Fermi-LAT Study of Cosmic-rays/Diffuse Gamma-rays and Implications on Particle Physics

Mar. 7, 2011 @ Kyoto Univ.

Tsunefumi Mizuno (Hiroshima Univ.)

On behalf of the Fermi-LAT collaboration

Fermi衛星による広がったガンマ線・宇宙線電子の観測と基礎物理への制限

2011年3月7日 @ 京都大学基礎物理研究所

水野　恒史 (広島大学理学部)

On behalf of the Fermi-LAT collaboration

Outline

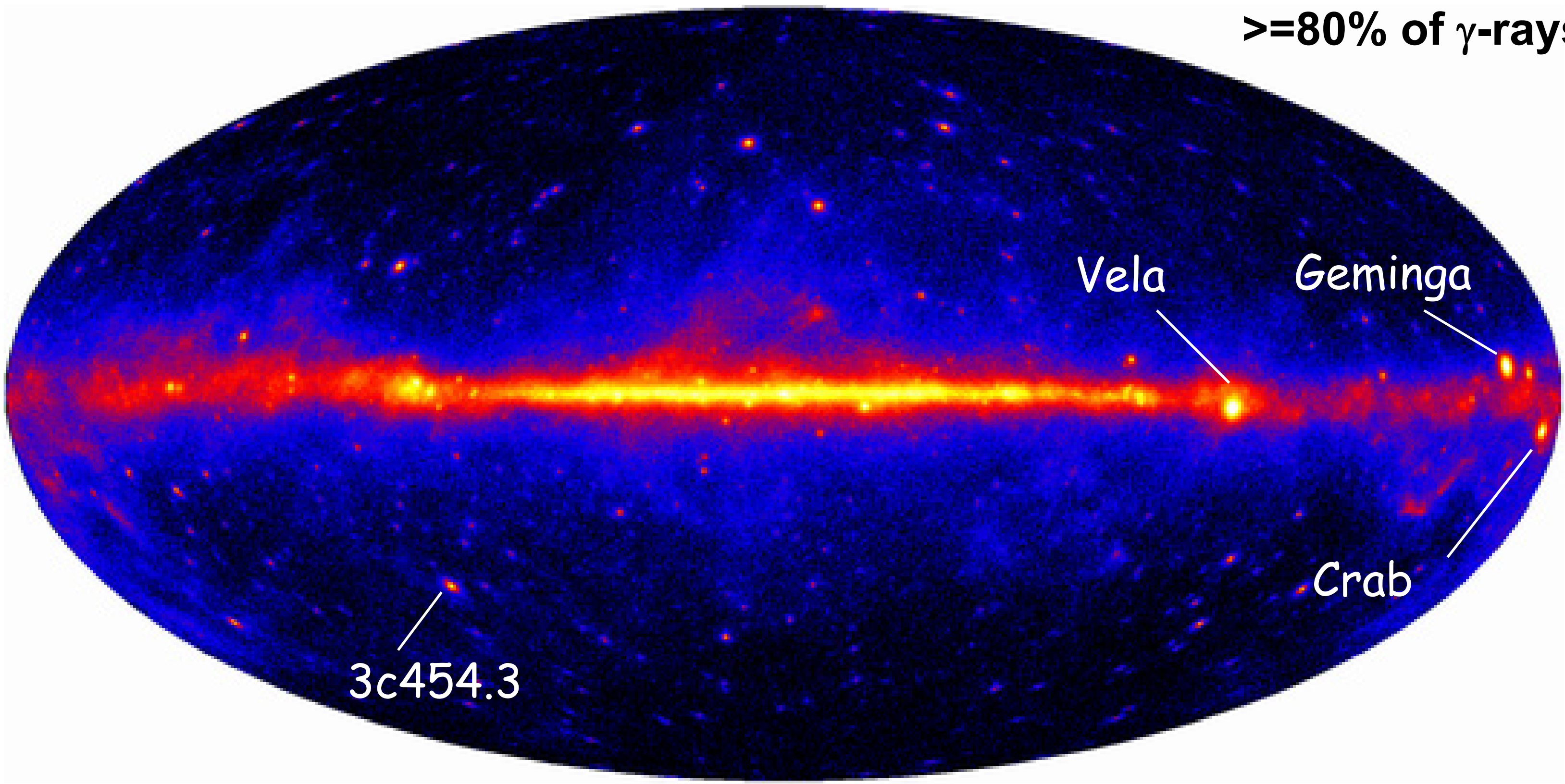
Introduction
Fermi LAT instrumentation
Galactic Diffuse Gamma-rays
Behind the diffuse γs: EGB and DM search
Cosmic-ray Electrons

Gamma-ray Sky

- GeV gamma-ray sky

  = Point sources + Diffuse Gamma-rays

>=80% of γ-rays



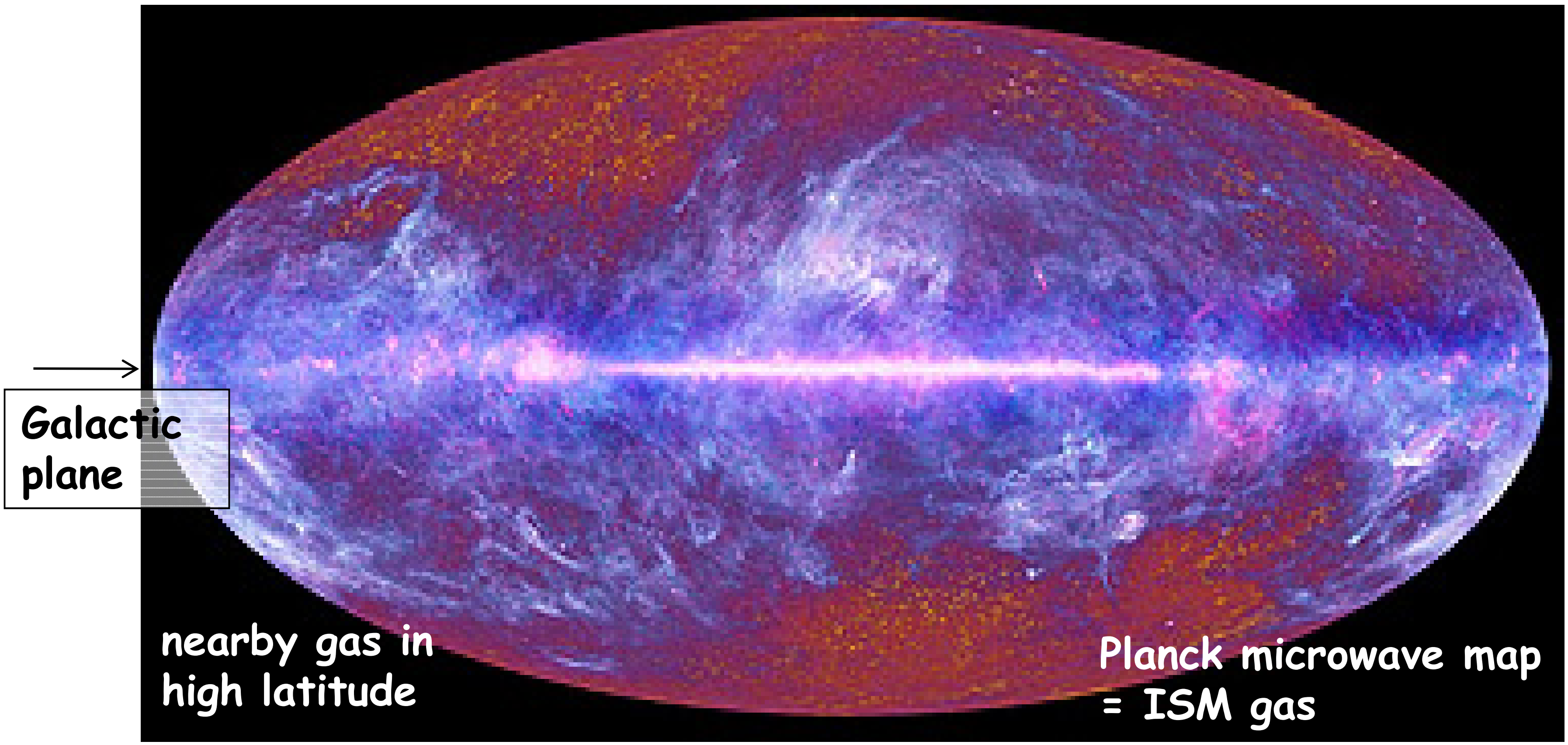
Fermi-LAT 1 year all-sky map

What makes Diffuse γ-rays?

- **Diffuse Gamma-rays**

InterStellar Medium
InterStellar Radiation Field

= Cosmic-rays x (ISM, ISRF)

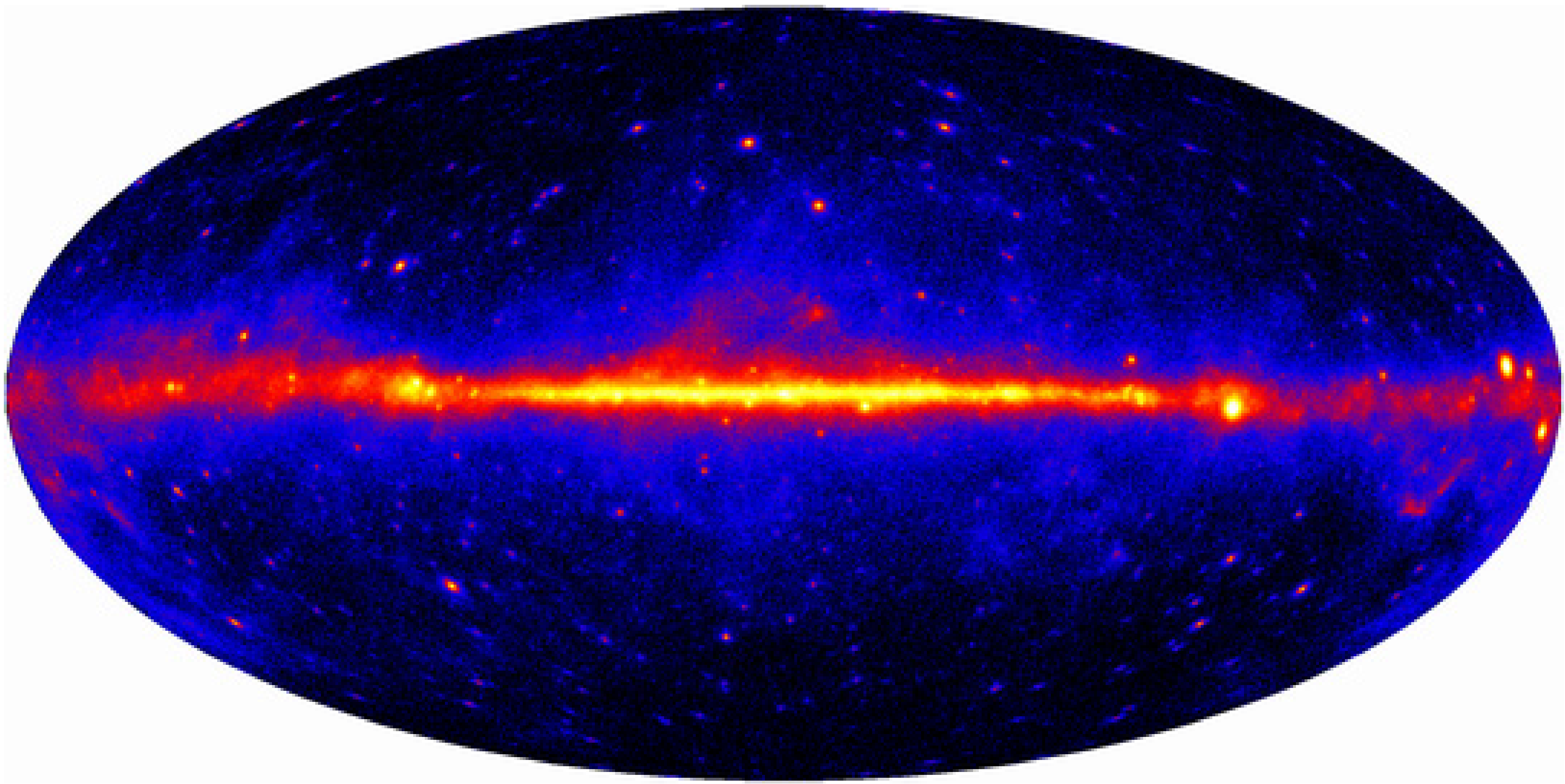


Gamma-ray Sky

- GeV gamma-ray sky

phys. processes are well understood

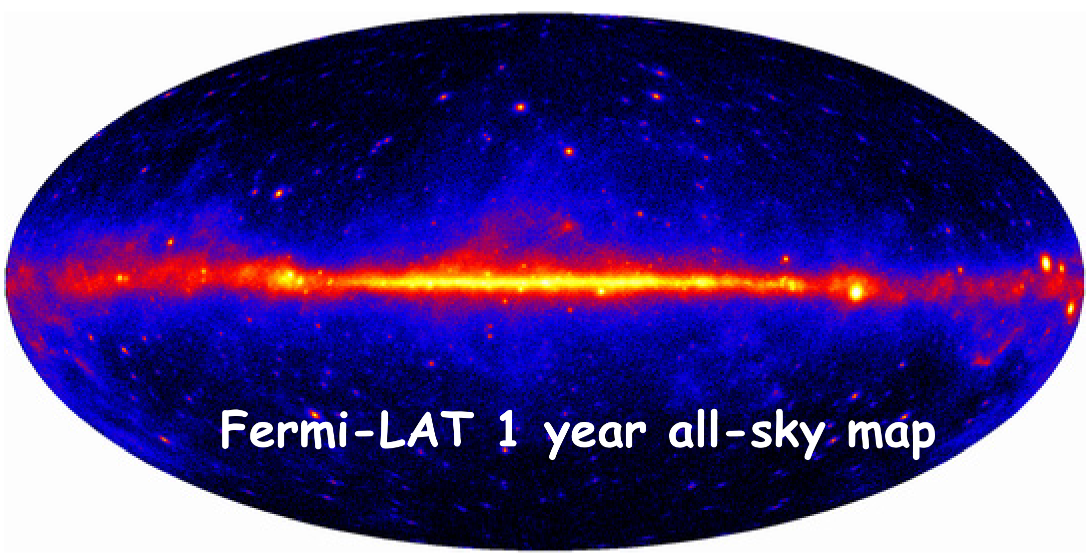
~ Diffuse Gamma-rays = CRs x (ISM, ISRF)



Fermi-LAT 1 year all-sky map

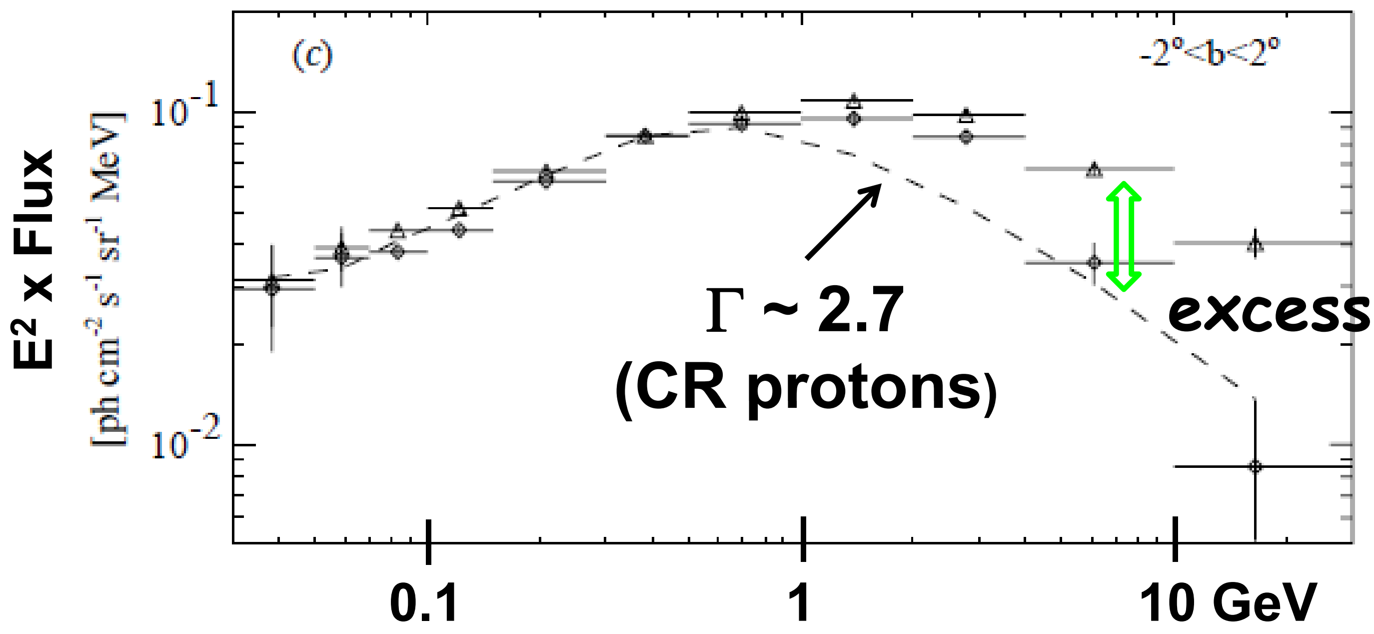
Why are they important?

