Sources of GeV Photons and the Fermi Results

Chuck Dermer, NRL
http://heseweb.nrl.navy.mil/gamma/~dermer/default.htm

1. GeV instrumentation and the GeV sky with the Fermi Gamma-ray Space Telescope
2. First Fermi Catalog of Gamma Ray Sources and the Fermi Pulsar Catalog
3. First Fermi AGN Catalog
4. Relativistic jet physics and blazars
5. **γ rays from cosmic rays in the Galaxy**
6. γ rays from star-forming galaxies and clusters of galaxies, and the diffuse extragalactic γ-ray background
7. Microquasars, radio galaxies, and the extragalactic background light
8. Fermi Observations of Gamma Ray Bursts
9. Fermi acceleration, ultra-high energy cosmic rays, and Fermi

Thanks to S. Funk, A. Strong, I. Moskalenko, N. Giglietto, W. Atwood, S. Digel

γ rays from cosmic rays

- Cosmic rays and GALPROP
- Estimate the Galactic γ-ray emissivity per H-atom due to
  - pion production by cosmic ray protons
- Solar and Lunar γ rays
- Cosmic-ray electron spectrum
- EGRET excess
- Supernova remnants
- Colliding Winds

- Nonthermal radiation processes requires an entire course to survey
- Can treat in δ-function (or step function) approximation
  - **Mean Energy Loss**
  - **Mean Energy of Secondary Particle or Photon**
- Detailed treatment can be found in my book with Govind Menon

Theory of Cosmic Ray Origin

- Cosmic rays: energetic cosmic particles composed mainly of protons and ions
- Cosmic rays: an important particle background in the space radiation environment

1. **Particle radiations: Solar Energetic Particles, Cosmic Rays, Neutrinos**

3. **Photon Radiations**

   Radio emission (cosmic ray electrons)

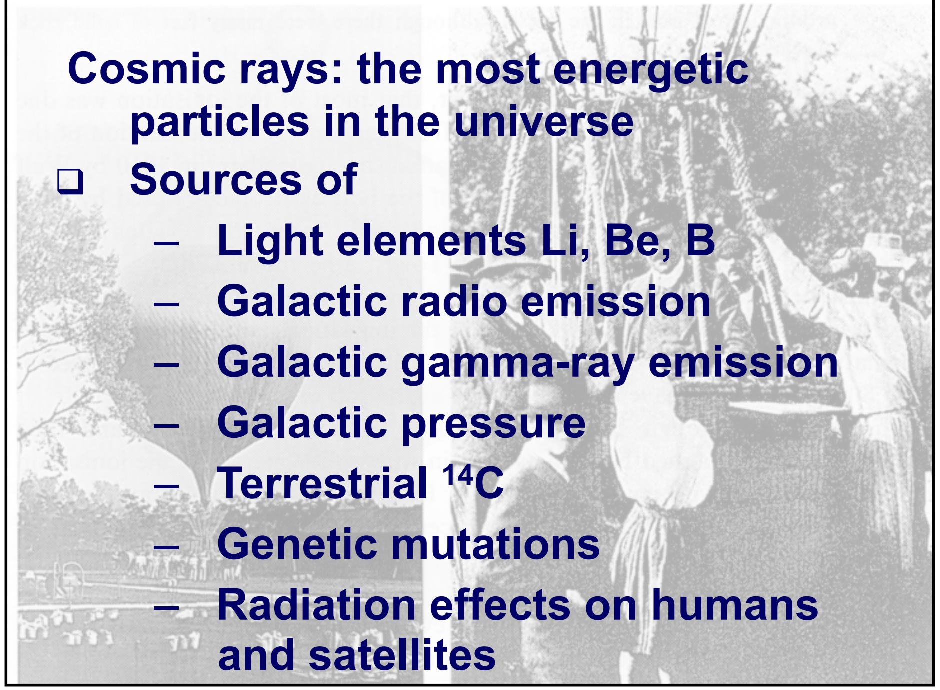
   X-rays and γ rays (cosmic ray electrons, protons, and ions)

- Cosmic Ray Origin

  Galactic GeV- PeV Cosmic Rays (accelerated by Supernova Remnants?)

  Ultra-high Energy Cosmic Rays (powered by black holes?)

- ***Cosmic rays*** do not point directly to their sources, because of magnetic fields in space.
- ***Gamma rays*** indicate sites of high-energy particles, but can be attenuated by matter or other photons at the source or in transit from the source to Earth.
- ***Neutrinos*** would unambiguously point to the sources of the cosmic rays, but are faint and difficult to detect.

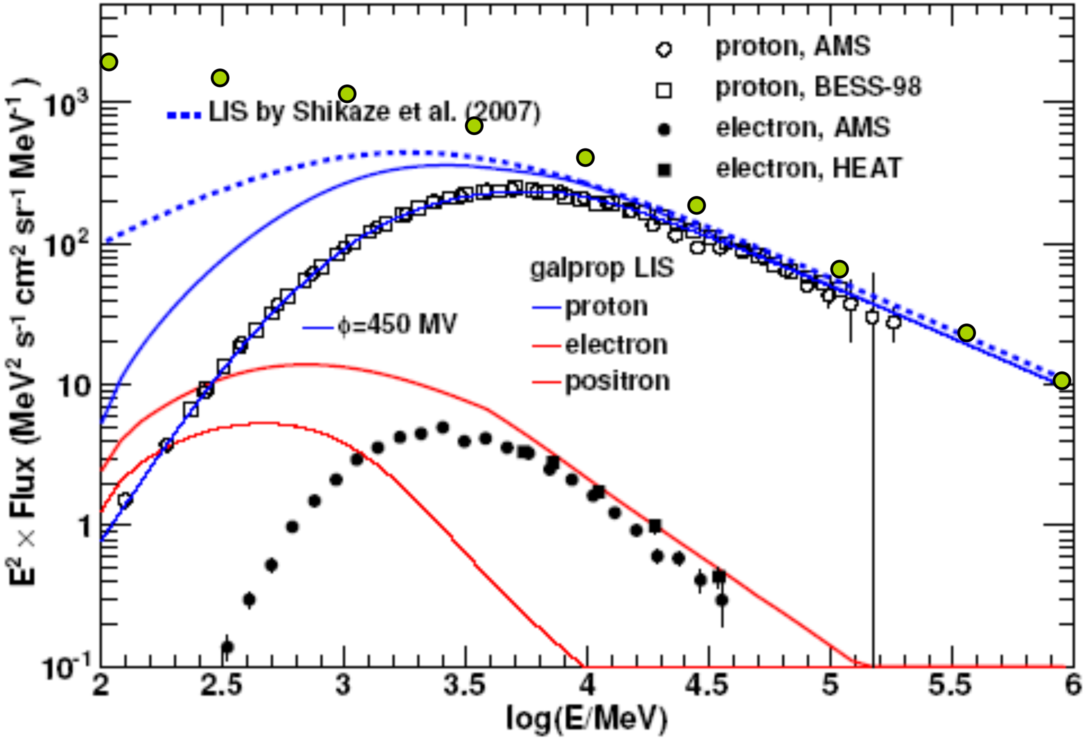


Cosmic rays: the most energetic particles in the universe

- **Sources of**
  - **Light elements Li, Be, B**
  - **Galactic radio emission**
  - **Galactic gamma-ray emission**
  - **Galactic pressure**
  - **Terrestrial ^{14}C**
  - **Genetic mutations**
  - **Radiation effects on humans and satellites**

Discovery of cosmic rays by Victor Hess in 1912

Local Cosmic Ray Intensity



$$J_p(T_p, \Omega_p) = \frac{2.2}{E_p^{2.75}} \;\; \text{CR p cm}^{-2}\ \text{s}^{-1}\ \text{GeV}^{-1}\ \text{sr}^{-1}$$

Fit of Dermer (A&A, 1986)

(green circles)

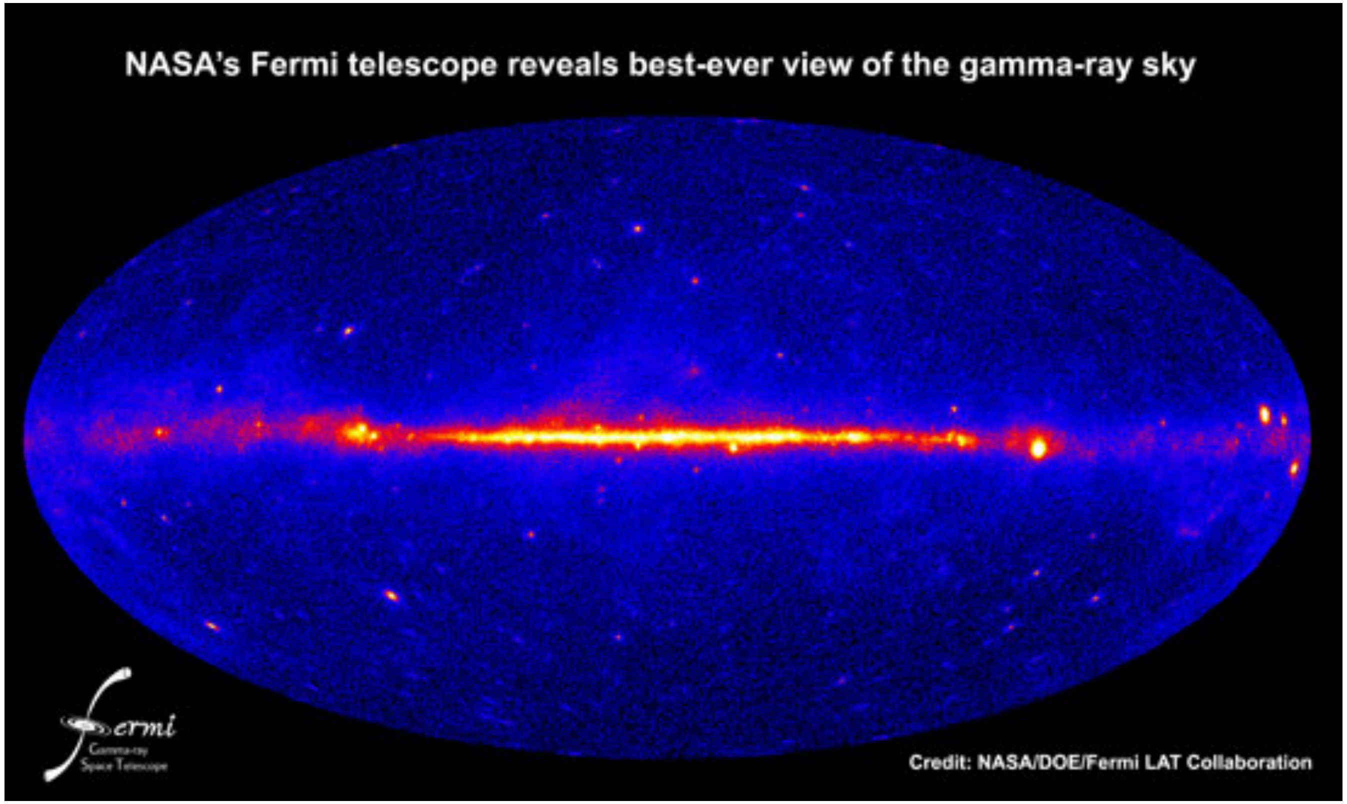
Kinetic Energy (MeV/Nucleon)

Figure 2. The differential energy spectra of the primary cosmic ray H, He, C, and Fe at Earth. [*Reproduced with permission from* J. A. Simpson (1983). Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

$$\langle u_p \rangle = \frac{4\pi}{c} \int_0^\infty dT_p\, T_p\, J_p(T_p, \Omega_p) \approx 0.7\, eV/cm^3$$

