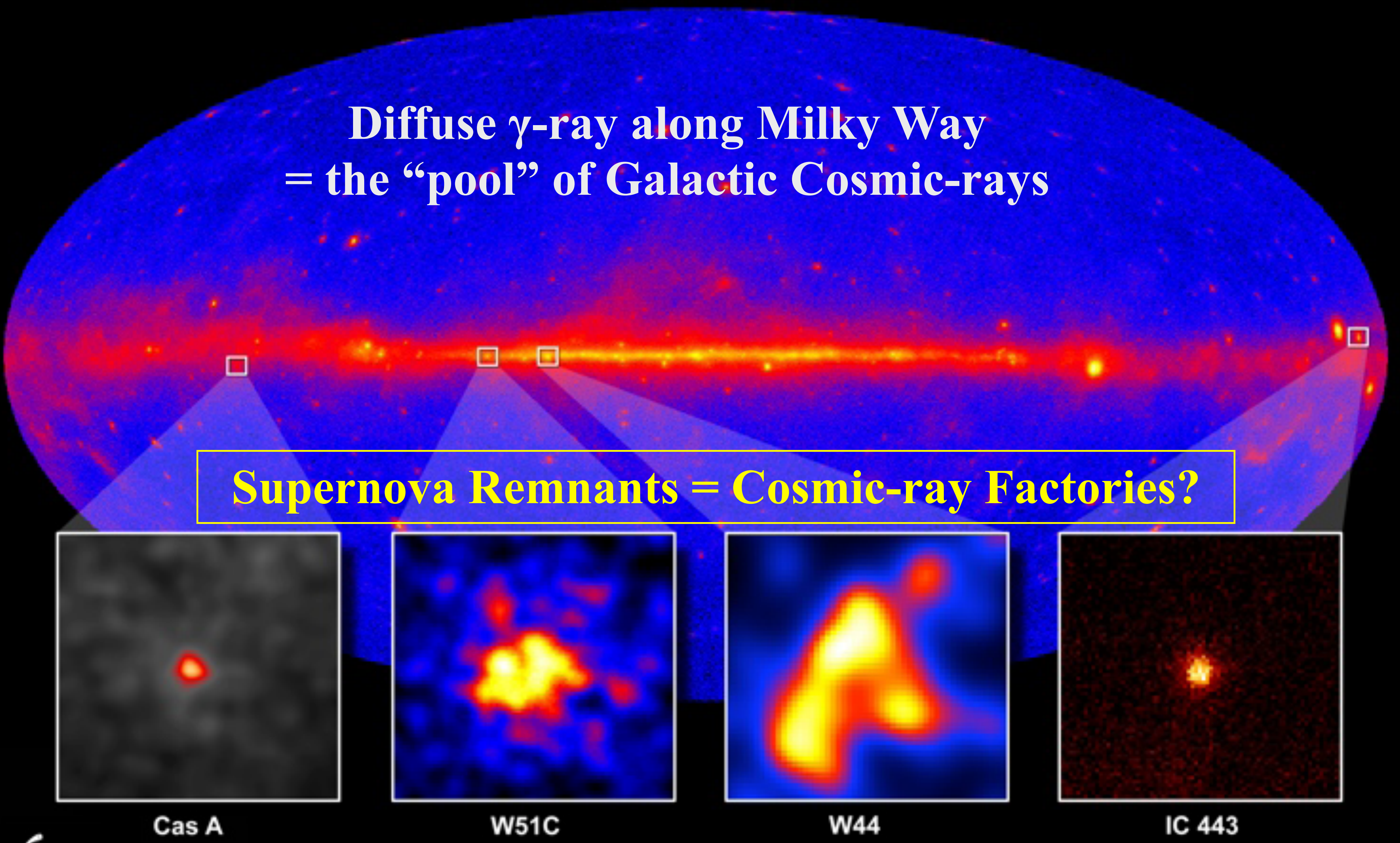
JPS Meeting: September 13th 2010

Gamma-Rays from Supernova Remnants: Illuminating the Origin of Cosmic-Rays

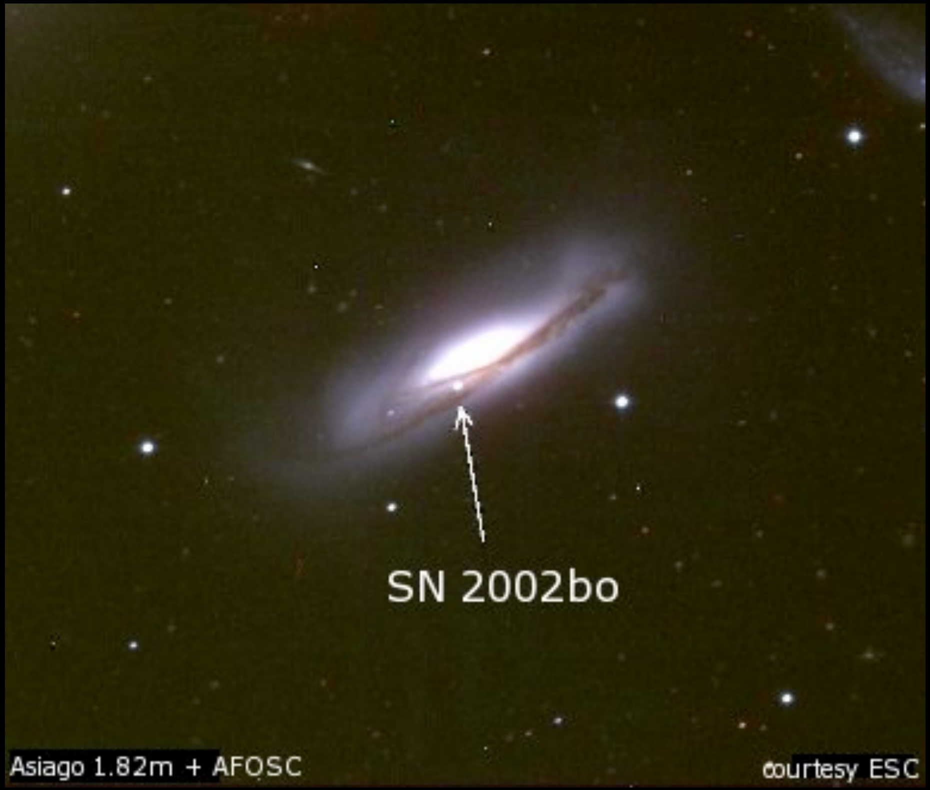
Yasunobu Uchiyama (SLAC)
on Behalf of the Fermi-LAT Collaboration

