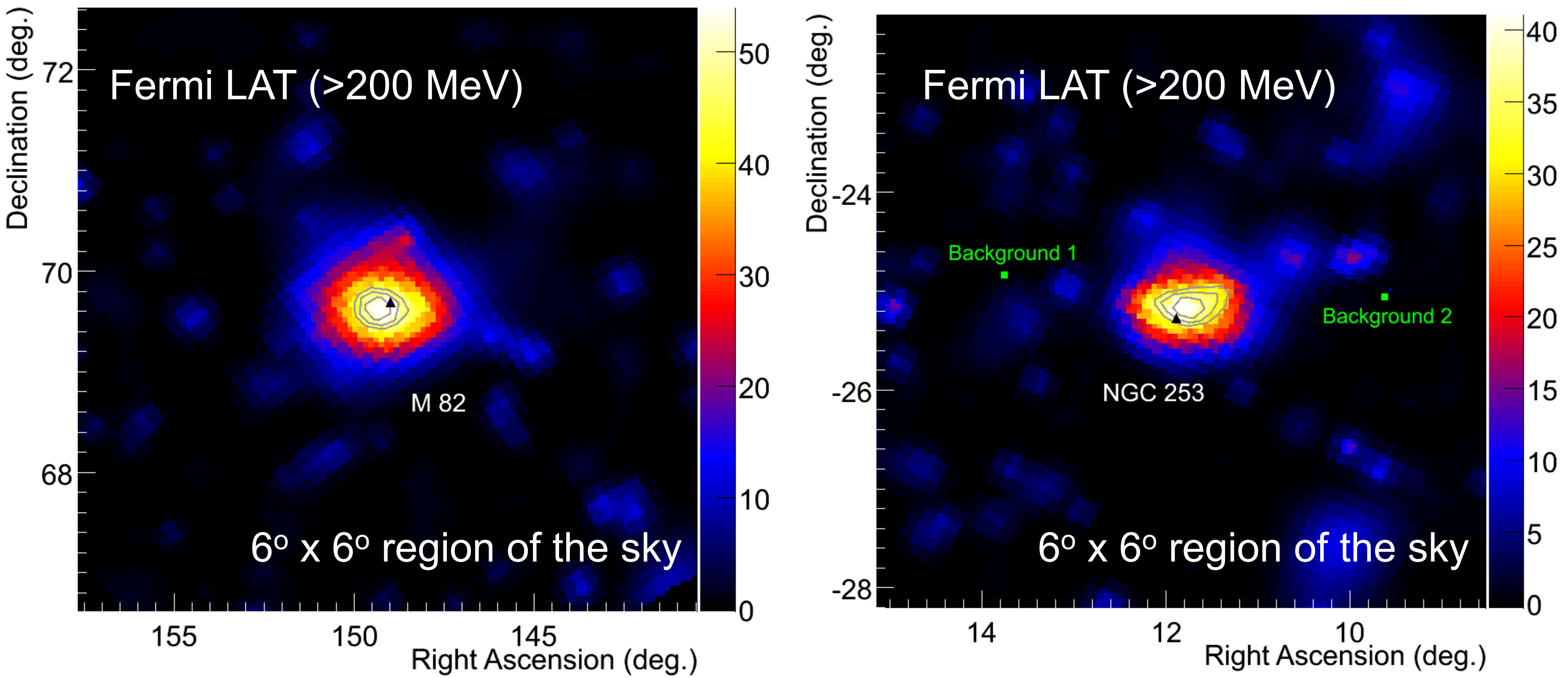




No confirmation of the GeV excess
Basic physics of diffuse emission understood

THE ASTROPHYSICAL JOURNAL LETTERS, 709:L152–L157, 2010 February 1 doi:10.1088/2041-8205/709/2/L152

DETECTION OF GAMMA-RAY EMISSION FROM THE STARBURST GALAXIES M82 AND NGC 253 WITH THE LARGE AREA TELESCOPE ON *FERMI*



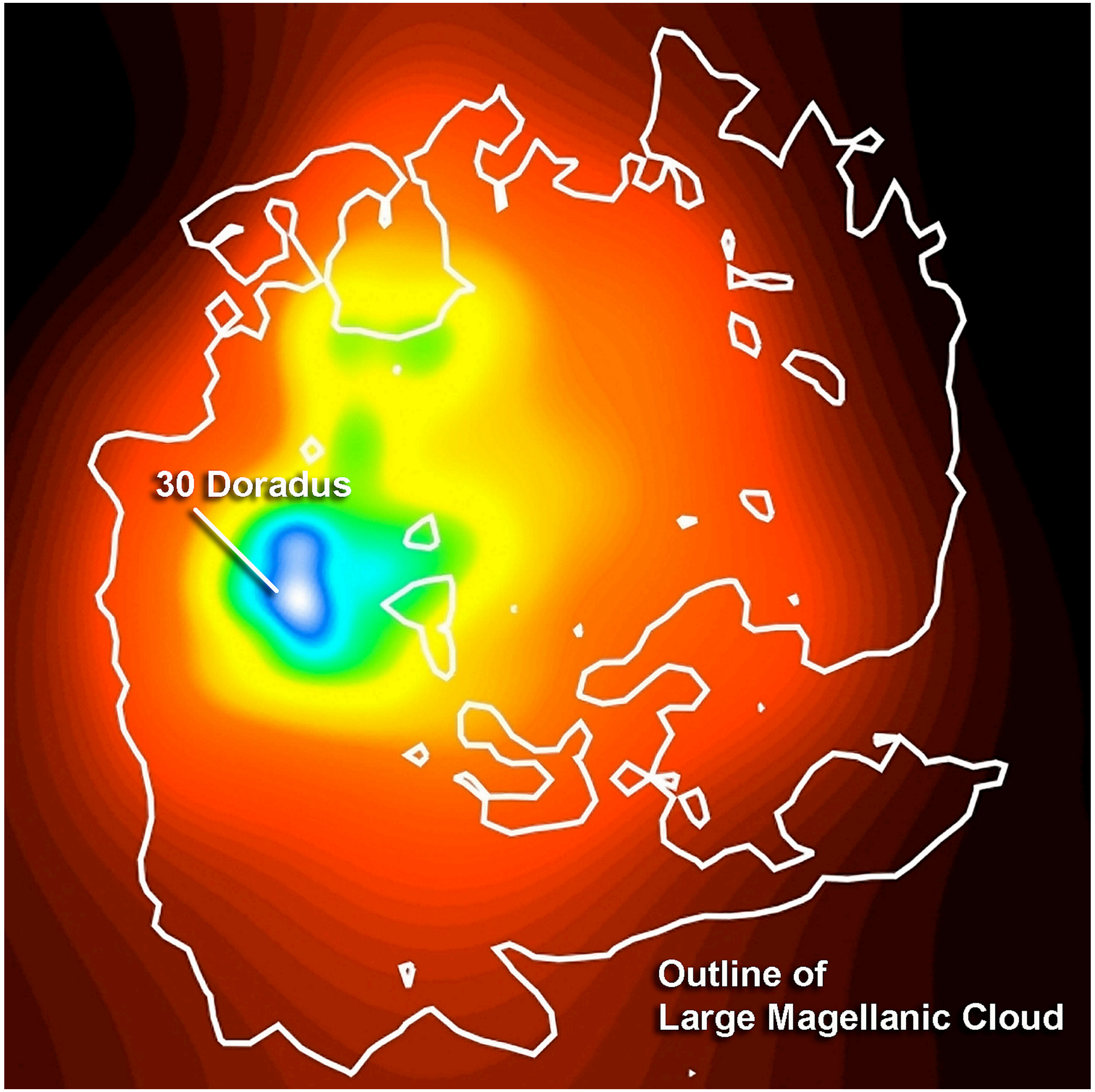
Seen as point sources

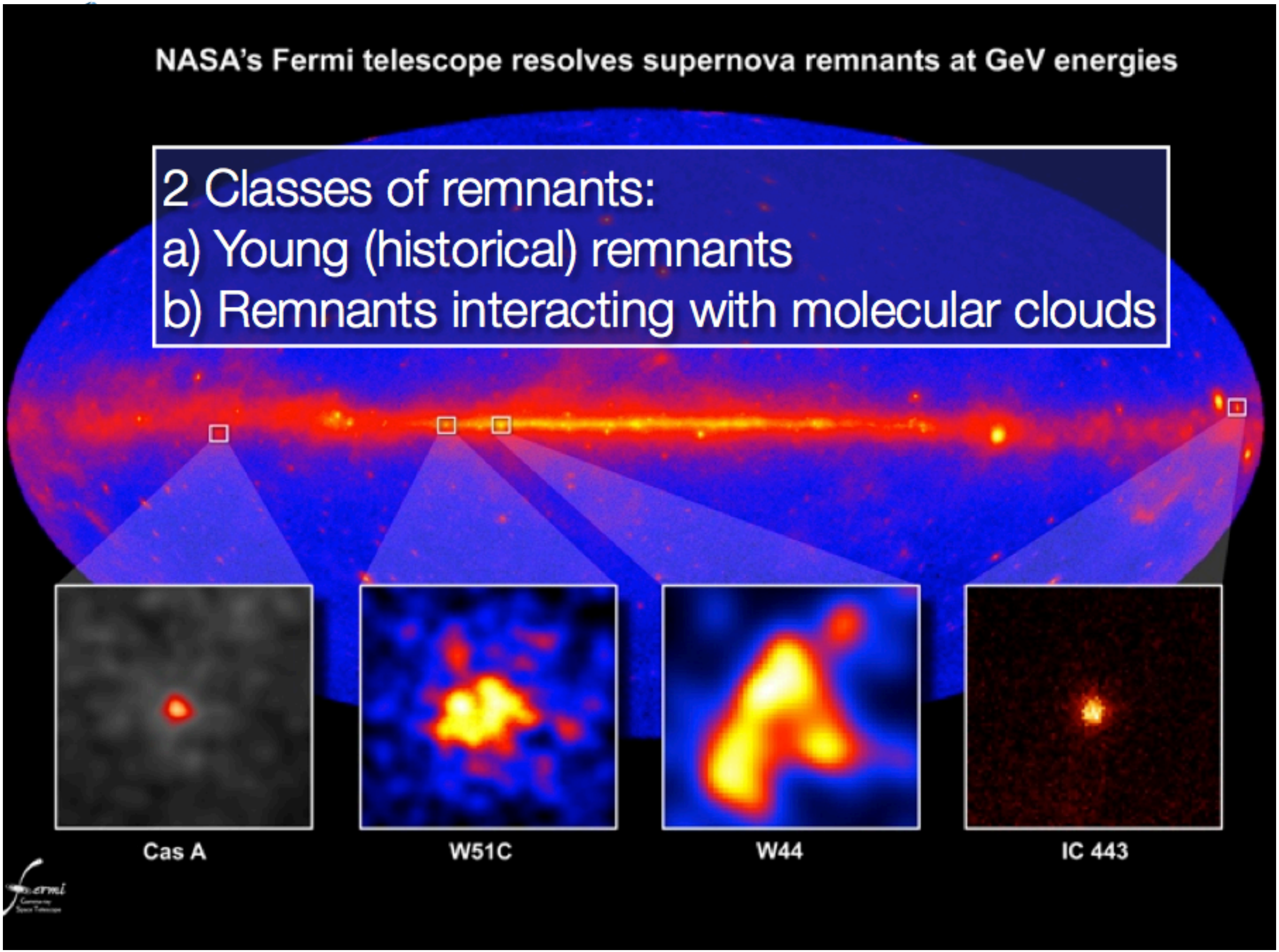
Spectrum consistent with hadronic acceleration

A&A 512, A7 (2010)
DOI: 10.1051/0004-6361/200913474

Astronomy & Astrophysics

Observations of the Large Magellanic Cloud with *Fermi*

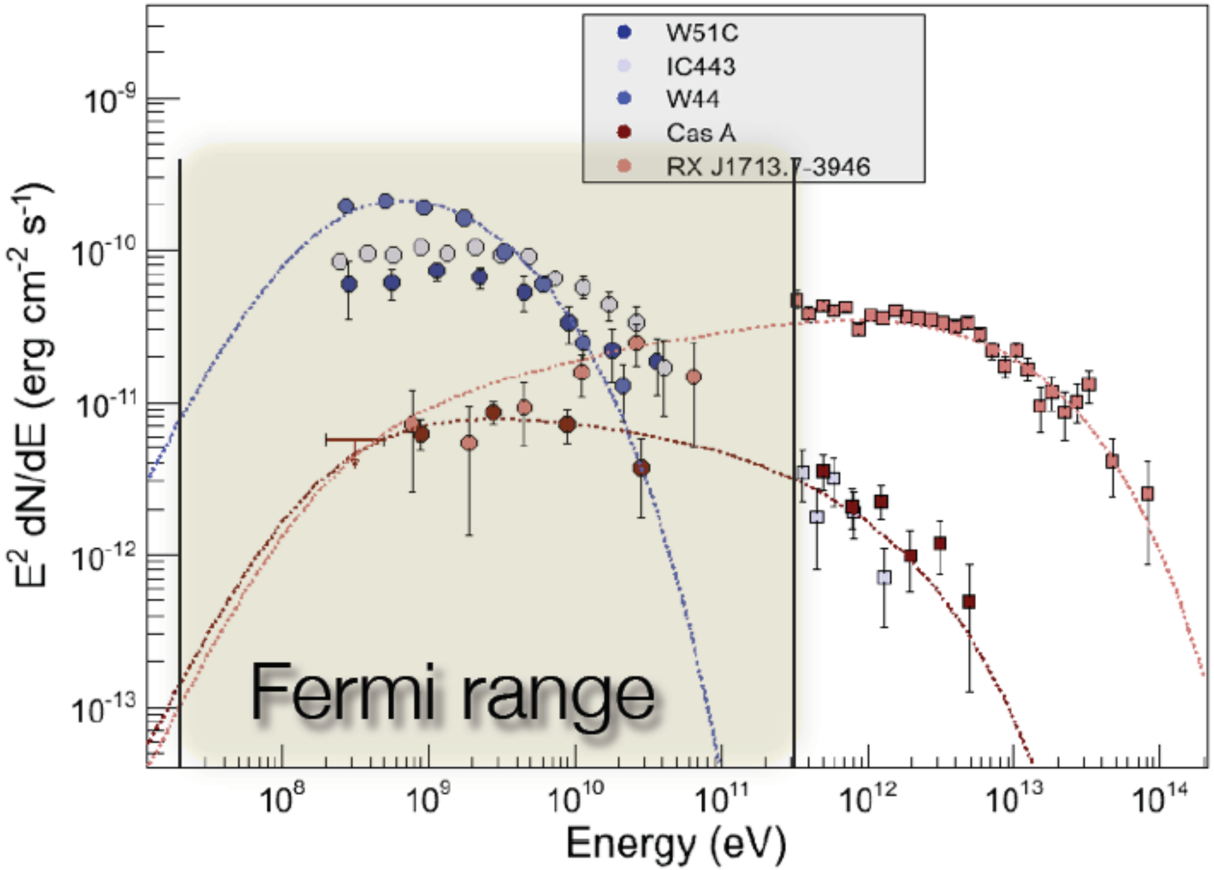



NASA's Fermi telescope resolves supernova remnants at GeV energies
2 Classes of remnants:
a) Young (historical) remnants
b) Remnants interacting with molecular clouds
Cas A
W51C
W44
IC 443

γ-ray SNRs and cosmic ray origin

- Young SNRs have nonthermal synchrotron X-rays, strong TeV detections, X-ray/TeV correlation; γ-rays likely leptonic in origin
- RXJ 1713.7-3946 has hard Fermi GeV spectrum, rising in νF_ν
- Middle-aged SNRs have steep spectrum from GeV to TeV; γ-rays likely hadronic in origin

- Spectral evolution with age
- Energy in cosmic rays represents few to tens of percents of SN energy
- IC 443 with intermediate age (~10000 yrs), shows intermediate spectrum



Importance of a direct CRE measurement

- ❑ **Probe CR models**
  - **Sources (including DM), interactions, propagation, diffusion**
- ❑ **Probe CR targets (ISM, ISRF)**
  - **Propagation and diffusion**
  - **Strong connection with diffuse gamma-ray radiation**
- ❑ **Probe possible nearby sources**
  - **limited electron lifetime within Galaxy**
- ❑ **Answers to long-standing questions and vast literature**

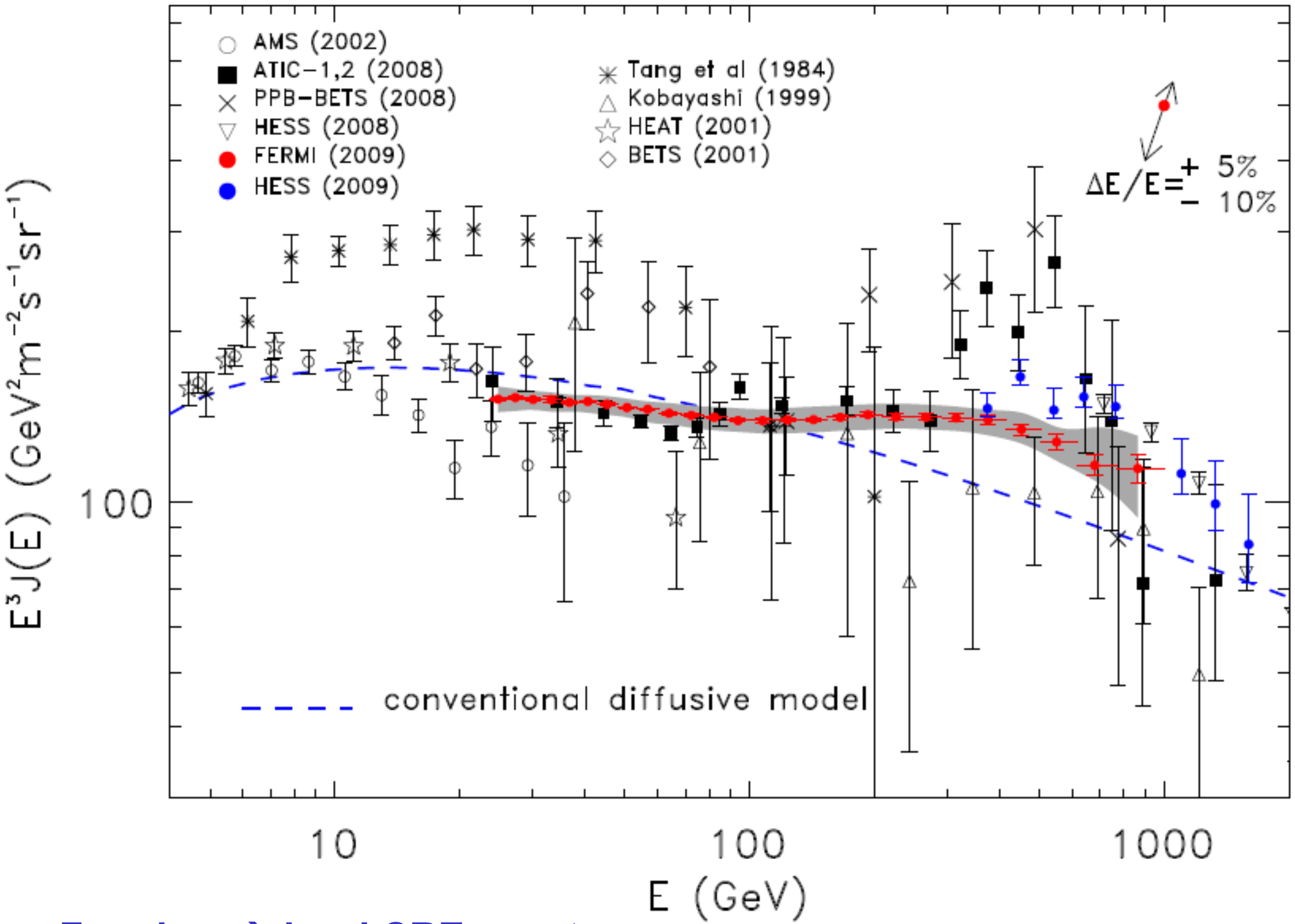
THE ASTROPHYSICAL JOURNAL, 162:L181–L186, December 1970

