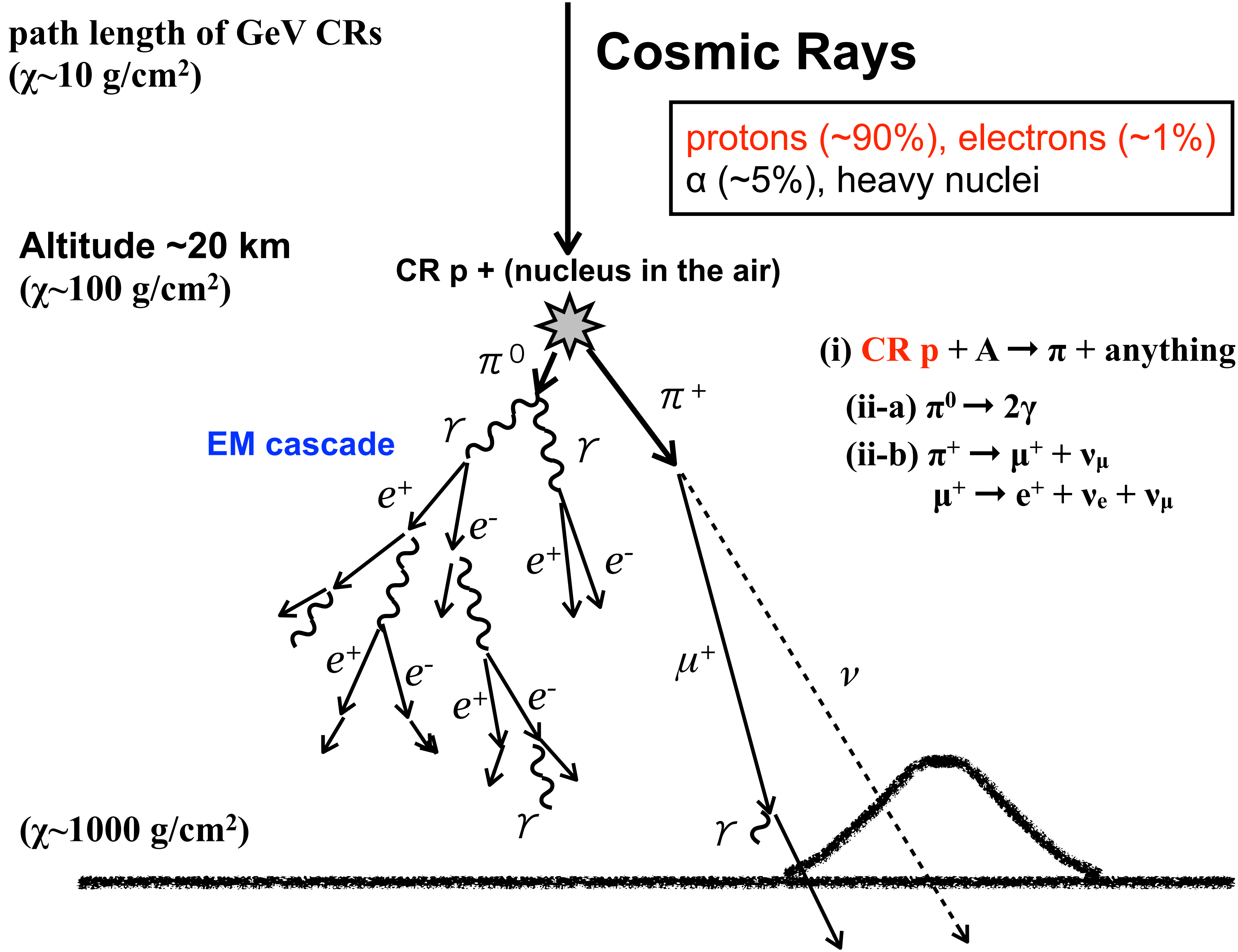
IPMU Colloquium 2011,
Kashiwa, JAPAN

The Supernova Origin of Galactic Cosmic Rays

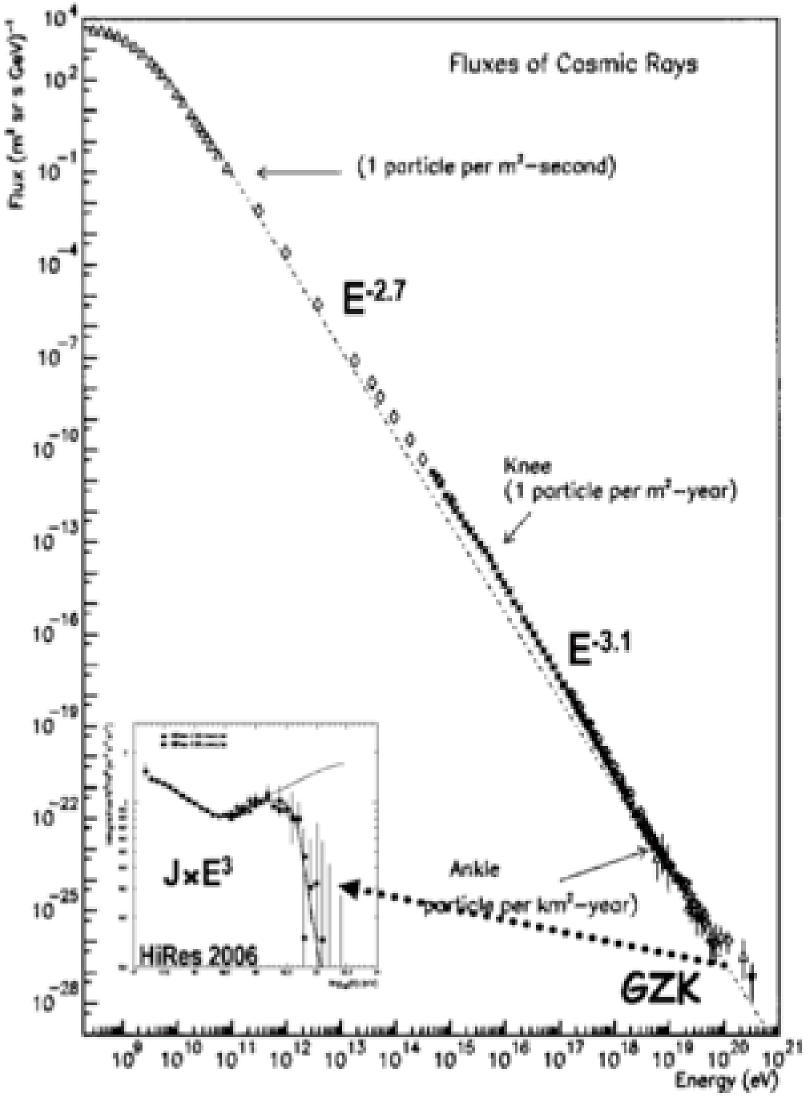
Yasunobu Uchiyama (SLAC)
on behalf of
the Fermi LAT Collaboration

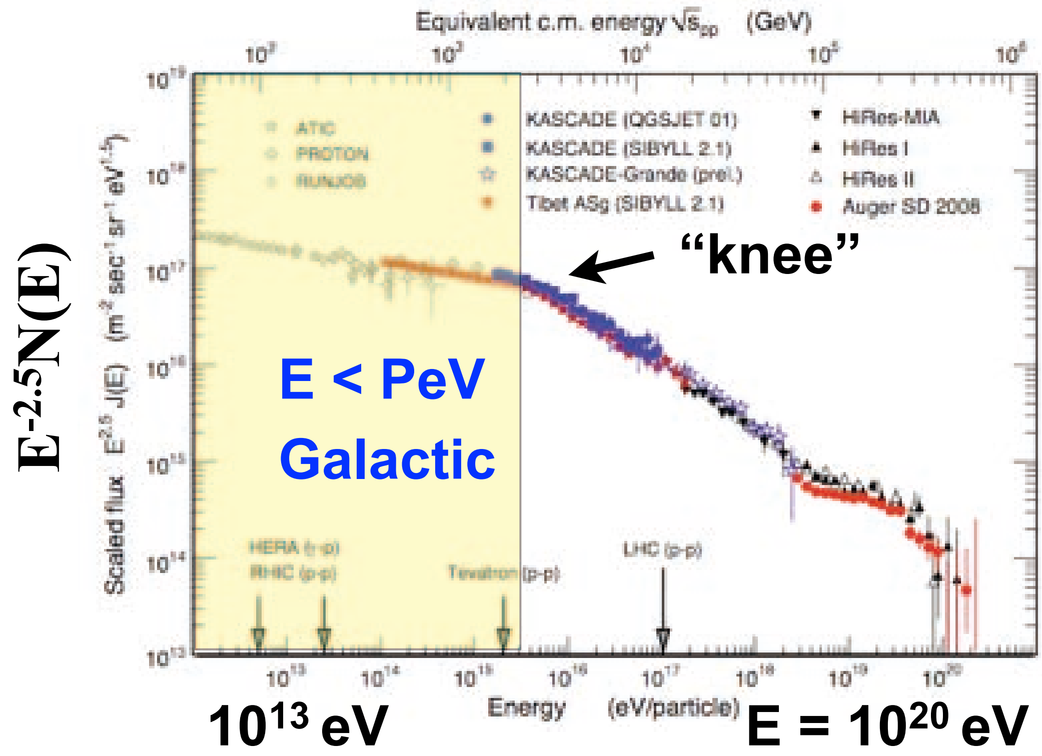


path length of GeV CRs
(χ~10 g/cm²)
Cosmic Rays
protons (~90%), electrons (~1%)
α (~5%), heavy nuclei
Altitude ~20 km
(χ~100 g/cm²)
CR p + (nucleus in the air)
(i) CR p + A → π + anything
(ii-a) π⁰ → 2γ
(ii-b) π⁺ → μ⁺ + ν_μ
μ⁺ → e⁺ + ν_e + ν_μ
π⁰
π⁺
EM cascade
γ
e⁺
e⁻
μ⁺
ν
(χ~1000 g/cm²)

Cosmic Rays: Spectrum

Energy distribution: power-law type ($N \propto E^{-2.7}$ below "knee")

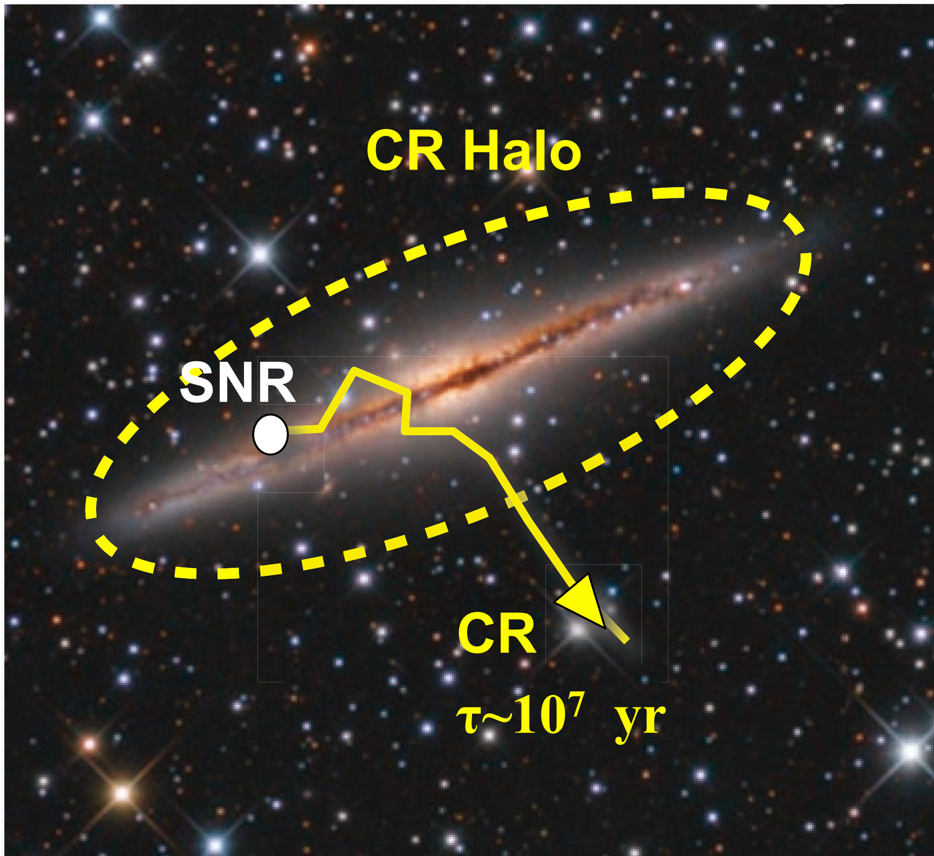




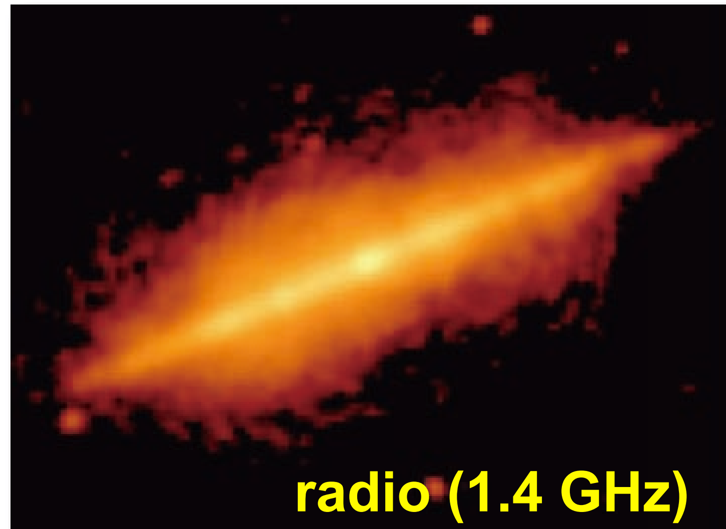
Sources of Galactic CRs:
Supernova Remnants (SNRs)?

Galactic Cosmic Rays (GCRs)

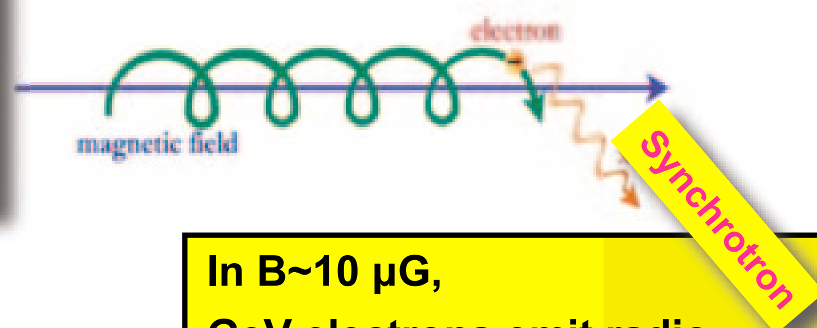
Alien’s view of our Galaxy



NGC 891: edge-on spiral galaxy



Synchrotron radiation by CR e



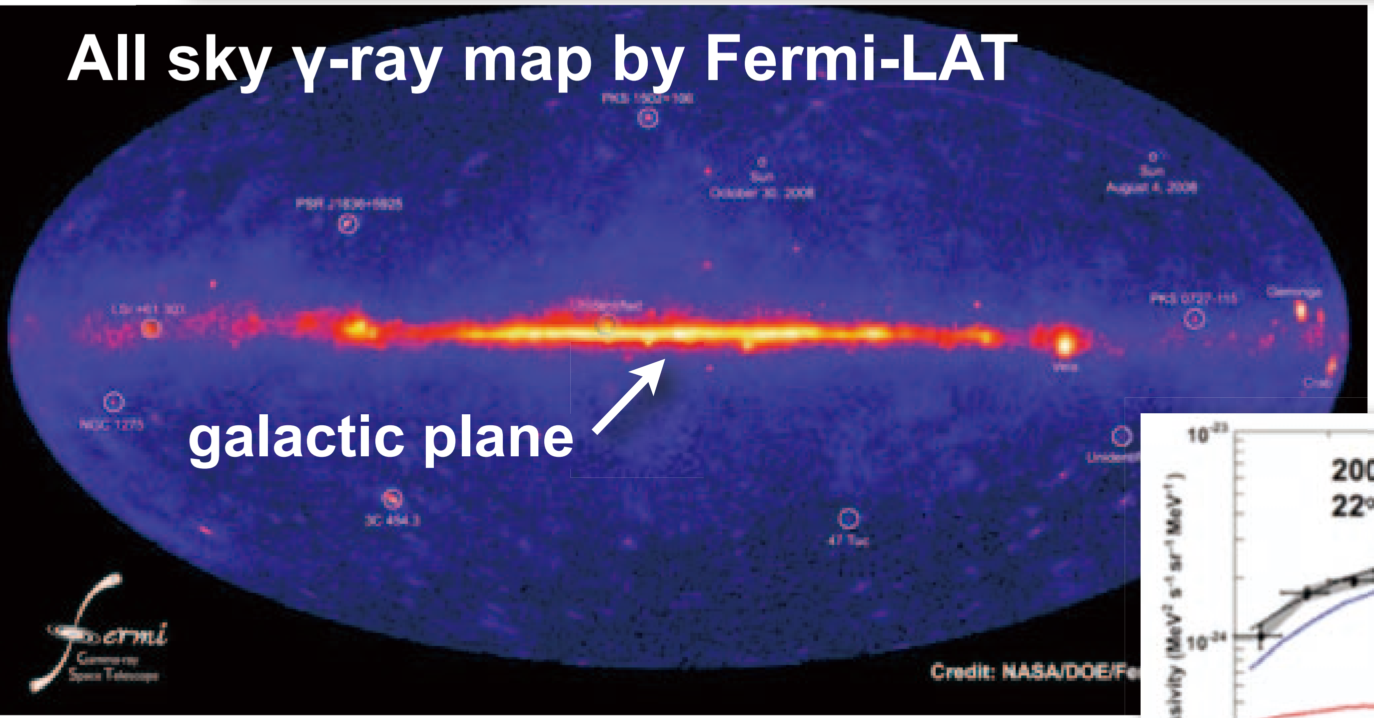
In B~10 μG,
GeV electrons emit radio
PeV electrons emit hard X-rays

GCRs: probed by GeV γ-rays

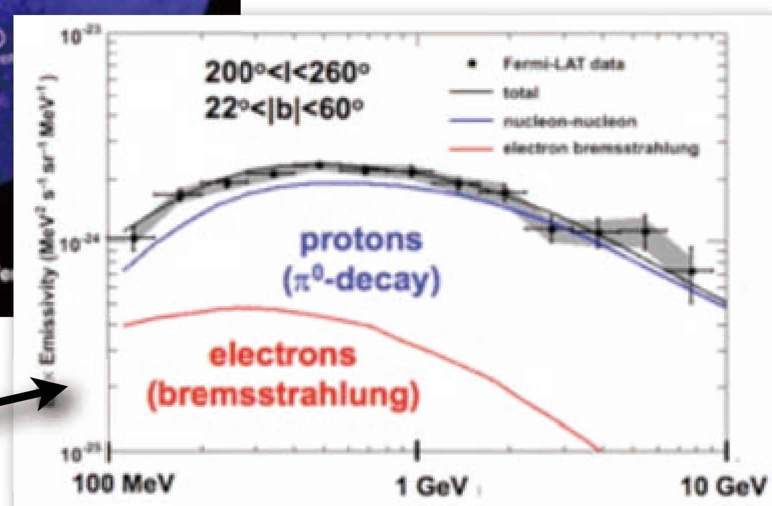
Galactic CRs (p/e) produce γ-rays:

π^0-decay γ-rays (CR p + H → π^0 → 2γ)

bremsstrahlung/inverse Compton scattering by CR e



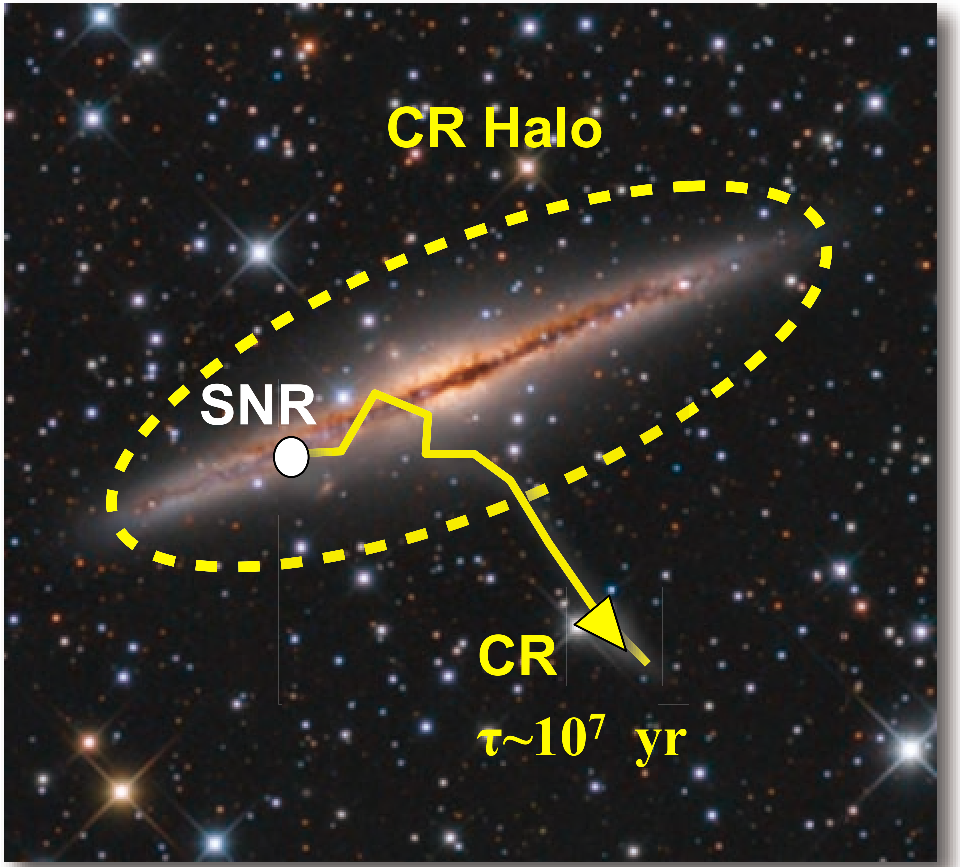
γ-ray spectrum (mid-latitude)



