Fermi/LAT and the Origin of Cosmic Rays

Fermi Symposium
Washington, DC
Nov. 2, 2009

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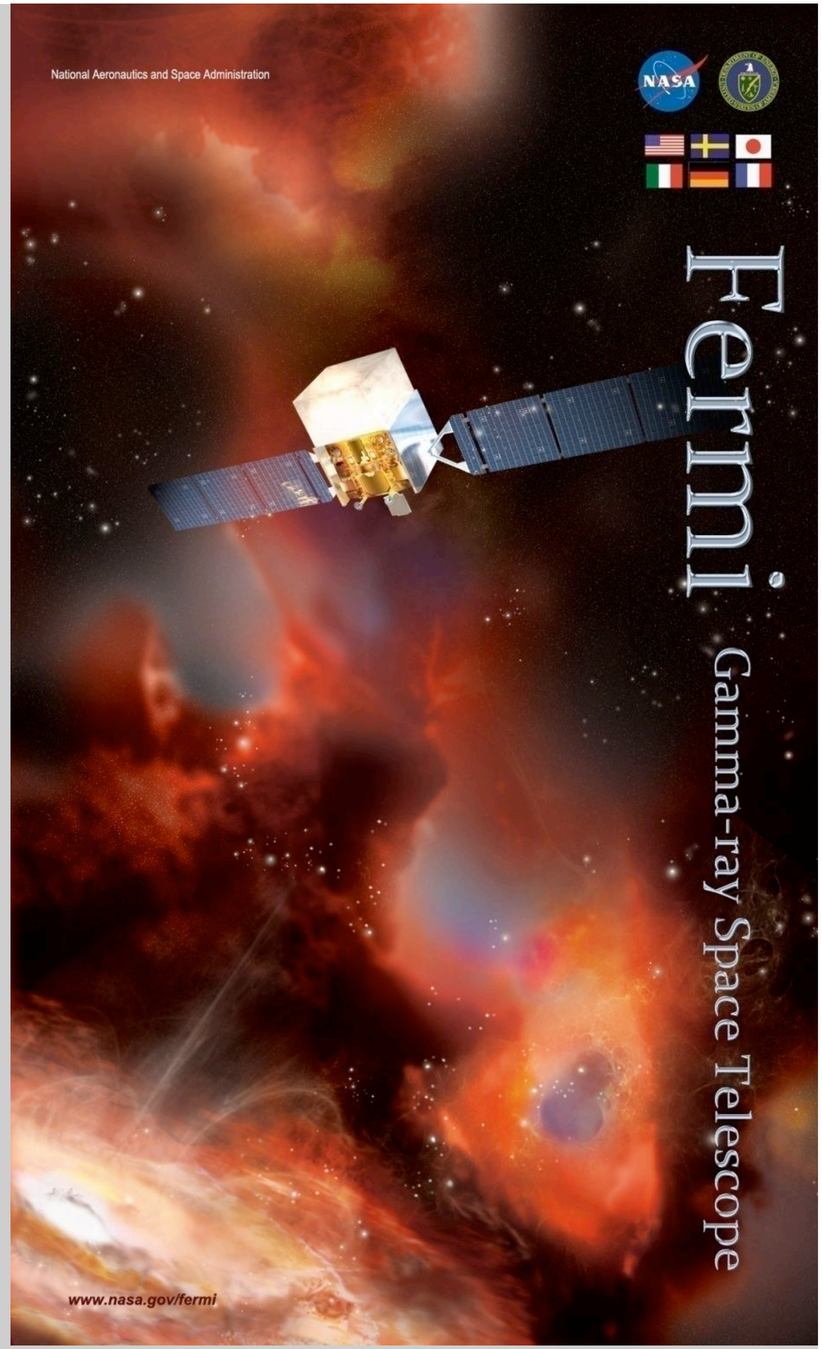
with thanks to my colleagues on
the *Fermi* LAT Collaboration

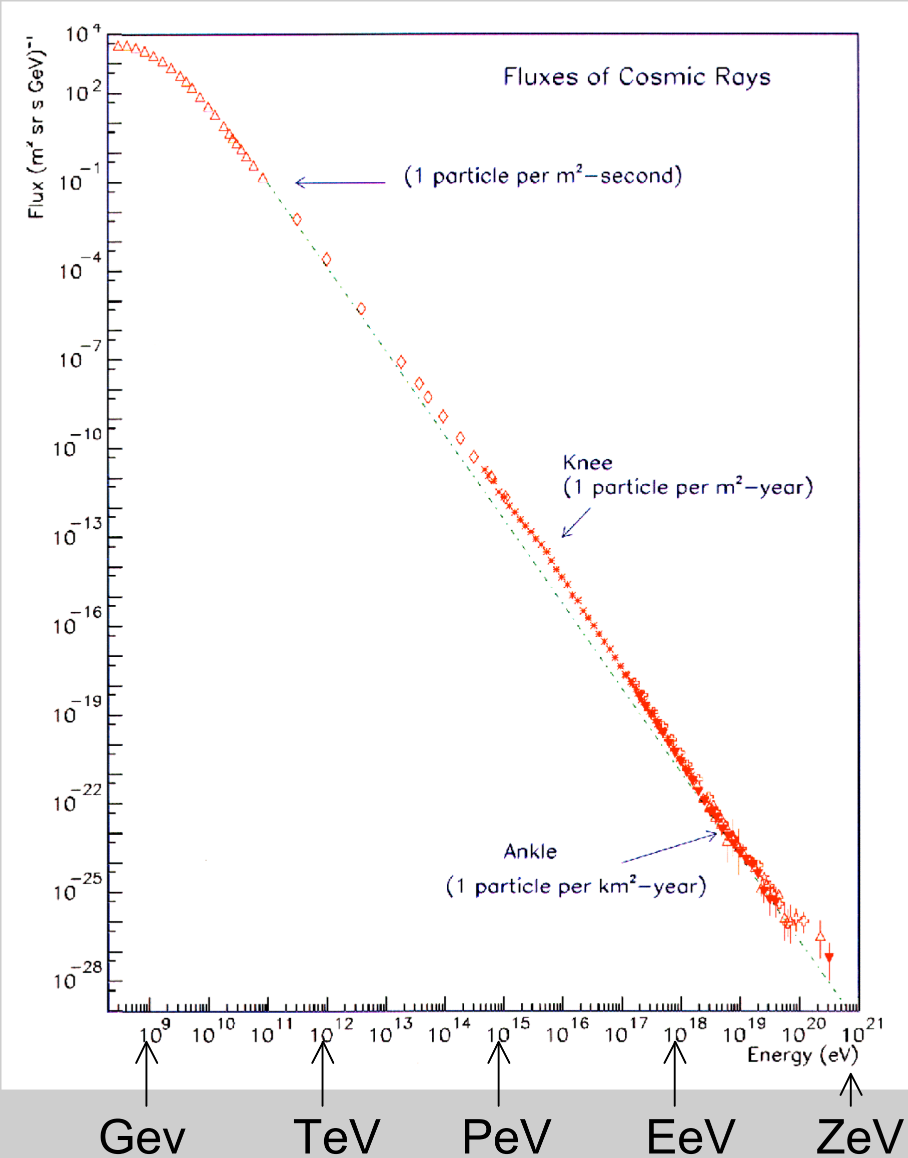
JFOrmes at comcast.net



Some Questions *Fermi* addresses

- **How do super massive black holes in Active Galactic Nuclei create powerful jets of material moving at nearly light speed? What are the jets made of?**
- **What are the mechanisms that produce Gamma-Ray Burst (GRB) explosions? What is the energy budget?**
- **How does the Sun generate high-energy gamma-rays in flares?**
- **How has the amount of starlight in the Universe changed over cosmic time?**
- **What are the unidentified gamma-ray sources found by EGRET?**
- **What is the origin of the cosmic rays that pervade the galaxy?**
- **What is the nature of dark matter?**

Galactic cosmic rays: all particle spectrum



0.1 GeV to 1 TeV our range of interest

low energy interstellar spectrum below few GeV is uncertain
affected by solar modulation
- Force field approximation
- Drift, helicity effects?

1 eV/cm^3

Thought to be accelerated in SNR by diffusive shock acceleration.

How are particles accelerated to "knee" and beyond in Supernova remnants?
- 10% efficiency required
- magnetic field amplification

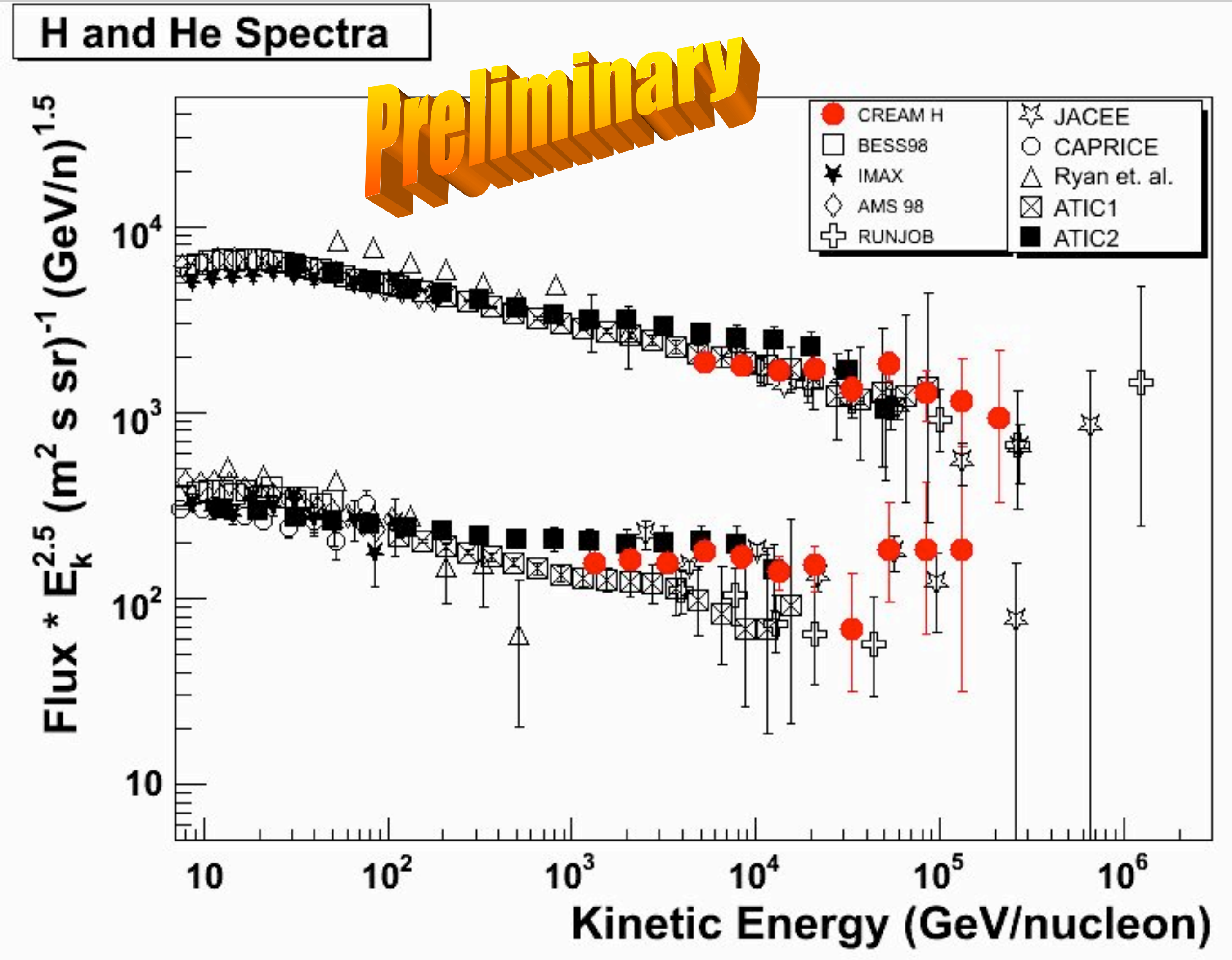
Some outstanding questions regarding the origin of cosmic rays that can be addressed by gamma-ray observations

- Can we actually see diffusive shock acceleration with magnetic field amplification accelerating cosmic ray protons in supernova remnants?
- What is the scale on which cosmic rays are uniform in the galaxy and what does this imply about their diffusion? Is the diffusion coefficient the same everywhere?
- How universal are CR? Are they a common feature of galaxies?
- How do we understand the local abundance ratio of electrons to protons in cosmic rays?
- What is the interstellar cosmic ray spectrum at energies below a few GeV, and hence get a better handle on the energy density of cosmic rays?
- Can a signature of dark matter be found in the spectra of the locally observed CR components? What constraints are implied by not seeing any signature?
- What is the distribution of sources in the galaxy, and how close are we to the nearest one? Discrete sources vs. uniform distribution of sources in models.

