Fermi Gamma-ray Space Telescope

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on behalf of Fermi LAT and GBM Collaborations
KIPAC
SLAC National Accelerator Laboratory
(Stanford Linear Accelerator Center)

銀河系とダークマター

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Outline

- Overview of Fermi Large Area Telescope (LAT)
- Instrument Performance after Launch
- Cosmic-ray interaction and propagation in the Milky-way
- Cosmic-ray electron
- Dark matter searches
- Summary and Prospects

- This is a part of broad Fermi LAT science program

Note: Many results in this talk are preliminary

Fermi/LAT Collaboration

Stanford University & SLAC
NASA Goddard Space Flight Center
Naval Research Laboratory
University of California at Santa Cruz
Sonoma State University
University of Washington
Purdue Univeristy-Calumet
Ohio State University
University of Denver

Commissariat a l'Energie Atomique, Saclay
CNRS/IN2P3 (CENBG-Bordeaux, LLR-Ecole polytechnique, LPTA-Montpellier)

Hiroshima University
Institute of Space and Astronautical Science
Tokyo Institute of Technology
RIKEN

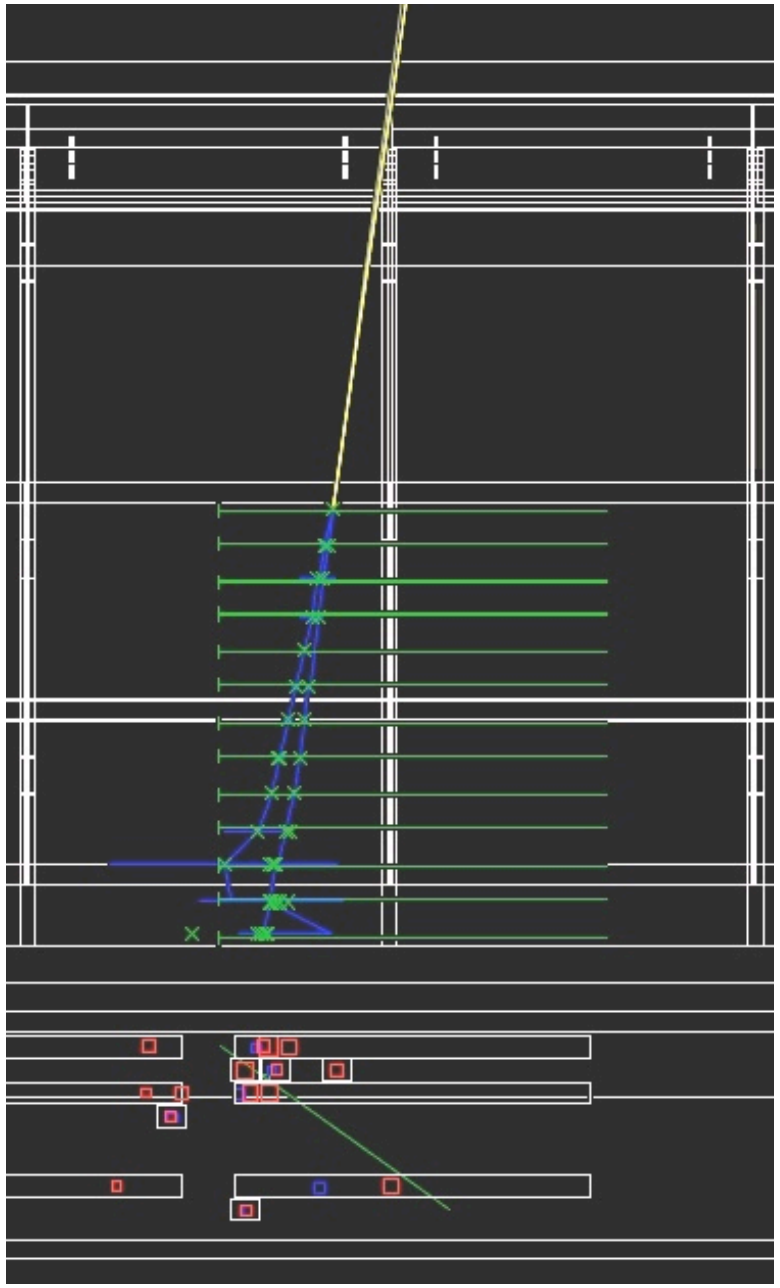
Instituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana
Istituto di Astrofisica Spaziale e Fisica Cosmica

Royal Institute of Technology, Stockholm
Stockholms Universitet

Fermi/LAT Overview

- Satellite experiment to observe gamma rays from Universe
  - Wide energy range: 20 MeV to >300 GeV
  - Large effective area: > 8000 cm^2 (~6xEGRET)
  - Wide field of view: > 2.4 sr (~5xEGRET)

- Pair-conversion telescope
  - "Clear" signature
  - Background rejection



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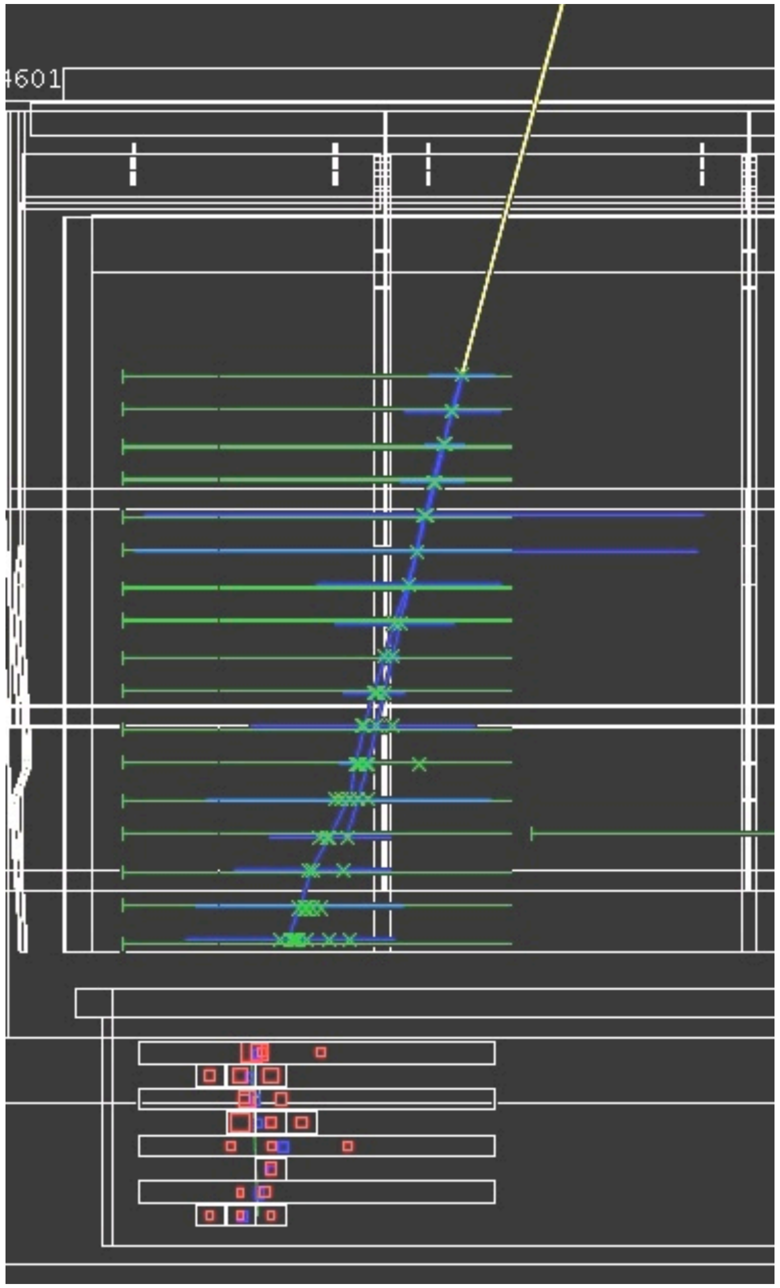
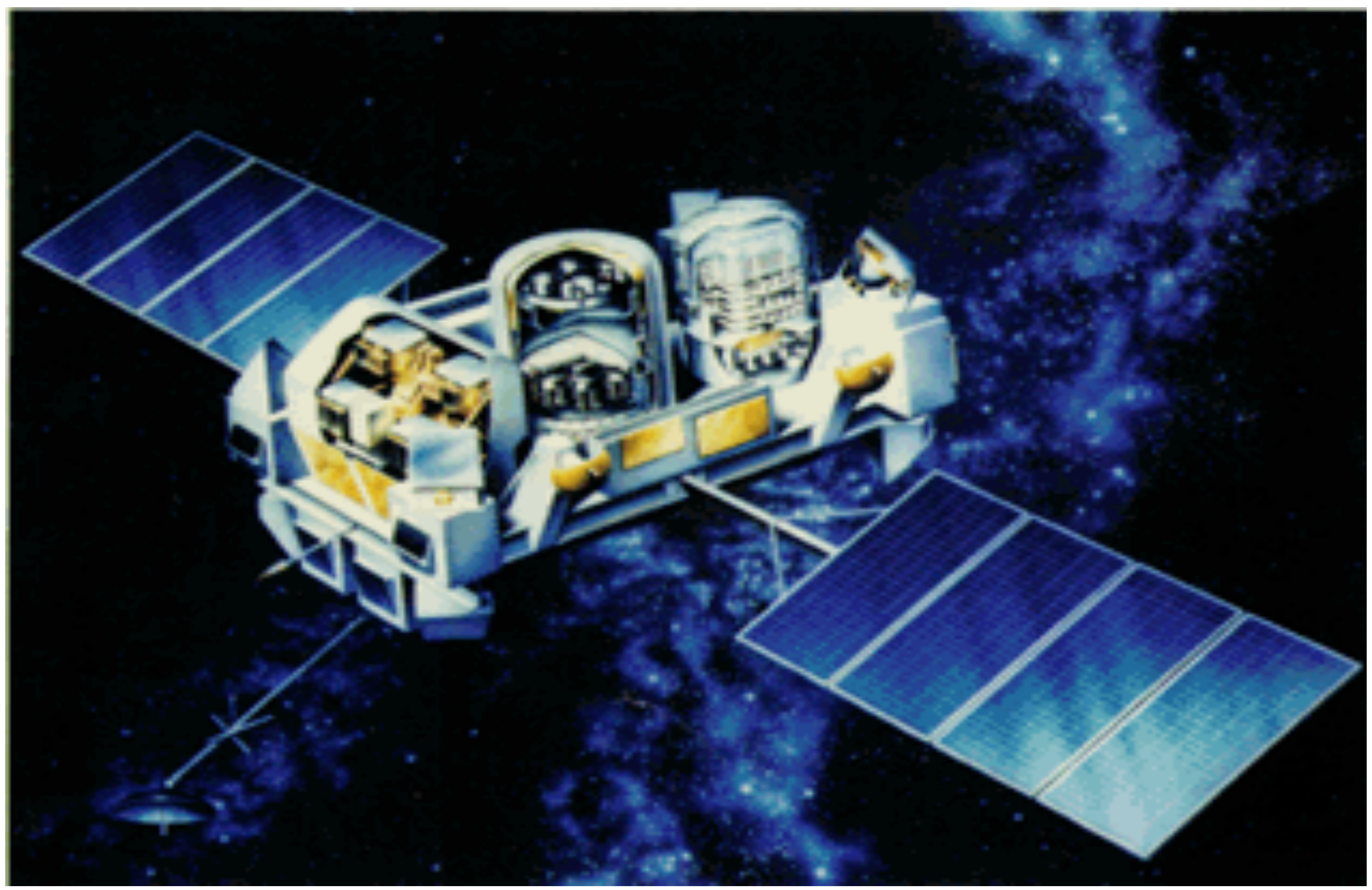
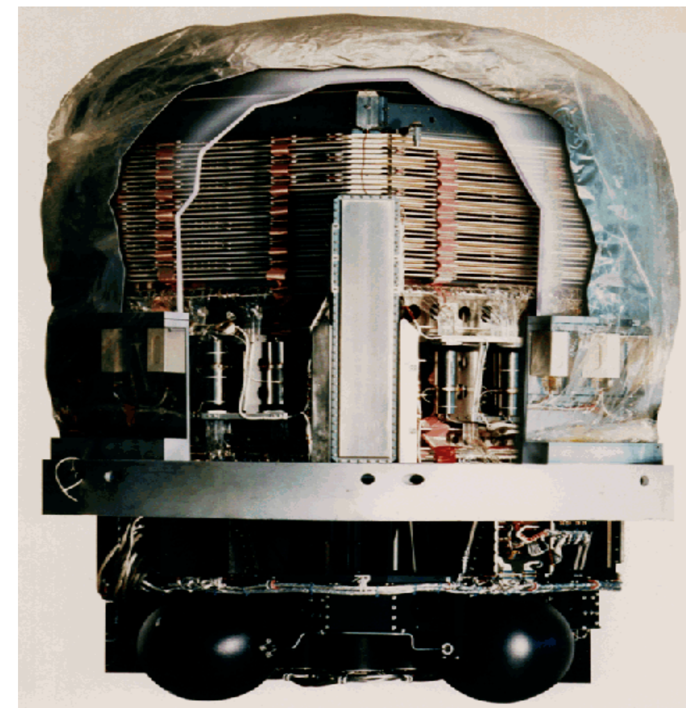


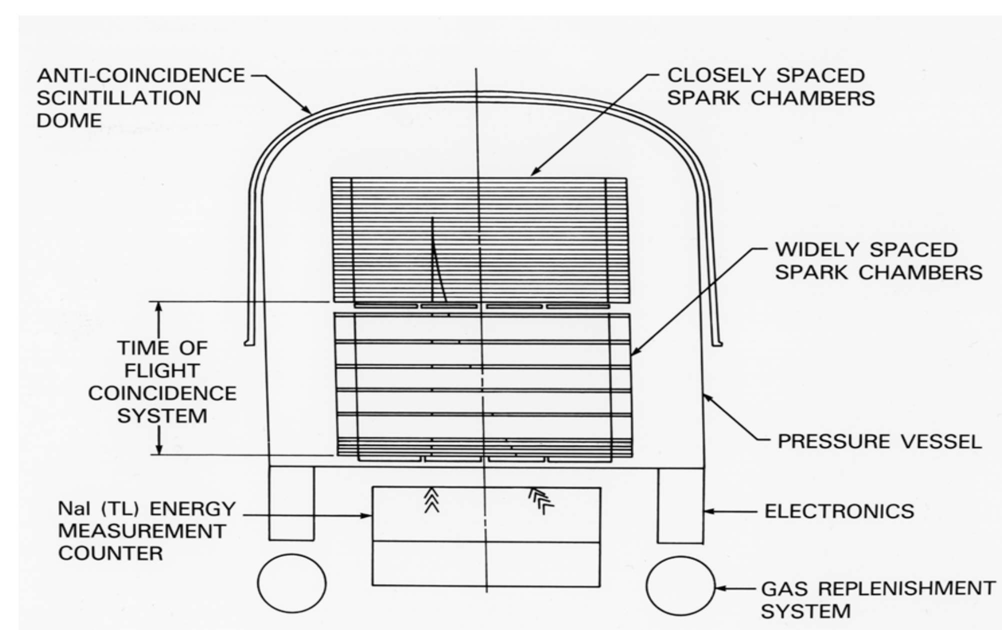
EGRET

High energy gamma-ray instrument onboard Compton Gamma-Ray Observatory

- **Consists of tracker (spark chamber), Calorimeter (NaI crystal) and Anti-Coincidence Scintillation Dome.**
- **Energy range (20 MeV – 20 GeV)**



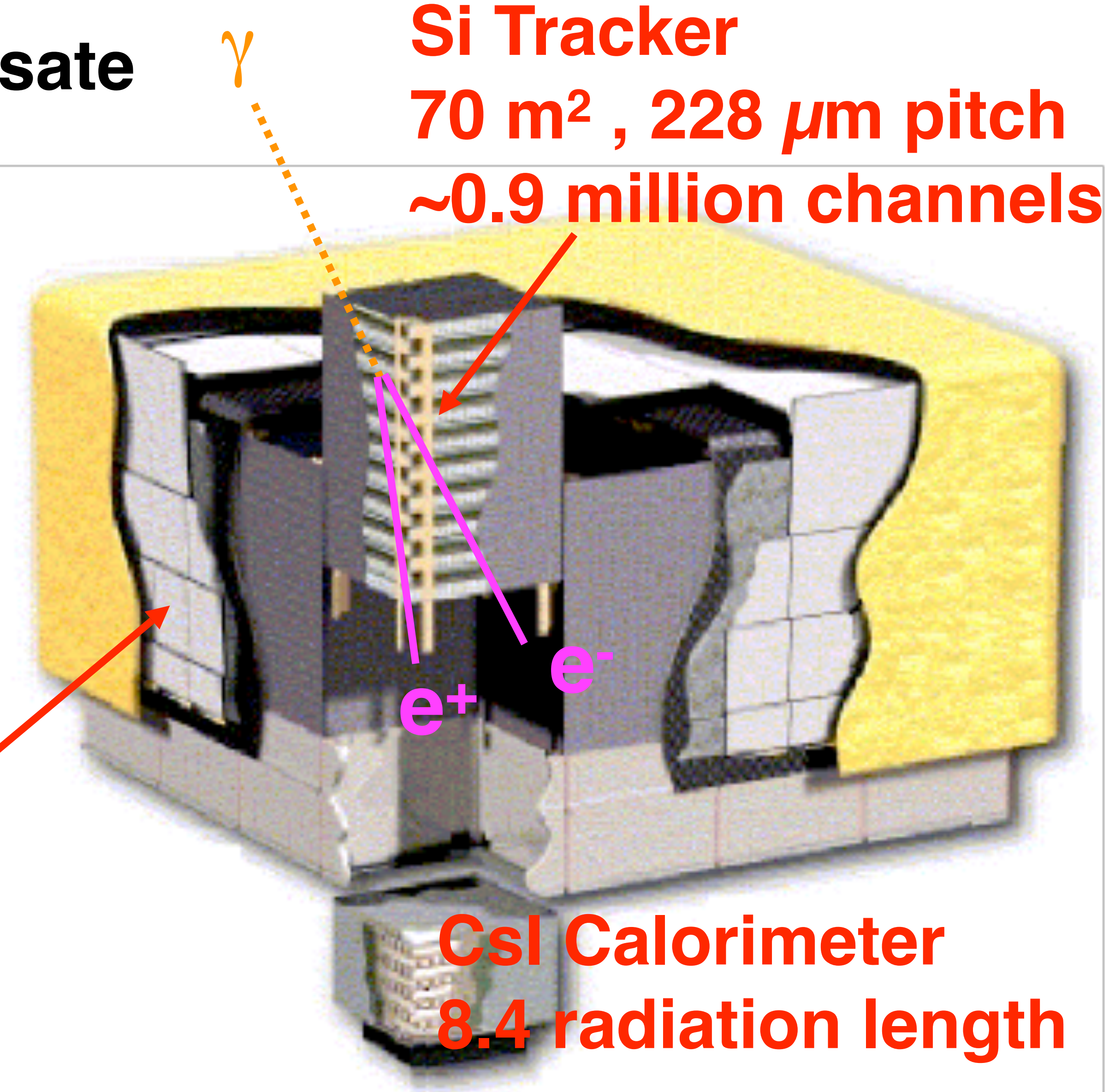




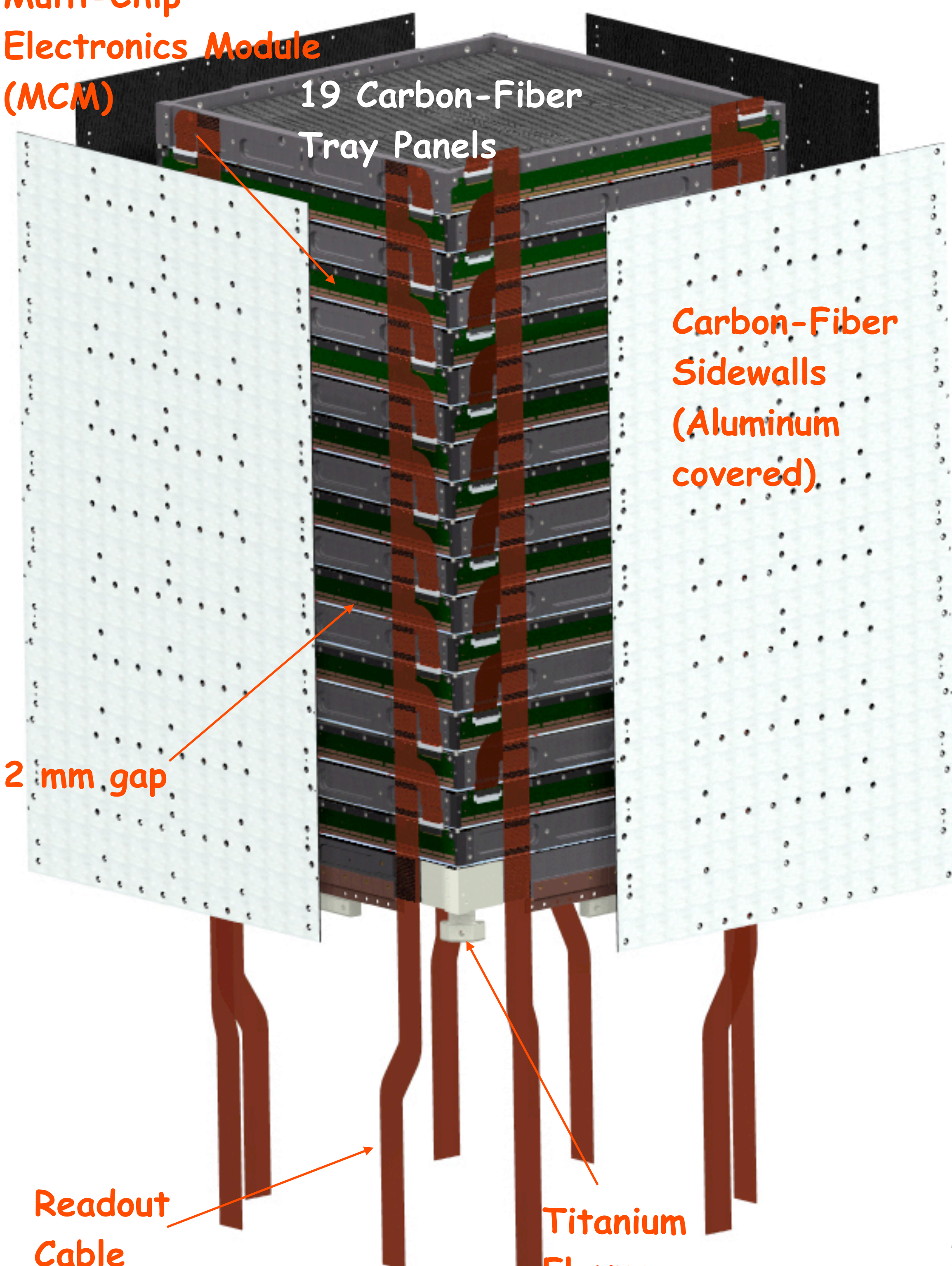
Instrument Configuration

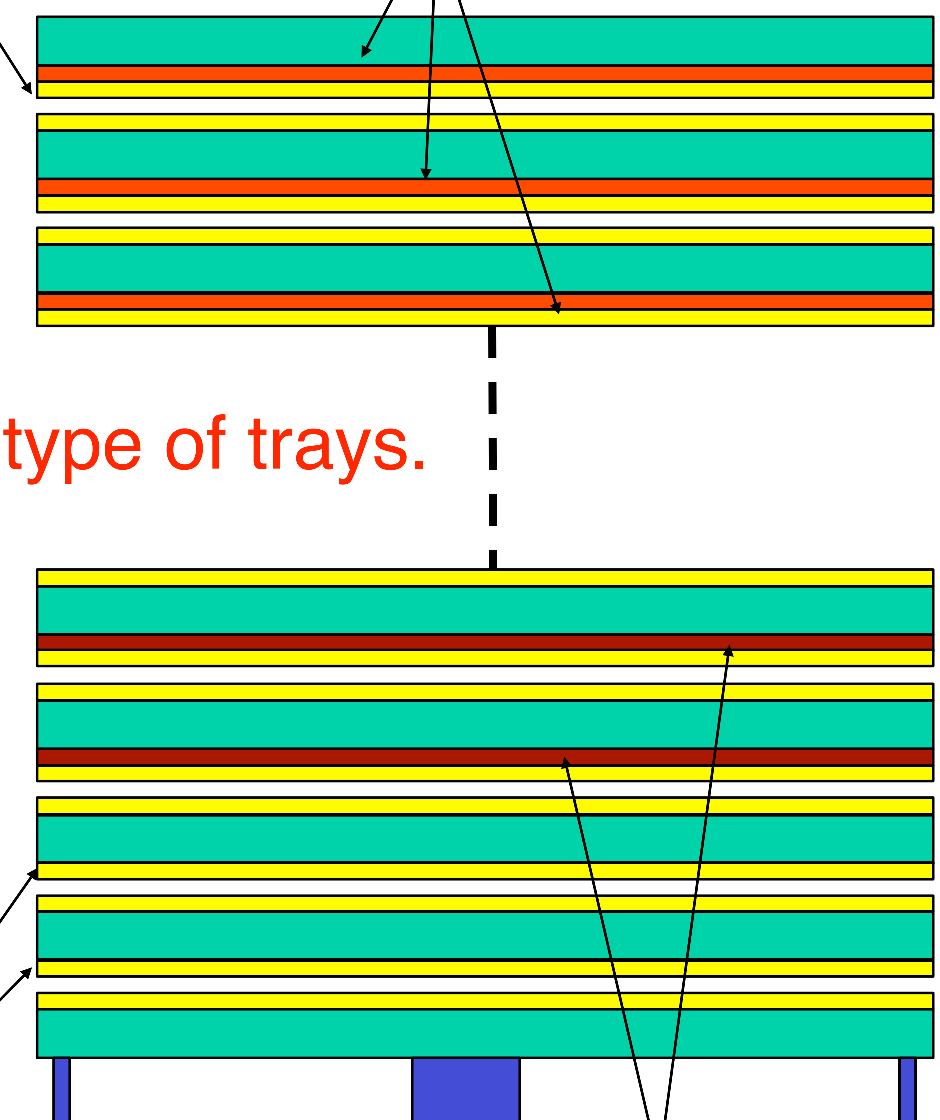
- Tracker (TKR): conversion, tracking
  - Angular resolution is dominated by scattering below ~GeV
  - Converter thickness optimization (1.5 radiation length)
- Calorimeter (CAL): energy measurement
  - 8.4 radiation length
  - Use shower development to compensate for the leakage above ~20 GeV
- Anti-coincidence detector (ACD):
  - Efficiency > 99.97%
  - Segmented to avoid “self-veto”

- Weight: ~3000 kg
- Size: ~1.5 m (W) x 0.6 m (H)
- Power: ~650 W

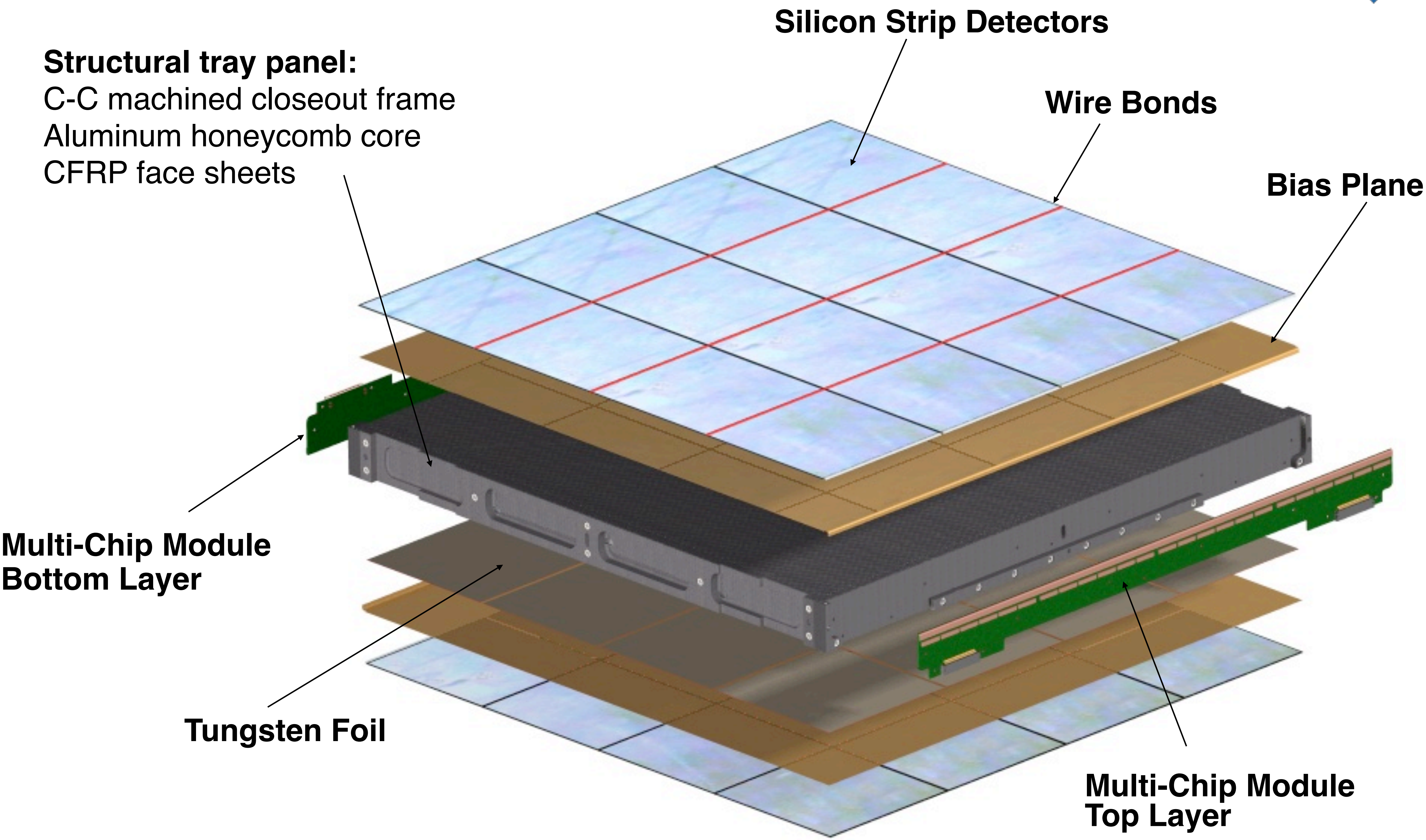


TKR Mechanical Design



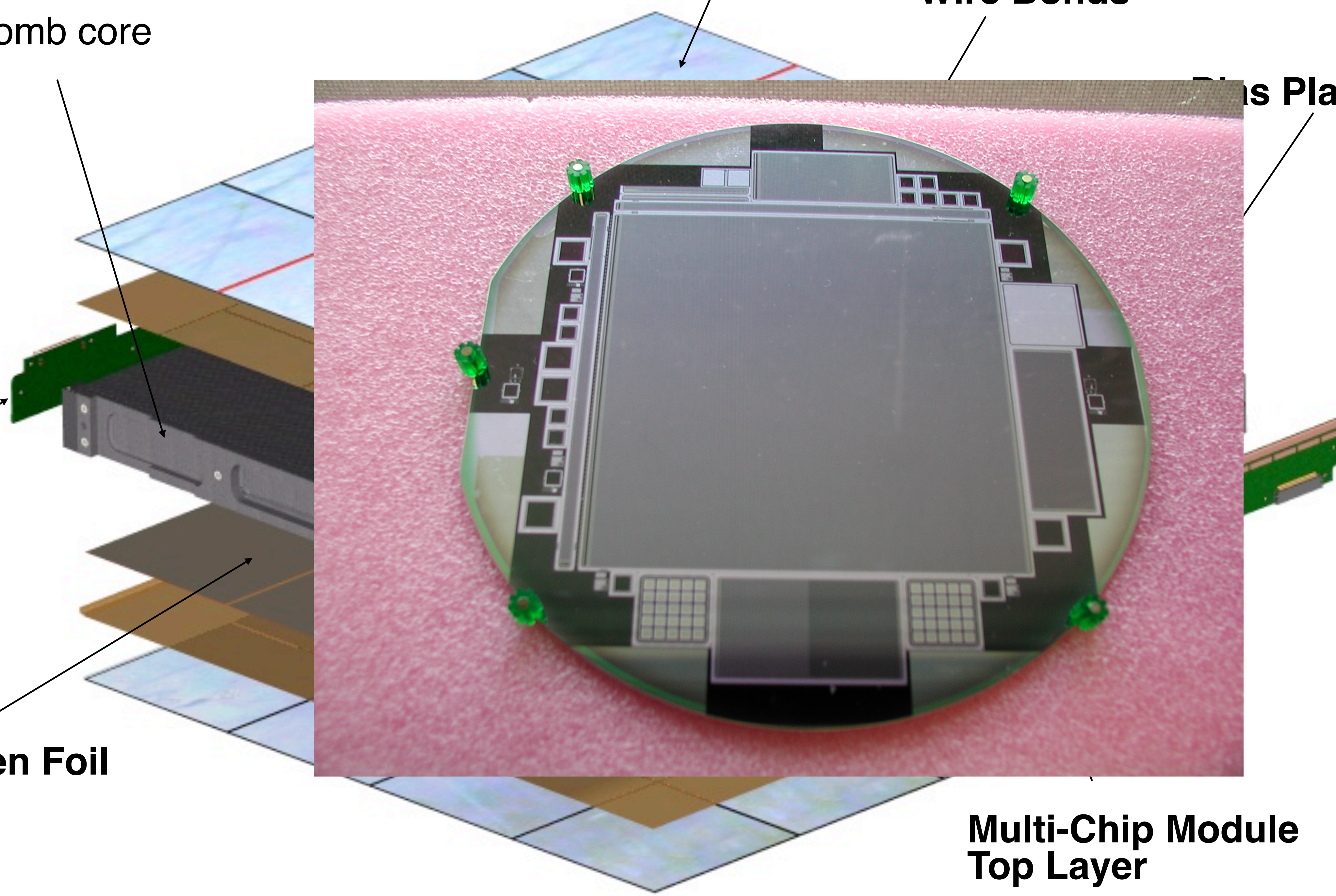


Tray Structure



Tray Structure

Structural tray panel:
C-C machined closeout frame
Aluminum honeycomb core
CFRP face sheets



Tray Structure

Silicon Strip Detectors

Structural tray panel:
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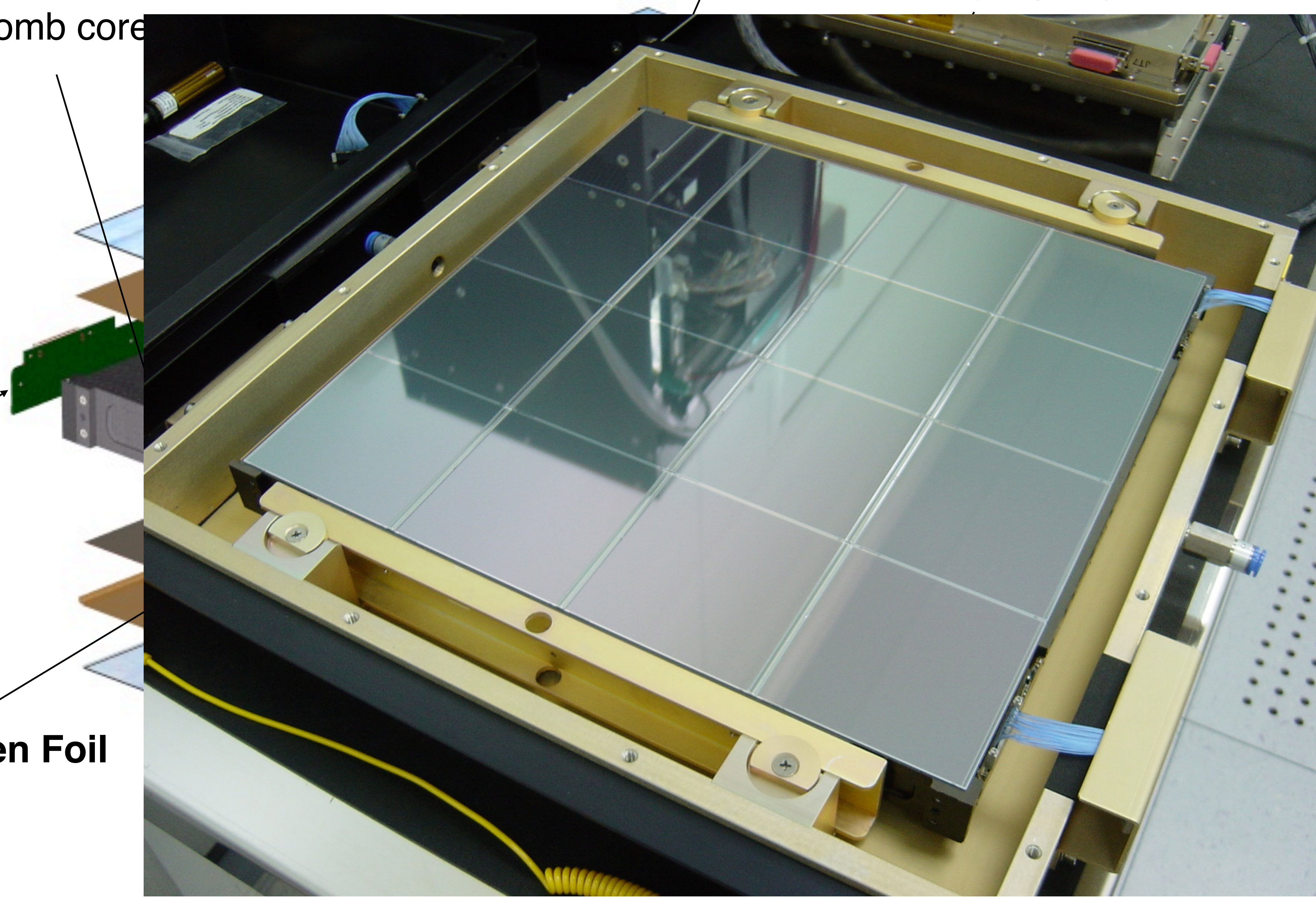
Wire Bonds