CRs of solar neighborhood

~ CRs arriving at Earth

Cosmic Rays: Energetics



Energy density (~ GeV protons):

$u_{CR} \sim 1\ \mathrm{eV/cm^3}$

Residence time of GeV protons in the Galaxy: ($^{10}Be/^{9}Be$: $\tau(^{10}Be)=1.6\times10^6$ yr)

$\tau_{CR} \sim 10^7\ \mathrm{yr}$

CR supply rate:

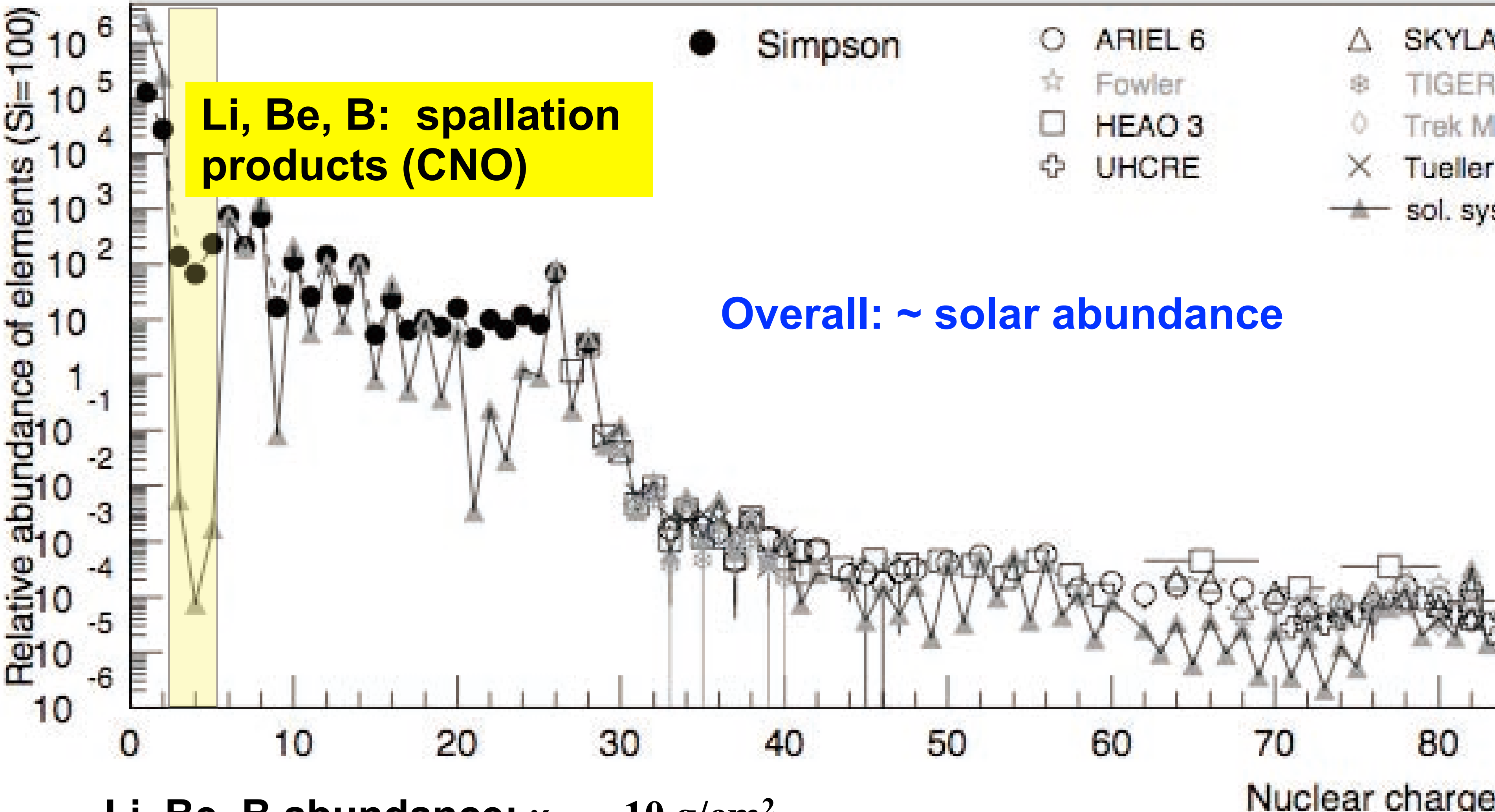
$L_{CR} \sim u_{CR} V_{halo}/\tau_{CR} \sim 10^{41}\ \mathrm{erg/s}$

Total mechanical power by SNe:

$L_{SN} \sim 10^{51}\ \mathrm{erg}/ 50\ \mathrm{yr}$

$\sim 10^{42}\ \mathrm{erg/s}$

CRs: Composition



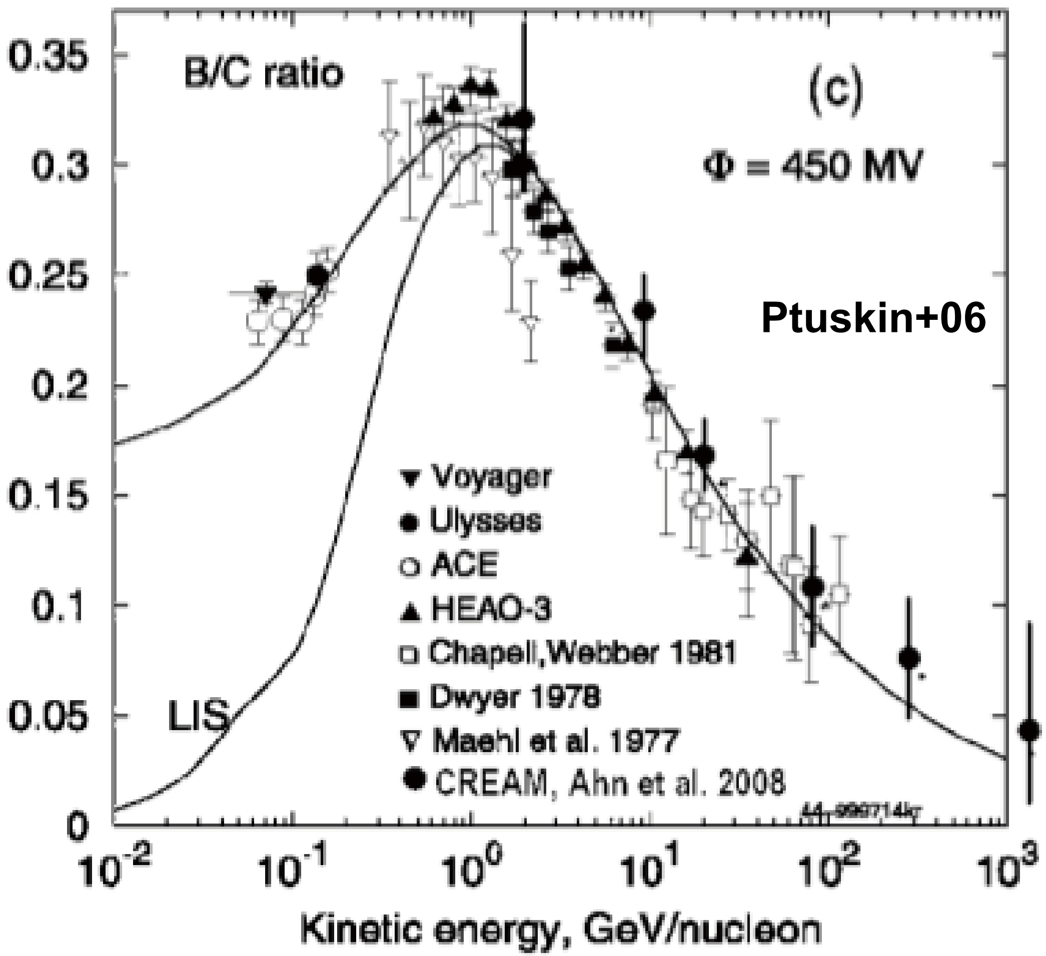
Nuclear charge (Z)

Li, Be, B abundance: $\chi_{CR} \sim 10$ g/cm^2

NOTE: hadronic pp interactions: $\chi \sim 40$ g/cm^2

CRs: Source Spectrum

B/C ratio



$\chi \sim 10\ (R/4\ \mathrm{GV})^{-0.45}\ \mathrm{g/cm^2}$

$R \equiv cp/eZ$: rigidity

$\rightarrow \tau_{esc}(E) \propto E^{-0.45}$

Source Functions of CRs:

$$Q(E) = N(E)/\tau_{esc}(E)$$
$$\propto E^{-2.7} / E^{-0.45}$$
$$\propto E^{-2.25}$$

Given uncertainties,

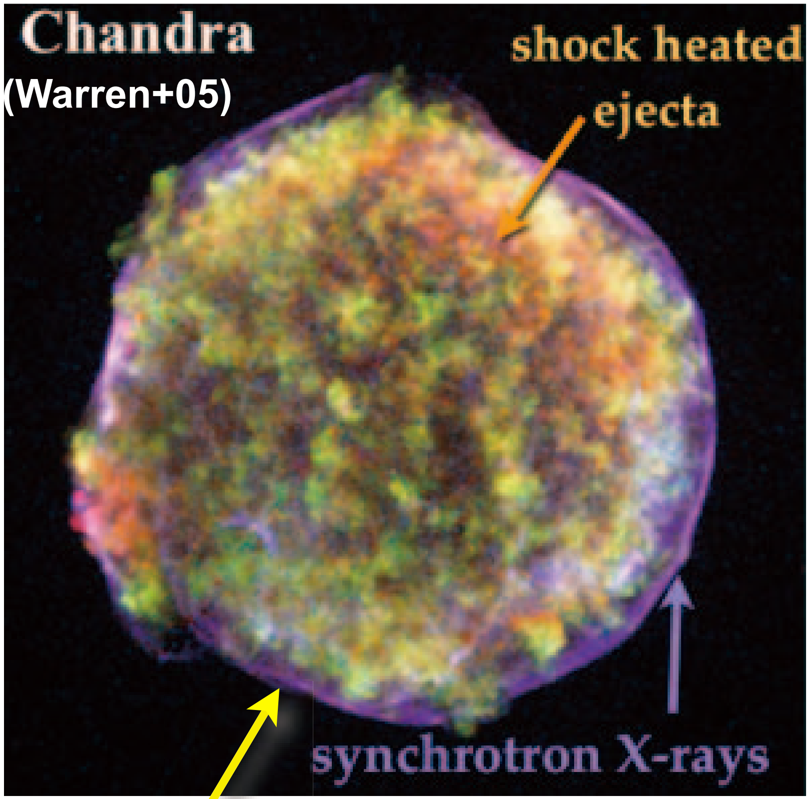
$Q(E) \propto E^{-2.1} \sim E^{-2.4}$

Observed spectrum of CRs ($N(E) \propto E^{-2.7}$)

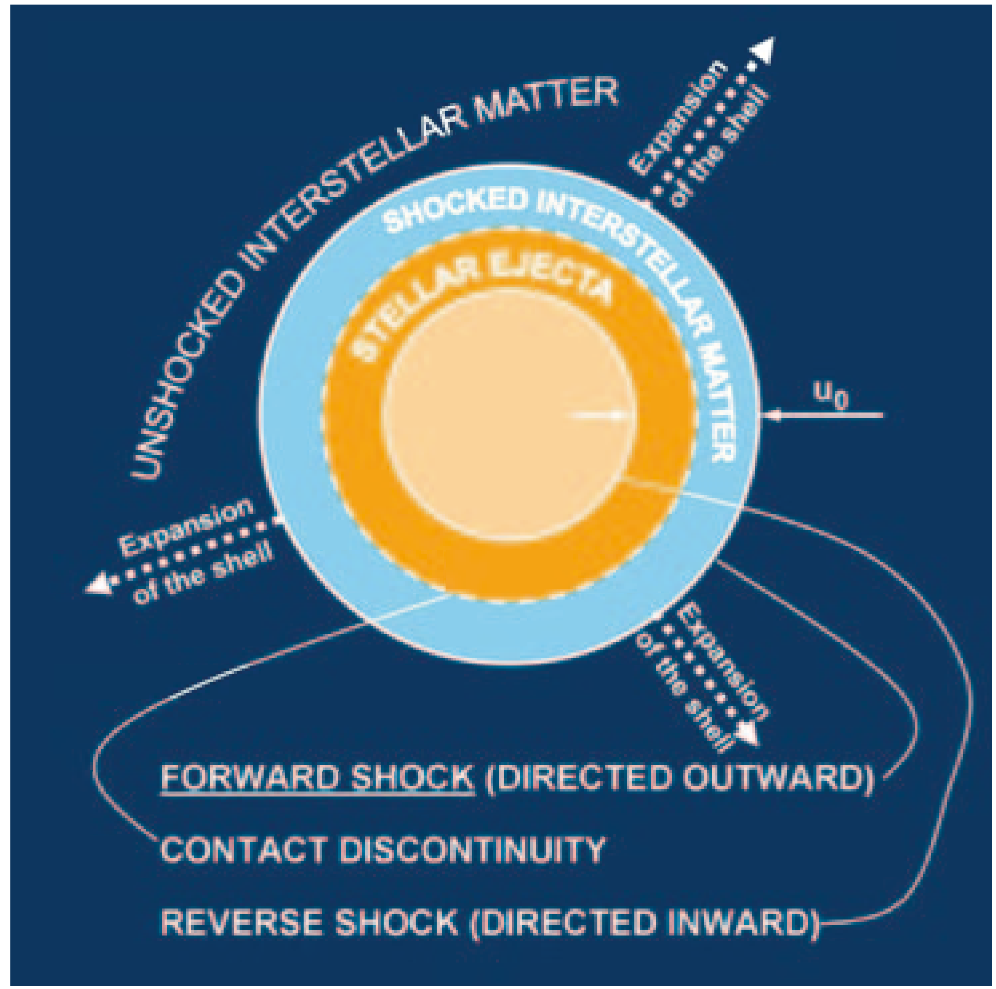
$\neq$ **Source spectrum** ($Q(E) \propto E^{-2.1\text{-}2.4}$)

Supernova Remnants (SNRs)

Evidence for very high energy particles in SNRs

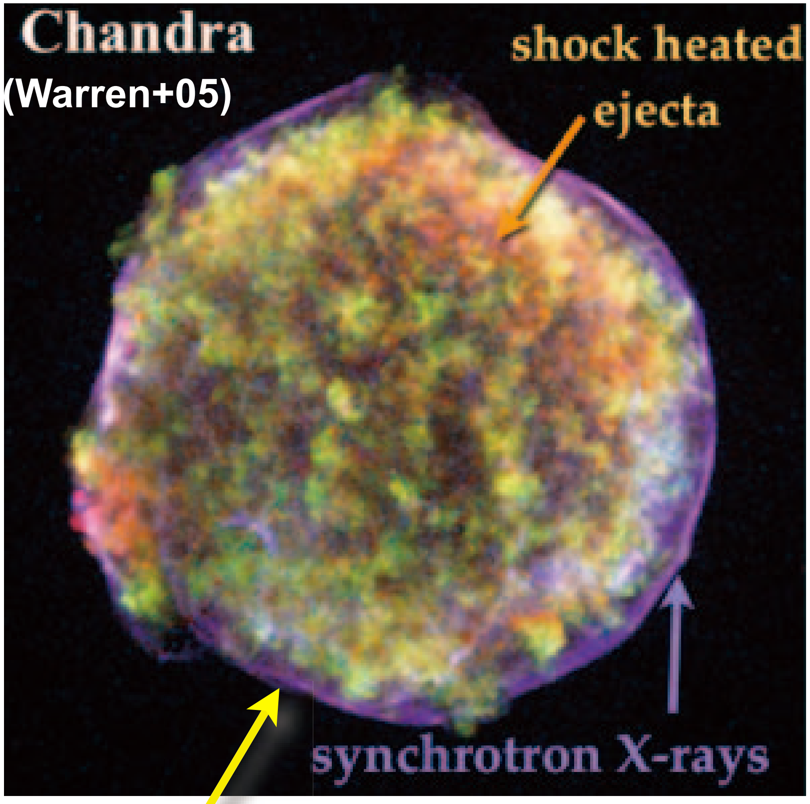


Expanding shock wave (currently ~4000 km/s) driven by SN into ISM



Supernova Remnants (SNRs)

Evidence for very high energy particles in SNRs



Expanding shock wave (currently ~4000 km/s) driven by SN into ISM

(i) TeV Gamma-ray Observations

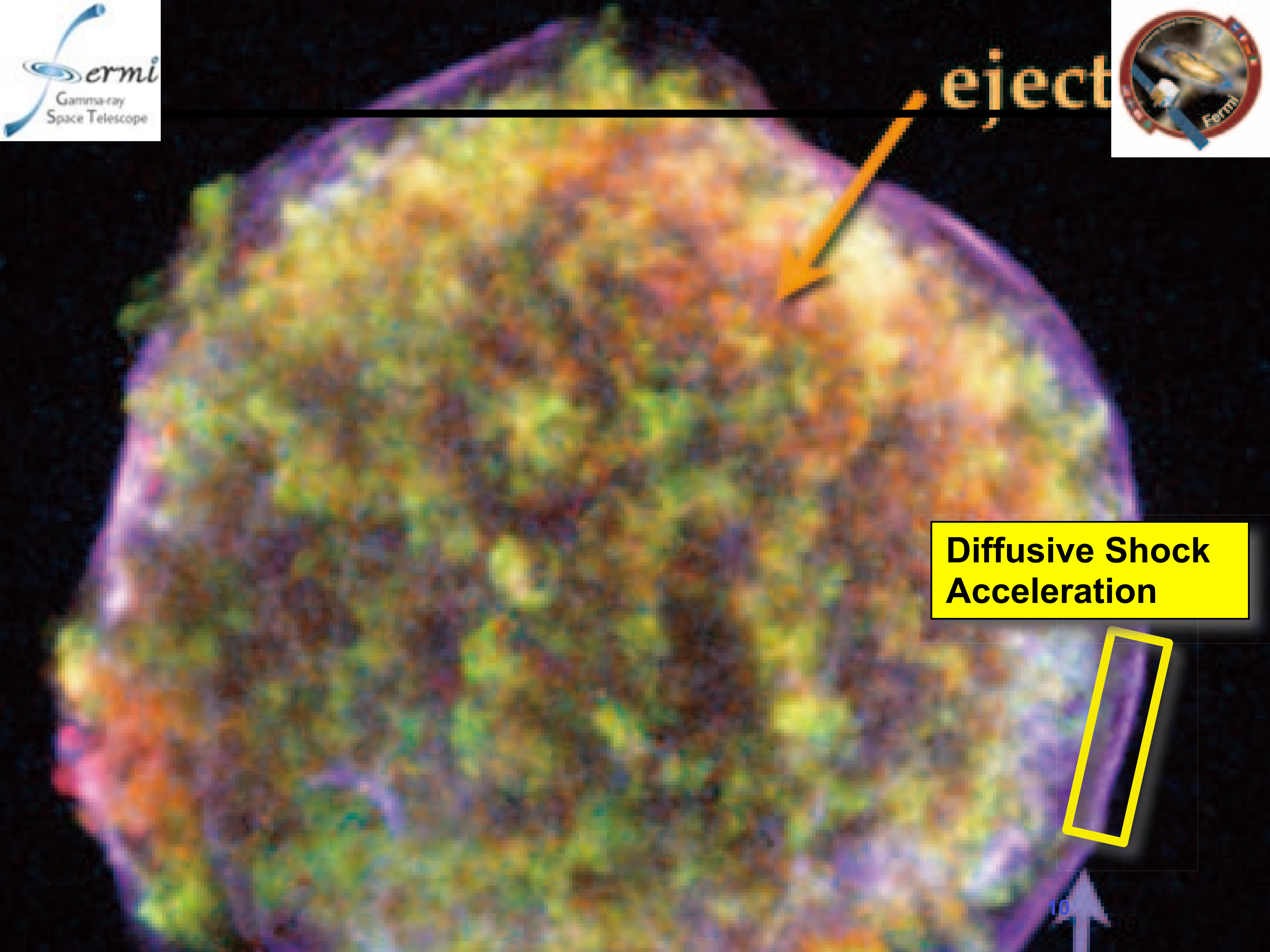
Direct evidence for >100 TeV particles.
(emission mechanisms: unsettled)

