9th AGILE Science Workshop
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@ESRIN, Frascati (Rome) Italy

Fermi-LAT Observations of Supernova Remnants

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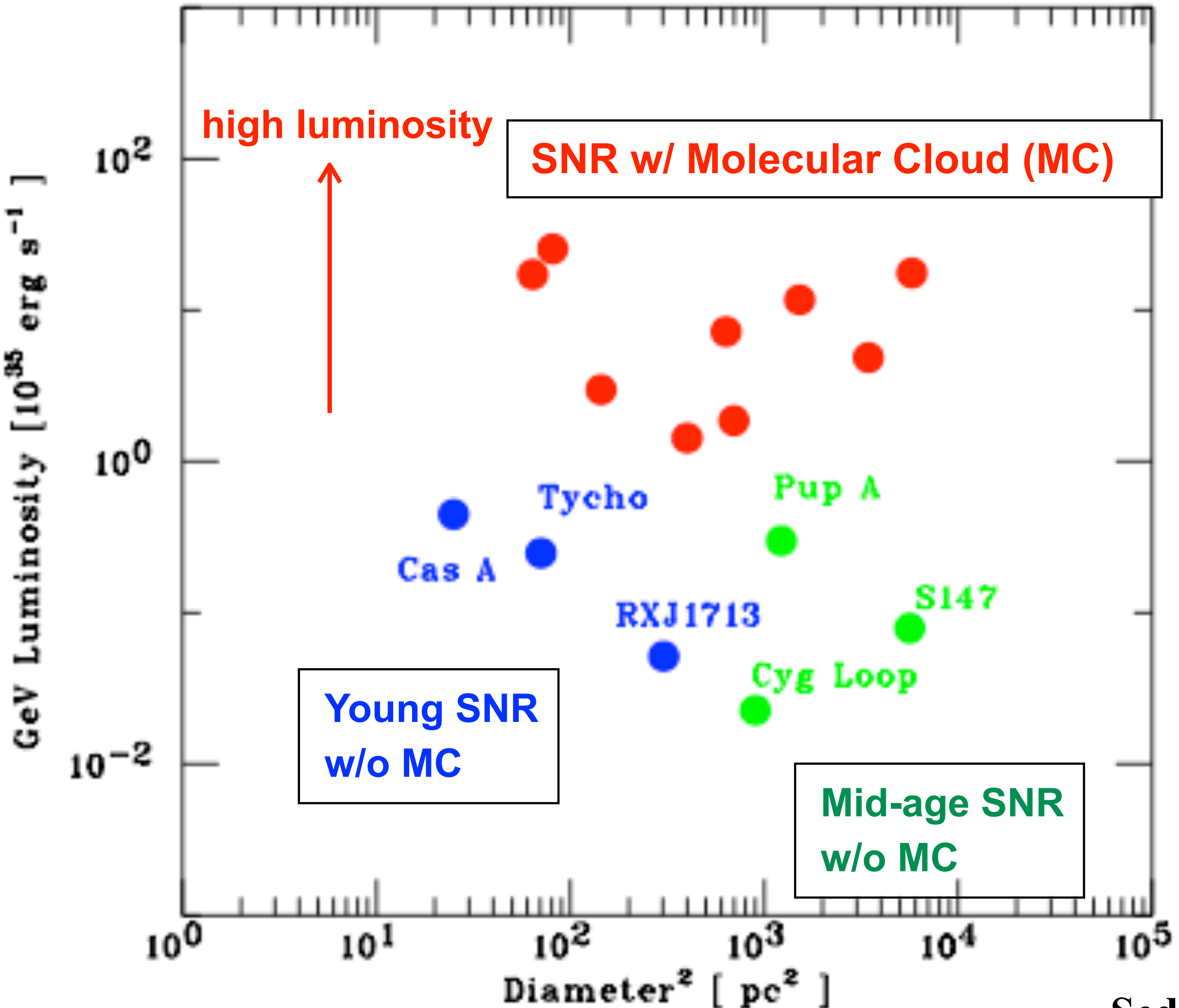
for the Fermi LAT Collaboration

Fermi-LAT Detections of SNRs



Sedov: $D^2 \propto t^{0.8}$

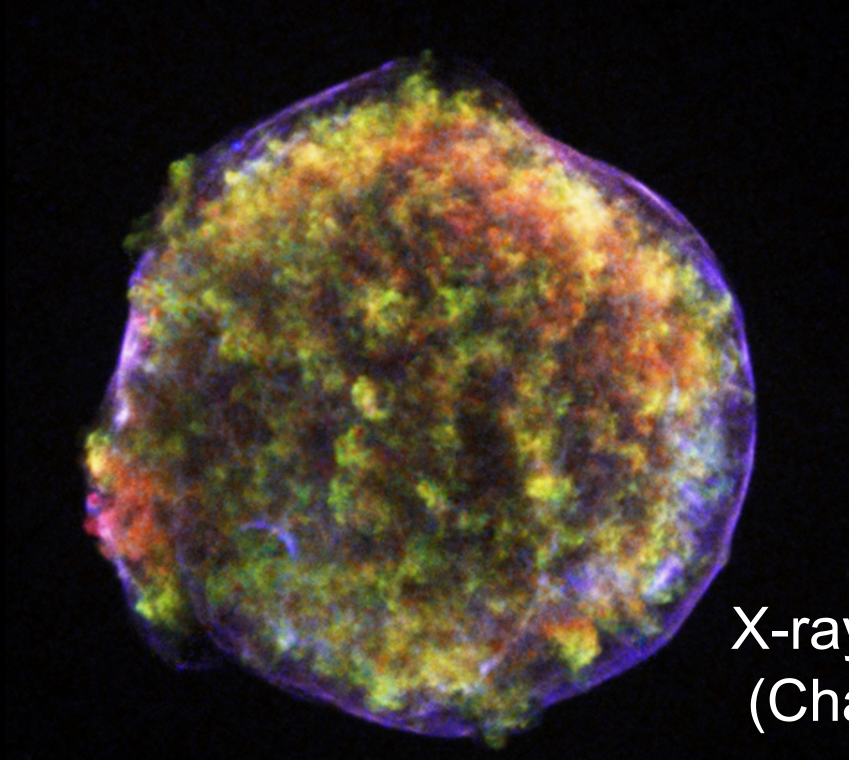
Updated from Thompson, Baldini, & Uchiyama (2012)

★ Tycho's SNR

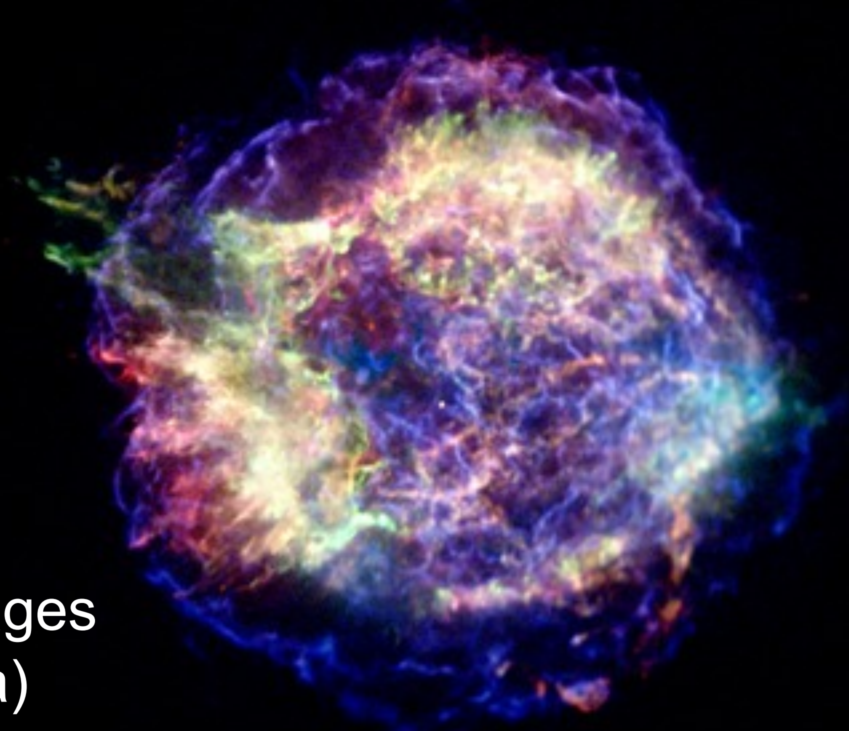
- SN 1572
- SN type: Ia
- distance: ~3 kpc
- radius: ~3.7 pc