PULSARS AND VERY HIGH-ENERGY COSMIC-RAY ELECTRONS

C. S. SHEN*
Department of Physics, Purdue University, Lafayette, Indiana 47907
Received 1970 June 8; revised 1970 September 19

PRL 102, 181101 (2009)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 8 MAY 2009

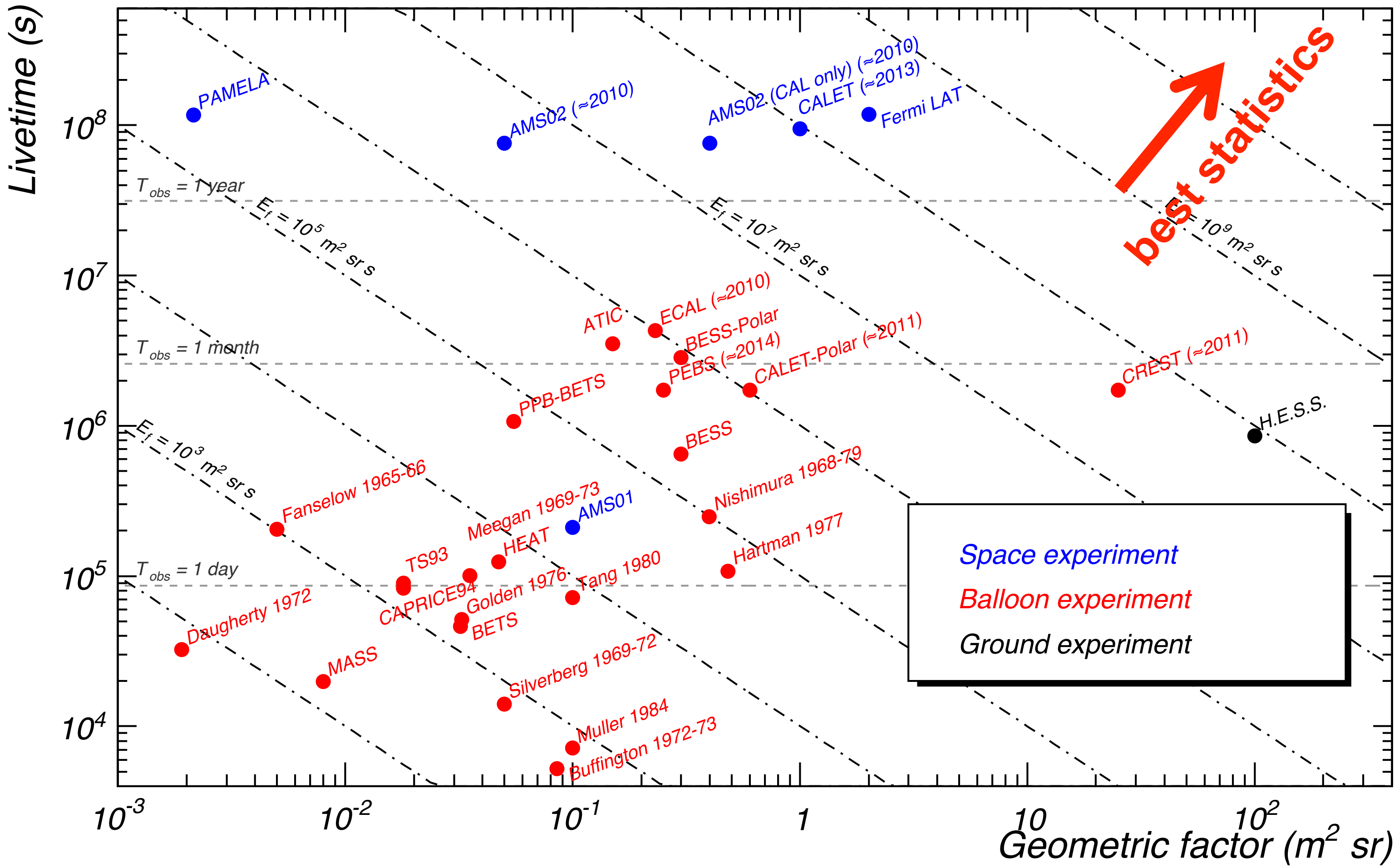
Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope



- **Most cited Fermi paper**
- **8th most cited in 2009 (ADS)**

Fermi → hard CRE spectrum
PAMELA → positron excess
→ ***Cosmic Ray Lepton puzzle*** → **Several 100s articles**

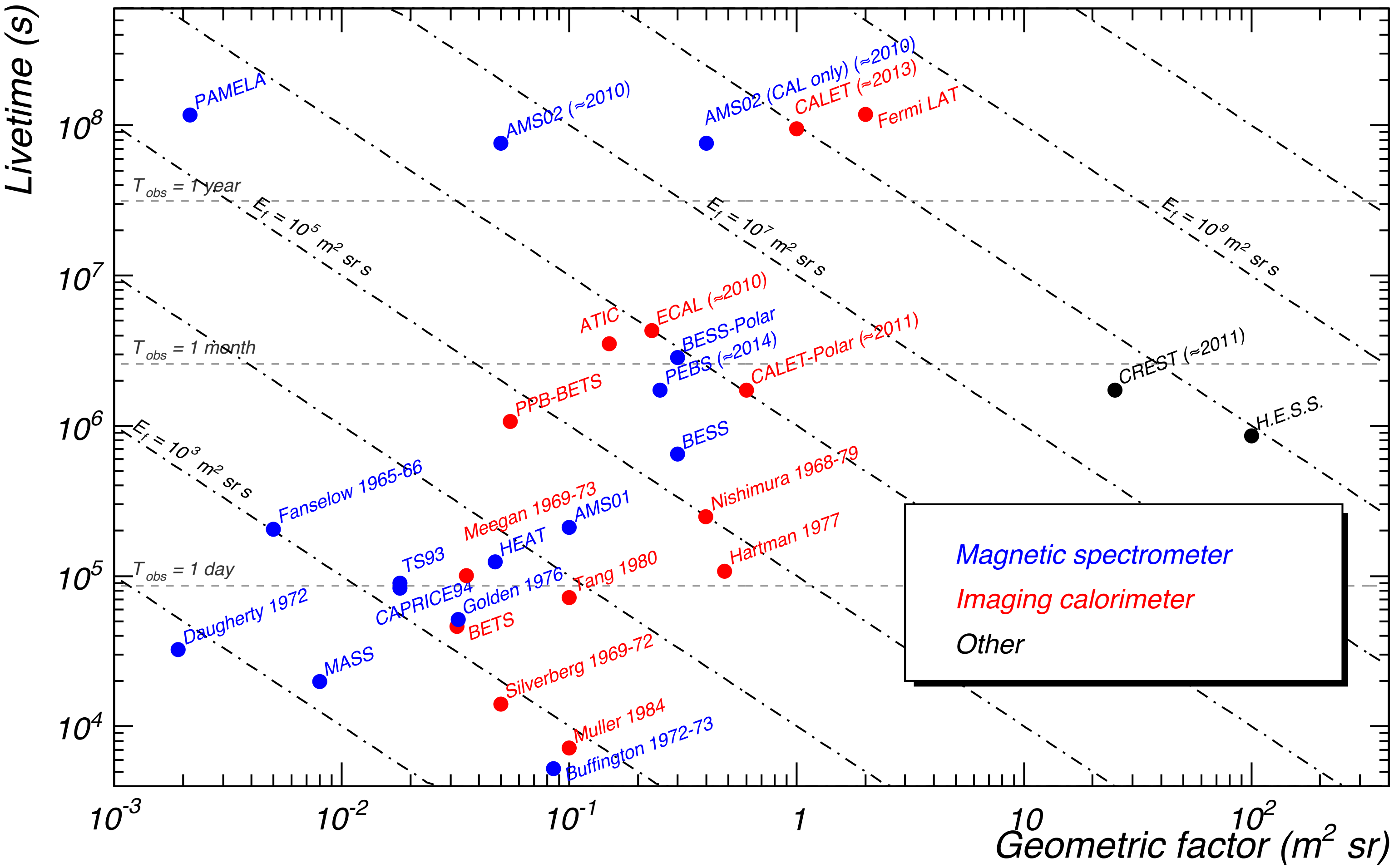
Fermi and the others



caveat1 – illustrative - 2x corrections possible

caveat2 - statistics is not enough

Fermi and the others



different techniques have different systematics

Fermi CRE measurement peculiarities

- Highest statistics
  - >> balloons (short exposure)
  - > spectrometers (smaller acceptance)
  - Forces careful study of systematic effects
- High quality data between old data and HESS
  - Disprove ATIC claim of strong spectral feature
  - Confirm harder spectrum
- Unable to separate e- from e+ (no magnet on-board)
  - On-going effort to use earth magnetic field to do this
- On-going developments
  - Anisotropies (close to submission)
  - Energy extentions
    - Low energy: orbit-dependent, see later in this talk
    - High energy (> 1TeV): require specific new CAL recon

How the LAT detects electrons

Trigger and downlink

Very versatile and configurable

- Triggering on ~ all particles that cross the LAT
  - Including electrons (8M/yr)

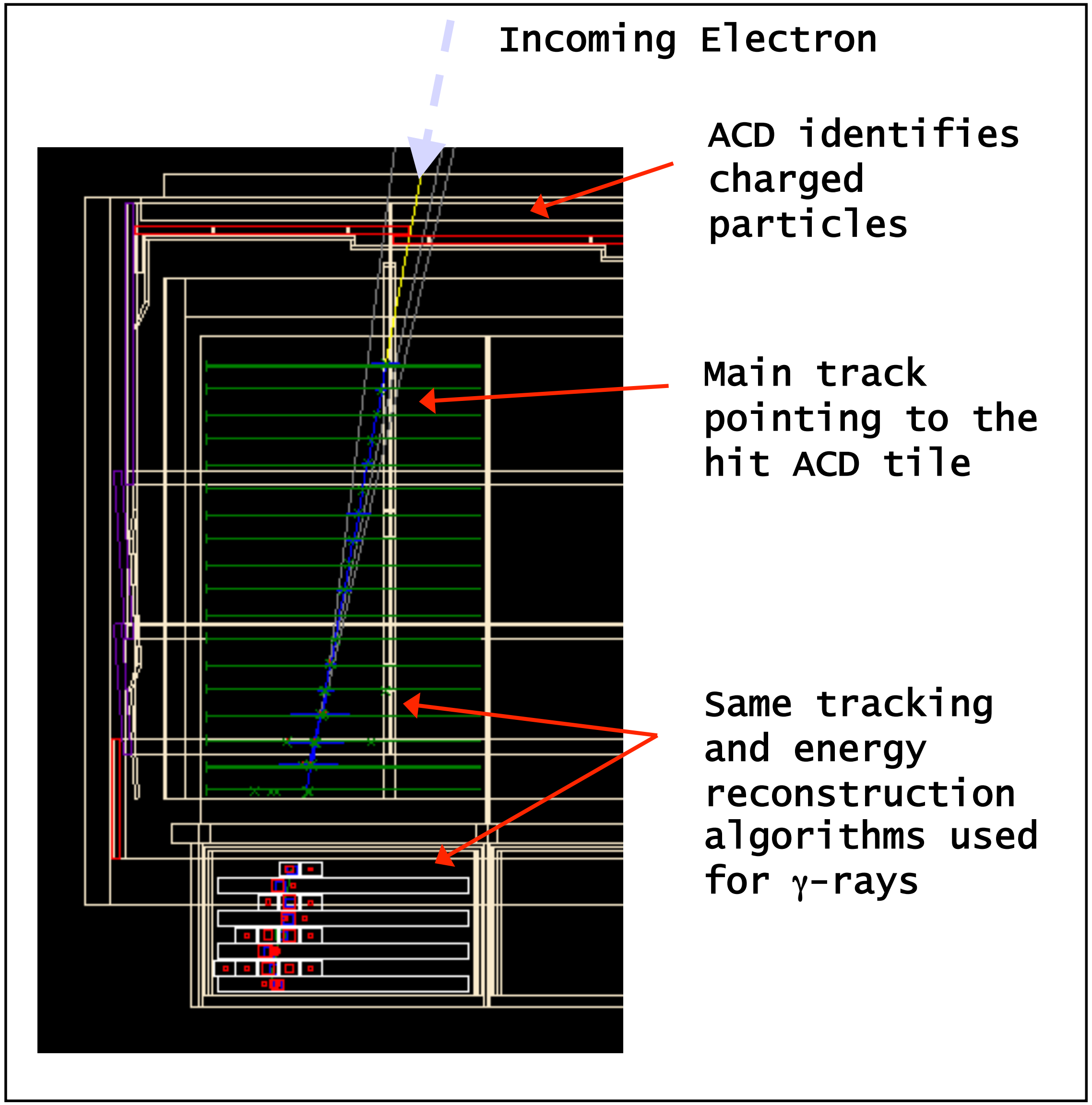
On board filtering to fit bandwidth

- Remove many charged particles
- Keeps all events with more than 20 GeV in the CAL (HE)
- Prescaled (1:250) sample of unfiltered triggers (LE)

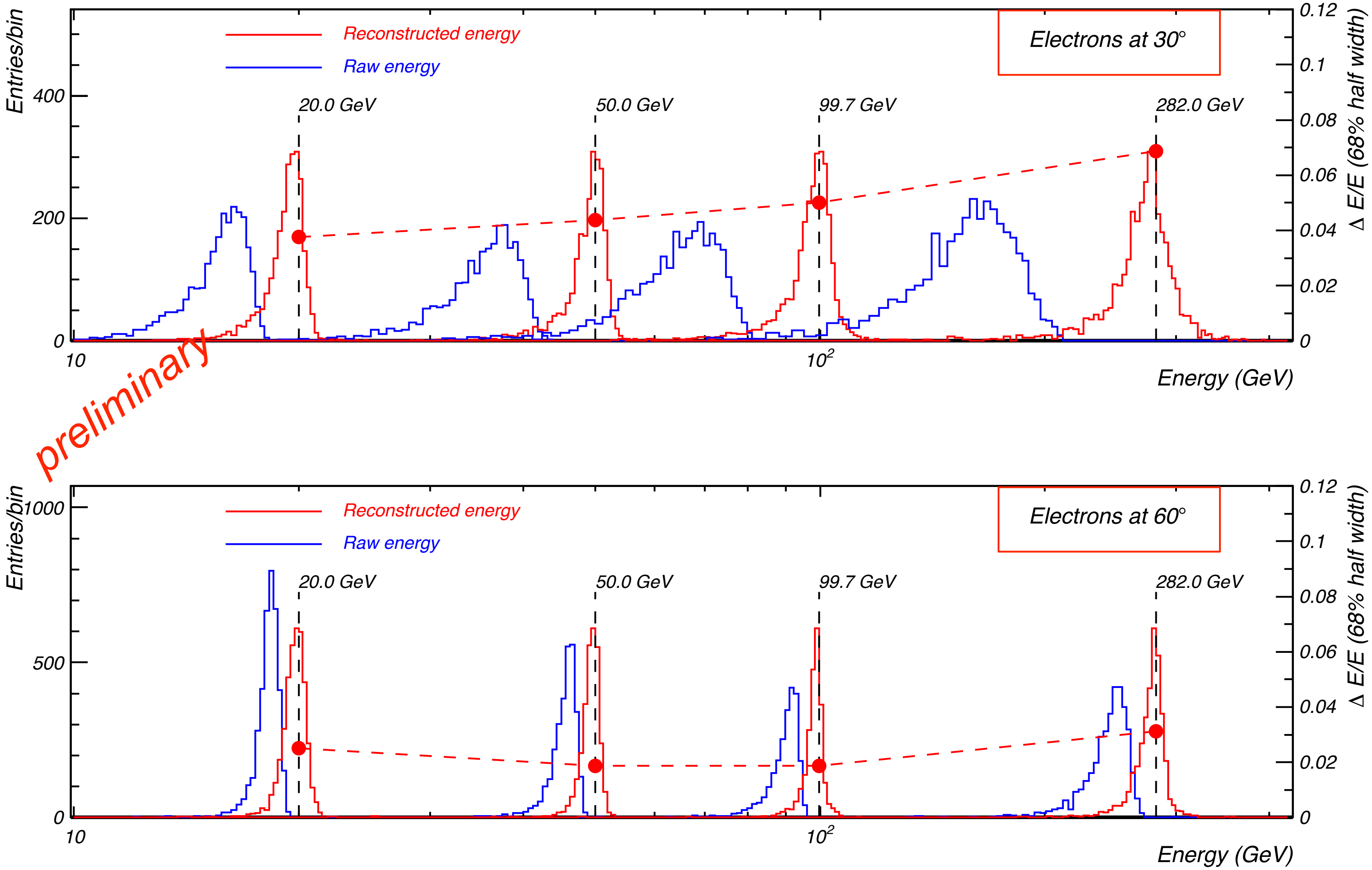
Electron identification

The challenge is identifying the good electrons among the proton background

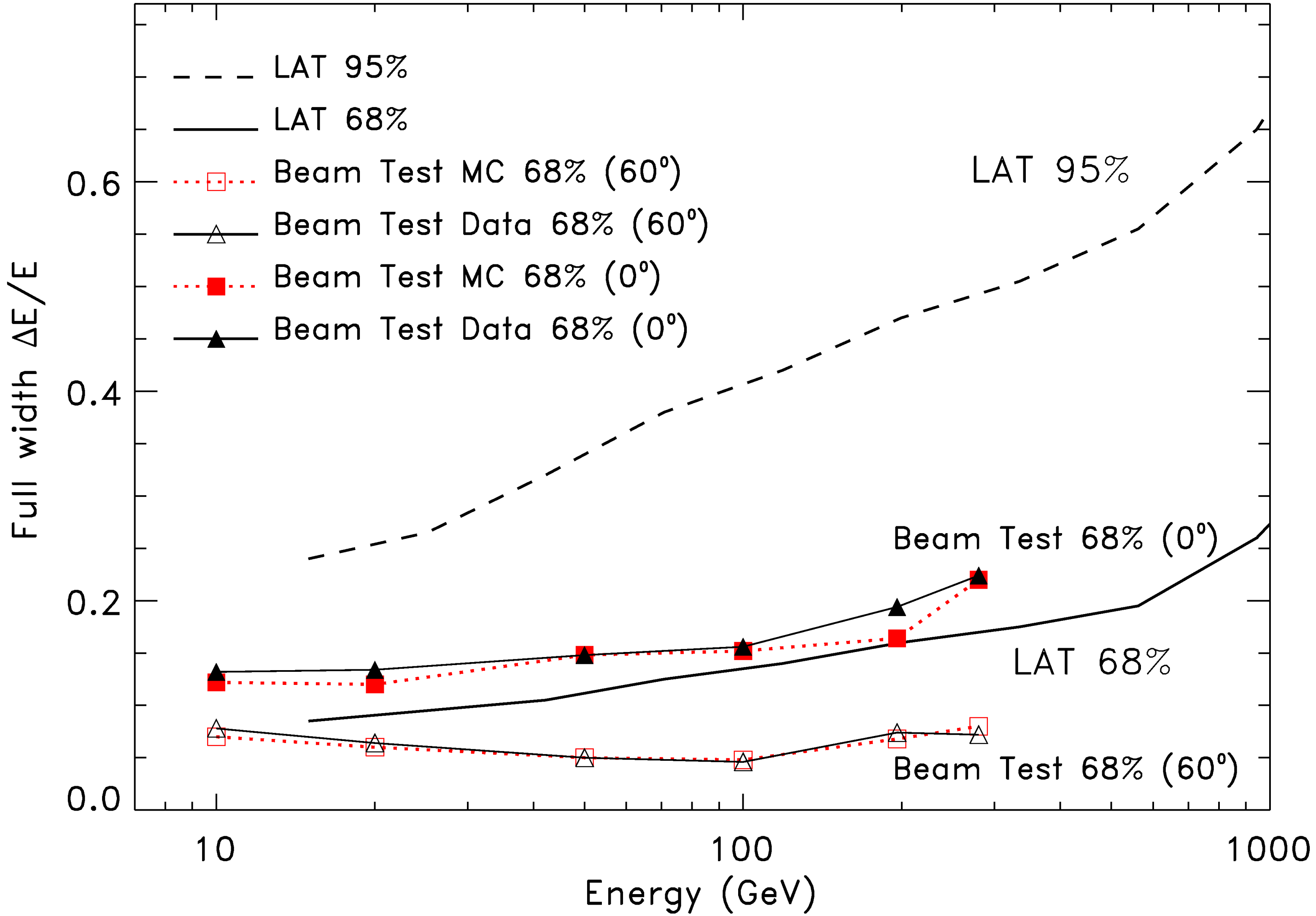
- Rejection power of $10^3 - 10^4$ required
- Can not separate electrons from positrons
- → Dedicated high energy electron event selection

