Cosmic Rays and Supernova Remnants with Fermi

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On behalf of the **Fermi Collaboration**

Outline

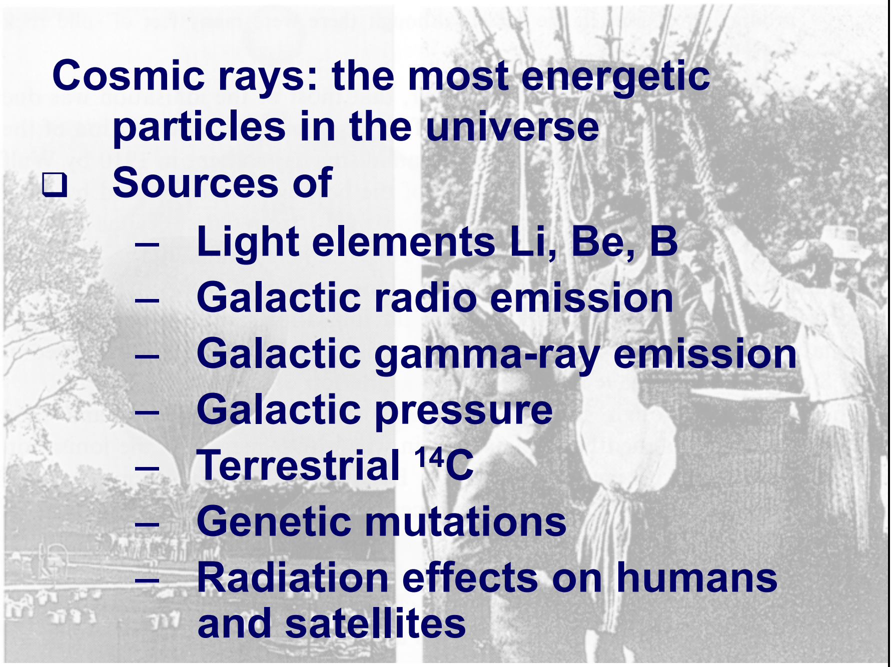
Cosmic ray history and properties
Cosmic ray propagation and GALPROP
Galactic γ-ray emissivity
Solar and Lunar γ rays
Cosmic-ray electron spectrum
EGRET excess
Supernova remnants
Normal, Starburst and IR Luminous Galaxies

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**
2. **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**

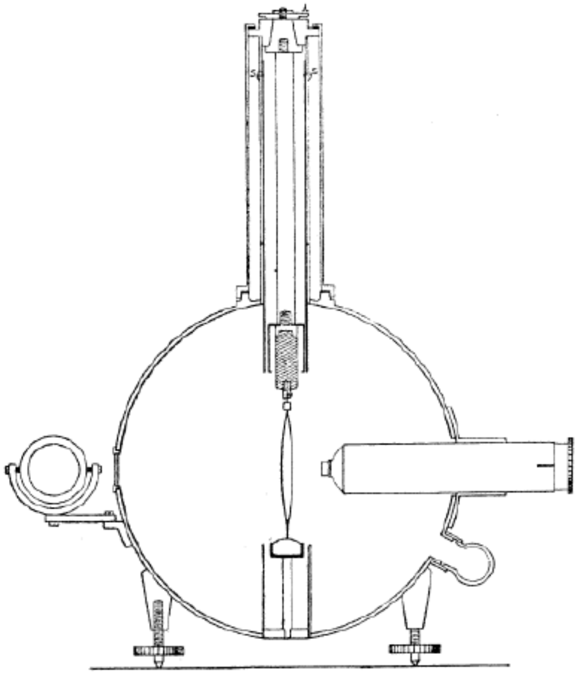
Discovery of cosmic rays by Victor Hess in 1912

Cosmic Ray History

- 99 yrs and counting
- arXiv:1012.5068 *Nationalism and internationalism in science: the case of the discovery of cosmic rays*

(Domenico Pacini) Per Carlson, Alessandro De Angelis

  - extra-terrestrial radiation possibly from the Sun
  - radioactivity from the crust of the Earth
  - radioactivity in the atmosphere



(Kurz 1909)

- Identification of cosmic rays as charged particles/ions
- Particle physics
  - Positron, by Anderson, in 1933
  - Muon by Neddermeyer and Anderson in 1937
  - Charged pion by Powell, Lattes and Occhialini in 1947
  - Discovery of strangeness
- Extensive air showers
  - Rossi and Auger in the 30s
  - Air shower arrays: HiRes, Auger
- Radio astronomy
- Gamma ray astronomy
- Multi-messenger astronomy

Local Cosmic Ray Intensity

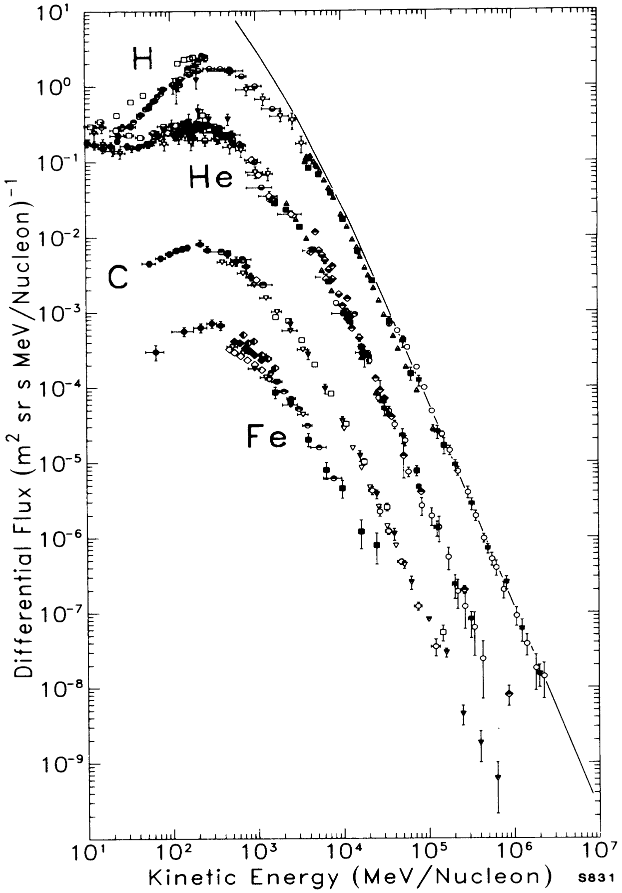
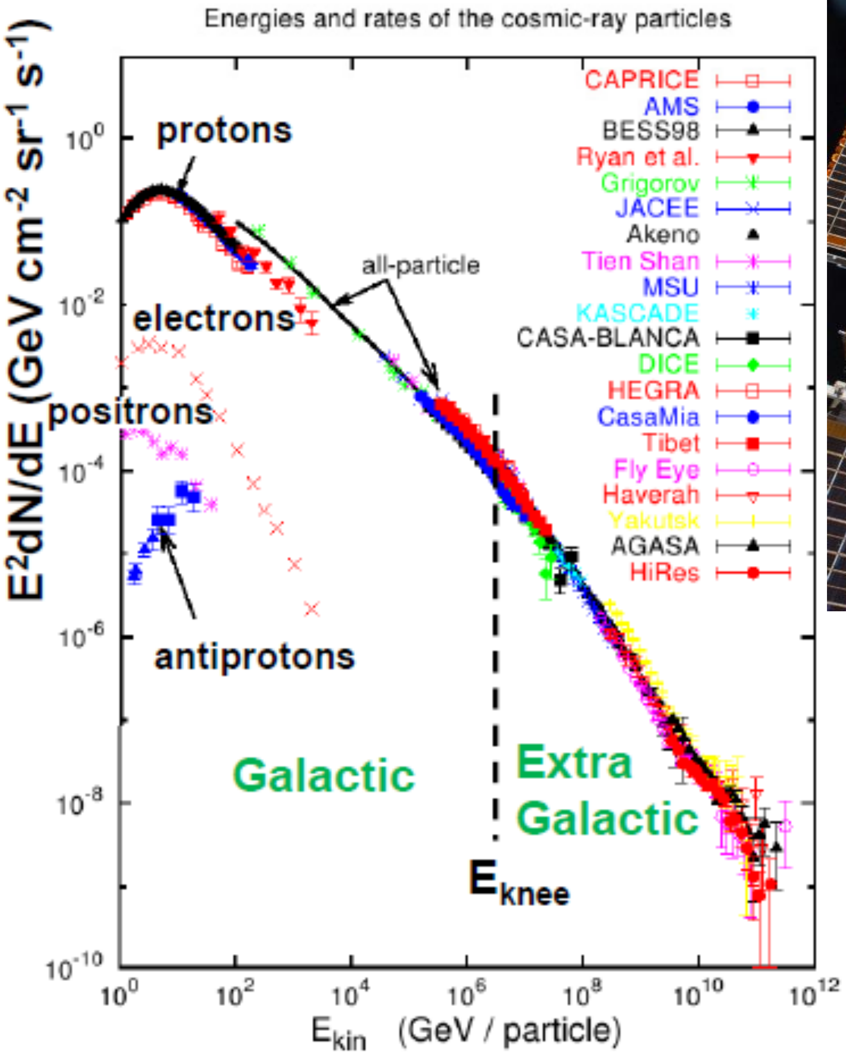
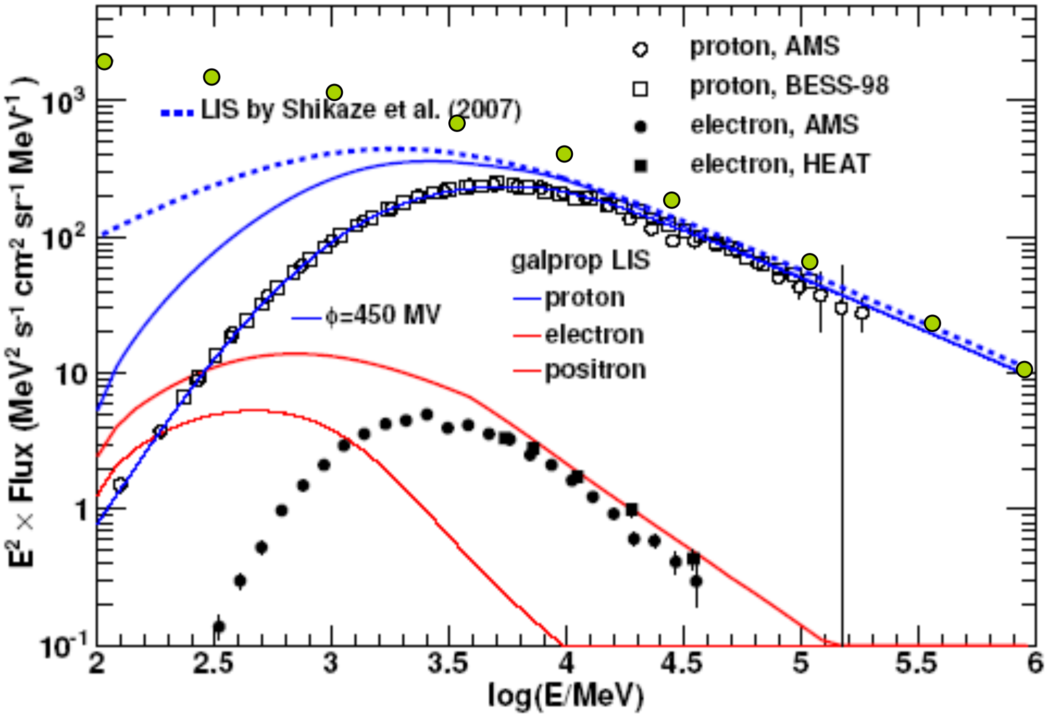


Figure 2. The differential energy spectra of the primary cosmic ray H, He, C, and Fe at Earth. [*Reproduced with permission from J. A. Simpson (1983)*. Ann. Rev. Nucl. Part. Sci. **33** *by Annual Reviews, Inc.*].

Cosmic Rays


Energies and rates of the cosmic-ray particles
E²dN/dE (GeV cm⁻² sr⁻¹ s⁻¹)
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
protons
all-particle
electrons
positrons
antiprotons
Galactic
Extra Galactic
E_knee
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
10^0
10^2
10^4
10^6
10^8
10^10
10^12
E_kin (GeV / particle)

Local Cosmic Ray Intensity



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

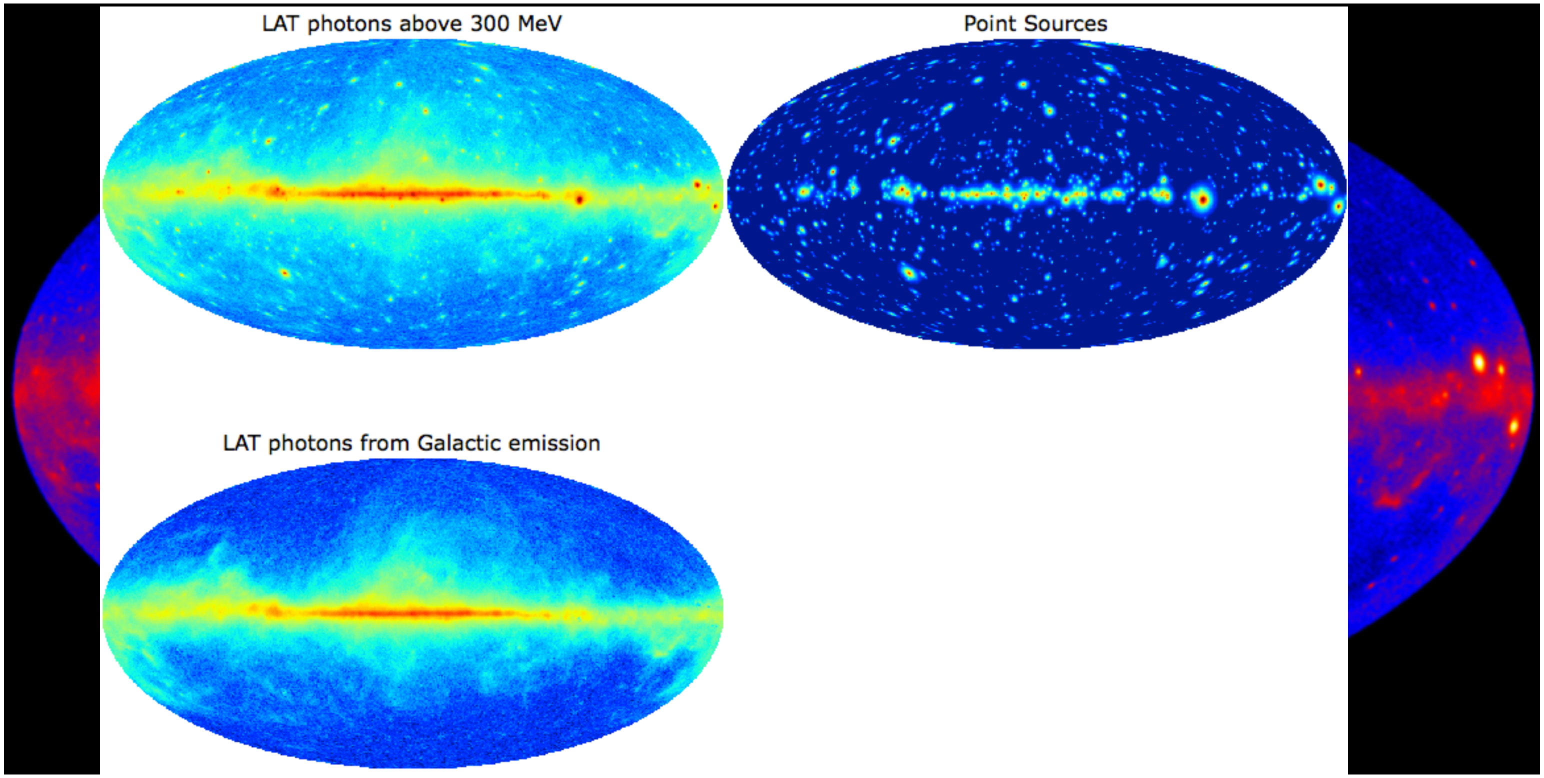
(green circles)

Fit of Dermer (A&A, 1986)