Outline

- Recent cosmic ray measurements
- Electrons by Fermi
- Cosmic ray intensity gradients
- Other galaxies (LMC, starbursts)
- Supernova remnants as sources of cosmic rays

Proton and helium spectra (CREAM 1)

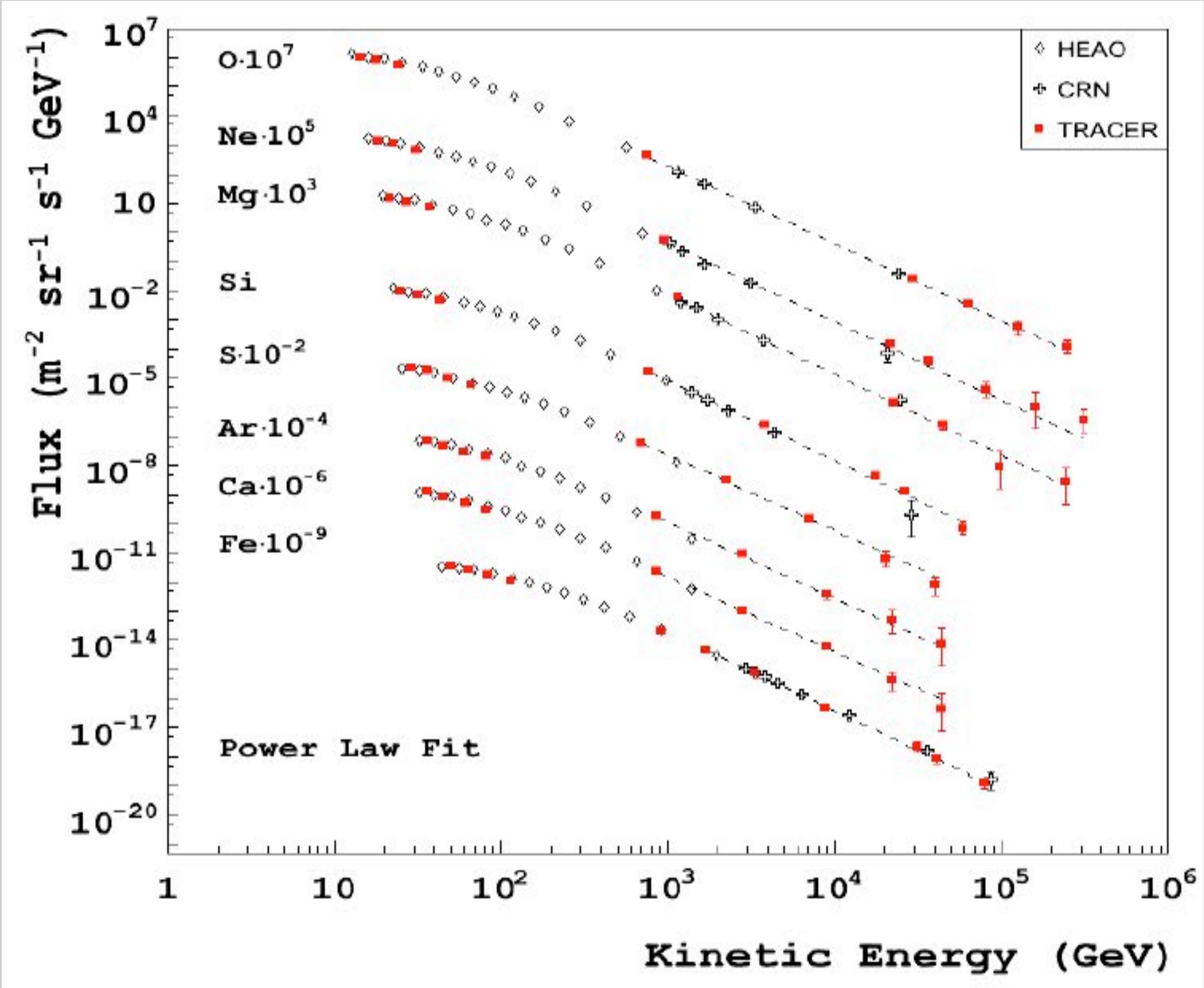


Spectra to 100 GeV/amu: $E^{-2.75}$

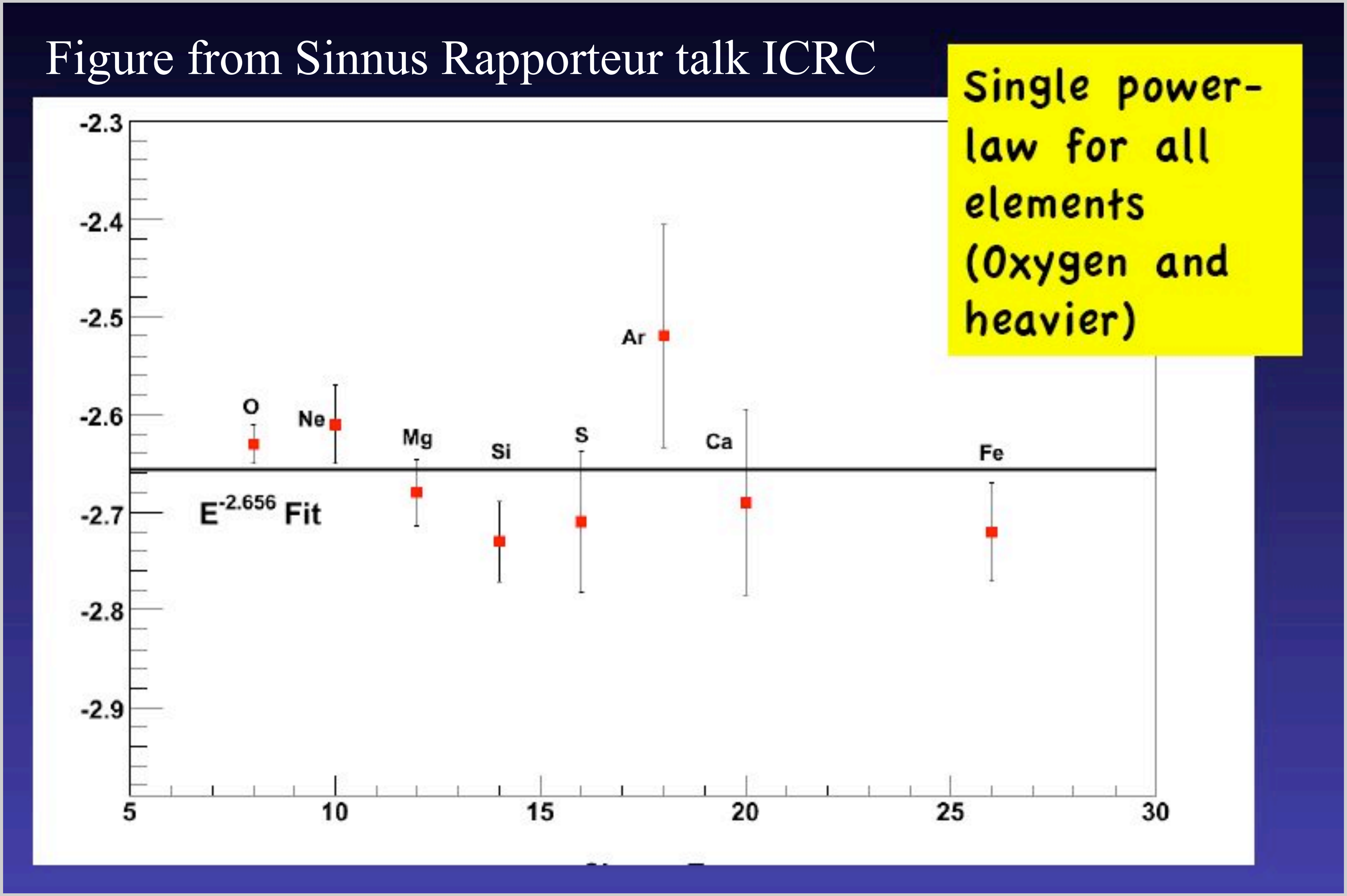
May be harder at higher energies.

Spectral hardening at highest energies predicted by modeling of diffusive shock acceleration.

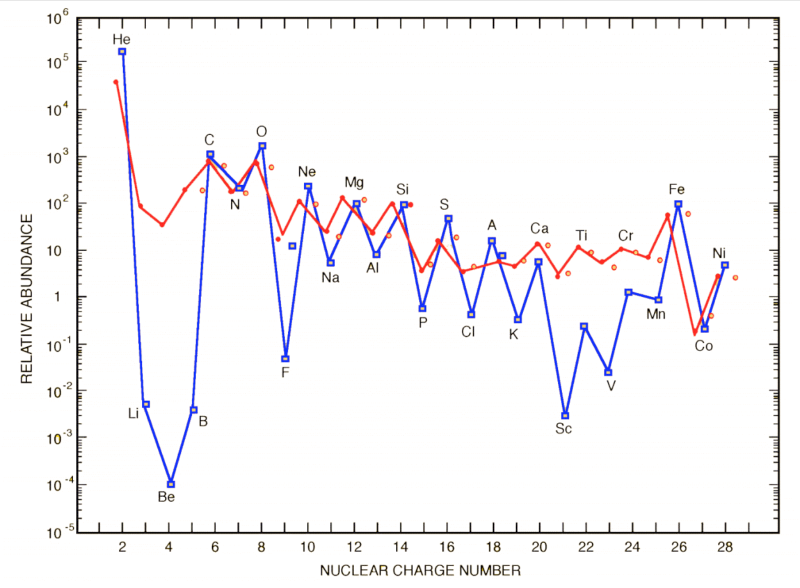
Spectra of heavy nuclei: U. of Chicago group



CREAM and TRACER data agree



Going at c, particle would leave the galaxy edge in (10-30) 10^3 years.



No Be, B at source, implying production by spallation and traversal through 5-10 g/cm^2. Consistent numbers come from antiprotons, other secondaries.

^{10}Be has half-life of 1.5×10^6 years.
Its partial survival => cosmic ray lifetime is ~3×10^7 years in galaxy.

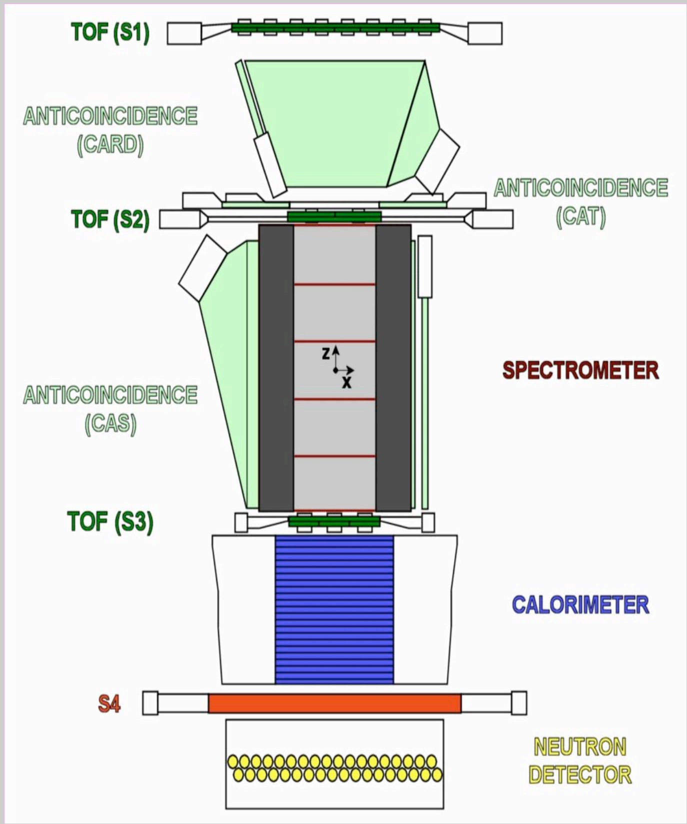
- **Charged particles are deflected by the Galactic Magnetic Field**

Proton Larmor radius in a 3 μG field:

