Recent Results on Cosmic-Rays by Fermi-LAT

Sep. 13, 2010 @ JPS meeting

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On behalf of the Fermi-LAT collaboration

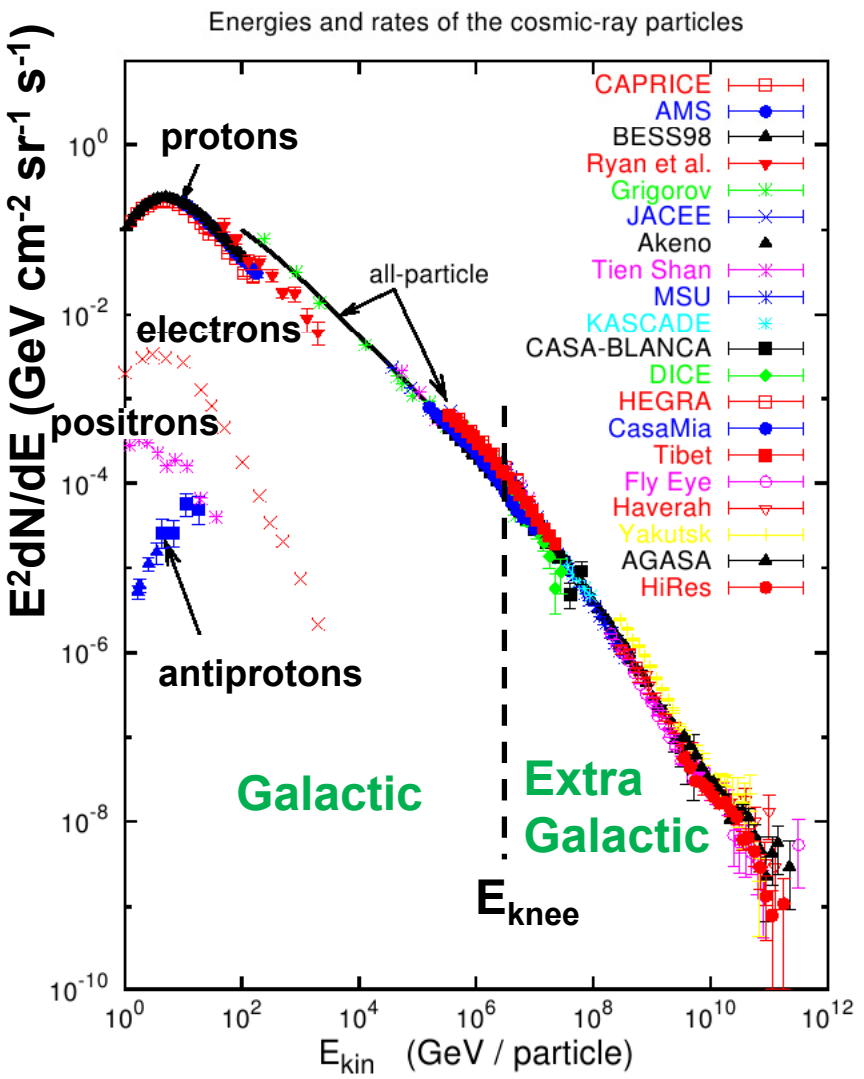
Outline

Introduction
Direct measurement of CRs
CRs in the Milky Way/external galaxies

Cosmic-Rays (CRs) at the Earth

- **Discovered by Hess (1912), Nobel Prize (1936)**
- **Majority protons, 0.1-1% contribution from e^-/e^+**
- **Galactic ($E<E_{knee}$), ExtraGalactic ($E>E_{knee}$)**
- **U_{CR} ~1 eV cm^{-3}, comparable to U_B and U_{photon}**

- **<u>Origin and propagation of CRs</u> is one of main topics of modern astrophysics.**



http://wwwiexp.desy.de/groups/astroparticle/score/en/

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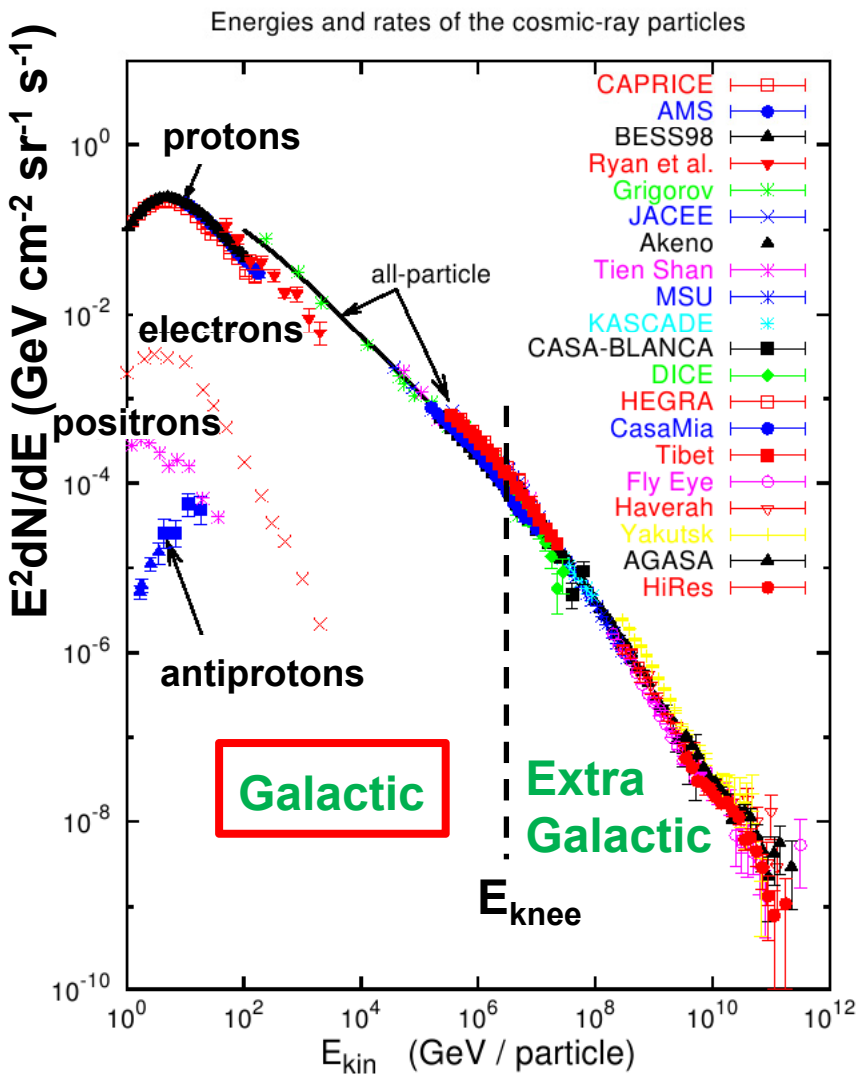

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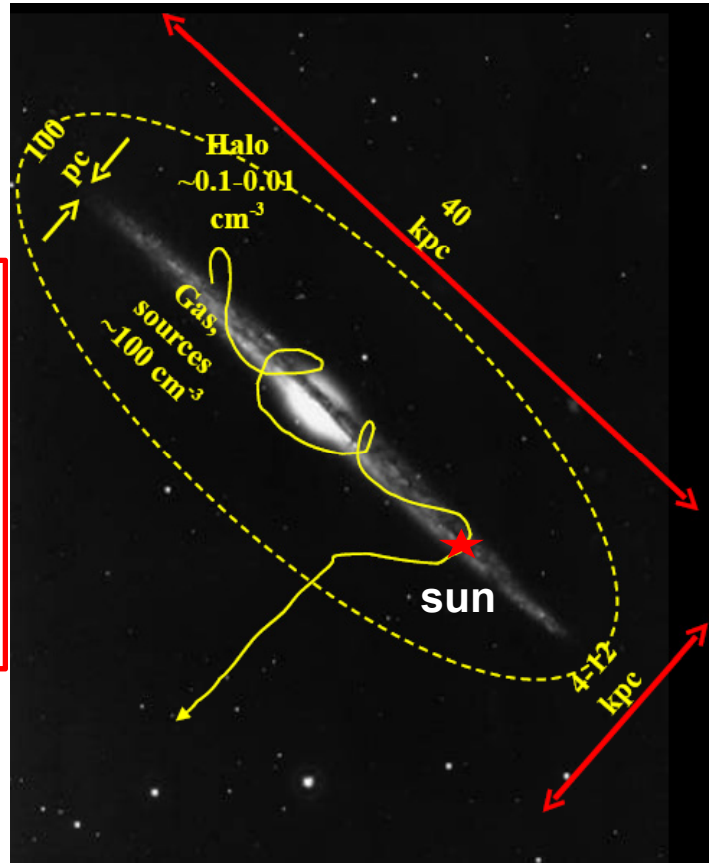
CR Propagation in Milky Way

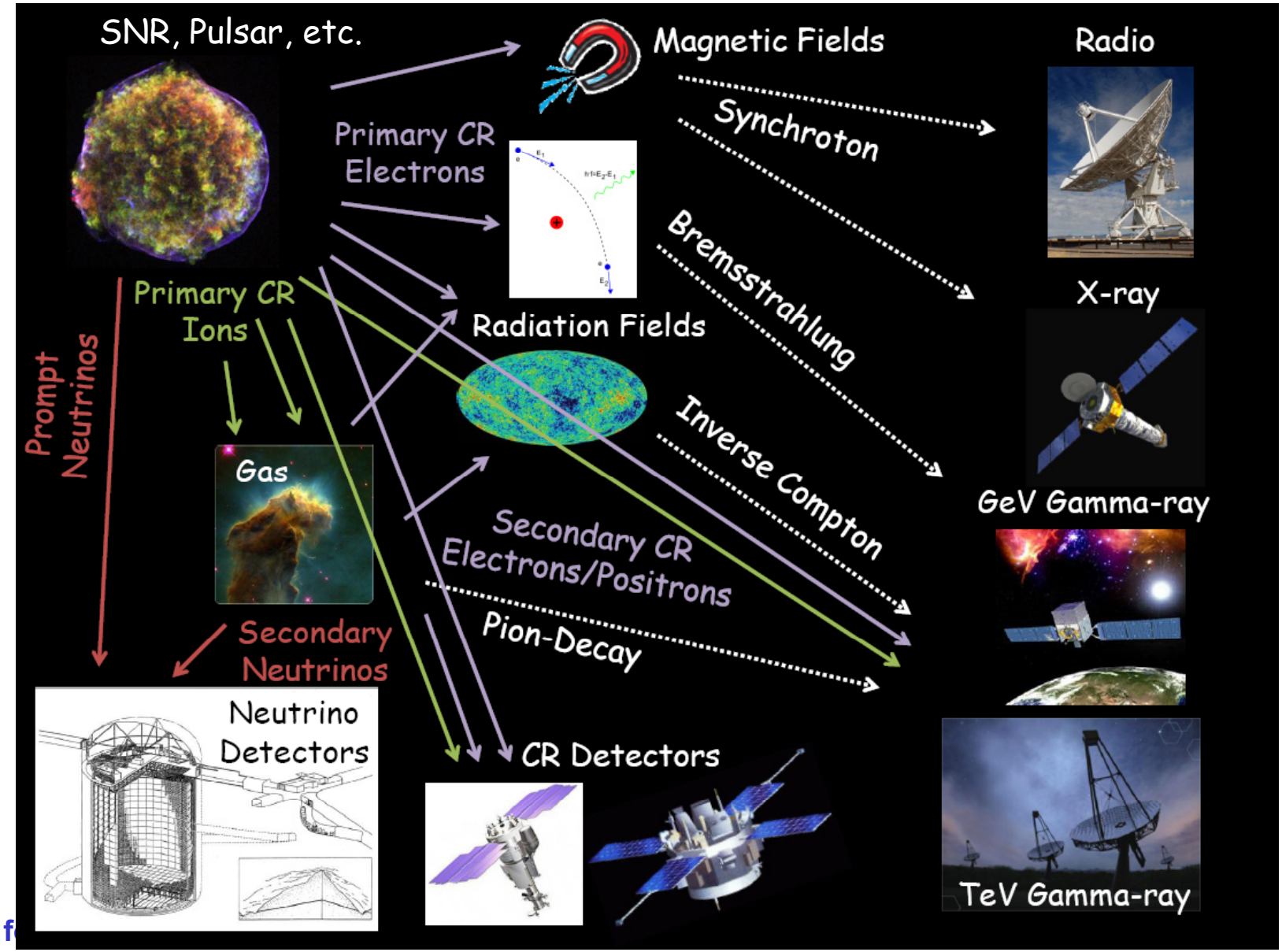
- CRs propagate for ~10^7 years before escaping to intergalactic space
- During the propagation they produce EM radiations

- Direct measurements show the spectrum averaged over time (~10 Myr) and space (~kpc)
- Indirect measurements through EM radiation provide a snapshot of CRs in distant locations.

- High energy CR electrons suffer rapid energy loss, hence may probe a few nearby sources.



