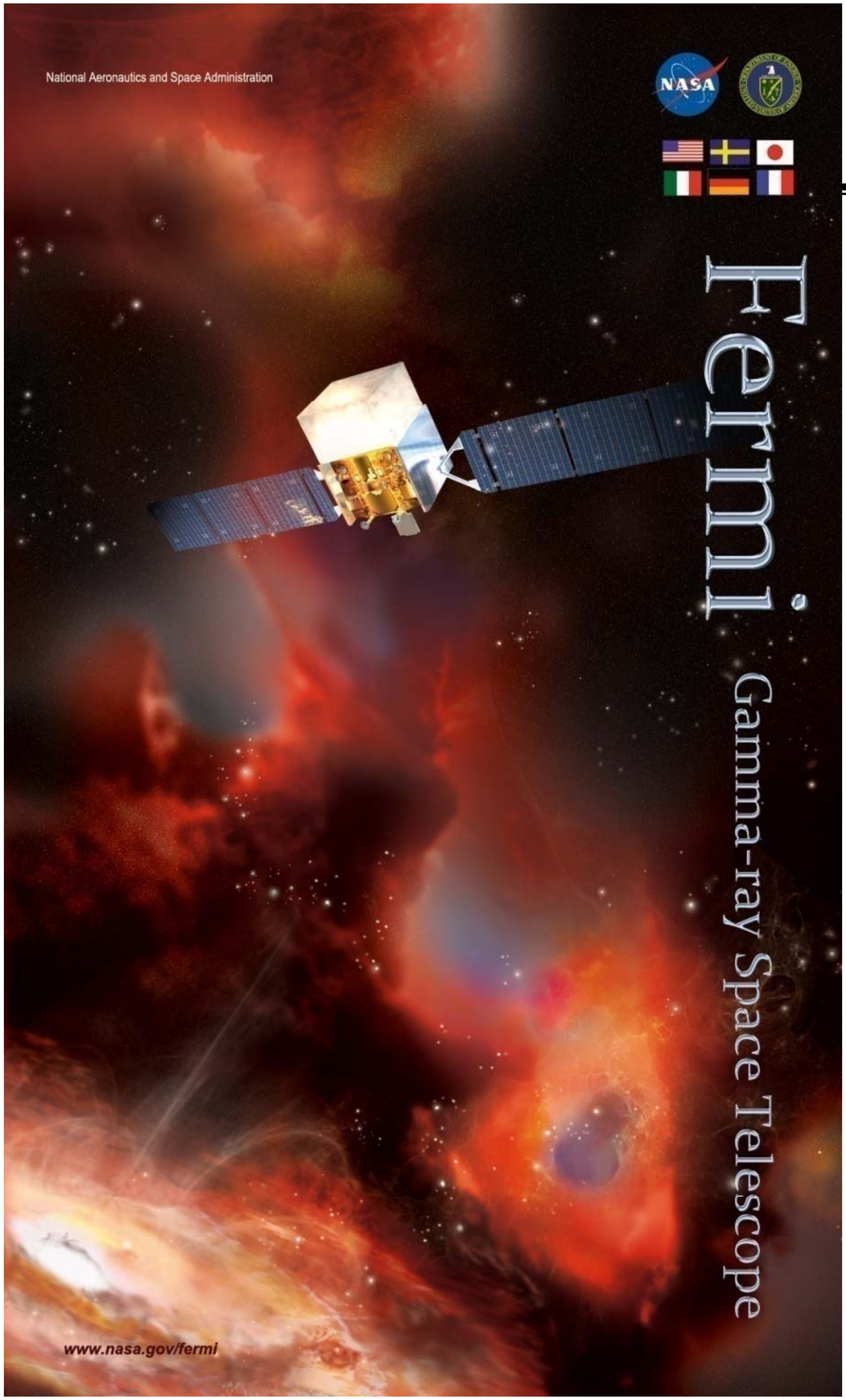

Galactic Cosmic-Rays Observed by Fermi-LAT

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Hiroshima Univ.
on behalf of the Fermi-LAT Collaboration

JPS 2009 Autumn Meeting
September 11, 2009, Kobe, Japan

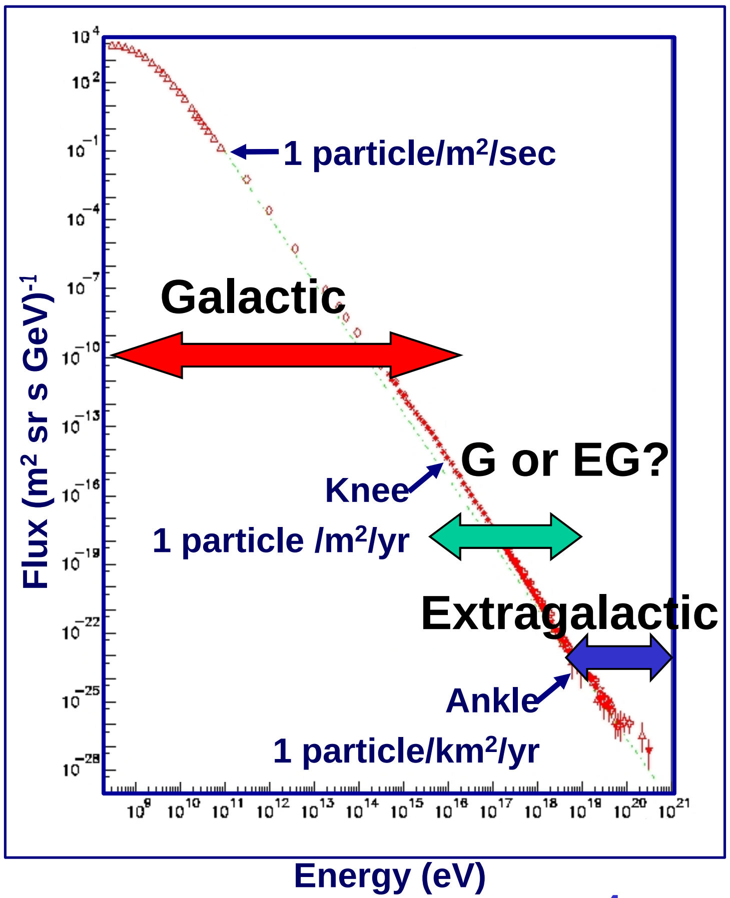
Plan of the Talk

1. **Cosmic-ray overview and Fermi Gamma-ray Space Telescope**
2. **Cosmic-ray electrons seen by Fermi-LAT (<u>direct measurement of CRs</u>)**
3. **Galactic CRs revealed by diffuse γ-ray emission observed by Fermi-LAT (<u>CRs in distant location</u>)**

Introduction:
Cosmic-Rays and the
Fermi Gamma-ray Space Telescope

Cosmic-Rays Overview

- **Discovered by V. Hess in 1912**
- **Globally power-law spectrum with some structures (knee and ankle)**
  - ➢ **hint of the origin**
  - ➢ **$E<E_{knee}$ are (probably) Galactic origin**
- **Composition:**
  - ➢ **e^- ~ (1/100 - 1/1000) x p, e^+ ~ (1/10) x e^-**
- **Large energy density: ~1 eV cm^{-3}**
  - ➢ **comparable to U_B and U_{rad}**
- **Studied by <u>direct</u> and <u>indirect</u> measurements**



Introduction (1): What Can We Learn from HE e^-/e^+ (and $p/\bar{p}$) ?

- Inclusive spectra: $e^- + e^+$
  - Electrons, unlike protons, lose energy rapidly by Synchrotron and Inverse Compton: at very high energy they probe the nearby sources

- Charge composition: $e^+/(e^- + e^+)$ and $\bar{p}/(\bar{p} + p)$ ratios
  - e^+ and $\bar{p}$ are produced by the interactions of high-energy cosmic rays with the interstellar matter (secondary production)
  - There might be signals from additional (astrophysical or exotic) sources

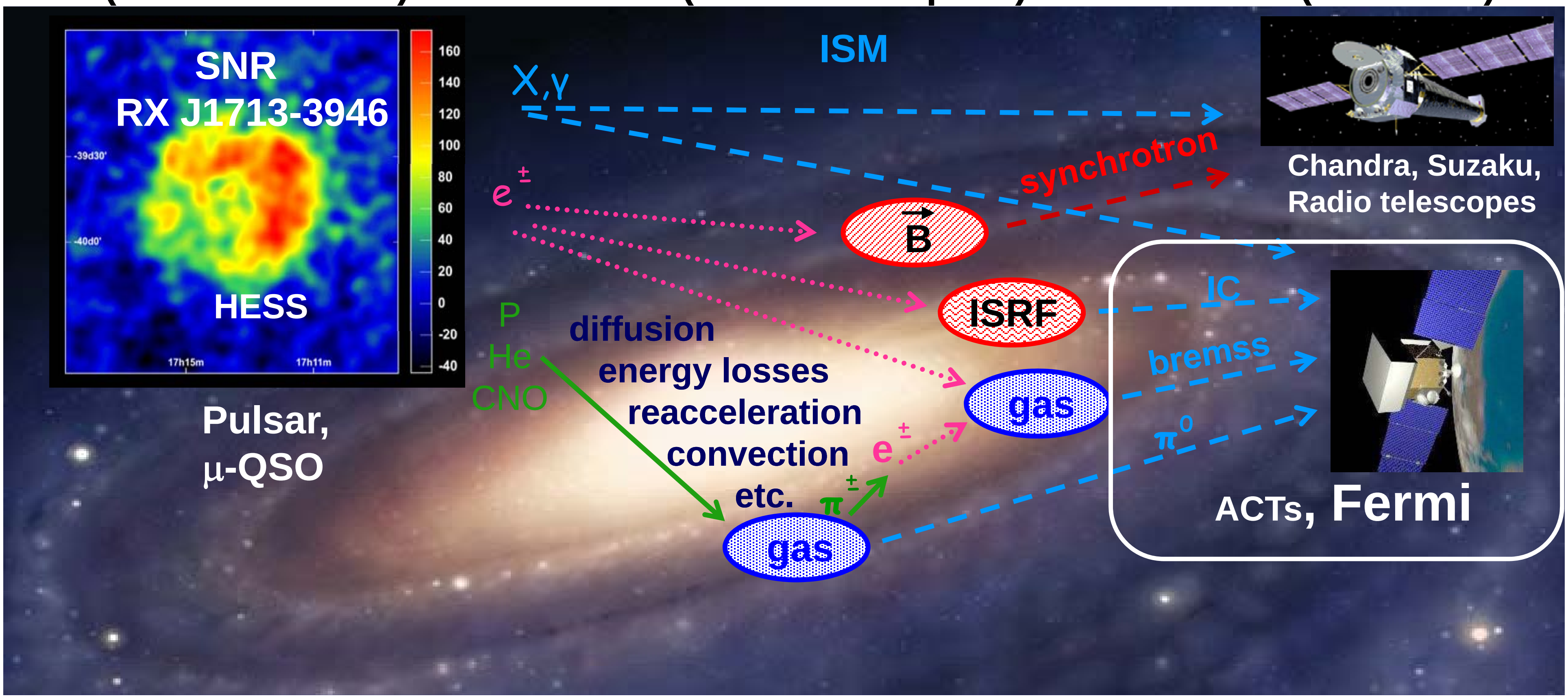
- Different measurements provide complementary information of the origin, acceleration and propagation of cosmic rays
  - All available data must be interpreted in a coherent scenario

Study nearby sources (astrophysical or exotic)

Introduction (2):
What Can We Learn from Galactic Diffuse Gamma-Rays?