★ Cassiopeia A

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



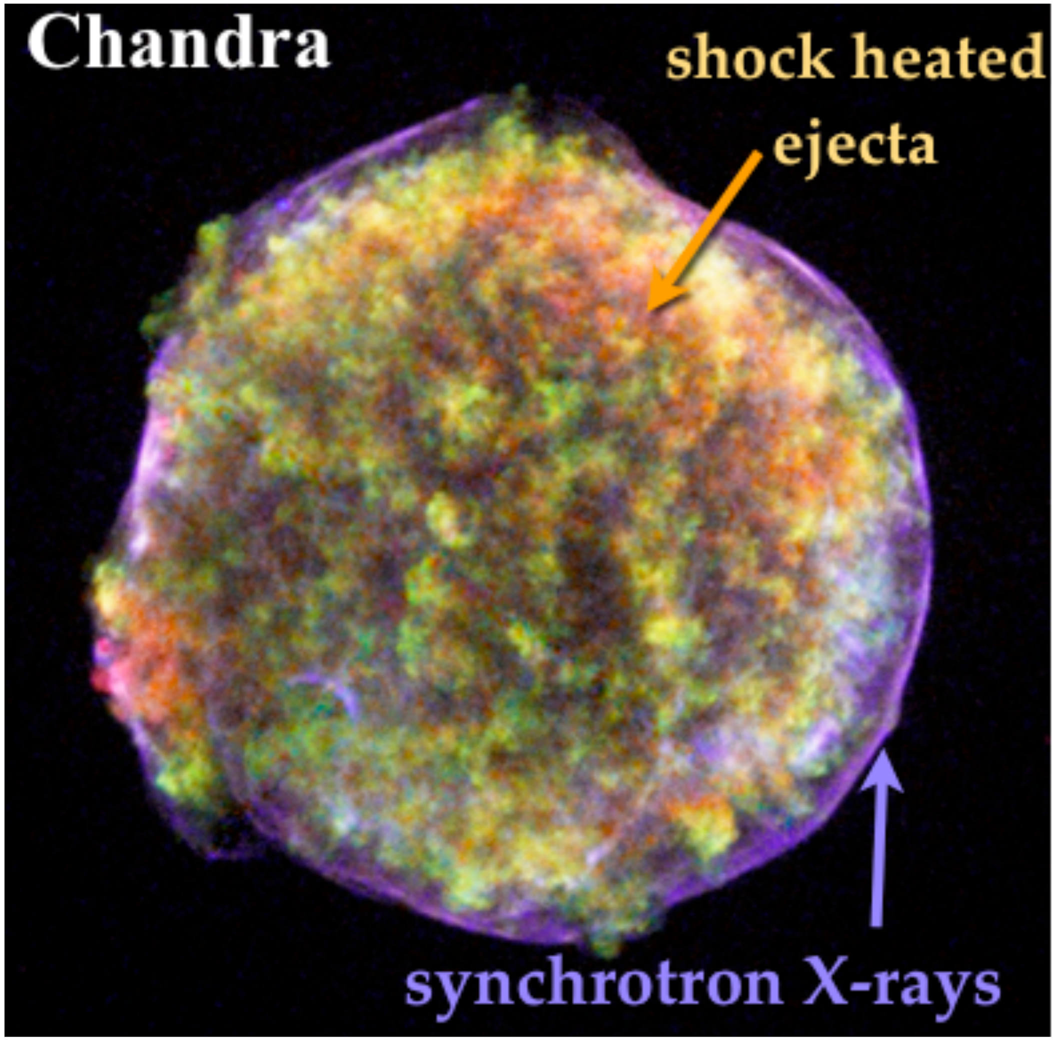
X-ray Images
(Chandra)



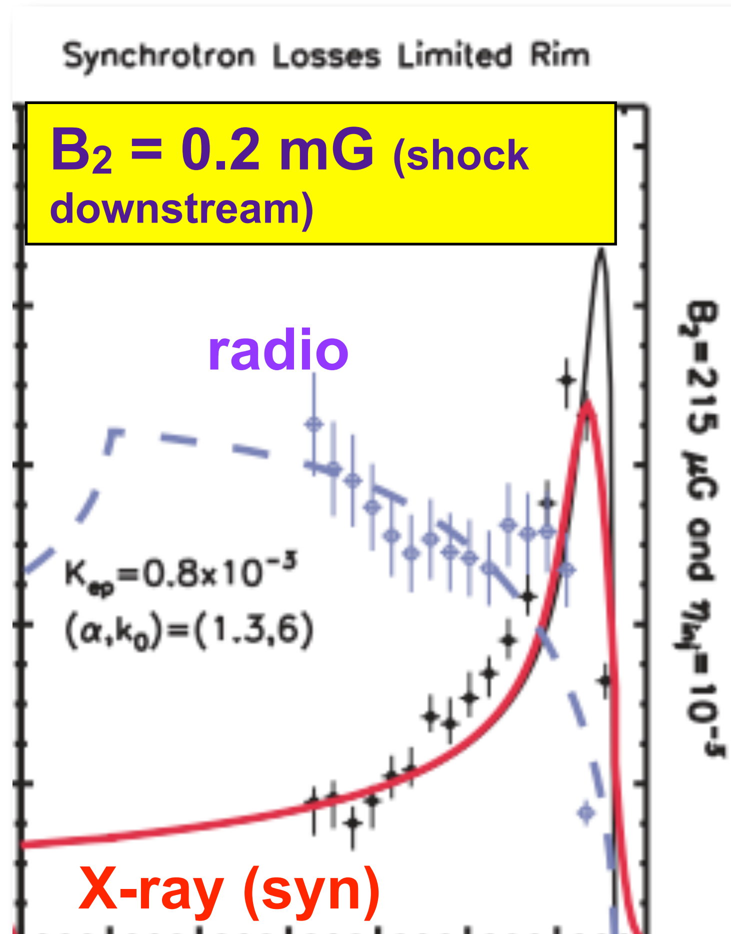
Most parameters are reasonably well known.
→ largely help us interpret gamma-ray results.

Tycho: Synchrotron & B-field

Warren+05



X-ray/radio radial profile

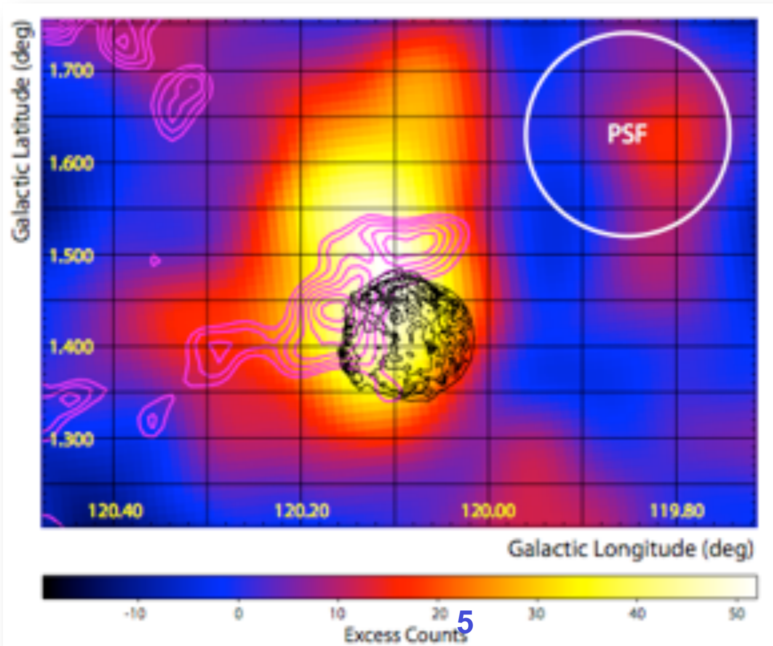


Cassam-Chenai+07

B_2 = 0.1-0.2 mG is inferred from the width of X-ray filaments
n_1 ~ 0.2 cm^{-3} from SNR dynamics

Tycho: TeV Detection

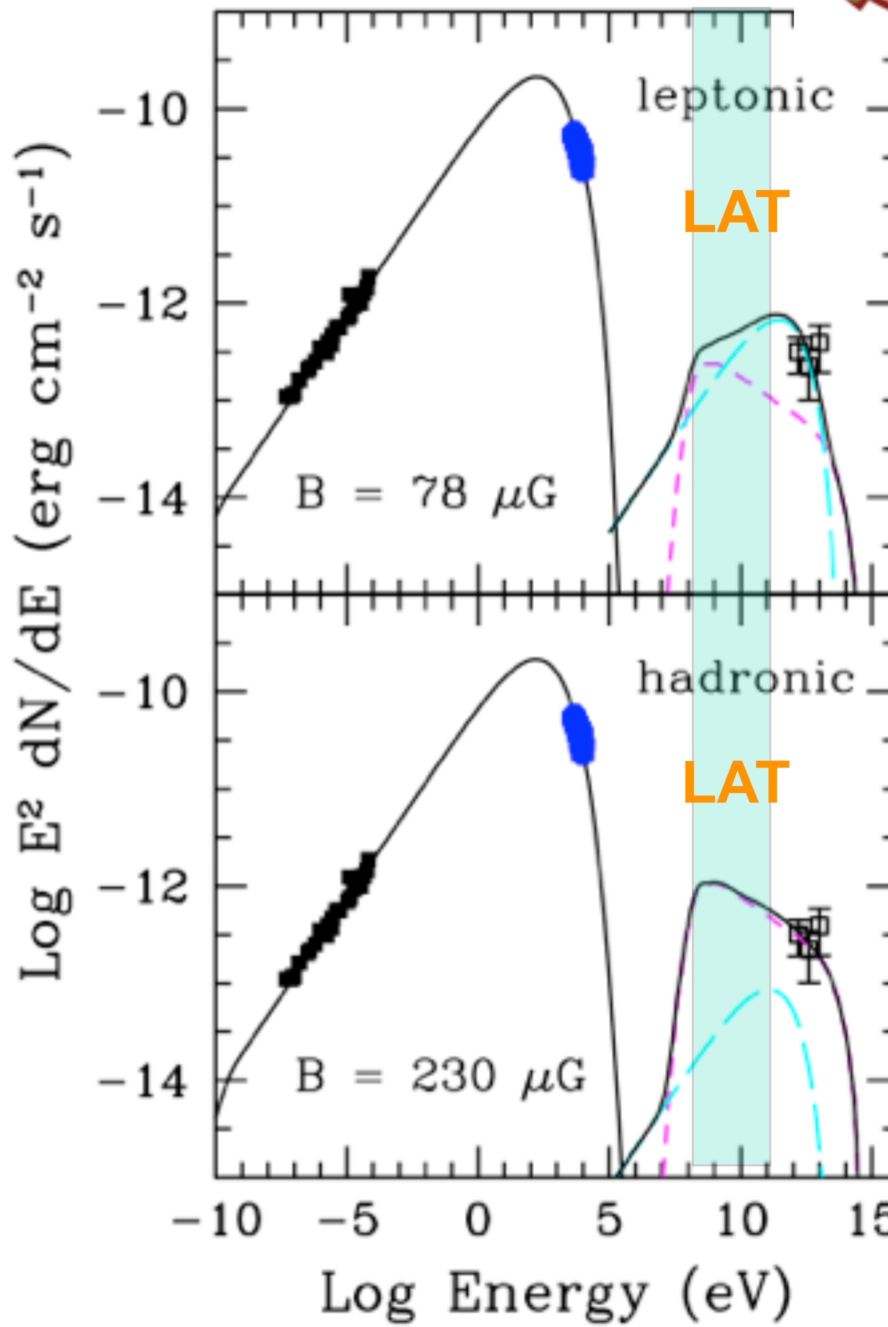
VERITAS Collaboration (2011)