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Multi-Chip Module
Bottom Layer

Tungsten Foil

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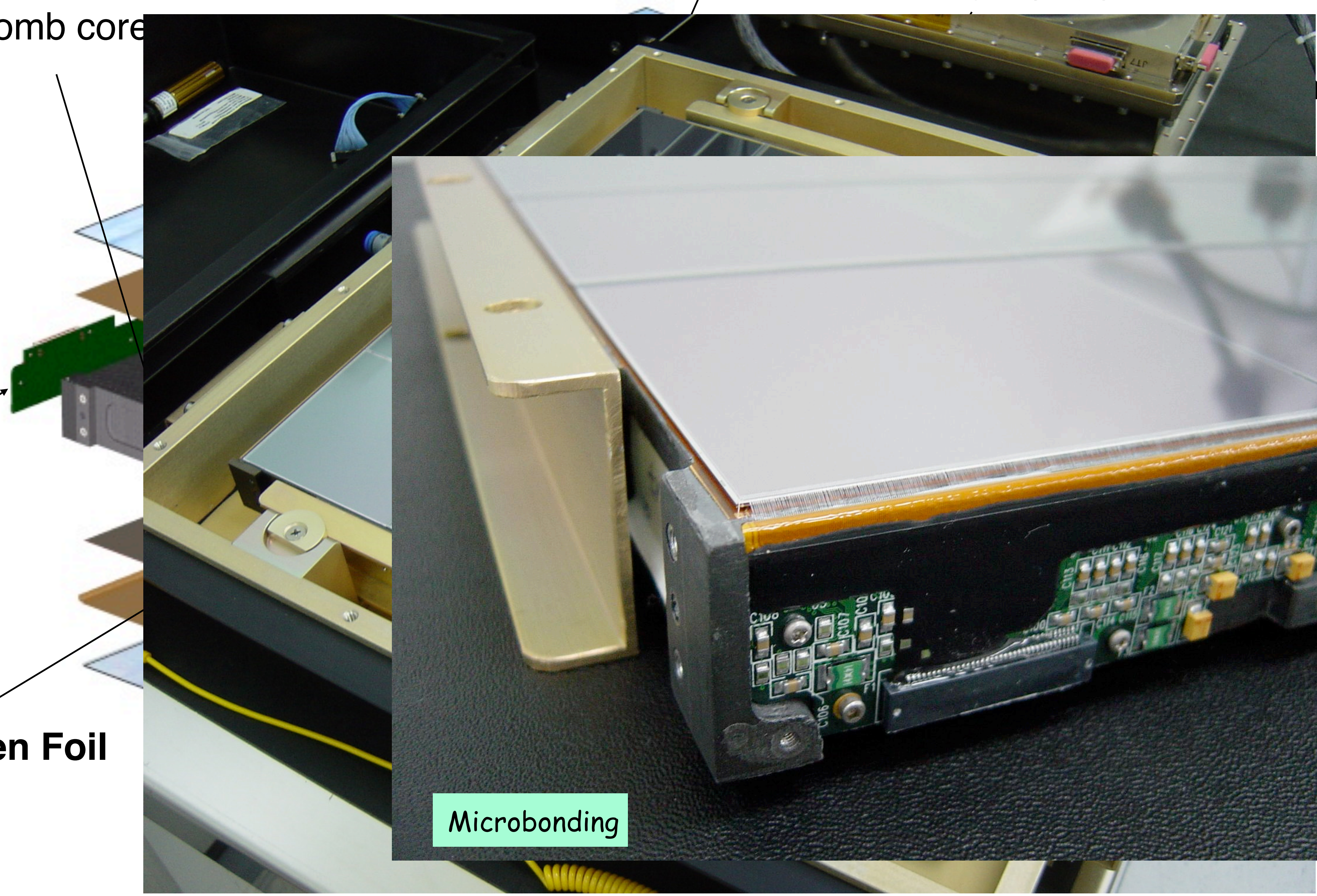
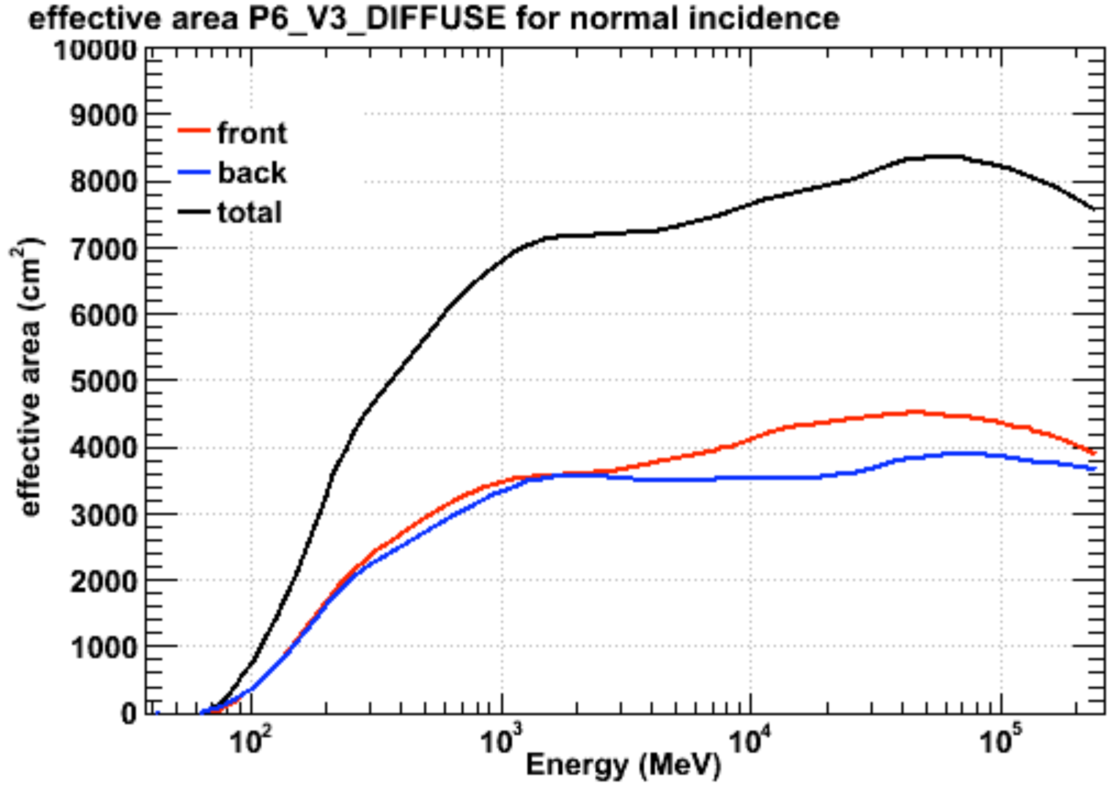
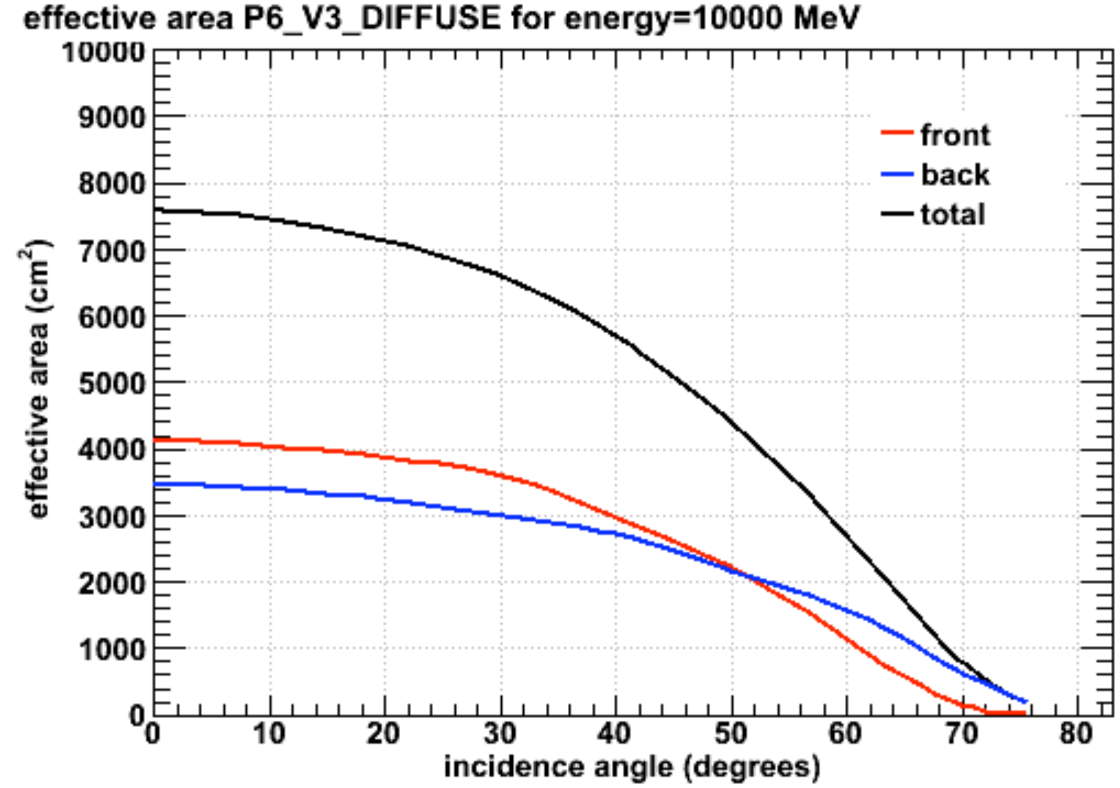


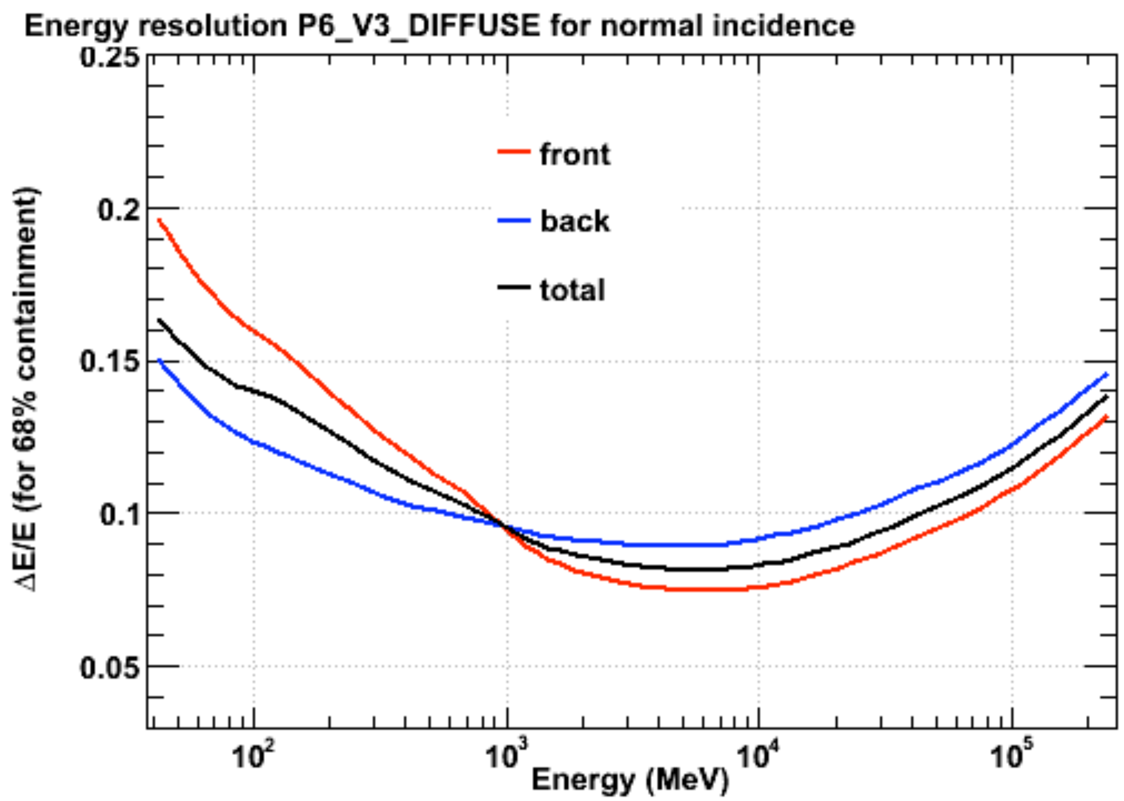
Multi-Chip Module Bottom Layer

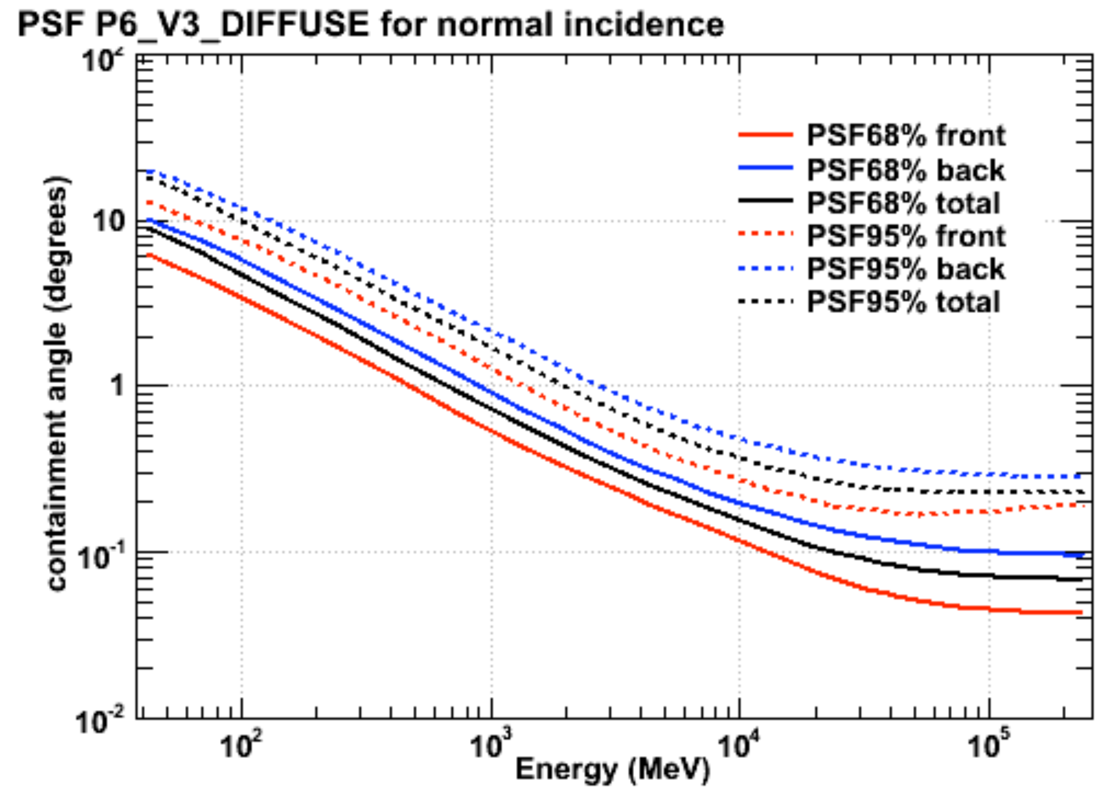
Tungsten Foil

LAT Performance



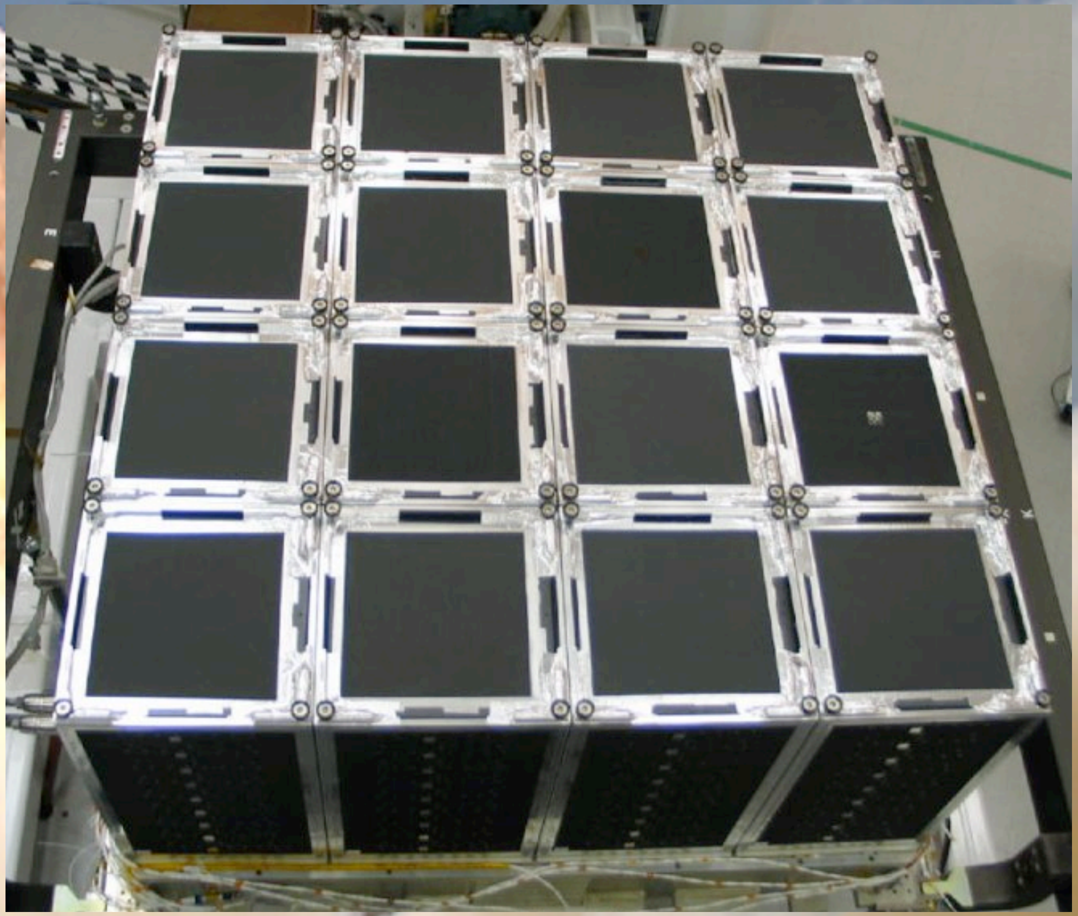






Launch

- Milestones toward launch
  - 2005/10: Final Tracker module delivered
  - 2006/05: LAT integration complete
  - 2006/10: LAT environmental test finished
  - 2007/10: GLAST integration complete
  - 2008/02: GLAST environmental test finished
  - 2008/06/11: GLAST launch
  - 2008/06/24: LAT power on



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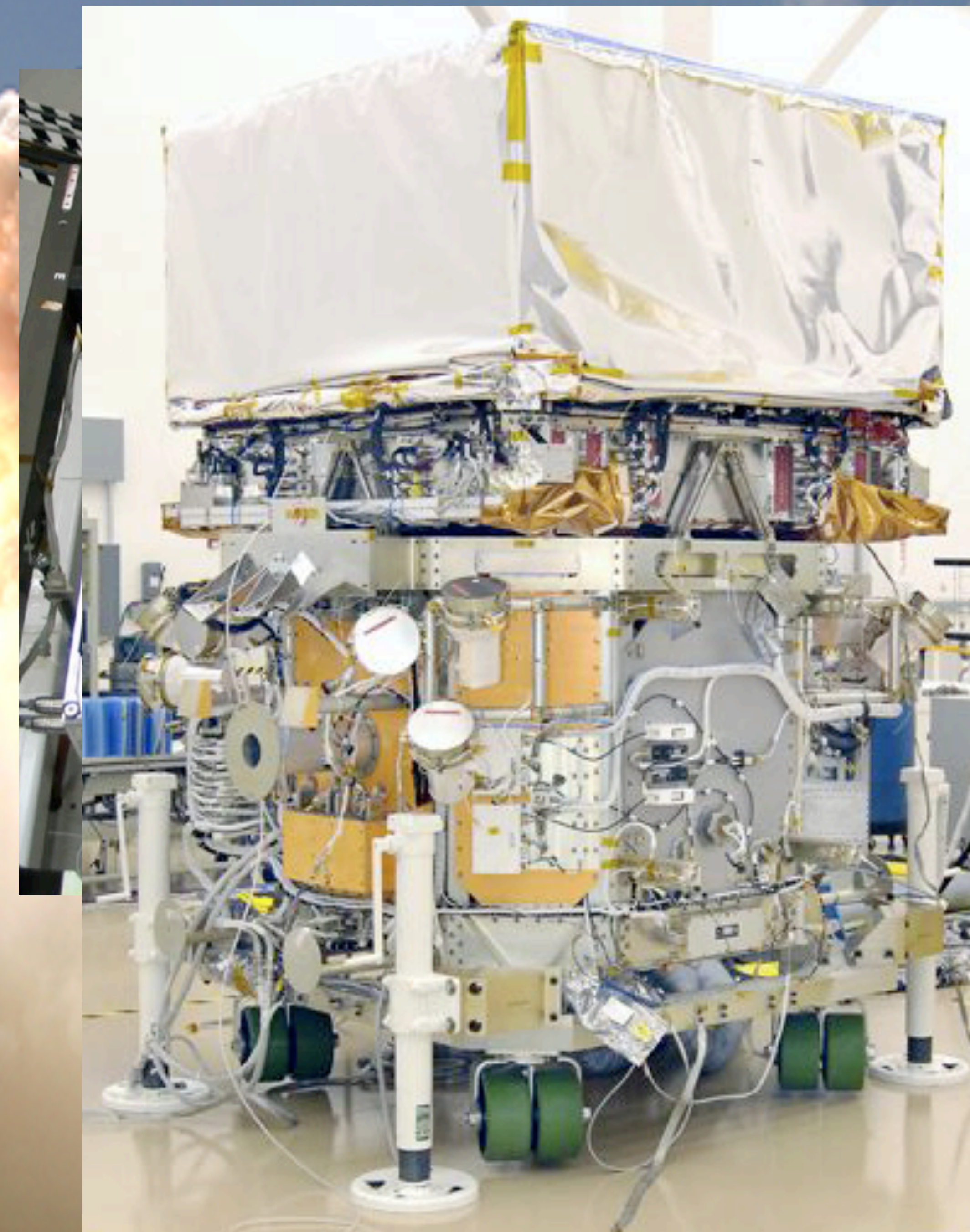

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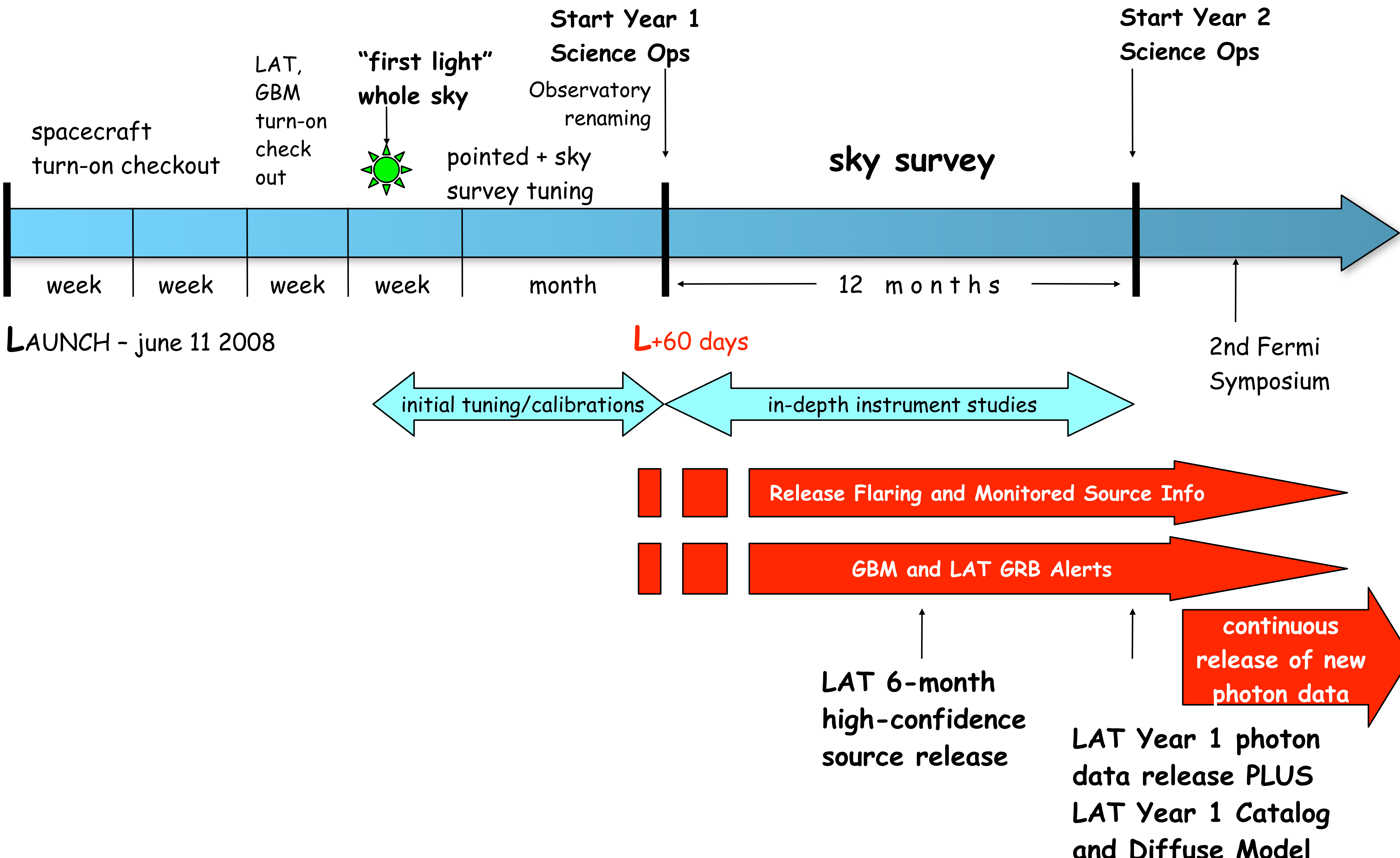
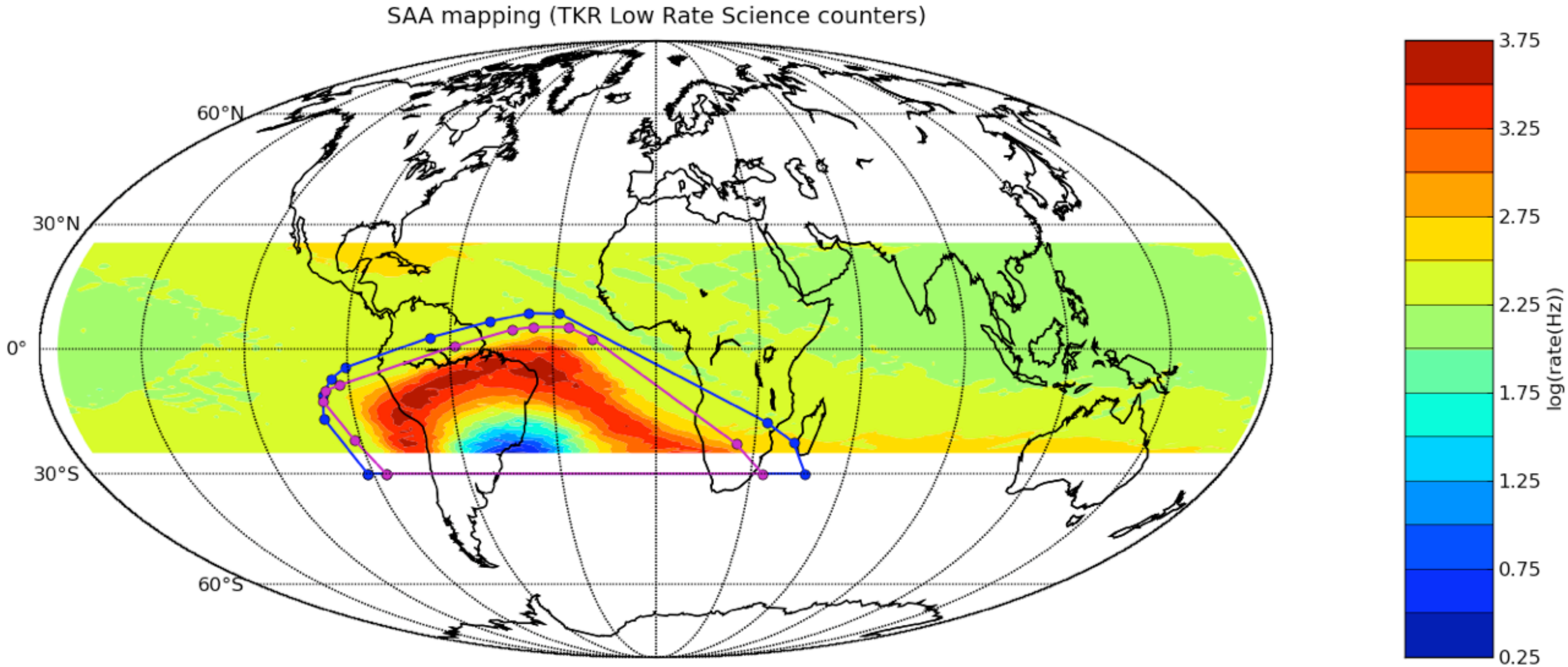
LAT Operations After Launch

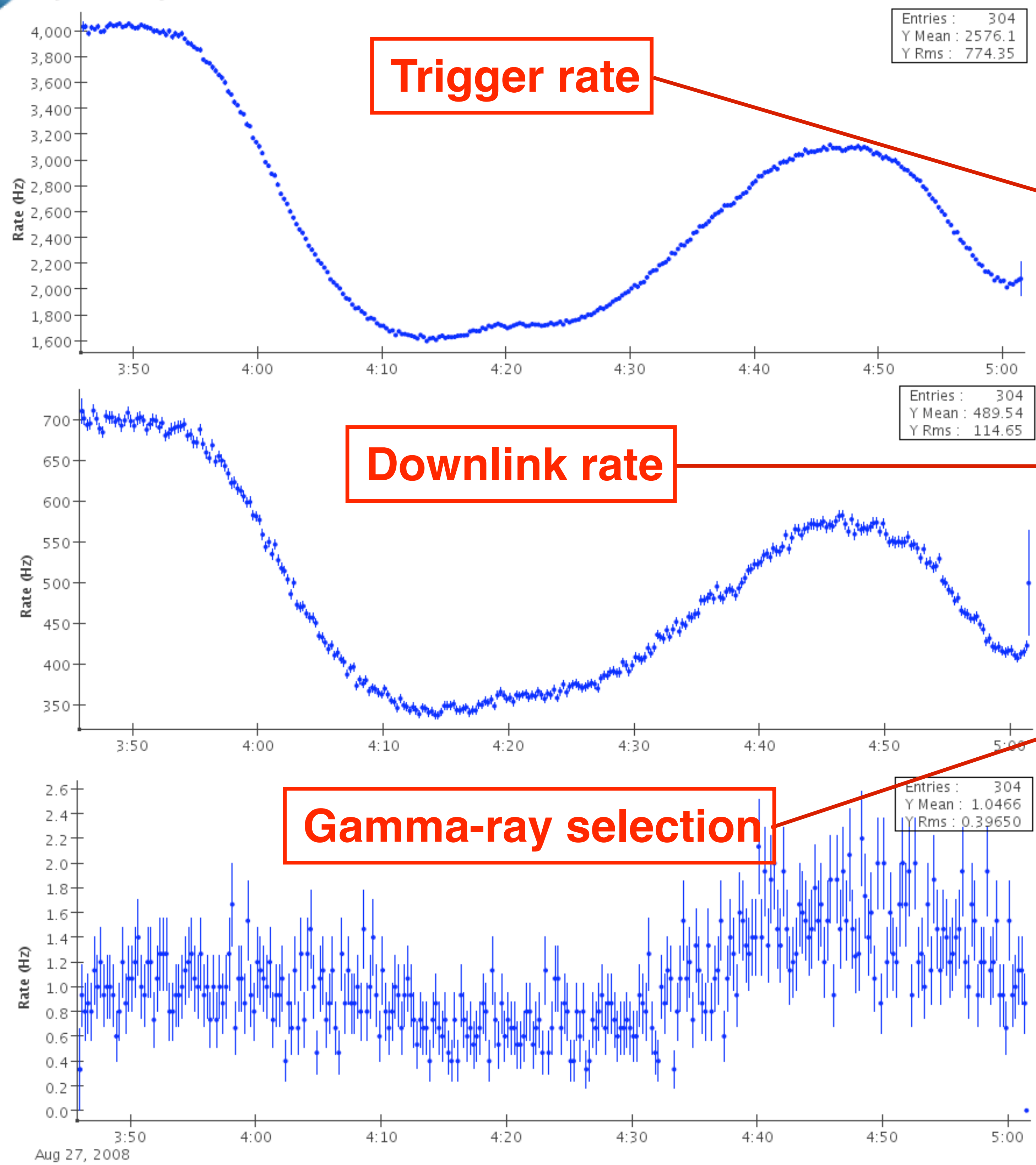


Particle Background Environment

- TKR trigger rate is monitored throughout SAA
  - Trigger rate saturates above ~3.7 kHz/layer



Event Rates



- ✓ Overall trigger rate: ~1–4 kHz
  - ✓ Huge variations due to orbital effects.