HE γ-rays are produced via interactions between Galactic cosmic-rays (CRs) and the interstellar medium (or interstellar radiation field)

(CR Accelerator) (Interstellar space) (Observer)

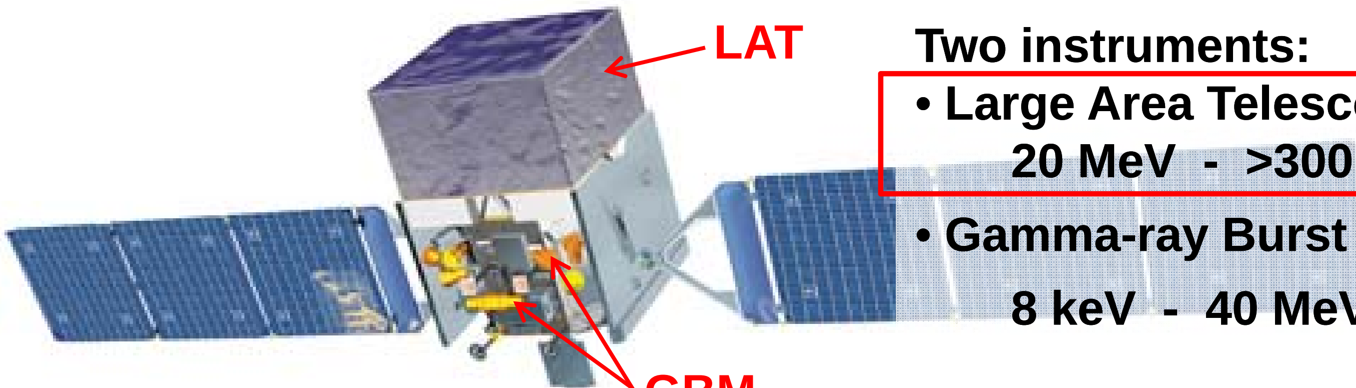


A powerful probe to study CRs in distant locations

Fermi Launch

- Launched from Cape Canaveral Air Station on June 11, 2008
- Science Operation on Aug 4, 2009
- Orbit: 565 km, 26.5^{o} (low BG)

Fermi Gamma-ray Space Telescope



Two instruments:

- Large Area Telescope (LAT)
  20 MeV - >300 GeV
- Gamma-ray Burst Monitor (GBM)
  8 keV - 40 MeV

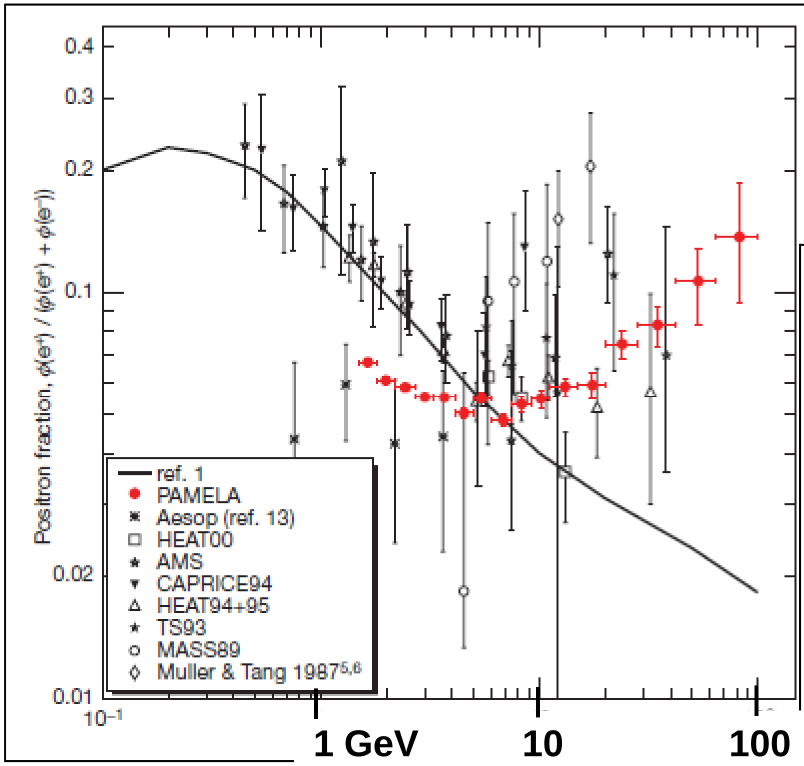
Fermi-LAT consists of three subsystems

- ACD: segmented plastic scintillators
  - BG rejection
- Tracker: Si-strip detectors & W converters
  - ~1.5 R.L. (vertical)
  - Identification and direction measurement of γ-rays
- Calorimeter: hodoscopic CsI scintillators
  - ~8.5 R.L. (vertical)
  - Energy measurement
  - Also serves as an Imaging Calorimeter

Ideal for the direct and indirect (through γ-ray obs.) measurement of CRs

Fermi-LAT Results (1): Direct Measurements of Galactic CR Electrons

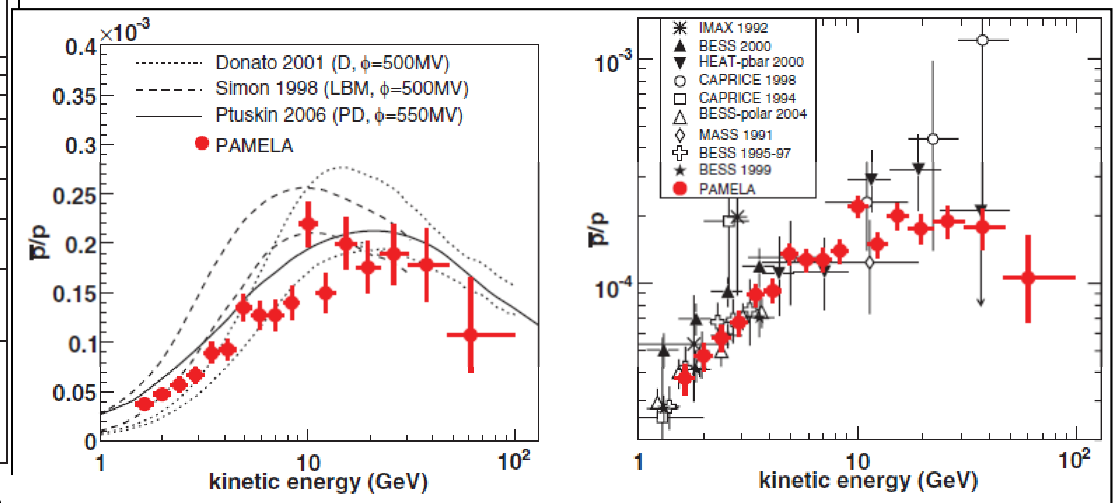
Quick Review of Positron and Antiproton Fraction: 2008-09



PAMELA positron and antiproton

Nature 458, 607 (2009)

PRL 102, 051101 (2009)



- **Antiproton fraction consistent with secondary production**
- **<u>Anomalous rise in the positron fraction</u> above 10 GeV**
- **Several different viable interpretations (>200 papers over the last year)**

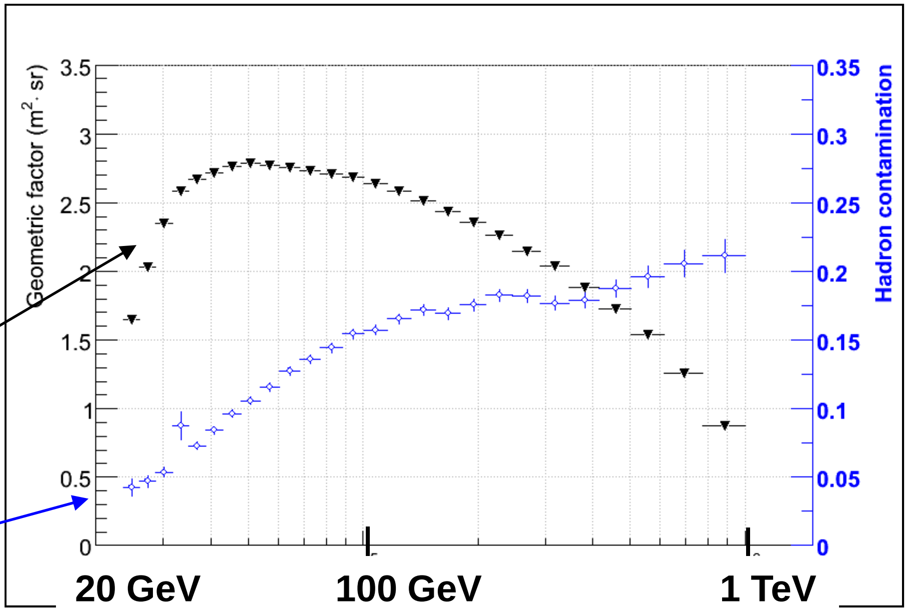
See also Nature 456, 362 (2008) and PRL 101, 261104 (2008) for pre-Fermi CRE spectrum by ATIC and HESS.