- **Diffuse Gamma-rays are**
  - “probe” to study Galactic CRs and ISM
  - “foreground” to study exotic physics, e.g.,
    - signal from dark matter (DM) — annihilation or decay
    - extragalactic γ-ray background (EGB) — new source classes or DM signal



Example: GeV Excess (EGRET Era)

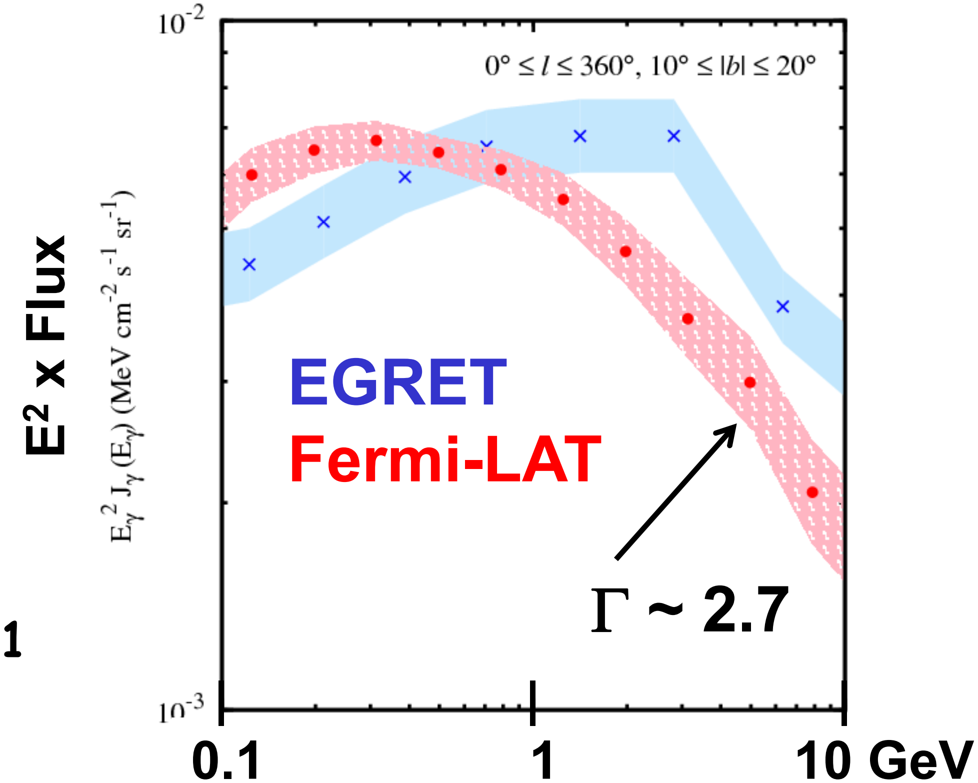
- **EGRET (1991-2000) reported excess emission when compared with a standard diffuse γ-ray model**
  - **variety of explanations including DM signal**



Hunter+97

Example: GeV Excess (Fermi Era)

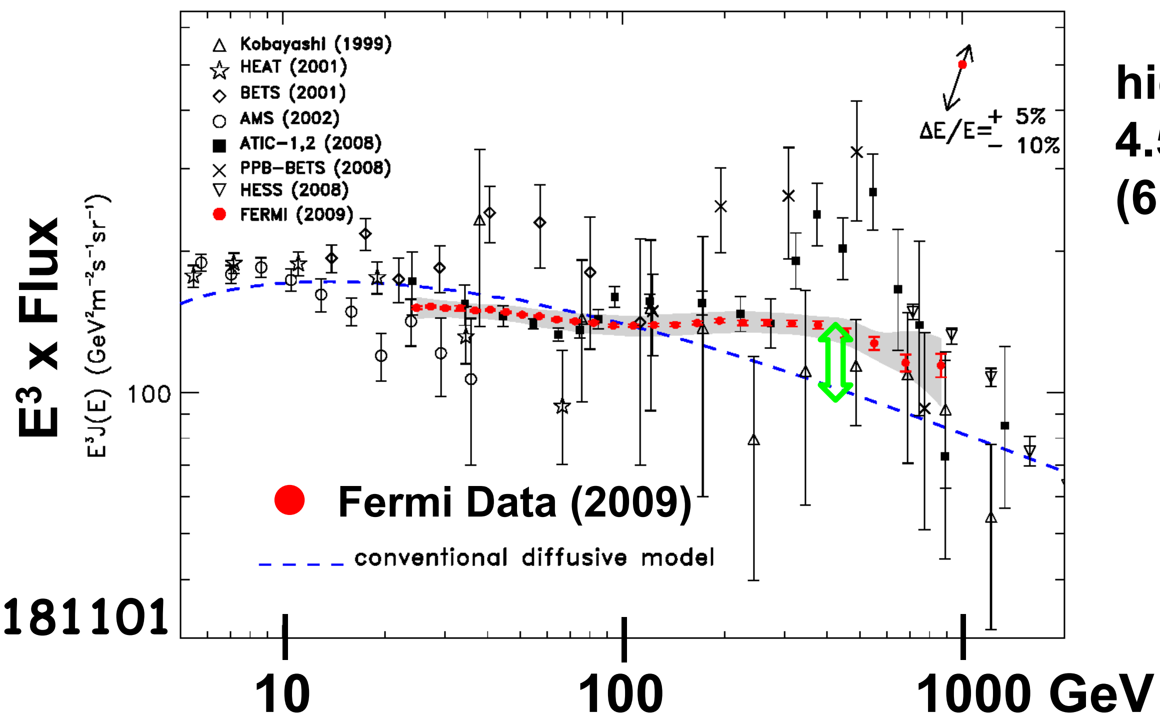
- EGRET GeV excess not confirmed.
- However, Fermi data allow us investigating more subtle "anomalies" (and detailed study of CRs/ISM)



Abdo+09
PRL 103, 251101

Fermi-LAT as Electron Detector

- **Fermi-LAT reported a harder CR e^- + e^+ spectrum compared with a conventional model**



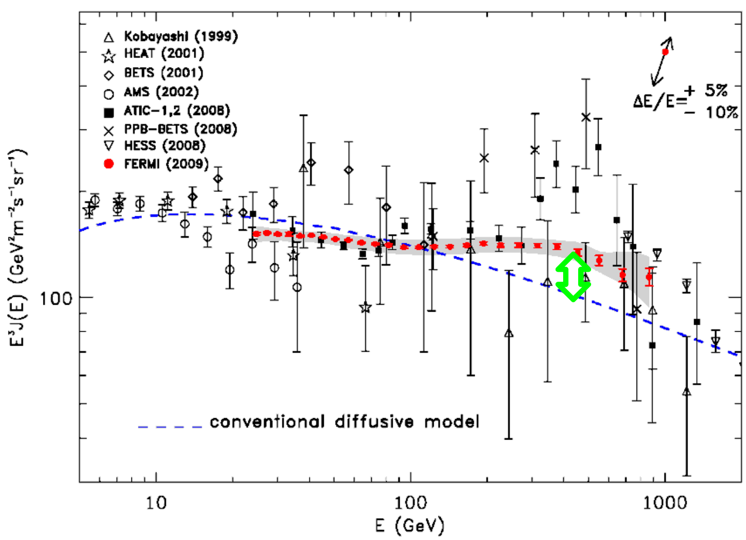
highest statistics: 4.5 M events (6 months)

Abdo+09
PRL 102, 181101

Fermi-LAT as Electron Detector

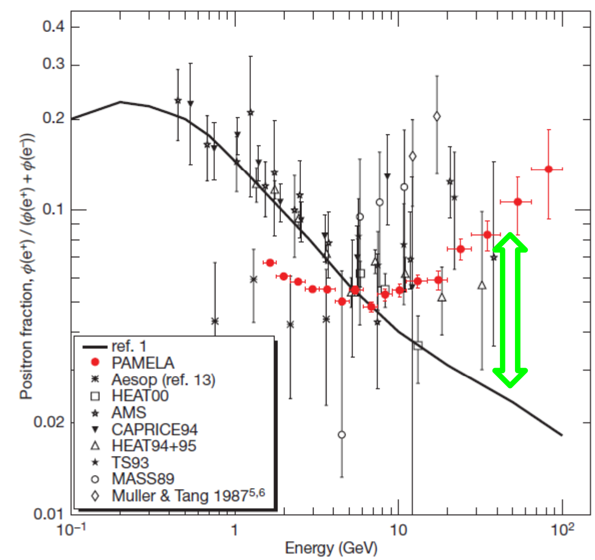
- **Fermi-LAT reported a <u>harder</u> CR e^- + e^+ spectrum compared with a conventional model**
  - **Lots of interpretations (astrophysical and exotic)**

Fermi e^- + e^+



+

PAMELA e^+ ratio



= **DM?**
Nearby objects?

Fermi-LAT as Electron Detector

- Fermi-LAT reported a harder CR $e^{-} + e^{+}$ spectrum compared with a conventional model
  - Lots of interpretations (astrophysical and exotic)

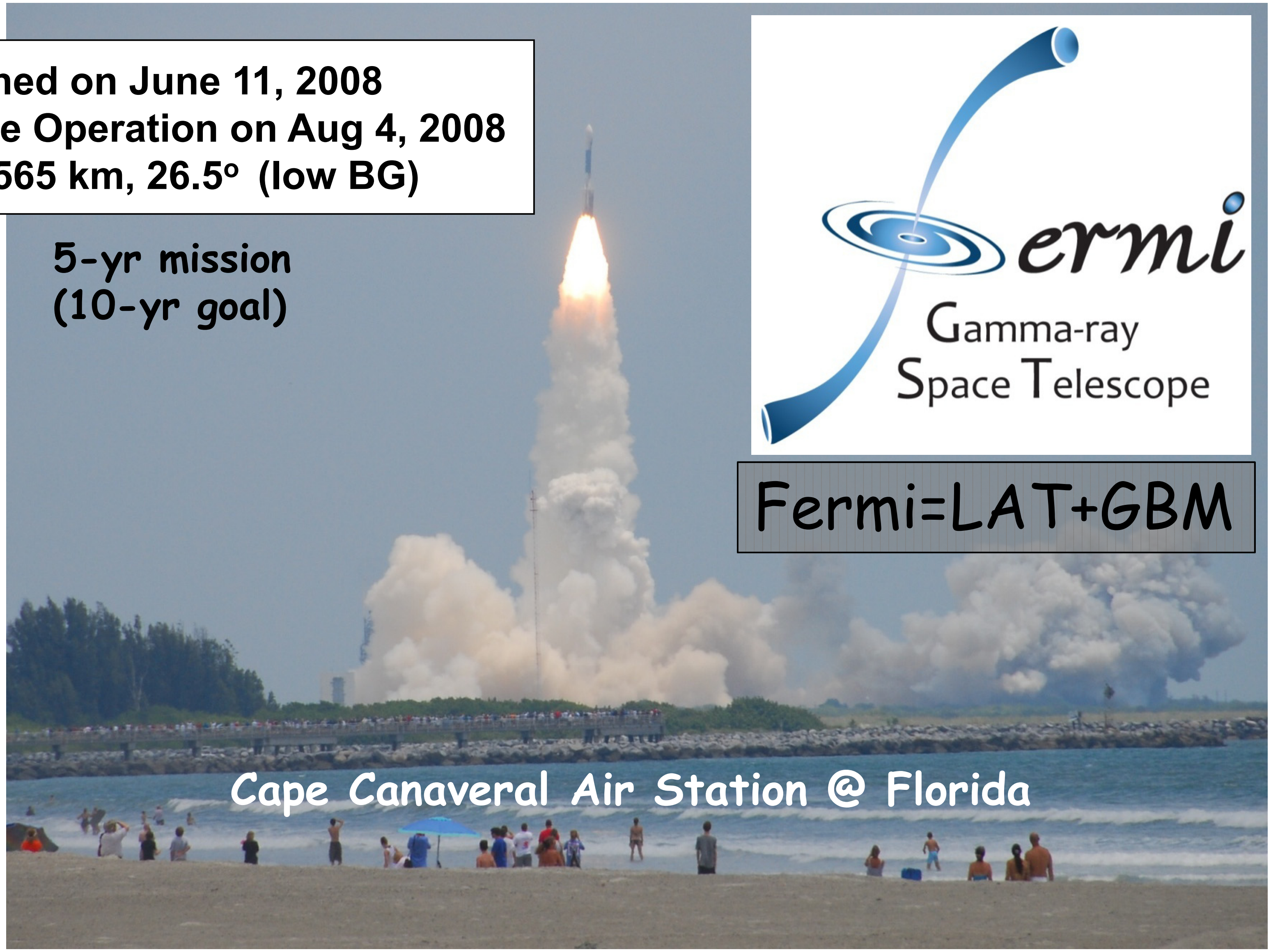
… and the paper is highly cited

- Paper citations (rankings from ADS for papers published since Jan. 2009)
  - CR electrons: 336 since May 2009 (#8)
  - LAT instrument paper: 291 since June 2009 (#13)
  - Bright Source List: 190 since July 2009 (#23)
  - LAT Bright AGN Sample: 154 since July 2009 (#36)
  - GRB 080916C: 139 since March 2009 (#48)

Fermi-LAT Instruments

Fermi Launch

- Launched on June 11, 2008
- Science Operation on Aug 4, 2008
- Orbit: 565 km, 26.5° (low BG)



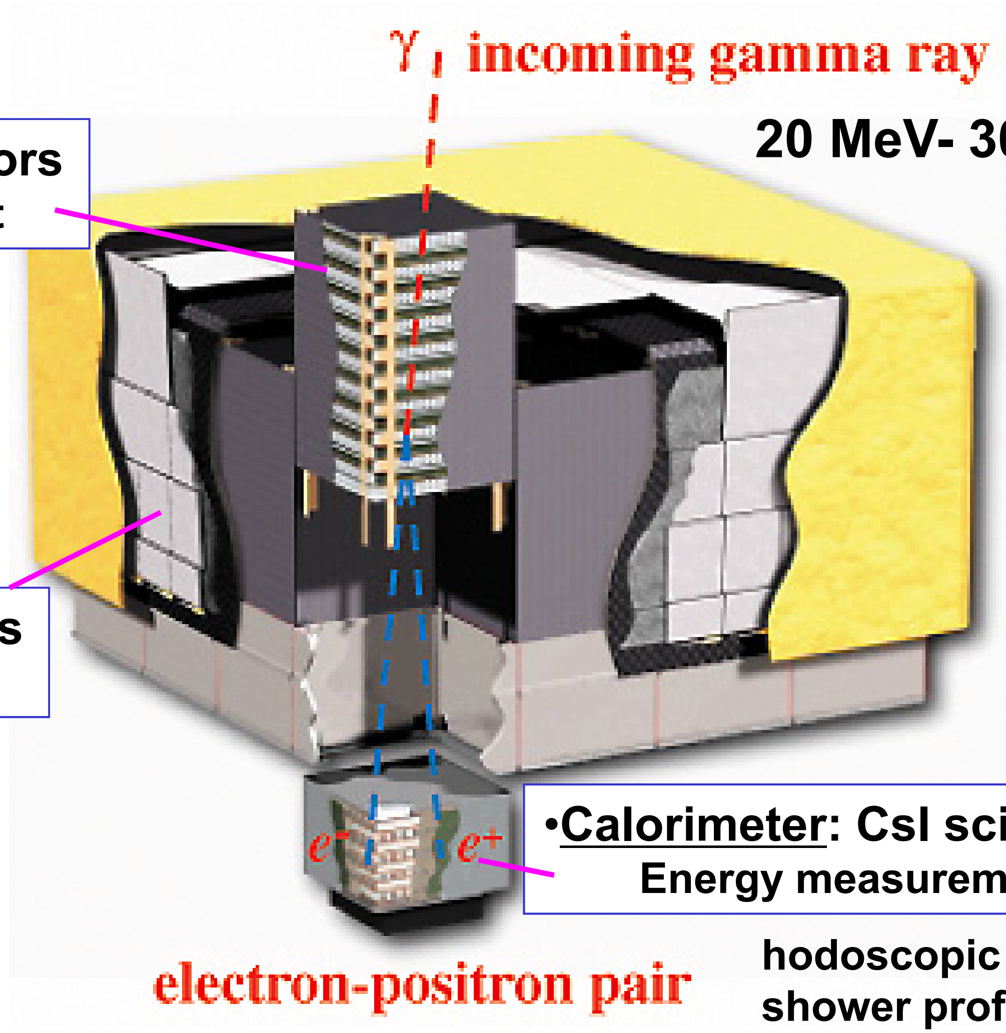
Fermi-LAT Collaboration

- France
- Italy
- Japan
  - Hiroshima Univ.
  - Tokyo Tech
  - ISAS/JAXA
  - Waseda Univ.
  - Tokyo Univ.
  - Nagoya Univ.
  - Aoyama Gakuin Univ.
- Sweden
- US