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

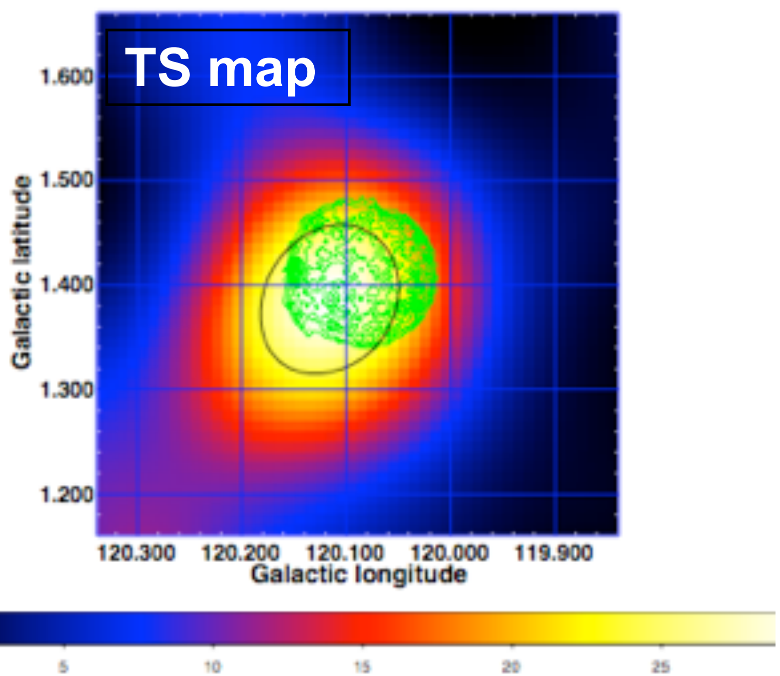
B-field constraint put by X-ray does *not* contradict IC origin.

Fermi-LAT can test "leptonic vs hadronic"

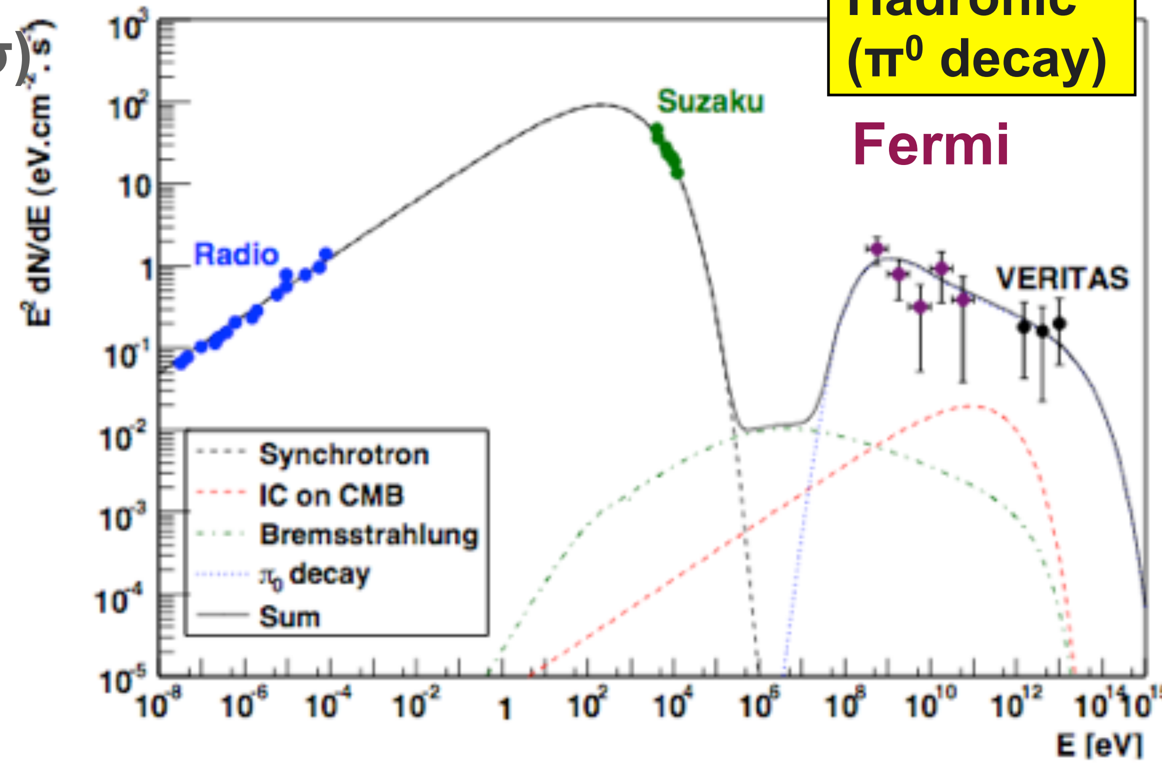


Tycho: LAT Detection

Fermi-LAT detection
of a point source at Tycho (~5σ)



Giordano+12



Hadronic (π^0 decay)

Fermi

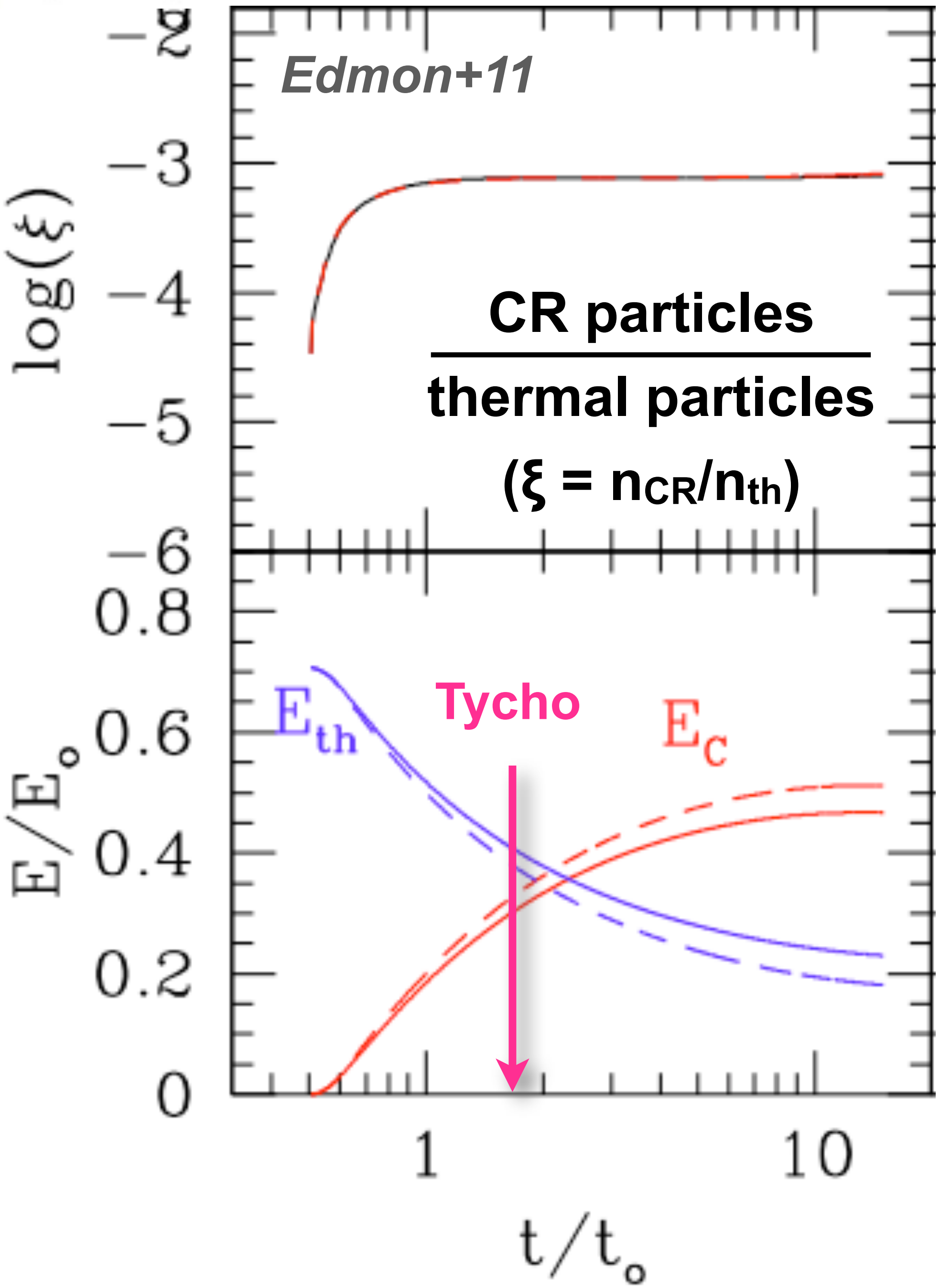
CR content

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

CR spectral index = 2.3

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

Eventually...

