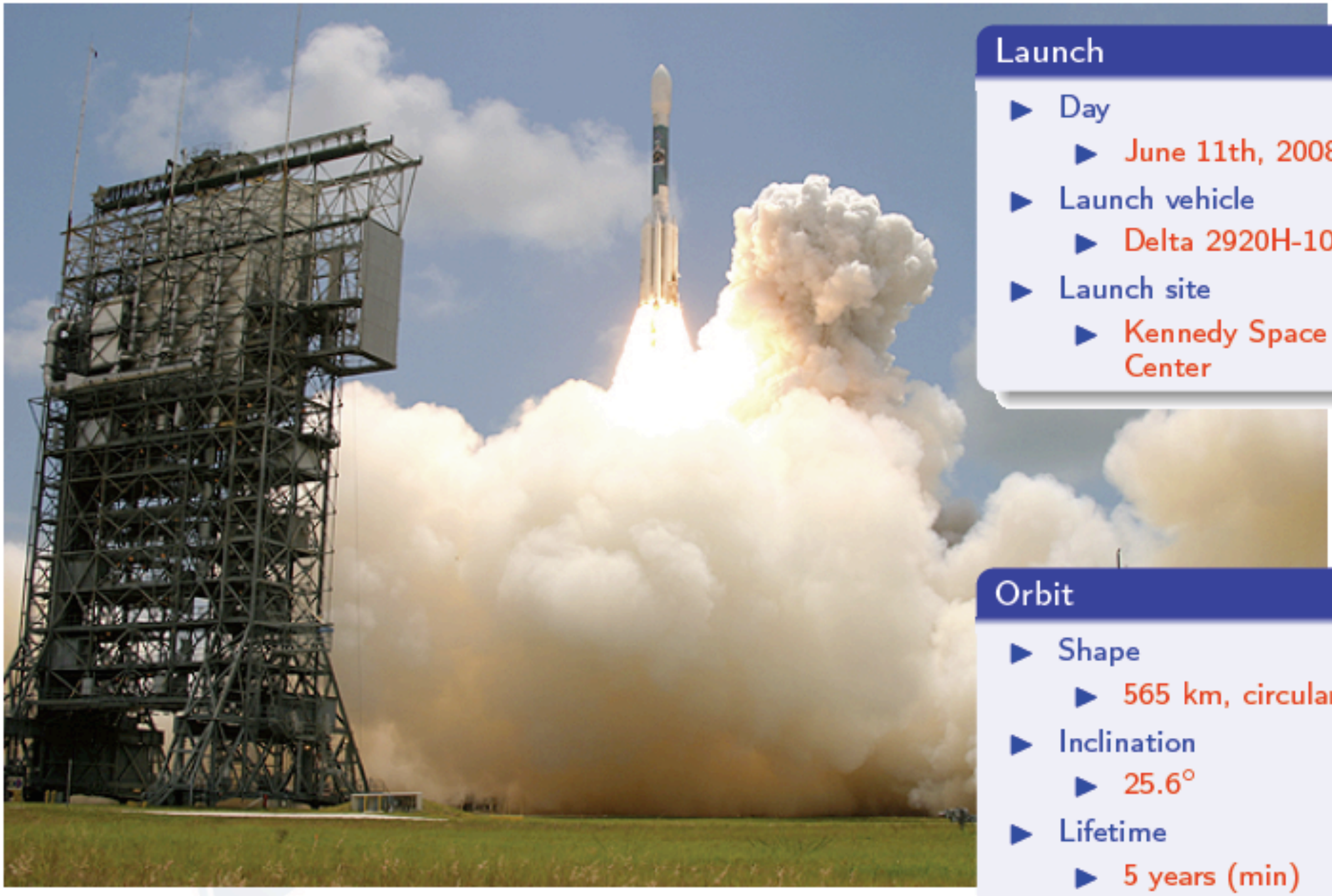
Fermi Searches for Dark Matter

Richard E. Hughes
The Ohio State University
Representing the Fermi LAT Collaboration

Launch of GLAST (soon to be Fermi)



Launch

- Day
  - June 11th, 2008
- Launch vehicle
  - Delta 2920H-10
- Launch site
  - Kennedy Space Center

Orbit

- Shape
  - 565 km, circular
- Inclination
  - 25.6°
- Lifetime
  - 5 years (min)

Fermi Collaboration

United States

- California State University at Sonoma
- University of California at Santa Cruz
- Goddard Space Flight Center
- Naval Research Laboratory
- Ohio State University
- Stanford University (SLAC and HEPL/Physics)
- University of Washington
- Washington University, St. Louis

PI: Peter Michelson (Stanford & SLAC)

- 390 Members (including 96 Affiliated Scientists, plus 68 Postdocs, and 105 Graduate Students)
- Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden
- Managed at Stanford Linear Accelerator Center (SLAC)

Japan

- Hiroshima University
- ISAS/JAXA, RIKEN
- Tokyo Tech.

Sweden

- Kalmar University
- Royal Institute of Technology
- Stockholm University

Spain

- ICREA
- Inst de Ciencies de l'Espi

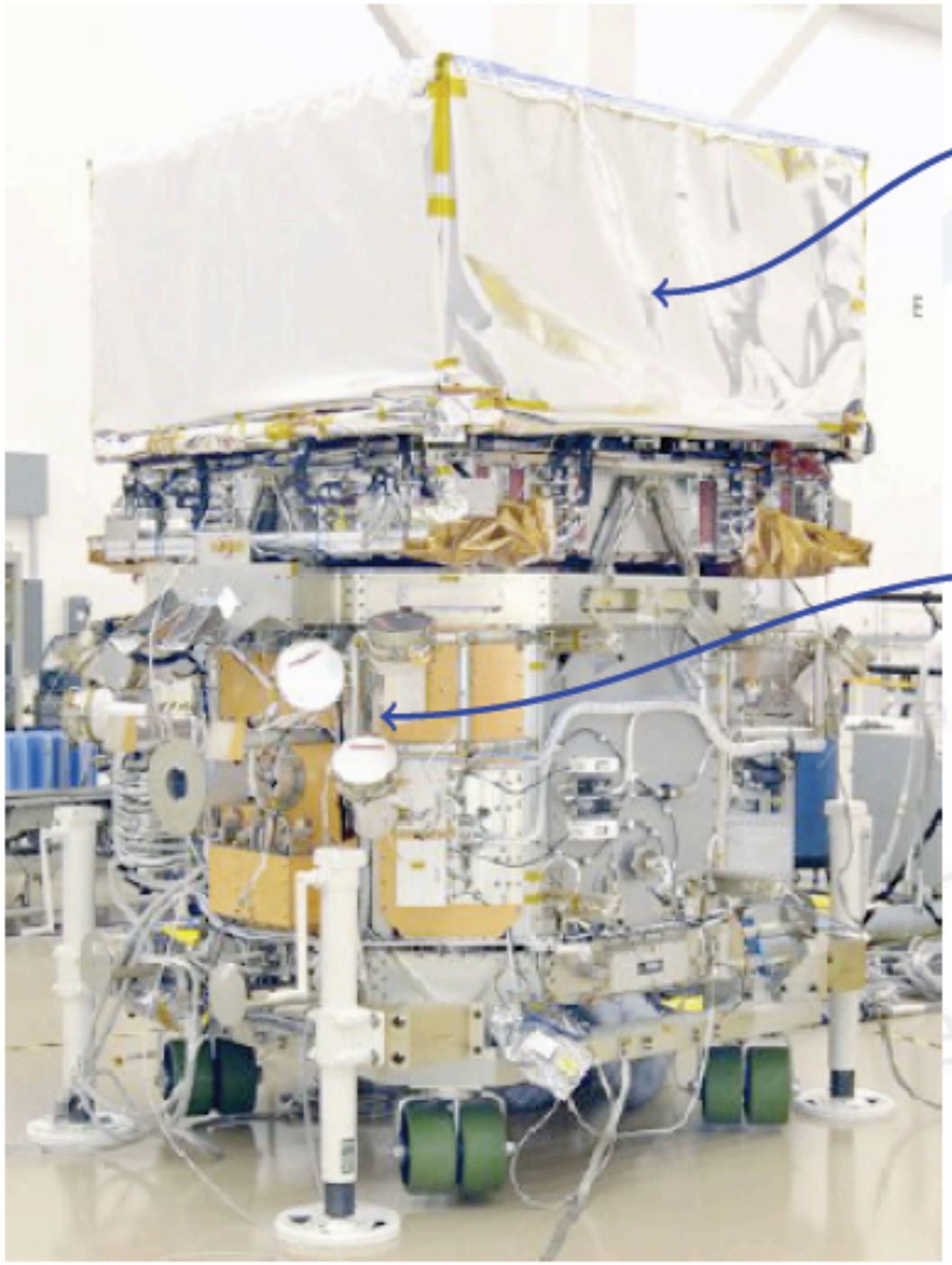
France

- IN2P3
- CEA/Saclay

Italy

- INFN
- ASI

The Observatory: LAT + GBM

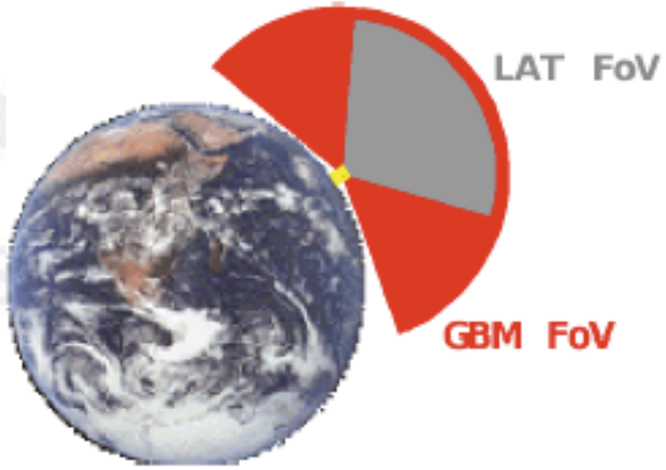


Large Area Telescope (LAT)

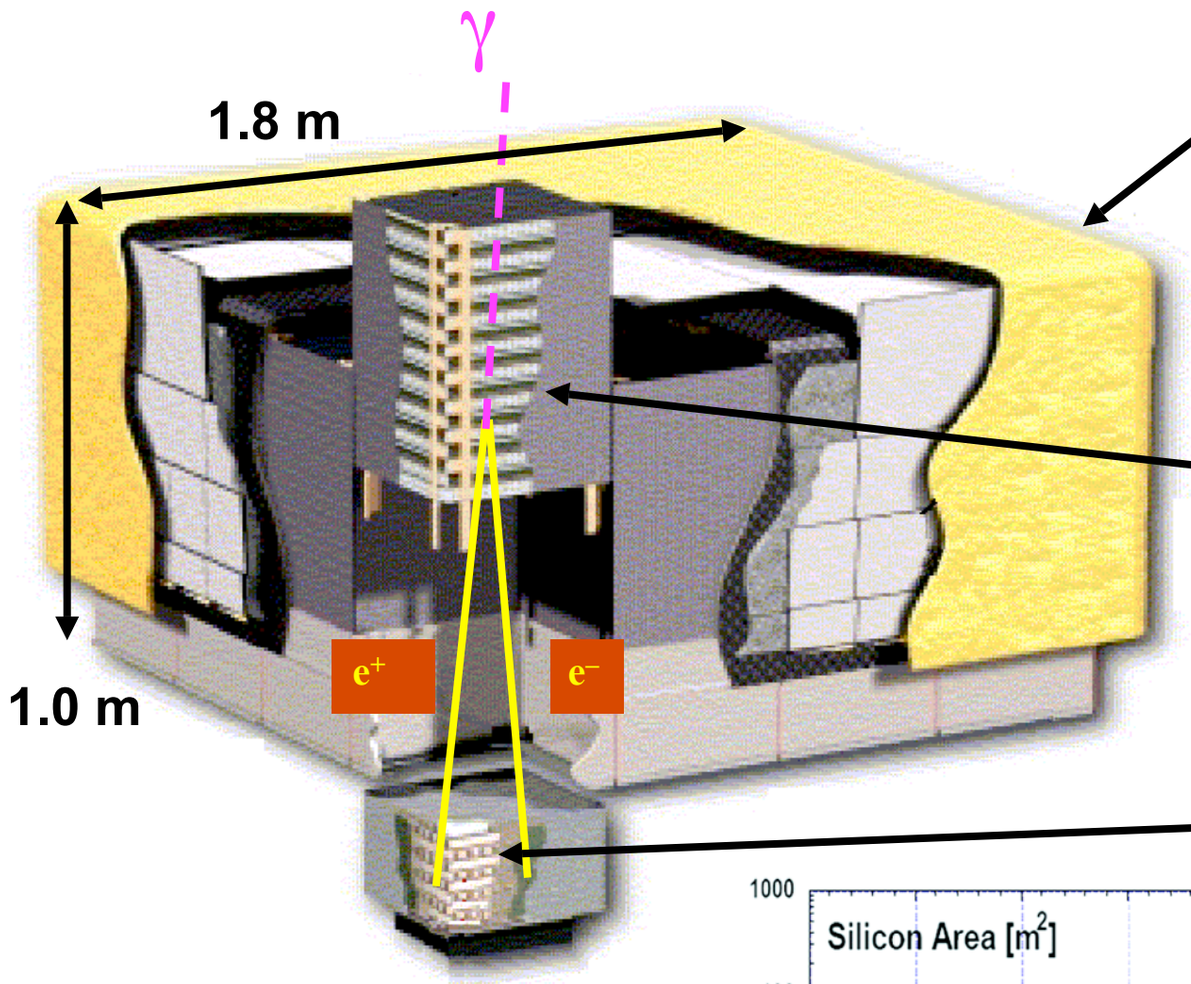
- Pair conversion telescope.
- Energy range: 20 MeV–300 GeV.

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.



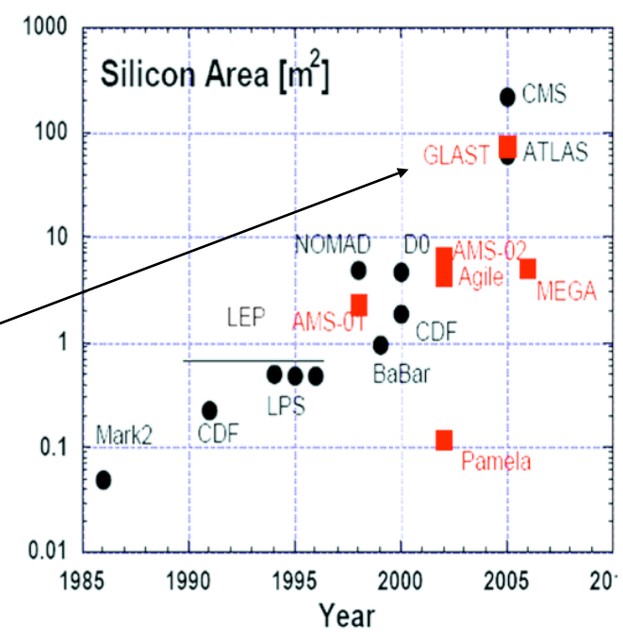
Fermi Large Area Telescope



Anti-Coincidence Detector
- 4% R.L.
- 89 scintillating tiles
- efficiency (>0.9997) for MIPs

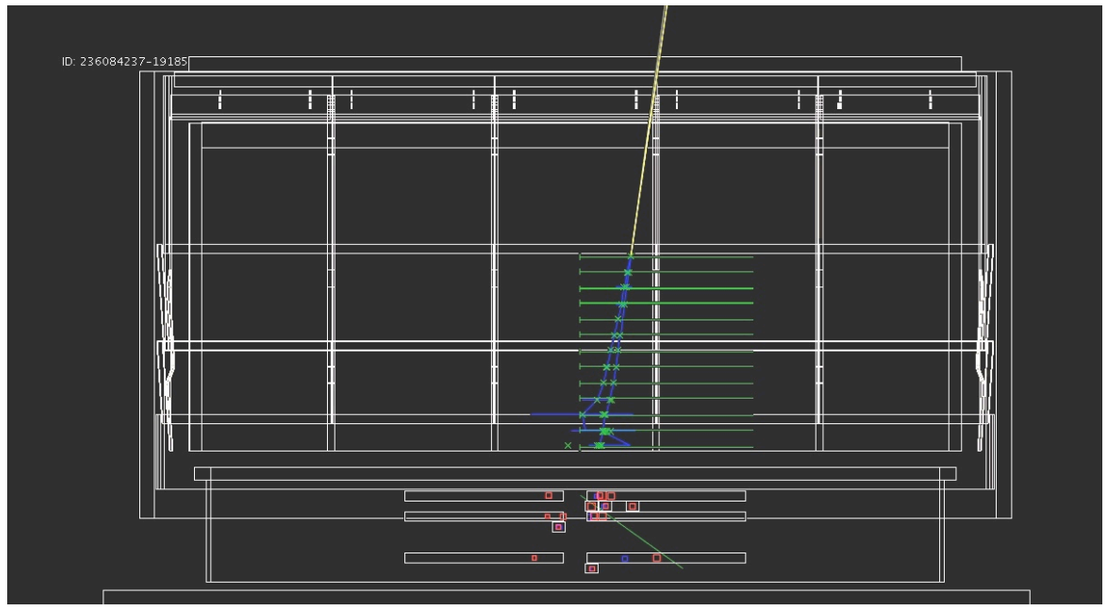
Tracking detector
- 16 tungsten foils (12x3%R.L.,4x18%R.L.)
- 18 pairs of silicon strip arrays
- 884736 strips (228 micron pitch)

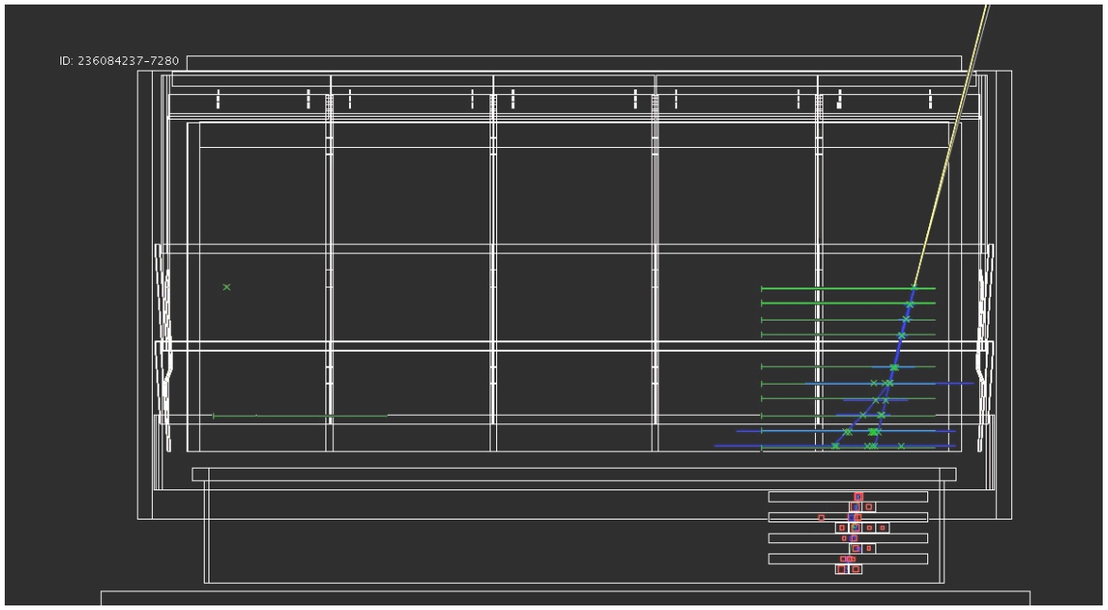
Calorimeter
- 8.5 radiation lengths
- 8 layers cesium iodide logs
- 1536 logs total (1200kg)

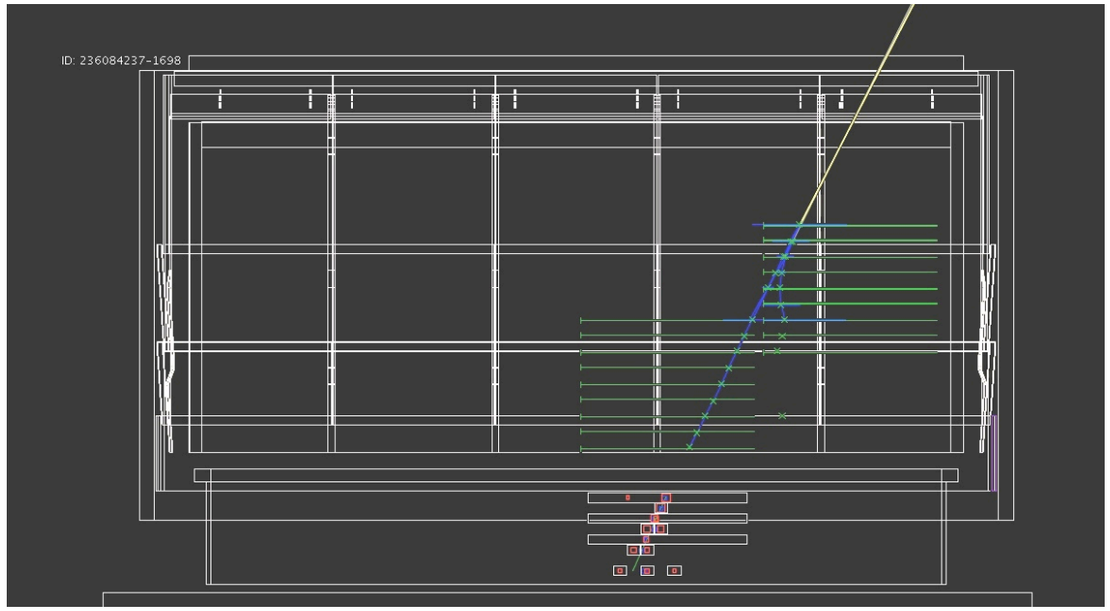


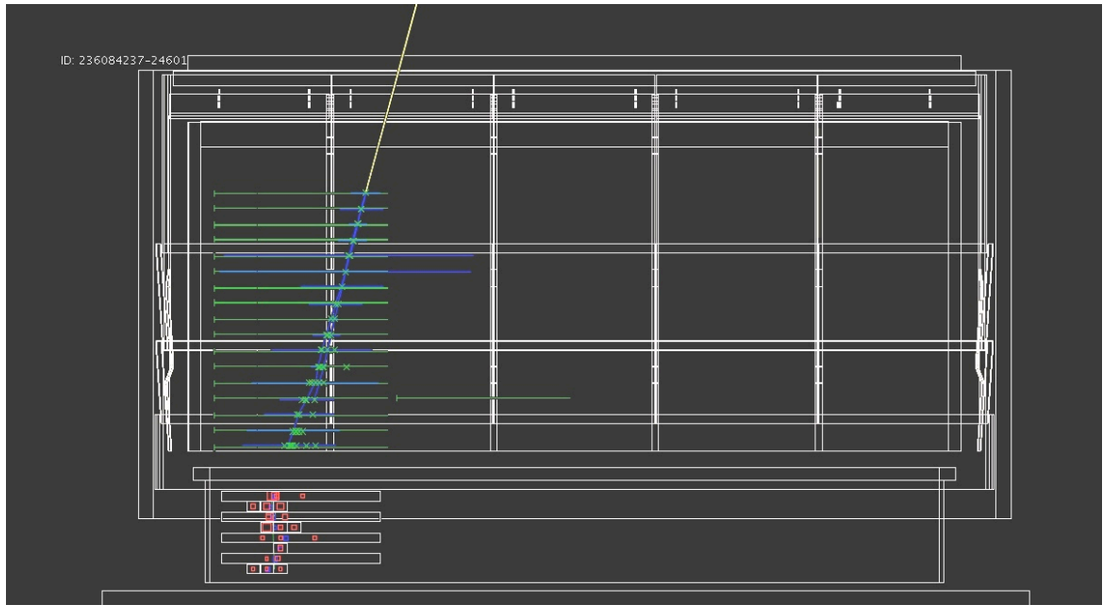
One of the biggest Silicon Tracking systems ever constructed.

