Cosmic Ray Astrophysics with GLAST

Aspen Workshop on Cosmic Ray Physics

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April 18, 2007

Aspen, Colorado

Outline

- Reminders about GLAST
- Cosmic ray accelerators
- GLAST as a cosmic ray electron detector
- Galactic diffuse gamma rays as cosmic ray tracer

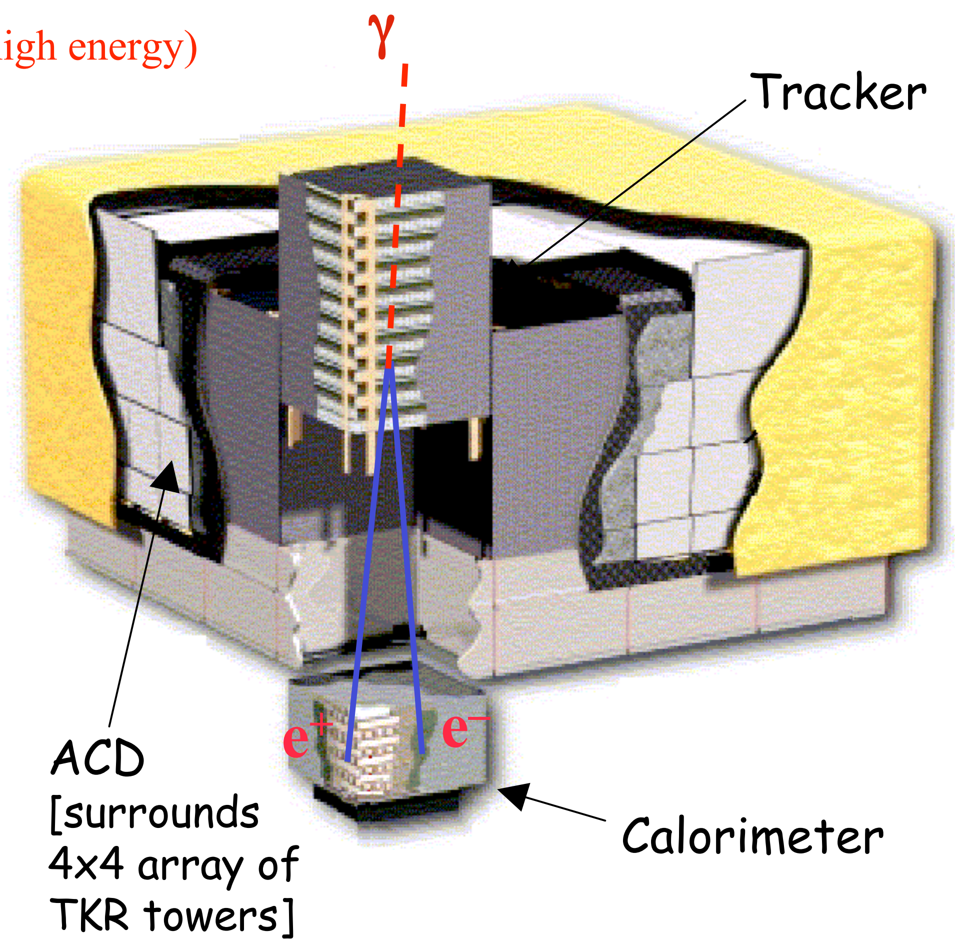
Large Area Telescope: 20 MeV - 300 GeV γ rays

- **<u>Precision Si-strip Tracker (TKR)</u>**
- 18 XY tracking planes.
- Good position resolution (ang. resolution at high energy)
  228 μm pitch

- **High efficiency. 1.08 X_o**
- front end => reduce multiple scattering.
  $12 \times 0.03\ X_o = 0.36\ X_o$
- back-end => increase sensitivity >1GeV
  $4 \times 0.18\ X_o = 0.72\ X_o$

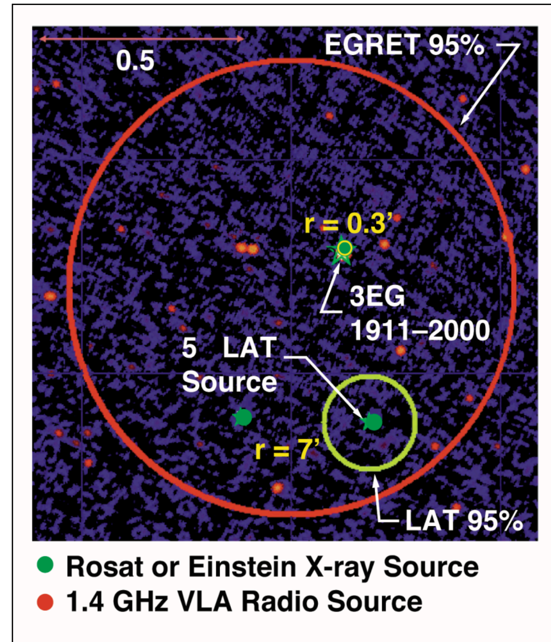
- **<u>CsI Calorimeter(CAL)</u>**
  Array of 1536 CsI(Tl) crystals in 8 layers.
  Hodoscopic => Cosmic ray rejection.
  => shower leakage correction.
  $8.5\ X_0$ => Shower max contained <100 GeV

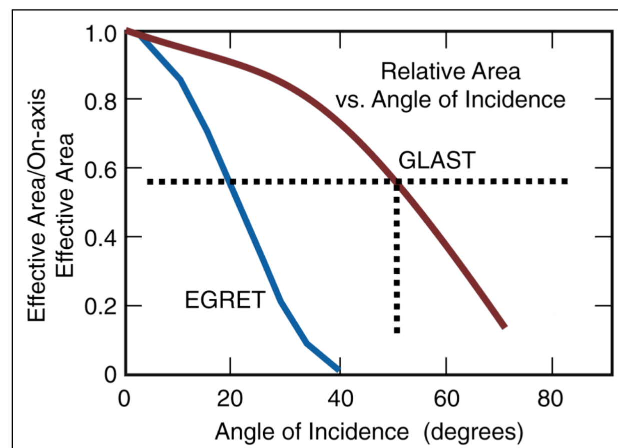
- **<u>Anticoincidence Detector (ACD)</u>**
  Segmented (89 plastic scintillator tiles)
  => minimize self veto



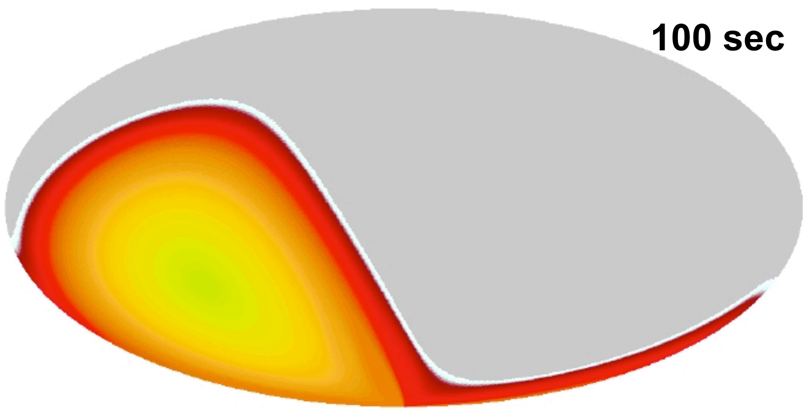
All sky survey instrument

- **Launch Dec. 14, 2007**
  - Expect early next year
  - Agile was scheduled April 18
- **EGRET sensitivity reached after ~1 day**
  - Wide field of view
  - Improved angular resolution
  - Sensitivity > 1 GeV
  - No Earth occultation
- **Expect to see 10^4 sources**
  - AGN
  - Pulsars
- **New**
  - SNR
  - Starburst galaxies
  - TeV sources
  - ??

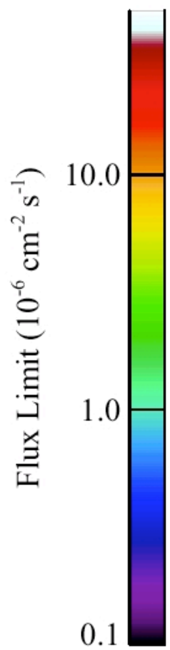




High energy source sensitivity: all-sky scan mode



EGRET Fluxes



- GRB940217 (100sec)
- PKS 1622-287 flare
- 3C279 flare
- Vela Pulsar

During the all-sky survey, GLAST will have sufficient sensitivity after O(1) day to detect (5σ) the weakest EGRET sources.

*zenith-pointed

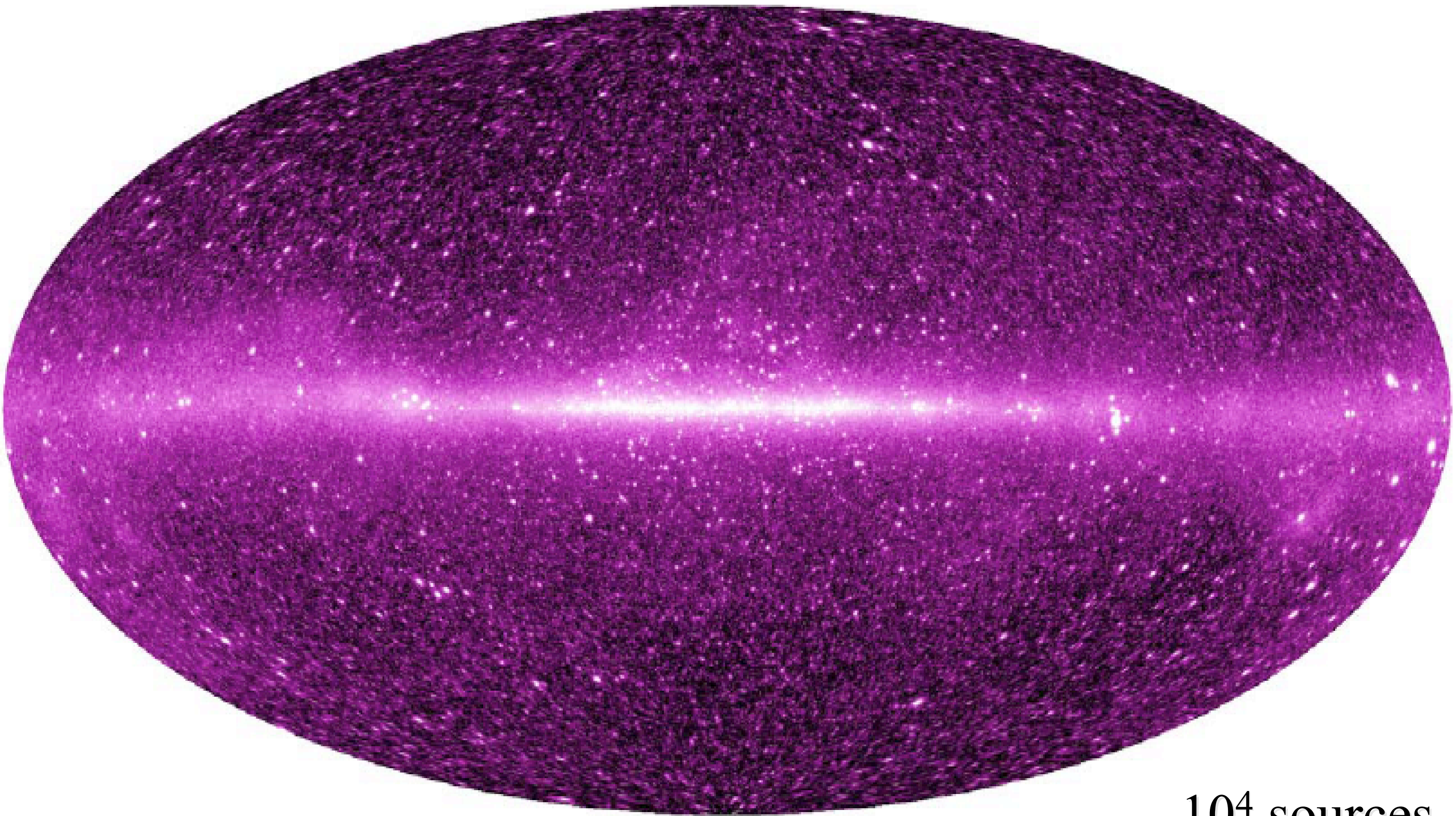
GLAST is integrated onto the spacecraft in Scottsdale, Arizona at the General Dynamics plant.