E_{CR} ~ 14% of E_{SN}

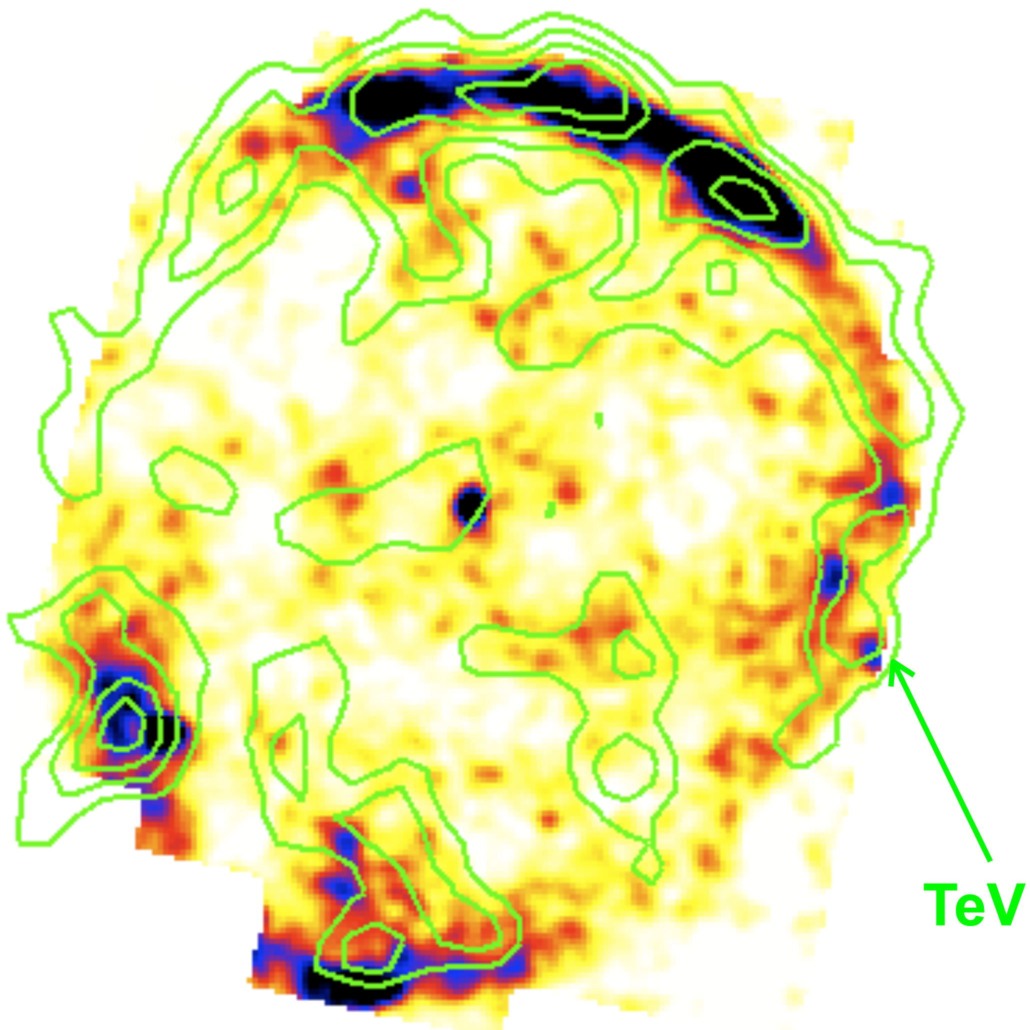
Supporting SNR origin of Galactic CRs

See also Morlino & Caprioli (2011) for non-linear DSA modeling

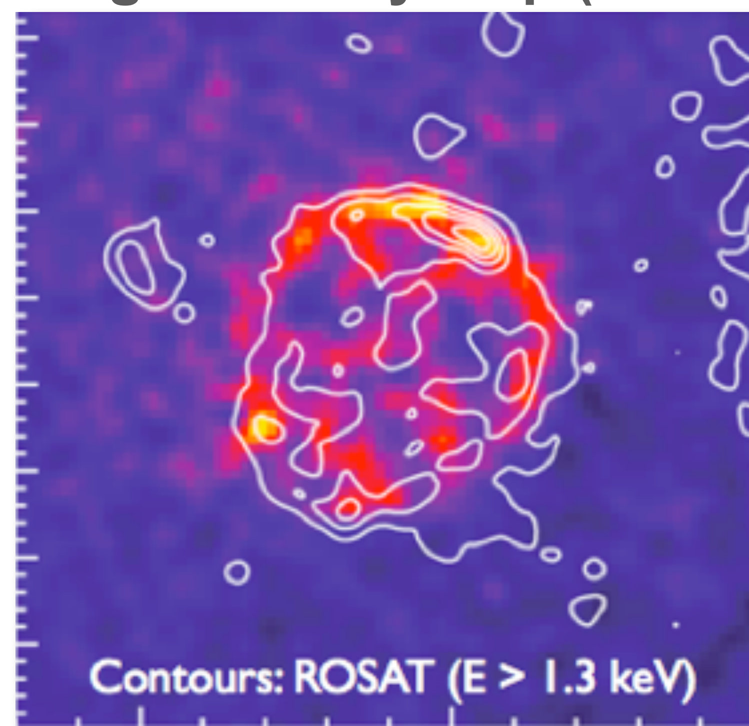
Vela Jr.: TeV-bright SNR

RX J0852.0-4622 (Vela Jr)

Suzaku X-ray (2-10 keV)
: synchrotron X-ray emission
(Y. Uchiyama)



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



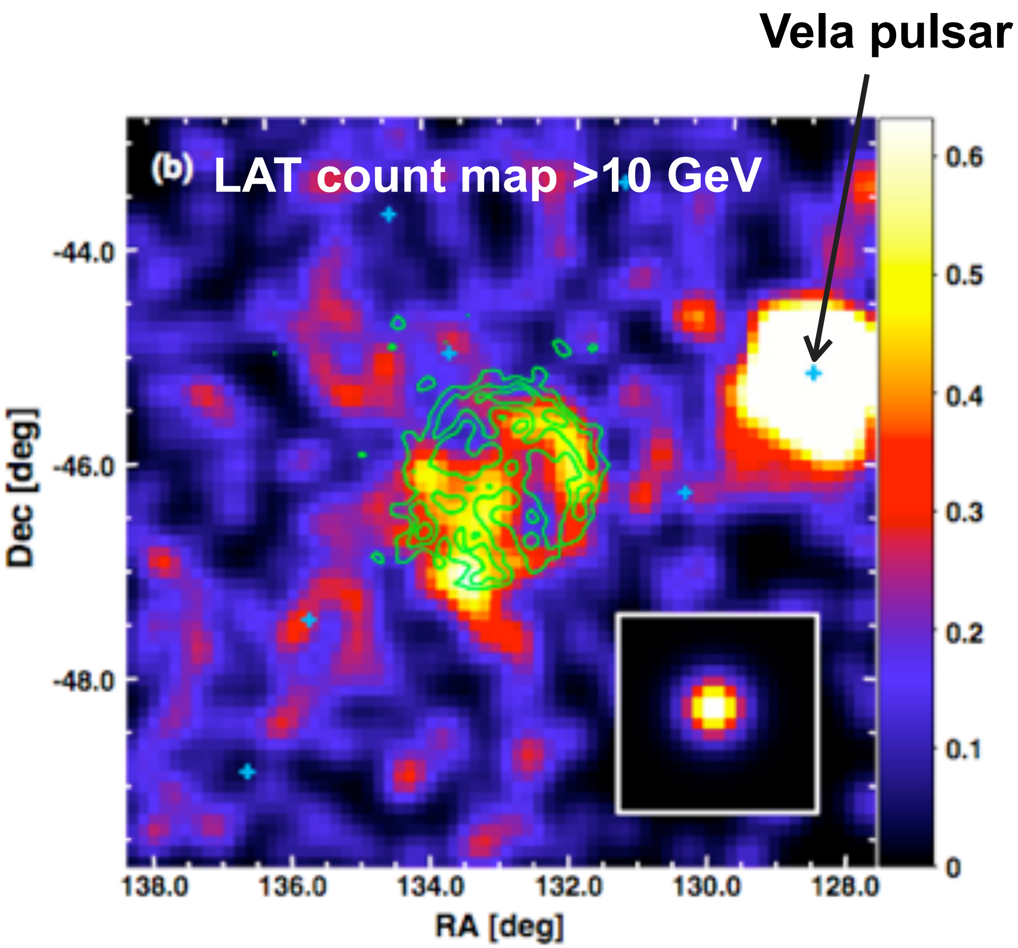
- age: 2000-4000 yr
- distance: ~0.75 kpc