H.E.S.S. arcmin image:
Shell-like morphology (Aharonian+2004)

(ii) X-ray Observations

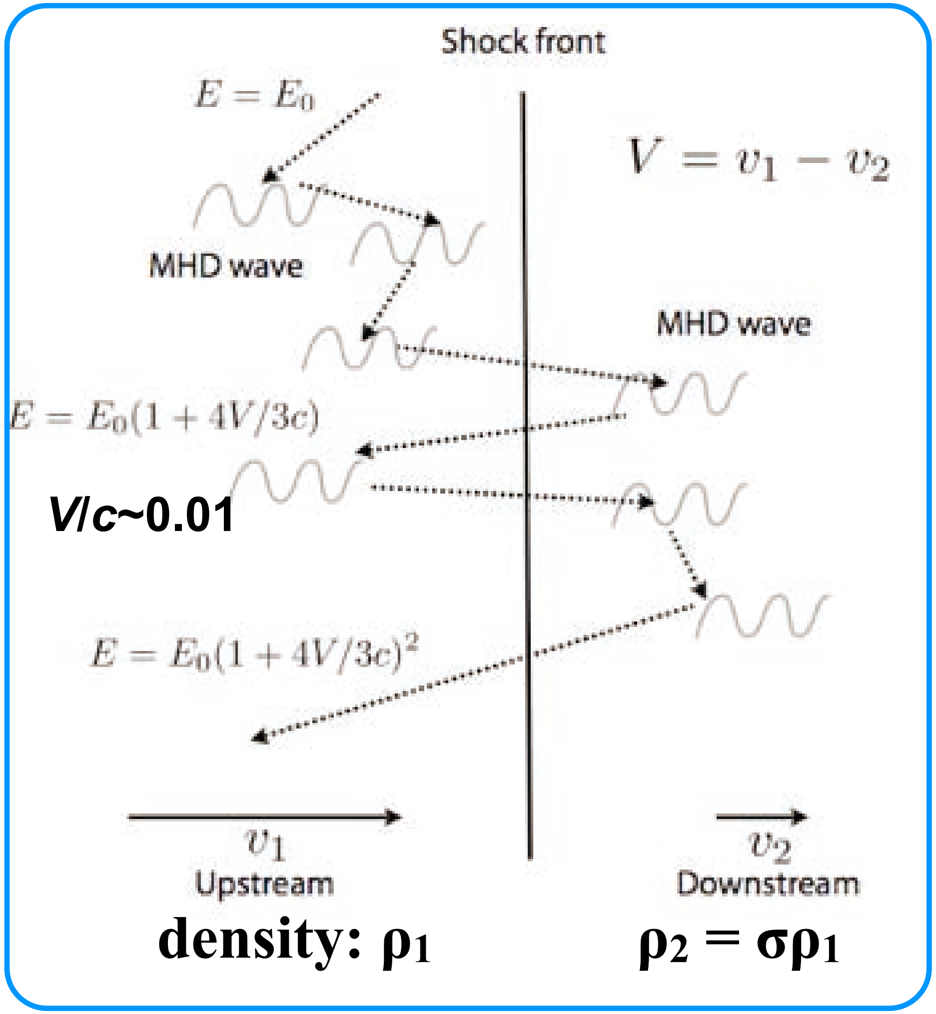
X-ray Synchrotron radiation (after ASCA satellite: Koyama+95):
Evidence for >10 TeV electrons.

Chandra arcsec image:
Indicates the operation of
Diffusive Shock Acceleration (DSA).


eject
Diffusive Shock Acceleration

Diffusive Shock Acceleration (DSA)

a.k.a. (1st order) Fermi Acceleration



"test particle" approximation:
hydrodynamics is given

$$Q(E) = K\,E^{-s}\,\exp(-E/E_{max})$$

(i) K (normalization)

Unpredictable

(ii) s (index)

$s = (\sigma+2)/(\sigma-1)$

$= 2.0$ for $\sigma = 4$ strong shock

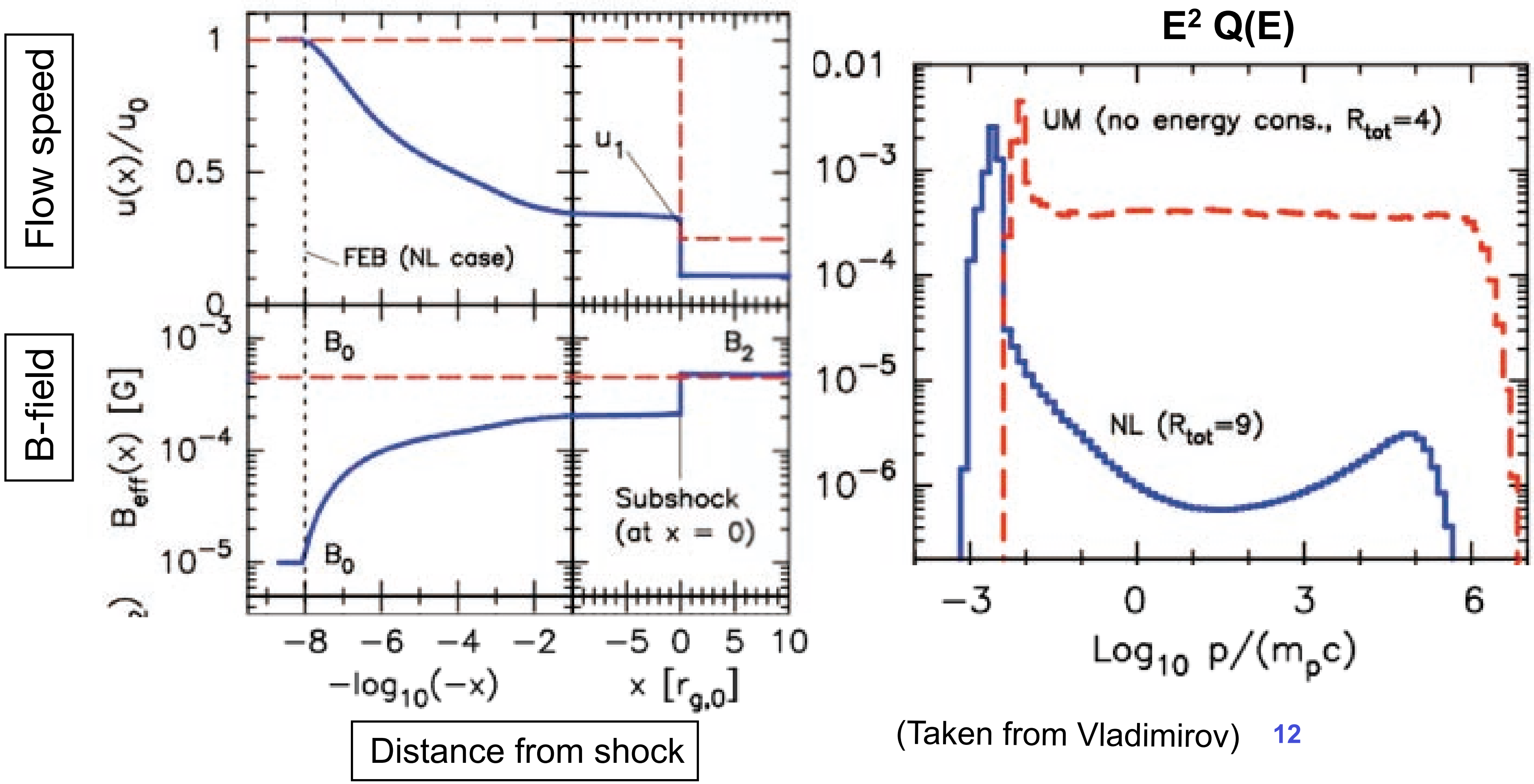
(iii) E_{max} (maximum energy)

$E_{max} \sim 10^{15}$ eV $(V/1000\ \mathrm{km/s})^2$ $(t/1000\ \mathrm{yr})$ $(B/100\ \mu\mathrm{G})$

Non-Linear DSA

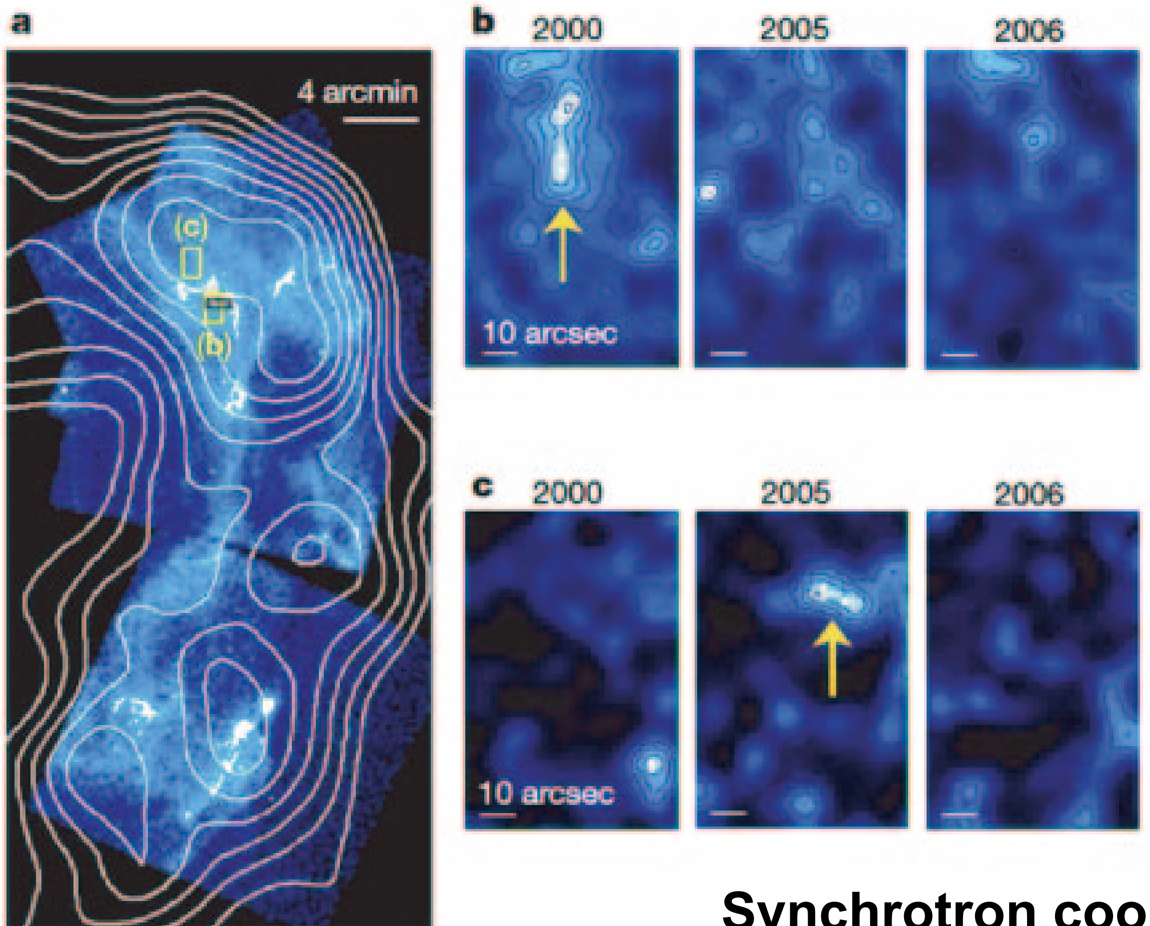
Cosmic-ray pressure ➜ Affect gas dynamics ➜ Change Q(E)
Cosmic-ray streaming instability ➜ Amplify turbulent B-field

Test Particle (TS) vs Non-Linear (NL)



(Taken from Vladimirov)

B-field Amplification in SNRs



Chandra X-rays (color)

H.E.S.S. TeV γ-rays (contours)

Uchiyama et al. (2007)

Most filaments (spatially extended) are variable in time!!

X-ray spectra: synchrotron radiation

Year-scale variability
→ B = 0.1-1 mG
>> B_{ISM}

Synchrotron cooling timescale:

$$t \sim . \left(\frac{B}{\quad}\right)^{-} \left(\frac{\epsilon}{\quad}\right)^{-}$$

SNRs as the Sources of CRs

Requirements for the Sources of Galactic CRs

i. **Energetics**: CR protons of ~10^{50} erg (~10% of E_{SN}) per SNR

Theory of diffusive shock acceleration (DSA) cannot predict the amount of CRs.

"injection" from thermal pool = poorly known process

ii. **Spectral Index**: s=2.1-2.4 $Q(E) \propto E^{-s}$

DSA theory: test particle (TP) approximation s=2.0

non-linear (NL) "concave" spectrum

B-field amplification may yield s~2.4

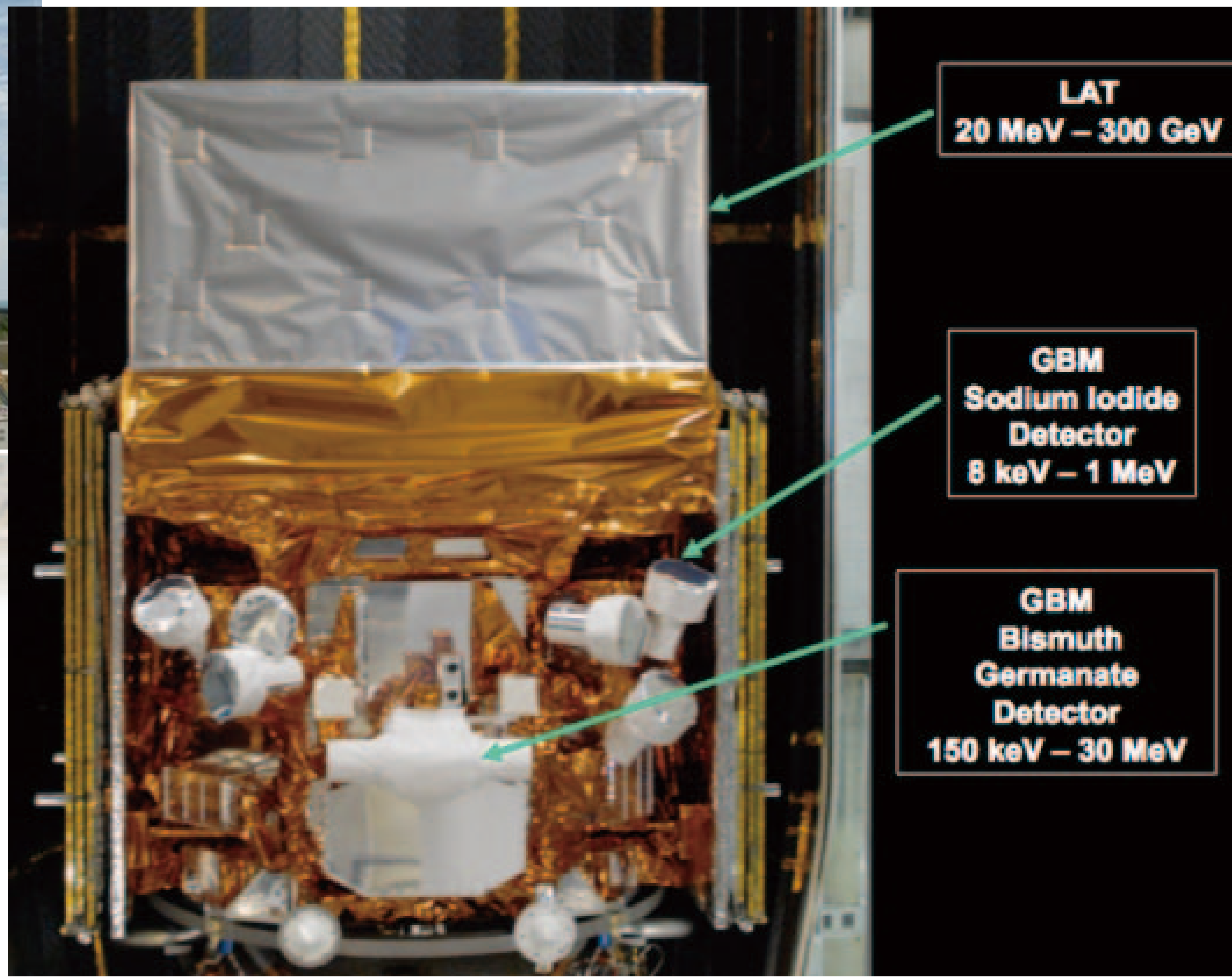
iii. **Maximum Energy**: ~ PeV (10^{15} eV) to reach "knee"

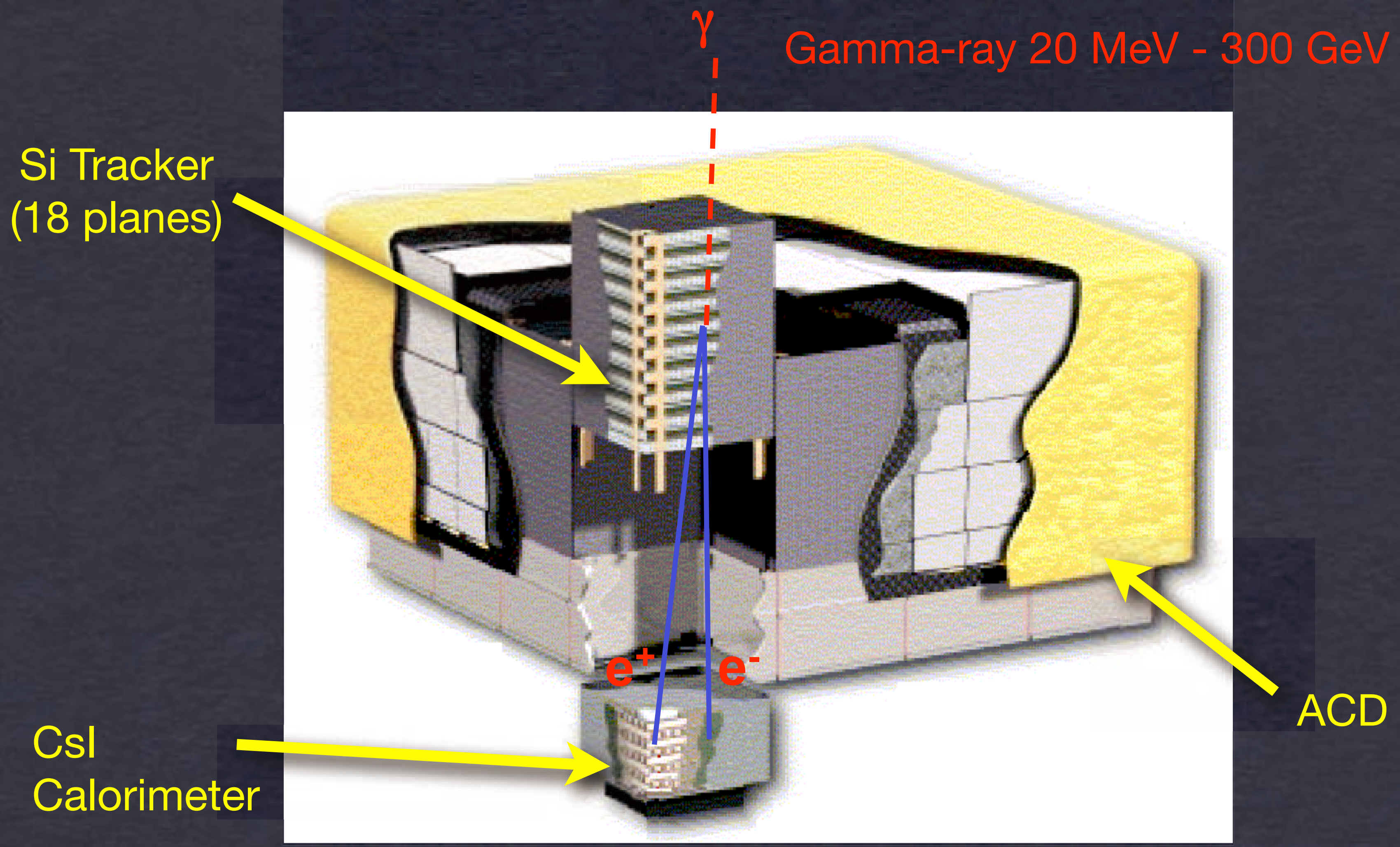
DSA theory: assuming Bohm limit and B-field amplification,

$E_{max} \sim 10^{15}$ eV (v/1000 km/s)^2 (t/1000 yr) (B/100 μG)

→ Fermi-LAT is capable to address many of these problems.