LAT Gamma Candidate Events

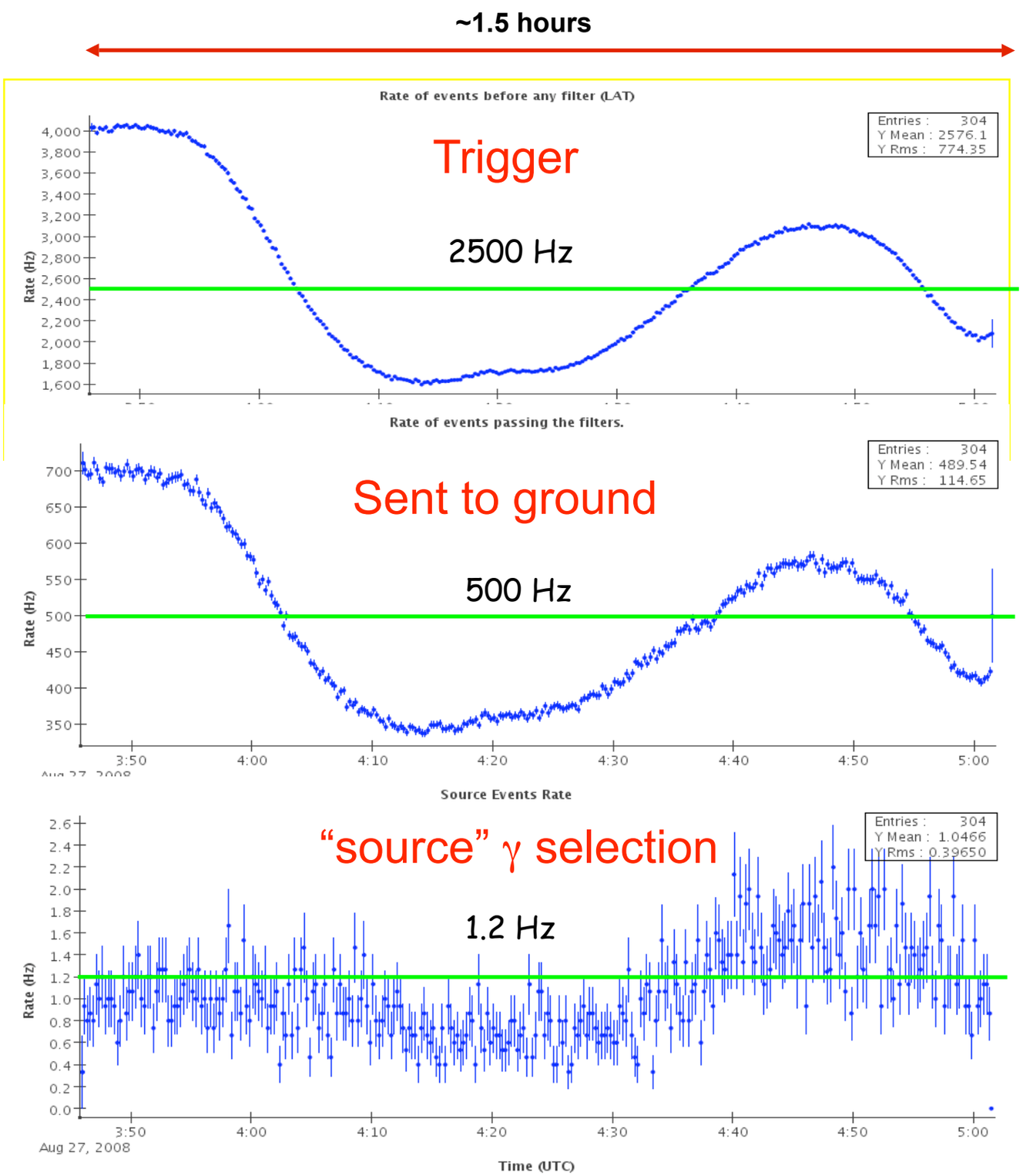








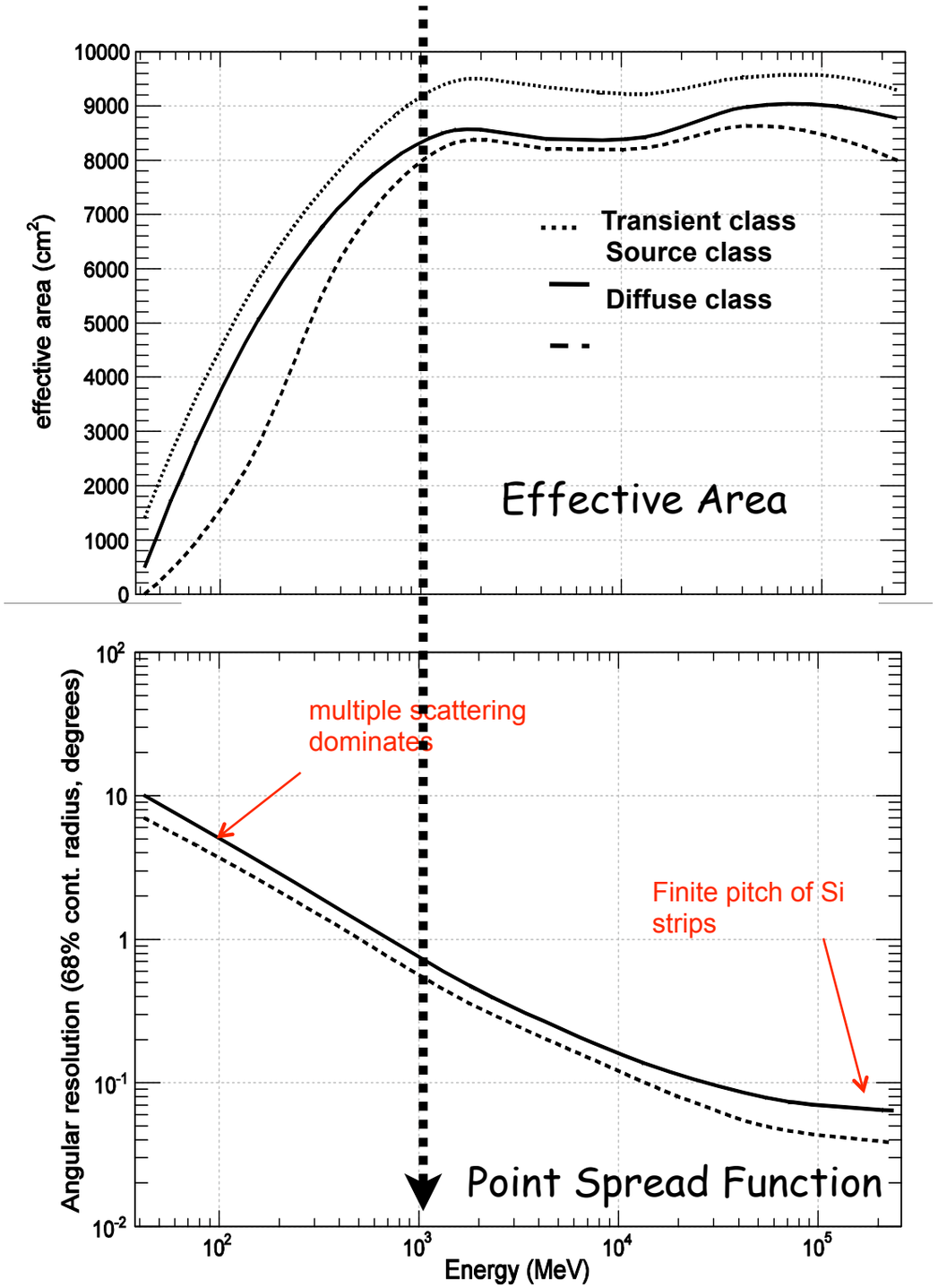
On orbit rates in nominal configuration



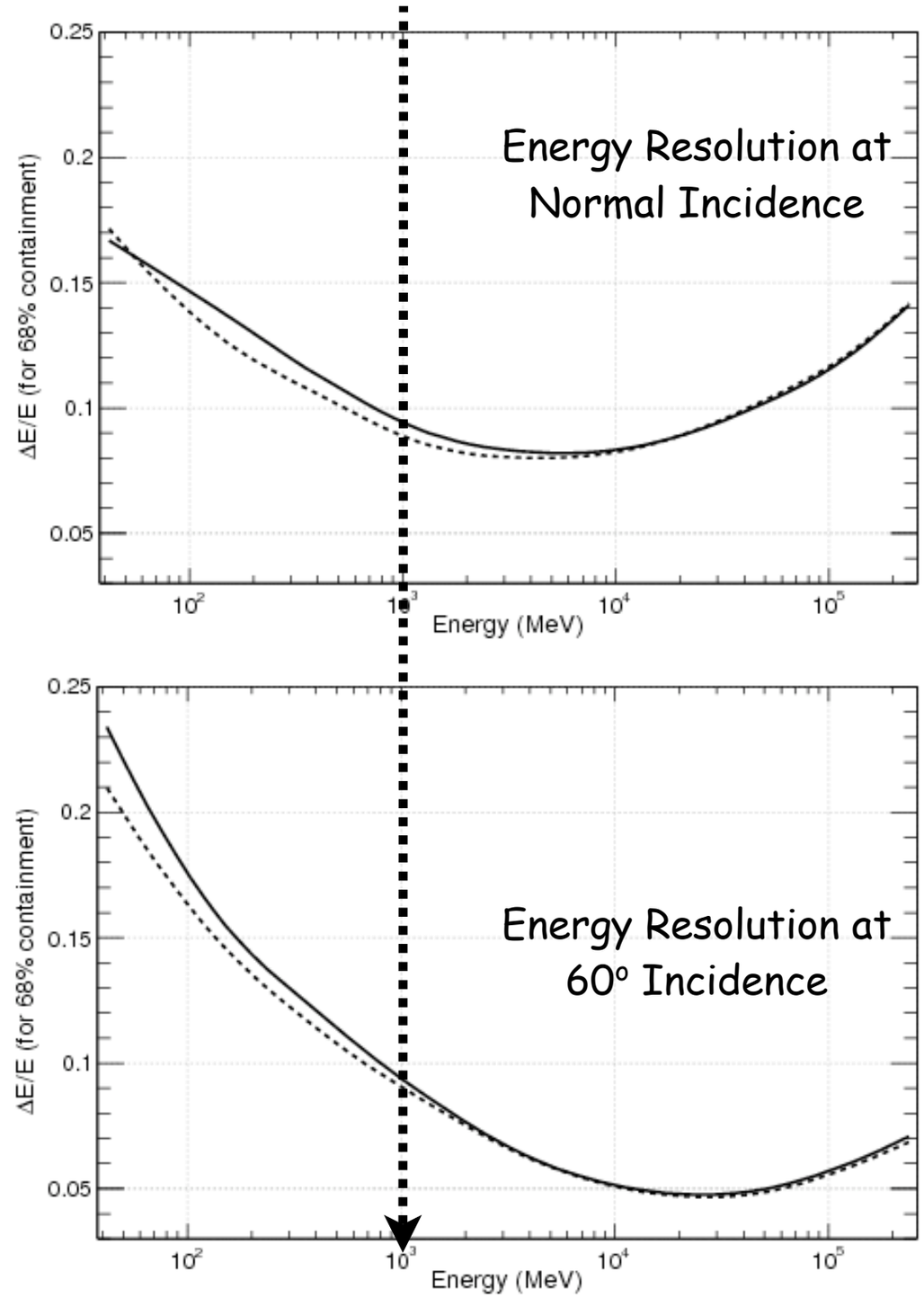
- Overall trigger rate: ~few KHz
  - ✓ Substantial variations due to orbital effects
- Downlink rate: ~400—500 Hz
  - ✓ ~90% from GAMMA filter
  - ✓ ~20—30 Hz from DGN filter
  - ✓ ~5 Hz from HIP filter
- Rate of photons after the standard background rejection cuts for source study: ~1 Hz
  - ✓ Most of the downlinked events are in fact background, final 100:1 rejection is done in ground processing.

Performance Plots

1 GeV

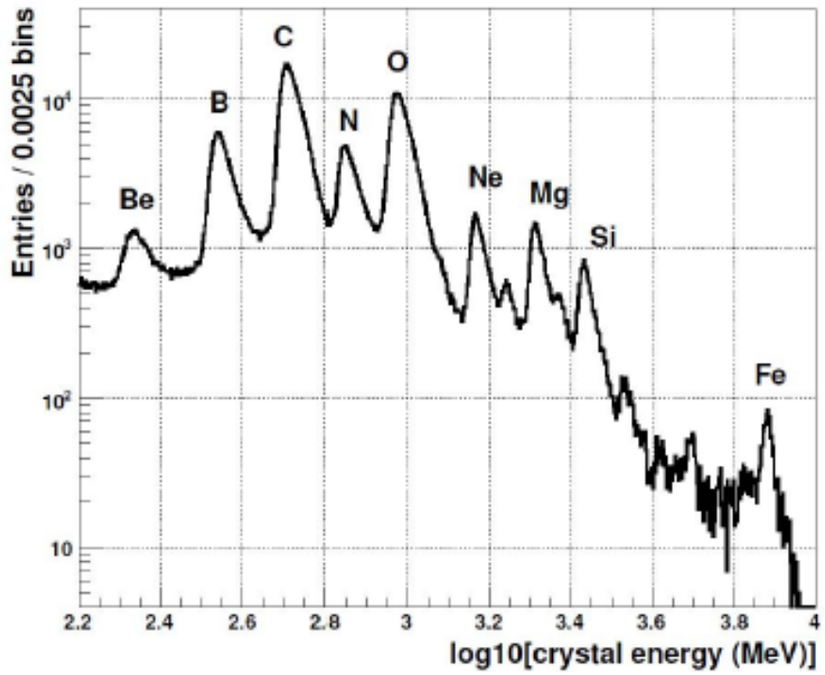


1GeV



Detector performance

CAL



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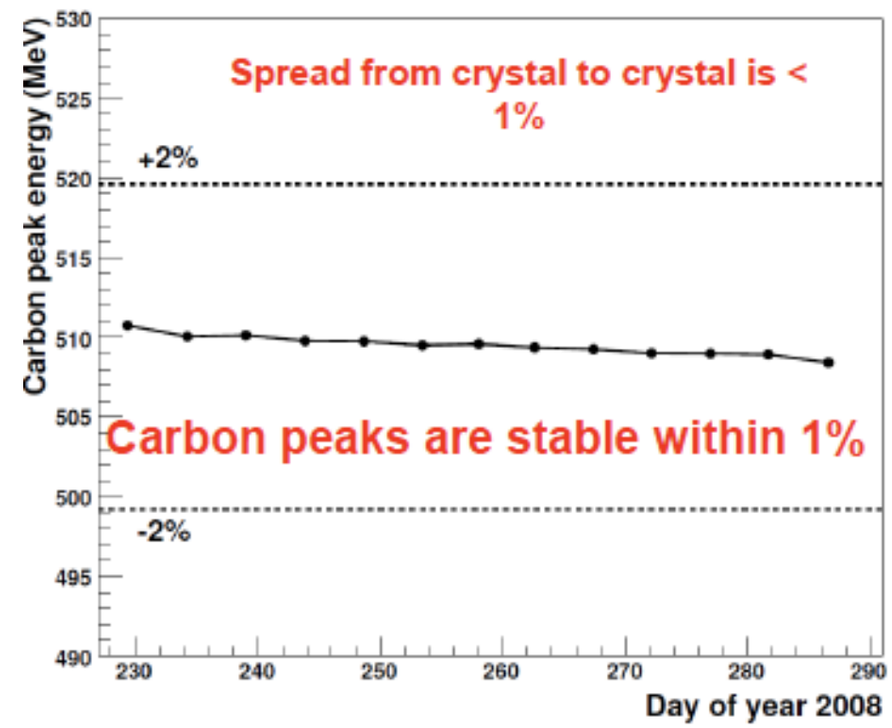
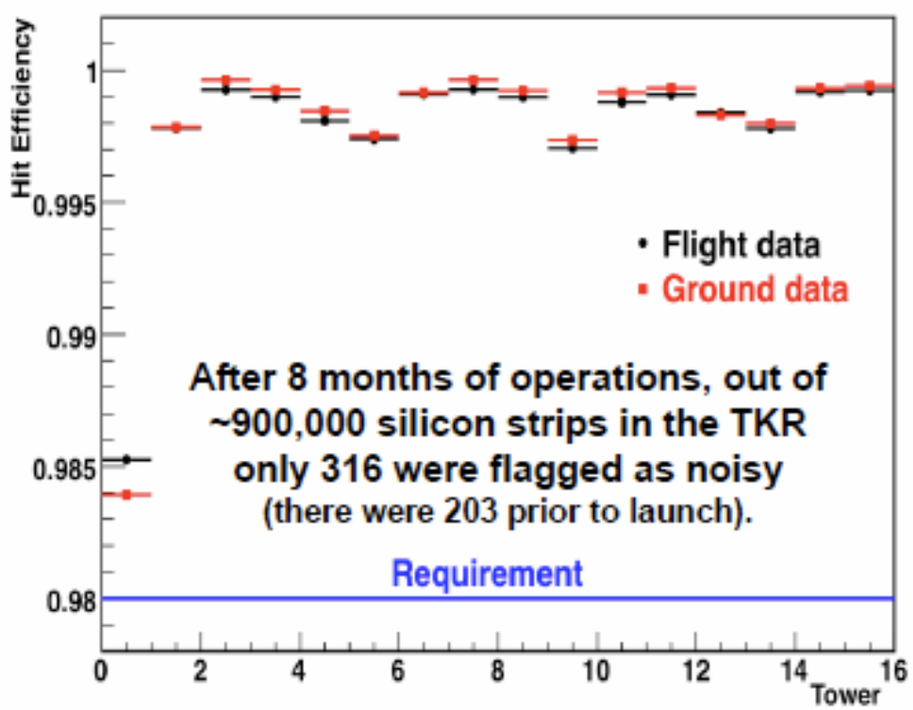
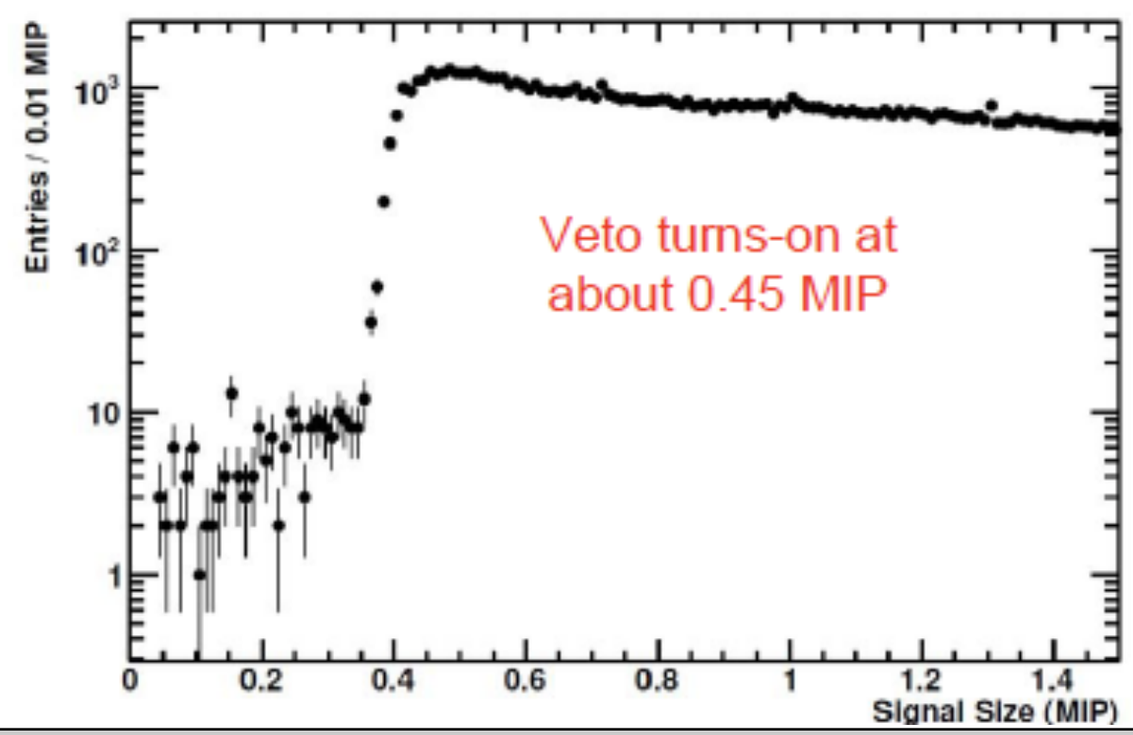