Map: Fermi-LAT 1-yr Observations



the “pool” of Galactic Cosmic-rays

Supernovae and their Remnants

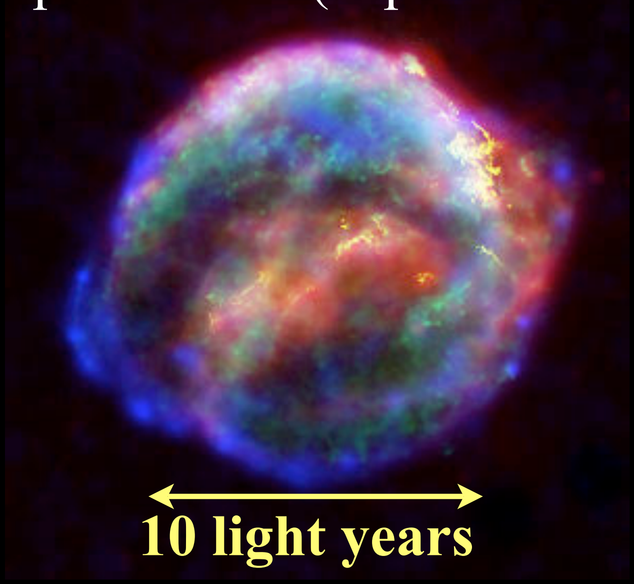


Supernova explosion:
10 billion times brighter than the Sun

Type 1a: energy = thermonuclear fusion
E = 2 MeV/nucleon
total energy: 10^{51} erg

Type II, Ib, Ic : energy = gravity
E = 200 MeV/nucleon
total energy: 10^{53} erg (99% neutrinos)
kinetic energy: 10^{51} erg

Kepler's SNR (exploded in 1604)