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

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

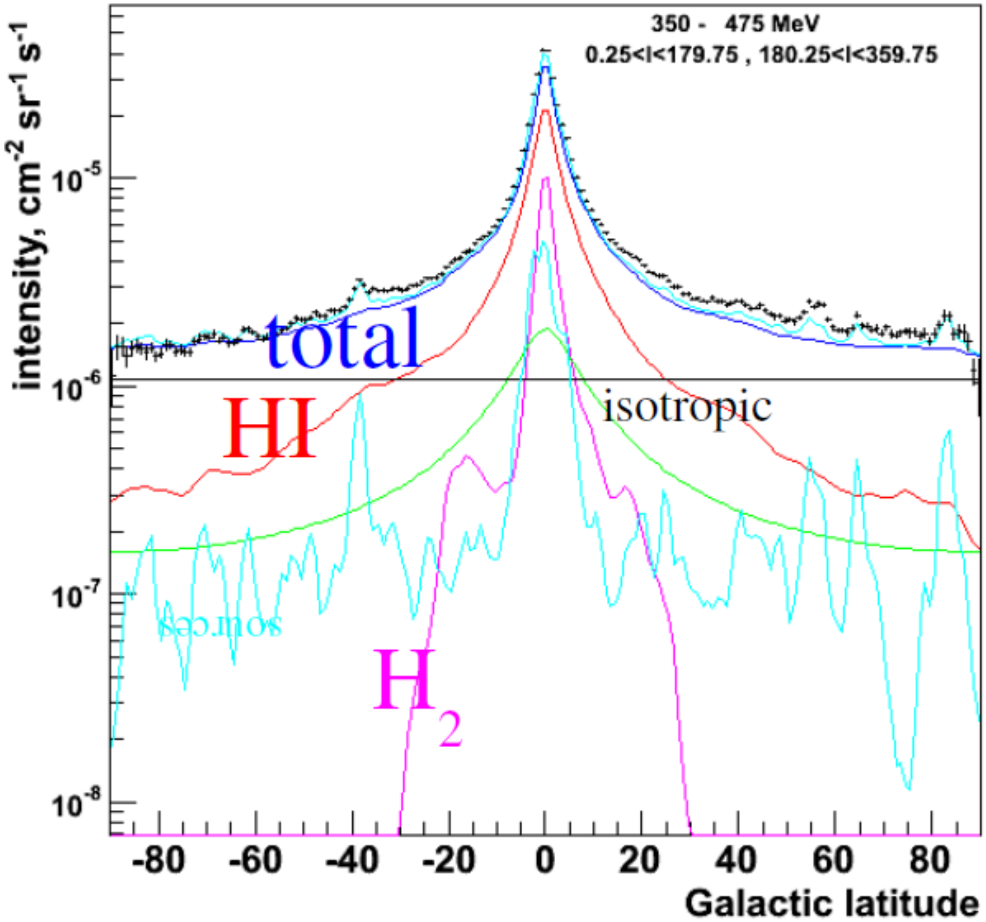
- **$CR_{protons}$ + gas $\rightarrow \pi^o \rightarrow 2\gamma$ Peaks at 70 MeV (in photon spectrum)**
- **$CR_{electrons}$ + radiation fields → Compton**
- **$CR_{electrons}$ + ambient protons → bremsstrahlung**
- **$CR_{electrons}$ + magnetic field → radio, optical, X-ray synchrotron**

Point/discrete source detection in the Galaxy requires background emission model

INPUTS AND OUTPUTS

HI, HII, H_2 surveys (X-factor)

- HI is traced by 21 cm line surveys
- H_2 derived indirectly using 2.6 mm line observations of CO (dark gas; Grenier et al. 2005; Casandjian & Grenier 2007)
- The total gas column density can also be traced indirectly from extinction and reddening by dust
- HII inferred from dispersion measures of pulsars.

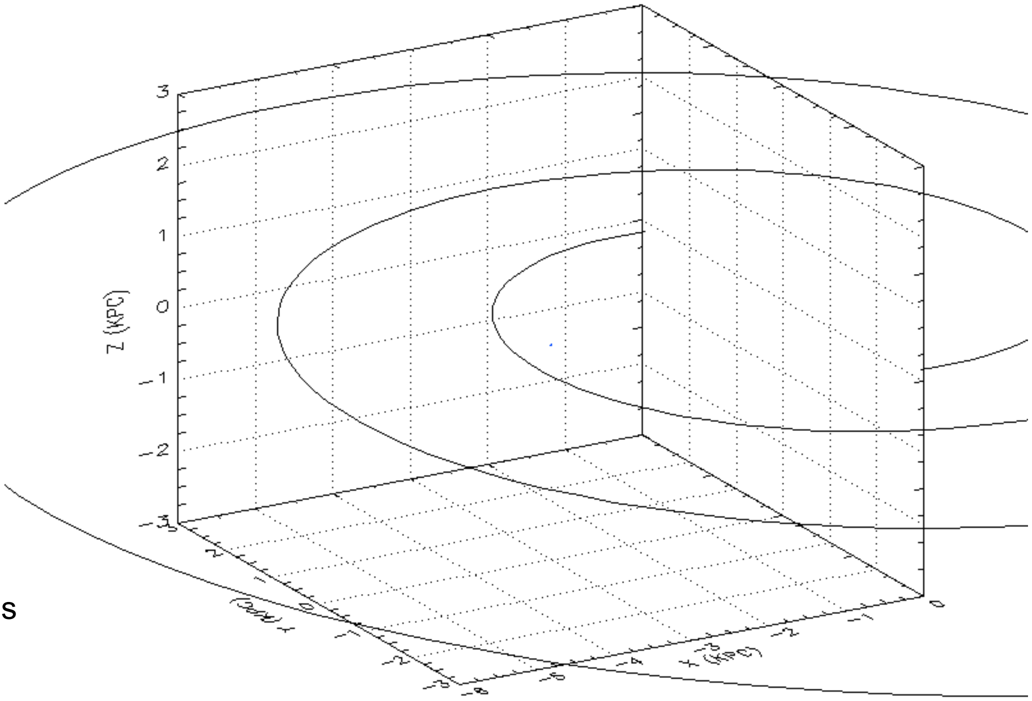


Cosmic Ray Propagation

- ❑ 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)

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



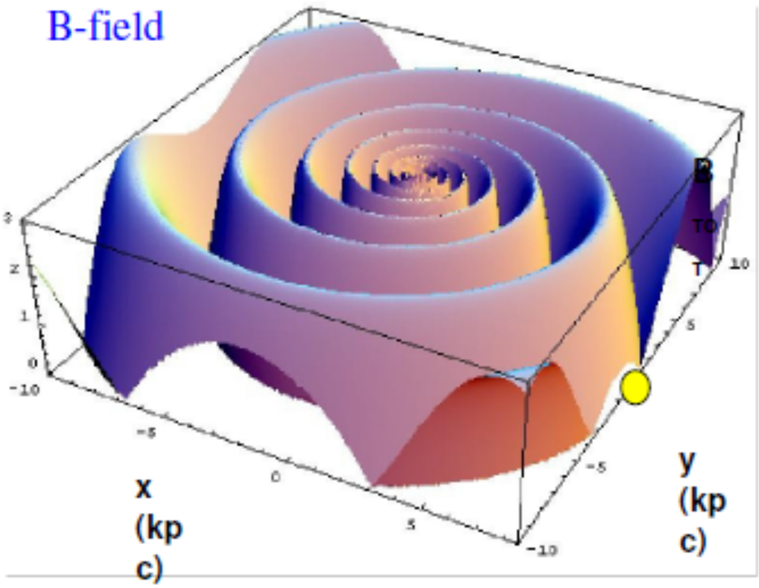
Dermer and Holmes 2005

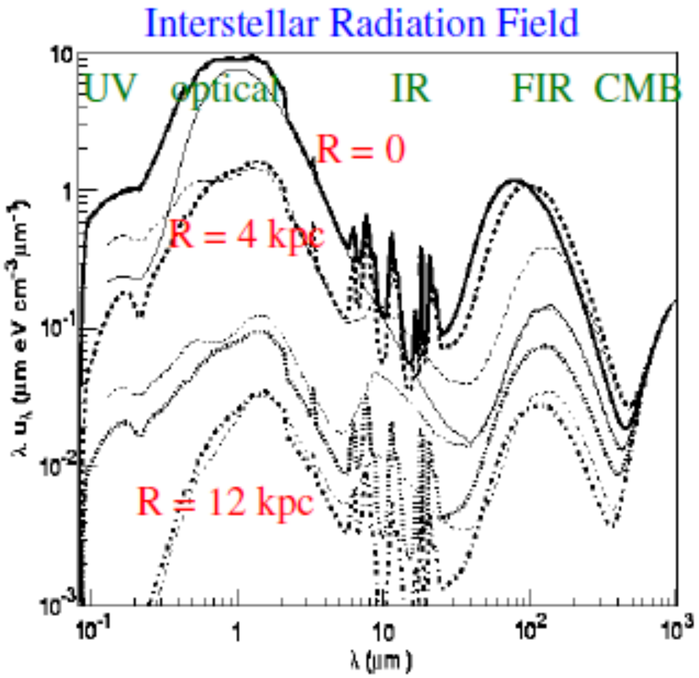
- Follow trajectories
- Guiding centers
- Diffusion equation

GALPROP (GALactic cosmic ray PROPagation model)

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

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

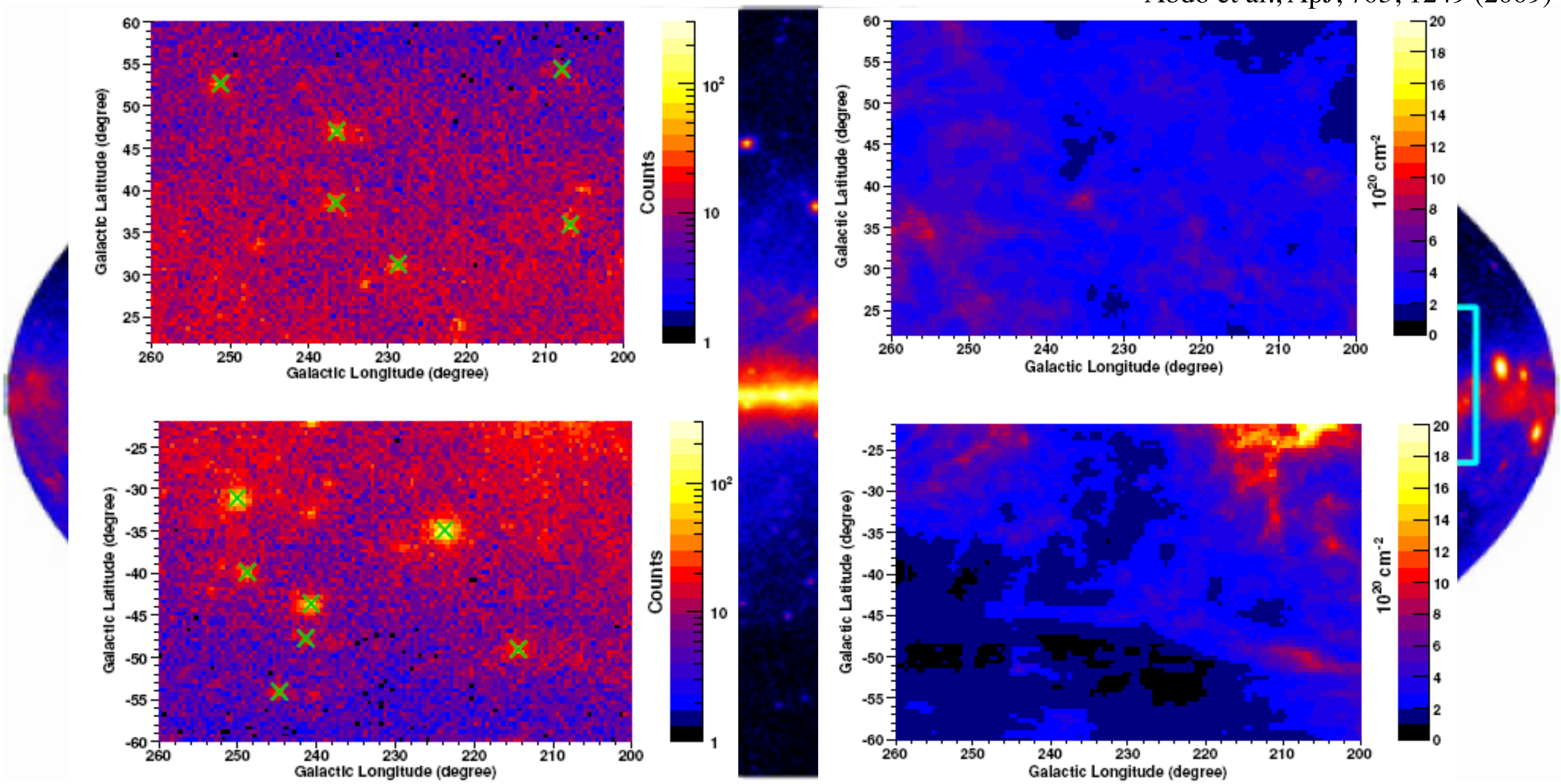



Interstellar Radiation Field

Template fitting to determine diffuse Galactic emissions from secondary nuclear production; GALPROP to determine diffuse scattered radiation fields (Compton, synchrotron)

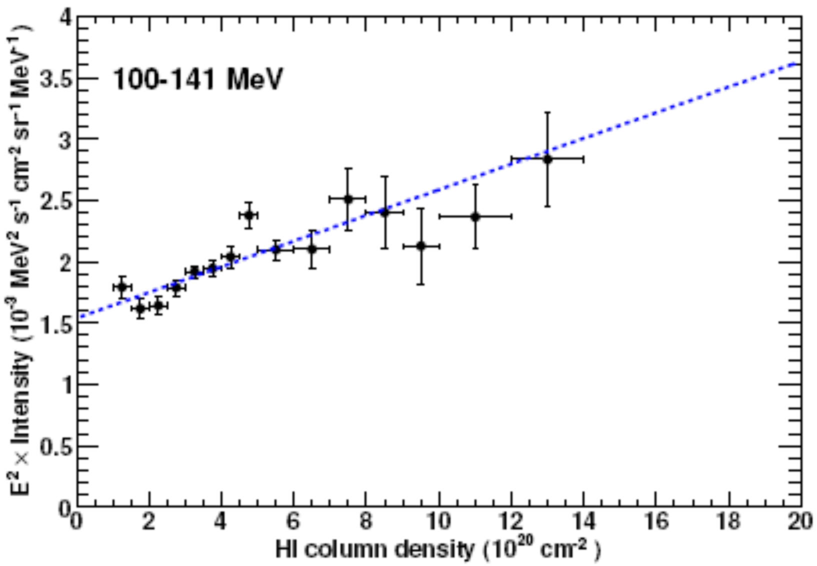
Diffuse γ-rays from Cosmic Ray Interactions in the Galaxy

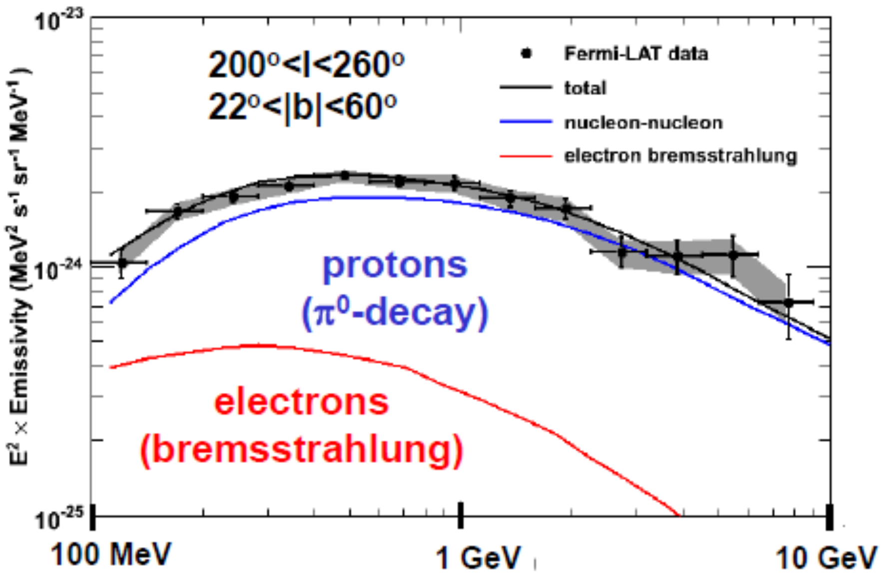
Abdo et al., ApJ, 703, 1249 (2009)