Launch Dec. 14, 2007 (or early 2008)

EGRET: First all-sky survey at high energies

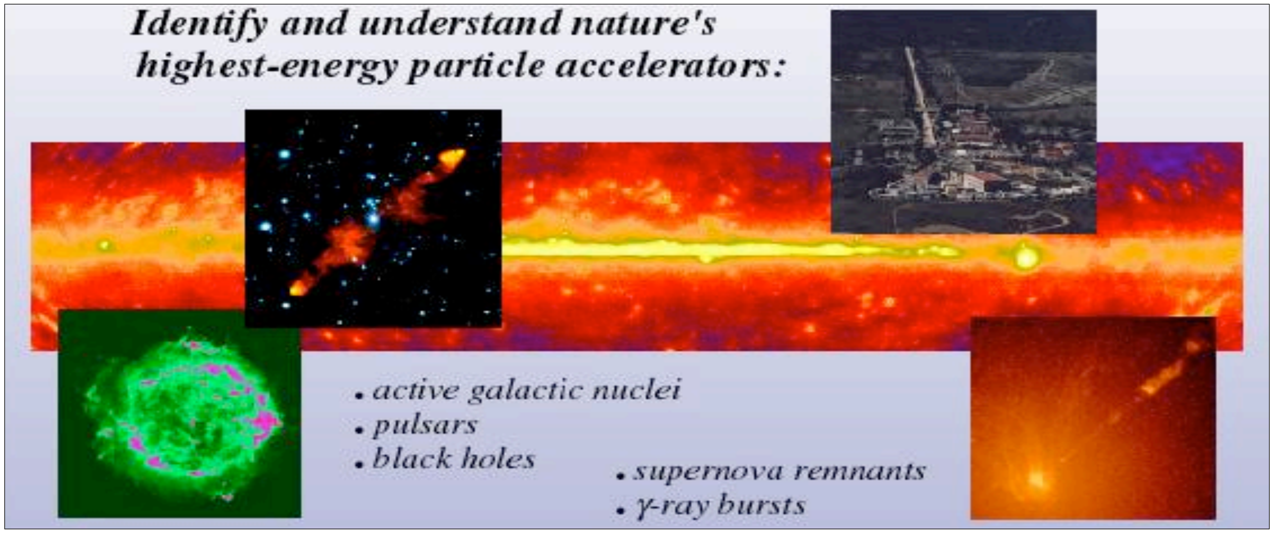
Gamma rays from galactic cosmic rays

>100 MeV, Phase 1-5



10^4 sources

Mission Objectives



- Understand the mechanisms of particle acceleration in astrophysical environments such as active galactic nuclei, pulsars and supernova remnants
- Determine the high energy behavior of gamma-ray bursts and other transients
- Resolve and identify point sources with known objects
- Probe dark matter and the extra-galactic background light in the early universe

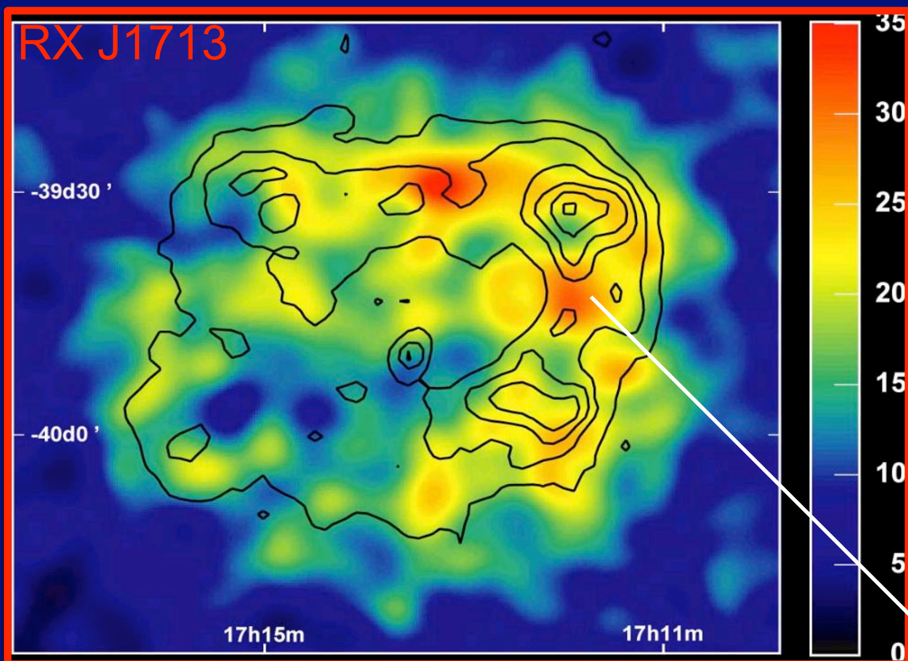
The science connection

- **Longstanding problems of the origin of cosmic rays**
  - Diffuse galactic gamma-ray background
  - Observe electrons from nearby SNR
  - Diffusive shock acceleration
    - RX J1713.7-3946, SN 1006 other possible sources
    - Shock acceleration theory
- **GeV Gamma-ray Observations likely to be key**
  - Signature of gamma rays from decay of π^o produced in collisions of cosmic rays with interstellar gas (and dust)
    - Finer spatial resolution
    - Gamma ray excess
  - Check supernova diffusive shock acceleration models
    - GLAST has the requisite angular resolution to see a few spatially resolved SNR
    - GLAST has the spectral sensitivity to check models

Cosmic Ray Accelerators ?

SNRs in our Galaxy: now 265 (see Green et al. 2001, updated)
http://www.mrao.cam.ac.uk/surveys/snrs/

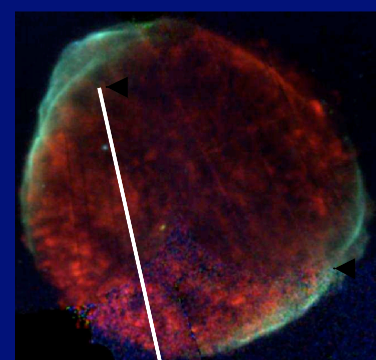
with nonthermal X-ray emission - 10 or so



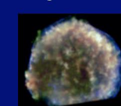
30 arcmin

Best candidates ...

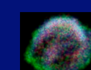
SN1006



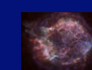
Tycho



Kepler



Cas A



TeV emission

Aharonian et al, 2004, Nature, **432**, 77

Supernova remnants

Free expansion to 10^3 years
Adiabatic expansion 10^3 to 10^4 years
Radiative phase 10^4 to 10^5 years

Acceleration at highest energy ends at around 10^3 years.

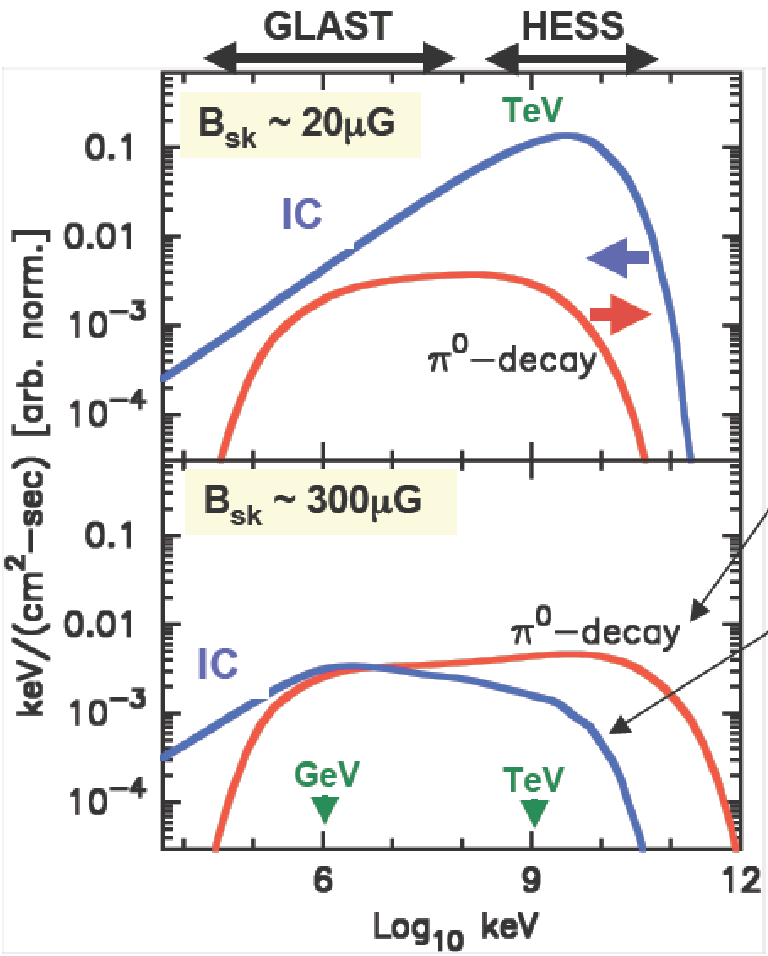
Esposito et al. 1996, ApJ, 461, 820

SNR as EGRET sources π^o from remnant or Pulsars ??

		Age 10^3 yrs	Dist 10^3 pc
γ Cygni	G078.2 +2.1	5	1.5
IC 443	G189.1 +3.0	5	1.5
W44	G034.7 -0.4	20	3
W28	G006.4 -0.1	36	3
Monoceros		50	1
Monogem		86	0.3
SN1006		1	1-2
HB21		7	0.8
Cassiopeia A		0.3	3
Tycho		0.43	2-4
Vela		10	0.25-0.5
RX J1713.7-3946		1	1

GeV-TeV Observations (IC/p-p) ratio :

Inverse-Compton (IC) and pion-decay emission from SNR with large shocked B-fields



Only difference in models is assumed B-field

Large magnetic fields :

Higher maximum energy for protons. Large B can extend pion-decay gamma-rays to beyond HESS detectable range

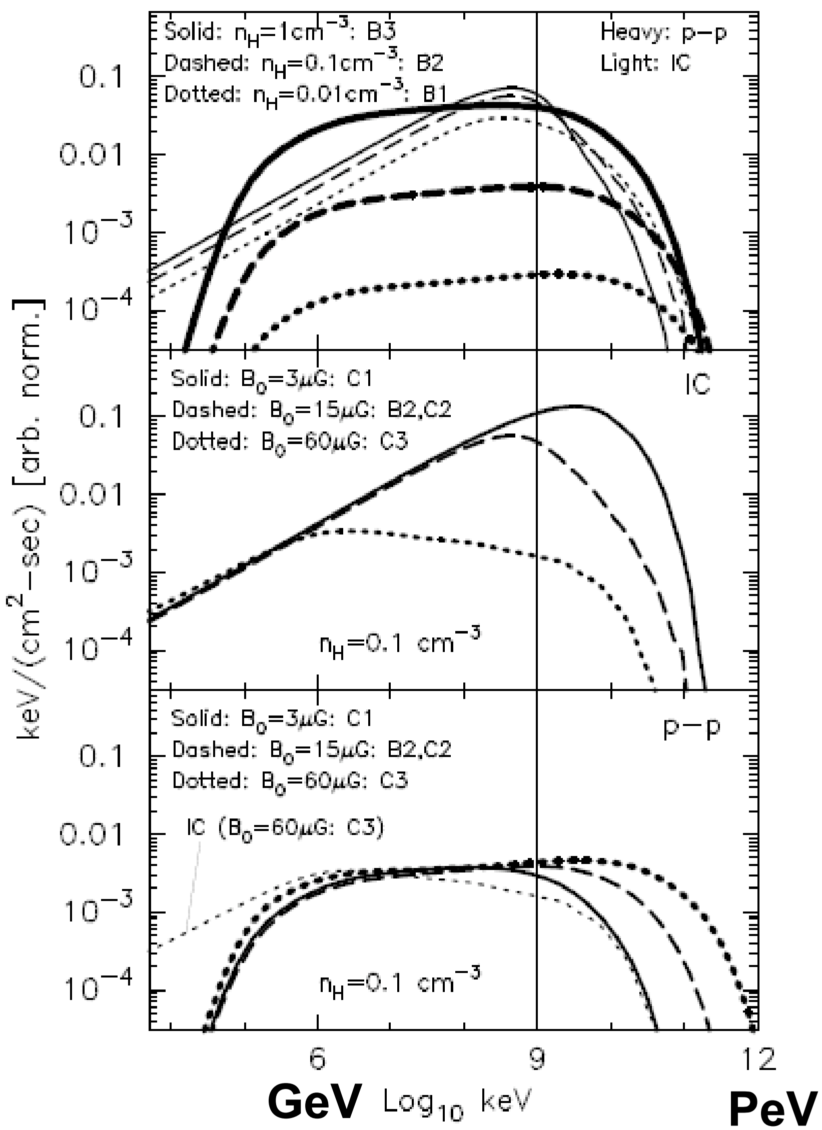
Lower maximum energy for electrons, due to severe synch losses

Shape of IC emission in GLAST range can be modified by strong losses in large magnetic fields in evolving SNR

Need broad-band fits

Example with preliminary results for one particular set of input parameters: adapted from Ellison, Patnaude, Slane, Blasi & Gabici et al. 2007 (Note: B-amp. NOT calculated in these models)

Particle Acceleration in Supernova Remnants and the Production of Thermal and Nonthermal Radiation



Density of matter important for gamma-ray production in hadron models.

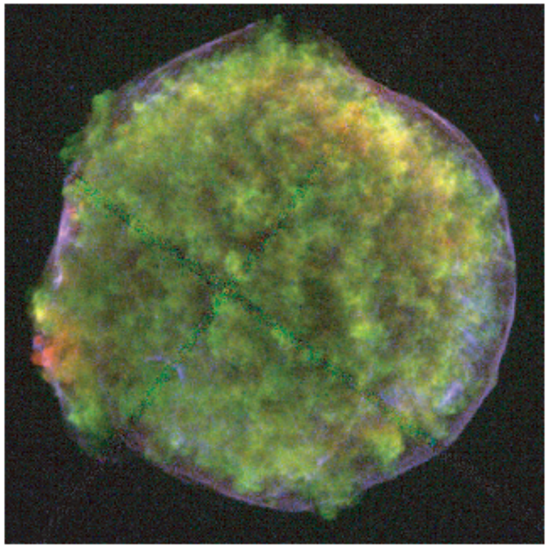
Magnetic field amplification (e.g. Bell, 2004) suppresses IC component, flattens IC spectrum.

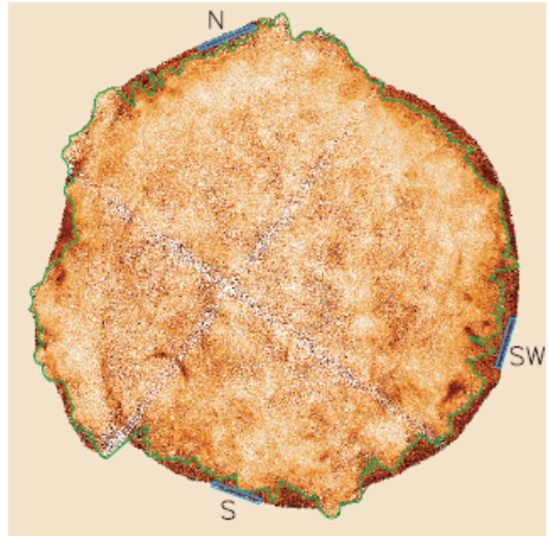
Magnetic field amplification helps make higher energy π^o γs.