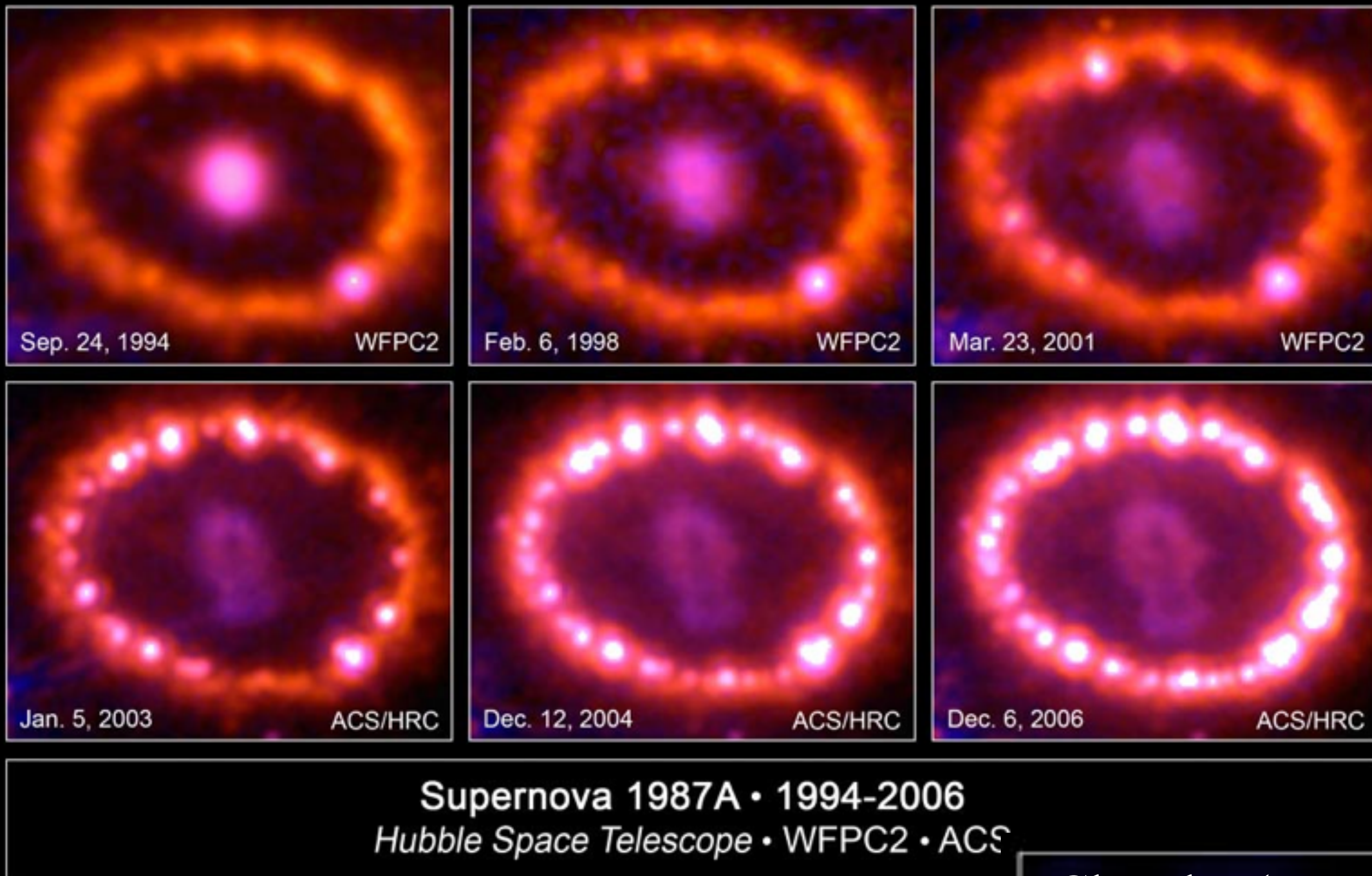


Kinetic Energy (10^{51} ergs) released as expanding stellar material (ejecta, ~M_{sun}) creates
a "**supernova remnant**" (SNR)

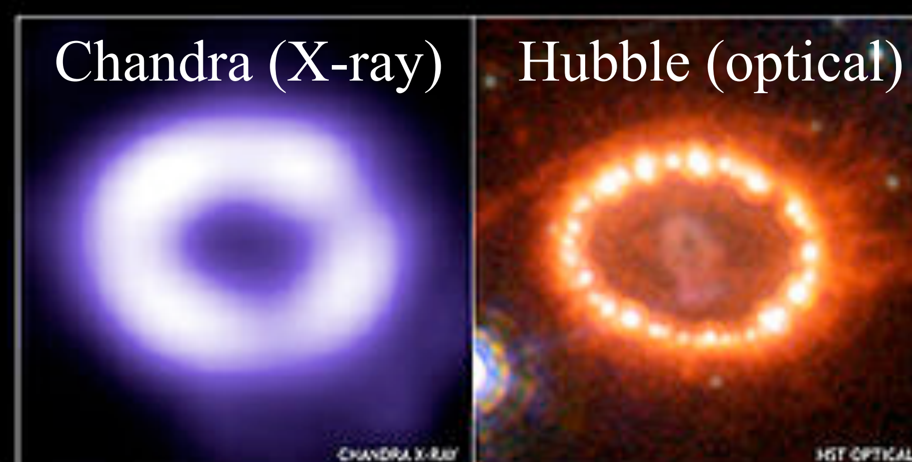
Sources of (heavy) elements
Sources of kinetic/turbulent energy in ISM
Sources of cosmic rays

23 years after SN explosion...

SNR 1987A



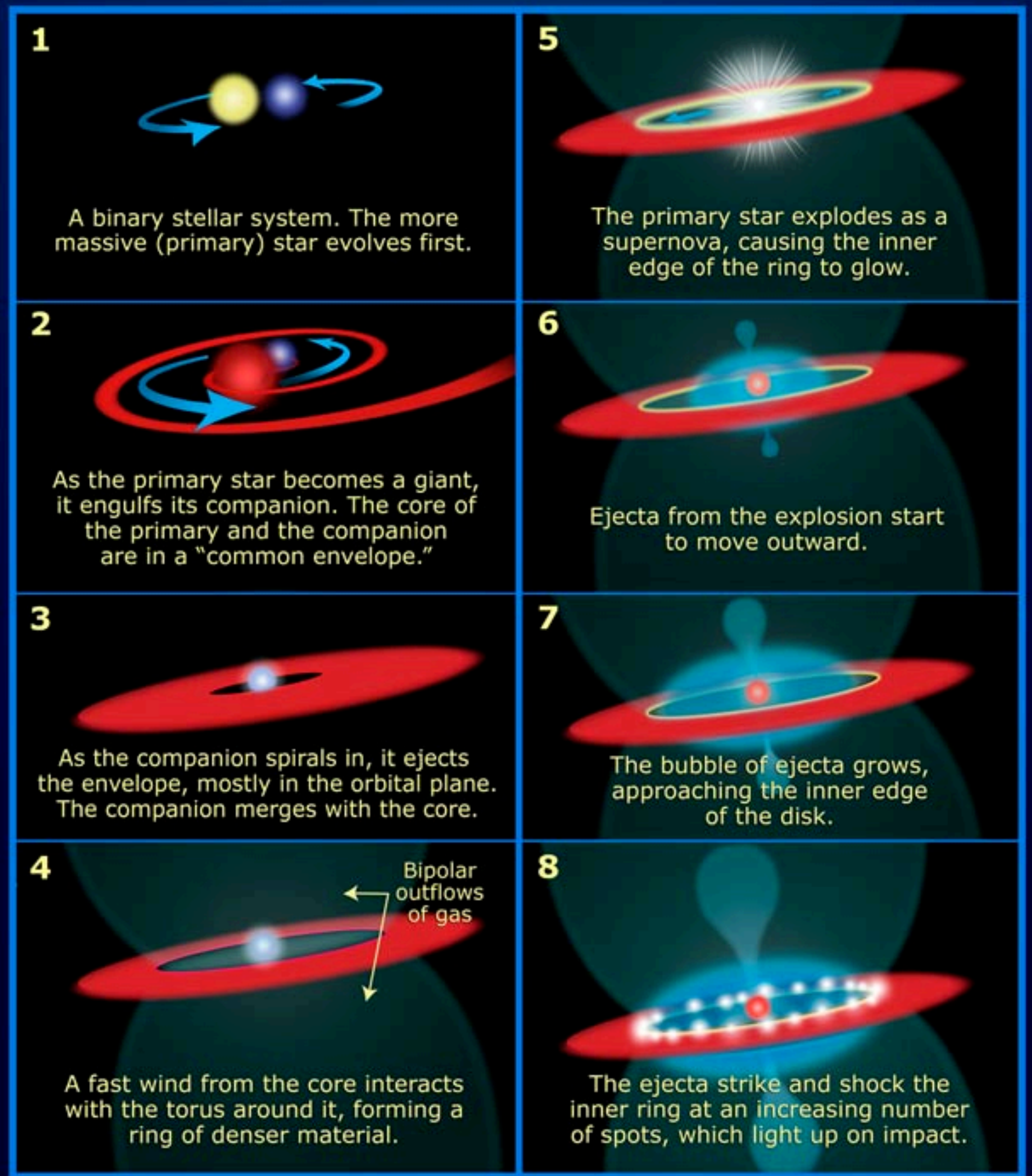
NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)



