Fermi Symposium 2011,
Rome, Italy

Fermi LAT Observations of Supernova Remnants

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

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Problems

SNRs as the Origin of Galactic Cosmic Rays

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

ii. **Index**: 2.0-2.3

iii. **Maximum Energy**: ~ PeV (to reach "knee")

SNRs as Laboratory for Diffusive Shock Acceleration

i. **Energetics**: poorly known (injection process)

ii. **Index**: 2.0 for TP (strong shock), NL predicts "concave" spectrum

iii. **Maximum Energy & Escaping CRs**

iv. **B-field Amplification**

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

Part I

Part I:

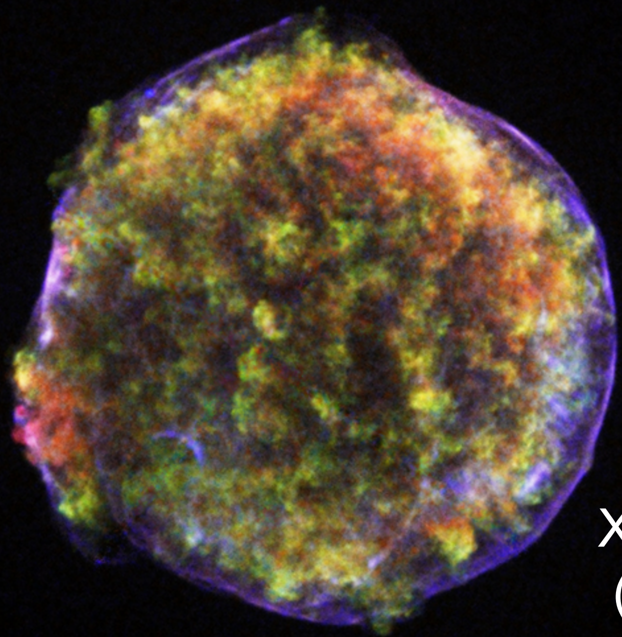
Historical SNRs

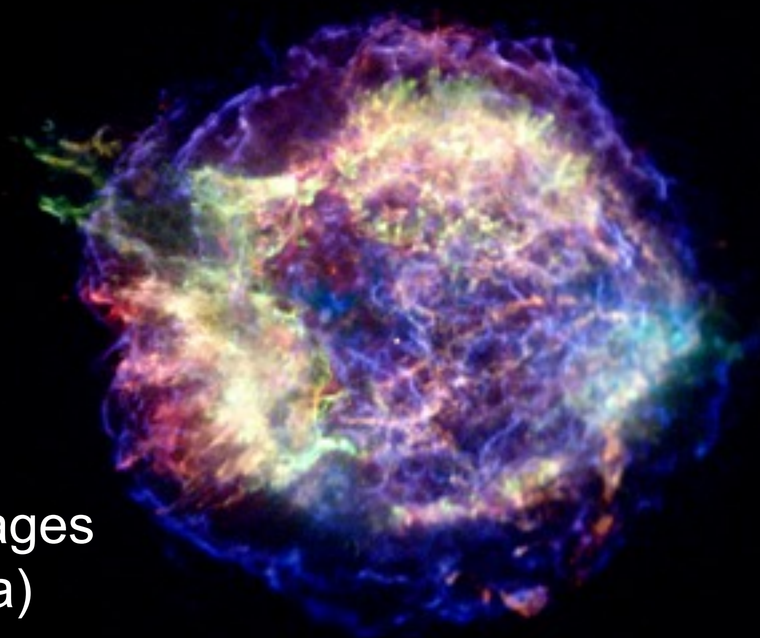
Tycho's SNR

- 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



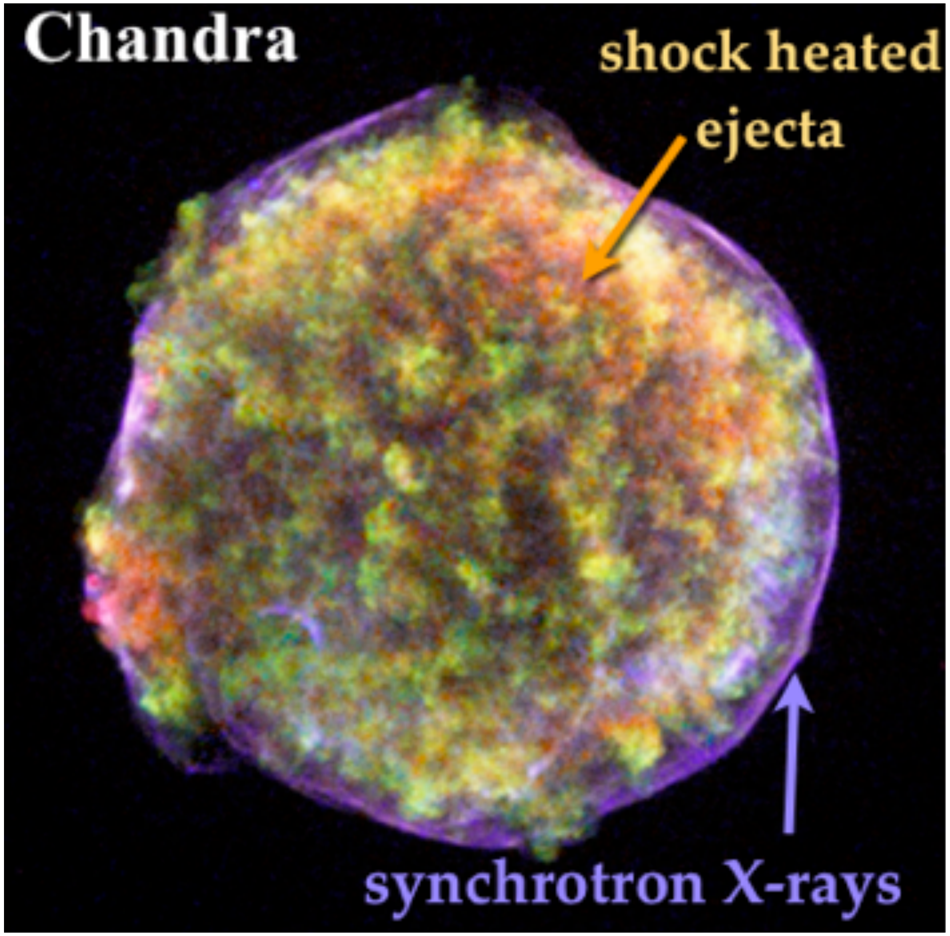


X-ray Images
(Chandra)

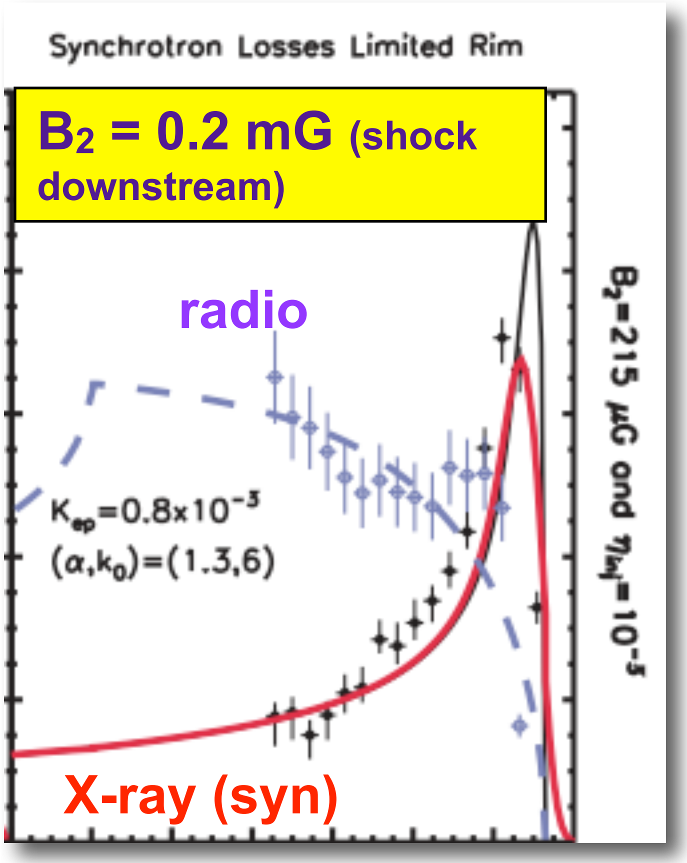
Most parameters are reasonably well known.
➔ largely help us interpret gamma-ray results.

Tycho: Synchrotron & B-field

Warren+05



X-ray/radio radial profile

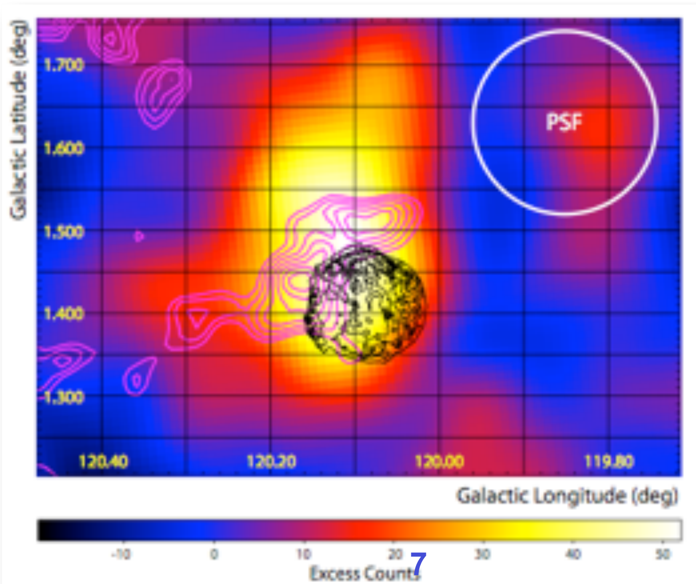


Cassam-Chenai+07

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

Tycho: Recent TeV Detection

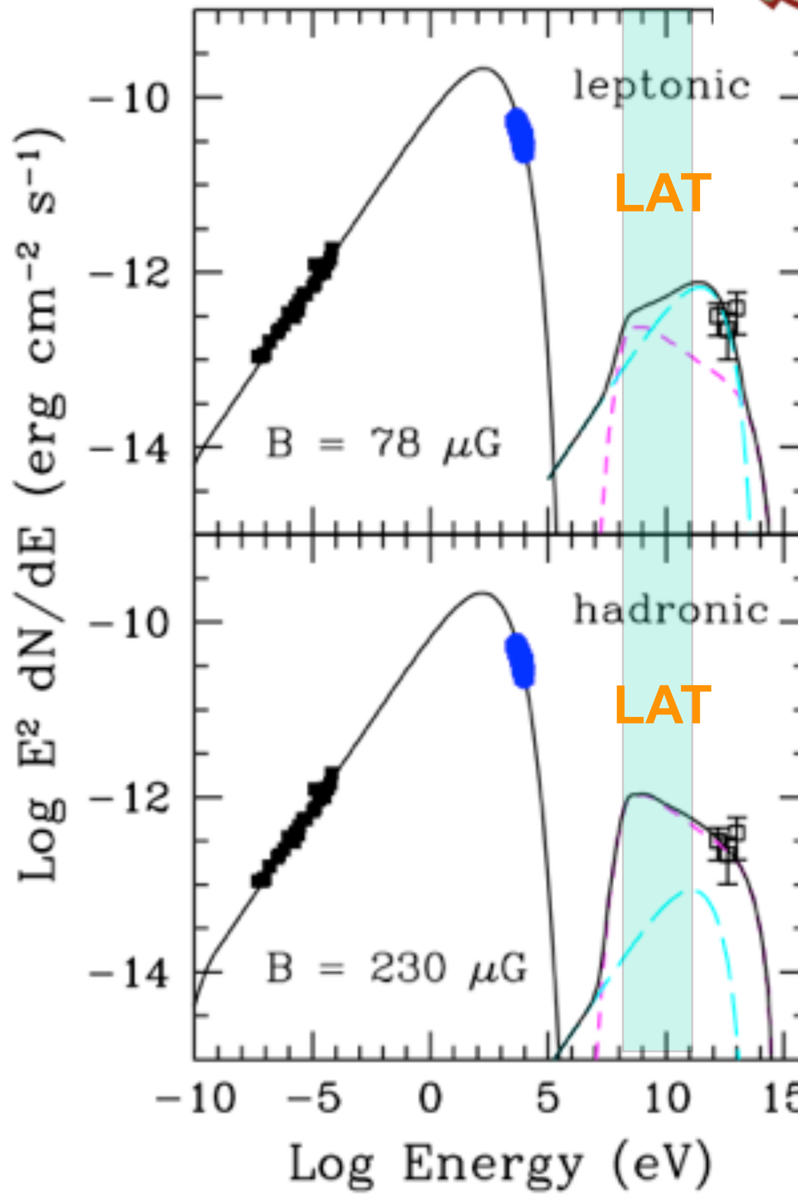
VERITAS Collaboration (2011)