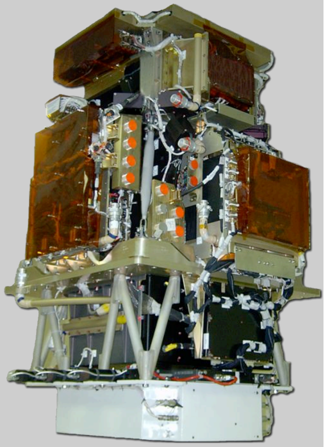
At E = 3 GeV, $r_g \cong$ 0.2 Astronomical units
At E = 3 $\times 10^{15}$ eV (knee), $r_g \cong$ 1 pc

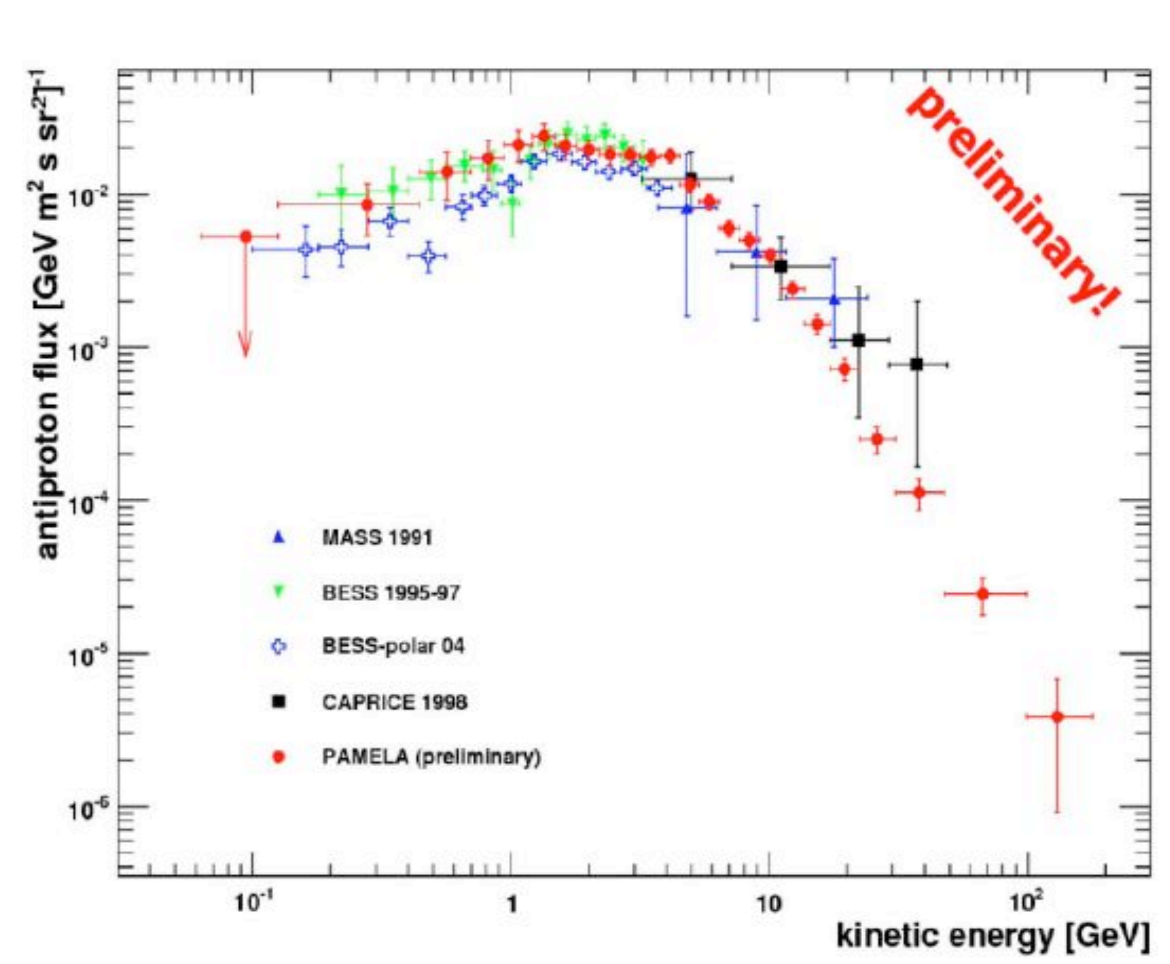
Cosmic Rays must *diffuse* from their sources to us!

Pamela antiprotons at high energy



antiprotons give a consistent "target depth"

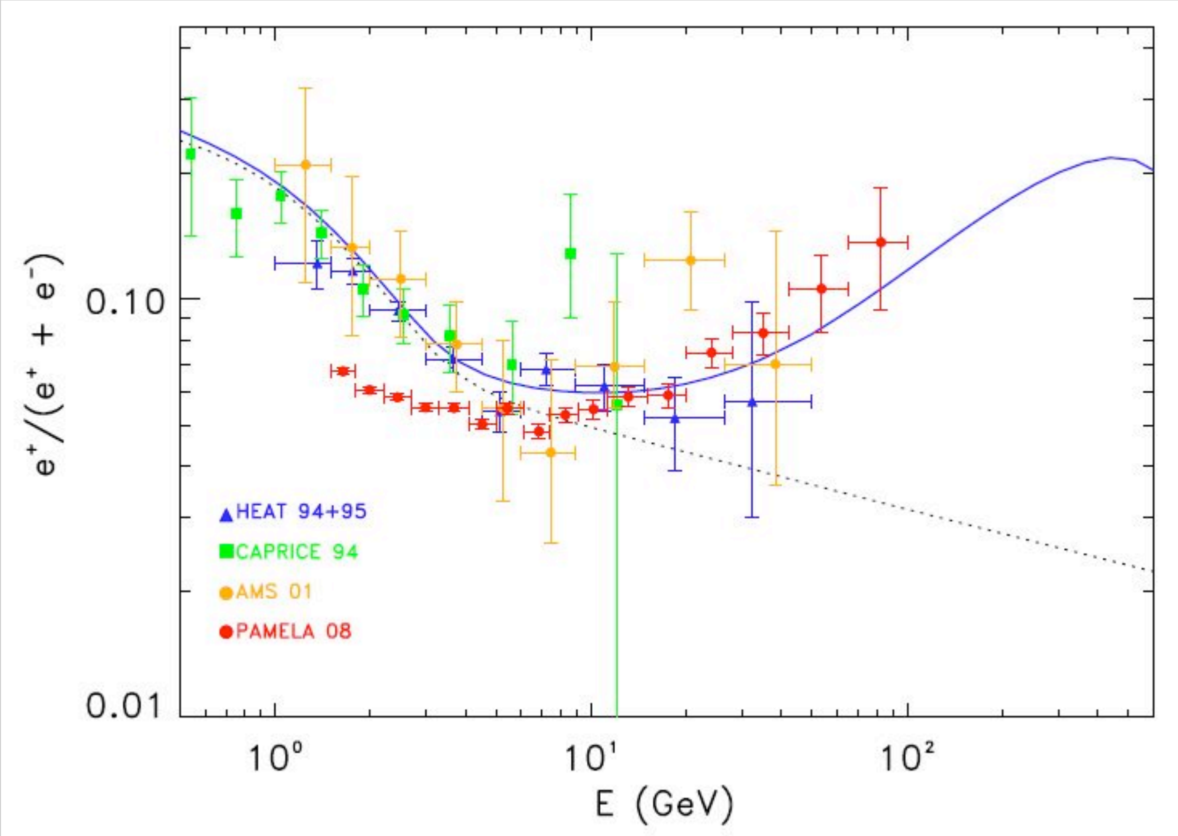




GF = 21.5 cm^2 sr

Launch 2006 June 15

Pamela measurements of positrons



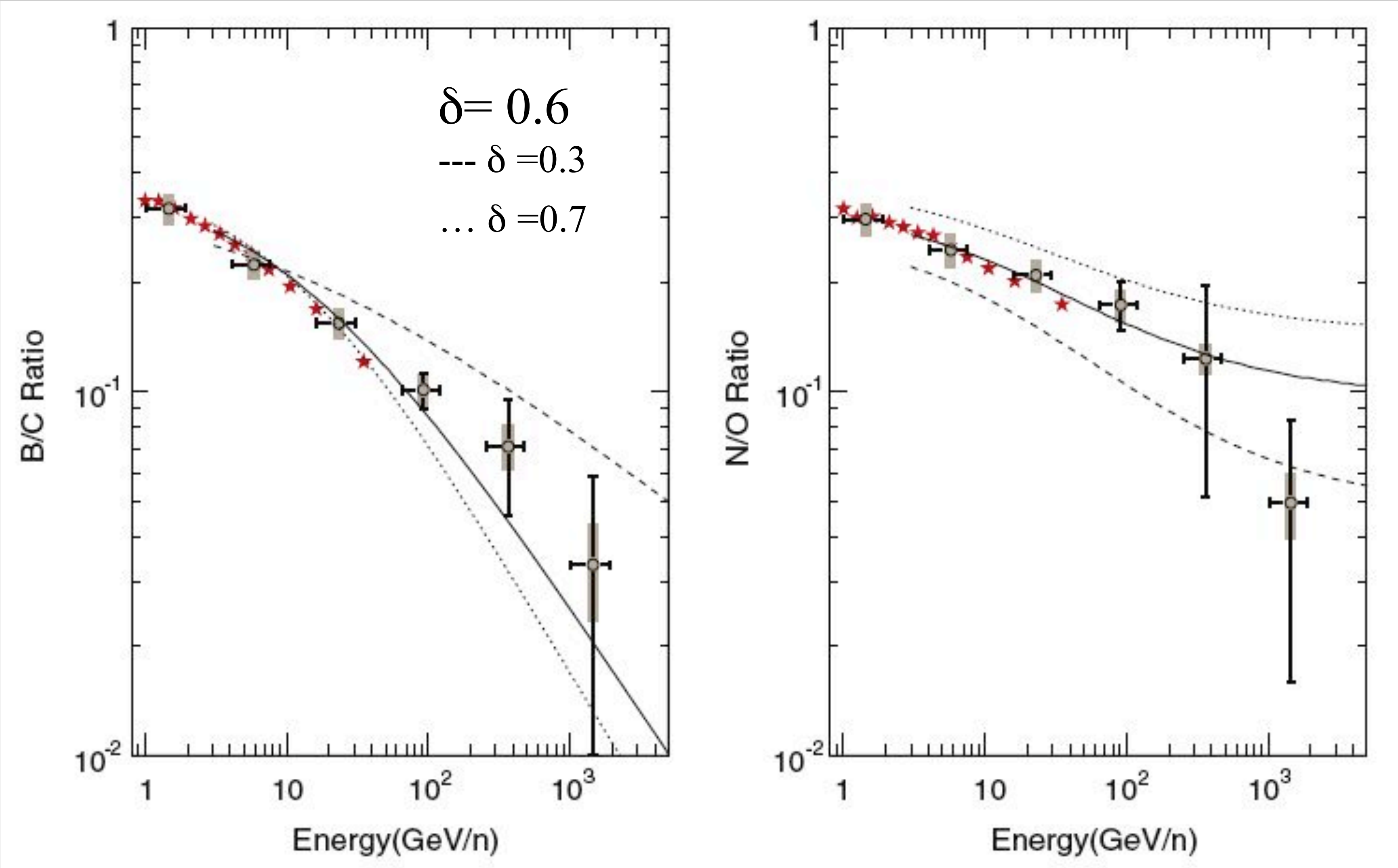
Low energy
solar modulation effect?

High energy increase requires component with a hard spectrum E^{-2} on top of secondary positron component.
Is there a hard e- component as well?