E_{grav} ~ 200 MeV/nucleon

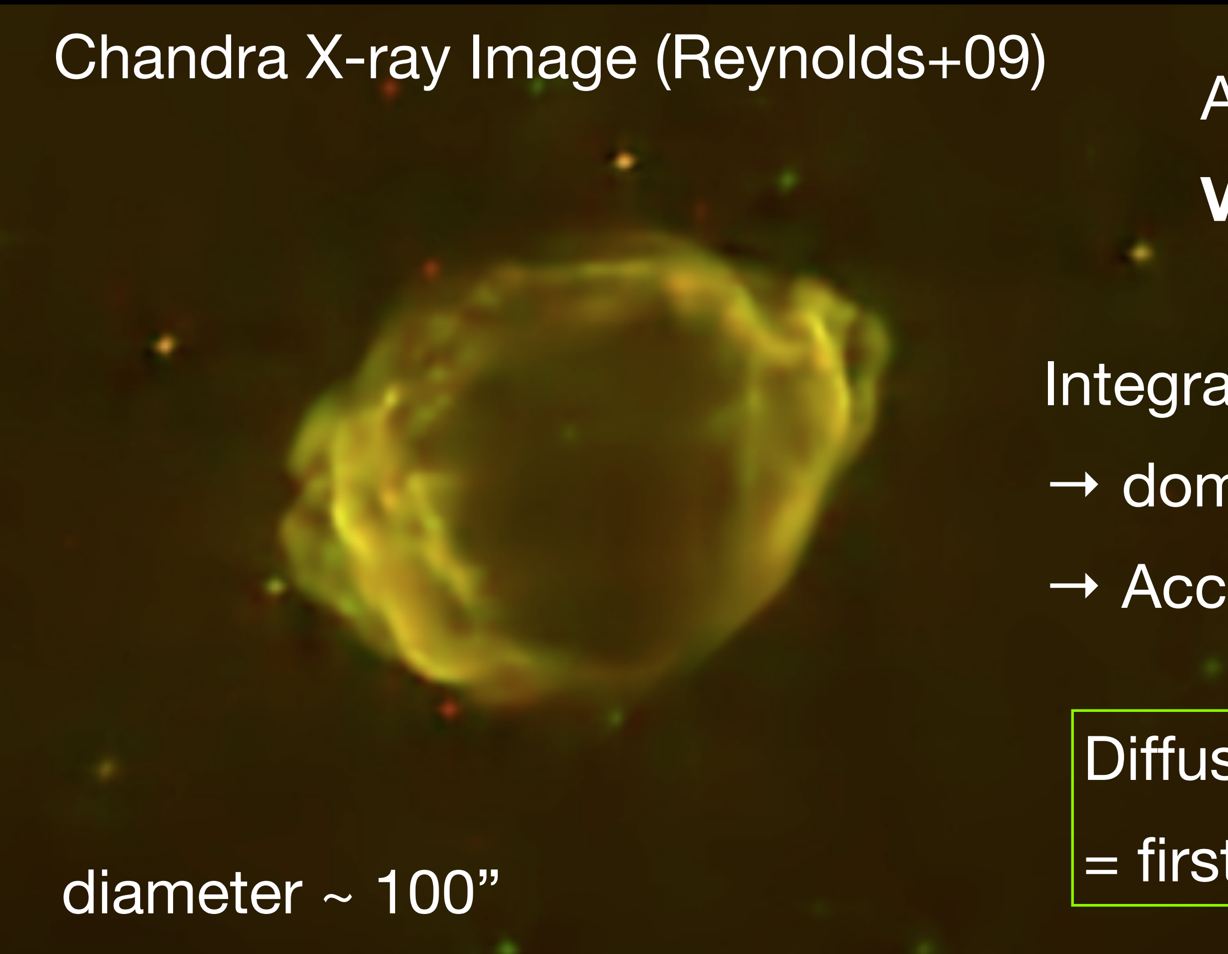
→ Ekin ~ 2 MeV/proton

→ X-ray emitting gas


1
A binary stellar system. The more massive (primary) star evolves first.
2
As the primary star becomes a giant, it engulfs its companion. The core of the primary and the companion are in a "common envelope."
3
As the companion spirals in, it ejects the envelope, mostly in the orbital plane. The companion merges with the core.
4
Bipolar outflows of gas
A fast wind from the core interacts with the torus around it, forming a ring of denser material.
5
The primary star explodes as a supernova, causing the inner edge of the ring to glow.
6
Ejecta from the explosion start to move outward.
7
The bubble of ejecta grows, approaching the inner edge of the disk.
8
The ejecta strike and shock the inner ring at an increasing number of spots, which light up on impact.