GeV cosmic ray flux: tens of protons /cm^2-s

Diffuse Galactic Gamma-ray Emission



Most striking feature of the GeV gamma-ray sky is the diffuse Galactic emission

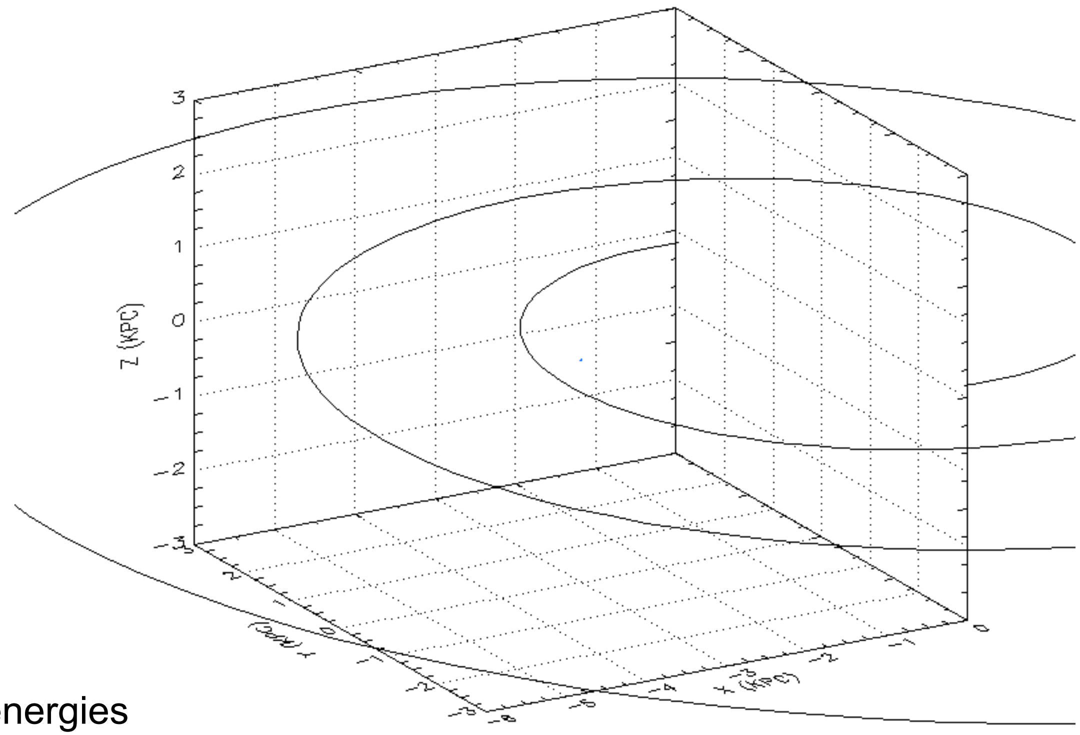
Cosmic rays interacting with interstellar medium

- $CR_{protons}$ + gas $\rightarrow \pi^o \rightarrow 2\gamma$ Peaks at 70 MeV (in photon spectrum)
- $CR_{electrons}$ + radiation fields $\rightarrow$ Compton
- $CR_{electrons}$ + ambient protons $\rightarrow$ bremsstrahlung

Cosmic Ray Propagation

- Cosmic rays move in large-scale galactic magnetic field and diffuse by scattering off magnetic turbulence
- Combined spatial transport + energy-loss required for constructing γ-ray maps of supernova remnants
- Simulation color-coded according to cosmic ray energy:

Red lowest energies (10^{16} – 10^{17} eV)
Green, yellow, and turquoise are intermediate energies
Dark blue/purple highest energies (10^{19} – 10^{20} eV)



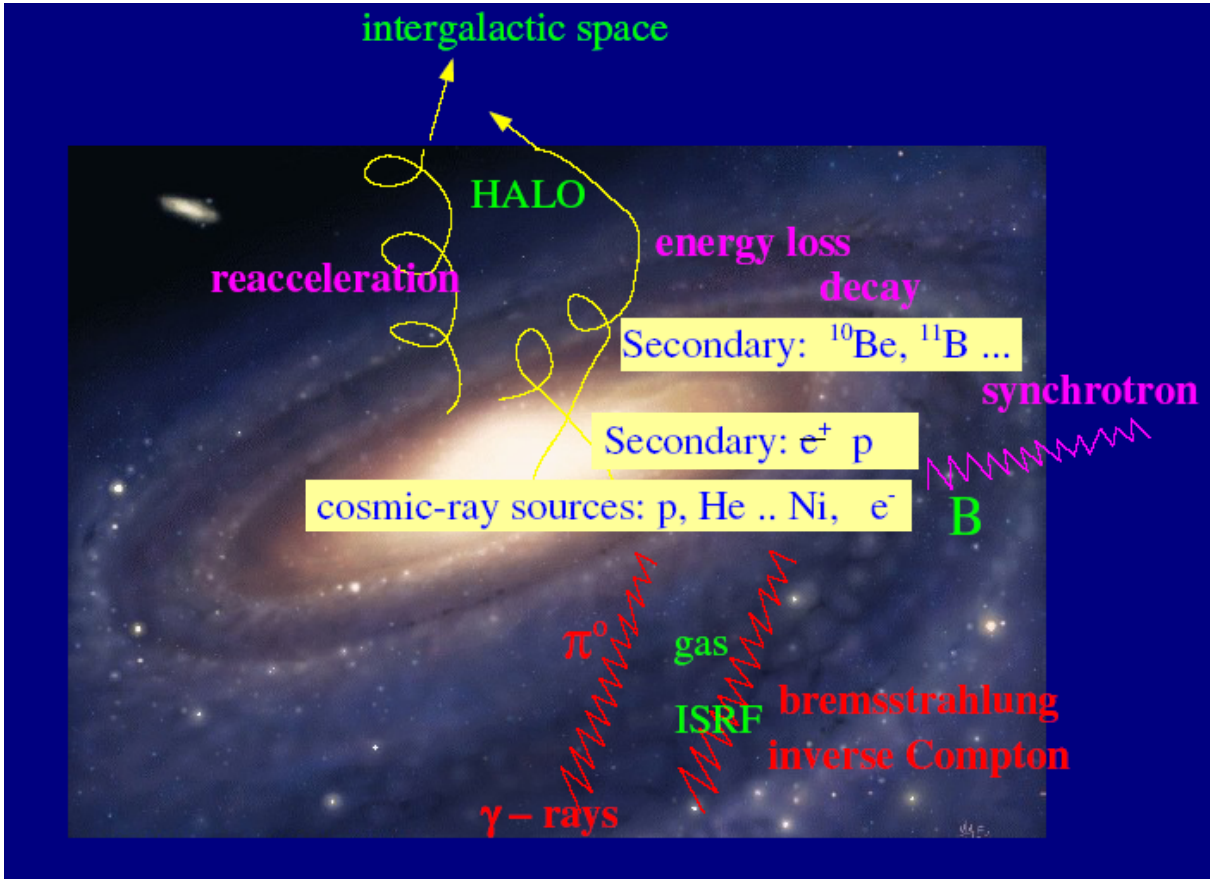
Dermer and Holmes 2005

- Half neutrons, half protons
- At lower energies, treat cosmic ray propagation with leaky box or diffusion model (GALPROP)

GALPROP: GALactic cosmic ray PROPagation model

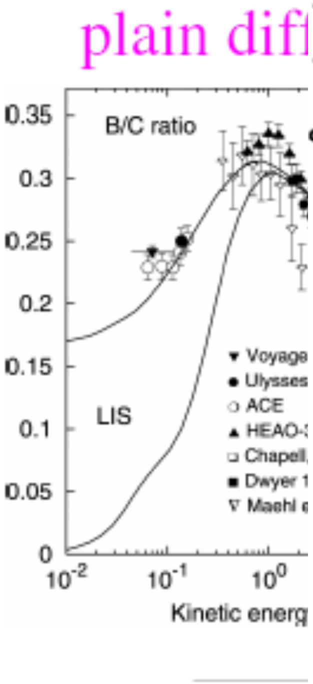
Strong & Moskalenko (1998) + Porter, Johannesson, Orlando, Digel

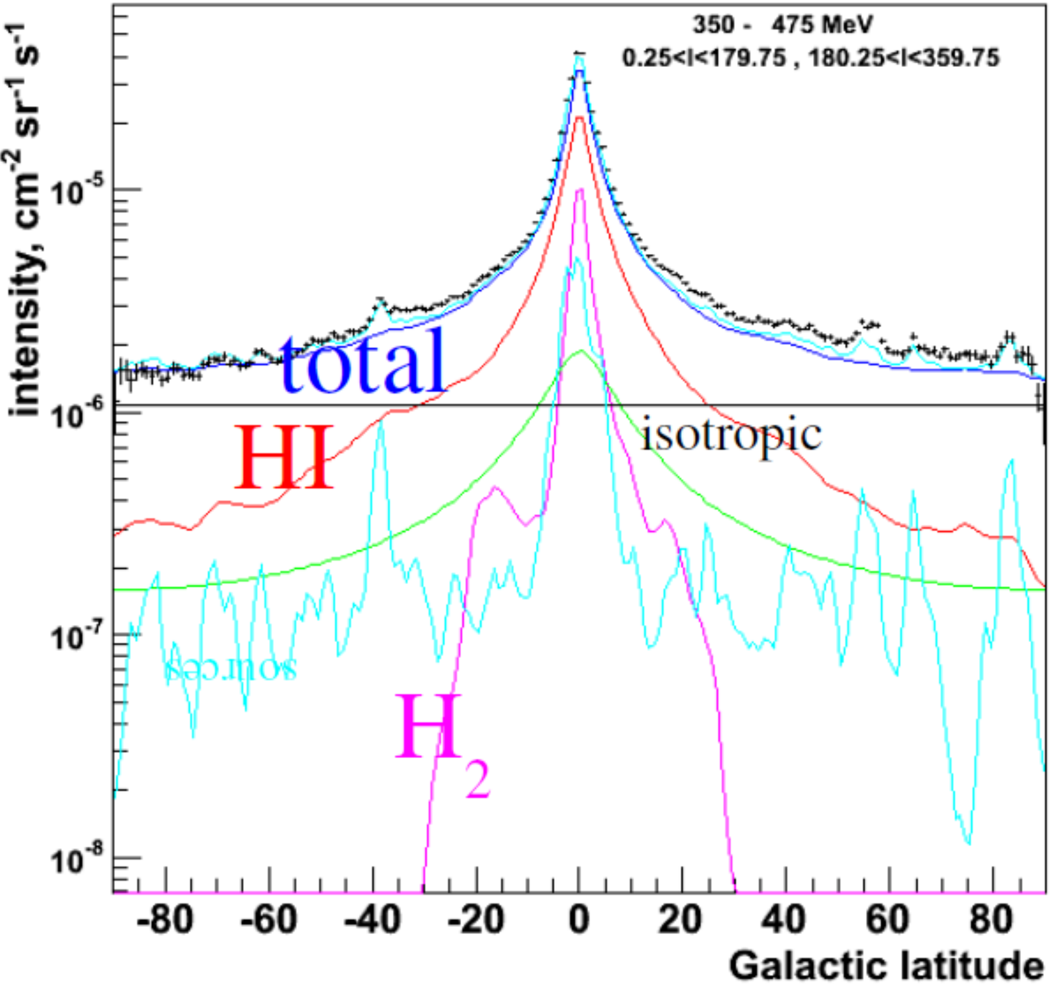
- **Detailed Fermi LAT Galaxy emission requires correspondingly detailed physical model for interpretation**
- **GALPROP model allows predictions of cosmic propagation and the resulting interstellar emission for gamma rays and synchrotron radiation**