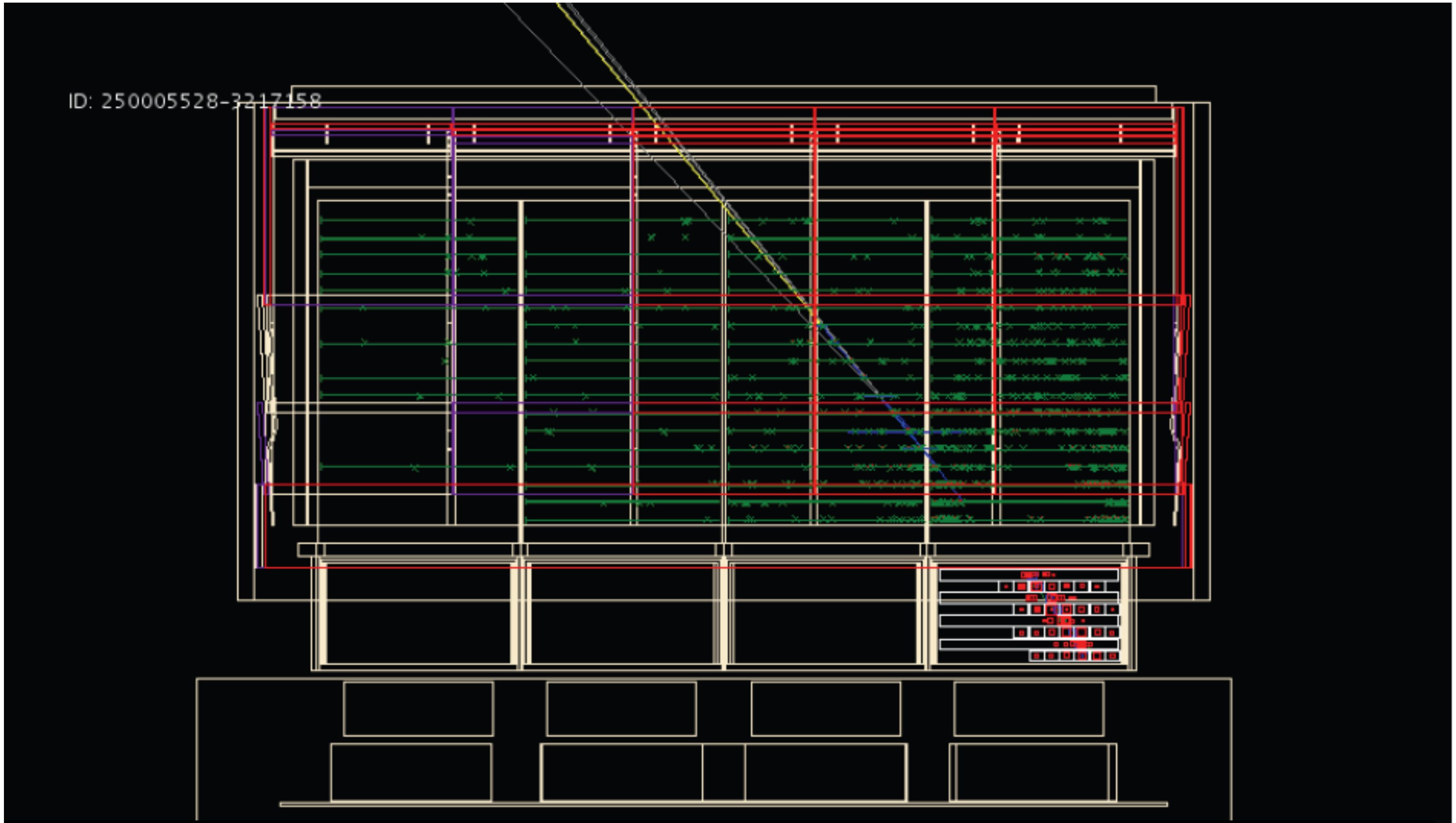


Energy resolution validations with BT electrons



Energy resolution – MonteCarlo vs BT electron data

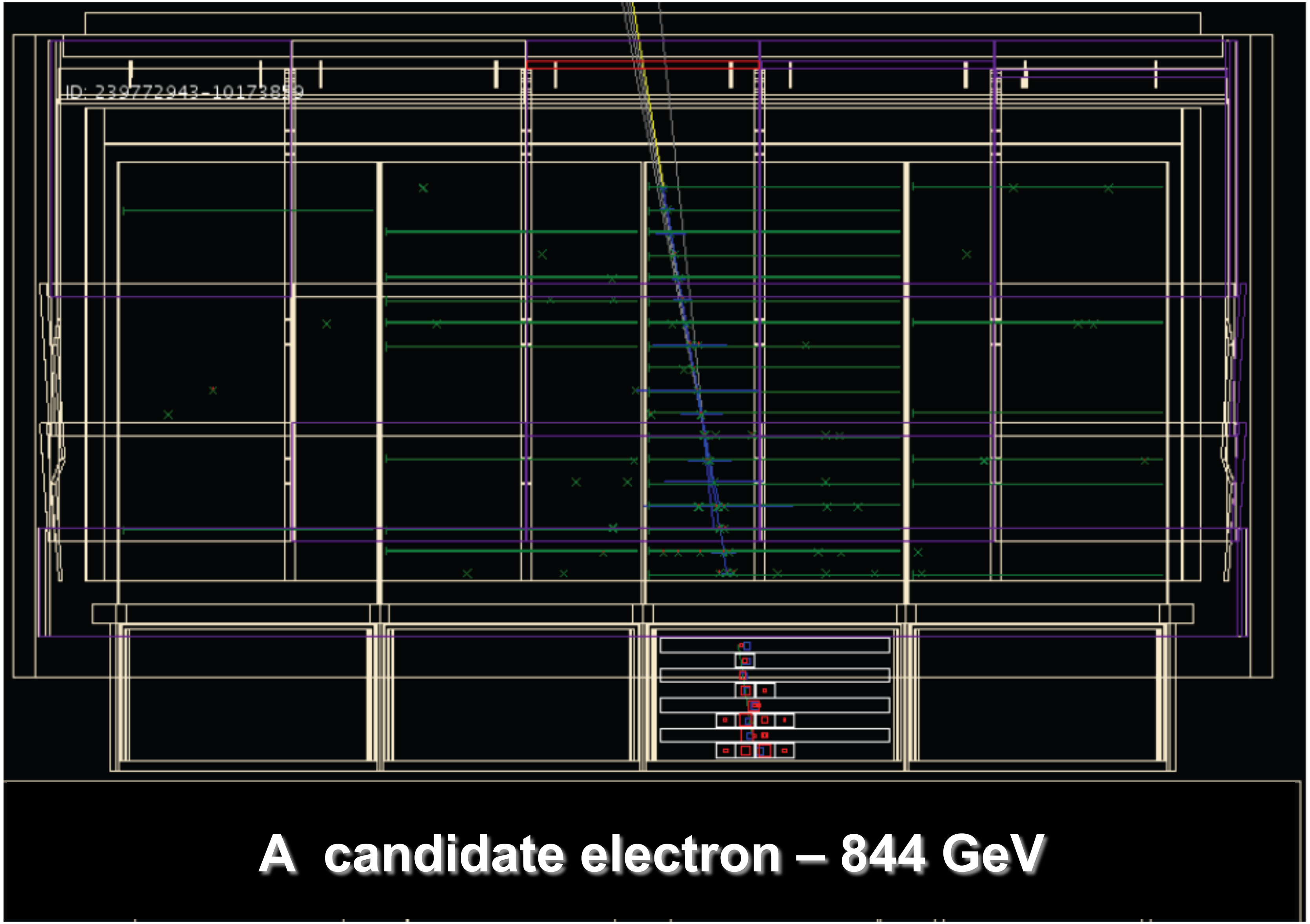




A candidate hadron event – raw energy > 800 GeV

CalEnergyRaw
8.228e+05
CTBBestEnergy
1.026e+06
CTBBestEnergyProb
0.146
TkrNumTracks
5
CalCsIRLn
10.9
CTBBestZDir
-0.387
CTBTKRHEEProb
N/A
CTBCALHEEProb
N/A
CalLRmsAsym
0.00419
CalTrSizeTkrT95
1022.6
CalTransRms
34.4
Tkr1CoreHC
1
Tkr1Hits
6
Tkr1ToTTrAve
0
AcdTotalEnergy
660.7
AcdTileCount
65

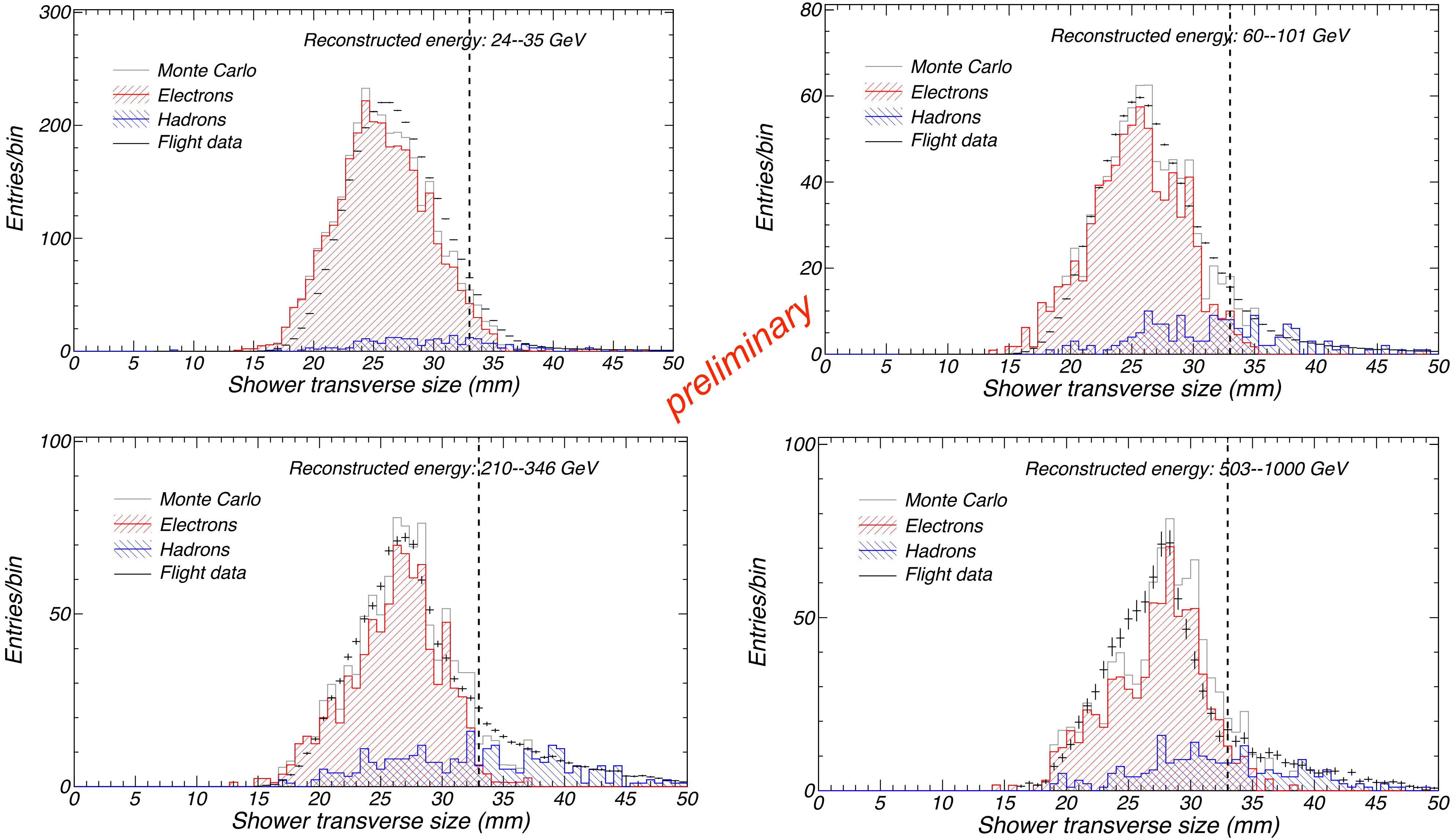
- **ACD: large energy deposit per tile**
- **TKR: small number of extra clusters around main track, large number of clusters away from the track**
- **CAL: large shower size, low probability of good energy reconstruction**



CalEnergyRaw	2.501e+05
CTBBestEnergy	8.443e+05
CTBBestEnergyProb	0.531
TkrNumTracks	5
CalCsIRLn	8.49
CTBBestZDir	-0.986
CTBTKRHEEProb	0.924
CTBCALHEEProb	0.733
CalLRmsAsym	0.0656
CalTrSizeTkrT95	9.73
CalTransRms	23.8
Tkr1CoreHC	29
Tkr1Hits	35
Tkr1ToTTrAve	5.40
AcdTotalEnergy	8.99
AcdTileCount	20

- **ACD: few hits in conjunction with track**
- **TKR: single clean track, extra clusters around main track clusters (preshower)**
- **CAL: clean EM shower not fully contained in CAL**

Shower size data-MC comparison vs energy

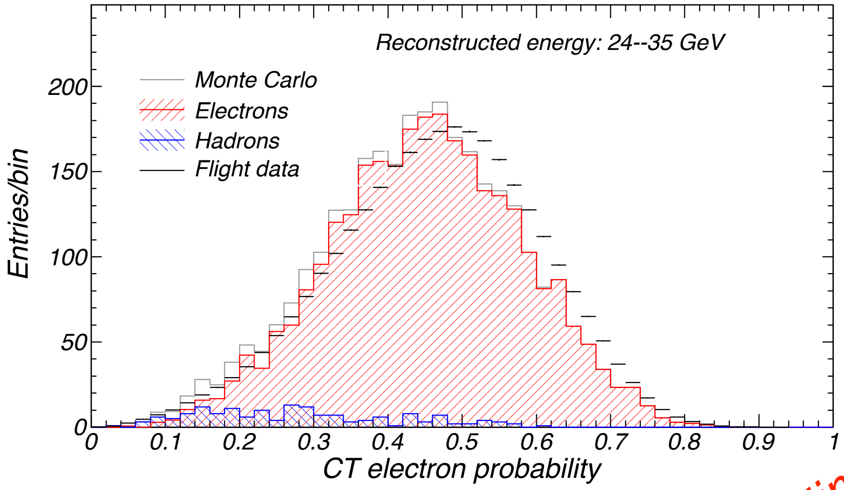


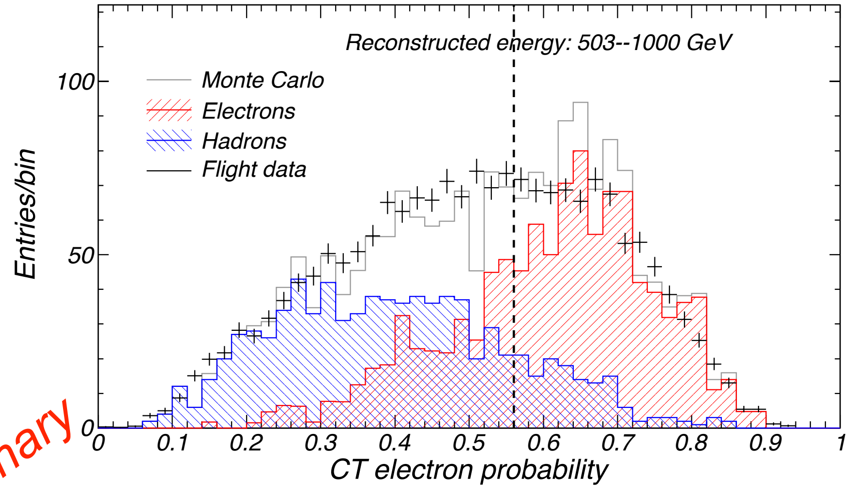
Good agreement over whole spectrum

HE event selection – cutting on CT variable

Energy dependent selection on combined electron probability from CAL and TKR probabilities

$$P^e_{comb} = \mathrm{sqrt}(p^e_{tkr} \times p^e_{cal})$$



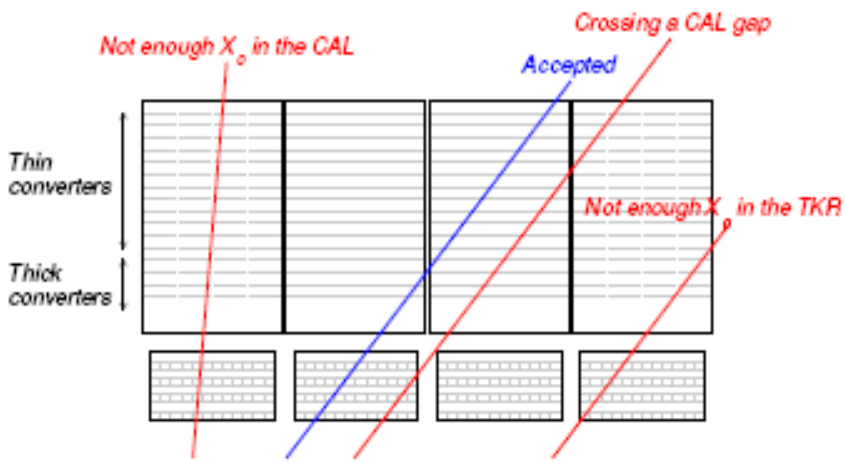


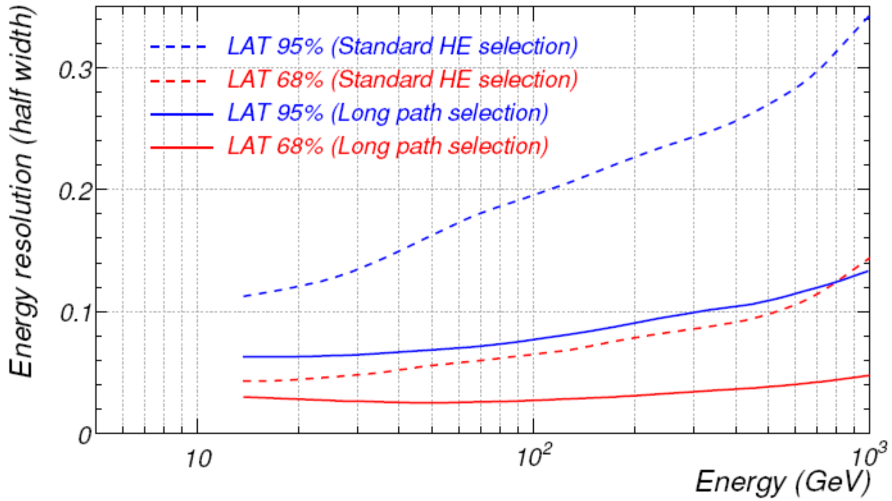
preliminary

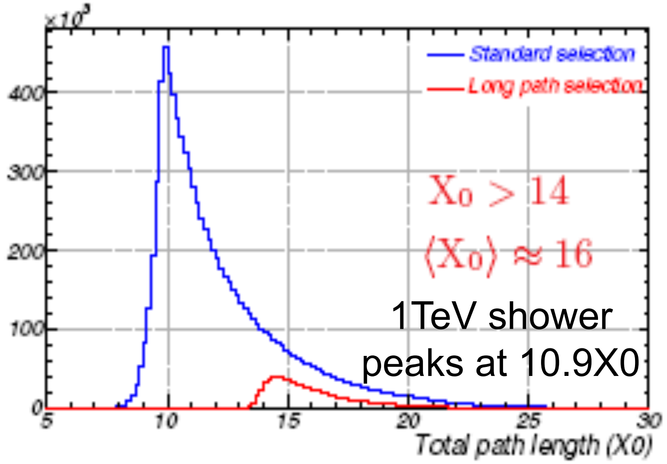
Good agreement over whole spectrum no CT cut need at low energies