~100 years after SN explosion...

The Youngest Galactic SNR: G1.9+0.3



Age < 140 yr (~100 yr)

Vs ~ 14,000 km/s (at 8.5 kpc)

Integrated X-ray spectrum

→ dominated by synchrotron radiation

→ Acceleration of TeV electrons

Diffusive Shock Acceleration (DSA)

= first order Fermi acceleration

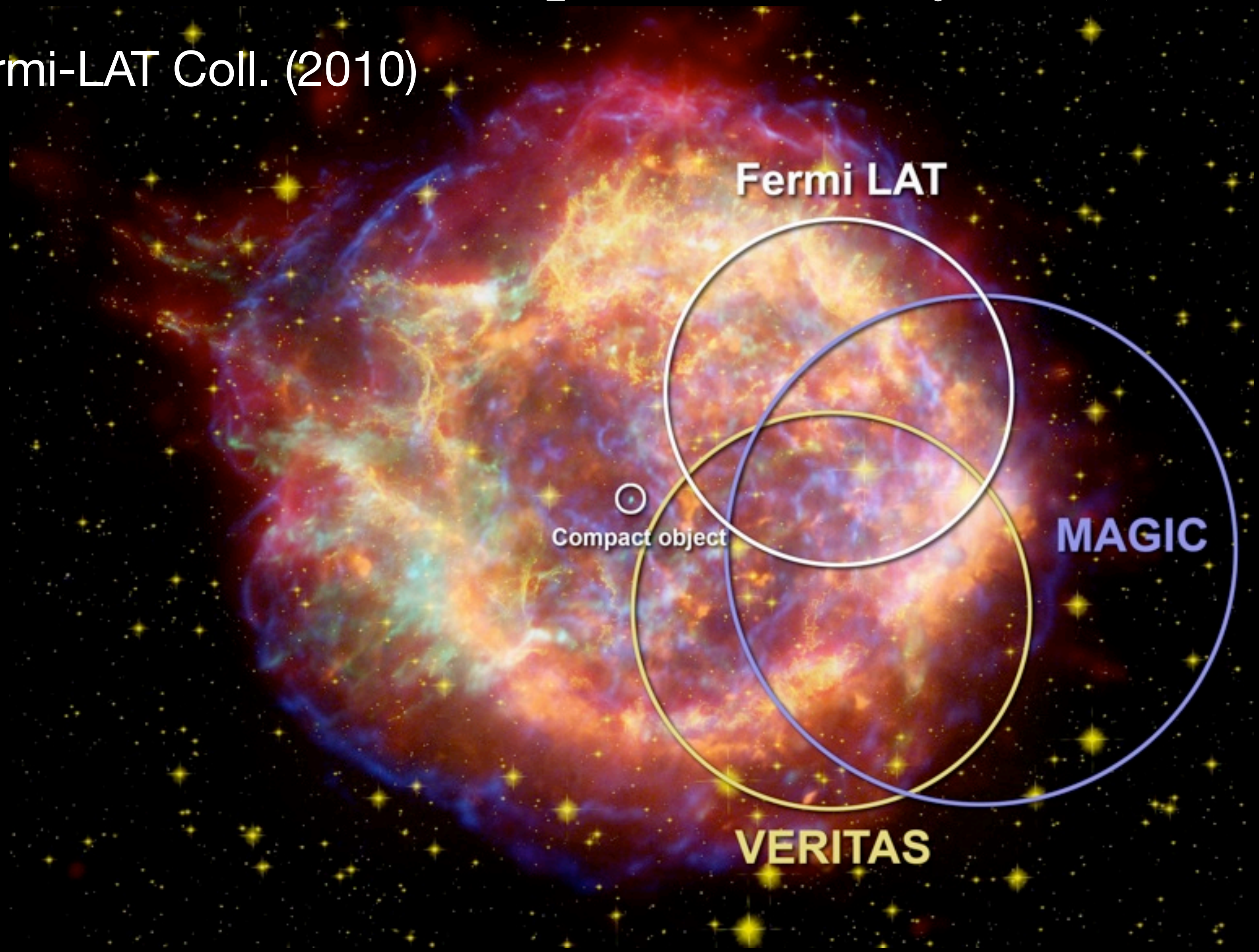
To understand the origin of cosmic-rays:

☛ Maximum attainable energy; but *e*$^-$ suffer from radiative losses

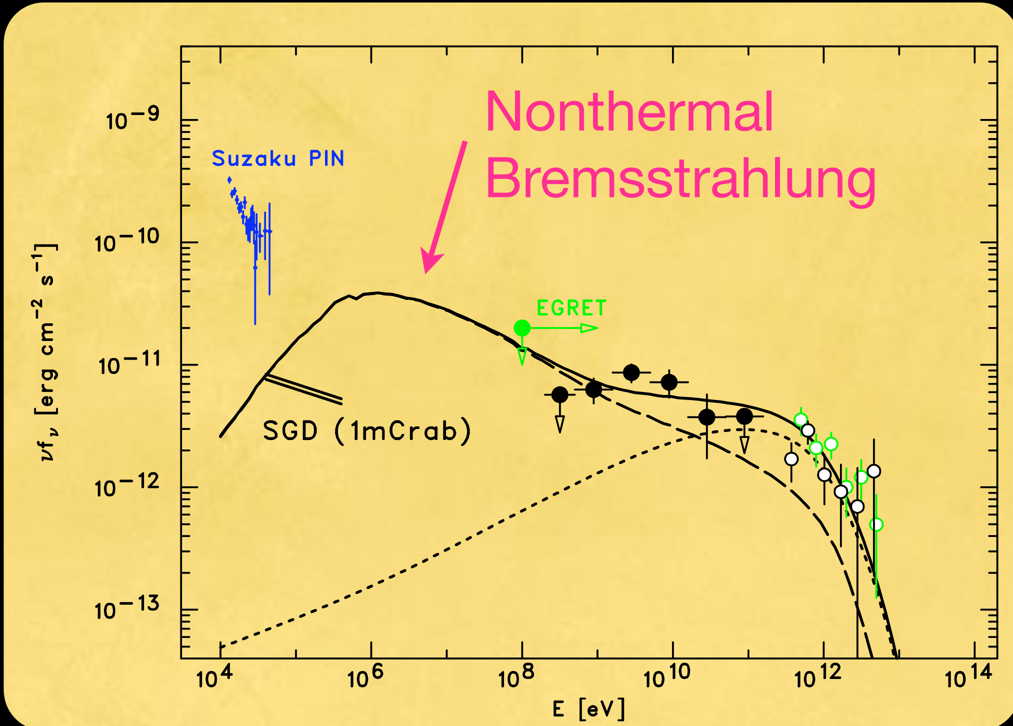
☛ Total energy content of accelerated *p*/*e*$^-$; but *e*$^-$ has a minor contribution

~340 years after SN explosion...

SNR Cassiopeia A (~340 yr old)



GeV γ-ray detection (Fermi-LAT)
TeV γ-ray detections (HEGRA,MAGIC,VERITAS)

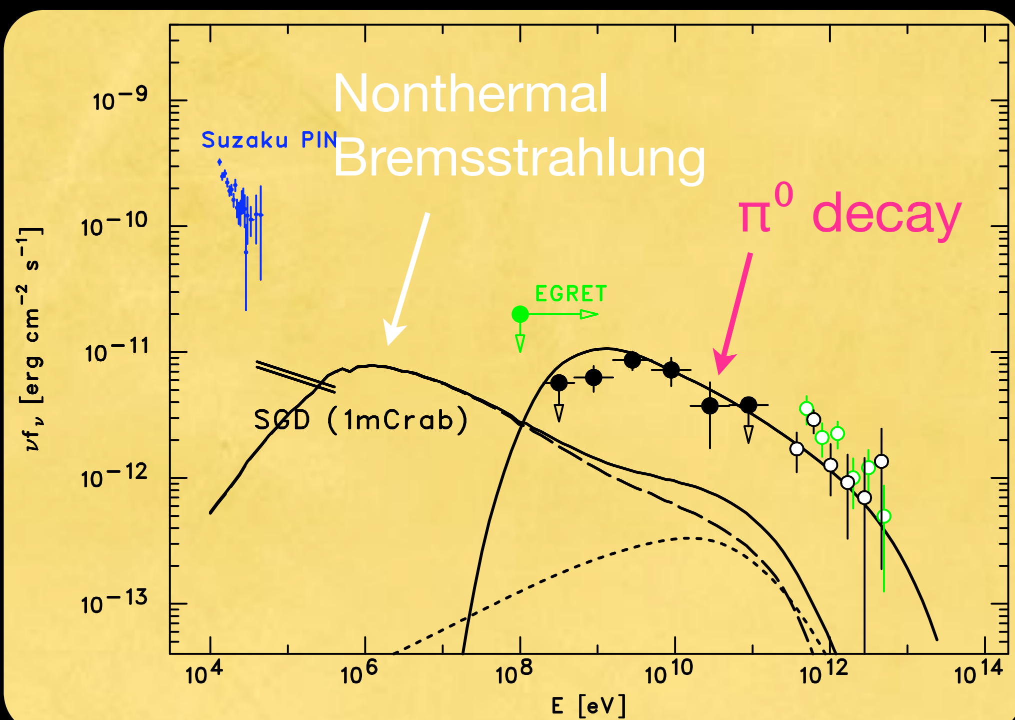


(a) **Leptonic** (Bremsstrahlung + IC)

B = 0.12 mG

CR electrons: $W_e = 1 \times 10^{49}$ erg

Not consistent with B ~ 0.5 mG (X-ray)



(b) **Hadronic** (π^0 decay)