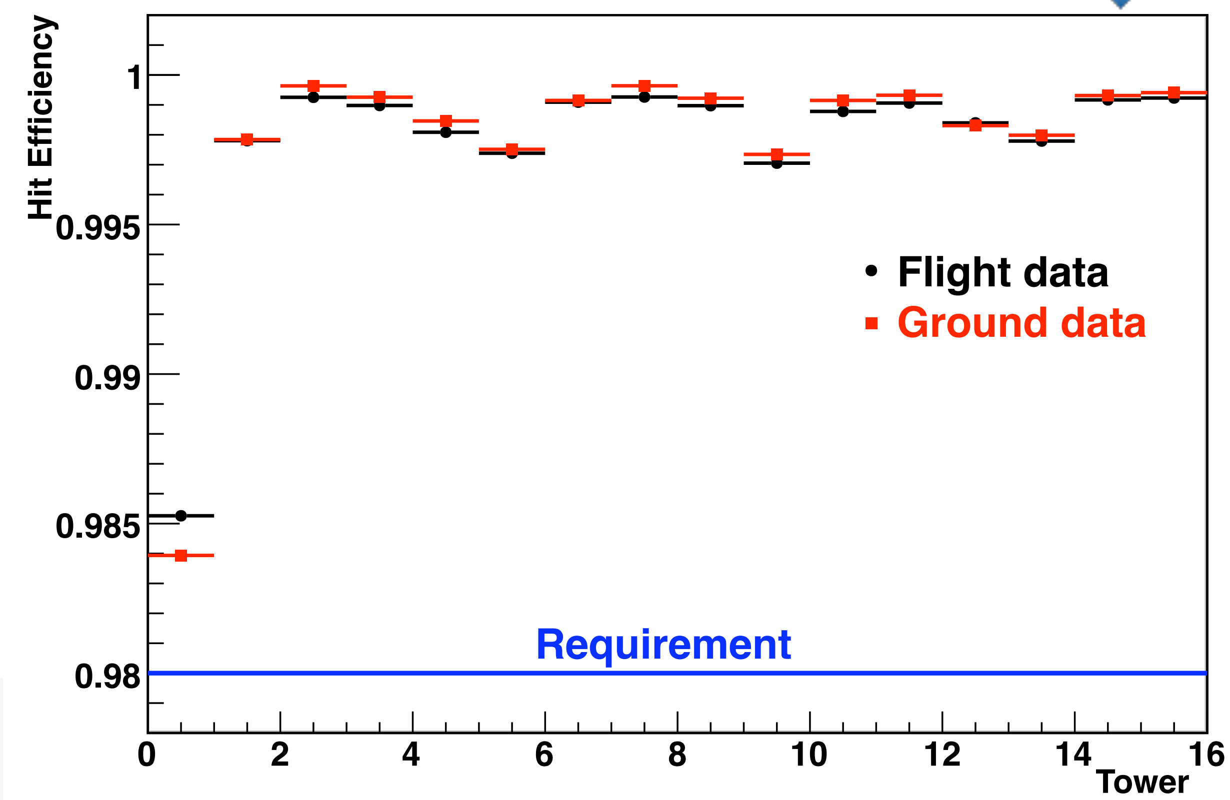
- ✓ Downlink rate: ~0.3–0.7 kHz
  - ✓ ~90% from GAMMA filter
  - ✓ ~30 Hz from minimum bias filter
  - ✓ ~5 Hz from heavy ion filter

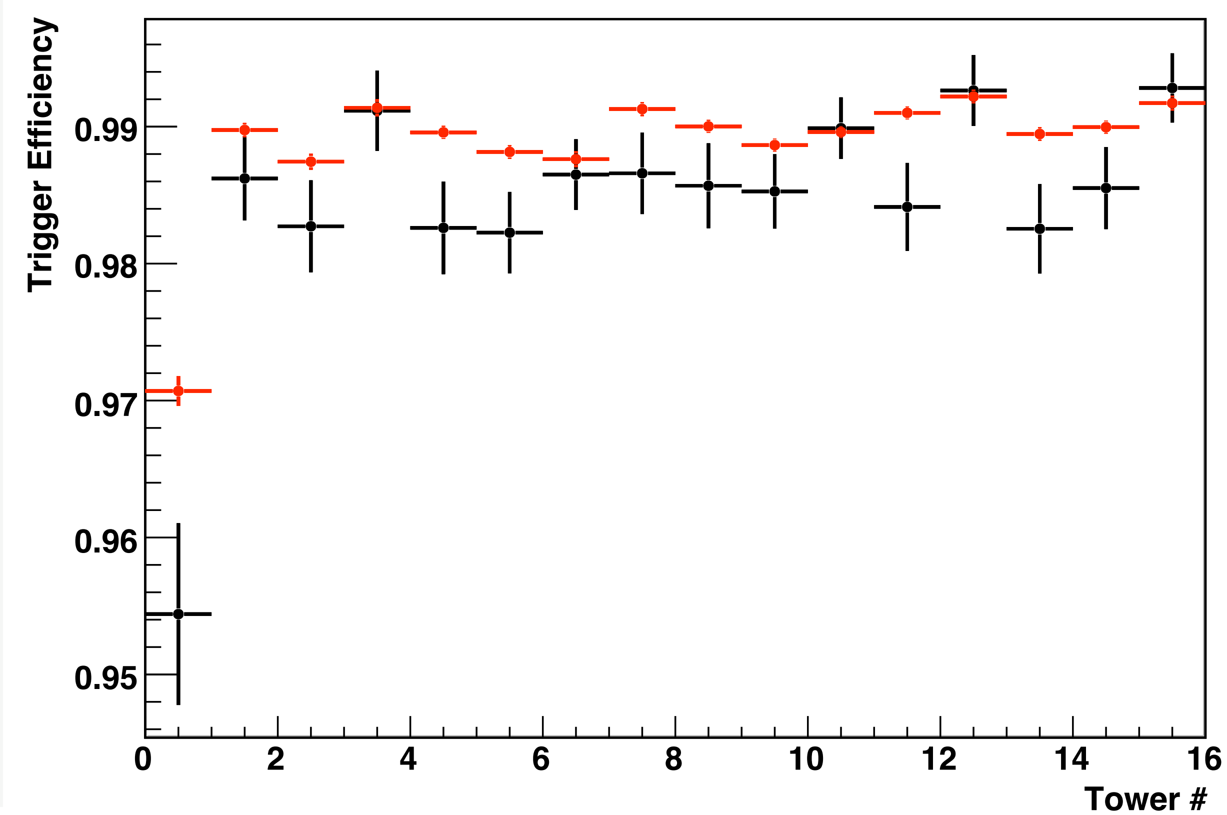
- ✓ Rate of photons after the standard background rejection cuts for source study: ~1 Hz

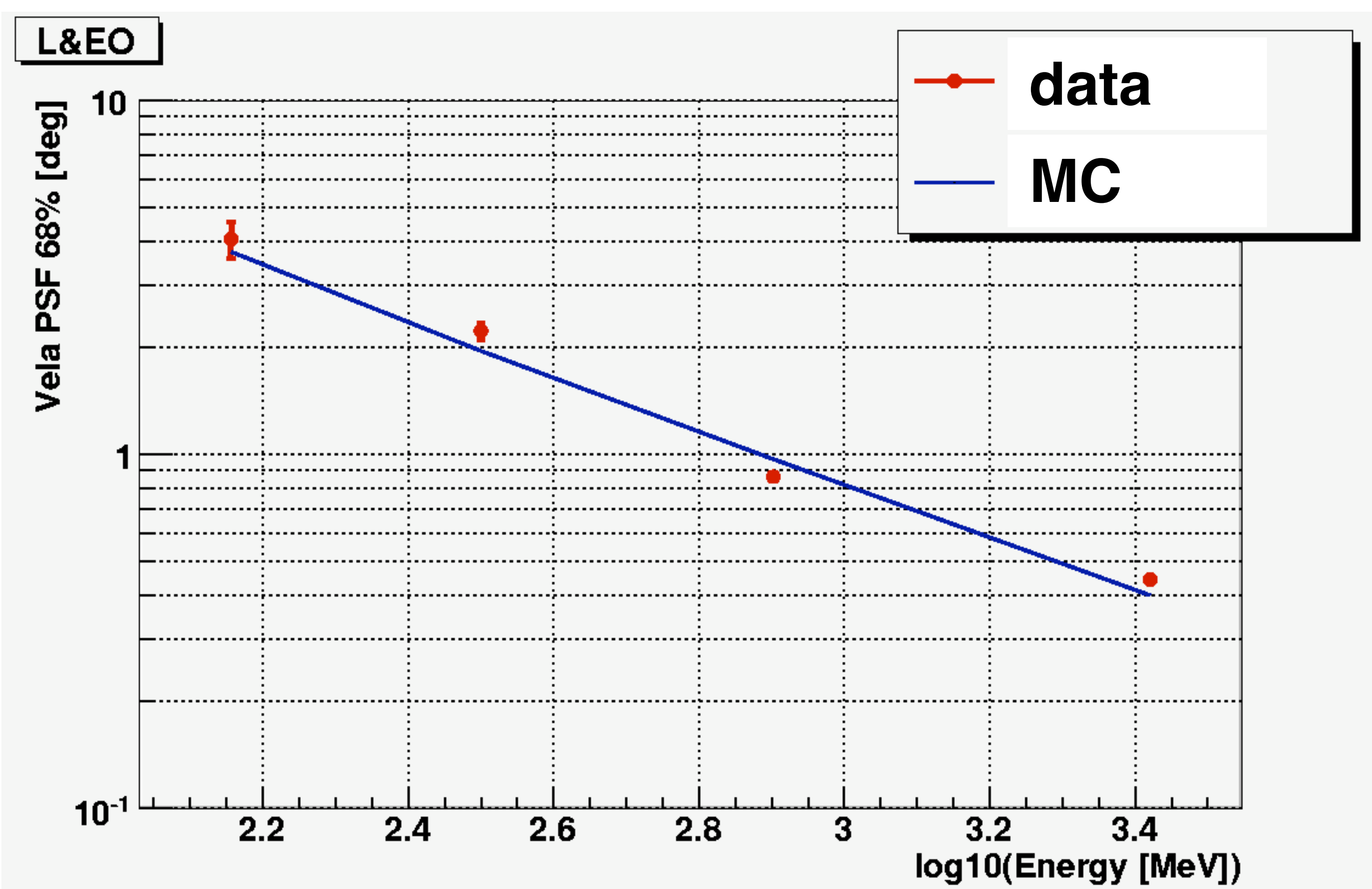
- ✓ Most of the downlinked events are in fact background, final ~ 1000:1 rejection is done in ground processing.

Performance After Launch

- Comparison before and after the launch
  - Apparent efficiencies slightly lower due to accidentals
- Point spread function (PSF) consistent between data and MC

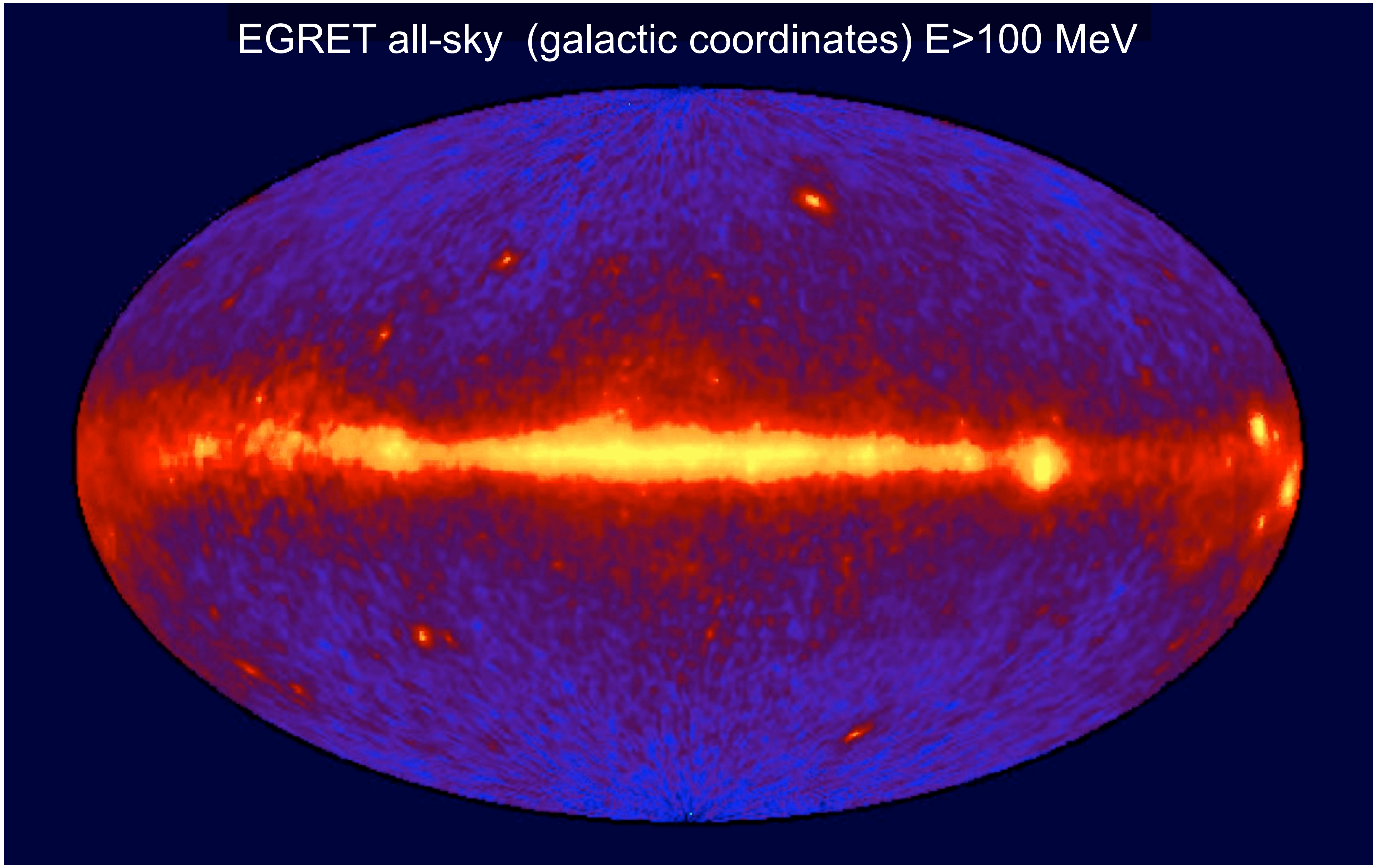






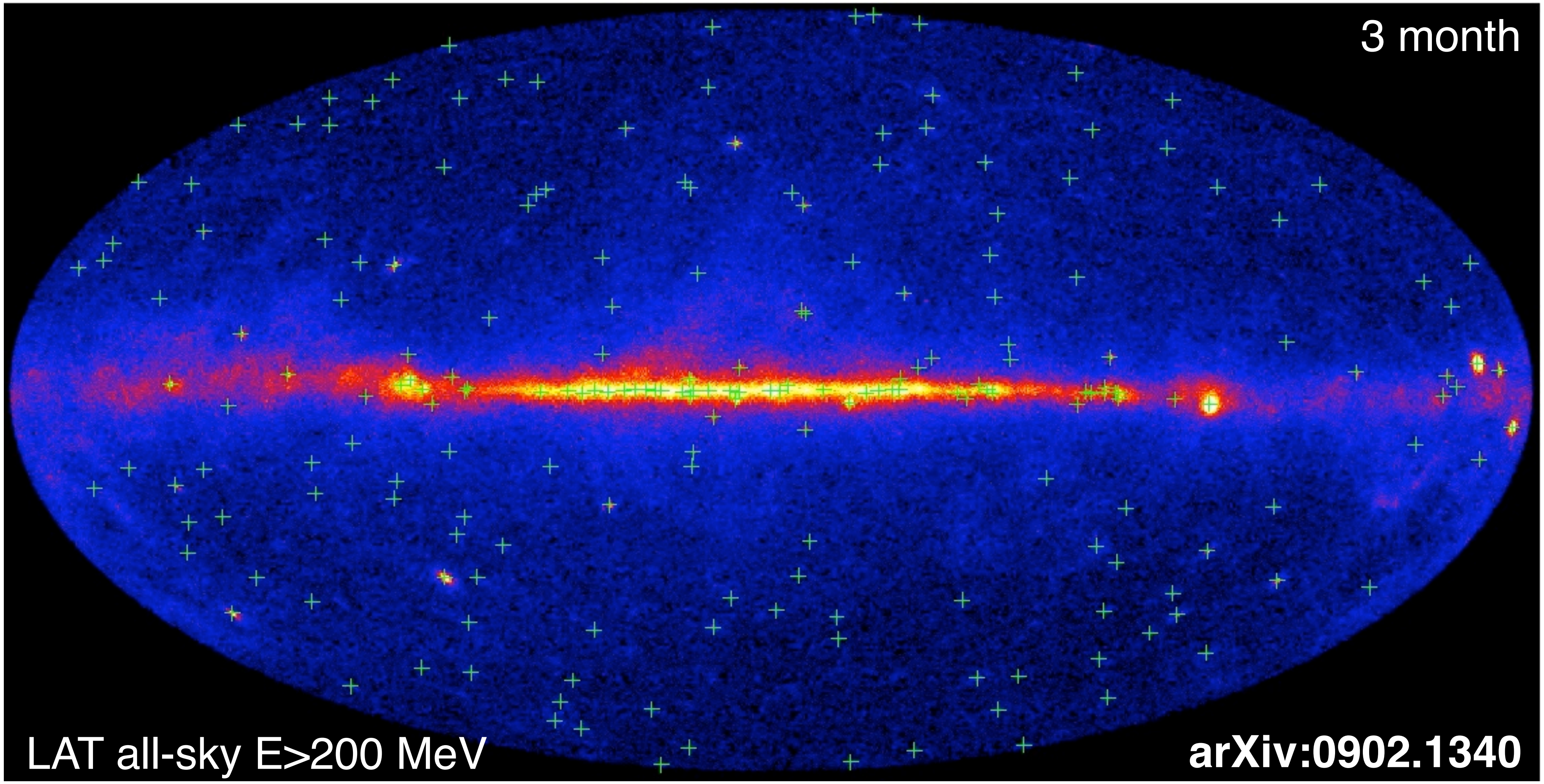
Predecessor, EGRET

- EGRET: 1991–2000
  - 271 gamma-ray sources (Hartman et al. 1999)
    - Only 38% (101 sources) have clear “identifications”



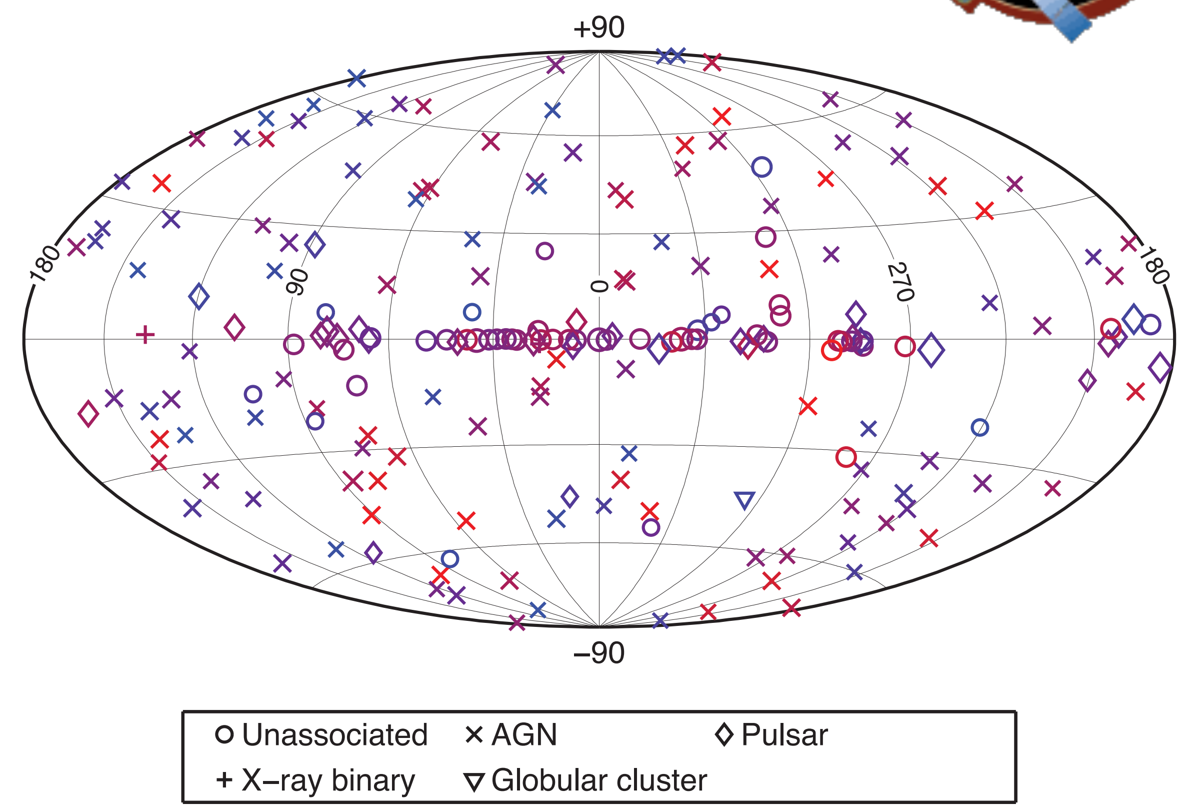
The LAT 3 Month All-Sky Map

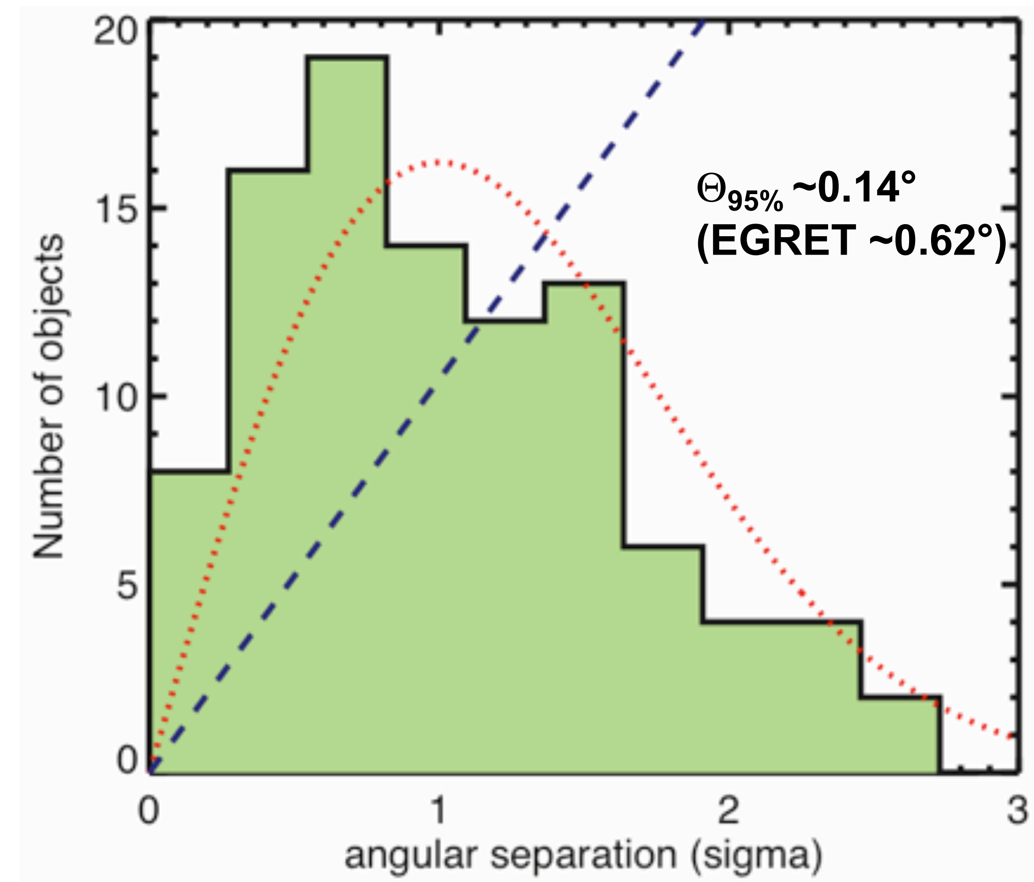
- Fermi LAT 3-month bright gamma-ray source list ≠ catalog
  - 207 sources above TS=100 (444 sources above TS=25)
  - Large number of citation (~60)
- LAT one-year catalog (based on 11-month data) soon
  - >1000s of sources expected



Source Associations

Class	Number
FSRQ	62
BL Lac	46
Radio galaxy	11
Other blazar	2
Radio/X-ray pulsar	15
LAT γ-ray pulsar	14
HMXB	2
Globular cluster	1
LMC	1
Special cases	13
Unidentified	38





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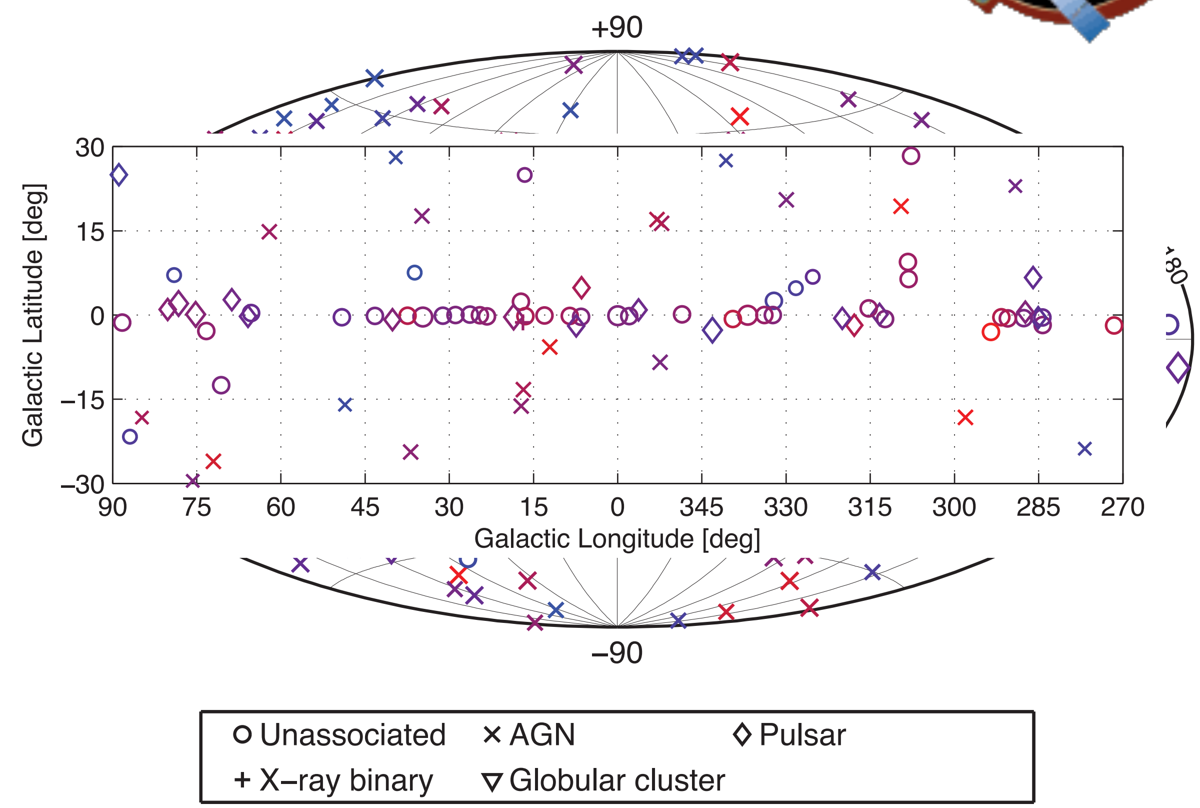
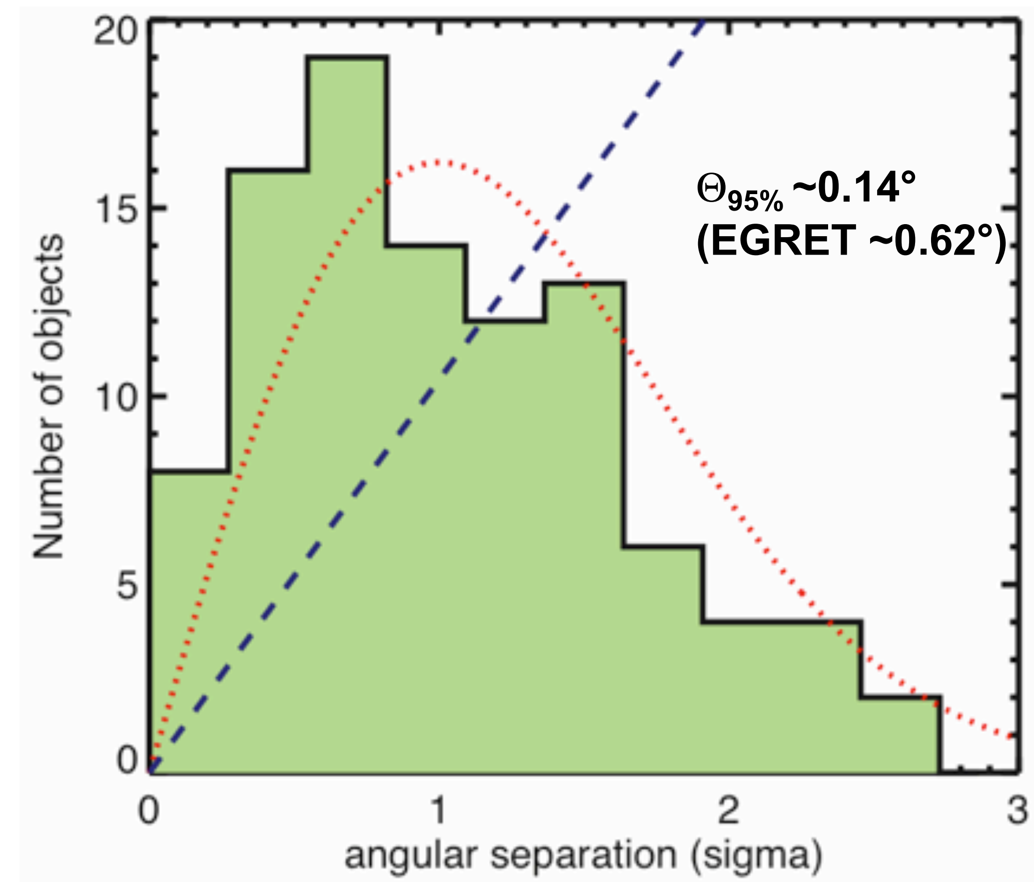
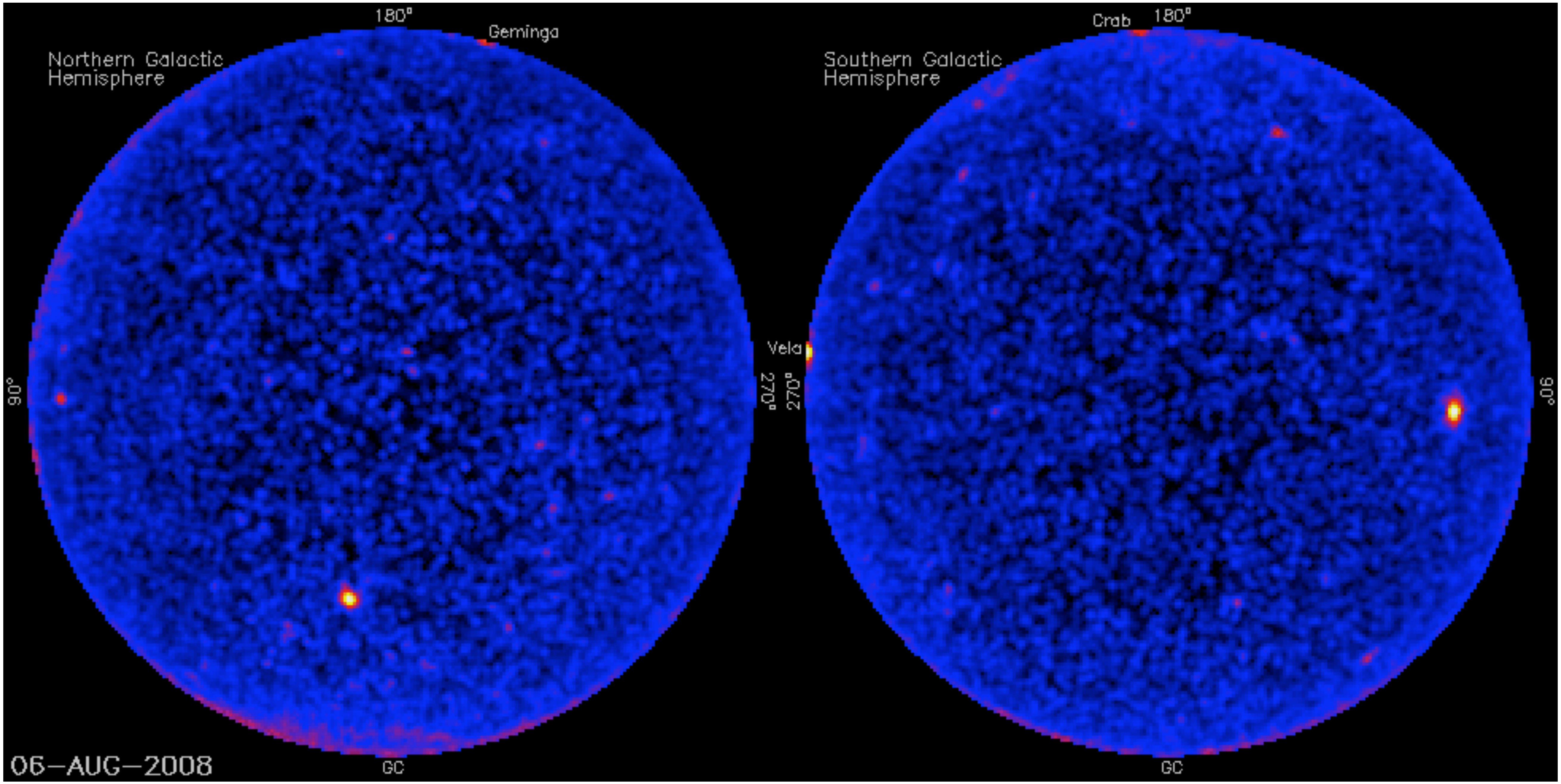


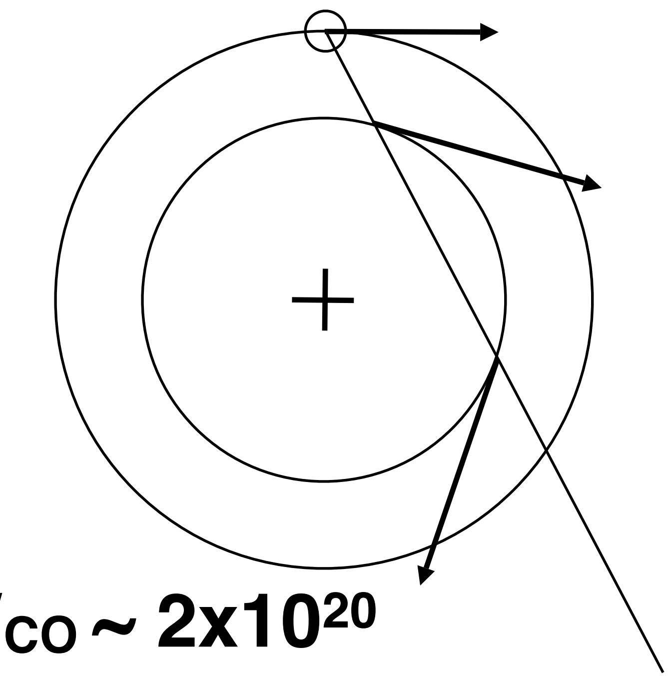


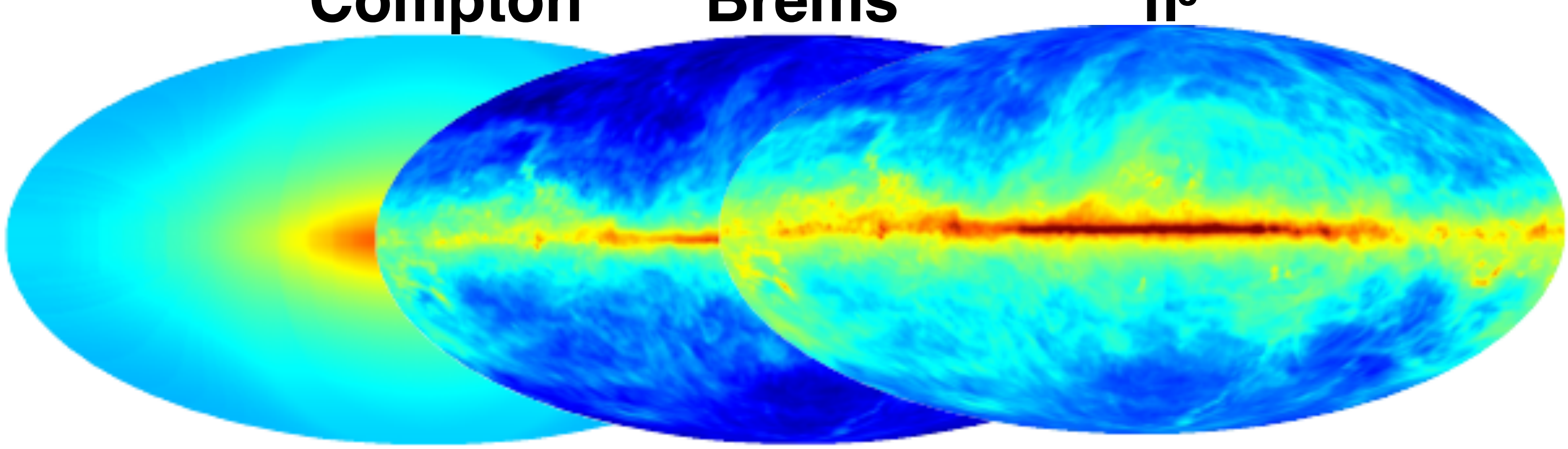
Variable Gamma-ray Sky

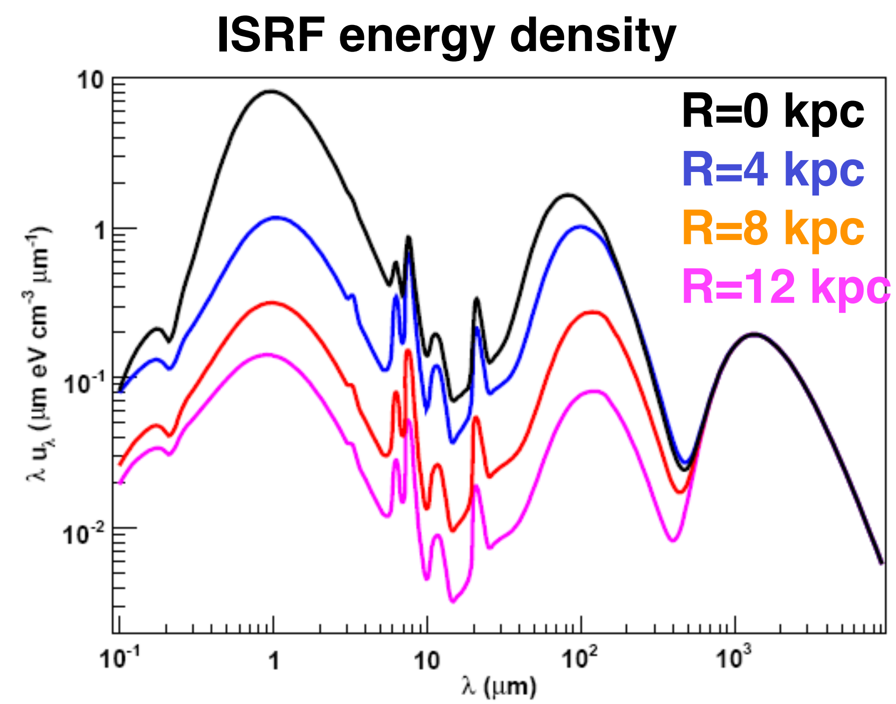


Modeling Galactic Diffuse γ-ray

- Cosmic-ray spectra: electrons, protons, ions
- Inter-Stellar Radiation Field
  - Starlight (~ 0.1 μm – 10 μm), Dust (~ 10 μm – 300 μm), CMB (>300 μm)
- Gas map
  - Distance from rotation curve
  - HI density from LAB survey
  - H_2 density from CO survey assuming $X_{CO} \equiv N(H_2)/W_{CO} \sim 2\times10^{20}$
- Interactions: Compton, Brems, π^0