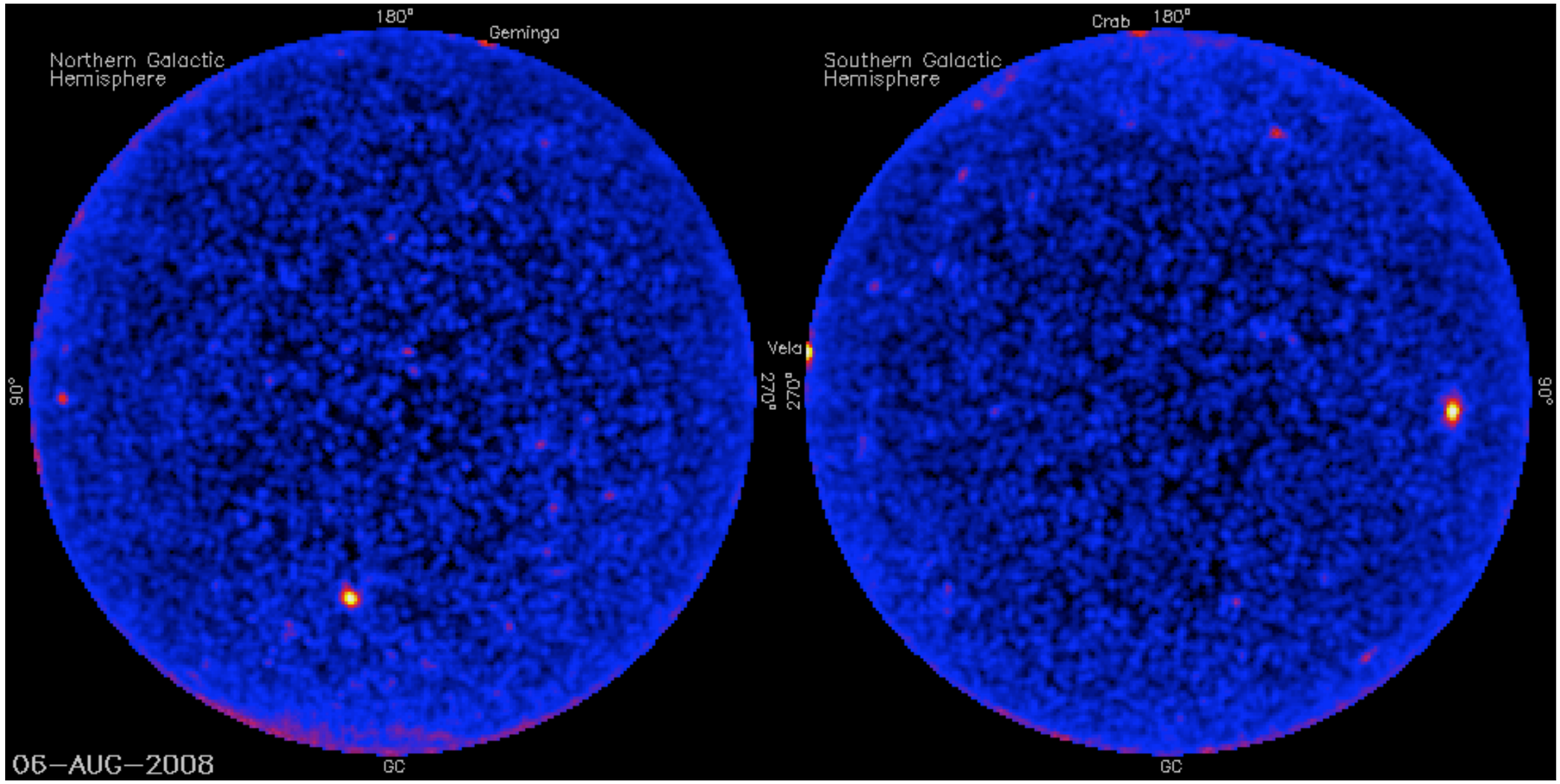
TKR

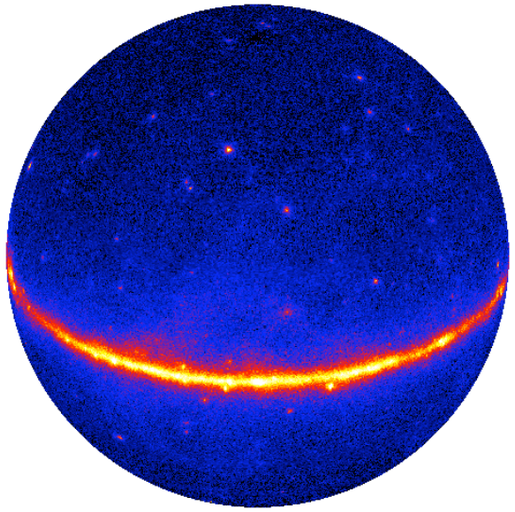


ACD



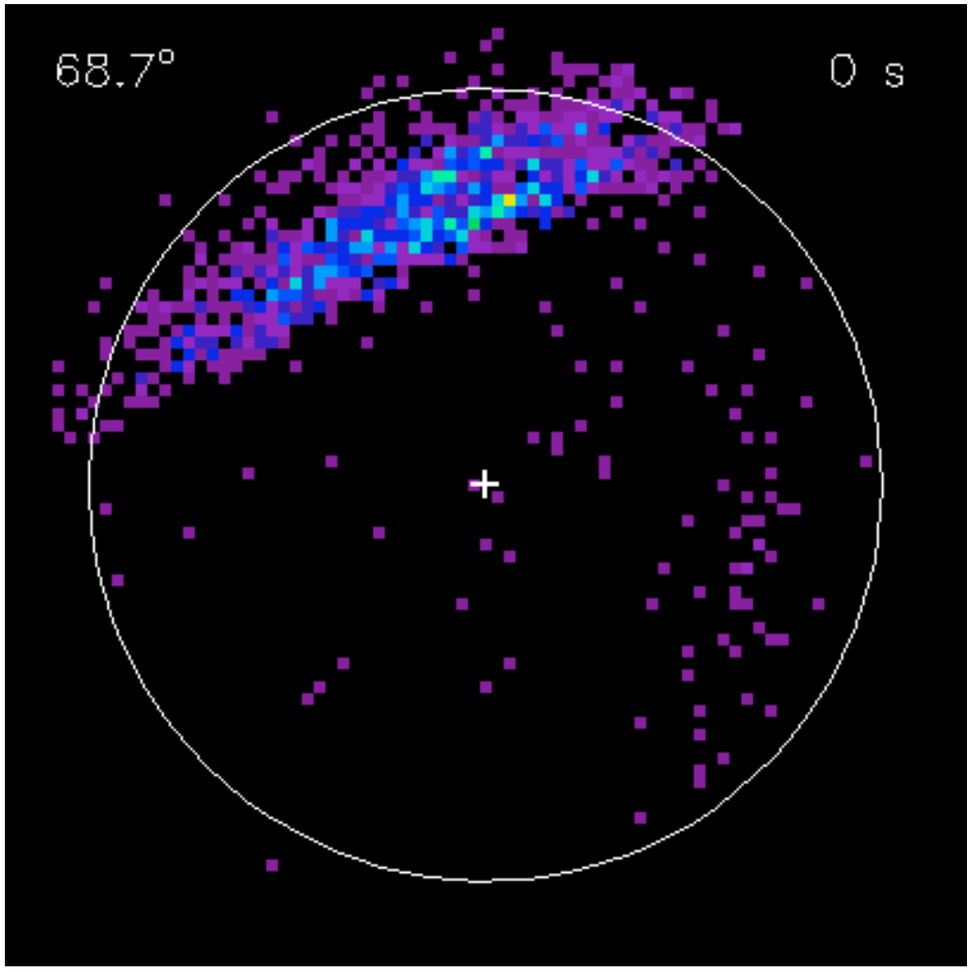
Animation of 3 month Data Set





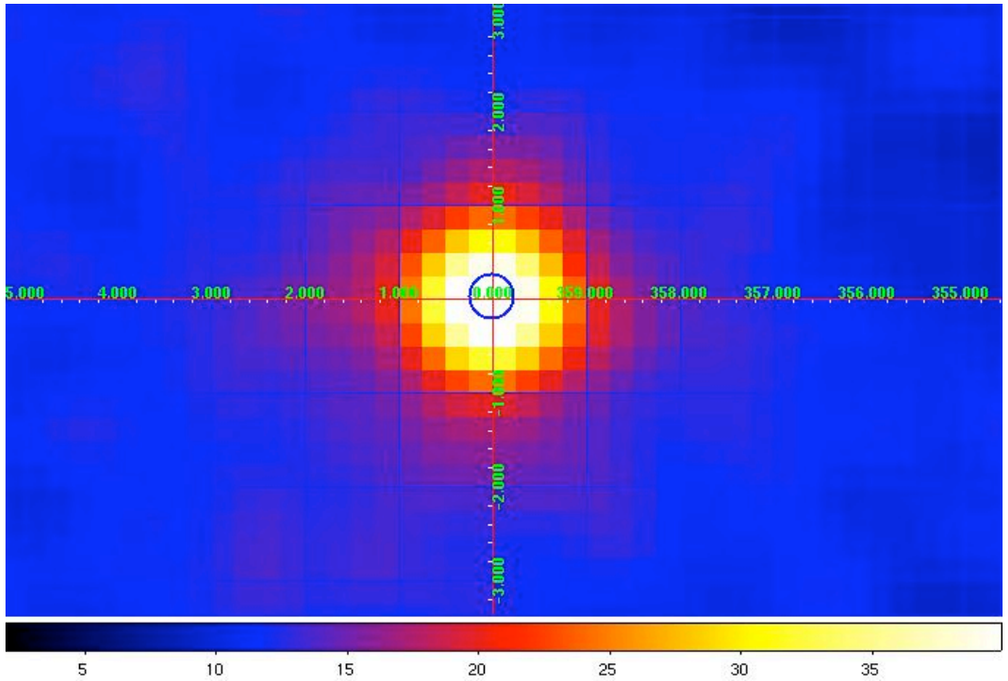
- 87 day animation, starting August 4
- pixel size 0.5deg in center
- |b|>1.0
- scale is sq root, square root, from 0 to 1.2E-3 cts/s/sq.deg

View of Earth Albedo



- Counts maps in instrument coordinates theta*cos(phi),theta*sin(phi); phi = 0 deg is to the right, the cross is the center of the FOV, and the white circle has a radius of 66 deg.
- The rocking angle at the middle of the time interval is indicated in the upper left and in the upper right the starting time of the interval relative to MET 244396000.
- Diffuse class events with energies >100 MeV are used, and the time step is 250 s. The average frame outside the SAA has 2952 gamma rays, i.e., about 12 Hz

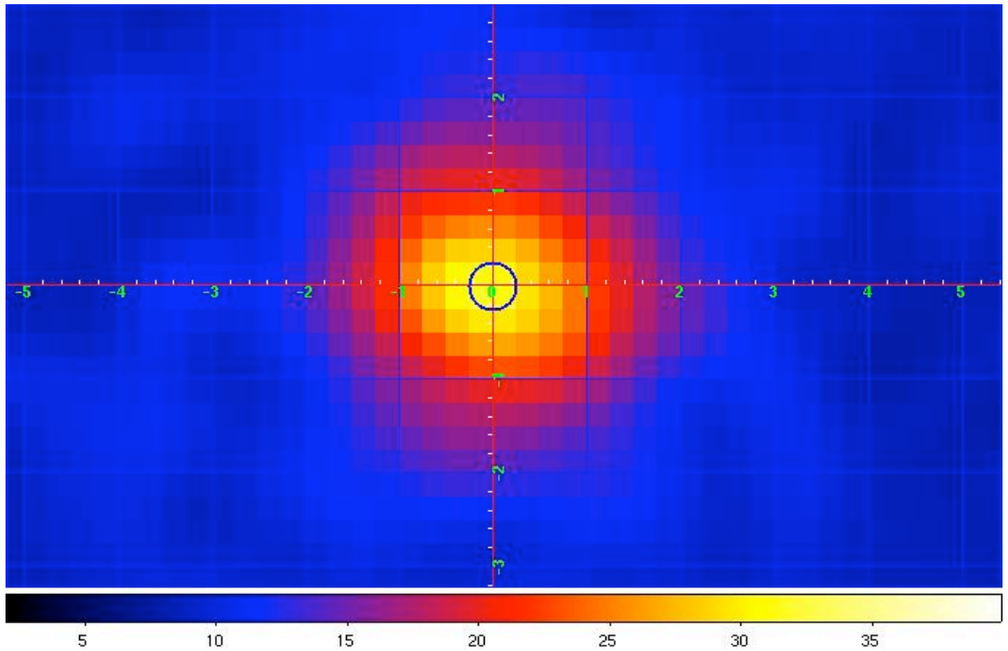
Seeing the Sun and Moon in Gamma Rays



Sun

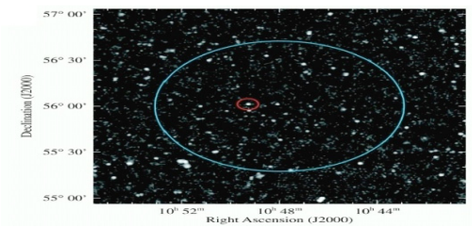
Data from: **2008-08-02** - **2009-01-2009**

- E>100MeV
- 0< ZENITH_ANGLE < 105 deg
- Diffuse class selected.
- 0.25 deg/bin, gaussion smoothed

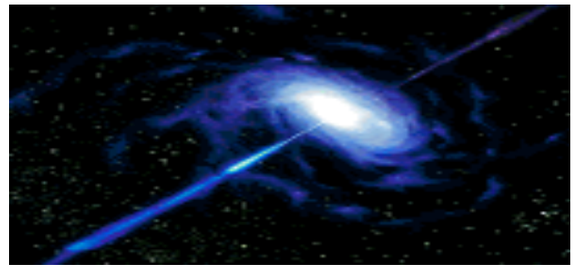


Moon

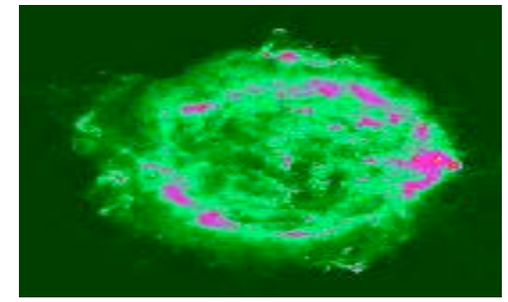
Fermi Science



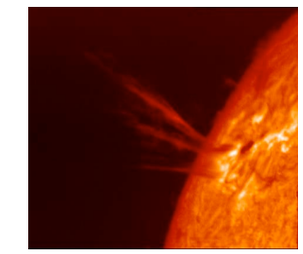
Unidentified sources



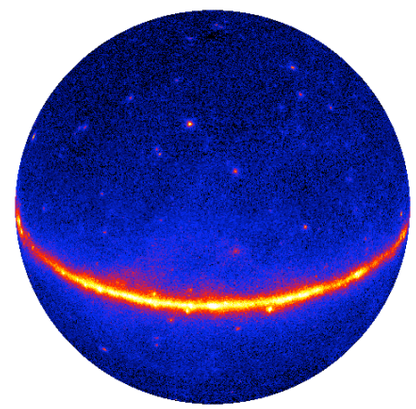
Active Galactic Nuclei

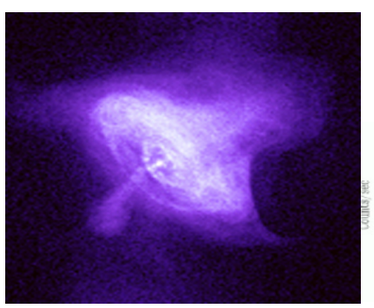


Cosmic ray acceleration

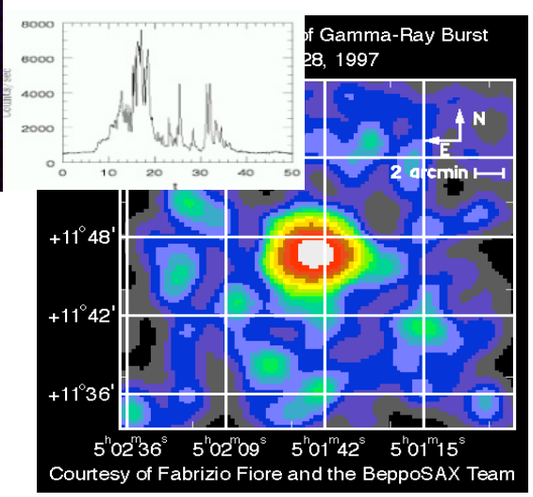


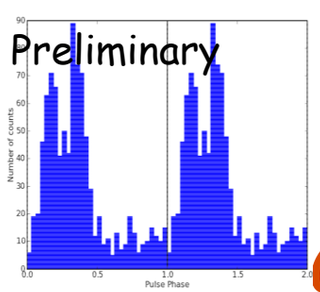
Solar flares



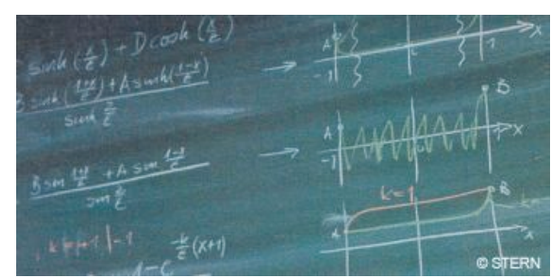


Pulsars

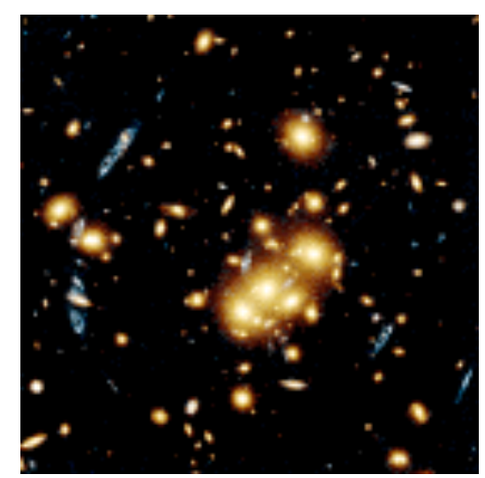




Gamma Ray Bursts

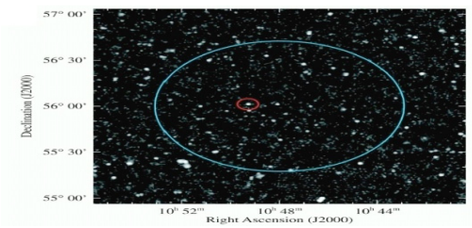


Quantum Gravity?



Dark matter

Fermi Science



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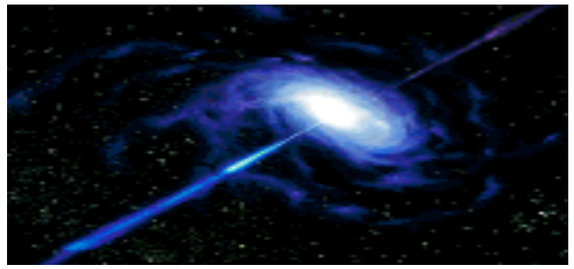

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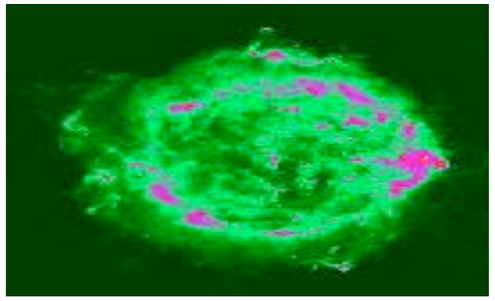

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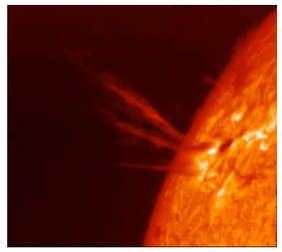
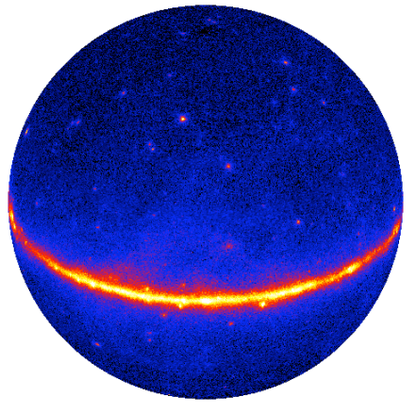
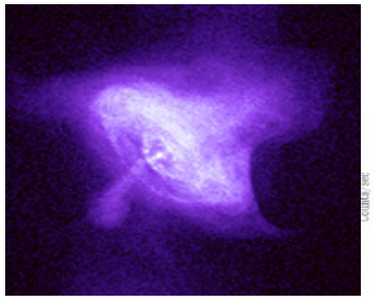


Solar flares





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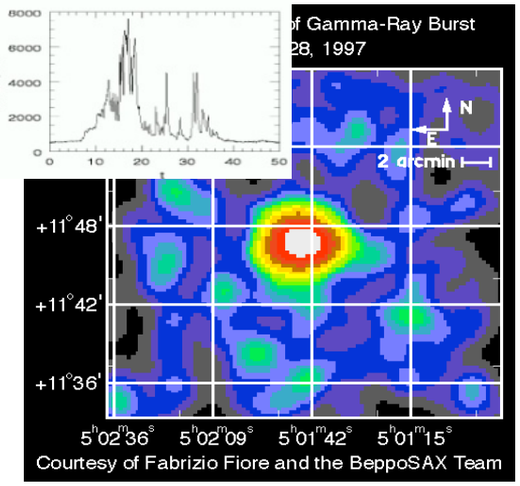

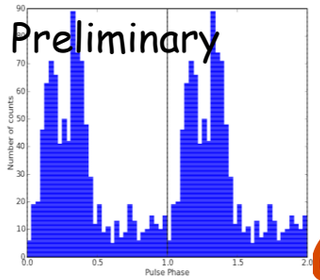

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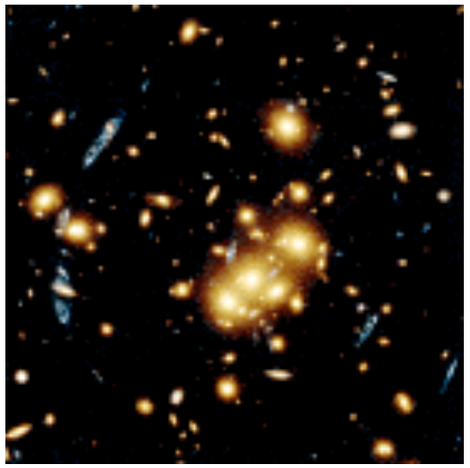
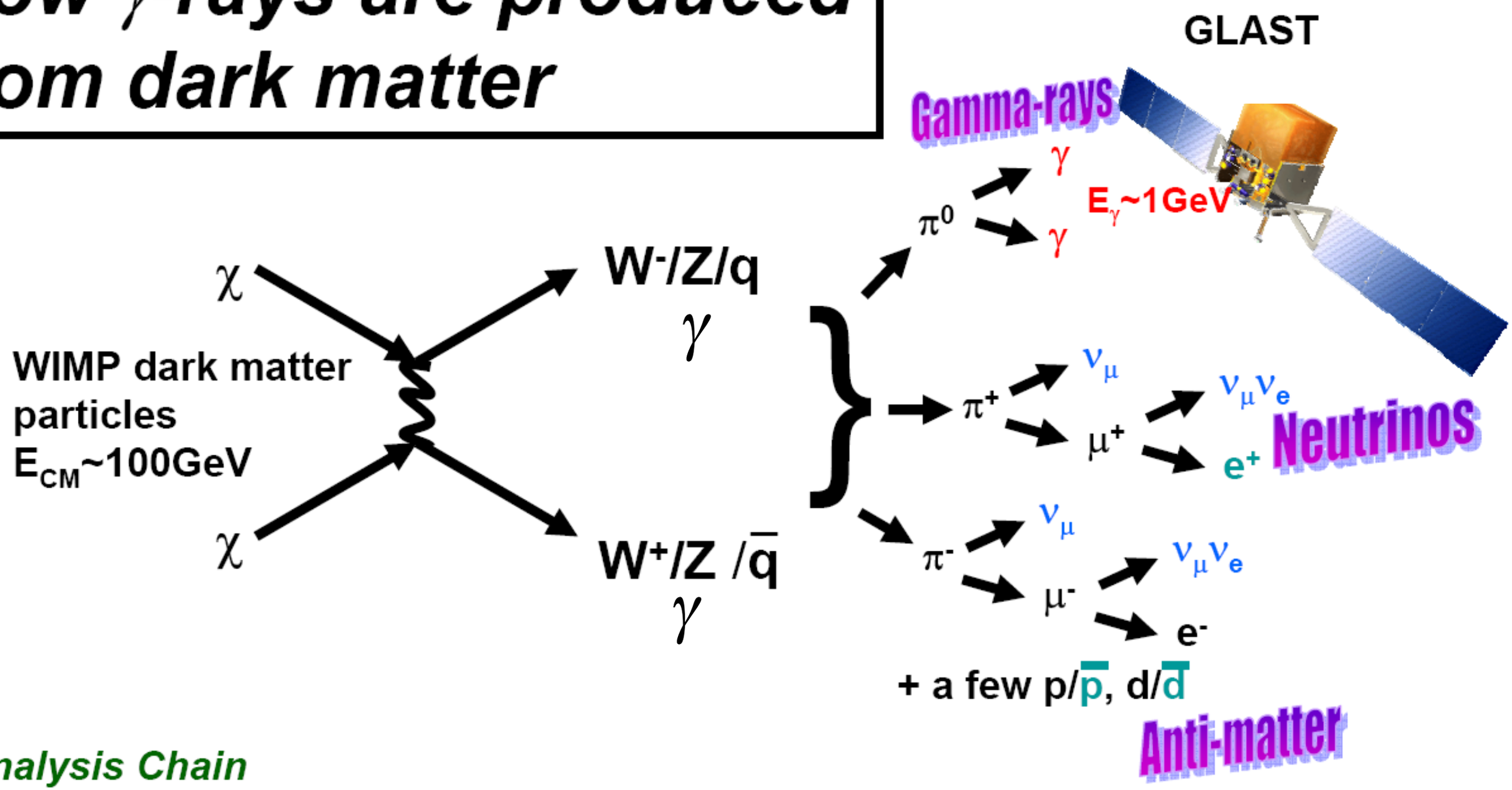


Dark matter

0.01 GeV | 0.1 GeV | 1 GeV | 10 GeV | 100 GeV | 1 TeV

How γ-rays are produced from dark matter



Analysis Chain

??

Dark matter density e.g. N-body simulation

??

New particle theory e.g. SUSY, extra-dim

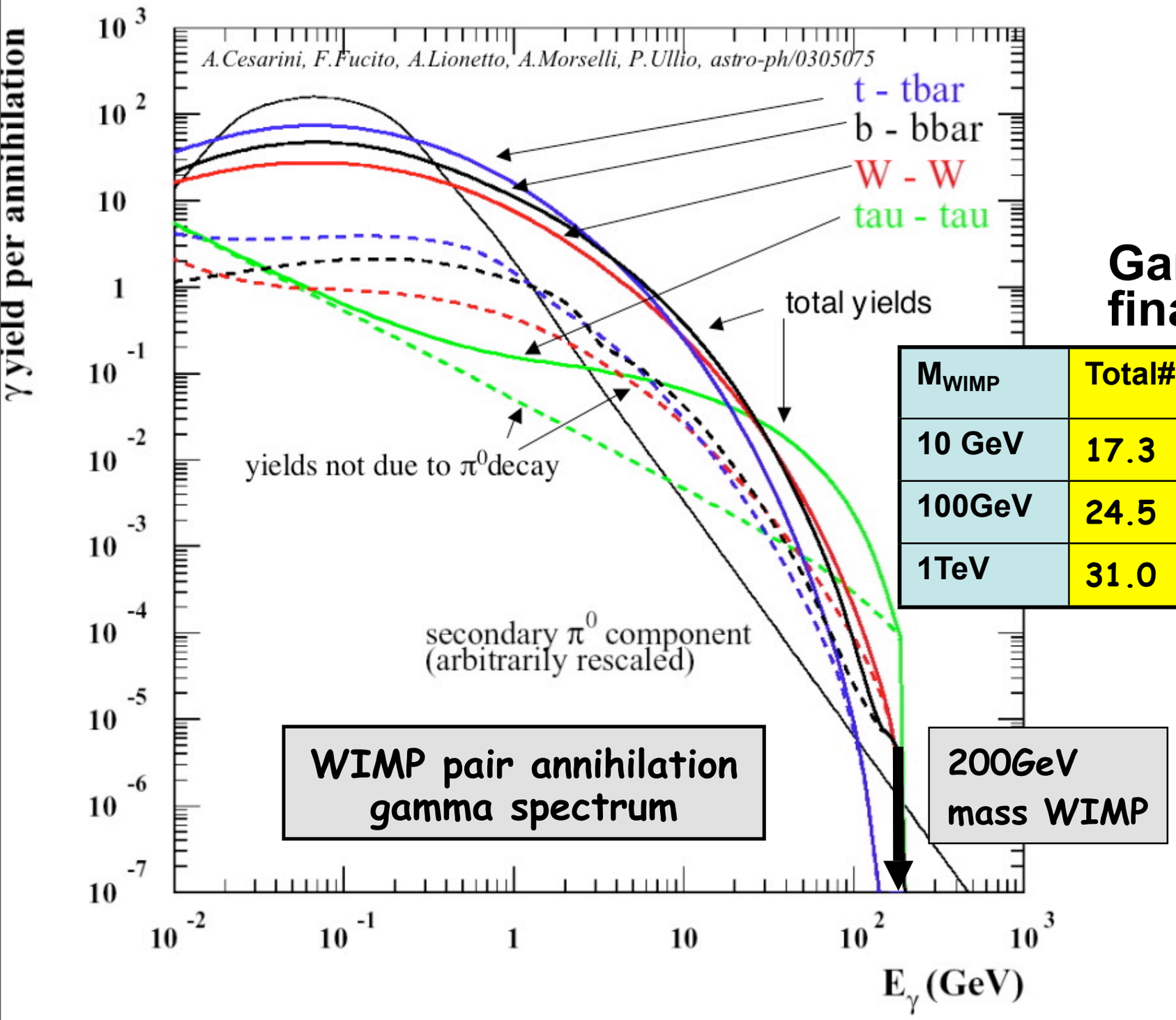
Final state hadronization e.g. PYTHIA simulation

?