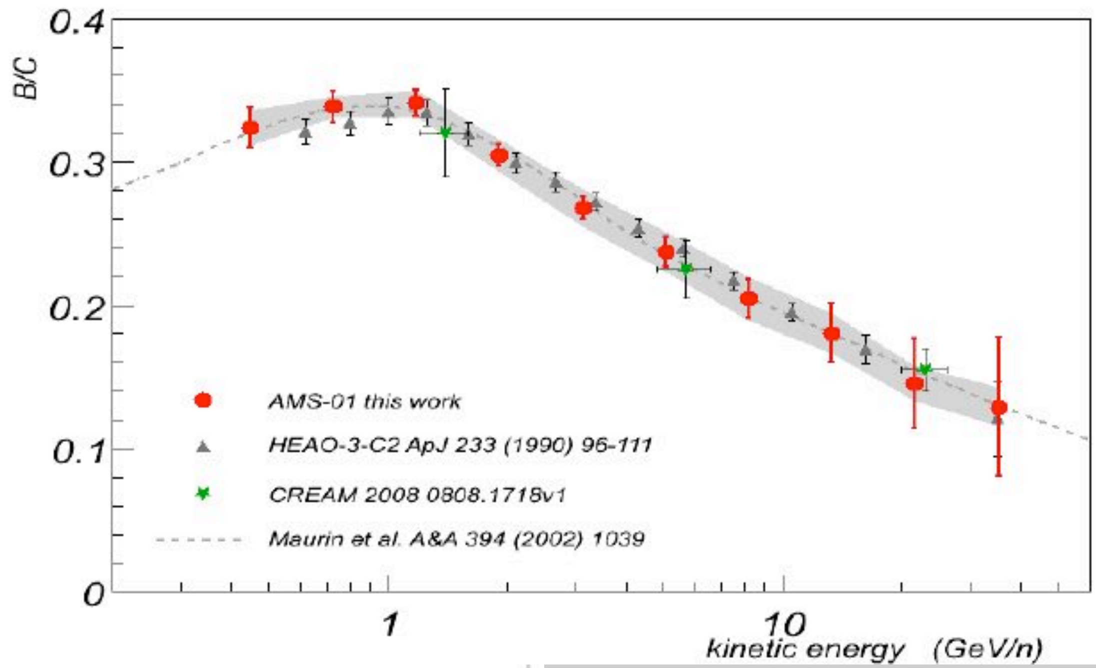
Dark matter, pulsars, positrons made in target material near sources?
Dark matter models constrained by antiprotons.

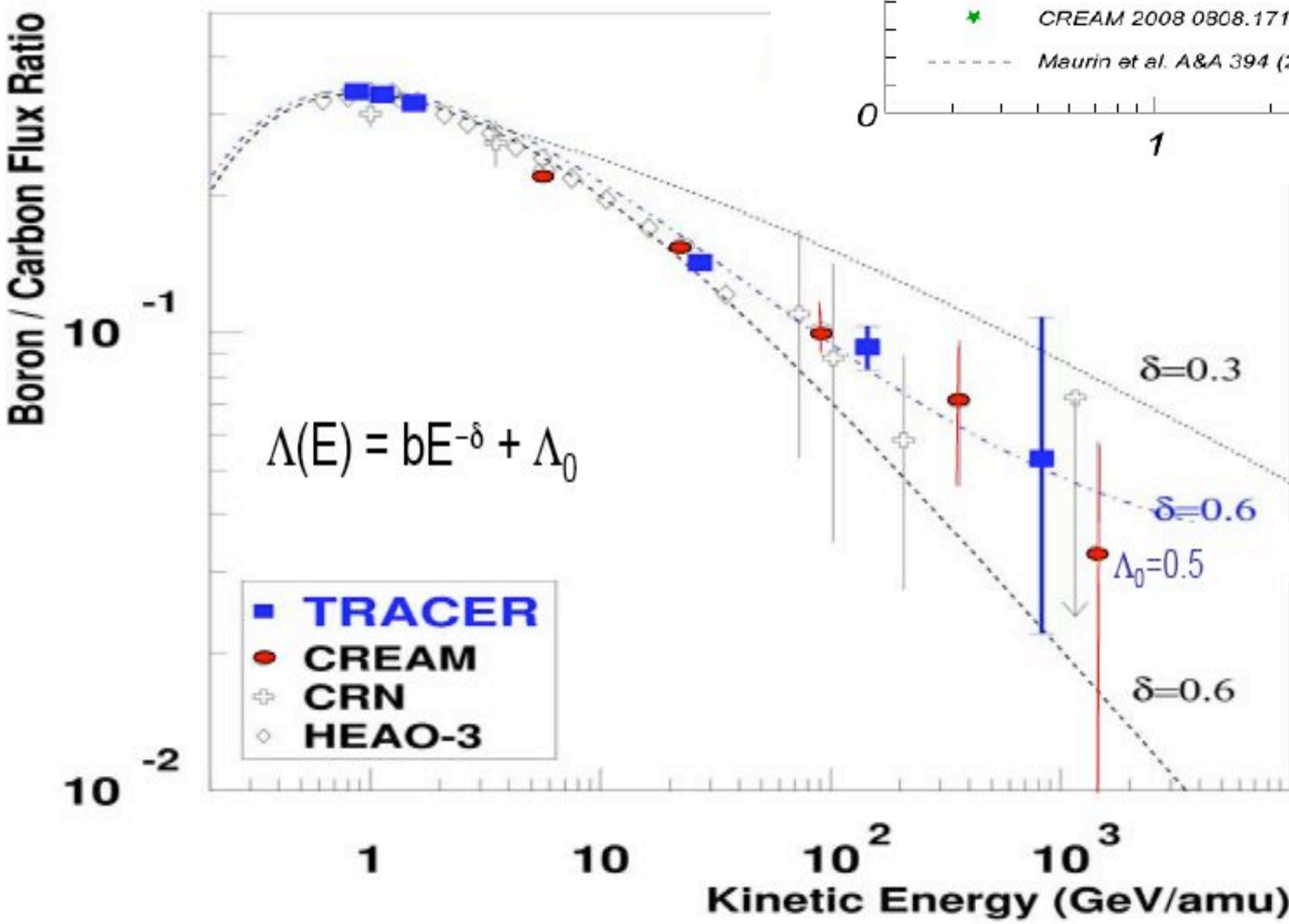
Extending the secondary to primary ratio to high energy

CREAM: Ahn et al. 2008, Astroparticle Phys. **30**, 133



Confirmatory evidence: AMS and TRACER





What is the source spectrum of cosmic rays?

Note: rigidity is total momentum per unit charge: R=Apc/(Ze)

- **Observed** $dN/dE = kE^{-\alpha}$

Observed index α is 2.75+/-0.05

- **Diffusion out of galaxy**

$$D(R,\beta) = \frac{1}{3}\lambda(R)\beta c$$

$$\lambda(R) = \lambda_0\left[R/R_0\right]^{\delta}$$

What is δ?
Observed 0.6±0.1
Iroshnikov-Kraichnan (0.5)
Kolomogorov 1/3=0.33
We don't know; it depends on 2nd order Fermi acceleration

- **Source** $dN/dE = kE^{-\alpha+\delta}$

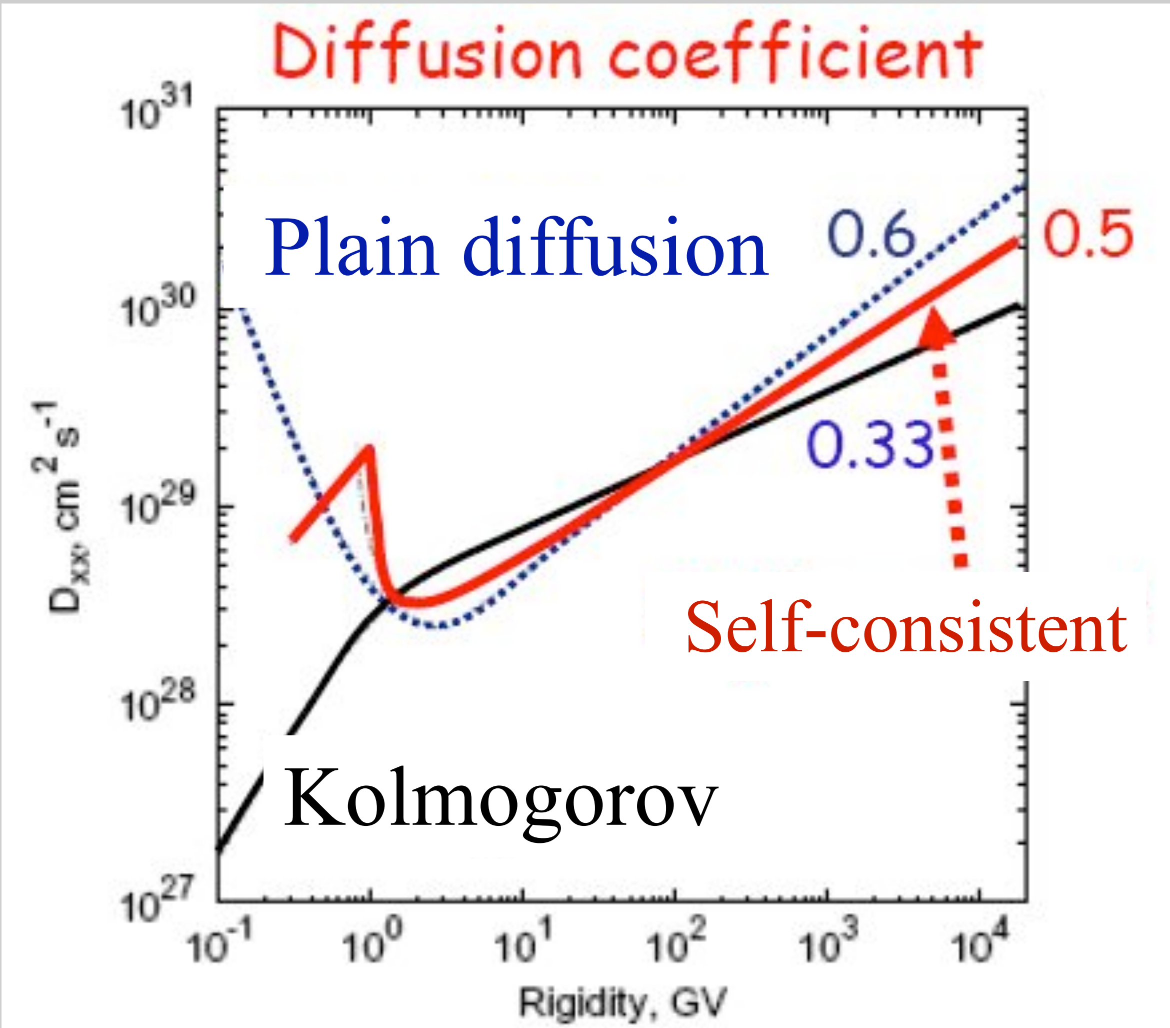
Source spectral index is unknown but expected by theory of diffusive shock acceleration to be between 2.1 and 2.4

It would be nice to observe the source spectrum through the gamma rays.

Iroshnikov-Kraichnan model with reacceleration and index 0.5.
Ptuskin et al., 2006, ApJ 642, 902-916

Diffusion coefficient

Note: rigidity is total momentum per unit charge: R=Apc/(Ze)



Parameters (model dependent):

$D \sim 10^{28} (R/GV)^{\delta}$ cm^2 s^{-1}

$0.38 < \delta < 0.57$

$Z_h \sim$ 4-6 kpc

($V_A \sim$ 30 km/s)

Iroshnikov-Kraichnan diffusion is significantly favored.