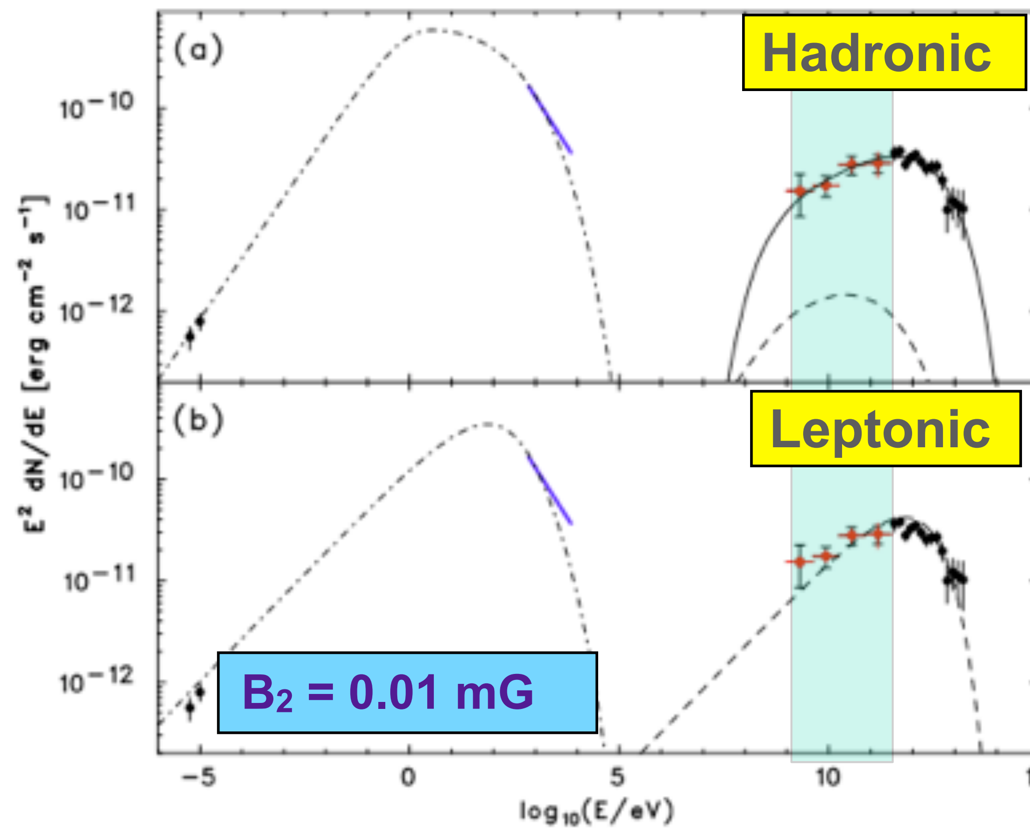
Katsuda+10

Synchrotron X-ray filament (Bamba+05):
≥ 0.1 mG (Berezhko+09)

Vela Jr.: LAT Results

Tanaka+2011



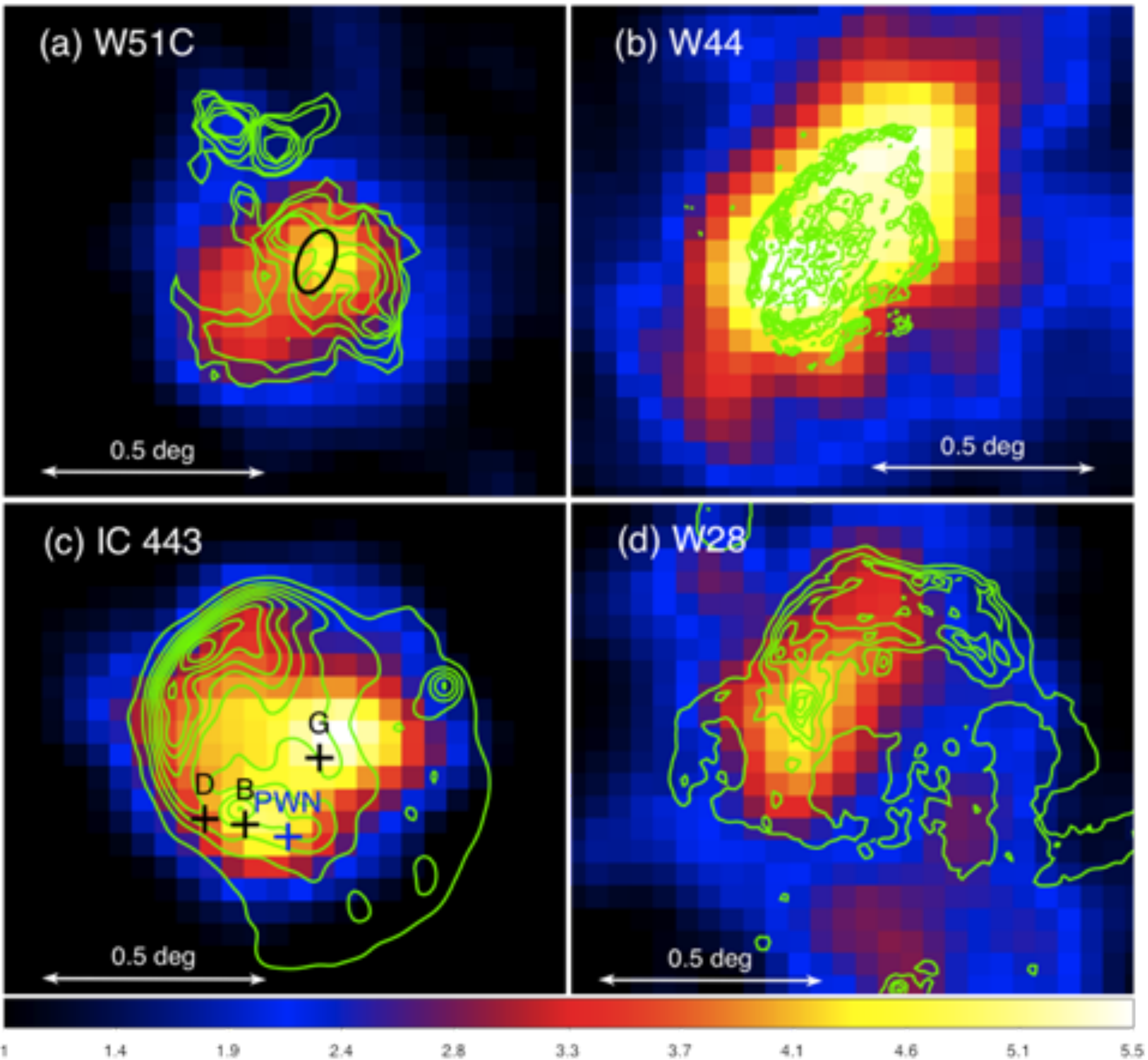


B_2 = 0.01 mG in leptonic model would be difficult to be reconciled with X-ray measurements.
Hadronic model would require a large CR content (5×10^{50} erg for n=0.1 cm^{-3})

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

LAT Observations of MC-SNRs

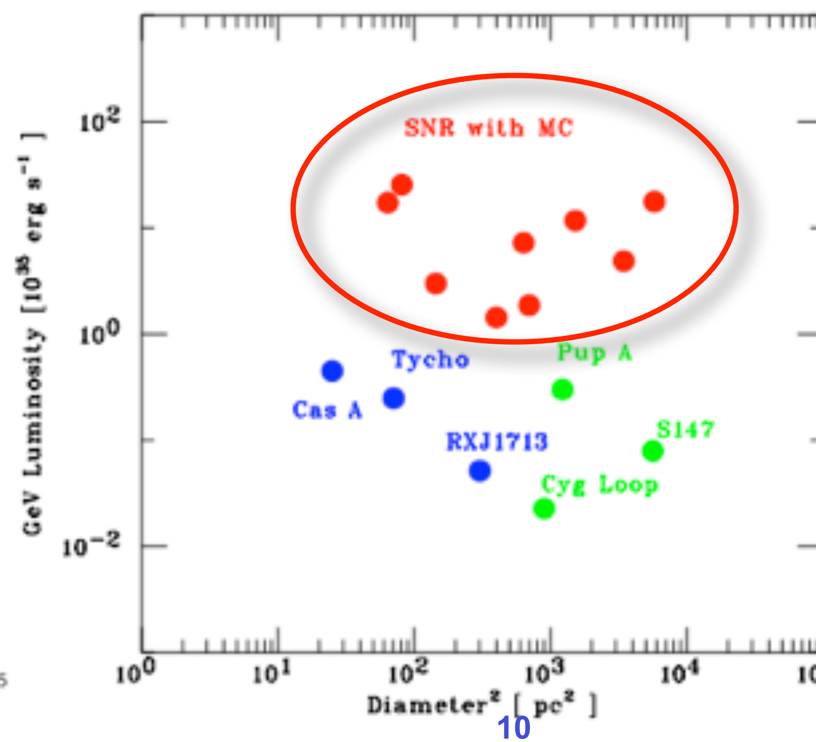
Fermi-LAT Collaboration (Uchiyama+) 2011