Ellison et al., 2007, ApJ submitted
Astro-ph/0702674

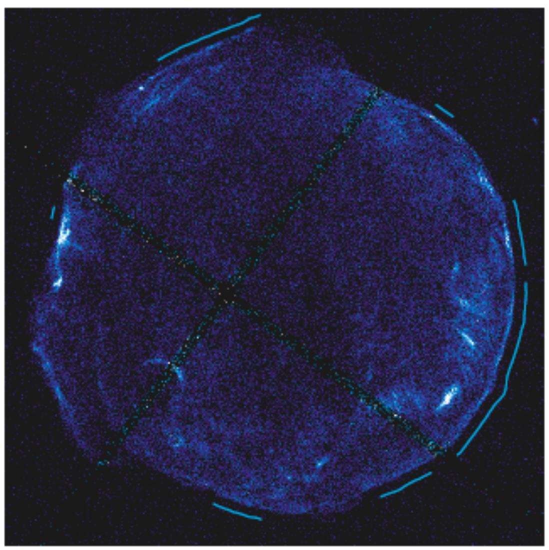
The point is

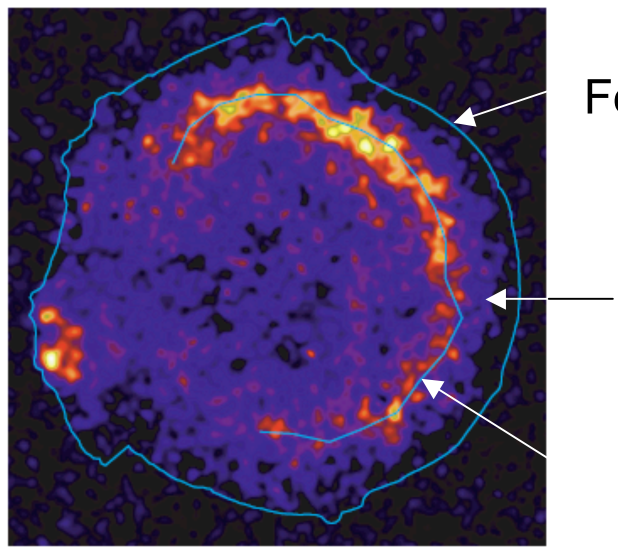
GLAST/LAT will measure the shape of the spectrum in the 20 MeV to 100 GeV band and should be able to resolve these models.





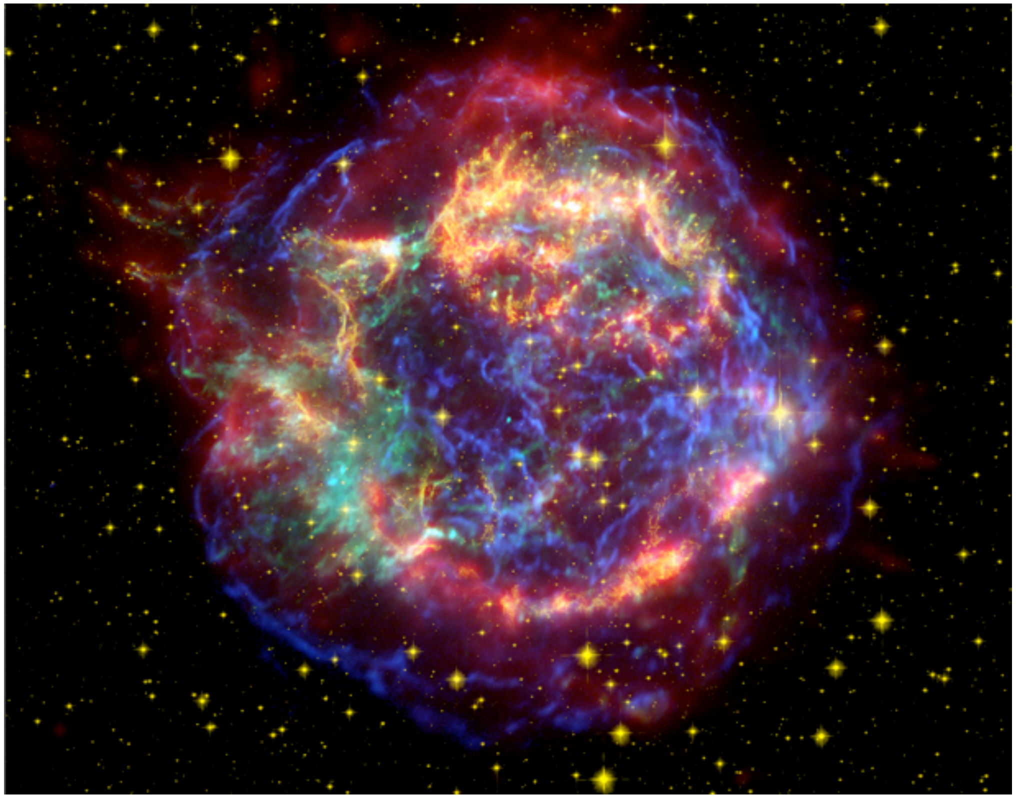
COSMIC-RAY ACCELERATION AT THE FORWARD SHOCK IN TYCHO'S SUPERNOVA REMNANT: EVIDENCE FROM CHANDRA X-RAY OBSERVATIONS, Warren et al. 2005 ApJ, **634**, 376.





Spatial relationships of the shocks and contact discontinuity imply hadrons dominate.

Supernova remnants possibly observable by GLAST

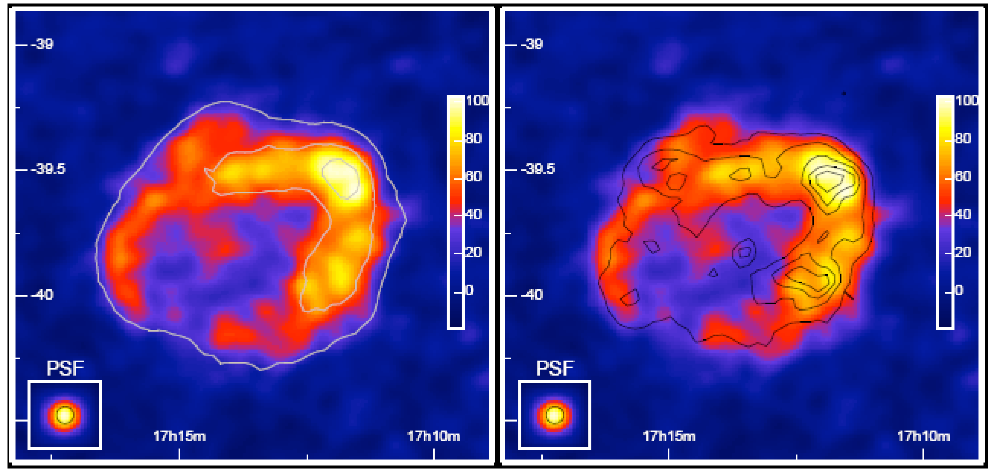


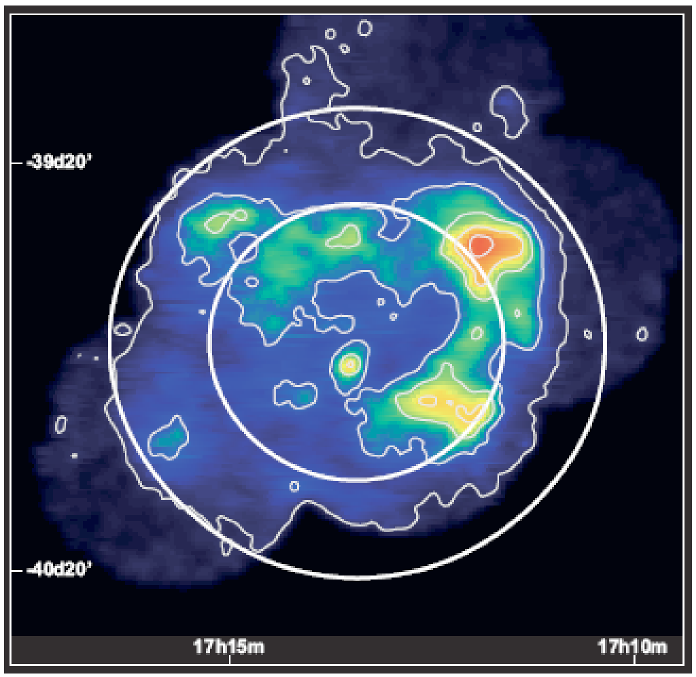
Cassiopeia A, 300 years old

SN1006, 1001 years old

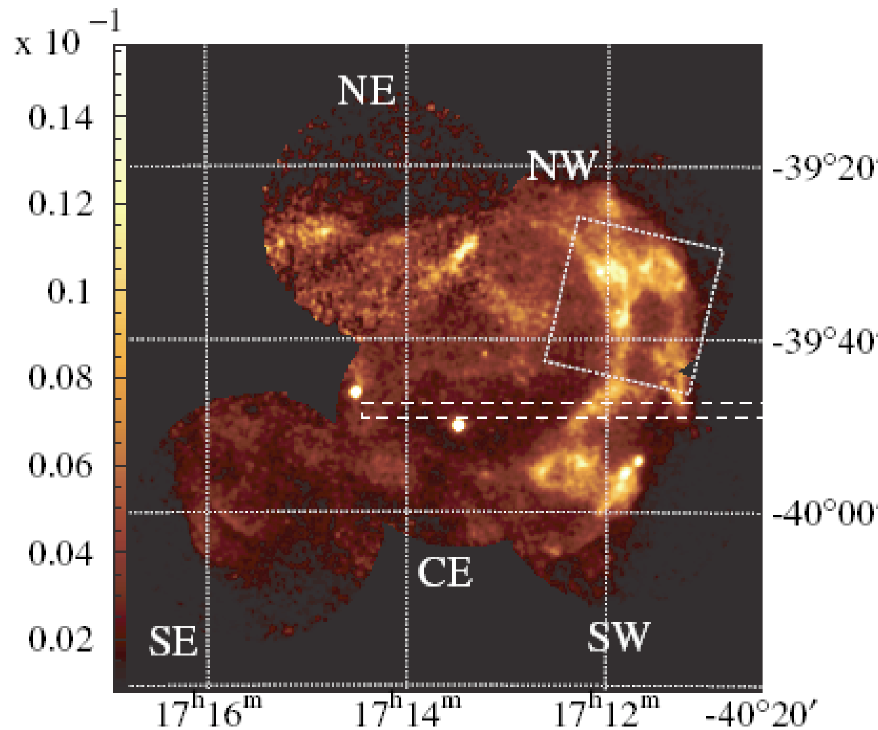
Chandra images

HESS RX J1713.7-3946
Aharonian et al. 2007, A&A, in press, astro-ph/0611813 and
Aharonian et al. 2006, A&A, **449**, 223



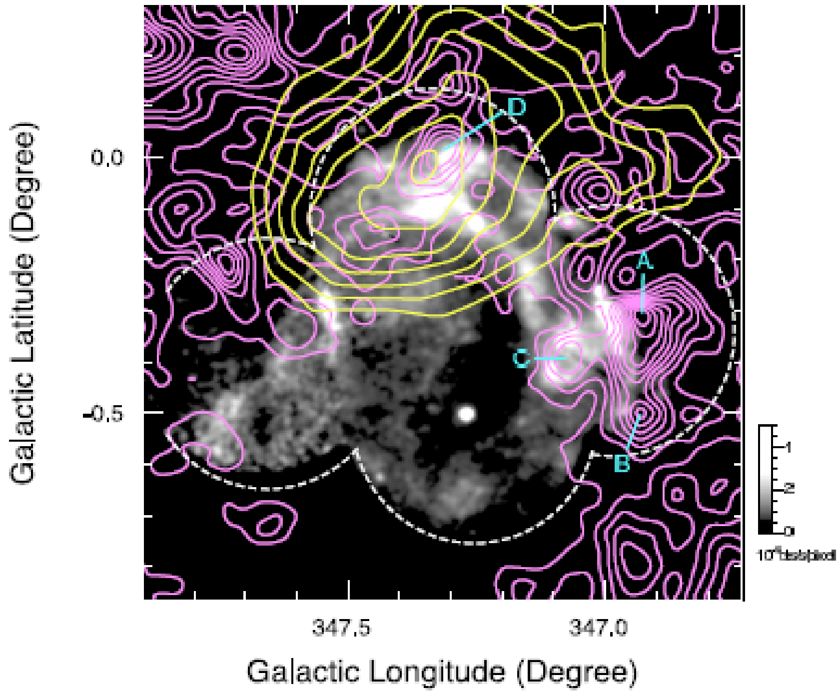


ASCA in X-rays: Uchiyama, Takahashi, & Aharonian, 2002, PASJ, **54**, L73



RX J1713.7-3946
J. Hiraga 2005, A&A 431, 953.