Cosmic ray propogation and galactic interaction i.e. GALPROP

Detector simulation i.e. GEANT4

Gamma-rays from Neutralino Annihilation



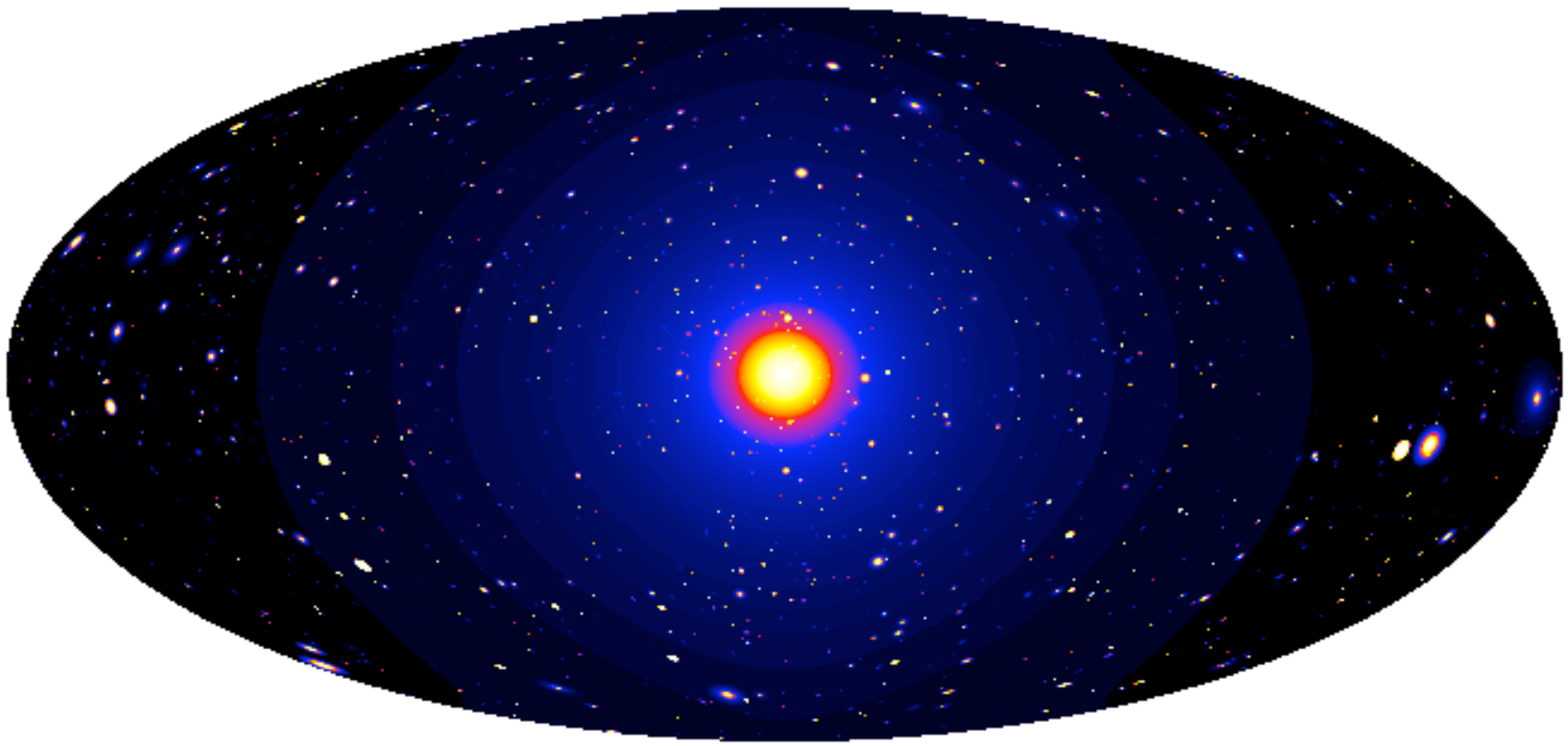
Gamma ray yield per final state bb

M_{WIMP}	Total# γ	>100MeV	>1GeV	>10GeV
10 GeV	17.3	12.6	1.0	0
100GeV	24.5	22.5	12.4	1.0
1TeV	31.0	29.3	22.4	12.3

Dark Matter in the gamma ray sky

Milky Way Halo simulated by Taylor & Babul (2005)

All-sky map of DM gamma ray emission (Baltz 2006)



Only dm annihilation radiation shown….

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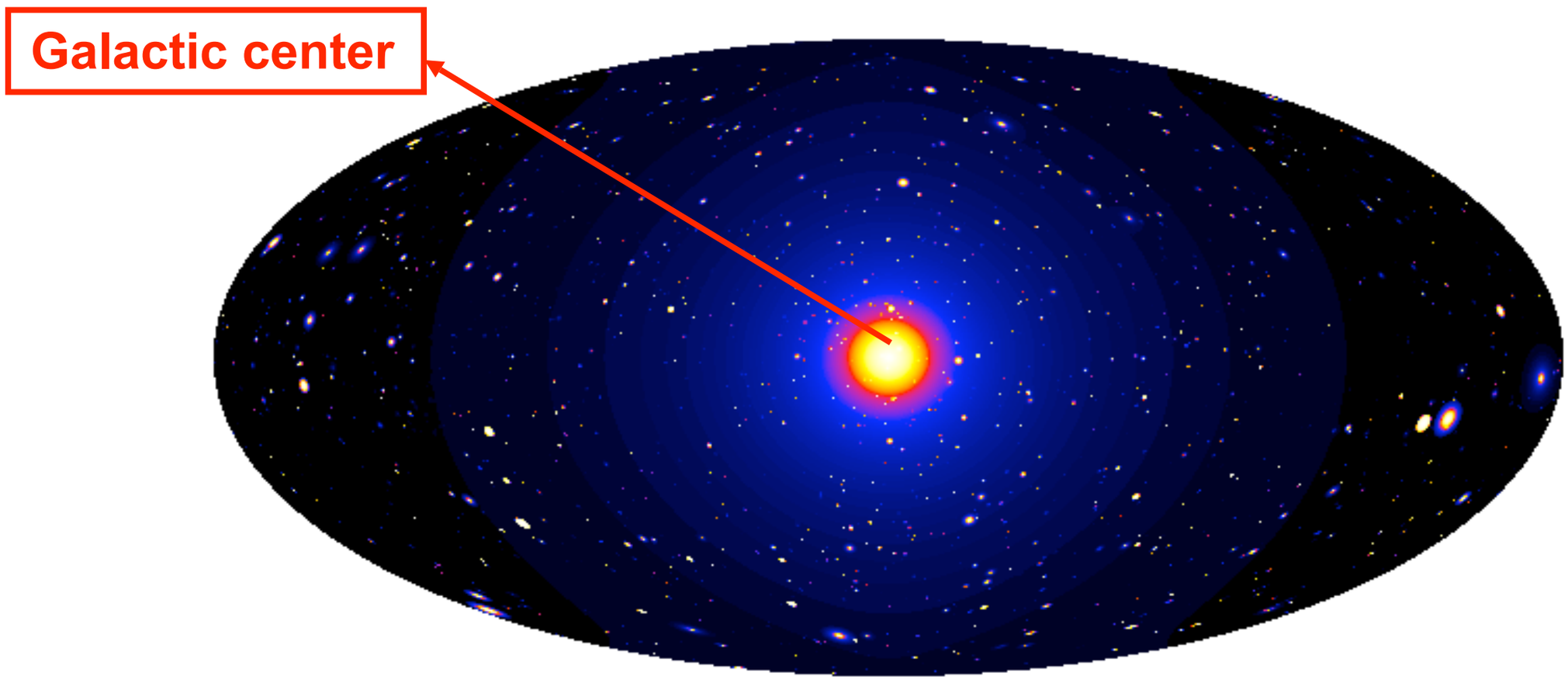

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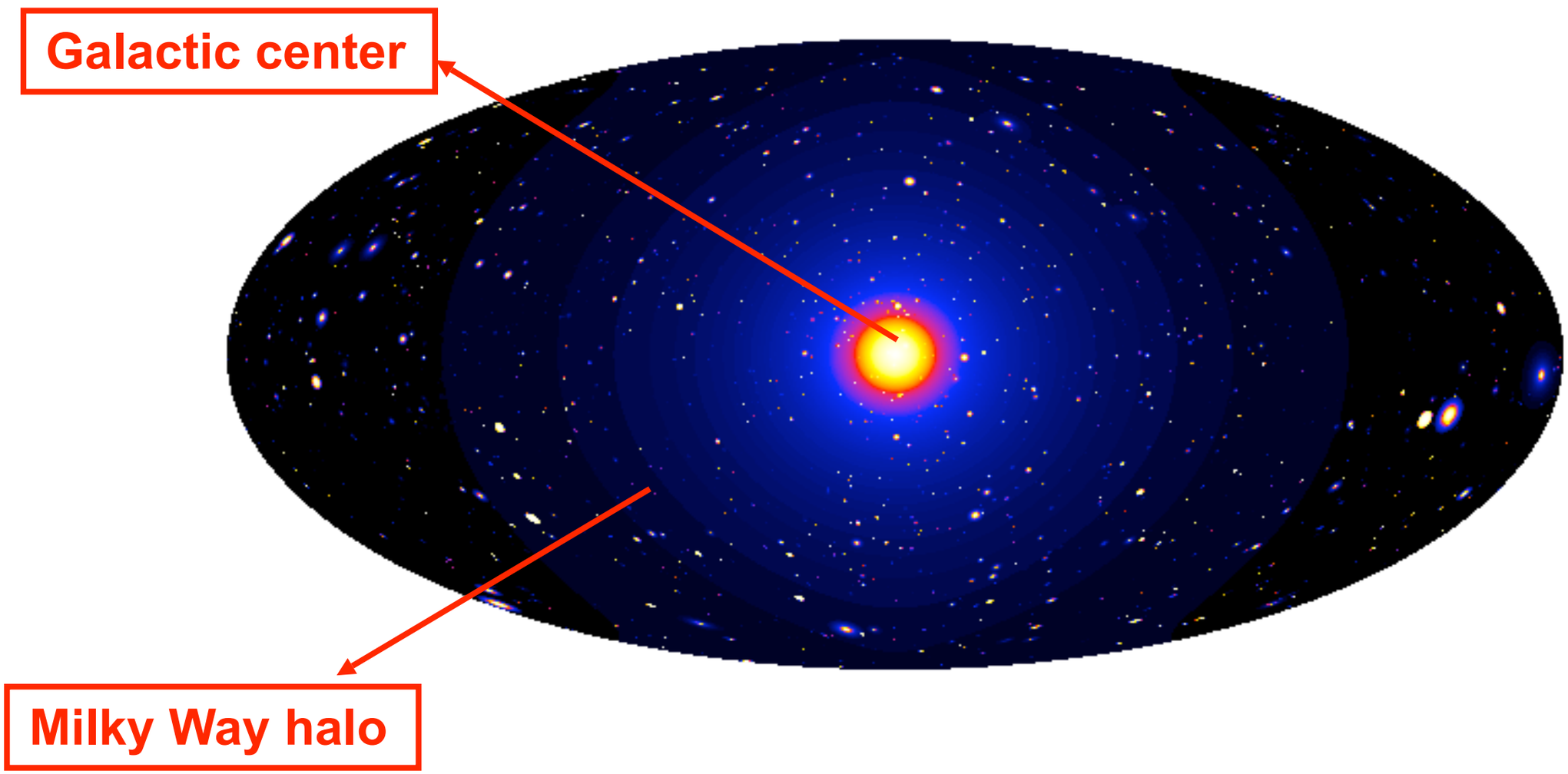

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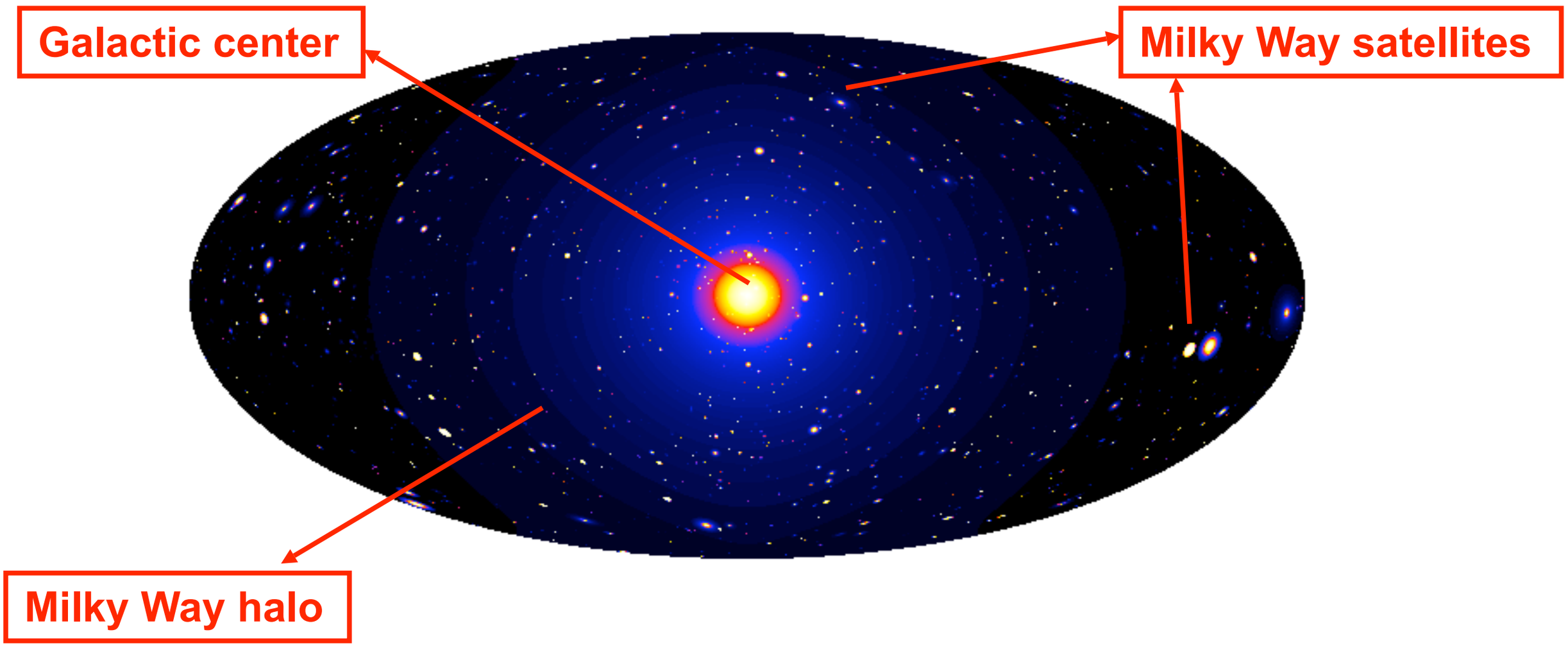

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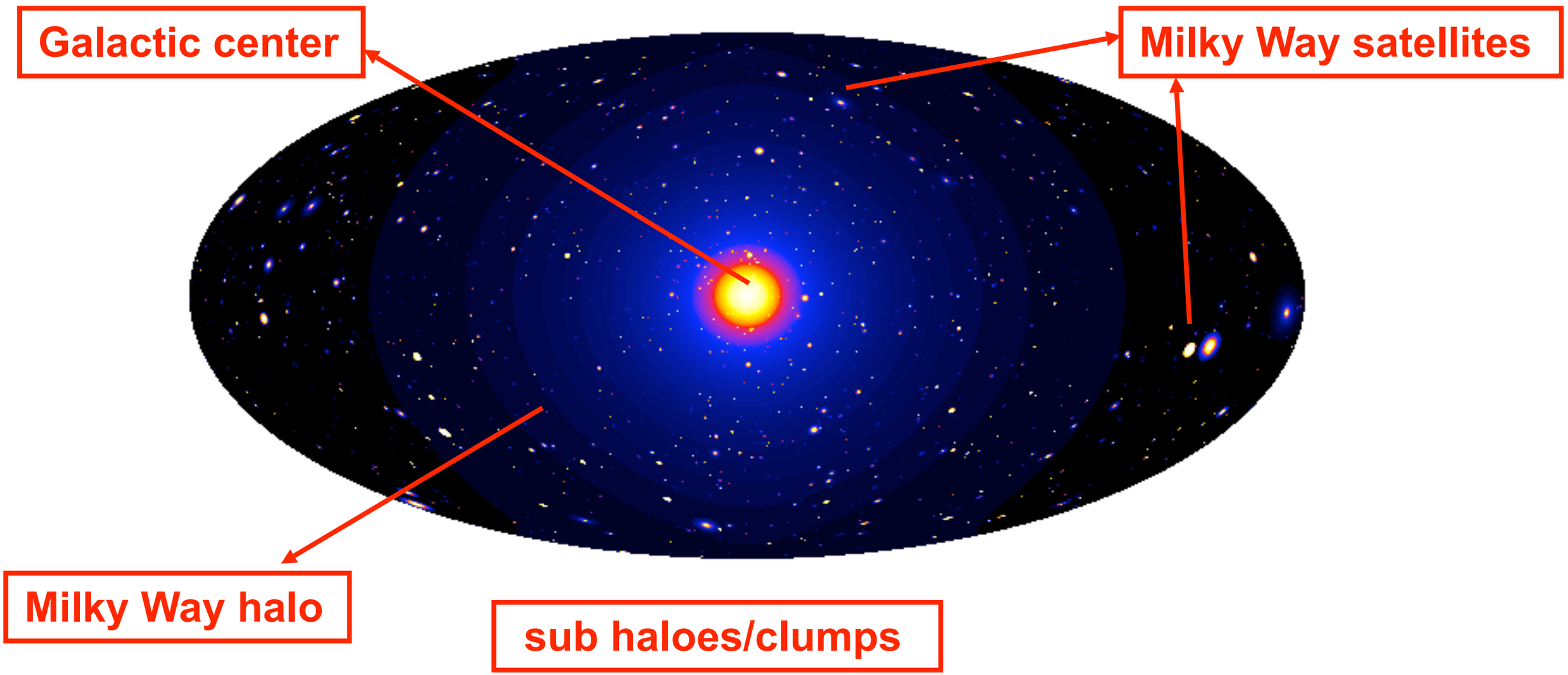

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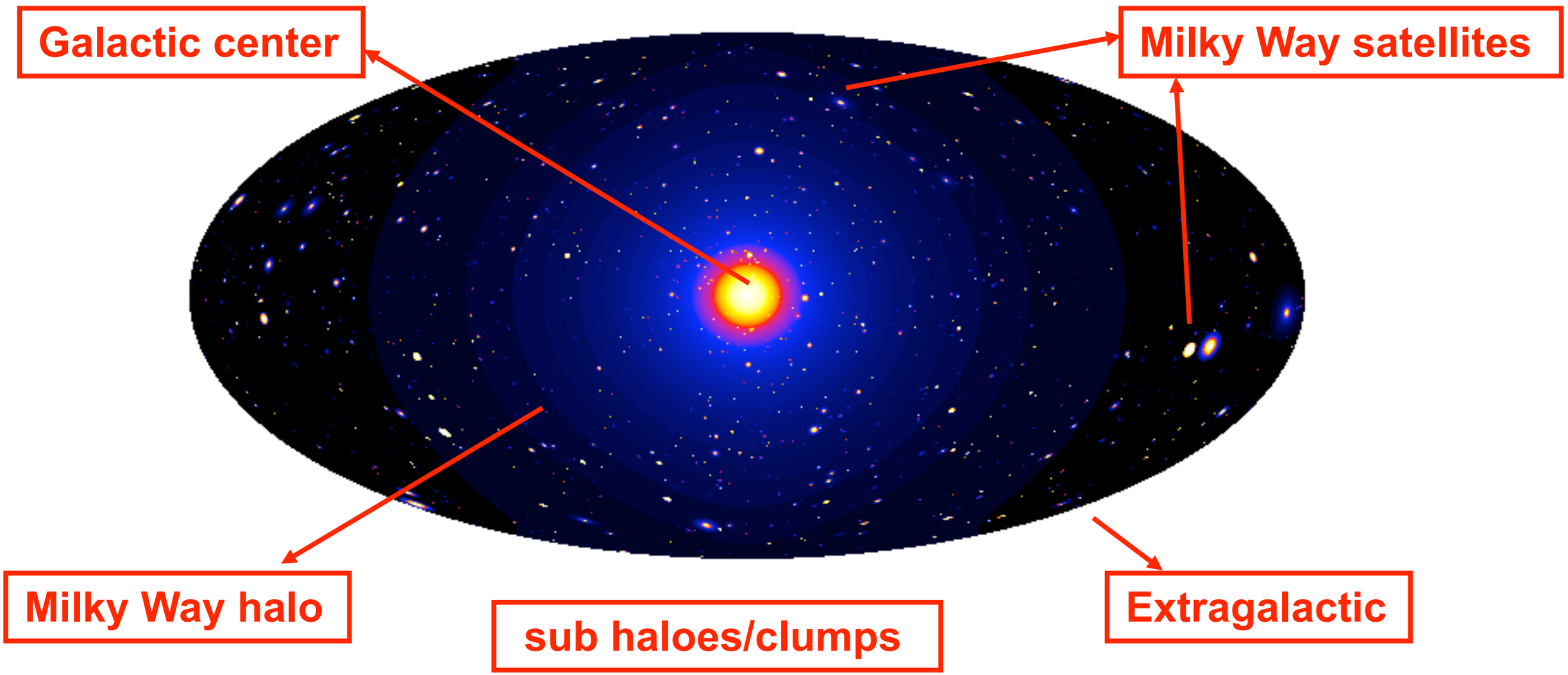