~400 members

Large Area Telescope

- **Pair-conversion type γ-ray telescope**



20 MeV- 300 GeV

• Tracker: Si-strip detectors
direction measurement

~200 um pitch =>
high precision tracking

•ACD: plastic scintillators
BG rejection

segmented tiles =>
prevent self-veto

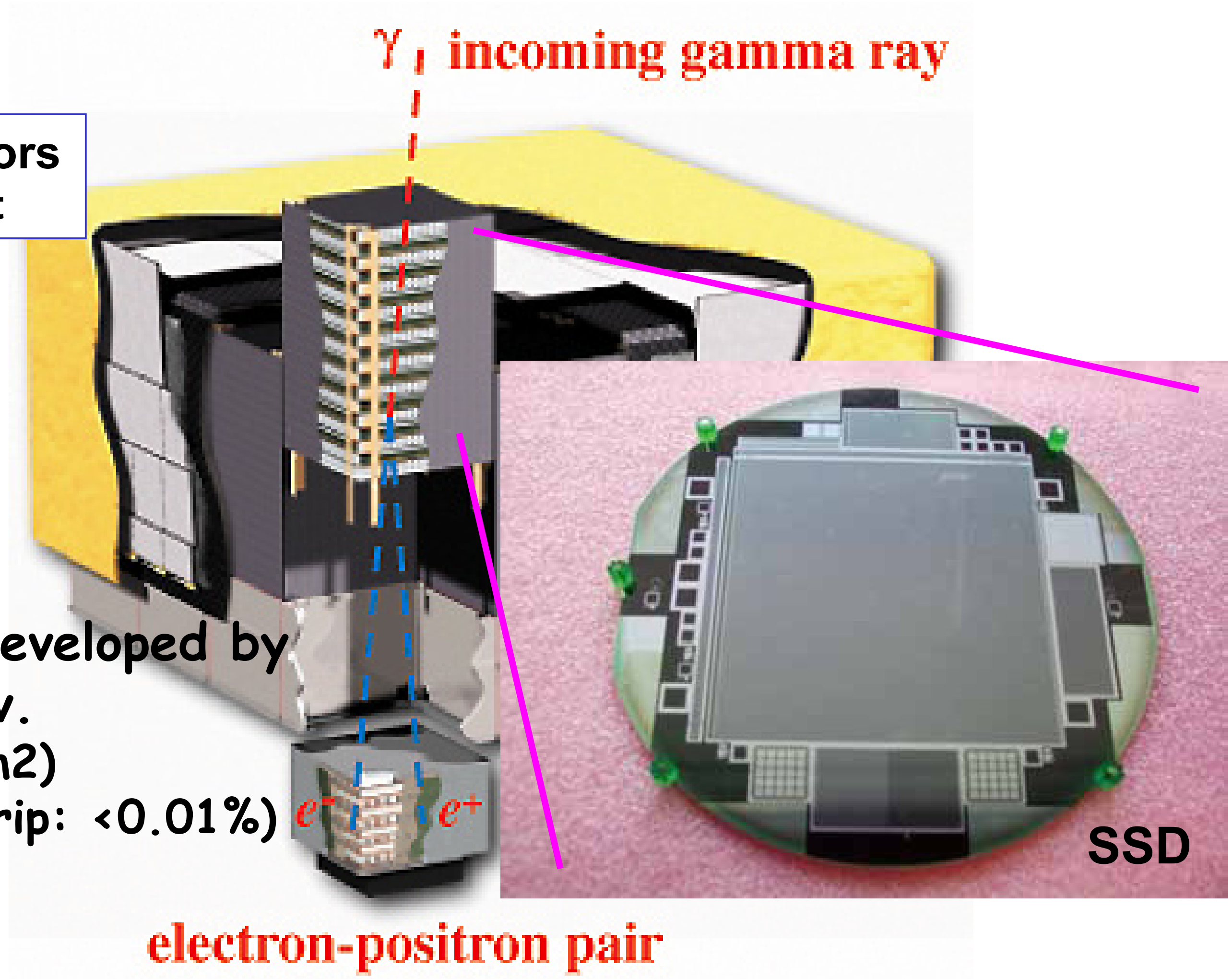
•Calorimeter: CsI scintillators
Energy measurement

hodoscopic crystals =>
shower profile

Large Area Telescope

- Pair-conversion type γ-ray telescope

- **Tracker**: Si-strip detectors
  direction measurement



Key-element of LAT, developed by HPK and Hiroshima Univ.

Low-noise (~2.5nA/cm2)
High-quality (dead strip: <0.01%)
~10^6 channels in total

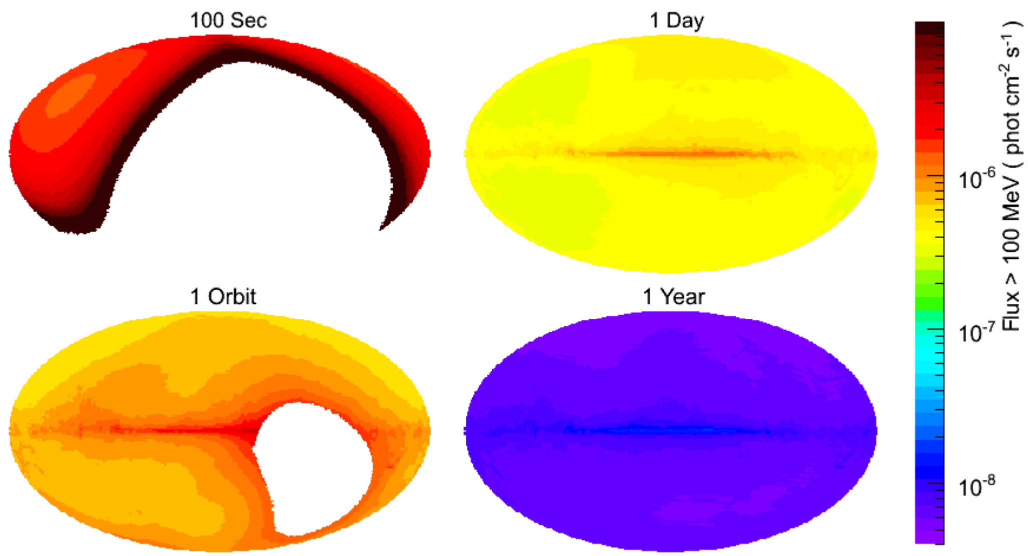
Performance of the LAT

- Large FOV (2.4 sr)
- Large Aeff (>=8000 cm2 in 1-100 GeV)
- Good PSF (0.6 deg@ 1GeV)

EGRET 3rd Catalog
271 sources

Fermi-LAT 1st year catalog
1451 sources

sensitivity to point sources



Atwood+09

Science Breakthroughs of 2009

- **Fermi is recognized as one of the top science breakthroughs**

THE

RUNNERS-UP >>

Opening Up the Gamma Ray Sky

LIKE A LIGHTHOUSE BLINKING IN THE NIGHT, A pulsar appears to flash periodically as it spins in space, sweeping a double cone of electromagnetic radiation across the sky. Since the discovery of the first pulsar 4 decades ago, astronomers have detected hundreds more of these enigmatic objects from the pulsing radio waves they emit. Now, astronomers have opened a new channel of discovery—the highly energetic gamma ray spectrum—to find pulsars that radio observations could not detect. The advance, part of a torrent of recent gamma ray observations, is giving researchers an improved understanding of how pulsars work, along with a rich haul of new pulsars that could help in the quest to detect gravitational waves.

The findings come from the Fermi Gamma-ray Space Telescope, which has been mapping the gamma ray universe since it was launched by NASA in June 2008. Combing through data the telescope collected in its first few months, an international team discovered 16 new pulsars; strong gamma ray pulsations from eight previously known pulsars with spin times of milliseconds, proving that these objects pulse brightly at gamma wavelengths as well as in the radio range; and high-energy gamma rays from the globular cluster 47 Tucanae indicating that the cluster harbors up to 60 millisecond pulsars.

Those Fermi results might be just the beginning. Armed with their new knowledge of pulsar behavior, researchers are checking whether some of the unidentified gamma ray sources Fermi has detected might be pulsars. In November alone, teams of astronomers in the United States and France discovered five new millisecond pulsars by training ground-based radio telescopes on candidate objects Fermi had pointed out—a much more targeted search technique than scanning the sky blindly with ground-based radio telescopes.

Gamma ray beams of pulsars are believed to be wider than their radio beams, so in principle a space-based gamma ray telescope should be more likely to encounter and discern a pulsar's sweep than a radio telescope on Earth is. However, Fermi's forerunner—

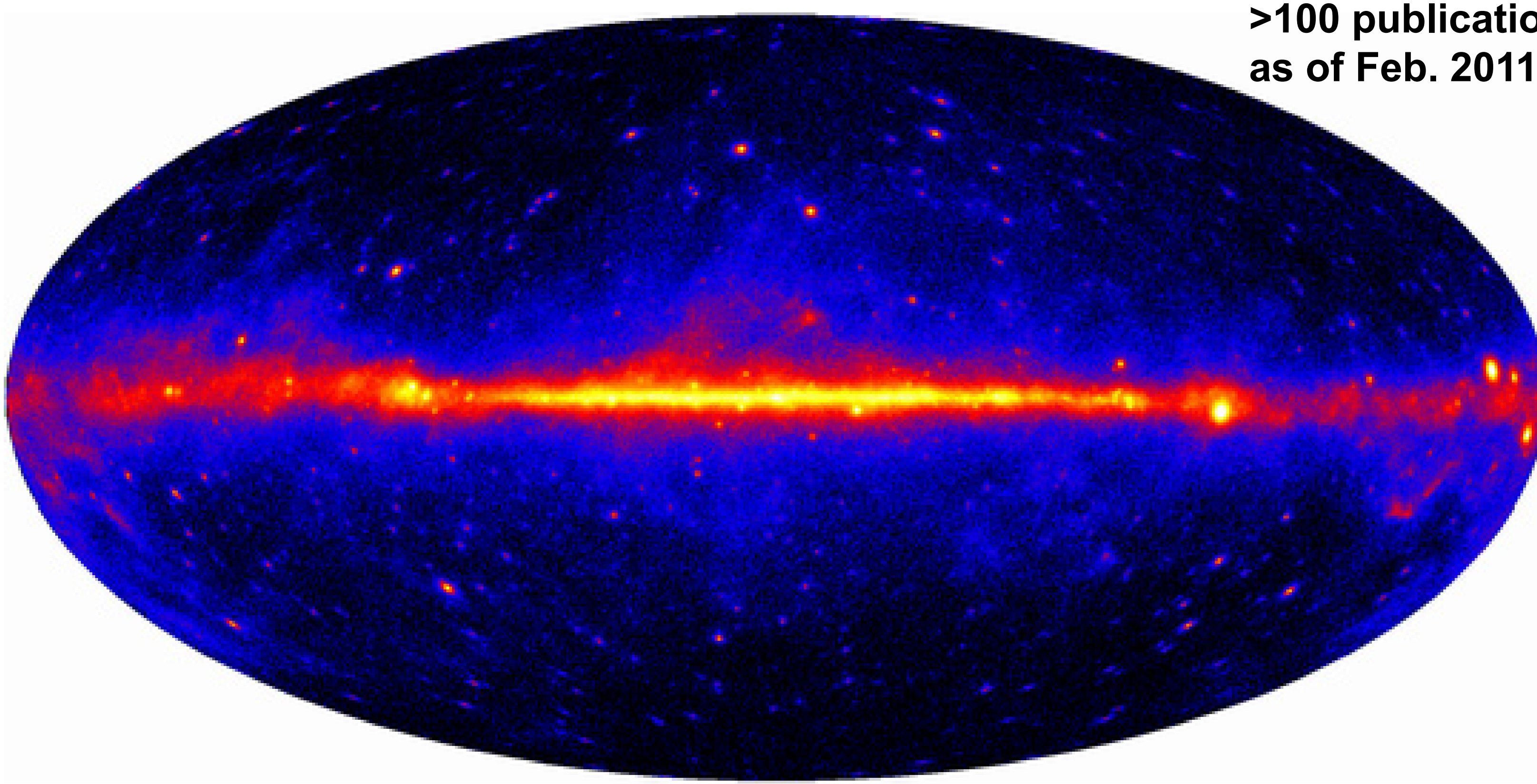
the Compton Gamma Ray Observatory, which flew from 1991 to 2000—did not have much luck finding these objects. What has made the difference is Fermi's high sensitivity, which enables it to detect pulsations that would have been too faint for Compton.

Already, the discoveries are shedding new light on the physics of pulsars. Researchers

GeV Gamma-ray Sky by LAT

- **and provides us with high-quality data!**
  - γ-ray sources, diffuse γ-rays and more

>100 publications as of Feb. 2011



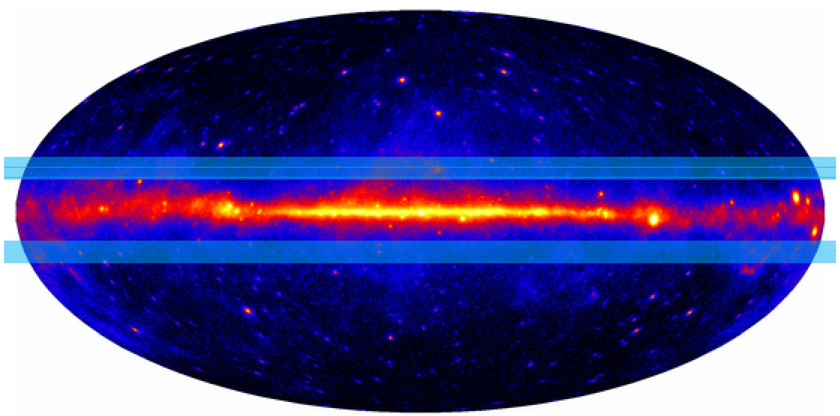
Fermi-LAT 1 year all-sky map

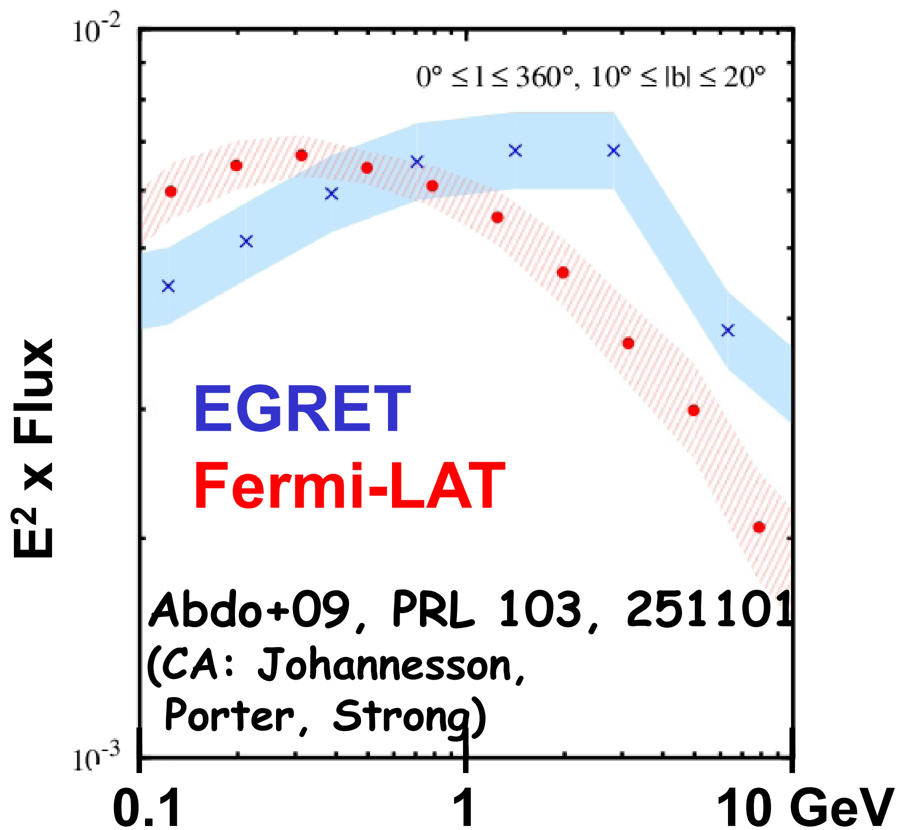
Diffuse γ-rays as probe of CRs and ISM

GeV "Non" Excess

- Fermi does not confirm EGRET GeV excess

local (<= 1 kpc from the sun)
Diffuse Gamma-rays



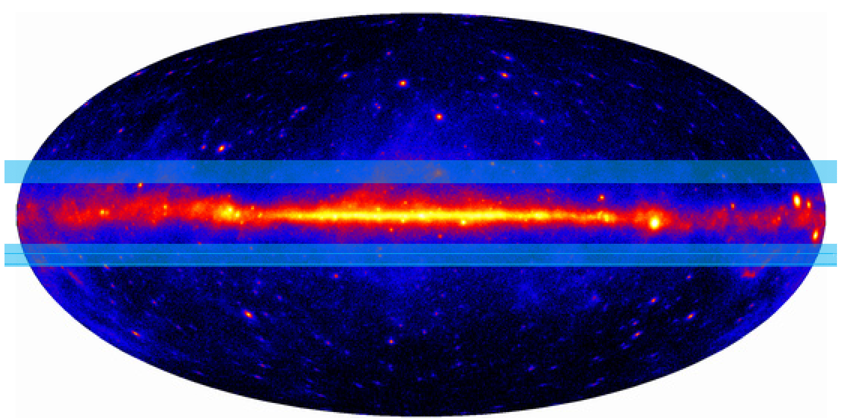


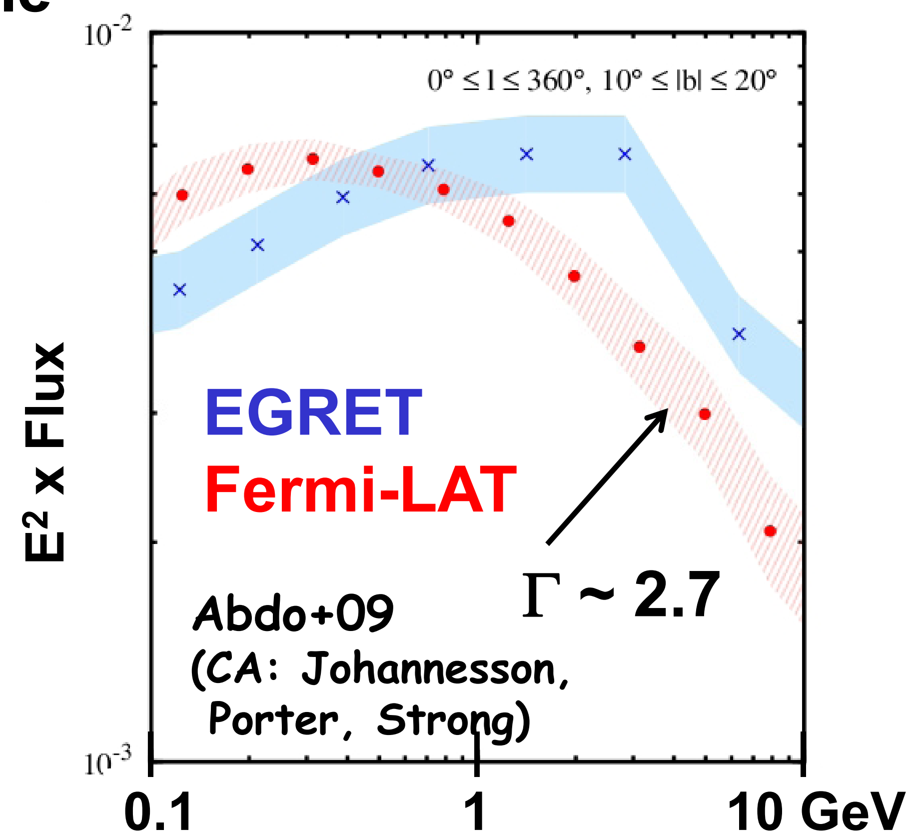
GeV "Non" Excess

- Fermi does not confirm EGRET GeV excess

Instead, data is compatible with a standard model

Gamma = CR x (ISM, ISRF)