B > 0.12 mG

CR protons: $W_p = 5 \times 10^{49}$ erg

CR content: 2% of E_{SN}

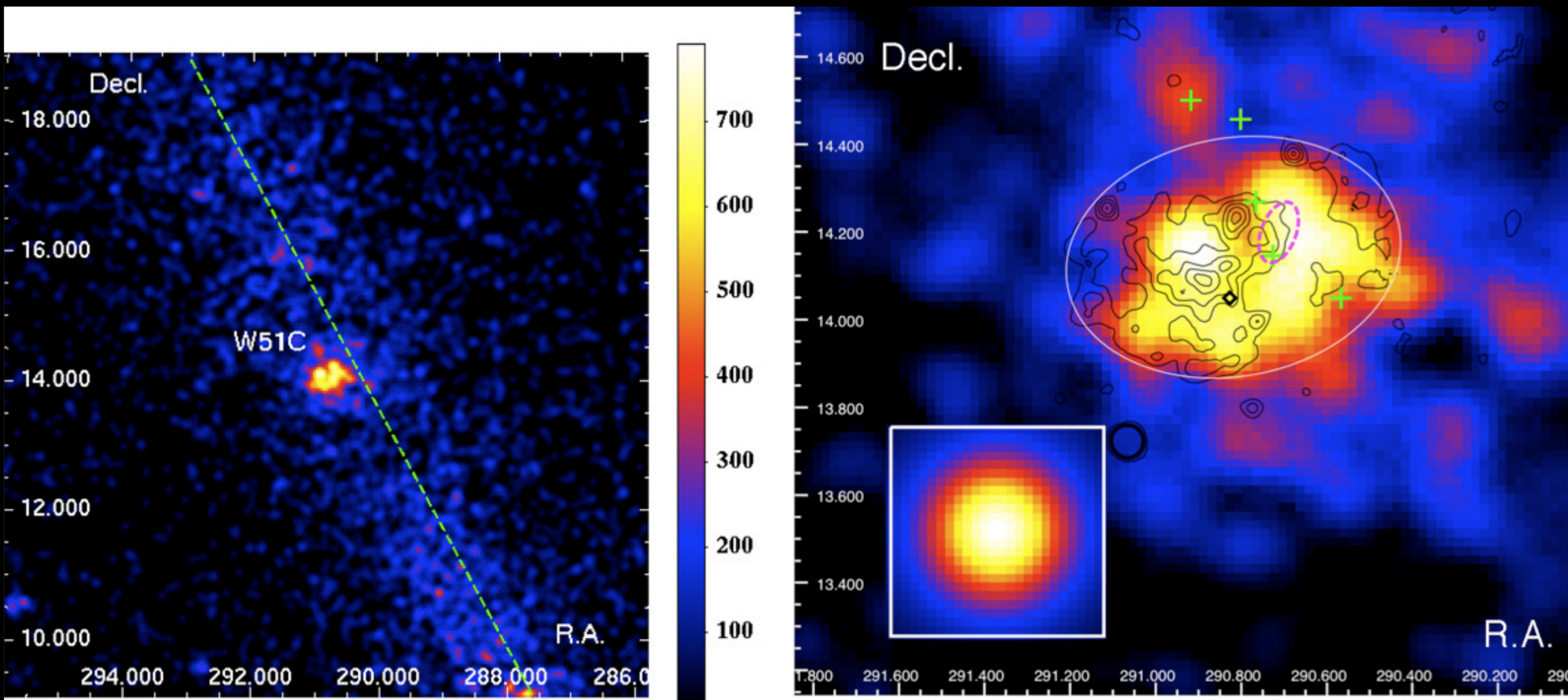
E_{max} : > 10 TeV

~10,000 years after SN explosion...

W51C

Abdo+ (2009)

- Middle-aged (~ 3 × 10^4 yr)   Distance: ~ 6 kpc
- Radio shell, thermal X-ray (black contours)
- **Interaction with a molecular cloud (Koo+)**



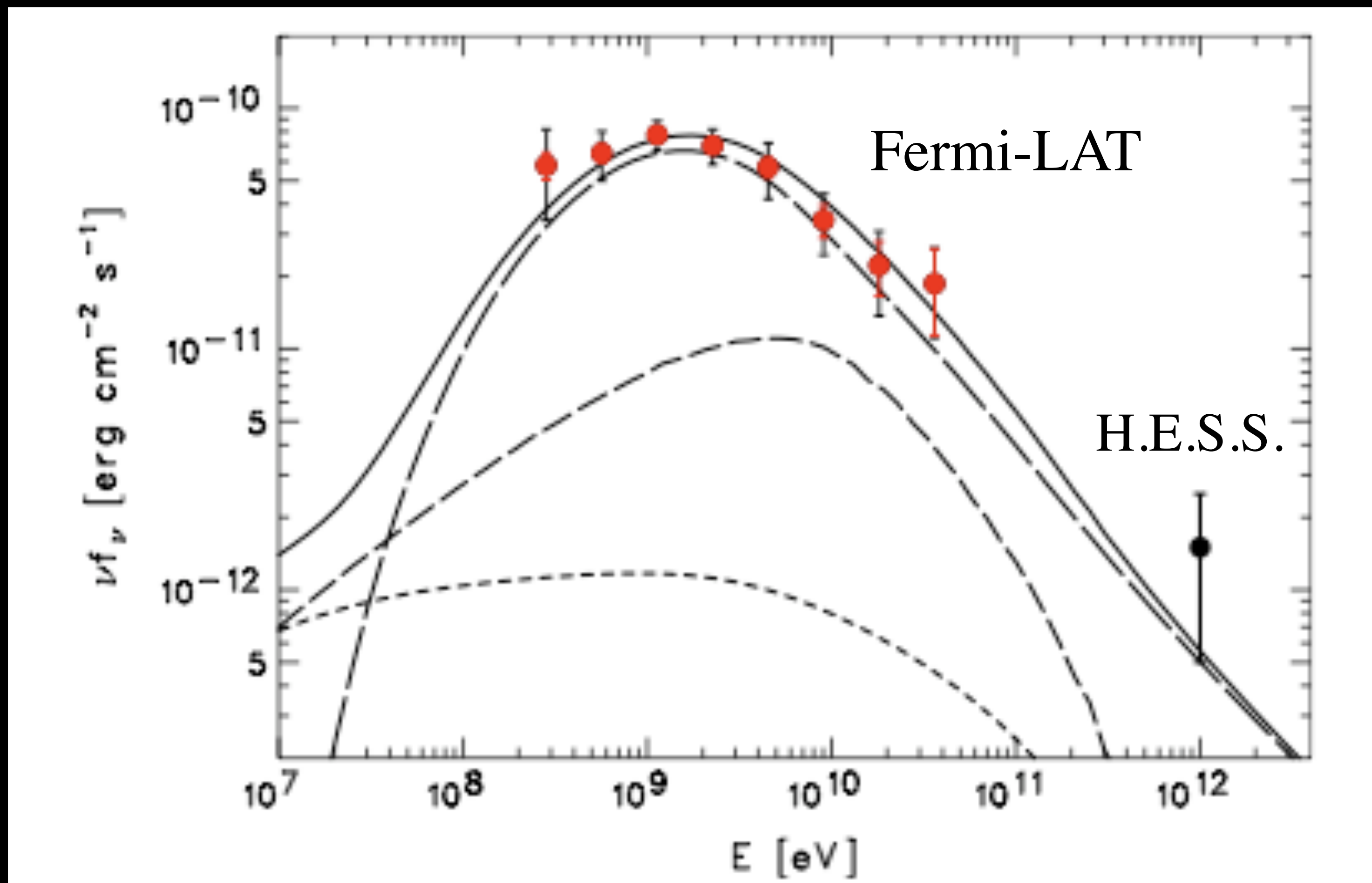
Fermi-LAT Count Map (Front Events; 2–10 GeV)