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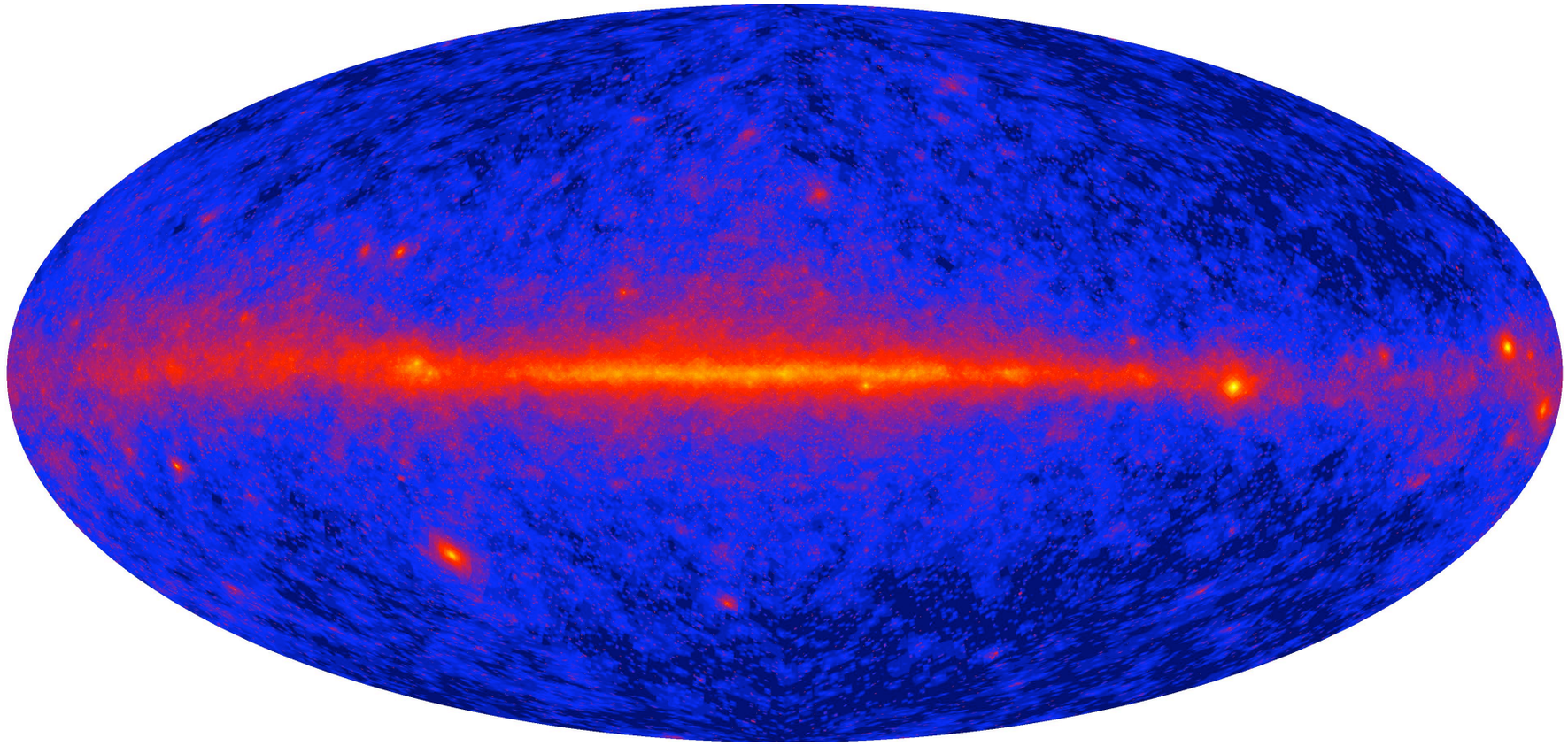
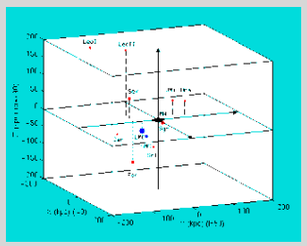
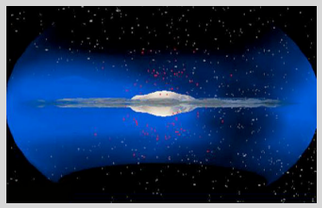
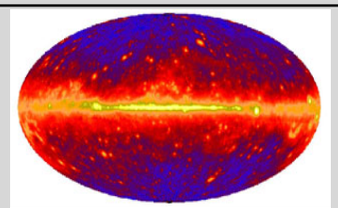
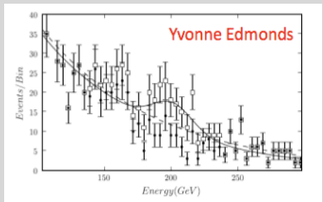
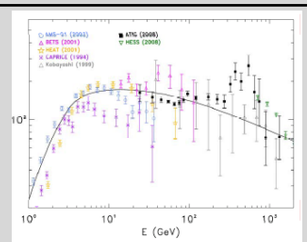


Searching for Dark Matter with Fermi

Search Technique	advantages	challenges
Galactic center	Good Statistics	Source confusion/Diffuse background
Satellites, subhalos Point sources 	Low background, Good source id	Low statistics
Milky Way halo 	Large statistics	Galactic diffuse background
Extra-galactic 	Large Statistics	Astrophysics, galactic diffuse background
Spectral lines 	No astrophysical uncertainties, good source id	Low statistics
Electrons 	Statistics	Background model

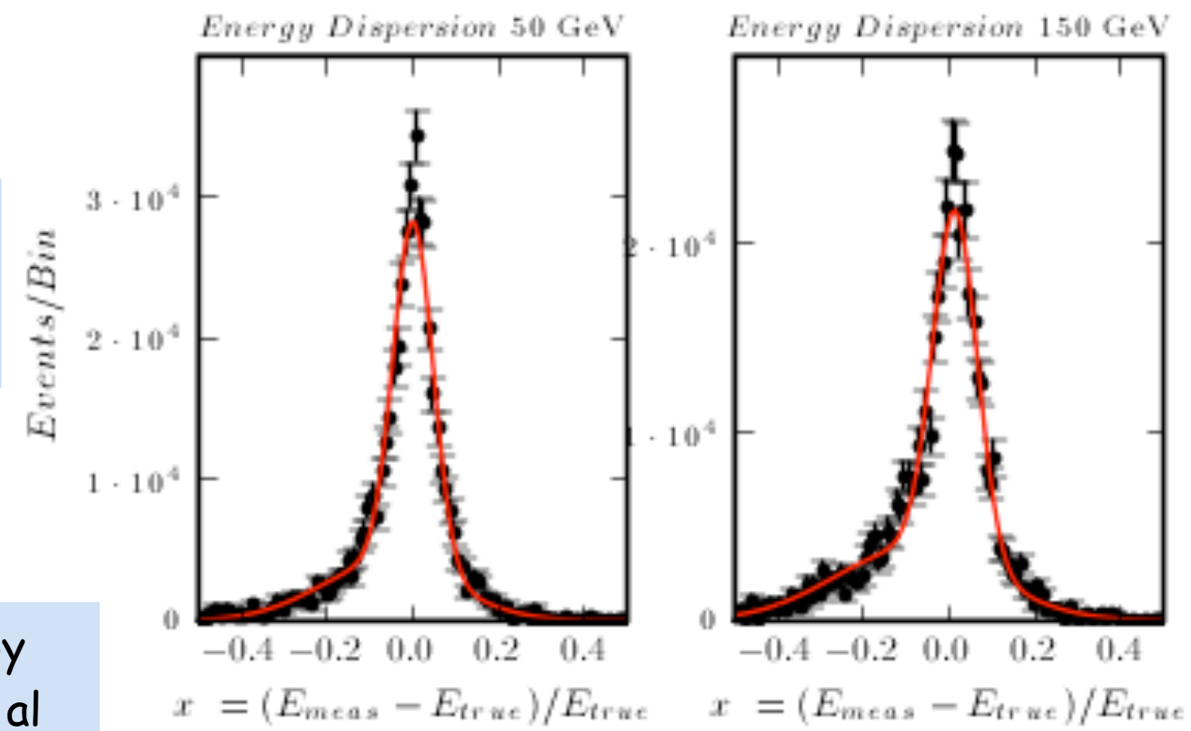
Dark Matter Line Search

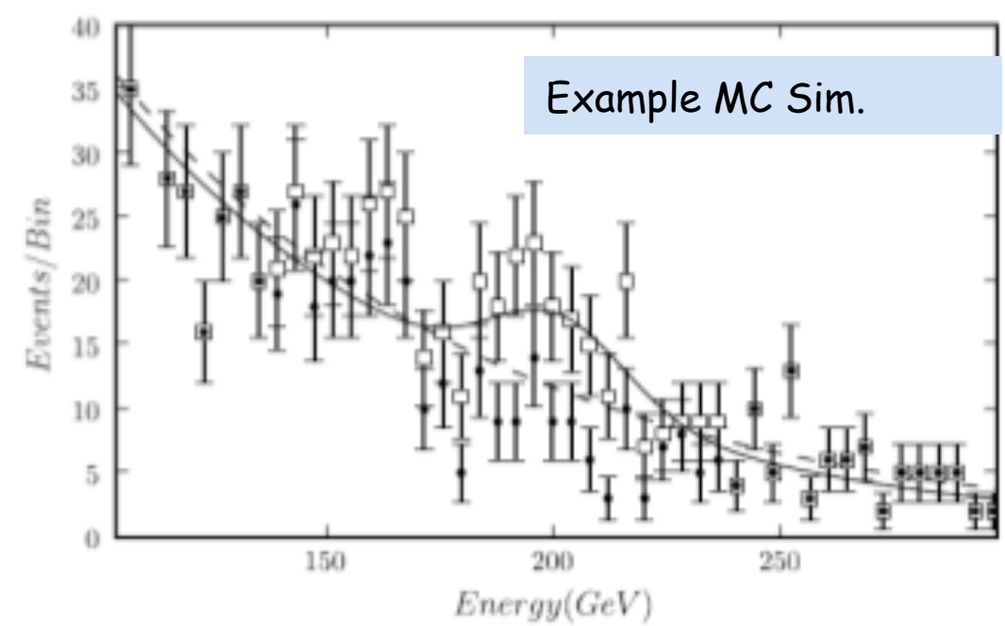
Simulated detector response to δ function in energy

- Advantage: ”Smoking Gun”
  - Backgrounds from data
- Challenges:
  - Small BR <10^{-3}
  - Energy Resolution.
- Initial Sensitivity Estimation
  - |b|>10°
  - DM Den High but reduced background
  - Scan through energy range
  - Fit Background to exponential
  - Signal Fit Double Gaussian

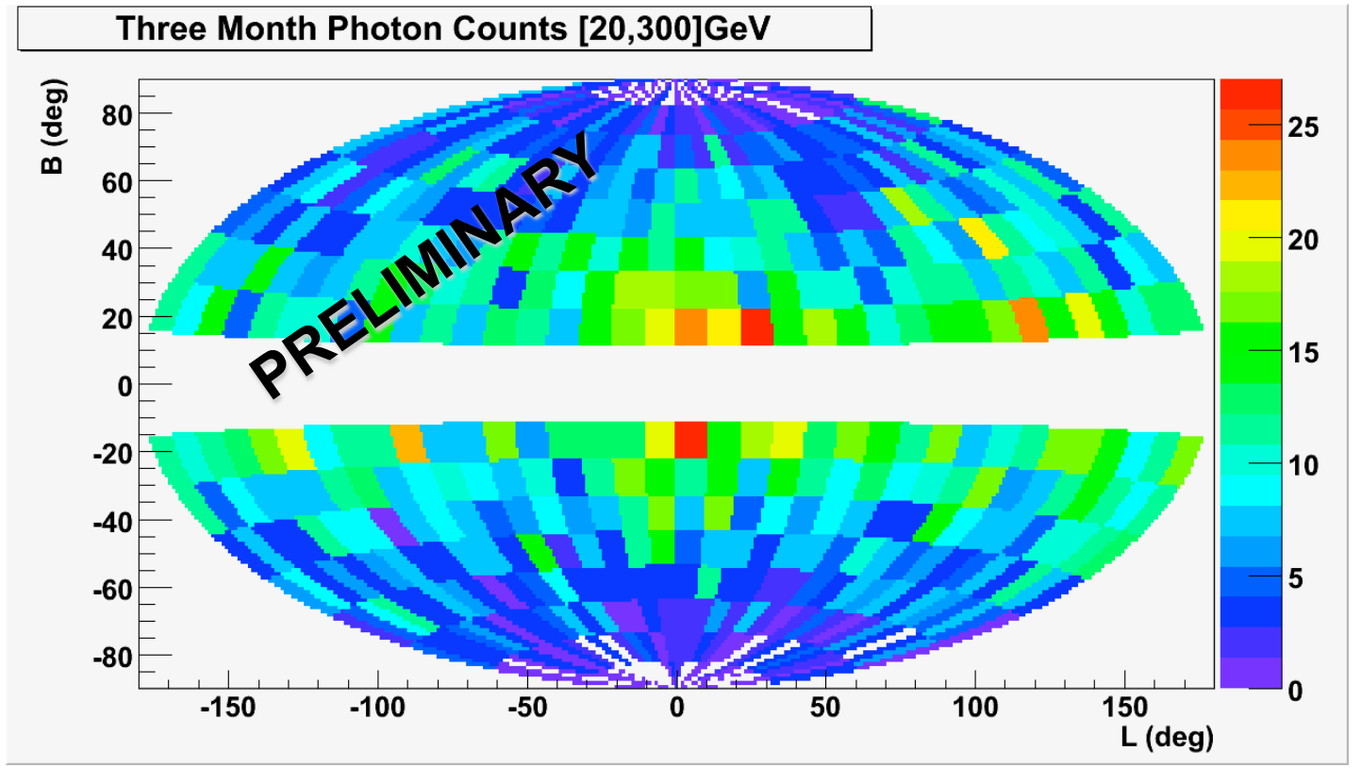
Some recent models predict enhancements.

Proposed by Stoehr, et al





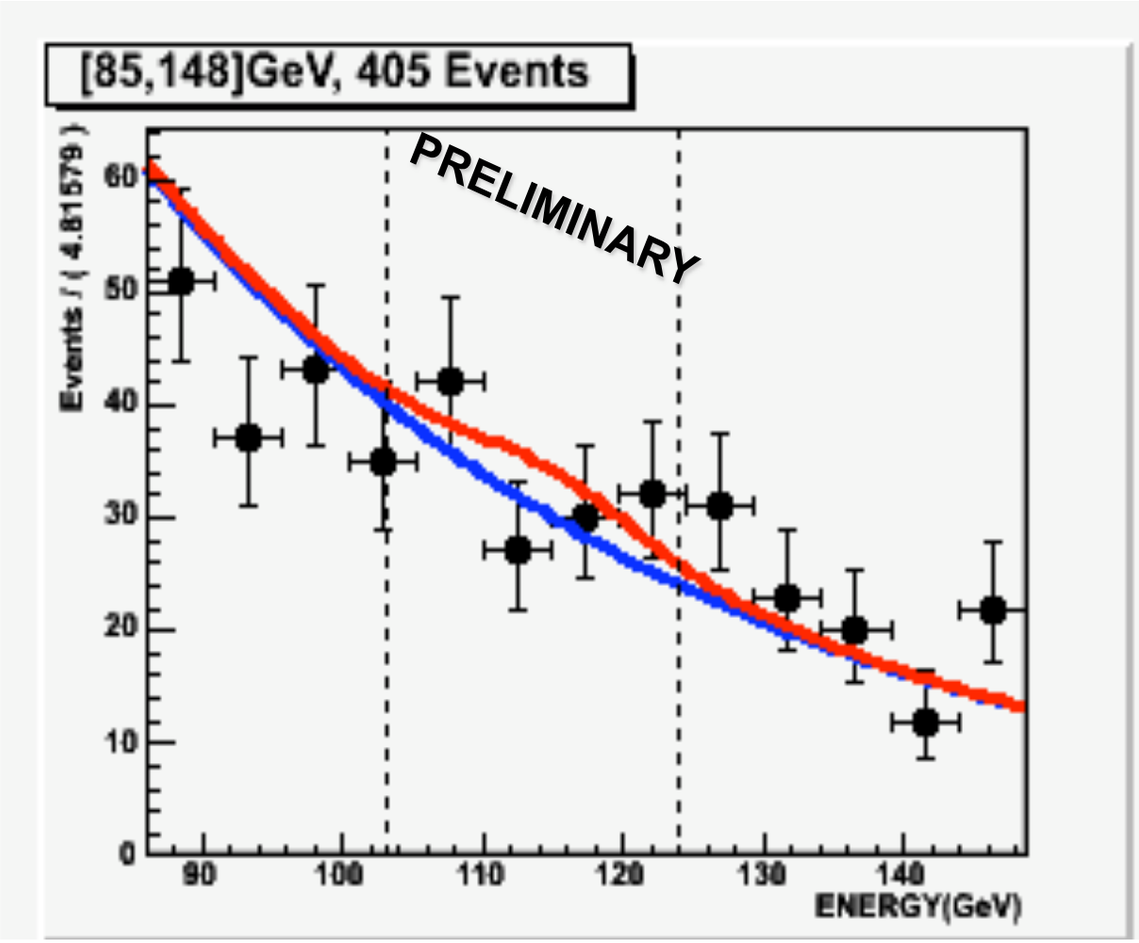
Search for Lines



- August 8th 2008 + 90 days: Used to prepare for "Blind" 1 year analysis
- All-sky survey mode
- Removed Galactic Plane |B|<10
- Energy : [20,300] GeV
- Diffuse Class Cuts
- PSF at 20 GeV is ~0.1°
  - Removed point sources using the Three Month Source Catalogue : 0.2° cut radius

Preliminary Three Month Dataset

- Instrument resolution ~10% at 100 GeV
  - Used bins of size $\Delta E/E$ = 20%
- **Background fitting**
  - Unbinned Maximum Likelihood Fit to sb region
  - Side bands of size $\Delta E/E$= 20%
  - $B(E) = e^{-\alpha E}$, background pdf
  - Normalized to sideband counts, N_{sb}
- **Signal + background fitting**
  - Fix background counts, N_b, and $B(E)$.
  - $S(E)$ = signal pdf, fixed at the center of bin
  - $PDF = N_b B(E) + N_s S(E)$
  - Unbinned ML Fit to sb+center region to find N_s
  - Signal constrained to be nonnegative
- For the one year analysis other statistical methods are being explored

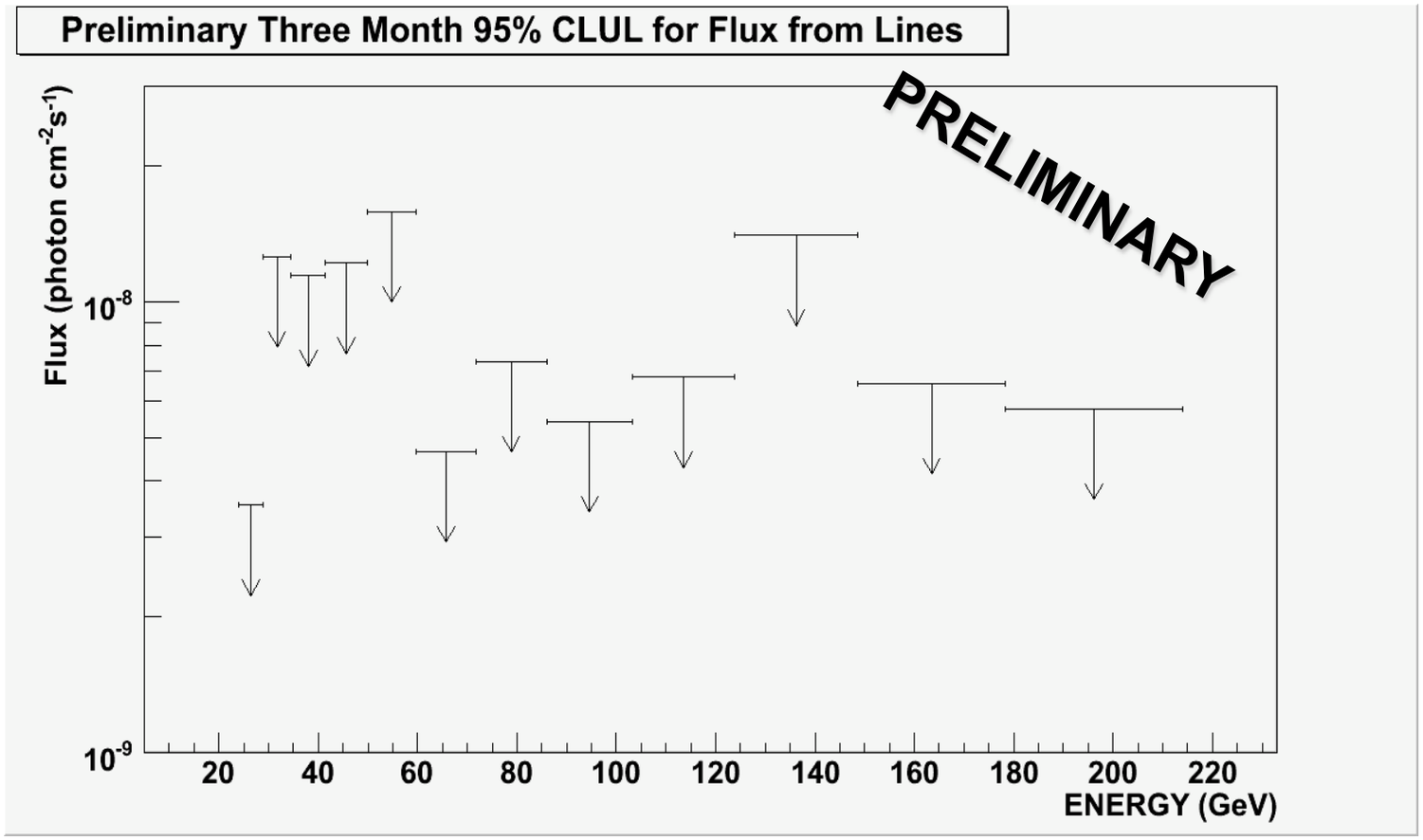


Example Fits and NLL for [85,148]GeV

95% CLUL Fitting

Preliminary Three Month 95%CLUL to Lines

(All Sky minus |B|<10)

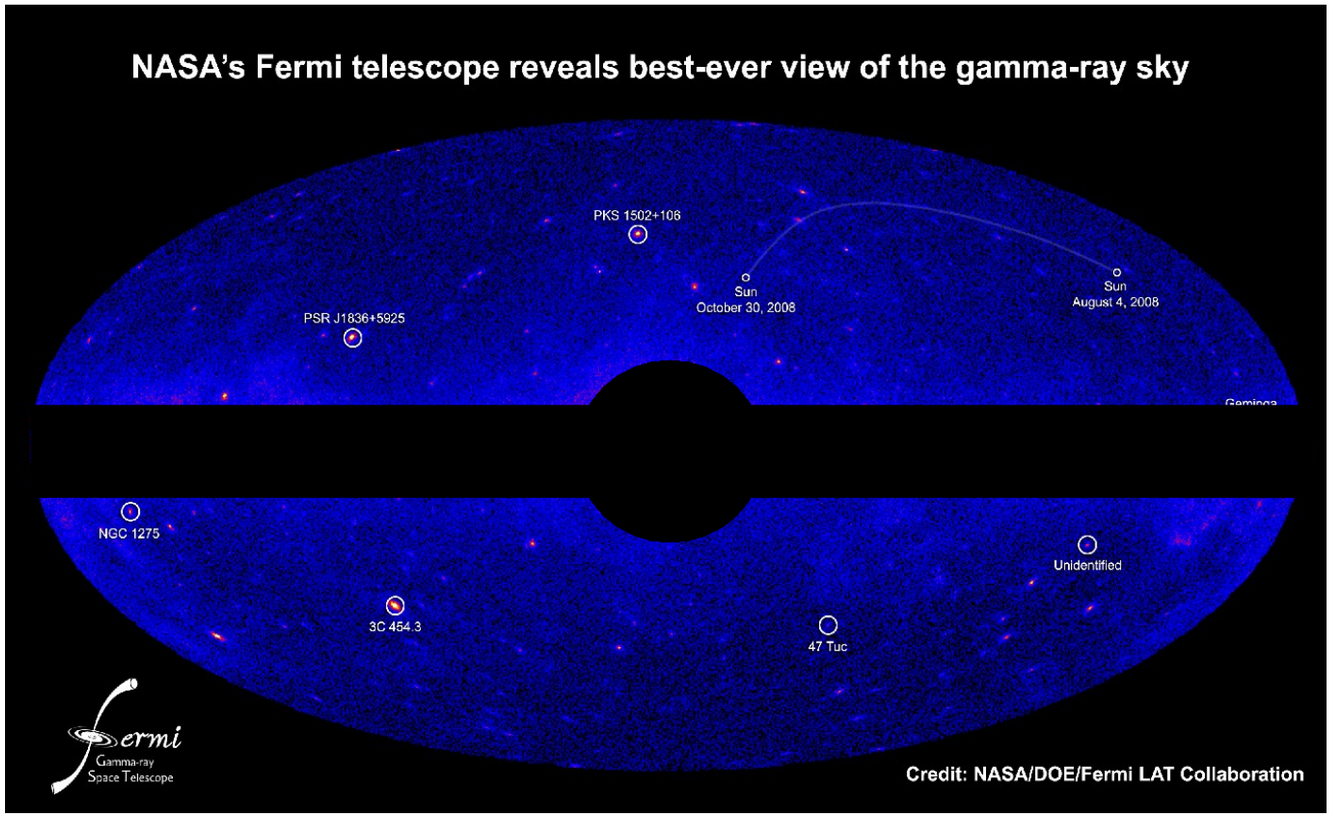


Note: No trial factor included

$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{4\pi M_{\chi}^{2} \Phi_{\gamma\gamma}}{\int_{0}^{\infty} dl \int_{ROI} d\Omega \rho^{2}(l, b, l)}$$