Di Bernardo et al. (2009) arXiv: 0909.4548v1; Maurin, Taillet &Donato (2002) A&A 394, 1039

Physical processes

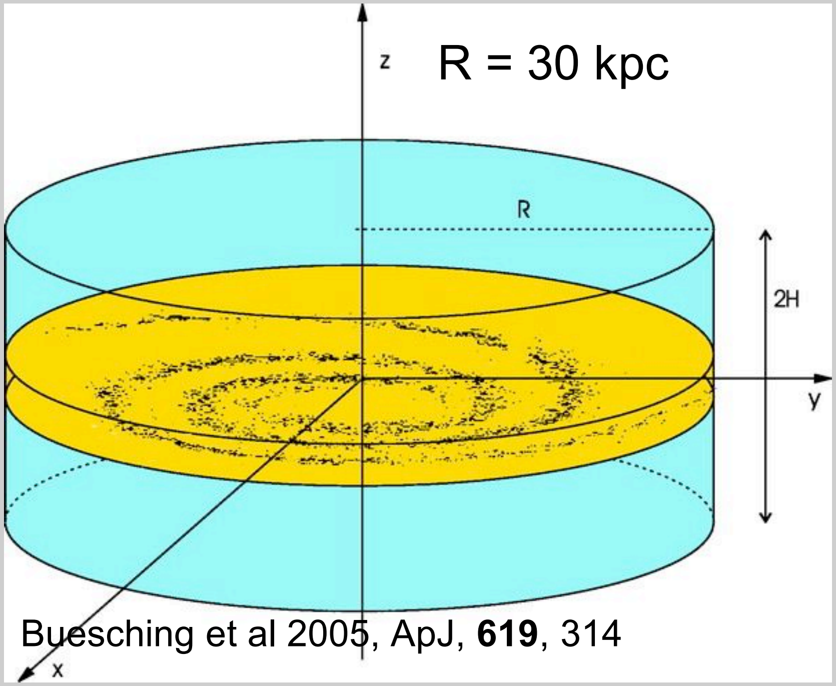
- **Sources (SNR) and spallation**
- **Diffusion (spatial), motion in magnetic fields**
  - **wave scattering**
  - **magnetic inhomogeneities**
  - **non-linear interactions**
- **Diffusion (energy) and escape**
  - **reacceleration**
  - **dispersion**
- **Convection (motion of the bulk plasma)**
  - **galactic wind**
  - **solar modulation**
- **Interactions**
  - **each nuclear species at least through iron**
  - **secondaries (Be, B, antiprotons, deuterium, sub-iron)**
- **Radioactive decay**
- **Energy loss (ionization, bremsstrahlung, Inverse Compton)**

Fit data, get parameters of model

- Data
  - Spectrum of nuclei and electrons
  - Relative abundances/spectra of secondaries
    - Antiprotons, B/C, [20<Z<2]/[Z=26], e+, ^{2}H and ^{3}H, gammas
    - Energy dependent
  - Gas distributions (HI, H_2 using CO as proxy, gas/dust via U(V-B) extinction)
  - Soft photon distributions (e.g. starlight, ir, microwave)
- Parameters
  - Source spectrum
    - power law index(es): nuclei, e-
    - breaks if required
  - Diffusion coefficient
    - magnitude
    - energy dependence
  - Relative importance of physical processes
- Check against new data, improve theoretical understanding and revise model

Modeling by GALPROP

Strong and Moskalenko, 1998, ApJ, **509**, 212



Buesching et al 2005, ApJ, **619**, 314

H = 2-10 kpc

h = 150 pc

$$D \approx \frac{v r_g}{3} \frac{B^2}{(\delta B_{res})^2}$$

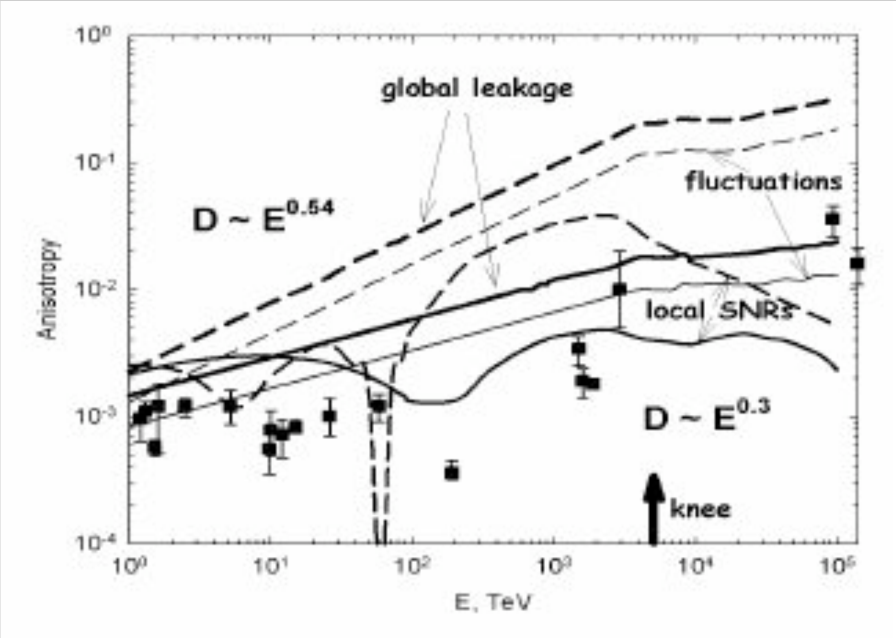
δB_{res} is the amplitude of the random field on the scale of the gyroradius of the particle

$$D = 3\times 10^{28} \beta R_{GV}^{1/3} cm^2 s^{-1}$$

Most GALPROP modeling to date with δ =0.33, hence with a source spectrum $E^{-(2.76-0.33)}=E^{-2.43}$

See e.g. Moskalenko et al., 2002, **565**, 280

The anisotropy problem



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δB_{res} is the amplitude of the random field on the scale of the gyroradius of the particle

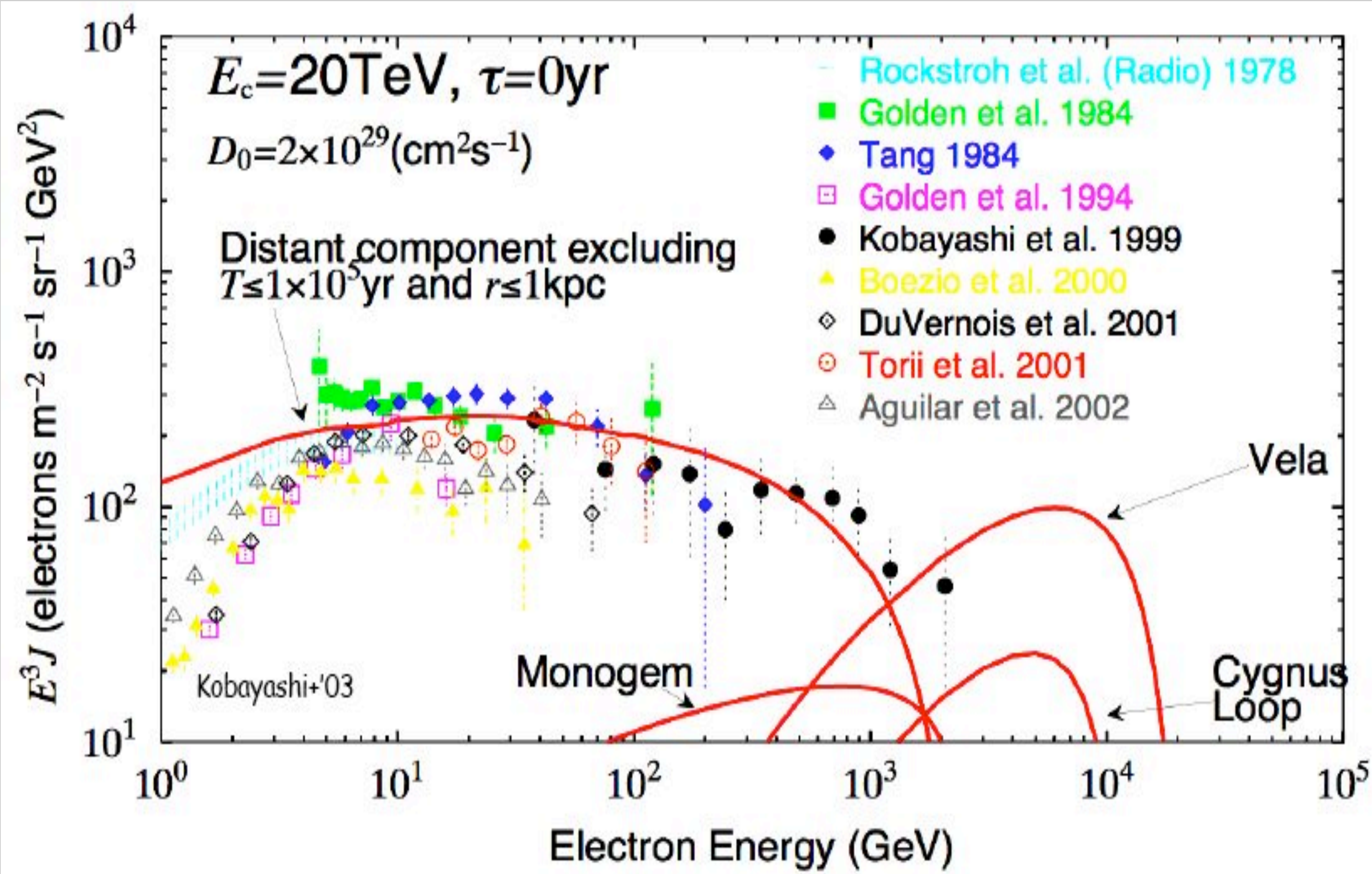
$$D = 3 \times 10^{28} \beta R_{GV}^{1/3} cm^2 s^{-1}$$

No slope change in spectrum, combined with the power law (almost) at the source, implies that the diffusion coefficient must have no change in slope either.

The observed anisotropy is << expected. May be due to our preferred location in the disk near the center of N-S symmetry.

Ptuskin, 2006, Journal of Physics: Conference Series **47,** 113–119

The situation before 2008



Original figure from Kobayashi et al. 2004, ApJ, **601**, 340.

Radiative energy losses by electrons (aka cooling)

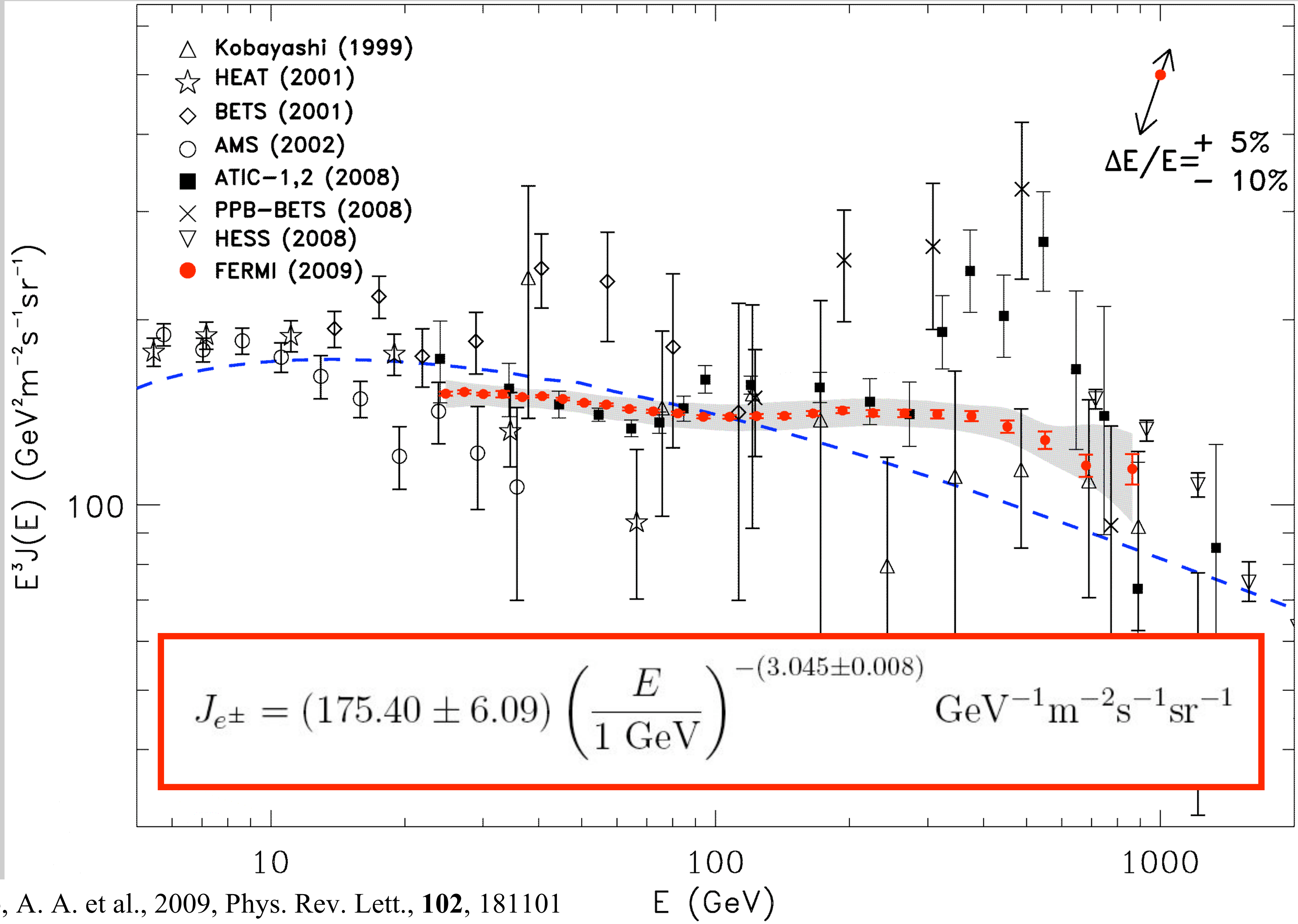
$$\frac{dE}{dt} = -bE^2 = -\frac{4\sigma c}{3(mc^2)^2}\left(\frac{B^2}{8\pi} + w_{ph}\right)E^2$$

σ is the Thompson cross section, B is the magnetic field and w_{ph} is the photon density.