Selection optimized for energy resolution

- To prove that we did not miss any spectral feature
- Select event with long path in the cal (in addition to the high energy electron selection)





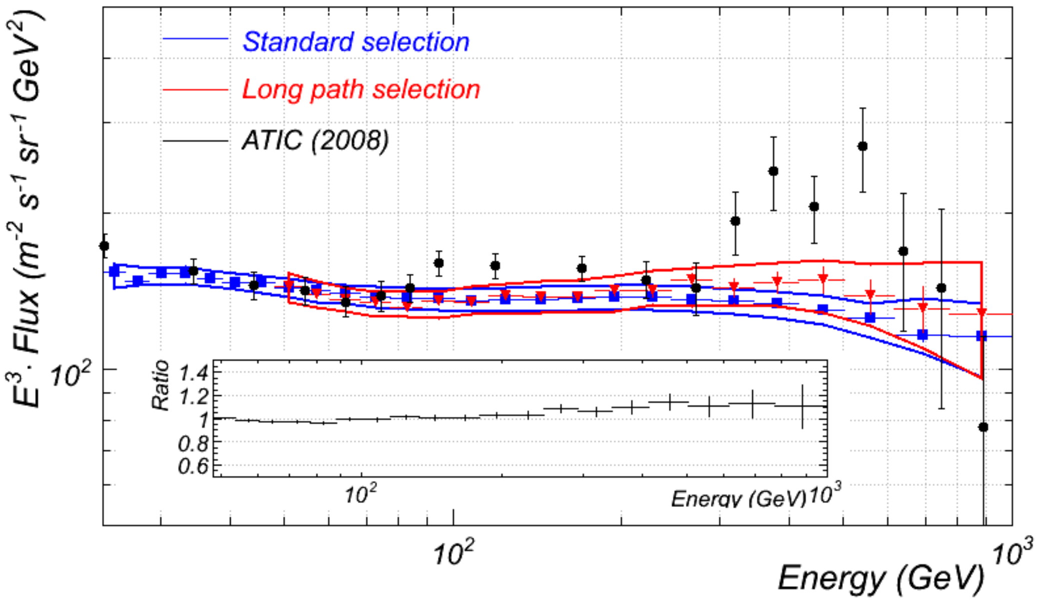


🡅Energy resolution X ~ 2 – 4
- Down to 5% at 1 TeV (68% containment half-width)
- No HE tails

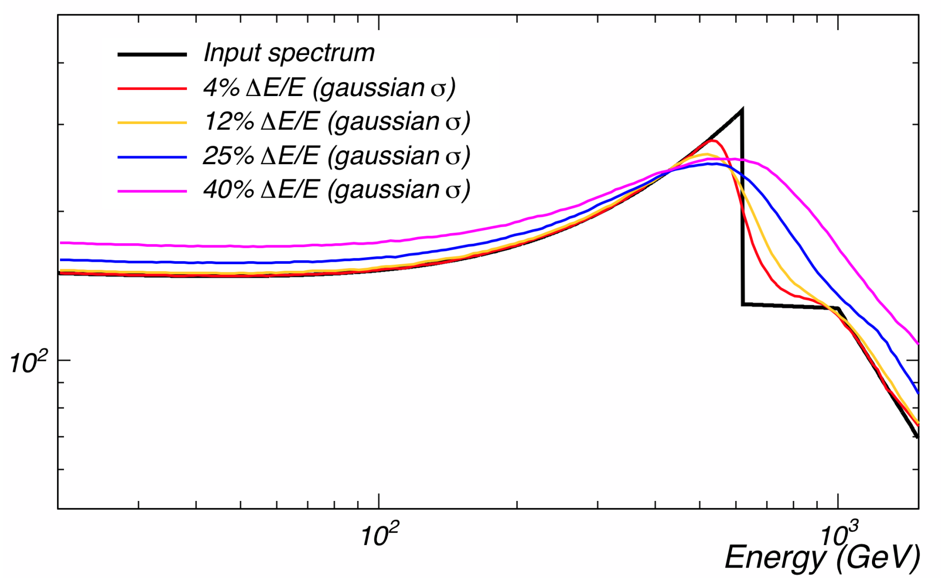
🡇 Instrument acceptance to ~ 5% of standard and limited to a specific portion of instrument phase space
- Much higher systematics

Comparison of standard and High-X0 spectra

- Consistent within their own systematics



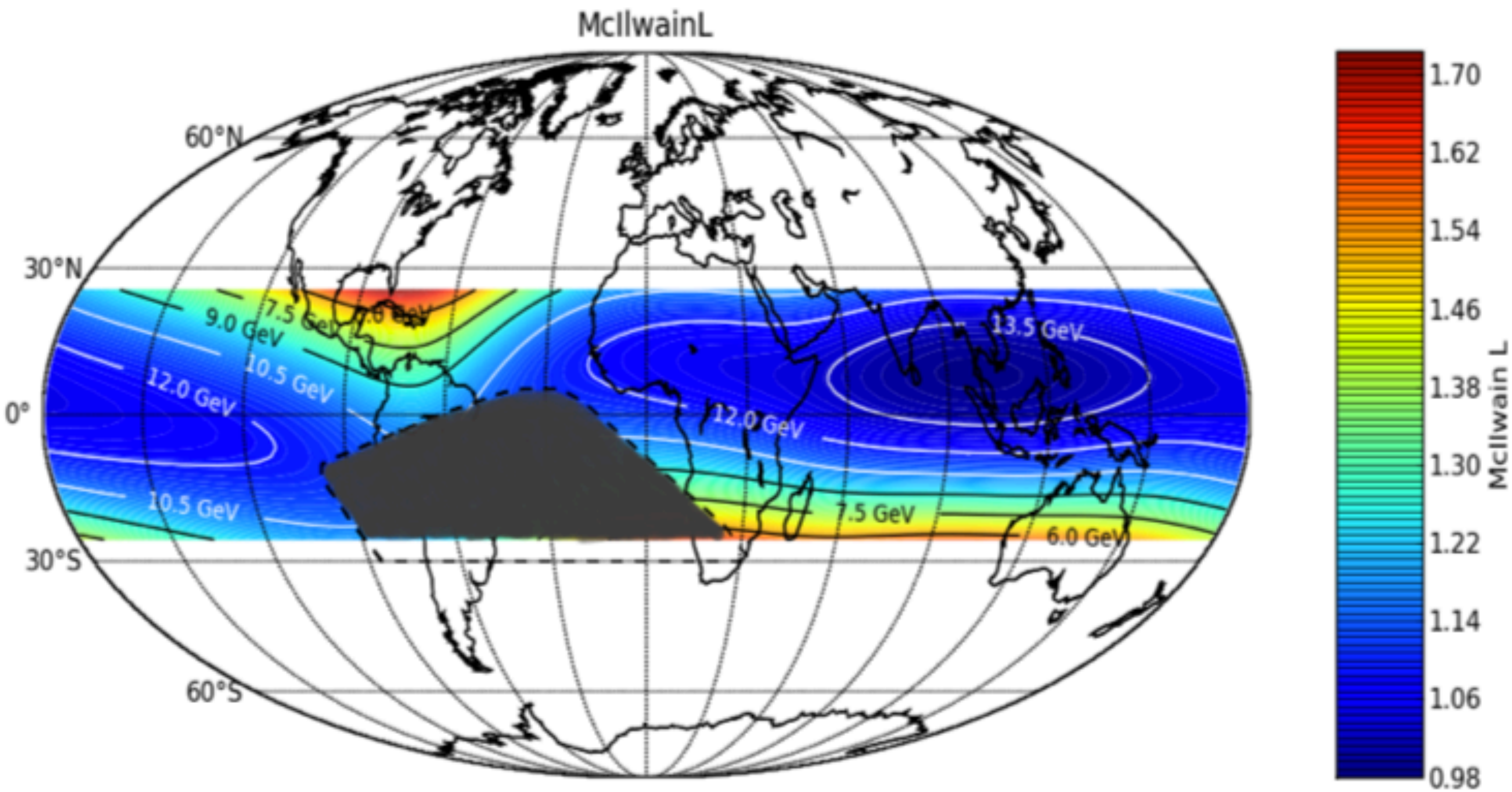
- already demonstrated by simulation of LAT response to spectral features with artificially worsened resolution



➔ the LAT energy resolution is adequate to detect prominent spectral features

➔ the Fermi spectrum is NOT dependent on the energy resolution of the bulk of the events

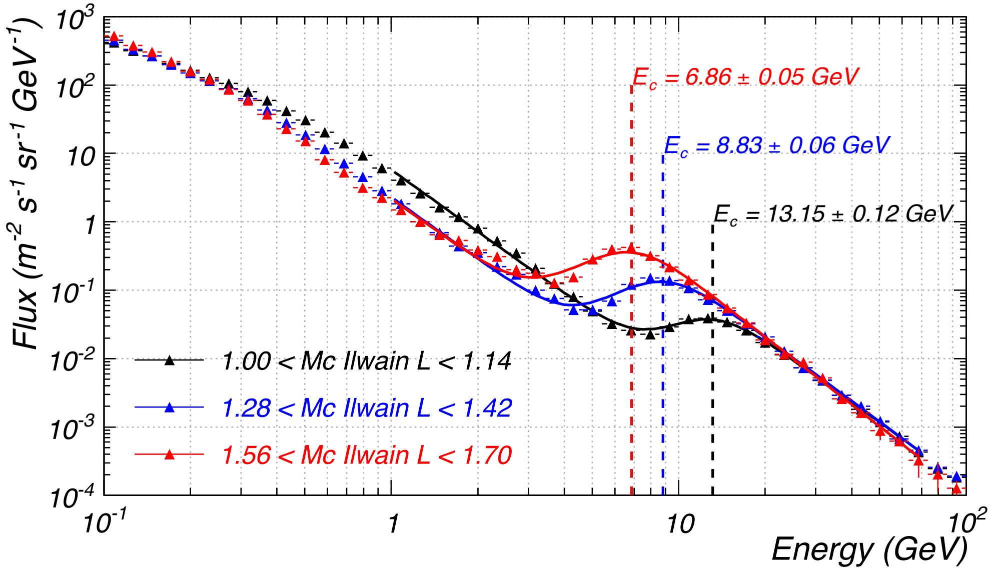
Extension to low energy measurements

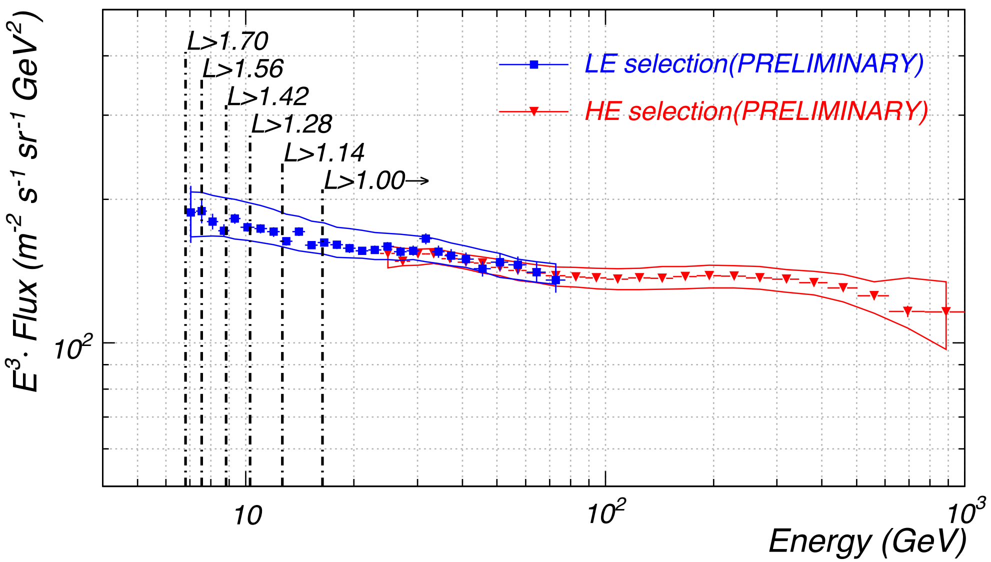


~ 7 GeV is the natural lower limit

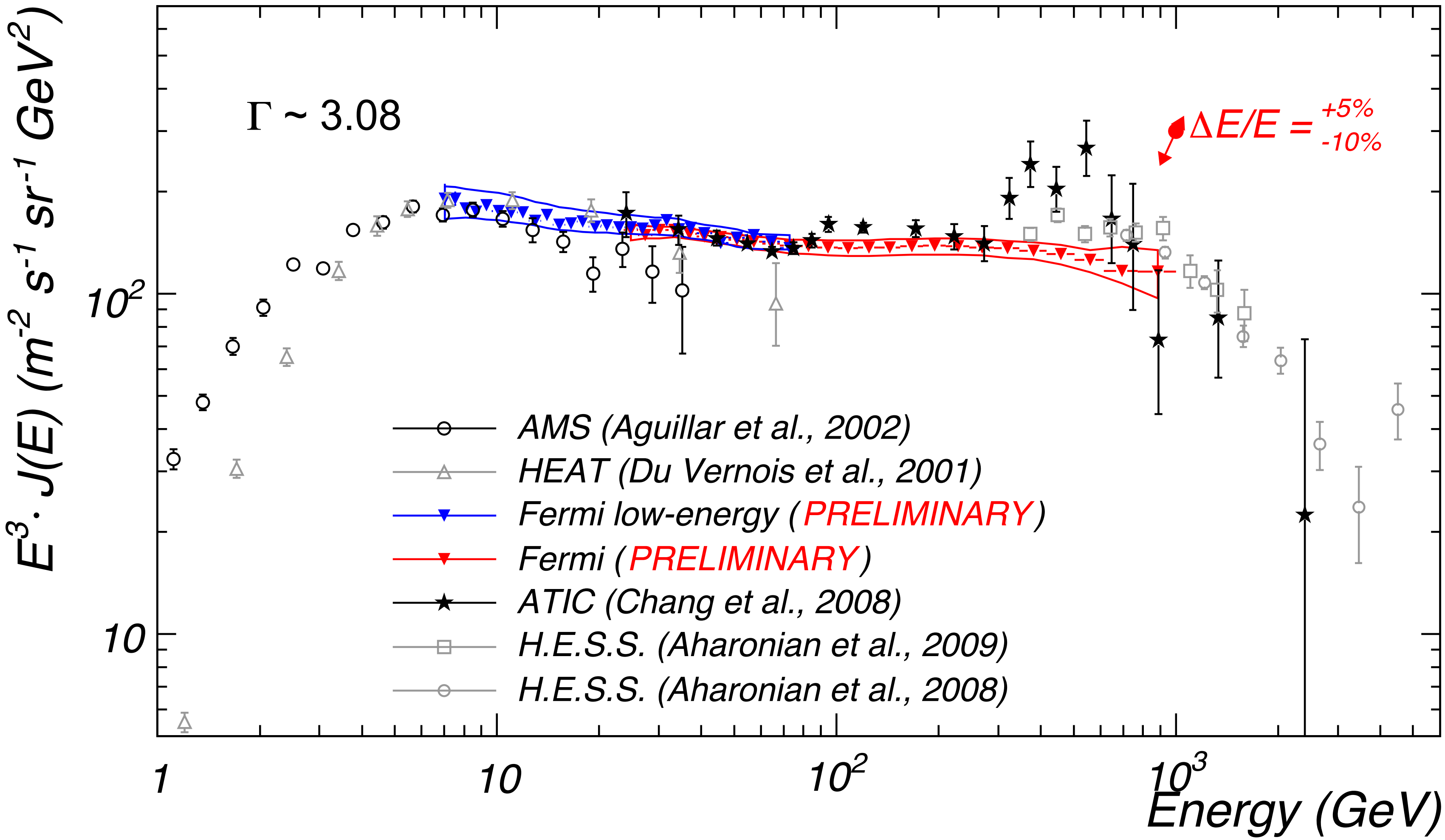
Extension to low energy measurements

- Determine geomagnetic cutoff energy as a function of geomagnetic orbital coordinates
  - Higher McIlwainL, lower cutoff energy
- Measure spectrum for primary component above cutoff
- Recombine spectra into global spectrum