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

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

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

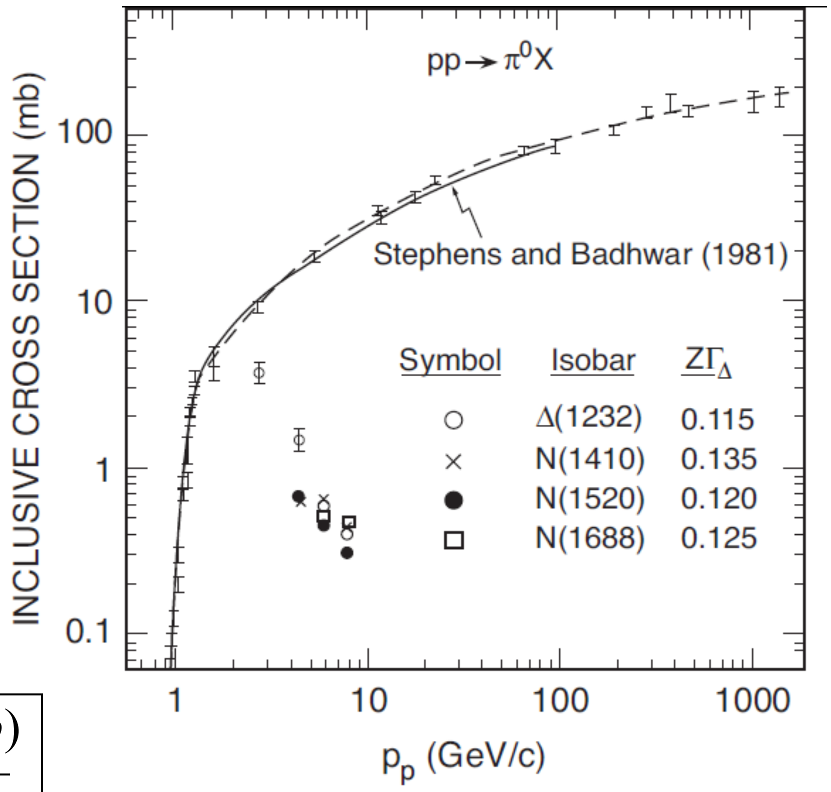
Secondary Nuclear Proton-Proton Cross Section

- **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
$p_p = 10 m_p,$	$E_p \cong 10\, GeV,$	30



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

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}**

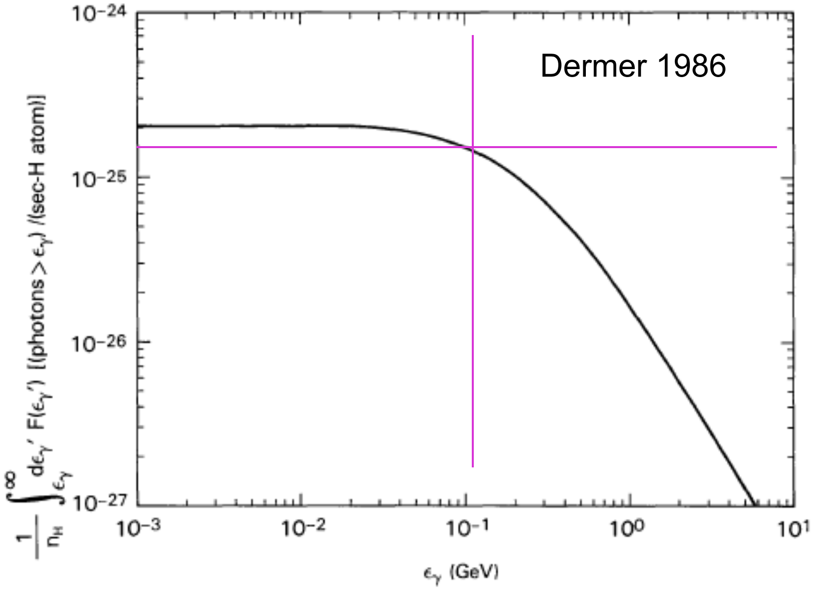


Fig. 9. The γ-ray emissivity per H atom integrated above photon energy ε_γ, using the differential emissivity of this work from Fig. 8

Total *γ*-ray emissivity:

2*γ* per π°

Correction for He and metals

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

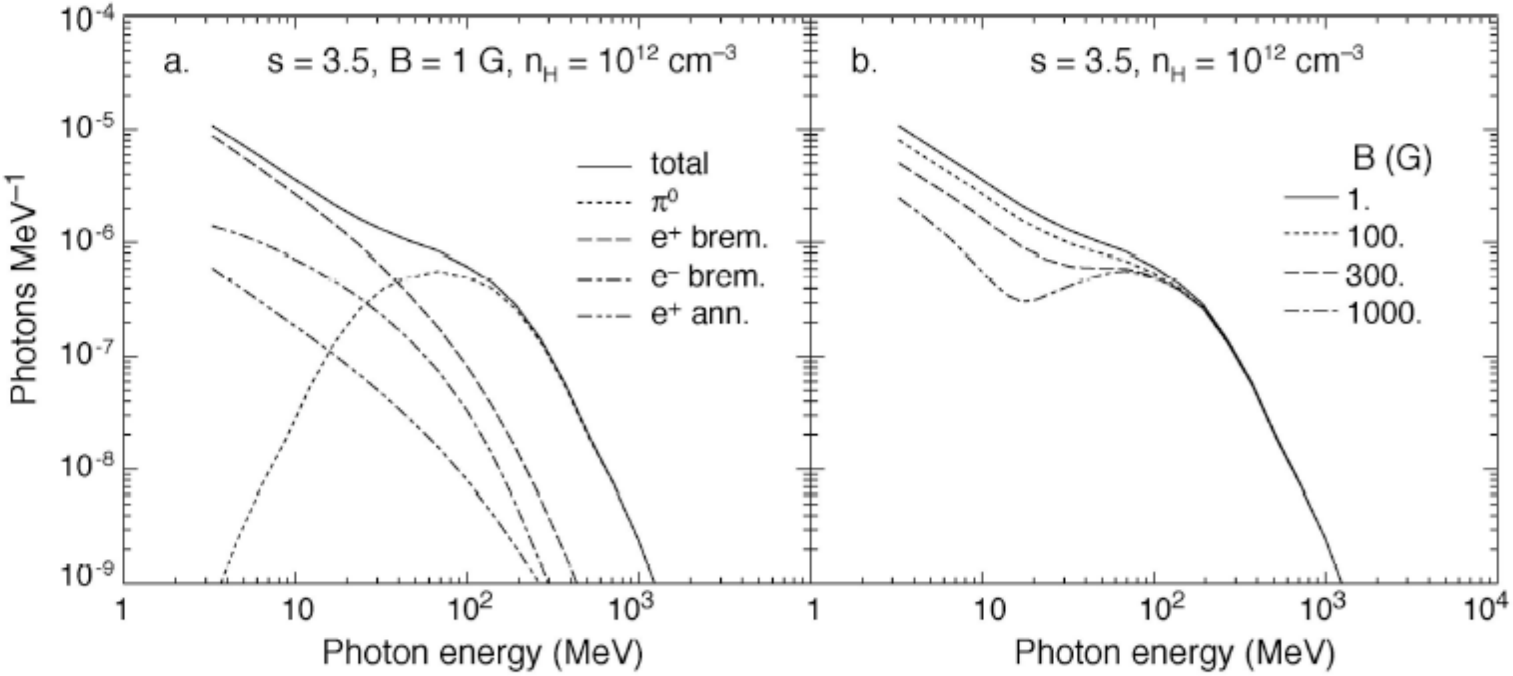
$$\frac{\frac{dN_\gamma}{dtdVd\Omega}}{n_H} \cong 2\zeta\cdot 4\text{mb}\cdot 2.2\int_{1.3}^{\infty} dE_p \frac{(E_p/1.3\text{ GeV})}{E_p^{2.75}} \cong \frac{2\cdot 2.2\cdot 4\times10^{-27}}{0.75(1.3)^{1.75}}$$

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

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

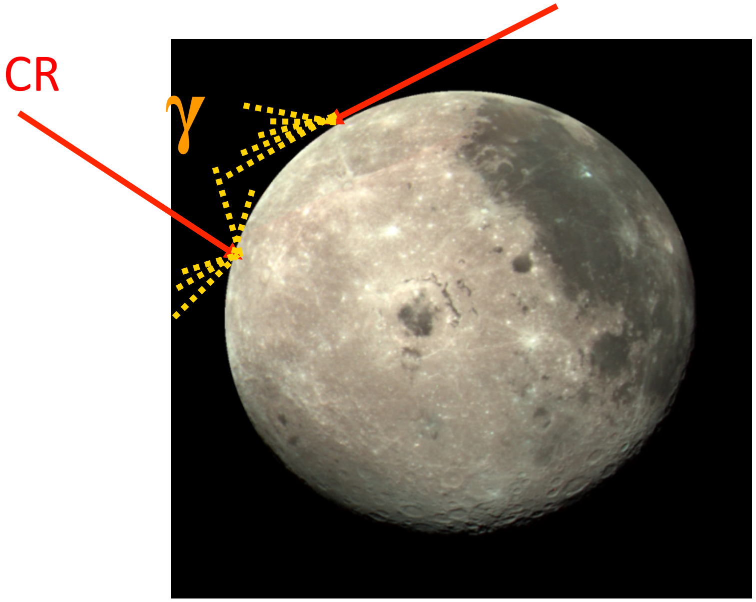
  cosmic rays, Solar flares

Murphy (2007)

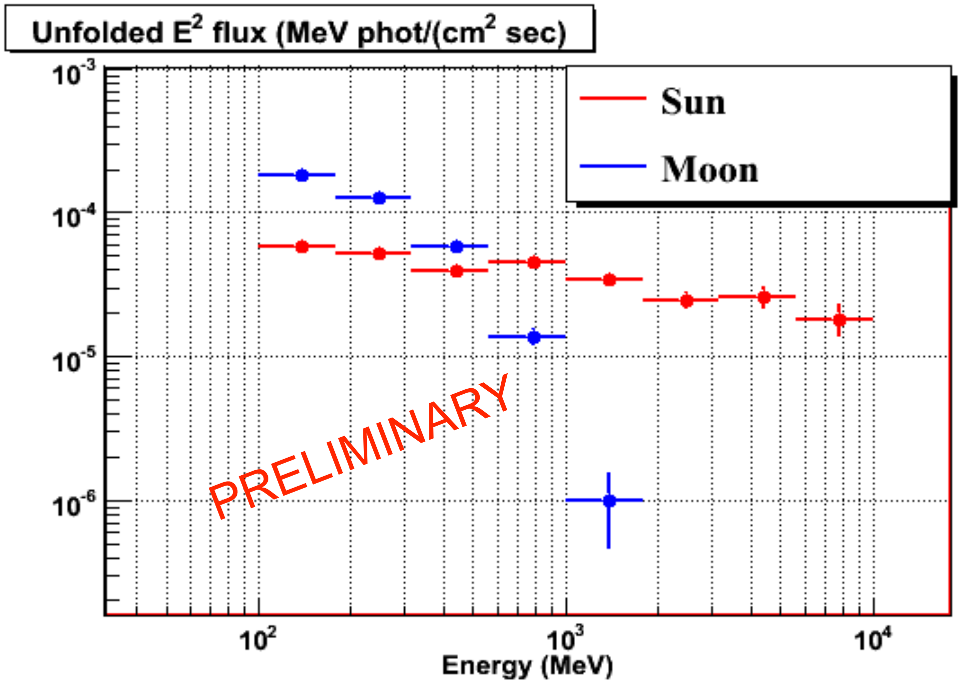
Quiet Solar and Lunar Gamma-ray Spectrum

- 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}



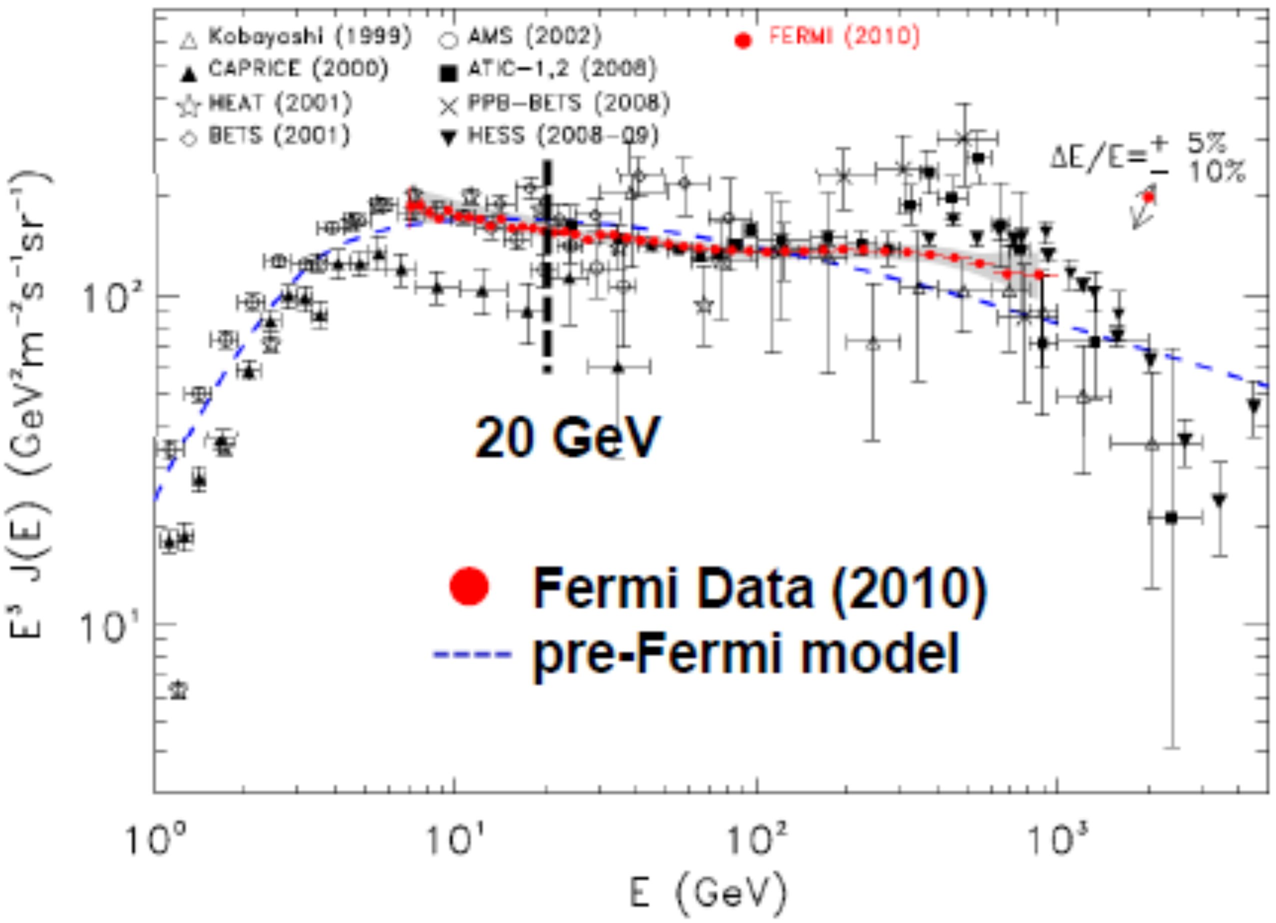
Expect limb-brightened emission



Solar γ-ray flares

Cosmic Ray Electron Spectrum

- PAMELA and early experiments show an increase in e^+/e^- ratio
- 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?