RX J1713.7-3946 X-ray (G347.3-0.5), TeV and molecular clouds



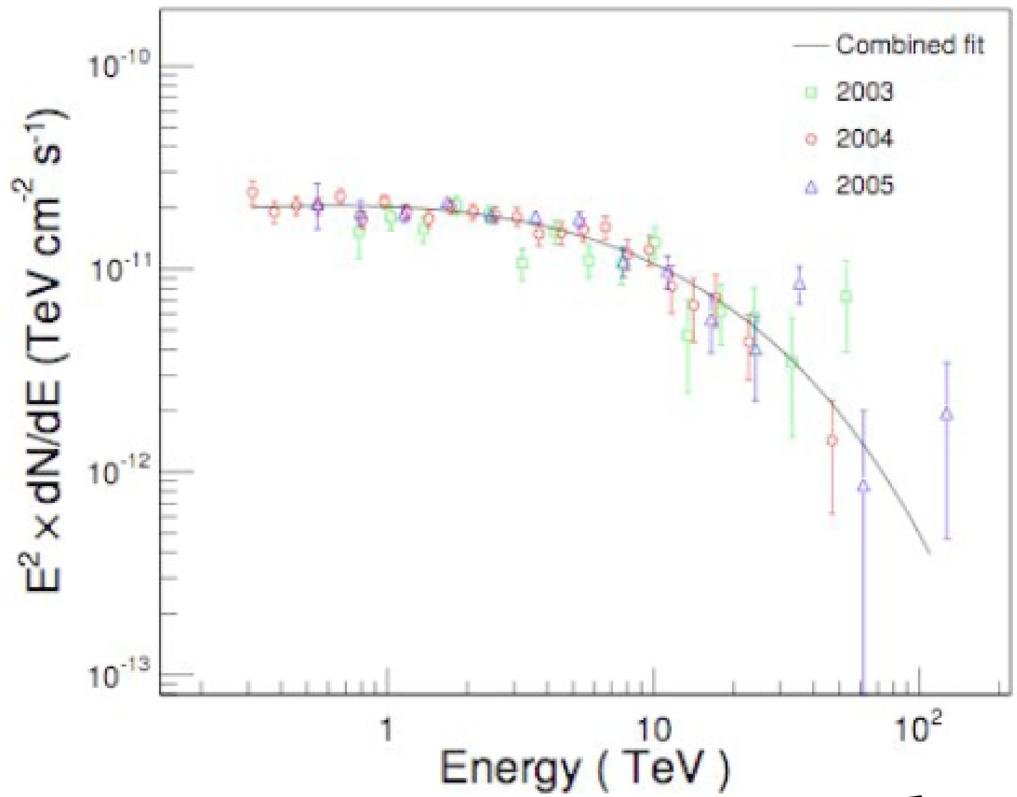
If π^o, why isn't TeV emission on top of the CO instead of where the X-rays are?

X-ray absorption if cloud in front.

The CO distribution is depicted by the pink contours. The TeV γ-ray significance map is superposed as the yellow contours. The X-ray image is also shown; it is the soft band image obtained by XMM-Newton.

Fukui, Y., Moriguchi, Y., Tamura, K., et al. 2003, PASJ, 55, L61 and J. Hiraga 2005, A&A 431, 953.

HESS RX J1713.7-3946
Aharonian et al. 2007, A&A, in press, astro-ph/0611813 and
Aharonian et al. 2006, A&A, **449**, 223



TeV spectrum fit with
E_{MAX} = 2-20 TeV
and α = 0.4-1.

Radio: ν_{cut} => $(E_{Max})^2 B$
$2 < B/\mu G < 16$
$2.0 \leq \gamma \leq 2.4$

Range not errors, but best fit varies from place to place.

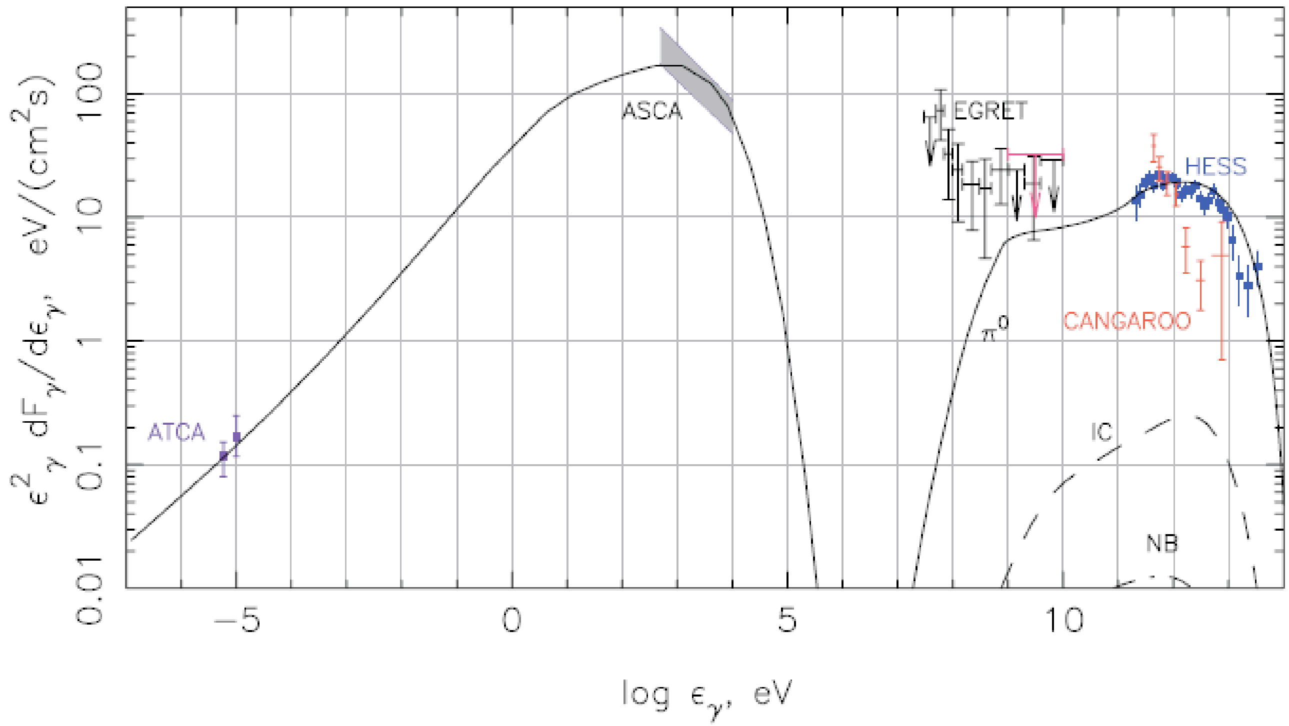
α allows for spread of E_{MAX}.

Parameter a is introduced to allow for spectral curvature.

$$\frac{dN}{dE} = A\left(\frac{E}{GeV}\right)^{-\gamma + a\log(E/GeV)} \qquad e^{-(E/E_{MAX})^{\alpha}}$$

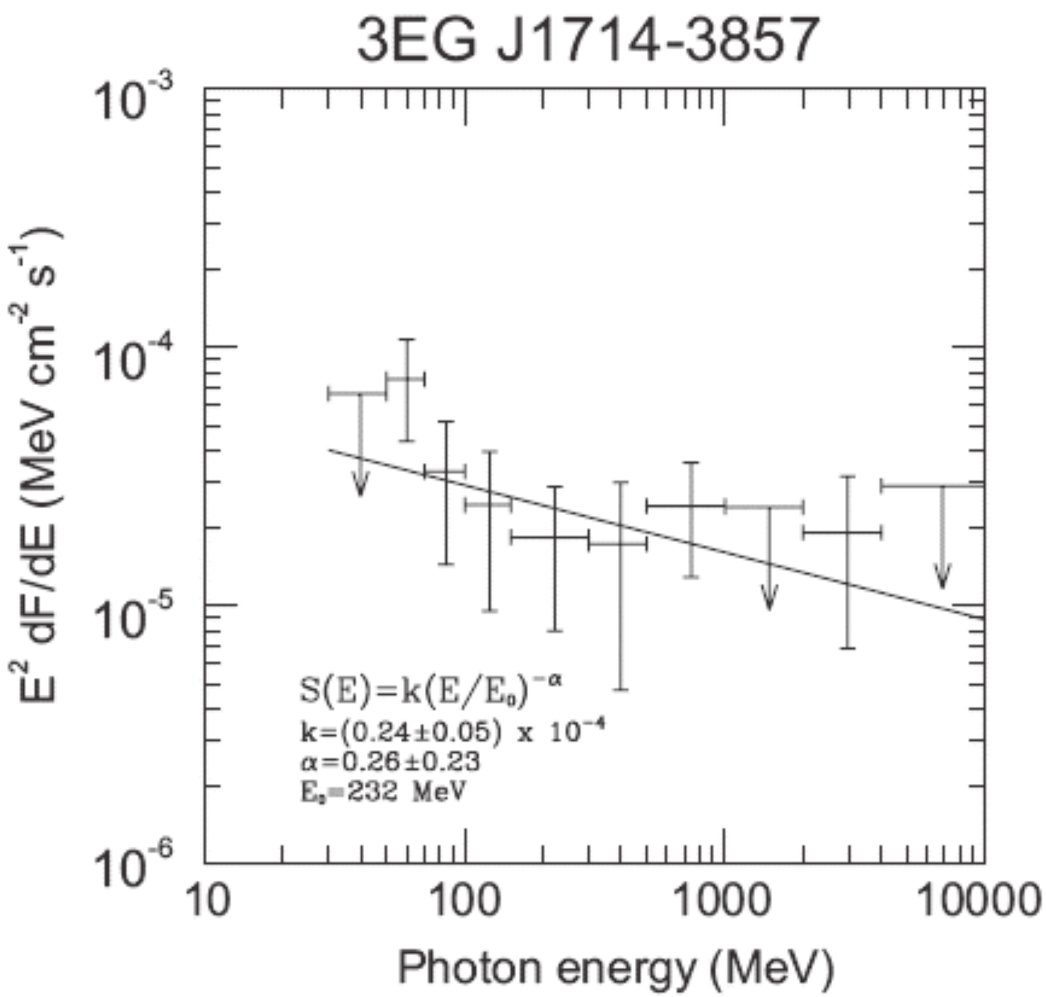
Source spectrum

Proton dominant model



Theory of cosmic ray production in the supernova remnant RX J1713.7-3946, E. G. Berezhko and H. J. Völk, 2006, A&A 451, 981–990 (2006).

No models fit the EGRET data



Reimer and Pohl, 2002, A&A, **390**, L43

3EG J1714−3857
Hartman et al., 1999, ApJS, **123**, 79

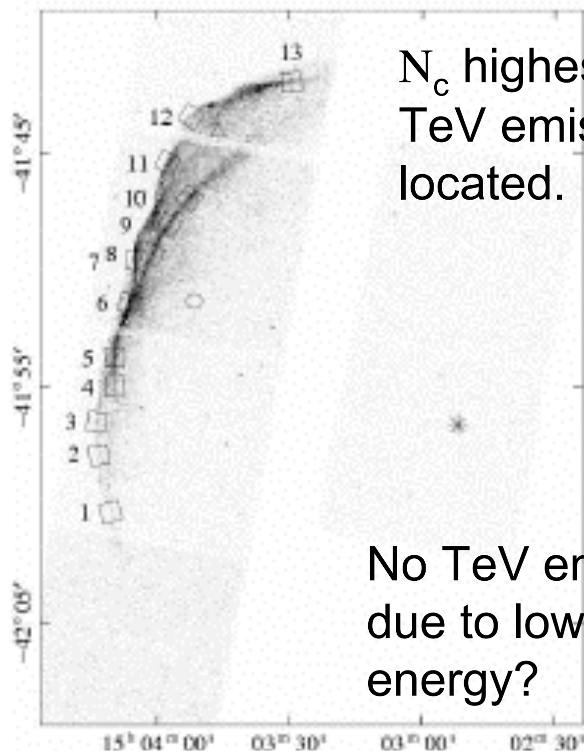
The EGRET data might be wrong, but GLAST will see either IC or π^o predictions and resolve.

Allen, Houck and Sterner, 2004,
Adv. Spa. Res., **33**, 440

radio spectrum of SN1006
- curved electron spectrum
  - a = 0.051+/-0.007
  - E_{MAX} = 22 +/-17 TeV.

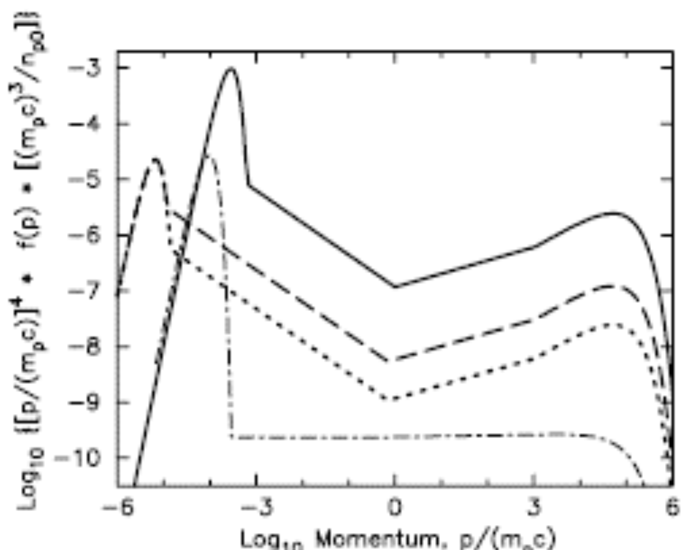
At 1 GeV the radio spectral index 0.6
=> cosmic ray electron index of 2.2.
At 30 TeV, the index is 1.99+/-0.09

Consistent with the predictions
- pressure of the cosmic rays on the shock
- electron pressure is not sufficient to cause the observed curvature
- Indirect evidence of protons



N_c highest where TeV emission is located.

No TeV emission due to lower cutoff energy?