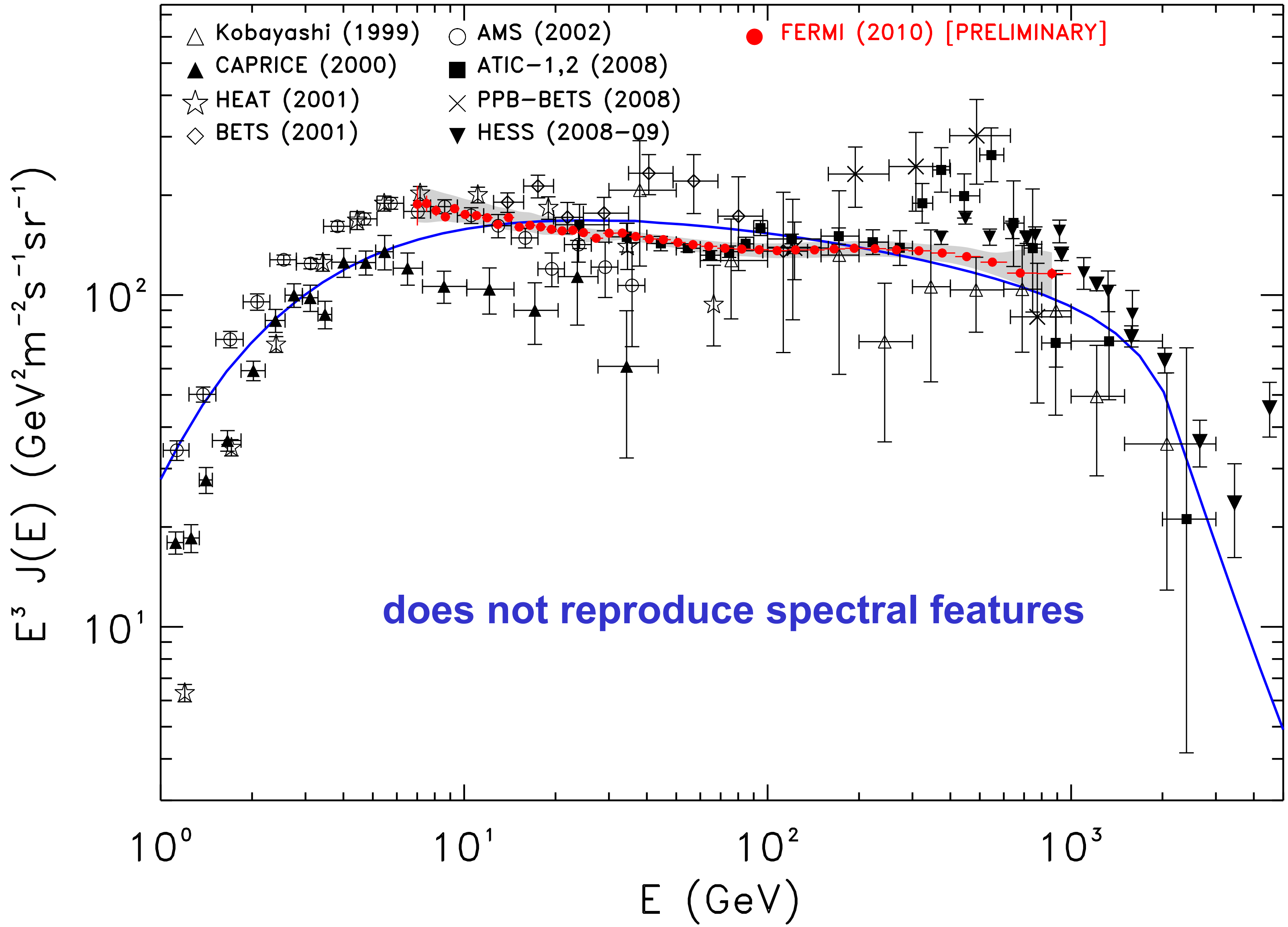




The Fermi CRE spectrum as of Nov. 2009

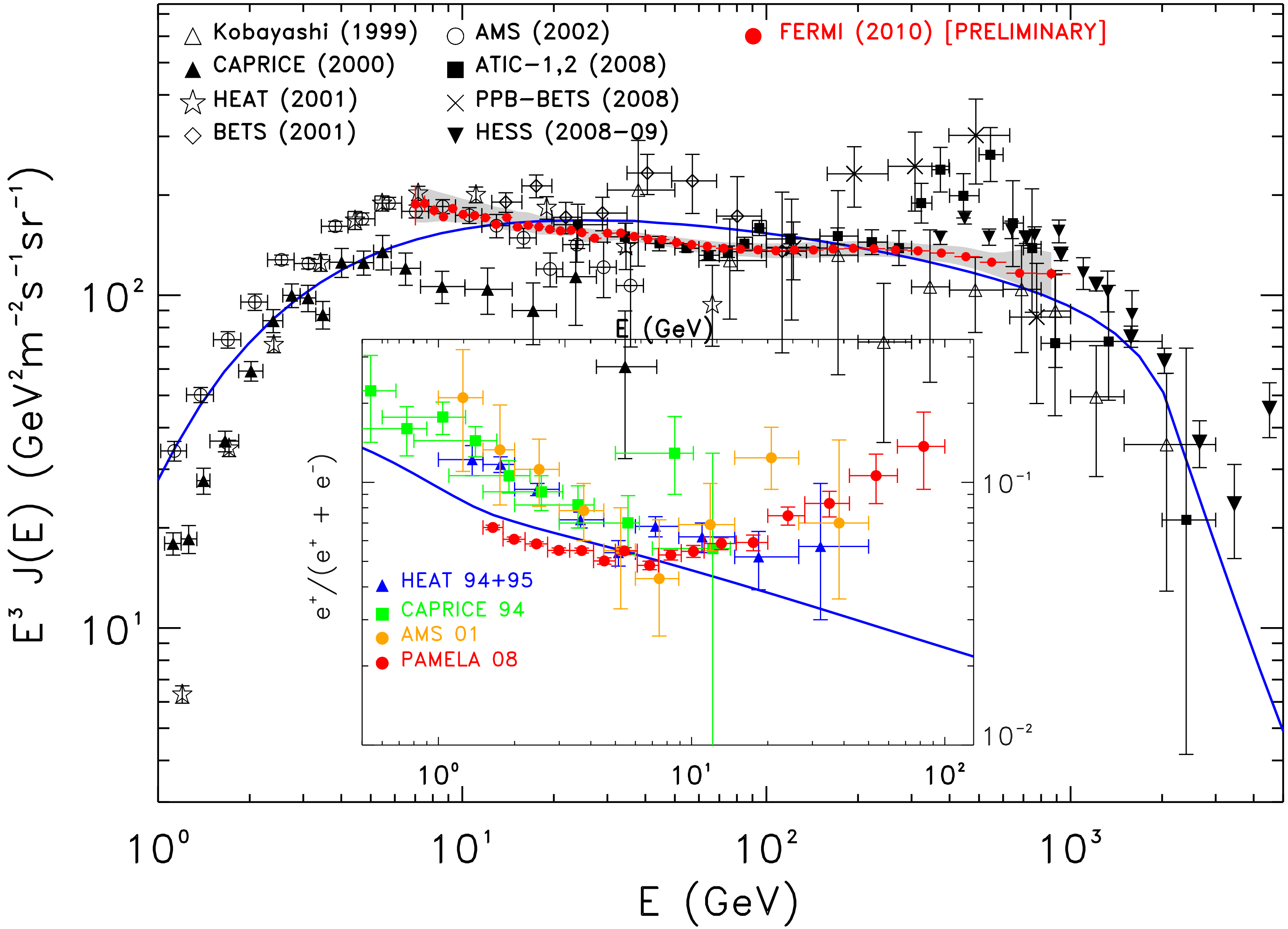


Possible interpretations – diffusive scenario

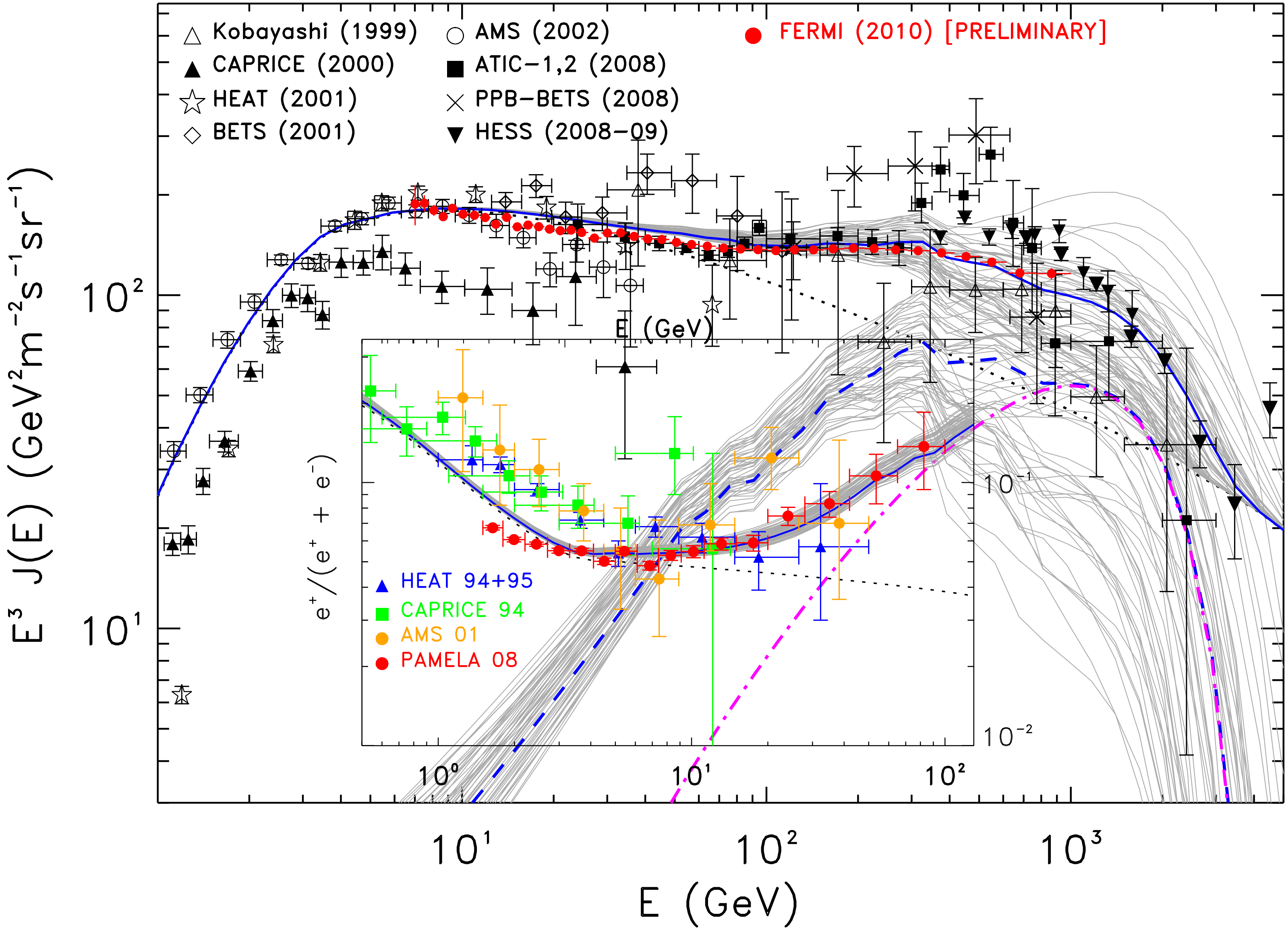


does not reproduce spectral features

Diffusive scenario, CRE and positron fraction

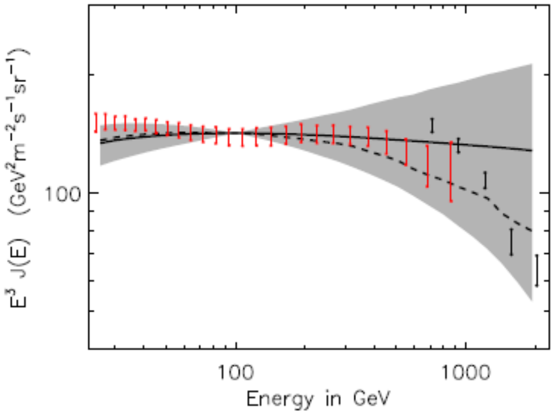


A secondary local CRE source? Pulsar?



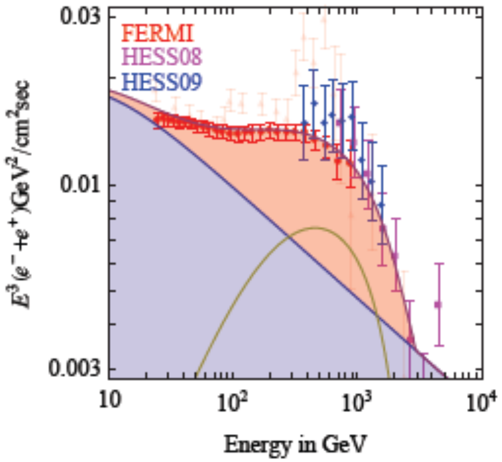
Other possible interpretations? Many !

1) Source stochasticity



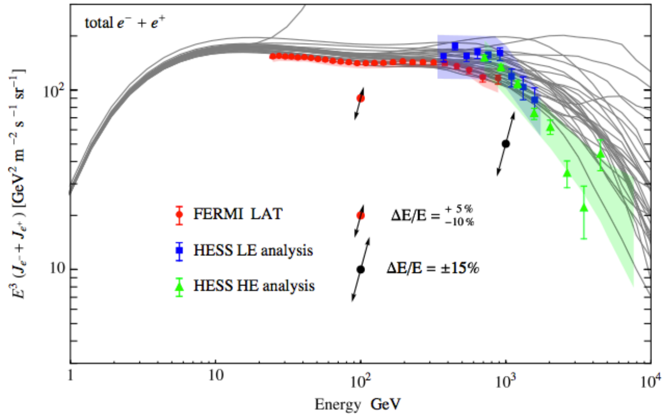
Grasso et al. arXiv 0905.0636

2) Dark Matter



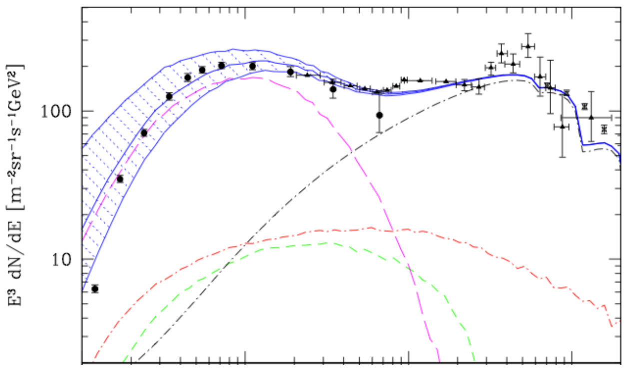
Strumia et al. arXiv 0905.0480

3) Secondary CR acc.



Blasi arXiv 0903.2794
Ahlers et al. arXiv 0909.4060

4) SNR inhomogeneity



Piran et al. arXiv 0902.0376

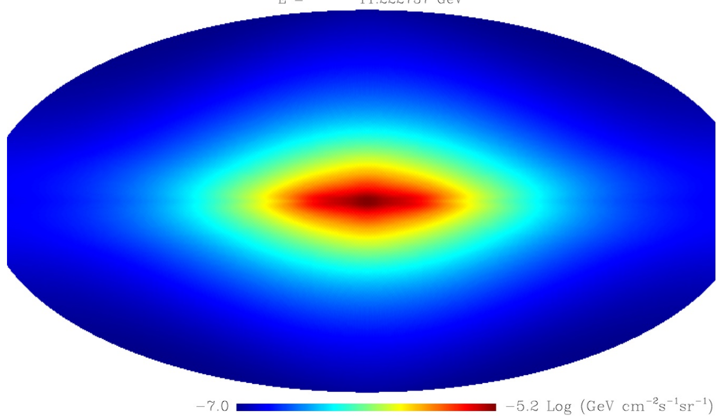
But with specific signatures

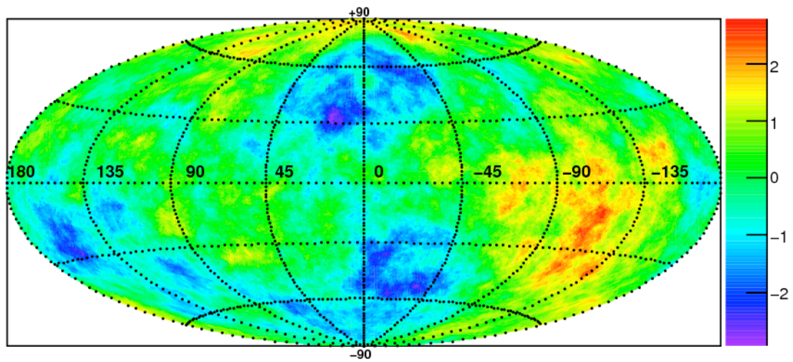
1. Spectral features
2. Excess in diffuse gamma ray emission
3. Rising nuclei ratio (i.e. B/C)
4. Falling positron ratio above 100 GeV

Models Discriminants from Fermi

- **Diffuse gamma-ray emission**
  - **Spectrum**
    - **IC excess from lepton excess**
  - **Shape**
    - **More spherical distribution for DM wrt PSR**
- **Measure CRE anisotropies**
  - **Tracer of local sources of electrons**
    - **Currently no evidence for anisotropy**

IC diffuse gammas from DM halo – GALPROP sim

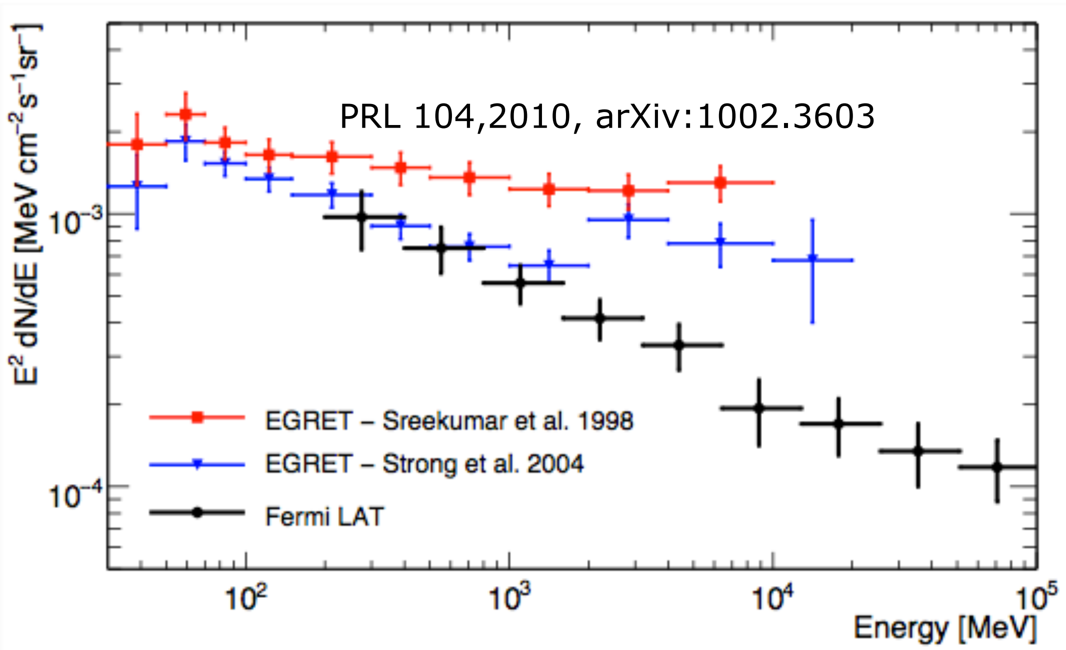


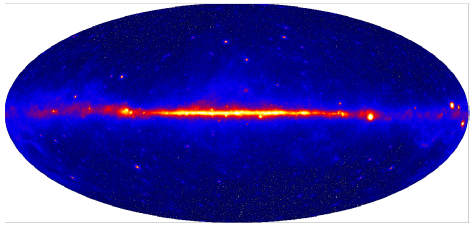


CRE anisotropy pre-trial significance map

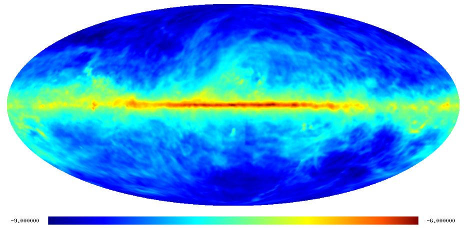
The new Fermi EGB

- **Simultaneous Maximum Likelihood fit to all |b|>10° sky with:**
  - **Equal area pixels (0.8 deg2)**
  - **Sky models compared to LAT data**
  - **All sources detected in 9-month**
  - **9 energy bind, 200 MeV<E< 100 GeV**
  - **10 months of LAT data, 19 Ms exposure**

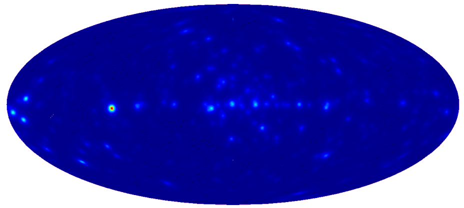




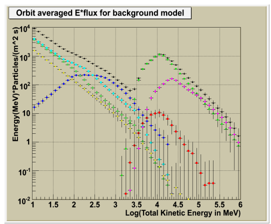
γ-ray sky



Galactic diffuse model



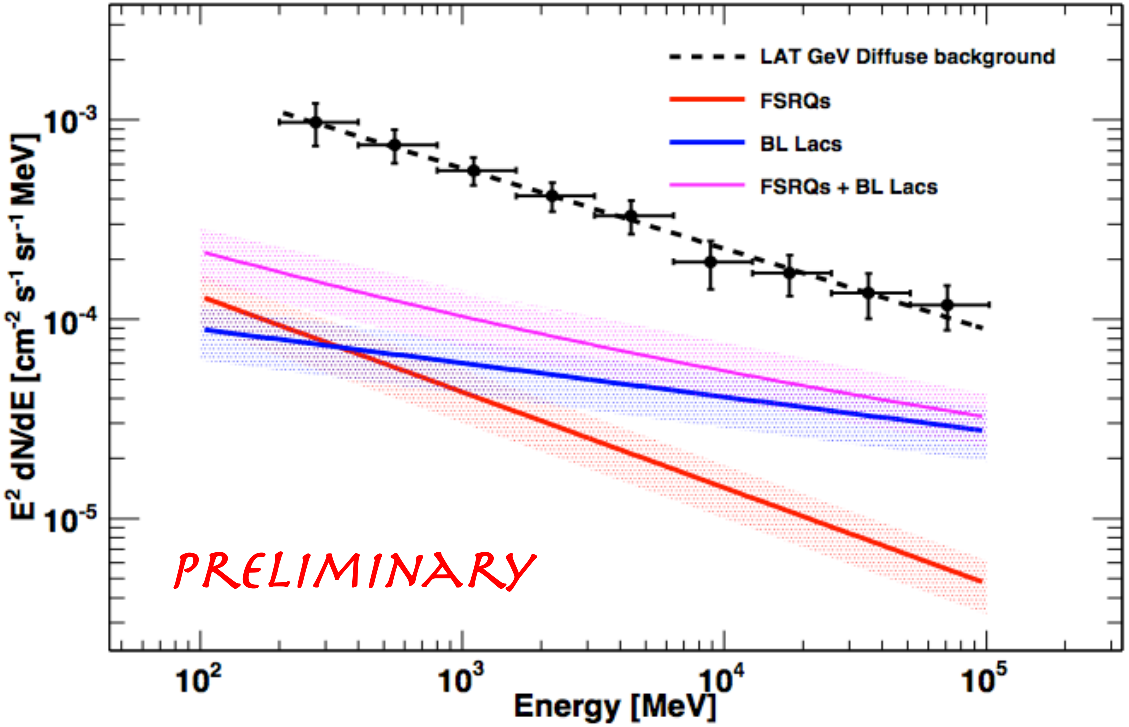
Known sources



Residual instrumental bkg

FSRQ and BL Lacs

BL Lacs dominate at high-E (caveat: broad band analysis)