6 mos: Abdo, et al. 2009, PRL, 102, 181101 (4.5 M events)
12 mos: Ackermann et al. 2010, PRD (8M events)

Cosmic Ray Anisotropy with Fermi

Search for possible CRE anisotropies with large statistics

– Local CR sources, propagation environment

- **Construct *no anisotropy* map from flight data**

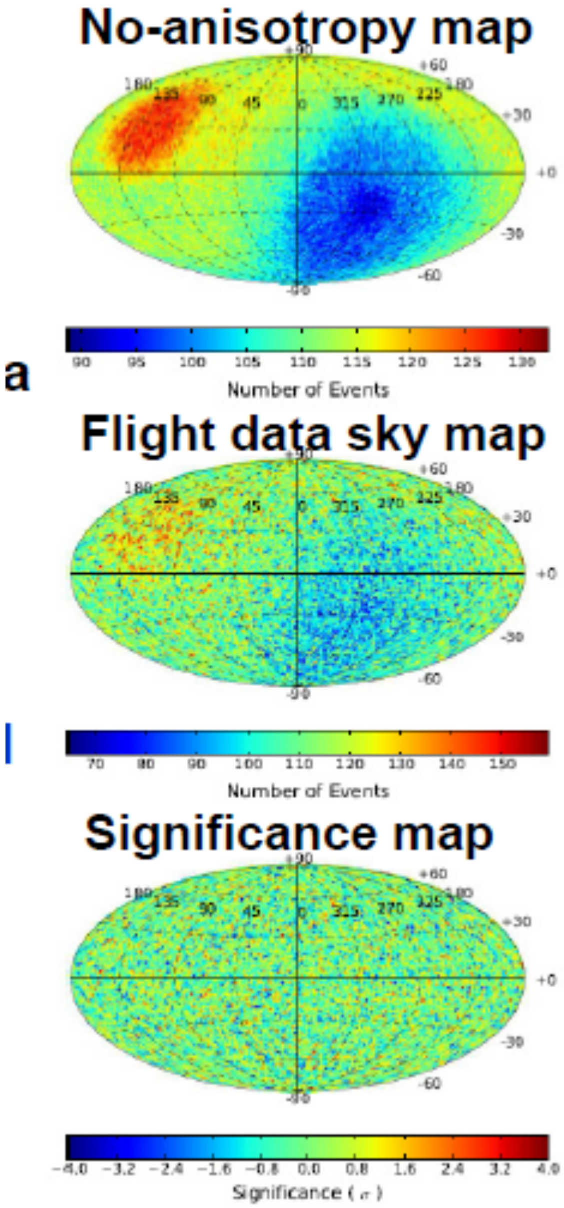
– shuffling and direct integration

- **Then search for anisotropies with different energy thresholds min) (60 GeV min.) and on different angular scales (10°-90°)**

– Direct bin-to-bin comparison or spherical harmonic analysis

- **No evidence of anisotropy above 60 GeV**

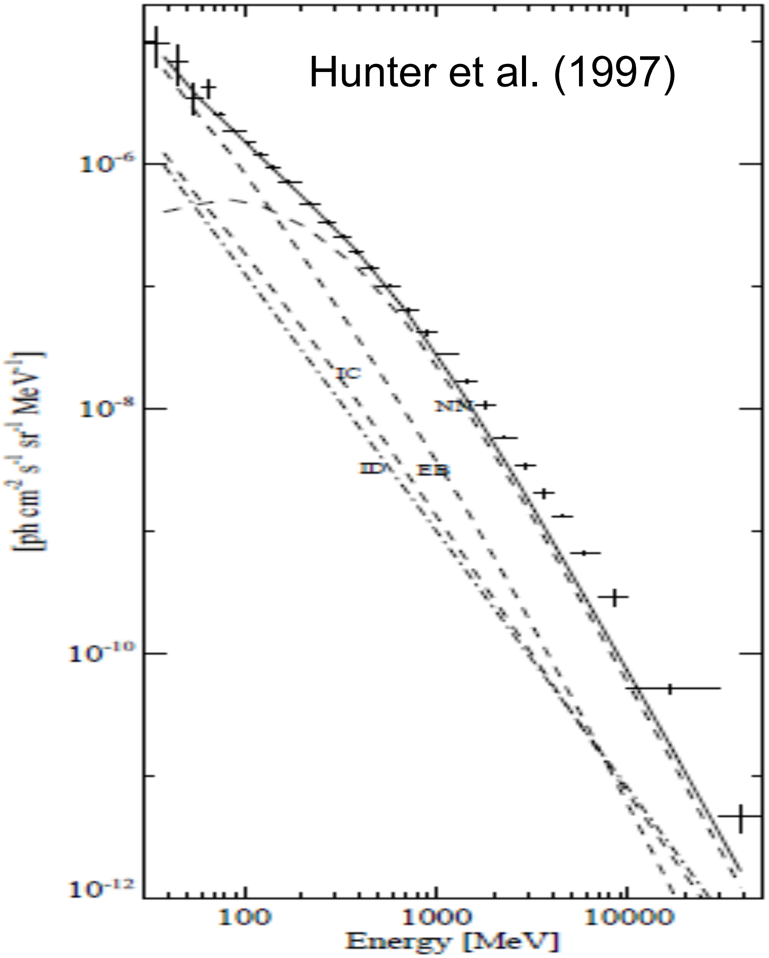
Only weak evidence for galactocentric radius



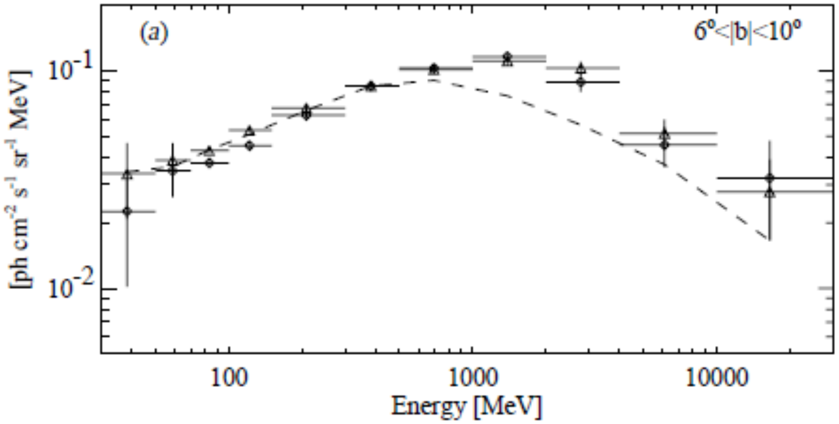
Ackermann et al. 2010, PRD

EGRET GeV Excess Galactic Diffuse Emission

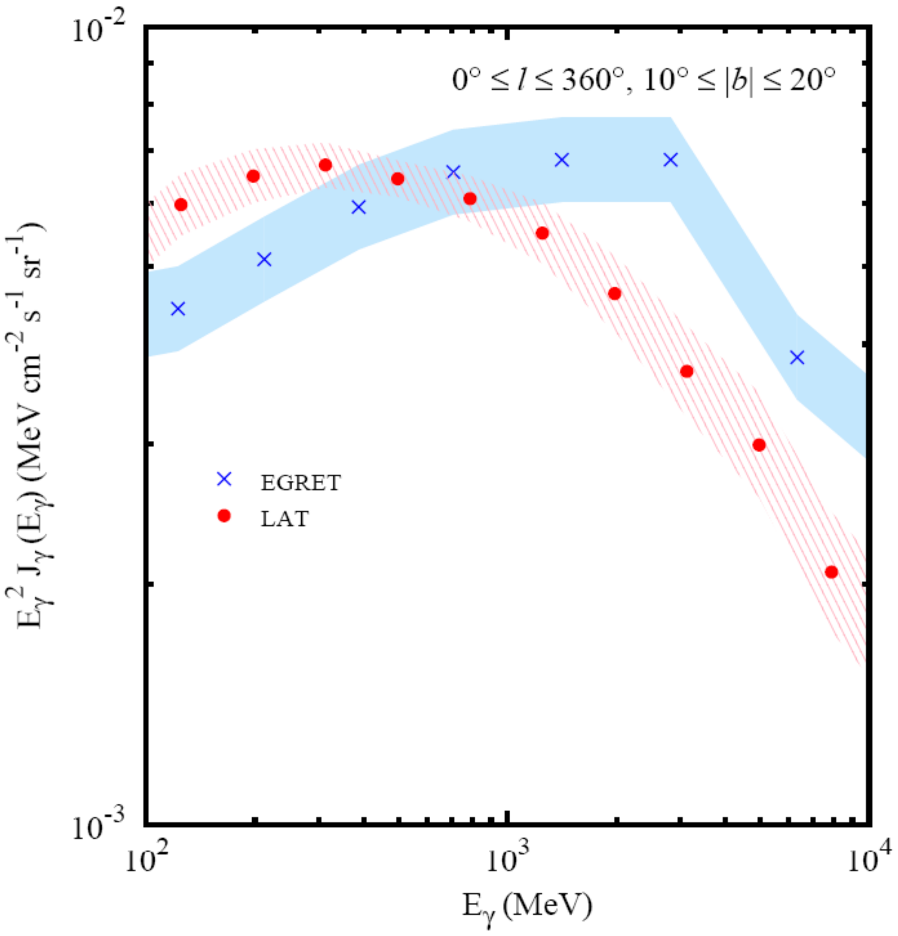
- ❑ Excess γ-ray emission, over that predicted using local demodulated cosmic ray spectrum, observed with EGRET (in all directions)
- ❑ Possible explanations:
  - – Unusual location and cosmic ray spectrum
  - – Nuclear physics wrong
  - – γ rays from annihilating dark matter
  - – EGRET miscalibration



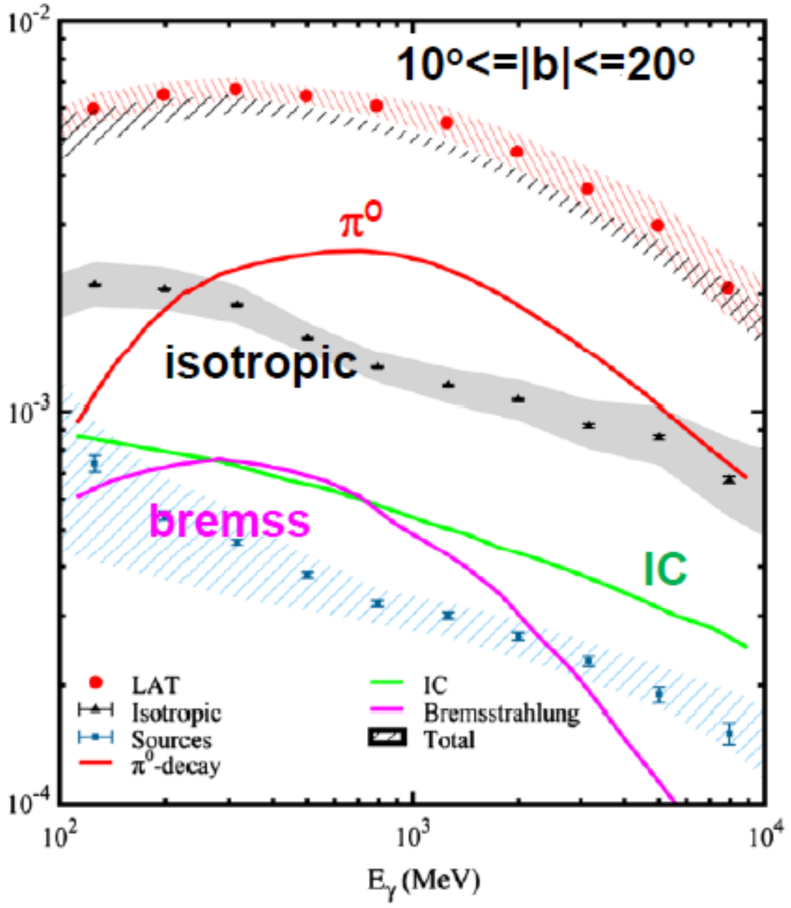
Average diffuse γ-ray spectrum of the inner Galaxy region, 300° < l < 60°, |b| <10°(0.73 sr)



No EGRET GeV Excess and the Galactic Diffuse Emission



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

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

$t_{esc} \approx 2\times10^{7}\, yr$ from analysis of cosmic ray ^{10}Be ($\tau \approx 2\times10^{6}$ yr)

$$V_{gal} \sim \pi(200\, pc)(15\, kpc)^{2} \sim 4\times10^{66}\, cm^{3}$$

- 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)