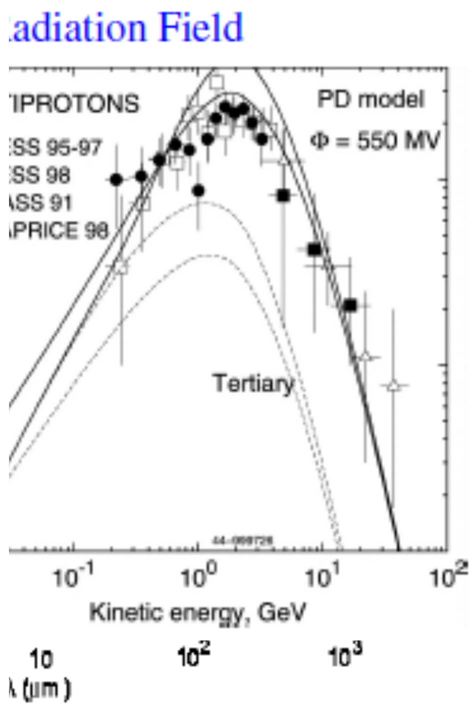


GALPROP INPUTS AND OUTPUTS

- Solve spatial/momentum diffusion-convection equation with sources, energy and fragmentation losses, and energy gains for protons, ions, electrons

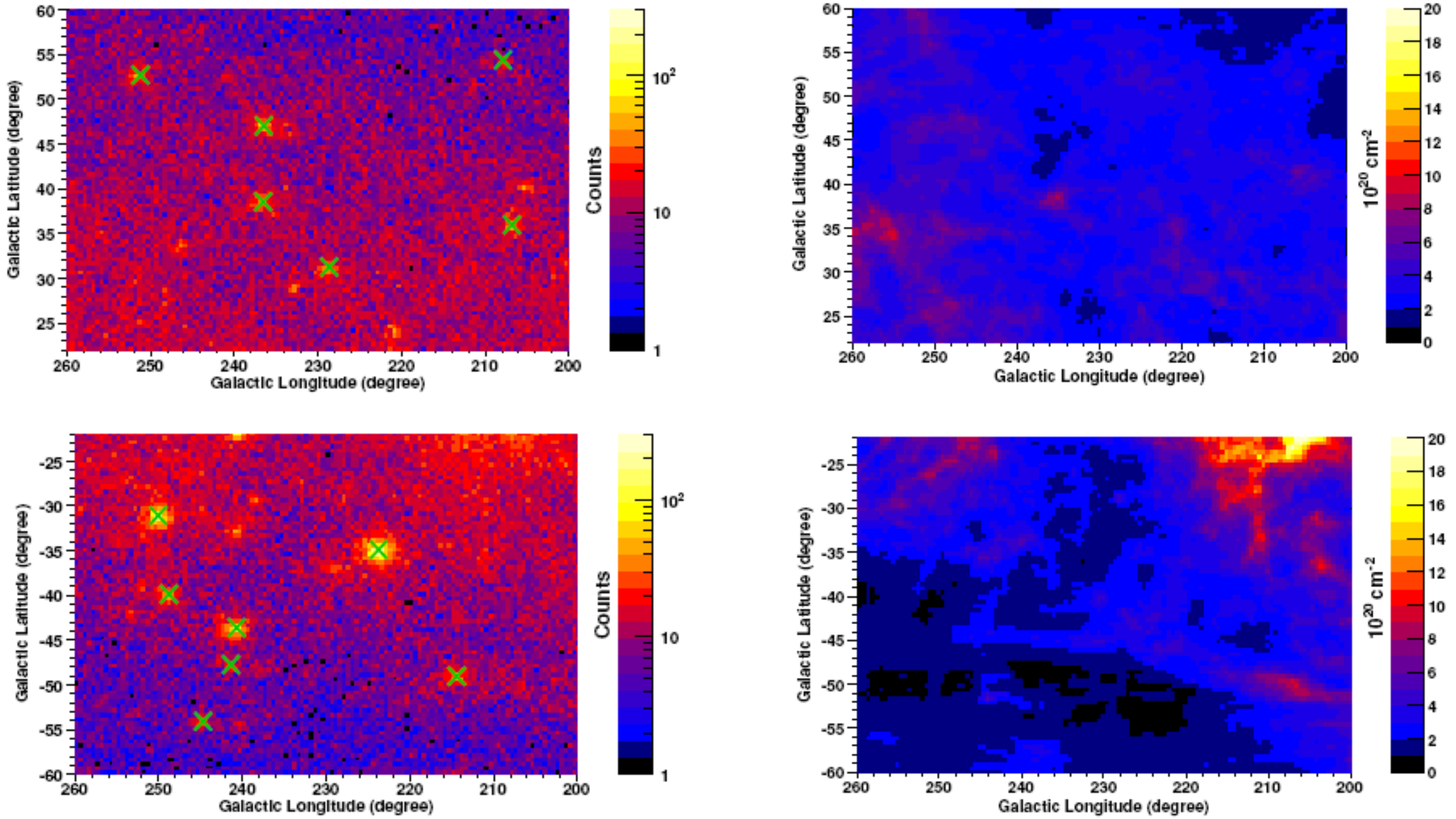






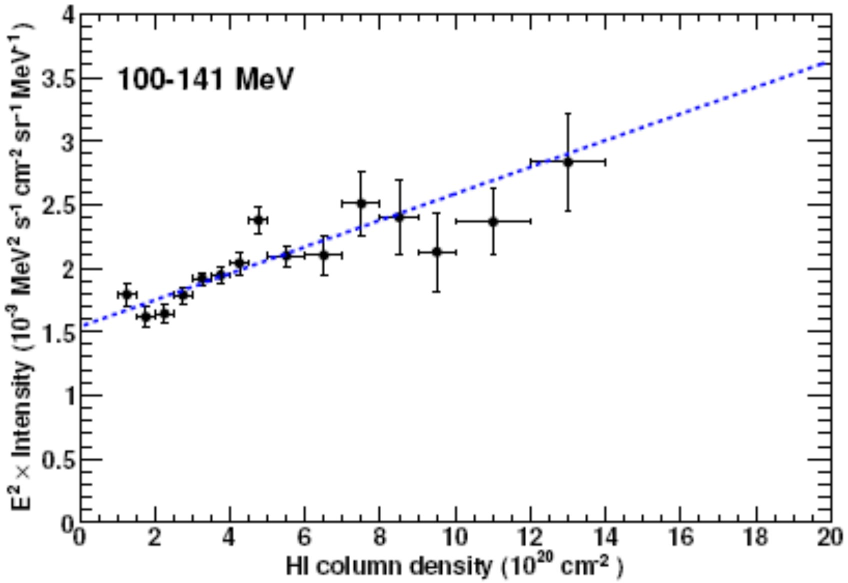
Diffuse γ-rays from Cosmic Ray Interactions in the Galaxy

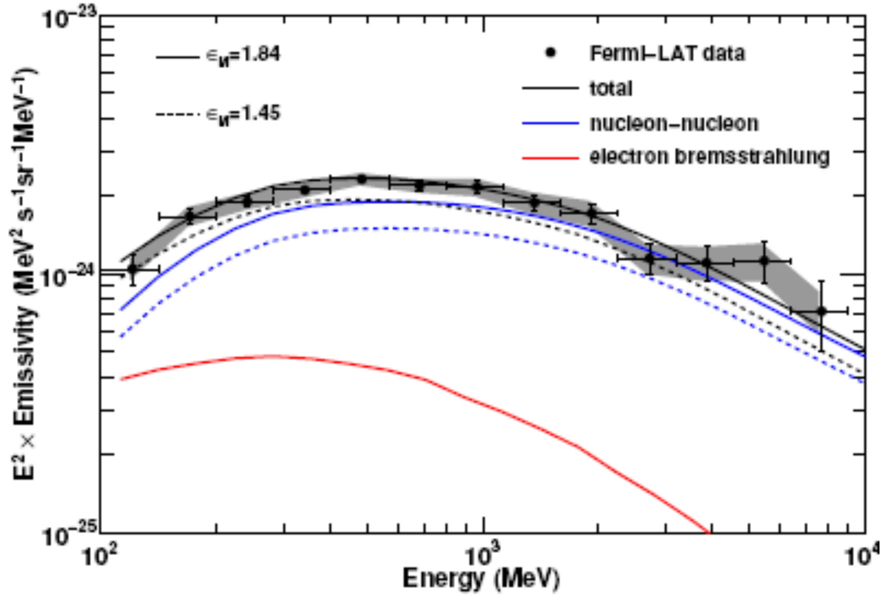
Abdo et al., ApJ, 703, 1249, 2009



LAT observations of γ-ray emission in the third quadrant (Galactic longitude from 200° to 260° and latitude from 22° to 60°) with no known molecular clouds, after subtracting point sources and Compton emission. Residual γ -ray intensity exhibits a linear correlation with the atomic gas column density in energy from 100 MeV to 10 GeV. N(HII)~1-2×10^{20} cm^{-2}

Diffuse γ-rays from Cosmic Ray Interactions in the Galaxy





The measured integral γ-ray emissivity is **(1.63±0.05)×10^{-26} photons s^{-1}sr^{-1} H−atom^{-1}** and (0.66 ± 0.02) × 10^{-26} photons s^{-1}sr^{-1} H−atom^{-1} **above 100 MeV** and above 300 MeV, respectively, with an additional systematic error of ~10%.

How to explain these numbers? If due to cosmic rays colliding with gas in the Galaxy

$$\dot{n}_{pH\to\pi^0}(T_\pi) = 4\pi n_H \int_0^\infty dT_p\, J_p(T_p,\Omega_p)\, \frac{d\sigma_{pH\to\pi^0}(T_p)}{dT_\pi} \qquad \pi^0 \to 2\gamma$$

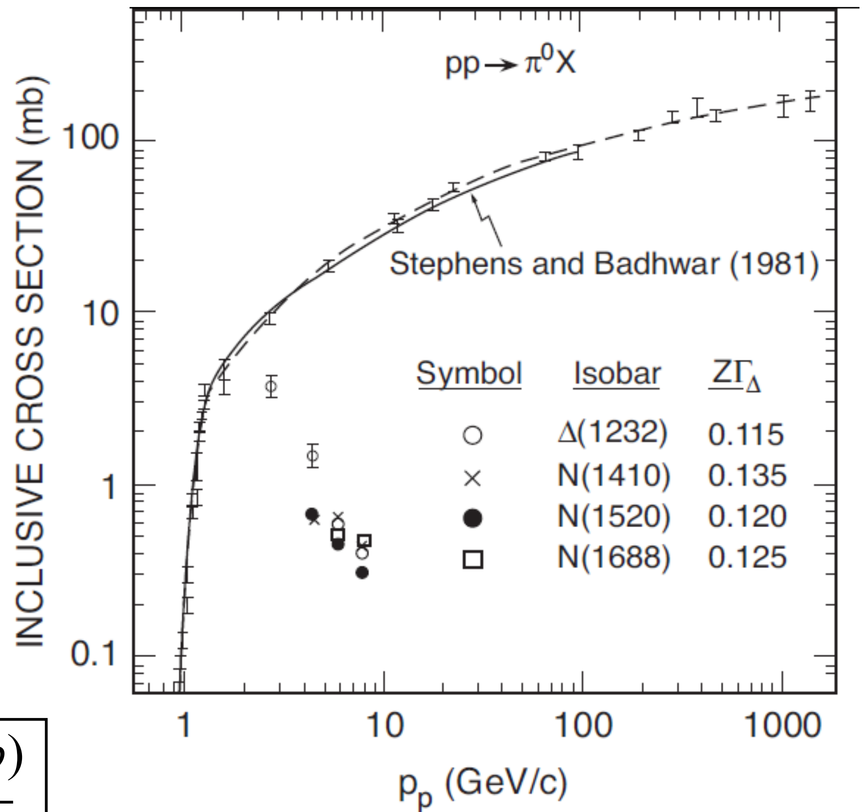
Kinetic energy $T_p = E_p - m_p c^2$; Total energy E_p