At these energies, we need to use the Klein-Nishina cross section. We get b = 10^{-16} GeV/s and is slightly energy dependent using B = 5 μ-gauss.
In this B field, a 1 TeV particle loses half its energy in 150,000 years.
(See Stawarz, Petrosian and Blandford, 2009 arXiv 0908.1094)

The energy densities of photons are 0.26 eV cm^{-3} for CMB, 0.20 eV cm^{-3} for reemitted radiation from dust grains, and 0.45 eV cm^{-3} for stellar radiation, respectively (Mathis et al., 1983).

Fermi LAT result: cosmic ray electrons (e- + e+)

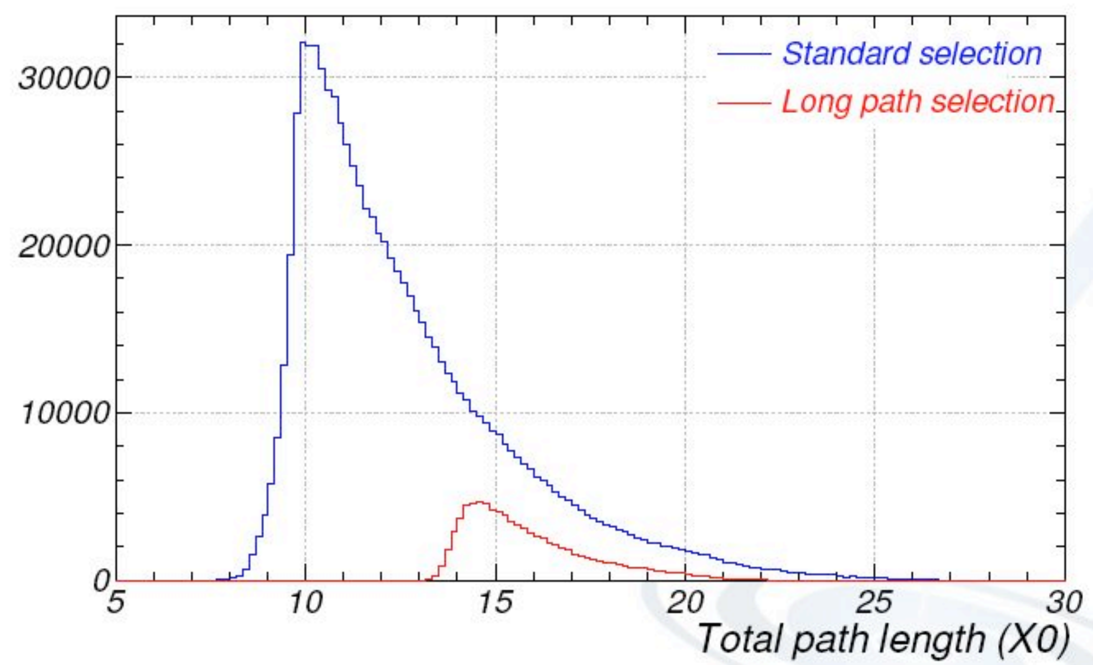


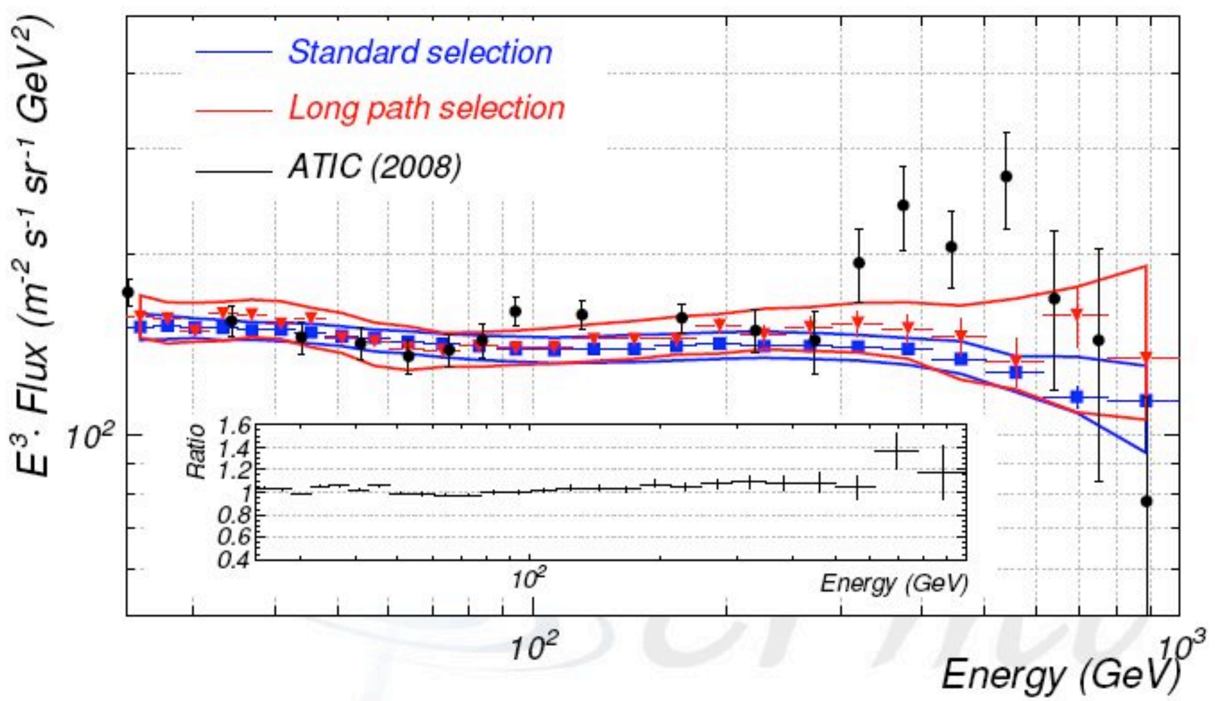
$$J_{e^\pm} = (175.40 \pm 6.09) \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-(3.045\pm0.008)} \mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

Abdo, A. A. et al., 2009, Phys. Rev. Lett., **102**, 181101

Checking the electron result

- Select events passing through only one calorimeter module
- Select events passing through at least 13 X_o
- Track starts in thin target or upper part of tracker