Fermi-LAT Capability for CR Electrons

- Candidate electrons pass through 12.5 X_0 on average (Tracker and Calorimeter added together)
- Simulated residual hadron contamination (5-21% increasing with the energy) is deducted from resulting flux of electron candidates
- Effective geometric factor (G_f) exceeds 2.5 [m^2 sr] for 30 GeV to 200 GeV, and decreases to ~1 [m^2 sr] at 1 TeV. G_f times live time has already reached several x 10^7 [m^2 sr s]. <u>(very high statistics)</u>
- Full power of all LAT subsystems is in use: Tracker, Calorimeter and ACD act together

Geometric Factor (G_f)

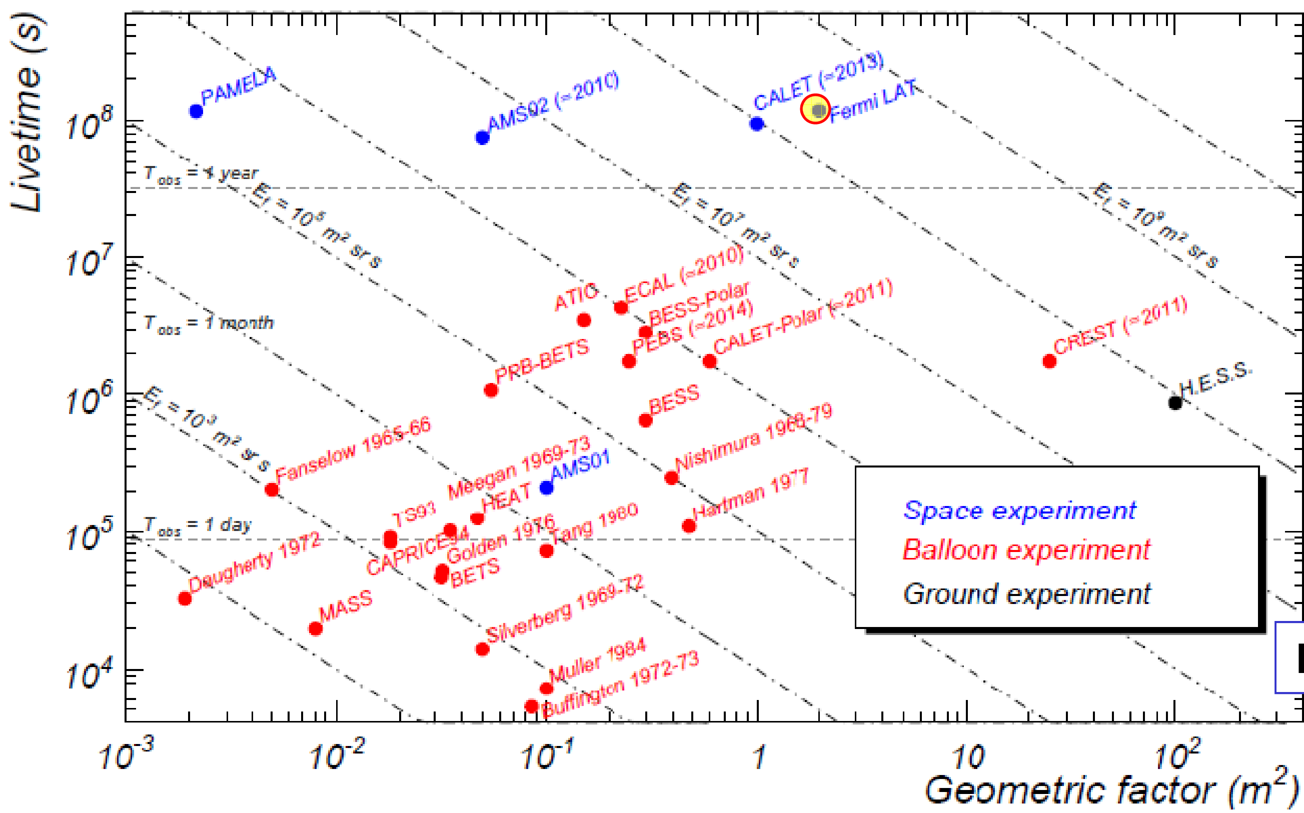
Residual hadron contamination



FOM for CRE Measurement

Exposure factor (effectively) determines the # of counts

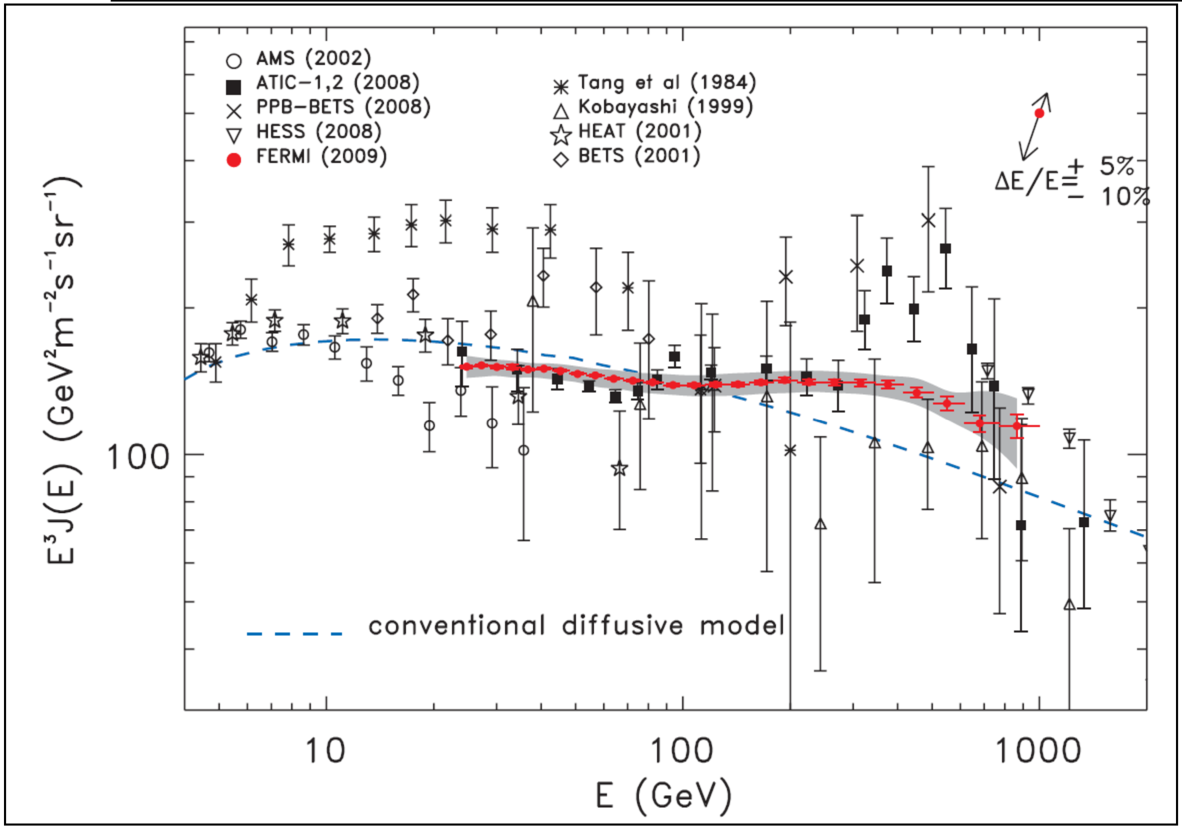
$$E_f(E) = G_f(E)*T_{obs}$$



L. Baldini

- The exposure factor determines the statistics
- <u>Imaging calorimeters</u> (vs. spectrometers) feature larger Gf
- <u>Space</u> (vs. balloon) experiments feature longer T_{obs}

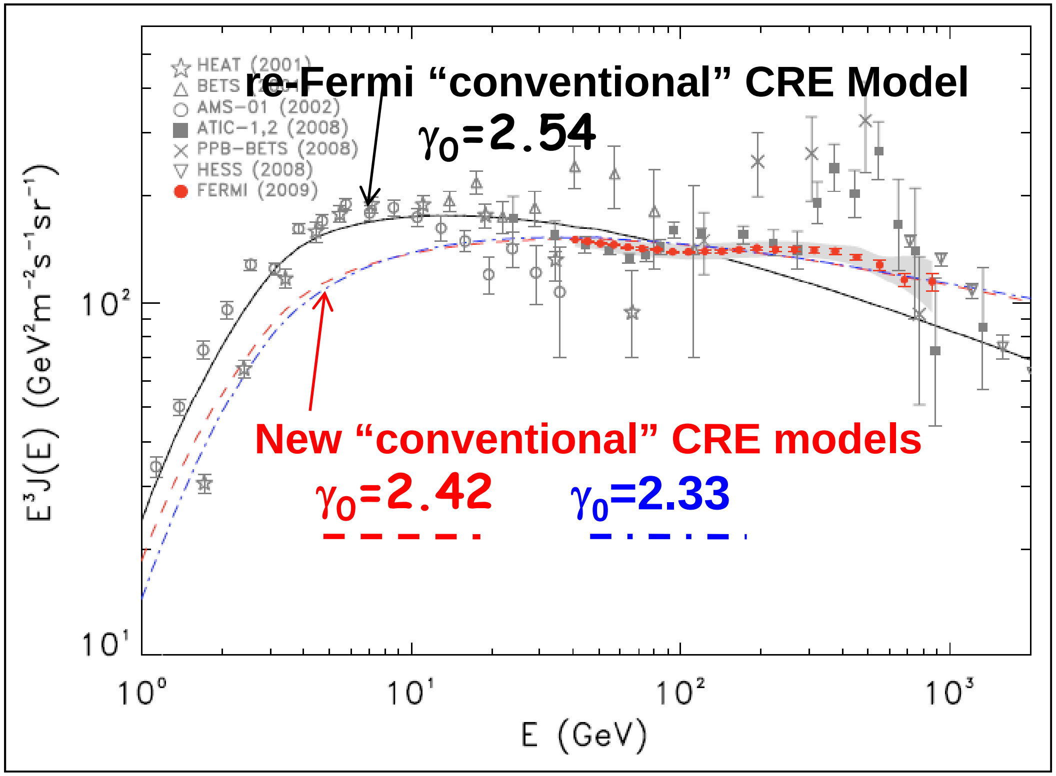
Fermi-LAT Electron Spectrum



- Abdo et al. Phys. Rev. Let. 102, 181101 (2009)
- statistics for 6 month data
  - >4 million electrons above 20 GeV
  - >400 electrons in the last energy bin
- Harder spectrum (spectral index: -3.04) than previously thought

- Pre-Fermi reference model (GALPROP conventional model): ----------
  - conventional source distribution (uniformly distributed distant sources)
  - source PL index: γ_0=2.54
  - diffusion coefficient index: δ=0.33

Implication from Fermi-LAT CRE (1)



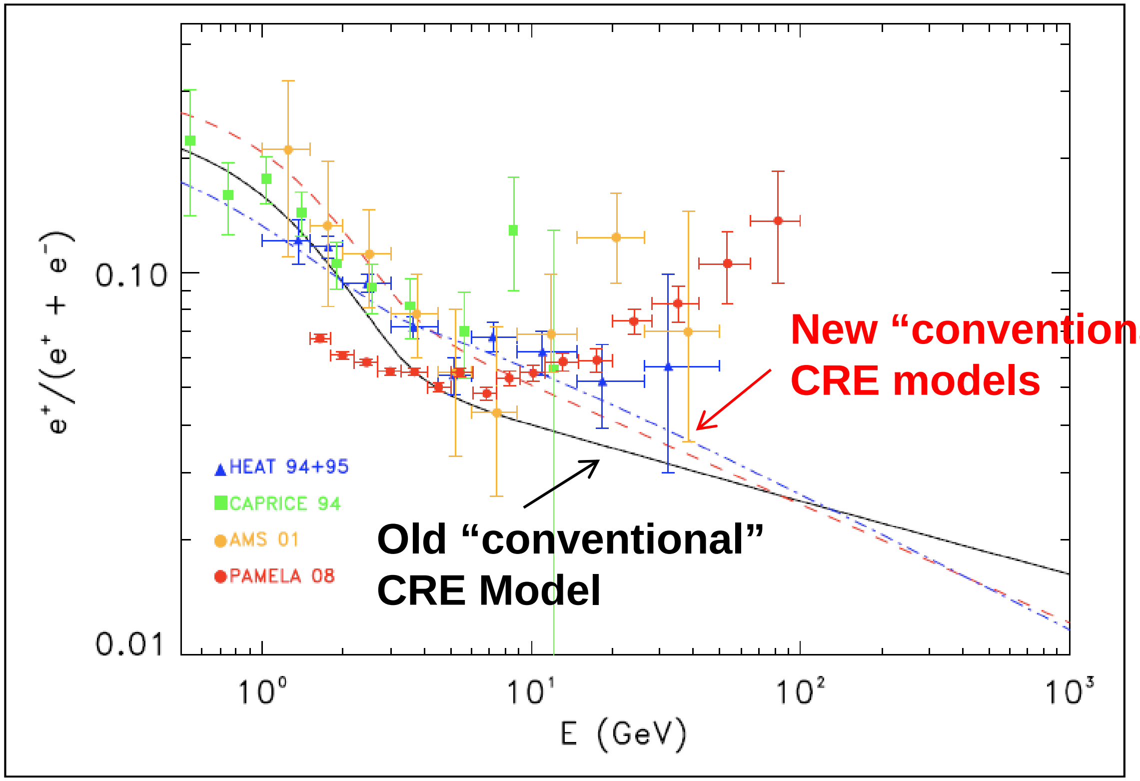
- for detail, see D. Grasso et al. arXiv:0905.0636 (accepted by Astroparticle Physics)