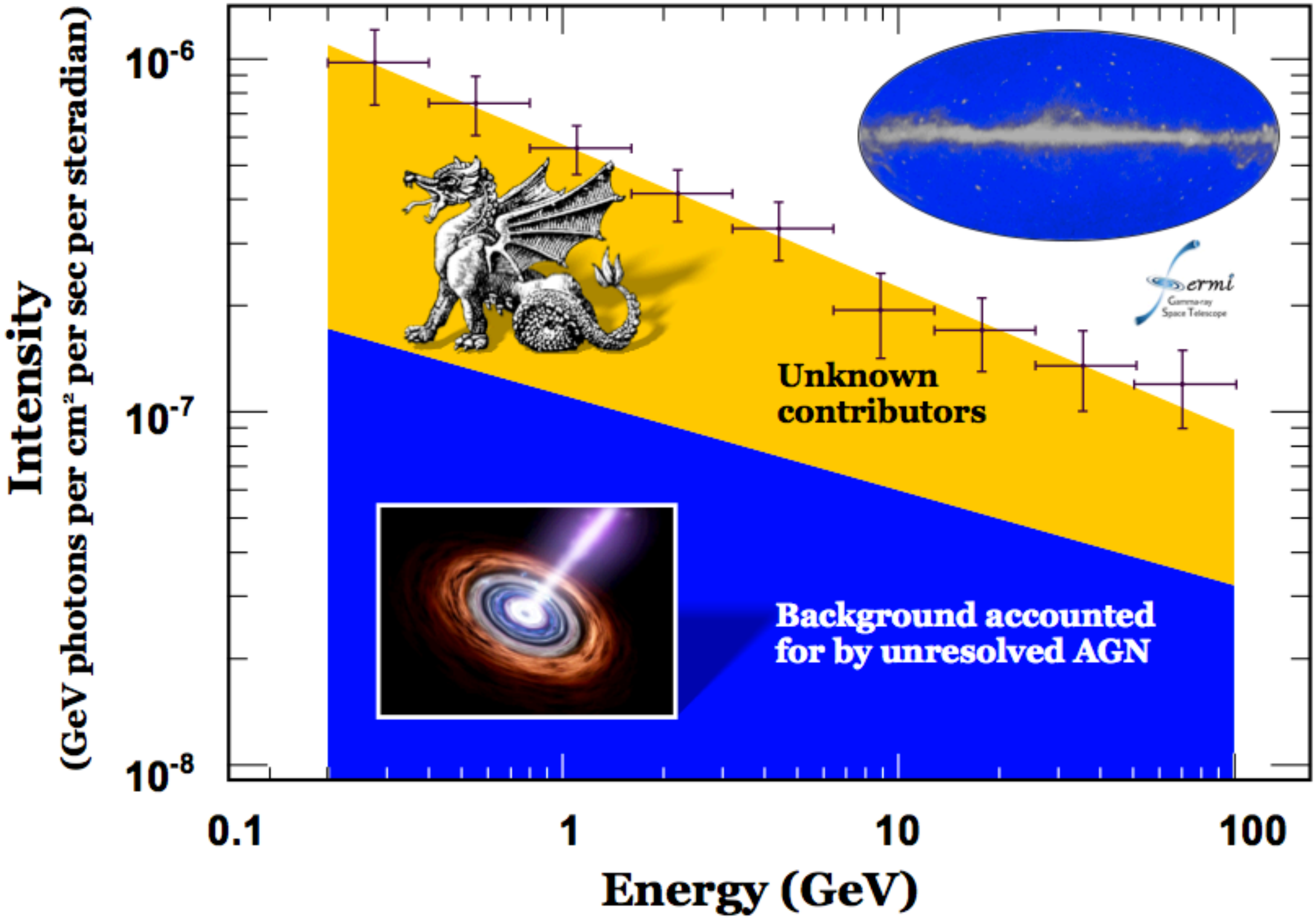
LAT EGB in the 0.2-100 GeV band: consistent with $E^{-2.4}$

Blazars account for <30% of the EGB

BL Lacs dominate diffuse emission E>10 GeV

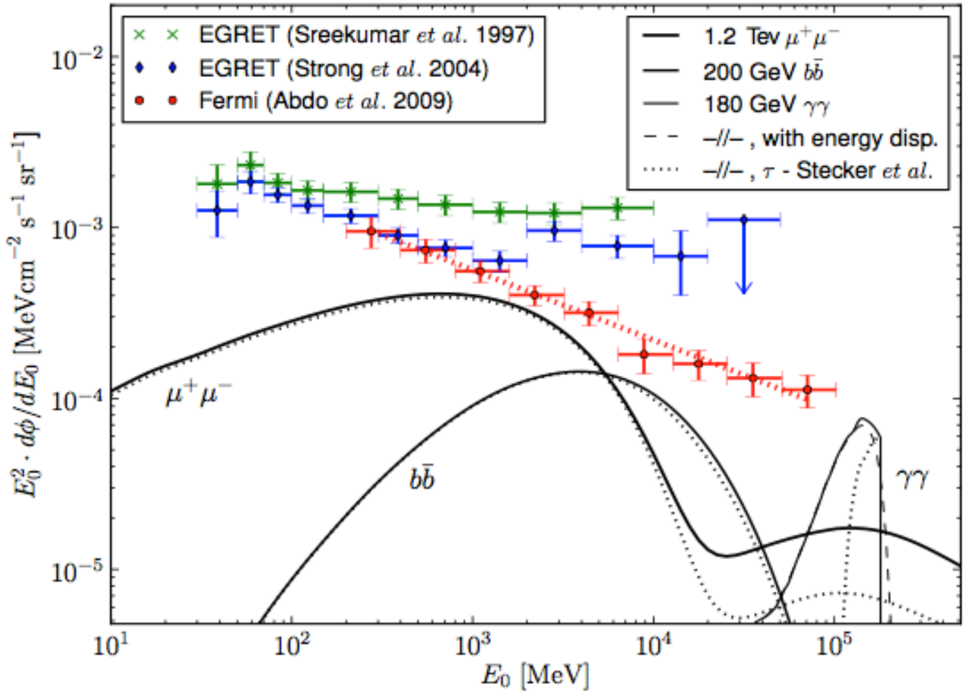
70% of the EGB currently unexplained

Fermi LAT Extragalactic Gamma-ray Background

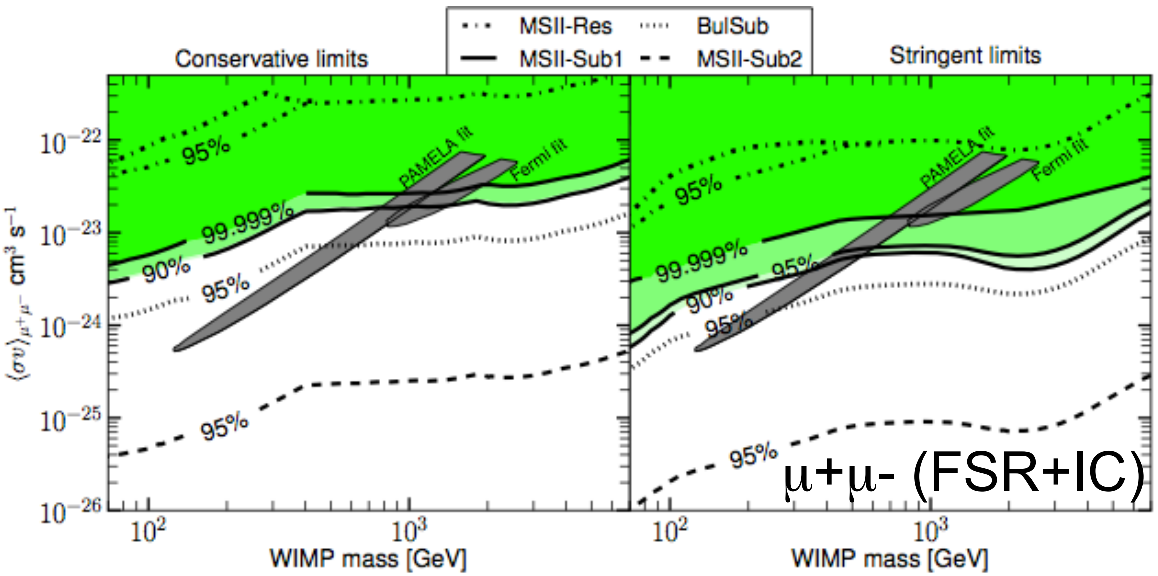


Constraints on Cosmological DM

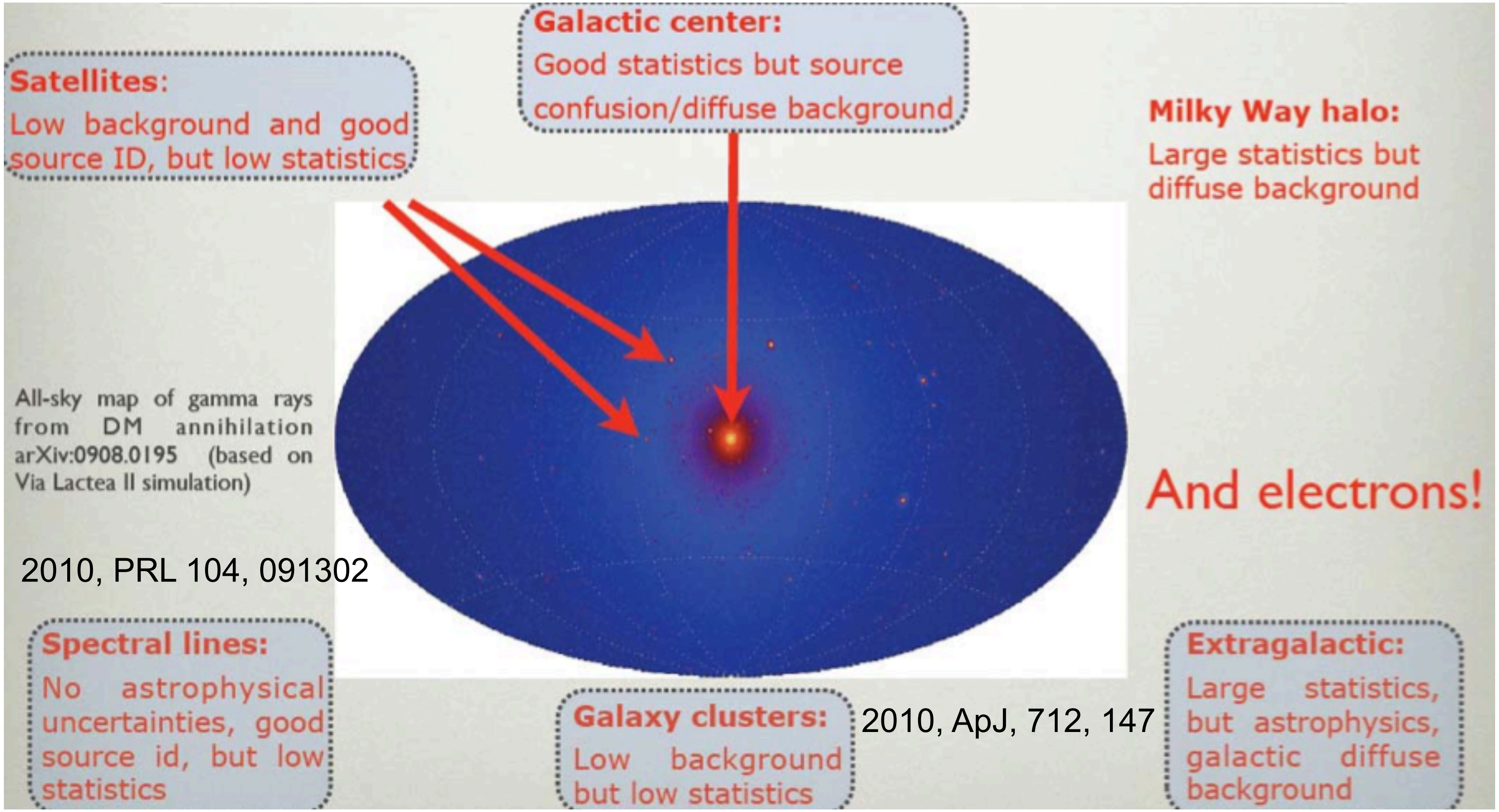
- Search for a DM signal from all halos at all redshifts
- Limits from Fermi EGB
- Predictions affected by
  - DM distribution
  - γ-ray opacity



- Under reasonable assumptions can exclude most DM models explaining CR lepton excess from Fermi and Pamela

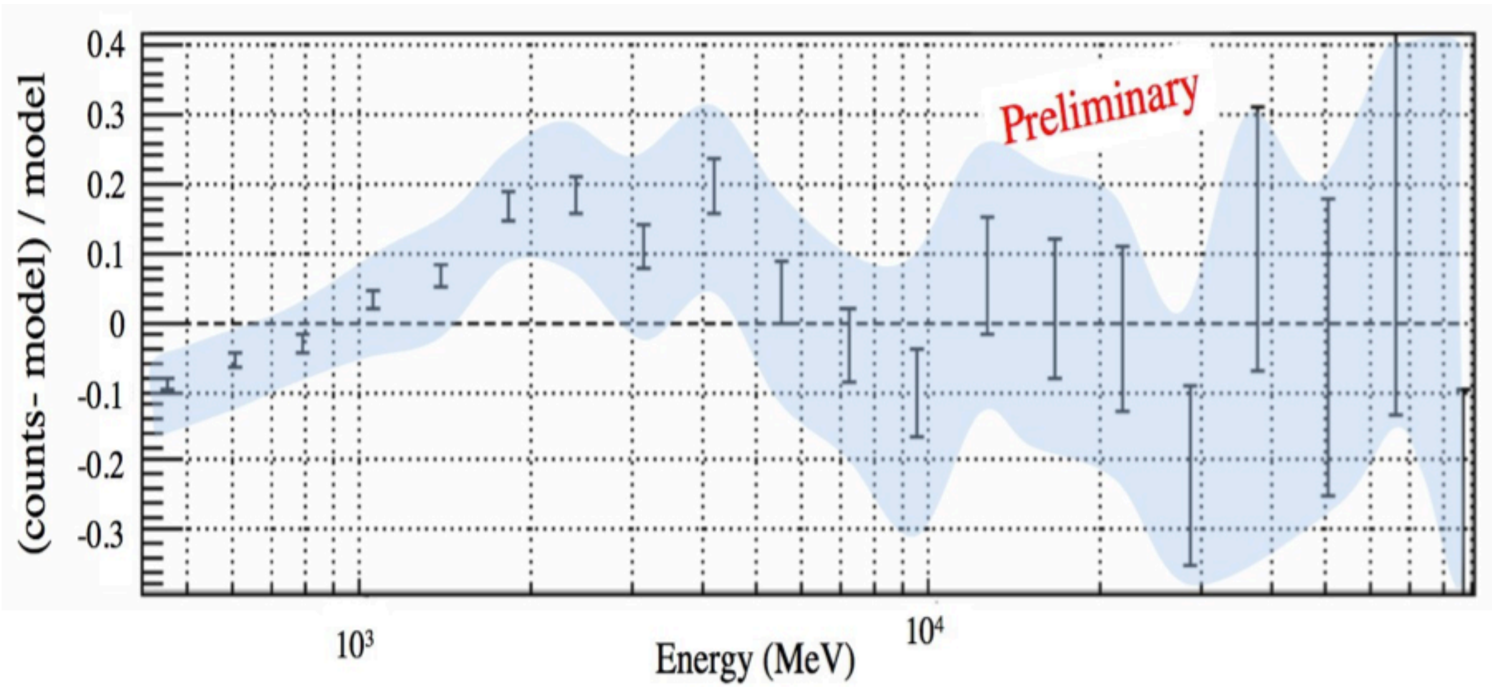


Indirect Dark Matter detection - active searches



- **No detection so far, but**
- **Upper limits start cutting into interesting parameter space**
  - **$<\sigma v> \sim 10^{-25}$ cm^{3}s^{-1} from Dwarph Spheroidal and cluster searches**

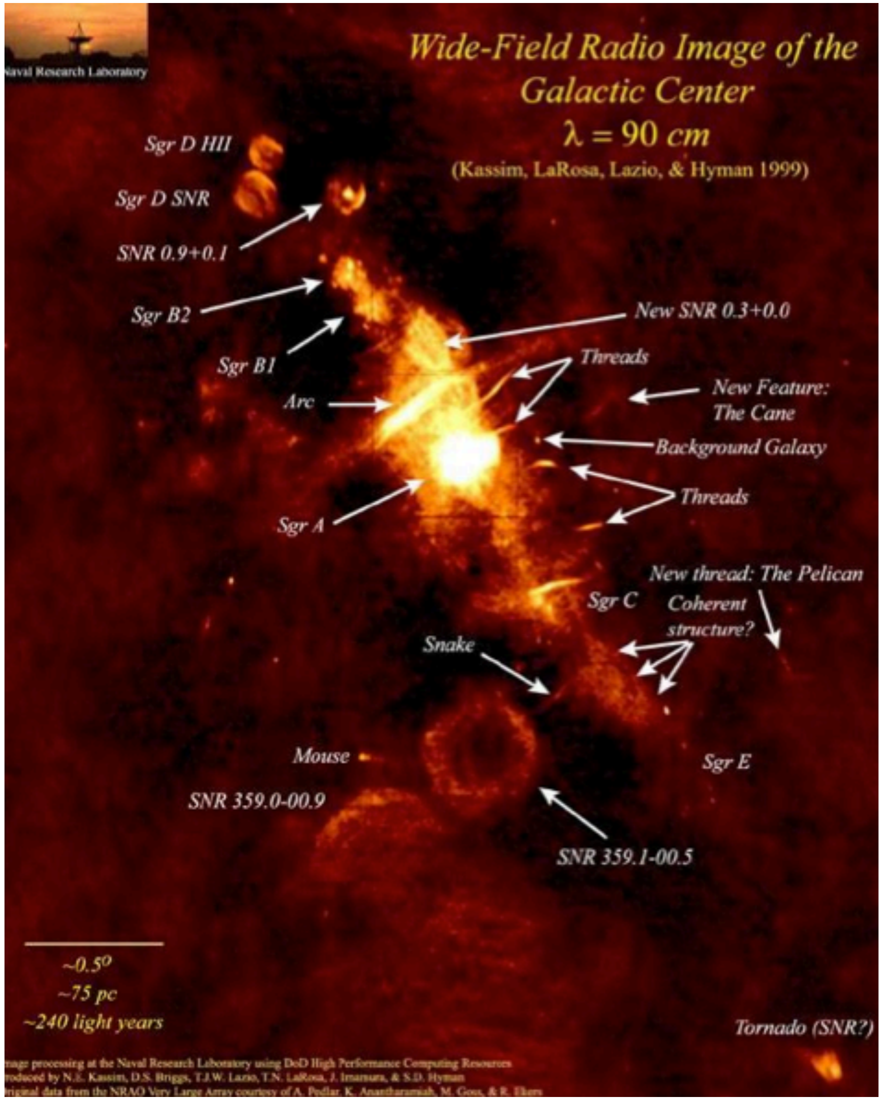
The Galactic Center



- ❑ **Likelihood analysis of 7°x7° region around GC**
- ❑ **GALPROP model: residuals show model under-predicts data in the few GeV range (spatial residuals under investigation)**
- ❑ **In a 3° region around the GC, the largest residual in the same energy range is ~40%, a ~2σ effect (sources not subtracted)**