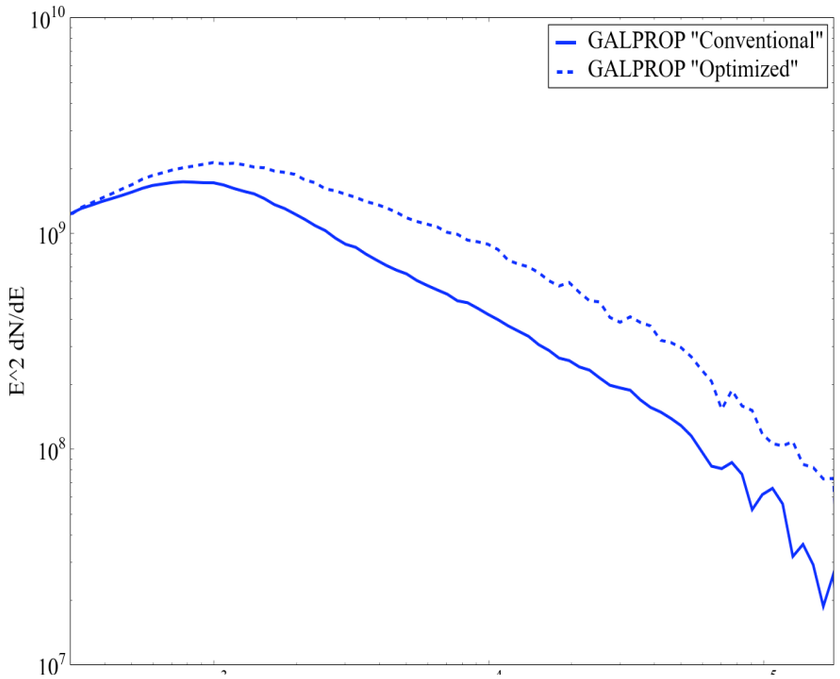
Galactic Halo Analysis

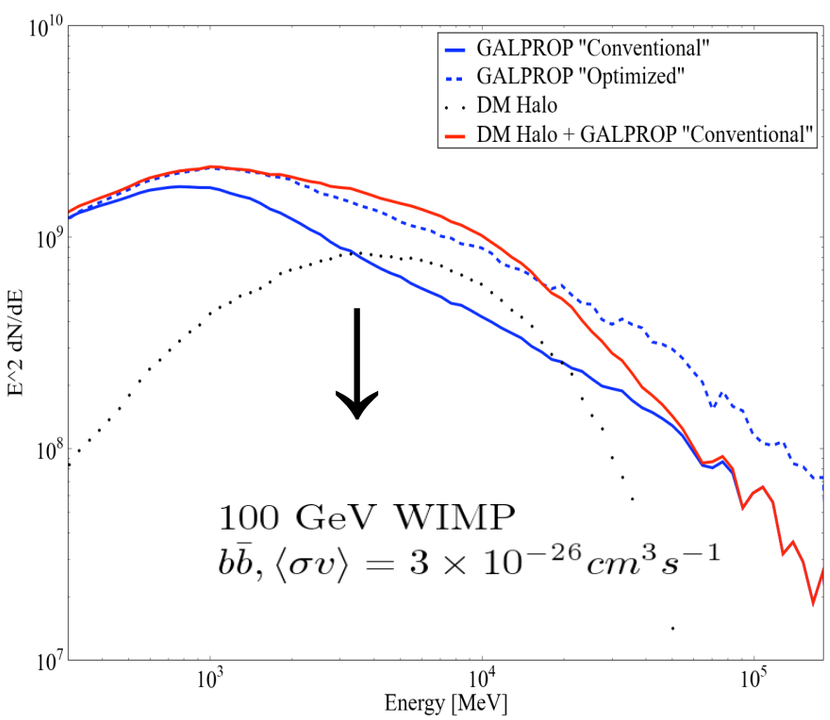
- Advantage:
  - ★ Use the large statistics of the full sky.
- Challenge:
  - ★ Critically Dependent on Diffuse Background
- Measure the sensitivity to observing a signal.
  - ★ ROI = R>10° or |b|>10°
  - ★ NFW Profile.
  - ★ Diffuse Background:
    - ✦ GALPROP (Conv., Opt.)
  - ★ Simultaneous Fit to both spatial and energy distributions

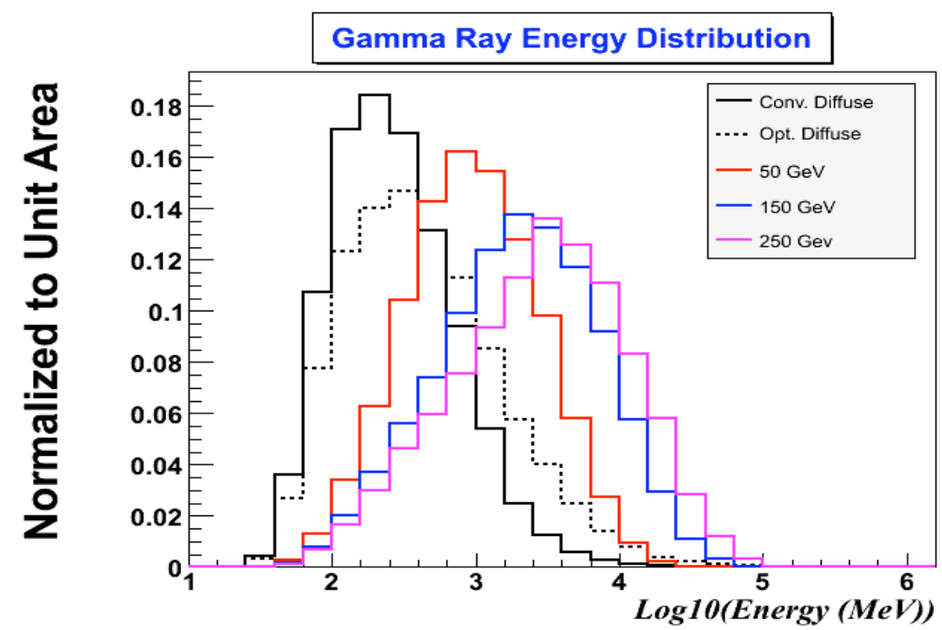


Energy Spectrum including DM

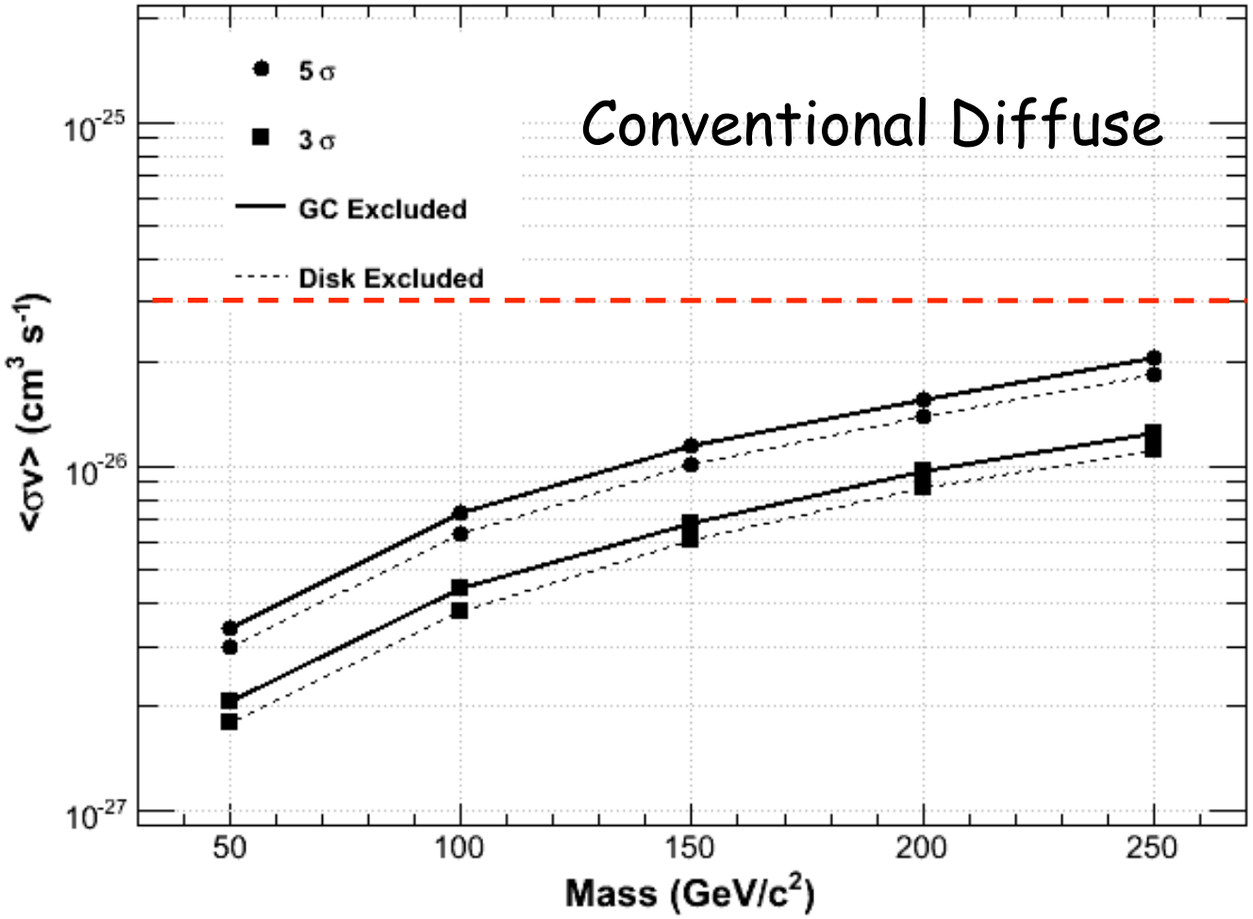
One Year MC, All-sky, using LAT Science Tools







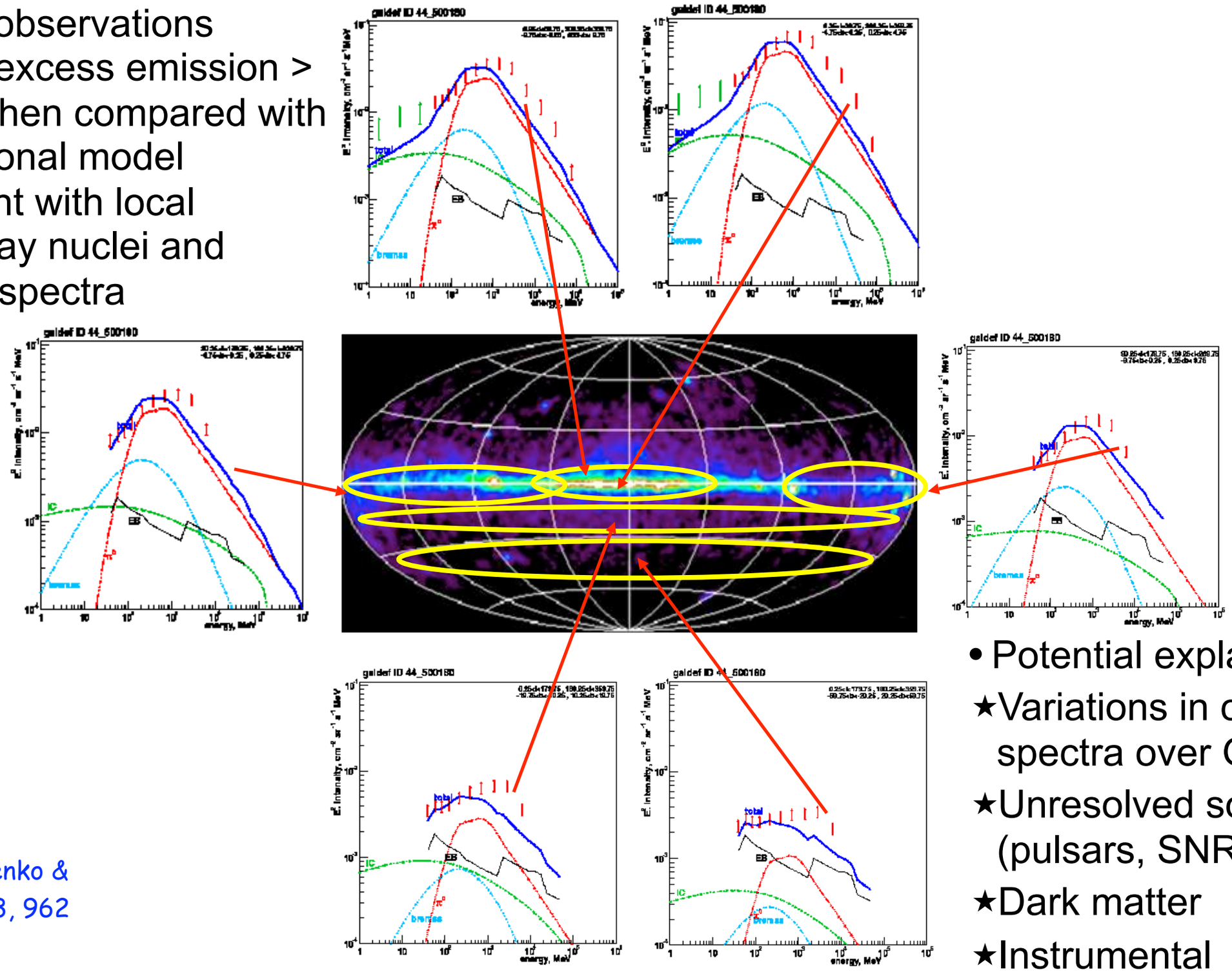
Expected Sensitivity for Galactic Halo Analysis



- Annihilation cross section required for a 5-sigma signal after one year of exposure.
- Only statistical fluctuations taken into account – background assumed known.
- LAT is now in a position to begin to measure this background

EGRET GeV Excess

- EGRET observations showed excess emission > 1 GeV when compared with conventional model consistent with local cosmic-ray nuclei and electron spectra

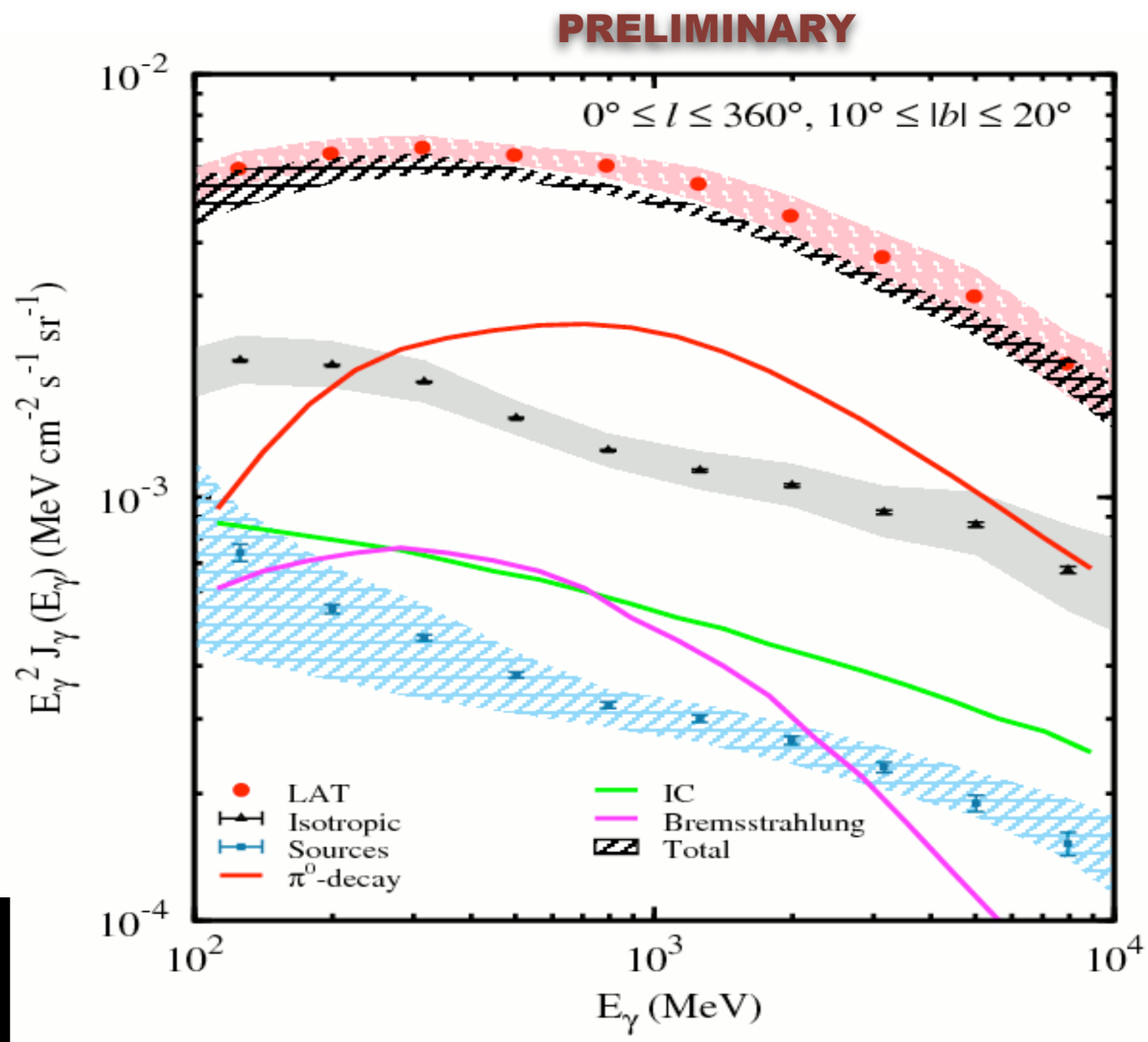


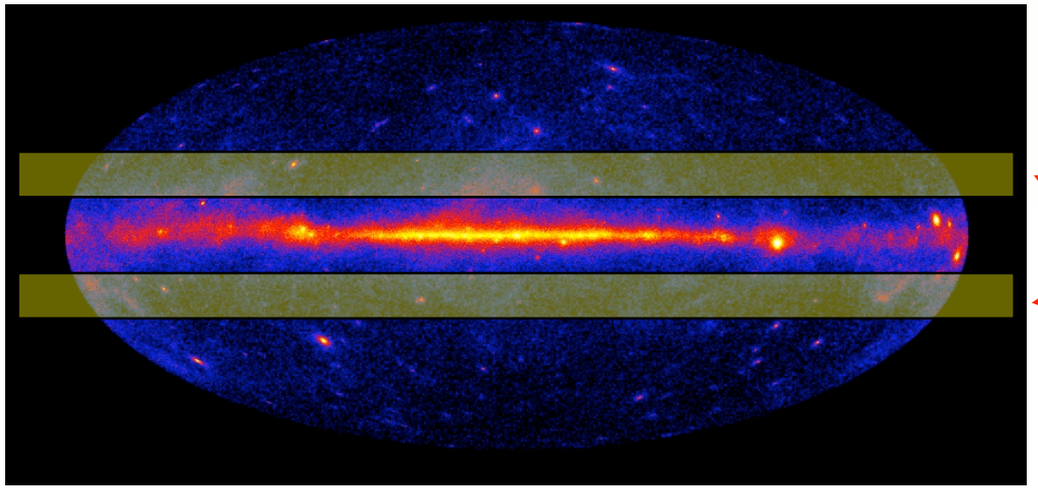
- Potential explanations
  - ★Variations in cosmic-ray spectra over Galaxy
  - ★Unresolved sources (pulsars, SNRs, …)
  - ★Dark matter
  - ★Instrumental

Strong, Moskalenko & Reimer ApJ 613, 962 (2004)

LAT Measurements vs Assumed Model

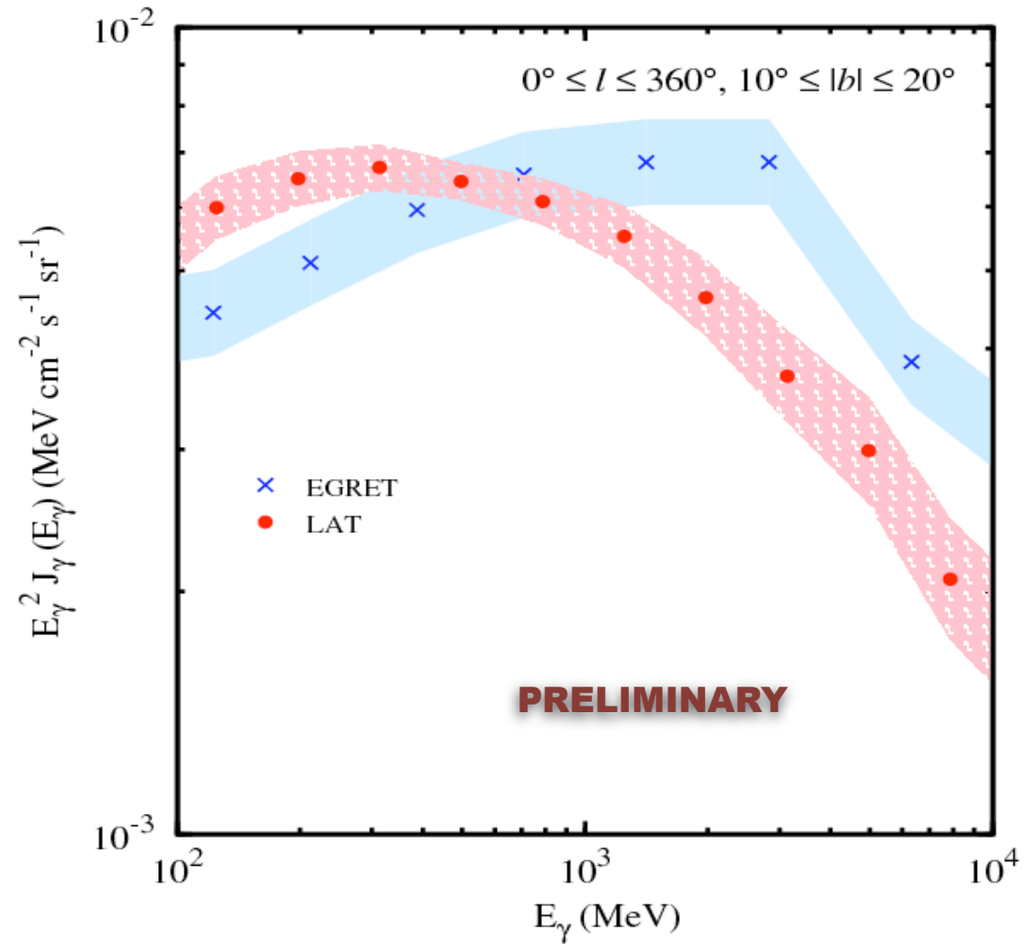
- Model is assumed (based on pre-Fermi data)
  - ✓ π^0-decay
  - ✓ Bremsstrahlung
  - ✓ inverse Compton
- Source and isotropic (including residual background) component come from fitting the data with model fixed
- Results: spectral shape is consistent with data but overall emission lower for whole energy range

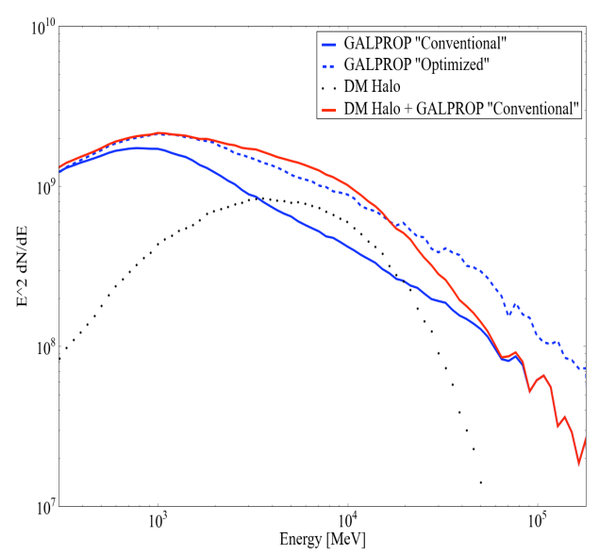




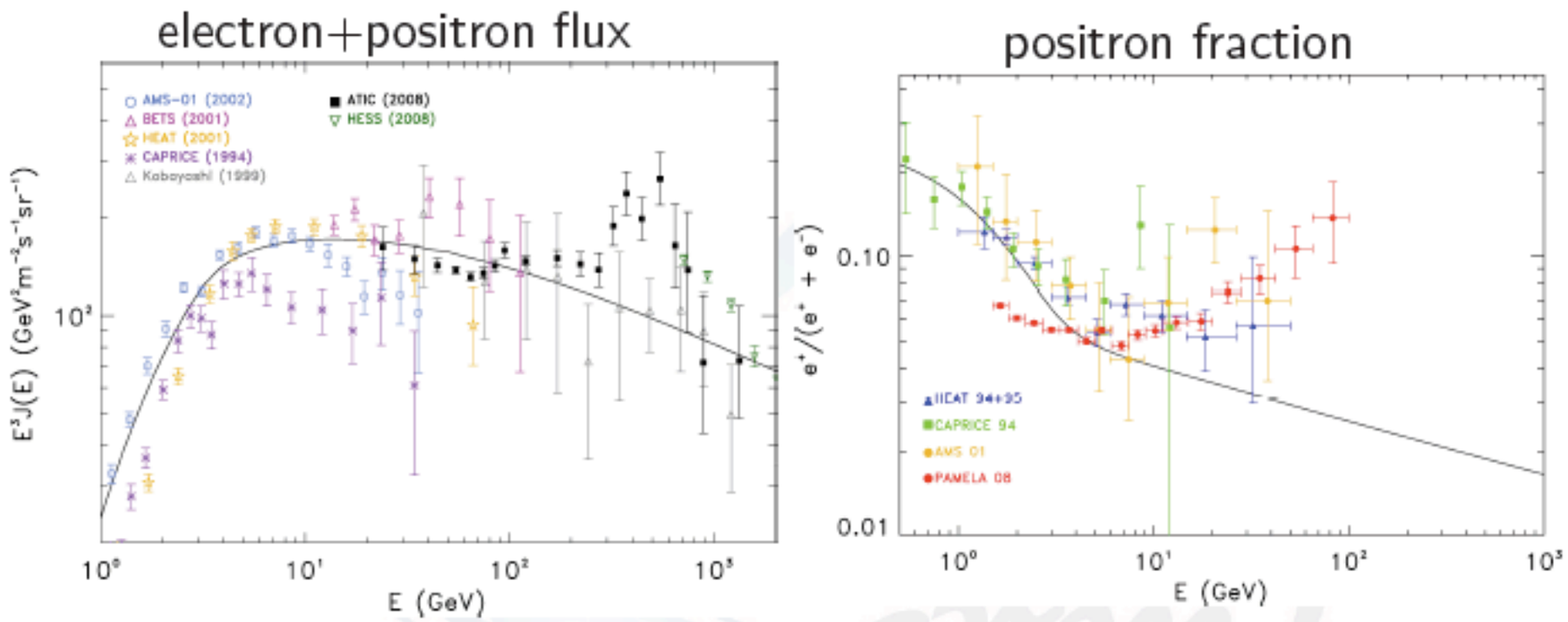
EGRET vs. LAT mid-latitude region

- Data from mid-August to end of December for 10°≤|b|≤20°
- EGRET data retrieved from GSSC (counts, exposure), processed, spectrum extracted for same region
- LAT spectrum is significantly softer than EGRET → we do not confirm the EGRET GeV excess
- The model uncertainties in the galactic diffuse emission can not be neglected with respect to the expected signal from dark matter.