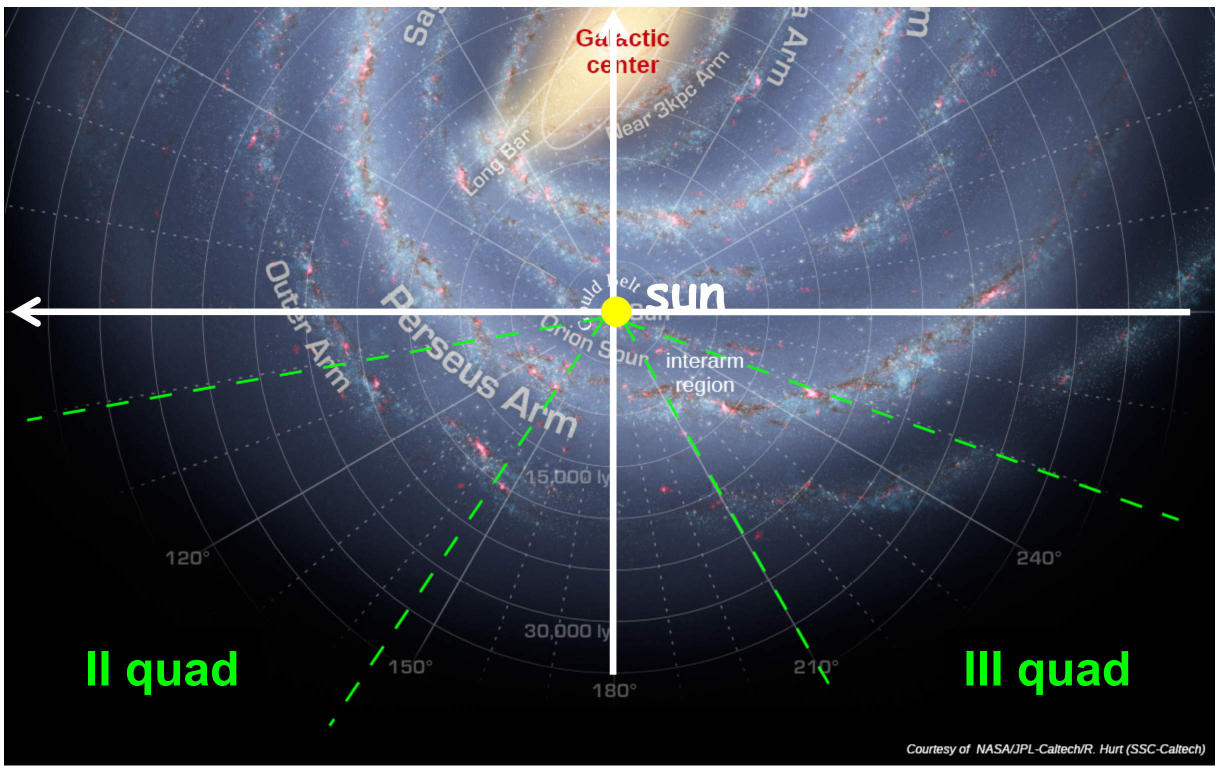




Diffuse γs in the Outer Galaxy

- **Any unexpected in diffuse γs?**
  - **Yes. New information on CRs and ISM**

The outer Galaxy (from outside)



L=90deg

L=270deg

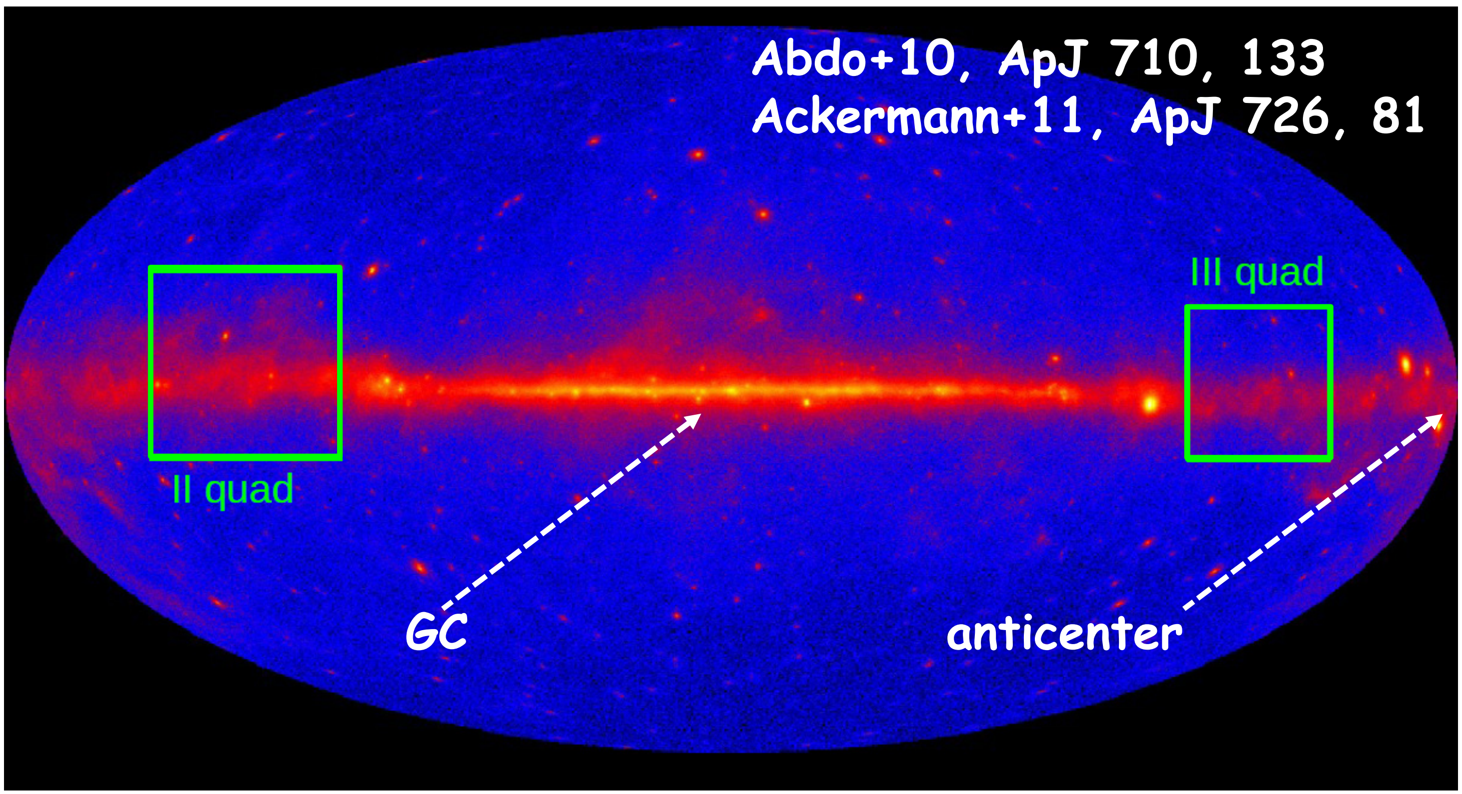
L=180deg

T. Mizuno et al.

Diffuse γs in the Outer Galaxy

- Any unexpected in diffuse γs?
  - Yes. New information on CRs and ISM

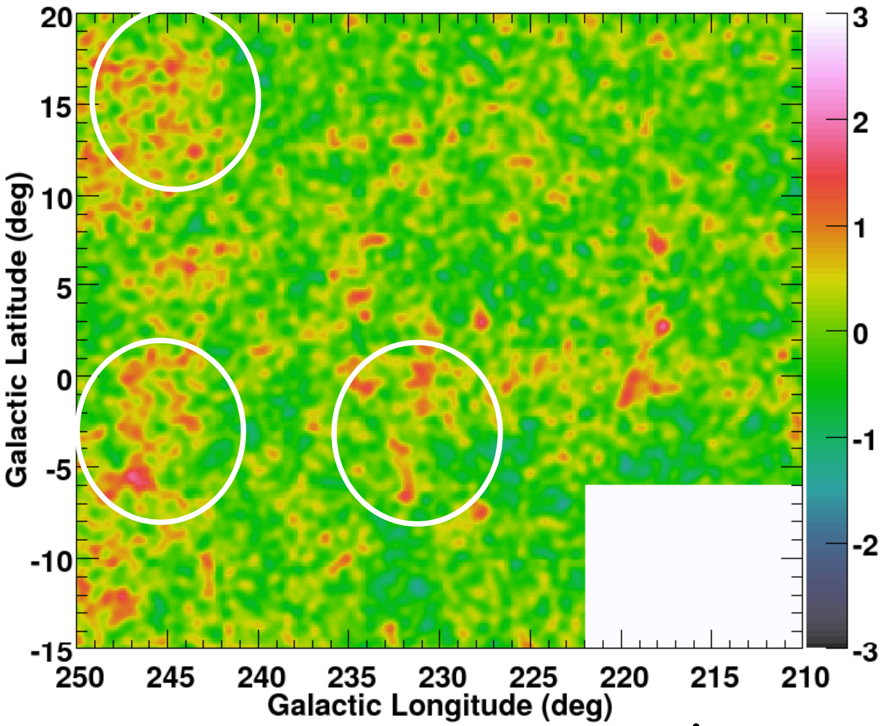
The outer Galaxy (from the Fermi-LAT)



ISM not visible by Standard Tracers

- Fermi revealed ISM gas <u>not traced</u> by radio surveys

Residual when fitted by N(H_I)+CO



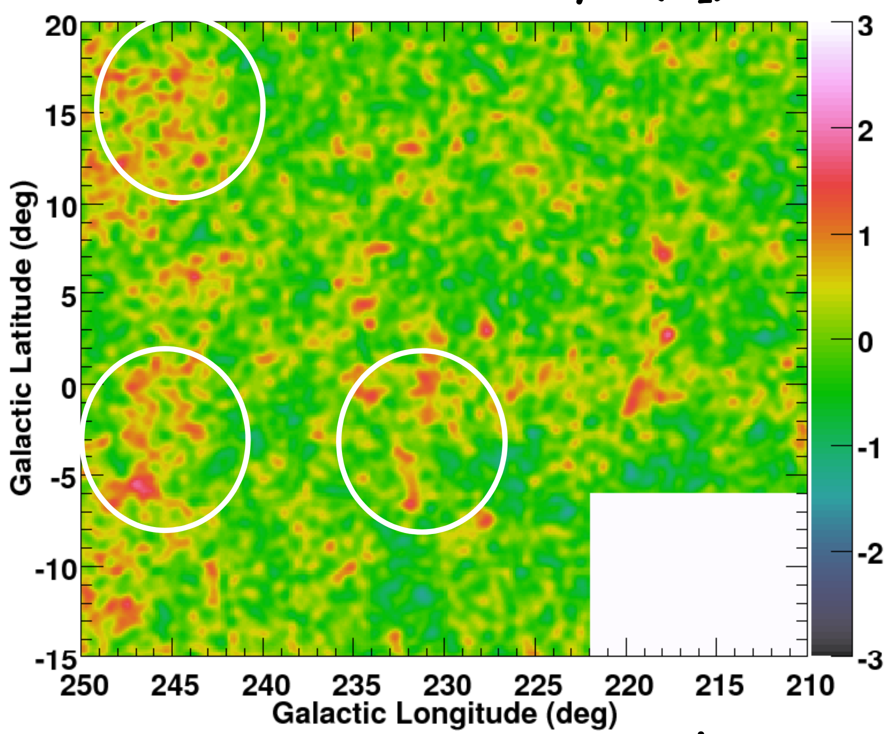
excess gammas
= residual gas

Ackermann+11, ApJ 726, 81
(CA: Grenier, Mizuno, Tibaldo)

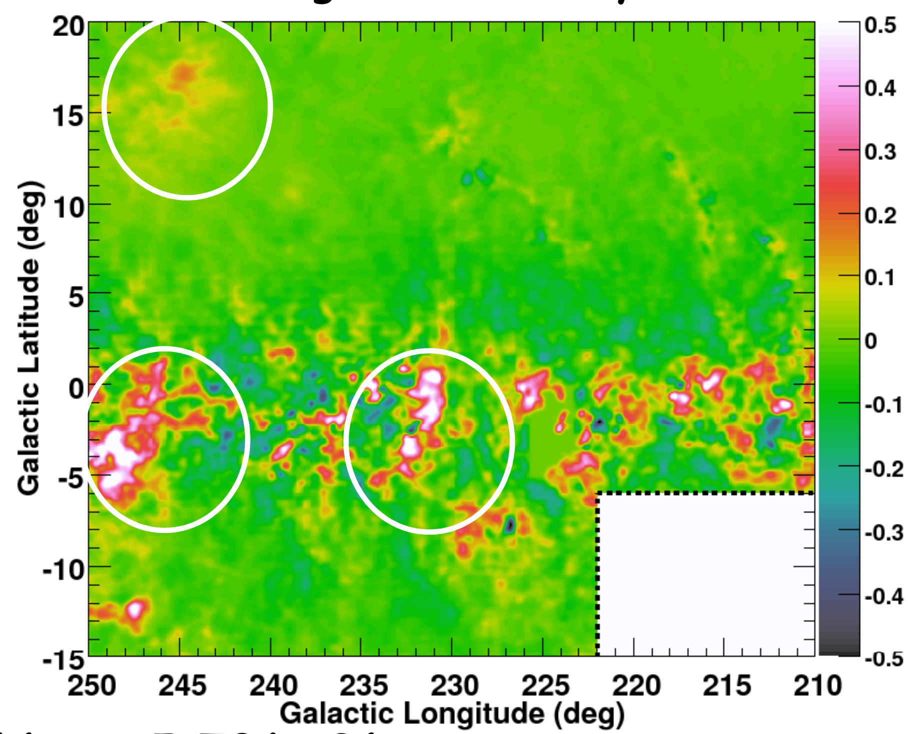
ISM not visible by Standard Tracers

- **Fermi revealed ISM gas <u>not traced</u> by radio surveys**
  - **confirming an earlier claim based on EGRET study (Grenier+05)**