Secondary Nuclear Proton-Proton Cross Section

- **Exclusive Cross Sections**
  - Specific channel
- **Inclusive Cross Sections**
  - Product of cross section x multiplicity
- **Inelasticity**
  - Fraction of original energy lost in collision

$$E_p^2 = m_p^2 + p_p^2 \ (units\ of\ GeV, c = 1)$$

$$T_p = E_p - m_p$$



	$\sigma_{pp\to\pi^0}(mb)$
$p_p = m_p (\approx GeV/c),\ E_p \cong 1.3\,GeV,$	4
$p_p = 10 m_p,\qquad E_p \cong 10\,GeV,$	30

$$\therefore \sigma_{pp\to\pi^0}(mb) \approx 4\,mb\,\left(\frac{E_p}{1.3GeV}\right) \quad (approximately\ linear)$$

γ-ray emissivity: model vs. data

Measured integral γ-ray emissivity is **$(1.63\pm0.05)\times10^{-26}$ ph(>100 MeV) s^{-1}sr^{-1} H−atom^{-1}**

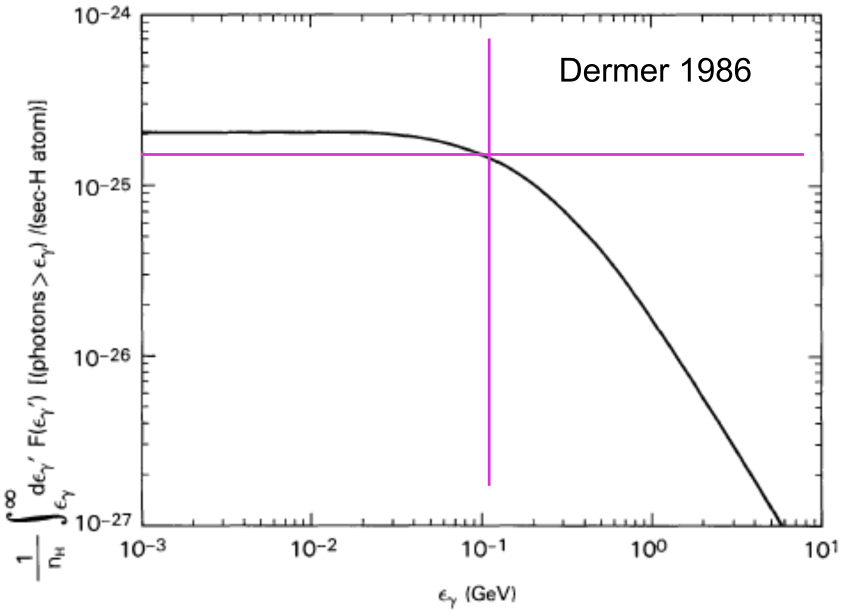


Fig. 9. The γ-ray emissivity per H atom integrated above photon energy ε_γ, using the differential emissivity of this work from Fig. 8

Total γ-ray emissivity:

2γ per π^o

Correction for He and metals

$$\frac{\frac{dN_\gamma}{dtdVd\Omega}}{n_H} \cong 2\zeta\int_{T_{p,thr}}^{\infty} dT_p J_p(T_p,\Omega_p)\sigma_{pp\to\pi^o}(T_p) \quad [s^{-1}sr^{-1}\text{H atom}^{-1}]$$

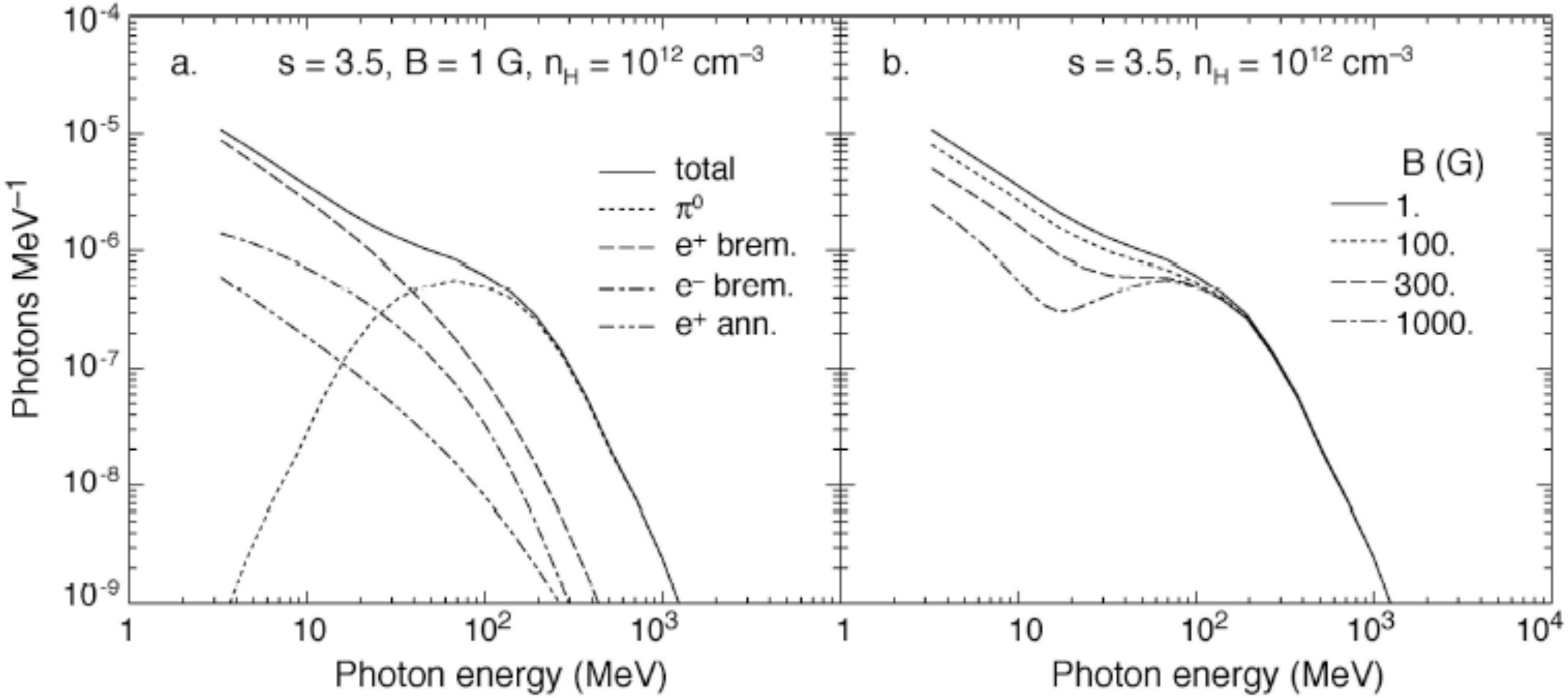
$$\frac{\frac{dN_\gamma}{dtdVd\Omega}}{n_H} \cong 2\zeta\cdot 4\text{mb}\cdot 2.2\int_{1.3}^{\infty} dE_p \frac{(E_p/1.3\text{ GeV})}{E_p^{2.75}} \cong \frac{2\cdot 2.2\cdot 4\times10^{-27}}{0.75(1.3)^{1.75}}$$

$$\cong 2.2\times10^{-26}\left(\frac{\zeta}{1.5}\right) \quad [s^{-1}sr^{-1}\text{H atom}^{-1}]$$

Nuclear and Bremsstrahlung Cross Sections

- Secondary nuclear production cross sections

  $p + p, \mathrm{He} \rightarrow \pi^o, \pi^\pm + X \rightarrow \gamma, e^\pm, \nu + X$



- Pion emission from supernova remnants

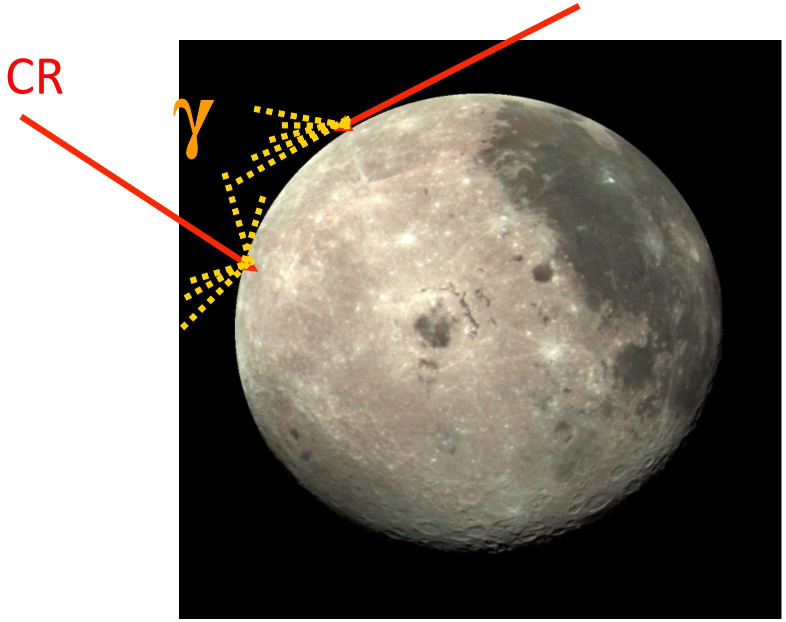
  cosmic rays, Solar flares

Murphy (2007)

Quiet Solar and Lunar Gamma-ray Spectrum

- Lunar γ-ray emission depends on the flux of CR nuclei near its rocky surface
- Quiet solar γ-ray emission has two components: Compton γ rays from CR electrons and CR nuclei interactions with the gaseous solar atmosphere
- New probe of CR fluxes in the solar system during the entire solar cycle

LAT Lunar Flux (E>100MeV) = (1.1 +/- 0.2) x 10^{-6} ph cm^{-2} s^{-1}
(EGRET Flux(E>100MeV) =(5.55+/-0.65)x 10^{-7} ph cm^{-2} s^{-1}



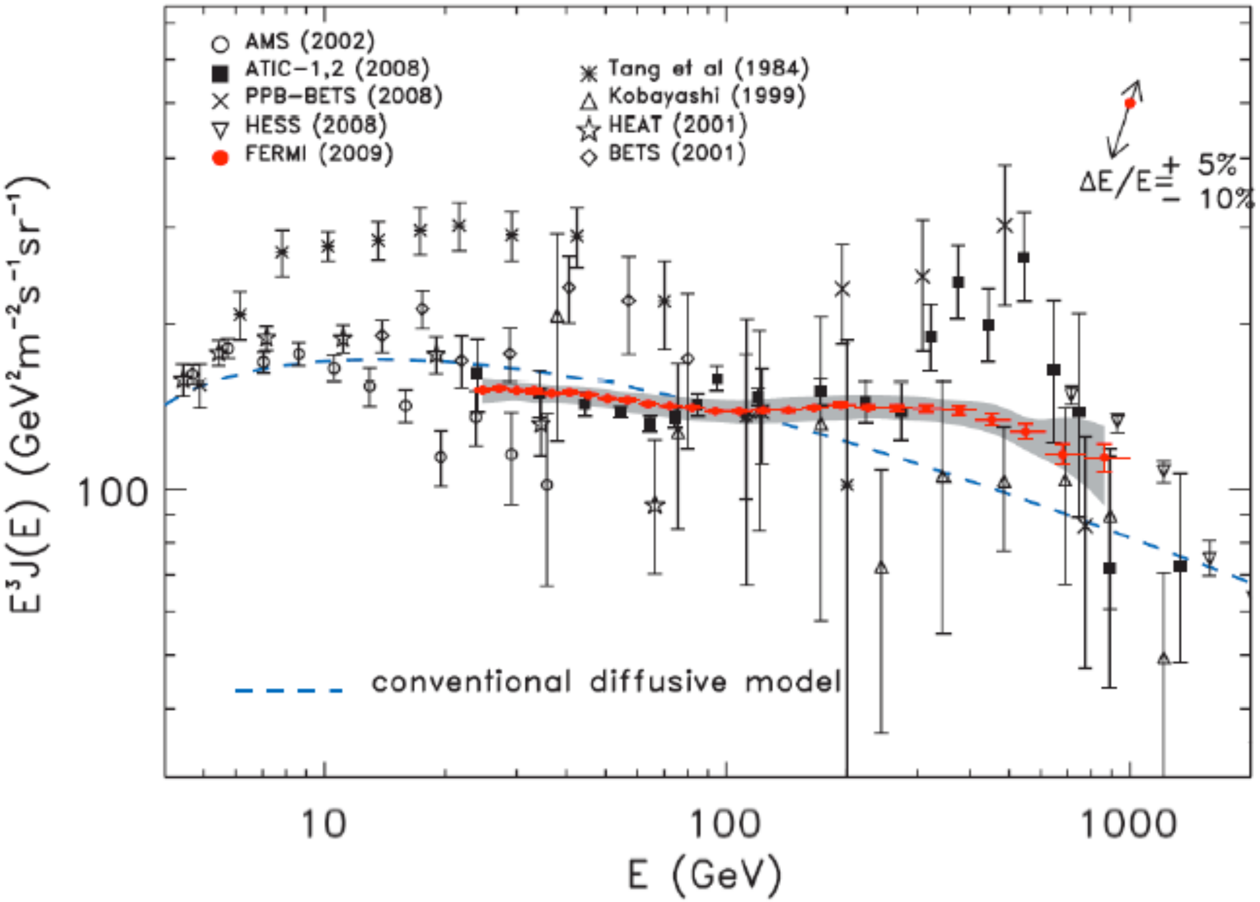
Expect limb-brightened emission

Preliminary—not for distribution

Waiting for Solar γ-ray flares!