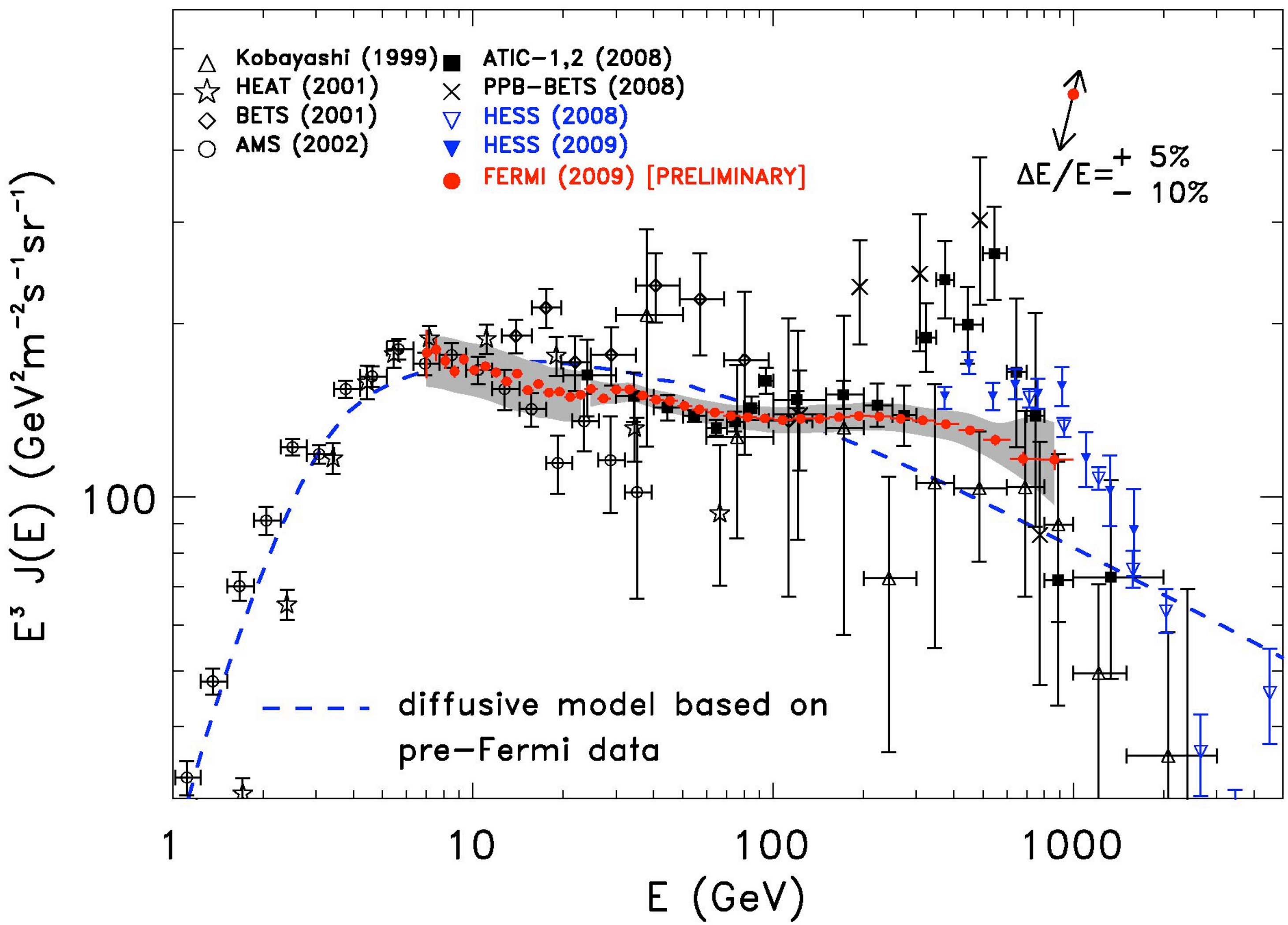




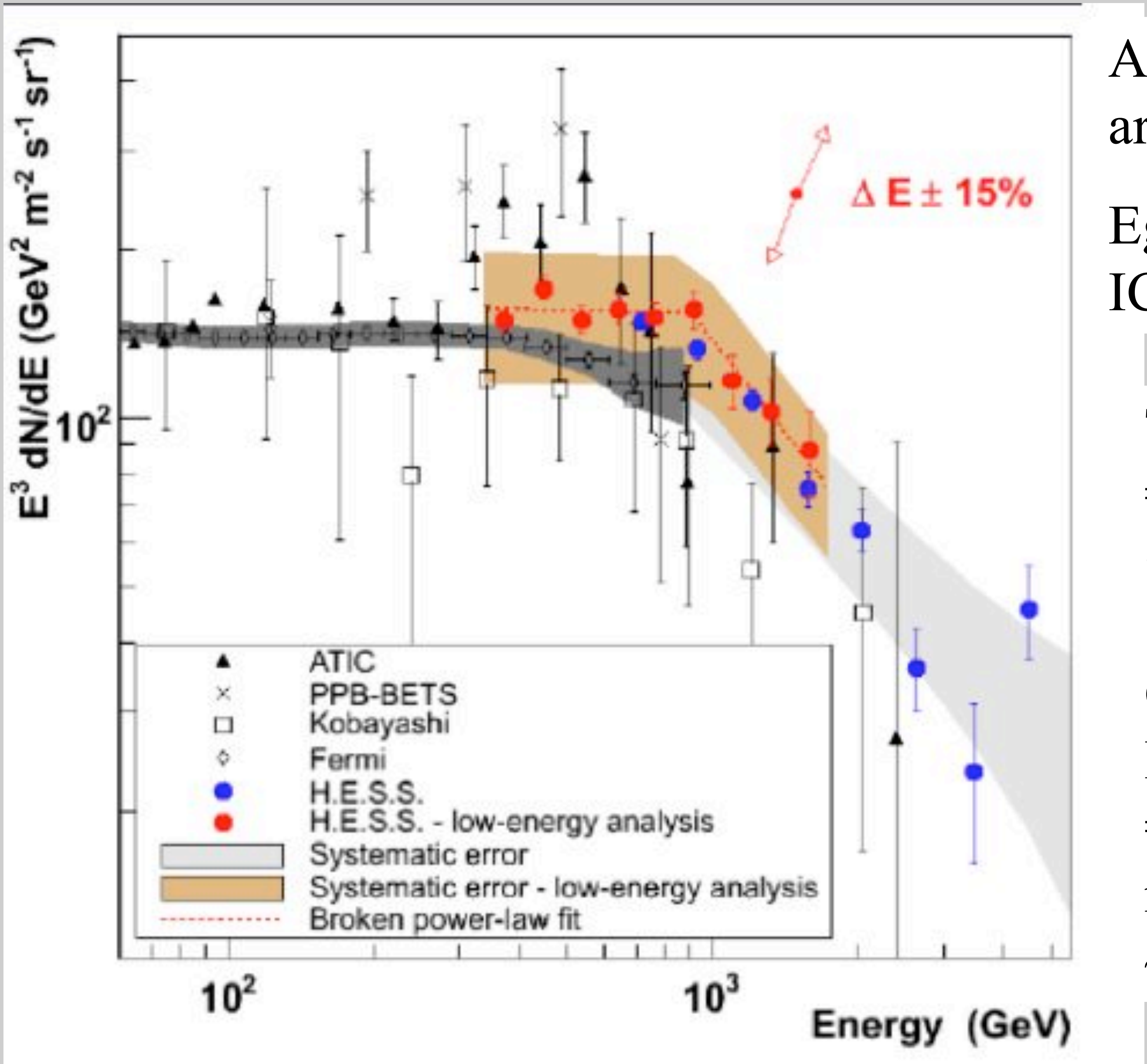
J. F. Ormes Fermi LAT

Fermi electrons:
Extended to lower energies

More in upcoming talk by L. Latronico



HESS electrons



Aharonian et al., 2009
arXiv: 0905.0105v1

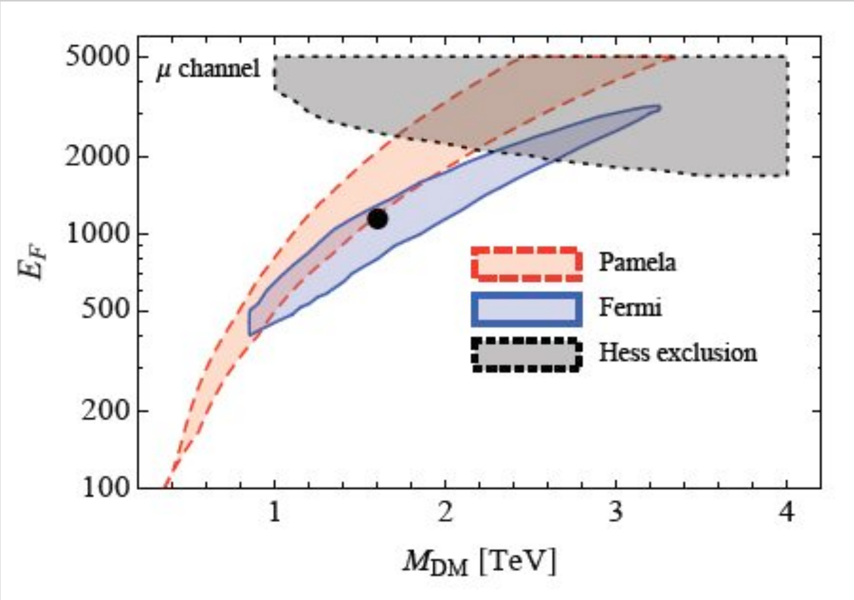
Egberts et al. 2009
ICRC0983

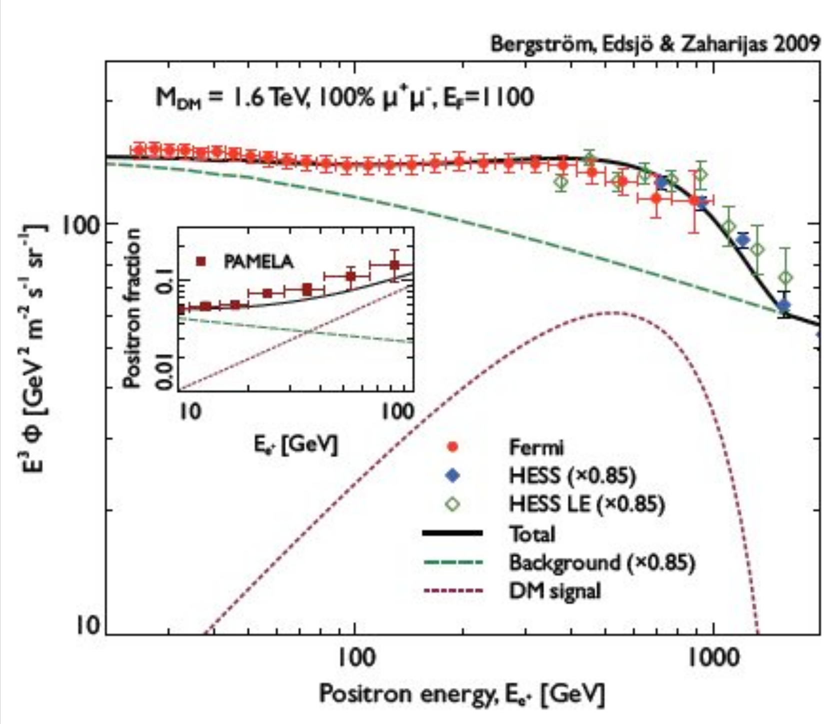
TeV electrons
=>
source within kpc

Cooling cutoff &
D=3x10^{28} cm^2 s^{-1}
=>
no source within
~400 pc

Dark matter interpretation of recent electron and positron data

Many models being published. Postulates constrained by antiproton spectrum to leptonic channels, maybe even to muonic decay channels if "feature" is to be explained by dark matter.



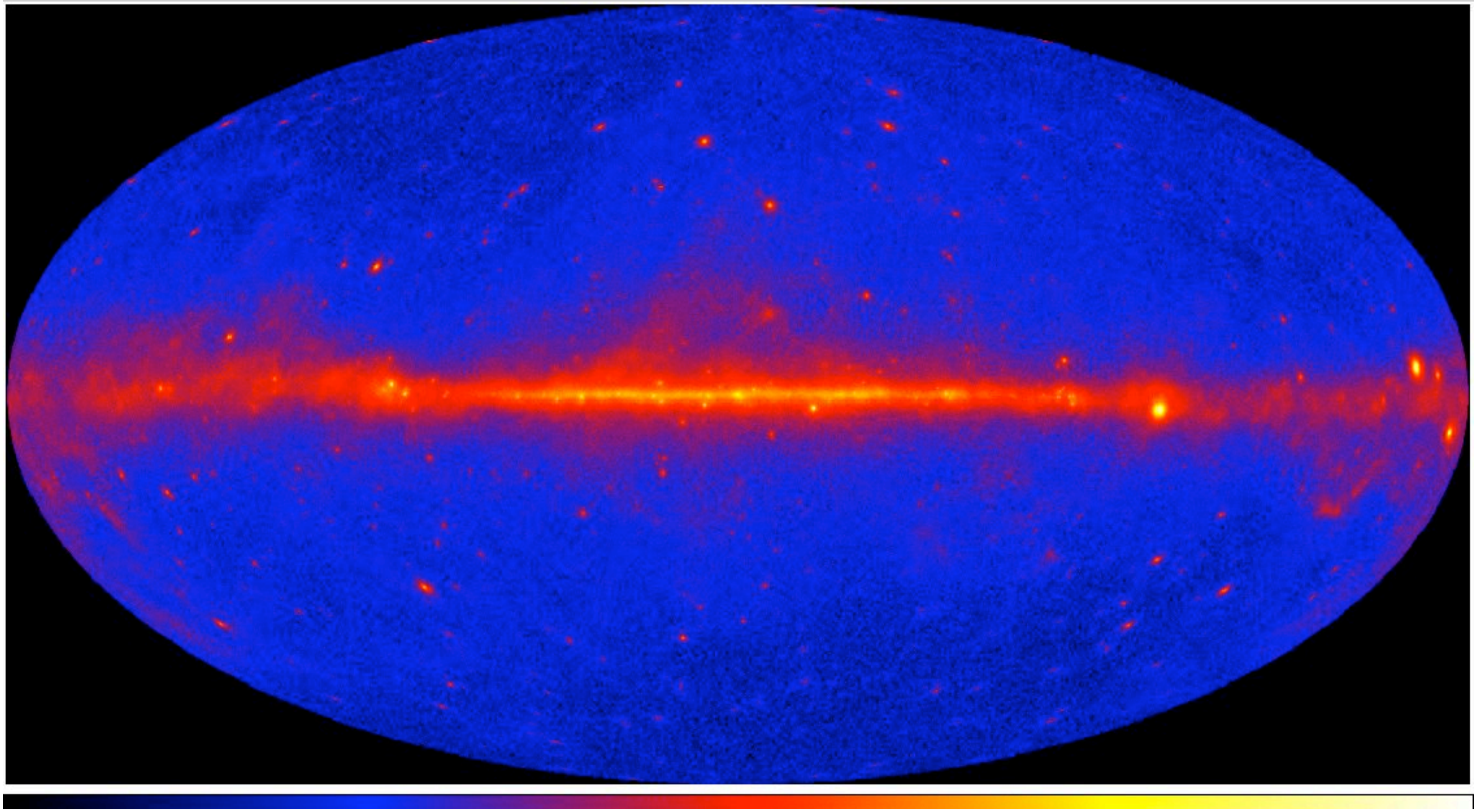


Bergrström, Edsjö and Zaharijas, 2009, arXiv: 0905.033v1, astro-ph, May 4, 2009

Electron summary

- Source spectrum probably harder than thought
  - Equilibrium CR spectrum 20 GeV to 1 TeV determined
    - by escape? $E^{-(3.05-0.56)} = E^{-2.5}$ or $E^{-(3.05-0.33)} = E^{-2.72}$
    - by electron cooling? $E^{-(3.05-1.0)} = E^{-2.05}$
  - Same as protons?
- Nearby source required?
  - Pamela positrons plus "harder e+e- specrum"
  - Are we seeing structure due to multiple sources?
    - pulsars (suggested by the positrons)
    - Supernova remnants (whence cometh the e+?)
      - $\gamma+\gamma$ in high photon density environment near the sources?
    - dark matter (if so, highly constrained models)