CR Measurements



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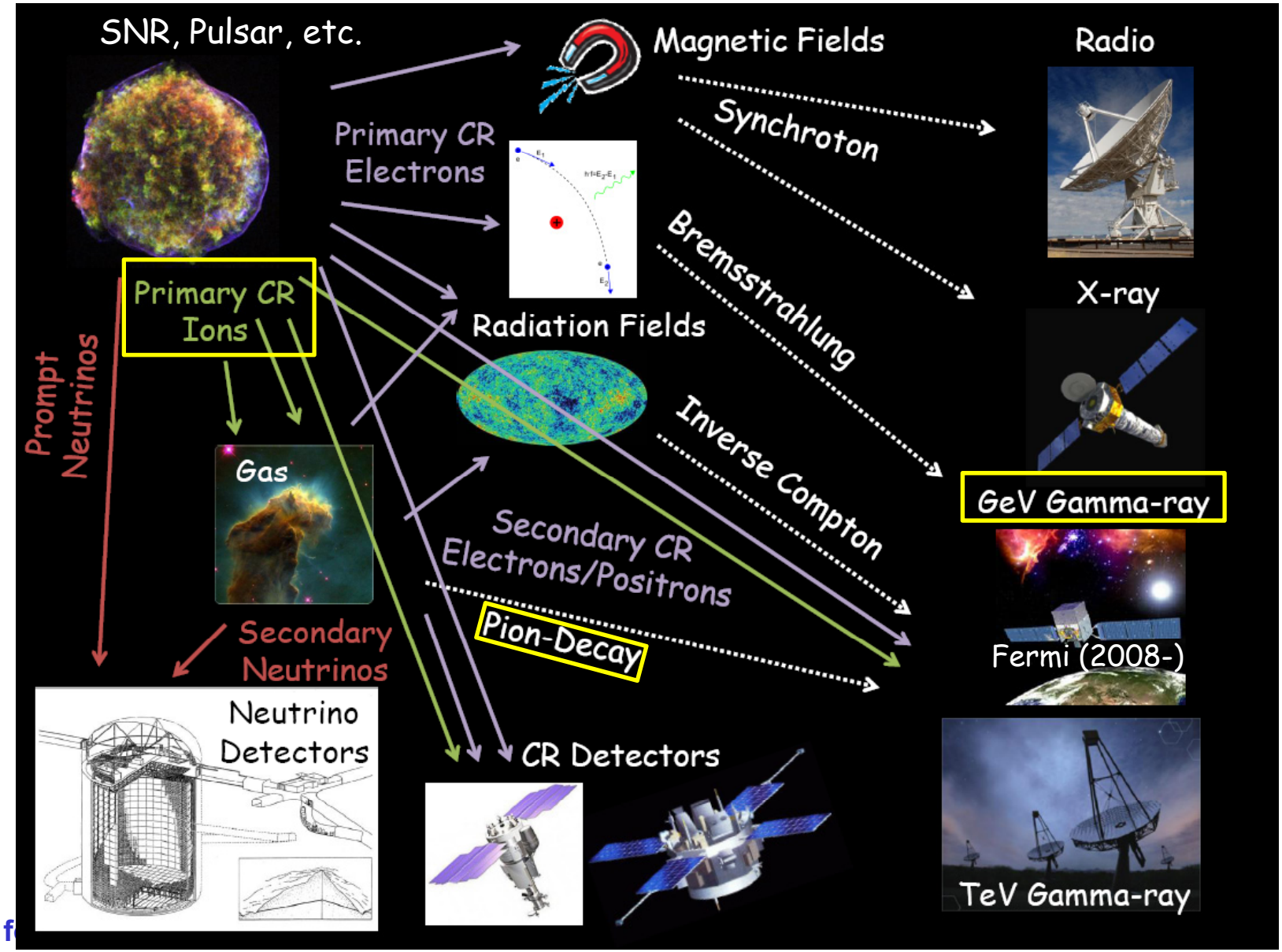
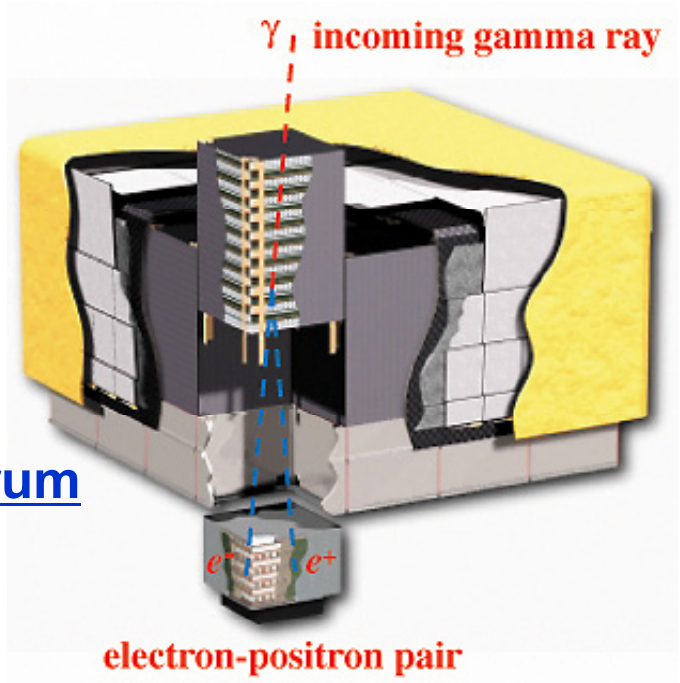


Fermi Gamma-ray Space Telescope

- **Launched in 2008**
  - Large Area Telescope (LAT) and Gamma-ray Burst Monitor (GBM)
- **LAT as a "GeV" Gamma-ray Telescope**
  - 20 MeV - >300 GeV,
    8000 cm^2 Aeff (>1GeV), ~2.4 sr FOV
  - Sky survey to probe Galactic CRs
- **LAT as a CRE detector**
  - Imaging calorimeter + ACD/TKR
  - Exposure factor > 10^8 m^2 sr s
  - Precise measurement of CRE spectrum

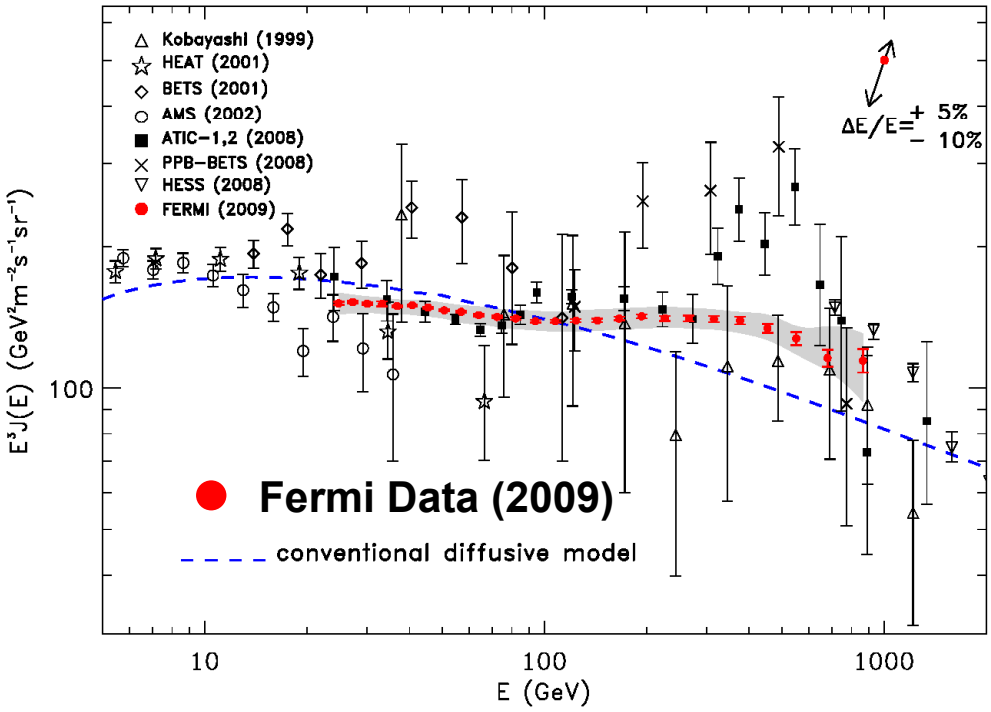


Atwood et al., ApJ 697 1071 (2009)

Part I:
Direct Measurement of CRs

CRE by Fermi-LAT (2009)

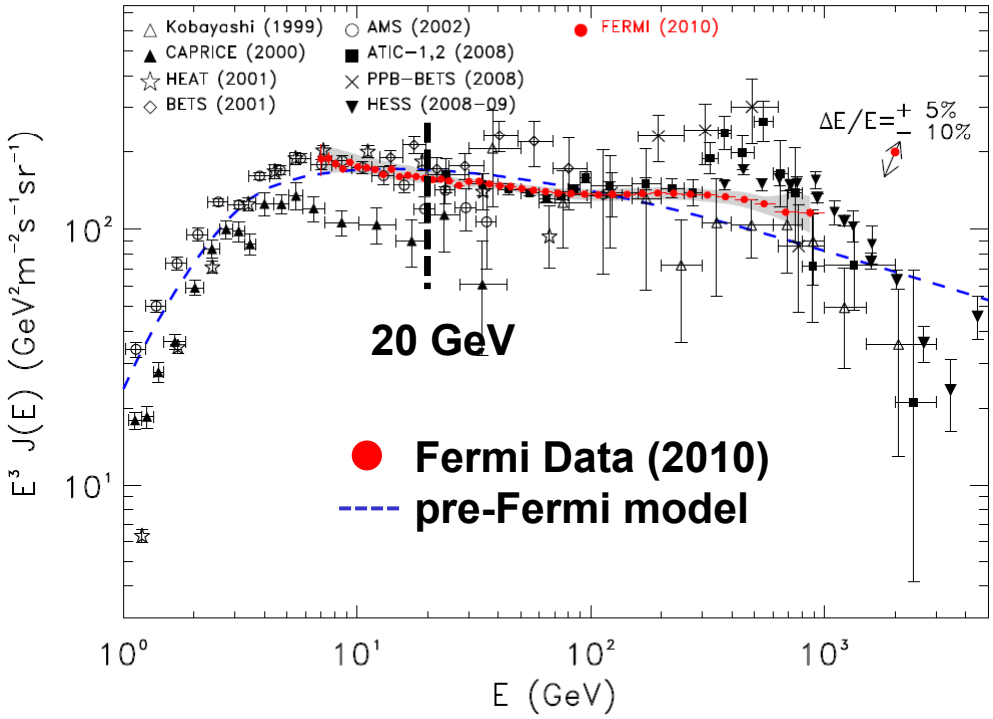
- High energy CREs may probe nearby sources
- An initial study used CREs collected for 6 month
  - 4.5M above 20 GeV, >400 events in highest energy bin
- flat and relatively hard (~E^{-3}) spectrum
  - Pure diffusive models with proper choice of params, or models with additional e^-/e^+ sources fit data well



Ackermann et al., PRL 102 181101 (2009)

CRE by Fermi-LAT (2010)

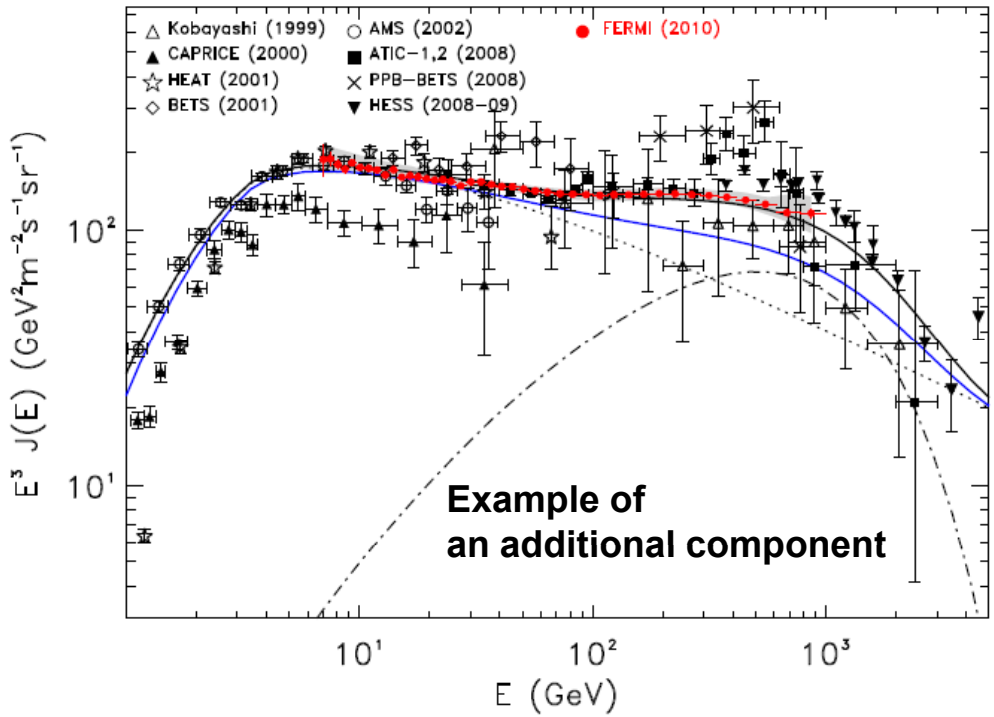
- **CREs collected for 12 month**
  - **8M above 7 GeV, >1000 events in highest energy bin**
  - **Careful examinations of systematic uncertainty incl. cross-check with events with long path in CAL (>=13X_0)**
- **<u>Noticeable deviation from single PL</u>**



Ackermann et al., accepted by Phys. Rev. D

CRE by Fermi-LAT (2010)