Cosmic Ray Electron Spectrum

- ❑ Fermi measures cosmic ray $e^{-}+e^{+}$ with >2 m^2-sr acceptance (need to reject CR proton background)
- ❑ CR e spectrum $\propto E^{-3.04}$ between ~25 and 900 GeV
- ❑ featureless; consistent with power law
- ❑ CR e spectrum harder than predicted by GALPROP
- ❑ Local sources?
- ❑ Dark matter?

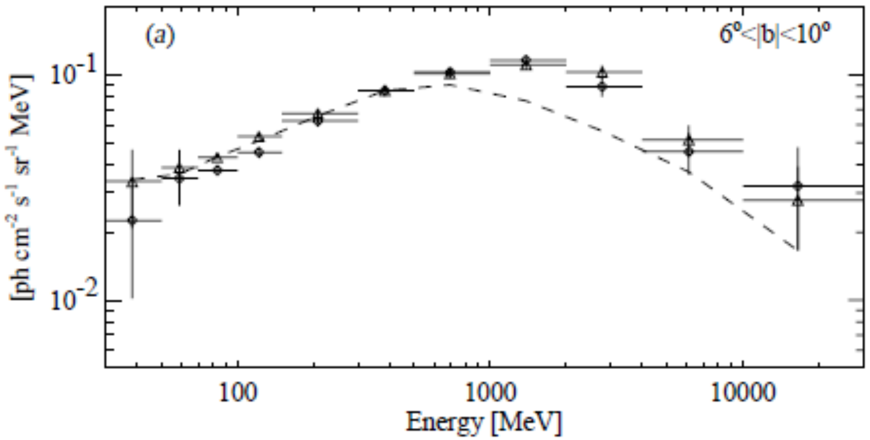


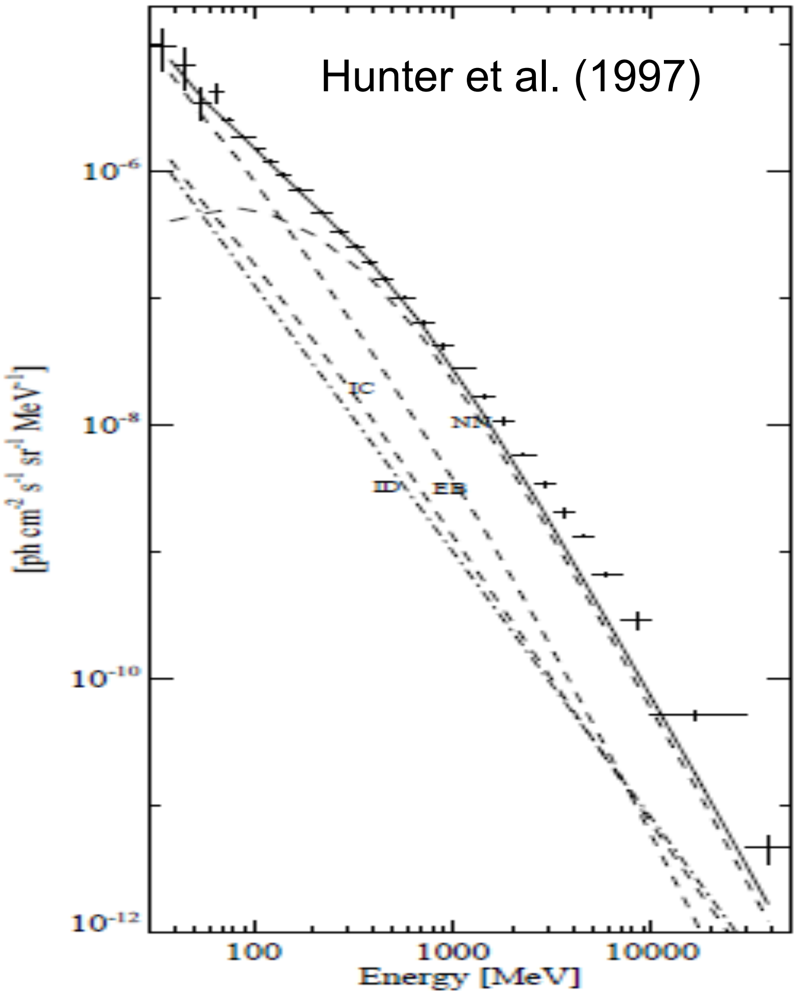
(see lecture by Lars Bergström)

Abdo, et al. 2009, PRL, 102, 181101

EGRET GeV Excess Galactic Diffuse Emission

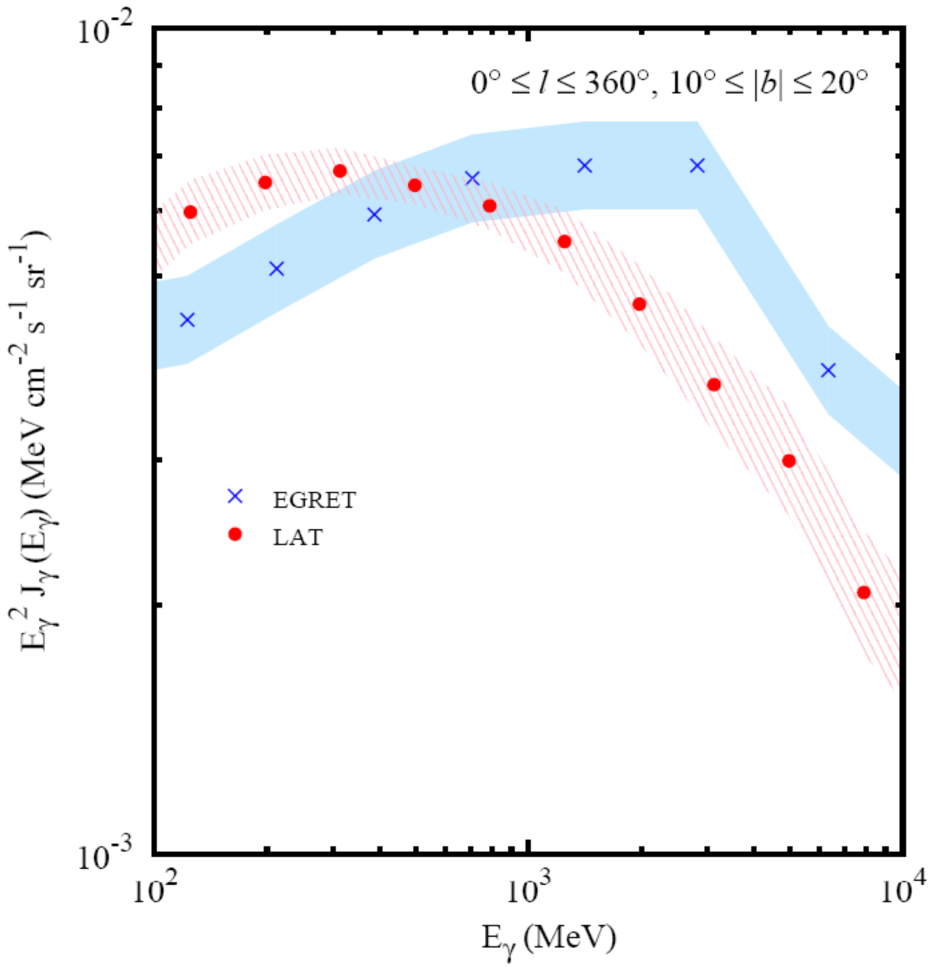
- Excess γ-ray emission, over that predicted using local demodulated cosmic ray spectrum, observed with EGRET (in all directions)
- Possible explanations:
  - Unusual location and cosmic ray spectrum
  - Nuclear physics wrong
  - γ rays from annihilating dark matter
  - EGRET miscalibration



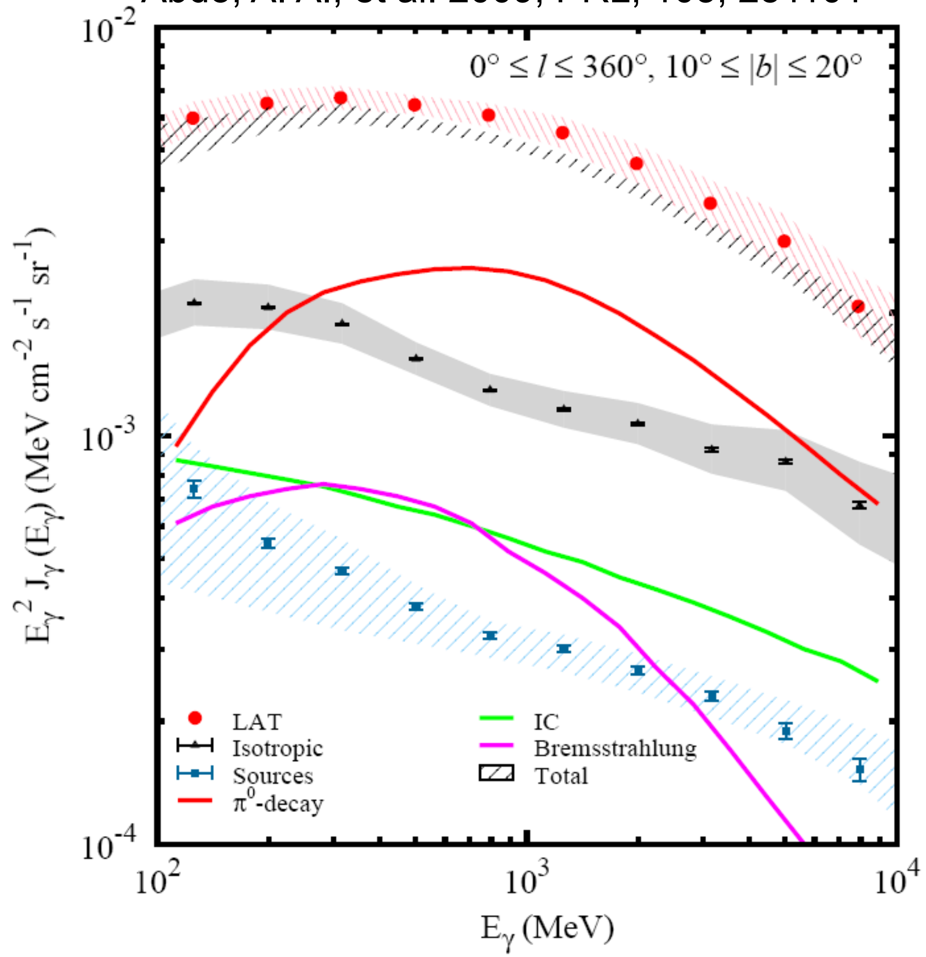


Average diffuse γ-ray spectrum of the inner Galaxy region, 300° < l < 60°, |b| <10°(0.73 sr)