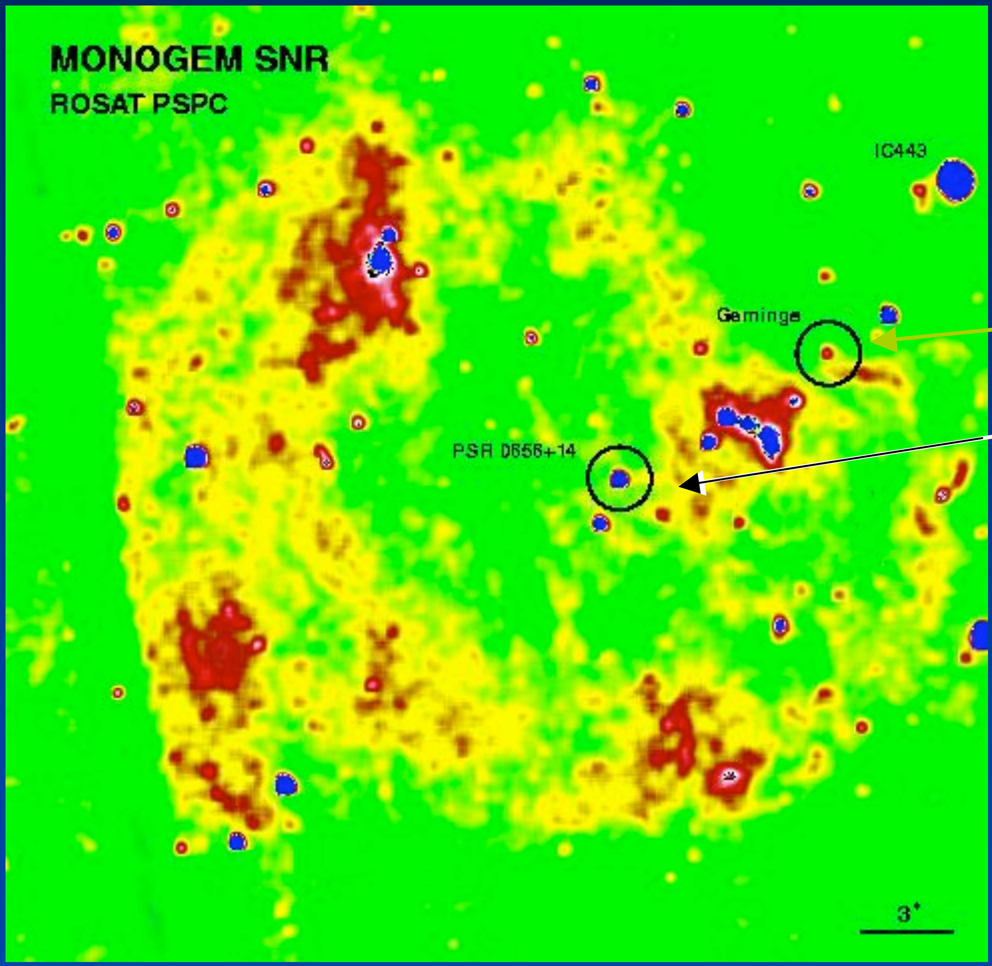
Ellison, Berezhko, and Baring, 2000, ApJ, **540**, 292

SNR acceleration issues

- **SN1006: TeV data from CANGAROO not confirmed by HESS so modelers cannot use TeV data with confidence.**
  - Indirect evidence for protons from electron spectral curvature
- **RXJ1713.7-3946 (G347.3-0.5) best case for π^o model**
  - Magnetic field amplification can suppress the IC and NB
  - Get protons from source to target
  - Radio => electron spectrum in SN1006 with curvature, implying the presence of protons
- **E_{MAX} = 20 TeV falls short of “knee” by factor of 100**

What about nearby Supernova remnants?