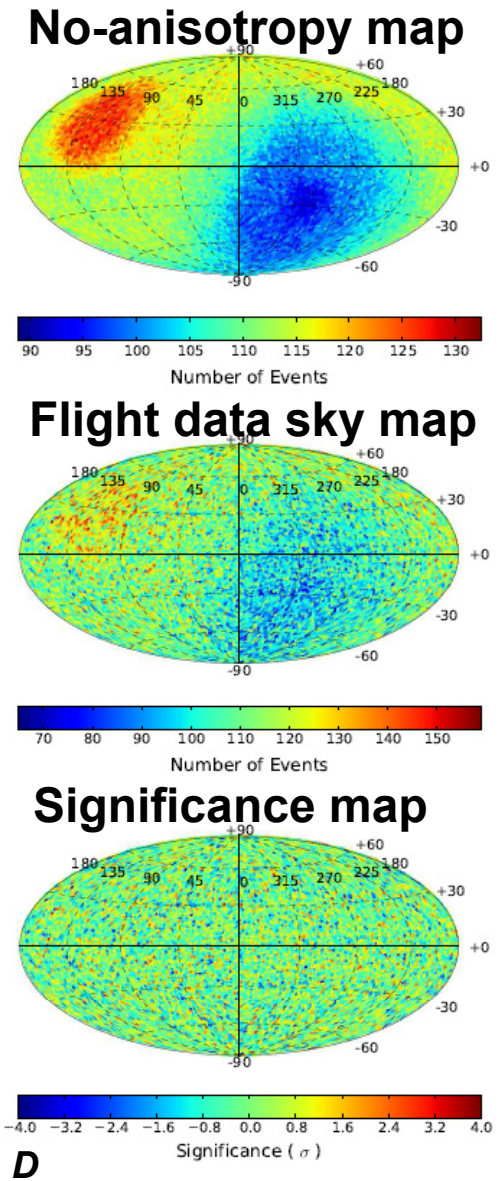
- **Noticeable deviation from single PL**
  - **Additional e^-/e^+ sources can provide a good fit to Fermi CRE and PAMELA $e^+/(e^- + e^+)$**
  - **Nature still in question. Astrophysical (pulsar), exotic (DM) or others**



Ackermann et al., accepted by Phys. Rev. D

CRE Anisotropy

- Fermi offers an opportunity to search for possible CRE anisotropies (large statistics)
  - Local CR sources, propagation environment
- Construct *no anisotropy* map from flight data
  - shuffling and direct integration
- Then search for anisotropies with different energy thresholds (60 GeV min.) and on different angular scales (10°-90°)
  - Direct bin-to-bin comparison or spherical harmonic analysis
- <u>No evidence of anisotropy above 60 GeV</u>

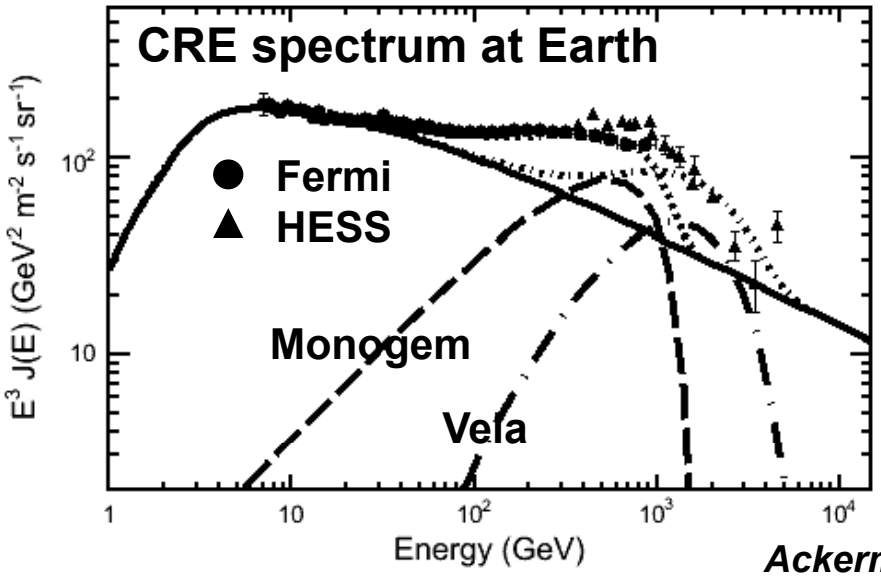


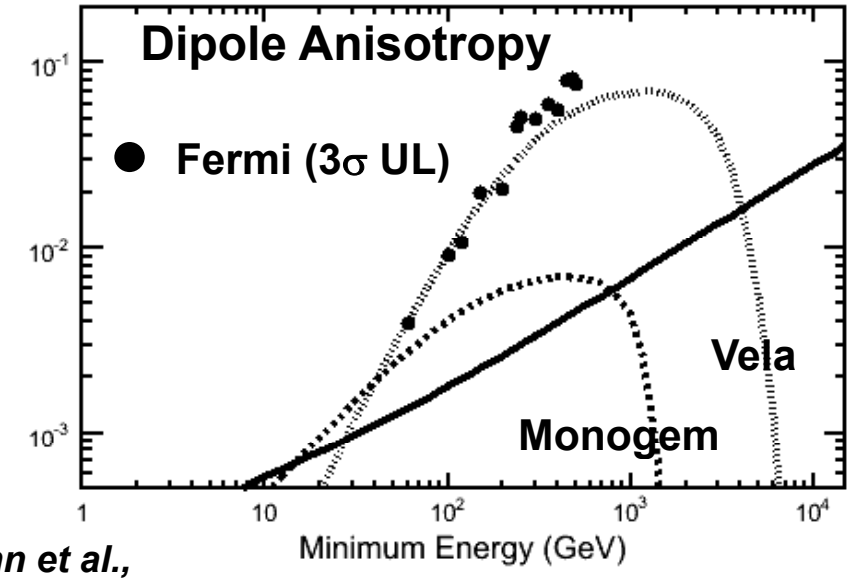
Ackermann et al., accepted by Phys. Rev. D

CRE Anisotropy (cont.)

- **No evidence of anisotropies above 60 GeV and 10°-90°**
  - **Upper limit for the dipole anisotropy: 0.5-5%**
- **<u>This limit is comparable to the value expected</u> for a single nearby source dominating HE spectrum.**
  - **will improve as more data are collected**

Example: Single astrophysical source + (almost) homogeneous Galactic CRE





Ackermann et al., accepted by Phys. Rev. D

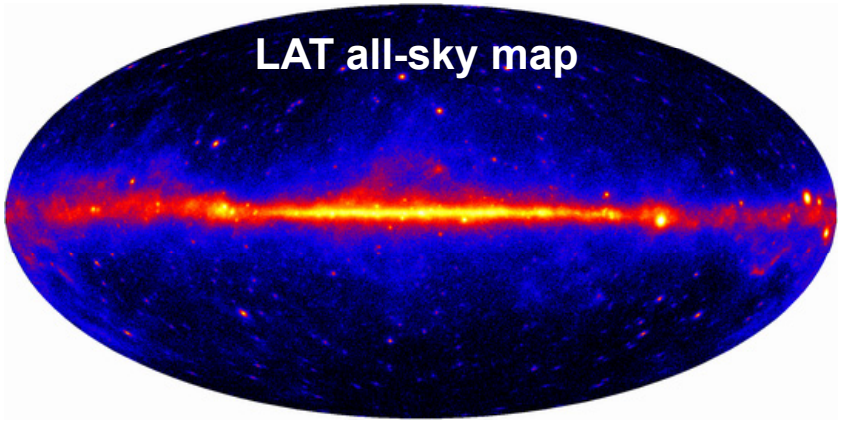
Summary (Up to Now)

- **Fermi-LAT can study CRs, directly (inclusive electron spectrum) and indirectly (γ-ray obs).**
- **Fermi has published precise CRE spectrum up to 1 TeV**
  - **allows quantitative discussion of additional sources**
- **No evidence of anisotropies in the arrival direction above 60 GeV**
  - **Upper limits are already interesting in terms of modeling**

Part II:
CRs in the Milky Way and external galaxies

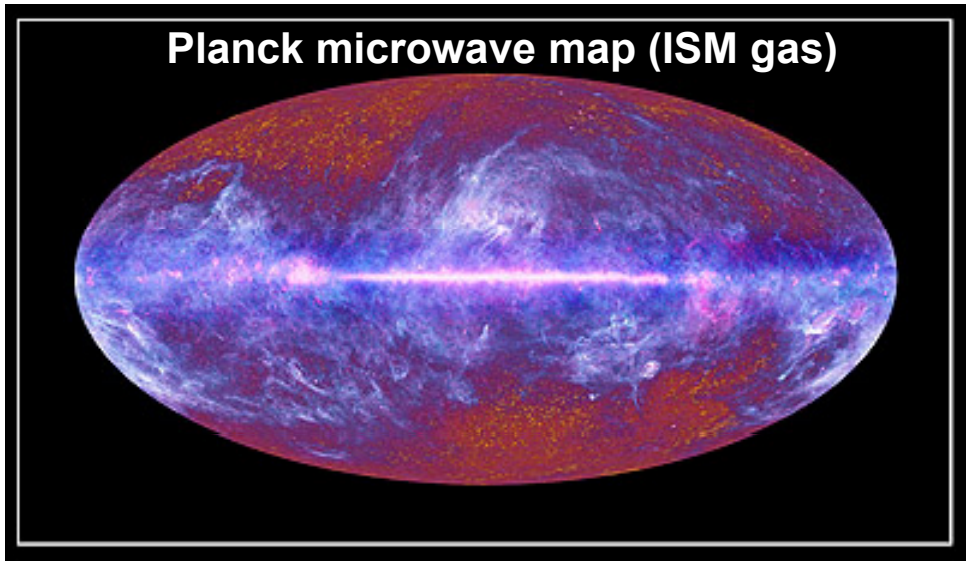
Diffuse Gamma-Rays to Probe CRs

- **CRs produce EM radiations during propagation**



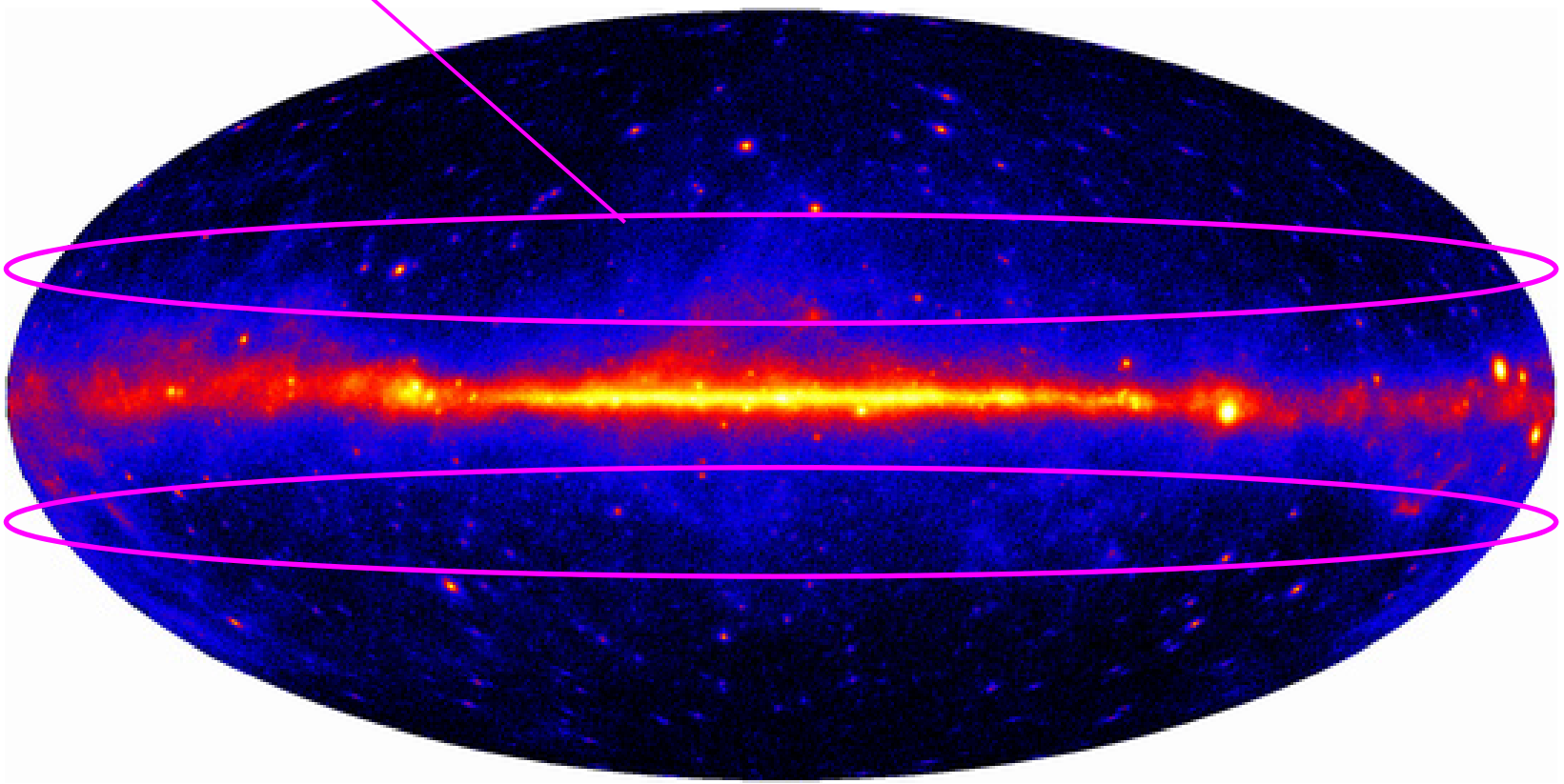
• ~90% of gamma-rays are diffuse emission, mostly produced via interaction of CR protons with the ISM gas

• GeV γ-rays are a powerful probe to study CRs incl. those in local group galaxies and nearby starburst galaxies.