Fermi LAT Symposium, arXiv:0912.3828

But the GC is a Hell's kitchen



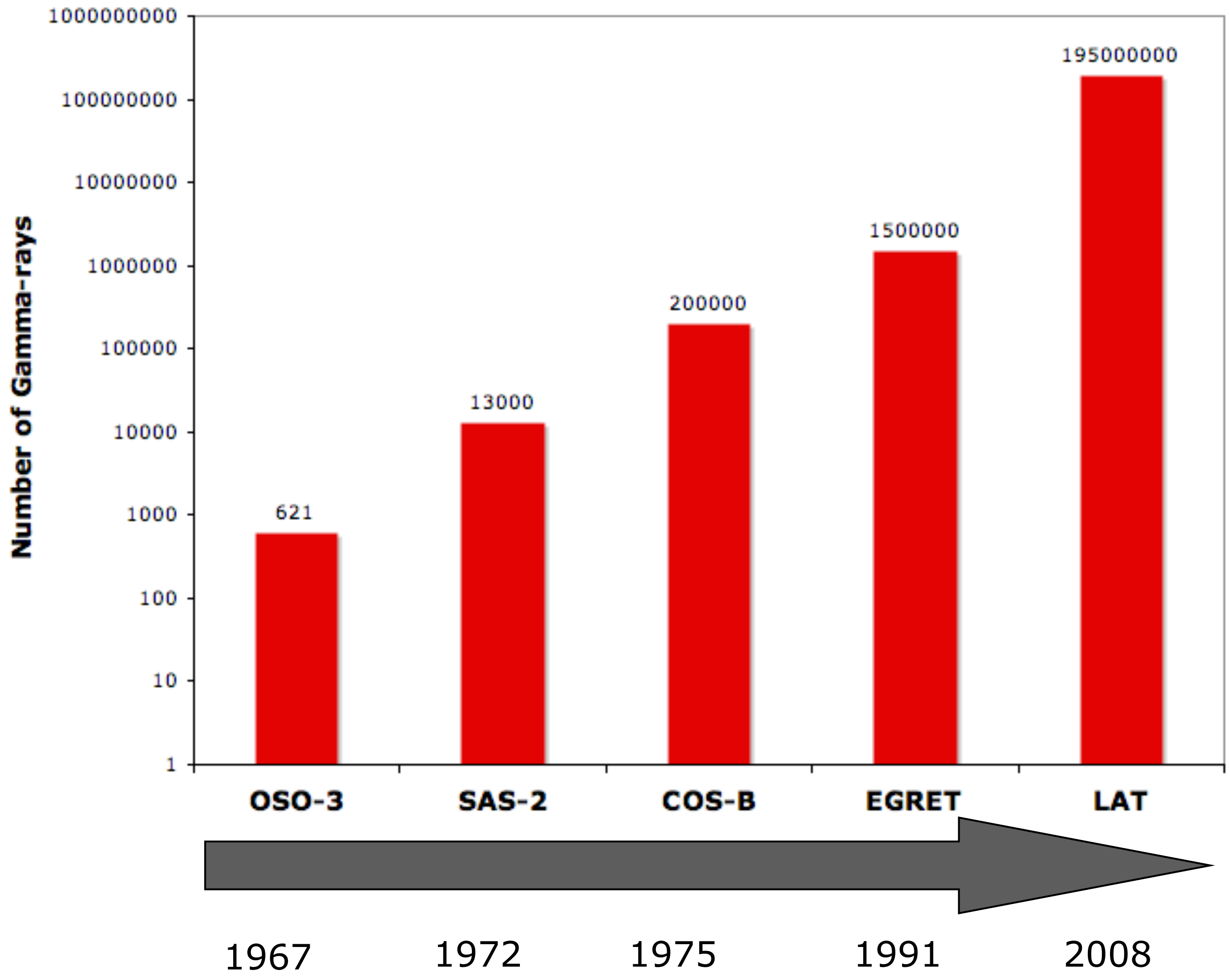
- ❑ One of the most complex regions in the sky!
  - Many sources
  - Diffuse radiation (much likely from unresolved sources)
- ➢ ***Caveat: any attempt to disentangle a potential Dark Matter signal from the Galactic Center region requires deep understanding of the conventional astrophysics background***

Conclusions and prospects

- The first 2 years of Fermi-LAT observations have changed our view of the high energy Universe
  - 1000+ new sources
  - Insight into engines powering known source classes
  - New classes of γ-ray emitters
  - High resolution measurements of galactic and isotropic diffuse emission
  - High resolution measurement of the CRE spectrum from 7 GeV to 1 TeV
- Hard CRE spectrum requires revision of standard paradigm of CR generation, diffusion and propagation
- Best constraints on Dark Matter can be obtained by combining e and γ observations from Fermi
  - On-going work on improving LAT observational capabilities will be key

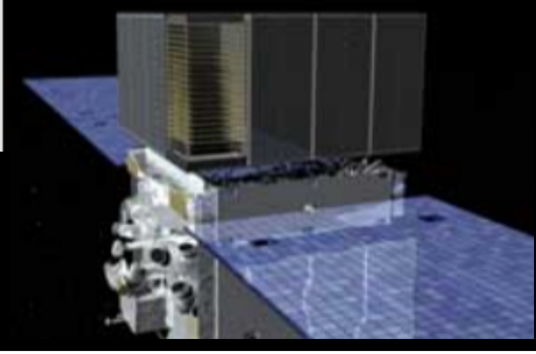
BACKUP

How many gammas?



NASA's Fermi Explores High-energy *Space Invaders*

Since its launch last June, NASA's Fermi Gamma-ray Space Telescope has discovered a new class of pulsars, probed gamma-ray bursts and watched flaring jets in galaxies billions of light-years away. Today at the American Physical Society meeting in Denver, Colo., Fermi scientists revealed new details about high-energy particles implicated in a nearby cosmic mystery.



Physics: Cosmic light matter probes heavy dark matter

May 4, 2009

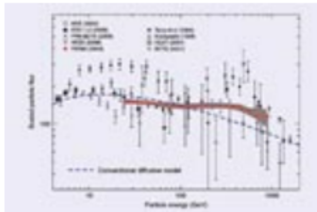
New results from the Fermi Gamma-Ray Space Telescope, the most precise to date in the energy range 20 GeV to 1 TeV, should help resolve whether cosmic rays composed of the lightest charged particles, i.e., electrons and positrons, come from dark matter or some other astrophysical source.

[Viewpoint on Phys. Rev. Lett. **102,** 181101 (2009)]

CERN COURIER

Jun 8, 2009

Fermi measures the spectrum of cosmic-ray electrons and positrons



Spectrum

The Fermi Gamma-Ray Telescope can find out about more than gamma rays. It has now provided the most accurate measurement of the spectrum of cosmic-ray electrons and positrons. These results are consistent with a single power-law, but visually they suggest an excess emission from about 100 GeV to 1 TeV. The additional source of electrons and positrons could come from nearby pulsars or dark-matter annihilation.

SLAC today

High-energy Electrons Could Come from Pulsars—or Dark Matter

by Michael Wall

Something in our galactic neighborhood seems to be producing large numbers of high-energy electrons, according

An artist's conception of the Fermi Gamma-ray Space Telescope. (Image: NASA.)

Lights Out for Dark Matter Claim?

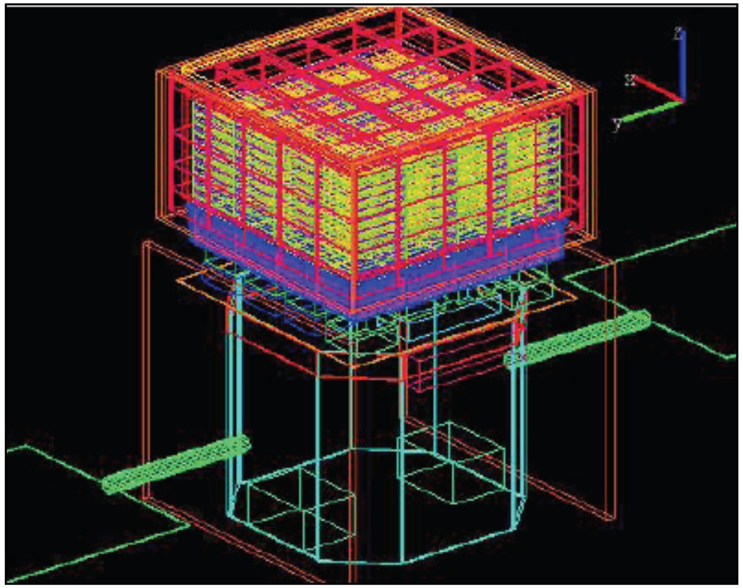
By Adrian Cho
*Science*NOW Daily News
2 May 2009

Last November, data from a balloon-borne particle detector circling the South Pole revealed a dramatic excess of high-energy particles from space--a possible sign of dark matter, the mysterious substance whose gravity seems to hold our galaxy together. But satellite data reported today stick a pin in that

+ Enlarge Image

Event Simulation and Reconstruction

- Very accurate Monte Carlo
  - >45k active volumes
  - Geant4 optimized physics
- Simulation is key for
  - Reconstruction tuning
  - Event selection and performance
  - Estimate residual contamination

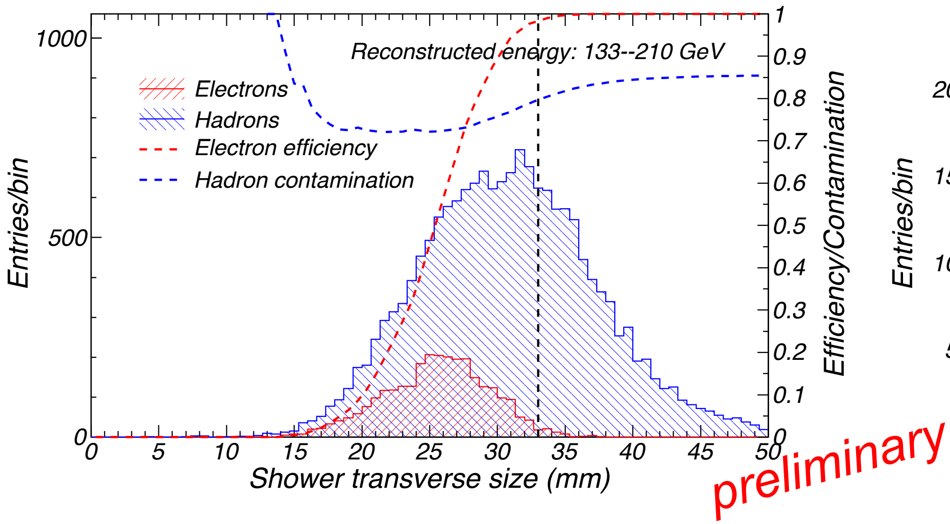


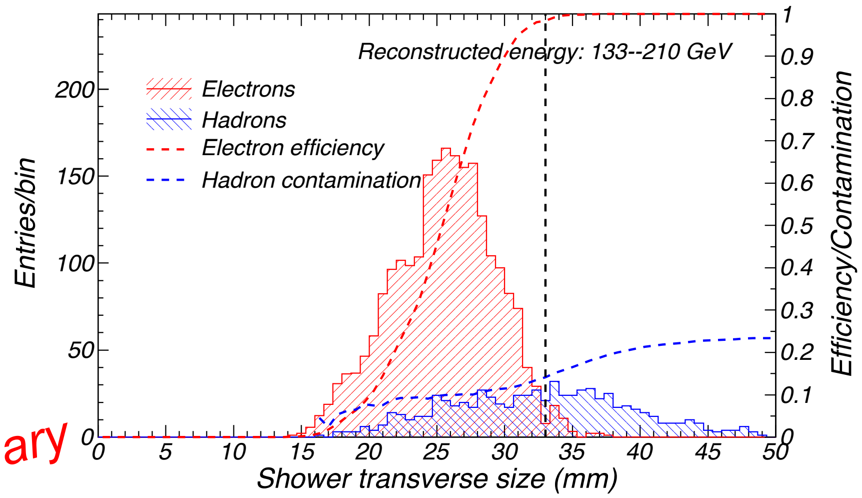
- Full subsystems reconstruction
  - ACD - PH analysis
  - TKR - powerful tracking
  - CAL - 3D shower profile recon, handles cracks and saturation

Event Selection, Global Performance and Systematics

- Event selection tuned on simulation and validated with real data
  - 100s variables describing key event topology in each subsystems
    - Prefilters +
    - Classification Trees (CT) optimizing electron efficiency and hadron rejection
- Peak geometry factor 2.8 m^2sr at 50 GeV, rejection power up to 1:10^4 at 1 TeV
- Systematic uncertainties kept below 20%
  - Data-MC disagreement and event selection effect on acceptance <20%
  - Proton spectrum <20%
  - Energy calibration uncertain (+5%,-10%)→ rigid shift of the spectrum

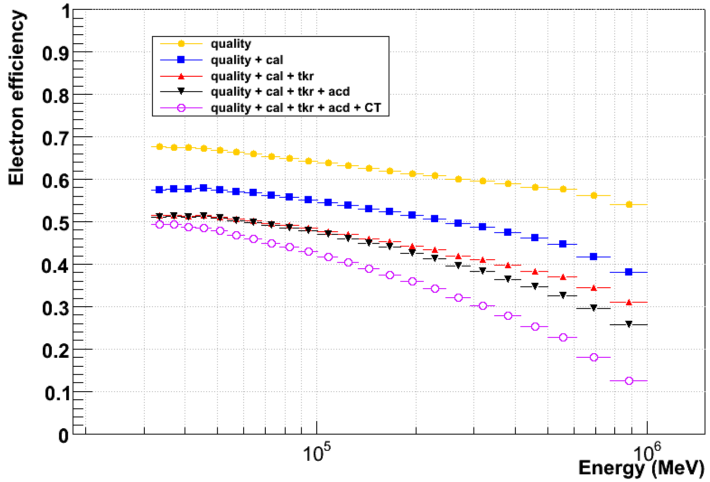
Shower size at different selection steps

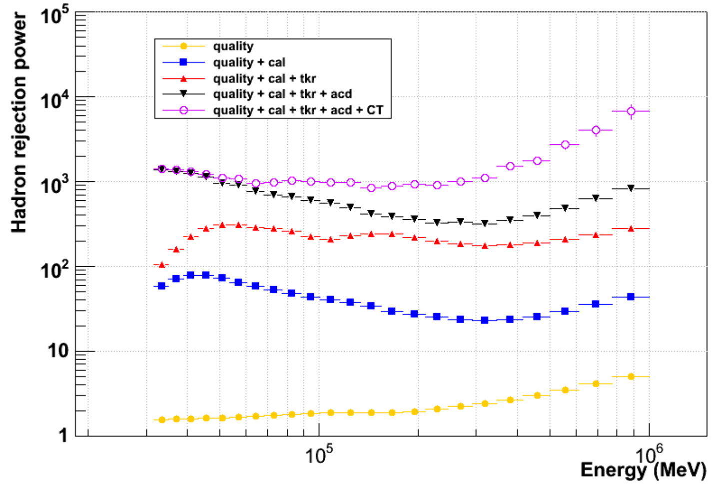




- **CAL variables cuts only**
  - **High electron efficiency**
  - **Large hadron contamination**
- **All cuts**
  - **acceptable hadron contamination**

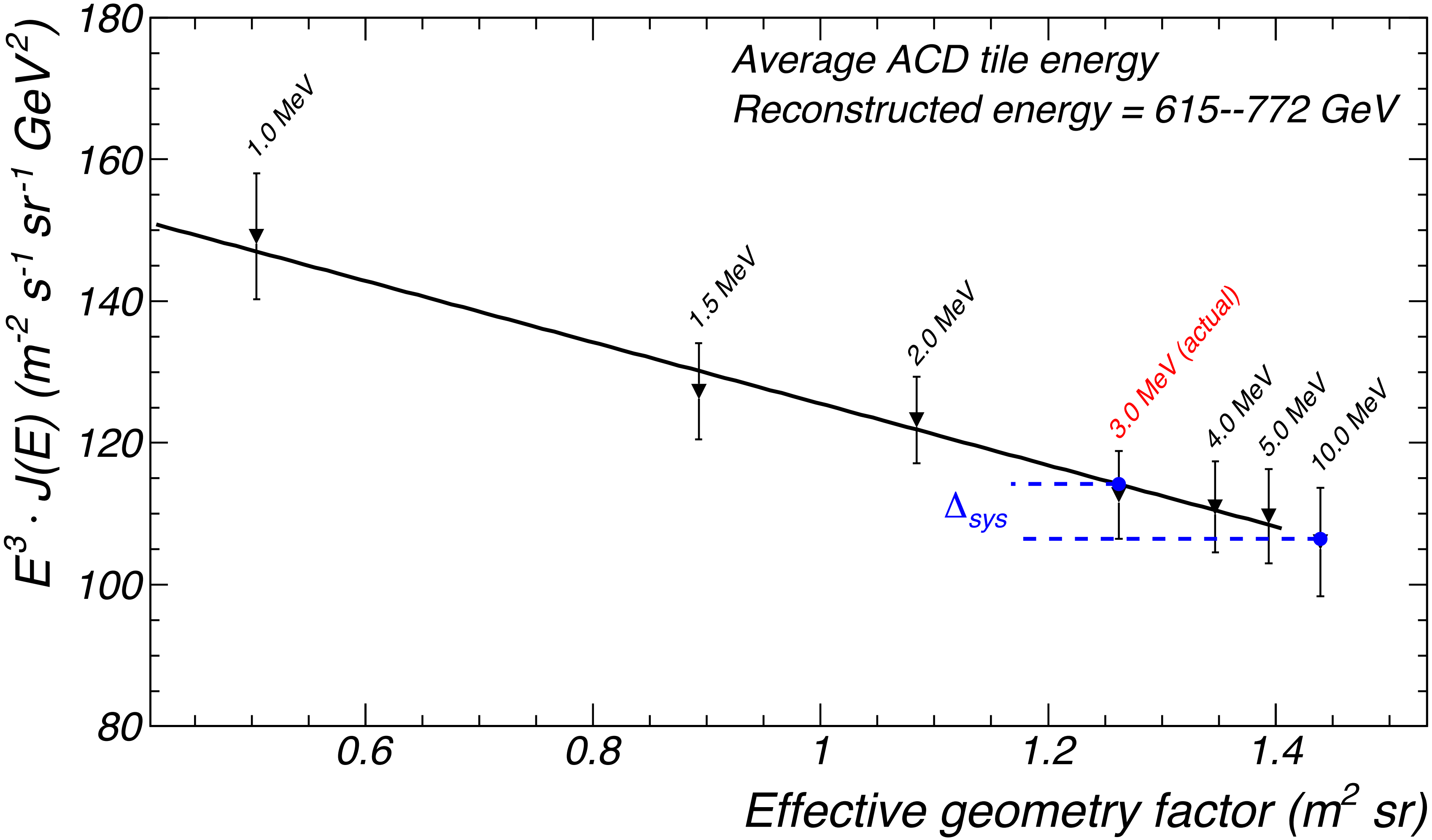
LAT Electron performance





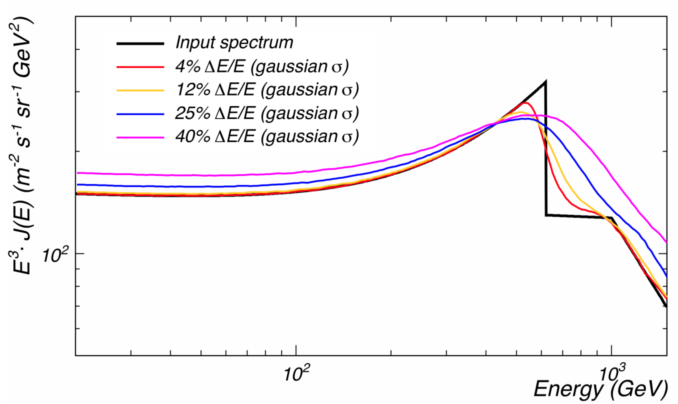
- Performance is a trade-off among:
  - electron-acceptance – hadron contamination - systematics
- Geometry factor
  - ~ 3 m^2sr (50 GeV) to ~ 1 m^2sr (1 TeV)
  - > 10x wrt previous experiments
- Rejection power: ~ 1:10^3 (20 GeV) to ~ 1:10^4 (1 TeV)
- Maximum residual contamination ~ 20% (1 TeV)
- Maximum systematic uncertainty ~ 20% (1 TeV)