Residual when fitted by N(H_I)+CO



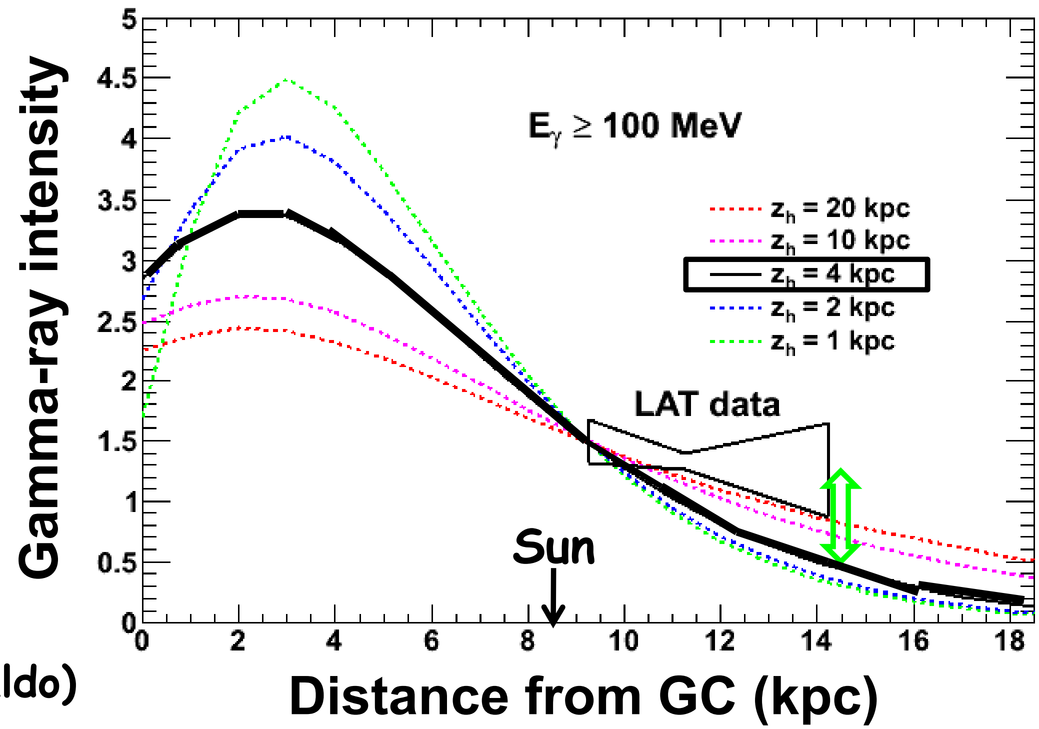
Residual gas inferred by dust



Ackermann+11, ApJ 726, 81
(CA: Grenier, Mizuno, Tibaldo)

More CRs than Expected

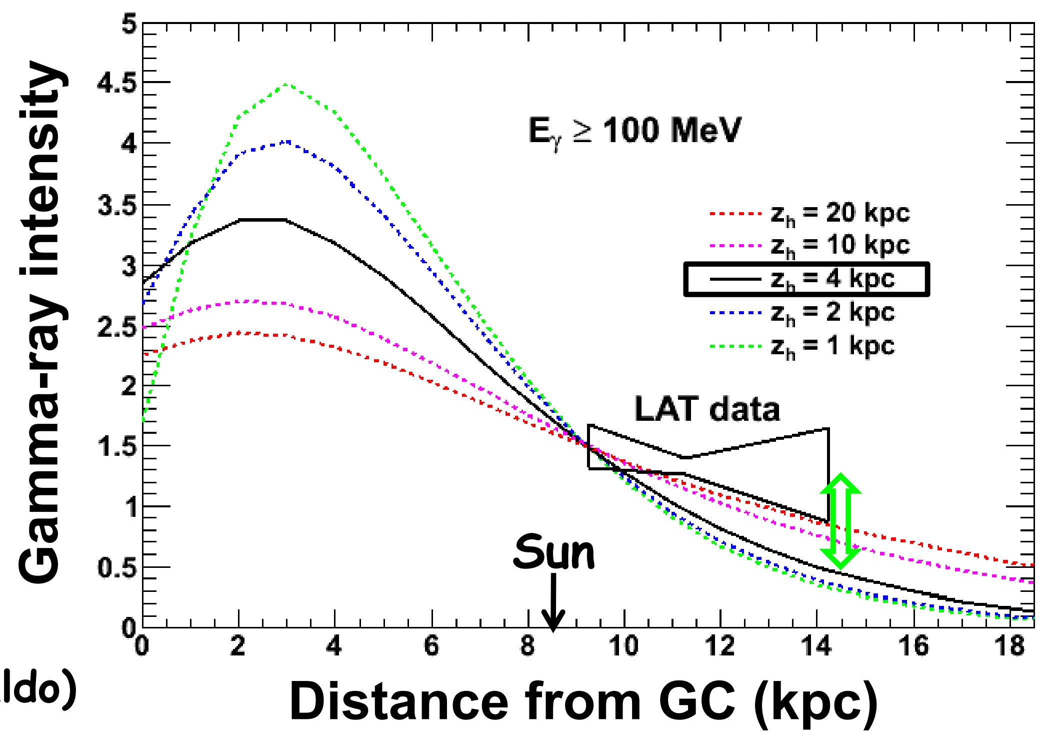
- Fermi detected more γs (more CRs) than a prediction based on SNR distribution and standard CR halo



Ackermann+11
ApJ 726, 81
(CA: Grenier, Mizuno, Tibaldo)

More CRs than Expected

- Fermi detected more γs (more CRs) than a prediction based on SNR distribution and standard CR halo
  - More CR sources or larger CR halo



Ackermann+11
ApJ 726, 81
(CA: Grenier, Mizuno, Tibaldo)

Remarks on Diffuse γs

- γ-rays = CR x (ISM, ISRF)
- "dark gas" is confirmed (more ISM gas)
- More CRs than expected in outer Galaxy

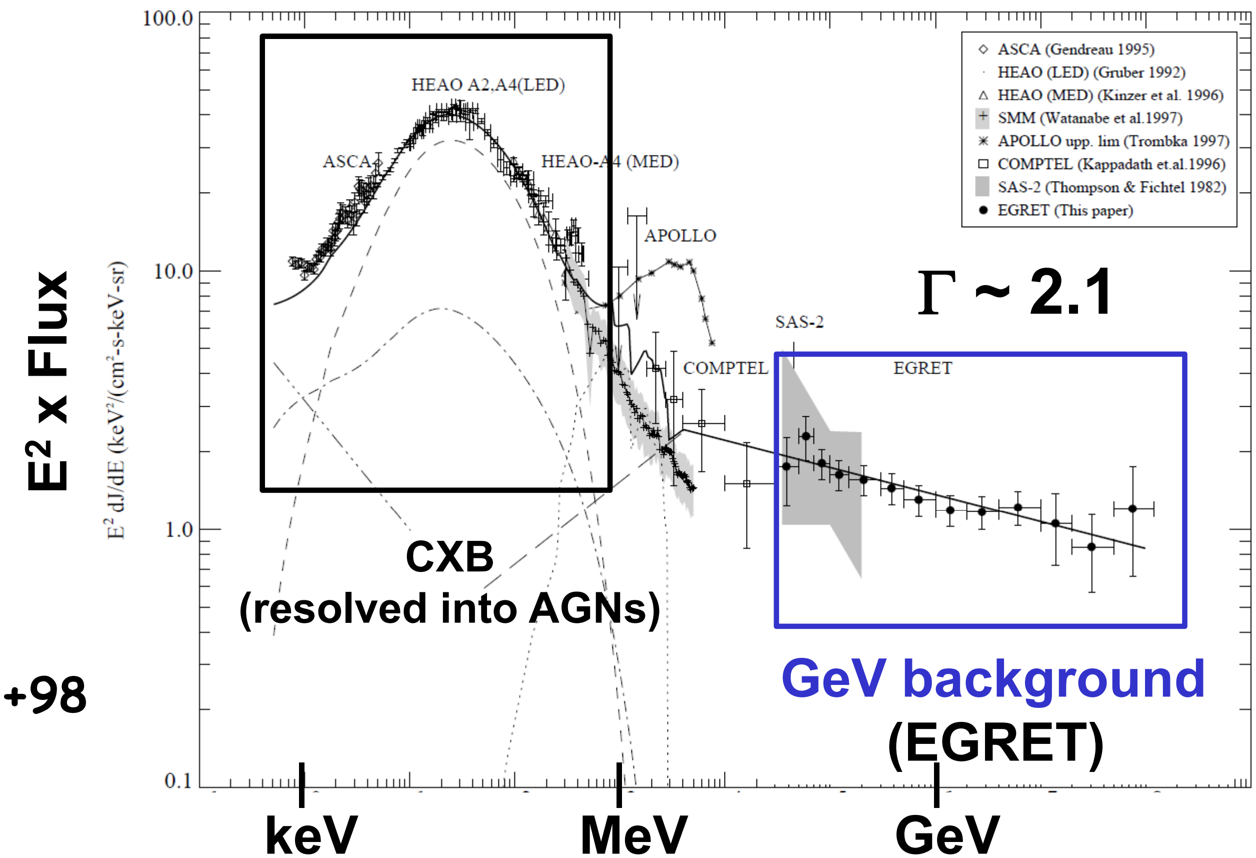
- Improvement of diffuse γ-ray model

Basis to search for anomalies
(in spectral and spatial distribution)

Behind Diffuse γ-rays: Study of EGB and DM search

Extragalactic Gamma-ray Background

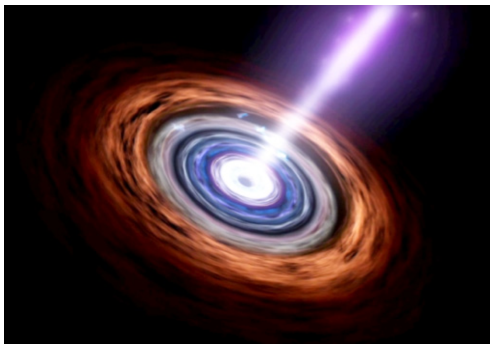
- "Cosmic" Extragalactic Gamma-ray Background (EGB) has been known since 1970s



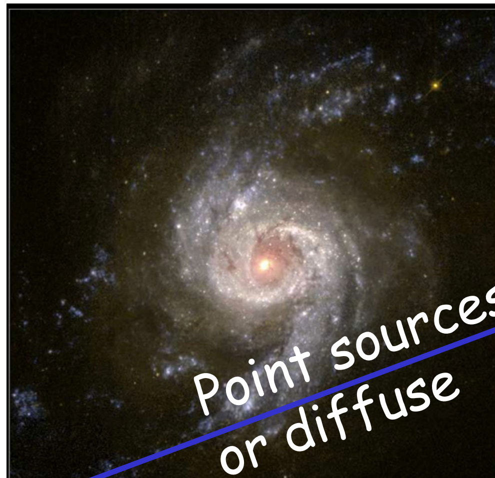
Sreekumar+98

Why is EGB Important?

- **The EGB may encrypt the signature of the most powerful processes in astrophysics**

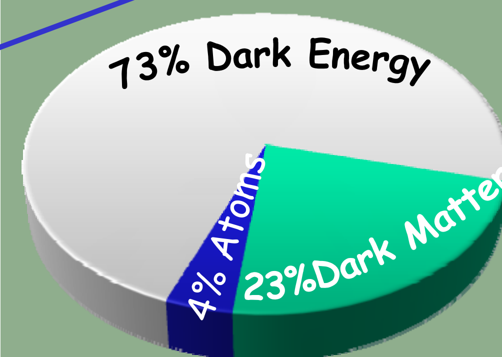


Blazars contribute 20-100% of the EGB



Star forming galaxies

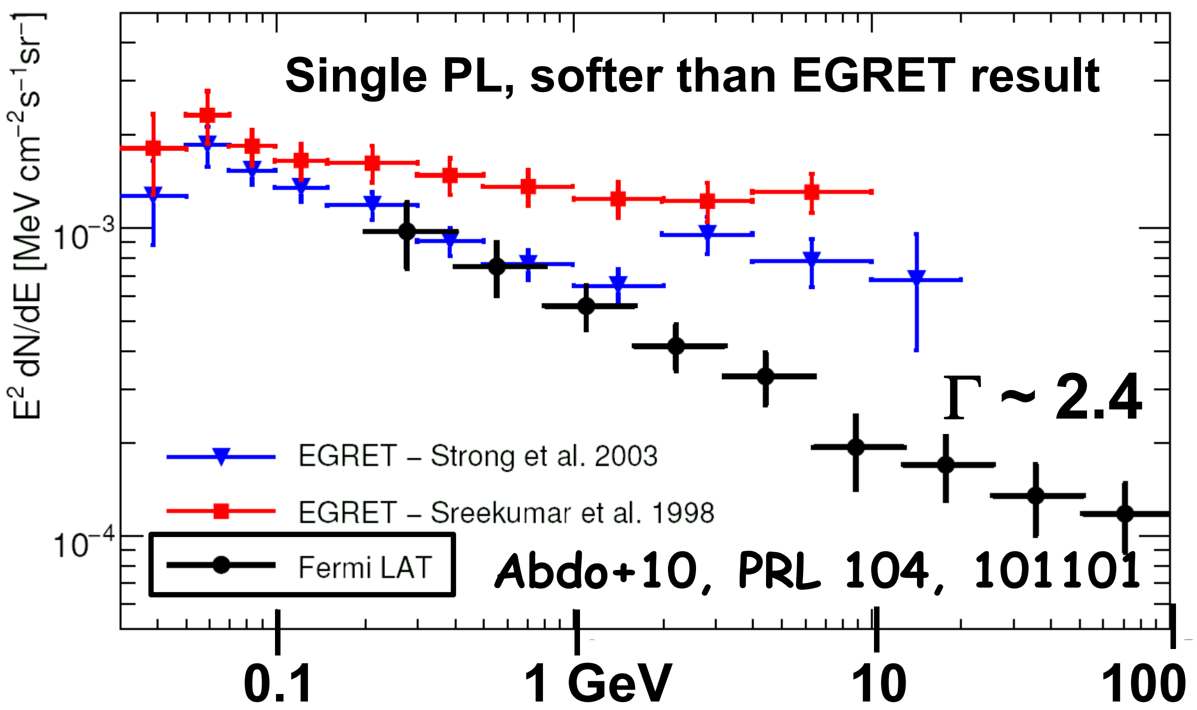
Particles accelerated in Intergalactic shocks

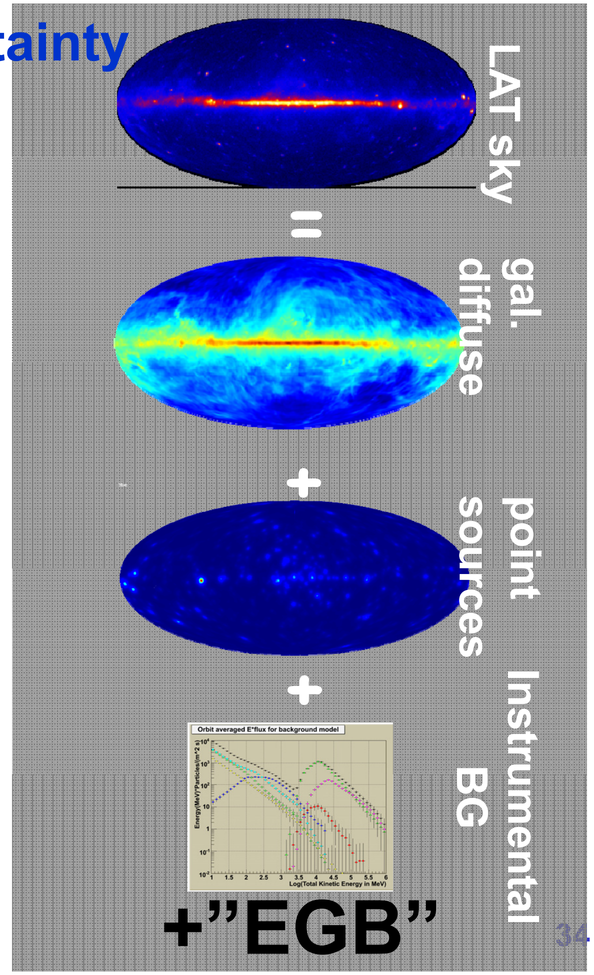


Annihilation of Cosmological Dark Matter

The Fermi EGB

- **Fermi data + improved diffuse model**
  - new EGB spectrum in 0.2-100 GeV
    - carefully examine systematic uncertainty





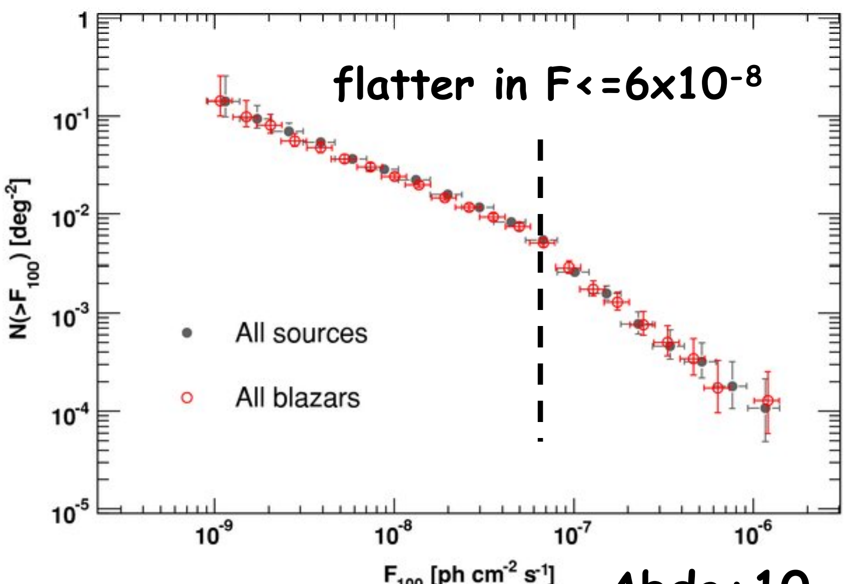
(CA: Ackermann, Porter, Sellerholm)