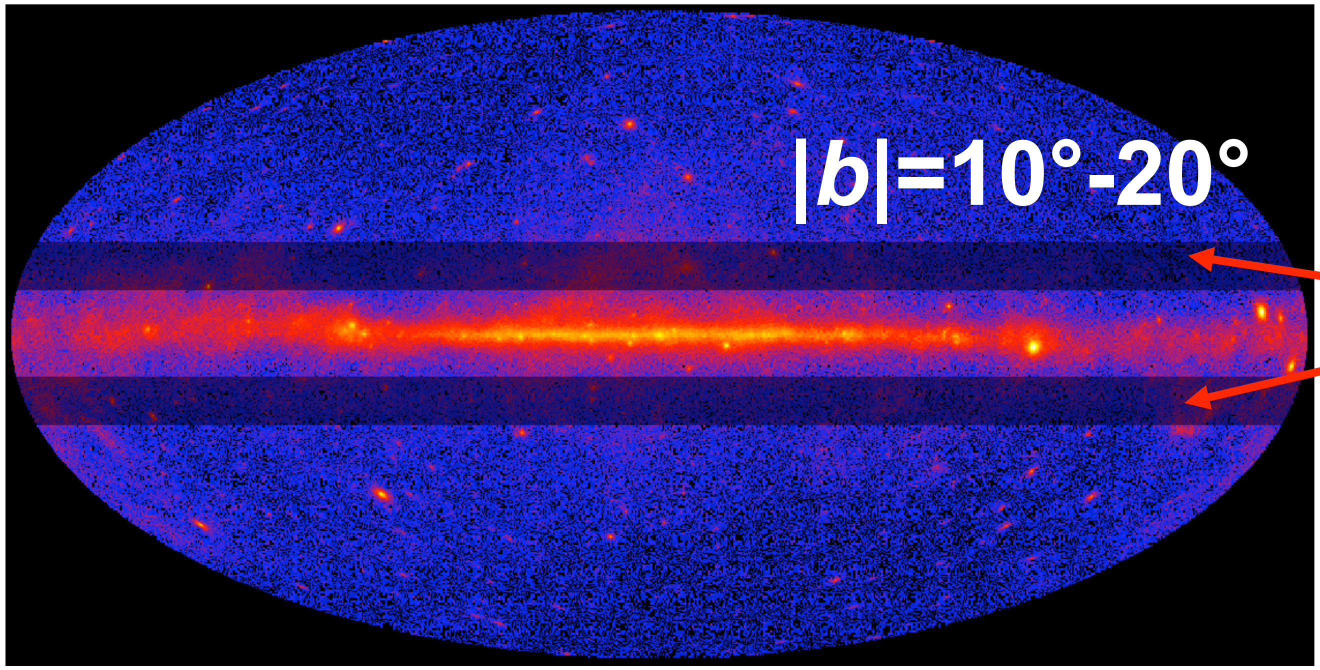


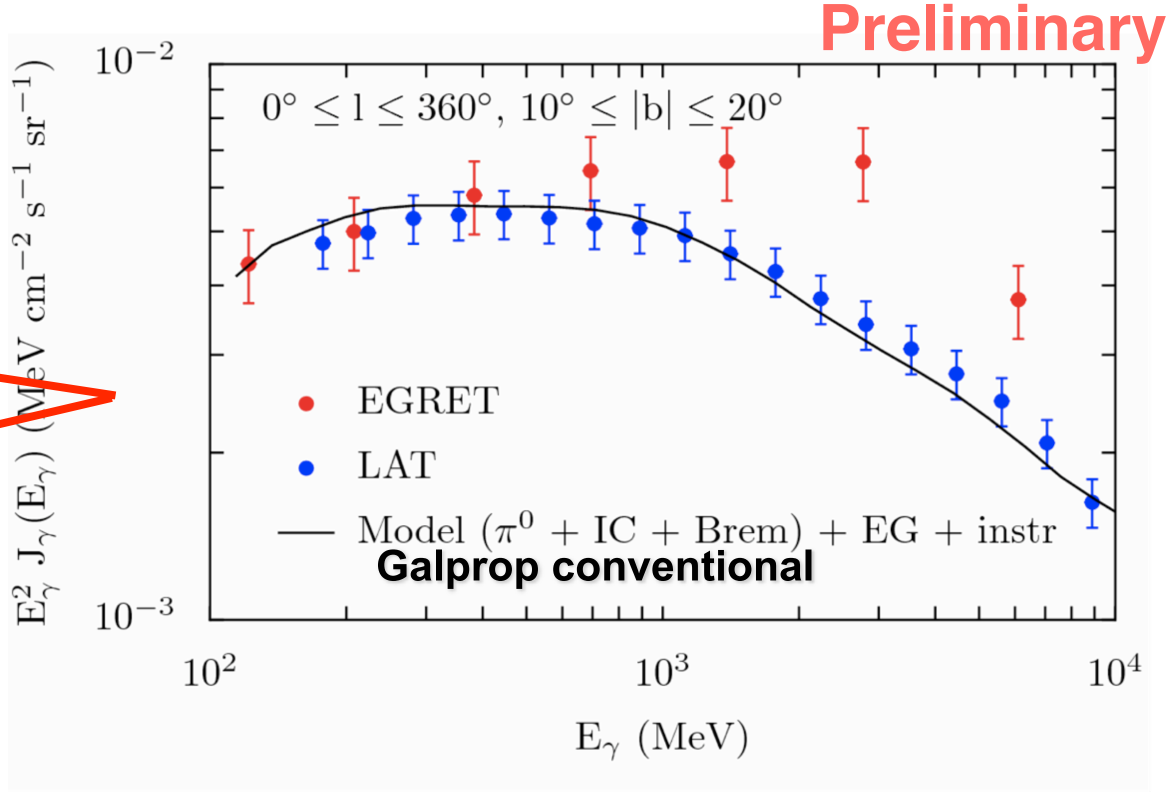


Porter et al. 2008

LAT Observation Galactic Diffuse

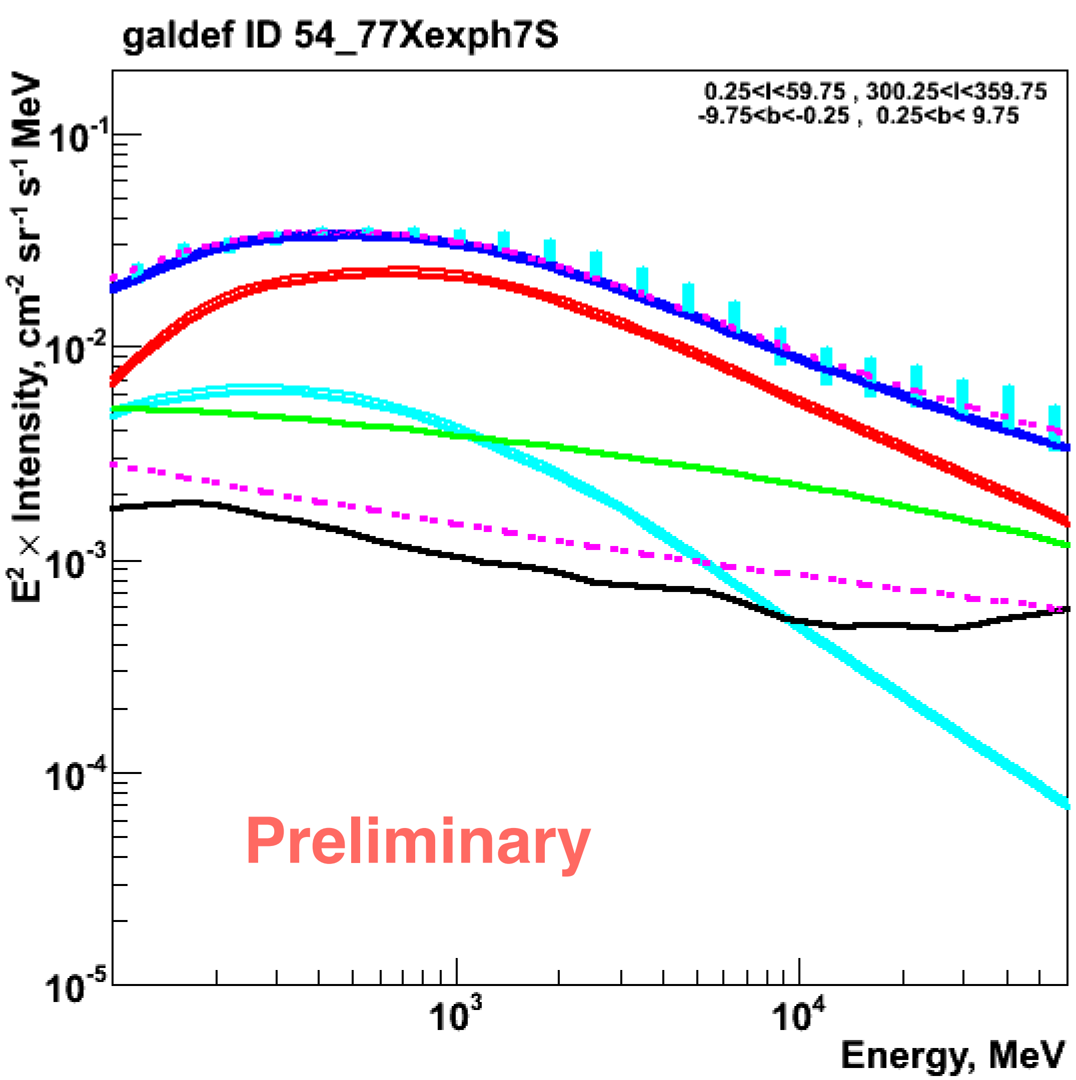
- Mid-latitude data shows no evidence of "GeV excess"
  - Point sources are not subtracted
  - LAT errors are dominated by systematic error (~10%)
- Implications
  - EGRET "GeV excess" might be instrumental
    - Similar effect seen in Vela spectrum
  - CR propagation model used in GALPROP can explain Galactic diffuse spectra in mid-latitude



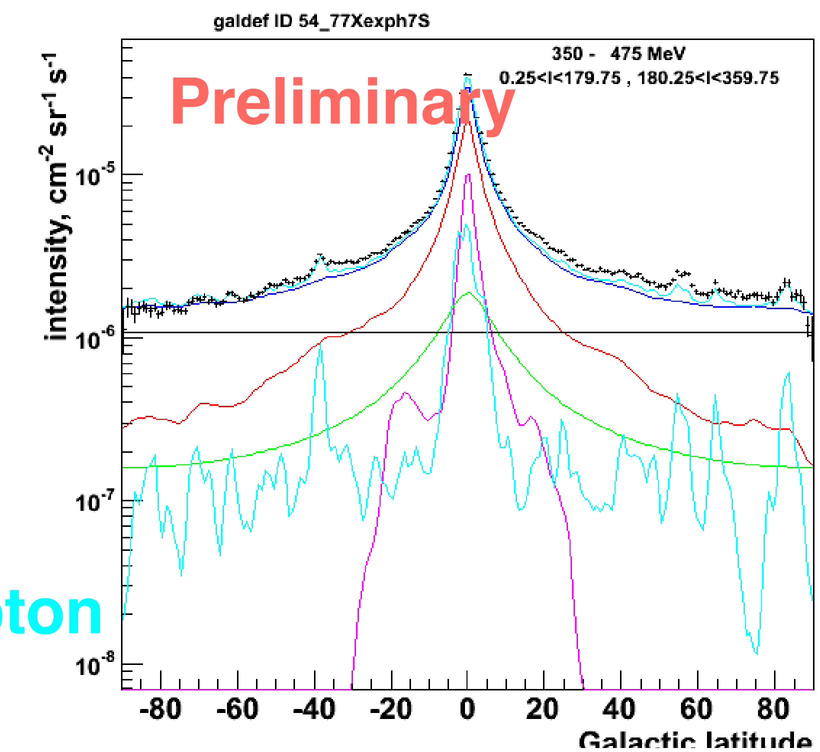


Improving Galactic Diffuse Model

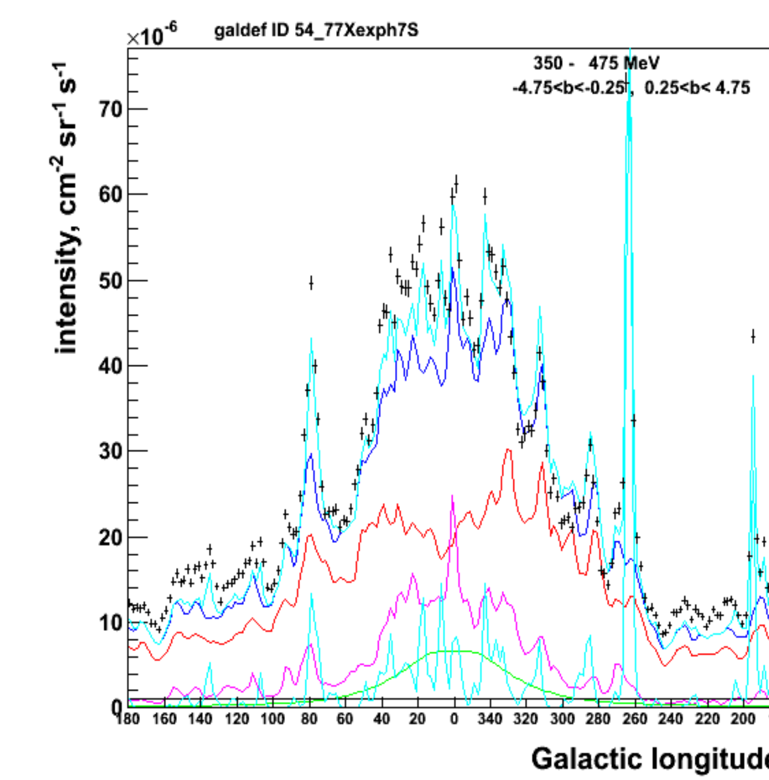
- Modeling of galactic diffuse is critical for studies of galactic sources including DM sources



π^0 decay
Inverse Compton
Brems
Sources
isotropic

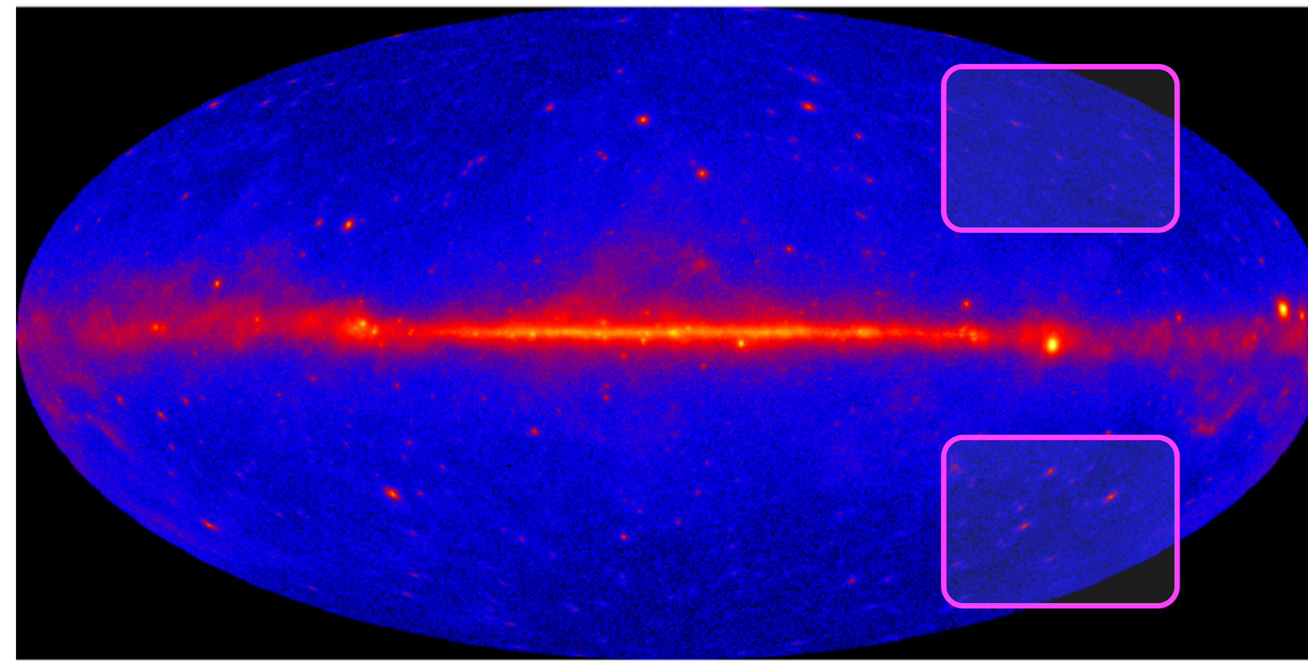


π^0 decay (HI)
Inverse Compton
Brems
π^0 decay (H2)
isotropic

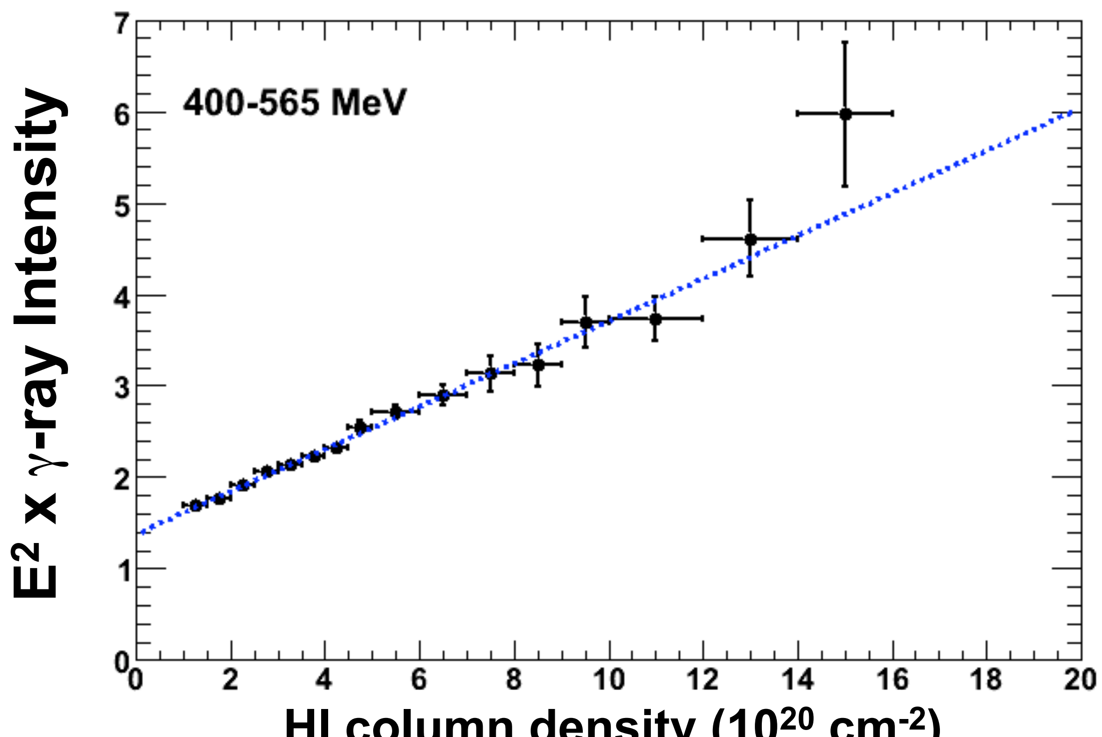


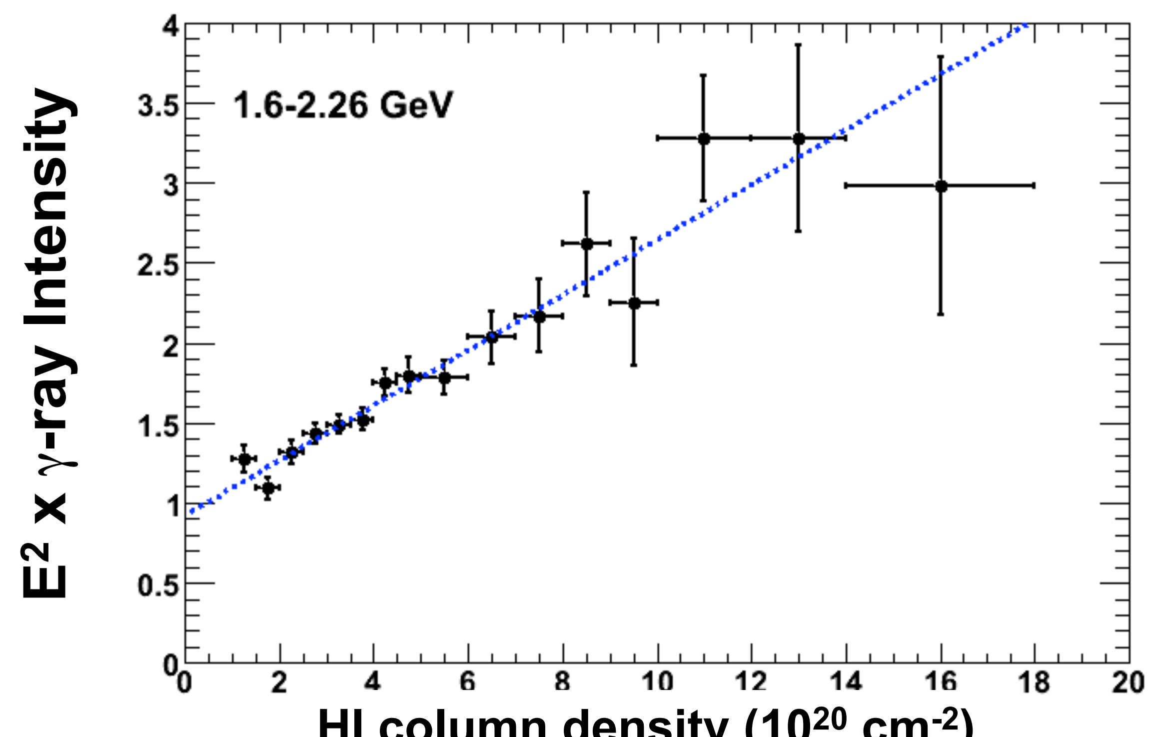
Study of local CR with Atomic H

- Use mid/high latitude region to study local CR flux&spectra
  - l=200–260°, |b|=22–60°
  - Less effect from Compton and galactic point sources
  - Less effect from H_2 gas (avoid uncertainties of W_{CO})
- Measurement of HI emissivity



Preliminary

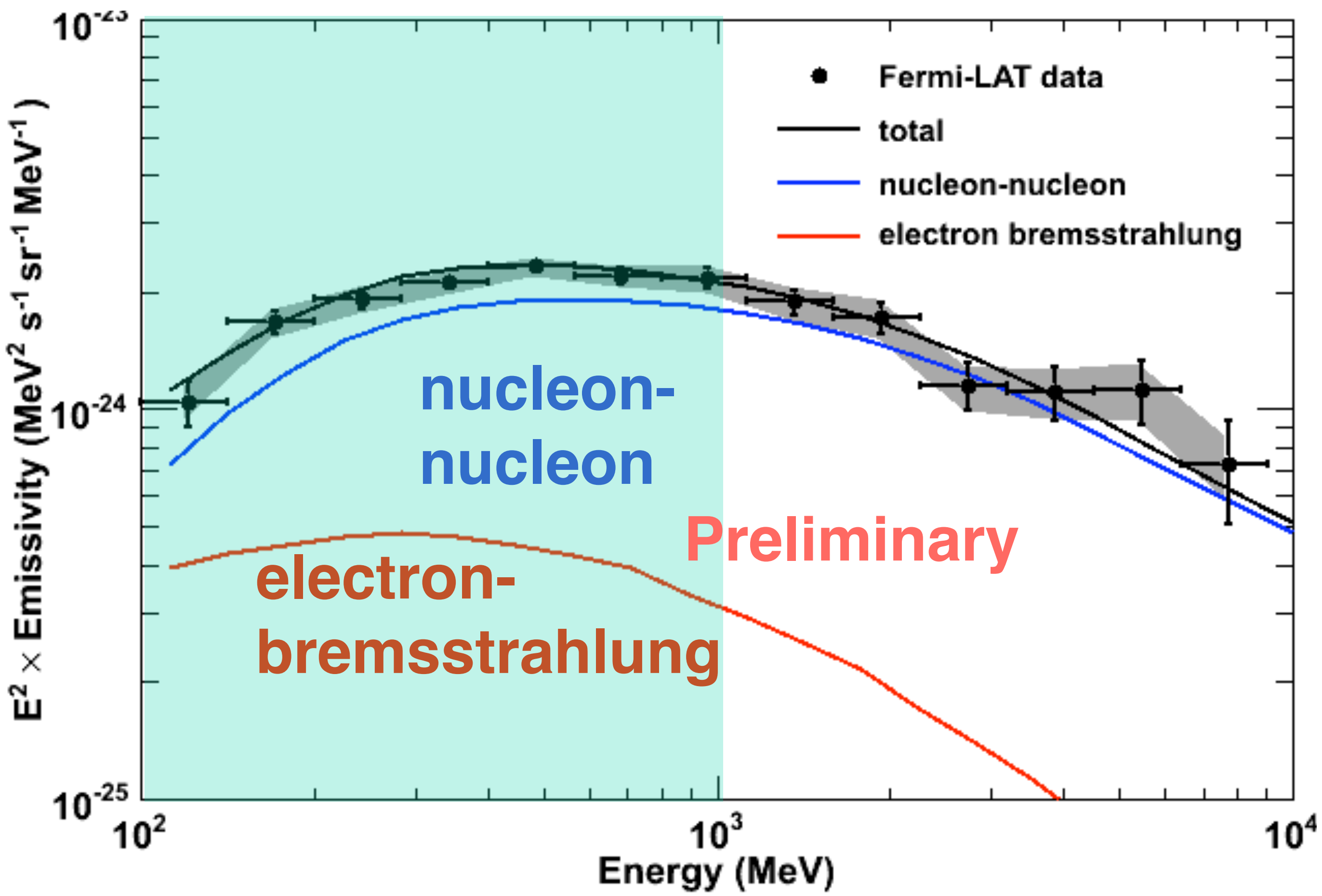




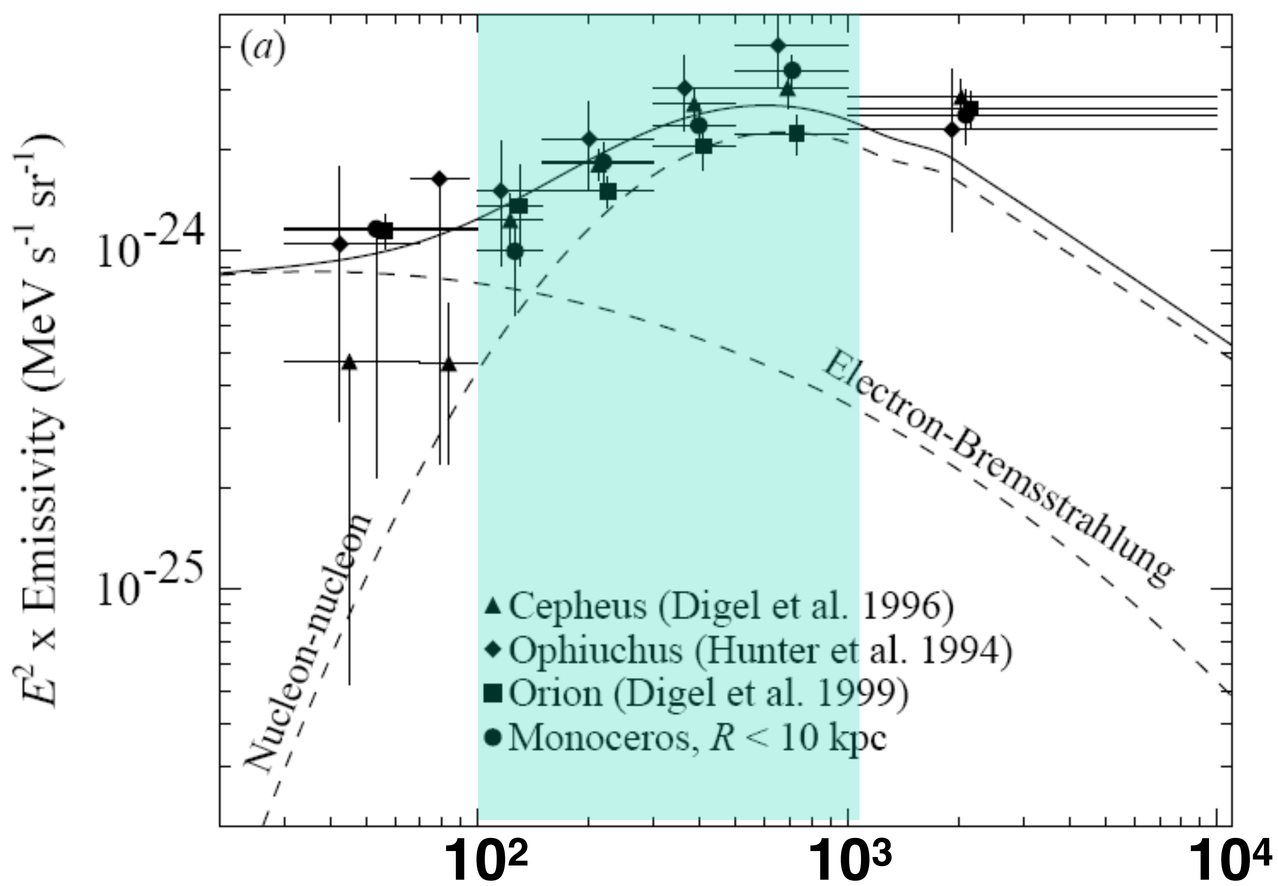
Emissivity of Local HI

- Improved statistics and wider energy coverage
- Model prediction using CR spectrum in the solar system agree with the measurement
  - Local CR spectrum is close to that in the solar system

Emissivity by Fermi-LAT



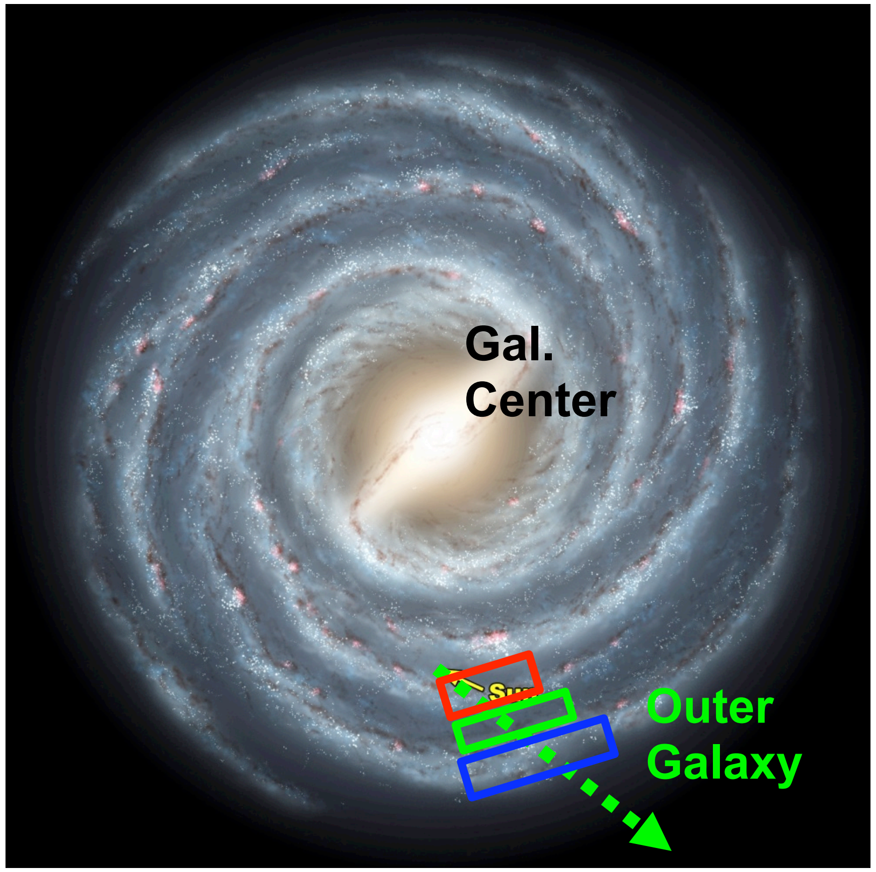
EGRET (Digel et al. 2001)

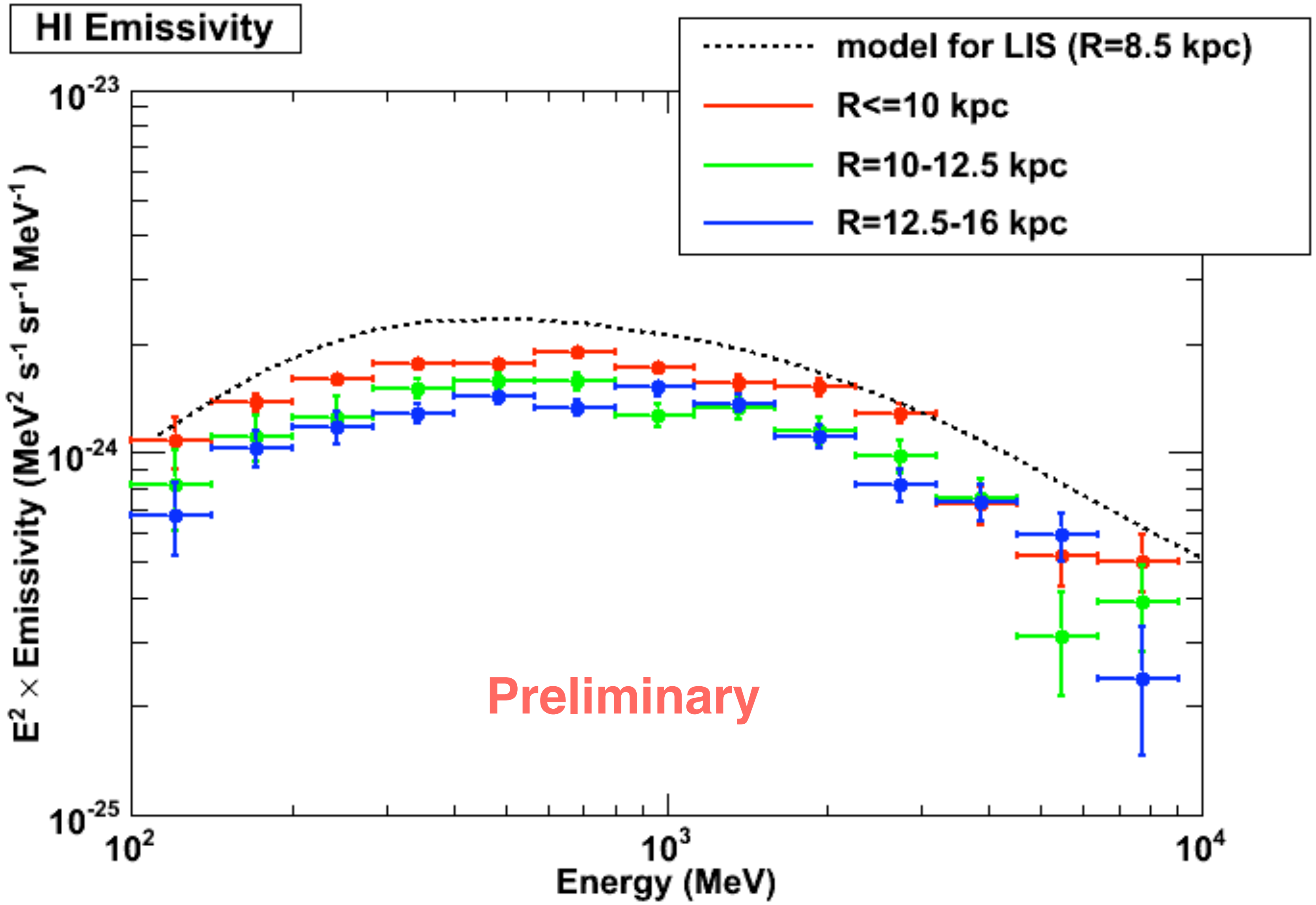


Different CR spectra assumed

Emissivity Dependence on R from GC

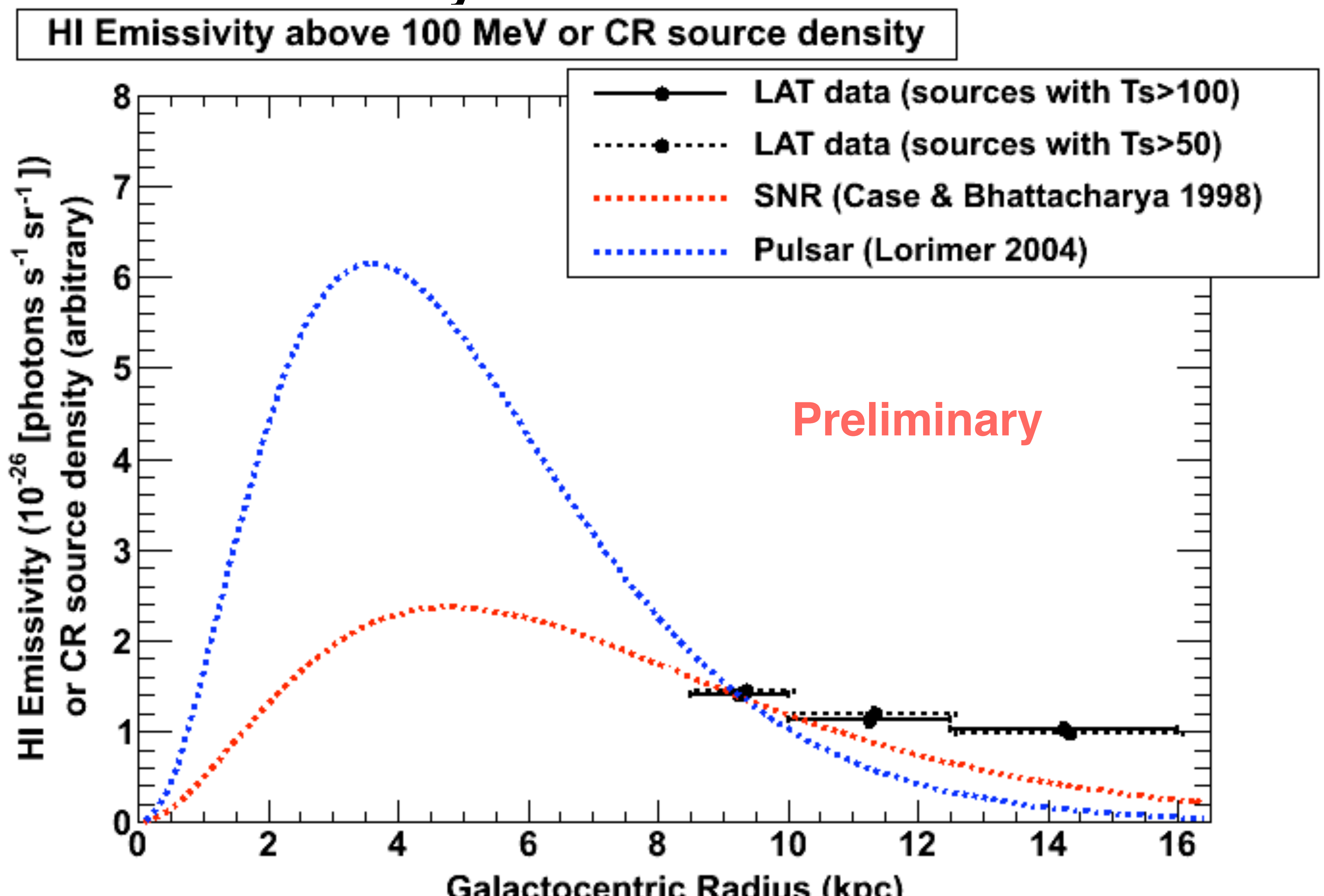
- CR density as function of distance from Galactic center can be studied by gamma-ray emissivity of outer Galaxy
  - Different HI distribution dependent on R
- Emissivity (CR spectrum) shape consistent up to R=16 kpc