Fermi LAT 1 year sky image (log scale): mostly galactic diffuse

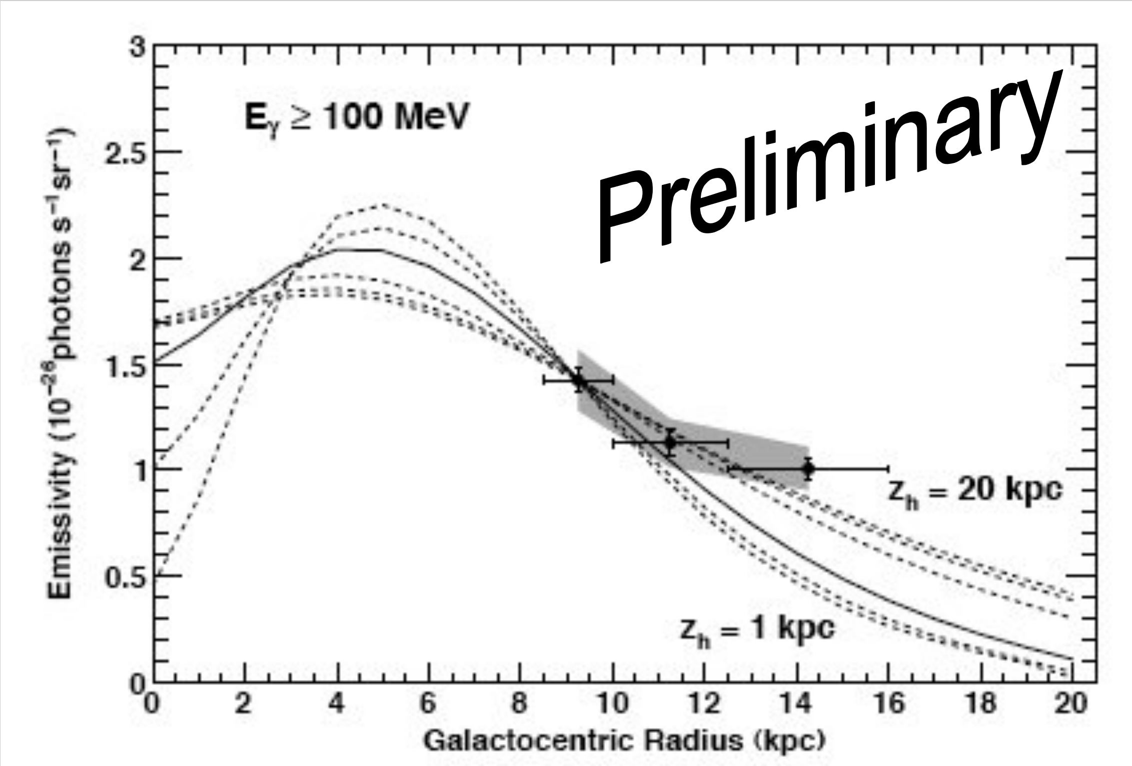


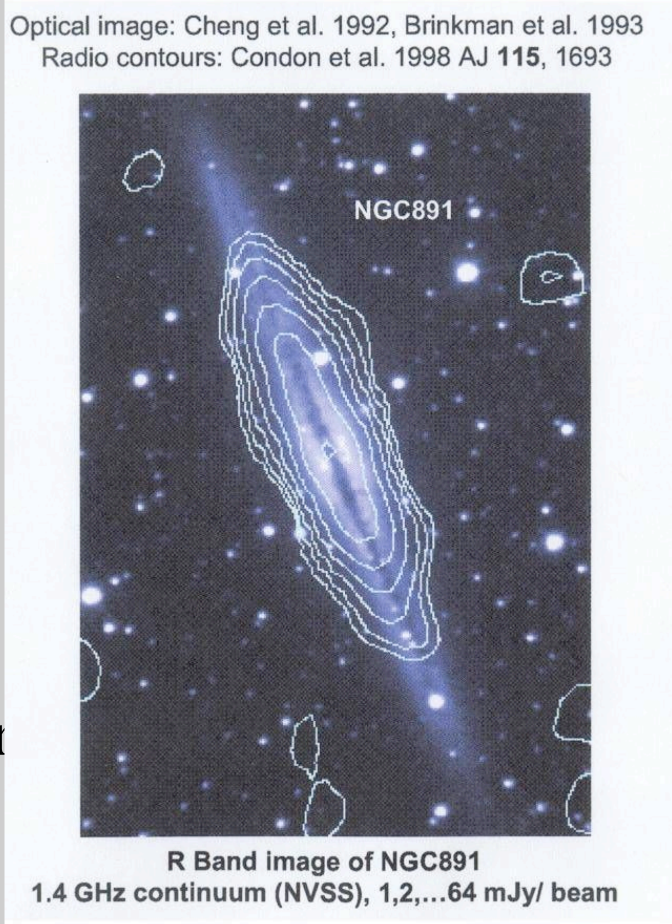
Cosmic ray intensities as inferred from gamma ray fits to galactic diffuse component.

- Cosmic ray intensities
  - Nearby (high latitude) same as at Solar system
  - No apparent arm/inter-arm contrast
  - CRs fully penetrate clouds
- Gould belt
  - Need 50% more matter to explain gamma rays assuming the same CR intensity
  - Correlation of results with E(B-V) extinction maps (gas/dust)
- Decrease of emissivity outside the solar circle.
  - Spectra remain the same
  - X_{CO} variable, rises in outer galaxy

More in following talk by Troy Porter

Gamma-ray emissivity in outer galaxy:
Longitude 210 to 250 degrees



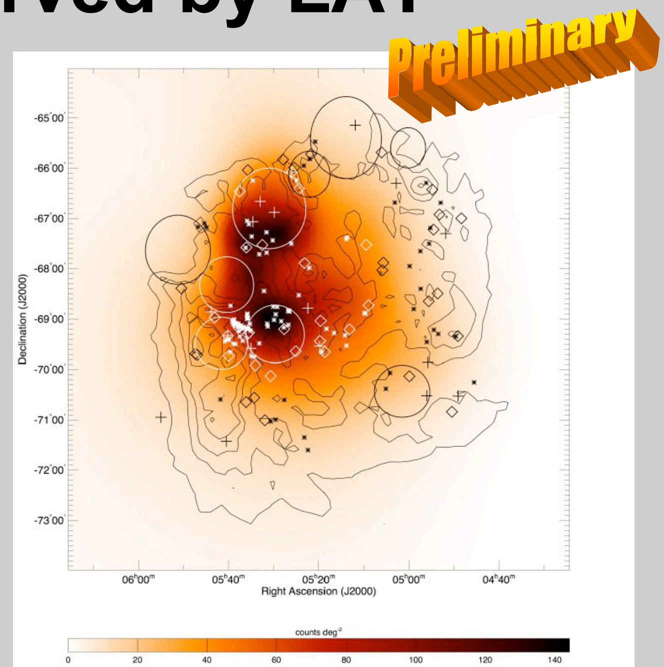


Curves are for GALPROP models with incr
Data suggest larger volume for halo and/or
outer galaxy than previously considered.

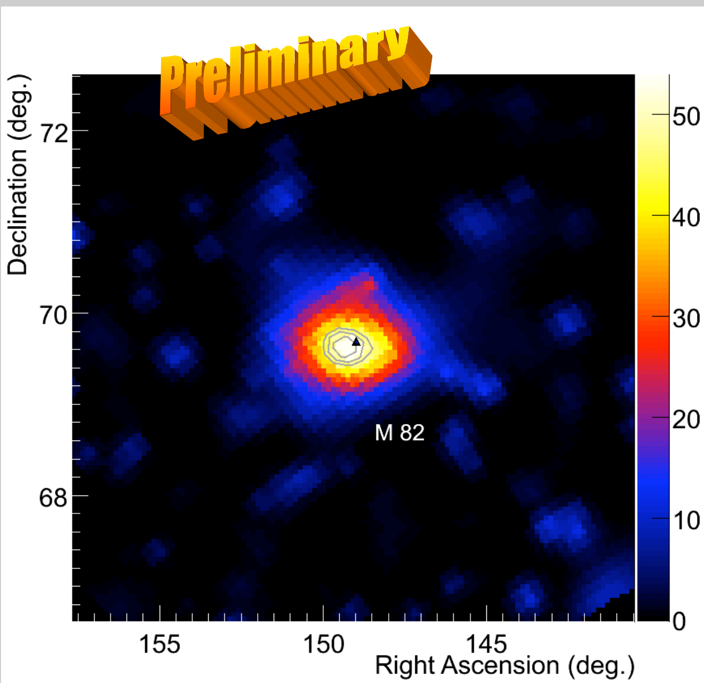
LMC, M82 and NGC253 observed by LAT

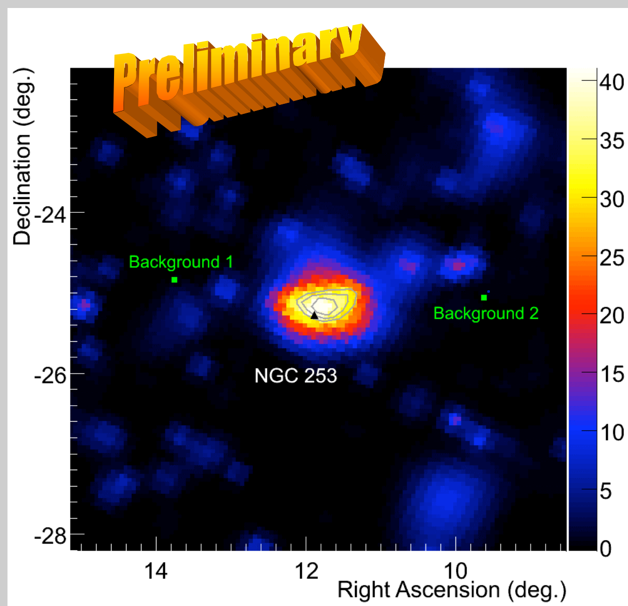
Hear plenary talks on Wednesday

- **LMC**
  - pulsar subtracted
  - emission is peaked in where star formation peaks (traced by H_{alpha}), not column density
- **M82 and NGC253**
  - starburst galaxies
  - spectra typically hard: $E^{-2.2}$

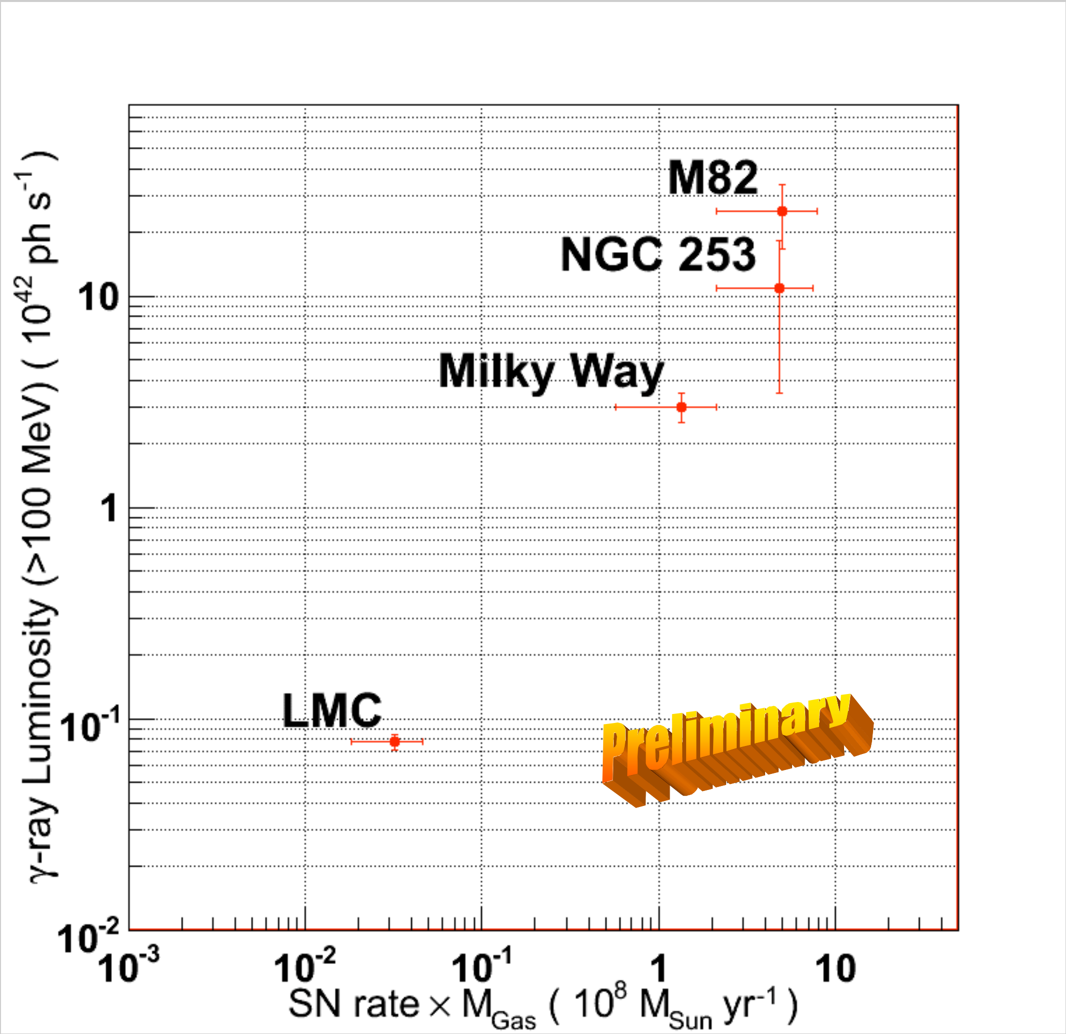


TS maps





Example of studies to come



- Gamma-ray luminosity is inferred from the observed flux
  - distance uncertainty is included
- SN rate, gas density, cosmic-ray intensity, etc. are not in general uniform throughout galaxies.
- LAT can spatially resolve the Large Magellanic Cloud and see that most of the high energy emission comes from the star forming region 30 Doradus.
- The majority of star formation in both M82 and NGC 253 is localized to small (order 100 pc) central starburst regions.

Conclusion and comments

- Fermi is *advancing* our detailed understanding of the origin of cosmic rays (CR)
  - direct measurements of local CR electron spectrum
- LMC and starburst galaxies are gamma-ray sources containing CR
  - intensity related to star formation rate * number of target nuclei
- CR intensity is fairly uniform within few kpc of sun (little arm/interarm contrast)
- Higher CR intensities may be associated with star forming regions
- Remote sensing: gamma ray spectra can identify the underlying CR spectra