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

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

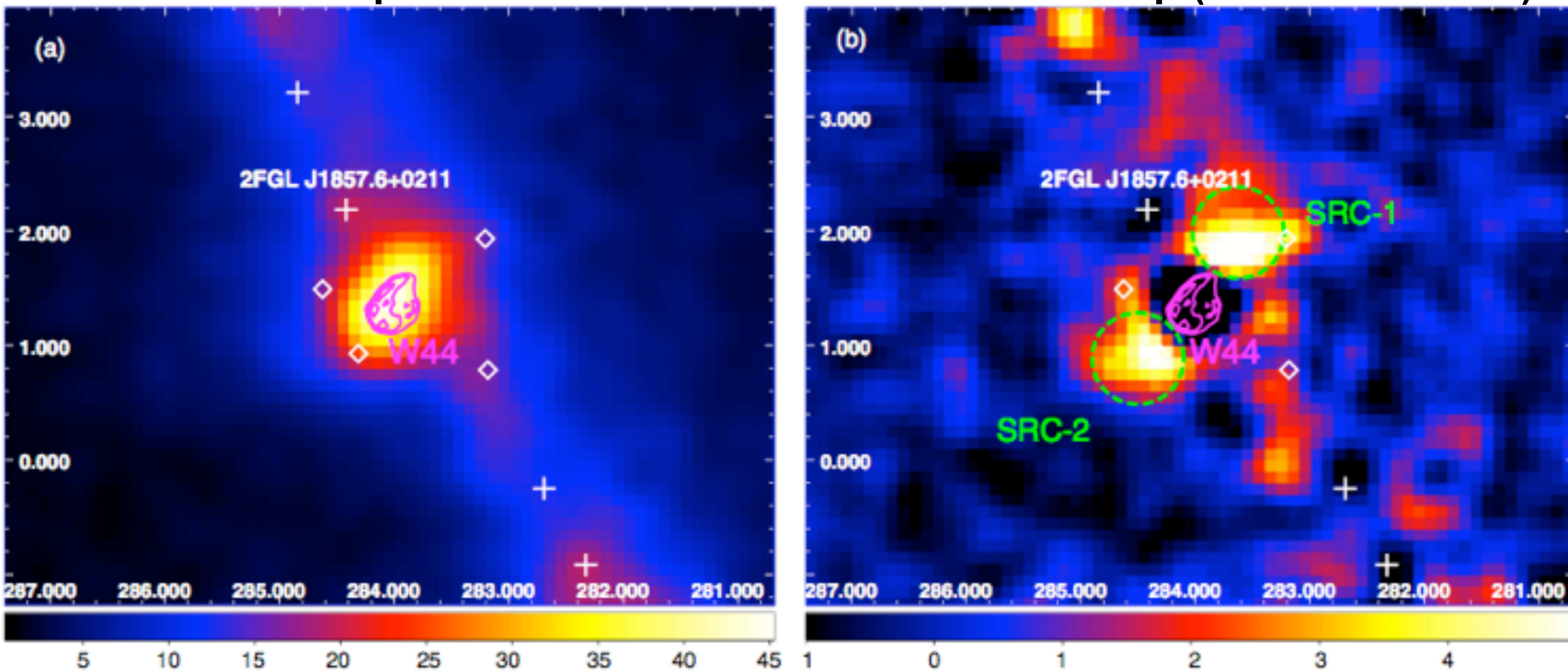
Spectral break in the GeV band
➜ GeV-bright objects
(GeV > TeV)



Fermi-LAT: W44 Region

Uchiyama+2012

count map 2-100 GeV **residual map (W44 subtracted)**

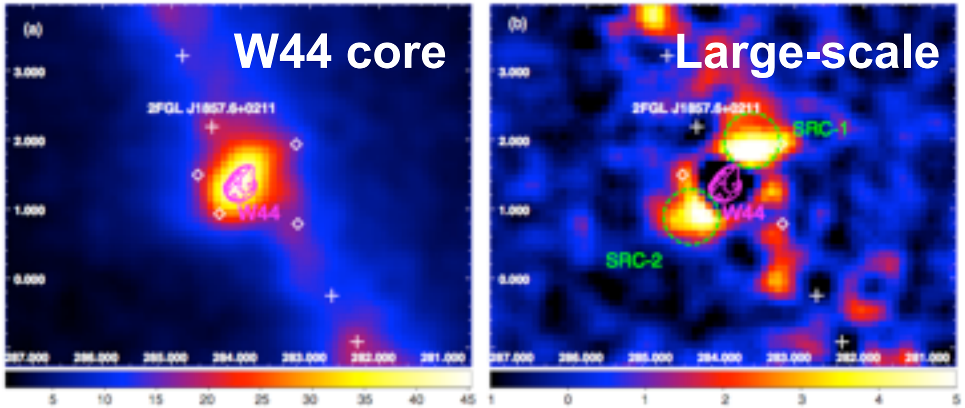


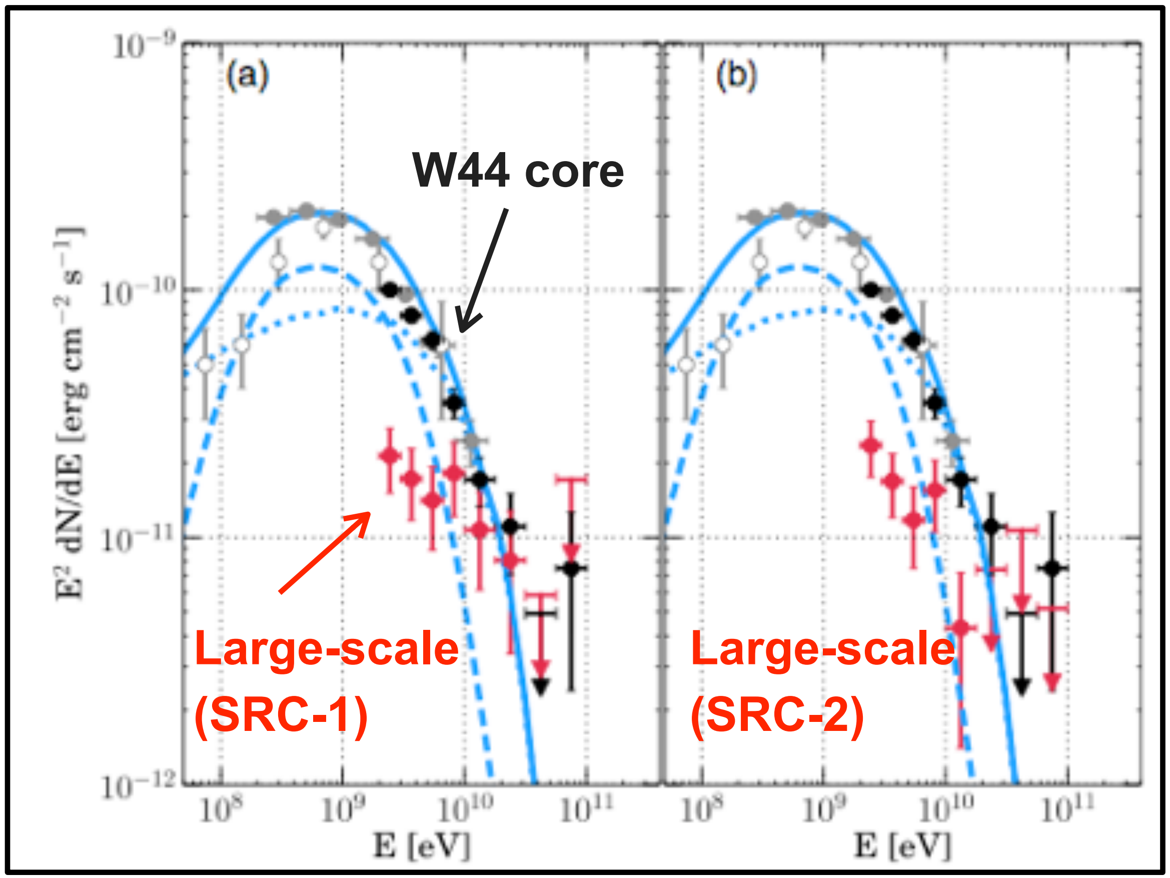
Gamma-rays from W44 itself are subtracted, assuming "radio map = gamma-ray map"

SRC-1 (disk template): TS = 75
SRC-2 (disk template): TS = 102

The presence of large-scale GeV emission was found in the vicinity of SNR W44

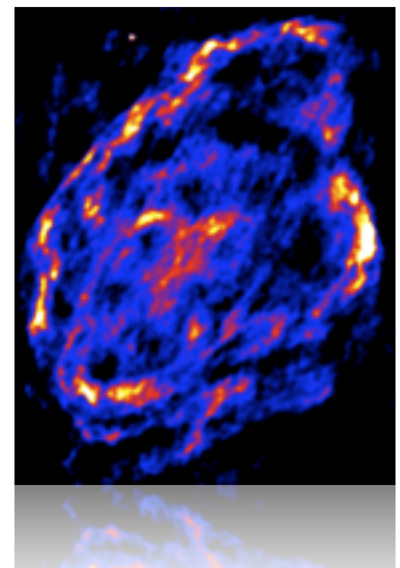
W44: “Core” and Large-scale Emission





W44 “Core”

π⁰-decay/brems from radio-emitting **dense filaments in SNR**
“Crushed Cloud” (Uchiyama+10)