Fermi Gamma-ray Space Telescope





LAT: 4x4 modular array
3000 kg, 650 W

Large Area Telescope (LAT)

GeV gamma-ray observations of SNRs

- Historical SNRs
  - Tycho
  - Cassiopeia A
- Young TeV-bright SNRs
  - RX J1713.7-3946
  - Vela Jr.
- SNRs interacting with molecular clouds
  - W51C, W44, IC443, W28, W49B, W30(G8.7-0.1), CTB37A, ...
- Evolved SNRs without molecular cloud interactions
  - Cygnus Loop, (Puppis A)

Part I

Part I:

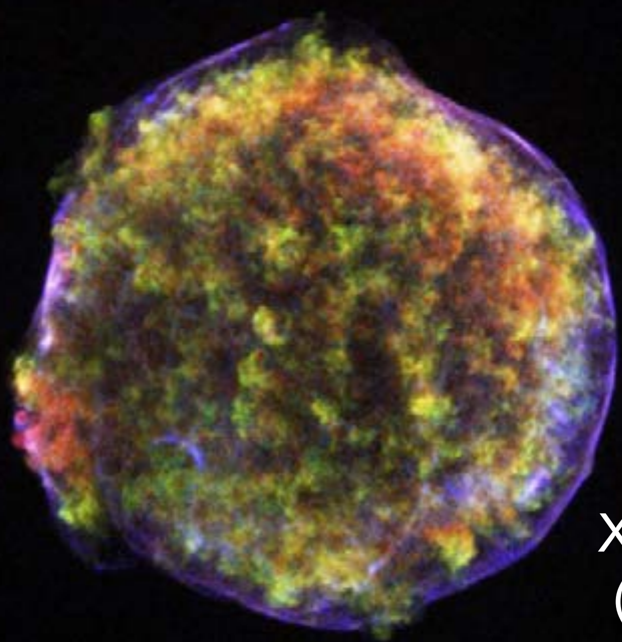
Historical SNRs

Tycho's SNR

- SN 1572
- SN type: Ia
- distance: ~3 kpc
- radius: ~3.7 pc

Cassiopeia A

- SN ~1680
- SN type: IIb
- distance: ~3.4 kpc
- radius: ~2.5 pc

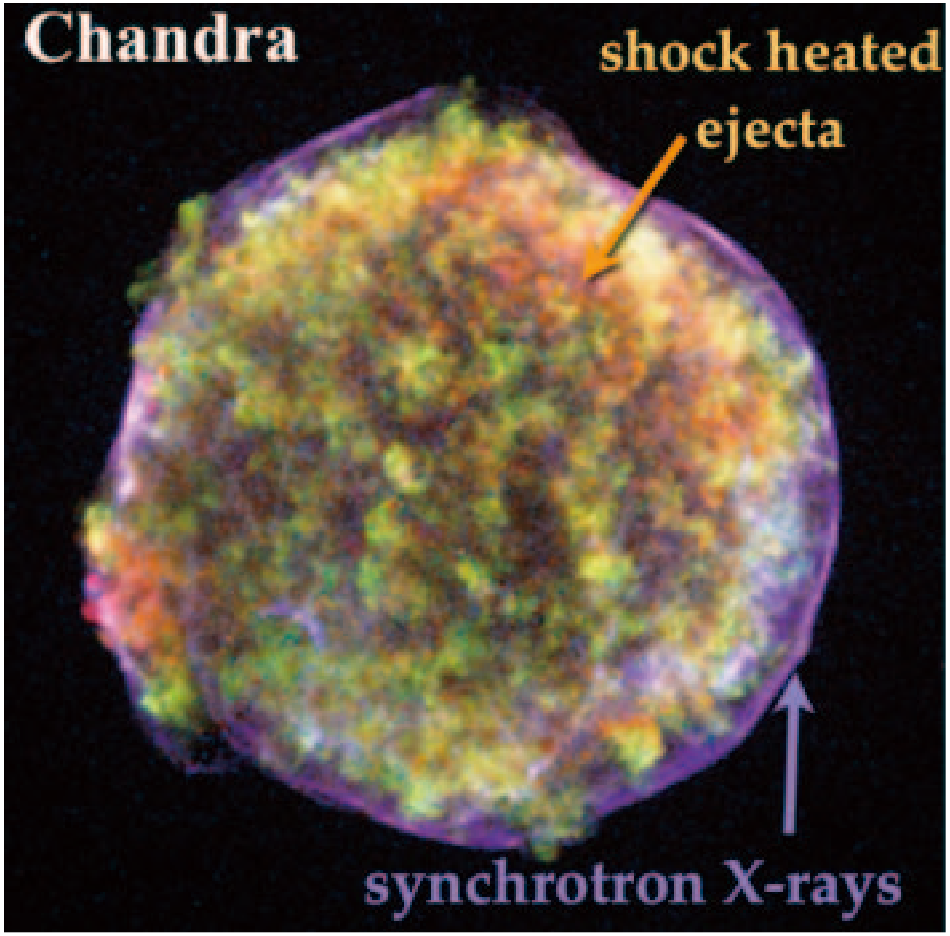


X-ray Images (Chandra)

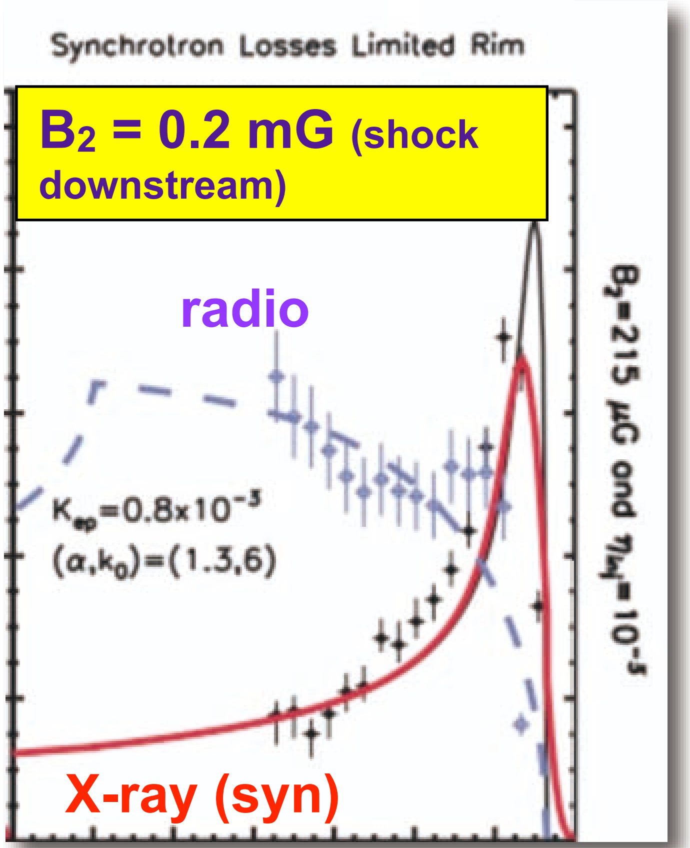
Most parameters are reasonably well known.
→ largely help us interpret gamma-ray results.

Tycho: Synchrotron & B-field

Warren+05



X-ray/radio radial profile

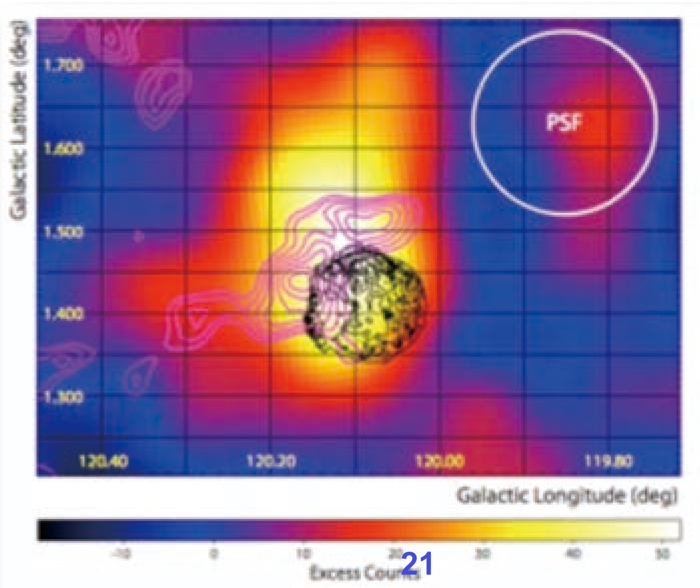


Cassam-Chenai+07

B_2 = 0.1-0.2 mG is inferred from the width of X-ray filaments

Tycho: Recent TeV Detection

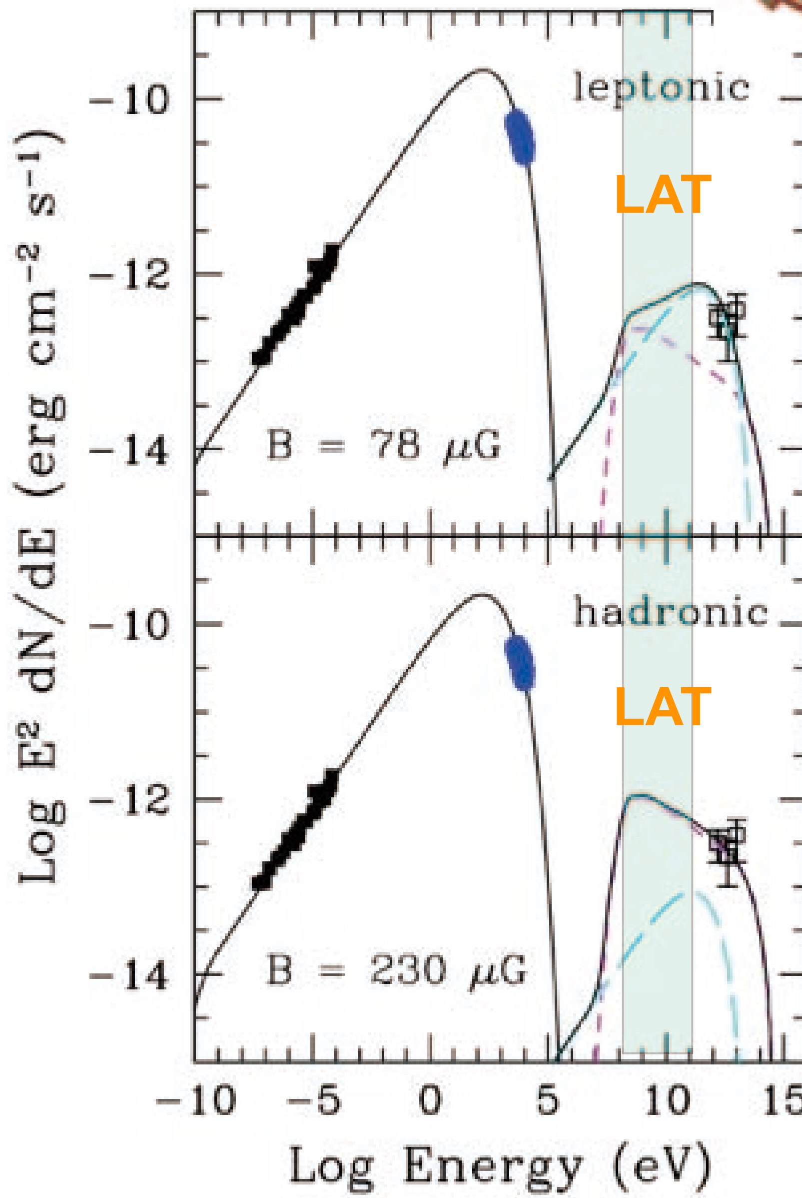
VERITAS Collaboration (2011)



Flux(>1 TeV) ~ 1% Crab
5.0σ detection (post-trial)

B-field constraint put by X-ray does *not* contradict IC origin.

Fermi-LAT can test “leptonic vs hadronic”



Tycho: New GeV Detection

Fermi-LAT Detection (5σ)

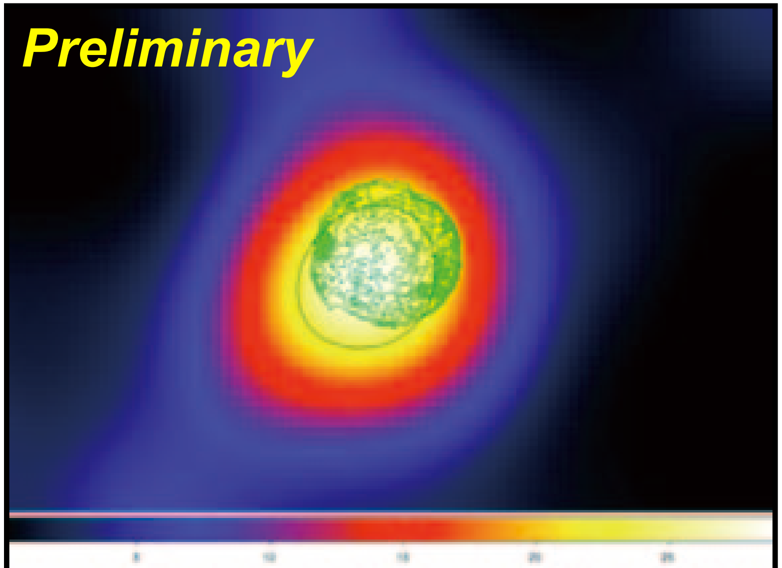
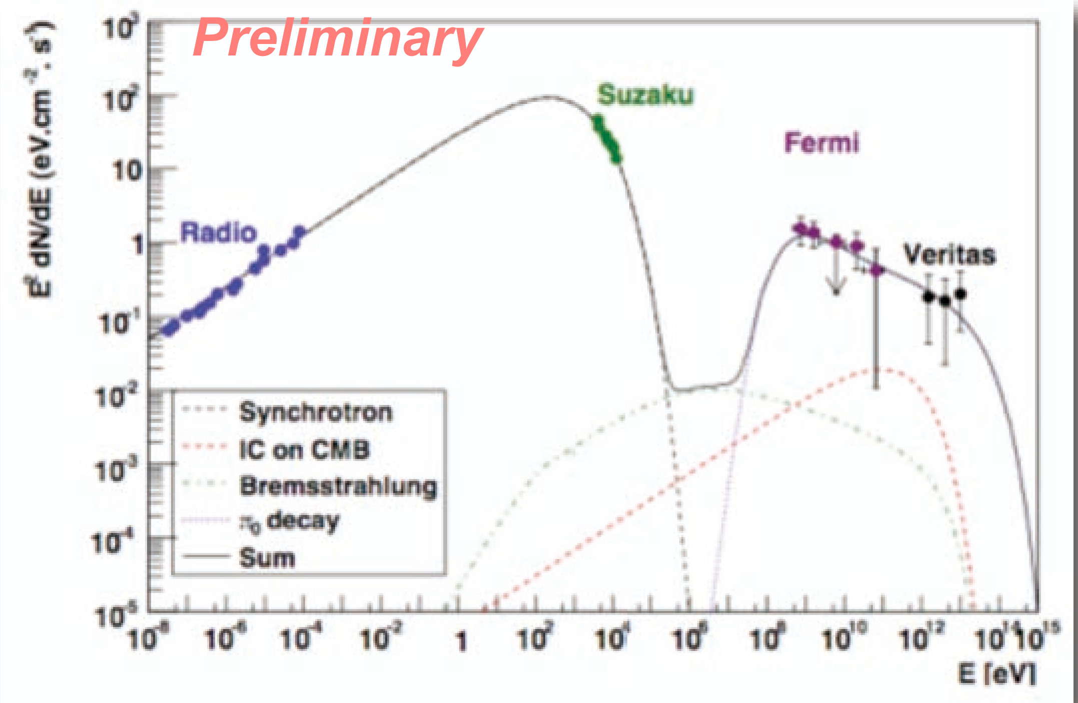


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*

See a poster by Fermi-LAT Collaboration (Naumann-Godo+)

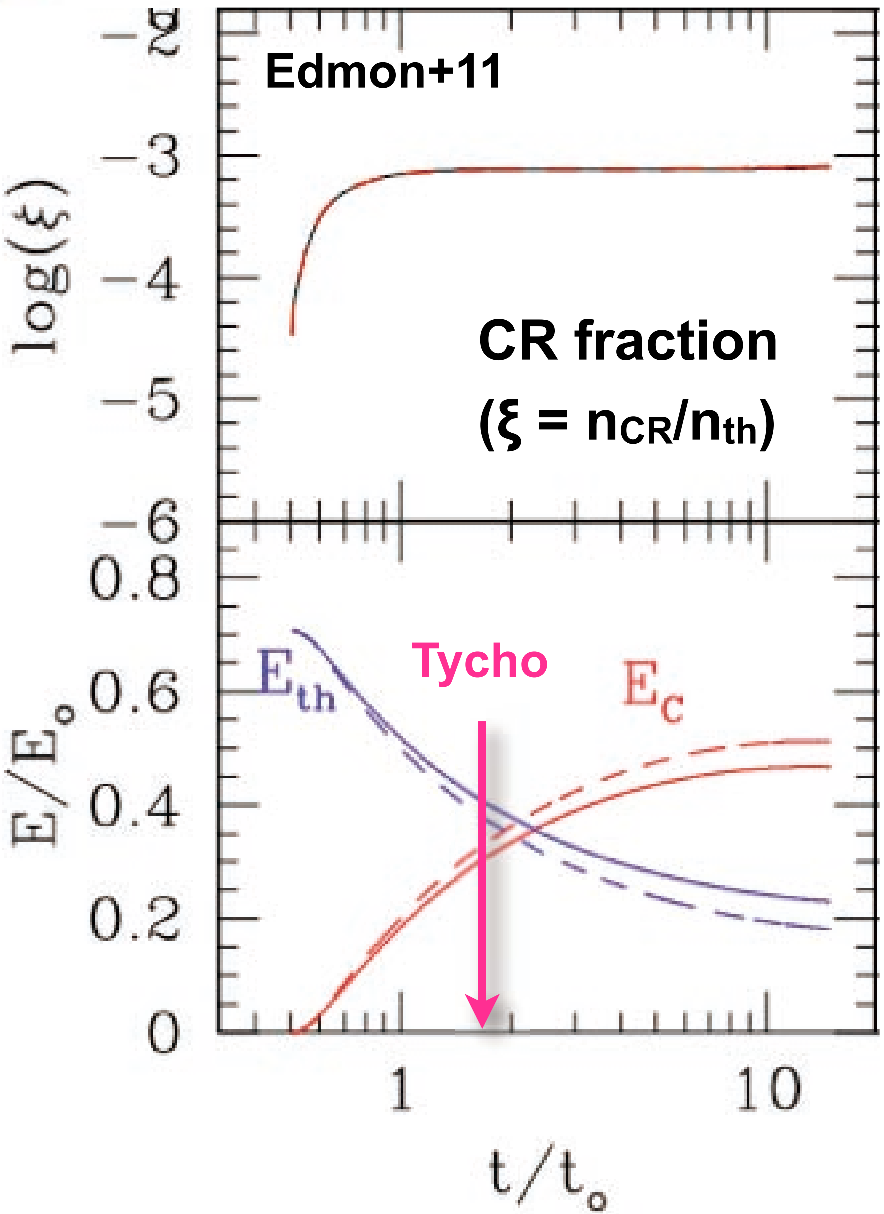


Case	D_{kpc}	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{51}erg]	K_{ep}
Far	3.50	0.24	2.0	0.150	4.5×10^{-4}
Nearby	2.78	0.30	1.0	0.061	7.0×10^{-4}

Photon index = 2.3 ± 0.1 (favors hadronic origin)

6-8% of E_{SN} transferred to CRs.