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)

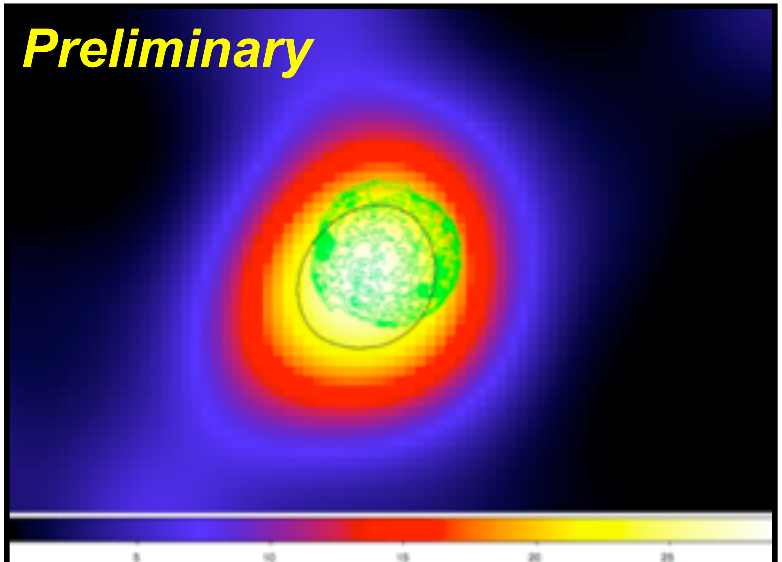
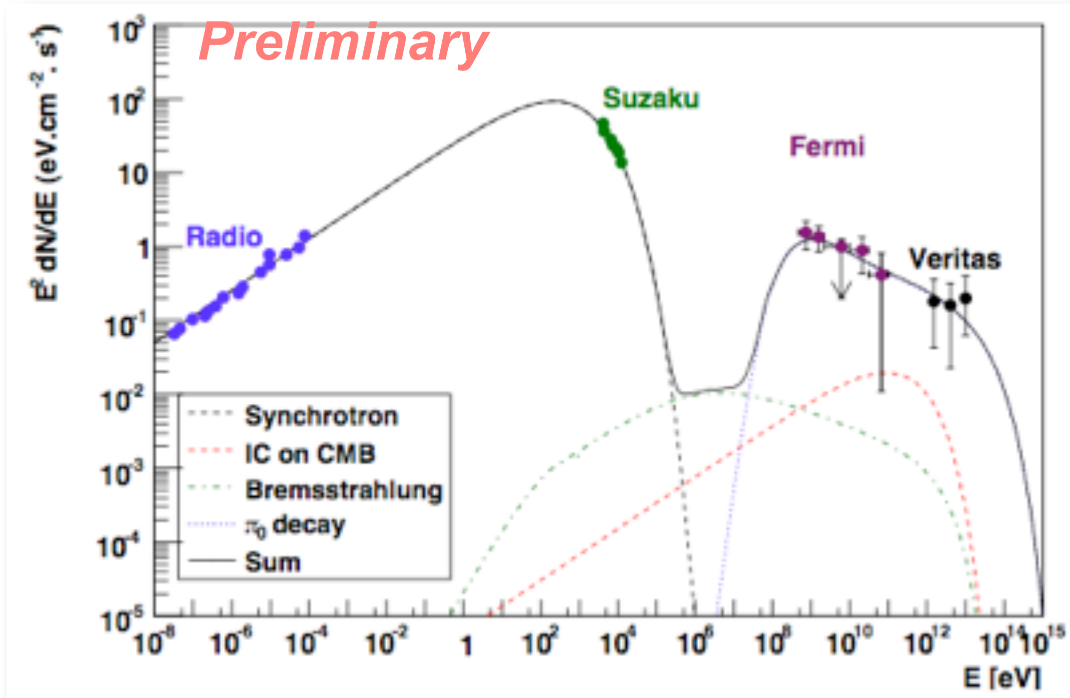


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*

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

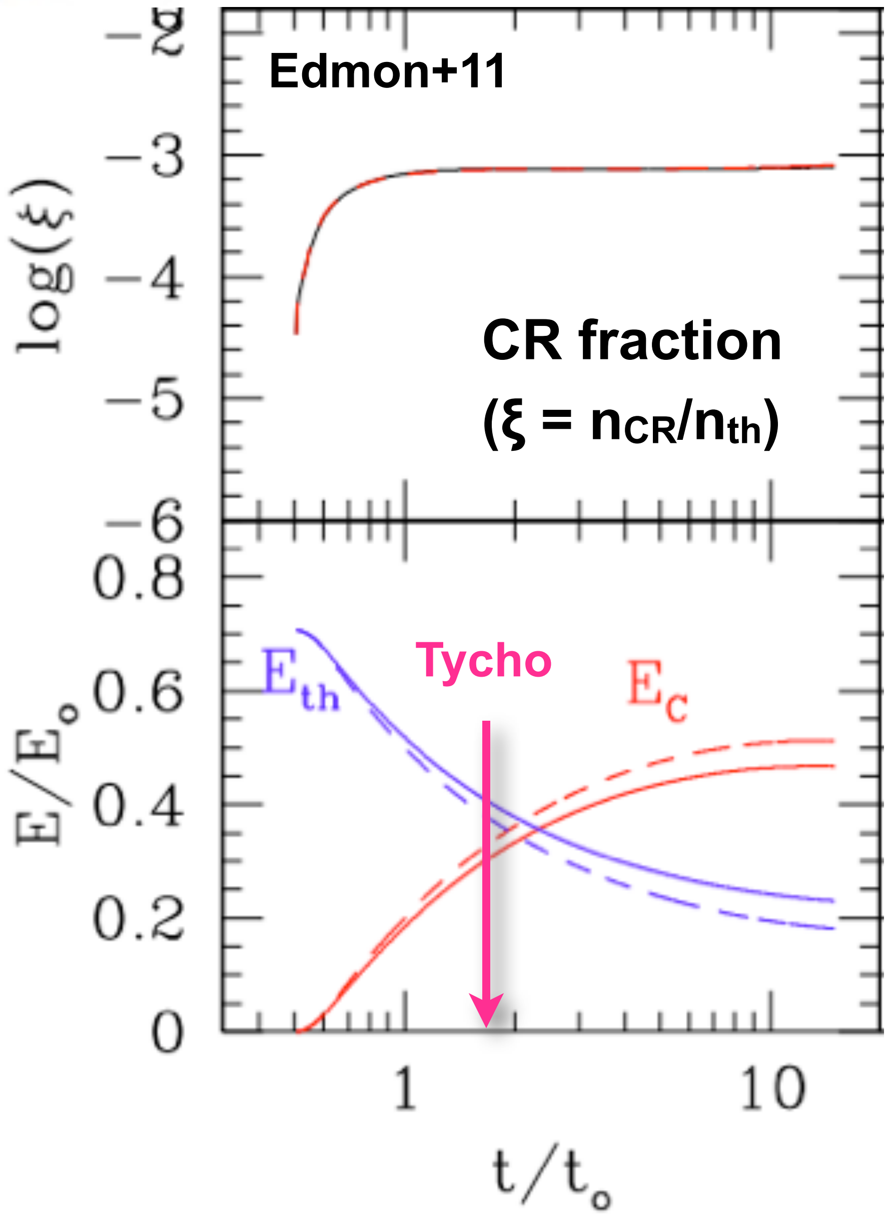


Case	D_{kpc}	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{51}erg]	K_{ep}
Far	3.50	0.24	2.0	0.150	4.5×10^{-4}
Nearby	2.78	0.30	1.0	0.061	7.0×10^{-4}

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

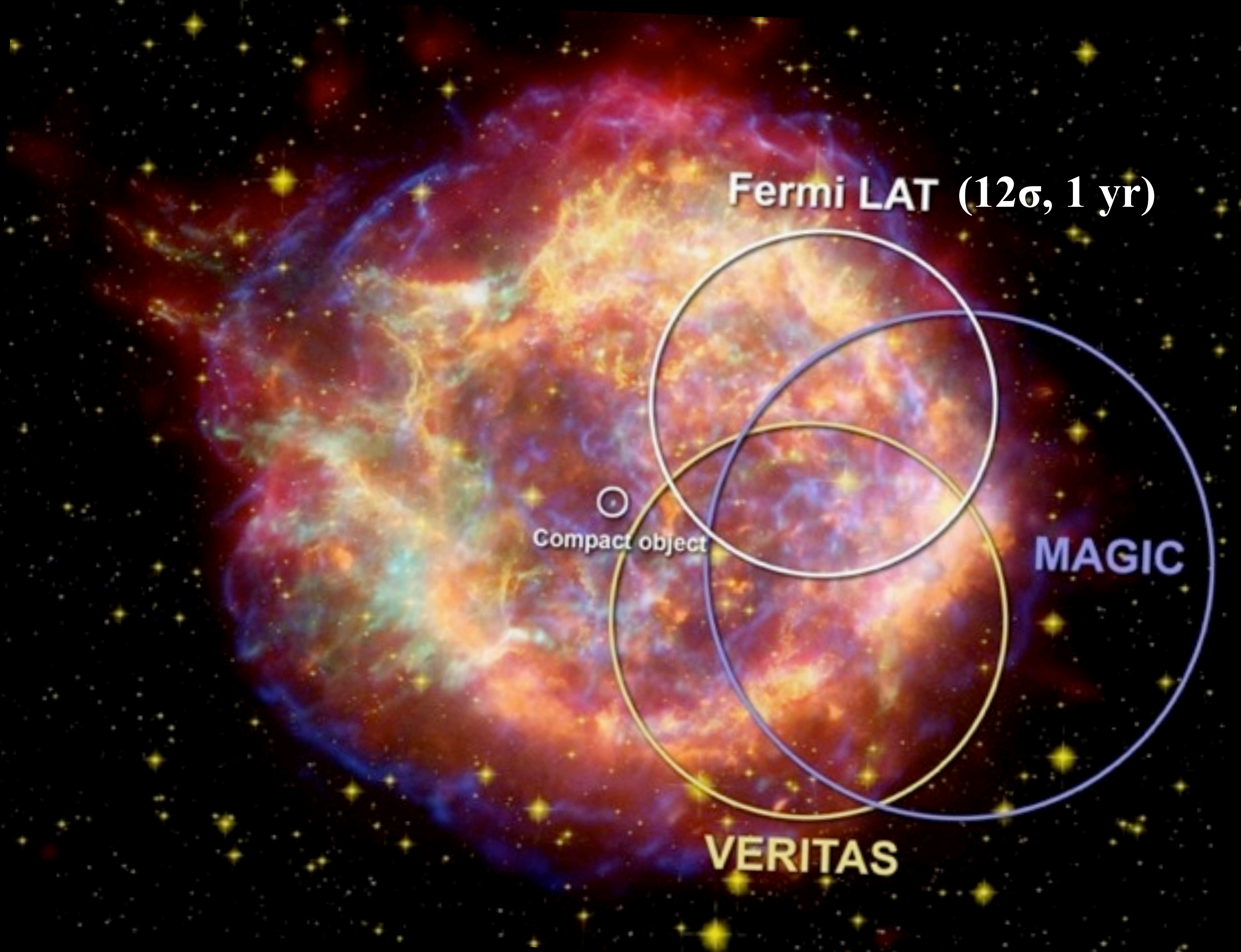
n_0 = 0.3 cm^{-3} (ISM density)
T_0 = 30000 K
B_0 = 30 uG (Upstream B-field)
Eo = 10^{51} erg (E_{SN})
→ to = 255 yr