CRs close to the Solar System

1) Intermediate lat. region: local ISM gas. Study CRs near Sun

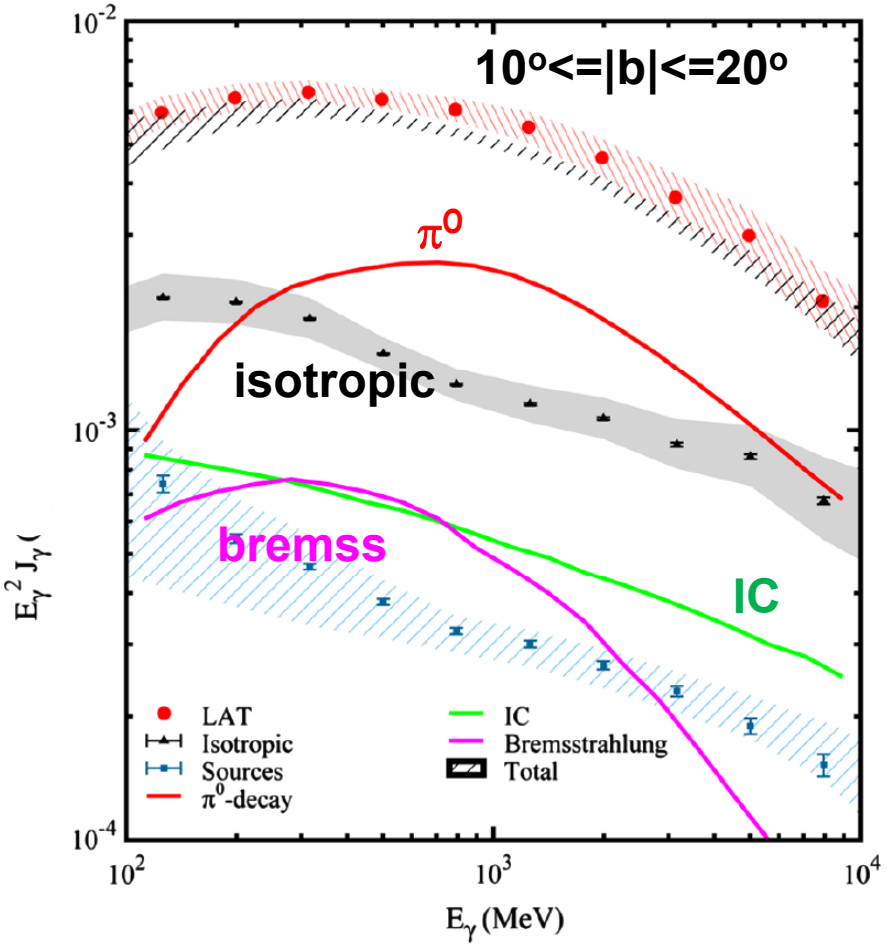


Abdo et al., ApJ 703, 1249 (2009)
Abdo et al., PRL 103, 251101 (2009)

CRs close to the Solar System

1) Intermediate lat. region: local ISM gas. Study CRs near Sun

- Data agree with the model based on the LIS
- CR protons directly measured ~ local CR pool



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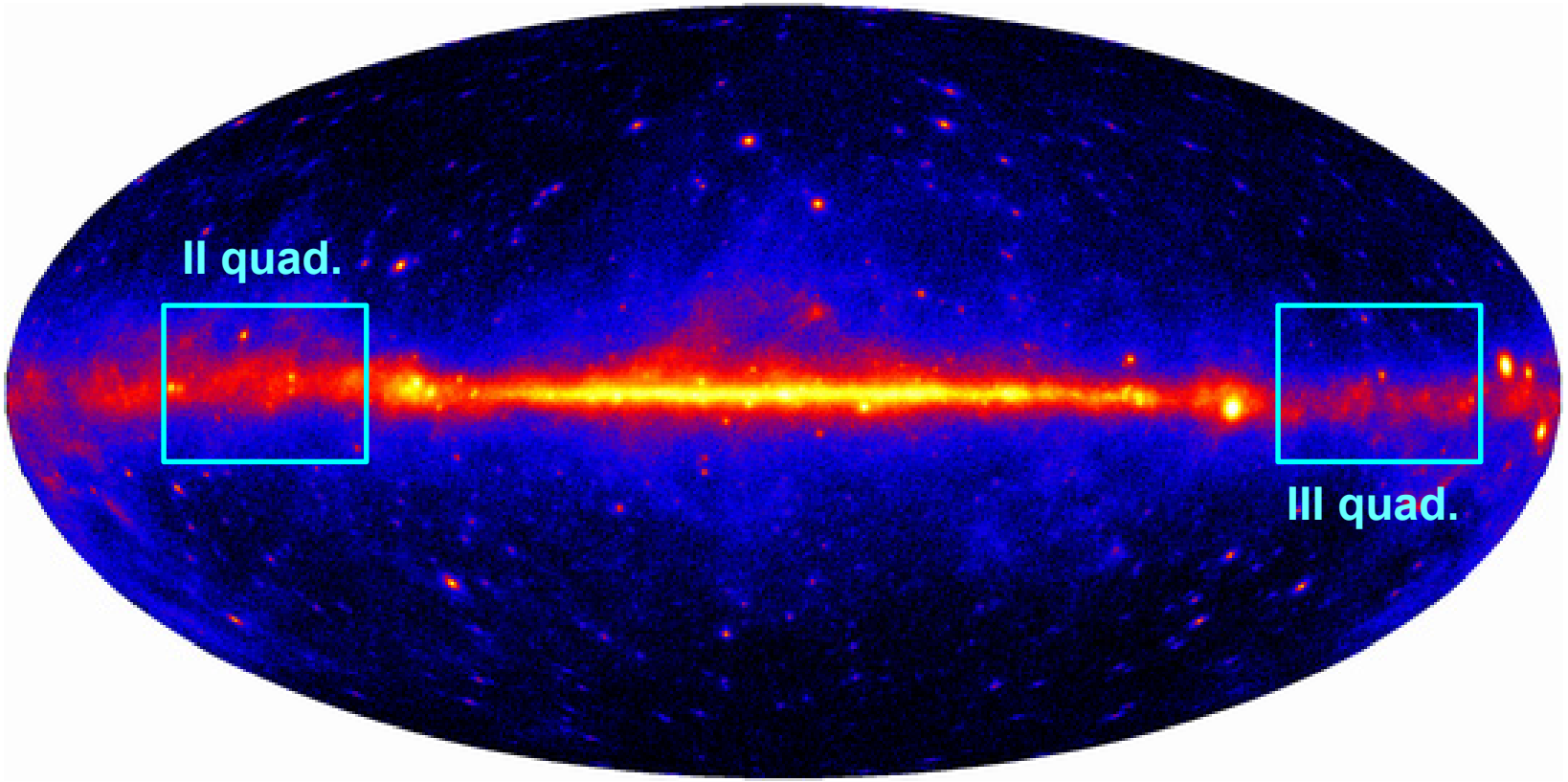
CR Distribution in Milky Way

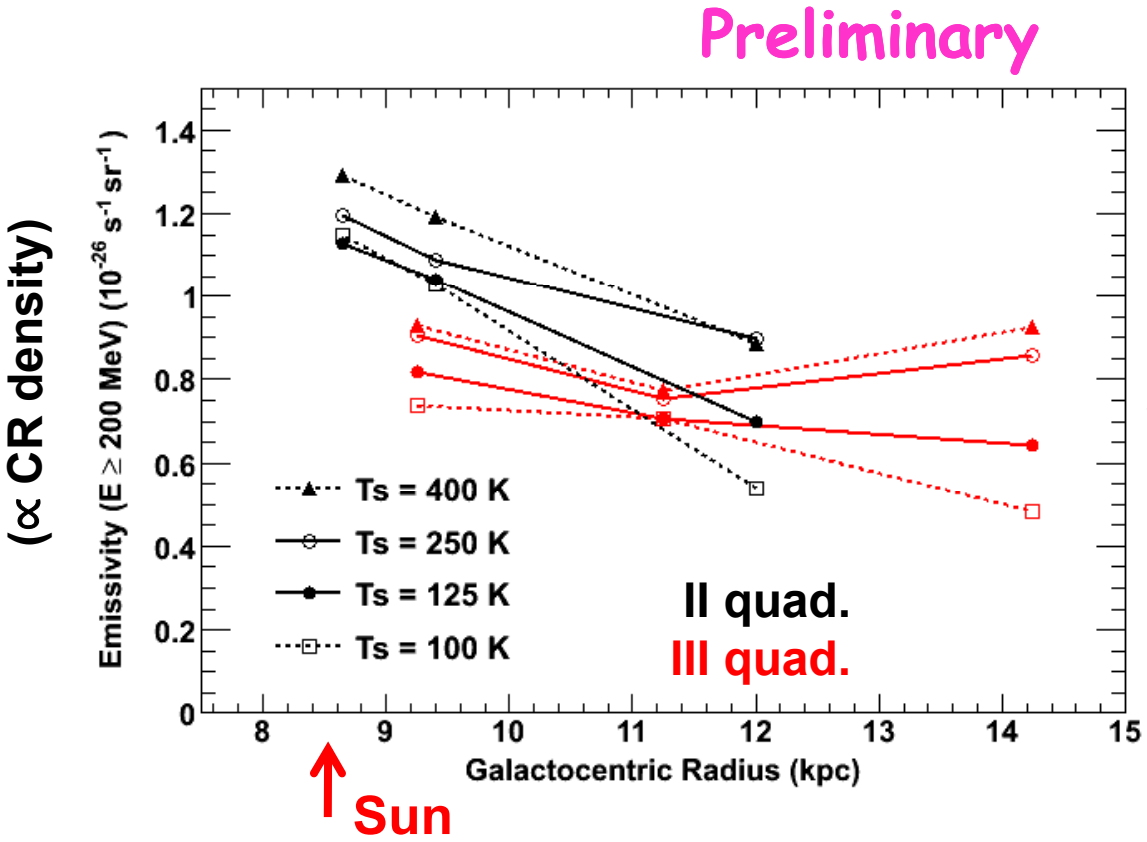


2) Obs. of the outer Galaxy provides an accurate measurement of CRs beyond solar circle

Abdo et al., ApJ 710, 133 (2010)
Ackermann et al., ApJ submitted

The Gradient of CR Densities

- **Emissivity = gamma-ray emission rate per H-atom gives an estimate of CR densities**

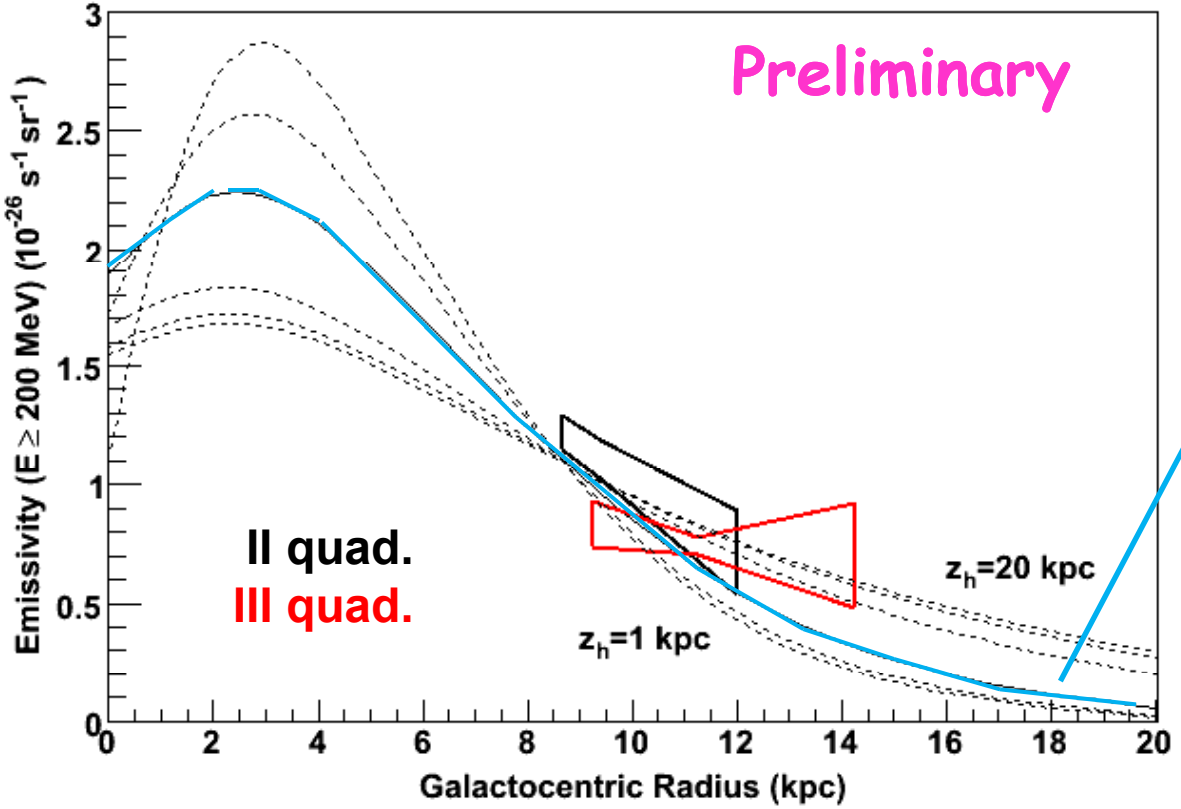


- **Uncertainties dominated by HI optical depth (often overlooked in the past)**
- **Hint of CR density variation near Sun**
- **No significant CR gradient**

Abdo et al., ApJ 710, 133 (2010)
Ackermann et al., ApJ submitted

The Gradient of CR Densities (cont.)