- New "conventional" model
  - γ_0=2.42 (δ=0.33, w/ reacceleration)
  - γ_0=2.33 (δ=0.6, plain diffusion)

- Fermi CRE spectrum can be reproduced by the "conventional" model <u>with harder injection spectral index</u> (-2.42) than in a pre-Fermi conventional model (-2.54), <u>within our current uncertainties</u> both statistical and systematic.

Implication from Fermi-LAT CRE (2)

- Now include recent PAMELA result on positron fraction



- If the secondary positrons only
  - $e^+/(e^- + e^+) \sim E\^(-\gamma_P+\gamma_0)$, $\gamma_P \sim 2.7$ (proton spectral index)
  - The hard $e^+ + e^-$ spectrum found by Fermi-LAT <u>sharpens the anomaly</u>

Implication from Fermi-LAT CRE (3)

- **It is becoming clear that we are dealing with at least 3 distinct origins of HE e^-/e^+**
  - **Uniformly distributed distant sources, likely SNRs.**
  - **Unavoidable e^+e^- production by CRs and the ISM**

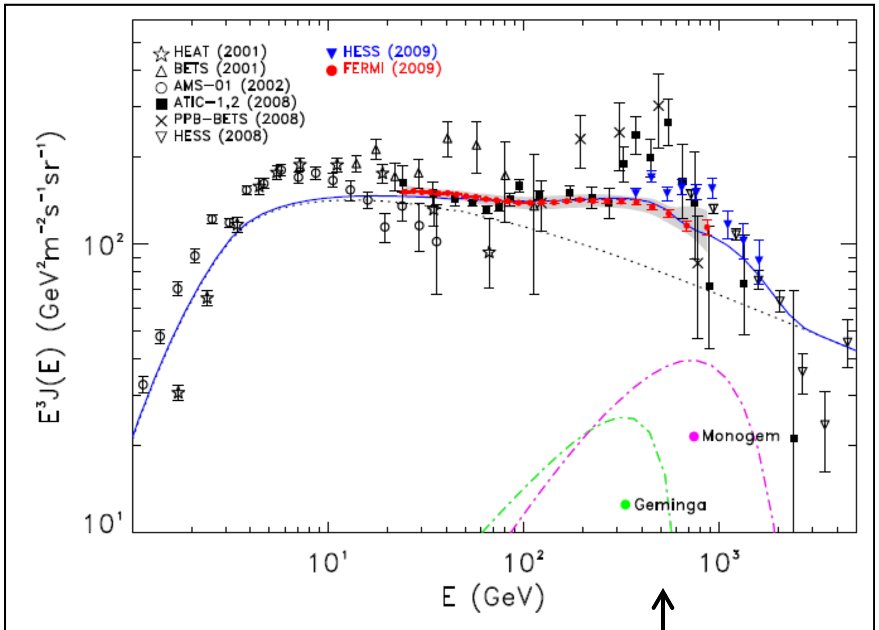
  "conventional" sources

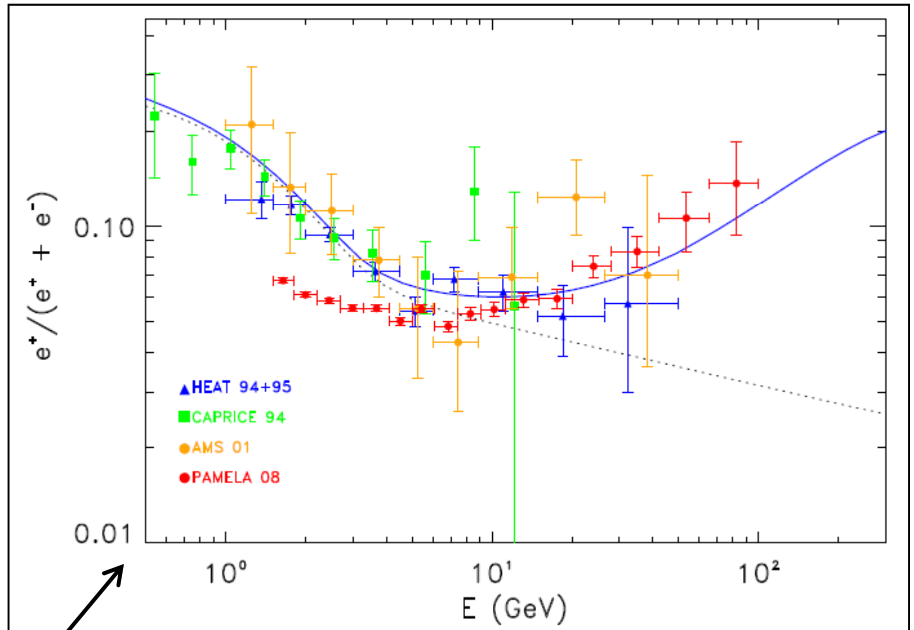
  - **<u>And those that create positron excess at high energies</u>. Nearby (d<1 kpc) and Mature (10^4 - 10^6 yr) pulsars? DM?**

- **Energy source: rotation energy of the NS**
- **Electron and positrons are re-accelerated at the pulsar wind/shock with a power law spectrum with index <u>Γ~1.5</u>**
- **e^-/e^+ are expected to be confined until T~10-100 kyr after the birth of pulsar. Only mature (10<T<1000 kyr) pulsars are expected to be relevant**
- **E_{cut}~10^3 TeV for young PWN. It is expected to decrease with the pulsar age (<u>E_{cut}~0.1-10 TeV</u> for mature pulsars)**

- **Fermi data requires an e-/e+ injection spectrum significantly harder than generally expected for shell-type SNRs**

Pulsar Scenario





• An example of the fit to both Fermi and PAMELA data with Monogem and Geminga with a nominal choice for the e+/e- injection parameter (blue lines).

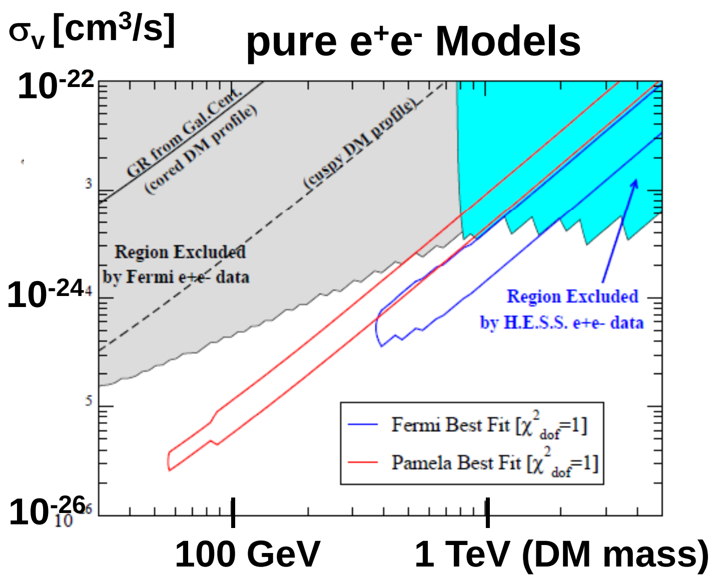
This particular model assumes:

- 40% e^-/e^+ conversion efficiency
- Γ=1.7
- E_{cut}=1 TeV
- Delay=60 kyr

(Discrepancy in positron fraction at low energies can be understood as the charge-sign effect of solar modulation)

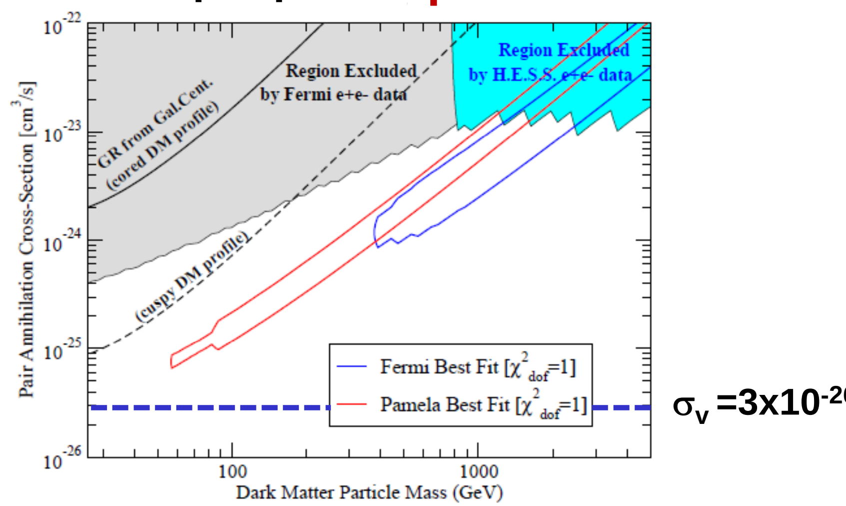
Dark Matter Interpretation

pure e^+e^- Models

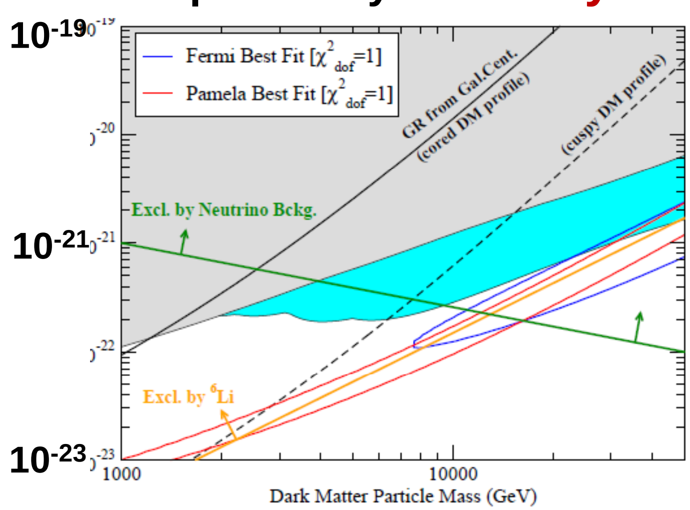


Like for the case of pulsars, <u>PAMELA and Fermi data tighten the DM constraints</u>

lepto-philic **preferred**



Super-heavy DM **likely excluded**



Model	Ann. Final State	Mass (GeV)	$\langle \sigma v \rangle$ (cm^3/s)
e^+e^-	e^+e^-	500	9×10^{-25}
Leptophilic	$33\%(e^+e^-)+33\%(\mu^+\mu^-)+33\%(\tau^+\tau^-)$	900	4.3×10^{-24}