Dark Matter Searches With Electrons



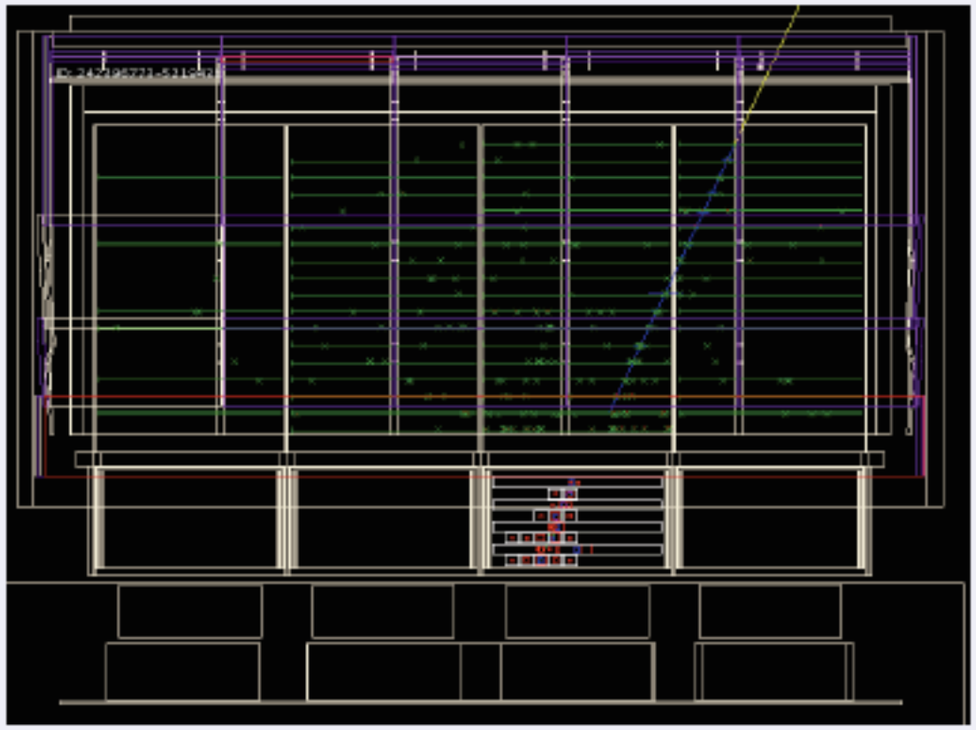
- Spectral features in the $(e^+ + e^-)$ spectrum
  - possible excess around 600 GeV reported by ATIC and PPB-BETS
  - spectral cutoff measured by H.E.S.S. around 1 TeV
- Pamela reports an excess in the positron fraction

$\Rightarrow$ $>$ 30 papers mentioned these results the past few months

$\Rightarrow$ Nearby sources expected ? astrophysical or exotic origin ?

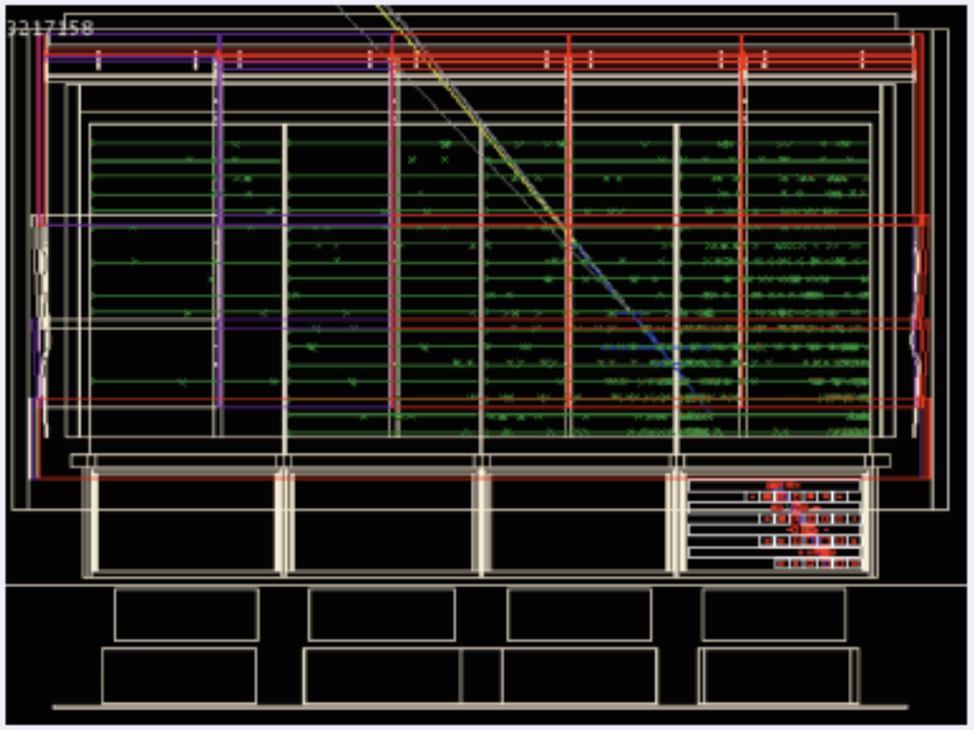
Electrons and Hadrons With Fermi

Electron candidate



- few ACD tile hits in conjunction with the track
- clean main track with extra-clusters very close to the track - note backsplash from the calorimeter
- well defined symmetric shower in the calorimeter, not fully contained

Hadron candidate

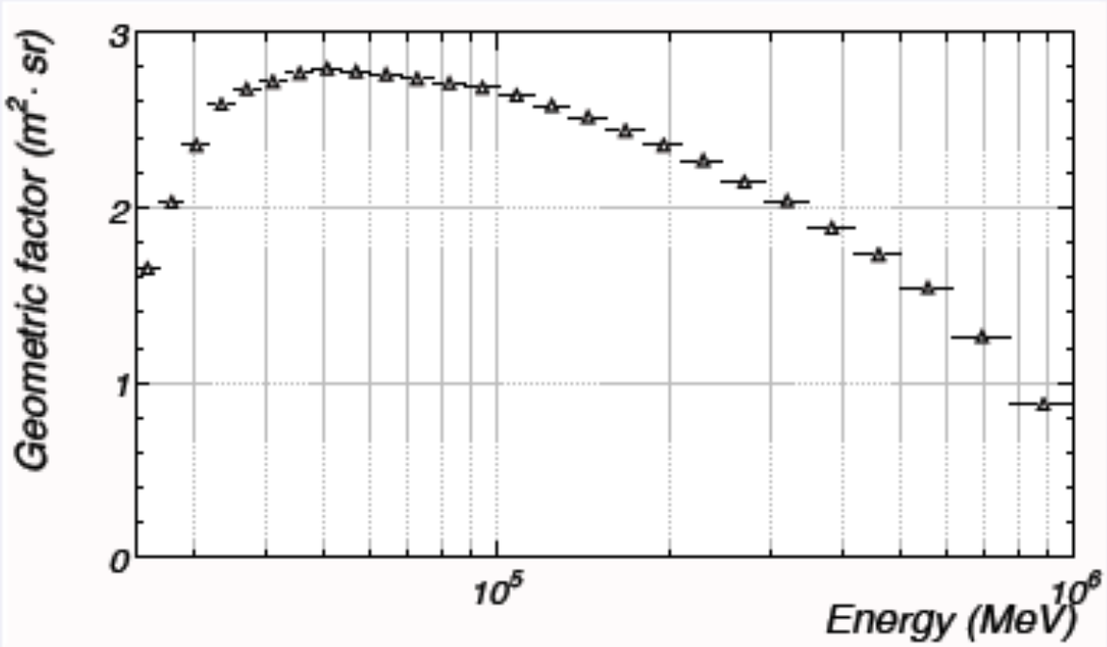


- large energy deposit per ACD tile
- small number of extra clusters around main track, large number of clusters away from the track
- large and asymmetric shower profile in the calorimeter

- *All* events with on-board energy greater than 20 GeV are sent to ground for offline analysis
- The LAT cannot distinguish between electrons and positrons
  - ⇒ hereafter, electrons will mean *electrons+positrons*

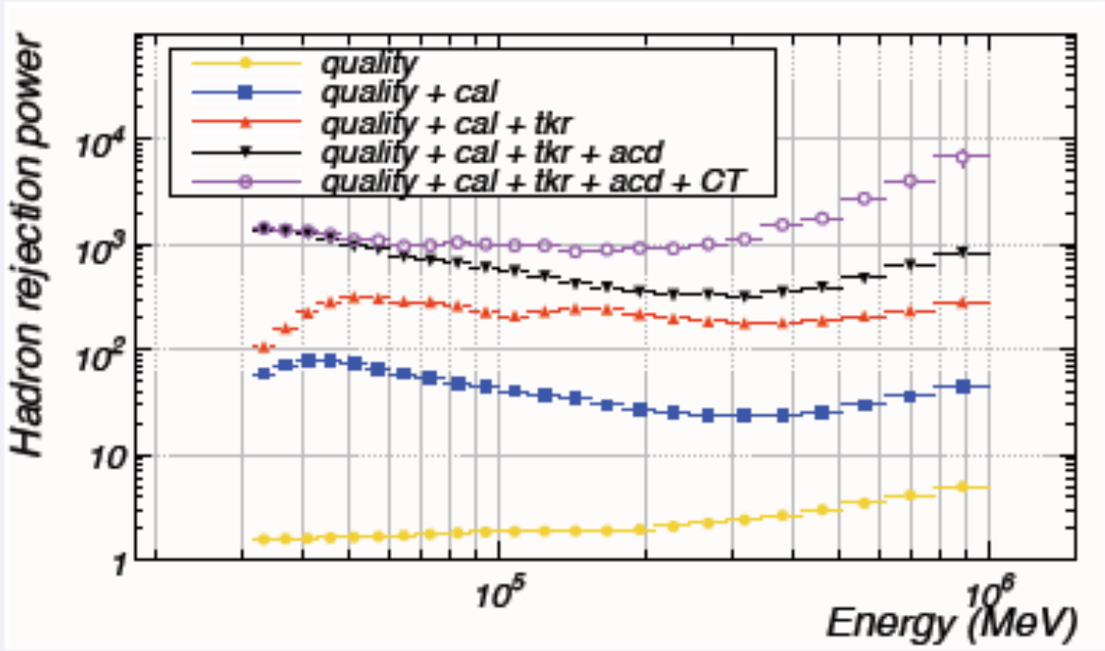
Fermi Electron Efficiency and Rejection

CRE geometry factor



- 2.8 m^2 peak geometry factor
- 2 m^2 at 300 GeV
- almost 1 m^2 at 1 TeV
- an order of magnitude larger than previous experiments

Hadron rejection power

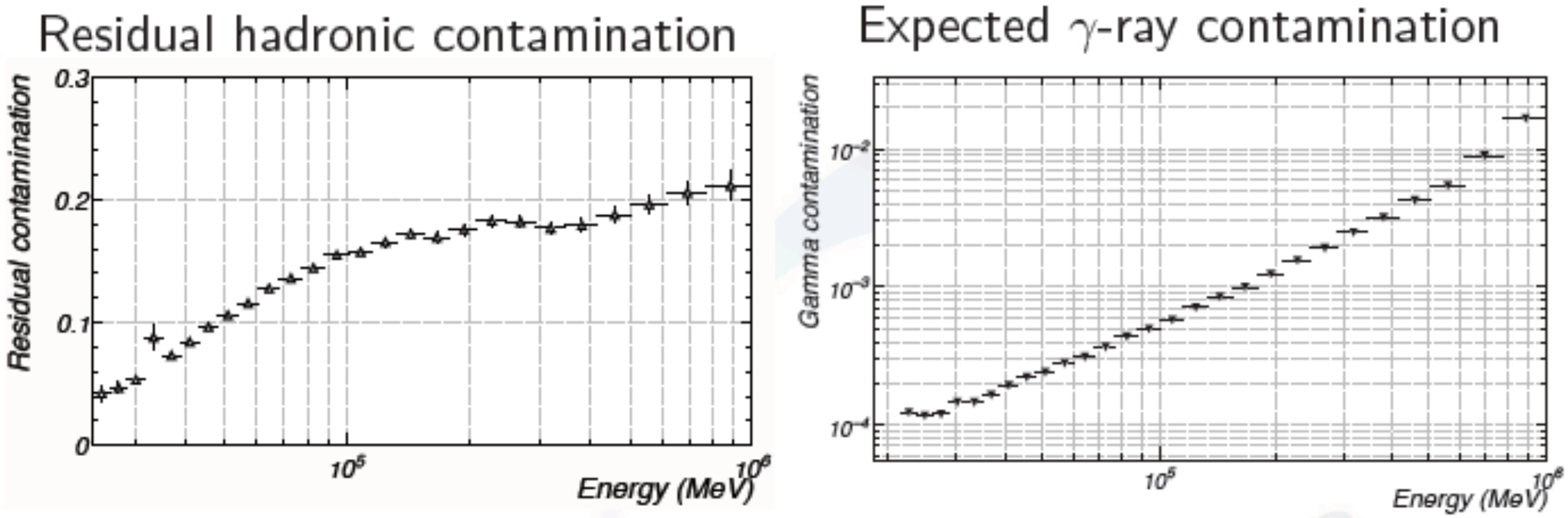


- rejection power with respect to what triggers
- pre-filter : all three sub-systems (ACD, TKR and CAL) contribute
- 2 classification trees combined, based on TKR and CAL variables

→ boost of the rejection power at high energy

⇒ Find the best trade-off between electron selection efficiency, hadron rejection power and reasonable systematic uncertainties

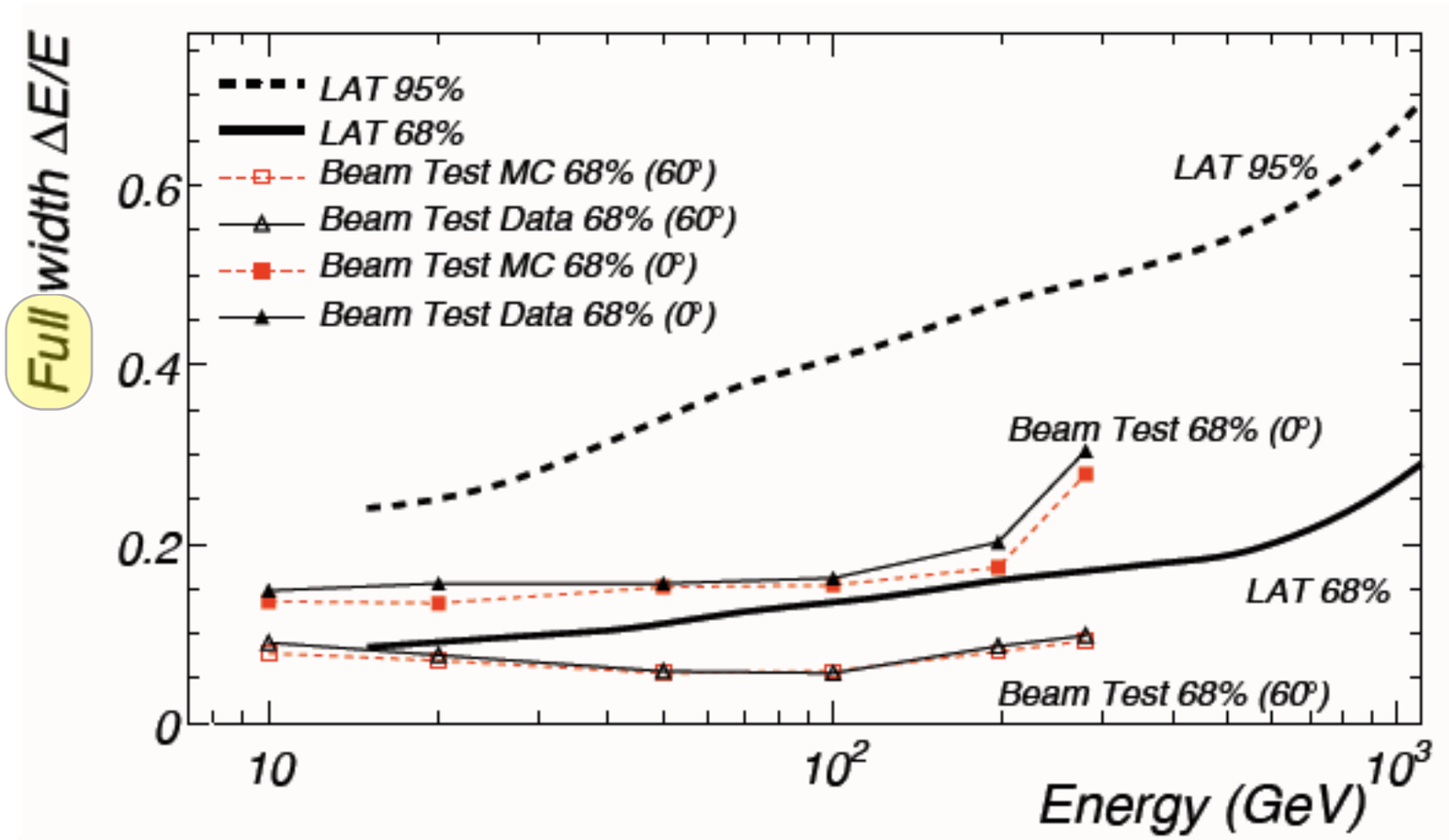
Fermi Residual Backgrounds



- Hadronic contamination rises from few percent to $\simeq$ 20% over the whole energy range
  - estimated from a large Monte-Carlo simulation, using *standard* cosmic ray models from 10 MeV to 10 TeV
  - subtracted from the candidate electrons
- γ-ray contamination is less than 2% in the highest energy bin
  - conservative estimation extrapolating EGRET total γ-ray flux measurement

  $\rightarrow$ not subtracted from the candidate electrons

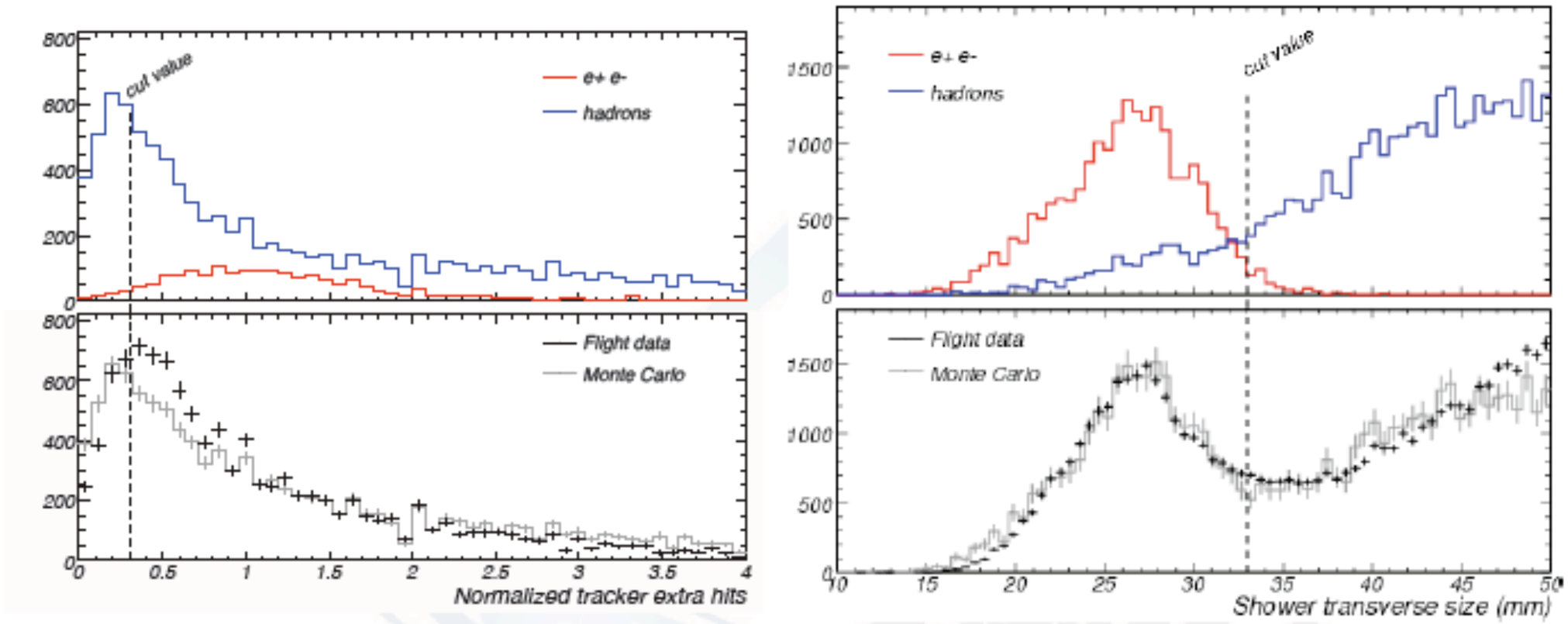
Fermi Energy Resolution for Electrons



- Validated with the Calibration Unit beam test up to 282 GeV
  - excellent agreement over the whole phase space
  - reasonable to trust the Monte-Carlo up to 1 TeV

⇒ The energy dispersion is adequate to measure the CRE spectrum up to at least 1 TeV