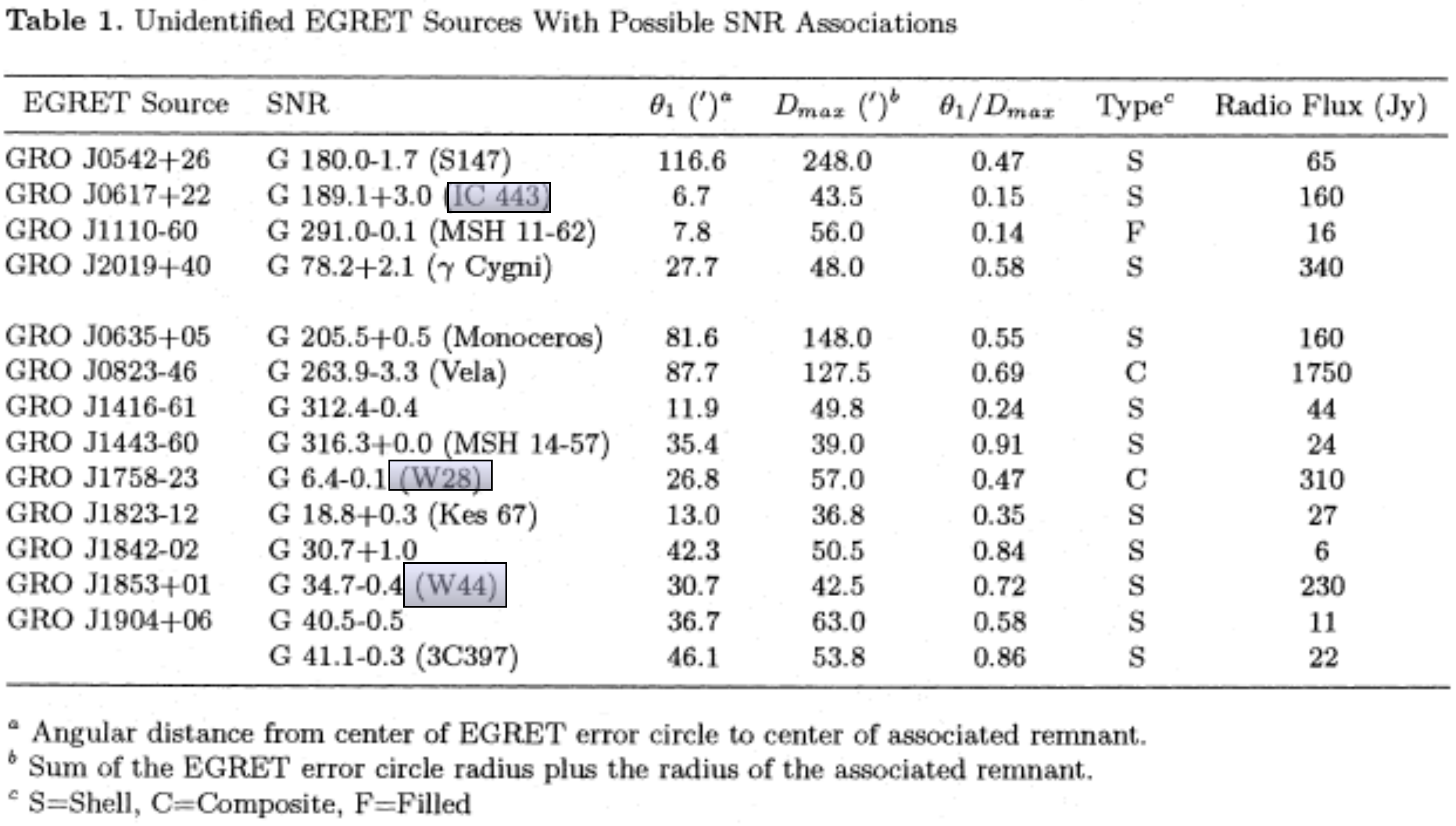


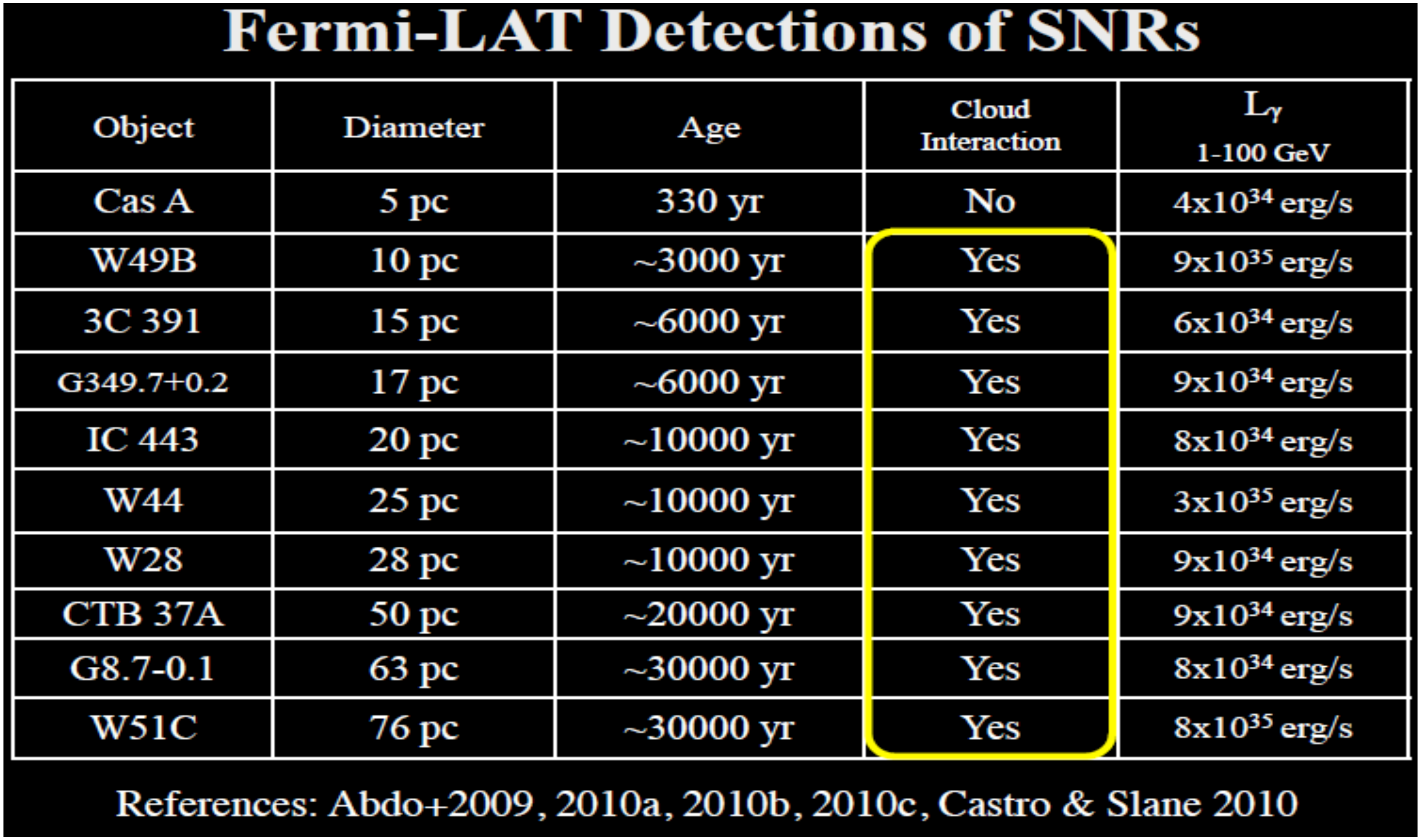
Table 1. Unidentified EGRET Sources With Possible SNR Associations

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

- Fermi has detected
  - – young (<~ 3000 yr) and historical SNRs: Cas A, RXJ 1713.7-3946 (1600 yr)
  - – Intermediate age (~ 10^4 yr) SNRs: IC443, W28
  - – Middle-aged (> 10^4 yr) SNRs: W51C, W44 (20000 yr), G349.7+0.2

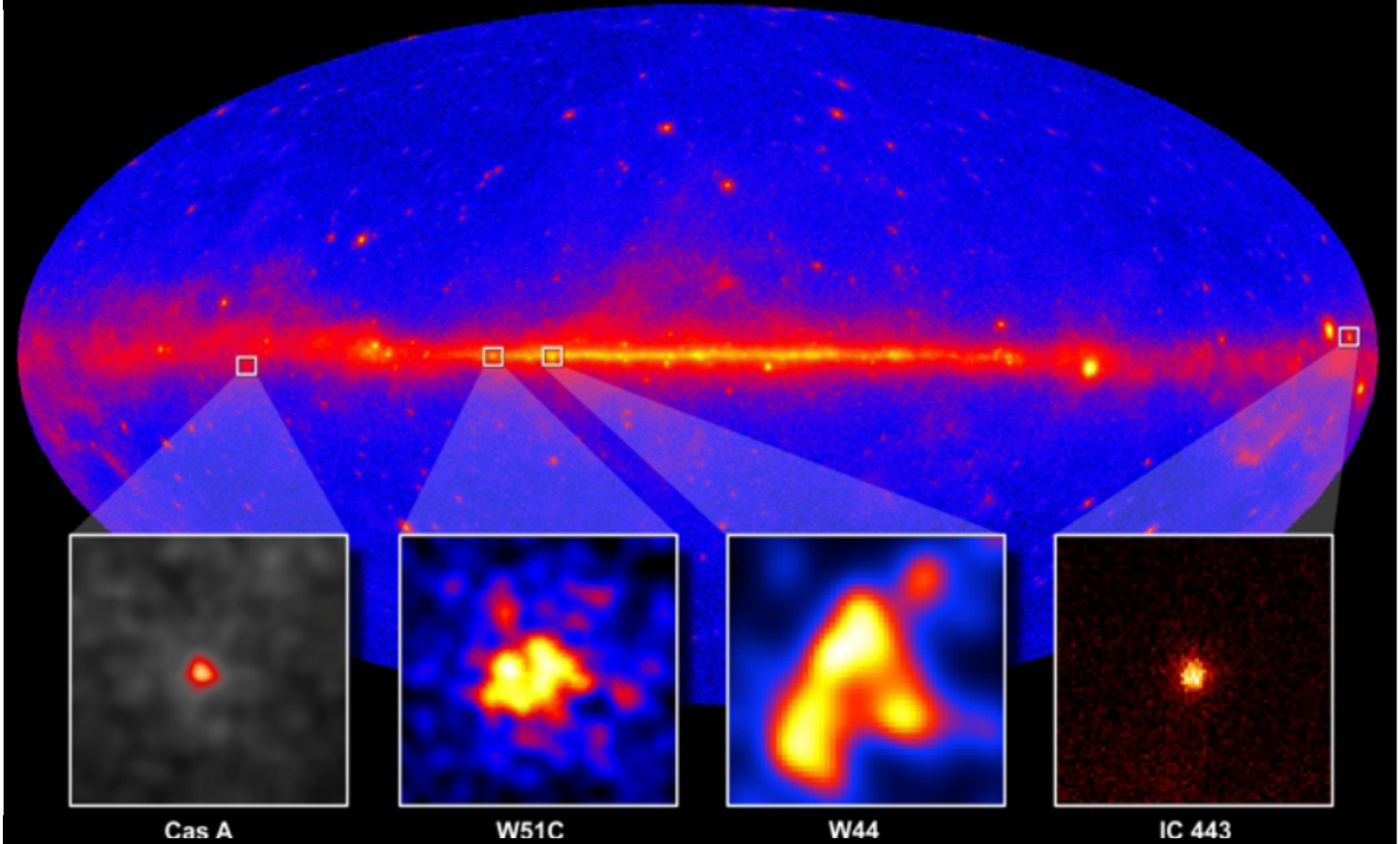


Fermi-LAT Detections of SNRs

Object	Diameter	Age	Cloud Interaction	L_γ 1-100 GeV
Cas A	5 pc	330 yr	No	4×10^{34} erg/s
W49B	10 pc	~3000 yr	Yes	9×10^{35} erg/s
3C 391	15 pc	~6000 yr	Yes	6×10^{34} erg/s
G349.7+0.2	17 pc	~6000 yr	Yes	9×10^{34} erg/s
IC 443	20 pc	~10000 yr	Yes	8×10^{34} erg/s
W44	25 pc	~10000 yr	Yes	3×10^{35} erg/s
W28	28 pc	~10000 yr	Yes	9×10^{34} erg/s
CTB 37A	50 pc	~20000 yr	Yes	9×10^{34} erg/s
G8.7-0.1	63 pc	~30000 yr	Yes	8×10^{34} erg/s
W51C	76 pc	~30000 yr	Yes	8×10^{35} erg/s

References: Abdo+2009, 2010a, 2010b, 2010c, Castro & Slane 2010

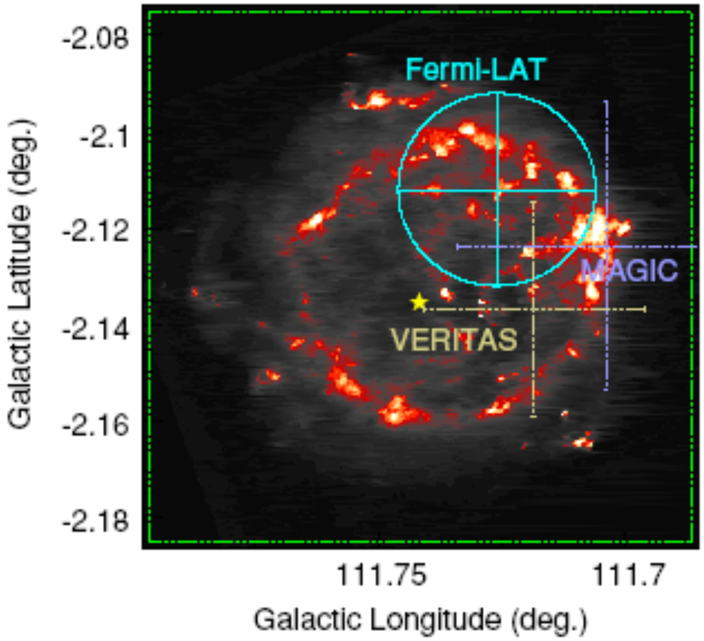
First GeV Maps of SNRs

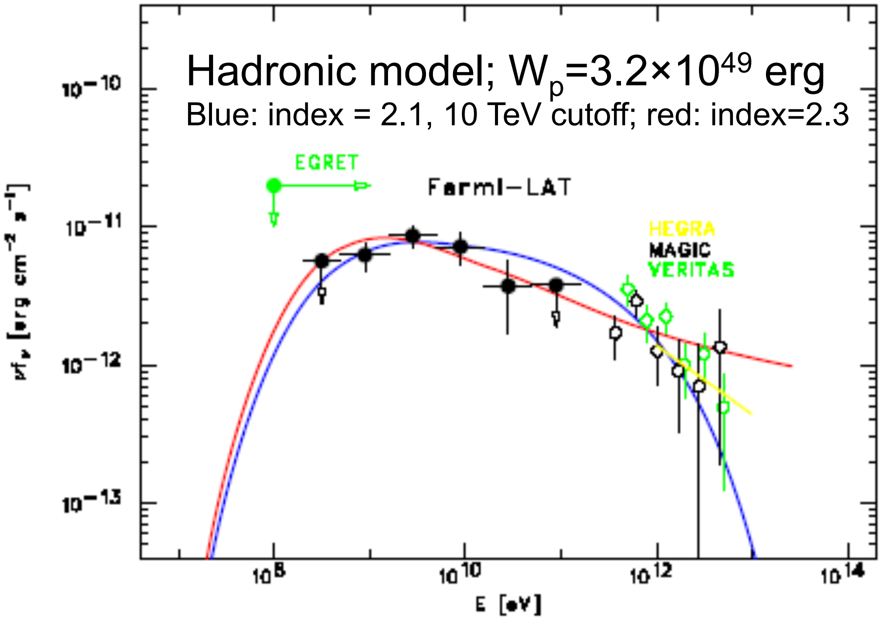


Fermi detects γ-ray emission from Cas A

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

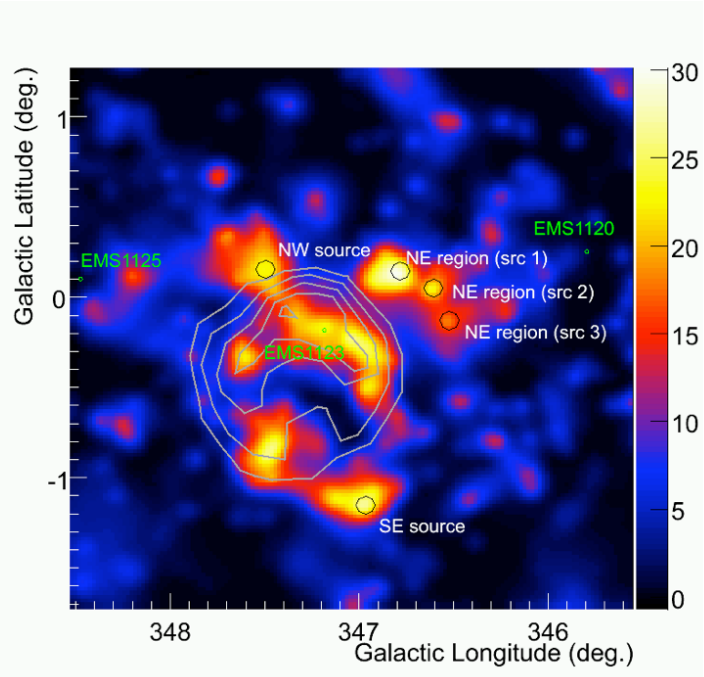


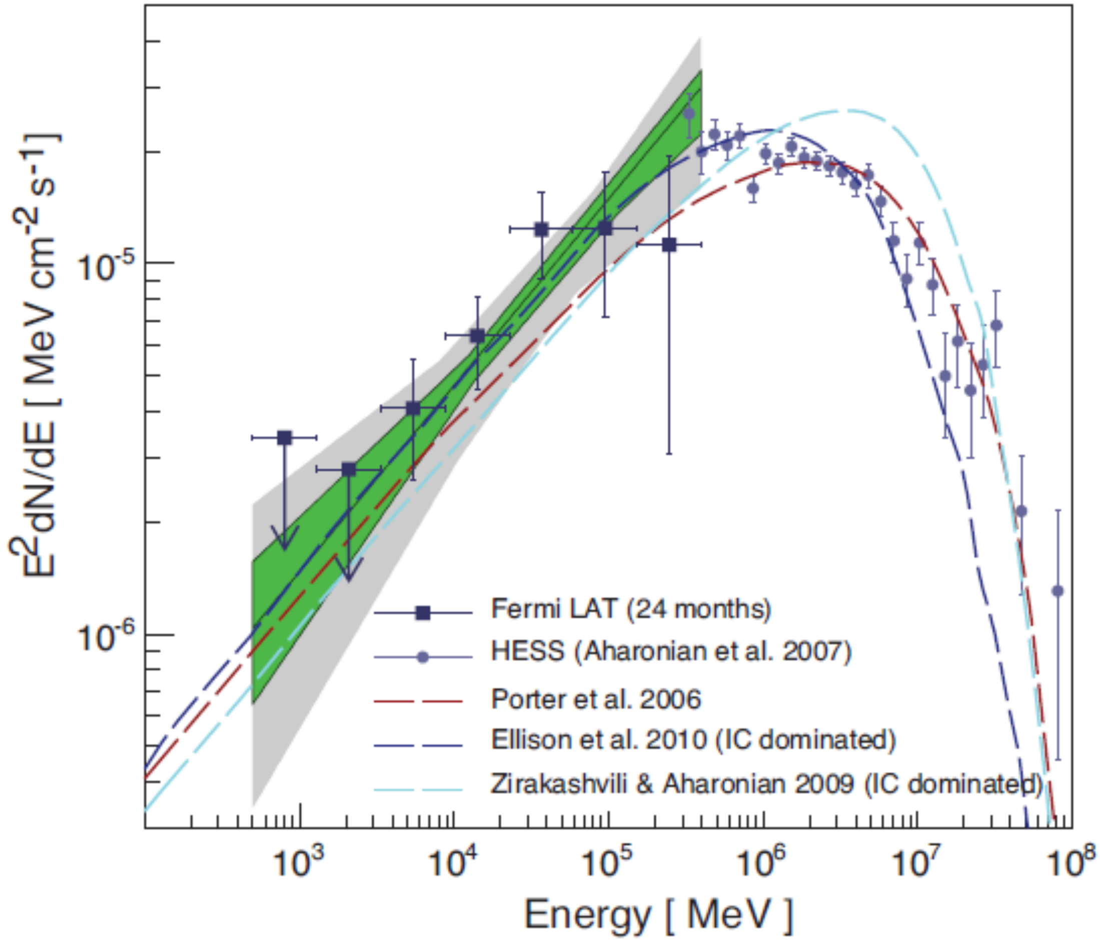

Hadronic model; $W_p=3.2\times10^{49}$ erg

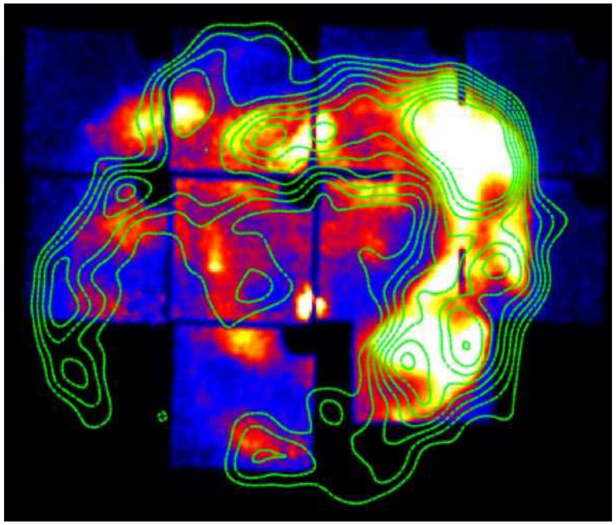
Blue: index = 2.1, 10 TeV cutoff; red: index=2.3