Both in the pure e^+e^- and lepto-philic models, a DM interpretation is possible w/ boost factors of 20-100

Summary of Fermi-LAT CRE

- Real breakthrough during last 1-1.5 years in CR electrons: ATIC, HESS, PAMELA and finally Fermi-LAT
- Fermi-LAT provides precise measurements of CR e^-/e^+ spectrum in 20 GeV-1 TeV
- With the new data more puzzles than was before. Fermi-LAT's hard e^-/e^+ spectrum contradicts with PAMELA's positron fraction.
- We may be coming close to the first detection of cosmic-ray sources
- Source nature (astrophysical or exotic) is still unclear but strongly constrained by data of Fermi-LAT (+ others)
- More results from Fermi-LAT are coming. Extending energy range to 5 GeV – 2 TeV and searching for the CRE anisotropy at a level of ~1%.

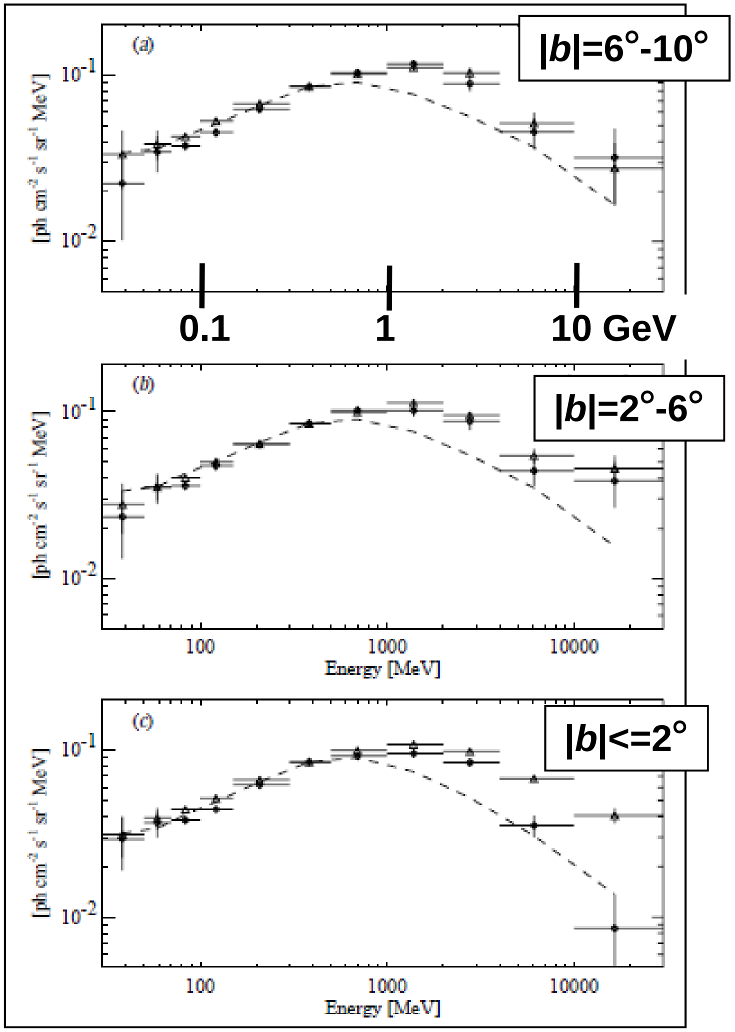
Fermi-LAT Result (2): Galactic Diffuse Gamma-ray Emission (Indirect Probe of Galactic CRs)

Outstanding Question: EGRET GeV Excess

- We can "measure" the CR spectrum in distant locations by observing diffuse γ-rays.

- EGRET observations showed excess emission > 1 GeV everywhere in the sky when compared with models based on directly measured CR spectra
- Potential explanations
  - ➢ Unexpectedly large variations in cosmic-ray spectra over Galaxy
  - ➢ Dark Matter
  - ➢ Unresolved sources (pulsars, SNRs, …)
  - ➢ Instrumental

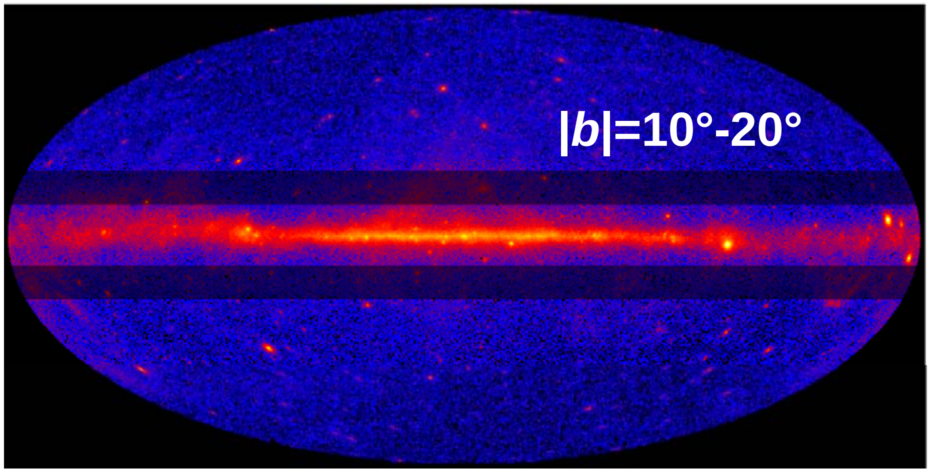
- Fermi-LAT is able to confirm or reject this phenomenon

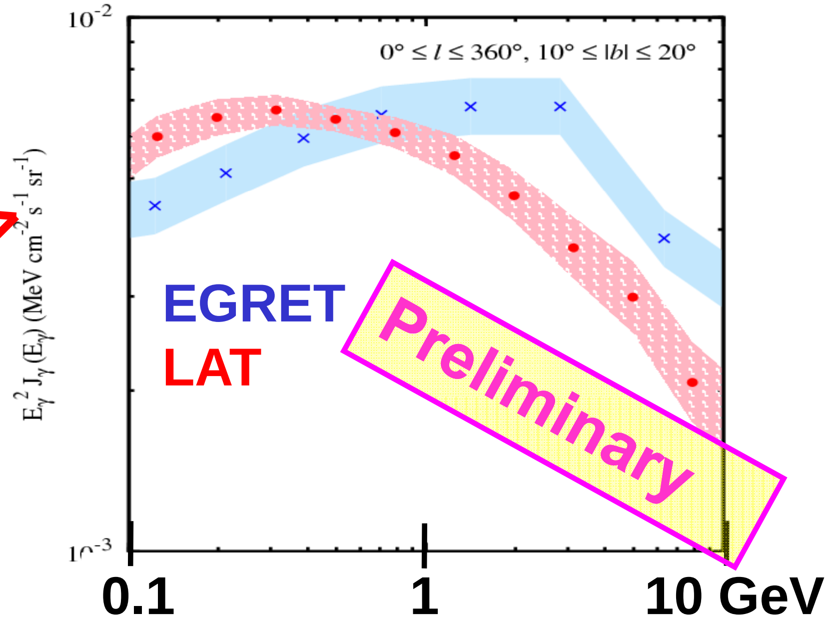


~100% difference above 1 GeV

Hunter et al. 1997

Intermediate Latitude Region seen by LAT





Abdo et al. submitted to PRL
Porter et al. 2009 (arXiv:0907.0294)

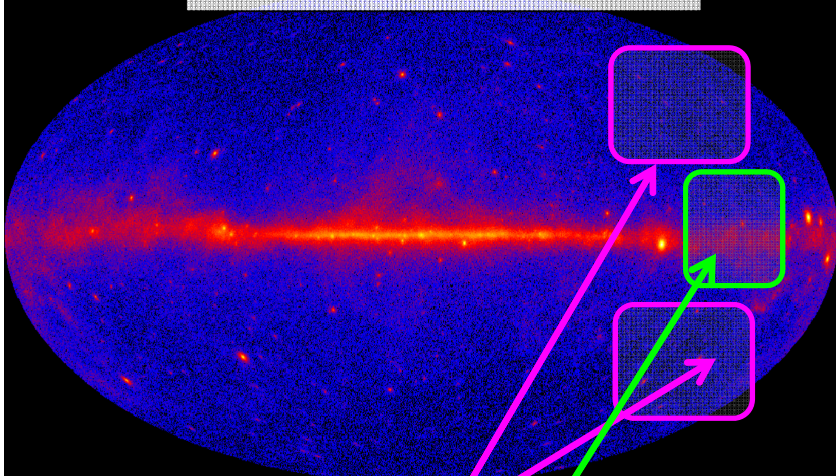
- **|*b*|=10°-20°: avoid Gal. plane but still have high statistics**
- **EGRET spectrum extracted for the same region**

- **LAT spectrum is significantly softer and does not confirm the EGRET GeV excess**
- **Strongly constrains the DM interpretation**

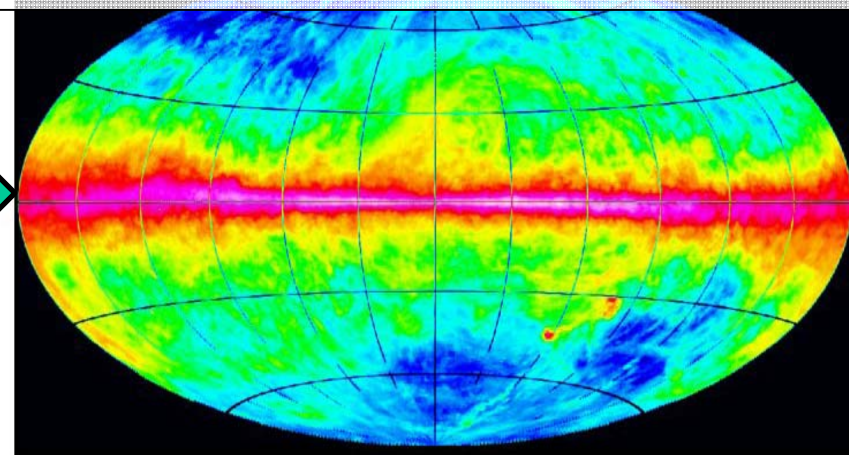
Probing CRs using Gamma-rays from ISM

- Correlation with gas column density <u>reveals the CR spectrum</u>
  - Method goes back to SAS-2/COS-B era
- Fermi-LAT's high performance + CR propagation model (e.g. GALPROP) to predict IC
  - Sensitivity significantly improved