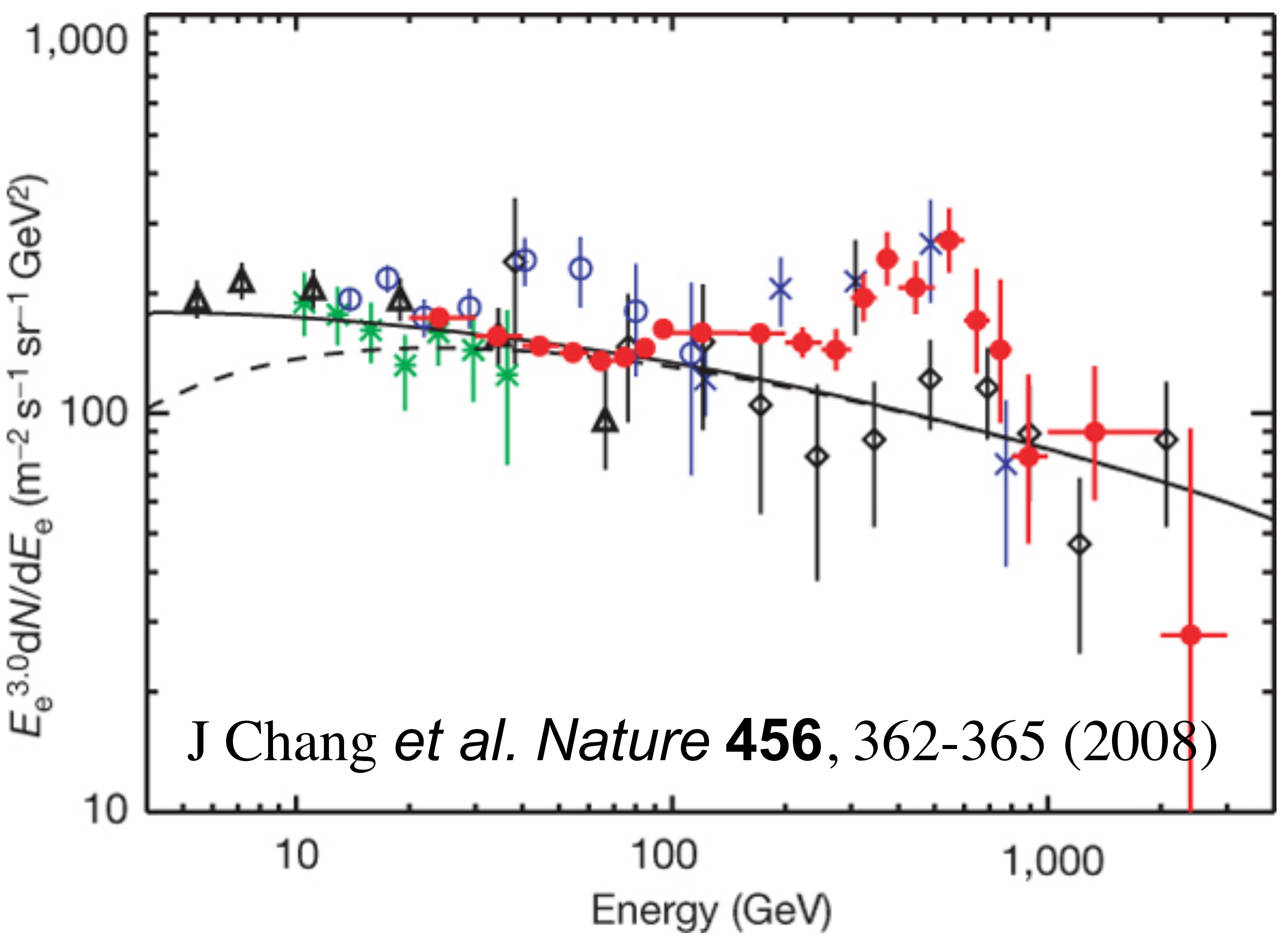
CR-Density Distribution

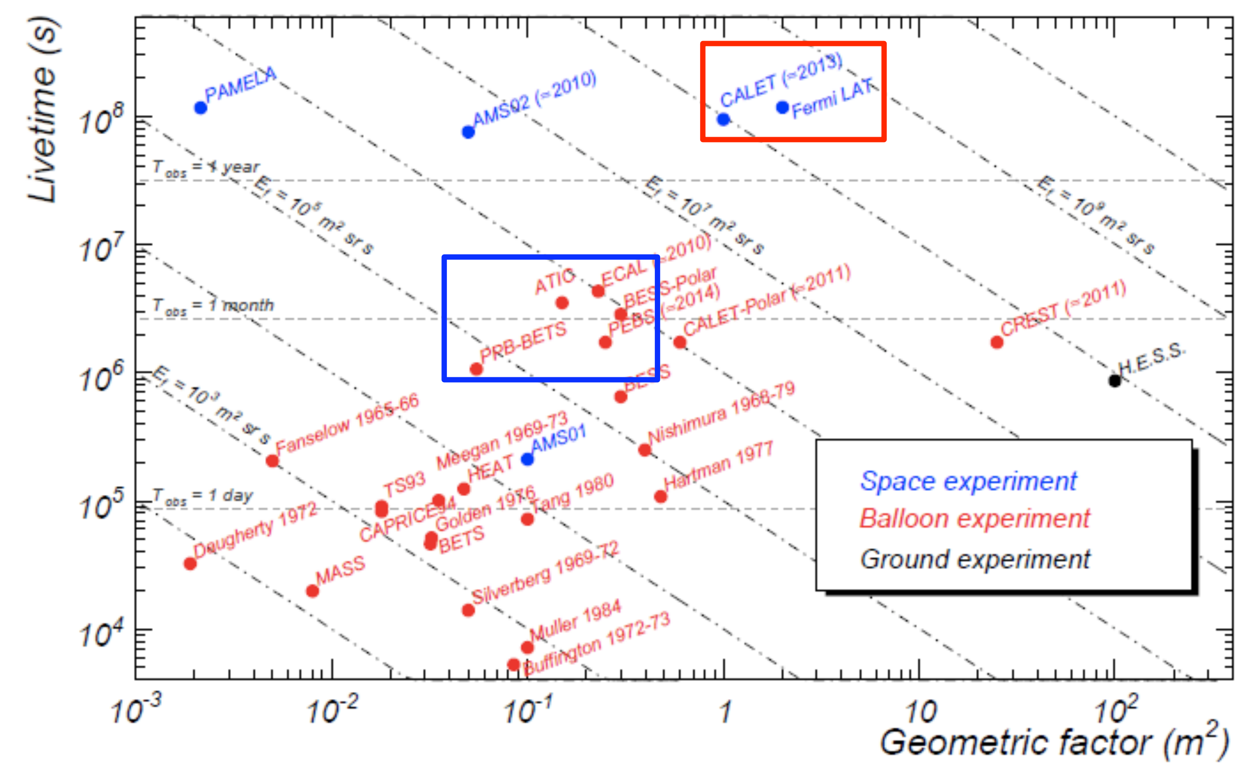
- SNR is considered to be a source of Galactic CR
  - Distribution slightly different
  - CR propagation effect
  - Unknown CR sources in outer Galaxy?



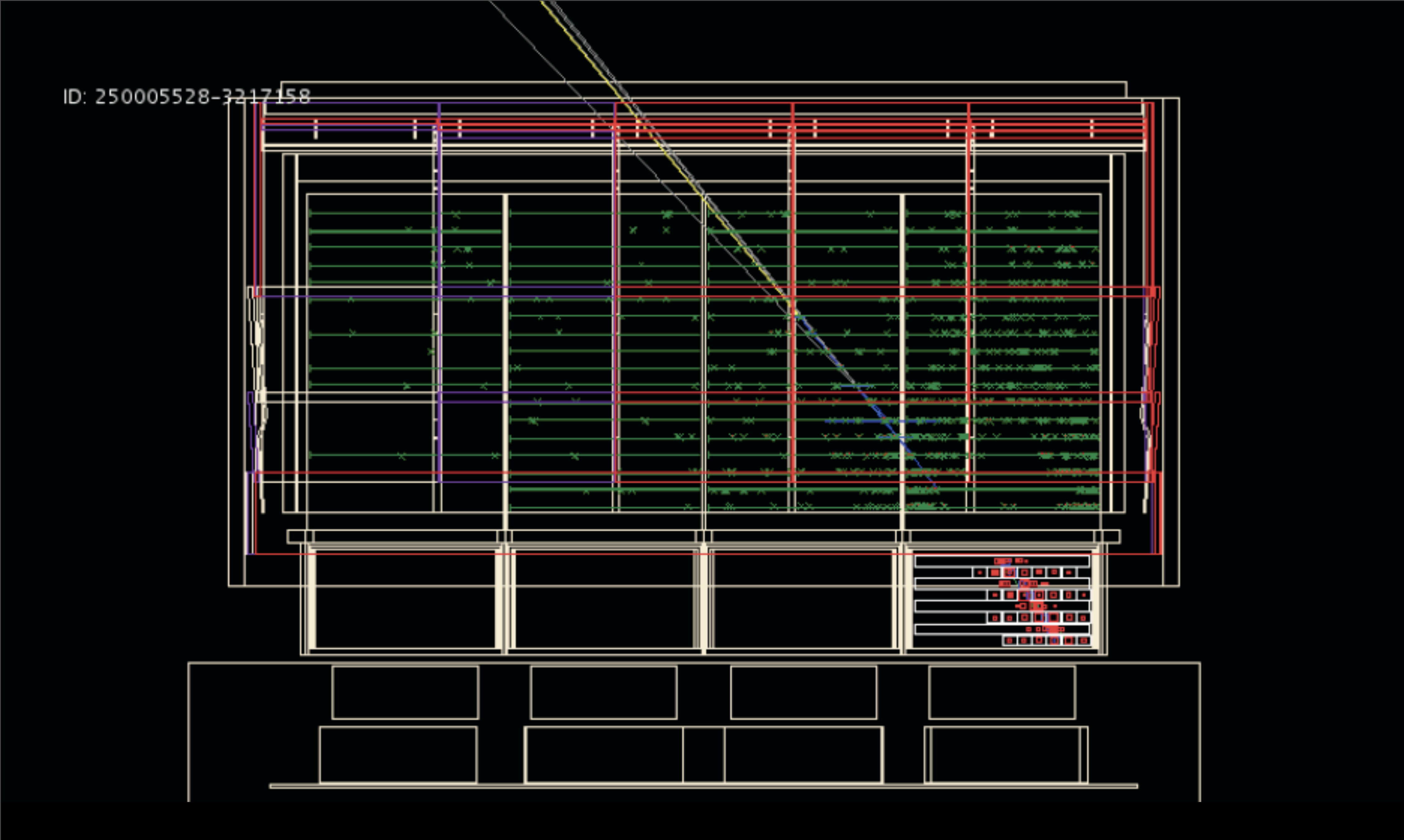
High-Energy Cosmic-ray Electron

- High-energy CR electron probes local electron sources
  - Rapid synchrotron loss at high energies
- Recent report by ATIC indicates high energy excess
  - Could be interpreted as evidence of dark matter
- LAT can measure CR electron spectrum with high statistics
  - All events above ~20 GeV are sent to ground
  - Hadron rejection > 10^3, large effective area, long observation





- The exposure factor determines the statistics.
- Imaging calorimeters (vs. spectrometers) feature larger G_f.
- Space (vs. balloon) experiments feature longer livetime.



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

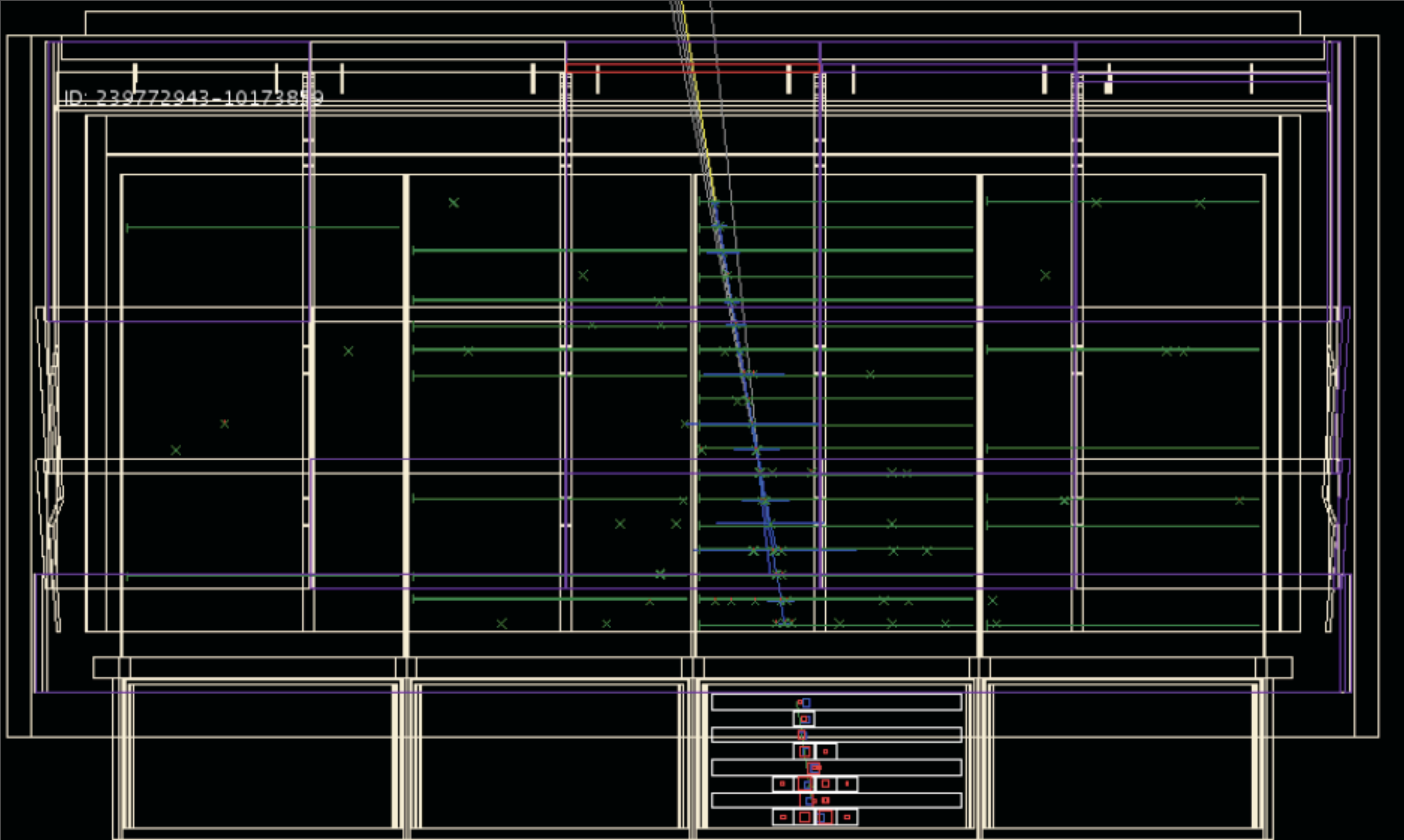
Tkr1Hits
6

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**



A candidate electron – 844 GeV

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

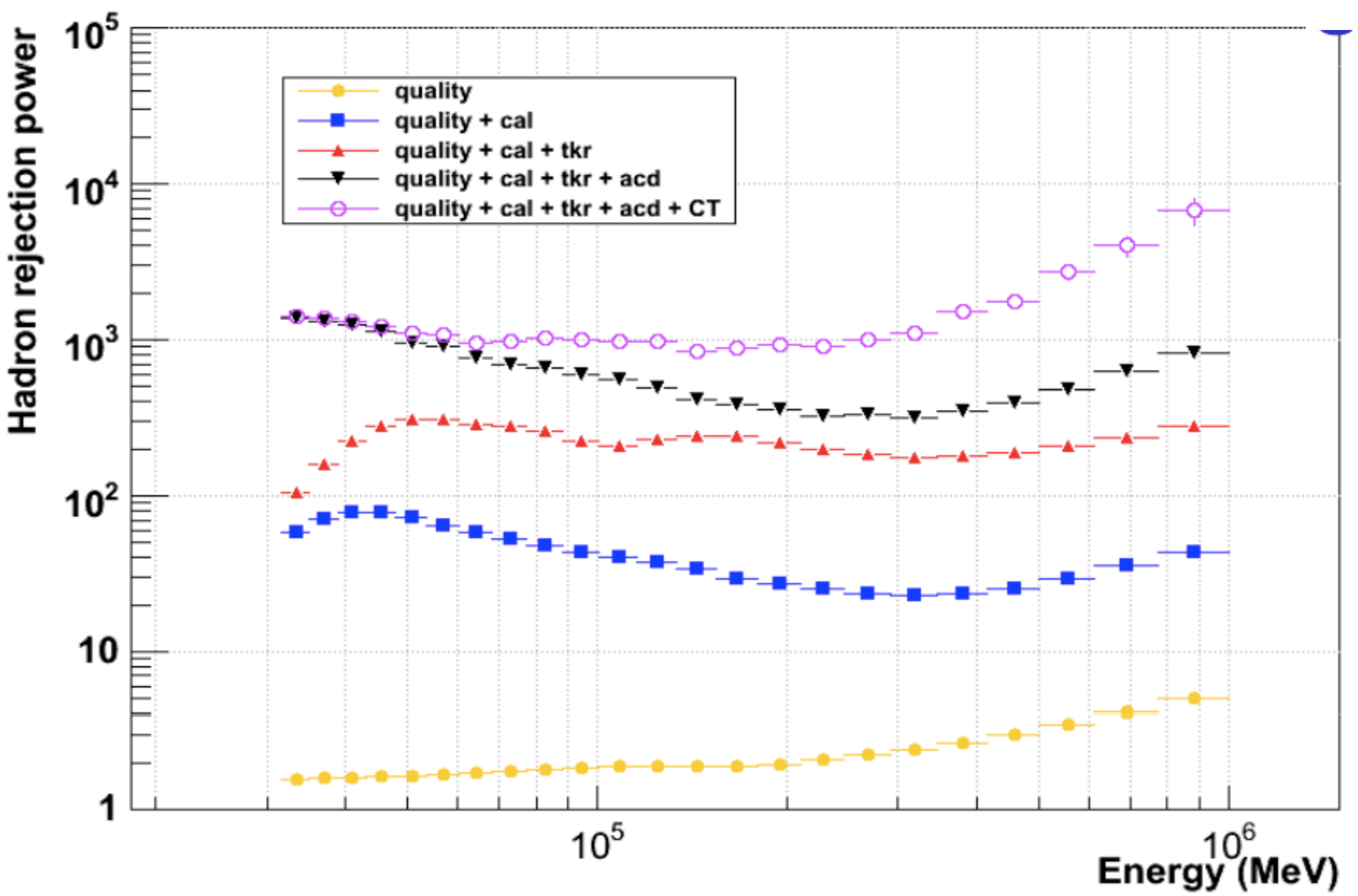
AcdTotalEnergy
8.99

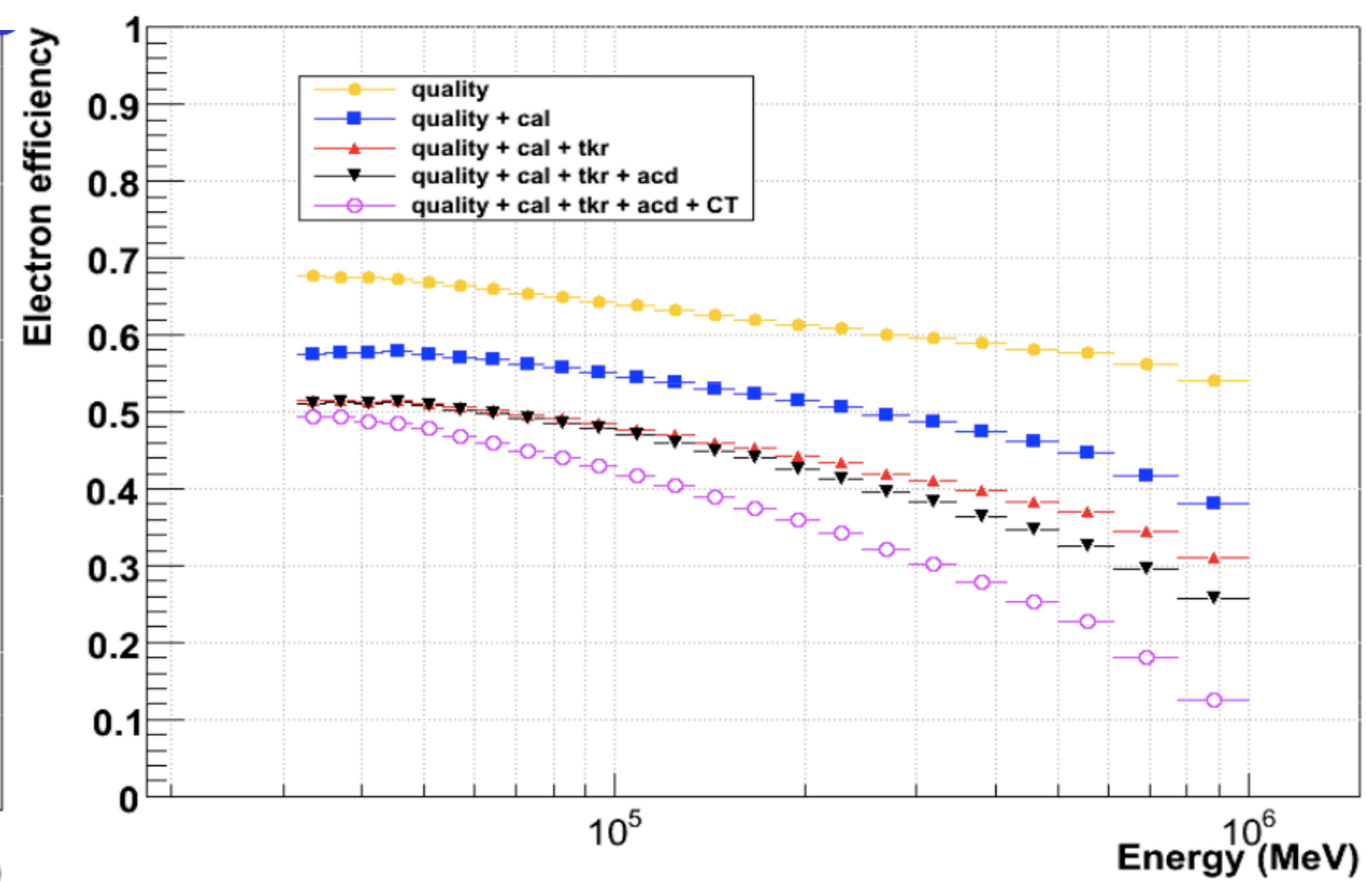
AcdTileCount
20

- **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**

CR Electron Event Selection

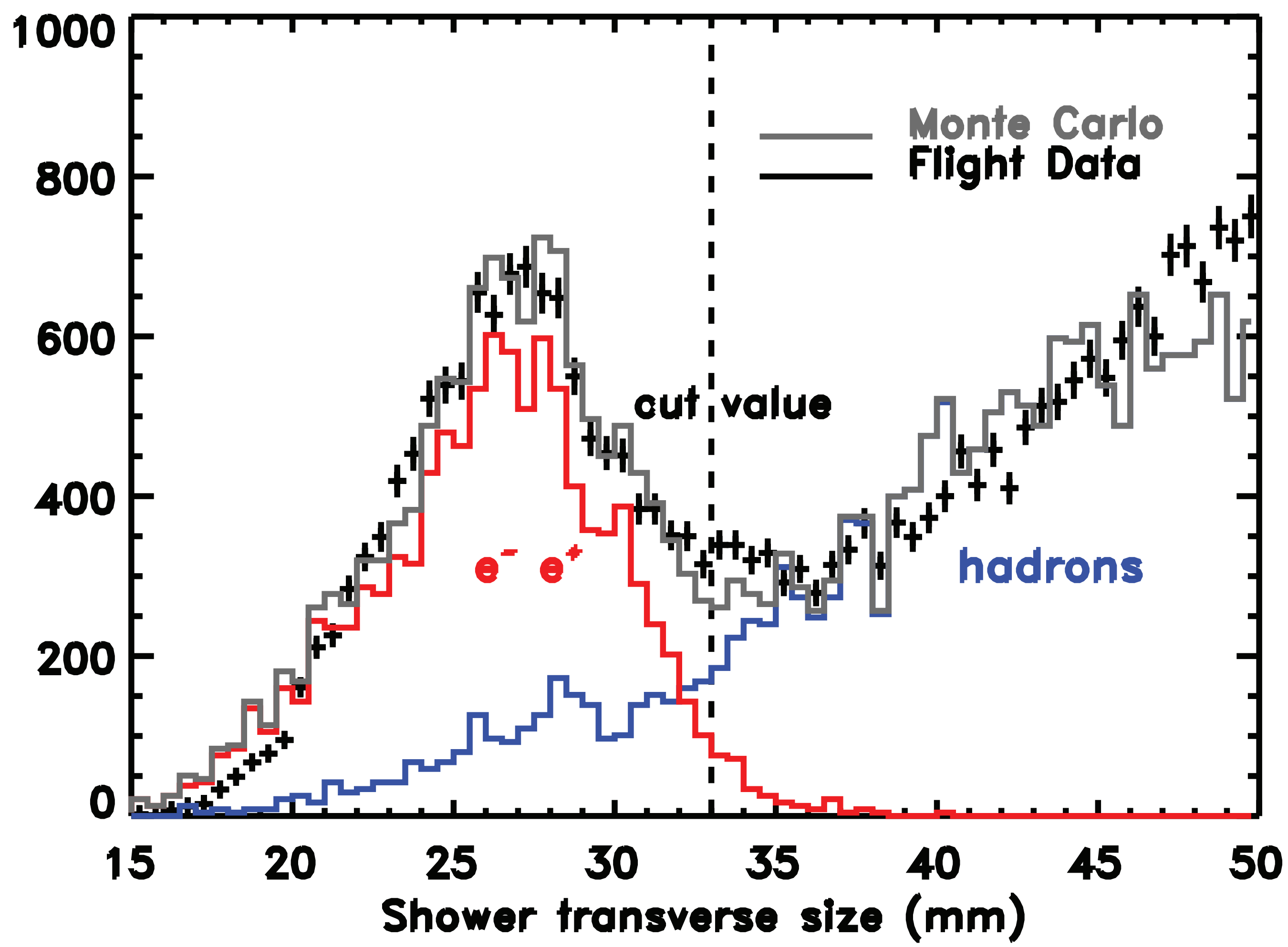
- Discrimination based on difference of EM (electromagnetic) and hadronic shower shapes
  - Measurement of lateral shower development
- Three step process
  - Basic quality cuts (require ACD signal to reject photons)
  - Event topology in TKR, CAL, ACD
  - Classification Tree (CT) analysis

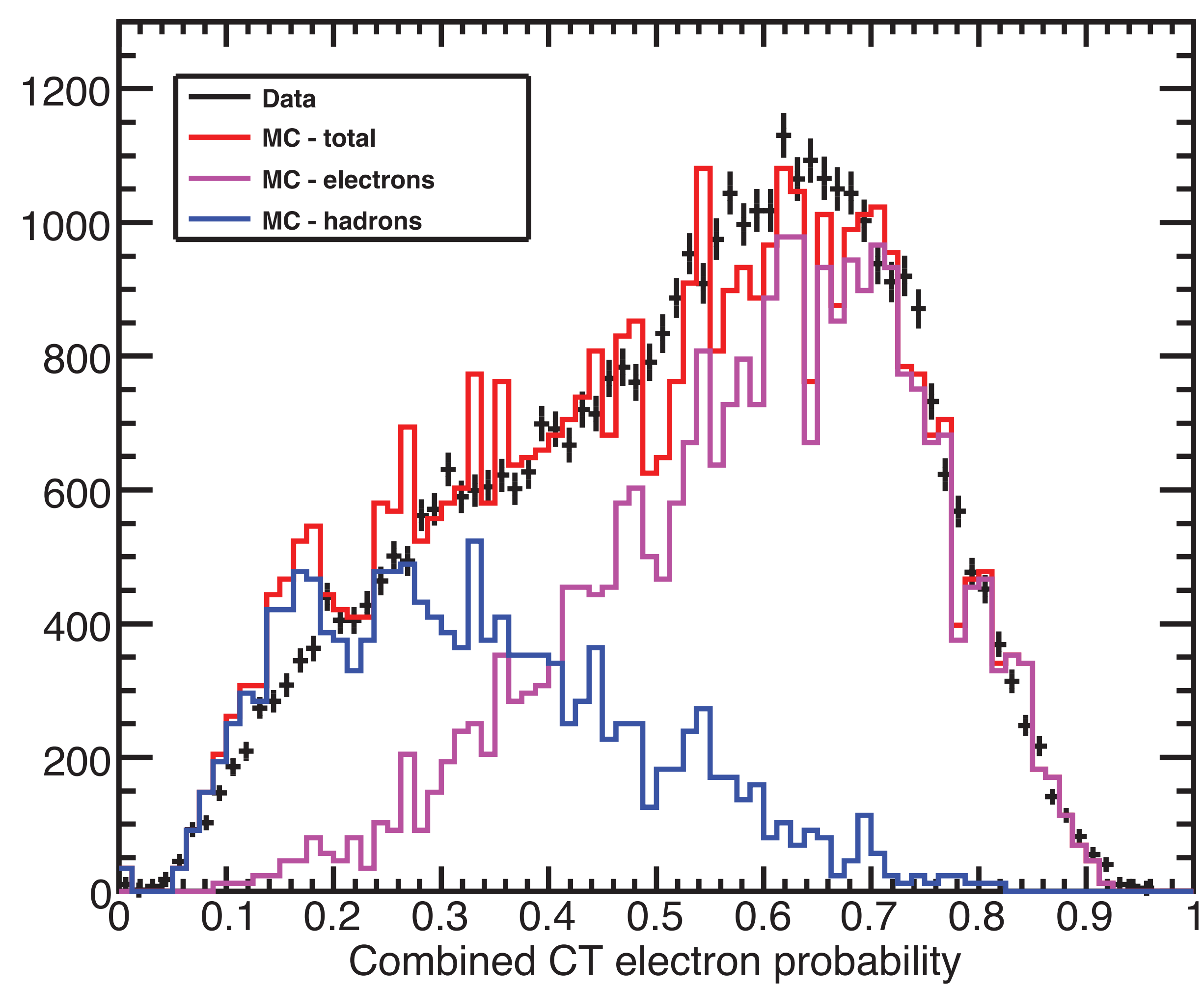




Validation of Event Selection Variable

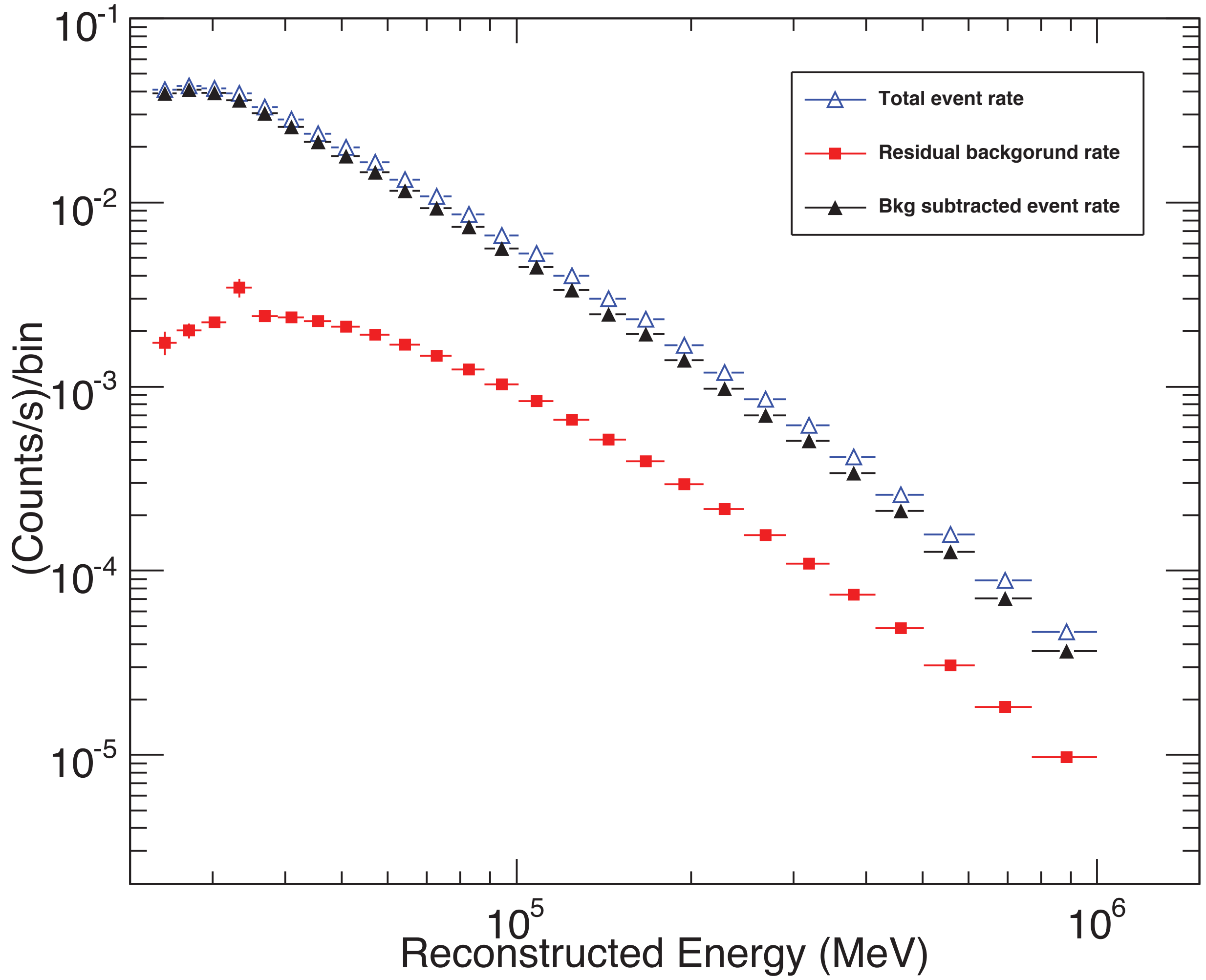
- Comparison of data and MC for event selection variables
  - Overall distribution is well reproduced by MC
  - Signal dominant after event topology cuts (E> 100 GeV)