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

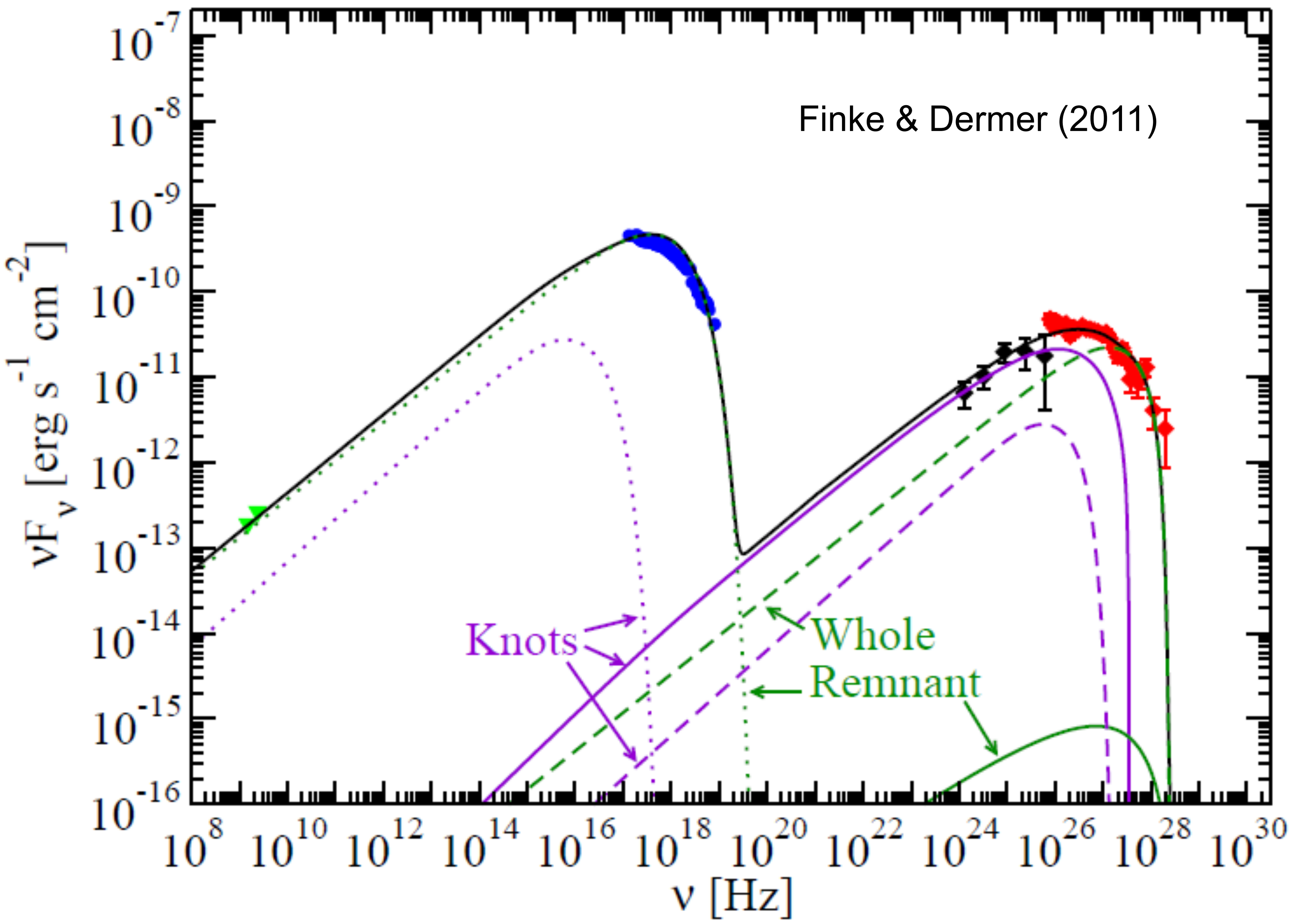






HESS/Suzaku (Tanaka et al. 2008)

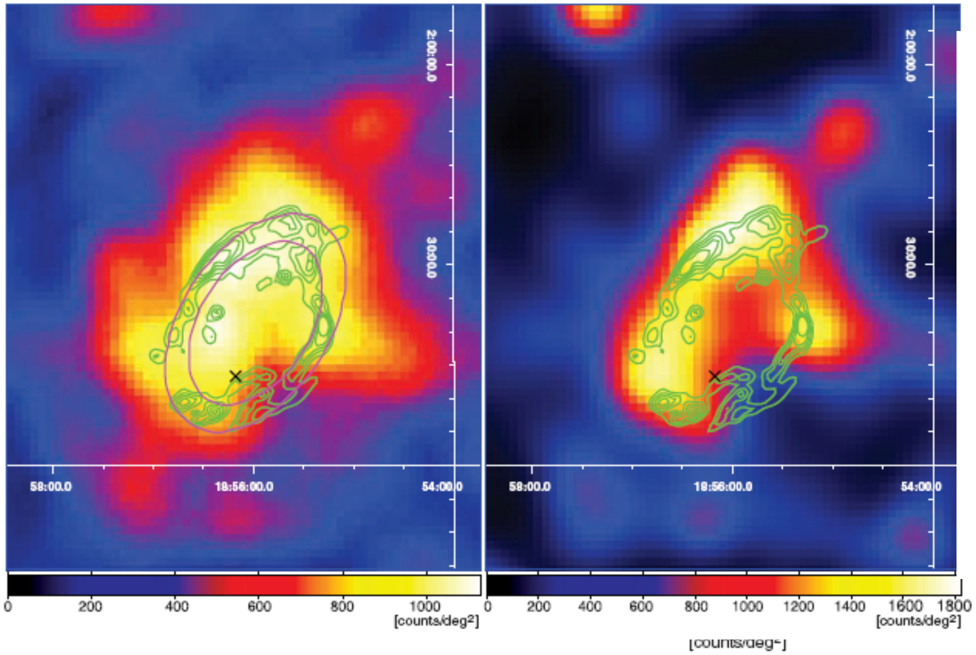
Multizone Leptonic Model for RXJ 1713

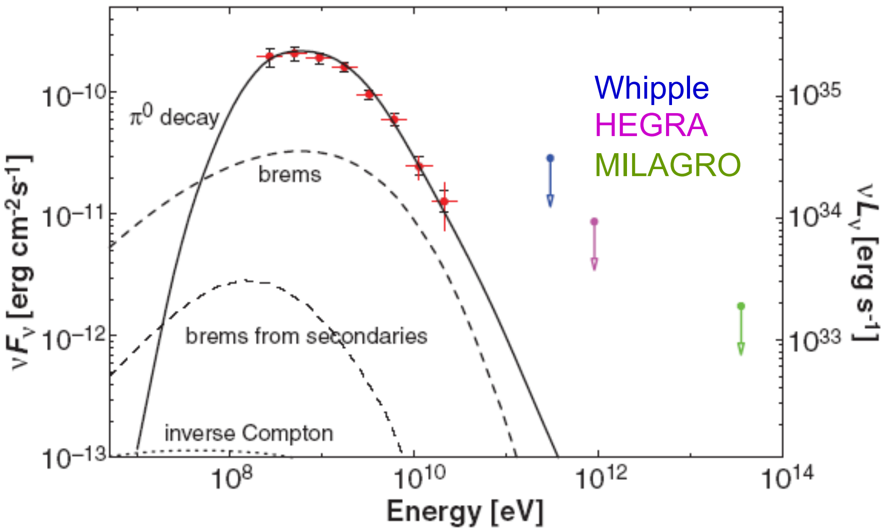


Fermi detects γ-ray emission from W44

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

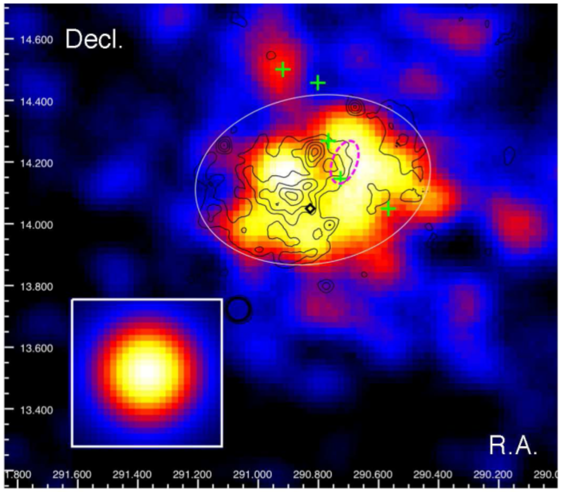


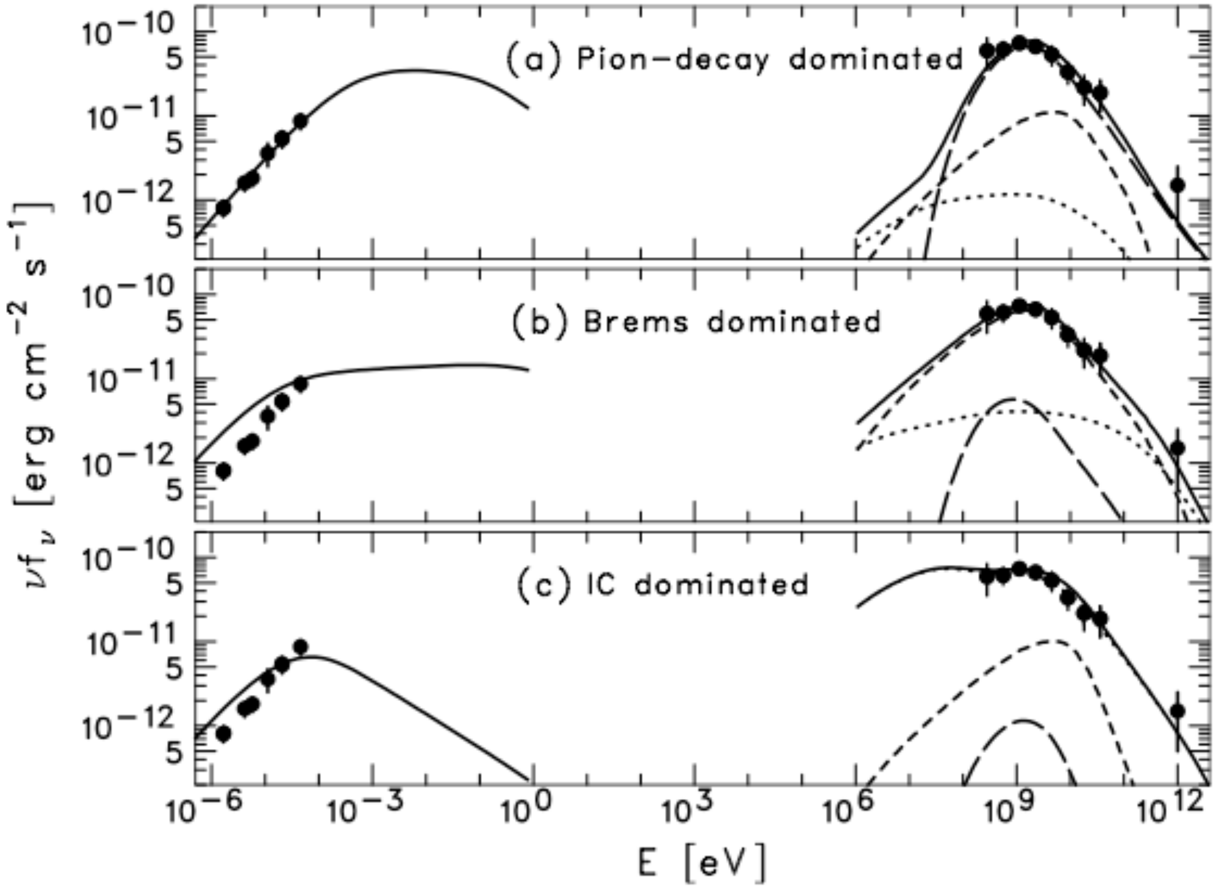


Broadband modeling of W51C

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



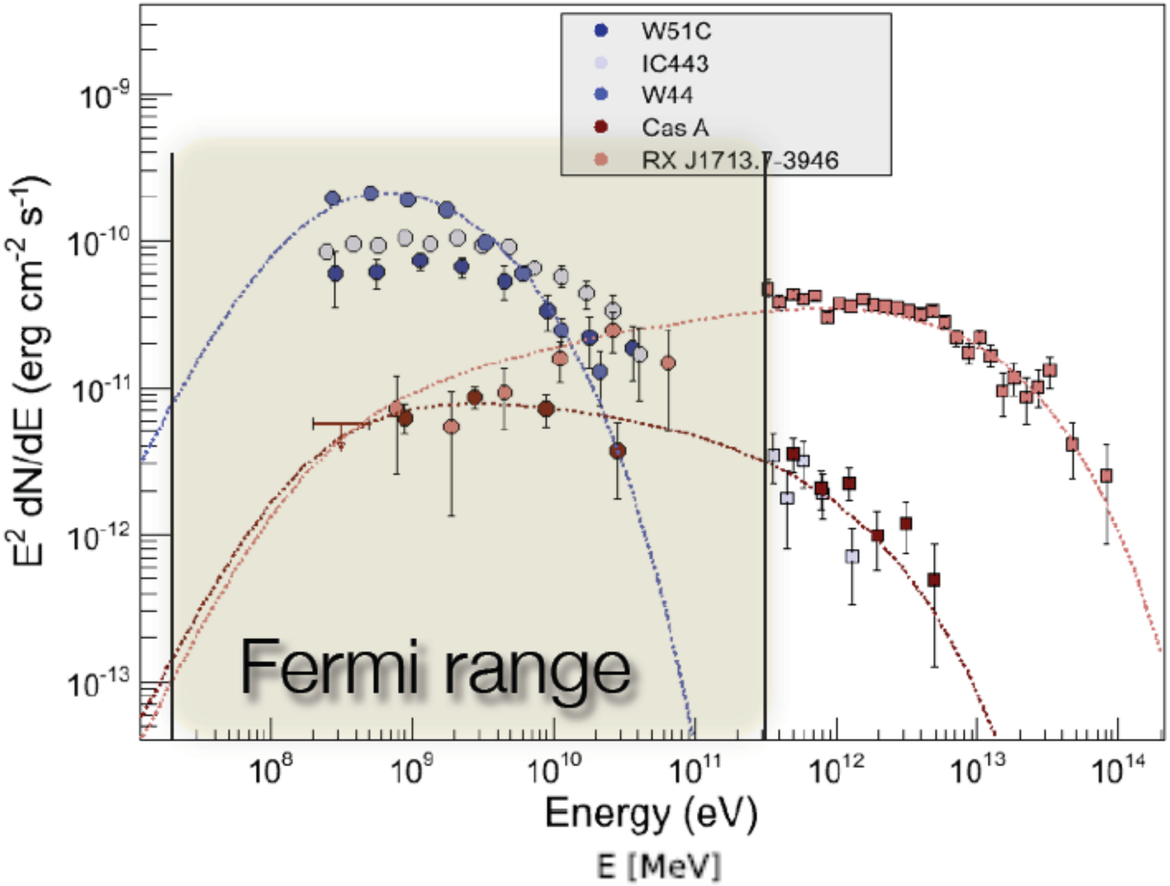


	W_p	W_e
	(10^{50}	erg)
(a) π^o-decay	5.2	0.13
(b) ff	0.54	0.87
(c) Compton	8.4	11