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

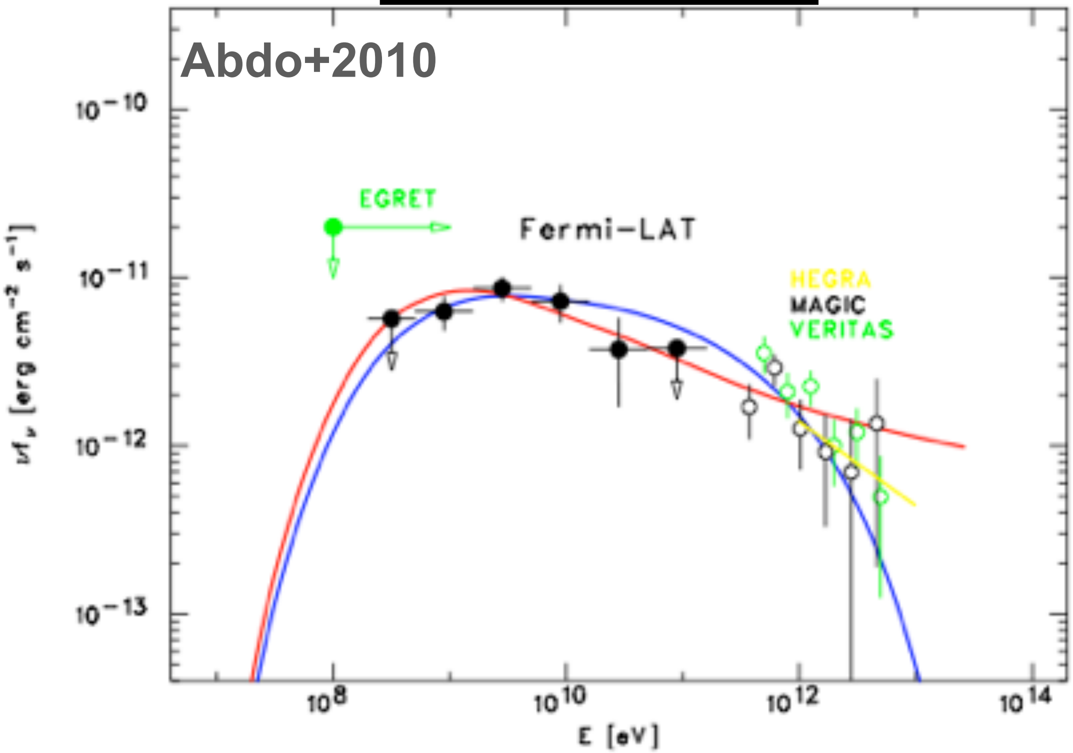
Cas A: GeV & TeV Detections



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:
$\Gamma = 2.0 \pm 0.1$

CR Proton: ~0.4×10^{50} erg

E_{CR} ~ 2% of E_{SN}=2×10^{51} erg

CR spectral index = 2.3

Part II

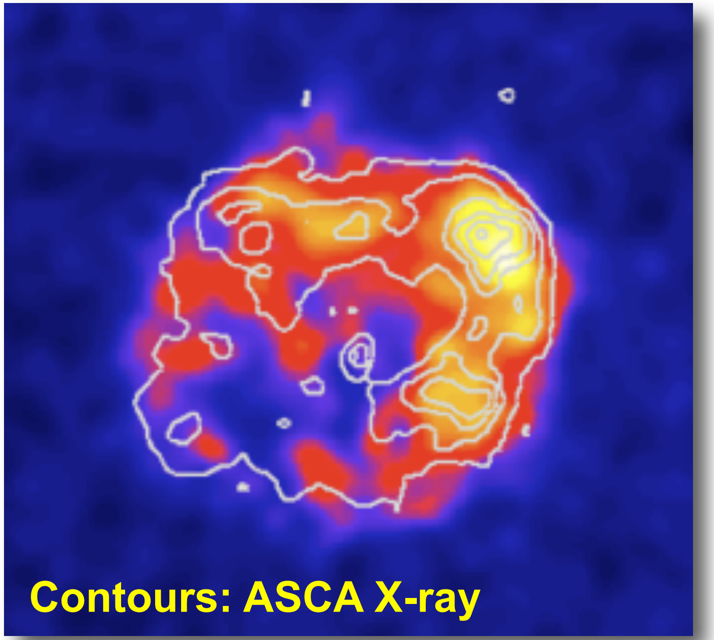
Part II:

Young TeV-bright SNRs

RX J1713.7-3946 & Vela Jr.

RX J1713.7-3946

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

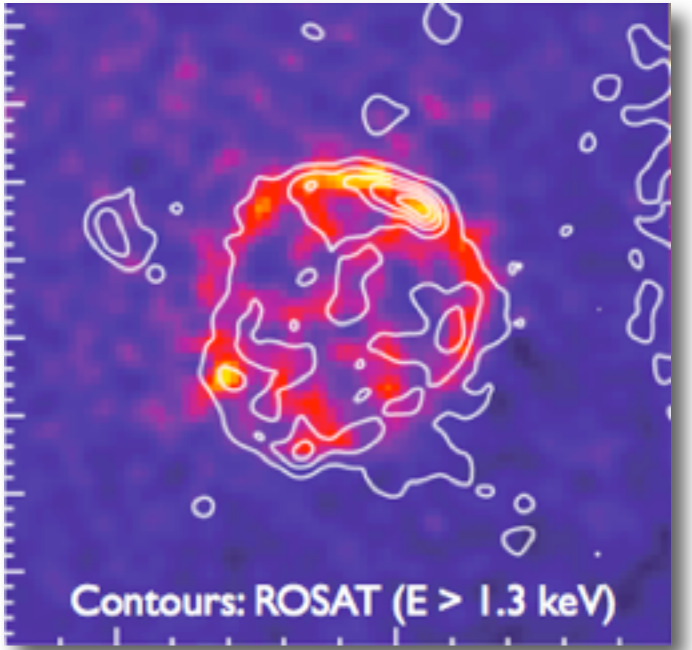


- age: ~1600 yr
- distance: ~1 kpc

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

RX J0852.0-4622 (Vela Jr)

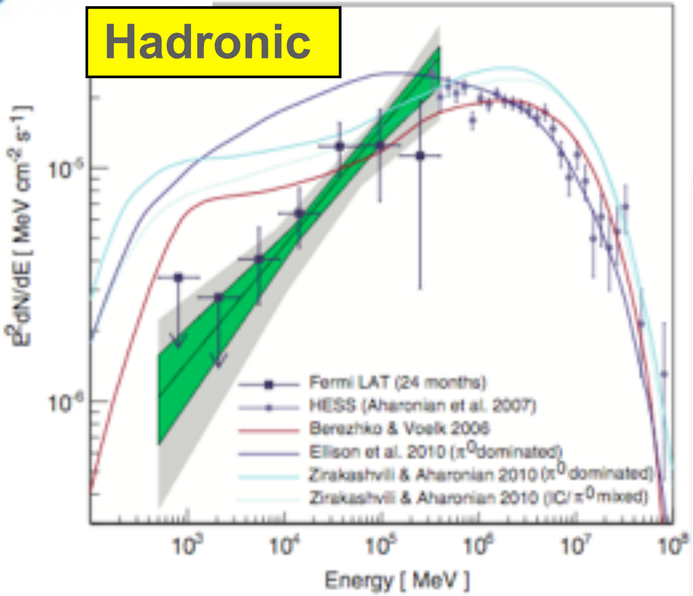
TeV gamma-ray map (H.E.S.S.)



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

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

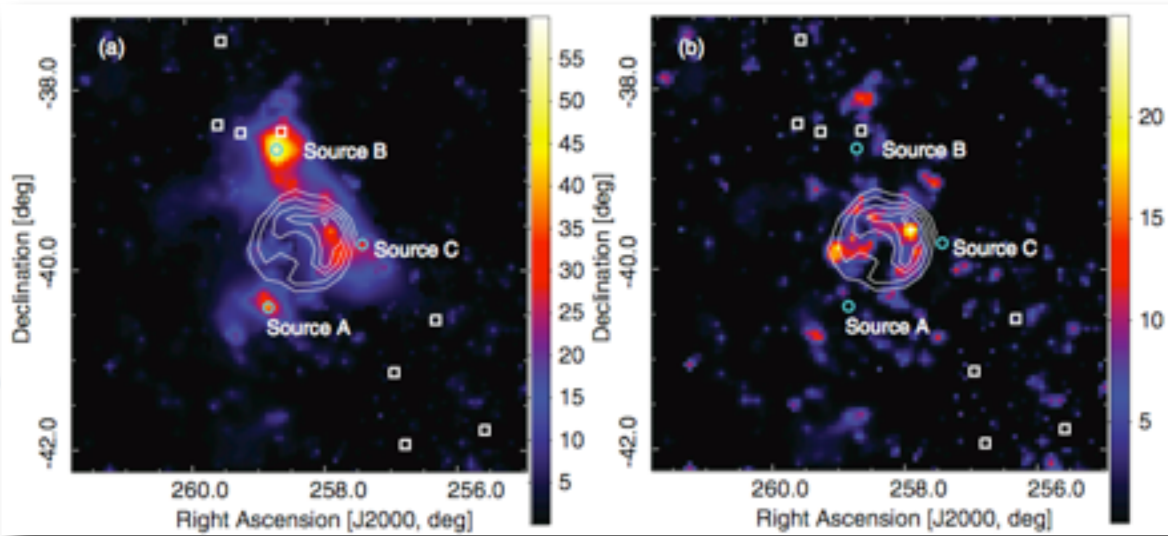
RX J1713.7-3946: LAT Results



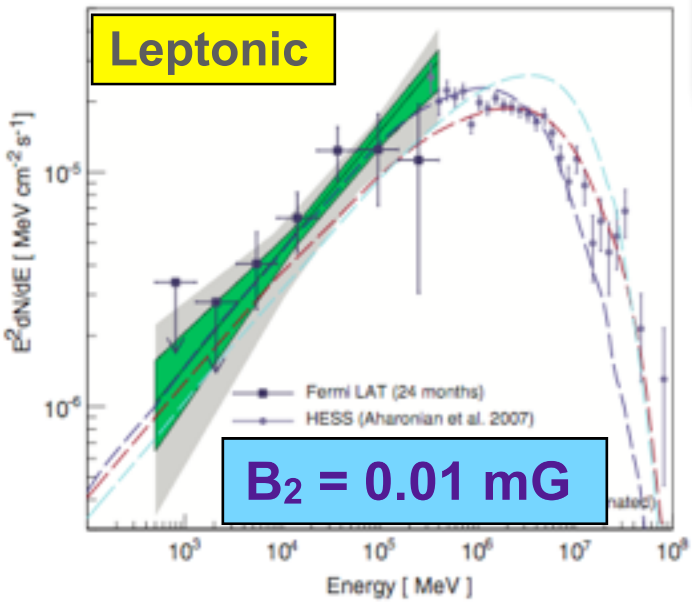
Abdo+2011 (in press)

TS map above 0.5 GeV

(using a point source hypothesis)



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



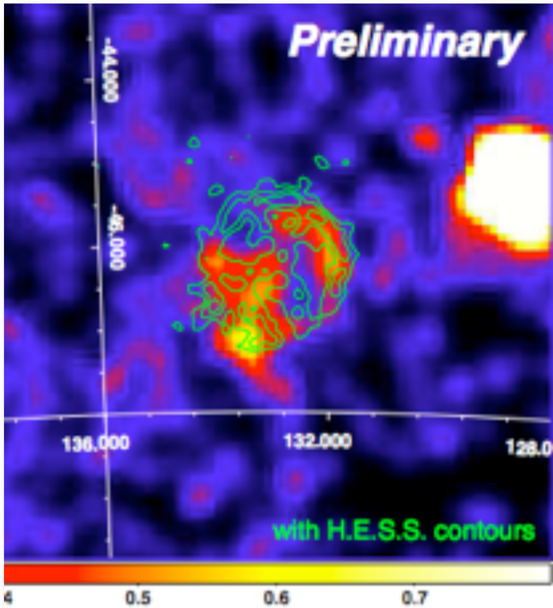
Photon index: Γ_{LAT} = 1.5 ± 0.1(sta) ± 0.1(sys)

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.