- **CR densities beyond 11 kpc are greater than expected even if we take account of systematic uncertainty.**
  - **Large CR halo**
  - **Flat CR source distribution**

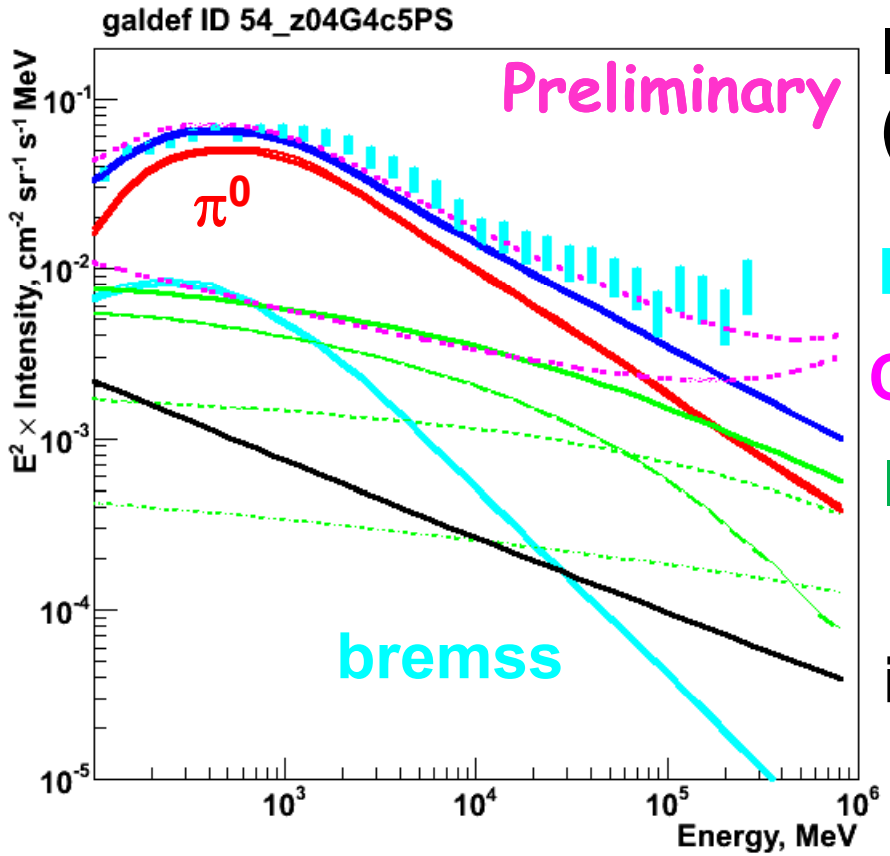


model from SNR distribution and a standard 4 kpc CR halo

Abdo et al., ApJ 710, 133 (2010)
Ackermann et al., ApJ submitted

The Large Scale Diffuse Emission

- **The large scale diffuse analysis (Gal. plane) in progress.**
  - **Already reproduces data well.**
  - **Will provide CR p/e$^-$ distribution in the whole MW.**



Inner Galaxy (|l|<30°,|b|<5°)

Fermi Data

Catalog sources

IC

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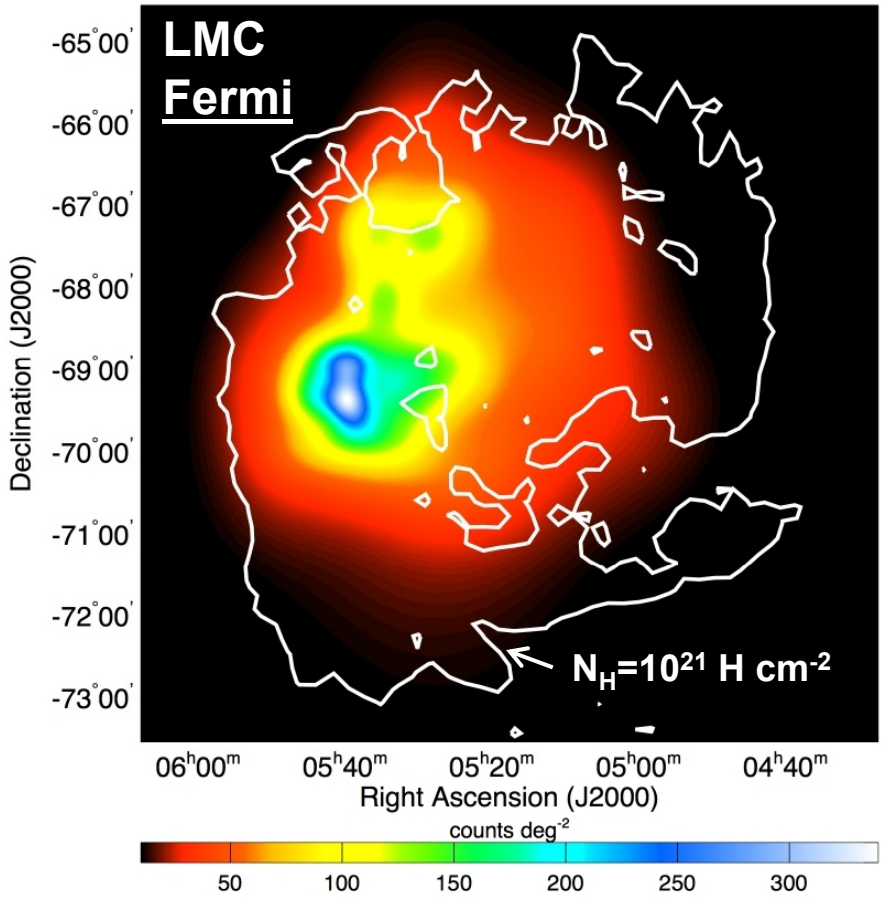
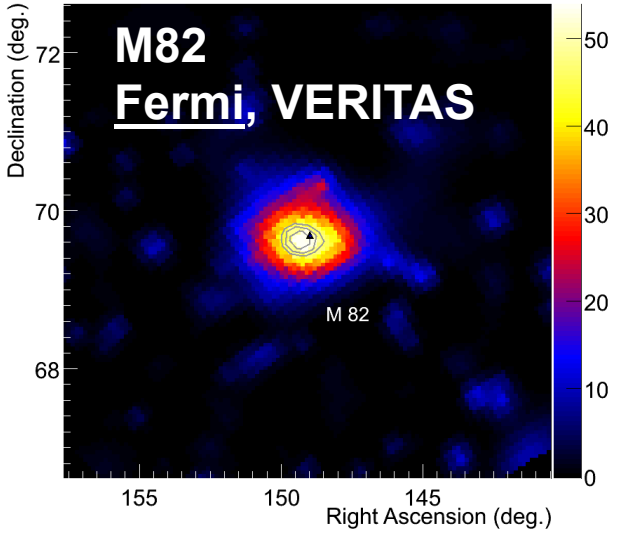
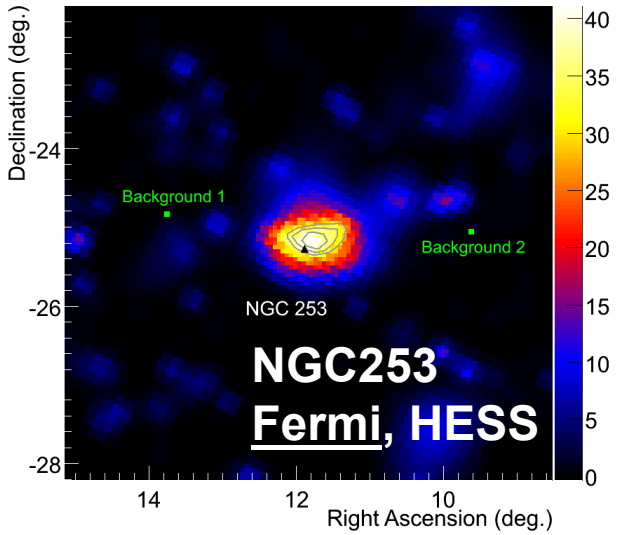
CRs in nearby galaxies

- **Study CR density distribution, correlation with SF activity**

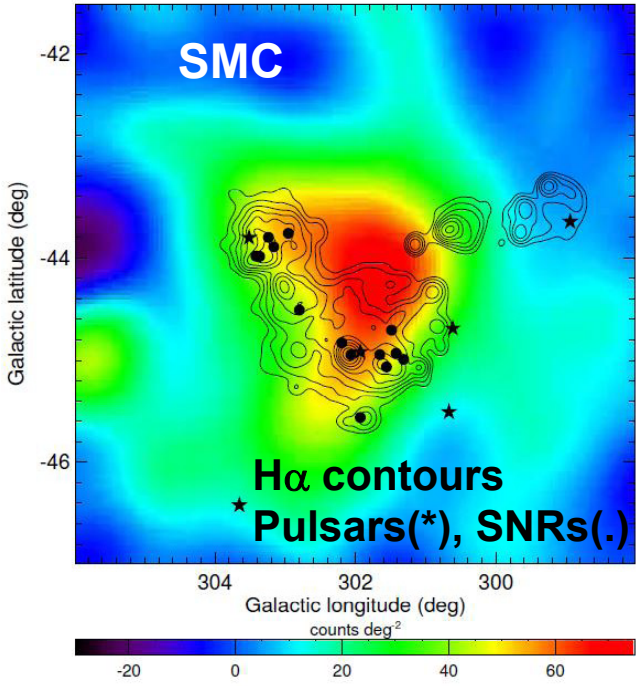






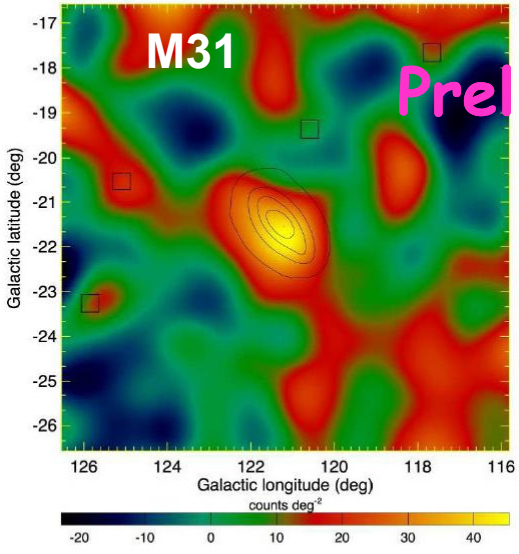
Local Group Galaxies

- Fermi, HESS and VERITAS reported detection of γ-rays from LMC, M82 and NGC 253. In addition,



Abdo et al., arXiv:1008.2127

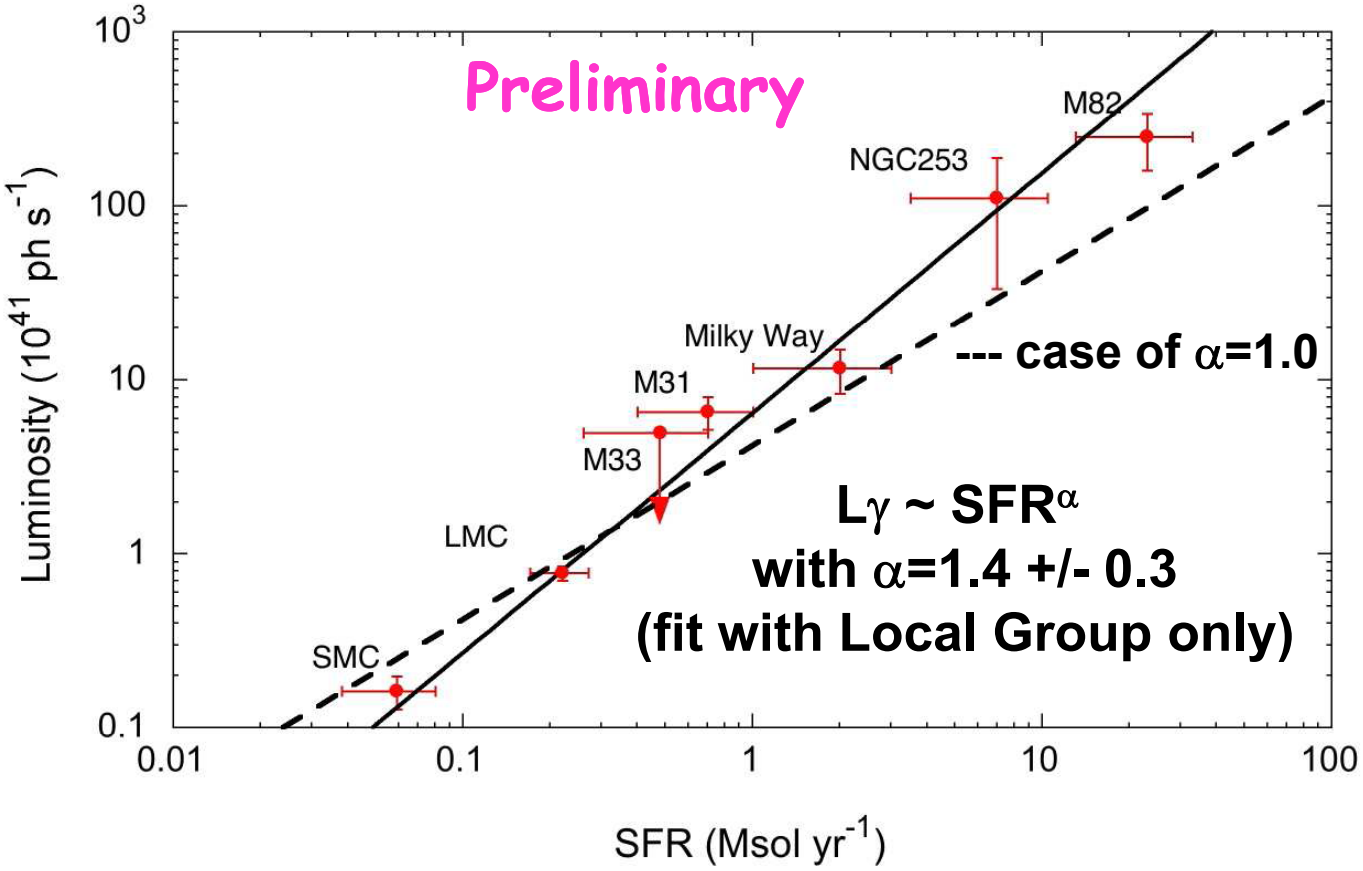
- First detection in gamma-rays
- CR density < 15% of local MW value
- Not a clear correlation between massive stars, neutral gas, pulsars or SNRs