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



Normal, Starburst and IR Luminous Galaxies

Detection of LMC with EGRET

$\phi_\gamma = \mathbf{19 \times 10^{-8}\ ph(>100\ MeV)\ cm^{-2}\ s^{-1}}$

(Sreekumar et al.1992)

Spectral shape consistent with that expected from cosmic ray interactions with matter

Scale Milky Way and LMC to

1. local galaxies (SMC, M31)
2. starburst Galaxies (M82, NGC 253; ≈ 3 Mpc)
3. IR Luminous Galaxies (Arp 220; ≈ 72 Mpc) (Torres 2004)

Detection of LMC with Fermi

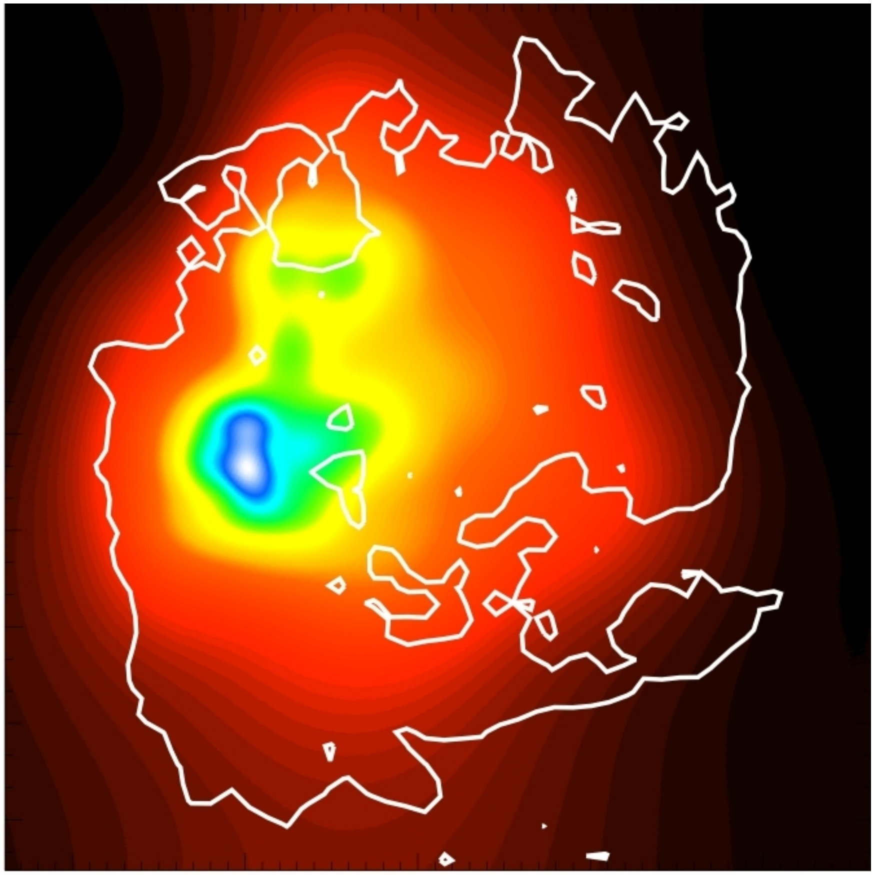
$\phi_\gamma = \mathbf{26.3(\pm 4.7)\times 10^{-8}\ ph(>100\ MeV)\ cm^{-2}\ s^{-1}}$

33σ

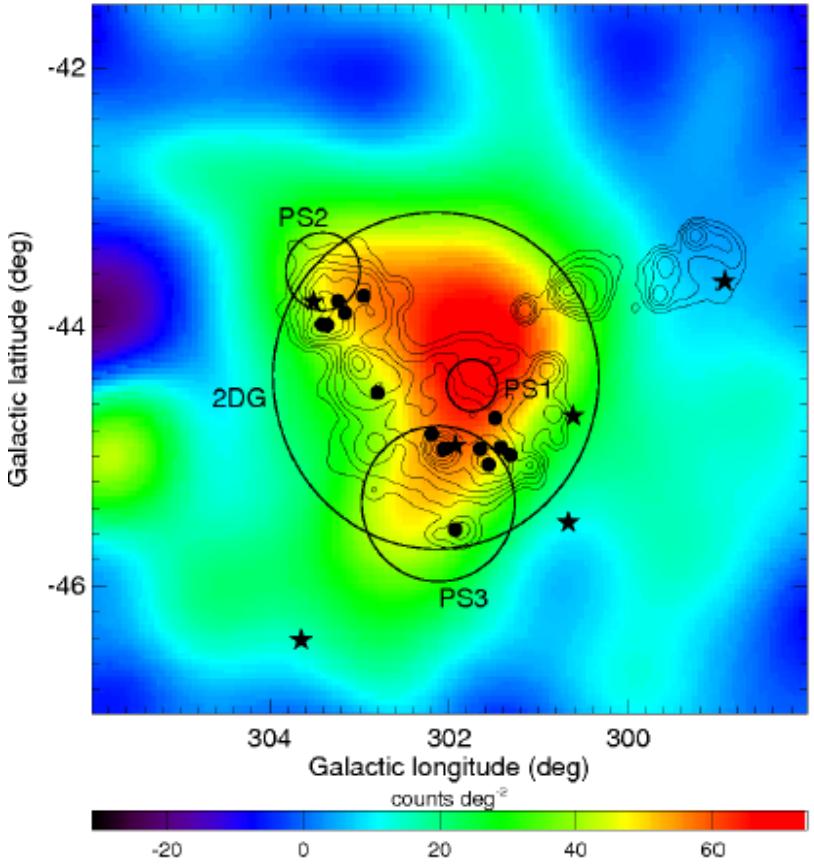
D ≈ 50 kpc, i ≈ 20°-35°, diameter ≈ 8°

$M_{gas} \cong 0.6\times10^9\ M_o$ (≈10% of Milky Way)
Supernova rate ≈0.2 of Milky Way

- LMC for the first time resolved in gamma rays
- 30 Doradus star forming region is a bright source of gamma rays and very likely a powerful cosmic-ray accelerator
- No significant point source contribution (no pulsations from PSRs J0540-6919 and J0537-6910)
- Gamma-ray emission correlates well with massive star forming regions and little with the gas distribution
- Compactness of emission regions suggests little CR diffusion
- Average CR density ≈ 0.2–0.3 that in solar vicinity
- 1.6 (±0.1)×10^{-10} erg cm^{-2} s^{-1}

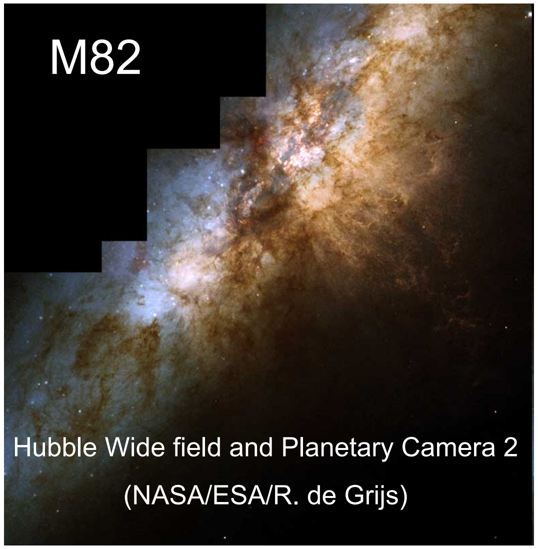


- SMC for the first time detected in γ rays
- Steady emission over ~3° but not clearly correlated with massive stars, neutral gas, SNRs or pulsars
- Average CR density ≈ 0.15 that in solar vicinity
- 3.7 (±0.7)×10^{-8} ph(>100 MeV) cm^{-2} s^{-1}



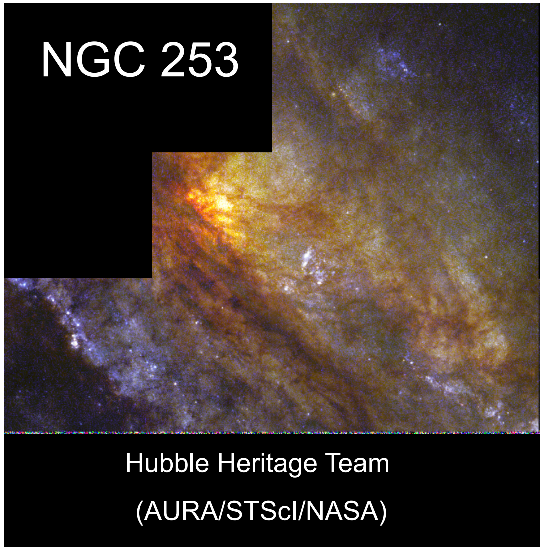
- **Residual counts maps after subtraction of fitted celestial background model and smoothing by a 2D Gaussian kernel with σ = 0.4°.**
- **Hα emission contours of the SMC in logarithmic scale are shown**
- **locations of the currently known pulsars and SNRs in the galaxy (stars and points respectively)**

Starburst Galaxies


M82

Hubble Wide field and Planetary Camera 2

(NASA/ESA/R. de Grijs)


NGC 253

Hubble Heritage Team

(AURA/STScI/NASA)

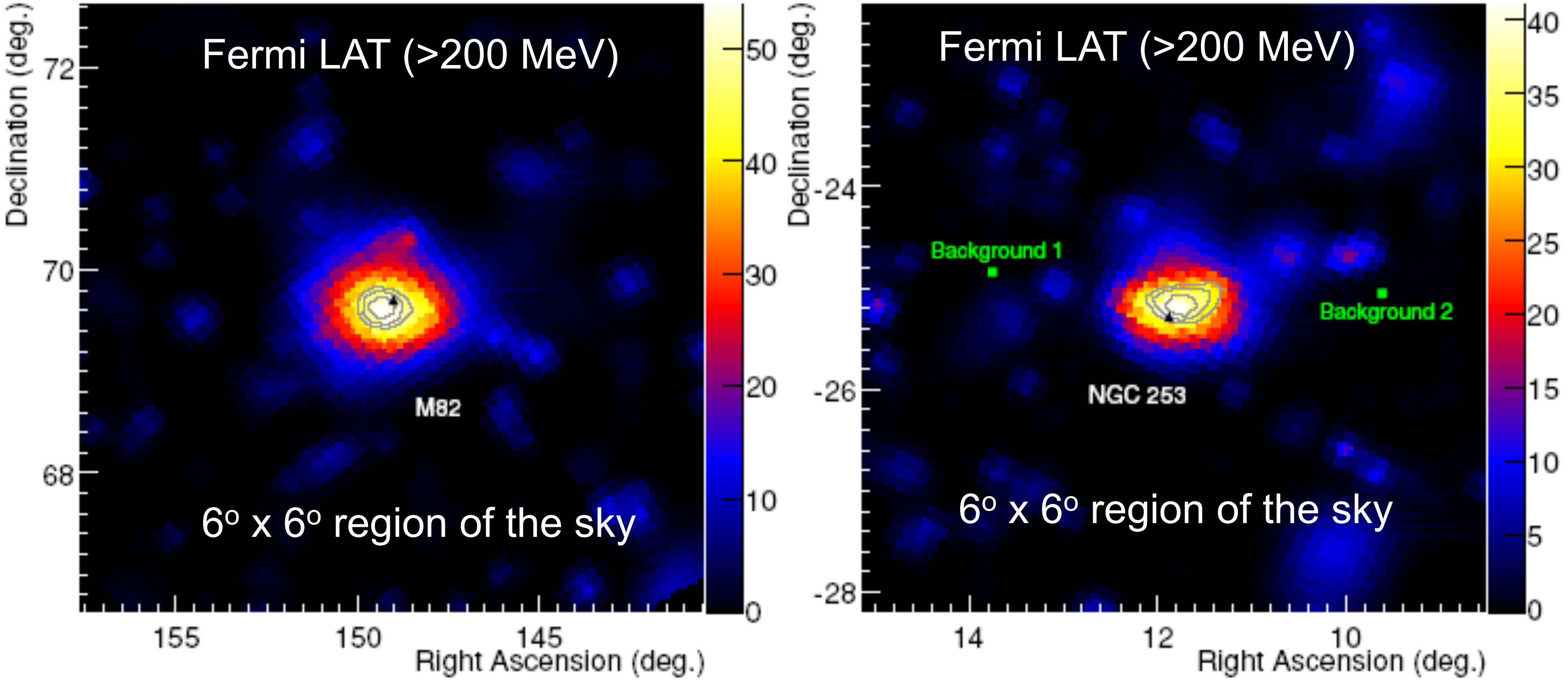
- Starburst galaxies distinguished by regions of rapid star formation, 10-1000 × Milky Way rate
  - Correspondingly high supernovae rates
  - Dense clumps of molecular gas
  - Highly luminous at infrared wavelengths, radio correlation
- M82 and NGC 253
  - Two closest starburst galaxies (~3.5 Mpc)
  - Edge-on viewing angles
  - Small (~100 pc scale) starburst regions
  - Star formation rate ~10 × Milky Way rate
  - Lack active nuclei
  - Extensively studied in multiple wavebands, detailed modeling/predictions

GeV/TeV Emission from Starburst Galaxies

- **Fermi LAT has detected steady, point-like, emission above 200 MeV from three starburst galaxies**
  - **M82 (6.8σ)**; also detected with VERITAS (summer 2009)
  - **NGC 253 (4.8σ)**; also detected with HESS (summer 2009)
  - **NGC 4945** (reported in 1LAC; also has Seyfert nucleus)
- **Diffuse gamma-ray emission from cosmic-ray interactions in star-forming galaxies is most probable origin of γ rays**
  - **Unresolved GeV emission, TeV emission predominantly in central region**
  - **LAT all-sky survey can point out additional candidates for TeV observatories**
- **Observations and results**
  - **Detection significance maps**
  - **Point-like and steady**
  - **Integral fluxes consistent with galactic diffuse emission**
- **Interpretation**
  - **Correlate star-formation with enhanced cosmic-ray intensity**

Detection Significance Maps

Galactic diffuse, isotropic diffuse, and point sources subtracted



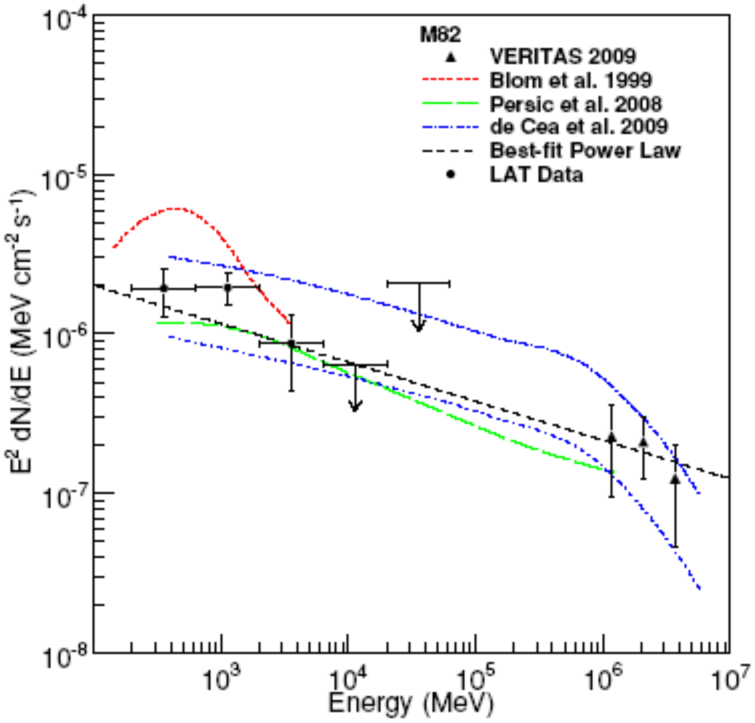
Test Statistic (TS) = $-2 \log(L_{\text{source}} - L_{\text{no source}})$