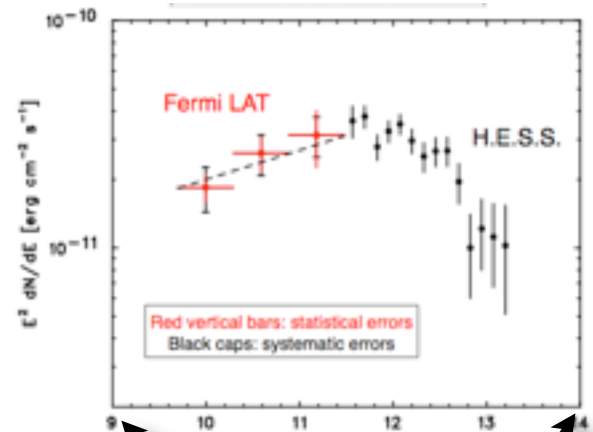
Vela Jr.: LAT Results

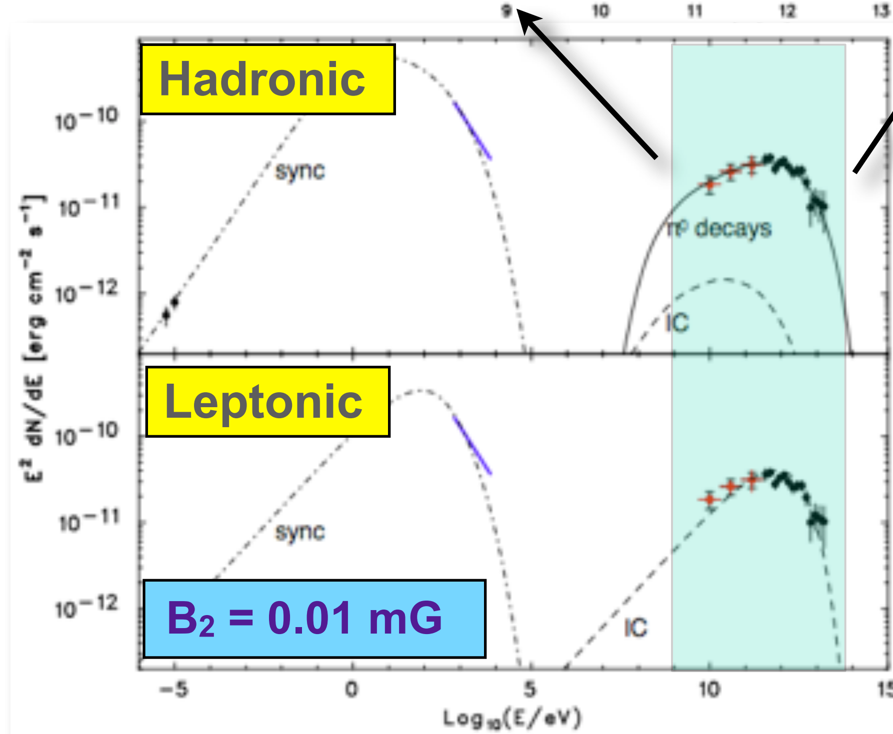
Fermi-LAT Collaboration (Tanaka+) in prep.

LAT count map above 10 GeV



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





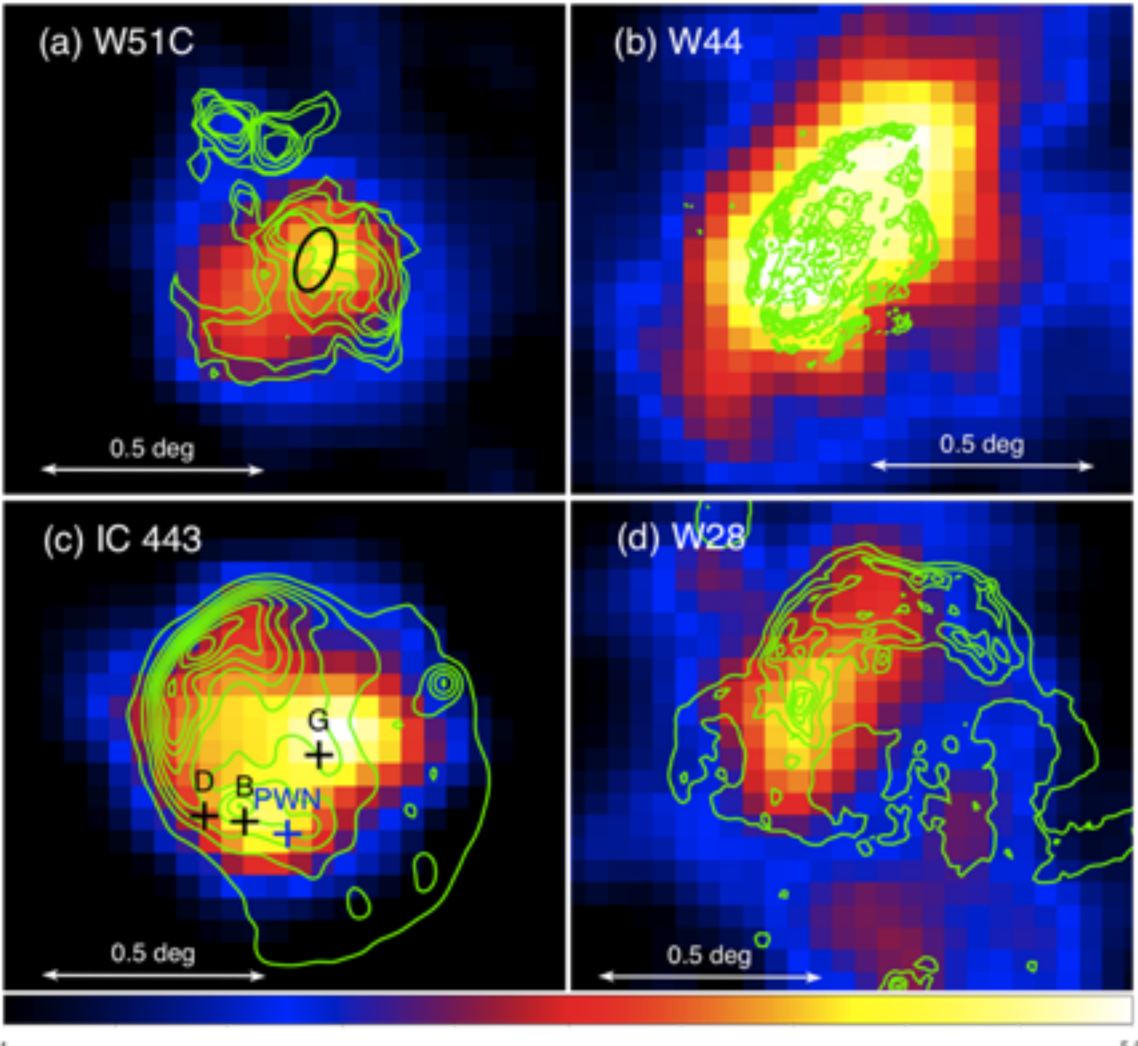
Again, B_2 = 0.01 mG in leptonic model would be difficult to be reconciled with X-ray measurements.
Hadronic model would require a large CR content (5×10^{50} erg for n=0.1 cm^{-3})

Part III:

SNRs Interacting with Molecular Clouds

LAT Discoveries of MC-SNRs

Fermi-LAT Collaboration (Uchiyama+) 2011



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

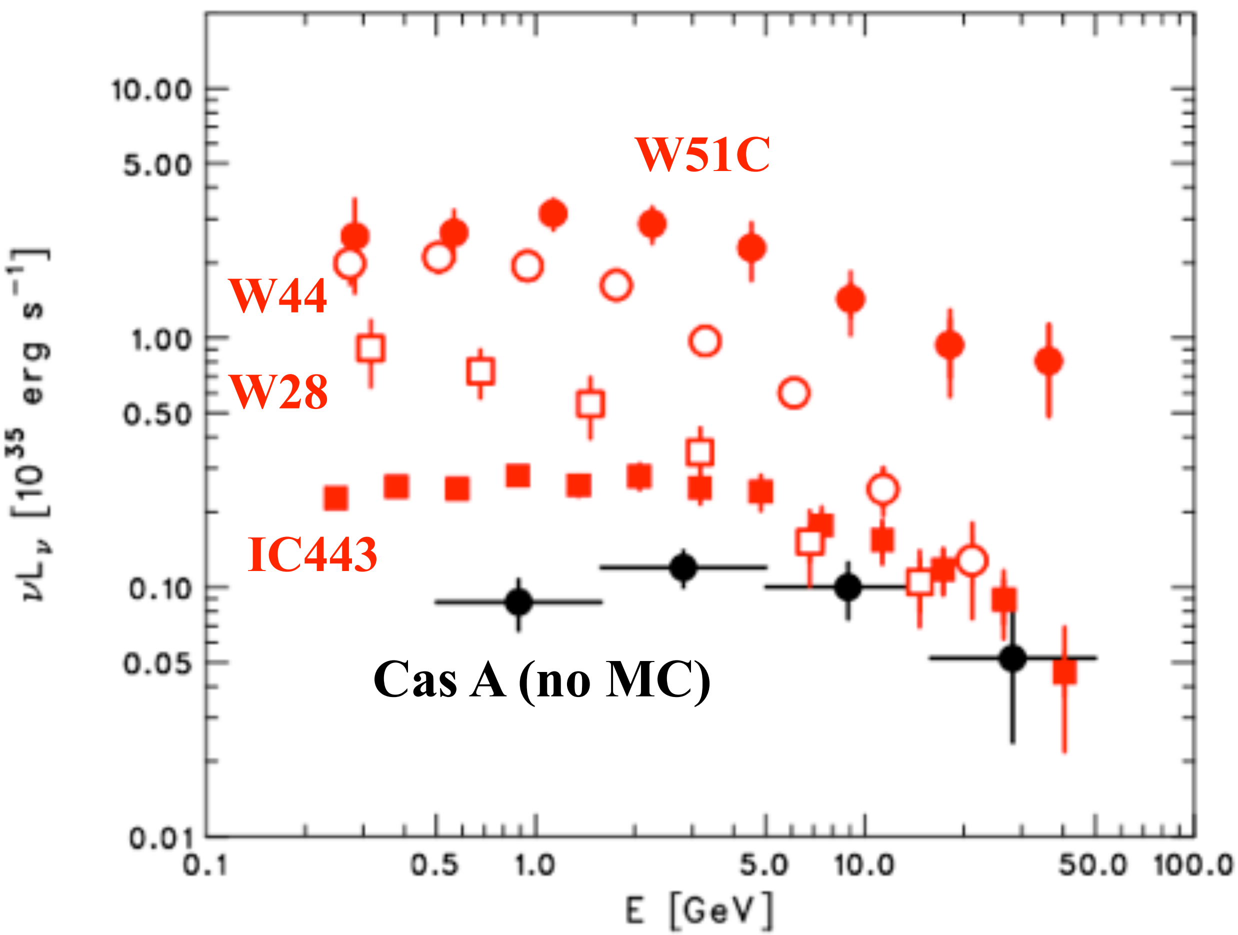
Extended GeV emission has been discovered from several SNRs, with molecular cloud (MC) interactions.

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:

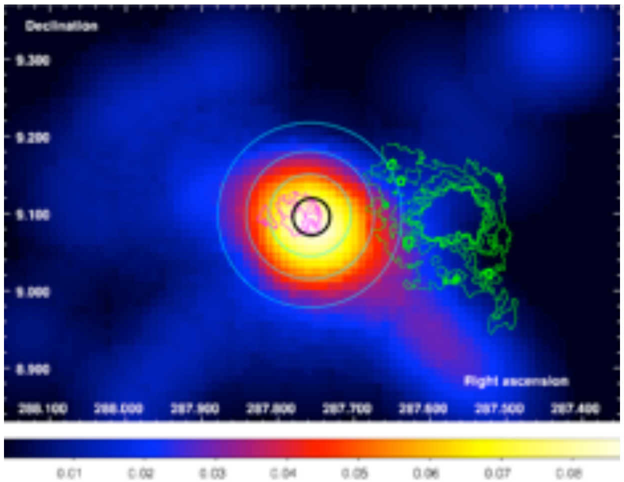
π^0-decay γ-rays in dense gas (>10 cm^{-3}).