Gamma-ray intensity (Fermi LAT data)



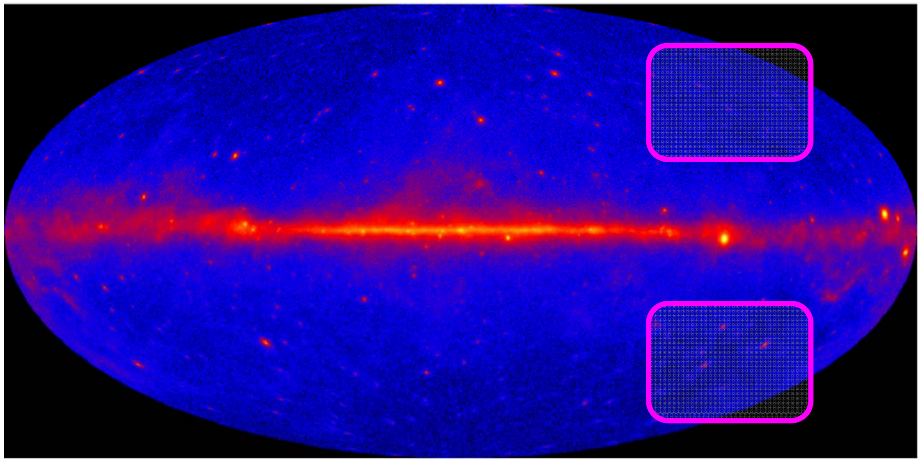
ISM (e.g., LAB HI survey)
(http://www.astro.uni-bonn.de/~webaiub/english/tools_labsurvey.php)



Mid/high latitude region:
Detailed study of local CRs (most of the gas is close to the solar system)

Galactic plane:
CR gradient in the Galaxy (need to resolve point sources)

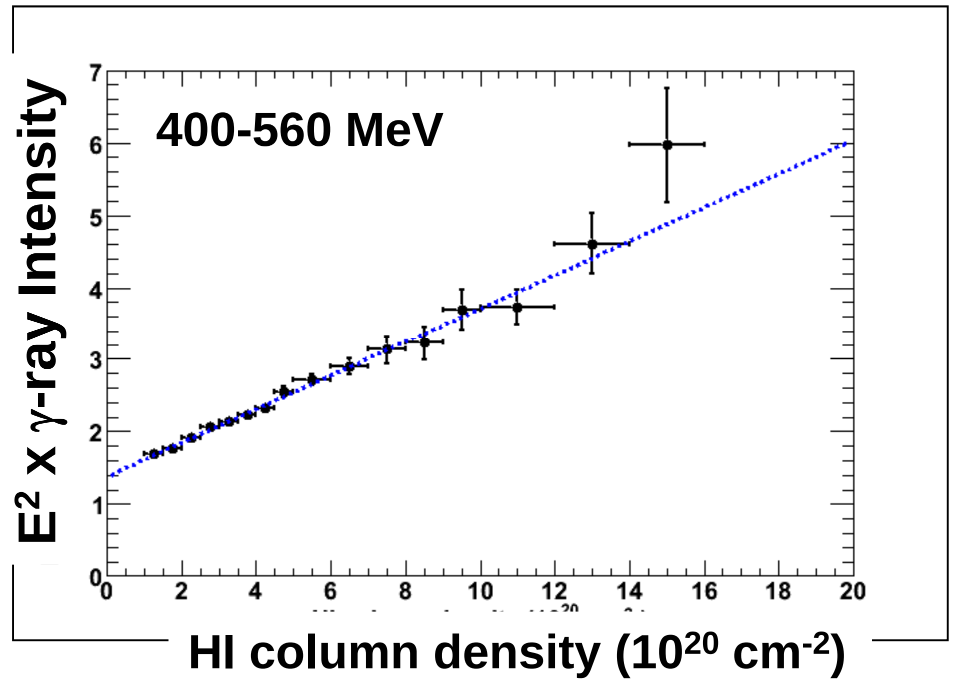
Accurate Measurements of Local CRs (1)

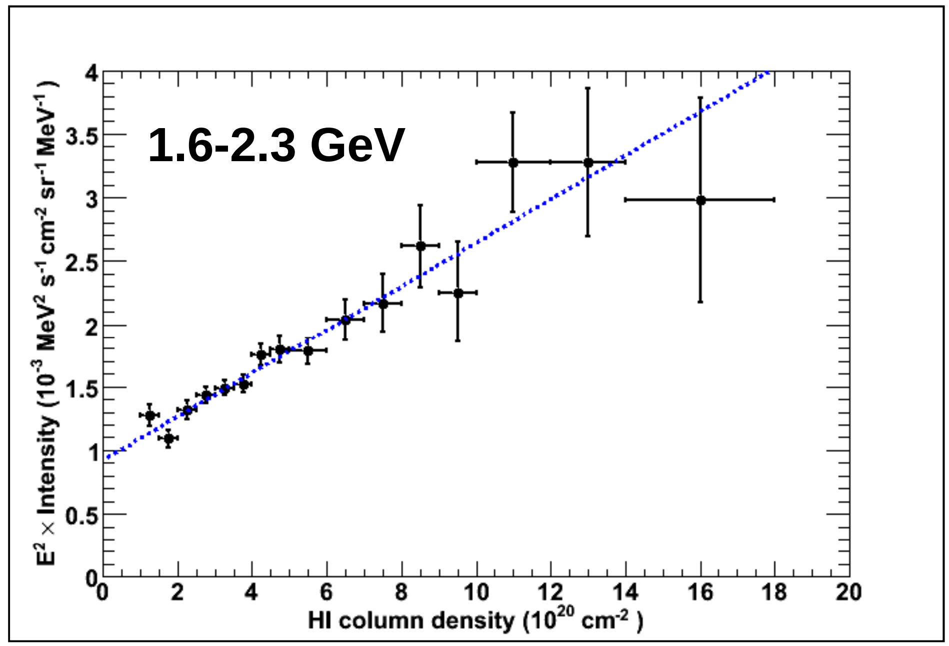


Mid-high lat. region in 3rd quadrant:

- **small contamination of IC and molecular gas**
- **correlate γ-ray intensity and HI gas column density**

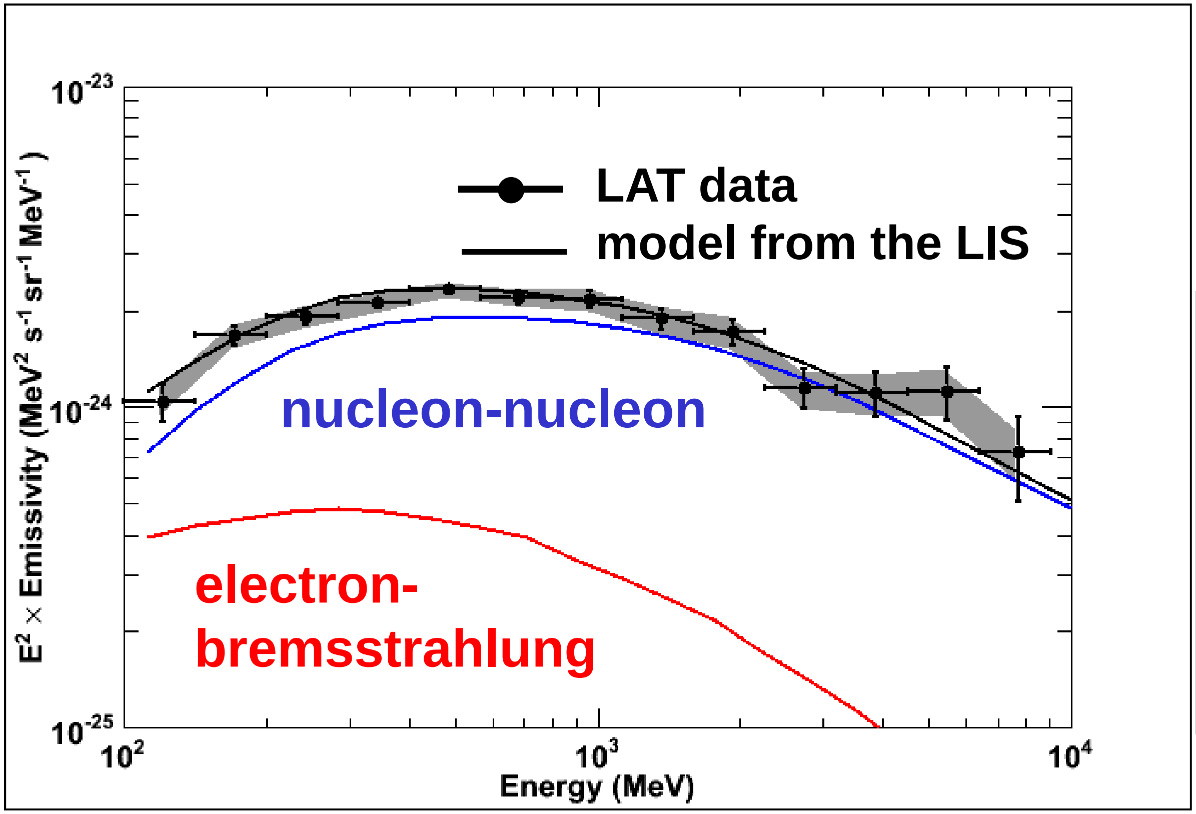
Abdo et al. 2009, accepeted by ApJ (arXiv:0908.1171) contact author: TM



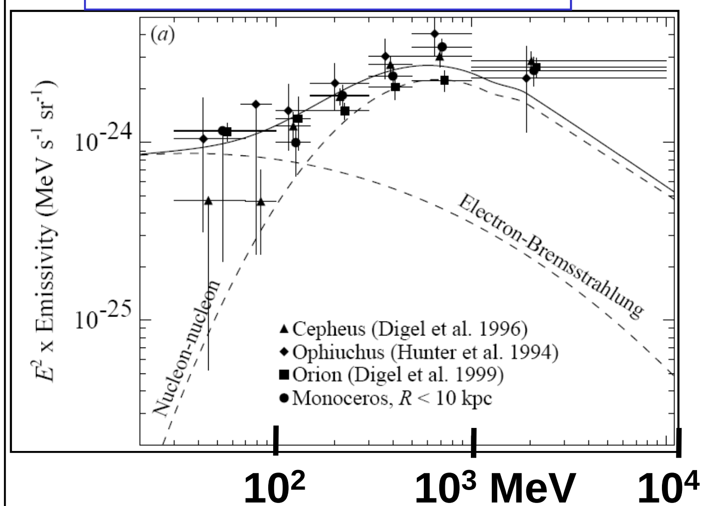


Accurate Measurement of Local CRs (2)