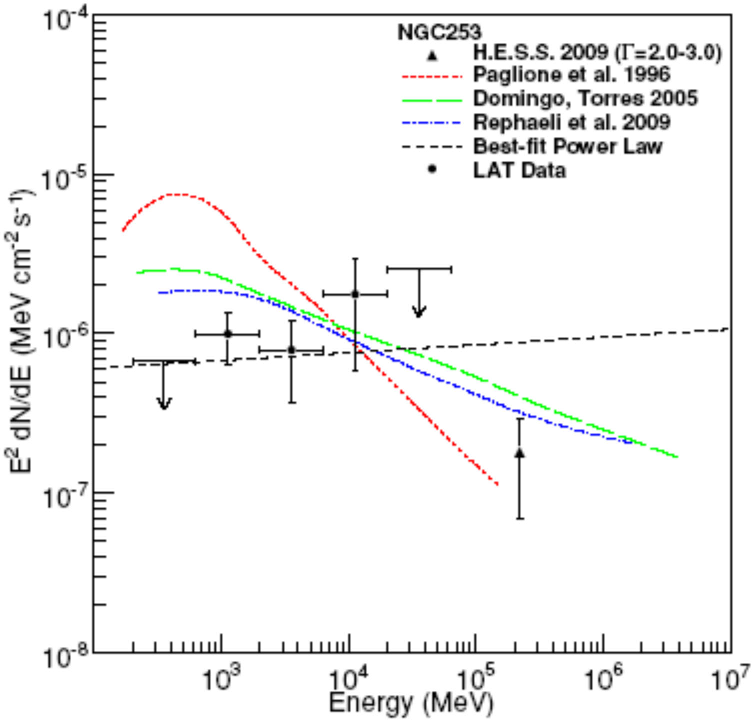
0.68, 0.95, 0.99 confidence level localization contours

Appear as LAT point sources, starburst regions unresolved

Spectra

Observed integral fluxes consistent with models of diffuse galactic gamma-ray emission, but data do not yet tightly constrain spectral shapes

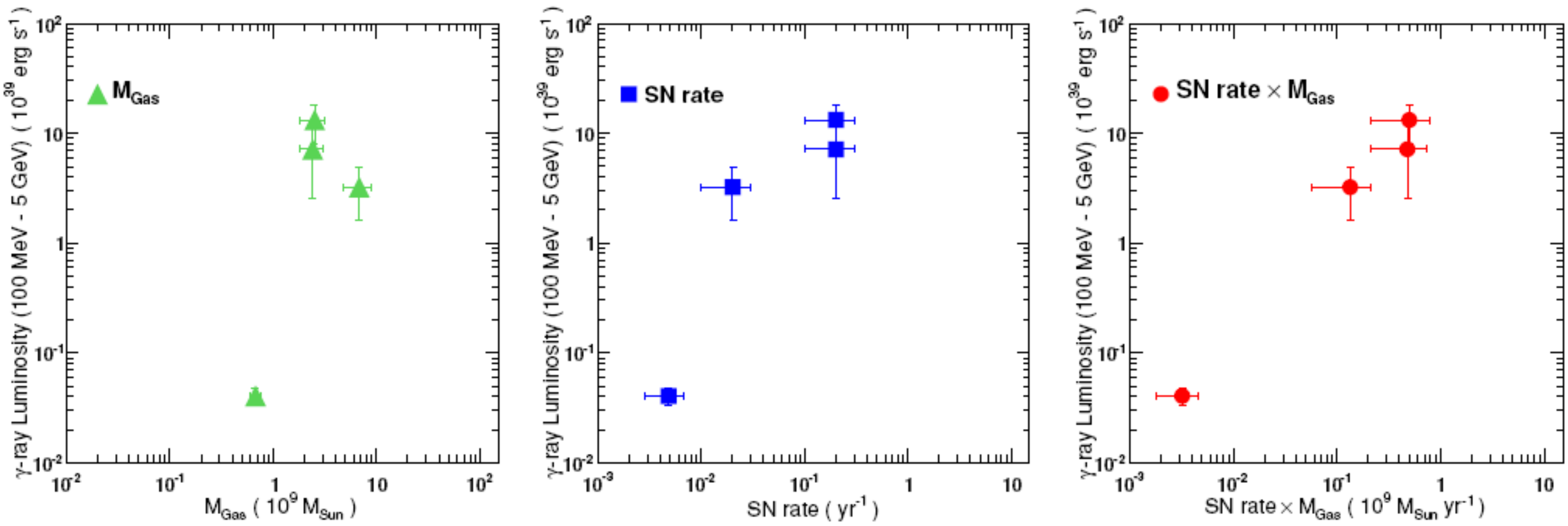




	Flux (>100 MeV) (10^{-8} ph cm^{-2} s^{-1})	Photon Index
M82	$1.6 \pm 0.5_{stat} \pm 0.3_{sys}$	$2.2 \pm 0.2_{stat} \pm 0.05_{sys}$
NGC 253	$0.6 \pm 0.4_{stat} \pm 0.4_{sys}$	$1.95 \pm 0.4stat \pm 0.05_{sys}$

Properties of Star-Forming Galaxies

Galaxy	d (kpc)	$\mathrm{R_{SN}}$ (century^{-1})	$\mathrm{M_{Gas}}$ ($10^9 M_\odot$)	$F_{-8}{}^{b}$	$4\pi d^2 F_\gamma$ (10^{41} ph/s)	L_γ^c (10^{39} erg/s)	Index
MW	–	2.0 ± 1.0	6.5 ± 2.0	–	11.8 ± 3.4^d	1.2 ± 0.5	2.2 ± 0.15
LMC	52 ± 2	0.5 ± 0.2	0.67 ± 0.08	26.3 ± 2.0	0.78 ± 0.08	0.041 ± 0.007	2.26 ± 0.11
SMC	61 ± 3	$\approx 0.12^e$	≈ 0.45	3.7 ± 0.7	0.16 ± 0.04	0.008 ± 0.003	2.23 ± 0.12
M31	780 ± 30	1.1 ± 0.2	7.7 ± 2.3	0.9 ± 0.2	6.6 ± 1.4	0.43 ± 0.09	2.1 ± 0.22
M82	3600 ± 300	20 ± 10	2.5 ± 0.7	1.6 ± 0.5	250 ± 90	13 ± 5	2.2 ± 0.2
N253	3900 ± 400	20 ± 10	2.5 ± 0.6	0.6 ± 0.4	110 ± 70	7.2 ± 4.7	1.95 ± 0.4



- ❑ **Enhanced cosmic-ray intensity explains the observed starburst gamma-ray fluxes**

  – **Star-formation rate and gas density *non-uniform* throughout galaxies**

  – **uncertainty in distance measurements**

Fermi and Cosmic Rays

- ☐ Fermi shock acceleration is established acceleration mechanism in SNRs
- ☐ Has Fermi established that (middle-aged) SNRs are sources of the hadronic cosmic rays?
- ☐ An apparent π^o decay feature is observed in some remnants
- ☐ Gas clouds/targets are found in most Fermi-detected SNRs
- ☐ 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

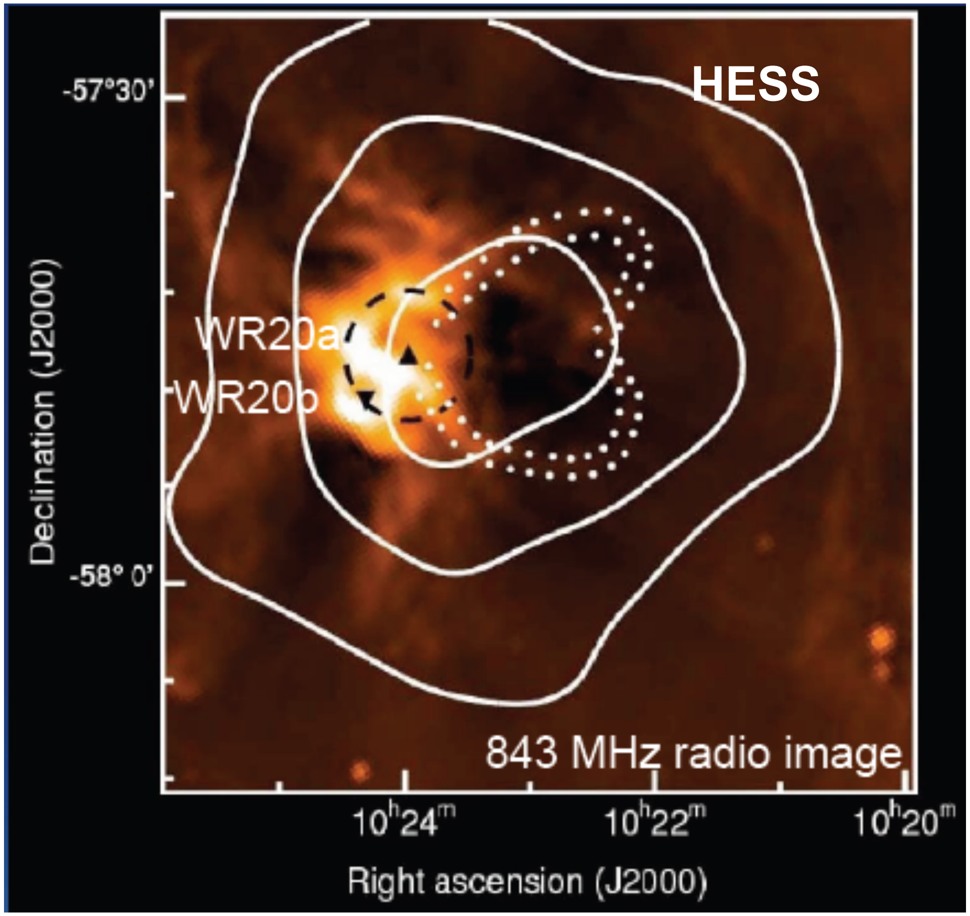
Back-up Slides

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)



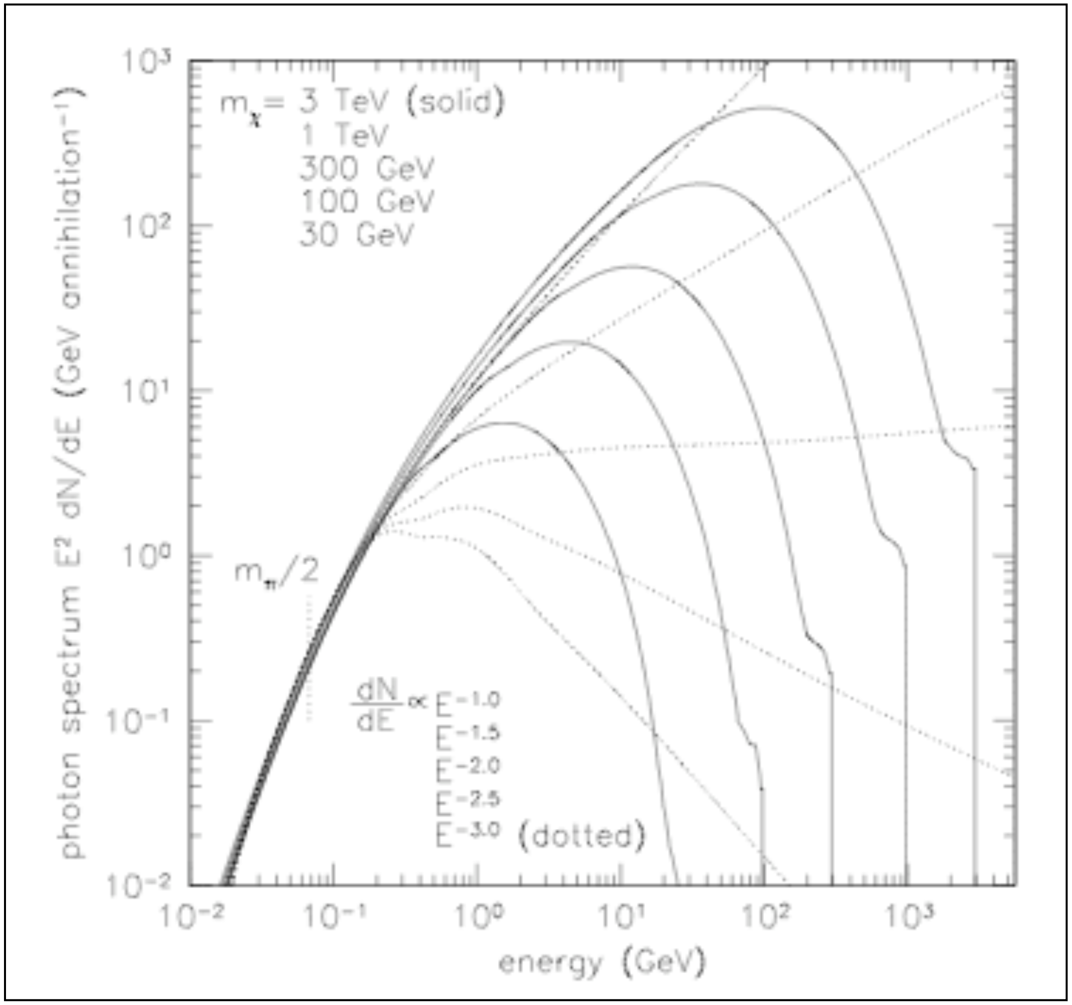
Gamma Rays from Dark Matter Annihilation

Consider supersymmetric neutralinos (~ vanilla CDM WIMP candidate)

Most γ via (non-rel.) quark-antiquark pairs ⇒ hadronization ⇒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

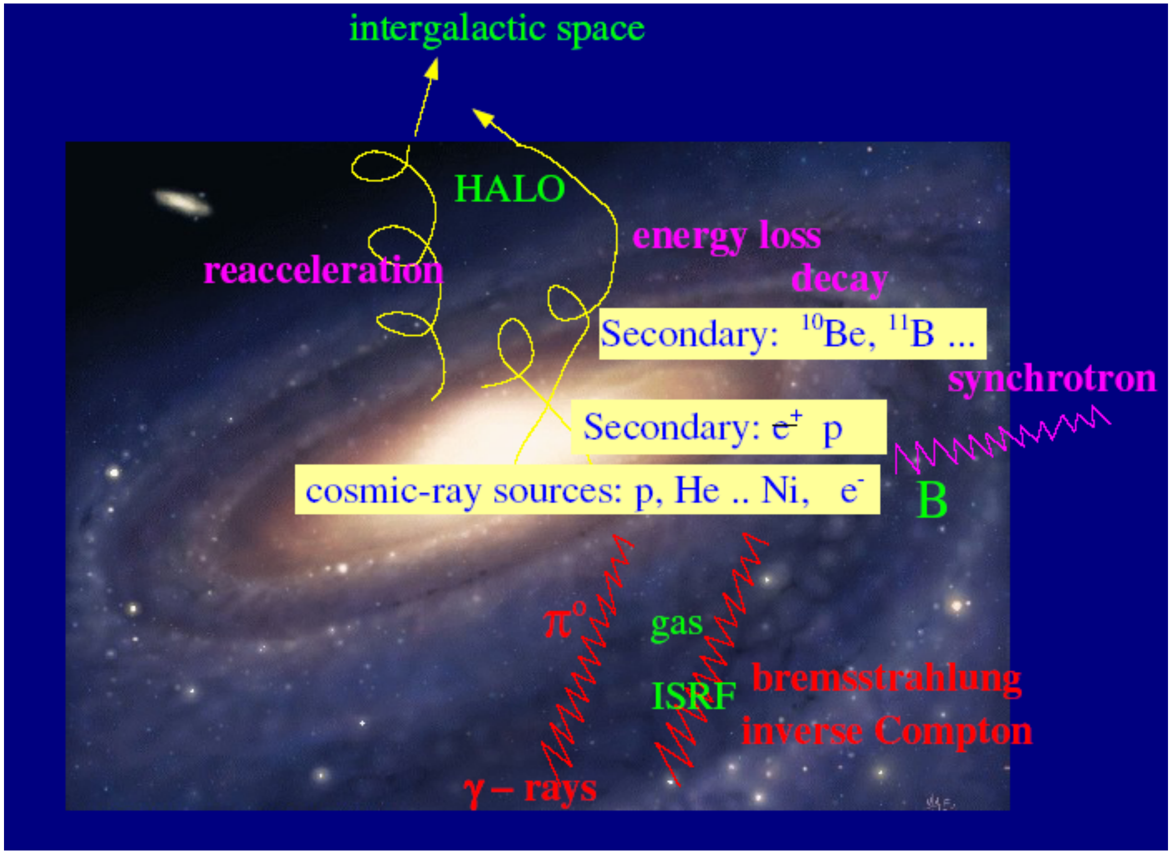


Baltz, Taylor & Wai 2007 - spectrum from DarkSUSY/Pythia

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**



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?**