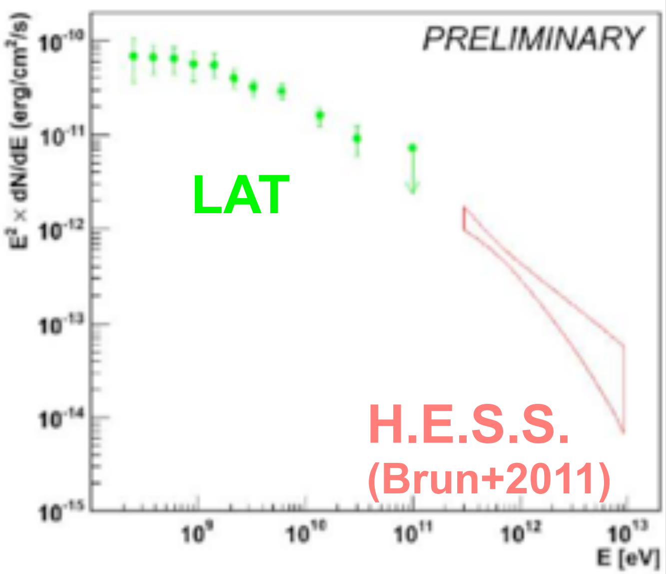
Spectral steepening in the GeV band

GeV luminosity >> TeV luminosity

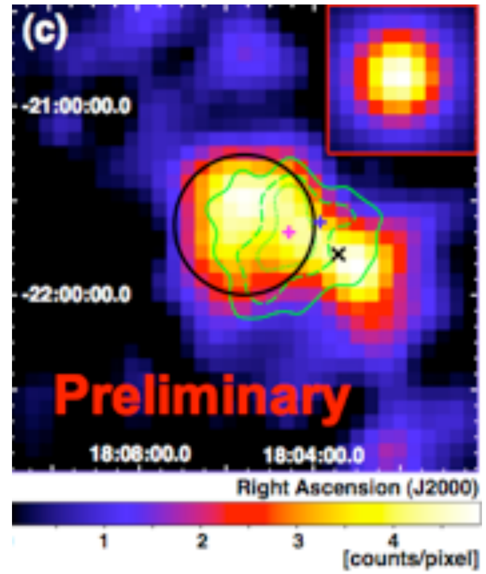
Growing Examples: MC-SNRs

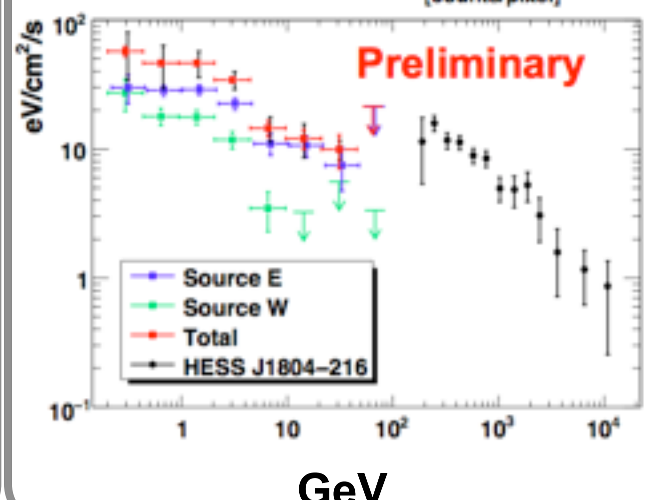
W49B Abdo+2010





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

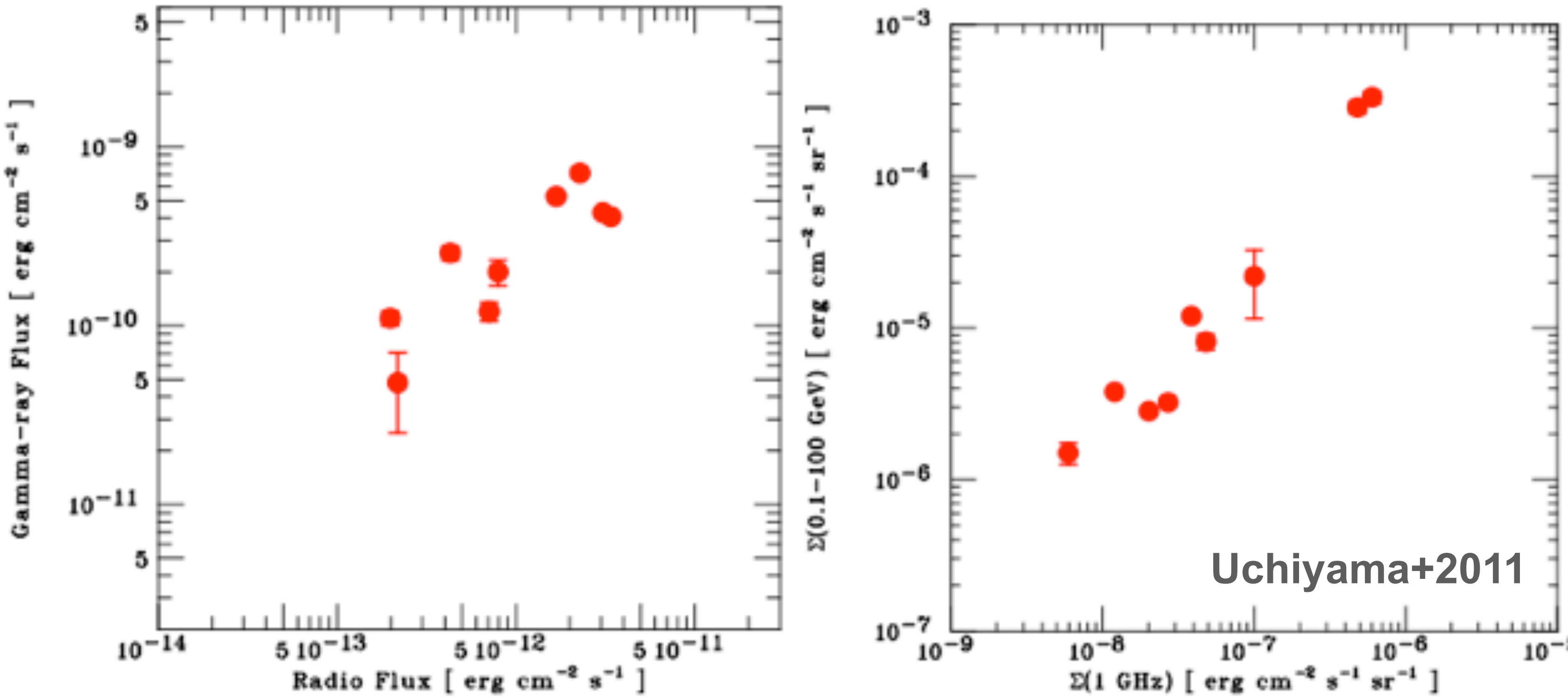
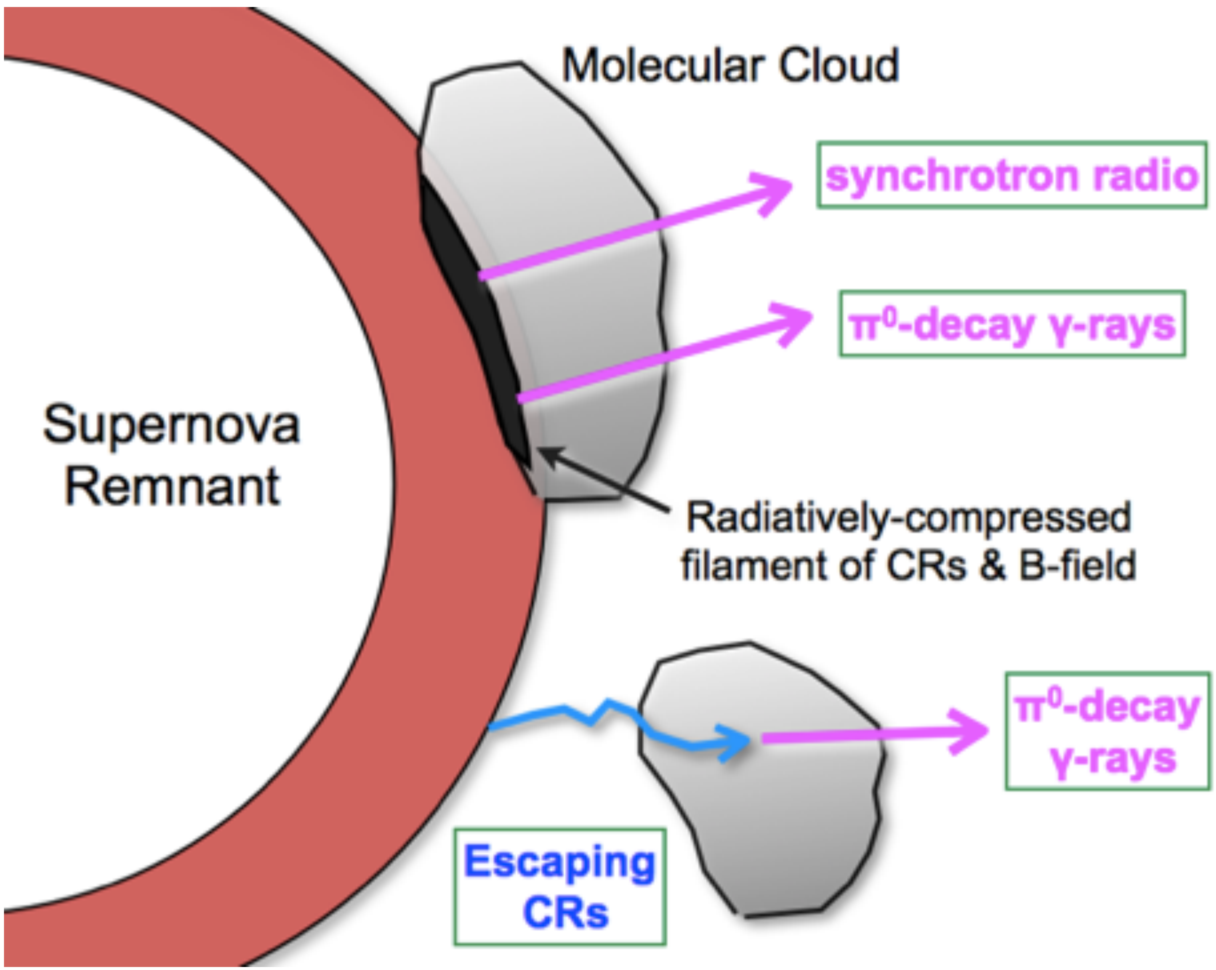


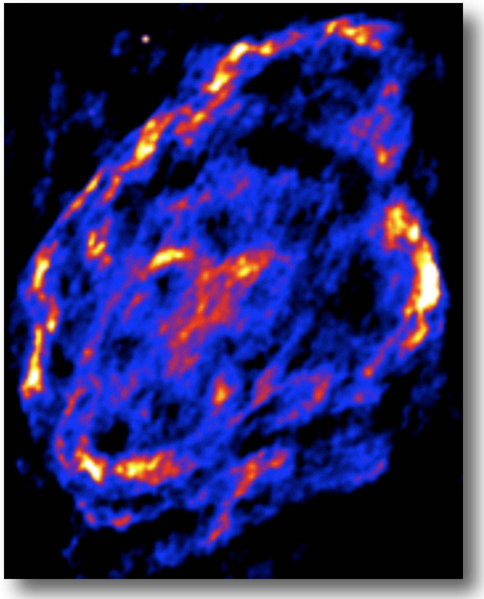
Figure 3: (Left) Radio flux (synchrotron) vs GeV γ-ray flux for MC-interacting SNRs. The γ-ray energy flux integrated over 0.1–100 GeV and the radio flux, νf_ν at 1 GHz, are shown. (Right) Mean surface brightness of the synchrotron radio emission and GeV γ-ray emission. The flux-flux plot is converted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

Gamma-ray Emission Sites

Radio & γ-ray emissions from radiatively-compressed filaments
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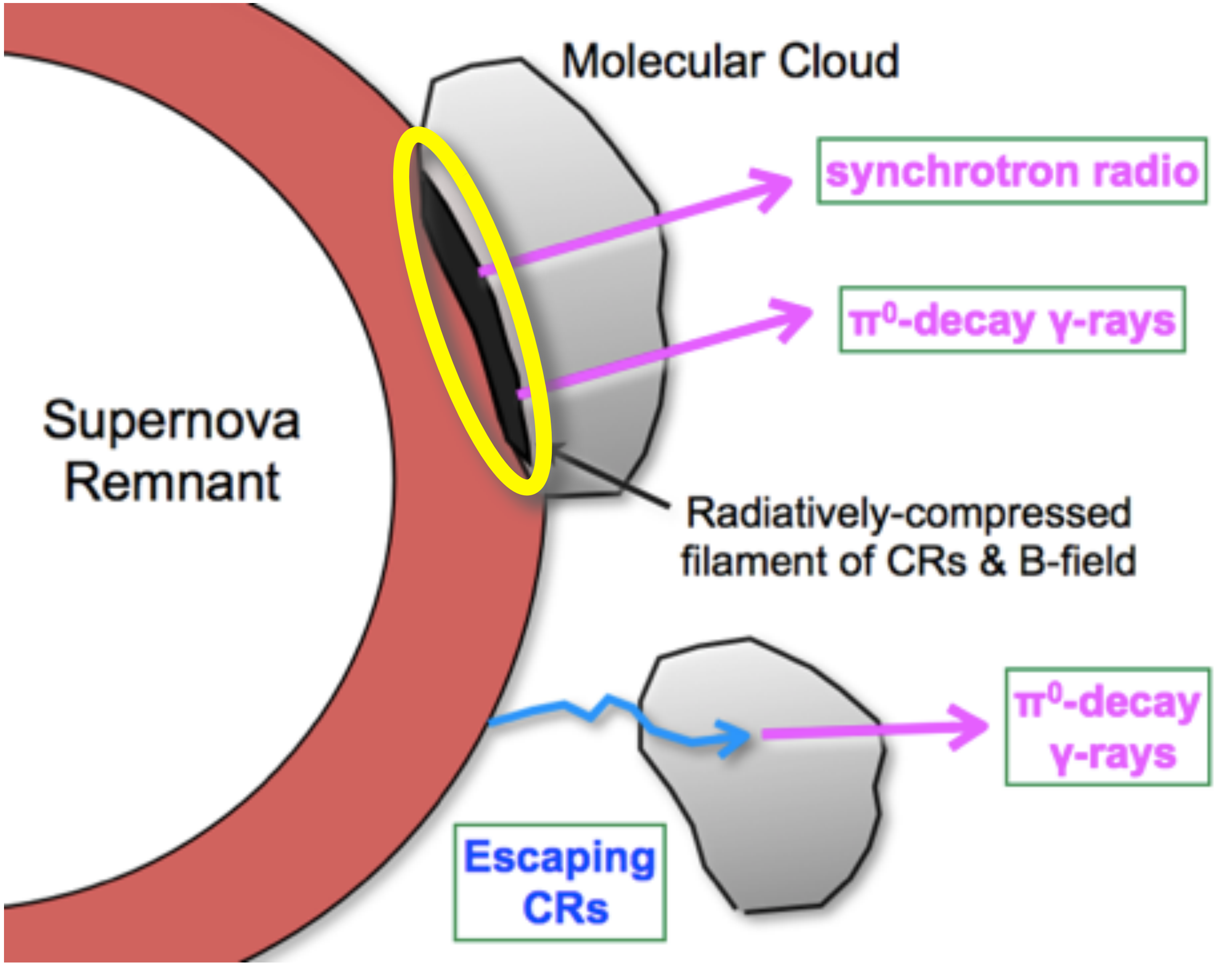
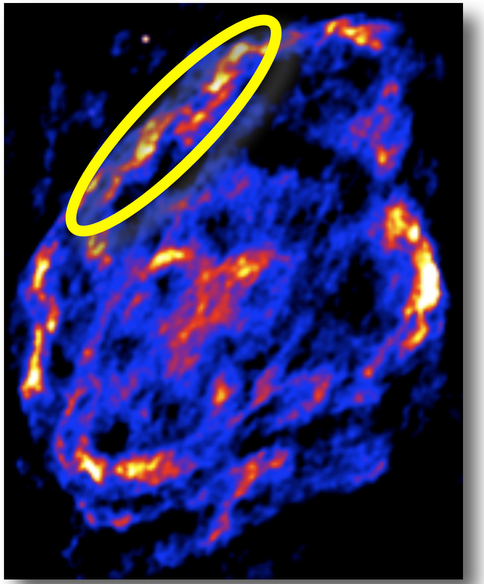