Tycho: CR Content



Input Parameters in Edmon+11

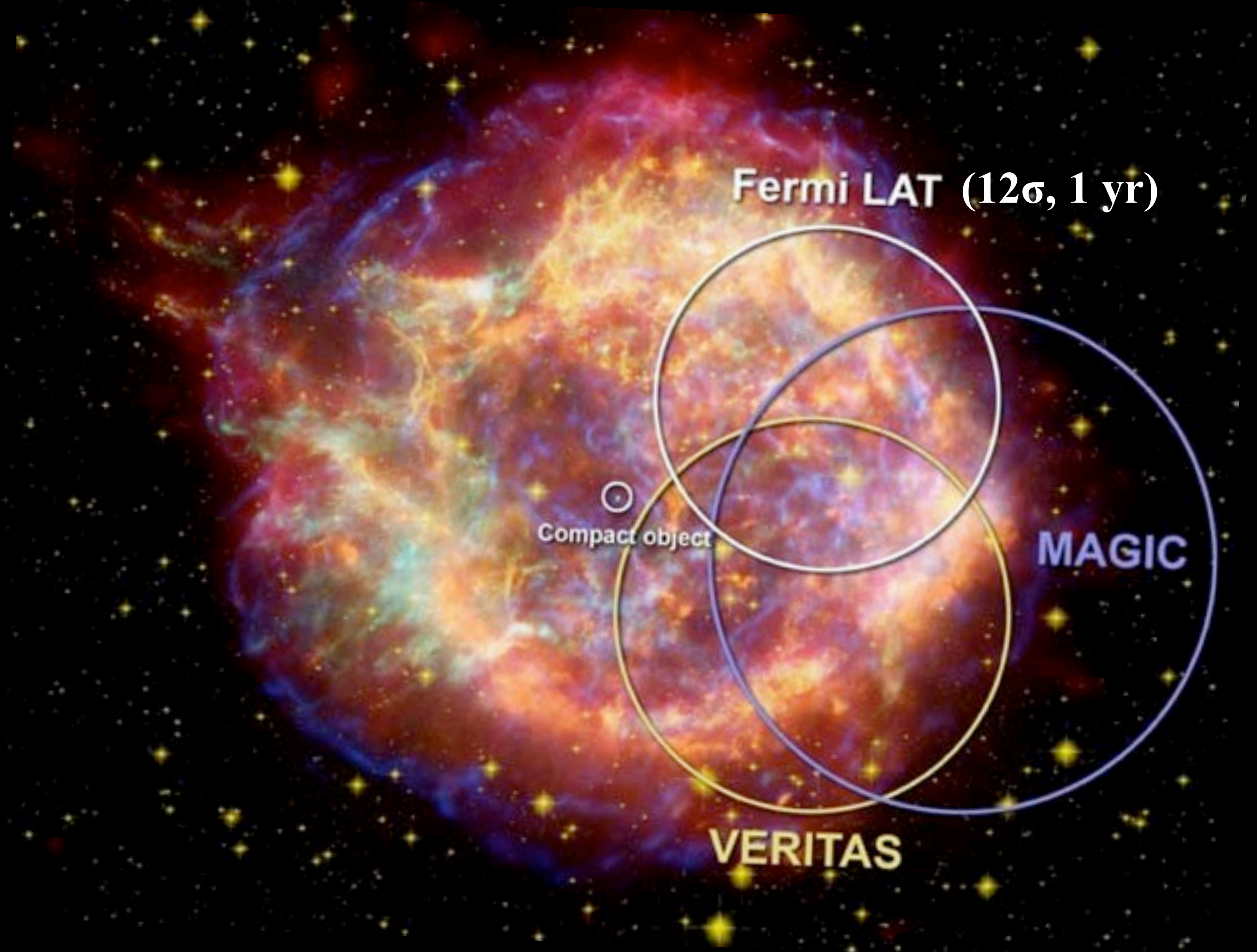
n_0 = 0.3 cm^{-3} (ISM density)
T_0 = 30000 K
B_0 = 30 uG (Upstream B-field)
Eo = 10^{51} erg (E_{SN})
→ to = 255 yr

Tycho's SNR at t = 439 yr:
E_{CR} ~ 7% of E_{SN}

Later on, say t = 2500 yr:
E_{CR} ~ 14% of E_{SN}

CR spectral index = 2.3

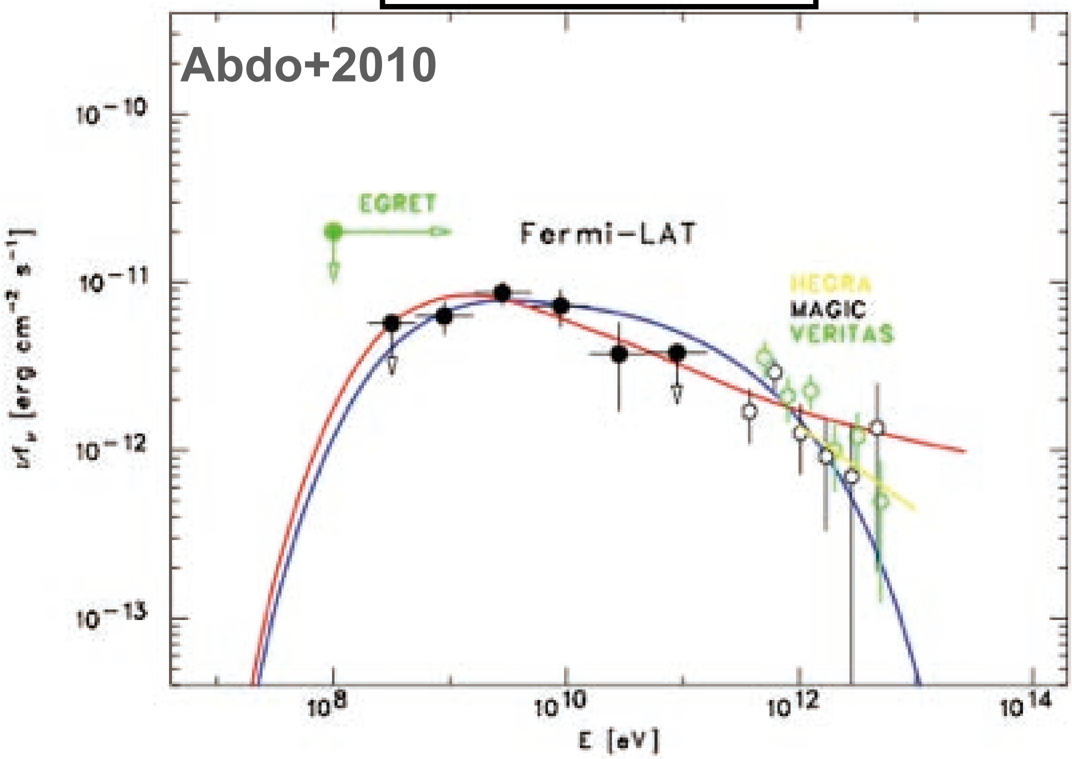
Cas A: GeV & TeV Detections



Cas A: Gamma-ray Spectrum

B_2 = 0.3-0.5 mG is inferred from the width of X-ray filaments (Vink & Laming 03; Parizot+06) **and X-ray time-variability** (Uchiyama & Aharonian 08)

π^0-decay model



Fermi-LAT spectrum:
Γ = 2.0 ± 0.1

CR Proton: ~0.4×10^{50} erg

E_{CR} ~ 2% of E_{SN}=2×10^{51} erg

CR spectral index = 2.3

Part II

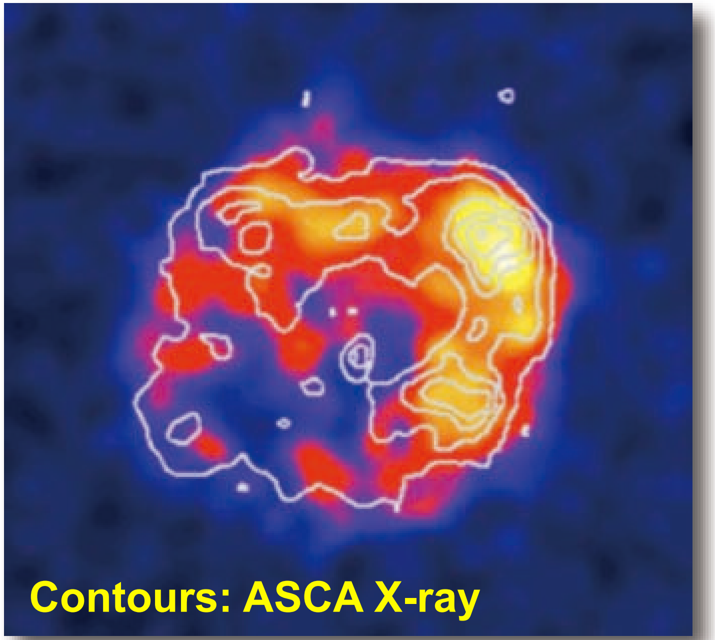
Part II:

Young TeV-bright SNRs

RX J1713.7-3946 & Vela Jr.

RX J1713.7-3946

TeV gamma-ray map (H.E.S.S.)

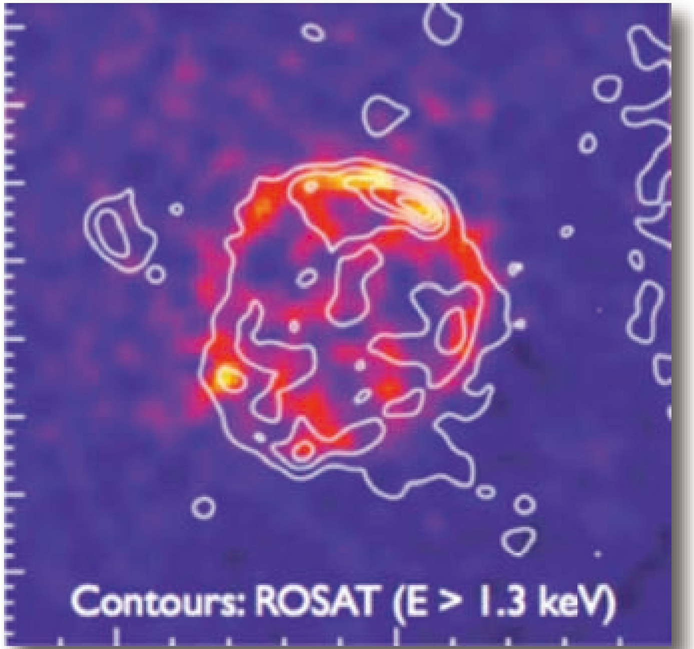


- age: ~1600 yr
- distance: ~1 kpc

Synchrotron X-ray variability:
~ **0.1-1 mG** (Uchiyama+07)
Synchrotron cutoff (Tanaka+08):
"**Bohm limit**"

RX J0852.0-4622 (Vela Jr)

TeV gamma-ray map (H.E.S.S.)

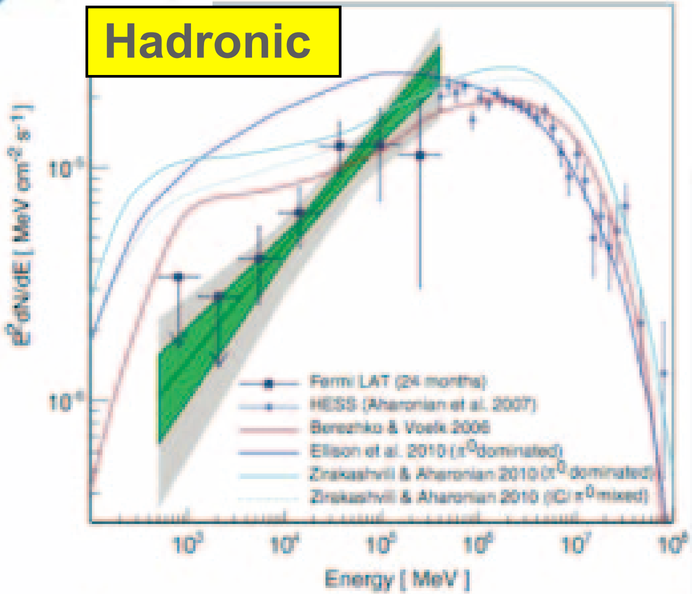


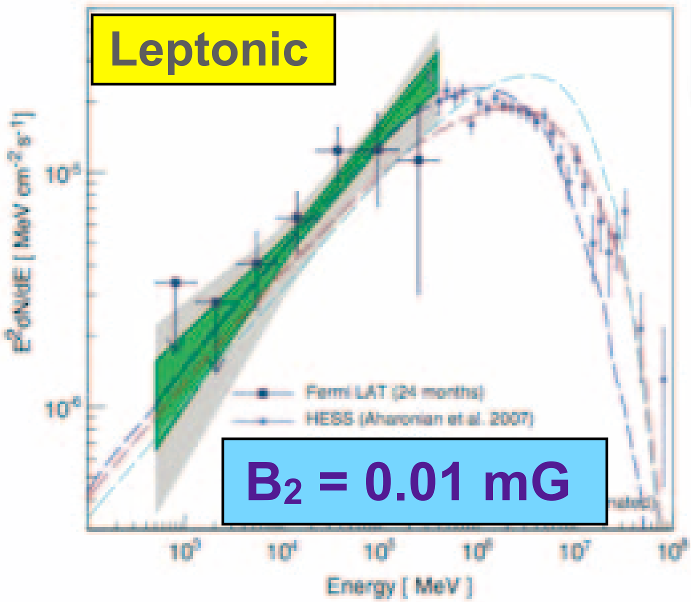
- age: 2000-4000 yr
- distance: ~0.75 kpc

Synchrotron X-ray filament:
≥ **0.1 mG** (Berezhko+09)

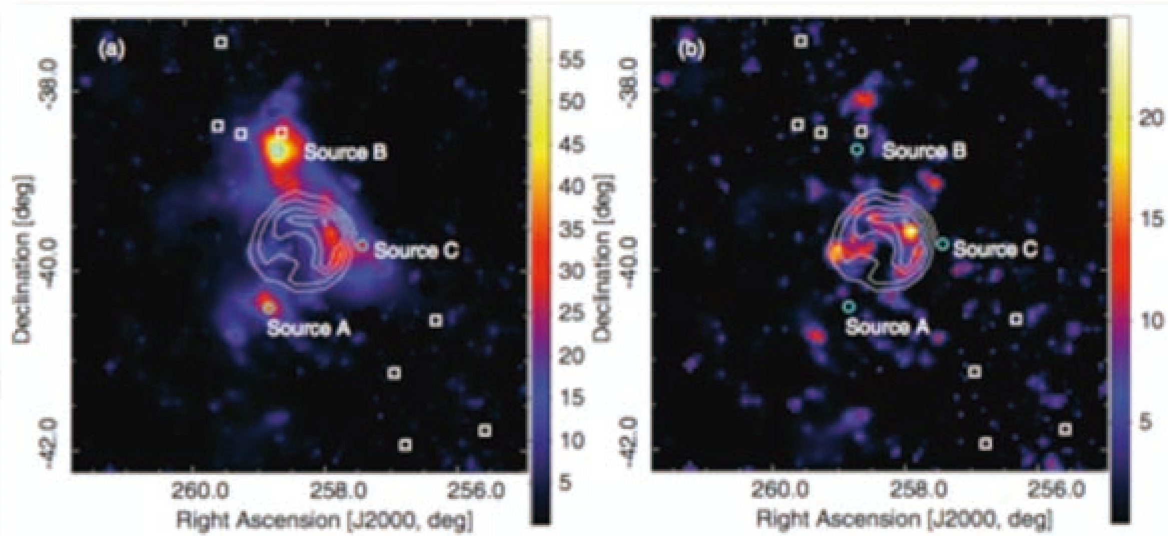
RX J1713.7-3946: LAT Results

Abdo+2011 (in press)





TS map above 0.5 GeV
(using a point source hypothesis)



1FGL sources in BGD model | SrcA,B,C also in BGD model

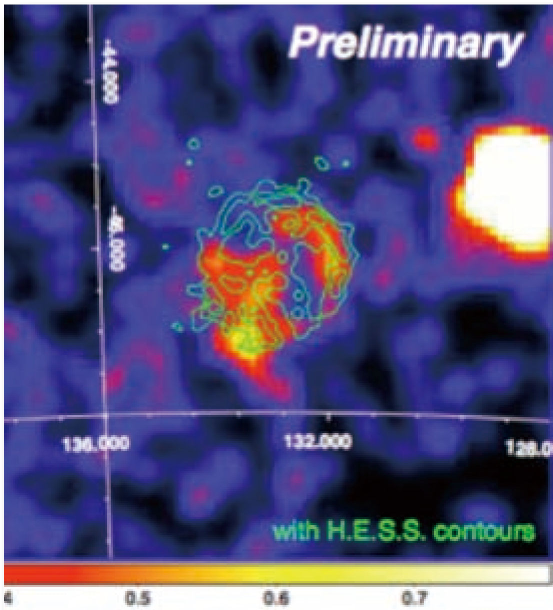
Photon index: Γ_{LAT} = 1.5 ± 0.1(sta) ± 0.1(sys)

LAT spectral shape is consistent what expected in leptonic scenarios (IC origin), though B_2 = 0.01 mG would be difficult to be reconciled with X-ray measurements. Hadronic origin requires very hard proton spectrum, which challenges current models.

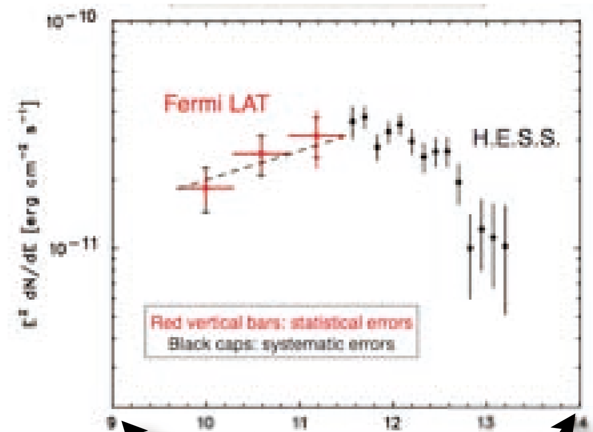
Vela Jr.: LAT Results

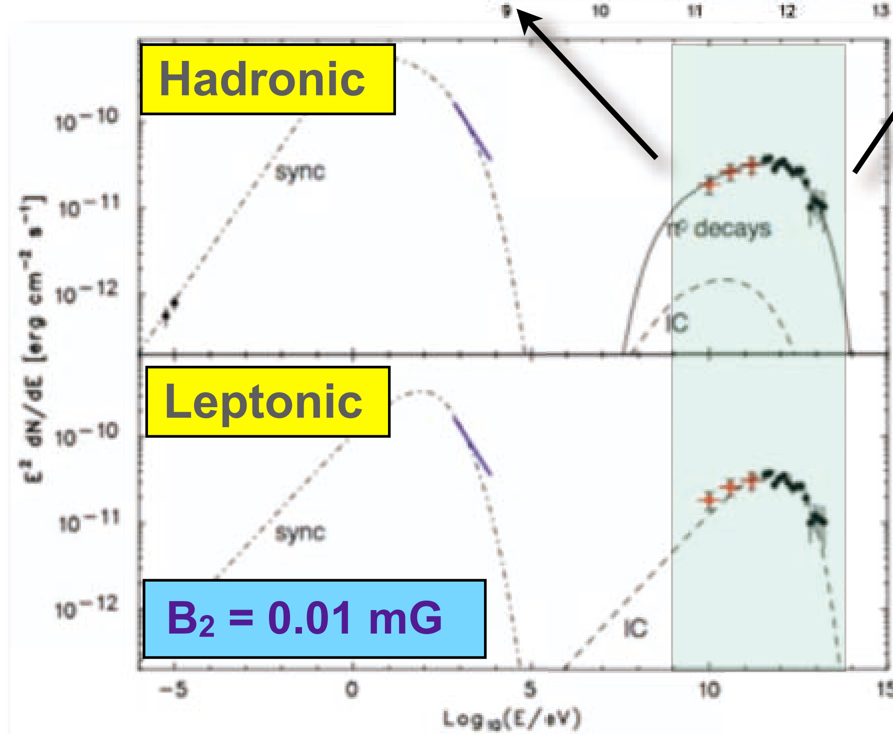
Fermi-LAT Collaboration (Tanaka+) in prep.