- residuals after BG model subtraction and IRIS 100 um contours (convolved with LAT PSF)
- First detection in gamma-rays

Gamma-ray Luminosity vs SFR

- **Correlation between gamma-ray luminosity and SFR over wide range in galaxy properties**
  - **Details of relationship not yet understood**



Summary

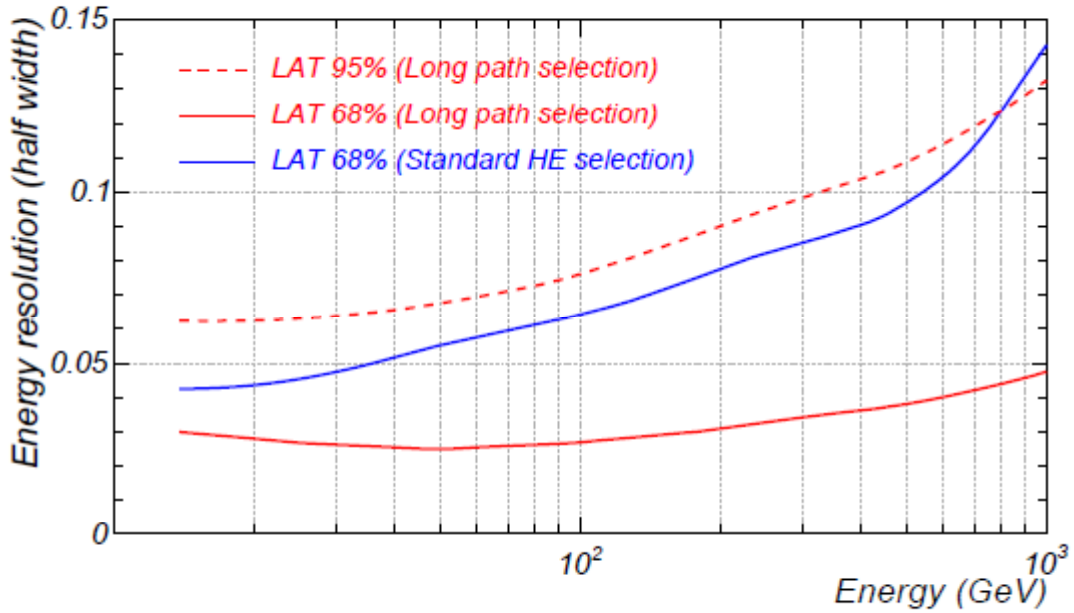
- Fermi-LAT can study CRs directly and indirectly.
- Updated CRE spectrum and (non-) anisotropy
  - provide a good constraint on additional e^-/e^+ component.
- Larger CR densities in the outer Galaxy than expected
  - Large CR halo and/or flat source distribution
- Detection of SMC and M31. Correlation found btw. gamma-ray luminosity and star-formation rate.
  - Details yet to be understood.

- Continued gamma-ray and CRE observation provides further insight into CR production and transport.

Backup Slides

Alternative Event Selection

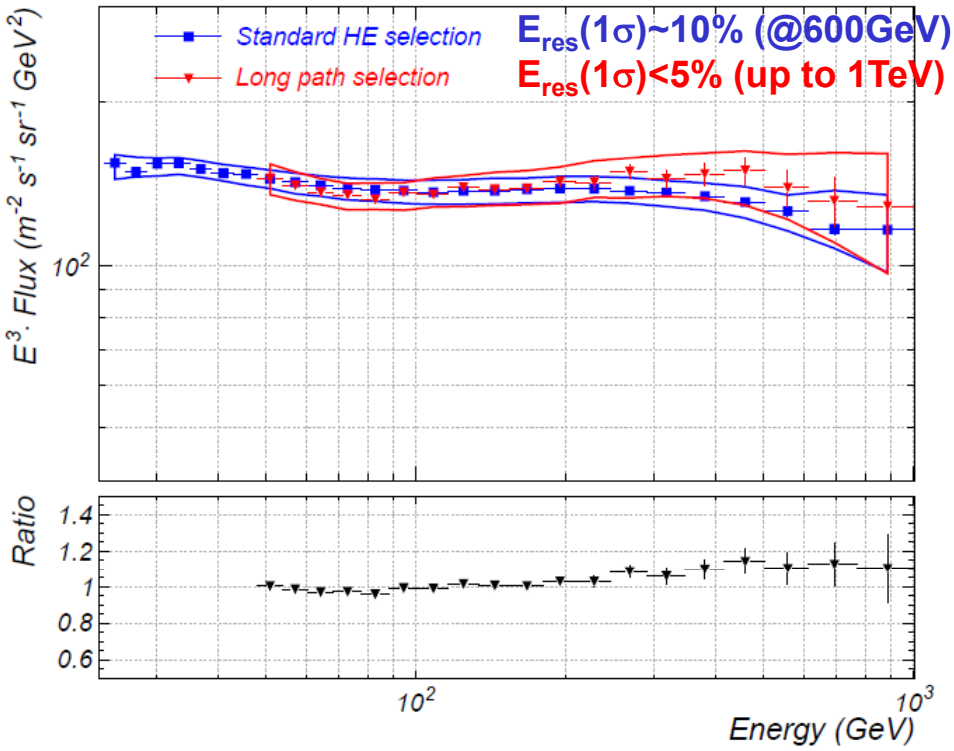
- Test possible systematic effect related to the energy resolution
- Events with long path (13 X_0 min, 16 X_0 ave.) in the instrument and contained in a single calorimeter module
  - Energy dispersion much narrower and more symmetric, energy resolution better than 5% (1σ) up to 1 GTeV.
  - Acceptance reduced to 5% of the standard one



Ackermann et al., accepted by Phys. Rev. D

Alternative Event Selection

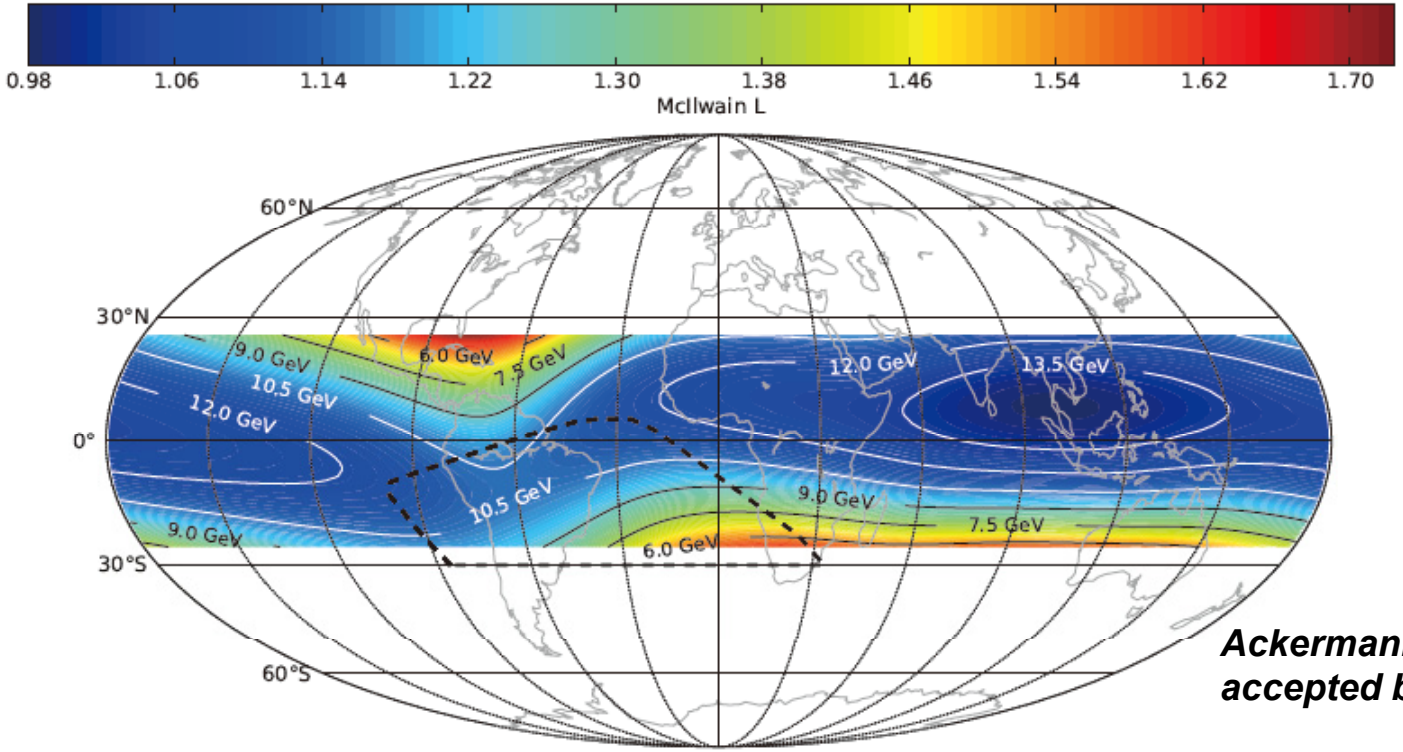
- Test possible systematic effect related to the energy resolution
- Two spectra are consistent within systematic errors
- Long path selection only optimized for energy resolution
  - More challenging in terms of systematics (small sample)
  - Not necessarily more accurate



Ackermann et al., accepted by Phys. Rev. D

Low-Energy Extension

- Rigidity cutoff depends on the detector geomagnetic position
  - ~7 GeV is the minimum energy accessible by Fermi orbit
- Data are divided in 10 independent McIlwain L bins
  - Use bin of low cutoff to reconstruct low-energy spectrum



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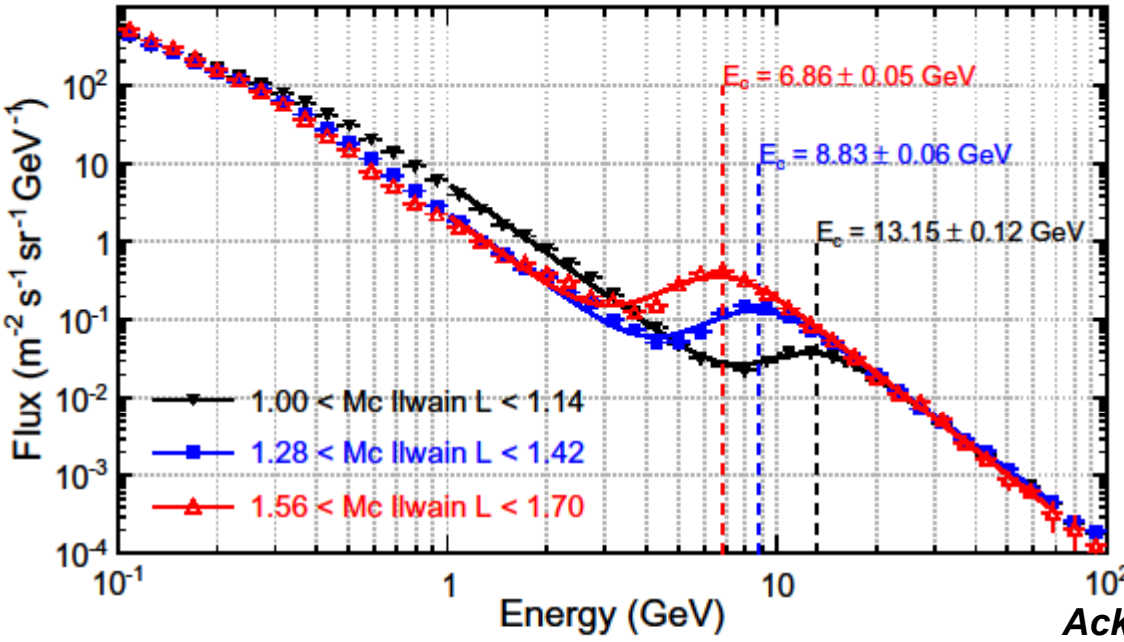
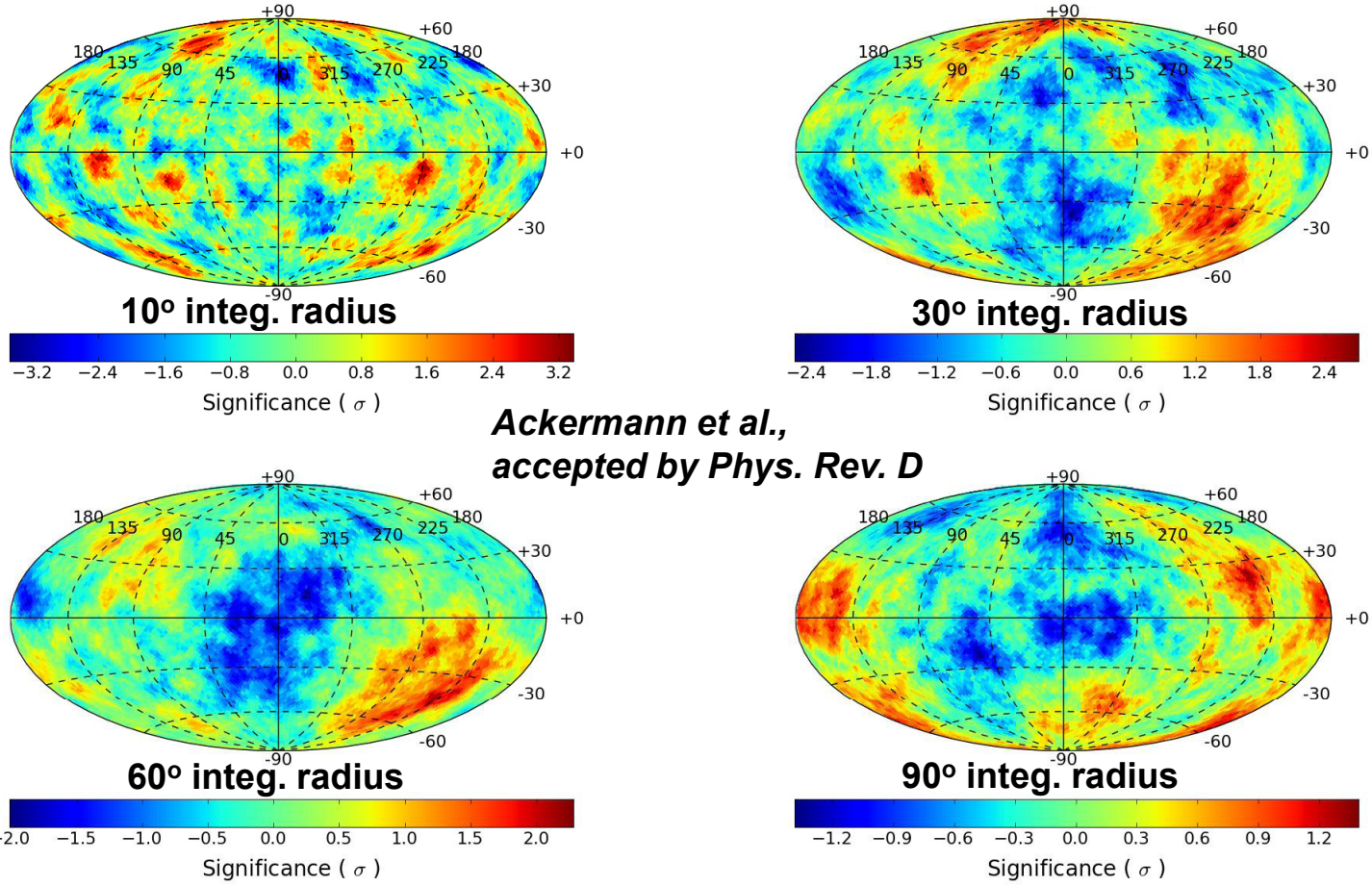