- Best quality γ-ray emissivity spectrum (per H-atom) in 100 MeV-10 GeV (Tp = 1-100 GeV)
- Agree with the model prediction from the local interstellar spectrum (LIS)



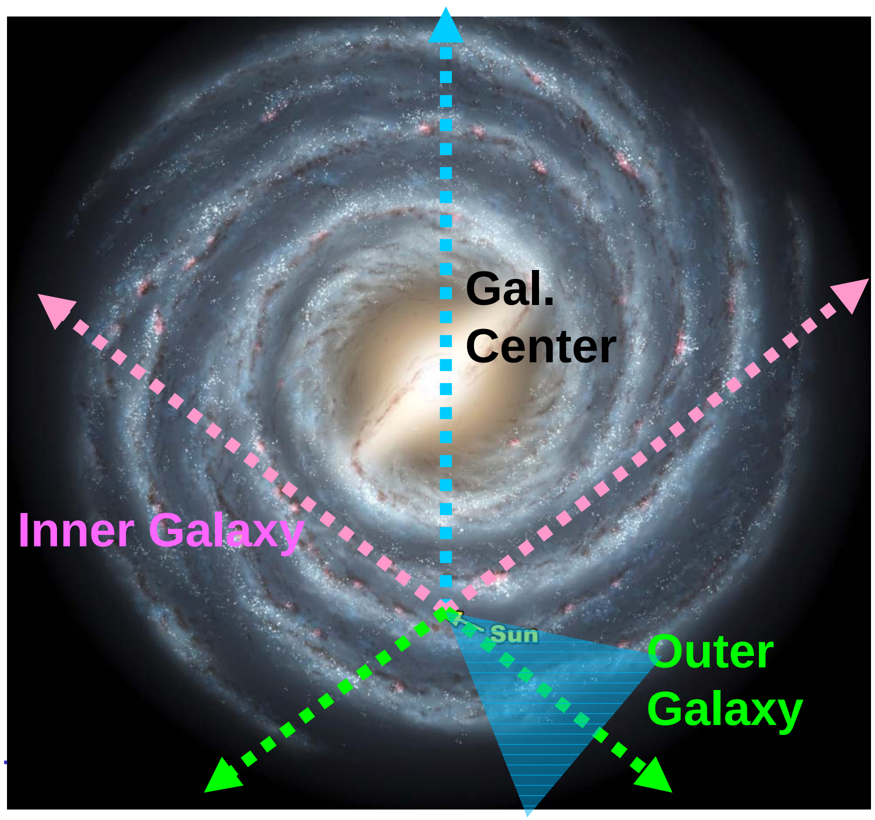
EGRET (Digel et al. 2001)

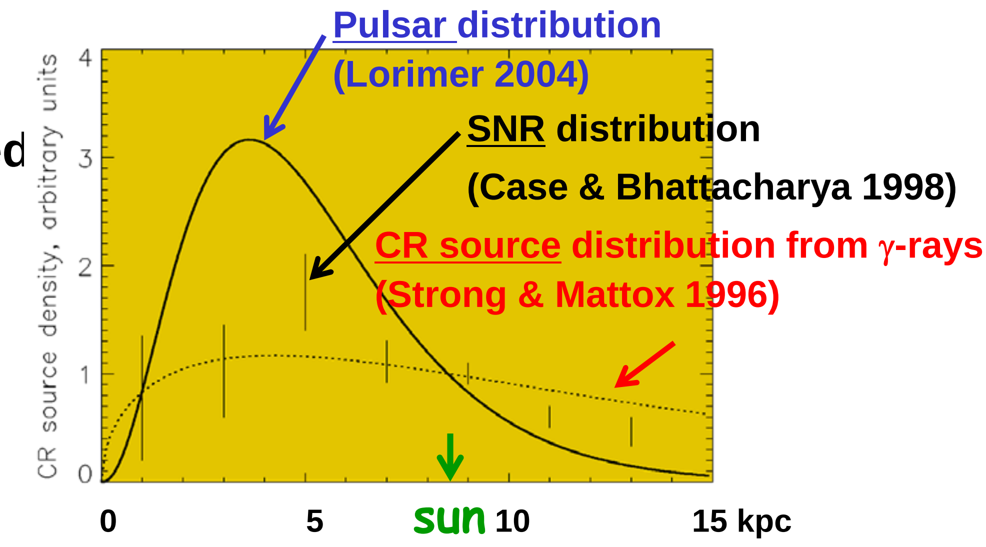


- Prove that local CR nuclei spectra are close to those directly measured at the Earth
- Eγ<100 MeV constrain the e- spectrum

CR Distribution in Galaxy

- CR distribution is a key to understand their origin and propagation
- Distribution of SNRs not well measured
- Previous Gamma-ray data suggests a flatter distribution than SNR/pulsar distributions (e.g., Strong et al. 2004)



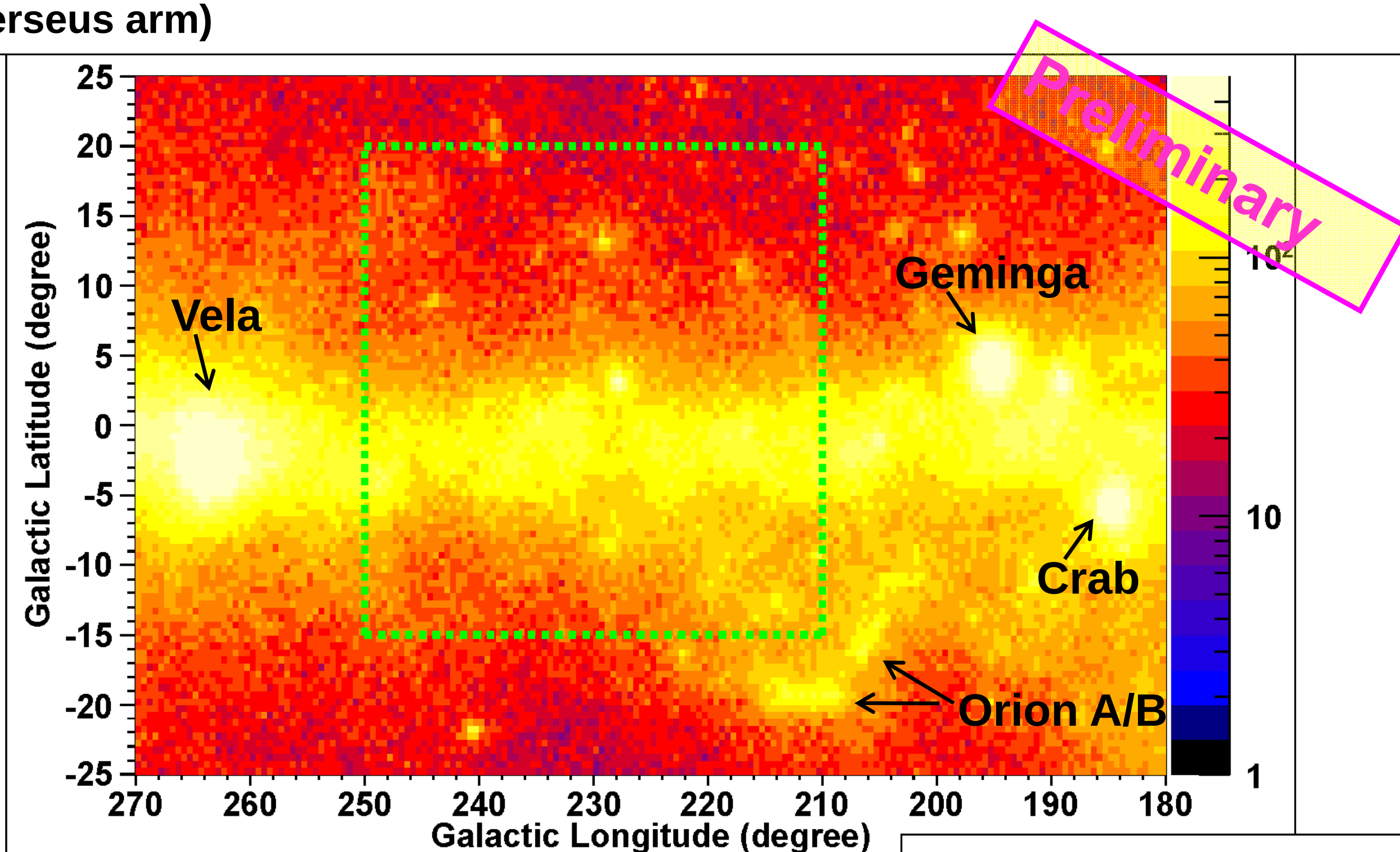


- Fermi-LAT is able to map out <u>CR distributions in the Galaxy</u> with unprecedented accuracy
- Large scale analysis in progress. (arXiv:0907.0304)

- <u>Preliminary analysis of the 3rd quadrant (outer Galaxy)</u> will be discussed. See also the relevant study of the 2nd quadrant (arXiv:0907.0312)

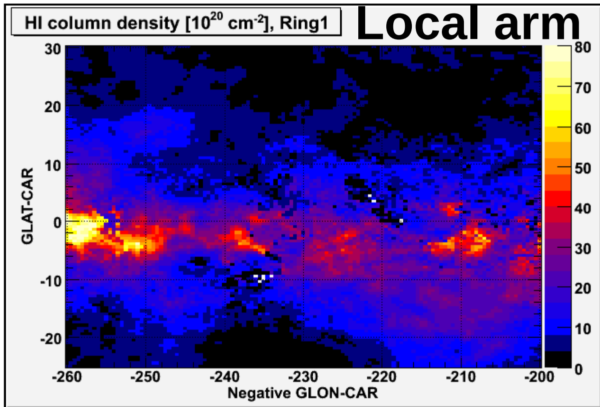
Fermi-LAT View of the 3rd Quadrant

- One of the best studied regions in γ-rays
  - ➢ Vela, Geminga, Crab and Orion A/B
- Galactic plane between Vela and Geminga (green square) is ideal to study diffuse γ-rays and CRs.
  - ➢ small point source contamination, kinematically well-separated arms (local arm and Perseus arm)



Count Map (E>100 MeV)