LAT count map above 10 GeV



Detection at ~15σ level
Γ_{LAT} = 1.87 ± 0.08(sta) ± 0.17(sys)





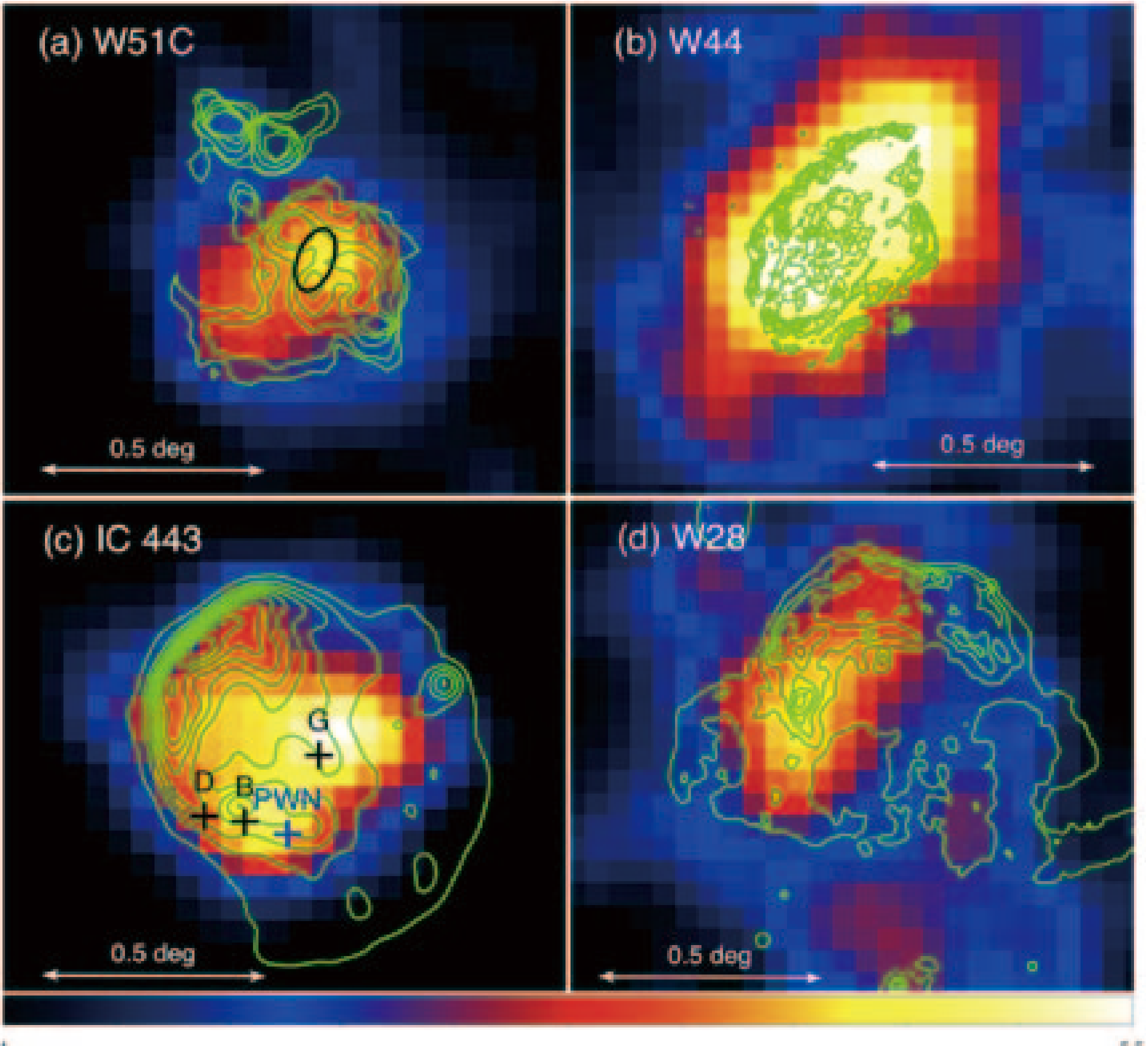
Again, B_2 = 0.01 mG in leptonic model would be difficult to be reconciled with X-ray measurements.
Hadronic model would require a large CR content (5×10^{50} erg for n=0.1 cm^{-3})

Part III

Part III:
SNRs Interacting with Molecular Clouds

LAT Discoveries of MC-SNRs

Fermi-LAT Collaboration (Uchiyama+) 2011



2.5 yr count maps (>2 GeV, front-converted)

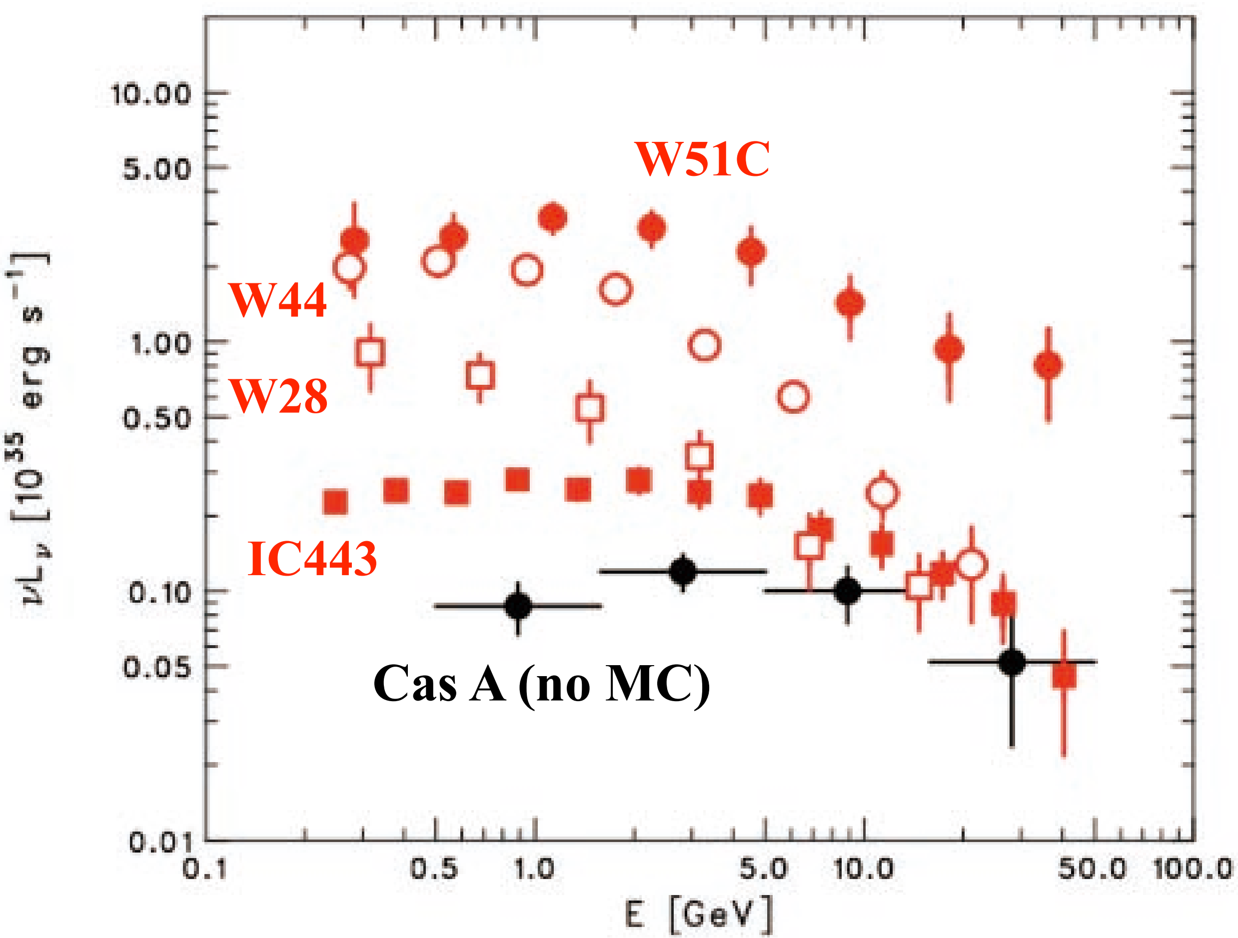
Extended GeV emission has been discovered from several SNRs, with molecular cloud (MC) interactions.

GeV extension is consistent with the size of a radio remnant (except for W28).

The dominant class of LAT SNRs.

GeV Spectra of MC-SNRs

Fermi-LAT Collaboration (Uchiyama+) 2011



High GeV luminosity up to 10^{36} erg/s

Assuming e/p ratio less than 10%, the only way to achieve the high luminosity is:

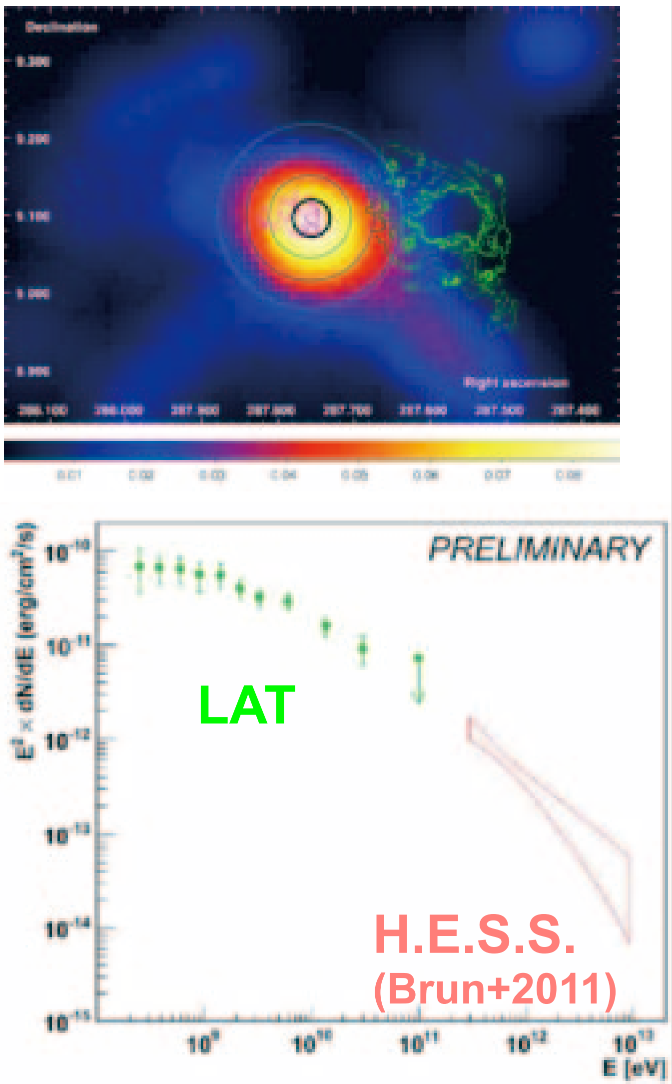
π^0-decay γ-rays in dense gas (>10 cm^{-3}).

Spectral steepening in the GeV band

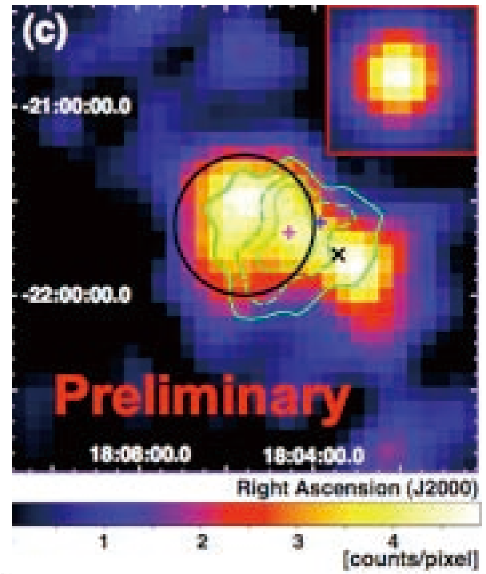
GeV luminosity >> TeV luminosity

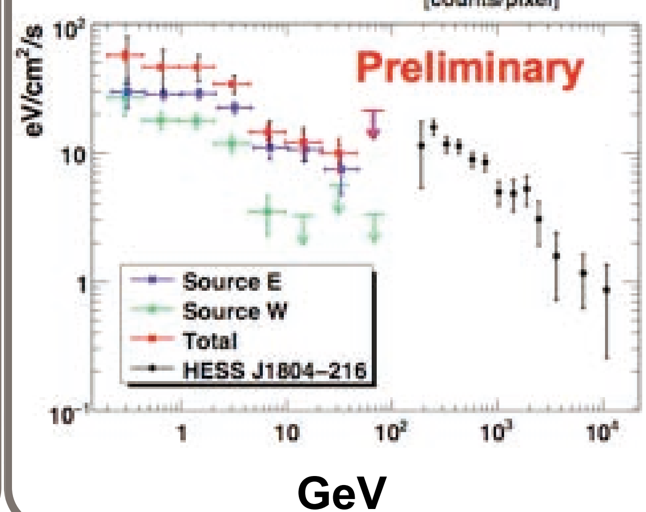
Growing Examples: MC-SNRs

W49B Abdo+2010



W30(G8.7-0.1) Hanabata+





G349.7+0.2
Castro & Slane 2010
Similar to W49B

CTB 37A
Castro & Slane 2010
Poster by Brandt+

3C391
Castro & Slane 2010

W41
Talk by Méhault+

Radio Connection

MC-SNRs:
LAT flux seems to correlate with radio flux

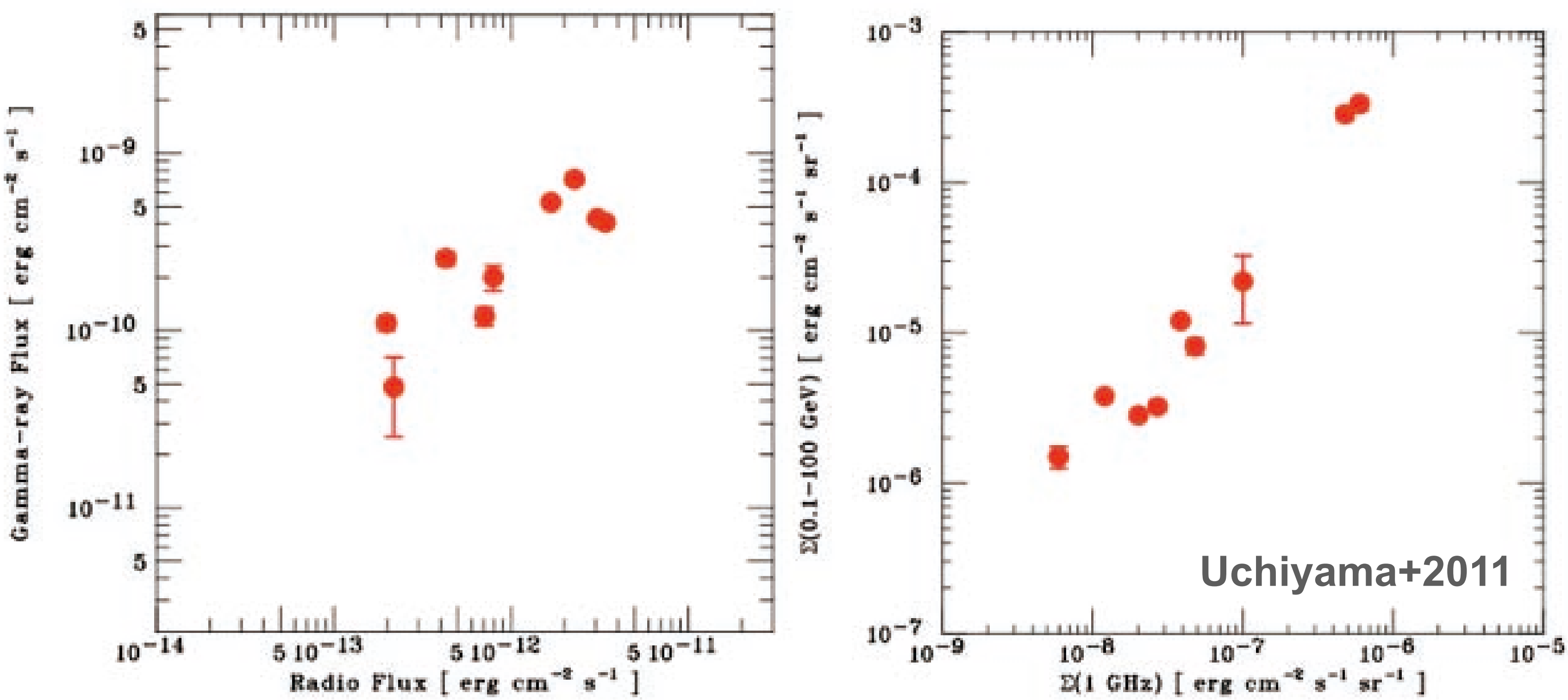
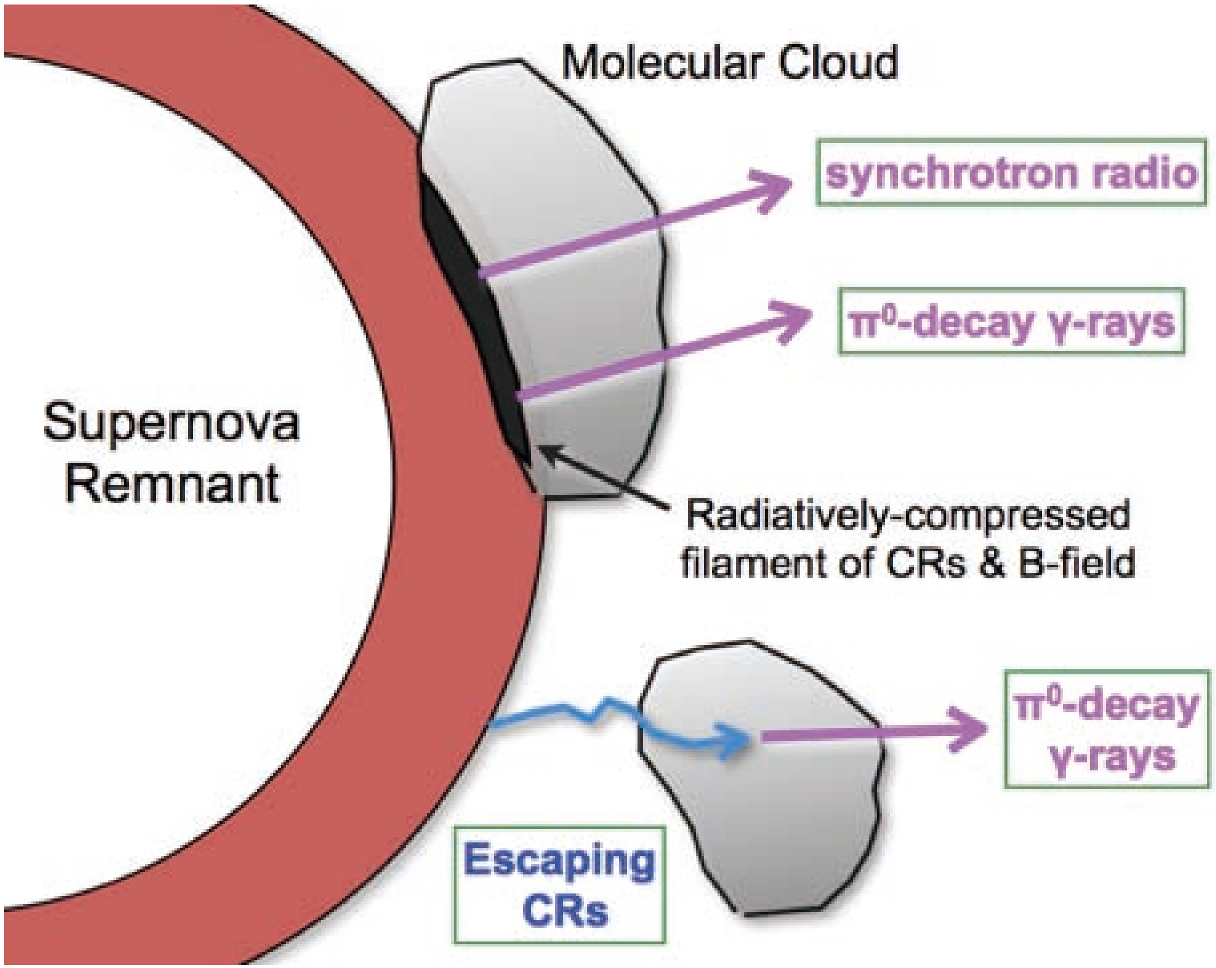


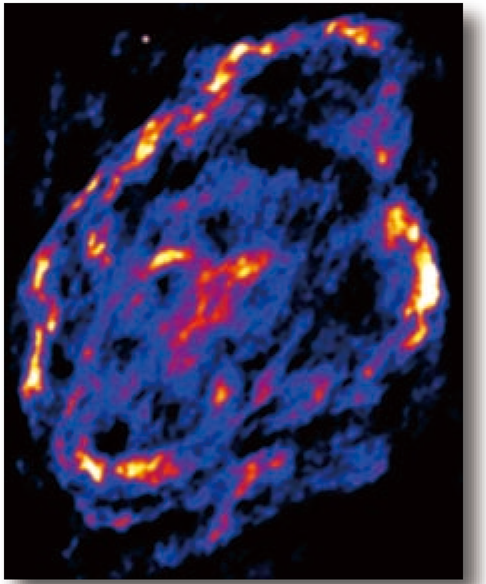
Figure 3: (Left) Radio flux (synchrotron) vs GeV γ-ray flux for MC-interacting SNRs. The γ-ray energy flux integrated over 0.1–100 GeV and the radio flux, νf_ν at 1 GHz, are shown. (Right) Mean surface brightness of the synchrotron radio emission and GeV γ-ray emission. The flux-flux plot is converted into this form using the solid angles of the radio remnants.