Ackermann et al., accepted by Phys. Rev. D

Significance Skymap

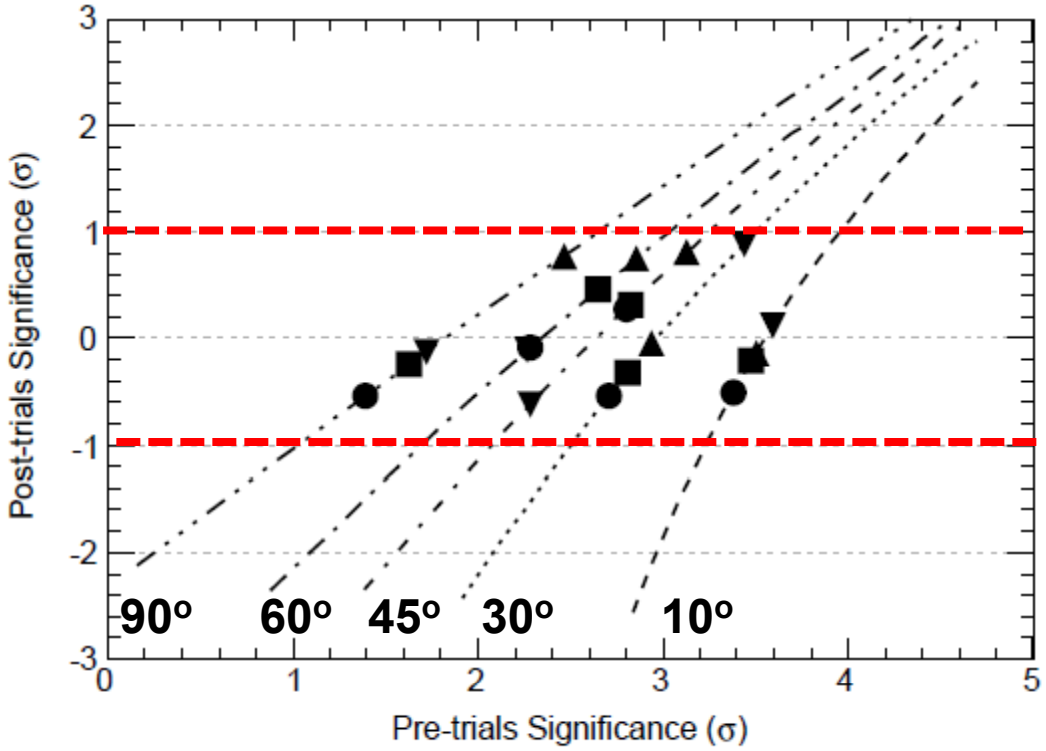
- A pre-trial significance map produced by a bin to bin comparison
- Because of the large number of trials (from ~100 trials at 90º up to ~ 5000 at 10º) all the observed fluctuation is insignificant



Ackermann et al., accepted by Phys. Rev. D

Bin to Bin Comparison

- Curves: Correspondence btw. a pre- and post-trials significance
- Markers: highest significance for different min. energy and radius
  - All results are post-trials insignificant



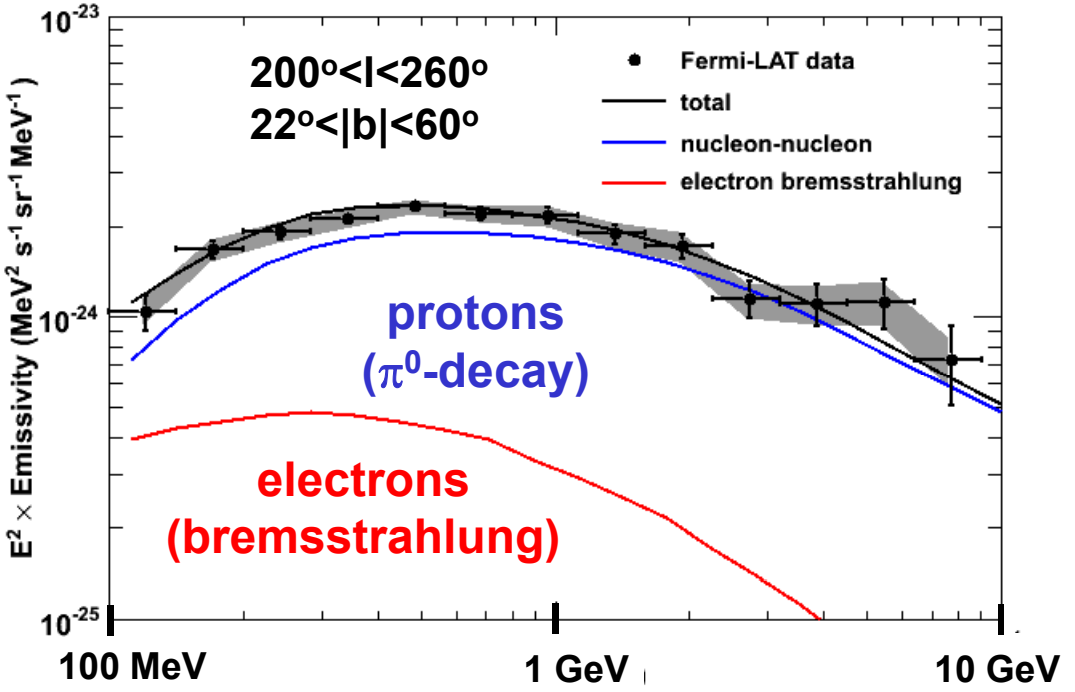
● E > 60 GeV
■ E >120 GeV
▲ E >240 GeV
▼ E >480 GeV

Ackermann et al., accepted by Phys. Rev. D

CRs close to the Solar System

- **Probe nearby CRs through obs. of mid-latitude region**
  - **gamma-rays ∝ HI column density**
  - **Agree with model from LIS**
- **CR protons directly measured ~ local CR pool**

Emissivity = γ-ray emission rate per H-atom gives an estimate of CR Spectrum (Ep~10Eγ)



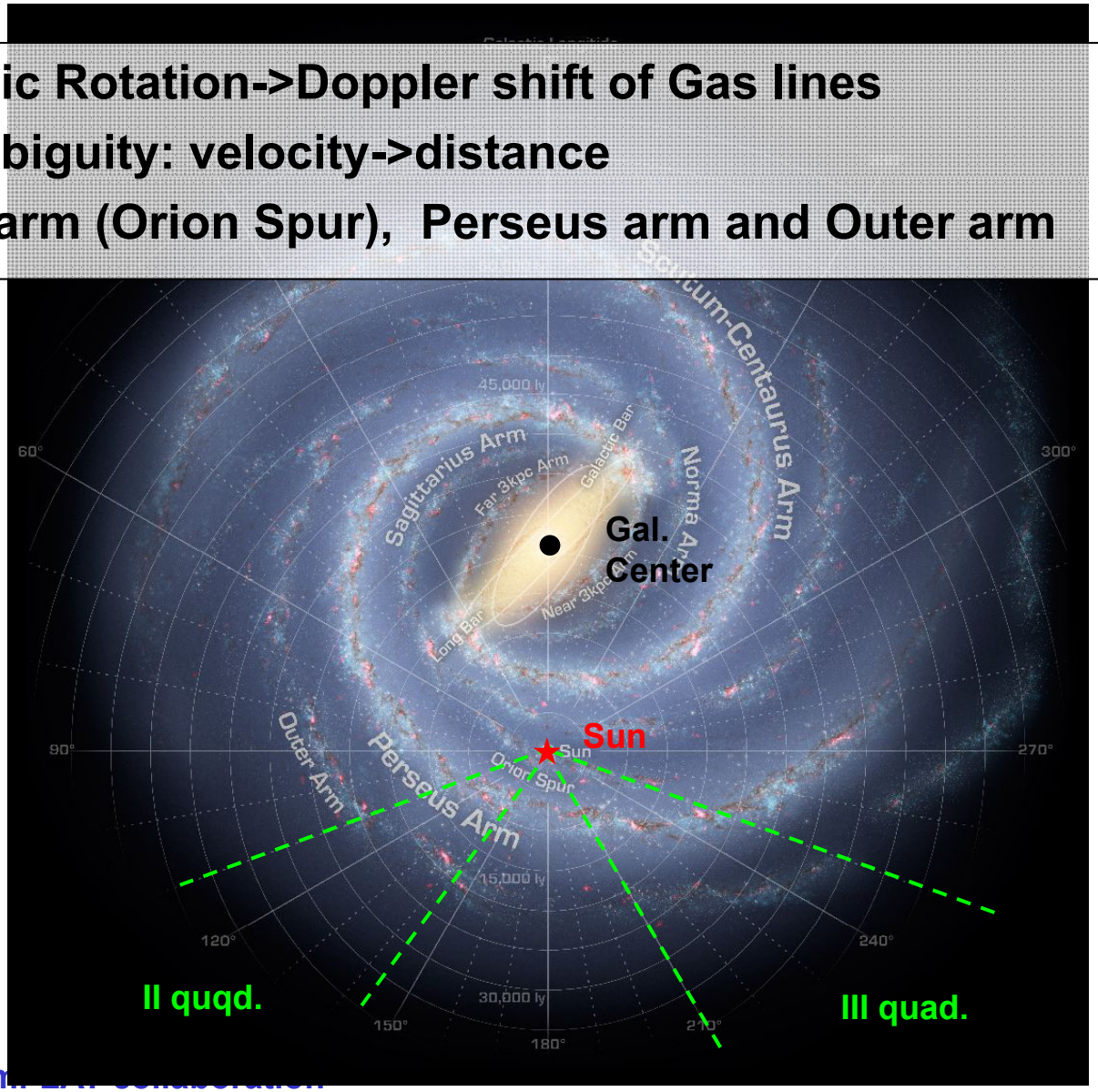
Abdo et al., ApJ 703, 1249 (2009)
Abdo et al., PRL 103, 251101 (2009)