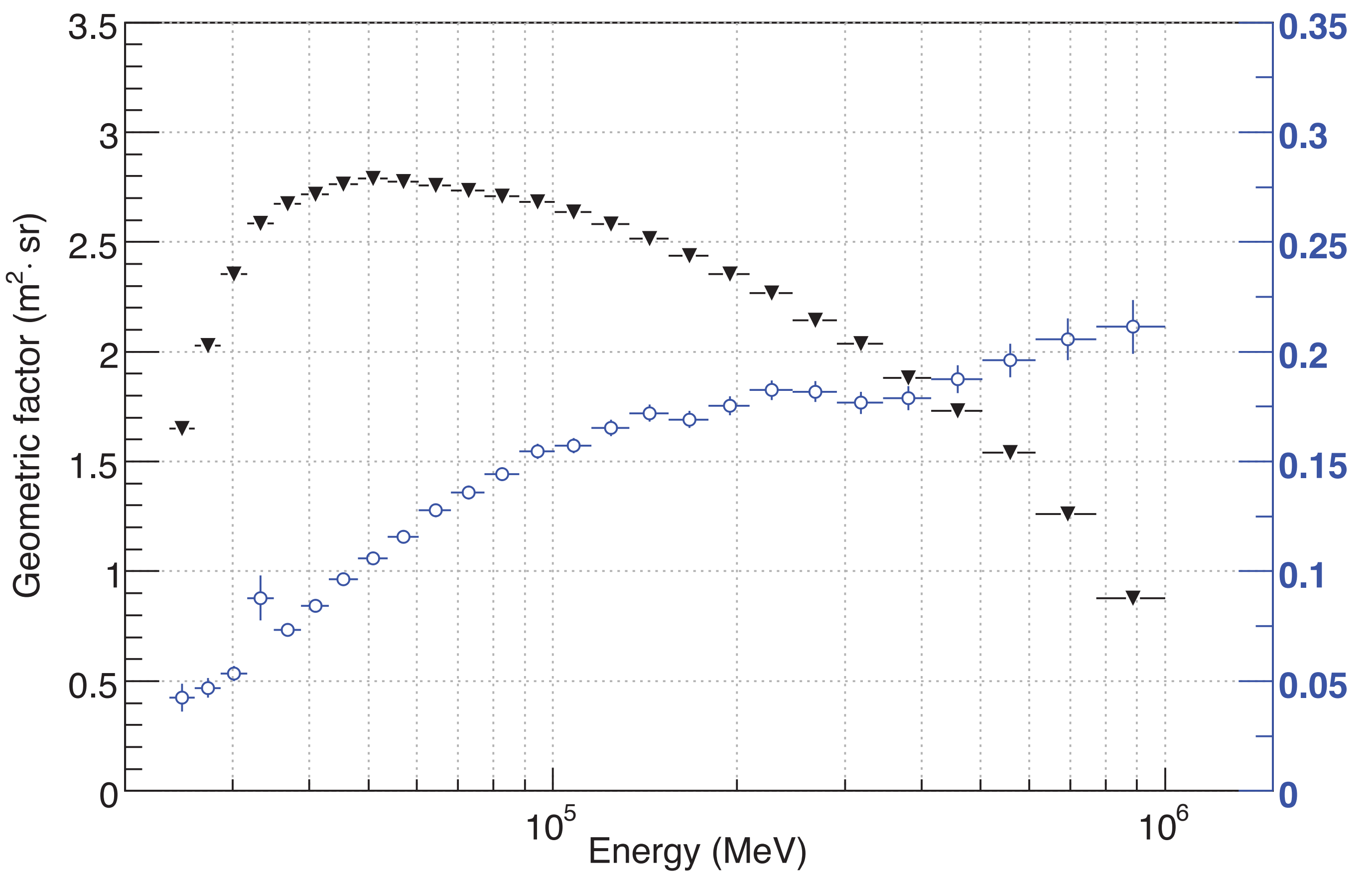




Background Contamination

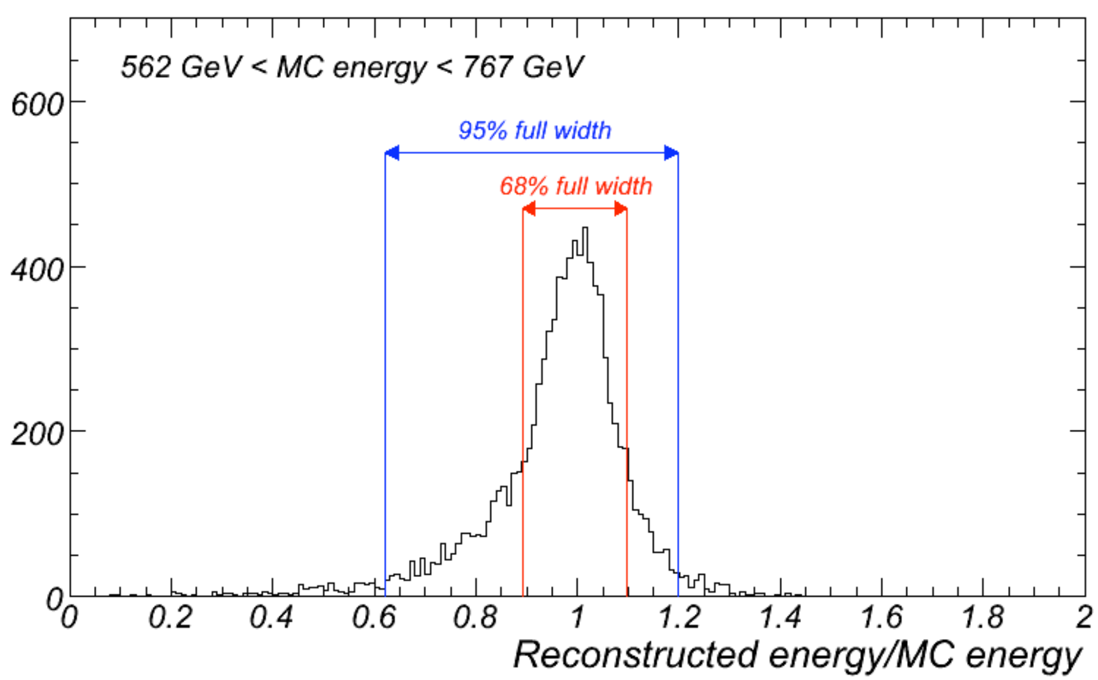
- Hadron contamination less than ~20%
  - Subtracted from electron candidates
- Photon contamination less than ~2%
  - No subtraction

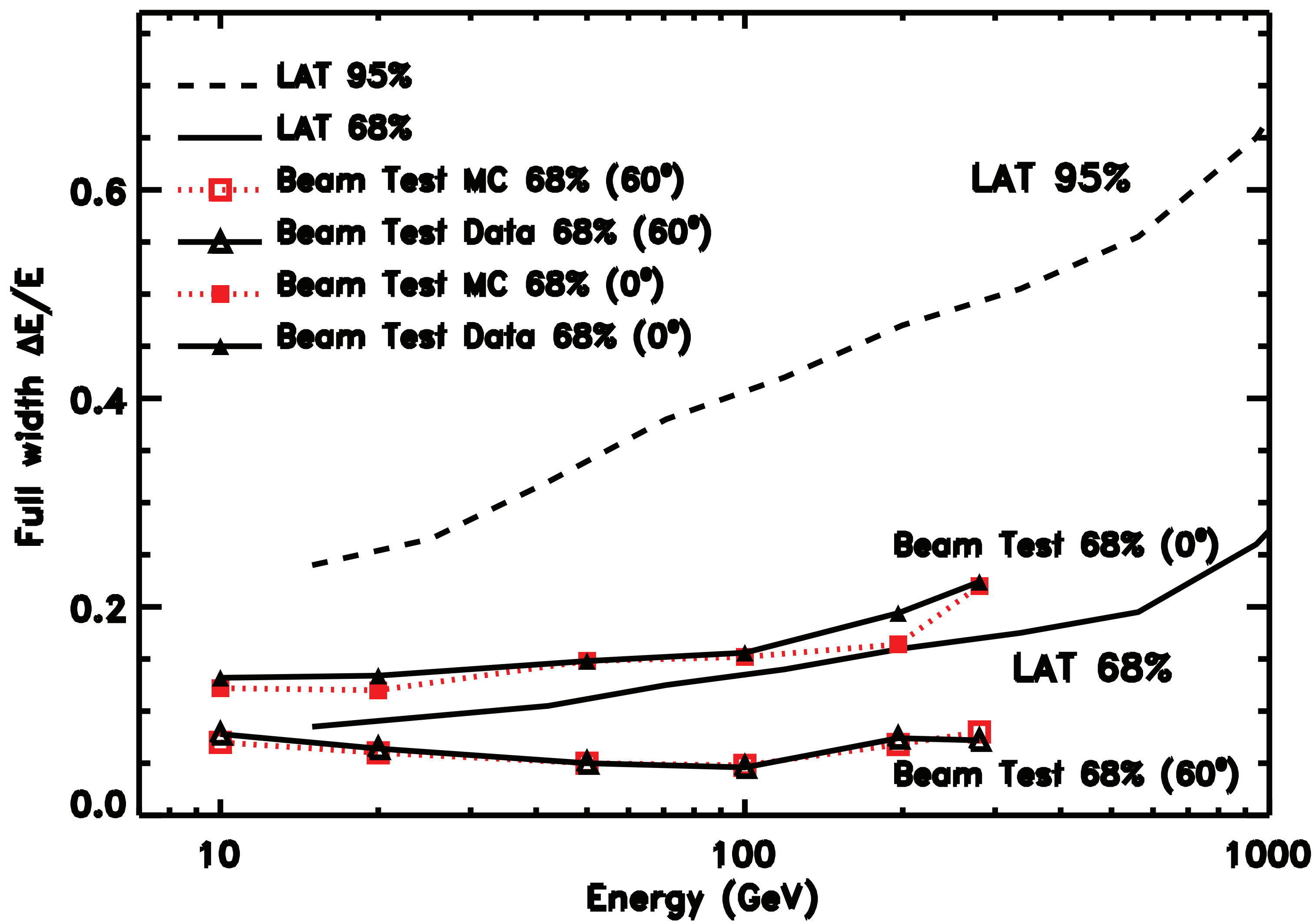




Energy Resolution

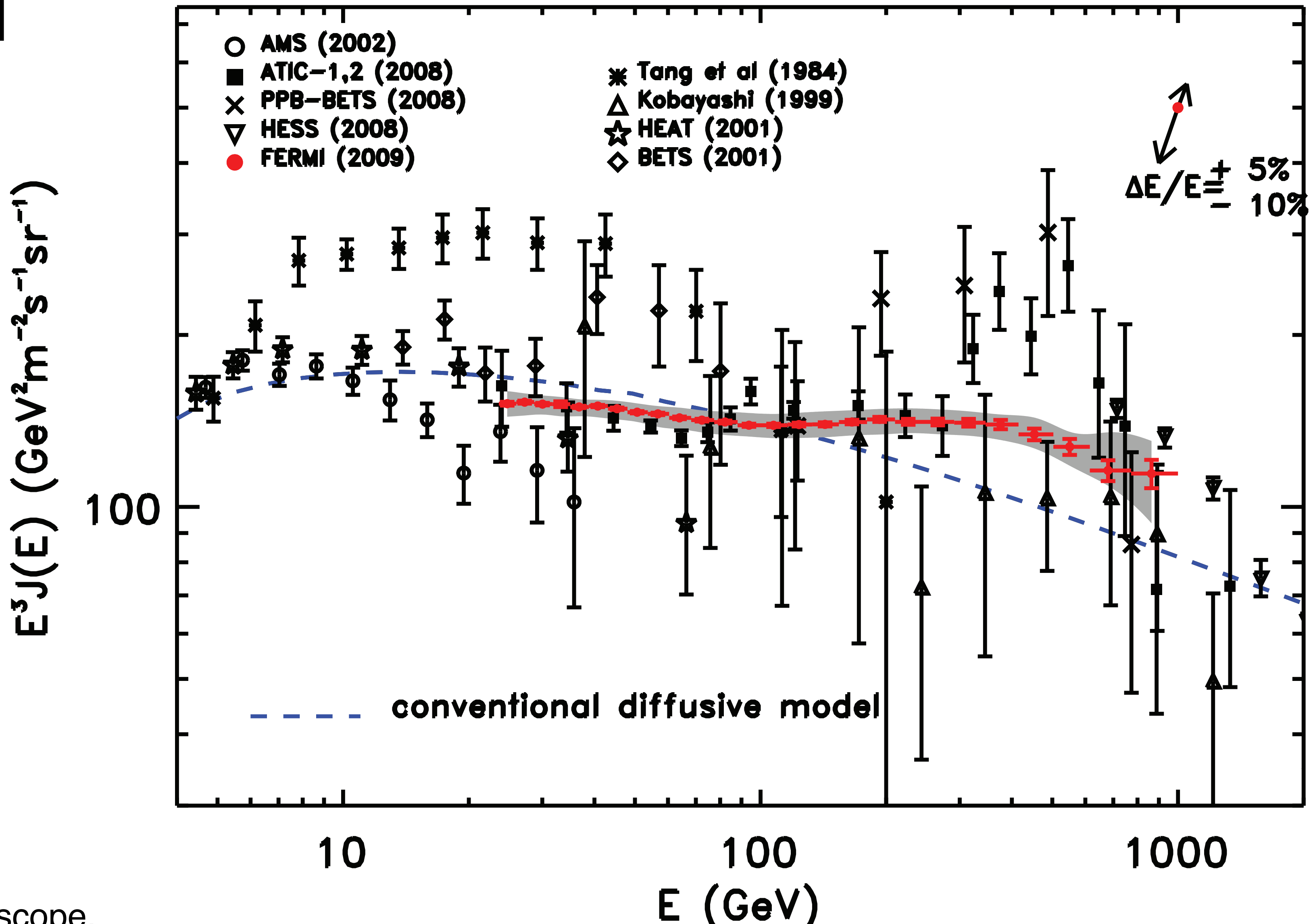
- Energy resolution is validated by beam test up to ~300 GeV





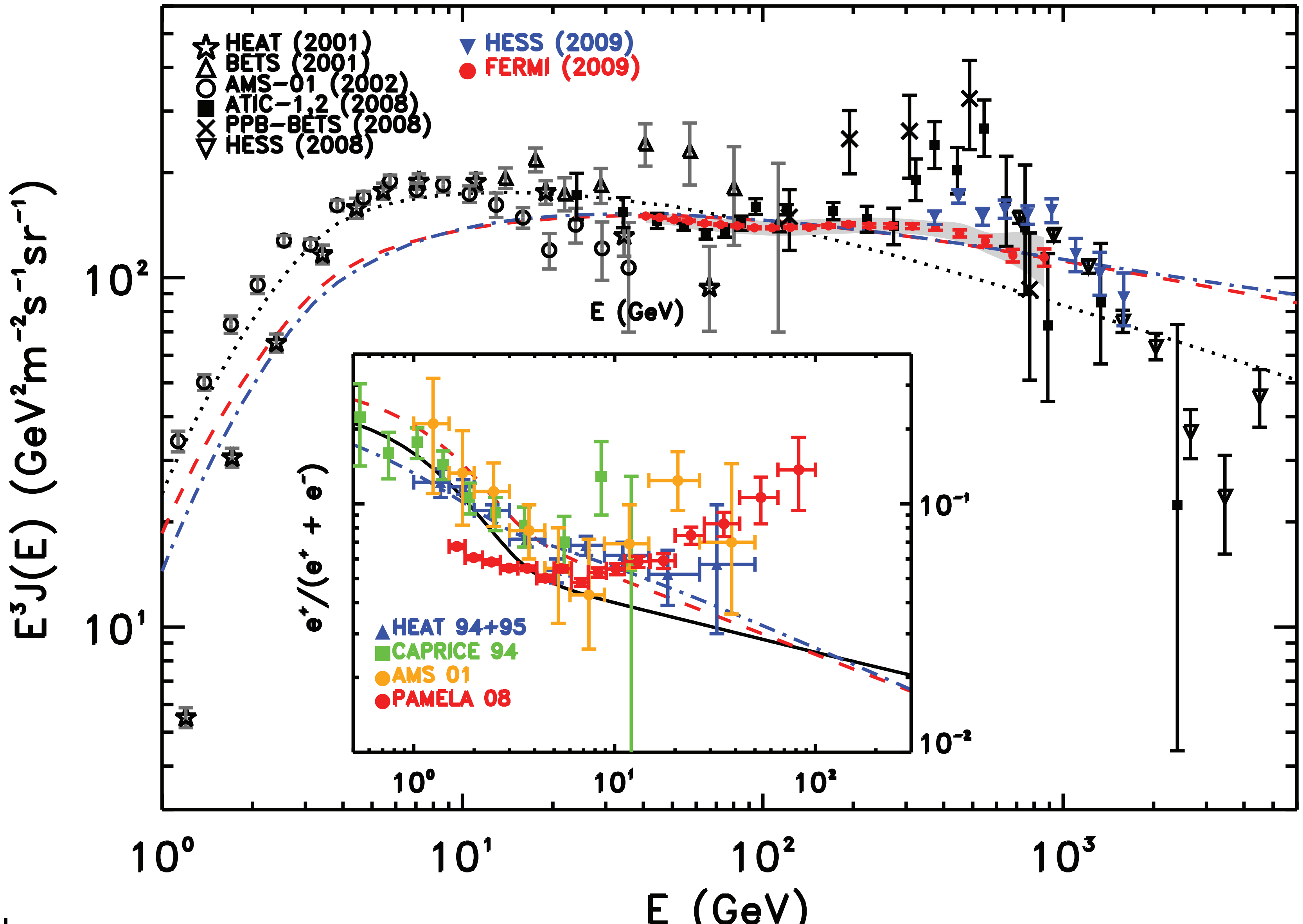
Fermi LAT CR Electron Spectrum

- LAT spectrum is consistent with simple power law $E^{-3.04}$
  - χ^2 = 9.7 for d.o.f. 24
- Systematic error < 20%
- Energy scale error +5% - 10%
- "Conventional diffuse model" is not a solid model
  - Continuously distributed electron sources
  - Source PL index: 2.54
  - Diffusion coefficient index: 0.33



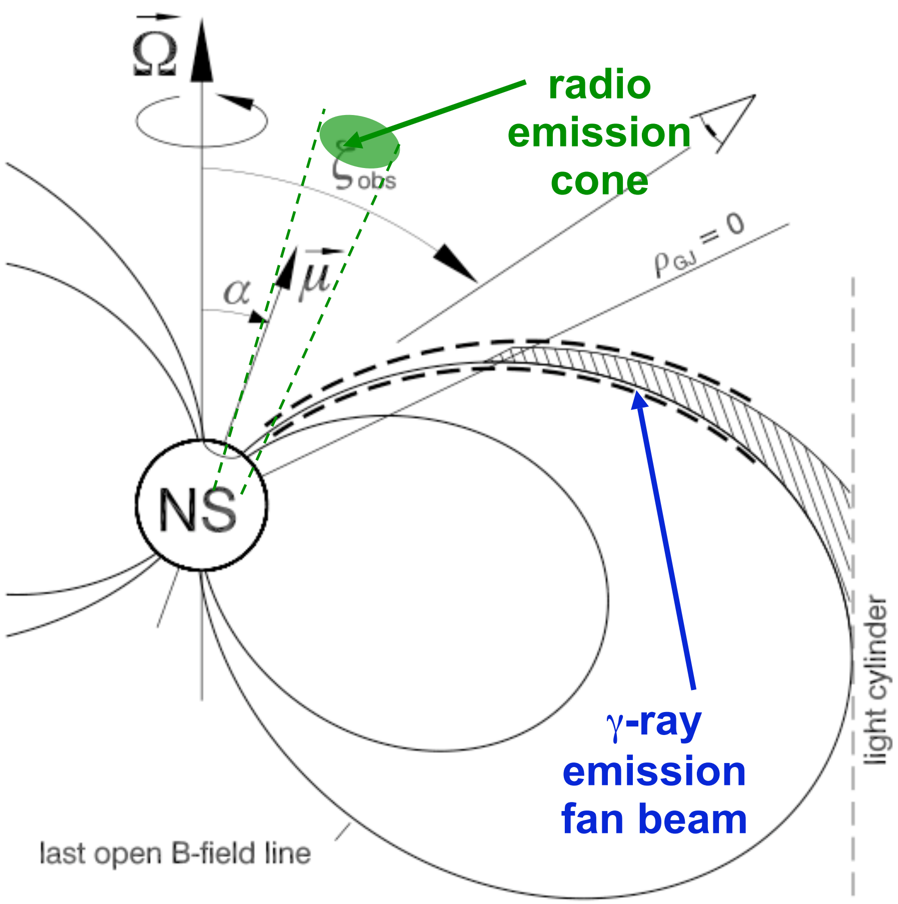
Simple Interpretation of Fermi CRE

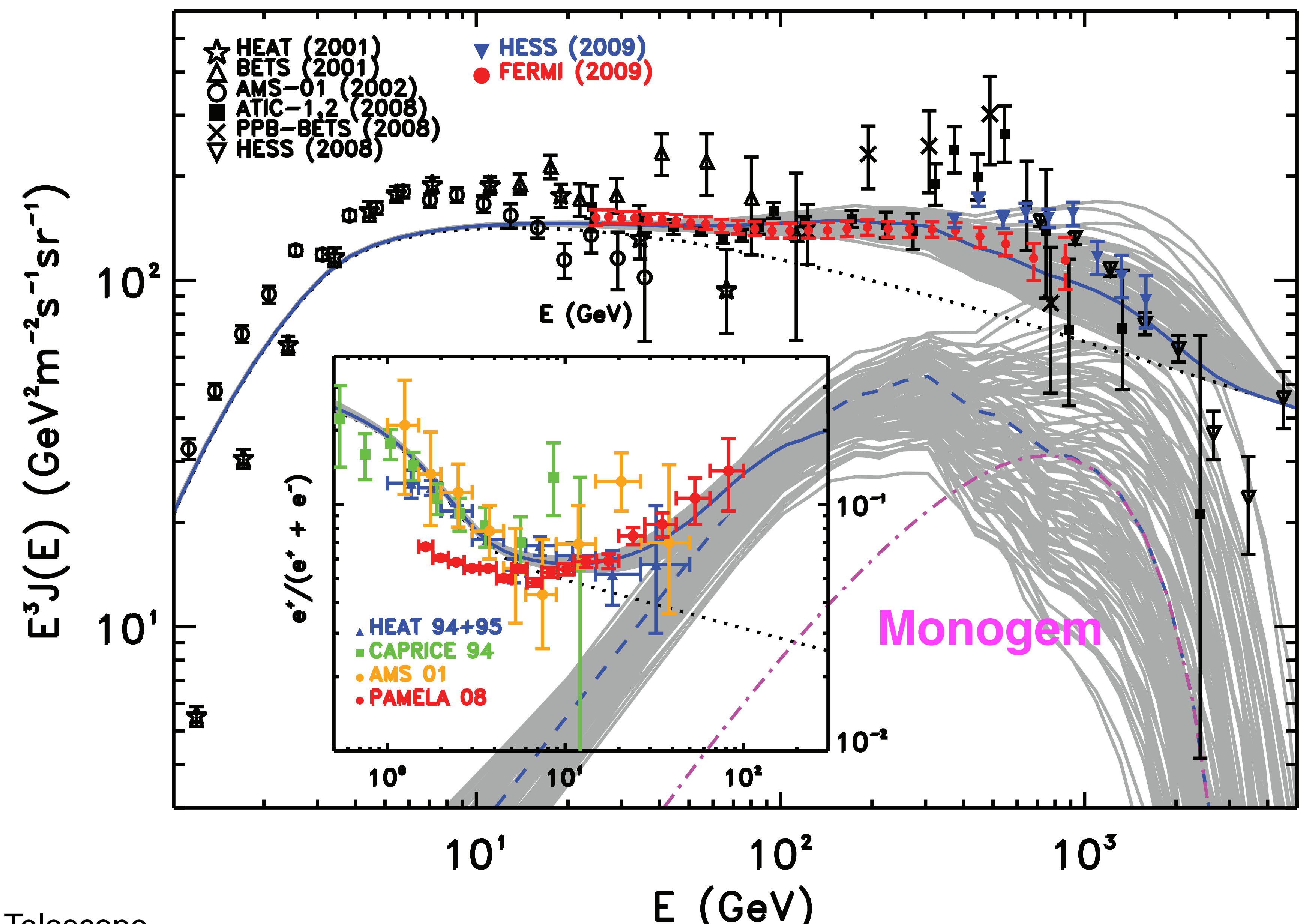
- Fermi CRE spectrum can be reproduced by harder source spectrum
  - Source PL index: 2.42, diffusion coefficient index: 0.33
  - Source PL index: 2.33, diffusion coefficient index: 0.6
- PAMELA spectrum not reproduced
  - Positron is 2ndary only
- Stawarz et. al. claims Klein-Nishina effect can produce bumps at high energies (arXiv:0908.1094)
  - Suppression of electron cooling



"Pulsar" Interpretation of Fermi CRE

- **"Pulsar"**
  - ***e+/e-* produced and accelerated at magnetosphere**
  - **Re-accelerated by pulsar wind or supernova remnant shocks**





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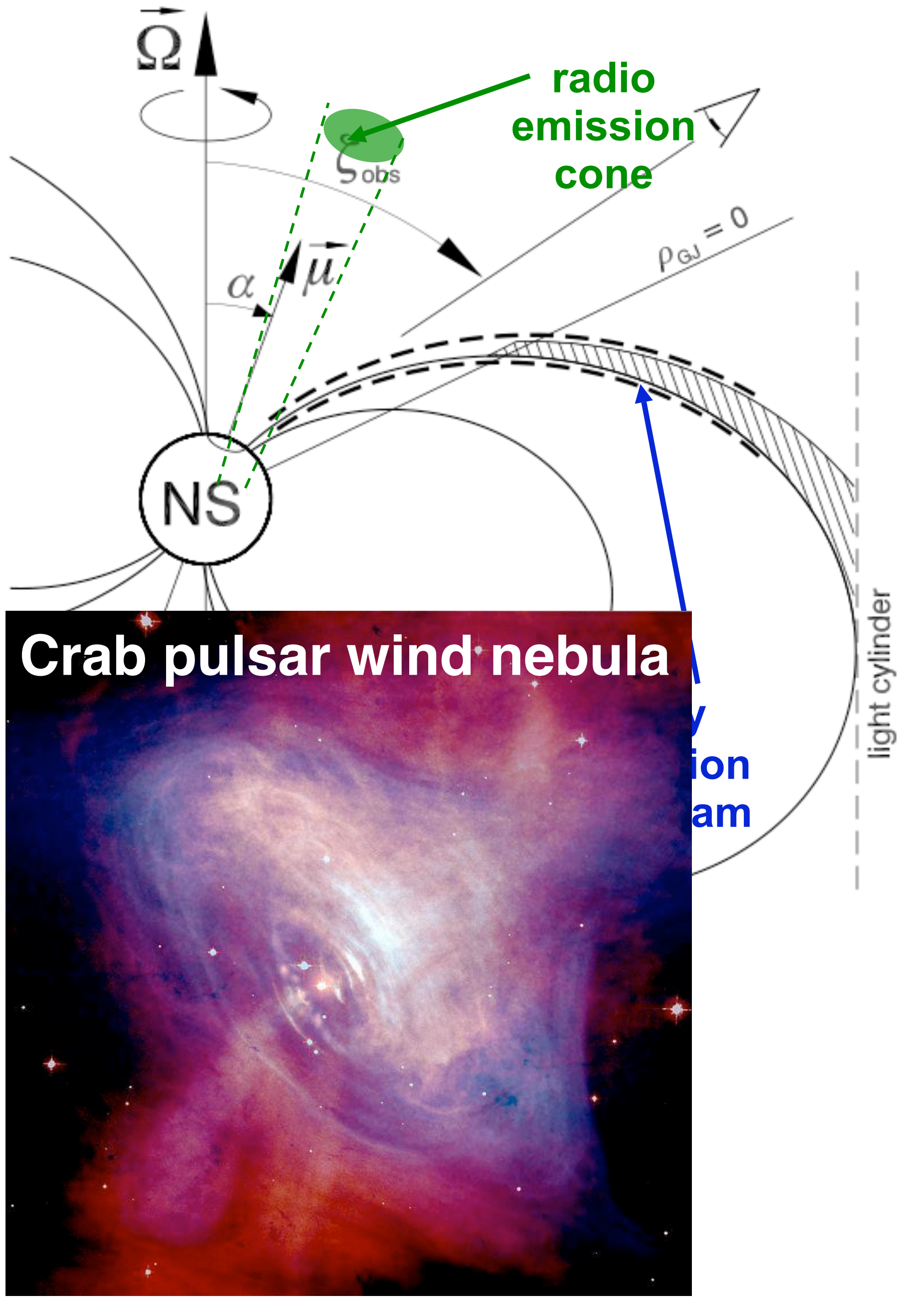