No EGRET GeV Excess



Abdo, A. A., et al. 2009, PRL, 103, 251101



- Excess evidently due to EGRET miscalibration (e.g., self-vetoing)
- No additional component required

Decompose medium latitude Galactic diffuse (LAT) into Sources; Bremsstrahlung; Compton; π^o; unidentified isotropic background consisting of extragalactic, unresolved, residual particle backgrounds

Cosmic rays from supernova remnants

- Need to supply ~5x10^{40} erg/s throughout the Galaxy

$$L_{CR} \sim (\frac{1\, eV / cm^{-3}}{t_{esc}}) V_{gal} \approx 10^{40} erg\ s^{-1}$$

$t_{esc} \approx 2 \times 10^7\, yr$ from analysis of cosmic ray ^{10}Be ($\tau \approx 2 \times 10^6$ yr)

$$V_{gal} \sim \pi (200\, pc)(15\, kpc)^2 \sim 4 \times 10^{66}\, cm^3$$

- 1 Galactic SN/30 yrs × 10^{51} erg/SN ×10% ≈ 10^{41} erg s^{-1}
- Other energy sources:
  - Novae
  - Stellar winds from young stars
  - neutron stars
- Confirming signature: π^o γ-ray bump

γ-ray emission from supernova remnants

❑ Association of EGRET unidentified sources with SNRs

– Sturner & Dermer (1995); Esposito et al. (1995)

Table 1. Unidentified EGRET Sources With Possible SNR Associations

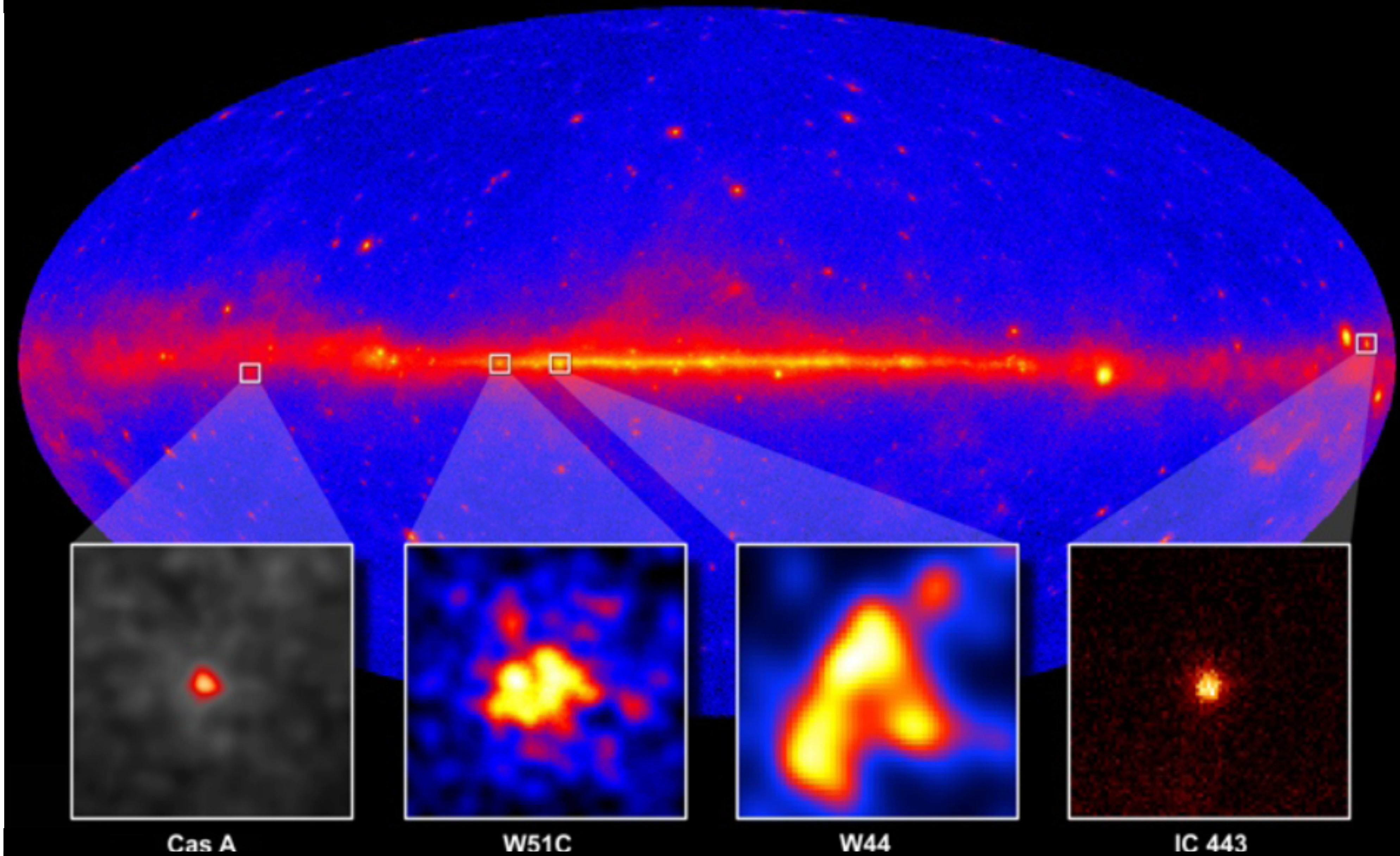
EGRET Source	SNR	θ_1 (′)[a]	D_{max} (′)[b]	θ_1/D_{max}	Type[c]	Radio Flux (Jy)
GRO J0542+26	G 180.0-1.7 (S147)	116.6	248.0	0.47	S	65
GRO J0617+22	G 189.1+3.0 (IC 443)	6.7	43.5	0.15	S	160
GRO J1110-60	G 291.0-0.1 (MSH 11-62)	7.8	56.0	0.14	F	16
GRO J2019+40	G 78.2+2.1 (γ Cygni)	27.7	48.0	0.58	S	340
GRO J0635+05	G 205.5+0.5 (Monoceros)	81.6	148.0	0.55	S	160
GRO J0823-46	G 263.9-3.3 (Vela)	87.7	127.5	0.69	C	1750
GRO J1416-61	G 312.4-0.4	11.9	49.8	0.24	S	44
GRO J1443-60	G 316.3+0.0 (MSH 14-57)	35.4	39.0	0.91	S	24
GRO J1758-23	G 6.4-0.1 (W28)	26.8	57.0	0.47	C	310
GRO J1823-12	G 18.8+0.3 (Kes 67)	13.0	36.8	0.35	S	27
GRO J1842-02	G 30.7+1.0	42.3	50.5	0.84	S	6
GRO J1853+01	G 34.7-0.4 (W44)	30.7	42.5	0.72	S	230
GRO J1904+06	G 40.5-0.5	36.7	63.0	0.58	S	11
	G 41.1-0.3 (3C397)	46.1	53.8	0.86	S	22

[a] Angular distance from center of EGRET error circle to center of associated remnant.
[b] Sum of the EGRET error circle radius plus the radius of the associated remnant.
[c] S=Shell, C=Composite, F=Filled

Fermi detection of γ-ray emission from SNRs

- Particle acceleration by shocks in Galactic SNRs
- ~274 known Galactic SNRs
- Fermi has detected
  - **– young (<~3000 yr) and historical SNRs: Cas A, RXJ 1713.7-3946**
  - **– Intermediate age (~ 10^4 yr) SNRs: IC443,**
  - **– Middle-aged (>~ 3×10^4 yr) SNRs: W51C, W44, W28, G349.7+0.2 (interacting with molecular clouds)**
- Important Questions:
  - **– Do SNR shocks accelerate particles?**
  - **– Do SNRs accelerate protons (p^+/e^- ratio)?**
  - **– What is the energy density of the accelerated particles?**
  - **– How efficiently is shock kinetic energy converted to CR energy? What is the maximum particle energy?**
  - **– Do SNRs accelerate CRs up to the knee?**
  - **–Is the magnetic field amplified in SNRs?**

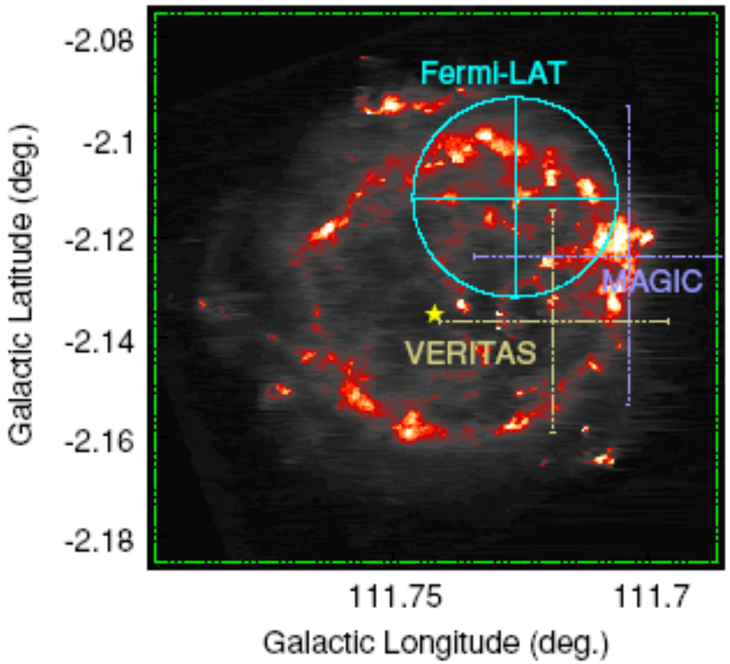
First GeV Maps of SNRs

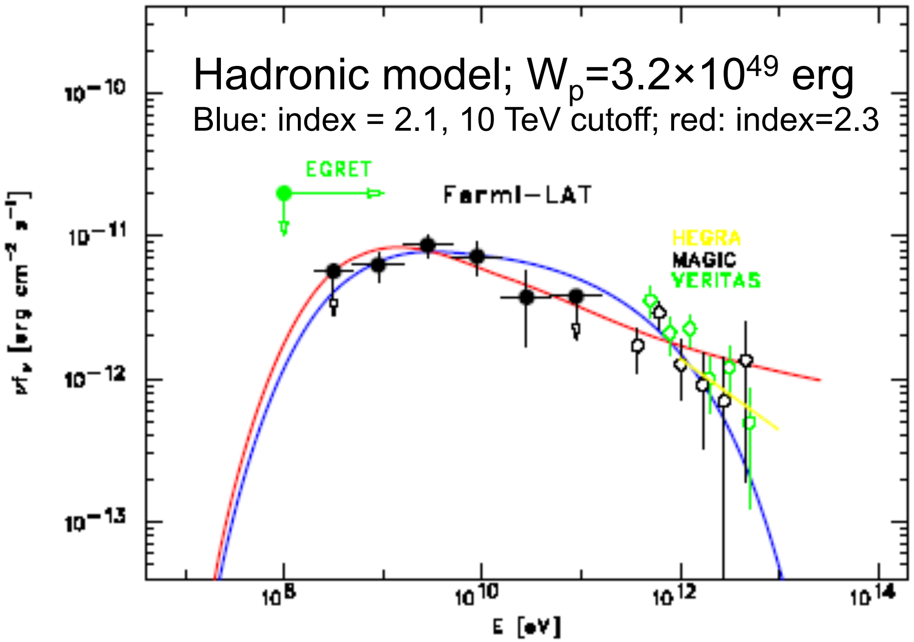


Fermi detects γ-ray emission from Cas A

Abdo et al. 2010, ApJ, 710, L92

- One of the youngest SNRs in our Galaxy (1680)
- One of the brightest radio sources in the sky
- Angular size of 2.5′ in radius ⇒ size of 2.34 pc at a distance of 3.4+0.3−0.1 kpc
- Consistent with point source
- Strong magnetic fields (up to 1 mG) implied from X-ray variability on short timescales