20 degrees

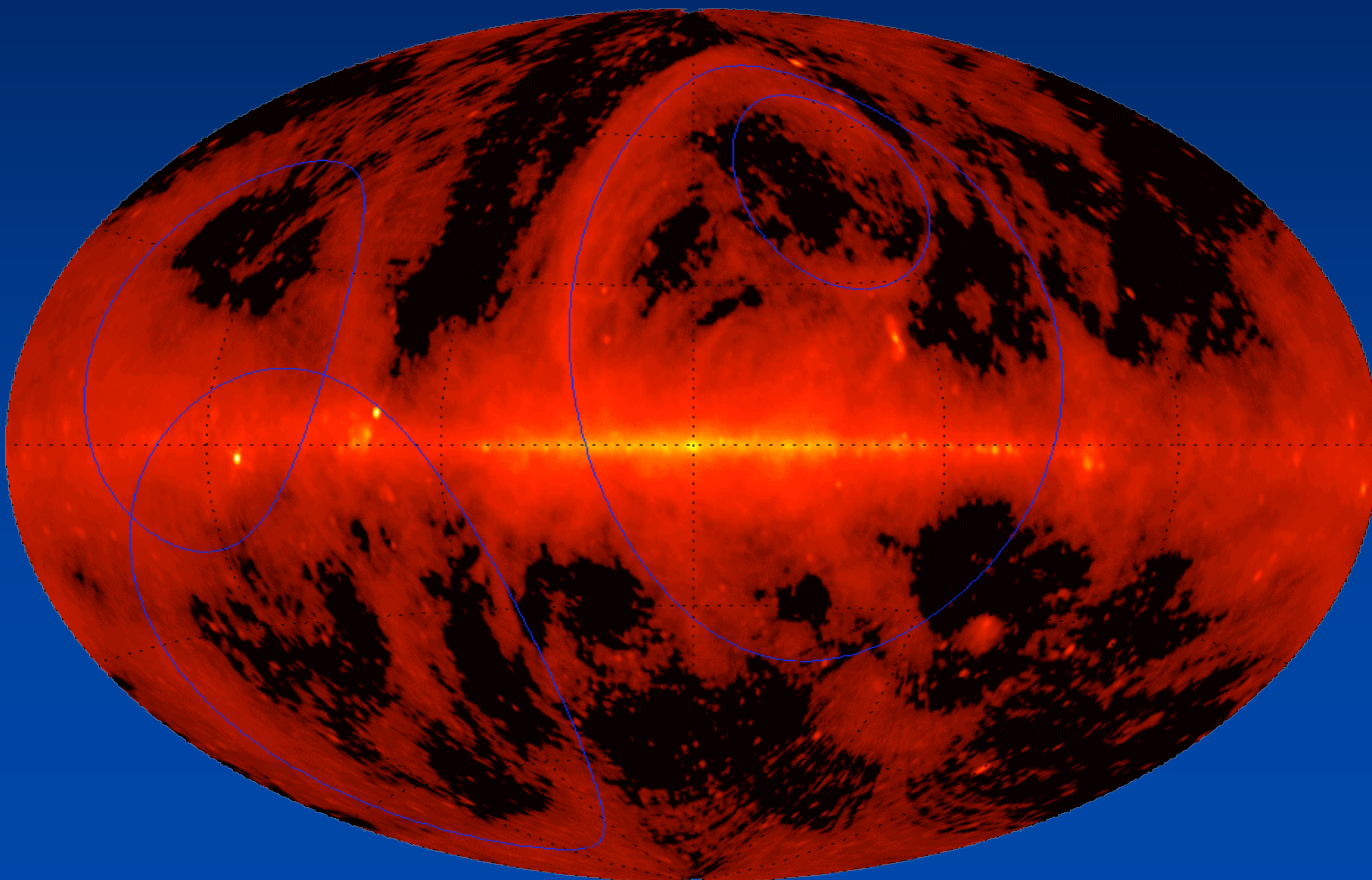


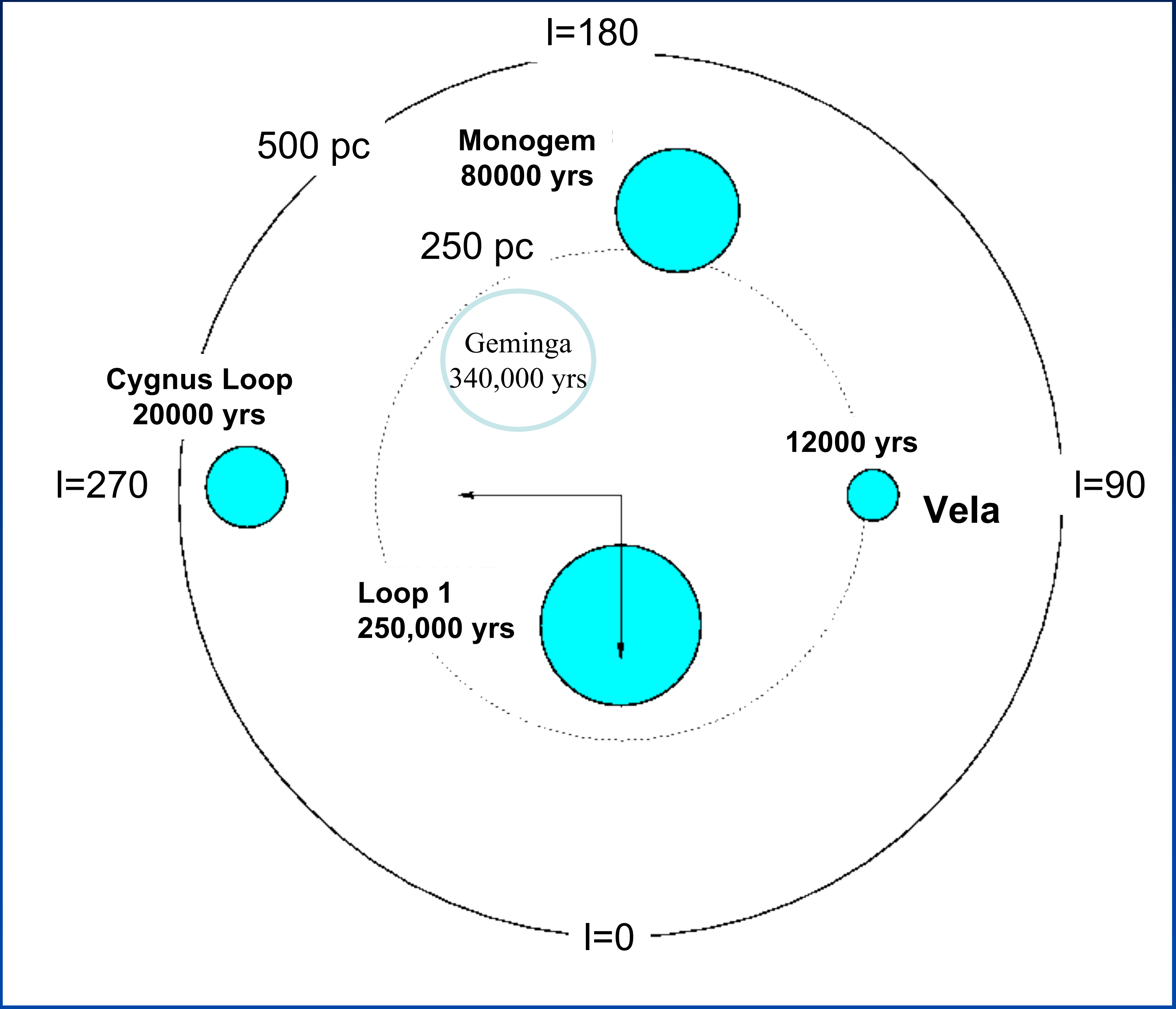
Geminga

PSR 0656+14

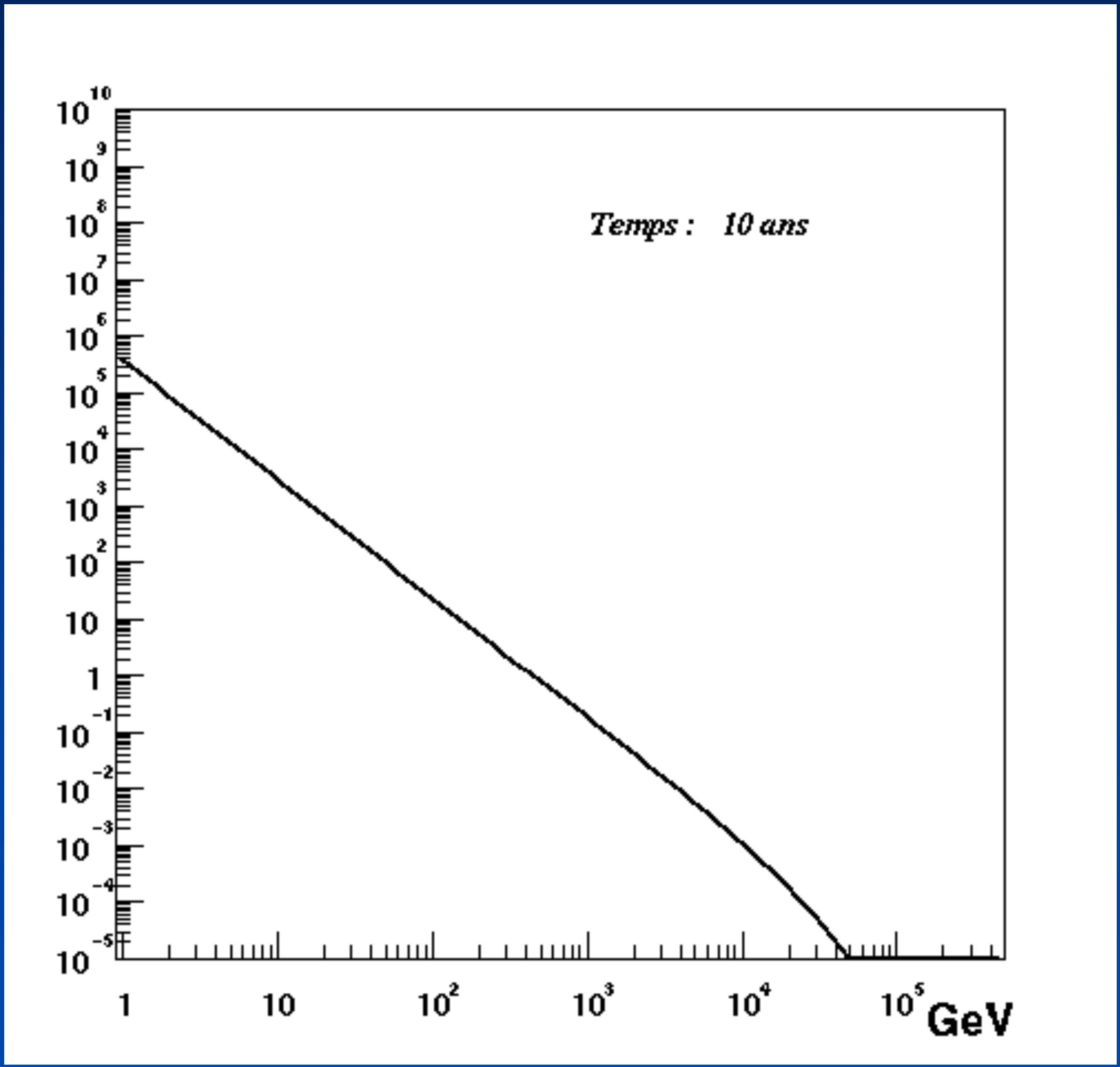
IC 443

408 MHz non-thermal radio maps shows nearest loops

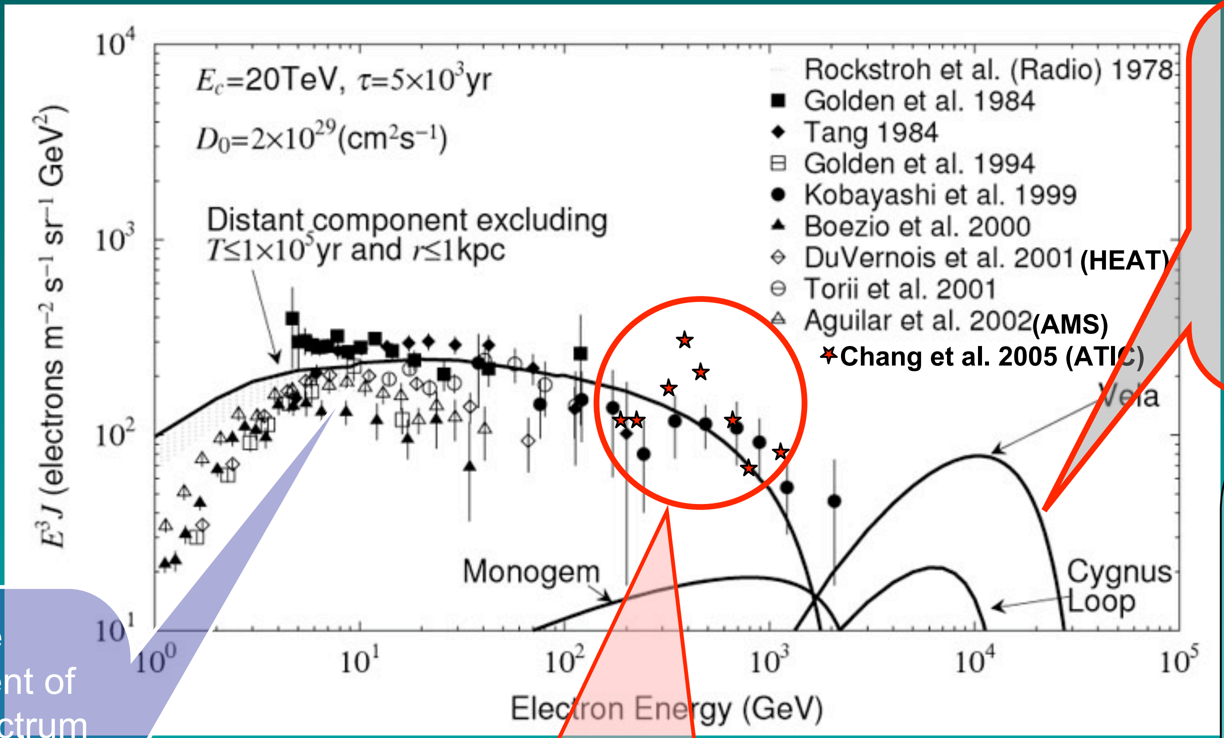



l=180
500 pc
Monogem
80000 yrs
250 pc
Geminga
340,000 yrs
Cygnus Loop
20000 yrs
12000 yrs
l=270
Vela
l=90
Loop 1
250,000 yrs
l=0

Time history of SNR by Grenier and Terrier



What can be learned from HE electrons (> 10 GeV)?



Precise measurement of electron spectrum above 10 GeV for calibration of the IC gamma ray flux model (GALPROP)

Search for Dark Matter Signatures (KKDM) – above ~100 GeV (see e.g. Baltz & Hooper, 2004)

Search for the signature of nearby HE electrons sources (believed to be SNR) in the electron spectrum above ~ TeV

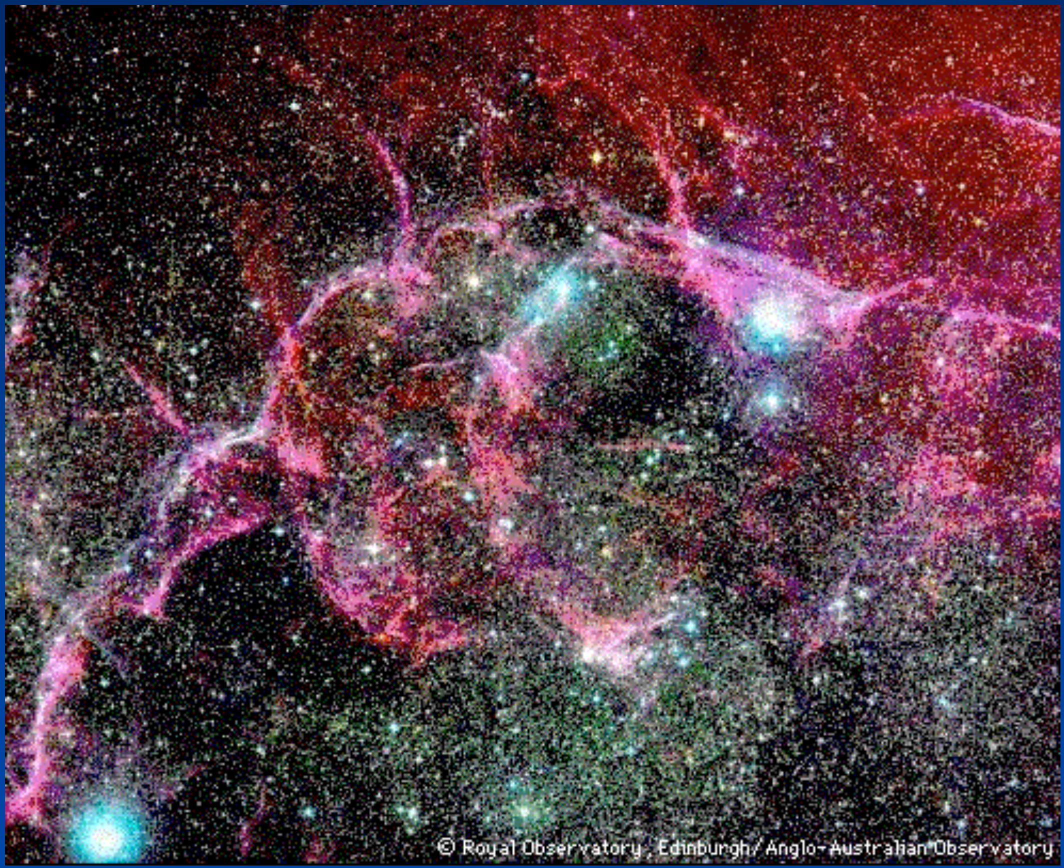
Search for anisotropy in HE electron flux (see e.g. Ptuskin & Ormes, XXIV ICRC, Rome, 1995 : nearby sources, streaming of local magnetic fields?

Current and Planned electron detectors (10 GeV – 1 TeV)

Experiment	Energy meas.	Collecting power	Top Energy
BETS balloon payload	calorimeter	1 m^2 sr day	100 GeV
ATIC balloon payload	calorimeter	10 m^2 sr days	1.5 TeV
CREAM balloon payload	calorimeter	30 m^2 sr days	2 TeV
CREST balloon payload	synchrotron	>300 m^2 sr day	3-50 TeV
AMS-1	magnet spect.	0.2 m^2 sr days	30 GeV
PAMELA satellite	magnet spect.	40 m^2 sr days	1-2 TeV
AMS-2	magnet spect.	400 m^2 sr days	2-3 TeV
CALET	calorimeter	700 m^2 sr days	5 TeV
GLAST	calorimeter	>3000 m^2 sr days	0.7 TeV

Required exposure to reach 10 TeV: 100 electrons in the range 5-10 TeV requires ~5 m^2 sr yr = 2000 m^2 sr days

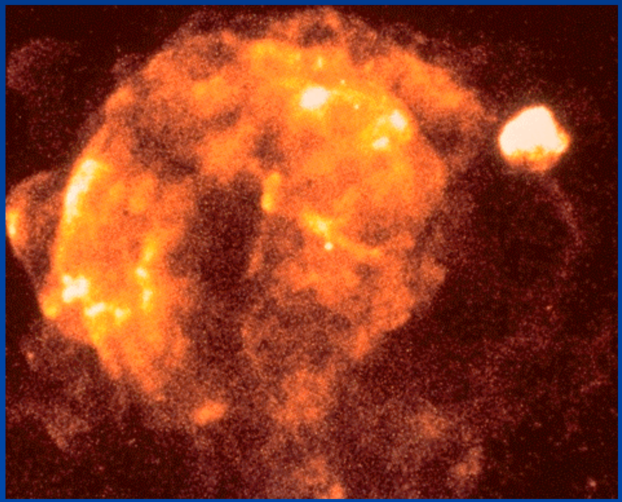
Vela supernova remnant



10-12 x 10^3 year old

250-500 pc away

70 pc, 8 degrees, in diameter

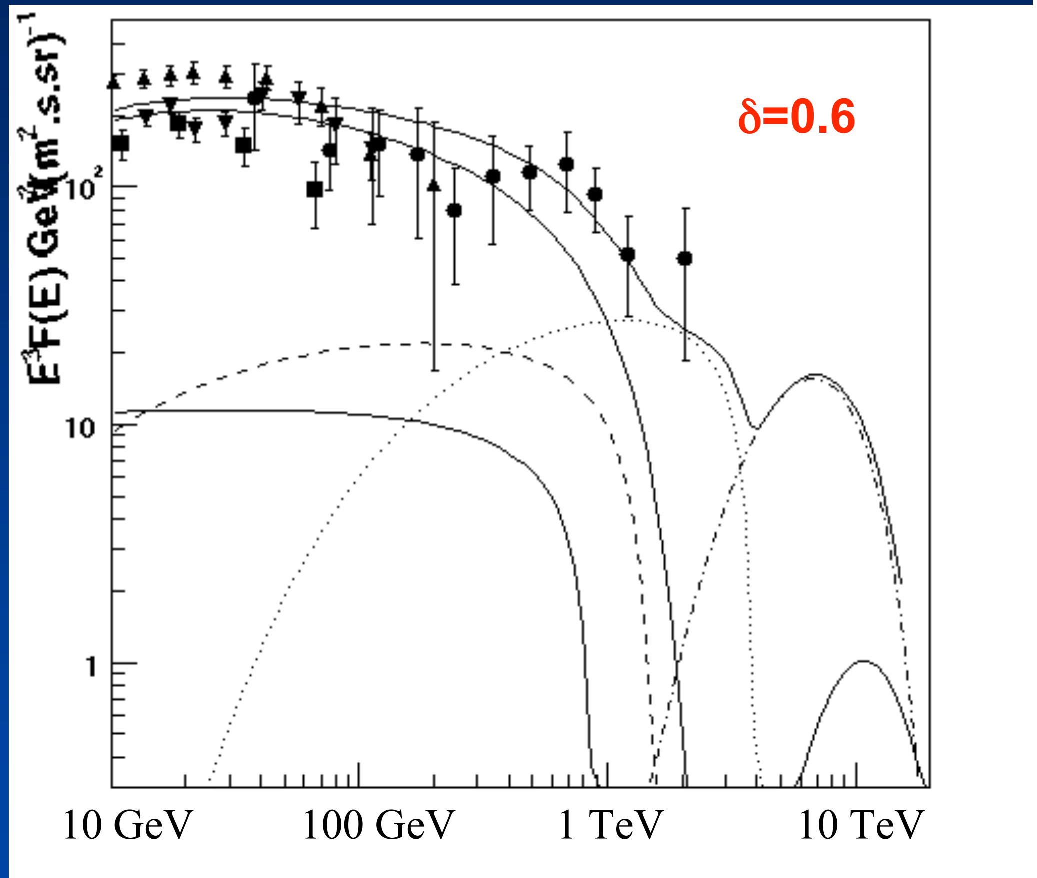


Grenier and Terrier: $\tau_{esc} \sim \tau_{rad}$

- Vela too young
  (e still trapped)
- Cygnus Loop has released all its e
- ⇒ Loop I & Monogem near TeV