Construction of the Model



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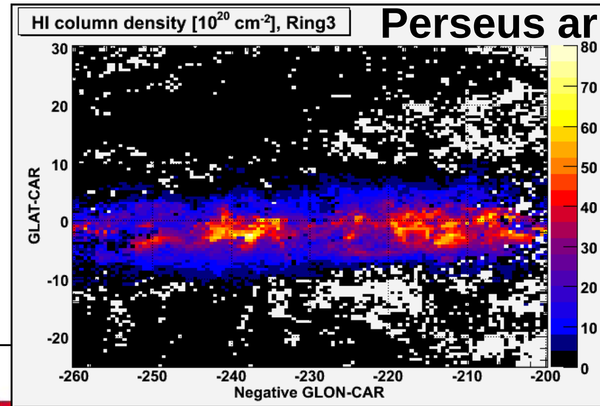
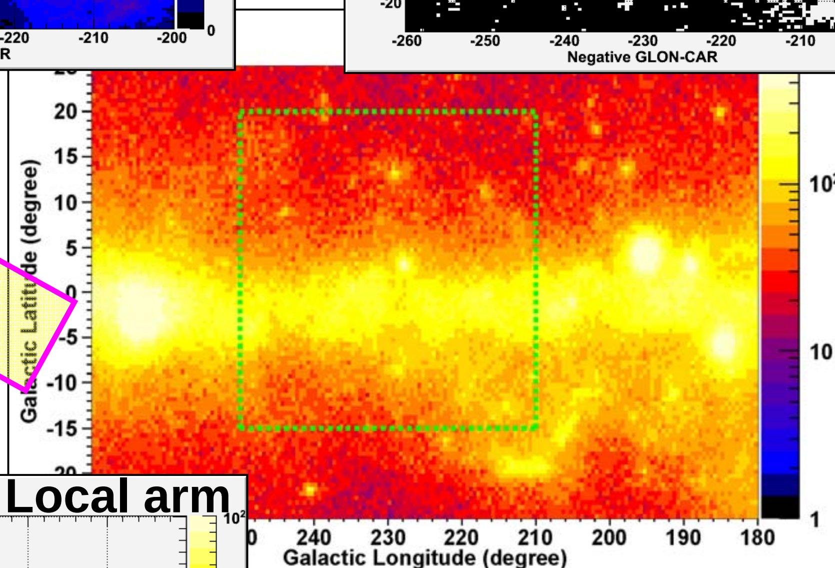
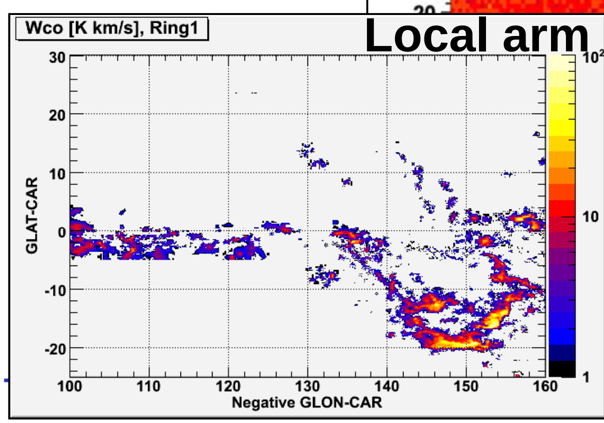


+2 HI maps
(profile fitting technique;
arXiv:0907.0312)



- Fit γ-ray data with 8 maps + 15 point sources (11 month source list)
- CR spectrum (γ-ray emissivity) is assumed to be uniform in each Galactocentric ring

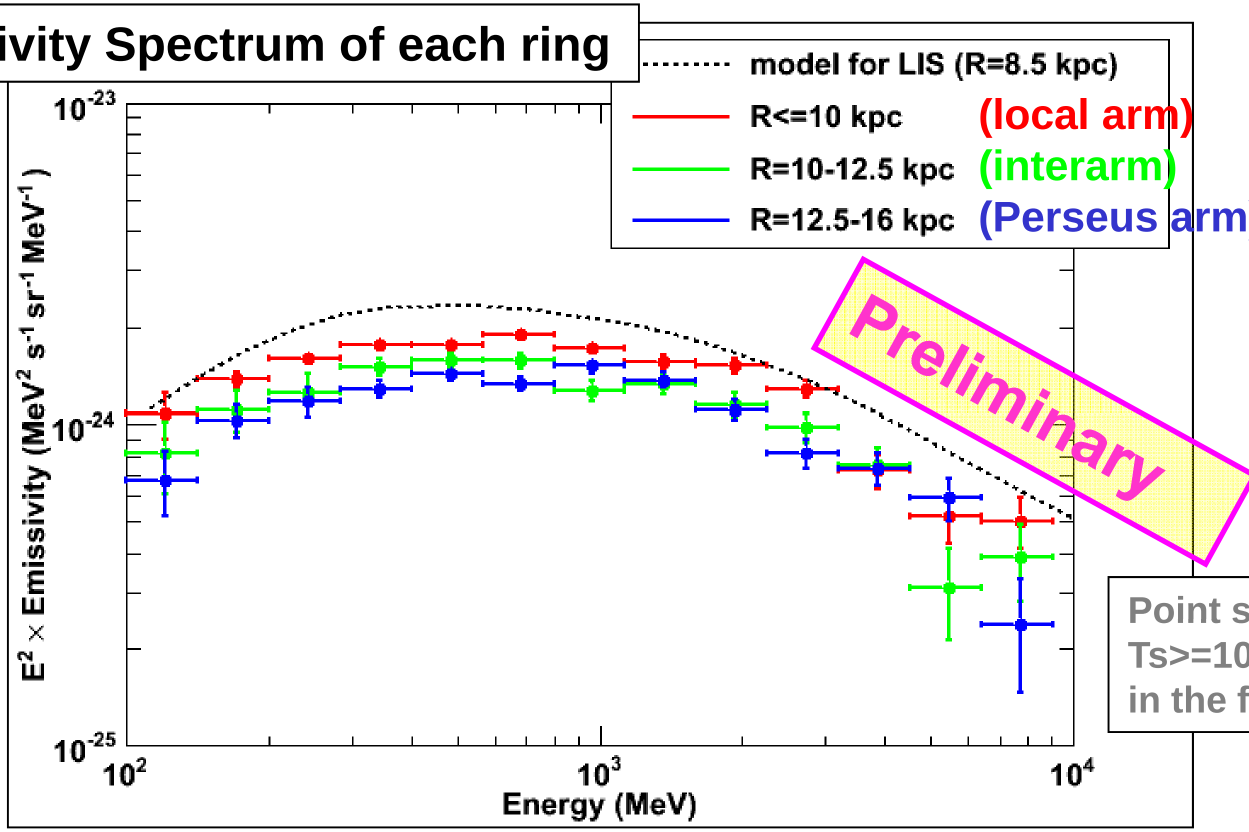


+ 1 CO map + excess E(B-V) map (Grenier et al. 2005)
+ IC map (galprop model) + point sources (11 month list)

Utilize new techniques, understanding of the ISM and power of the LAT

HI Emissivity (CR) Spectra

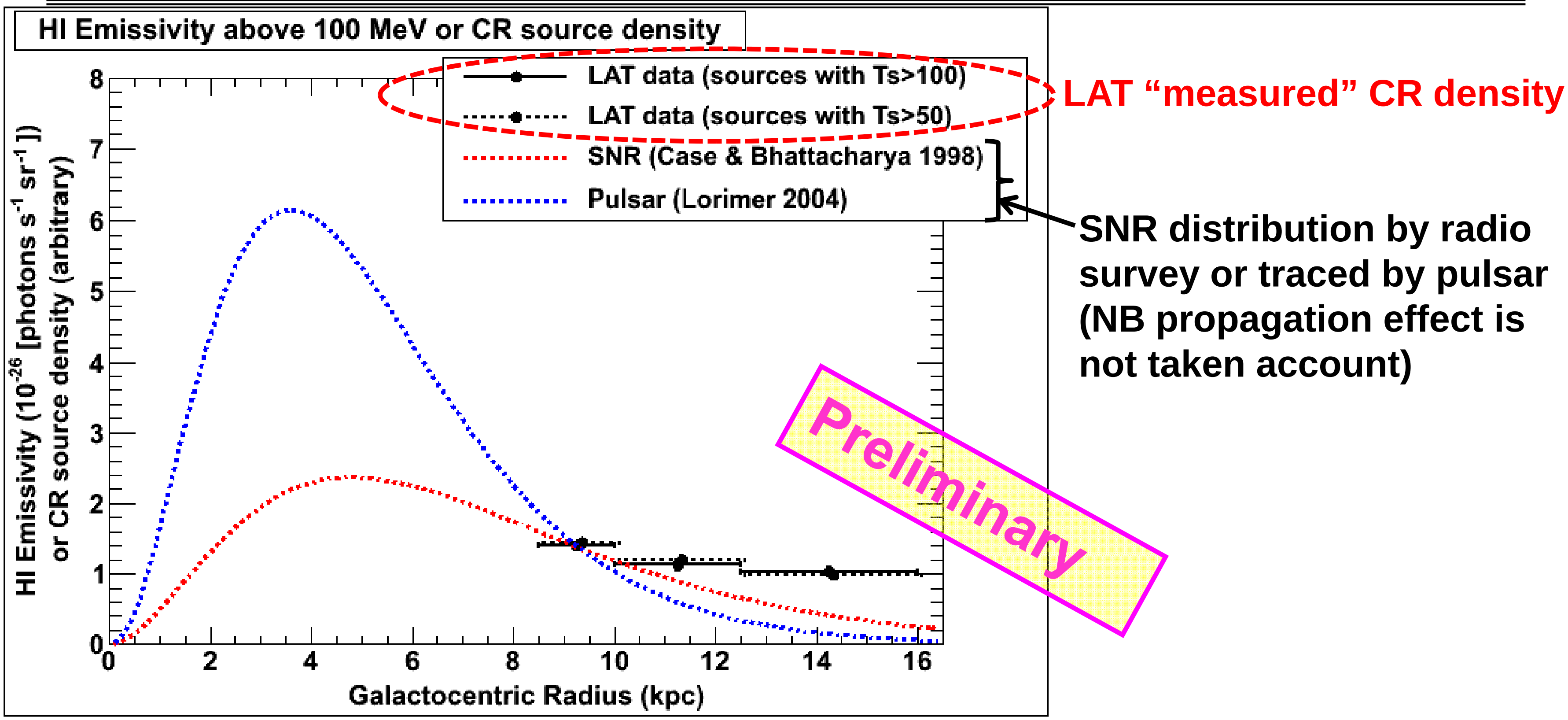
HI Emissivity Spectrum of each ring



Point sources with Ts>=100 are included in the fitting

- Emissivity (CR) spectrum of local arm (R=8.5-10 kpc) is slightly smaller than that of LIS
- Decreasing emissivity (local arm => interarm => Perseus arm) are consistent with decreasing CR density across the Galaxy
- Similar CR spectral shape up to R=16 kpc

CR Flux Distribution



- Emissivity gradient traces the CR density. Robust against the thresholds for point sources included.
- Significantly flatter than the SNR distributions
  - ➢ may indicate more CR sources than previously thought in the outer Galaxy, large halo size, etc.
- Comparison with the model prediction is in progress.

Summary

- Fermi-LAT is a powerful instrument to measure CRs either directly or indirectly

- Fermi-LAT provides largest statistics of high-energy CR e^-/e^+ spectrum.
  - Precise and hard CR electron spectrum by Fermi-LAT and PAMELA positron fraction require local sources (astrophysical or exotic)
  - Source nature is still unclear but strongly constrained.

- CRs in distant locations can be "observed" by diffuse γ-rays.
  - EGRET GeV-excess not confirmed.
  - Fermi proves that local CR nuclei spectra are close to those of LIS.
  - Flat and large CR density in the outer Galaxy is indicated.

Thank you for your attention!