The Outer Galaxy

Galactic Rotation->Doppler shift of Gas lines

No ambiguity: velocity->distance

Local arm (Orion Spur), Perseus arm and Outer arm

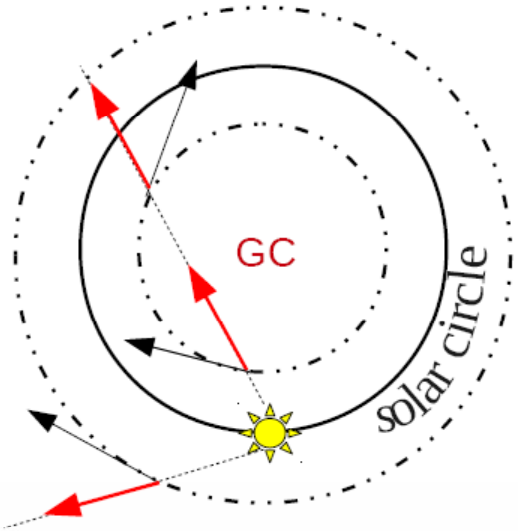


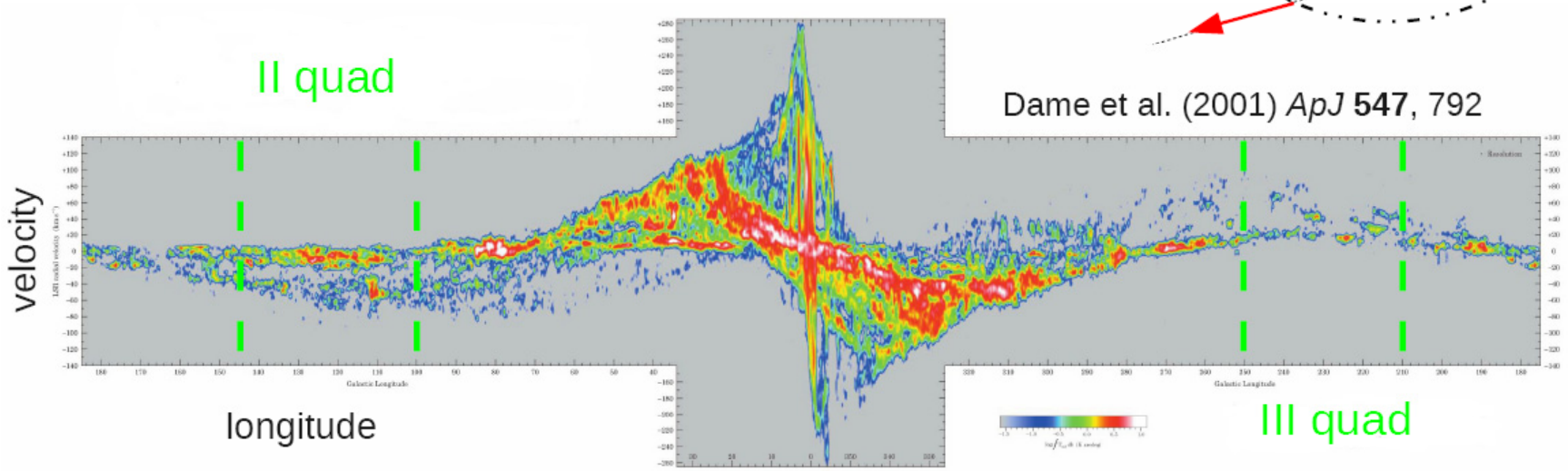
Why Outer Galaxy?

Galactic rotation → Doppler shift of gas lines

In the outer Galaxy

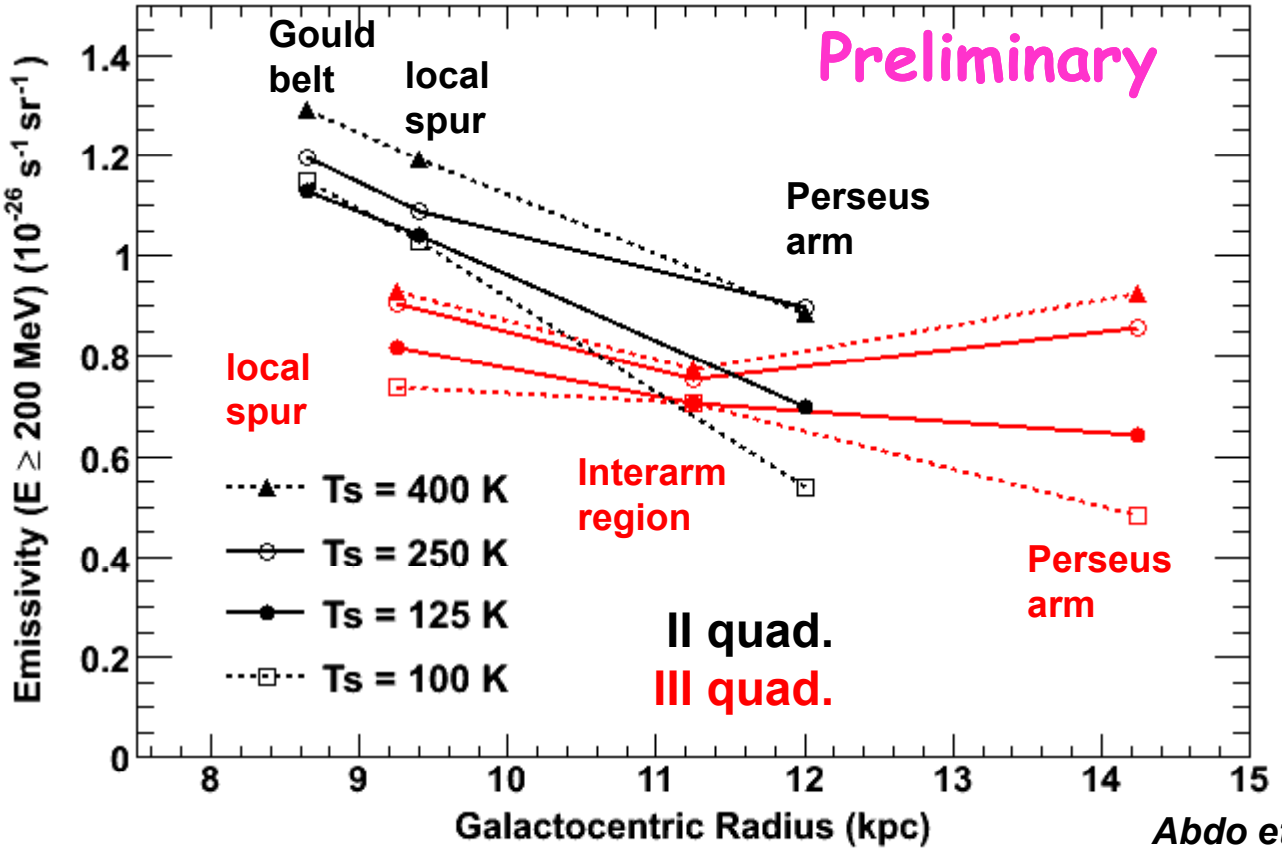
- no ambiguity: velocity → distance
- two regions with steep velocity gradient → good kinematic separation





The Gradient of CR Densities

- **Emissivity = gamma-ray emission rate per H-atom gives an estimate of CR densities**



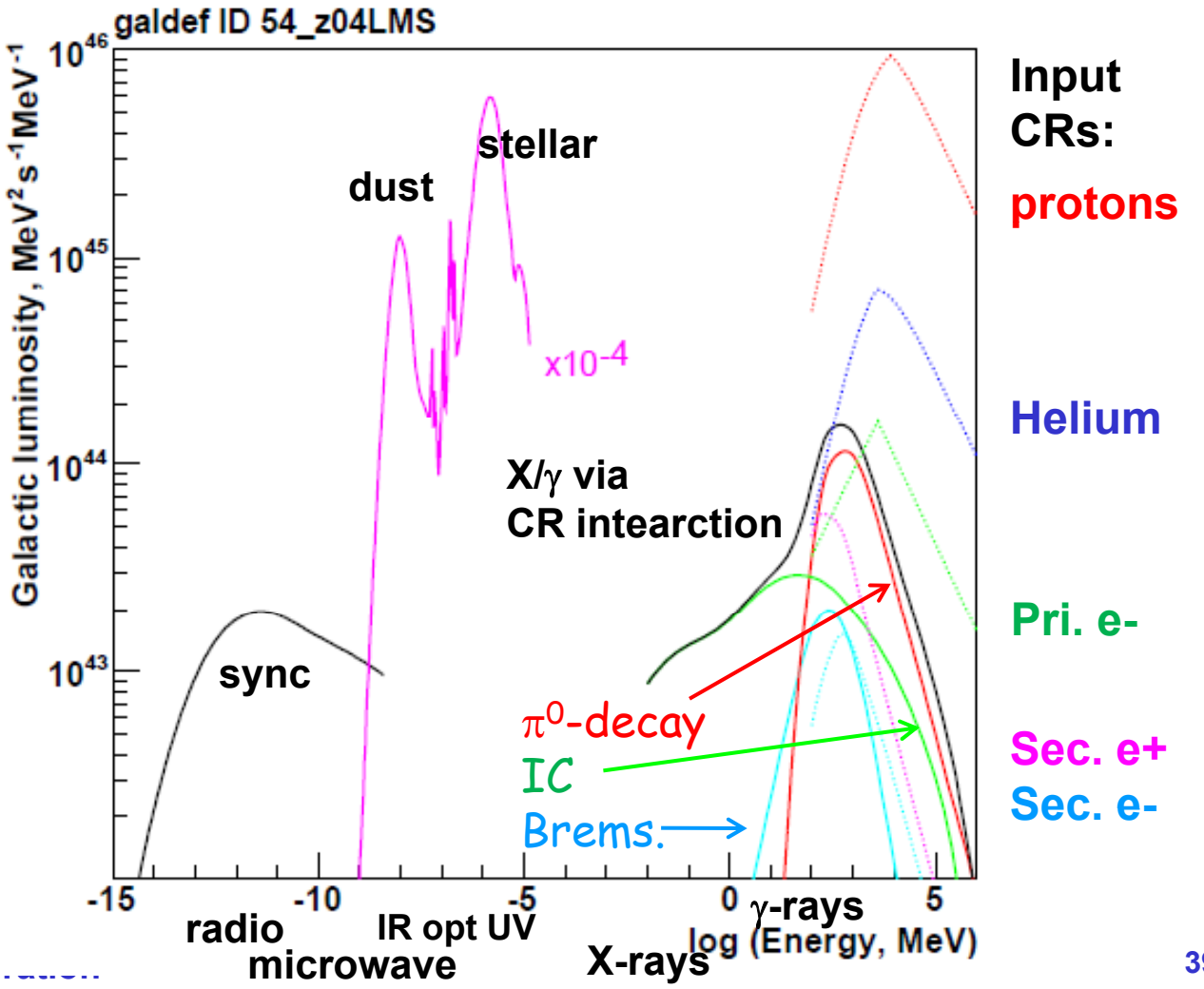
Abdo et al., ApJ 710, 133 (2010)
Ackermann et al., ApJ submitted

EM and CR Spectrum of MW

- Muti-frequency Spectrum of Milky Way (GALPROP model based on Fermi results)

CR e^-/e^+ energy input ~ output via sync. (1/3) and IC (2/3)

conversion efficiency up to ~80% (in case of large halo)

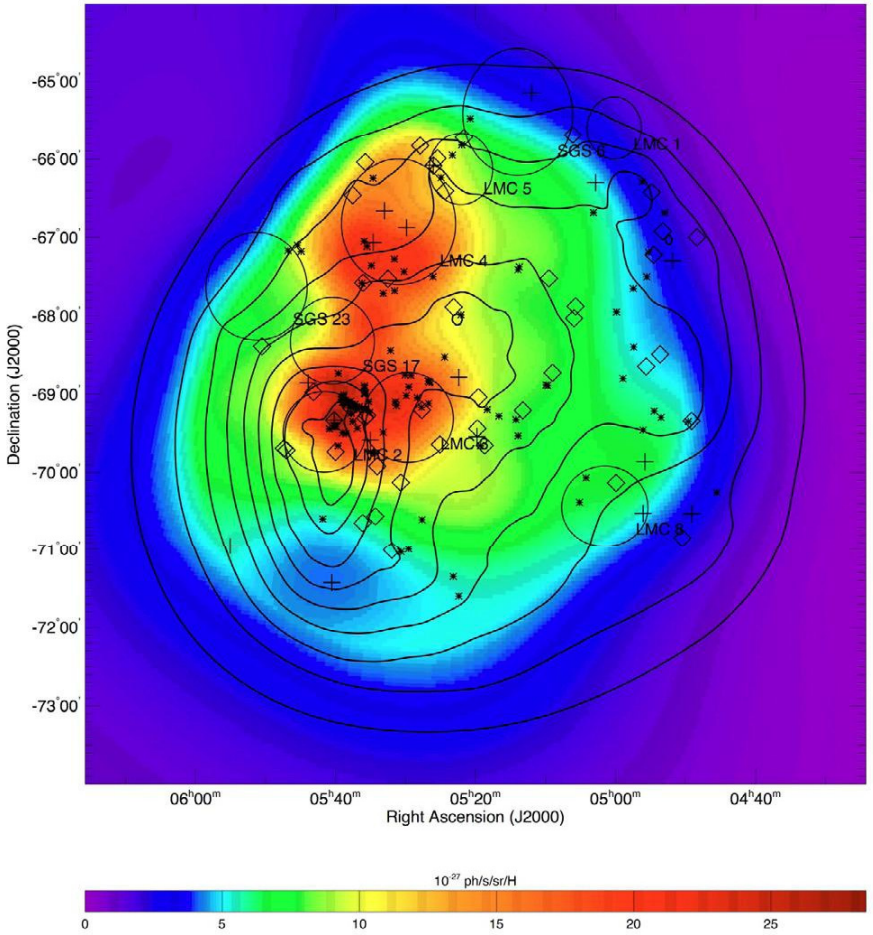


Strong et al., accepted by ApJL

Spatially Resolved LMC

- Gamma-ray Emissivity map
- Contours: N(H) column density

  Pulsars (+)
  WR start (*)
  SNRs (◊)
  Supergiant shells (circles)



CR density correlated with massive start-forming regions

Spatially Resolved SMC

- **Not a clear spatial correlation with massive stars, neutral gas, pulsars or SNRs**
- **Significant contribution from pulsars?**
- **Average CR density <15% of local MW value**