T. Mizuno et al.

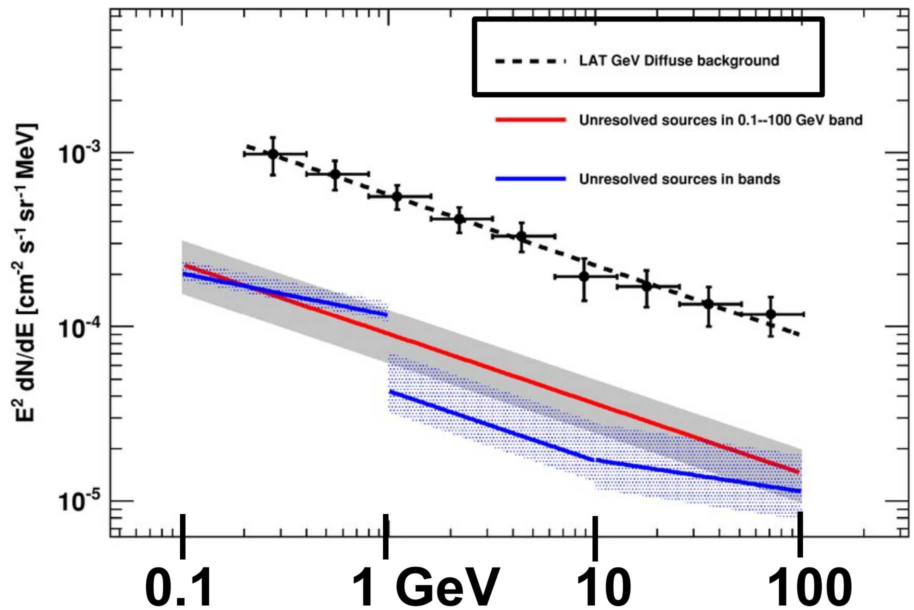
Blazar Contribution

- **Blazars account for a minimum of 16+-2%**
  - Even if we extrapolate and integrate logN-logS to zero, contribution is still <40%

logN-logS:
Most of un-associated sources are likely to be blazars



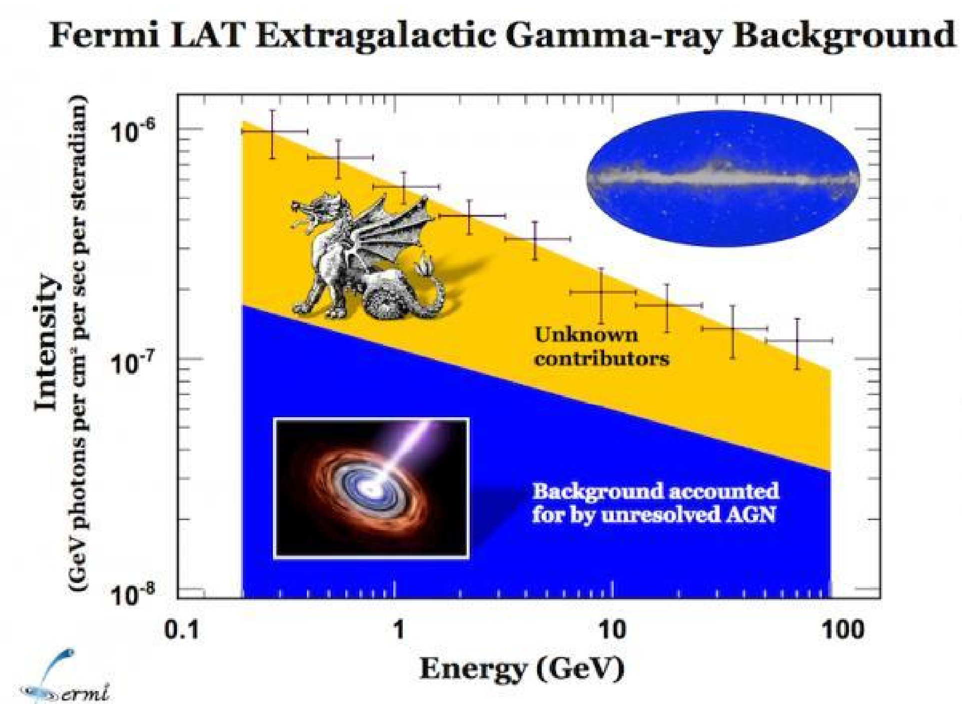
Fermi EGB vs. source contribution



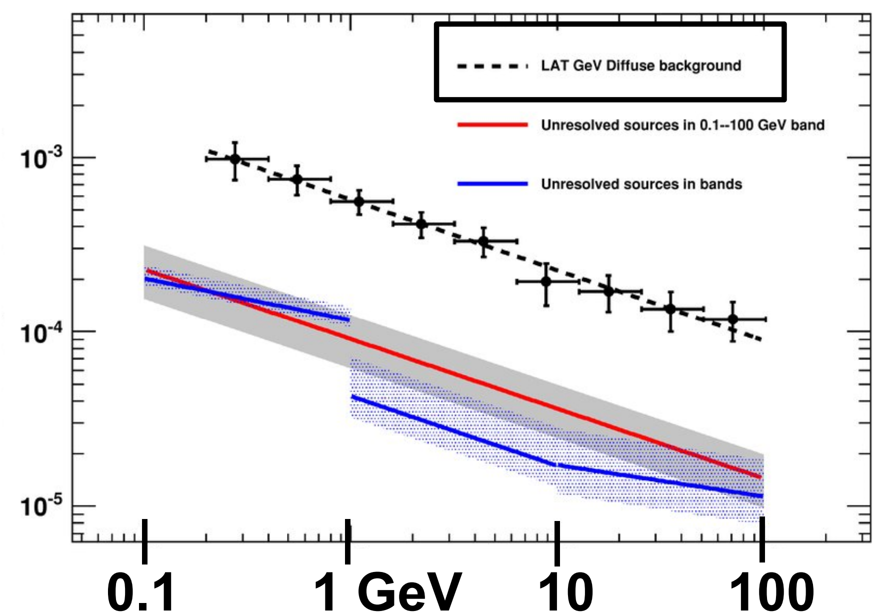
Abdo+10, ApJ 720, 435
(CA: Ajello, Tramacere)

Blazar Contribution

- **Blazars account for a maximum of 40% of EGB**
  - γ-ray "Fog" by Mysterious Dragons
  - star-forming galaxies, normal AGNs or truly diffuse?



Fermi EGB vs. source contribution

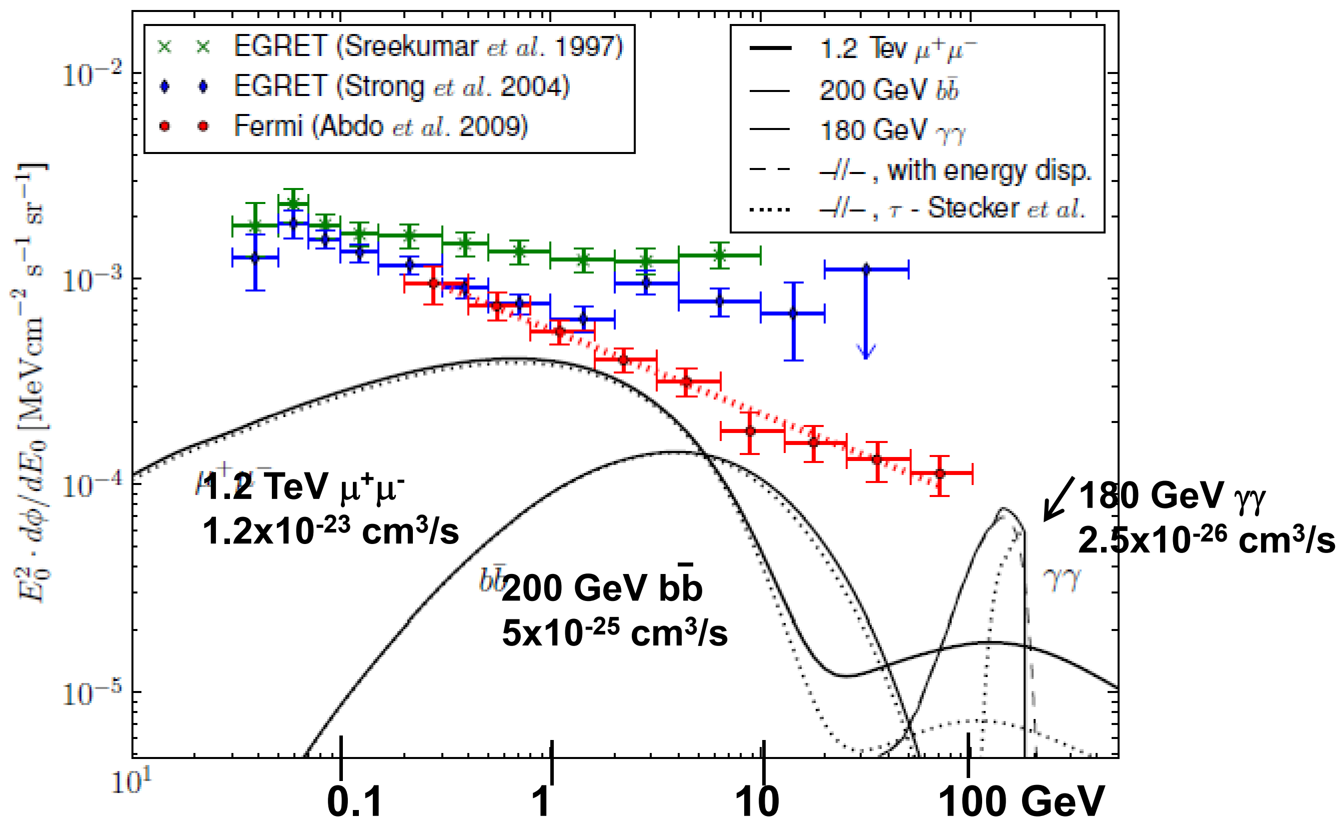


Abdo+10, ApJ 720, 435
(CA: Ajello, Tramacere)

T. Mizuno et al.

Limits on DM Annihilation

- Limits on DM by imposing the EGB is not violated



Abdo+10, JCAP 4, 14

(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)

Limits on DM Annihilation

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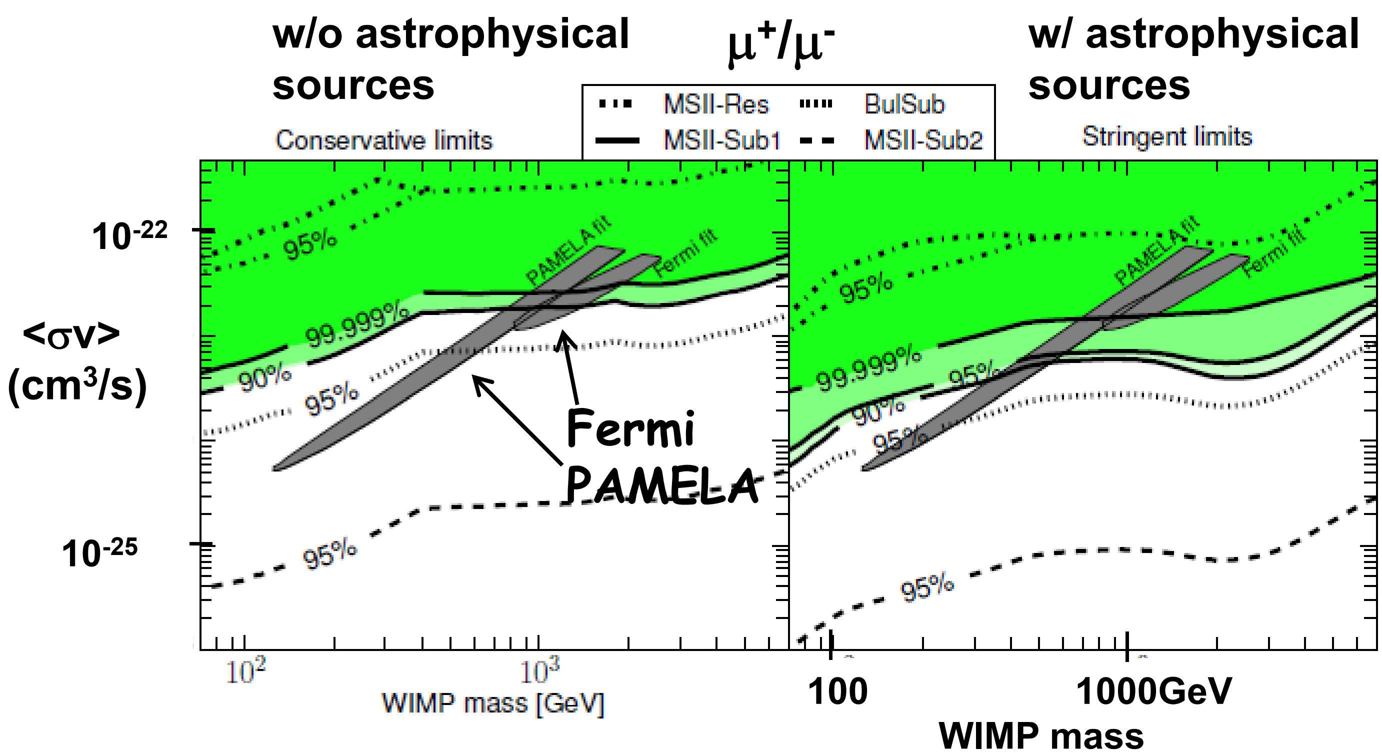
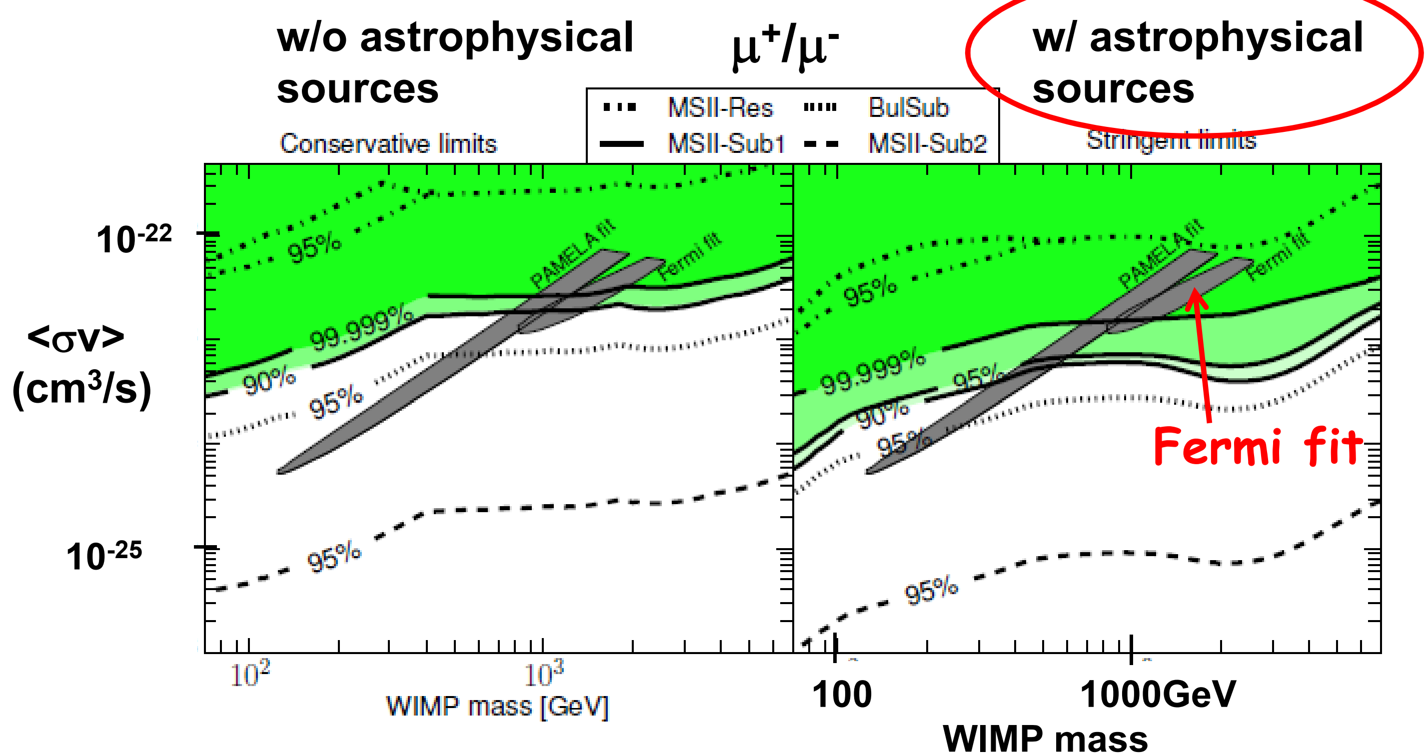


Abdo+10, JCAP 4, 14
(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)

Limits on DM Annihilation

- <u>Limits on DM</u> by imposing the EGB is not violated
  - already excluded some models, e.g., μ^+/μ^- channel favored by PAMELA/Fermi e^-/e^+