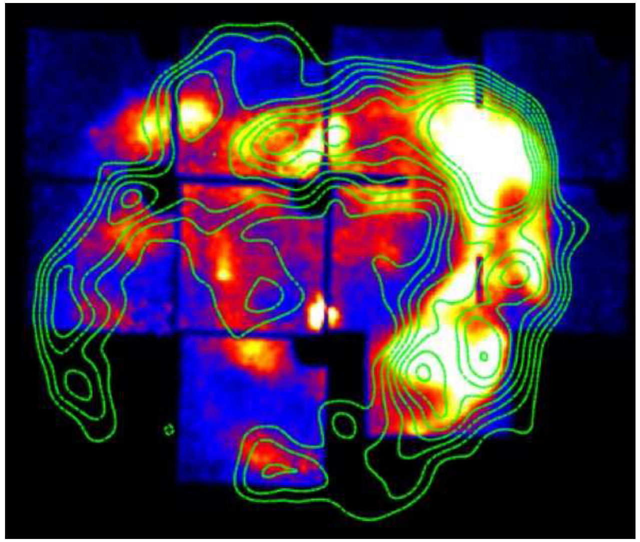




Fermi detection of RX J1713.7-2942

- Faint source in a complicated region
- Sources to the north coincide with mol. material (CO/HII)
- Hard spectrum in the Fermi-LAT band

Preliminary—not for distribution

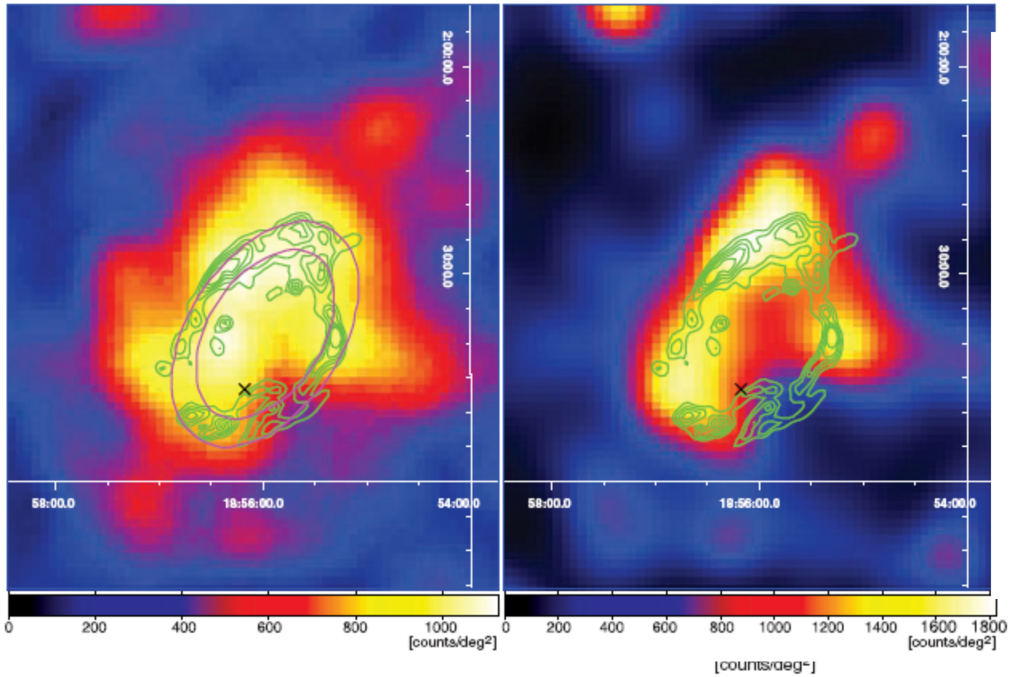


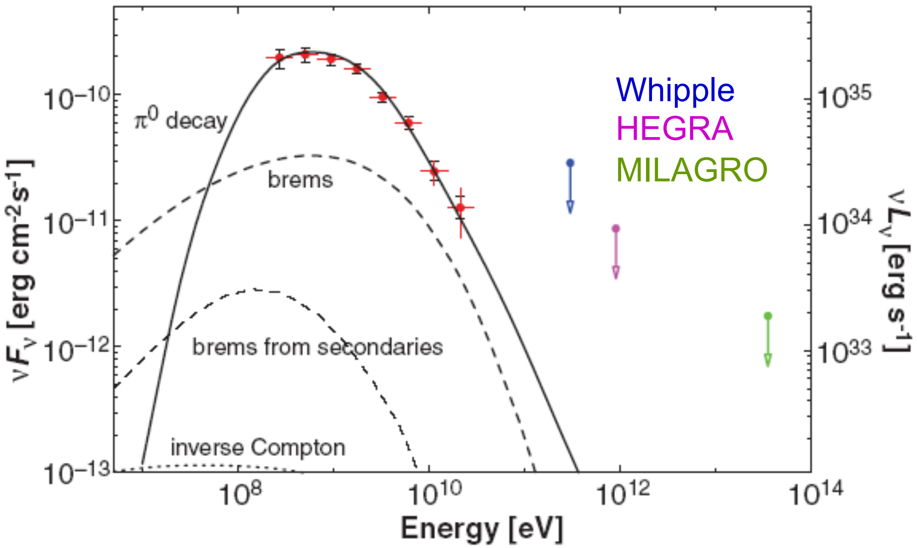
HESS/Suzaku (Tanaka et al. 2008)

Fermi detects γ-ray emission from W44

Abdo et al. 2010, Science, 327, 1103

- ~2×10^4 yr shell SNR; interacting with molecular clouds with n~100 cm^{-3}
- 2-10 GeV count map (left) and deconvolved image (right) , Spitzer 4.5μ IR contours
- cross marks pulsar, PSR B1853+01, with age ~2×10^4 yr
- Spectrum more consistent with hadronic than leptonic processes

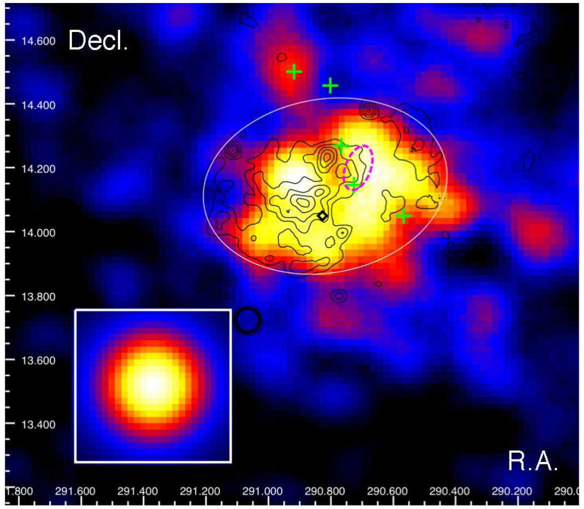


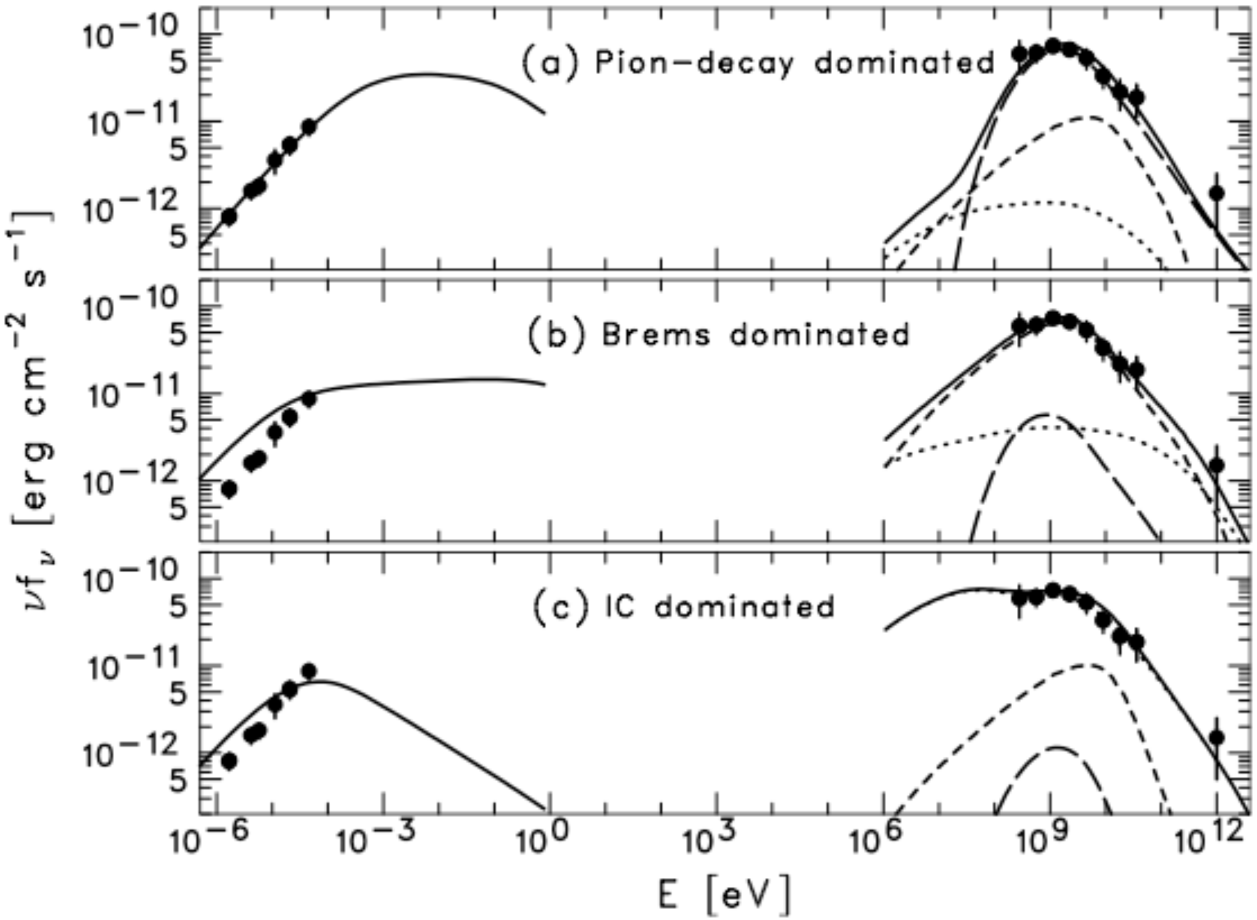


Broadband modeling of W51C

Abdo et al. 2009, ApJ, 706, L1

- Older than 20,000 years
- Interacting with molecular clouds (masers)
- Shell structure in radio
- Extended in the Fermi-LAT band beyond the PSF