Systematic uncertainties

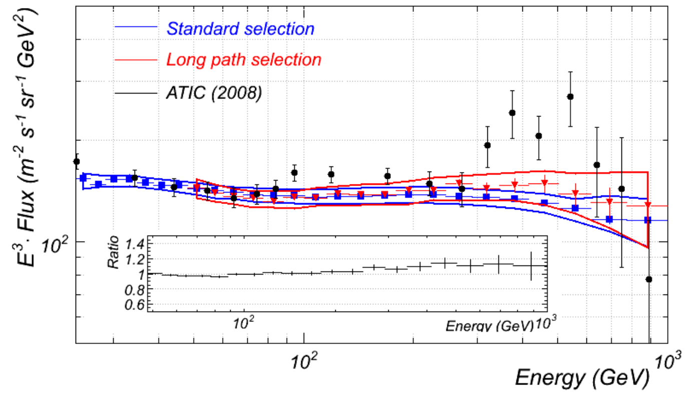


Absence of high energy features

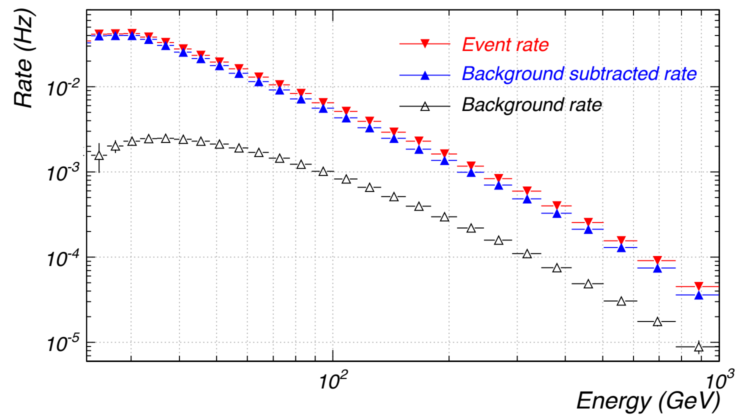
- Sensitivity to spectral features demonstrated



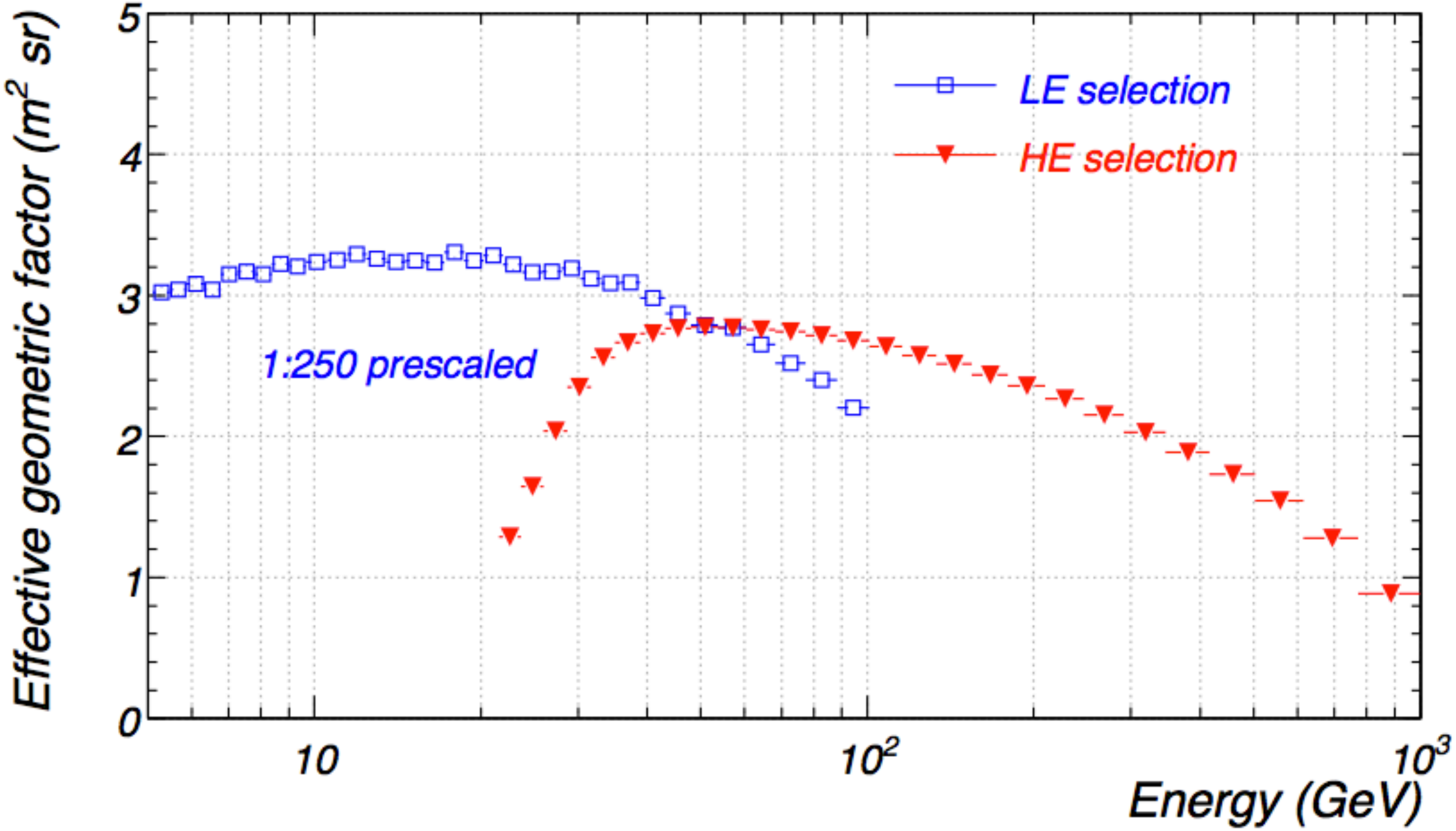
- Spectrum with best possible energy resolution compatible with main spectrum



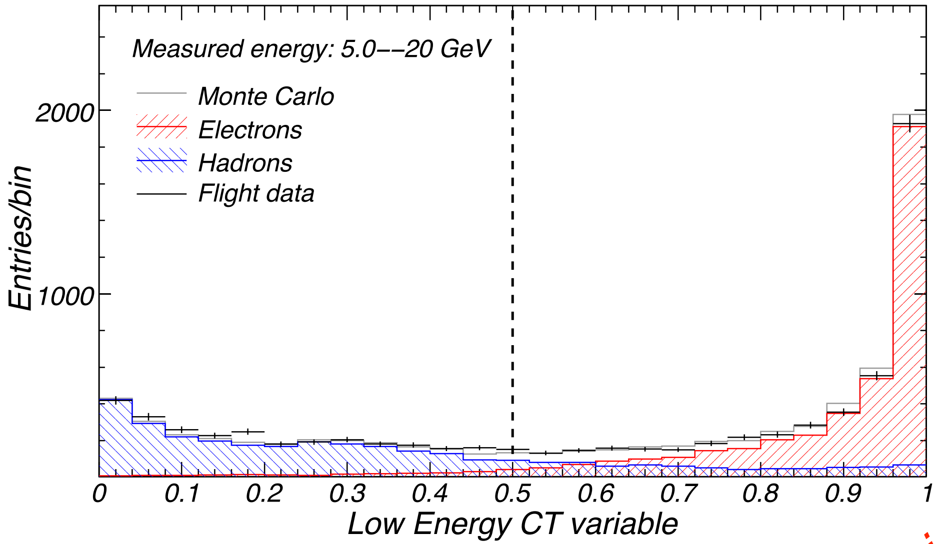
- Event rate before background subtraction does not show any feature

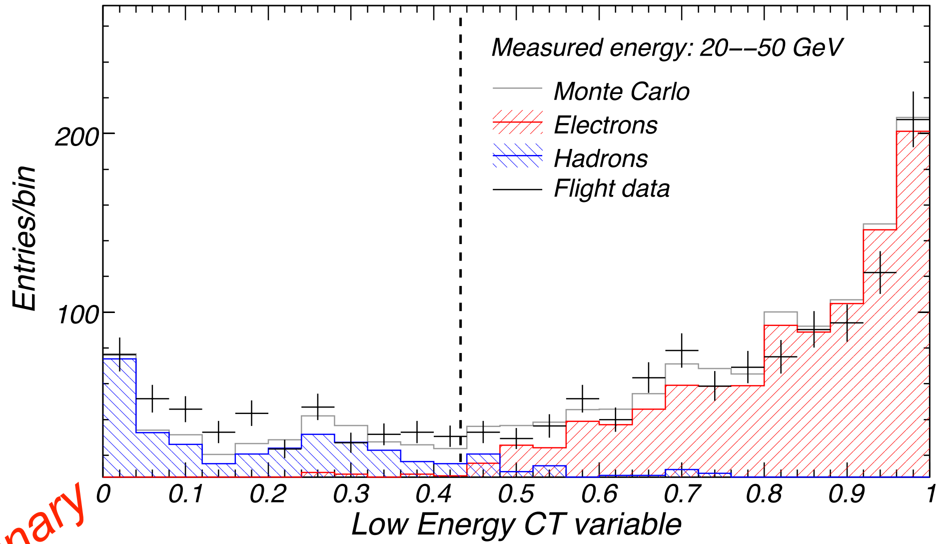


Extension to low energy measurements



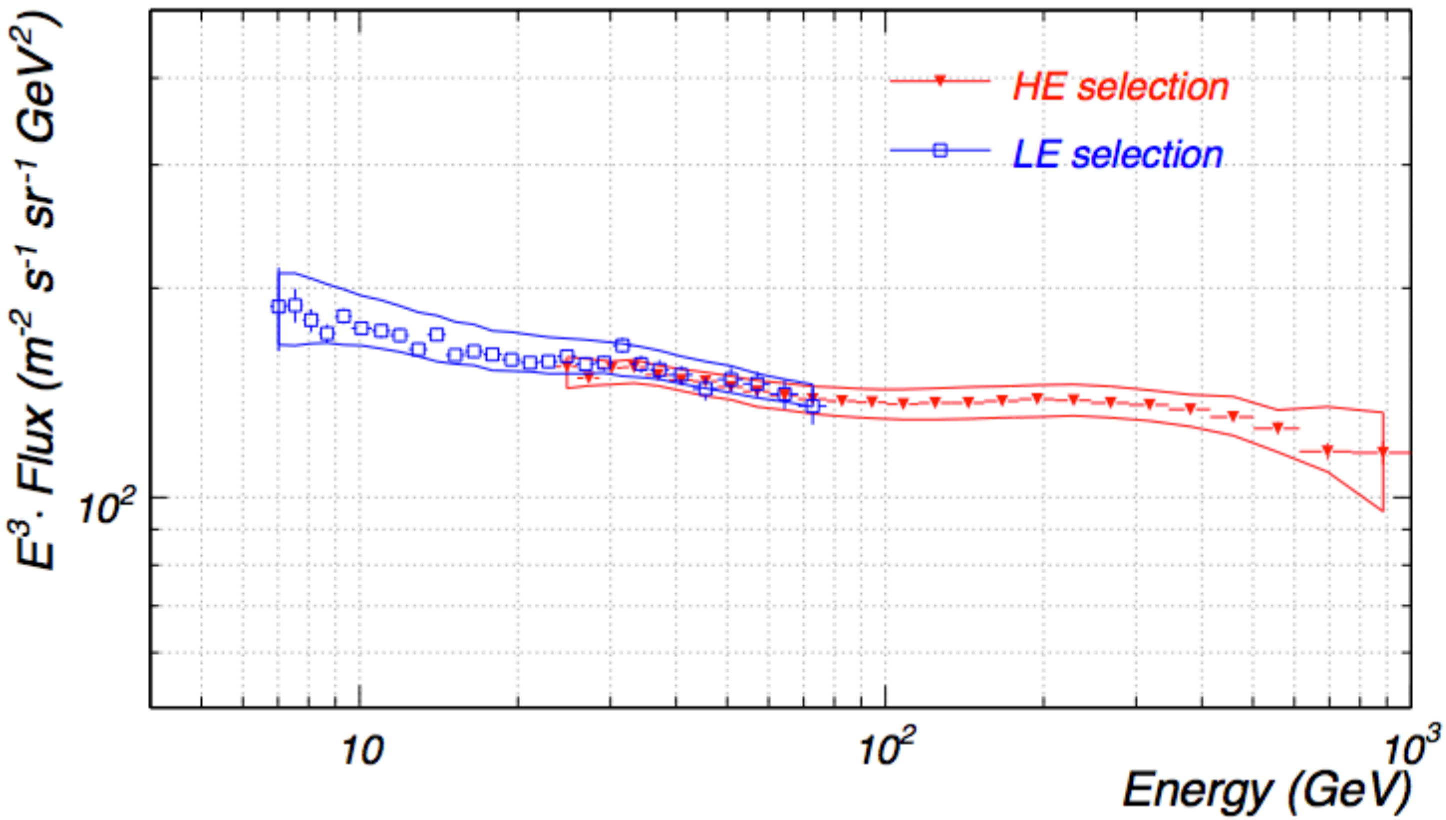
LE selection variables validation





preliminary

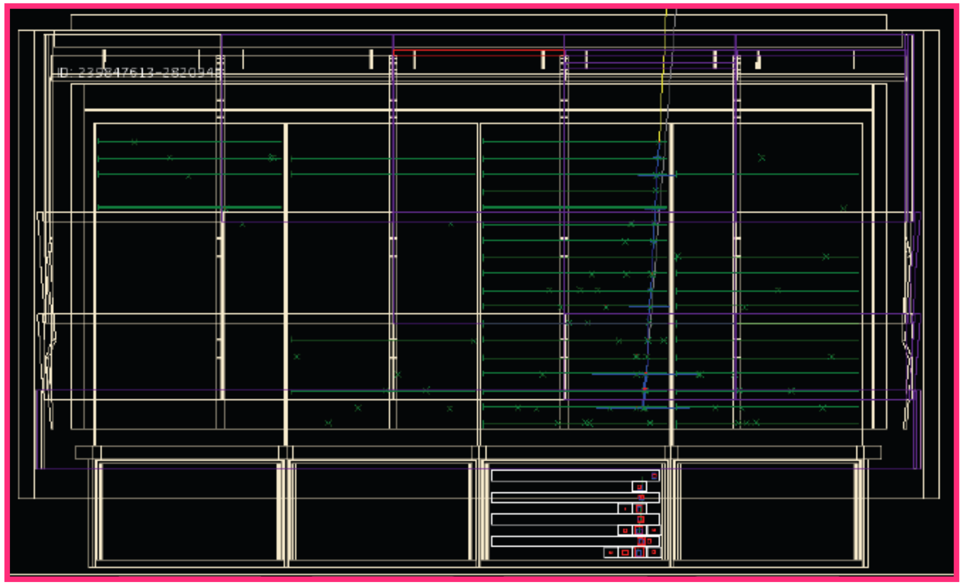
Combined Analysis

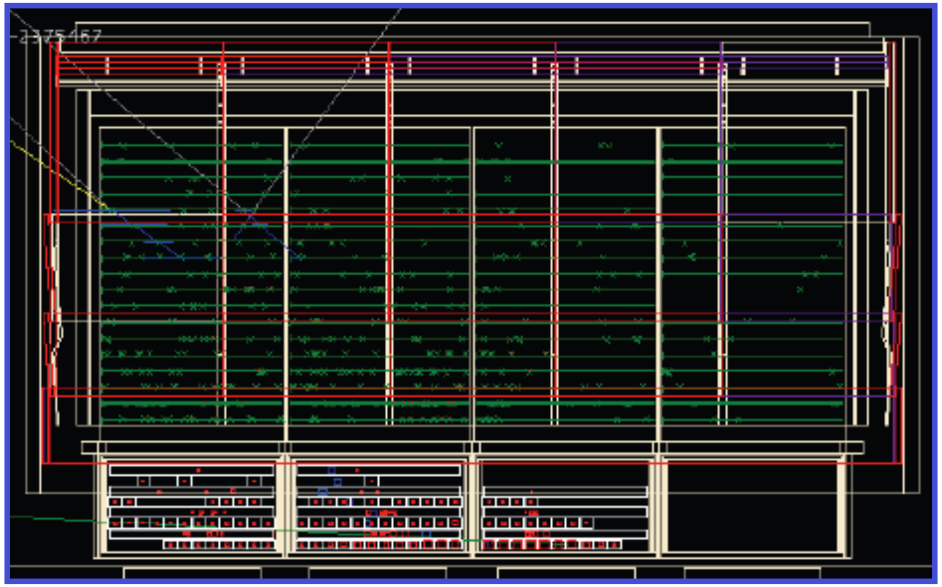


Provides extension to lower energies

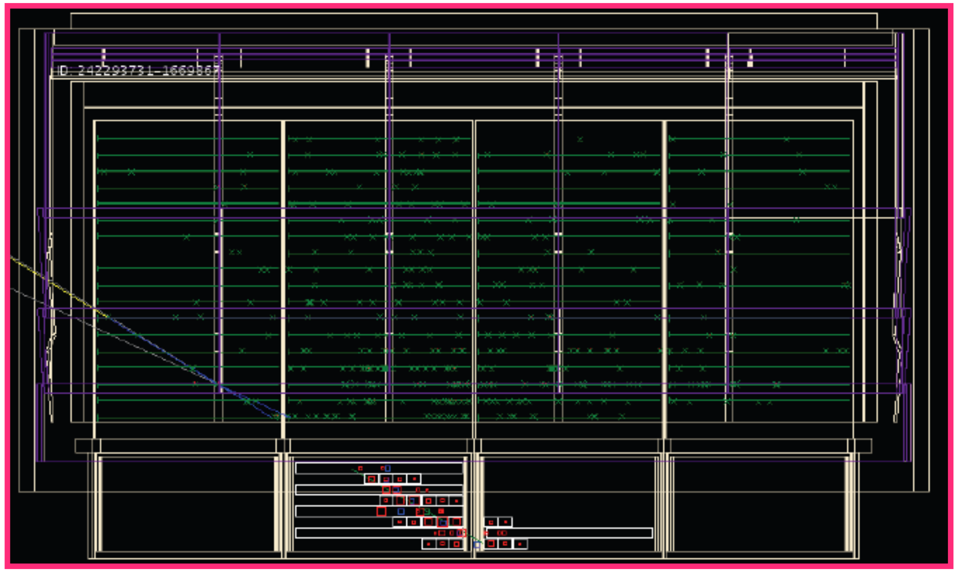
Provides consistency check with HE analysis up to ~100 GeV

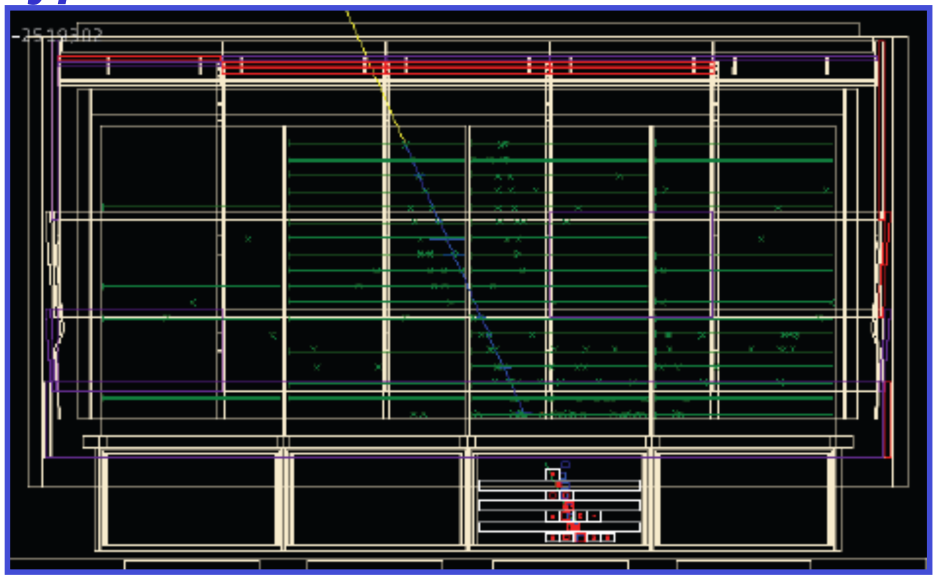
Electrons | Hadrons





more simple type events





Examples of less obvious events well tagged