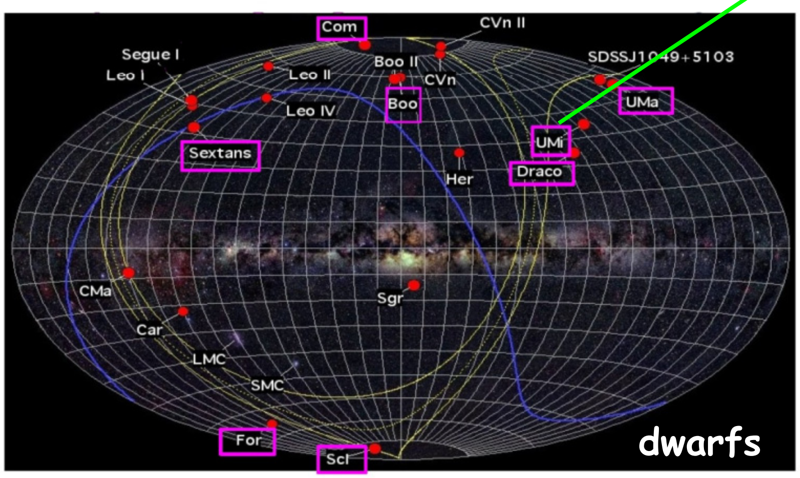
Abdo+10, JCAP 4, 14
(CA: Conrad, Gustafsson, Sellerholm, Zaharijas)

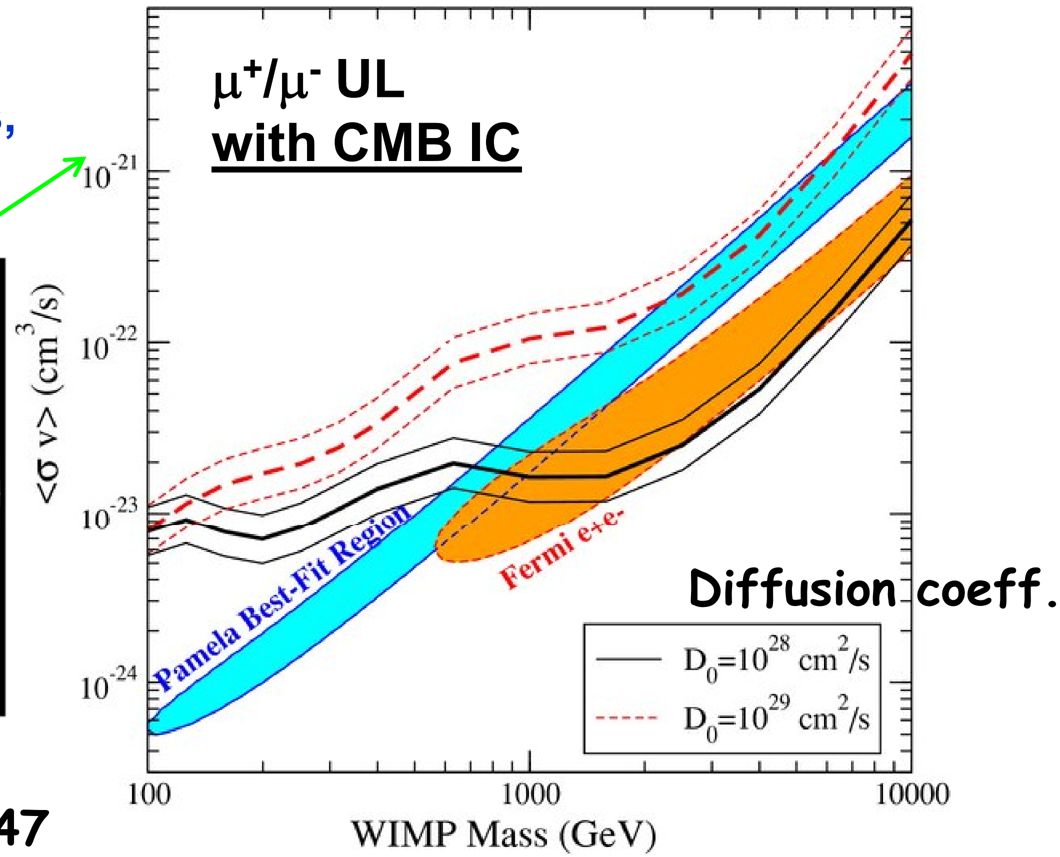
Other Constraints on DM

- Dwarf Spheroidal Galaxies are DM dominated
  - small BG (gas, star-forming activity)

No detection

give constraints on some models, particularly μ^+/μ^- channel





Abdo+10, ApJ 712, 147
(CA: Cohen-Tanugi, Farnier, Nuss, Profumo, Jeltema)

Remarks on EGB and DM search

- “New” EGB spectrum in 0.2-100 GeV
  - Blazars account for <40% of EGB
    - room for star-forming galaxies, normal AGNs or truly diffuse
- No evidence for DM annihilation
  - Constraints on models, in particular μ^+/μ^- channel
  - Astrophysical source contribution is important

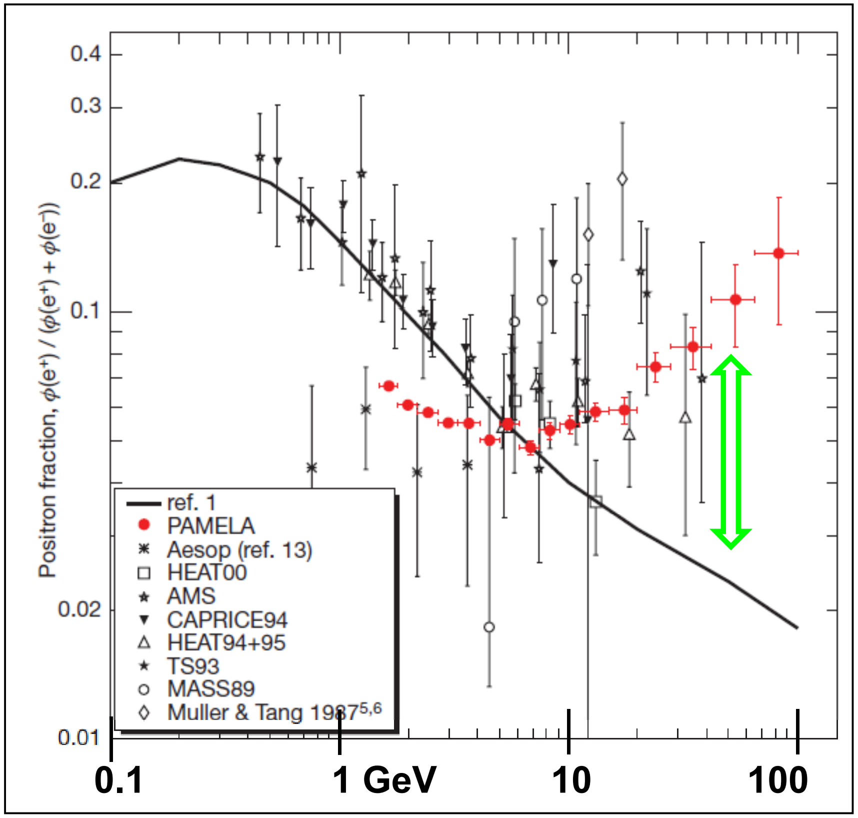
Cosmic-Ray Electrons

PAMELA Positron Excess

- Convincing evidence of e^+ ratio excess in >10 GeV
  - 2ndary e^+ should be softer than primary e^-

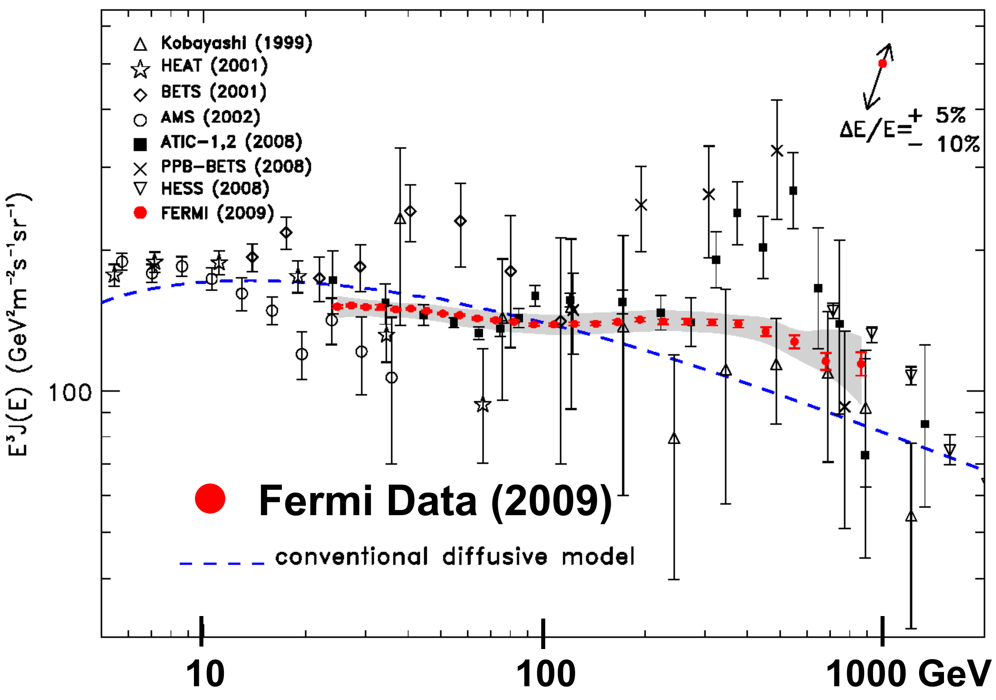
Sources of "Primary" e^+ are required

Adriani+08



CRE by Fermi-LAT (2009)

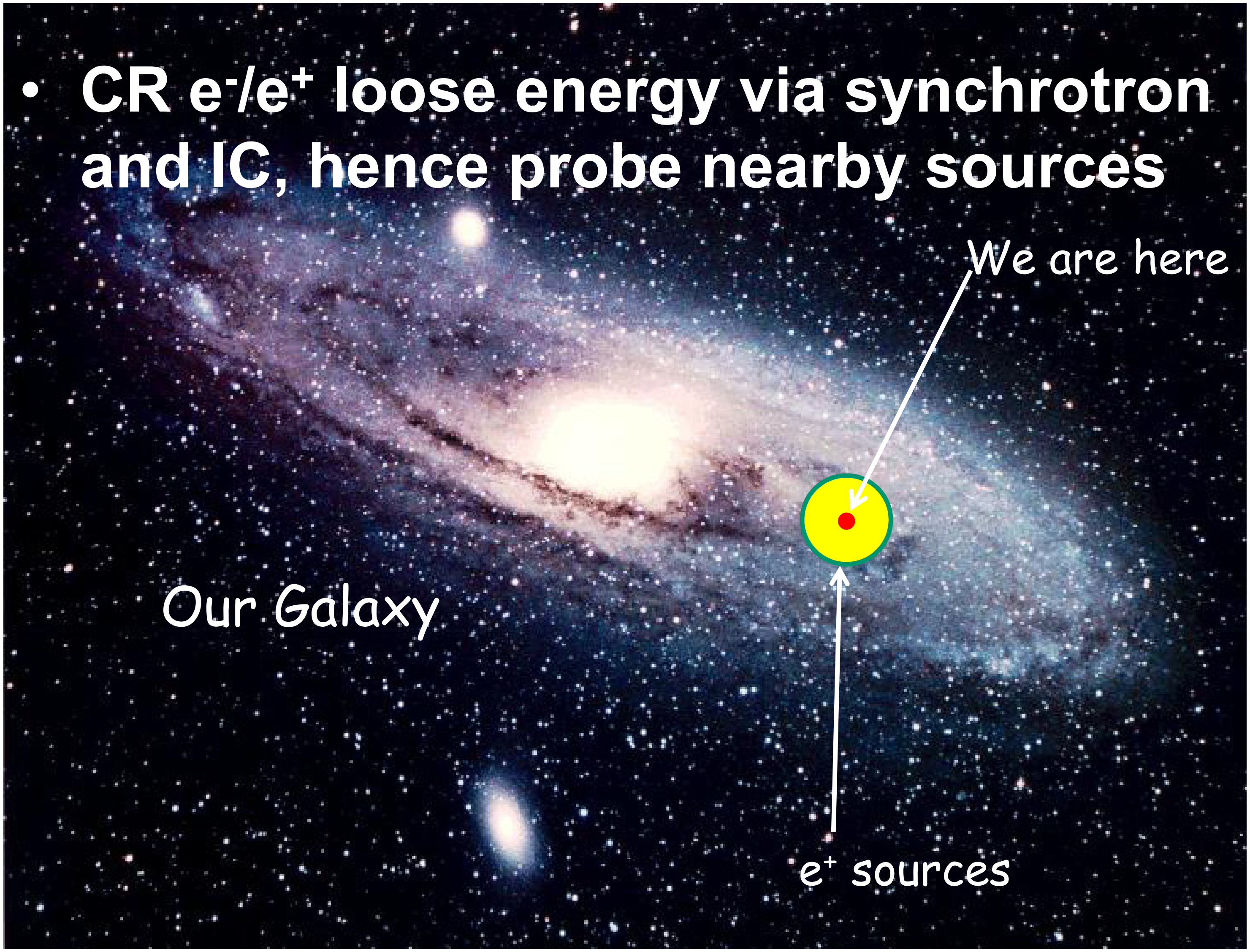
- **Fermi-LAT reported hard $e^- + e^+$ spectrum**
  - **Standard models with proper choice of params are able to reproduce Fermi data alone, but <u>not Fermi + PAMELA</u>**



6 months data
4.5 M events

Abod+09
PRL 102, 181101
(CA: Latronico, Moiseev)

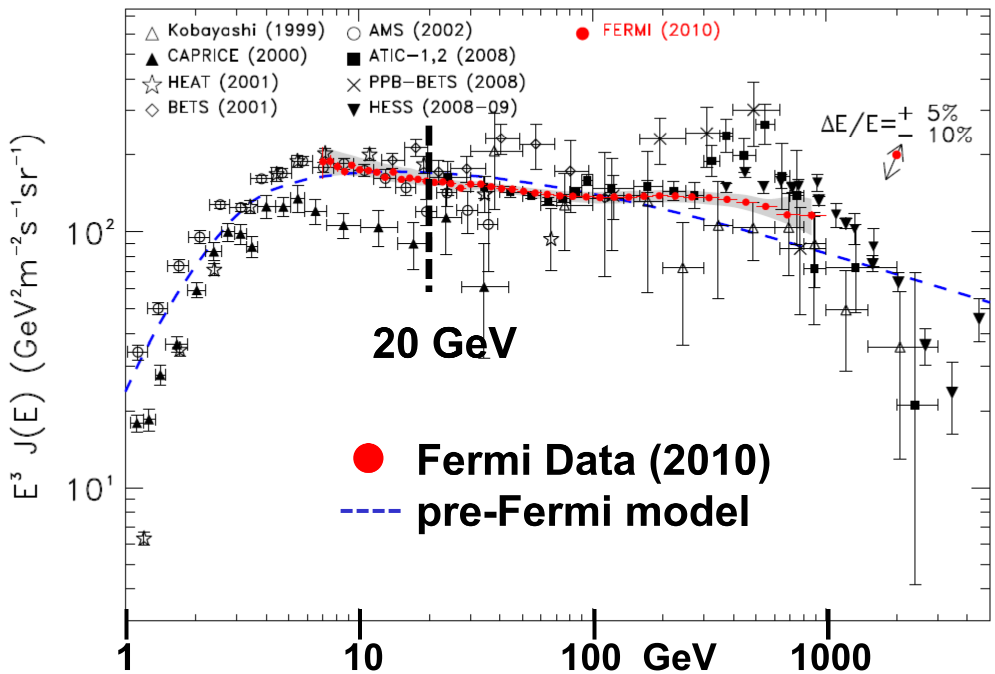
e^-/e^+ probe nearby sources



KEK 井岡氏のトラペより借用

CRE by Fermi-LAT (2010)

- CREs collected for 12 month (data is doubled)
  - Cross-check with events with long path in CAL (>=13X_0)
  - LE extention using high latitude (low cutoff) data
- <u>Noticeable deviation</u> from a single PL

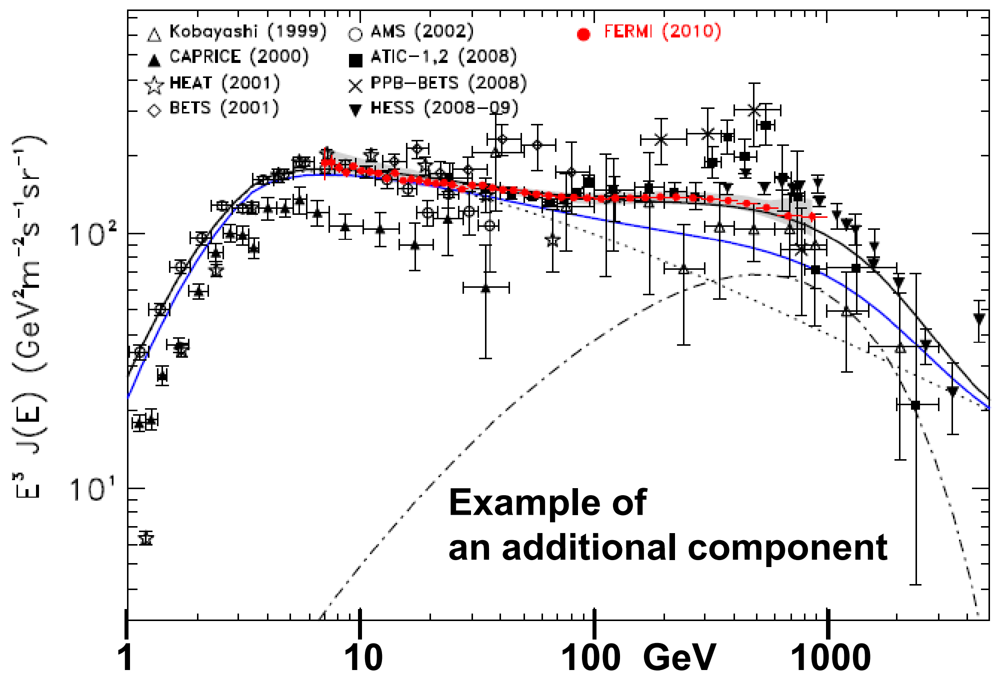


Ackermann+10
PRD 82, 092004
(CA: Moiseev, Sgro)