SNR W44



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Gamma-ray Emission Sites

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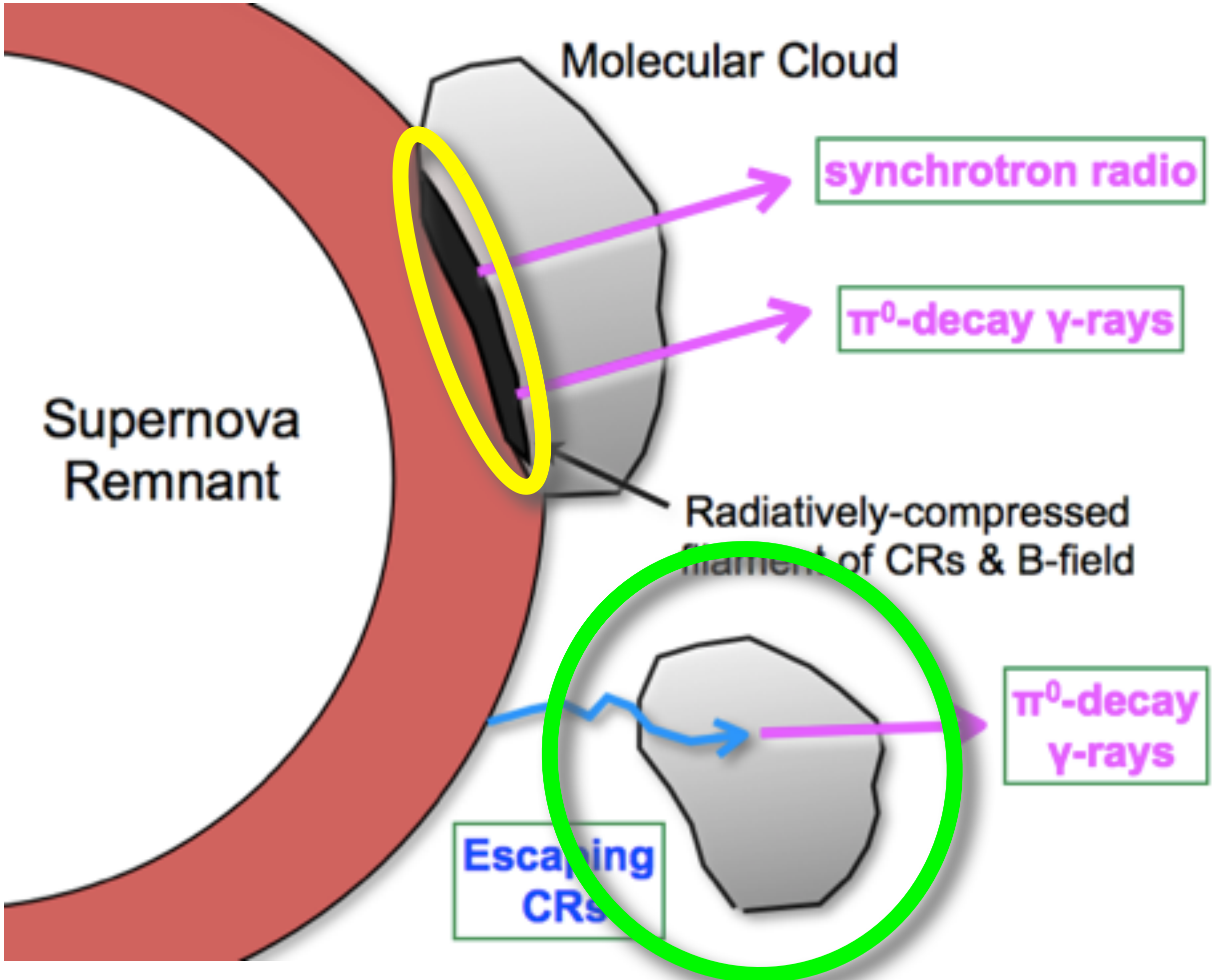
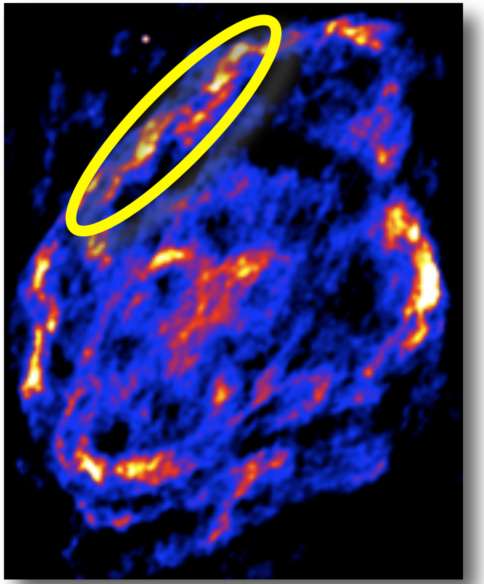


SNR W44



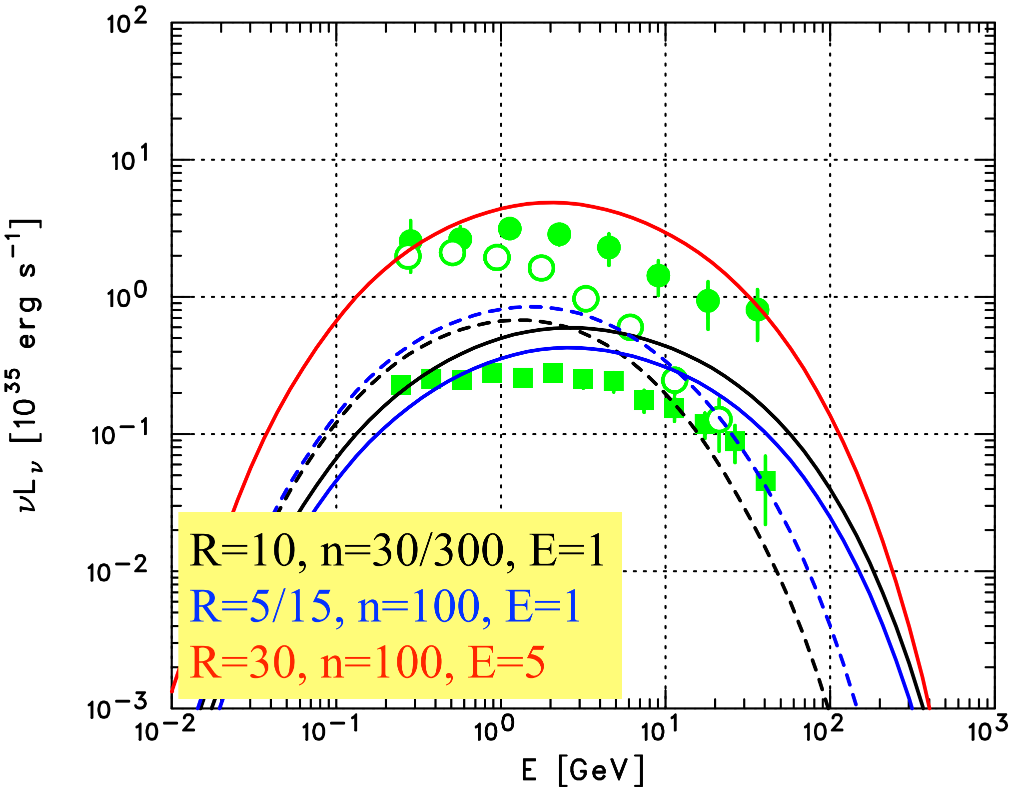
synchrotron radio emission correlated with shocked H_2 gas

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}

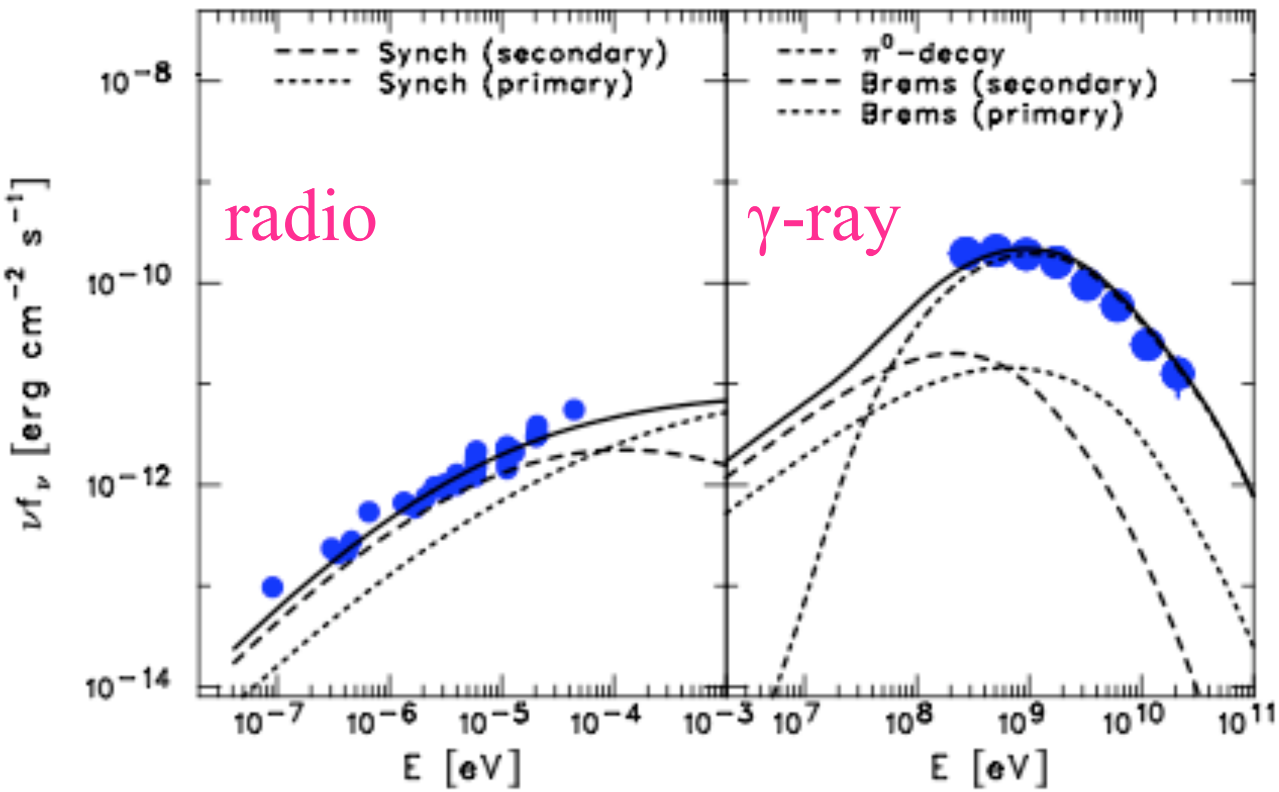
B: Preshock B-field in μG
B = 2 n$^{1/2}$ fixed