⇒ Cygnus Loop > TeV

⇒ δ = 0.33 favours older remnants



Loop I　　Monogem　　Cyg loop

Geminga　　　　Vela

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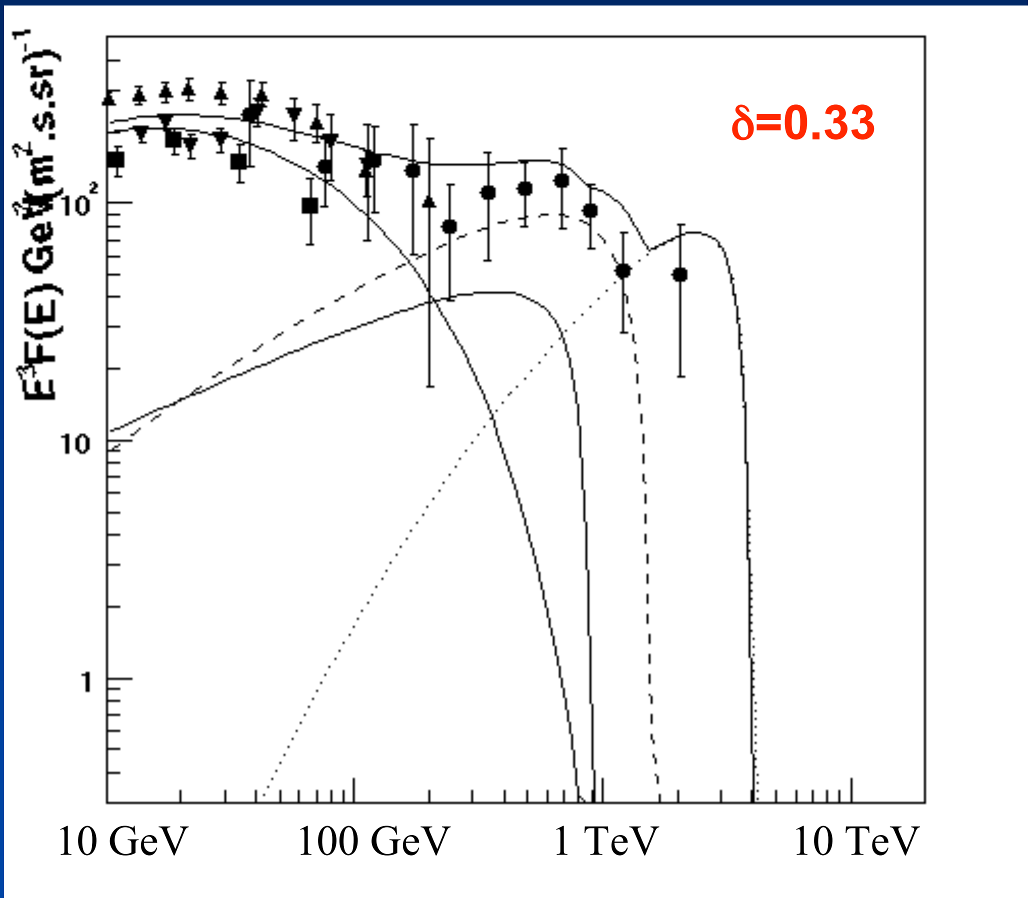


Loop I	Monogem	Cyg loop
Geminga		Vela

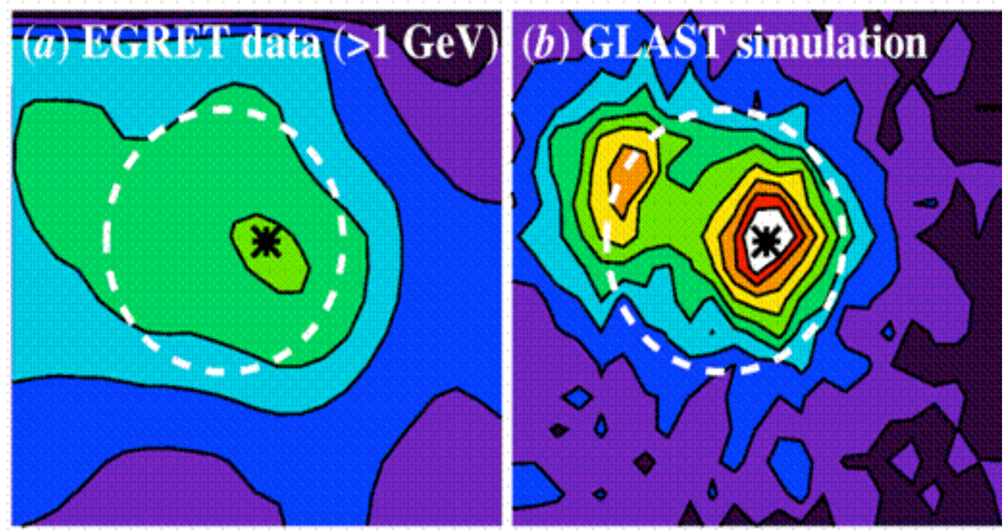
Spatial resolution: Simulation of Gamma Cygni SNR

Likely to be something like dozens of positional coincidences with SNR, a few will be spatially resolved.

- For some SNR candidates, the LAT sensitivity and resolution will allow mapping to separate extended emission from the SNR from possible pulsar components.

- Energy spectra for the two emission components may also differ.

- Resolved images will allow observations at other wavelengths to concentrate on promising directions.



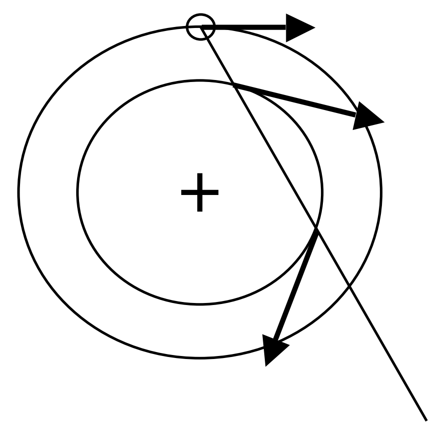
(*a*) Observed (EGRET) and (*b*) simulated LAT (1-yr sky survey) intensity in the vicinity of **γ-Cygni** for energies >1 GeV. The dashed circle indicates the radio position of the shell and the asterisk the pulsar candidate proposed by Brazier et al. (1996).

Galactic Structure and Cosmic Ray Distribution

- **Gamma ray intensity is a line-of-sight integral of the matter density times the cosmic-ray density.**
- **Matter distribution - directly observable**
  - HI (21 cm)
  - CO (115 GHz), tracer of H_2

  } Doppler-shifted velocity: kinematic deconvolution, if velocity field known
- **Low energy photons**
  - IR (12 μm - 240 μm)
- **Cosmic ray spectrum measured at only one point and the low-energy spectrum is affected by solar modulation.**
- **Requires a model.**

Near-far distance ambiguity



Cosmic Ray Density

- Three approaches
  - Build in coupling of cosmic-ray and gas; derive 3-dim distribution of gas (Hunter et al. 1997, ApJ, **481**, 205).
  - Let the cosmic-ray density (gamma-ray emissivity) be free for different distance ranges for which 2-dim maps of gas are used (Strong & Mattox 1996 A&A, **308**, L21, and studies of individual clouds).
  - Calculate the cosmic-ray density using source distribution and codes for cosmic-ray propagation (e.g., Pohl & Esposito 1998 ApJ 507, 327; Strong, Moskalenko, & Reimer 2000 ApJ, **537**, 763).

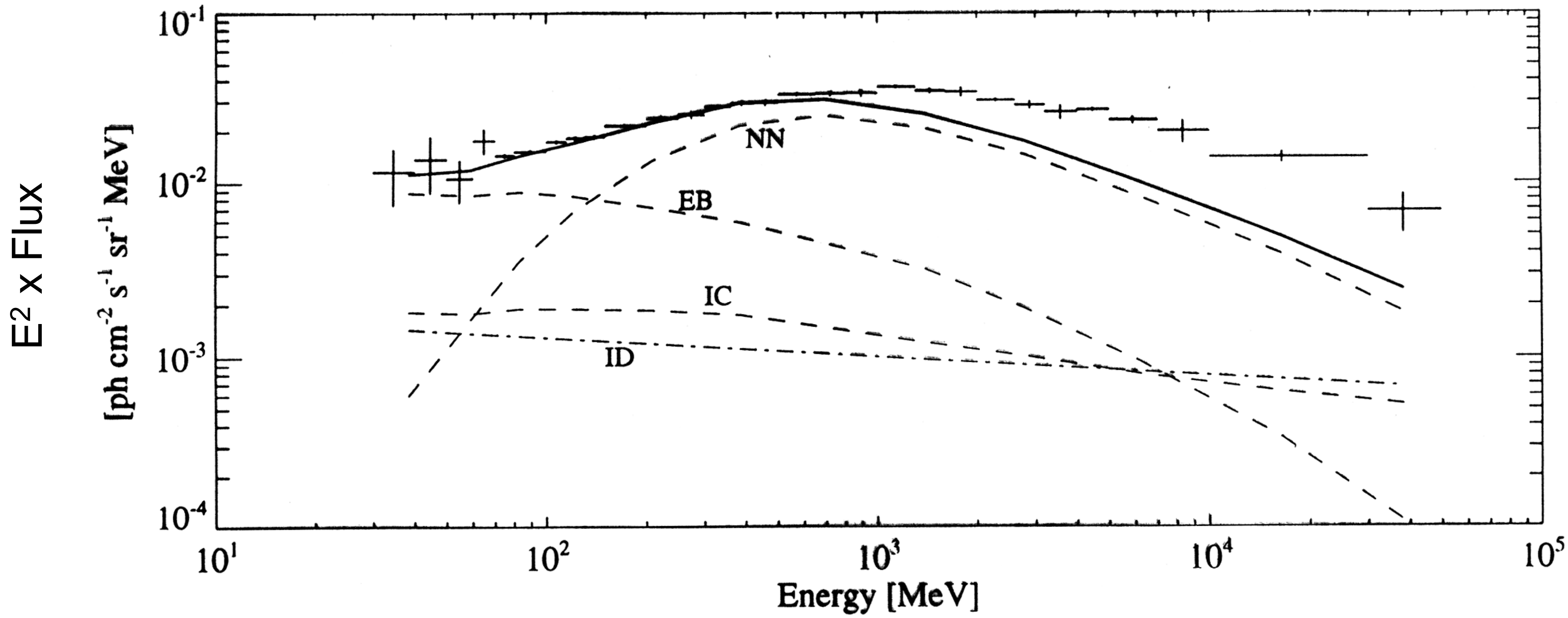
All reproduce structure observed in the diffuse emission

– spatial resolution of GLAST should improve the understanding

– GLAST responsible for producing a model of galactic diffuse

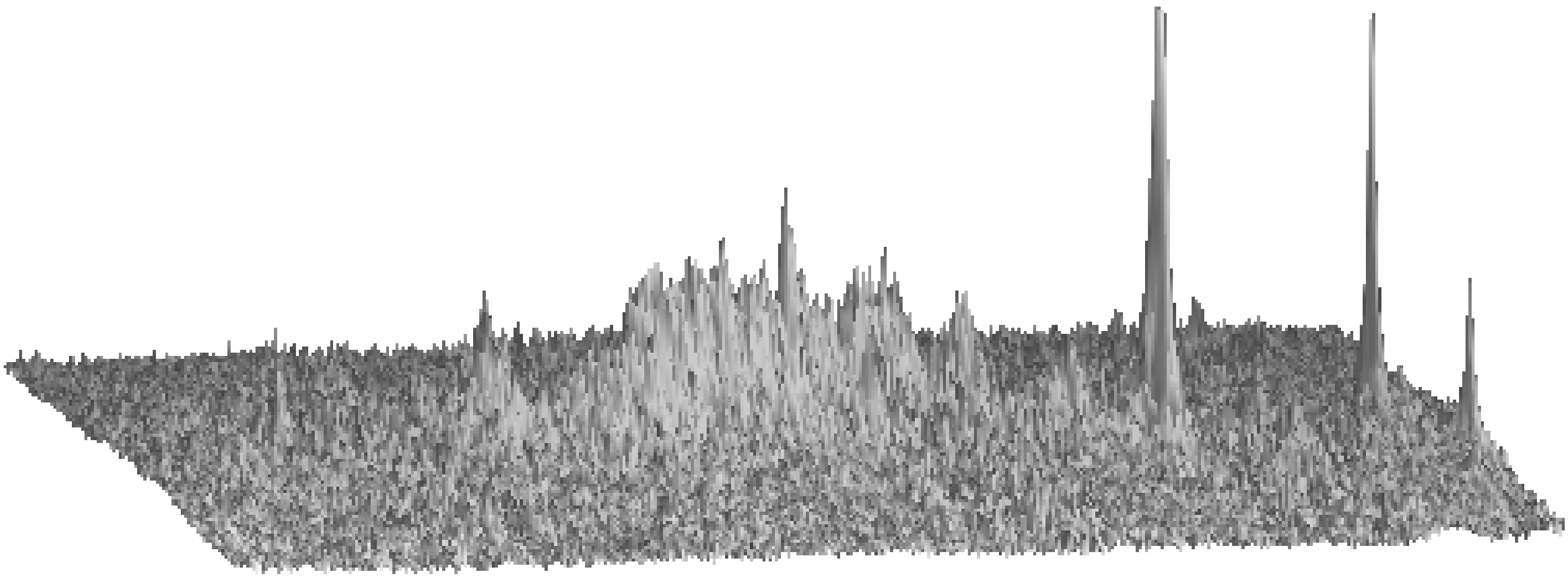
There is an excess of gamma rays at E > GeV

The GeV excess is most clearly clearly seen
in the plane looking toward the galactic center $-60^o < \ell < 60^o$, $|b| < 10^o$