CRE by Fermi-LAT (2010)

- **Noticeable deviation from a single PL**
  - Additional e^-/e^+ sources (astrophysical or extocis) can provide a good fit to Fermi CRE and PAMELA $e^+/(e^- + e^+)$

Anisotropy of arrival direction may reveal sources or give constraints



Ackermann+10
PRD 82, 092004
(CA: Moiseev, Sgro)

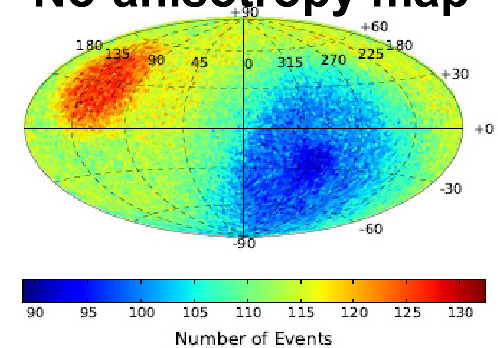
CRE Anisotropy

- Construct *no anisotropy* map from flight data
  - shuffling and direct integration
- Compare obtained map with data
  - search for anisotoropy

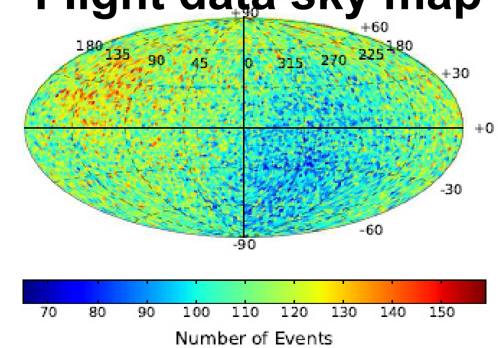
Eth: 60-480 GeV
Angular scale: 10-90 deg

No evidence of anisotropy in energies/angles investigated

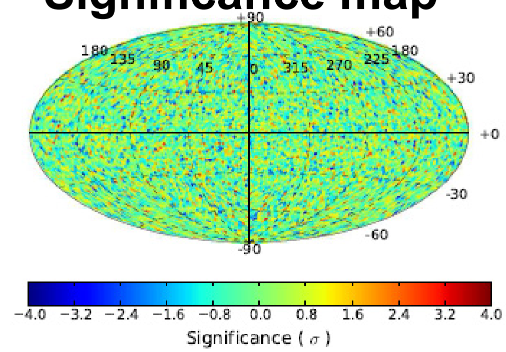
No-anisotropy map



Flight data sky map



Significance map



Ackermann+10
PRD 82, 092003
(CA: Mazziotta, Vasileiou)

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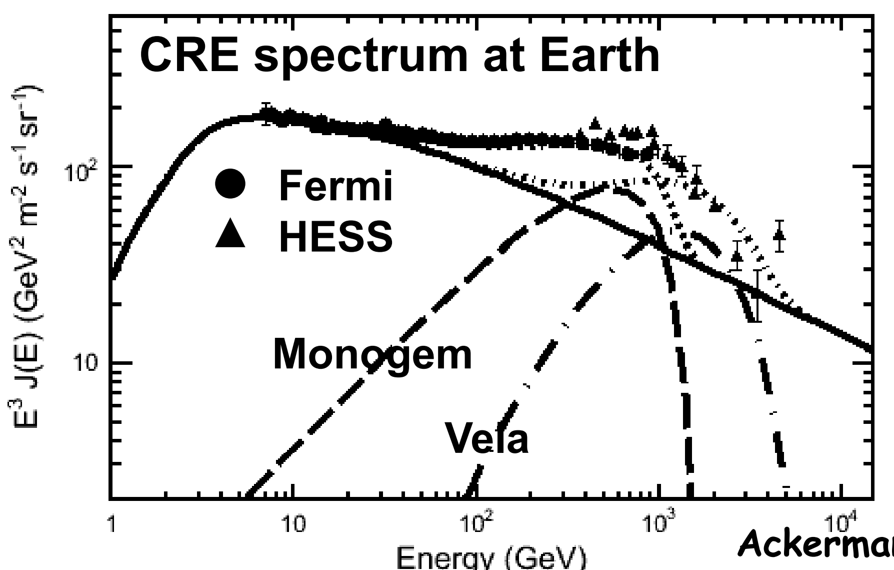
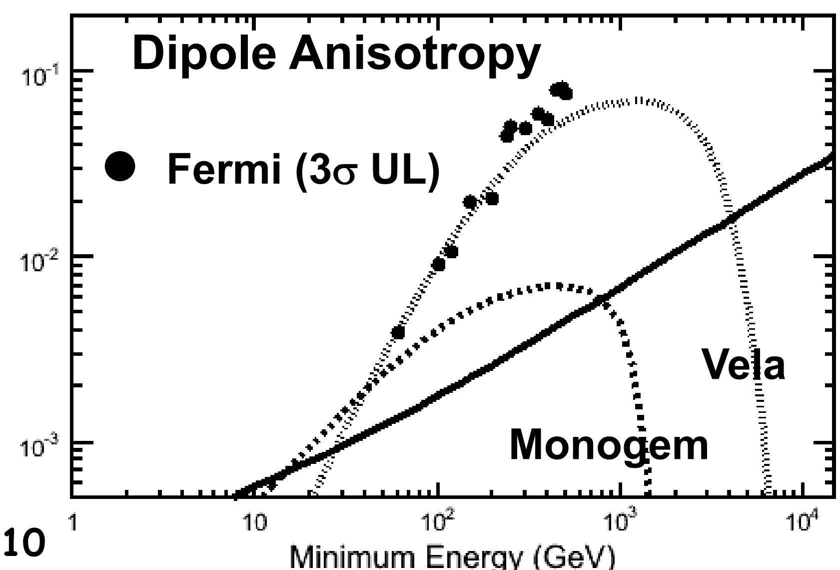
Limit on Sources

- No evidence of anisotropies
  - Upper limit for the dipole anisotropy: 0.5-5%
- Limit already <u>comparable</u> to the value expected for a single nearby source dominating HE spectrum
  - will improve as more data are collected





Ackermann+10
PRD 82, 092003
(CA: Mazziotta, Vasileiou)

Summary

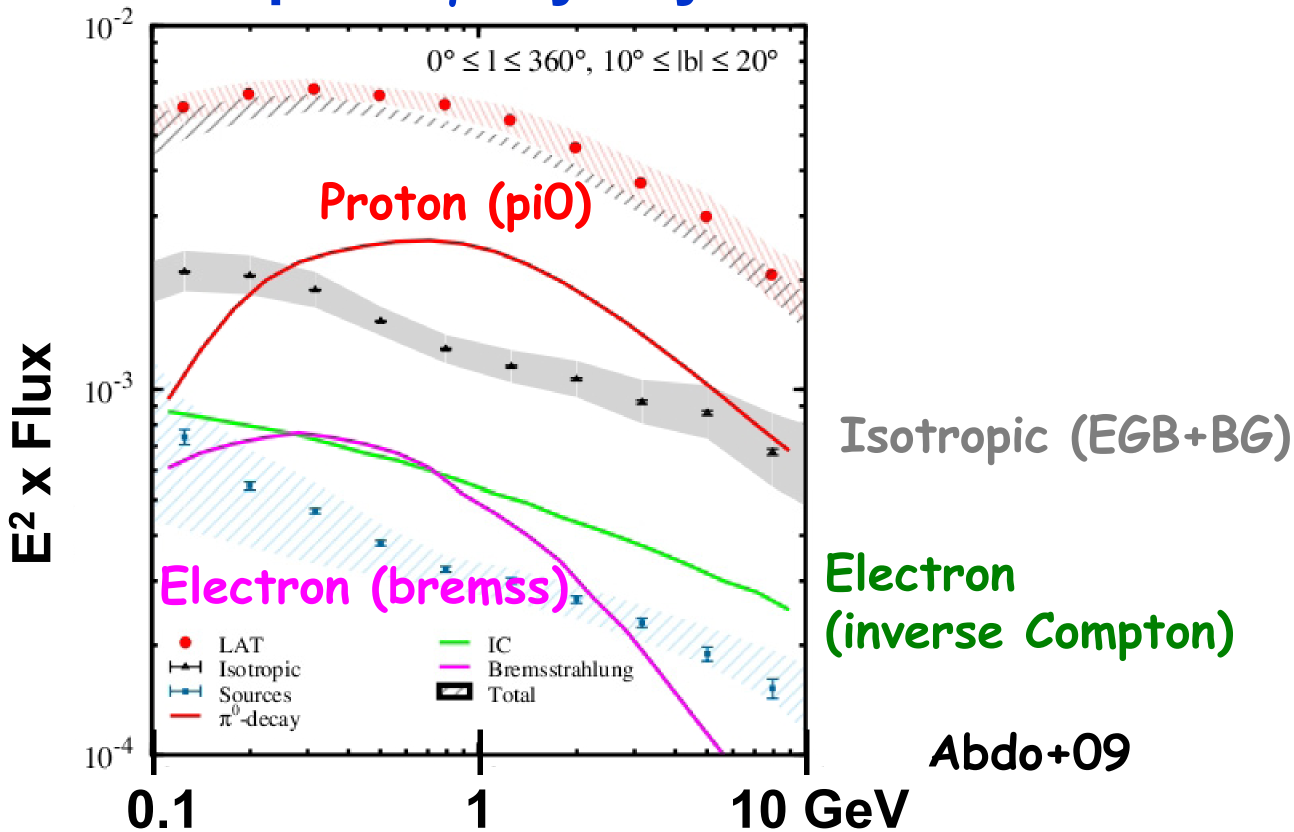
- 広がったガンマ線は, 宇宙線と星間ガスを研究する強力な手段.
- DM探査で意味のある上限値が得られている. 広がったγ線+ γ線天体の理解は, DM探査にも資する.
- 電子陽電子源スペクトル+等方性も, 意味のある上限に近いところまできている.

Thank you for your Attention

Backup Slides

GeV “Non” Excess

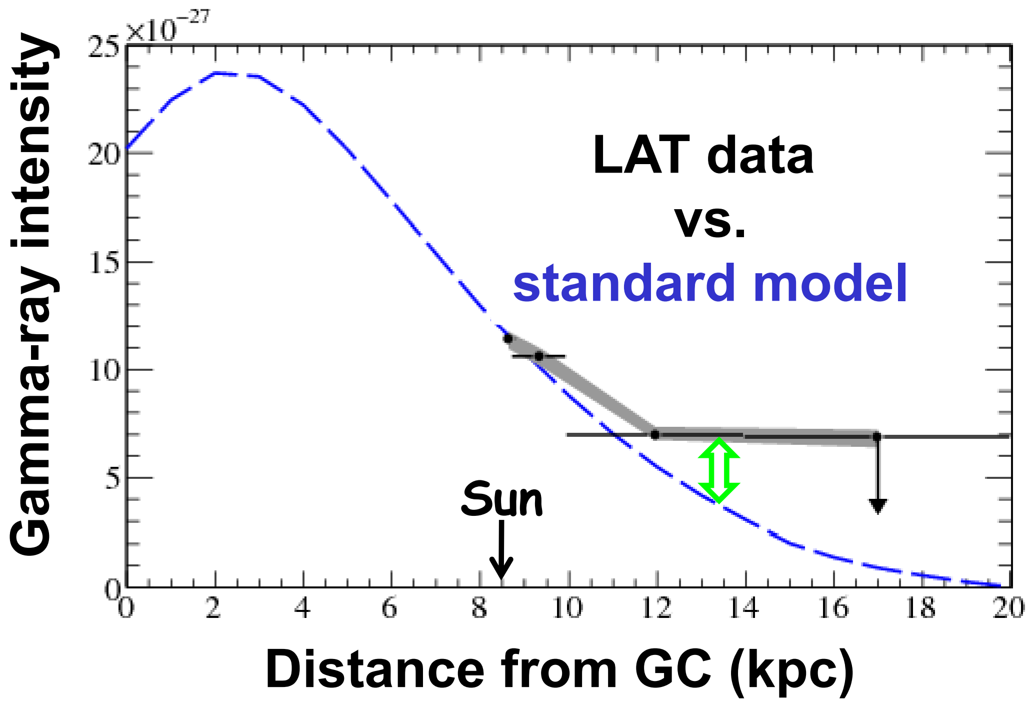
- instead, data is <u>compatible</u> with a model based on directly-measured CRs
  - solid basis to explore γ-ray sky



More CRs than Expected

- **Fermi detected more γs (= <u>more CRs</u>) than a prediction based on SNR distribution and standard CR halo.**

Abdo+10, ApJ 710, 133
(CA: Grenier, Tibaldo)



e^-/e^+ probe nearby sources

- They loose energy via synchrotron and IC
  - $dE/dt = -bE^2$
  - $T = 1/(bE) = 2.5 \times 10^5$ yr/(E/TeV)
- hence are not able to reach far from the source
  - $R = (2DT)^{0.5}$ = 0.4-0.8 kpc @ 1TeV

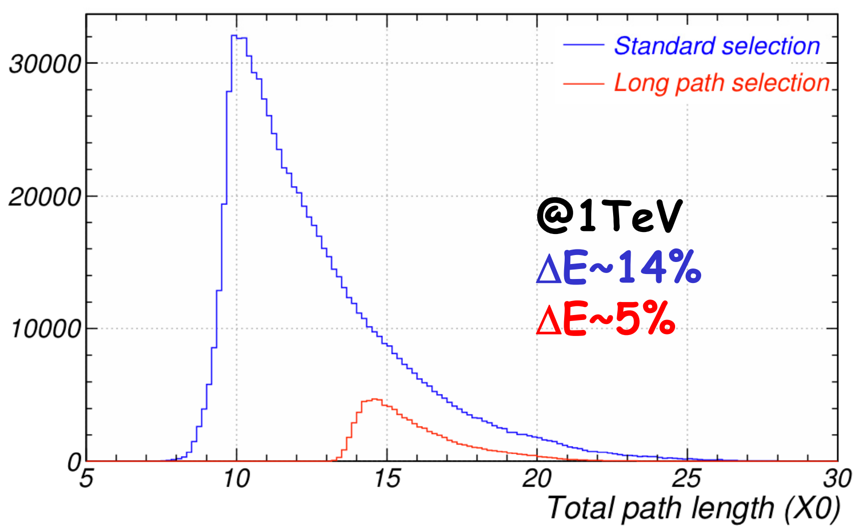
$D \sim (1\text{-}4) \times 10^{29}$ cm^2/s@TeV

- High Energy CR e^-/e^+ can probe nearby sources

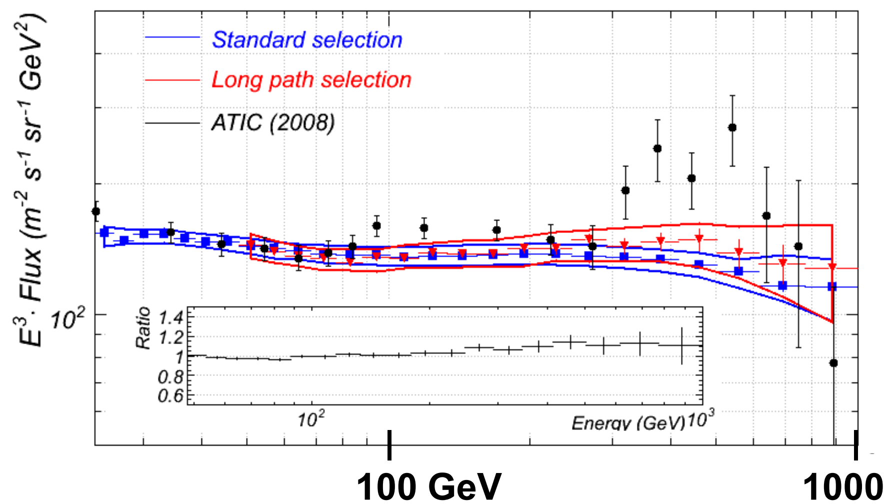
CRE by Fermi-LAT (2010)

- CREs collected for 12 month (data is doubled)
  - Cross-check with events with long path in CAL (>=13X_0)
  - LE extention using high latitude (low cutoff) data

15.9 X0 avg.
(1TeV shower peak @ 11 X0)



Consistent within their own systematics



T. Mizuno et al.

Summary

- **Diffuse γ-ray emission is a powerful probe for studying CRs and ISM**
- **Constraints on some DM models. Study of diffuse γ-rays and γ-ray object is important**
- **UL of CR anisotropy is close to what is expected for single nearby source**

Thank you for your Attention