R: SNR radius in pc

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

Crushed Cloud Model for W44

Uchiyama+2010



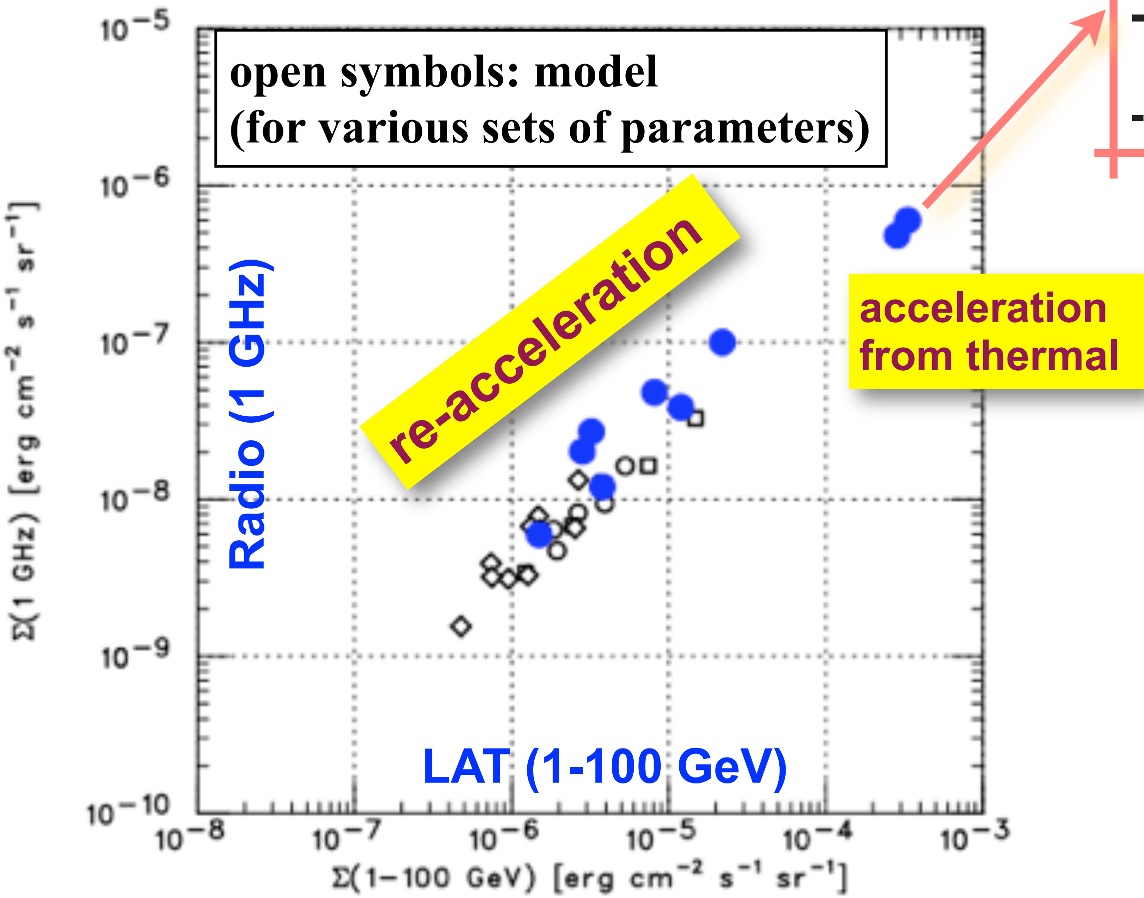
- radio & γ-ray fluxes can be explained by re-acceleration of the pre-existing GCRs

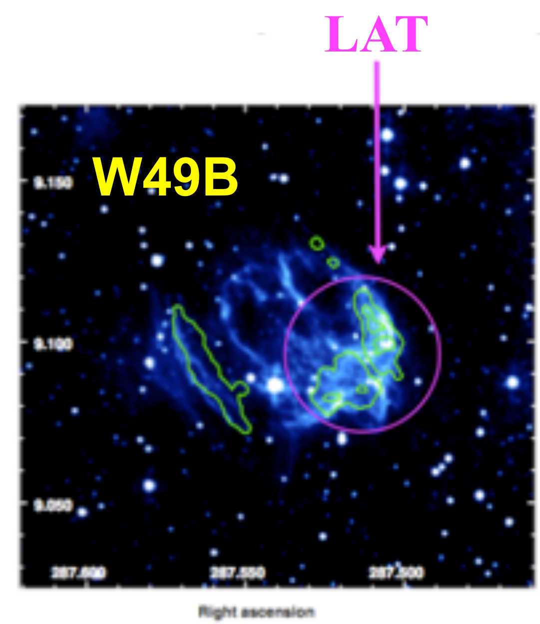
- flat radio index (α=0.37) is naturally explained

Crushed Cloud: GeV vs Radio

W49B & G349.7+0.2
- relatively young < 10000 yr
- “canonical” radio index ($\alpha = 0.5$)
- Strong infrared lines

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



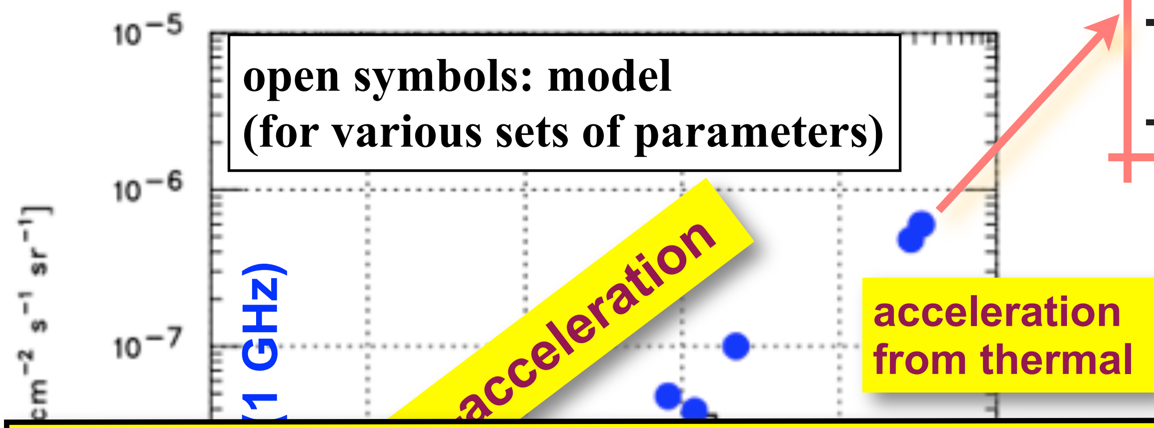


Color: Spitzer IRAC 5.8 um (Radiative shock)

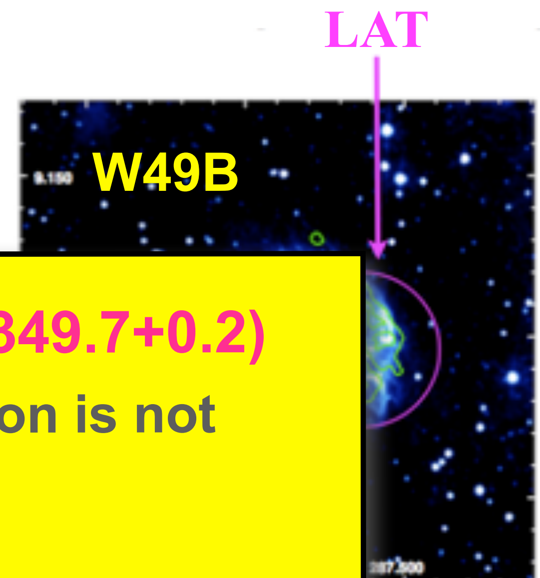
Contours: VLA 1.4 GHz (GeV electrons)

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)

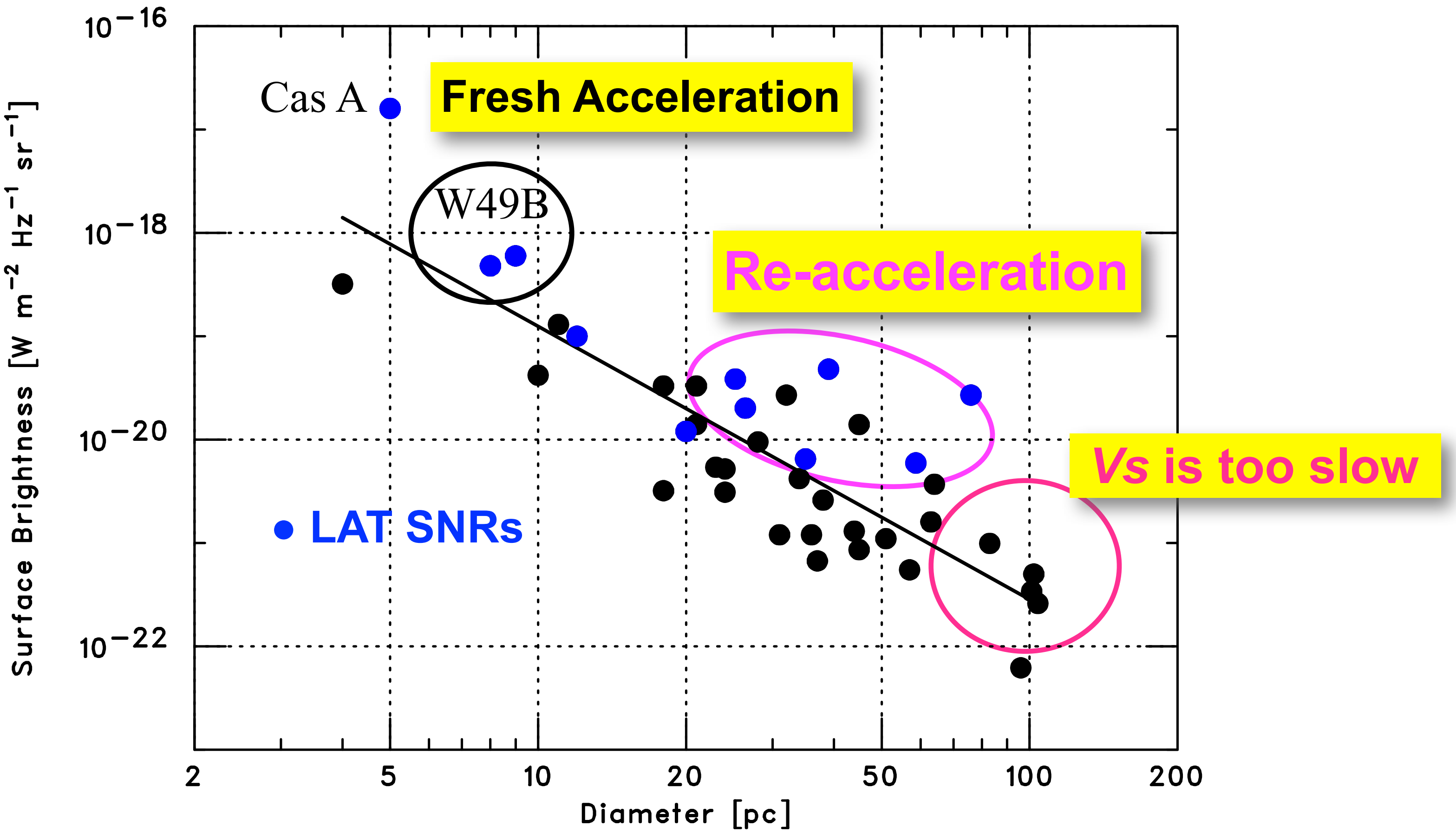
LAT flux implies $u_{CR} \sim 10^5$ eV/cm^3 (re-acceleration is not enough)