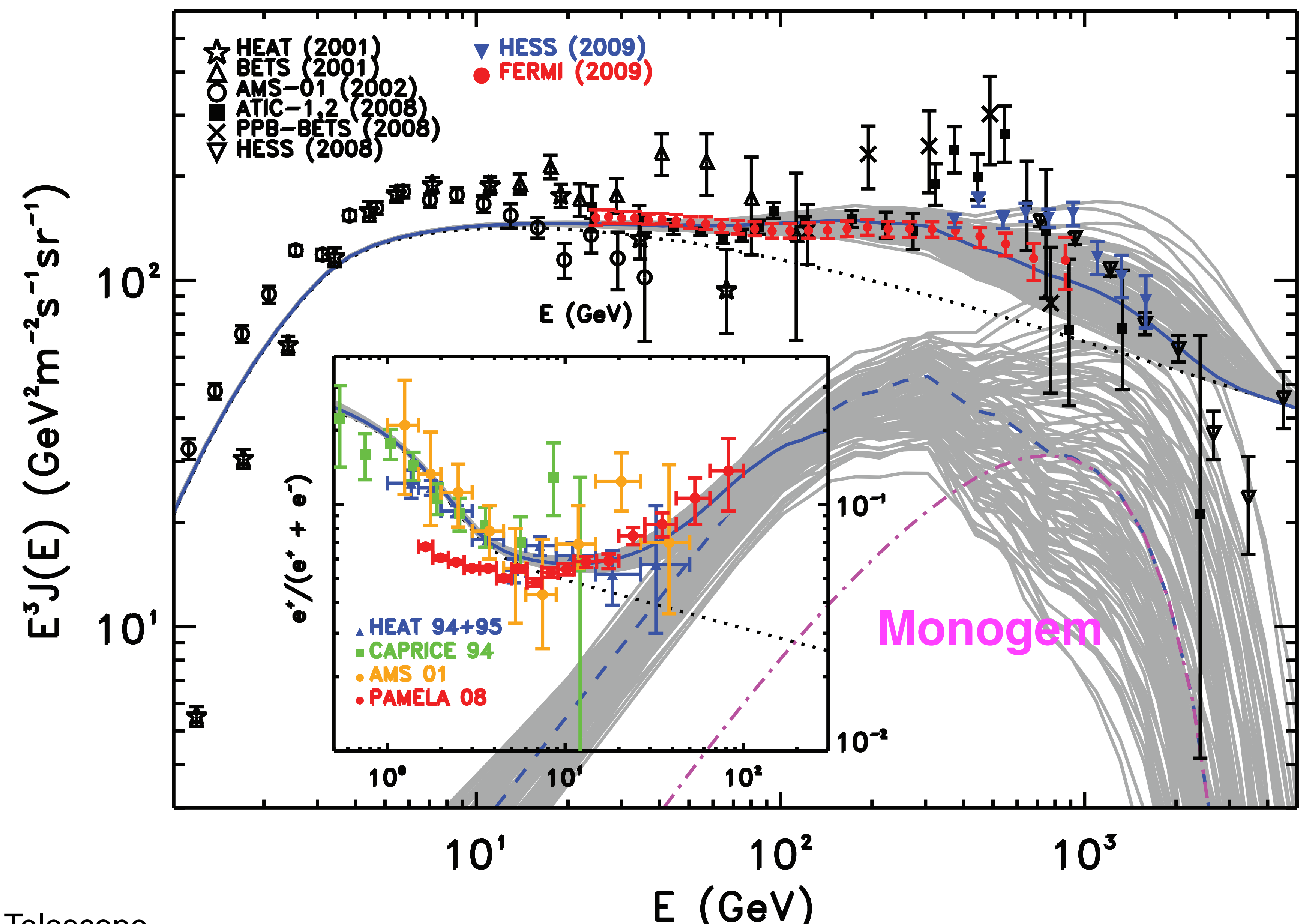

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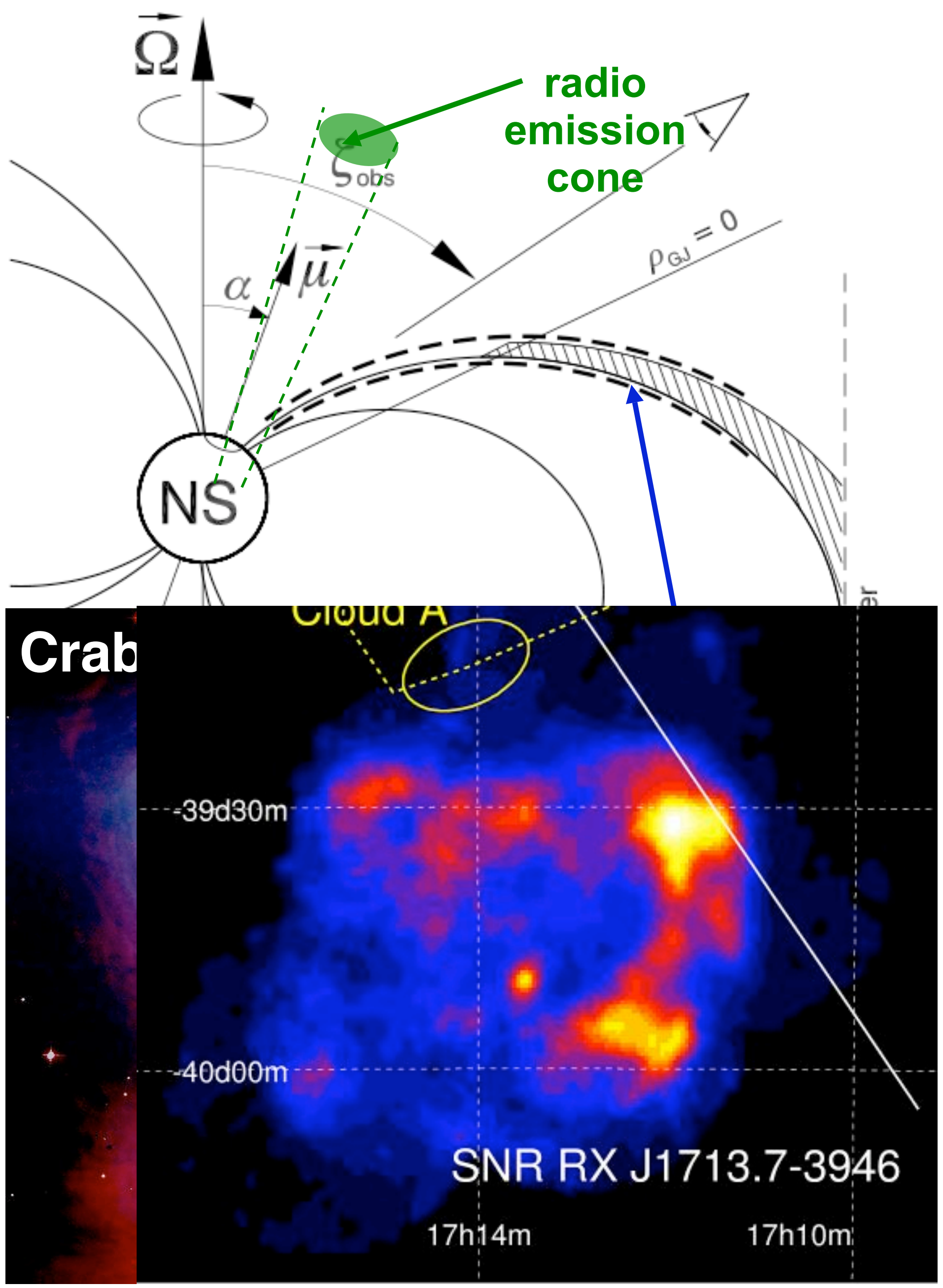
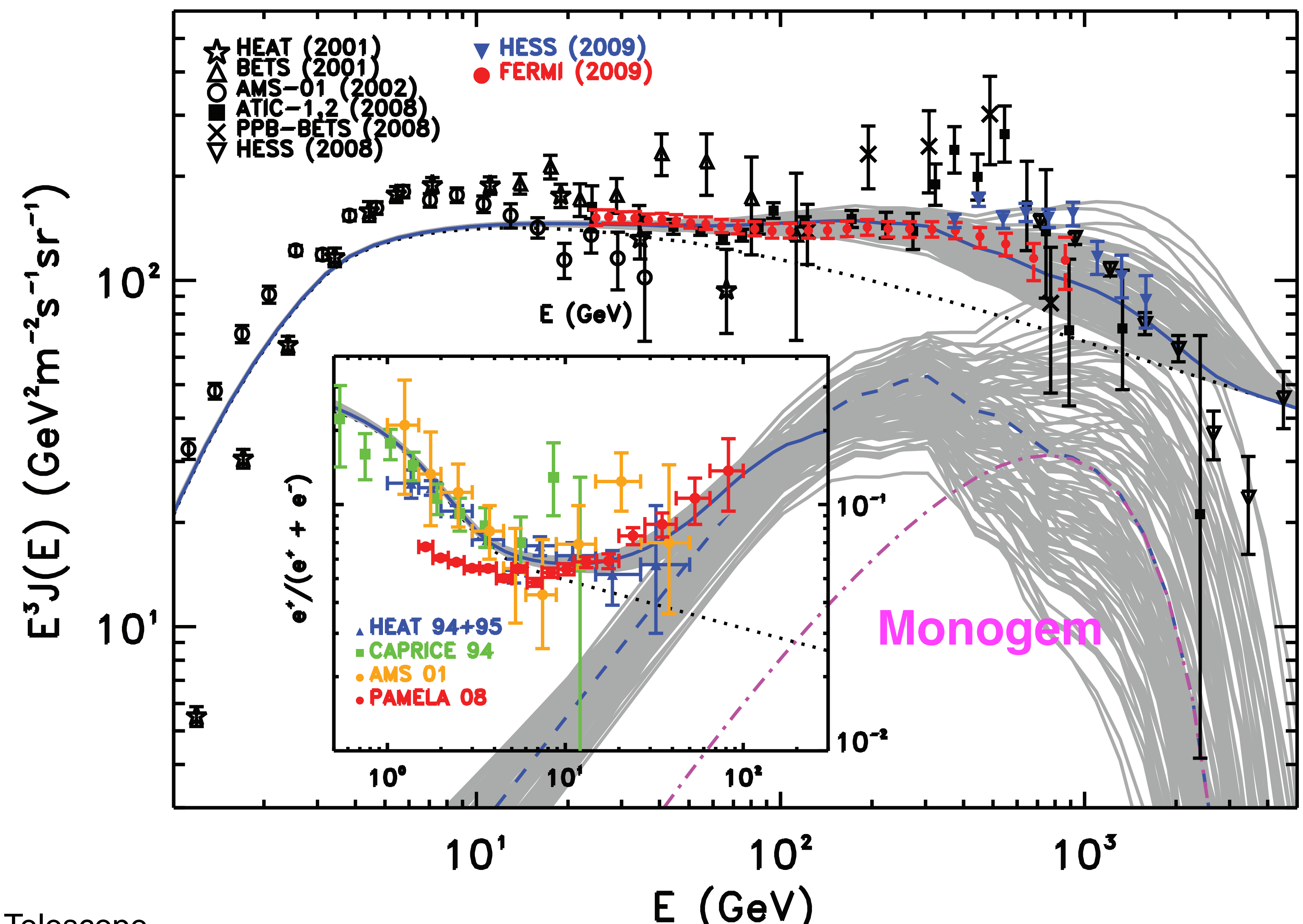
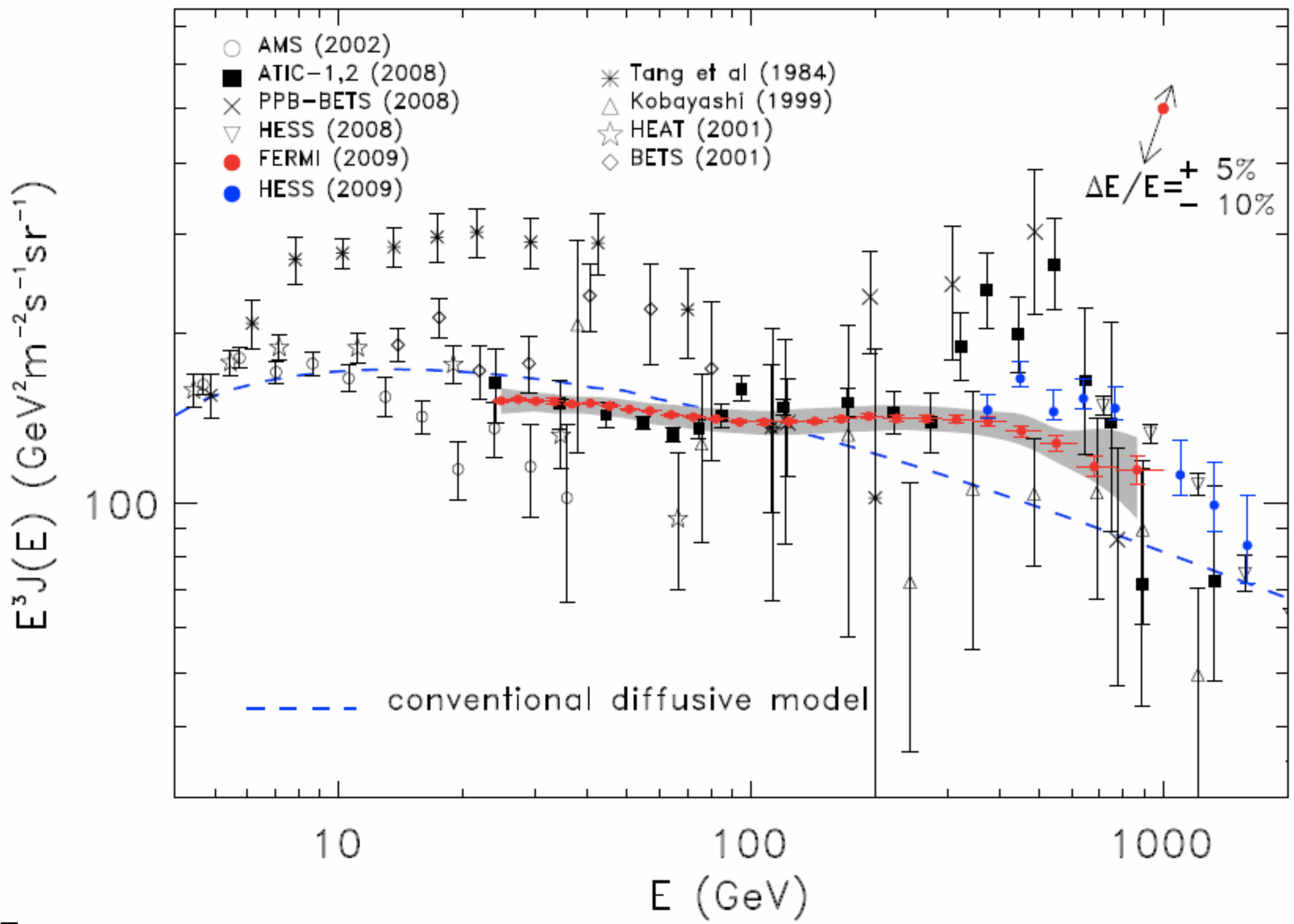




Cosmic-ray Electron Prospects

- Extend lower-end to ~ 5 GeV
  - Low energy region using minimum bias events
- Extend higher-end to ~2 TeV
  - Confirm a feature observed by H.E.S.S.
- Anisotropy measurement
- Reduce systematic errors
  - Angle dependence



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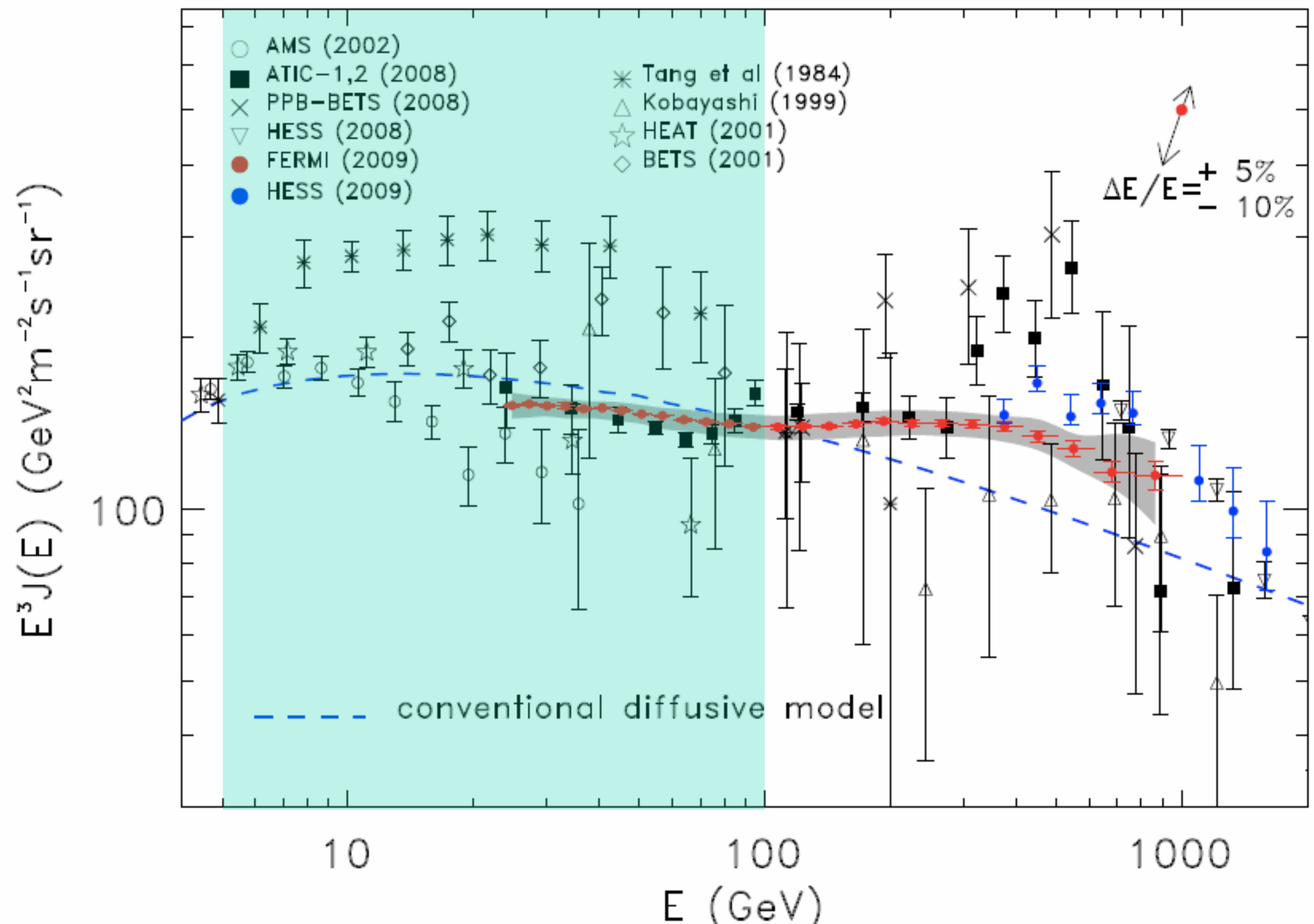

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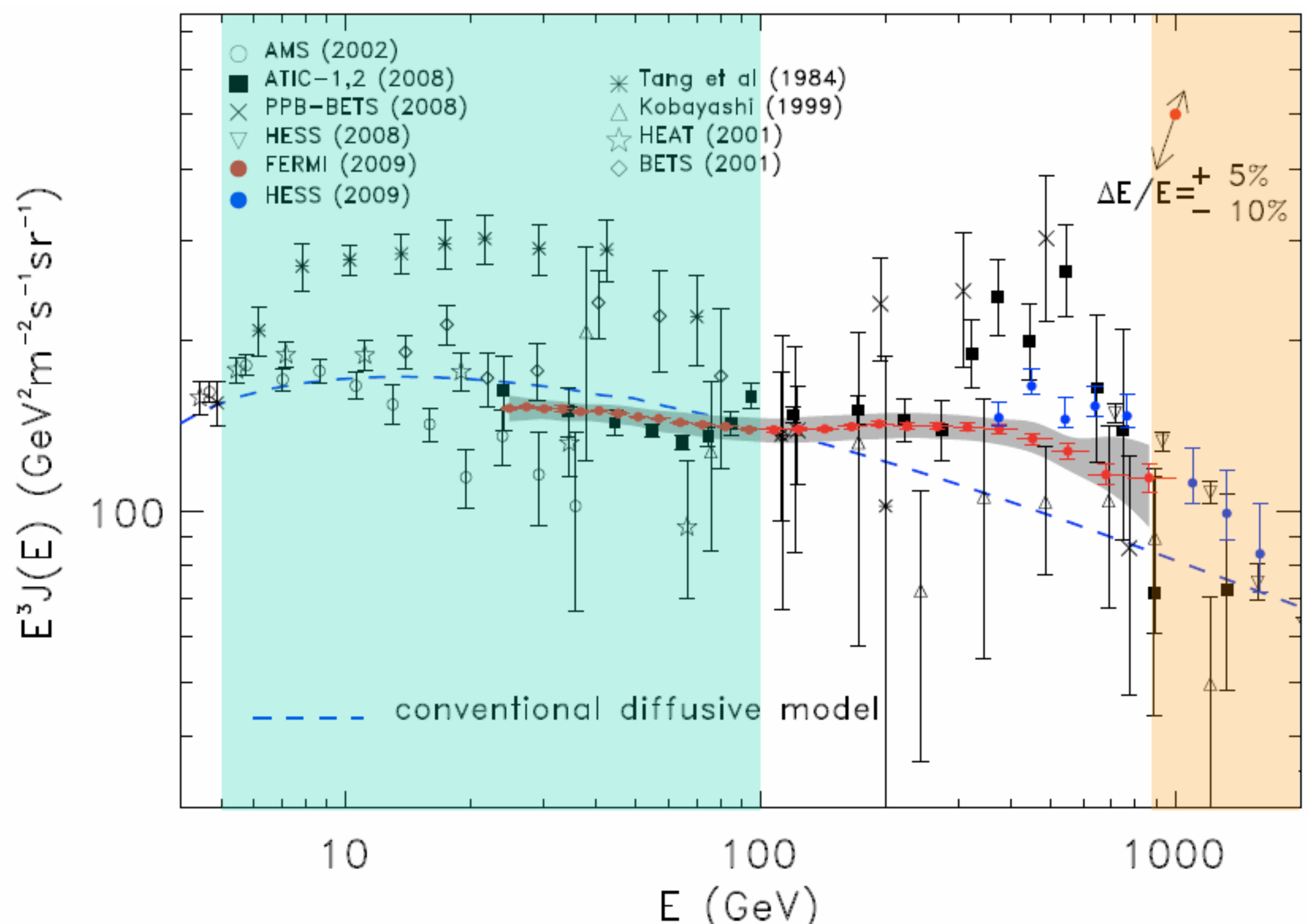


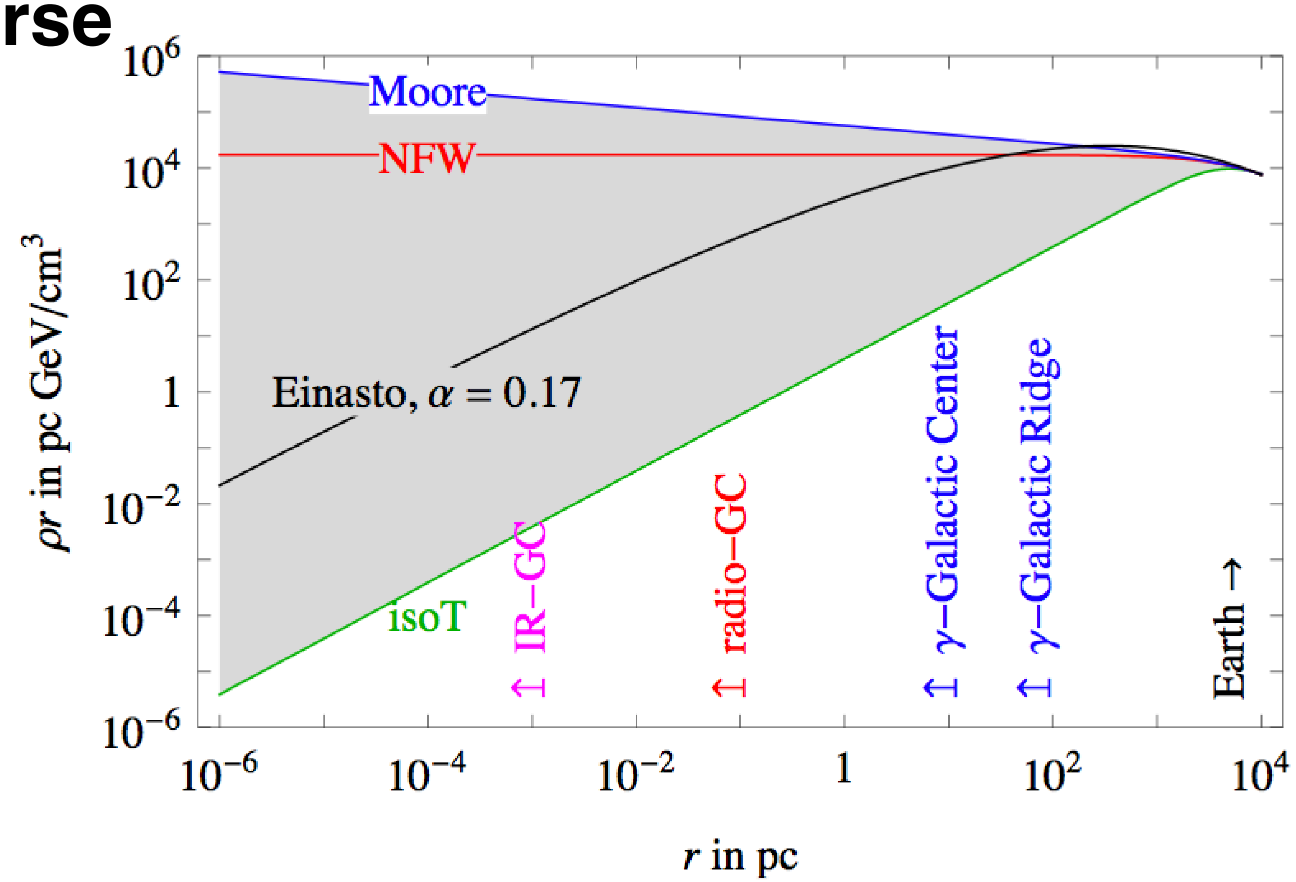
LAT Dark Matter Search

- Detection of dark matter signal from Space is complementary
  - Accelerator production
    - Precise measurements of DM properties: mass, cross section
    - UED (KK) vs SUSY
  - Direct detection
    - Good sensitivity to dark matter
    - Measurement of local dark matter density
  - Indirect detection
    - Distribution of WIMP in the Universe

particle physics

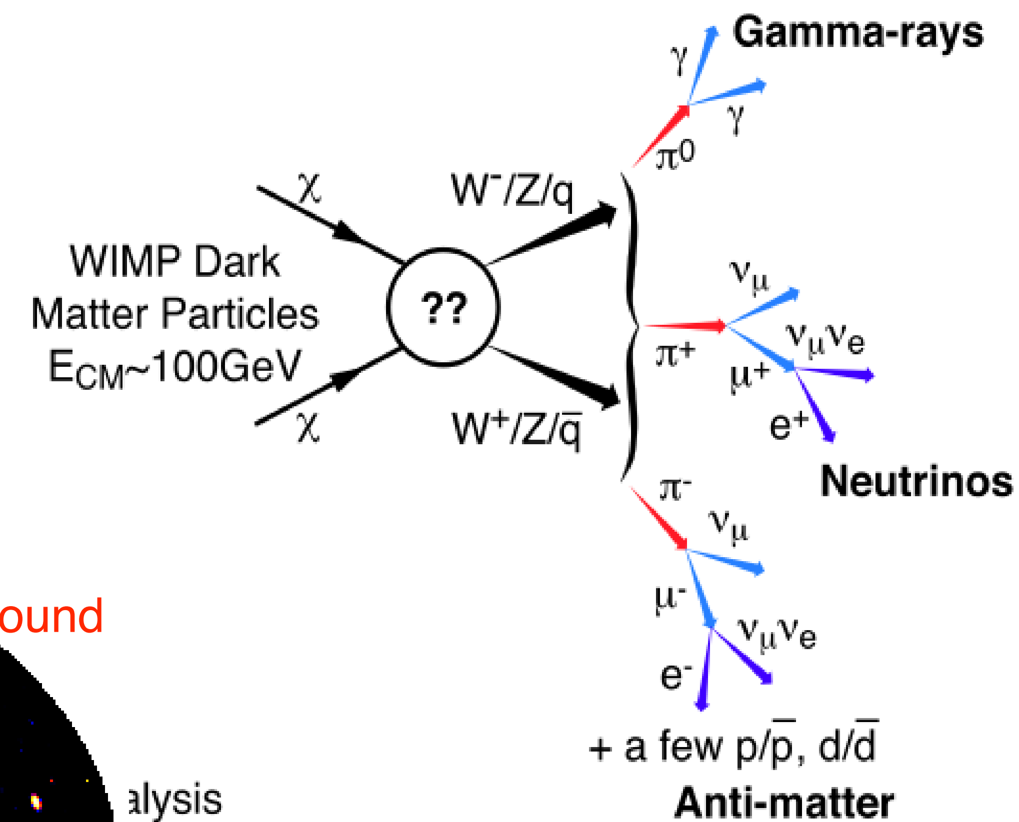
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \varphi, \theta) = \frac{1}{4\pi}\frac{<\sigma_{ann} v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\varphi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\varphi'))\, dl(r,\varphi')$$

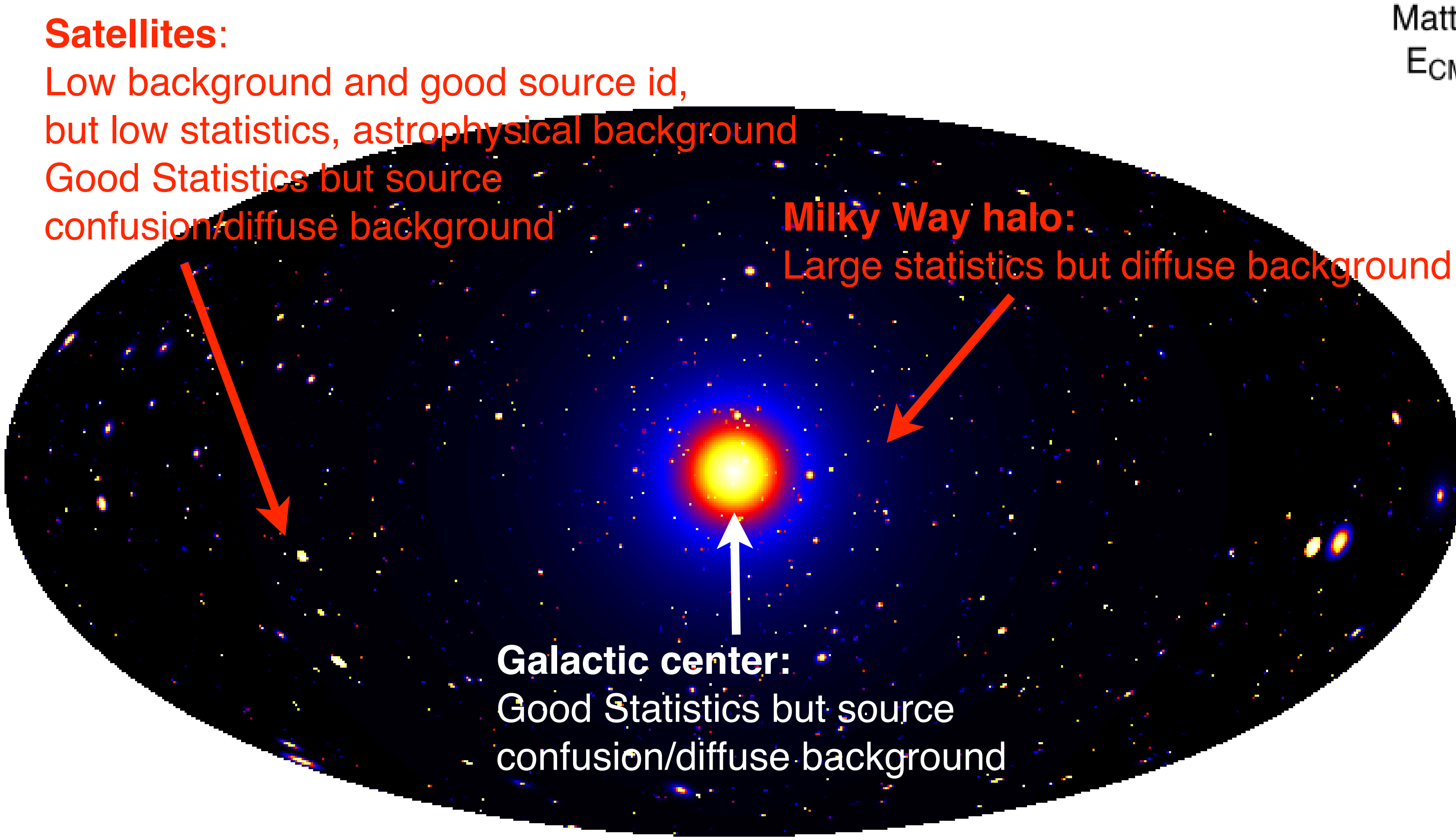
DM distribution



LAT Detection of WIMP Signal

- Multi-pronged approaches
  - Line emission, Continuum
  - Galactic center, Milky Way halo, Satellites
  - CR electrons, Diffuse gamma-ray background

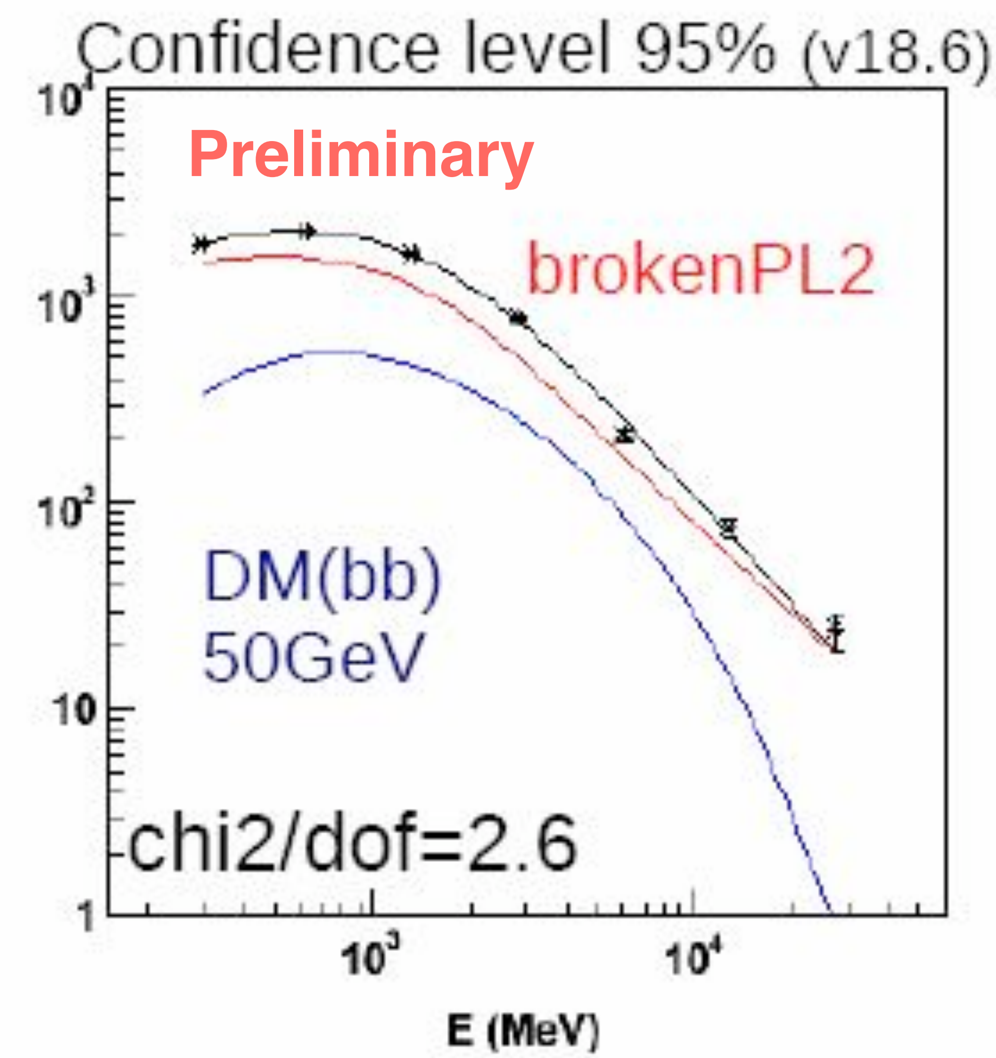




alysis

DM Search in Galactic Center

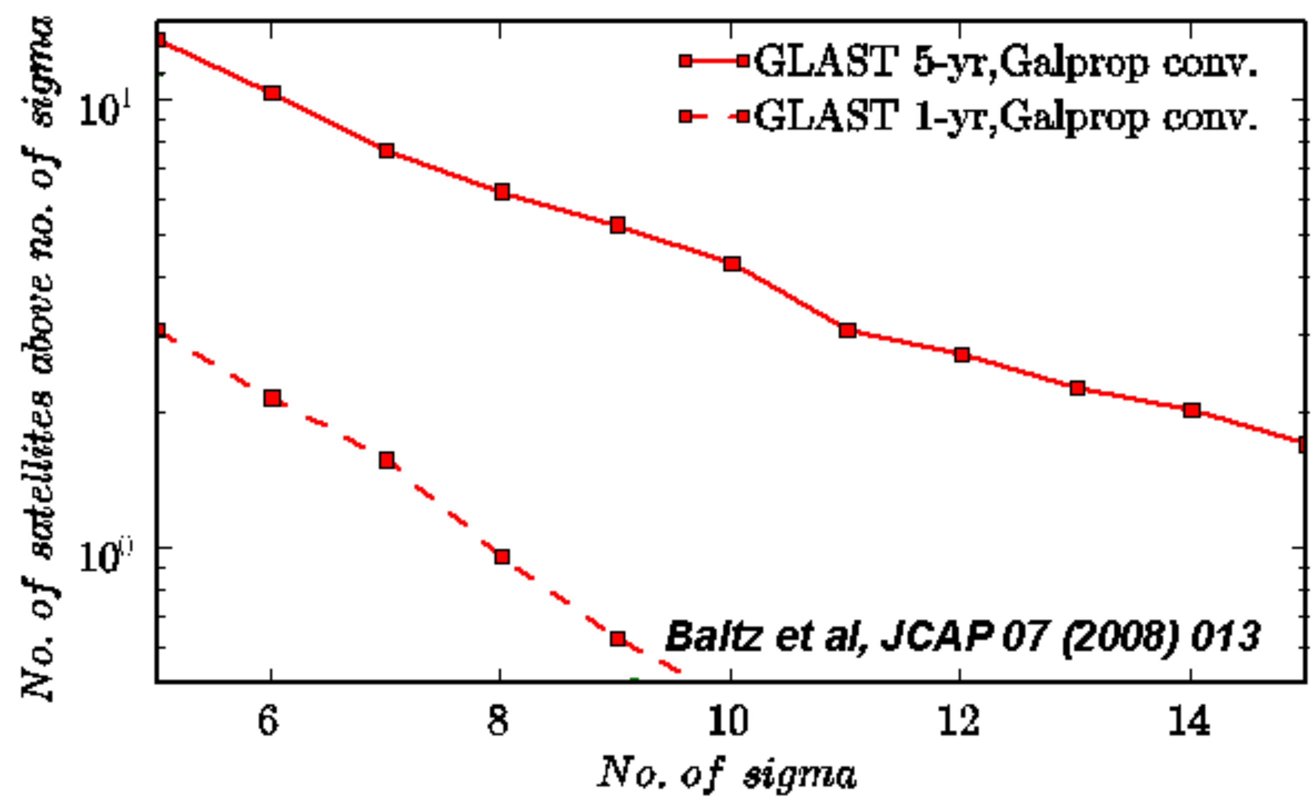
- N-body simulation predicts large DM signals from GC
  - Use spatial and spectral distribution to entangle DM contributions
  - Requires good understanding of diffuse and point sources
- GC: Current ULs without BG subtraction
  - Fit to broken power law and DM model
  - 95% C.L. upper limit (100 MeV-50 GeV)
    - Flux: $2.43 \times 10^{-7} cm^{-2} s^{-1}$
    - $<\sigma_V>$: $3.98 \times 10^{-25} cm^3 s^{-1}$



- Proper removal of sources to lower ULs (or find signal)
  - Image deconvolution to resolve source confusions

Subhalo DM Search

- Known dwarf spheroidal galaxies (dSph)
  - Mostly free from astrophysical gamma ray sources
  - Low content in dust/gas, very few stars
  - Select most promising candidates
- Unobserved DM substructures (satellites)
  - Search for extended sources in high galactic latitude
    - New tool developed to evaluate source extension quantitatively
    - 1~3 detection/year expected at 5σ significance
      - NFW consistent, no molecular cloud, spectral feature, stable
    - No candidate found yet



DM Search in Dwarf Galaxies

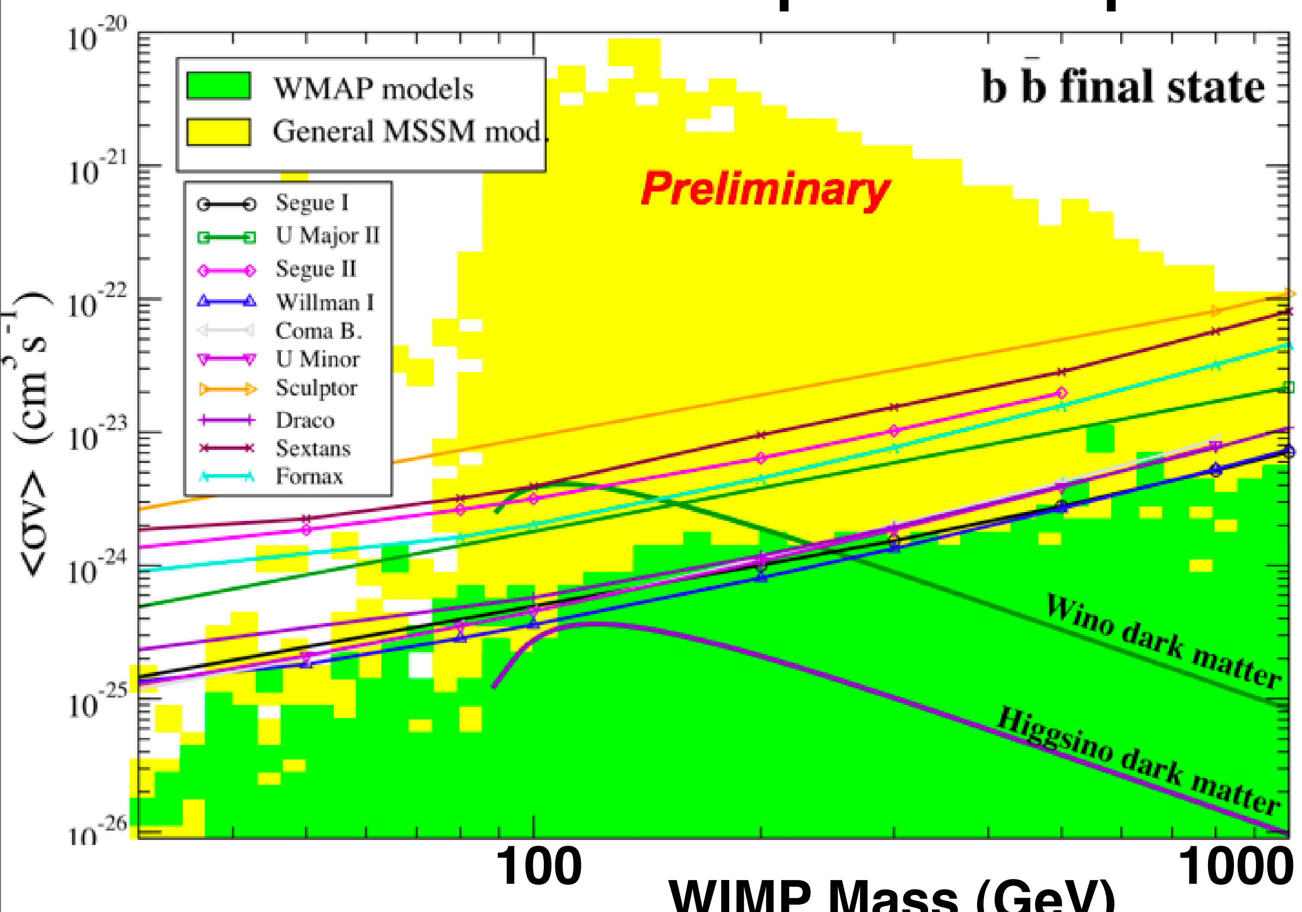
- 10 most promising dSph based on distance, M/L (Matter/Light)
  - New DM dominated dSph is being discovered recently

Name	Distance (kpc)	Discovered	M/L	Flux UL (E>0.1 GeV) 10^{-9} c/cm²/s
Segue 1	23±3	2007	1320±2680	1.8
Ursa Major II	30±5	2006	1722±1226	4.6
Segue 2	35	2009	650^{+1300}_{-380}	2.1
Willman 2	38±7	2004	~500	2.1
Coma Berenices	44±4	2006	448±297	1.0
Ursa Minor	66±3	1954	275±35	0.7
Sculptor	79±4	1937	158±33	4.8
Draco	76±5	1954	290±60	1.2
Sextans	86±4	1990	70±10	1.3
Fornax	138±8	1938	14.8±8.3	1.7