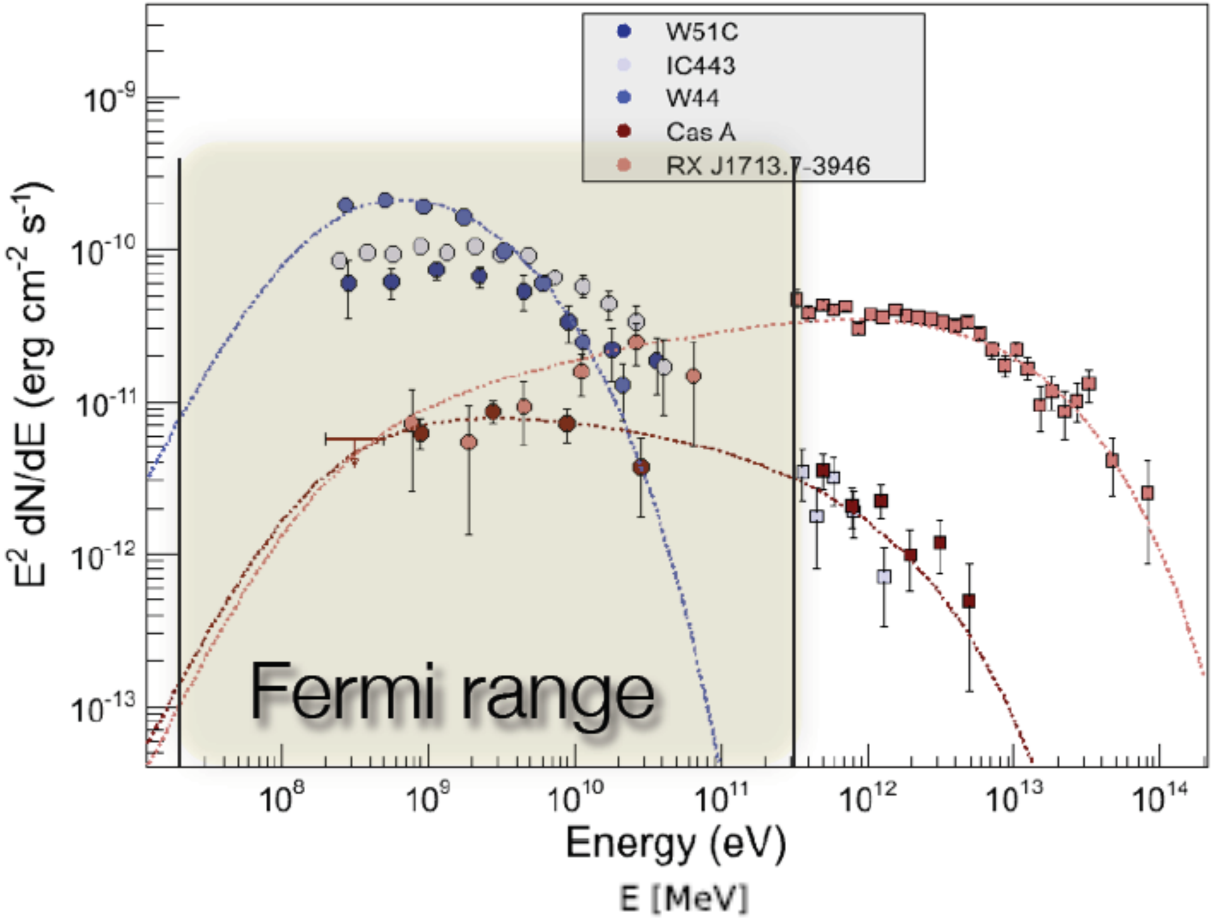


	W_p	W_e
	(10^{50} erg)	
(a) π^o-decay	5.2	0.13
(b) ff	0.54	0.87
(c) Compton	8.4	11

γ-ray SNRs and cosmic ray origin

- ❑ Young SNRs have nonthermal synchrotron X-rays, strong TeV detections, X-ray/TeV correlation; γ-rays likely leptonic in origin
- ❑ RXJ 1713.7-3946 has hard Fermi GeV spectrum, rising in νF_ν
- ❑ Middle-aged SNRs have steep spectrum from GeV to TeV; γ-rays likely hadronic in origin

- ❑ Spectral evolution with age
- ❑ Energy in cosmic rays represents few to tens of percents of SN energy
- ❑ IC 443 with intermediate age (~10000 yrs), shows intermediate spectrum



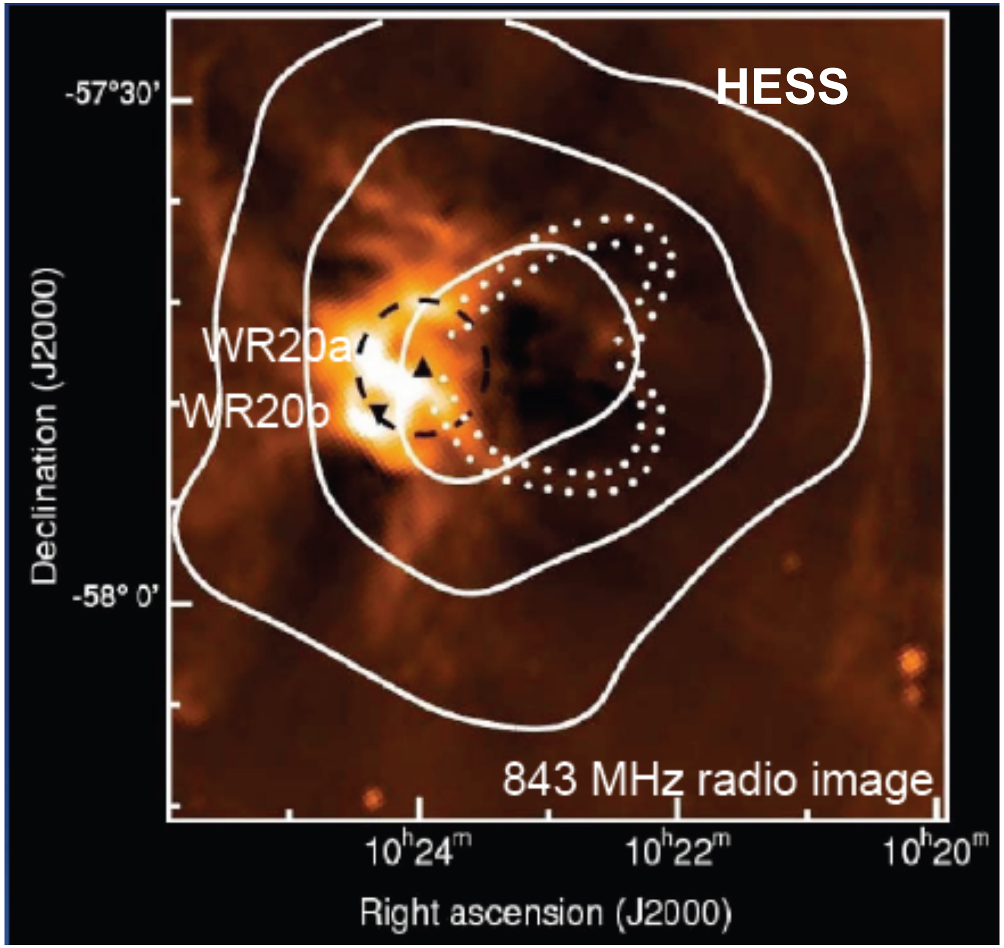
Fermi and Galactic Cosmic Rays

- Has Fermi established that (middle-aged) SNRs are sources of the hadronic cosmic rays?
- An apparent π^o decay feature is observed
- Gas clouds/targets are nearby for middle-aged remnants
- Systematic trend from young to middle-aged
- Need confirming neutrino detection to establish cosmic-ray origin
- Theory for transition from electron-dominated (young) to proton-dominated (middle-aged) needed

Back-up Slides

Wolf-Rayet Stars/ OB associations

- Colliding stellar winds as a source of γ rays
- Enhanced acceleration from shocked winds (compare high mass X-ray binary/ pulsar systems)
- example: Westerlund 2: 12 O + 2 WR stars
  - SNRs
  - Wolf-Rayet stars
  - OB stars
  - colliding stellar winds
    - Reimer, Pohl, Reimer (2006)
    - Romero, Benaglia, Torres (1999)



Gamma Rays from Dark Matter Annihilation

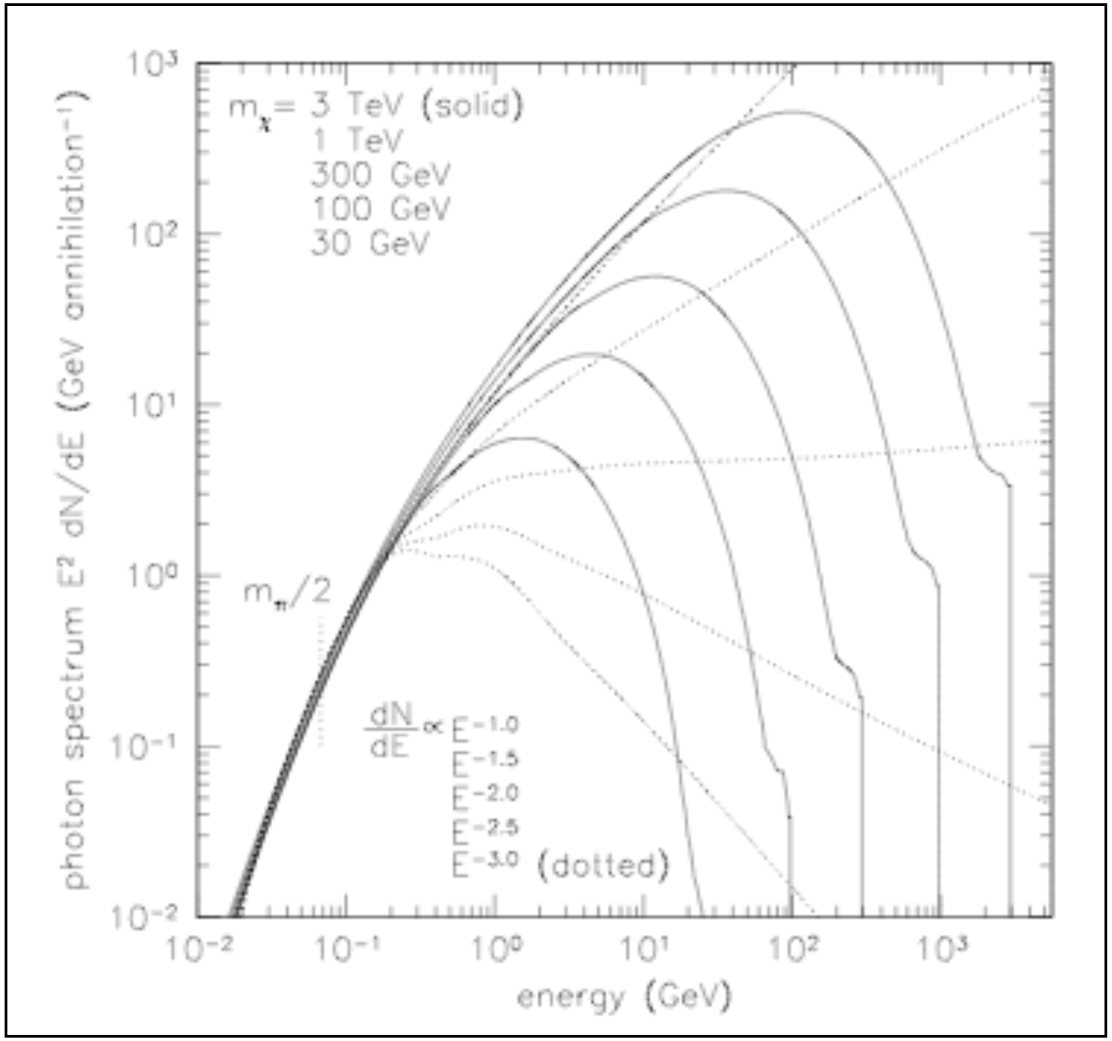
Consider supersymmetric neutralinos (~ vanilla CDM WIMP candidate)

Most γ via (non-rel.) quark-antiquark pairs $\Rightarrow$ hadronization $\Rightarrow$pions

Resulting pion bump at ~ $m_\chi/25$ ranges from 1-100 GeV depending on WIMP mass

Sharp energy cutoff, so very different from, e.g., emission from power-law cosmic-ray proton spectra

See lectures by Lars Bergström, this course



Baltz, Taylor & Wai 2007 - spectrum from DarkSUSY/Pythia