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

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

Σ-D Relation

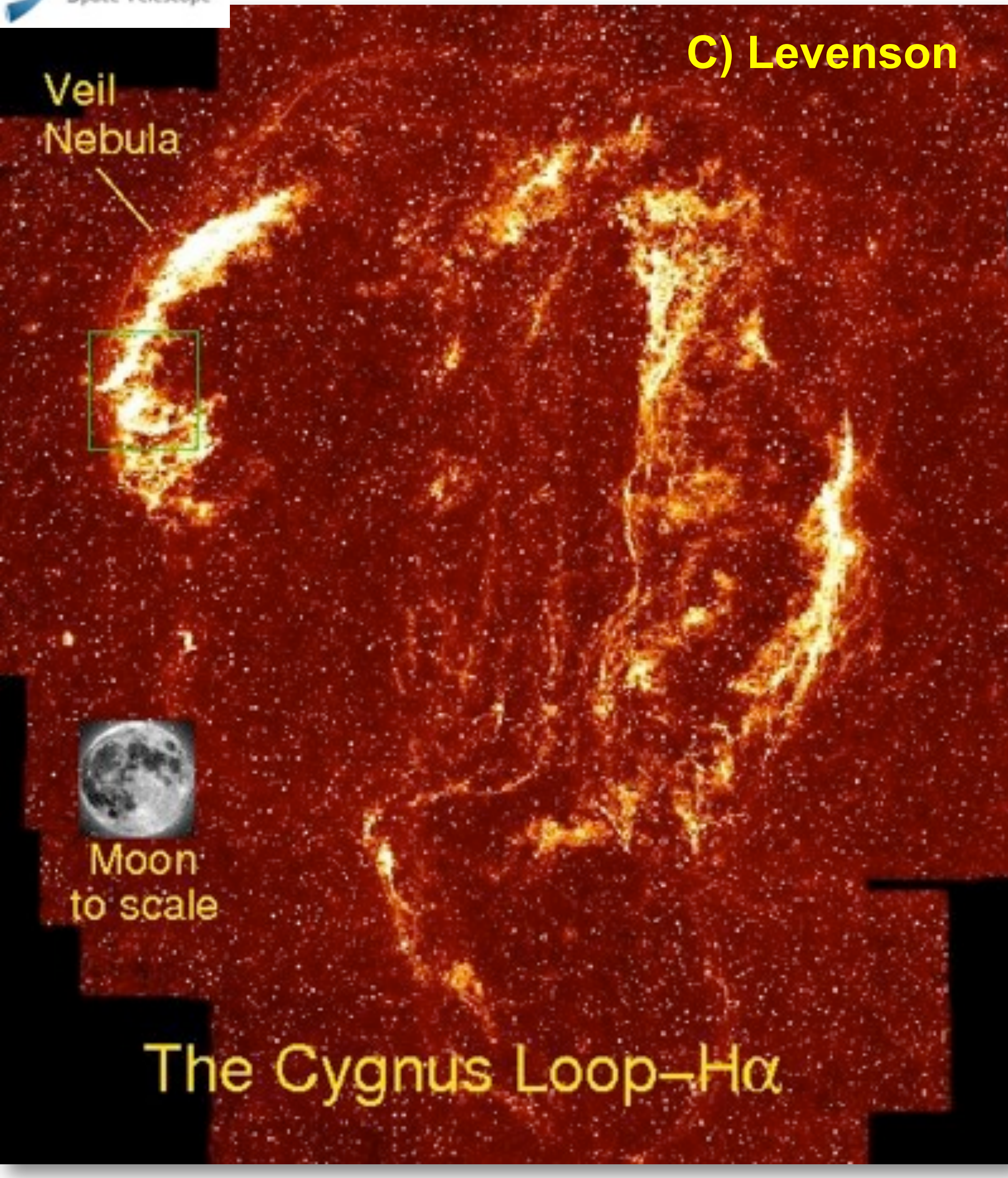
Radio Surface Brightness (Σ) - Diameter (D) Relation



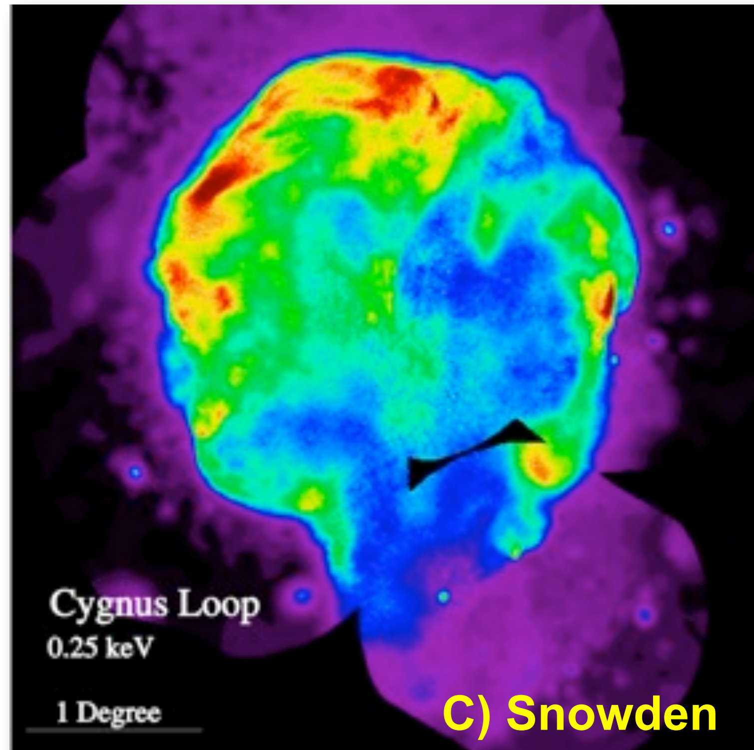
V~1000 km/s shock : CR acceleration > 10 TeV
V~100 km/s shock : CR (re-)acceleration < TeV

Part IV:
Evolved SNR without MC

Cygnus Loop

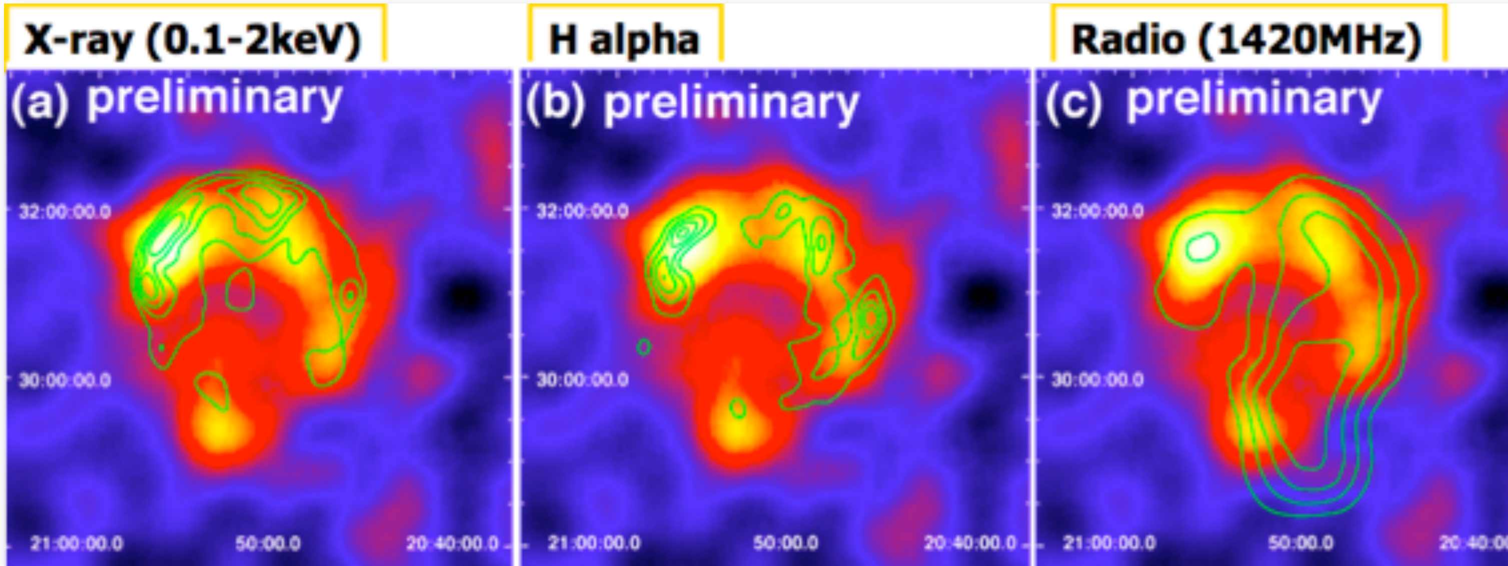


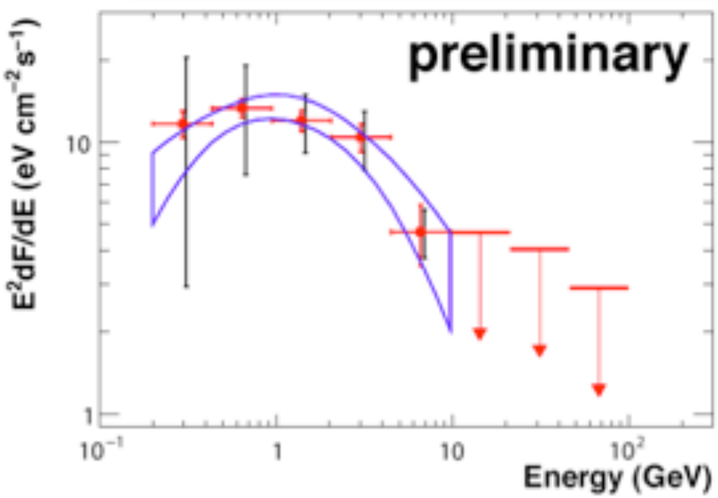
Middle-age ~ 2×10^4 yr
Large angular size (3 deg)
No clear MC interaction



Cygnus Loop: LAT Results

Katagiri+ (submitted)





Correlation with X-ray and Hα emissions

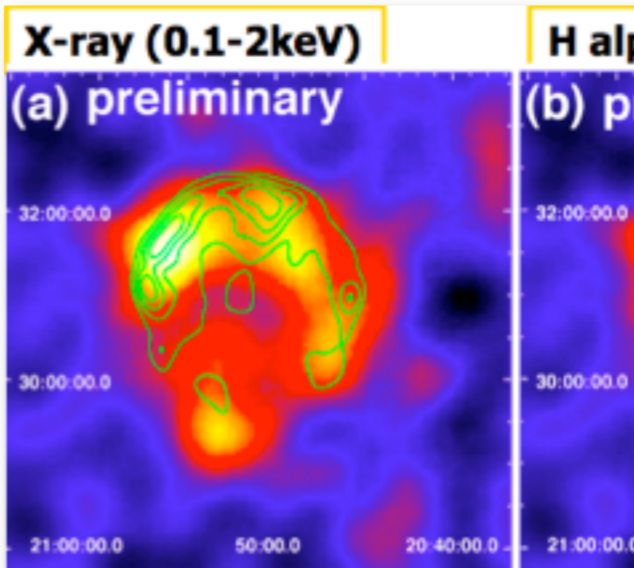
➔ Gamma-ray-emitting particles distribute near shock waves

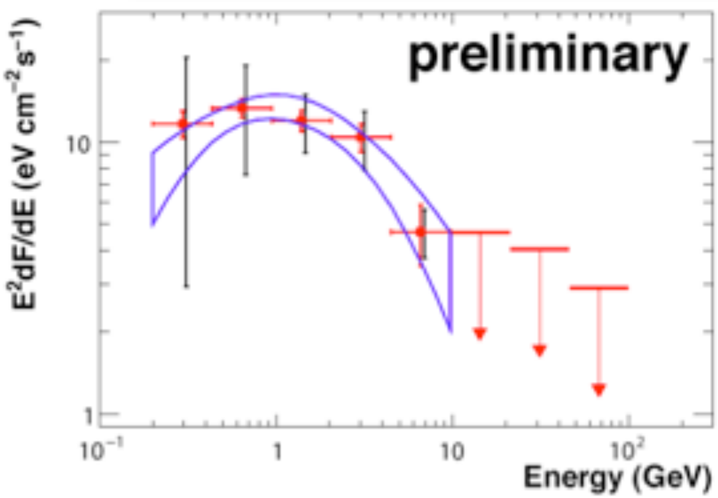
NOTE: southern radio emission would be another SNR.

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

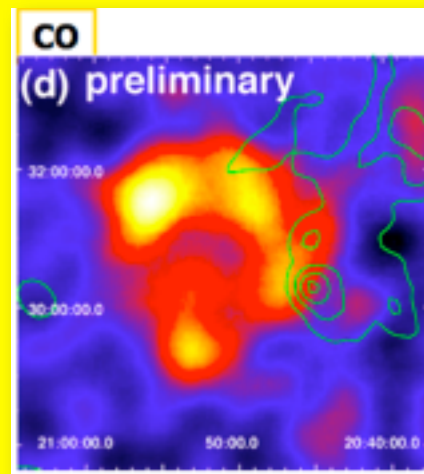
Cygnus Loop: LAT Results

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)