Radio map of W44

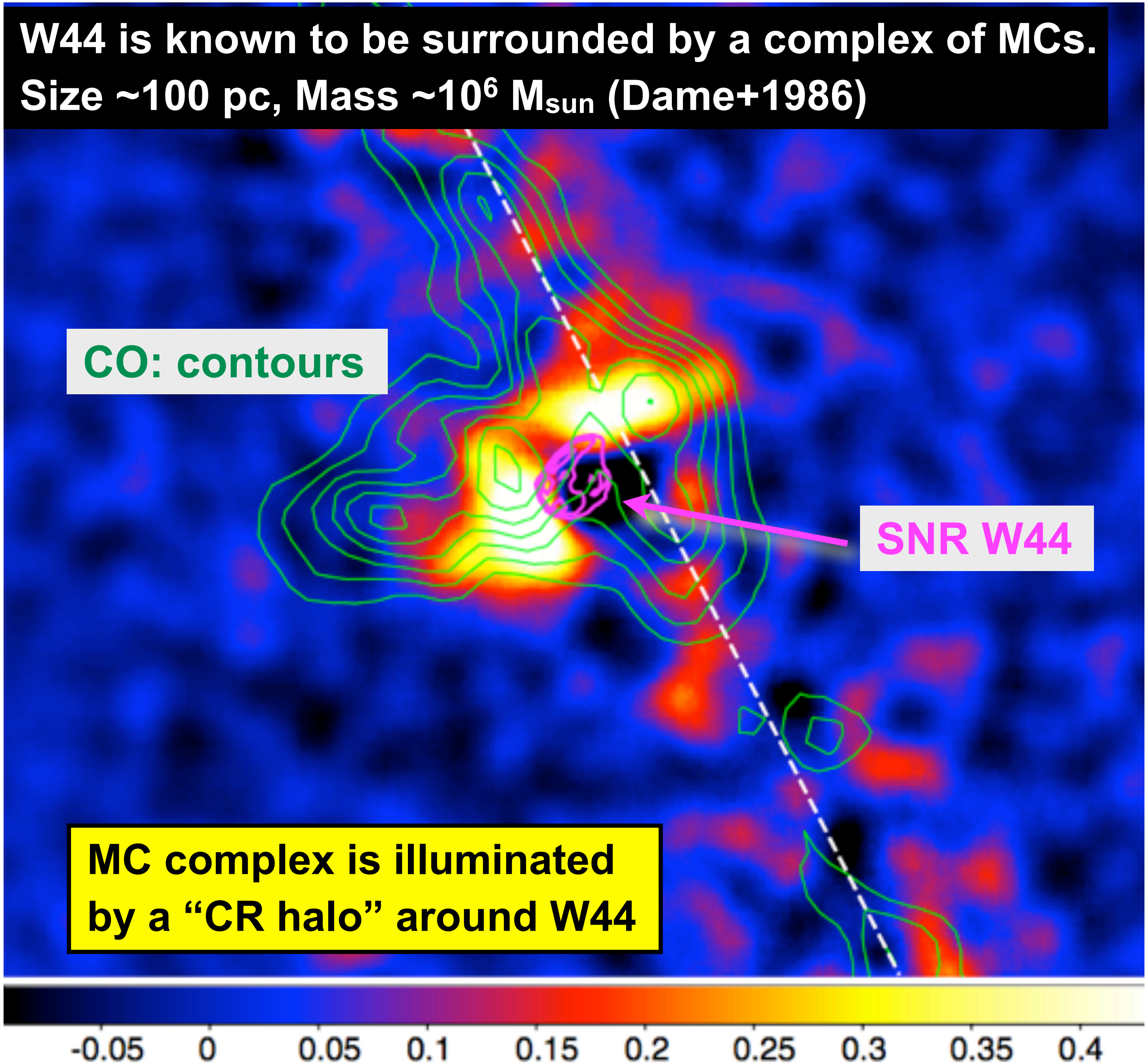
“Large-scale” around W44

π⁰-decay from **molecular cloud** outside SNR illuminated by **escaping CRs**

Large-scale GeV vs CO map

Uchiyama+2012

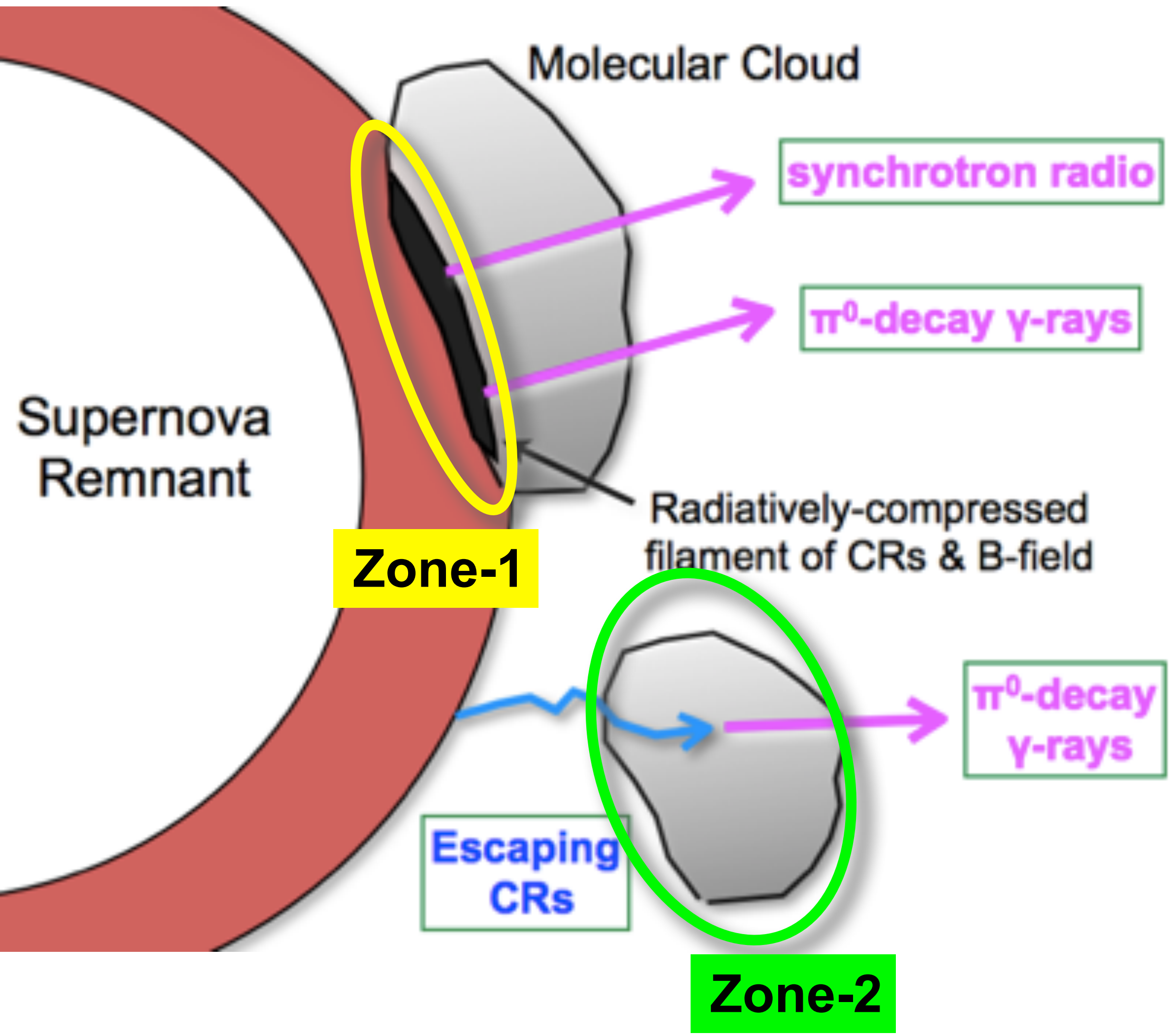
W44 is known to be surrounded by a complex of MCs.
Size ~100 pc, Mass ~10^6 M_{sun} (Dame+1986)

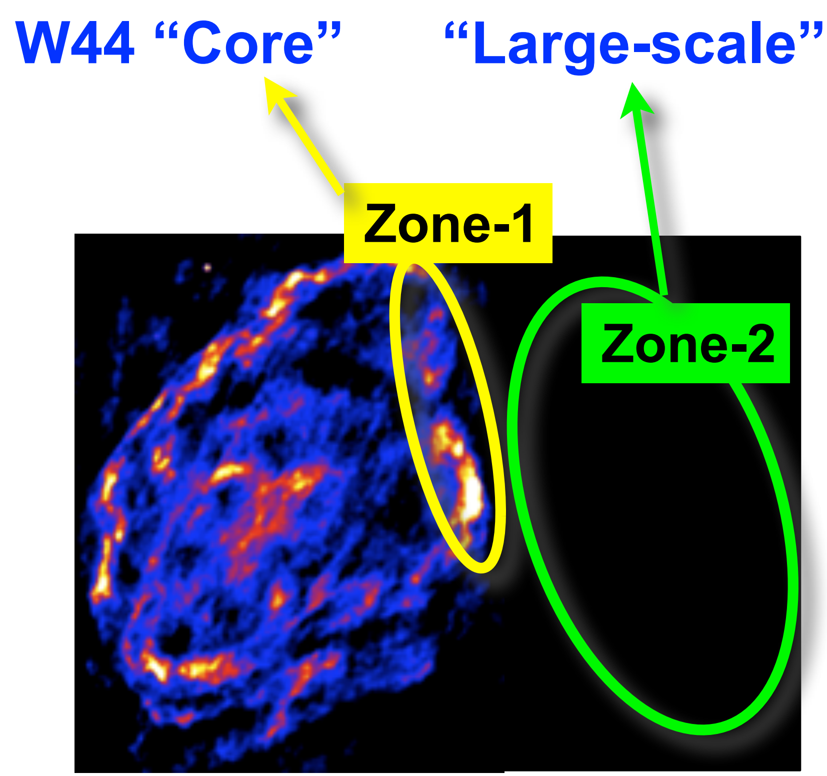


MC complex is illuminated by a "CR halo" around W44

Gamma-ray Production Regions

Zone-1: dense filaments = W44 "core"
Zone-2: surrounding MC hit by escaping CRs = "Large-scale" around W44