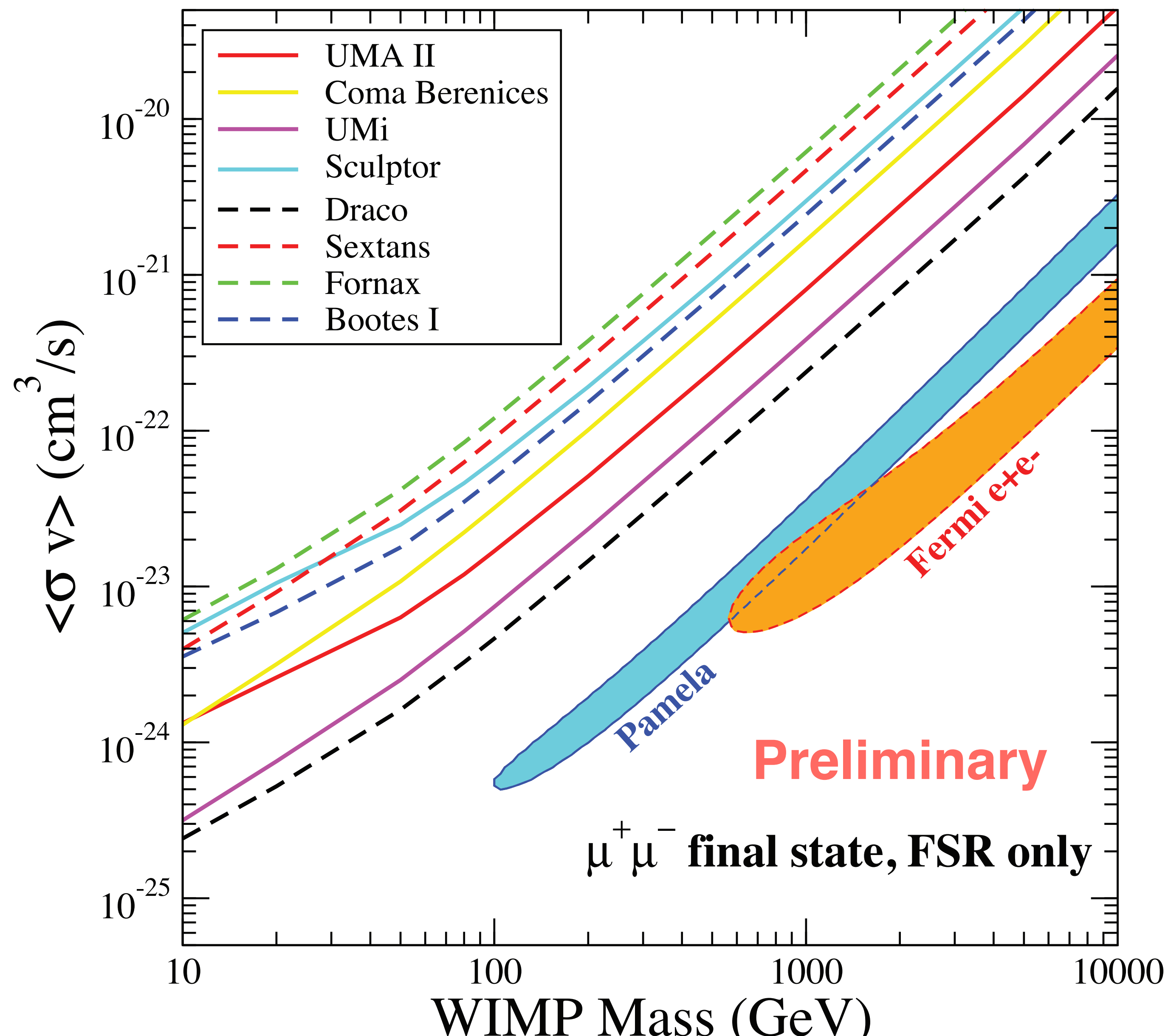
DM Model Constraints

- General MSSM includes temperature dependent resonance effect
- Constraints on UED $\mu^+\mu^-$ final state does not include inverse Compton effect
  - $\mu^+\mu^-$ final state is favored by PAMELA/Fermi CRE spectrum and anti-proton constraints

Constraints on MSSM parameter phase

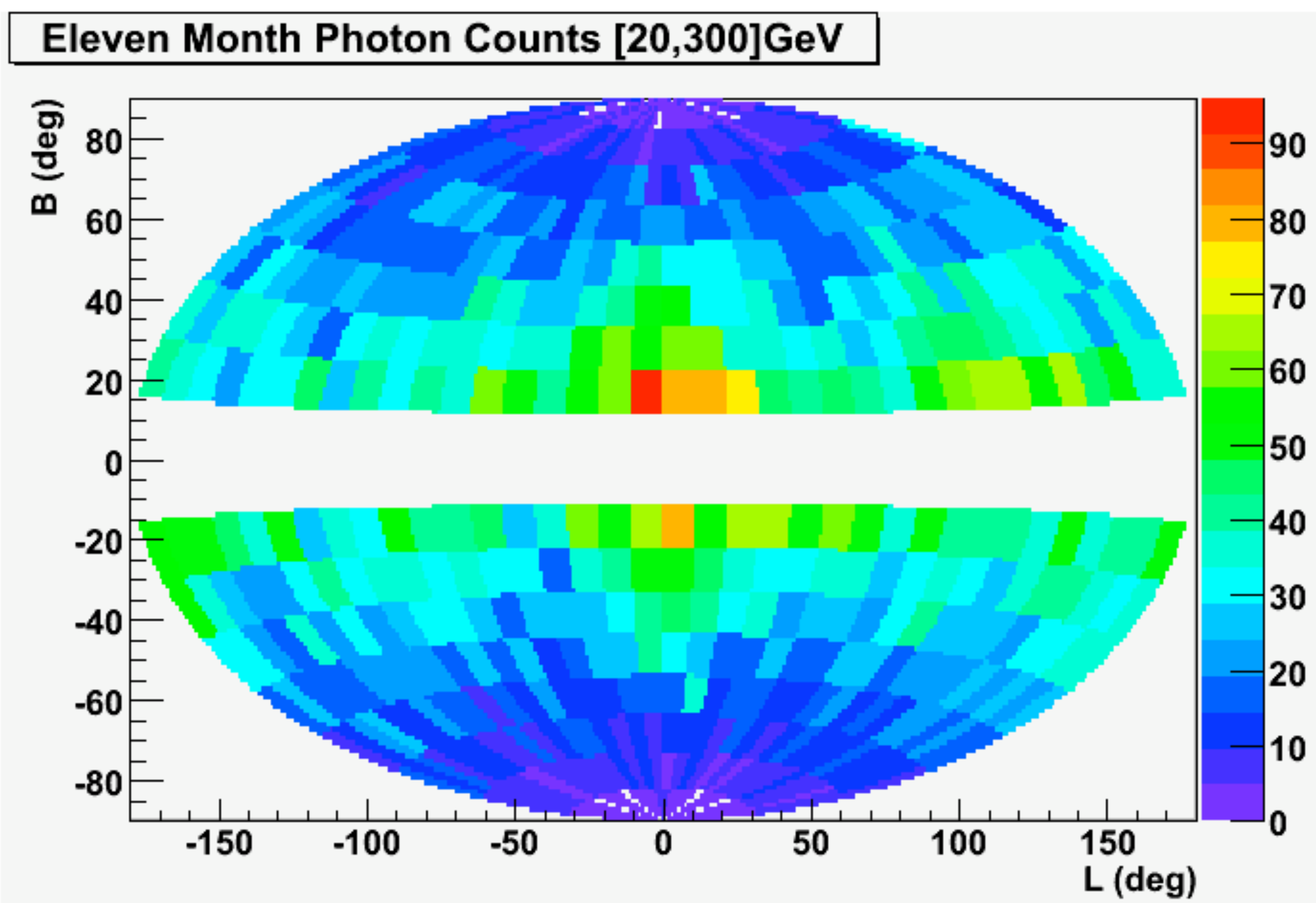


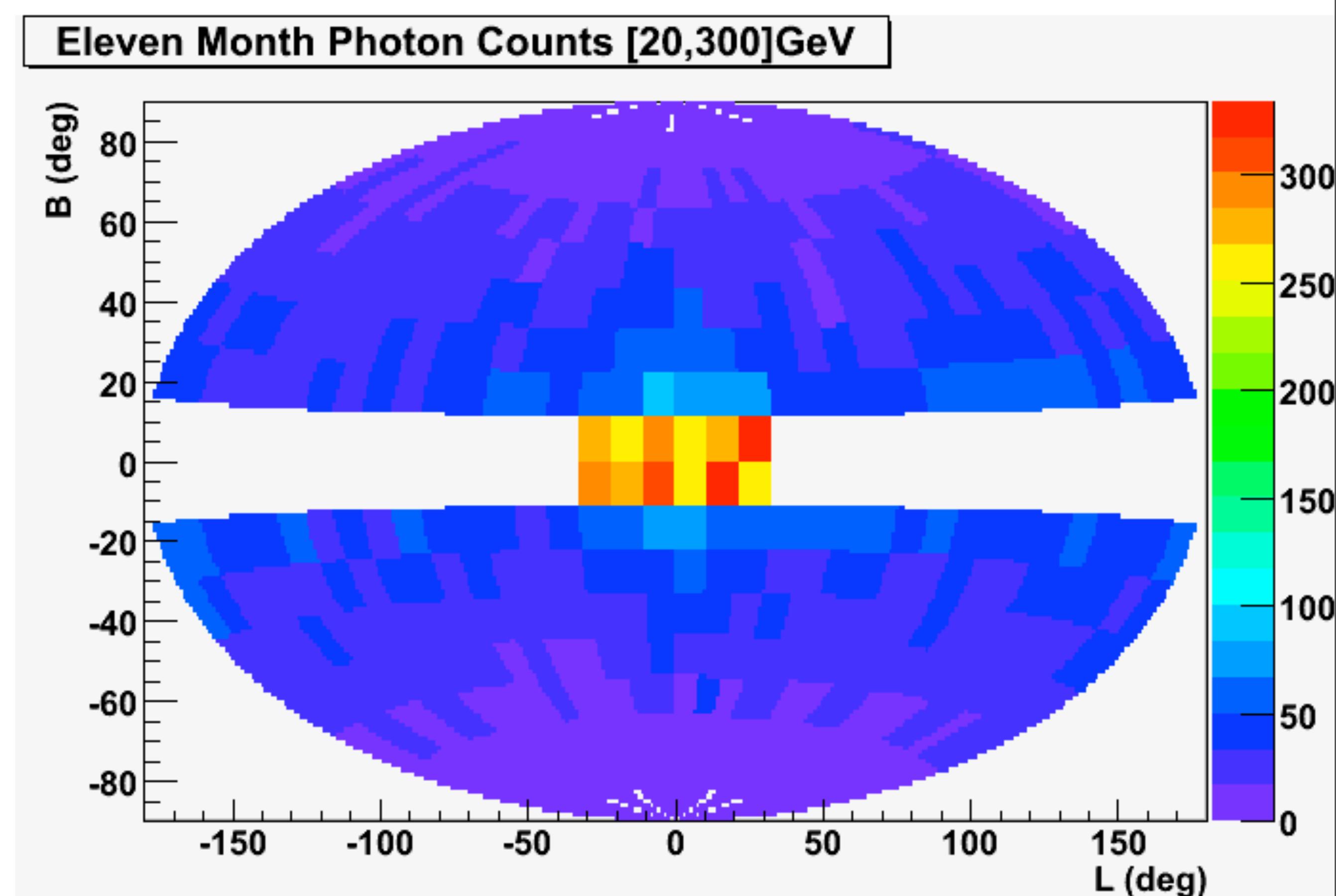
Constraints on μμ mode parameter phase



DM Spectral Line Search

- Smoking gun signal for exotic physics
- Search for lines in the first 11 months of Fermi data
- Search in two regions of the sky (to maximize signal):
  - |b|>10°
  - |b|>10°, keep 30° around galactic center
- Exclude point sources: remove 0.2° radius around the source
  - PSF =0.1° at 20 GeV

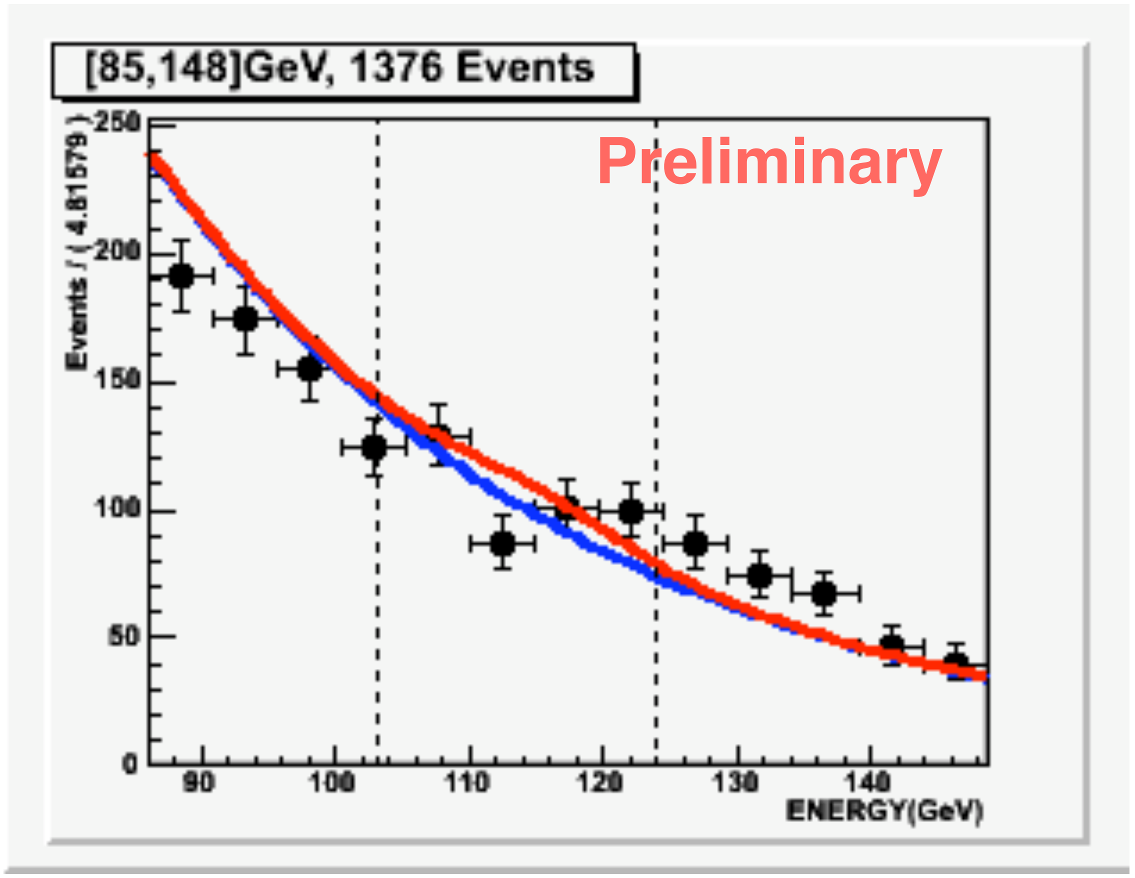


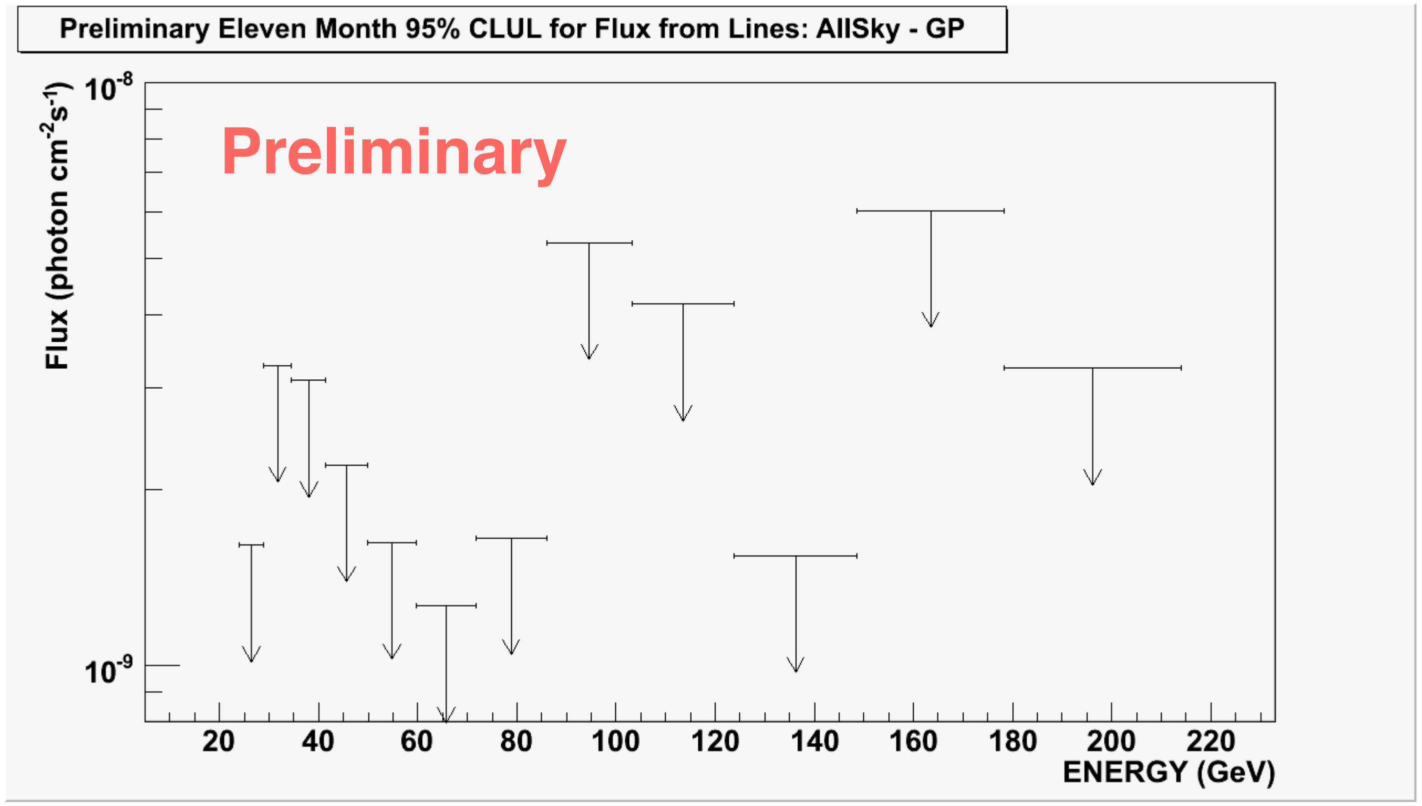


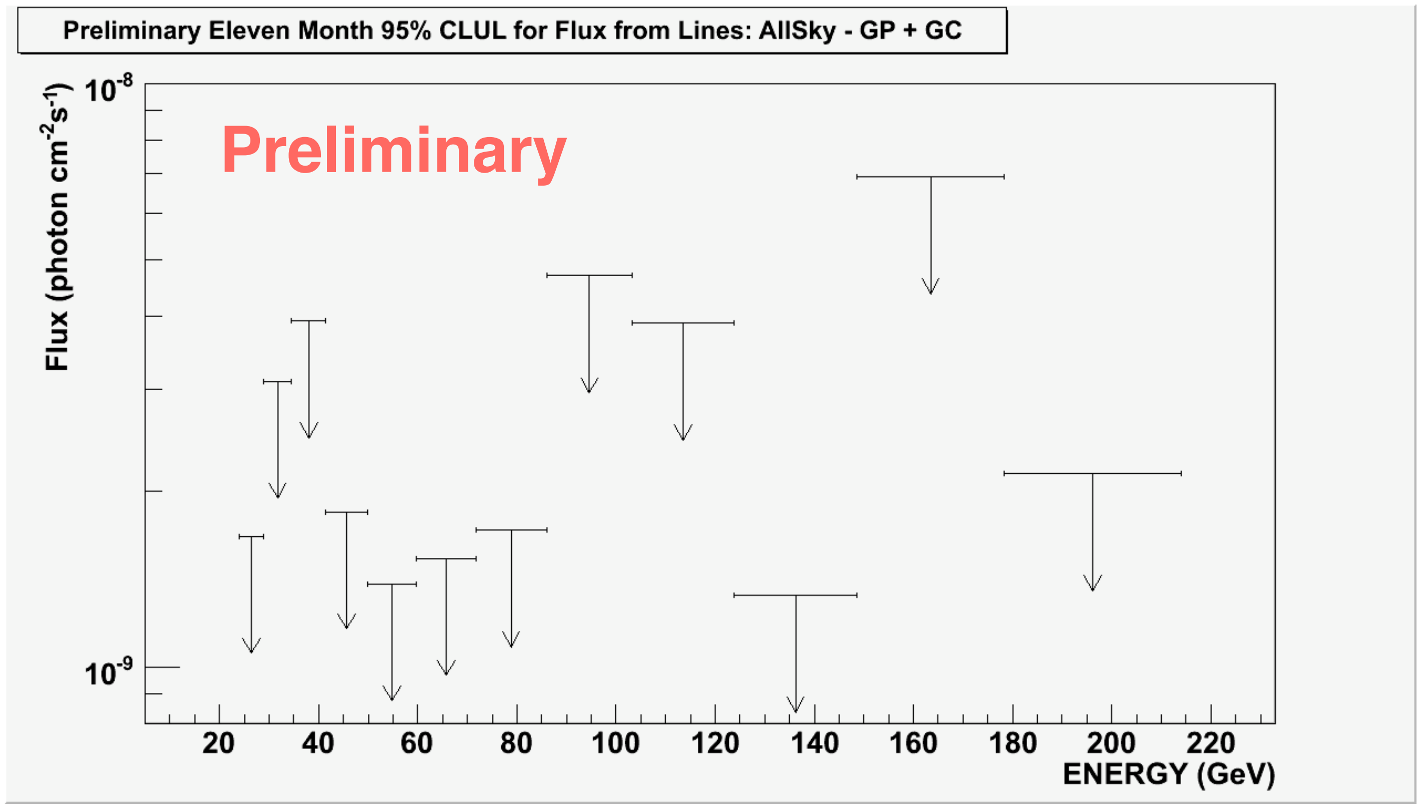
UL on LAT Spectral Line Search

- Look for a line signal in energy intervals in the 20-300 GeV range
- BG is constrained by energy sidebands
- No line detection

Example Fits for [85,148]GeV

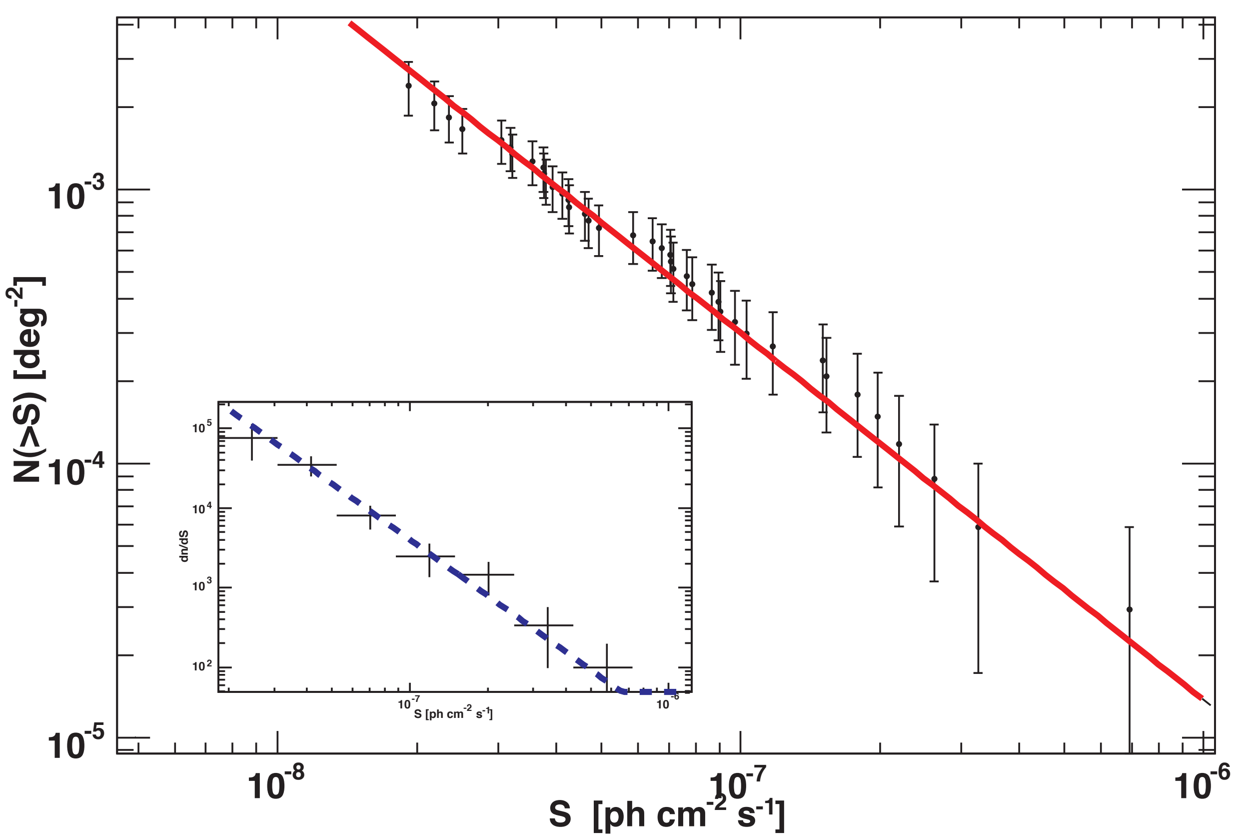


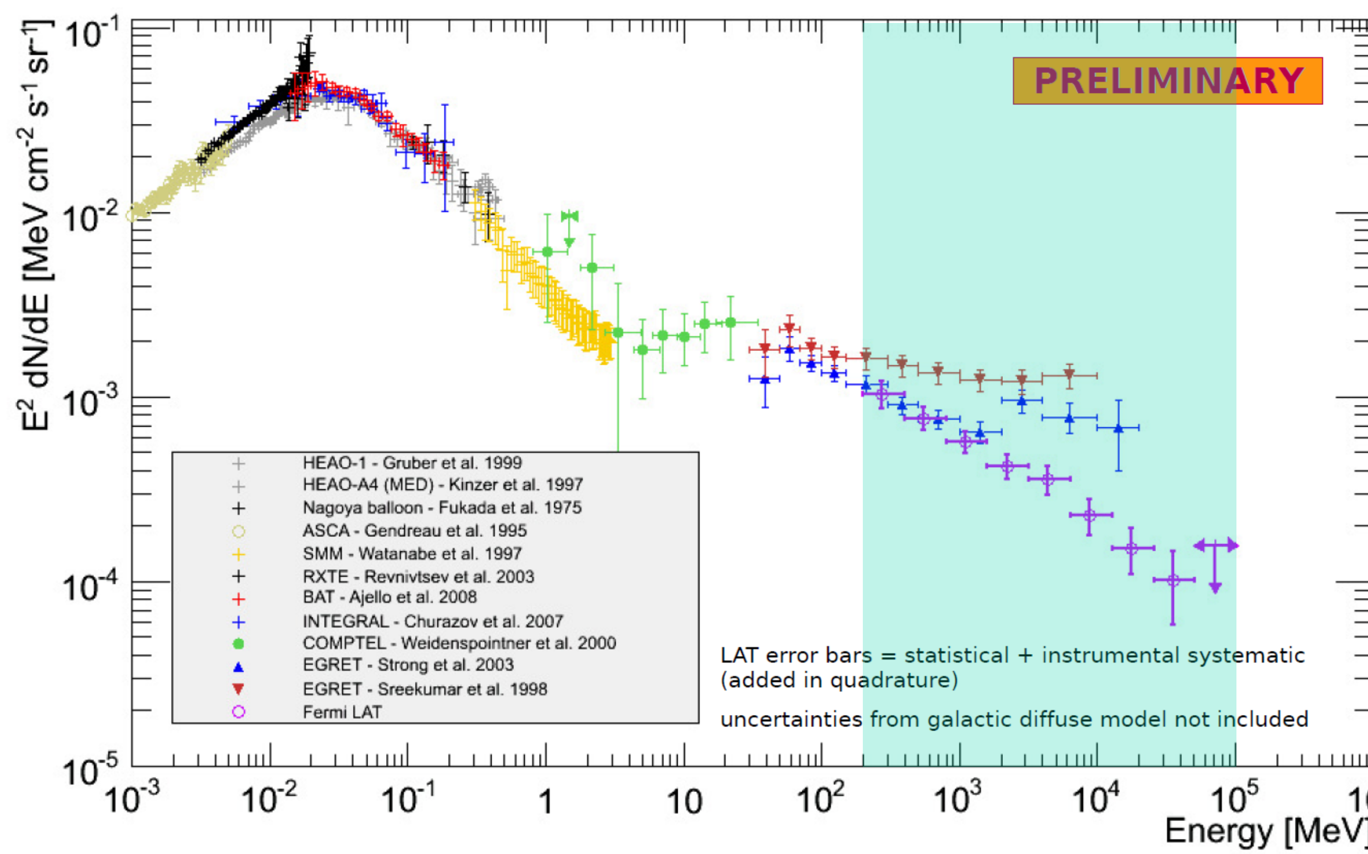




Cosmological DM

- Mostly due to unresolved sources
- Truly diffuse emission may arise from UCHE CRs interactions, WIMP annihilation, large scale structure formation
- Consistent with sum of blazars
  - Spectrum is compatible with a power law of index γ=2.45
  - logN-logS indicates 20–100% of EGB can be accounted for
- Flux will decrease as more source are resolved



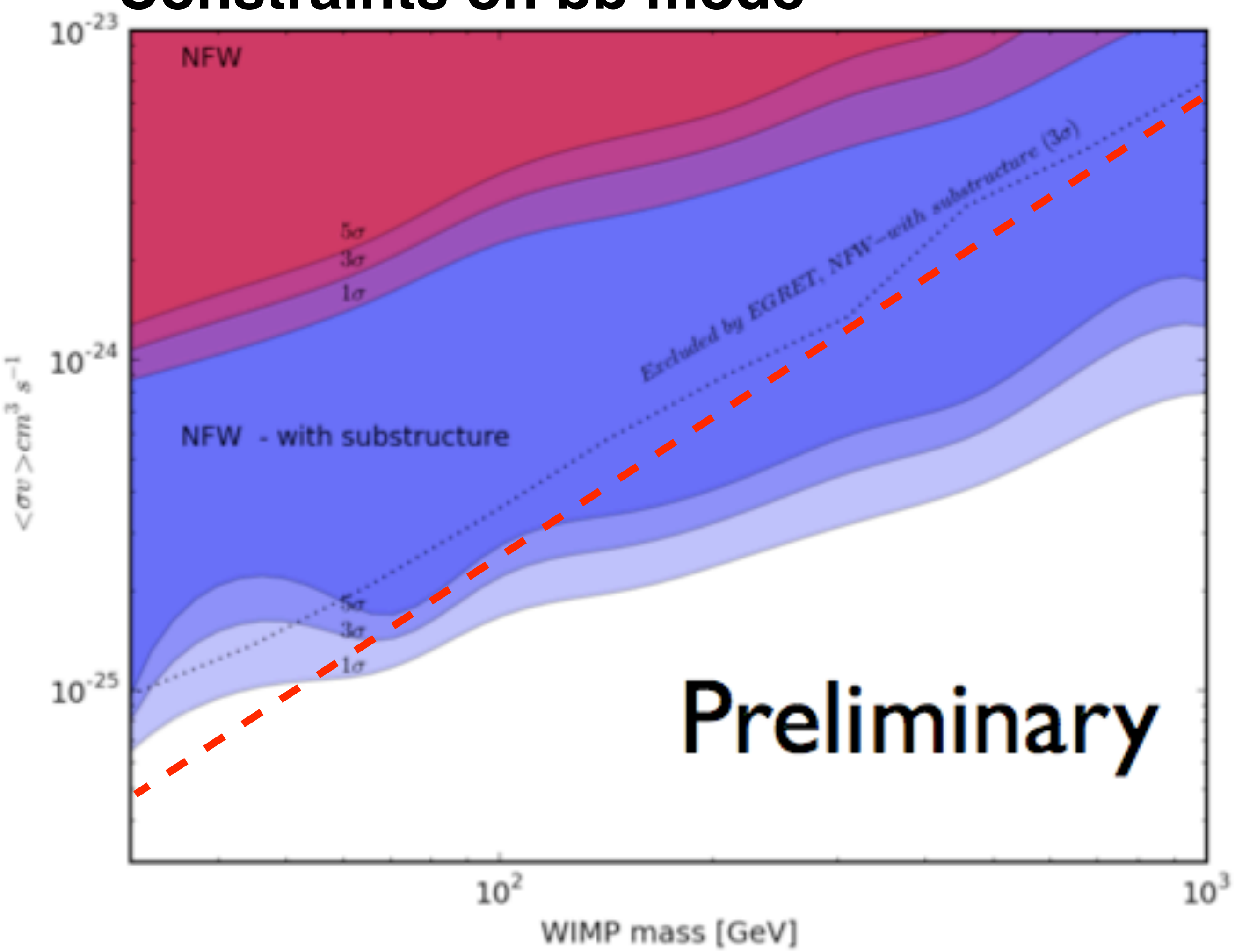


Fermi Gamma-ray Space Telescope,
H. Tajima 銀河系とダークマター, SEP 29, 2009

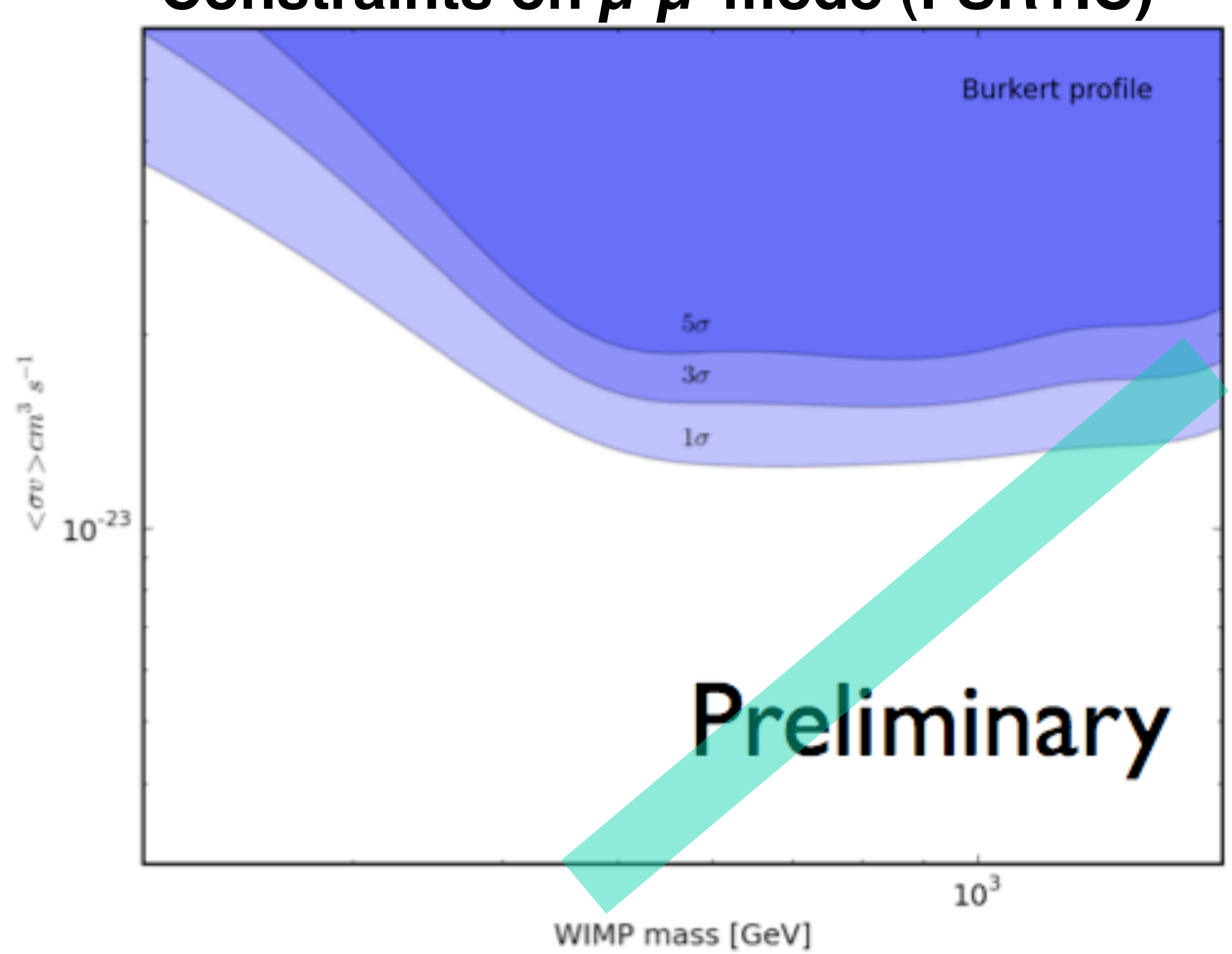
ULs on Cosmological DM

- UL calculated without BG subtraction
  - Proper subtraction of blazar contribution critical to obtain better ULs

Constraints on bb mode



Constraints on $\mu^+\mu^-$ mode (FSR+IC)



Summary and Prospects

- Fermi LAT making good progresses on understanding
  - Cosmic-ray interaction with inter-stellar medium
  - Cosmic-ray propagation in the Milky-way galaxy
  - Cosmic-ray electron spectrum
  - Already surpassing EGRET in many area
- No detection of gamma-ray signal from dark matter annihilation/ decay yet
  - Expected to search for large parameter space of SUSY/UED models

- Data are now public
  - Science support center: http://fermi.gsfc.nasa.gov/ssc/
  - Science tools: http://fermi.gsfc.nasa.gov/ssc/data/analysis/
  - Data access: http://fermi.gsfc.nasa.gov/ssc/data/access/
- 2nd International Fermi Symposium in Nov/2-5 2009 at DC
  - http://fermi.gsfc.nasa.gov/science/symposium/2009/
  - Many new results from Fermi LAT collaboration will be presented