Gamma-ray Emission Sites

Radio & γ-ray emissions from radiatively-compressed filaments
Crushed Cloud Model (Uchiyama+2010)



SNR W44



synchrotron radio emission correlated with shocked H_2 gas

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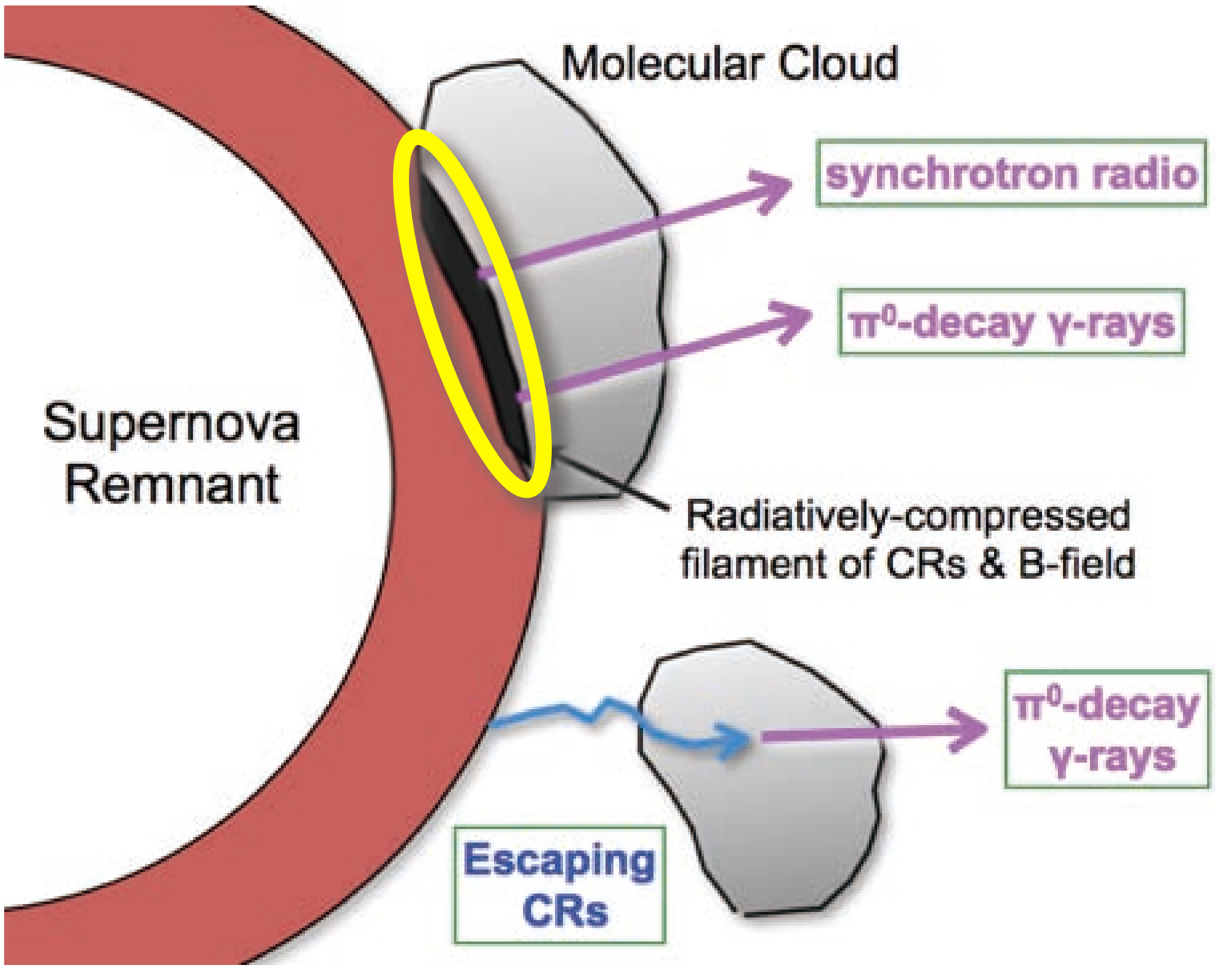
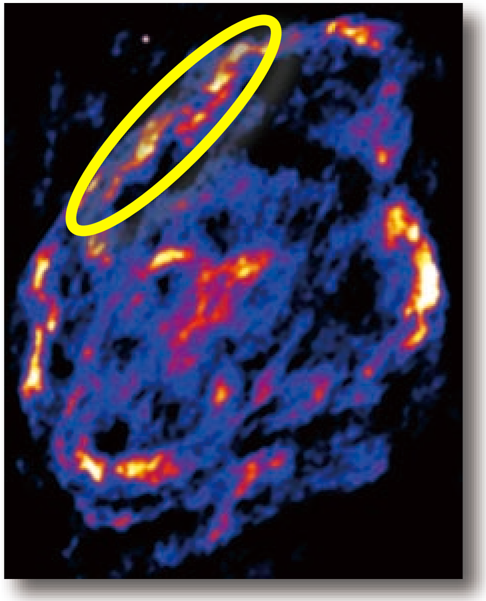


SNR W44



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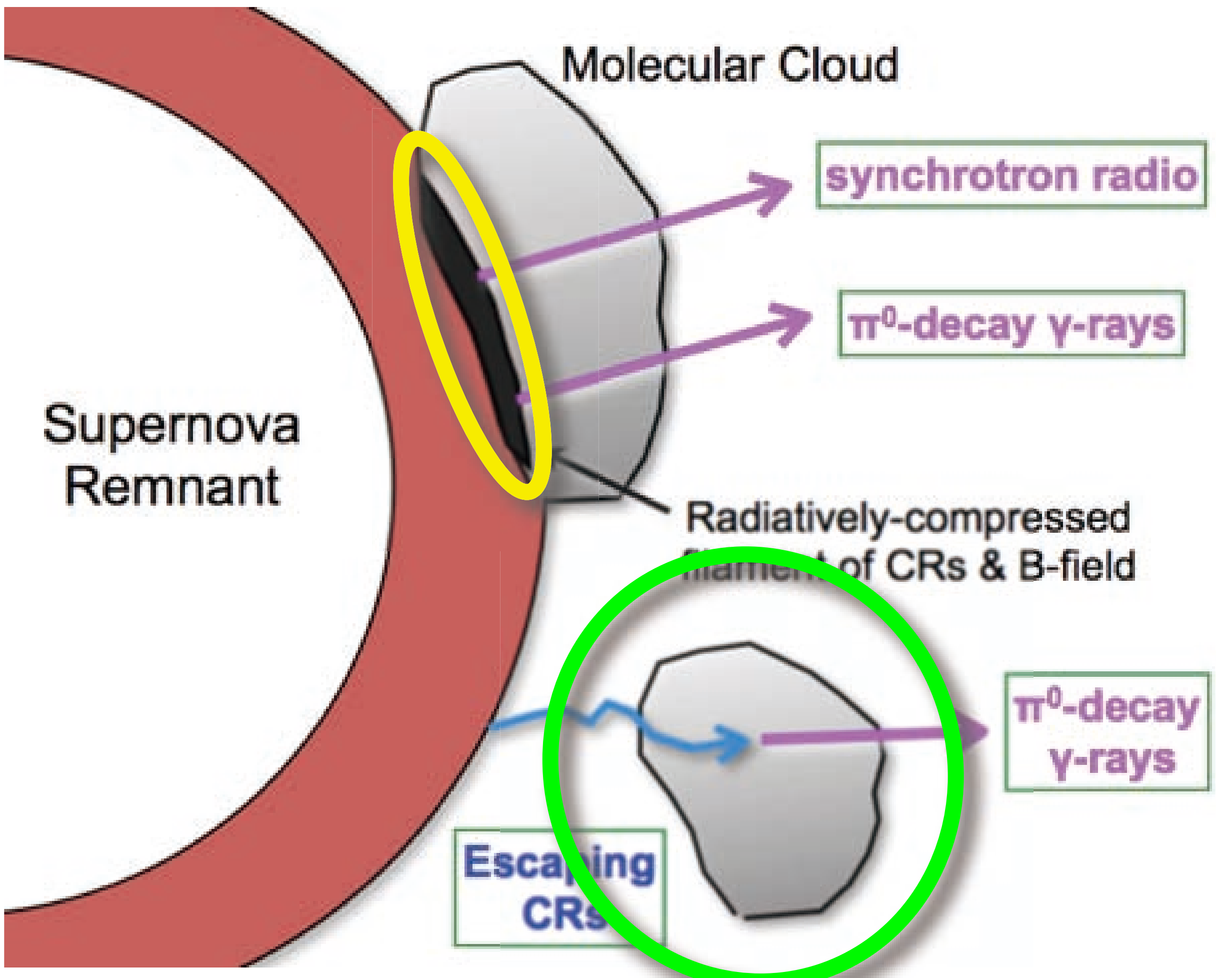
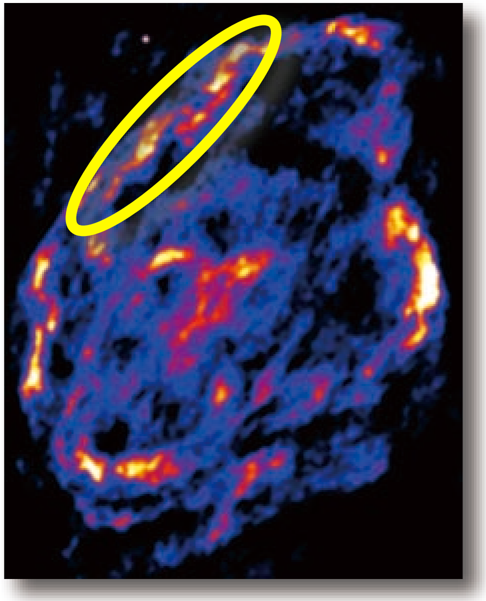


SNR W44



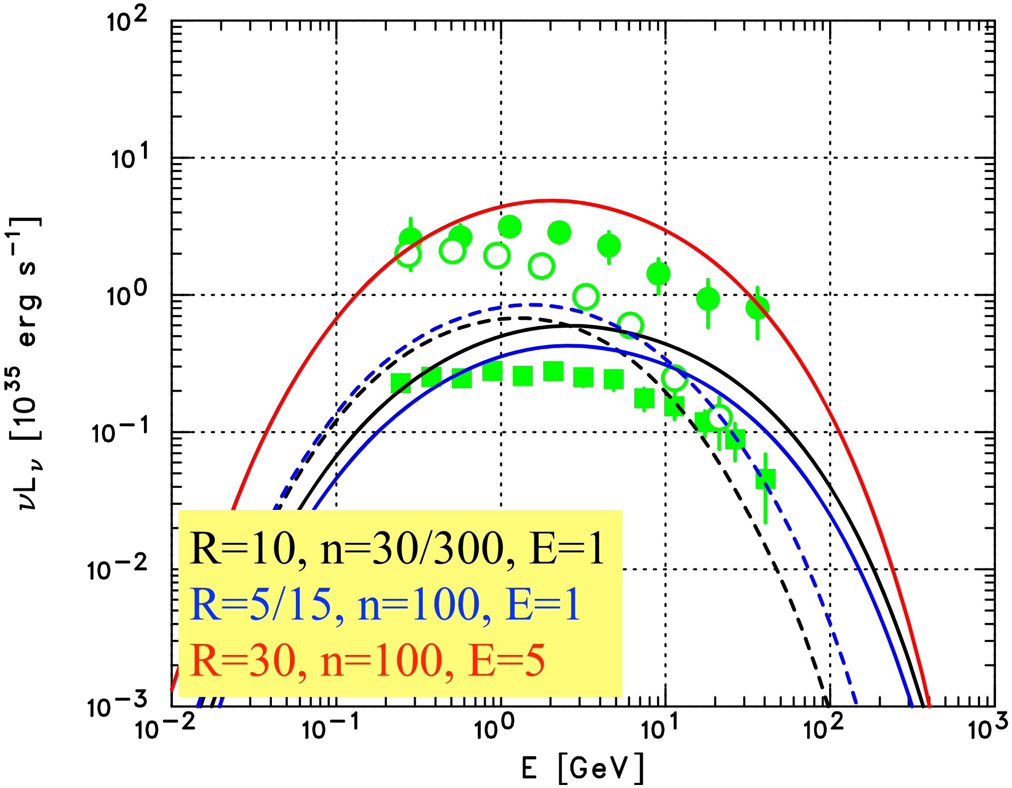
synchrotron radio emission correlated with shocked H_2 gas

Crushed Cloud Model

Uchiyama+2010

Re-acceleration of pre-existing CRs in MC at cloud radiative shock.
π^0-decay gamma-rays in a radiatively-compressed layer.

Naturally accounts for a gamma-ray luminosity of ~10^{35} erg/s
A slow (~100 km/s) shock explains spectral steepening in GeV range



Model Parameters

f: Preshock cloud filling factor
f = 0.2 fixed

n: Preshock cloud density in cm^{-3}

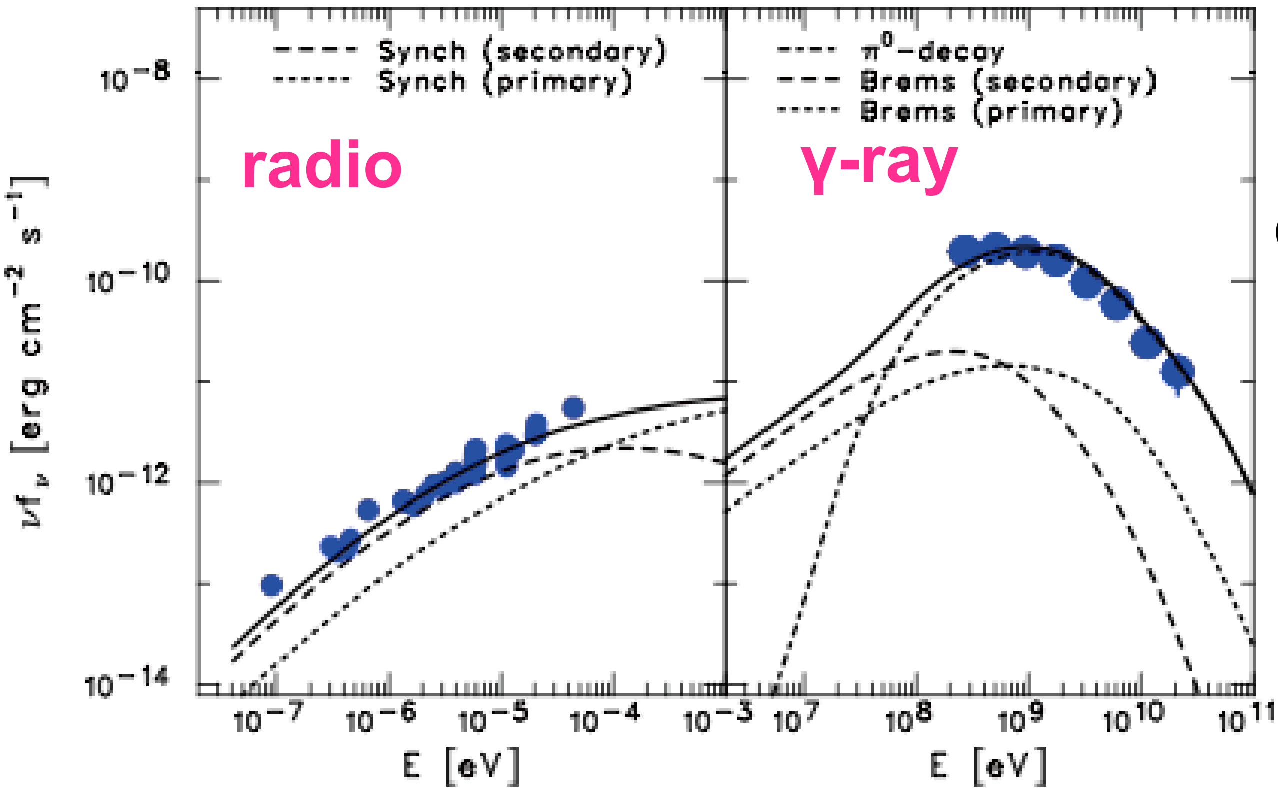
B: Preshock B-field in μG
$B = 2\, n^{1/2}$ fixed

R: SNR radius in pc

E: SN kinetic energy in 10^{51} erg

Crushed Cloud Model for W44

Uchiyama+2010



(i) CR p + H → π + etc

(ii-a) $\pi^0 \rightarrow 2\gamma$

(ii-b) $\pi^+ \rightarrow \mu^+ + \nu_\mu$

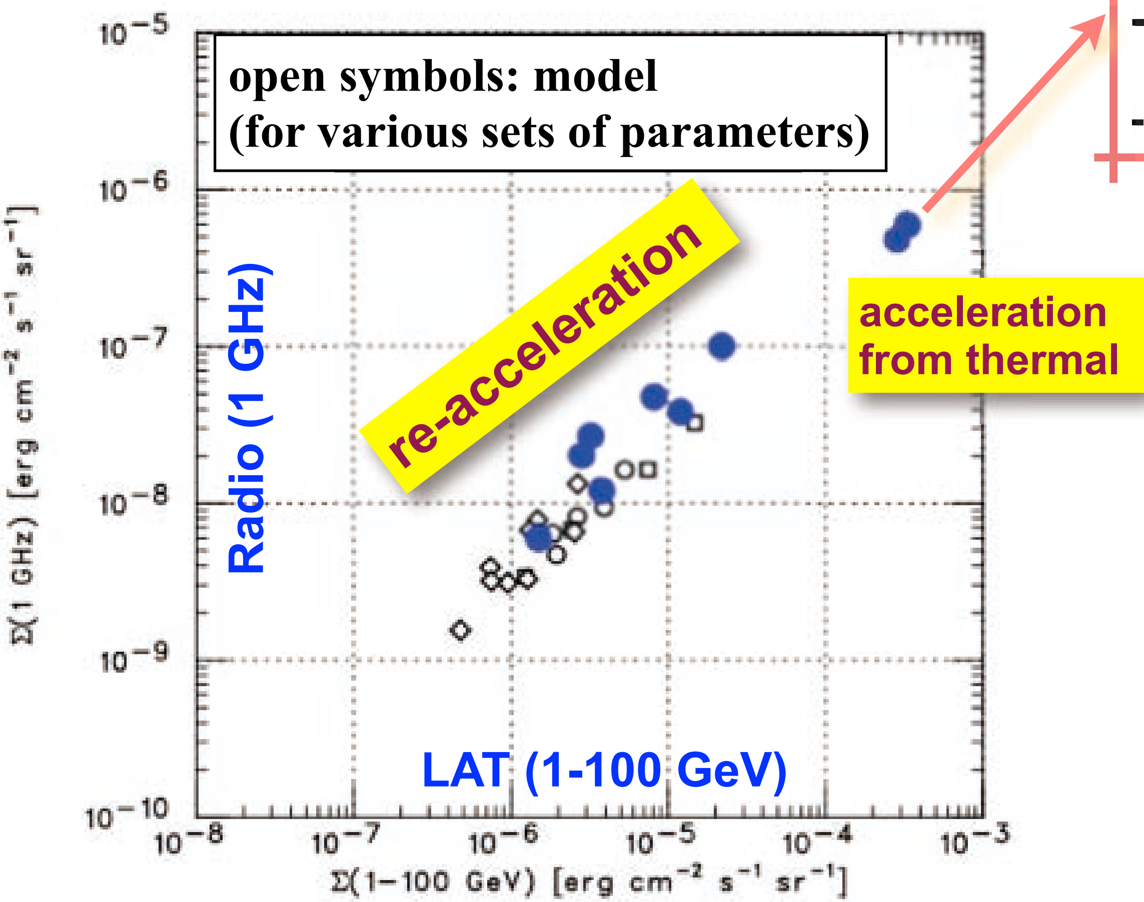
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$

(iii-b) e^+ + B → radio

- radio & γ-ray fluxes can be explained by re-acceleration of the pre-existing GCRs
- flat radio index (α=0.37) is naturally explained

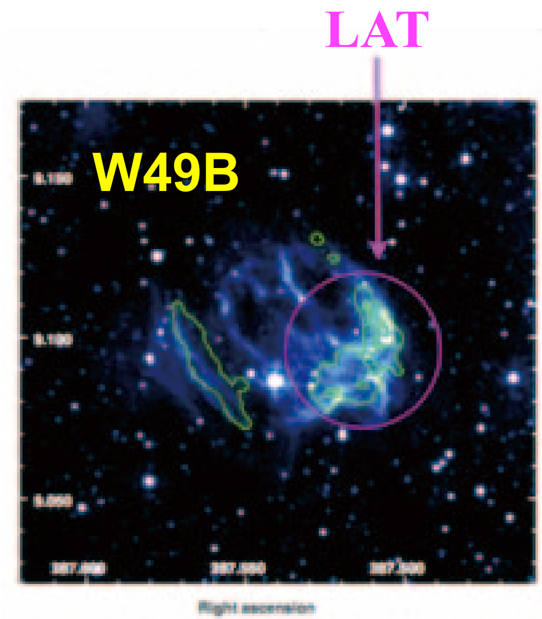
Crushed Cloud: GeV vs Radio

Surface Brightness Diagram (d-independent)
LAT (1-100 GeV) vs Radio (1 GHz)



W49B & G349.7+0.2

- relatively young < 10000 yr
- "canonical" radio index ($\alpha = 0.5$)
- Strong infrared lines