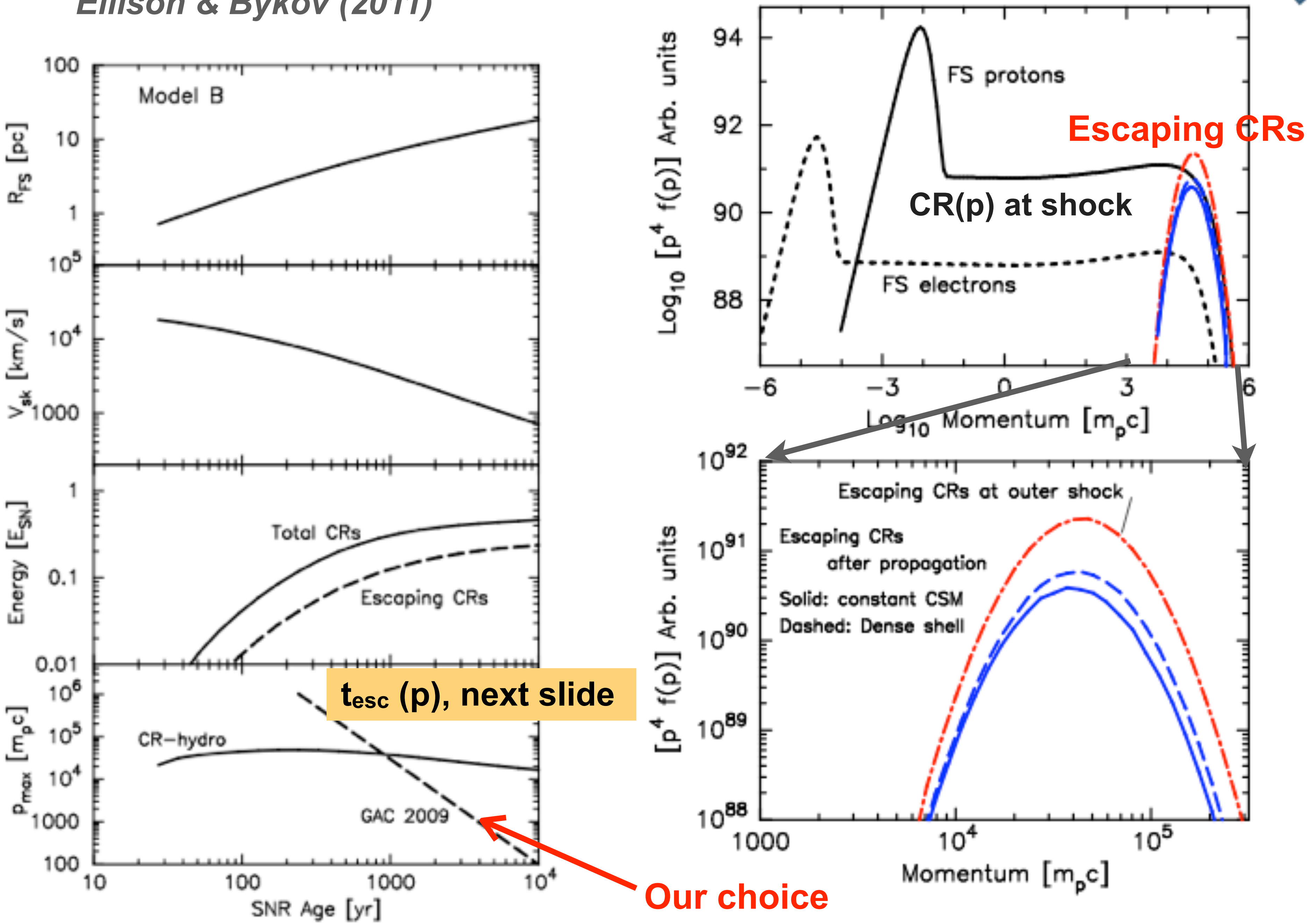




synchrotron radio emission
(correlated with shocked H_2 gas)

DSA: CR Escape

Ellison & Bykov (2011)



CR Halo around a SNR

n(p,r,t): CR distribution function (solving a diffusion equation) where "source term = expanding SNR surface" (Ohira+11)

Escaping CR (integrated) spectrum ← **free**

$$n(p,r,t) = \frac{N_{\rm esc}(p)}{4\pi^{3/2} R_d R_{\rm esc} r}\left[e^{-(r-R_{\rm esc})^2/R_d^2} - e^{-(r+R_{\rm esc})^2/R_d^2}\right], \quad (2)$$

where

Time-dependence of escaping CR energy (fixed, previous slide)

$$R_d(p,t) \equiv 2\sqrt{D_{\rm ISM}(p)[t - t_{\rm esc}(p)]}. \quad (3)$$

← **fixed**

The diffusion coefficient of the interstellar medium is often parameterized as

$$D_{\rm ISM}(p) = 10^{28}\, D_{28} \left(\frac{p}{10\ {\rm GeV}\ c^{-1}}\right)^{\delta} {\rm cm}^2\ {\rm s}^{-1}, \quad (4)$$

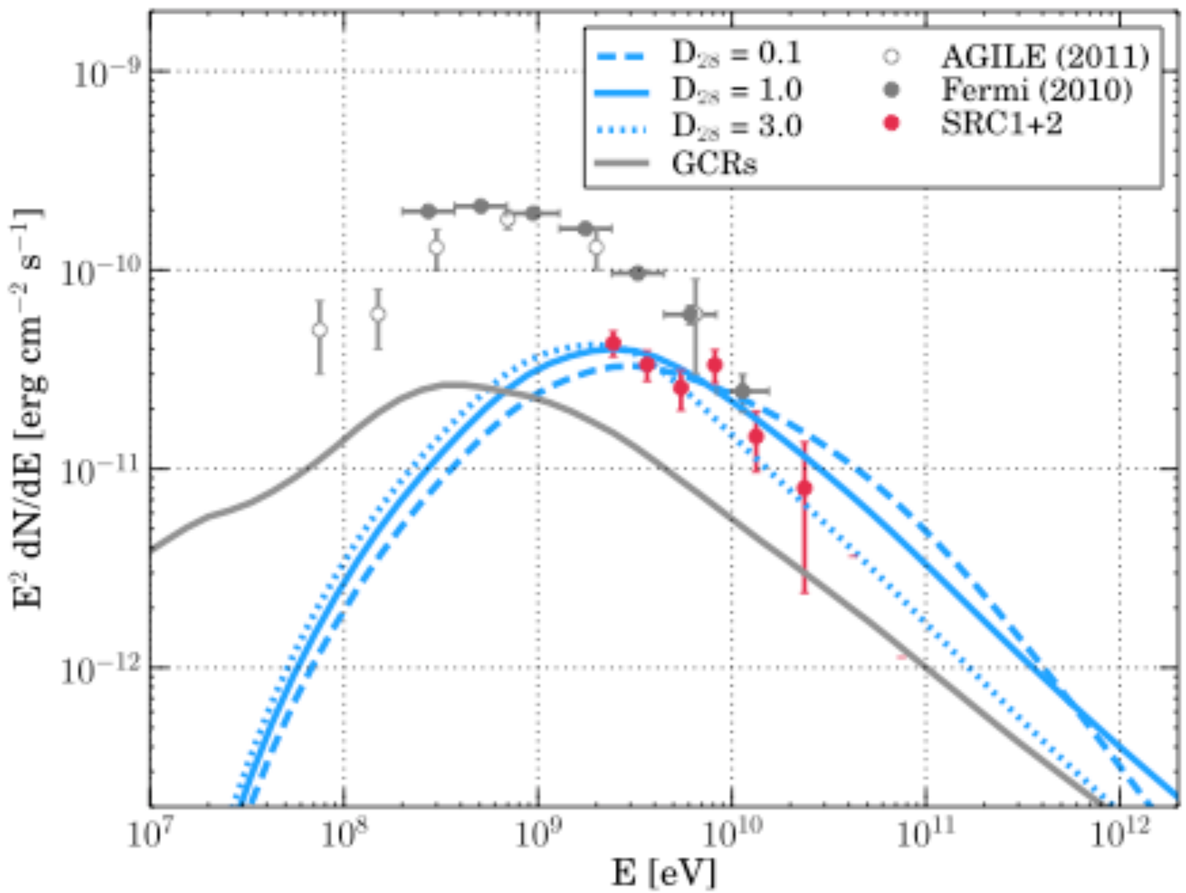
Diffusion coefficient: D_{28} : free, δ=0.6 fixed

free

Large-scale Emission around W44

MC cloud complex: R = 50 pc, Mass ~0.5×10^6 M_{sun}

$D_{28} > 0.1$ (source size)
$D_{28} < 3$ (energetics)



Case 1. slow diffusion ($D_{28} = 0.1$)

$N_{esc}(E) = k\, E^{-2.6}$

$W_{esc} = 0.3\times10^{50}$ erg

Case 2. standard ($D_{28} = 1$)

$N_{esc}(E) = k\, E^{-2.0}$

$W_{esc} = 1.1\times10^{50}$ erg

Case 3. fast diffusion ($D_{28} = 3$)

$N_{esc}(E) = k\, E^{-2.0}$

$W_{esc} = 2.7\times10^{50}$ erg

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? (But B-field too low?)
- SNRs interacting with molecular clouds
  - W51C, W44, IC443, W28, W49B, W30, ...
  - Hadronic origin is preferred
  - "Crushed Cloud" scenario works in many cases
  - Escaping CRs are responsible for W44 surroundings

For Tycho's SNR: $W_{CR} \sim 1\text{x}10^{50}$ erg
For SNR W44: $W_{esc} \sim 1\text{x}10^{50}$ erg
➜ Support SNR Origin of GCRs