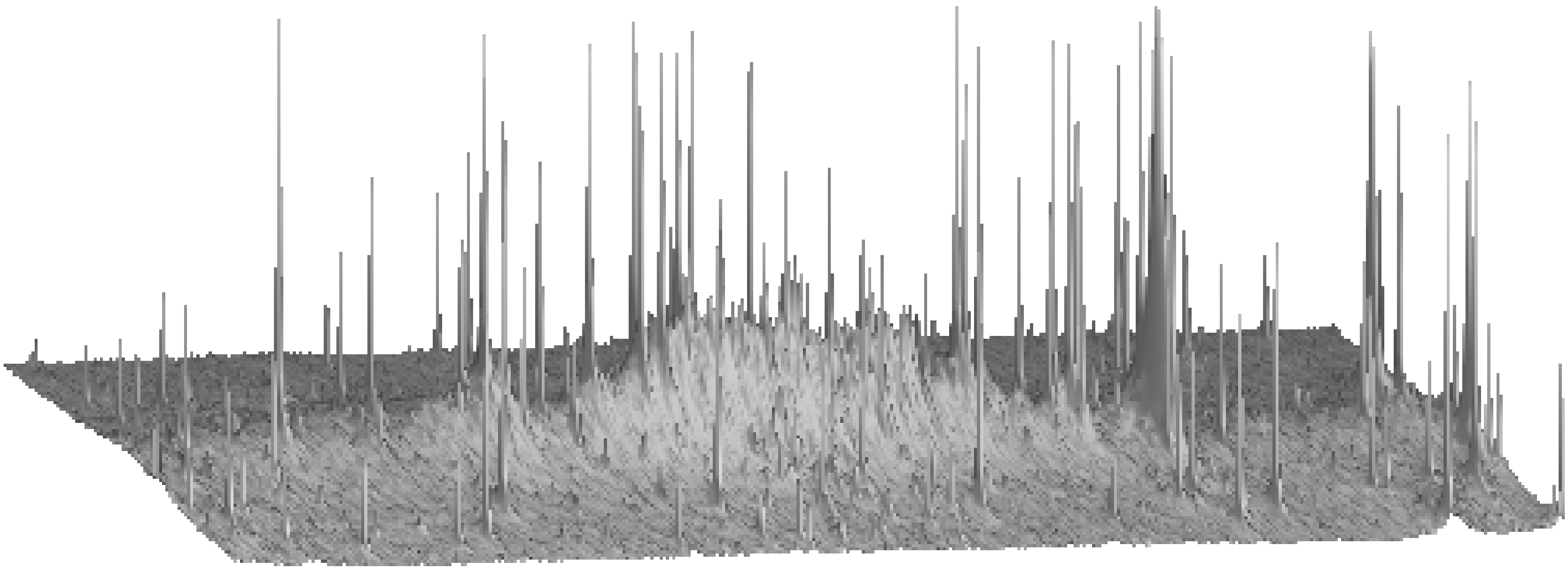


Hunter et al. 1997, ApJ **481**, 205

EGRET: galactic diffuse gamma rays



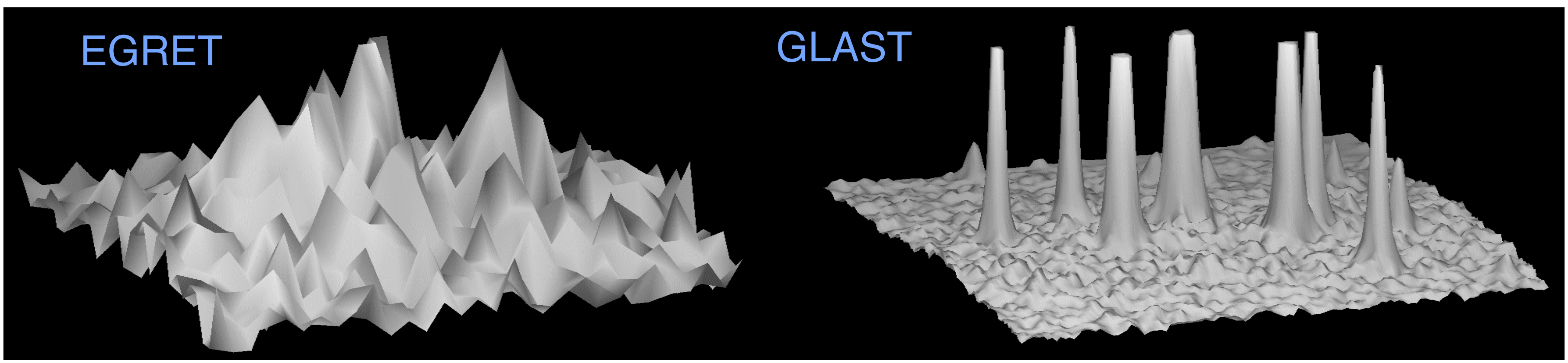
GLAST: galactic diffuse gamma rays



Source Confusion

- **Unresolved sources in the Milky Way?**
  - Hunter et al. 1997, ApJ **481**, 205 spectral evidence: unresolved source fraction is <10%
  - Pohl et al. (1997) and Zhang & Cheng (1998) both conclude that pulsars can contribute significantly to >1 GeV emission
  - However, Pohl et al. point out that latitude distribution of pulsars is narrower than the diffuse emission
- **GLAST's advantages for point sources**

Cygnus Region (15°x15°), E>1 GeV

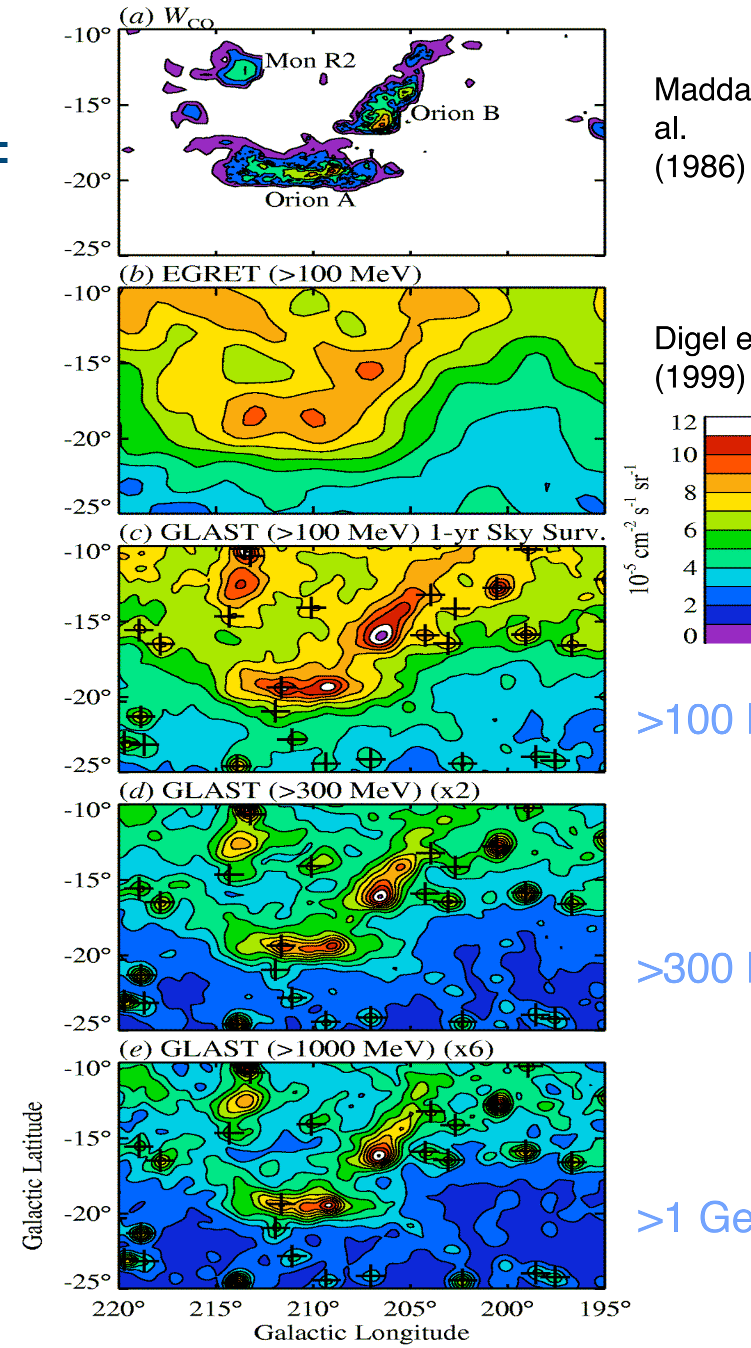


Phases 1-5

1-yr sky survey; bright sources (truncated) are from 3EG catalog (Hartman et al. 1999)

Extended "Sources"

- **GLAST will permit a real mapping of molecular clouds**
- **Example for diffuse emission: Orion (nearest GMCs)**
- **Rejection of point source contamination will facilitate studies of**
  - CR uniformity
  - $N(H_2)/W_{CO}$ (X-ratio) uniformity



Maddalena et al. (1986)

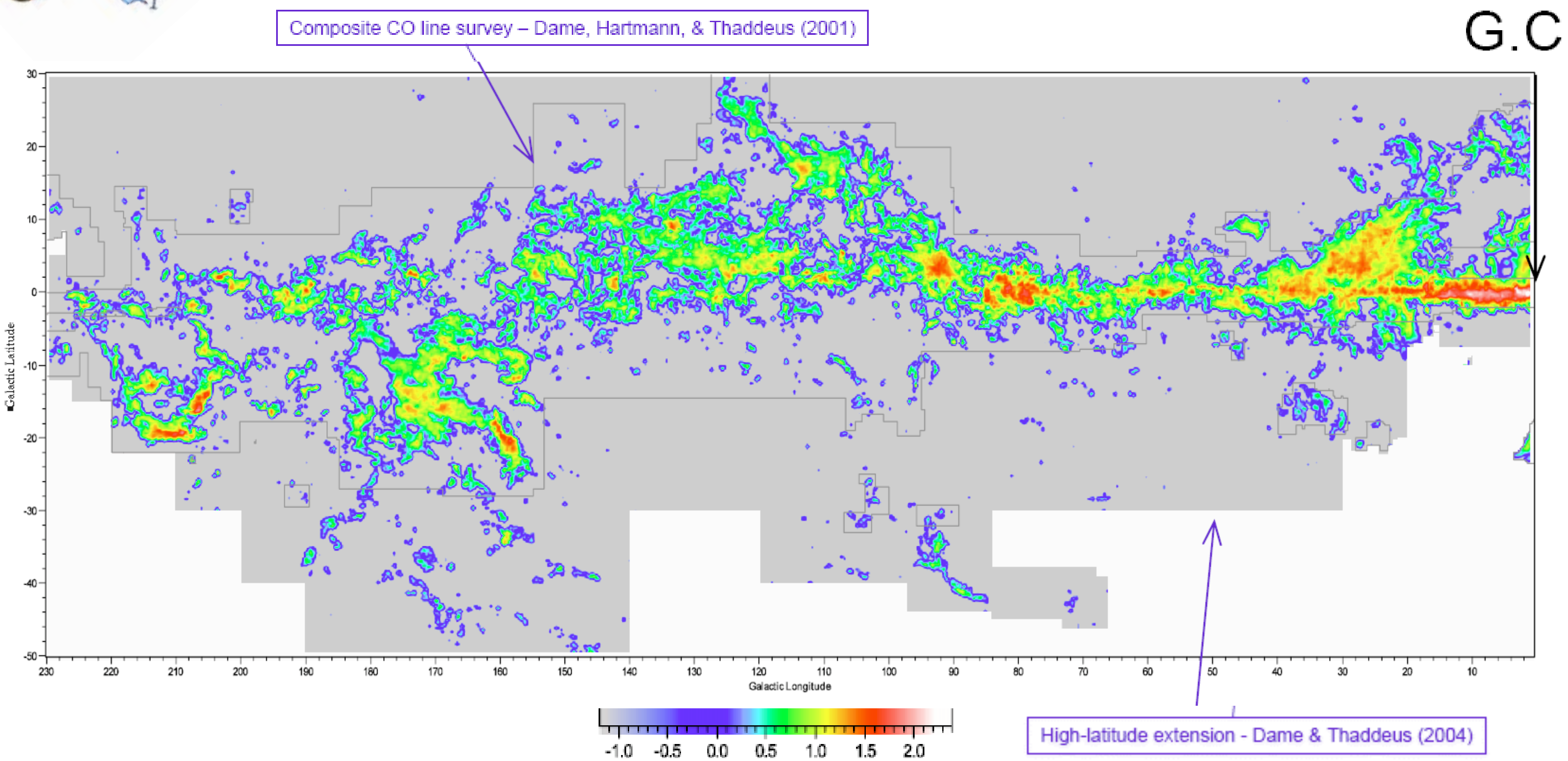
Digel et al. (1999)

>100 MeV

>300 MeV

>1 GeV

Details of nearby (|*b*| > 10°) interstellar gas



Dense (molecular), small interstellar clouds at high latitudes, with small filling factor make targets to determine cosmic ray density.

Cosmic ray - gamma ray connection: open issues

- **GeV γ-ray excess**
  - Inner disk
  - Molecular clouds
- **Halo in gamma rays (electron population and Inverse Compton)**
  - Solar halo, stellar halos
- **Acceleration model for galactic cosmic rays**
- **Sources**
  - Source spectra
  - Mix of components: π^o, IC, EB
  - Presence of point sources: an energy dependent contribution?
- **Spatial variations in cosmic ray spectra**
- **Spatial variations in matter and $X \equiv N(H_2)/W_{CO}$**
- **Can we find a "smoking gun" for the source of cosmic ray nuclei?**
  - Will there be too much confusion of γ-ray pulsars and/or CR nuclei accelerated by shocks, interacting with nearby molecular clouds
  - Can the π^o bump be detected in SNR?

The end