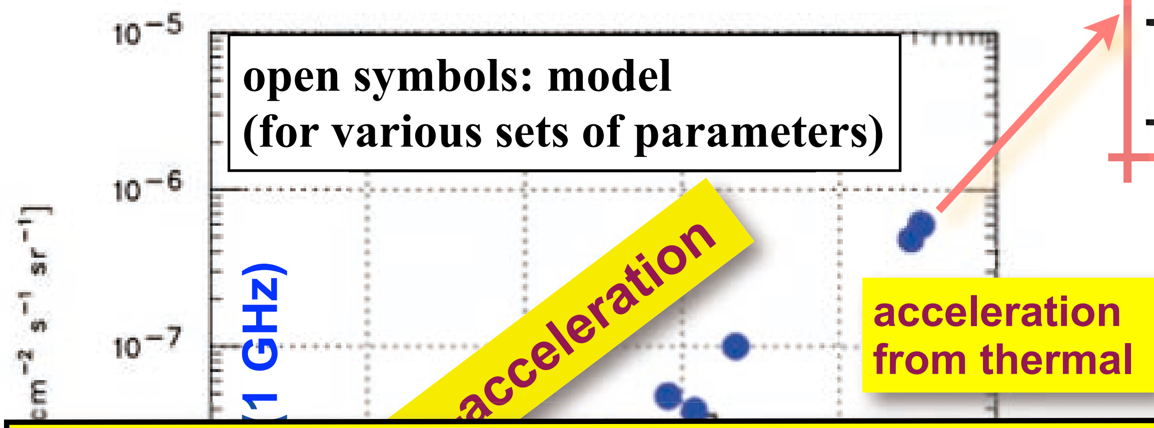


Color: Spitzer IRAC 5.8 um (Radiative shock)

Contours: VLA 1.4 GHz (GeV electrons)

Crushed Cloud: GeV vs Radio

Surface Brightness Diagram (d-independent)
LAT (1-100 GeV) vs Radio (1 GHz)



W49B & G349.7+0.2
- relatively young < 10000 yr
- "canonical" radio index
  (α = 0.5)
- Strong infrared lines

Contours: VLA 1.4 GHz
(GeV electrons)

Freshly Accelerated CRs in W49B (& also G349.7+0.2)

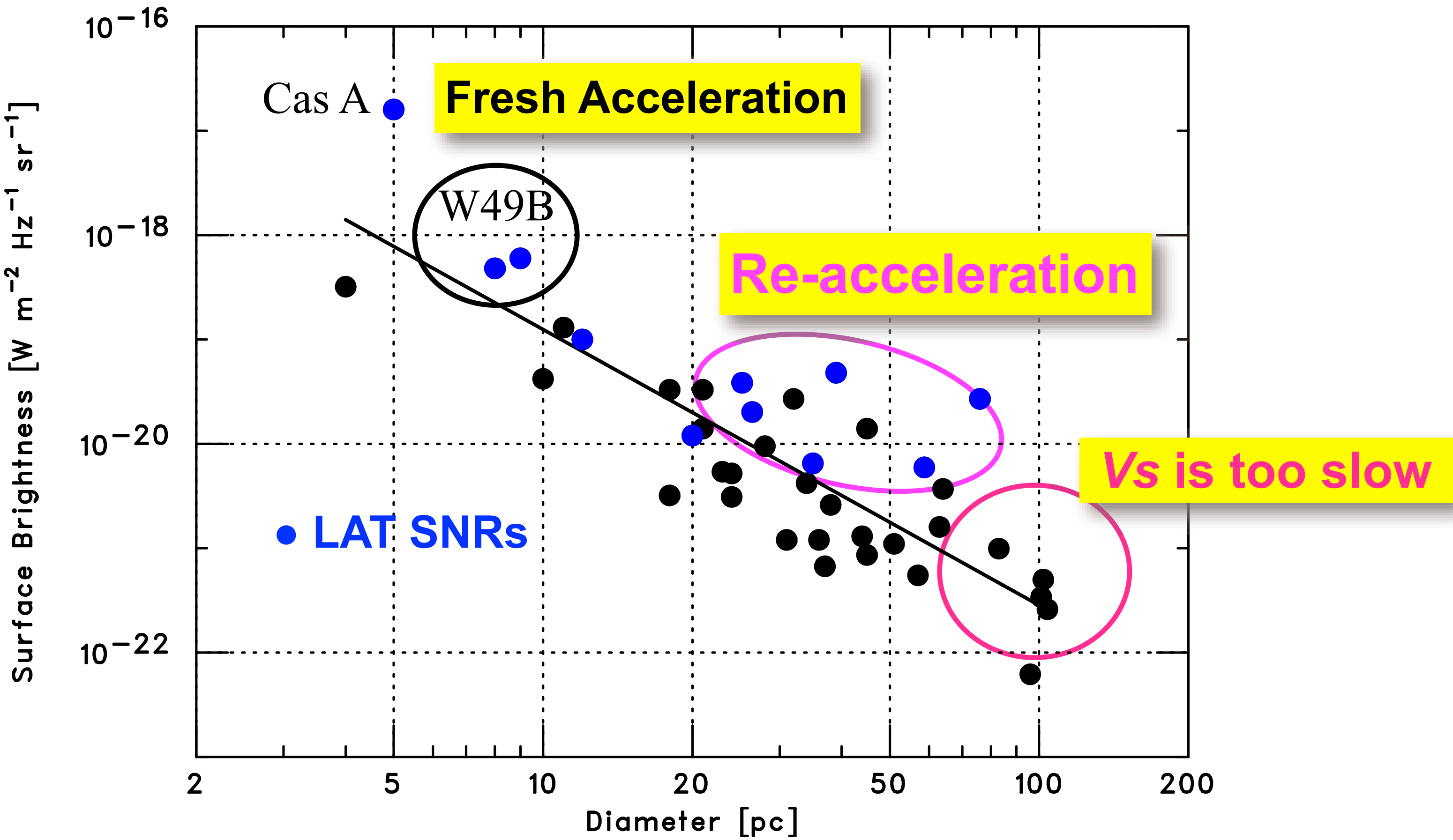
LAT flux implies $u_{CR} \sim 10^5$ eV/cm^3 (re-acceleration is not enough)

n=200 cm^{-3} , v=200 km/s (fully pre-ionized)

To get $u_{CR} \sim 10^5$ eV/cm^3, $\xi \sim 3\times10^{-5}$ (c.f. Tycho: $\xi \sim 5\times10^{-4}$)

Σ-D Relation

Radio Surface Brightness (Σ) - Diameter (D) Relation

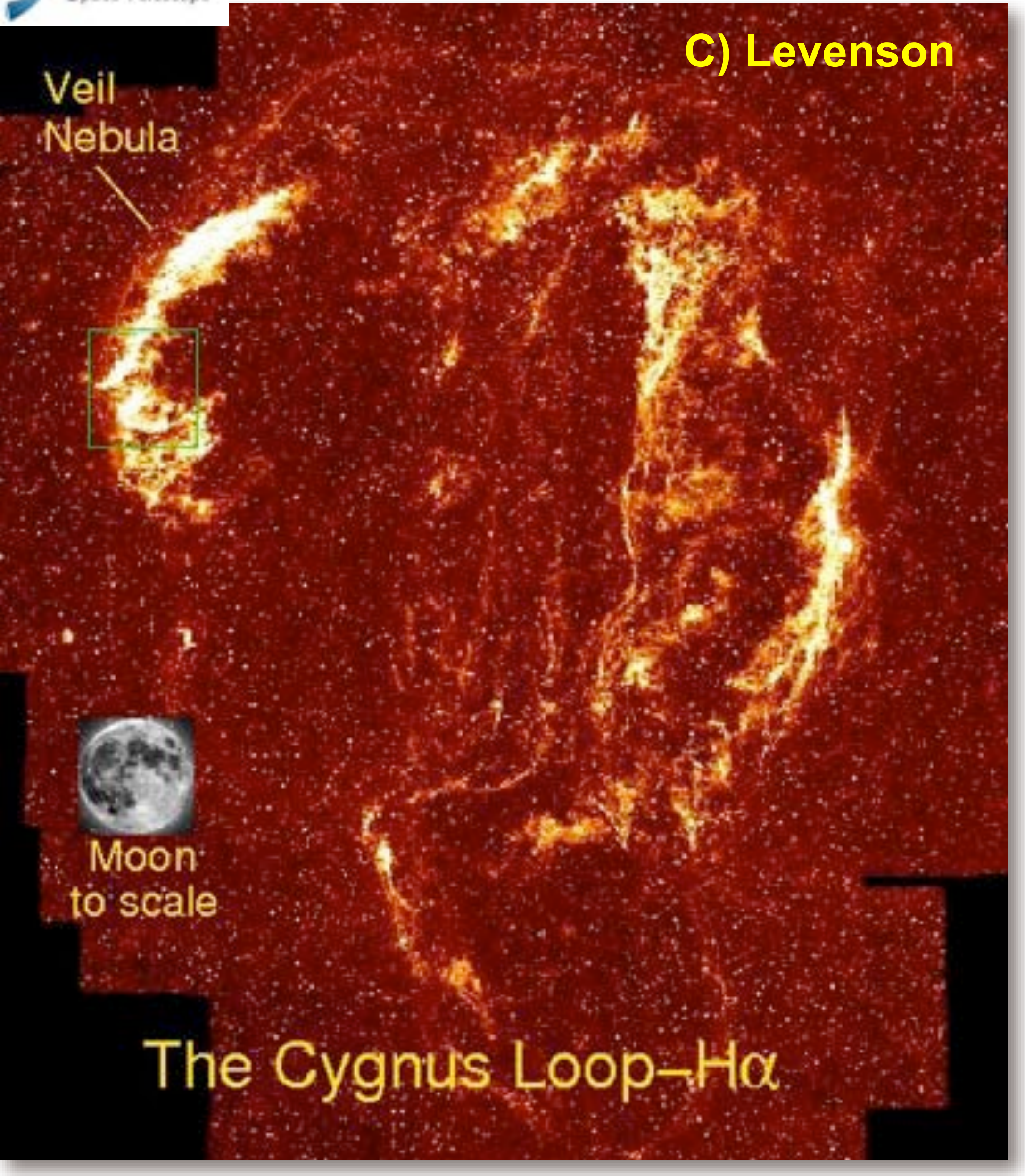


V~1000 km/s shock : CR acceleration > 10 TeV
V~100 km/s shock : CR (re-)acceleration < TeV

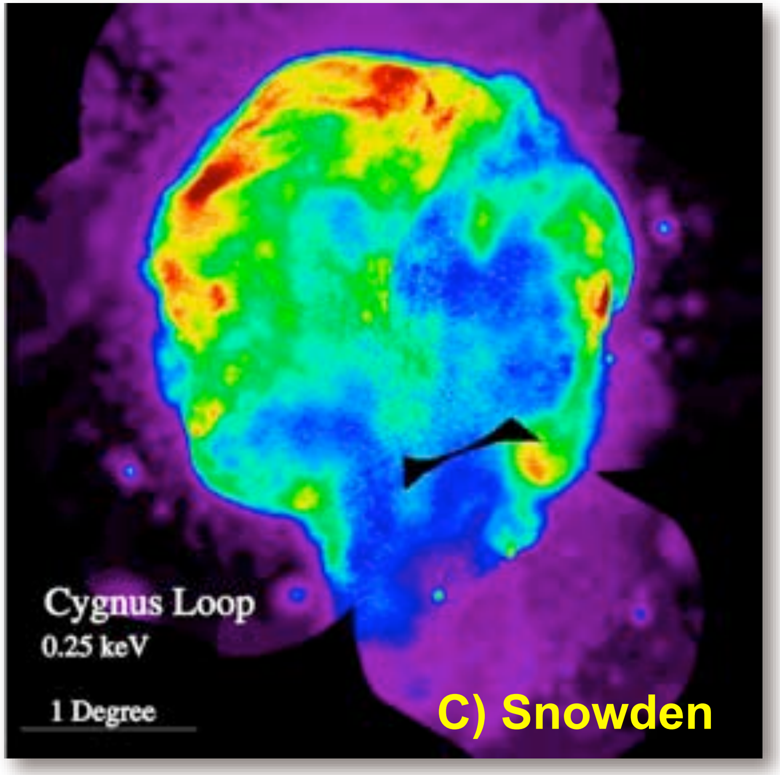
Part IV

Part IV:
Evolved SNR without MC

Cygnus Loop

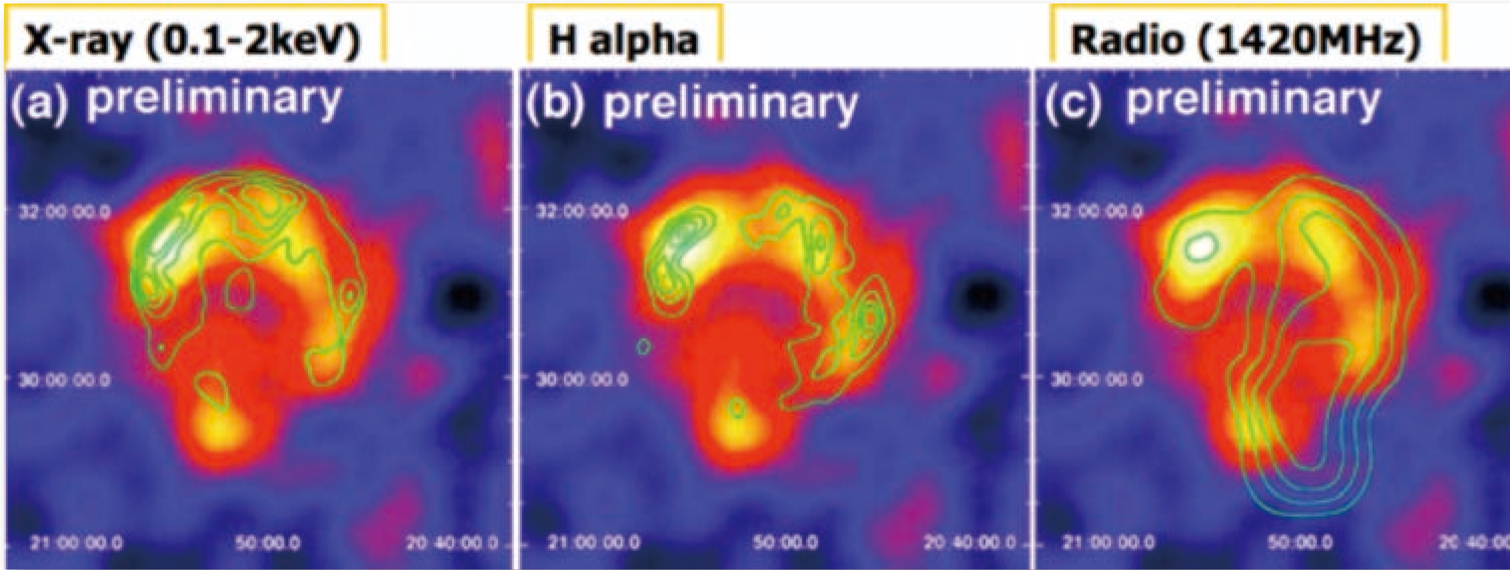


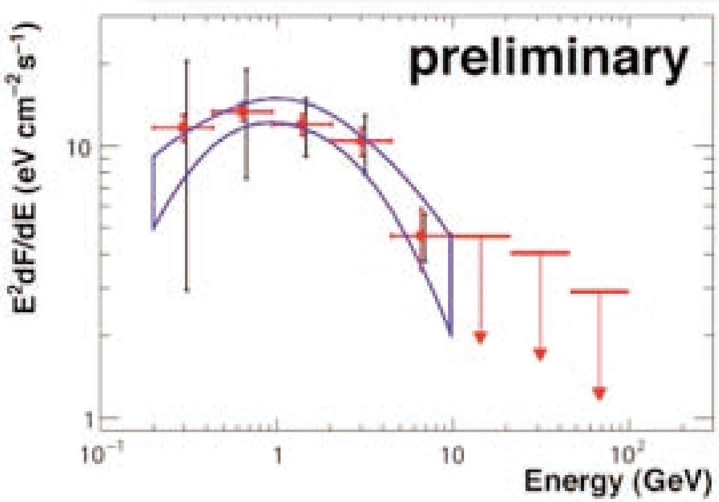
Middle-age ~ 2×10^4 yr
Large angular size (3 deg)
No clear MC interaction



Cygnus Loop: LAT Results

Katagiri+ (submitted)





Correlation with X-ray and Hα emissions

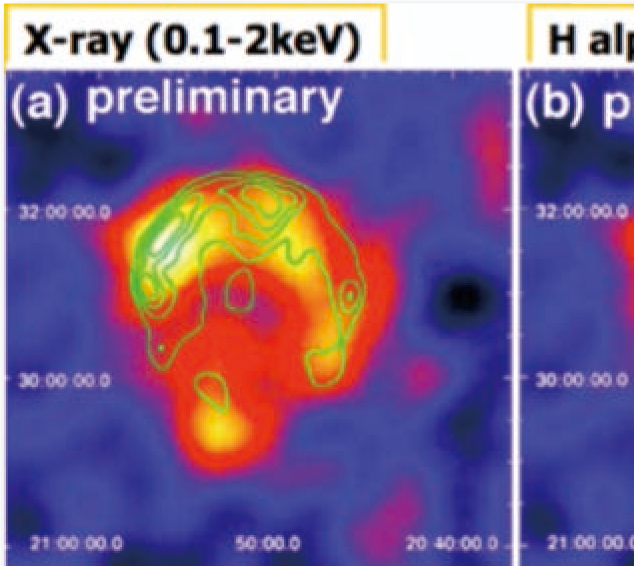
➔ Gamma-ray-emitting particles distribute near shock waves

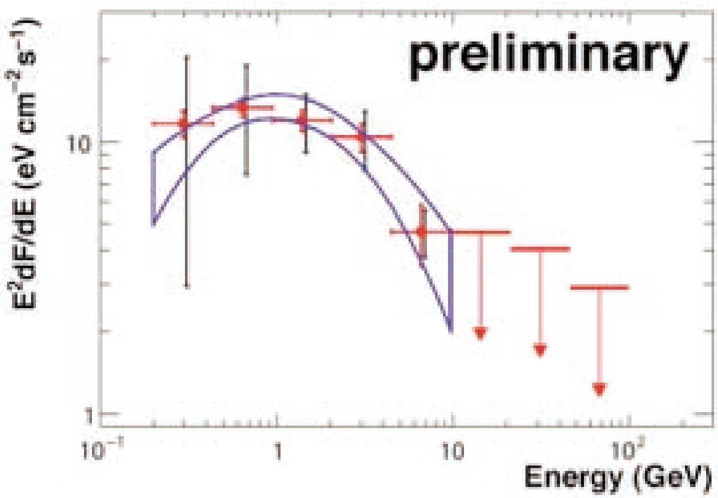
NOTE: southern radio emission would be another SNR.

Spectral steepening above ~ 2 GeV.
(simple power-law disfavored at 3.5σ level)
Gamma-ray Luminosity ~ 1×10^{33} erg/s (< other LAT SNRs)

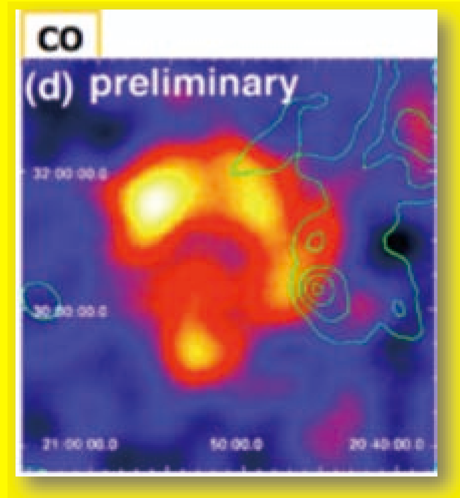
Cygnus Loop: LAT Results

Katagiri+ (submitted)





Unlike other middle-aged remnants, gamma-ray emission is not due to interactions with molecular cloud.



Gamma-ray emission comes from either (1) main blast wave regions (X-ray) or (2) radiative shock region (Hα).

Summary

- Historical SNRs
  - Tycho & Cassiopeia A
  - Hadronic origin, Magnetic field amplification, CR energy content
- Young TeV-bright SNRs
  - RX J1713.7-3946 & Vela Jr.
  - Leptonic origin? (B-field too low?)
- SNRs interacting with molecular clouds
  - W51C, W44, IC443, W28, W49B, W30, CTB37A, ...
  - Hadronic origin
  - Most cases: re-acceleration of ambient GCRs
  - Runaway CRs would be responsible for some cases
- Evolved SNRs without molecular cloud interactions
  - Cygnus Loop
  - Hadronic origin
  - Blast wave region? (X-ray) or Radiative shock? (Hα)

SNRs as the Sources of CRs

Requirements for the Sources of Galactic CRs

i. **Energetics**: CR protons of ~10^{50} erg (~10% of E_{SN}) per SNR

Theory of diffusive shock acceleration (DSA) cannot predict the amount of CRs.

"injection" from thermal pool = poorly known process

ii. **Spectral Index**: s=2.1-2.4 $Q(E) \propto E^{-s}$

DSA theory: test particle (TP) approximation s=2.0

non-linear (NL) "concave" spectrum

B-field amplification may yield s~2.4

iii. **Maximum Energy**: ~ PeV (10^{15} eV) to reach "knee"

DSA theory: assuming Bohm limit and B-field amplification,

$$E_{max} \sim 10^{15}\,\mathrm{eV}\,(v/1000\ \mathrm{km/s})^2\,(t/1000\ \mathrm{yr})\,(B/100\ \mu\mathrm{G})$$

→ Fermi-LAT is capable to address many of these problems.