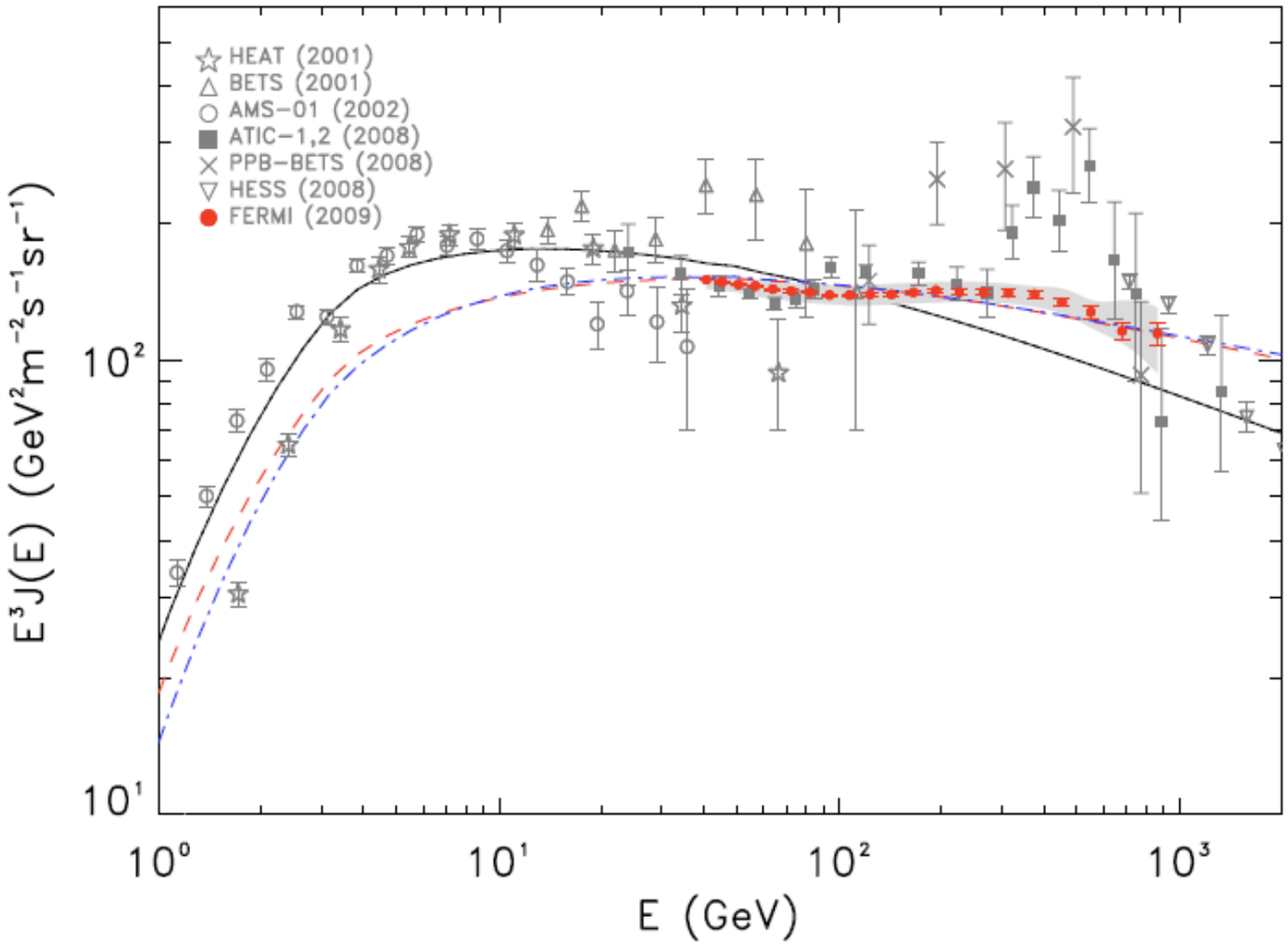
Cross Checks



- A tracker and a calorimeter variable at an intermediate stage of the analysis
  - good overall agreement between data and simulations
  - Monte-Carlo validation started from beam test data
  - analysis variables carefully check over the energy range with flight data

⇒ Residual discrepancies studied and included in the systematic uncertainties

Resulting Fermi Electron Spectrum

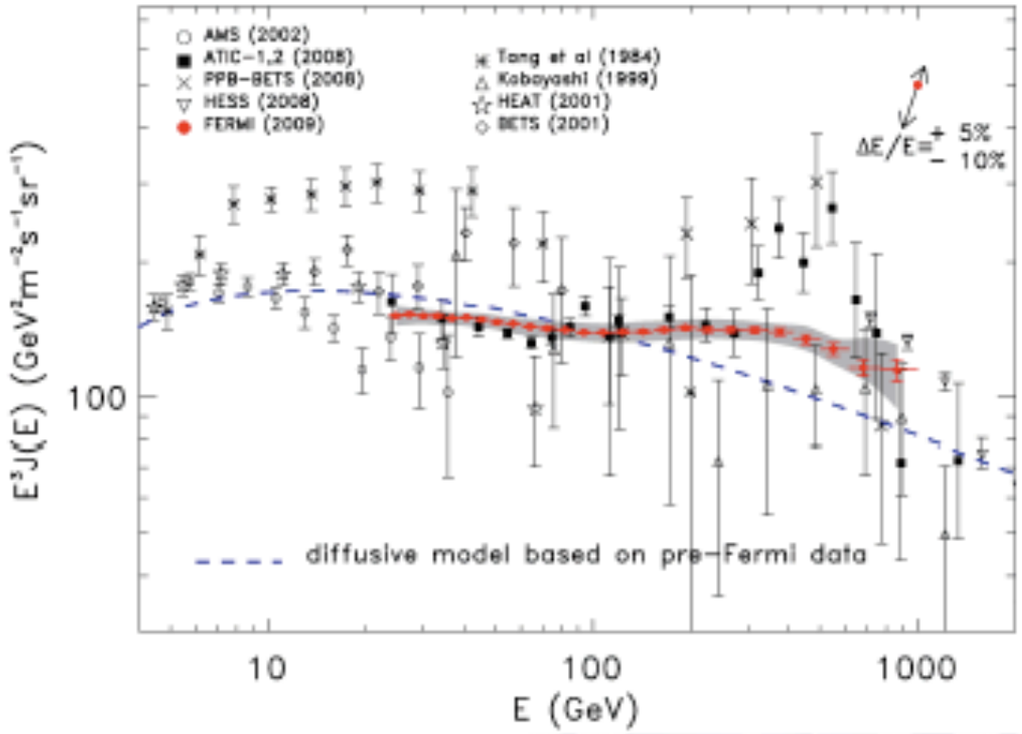


Measured spectrum well described by **power-law** within current values of **systematic** errors

$$J_{e^\pm} = (175.40 \pm 6.09)\left(\frac{E}{1\ \mathrm{GeV}}\right)^{-(3.045\pm0.008)} \mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

with χ^2 per degree of freedom of 9.7 / 23

Result Accepted By PRL April 21



Energy (GeV)	GF (m^2sr)	Residual contamination	Counts
...	...	...	...
291–346	2.04	0.18	7207
346–415	1.88	0.18	4843
415–503	1.73	0.19	3036
503–615	1.54	0.20	1839
615–772	1.26	0.21	1039
772–1000	0.88	0.21	544

more than 400 electrons in the last energy bin 772 GeV - 1TeV

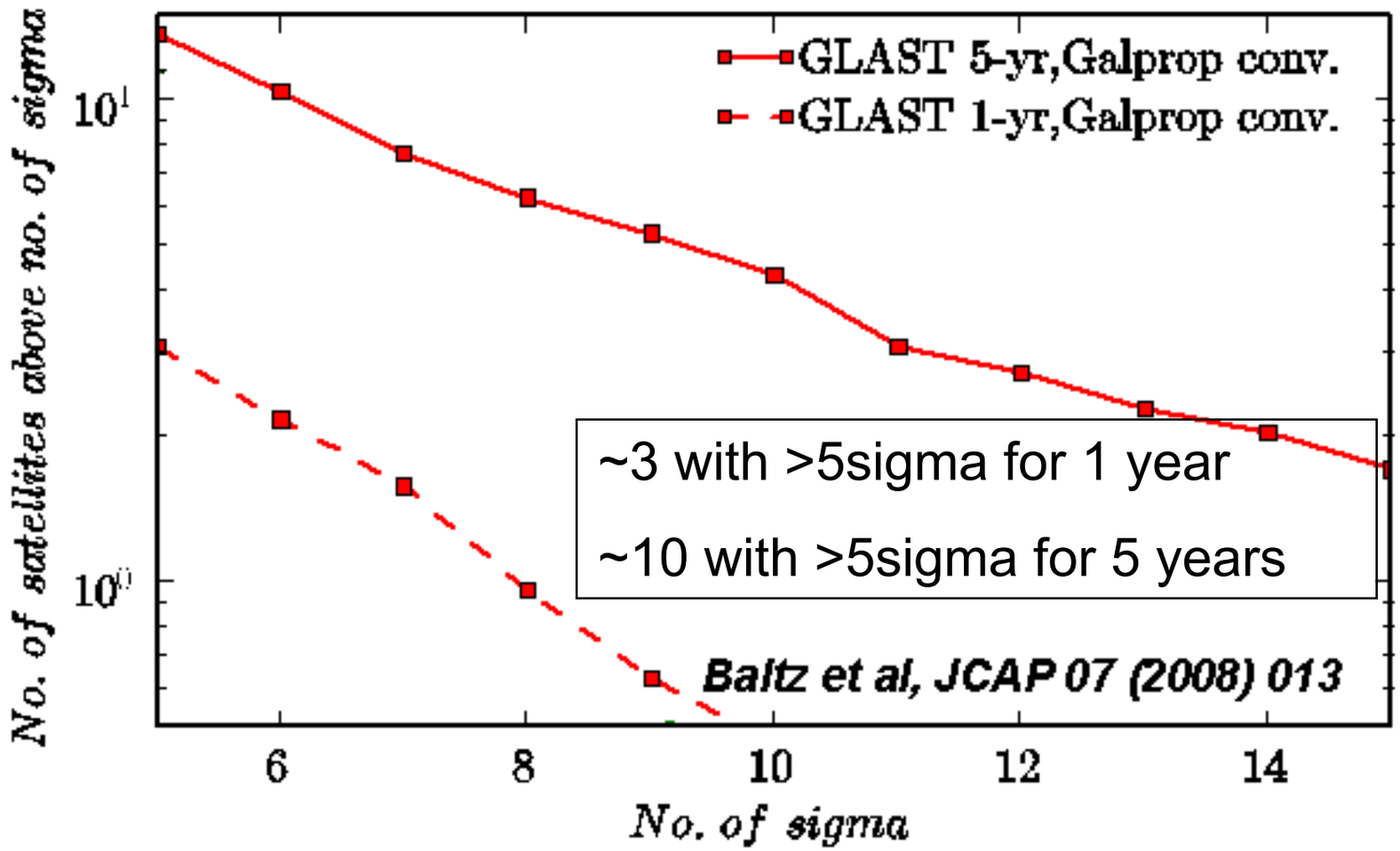
- High statistics : ~4.5 millions of events in 6 months
  - errors dominated by systematic uncertainties
- Not compatible with the the pre-Fermi data diffusive model ($E^{-3.3}$ whereas we measured $E^{-3.0}$)
- No evidence of a prominent spectral feature
  - ATIC excess: 70 electrons between 300 and 800 GeV

  → we would have seen an excess of 7000 electrons

Conclusions

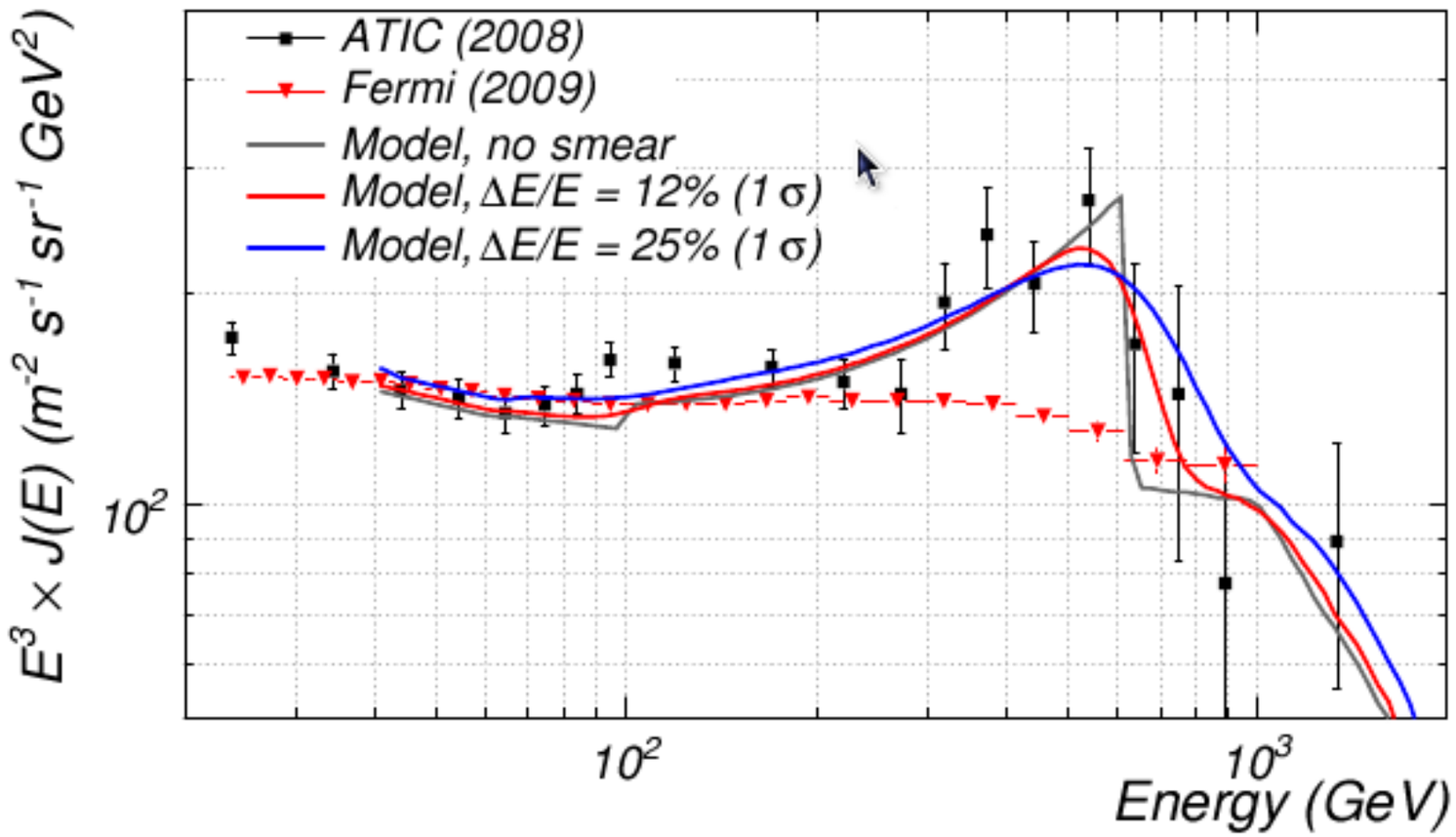
- Fermi has begun a number of searches for dark matter using photons, with some preliminary results already
  - Expect numerous results by the end of the summer!
- Measurements of the galactic diffuse at mid latitudes already tell us something regarding earlier dark matter interpretations from previous experiments
- Fermi LAT also has excellent electron identification capabilites
  - The Fermi CRE measurement shows an excess relative to pre-Fermi conventional models and shows an excess of electrons at high energy (although no prominent spectral feature)
- Stay tuned for new results in the near future

Fermi LAT Sensitivity to DM Satellites



- Simulation of Milky Way dark matter satellites with truncated NFW profile from Taylor & Babul, 2004, 2005
- Background estimate using Galprop diffuse and isotropic power law extragalactic diffuse (Sreekumar et al.)
- Generic WIMP model: WIMP mass 100GeV, cross-section 2.3e-26 cm^3/s, bb-bar only
  - This model can give the required relic density
- Compare the signal, background flux inside the tidal radius
- No. of sigma = signal / sqrt (bkgd + signal)

Energy Resolution Issues

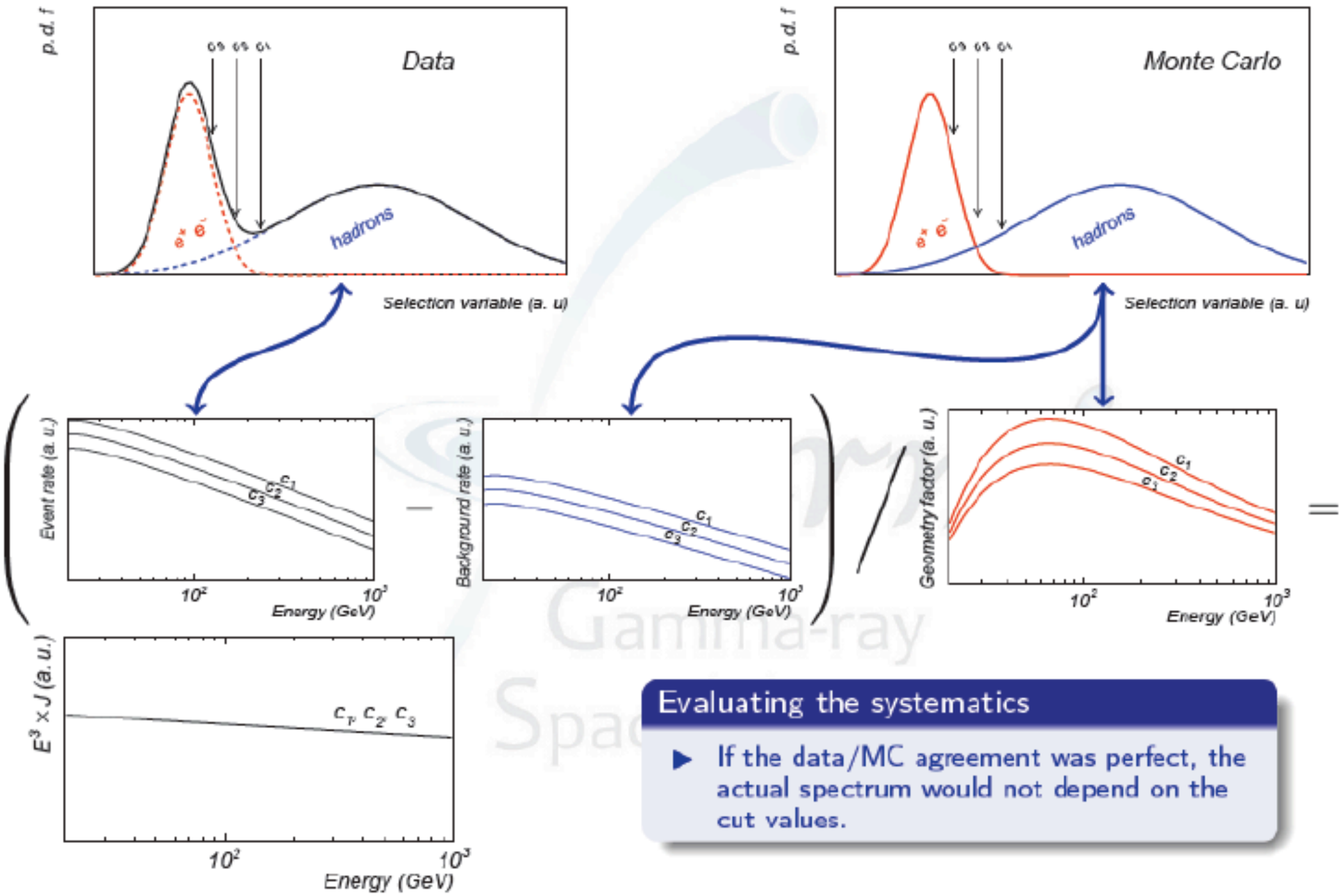


- The model is a broken power law with index -3.1 below 1 TeV and -4.5 above 1 TeV, upon which a much harder spectral feature (index -1.5) with a sharp break at 620 GeV has been superimposed
- The gray line is the model, which is then smeared with an energy resolution of 12% and 25% (1 gaussian sigma), resulting in the red and blue lines respectively.
- The red line (12% DeltaE/E) is conservatively appropriate for the LAT (as predicted by full simulation).

Systematic Uncertainties

1. Uncertainty in our knowledge of the geometry factor
   - data/Monte Carlo agreement extensively studied for each single variable involved in the selection (bin by bin)
   - all the residual discrepancies mapped and propagated to the actual spectrum.
   - ranging from a few % to $\simeq 20\%$ depending on energy
2. Normalization of the primary proton spectrum
   - the uncertainty on the proton cosmic ray model ranges from few % to $\simeq 20\%$ around 1 TeV
   - affecting the electron spectrum through the subtraction of the residual hadron contamination
3. LAT absolute calibration of the energy scale
   - unlike the other terms does not introduce energy-dependent modifications of the spectrum
   - from beam test data, calibration and flight data, the systematic uncertainty on the absolute energy is (+5%, -10%)

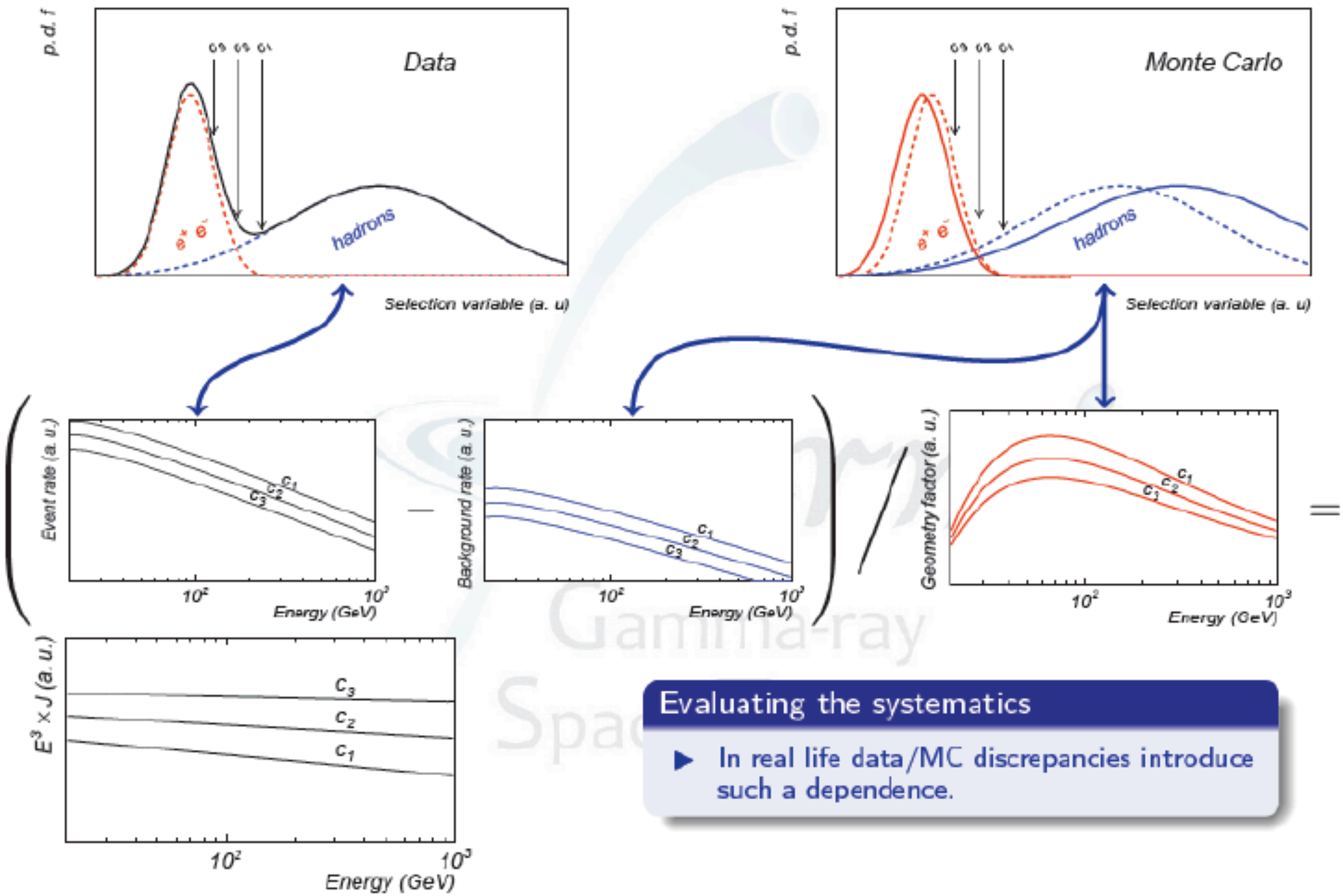
Systematic Uncertainties



Evaluating the systematics

- If the data/MC agreement was perfect, the actual spectrum would not depend on the cut values.

Systematic Uncertainties



Evaluating the systematics

- In real life data/MC discrepancies introduce such a dependence.