W51C

Abdo+ (2009)

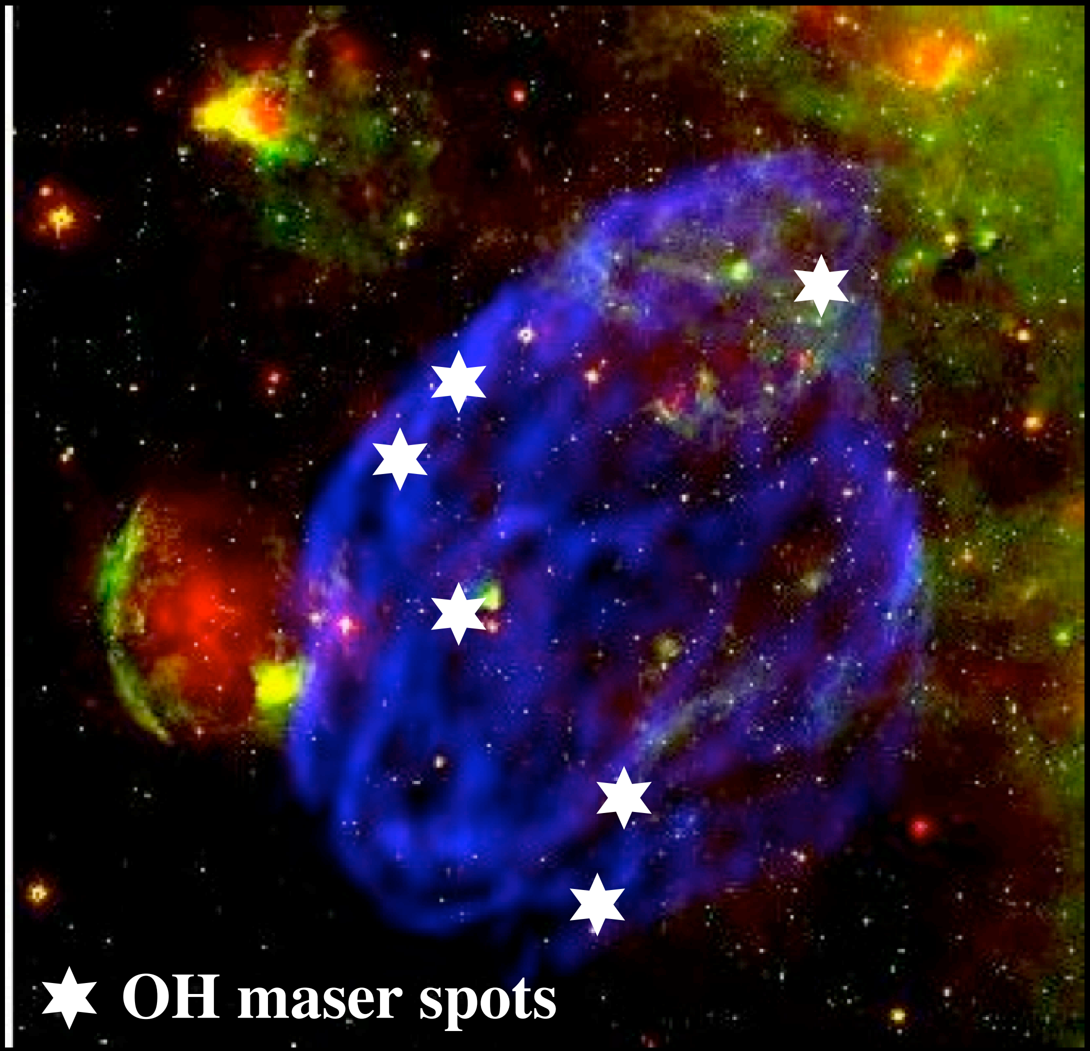
Fermi-LAT Spectrum

π^0-decay (long dash), bremsstrahlung (dash), IC (dot)



W44

Castelletti+2007



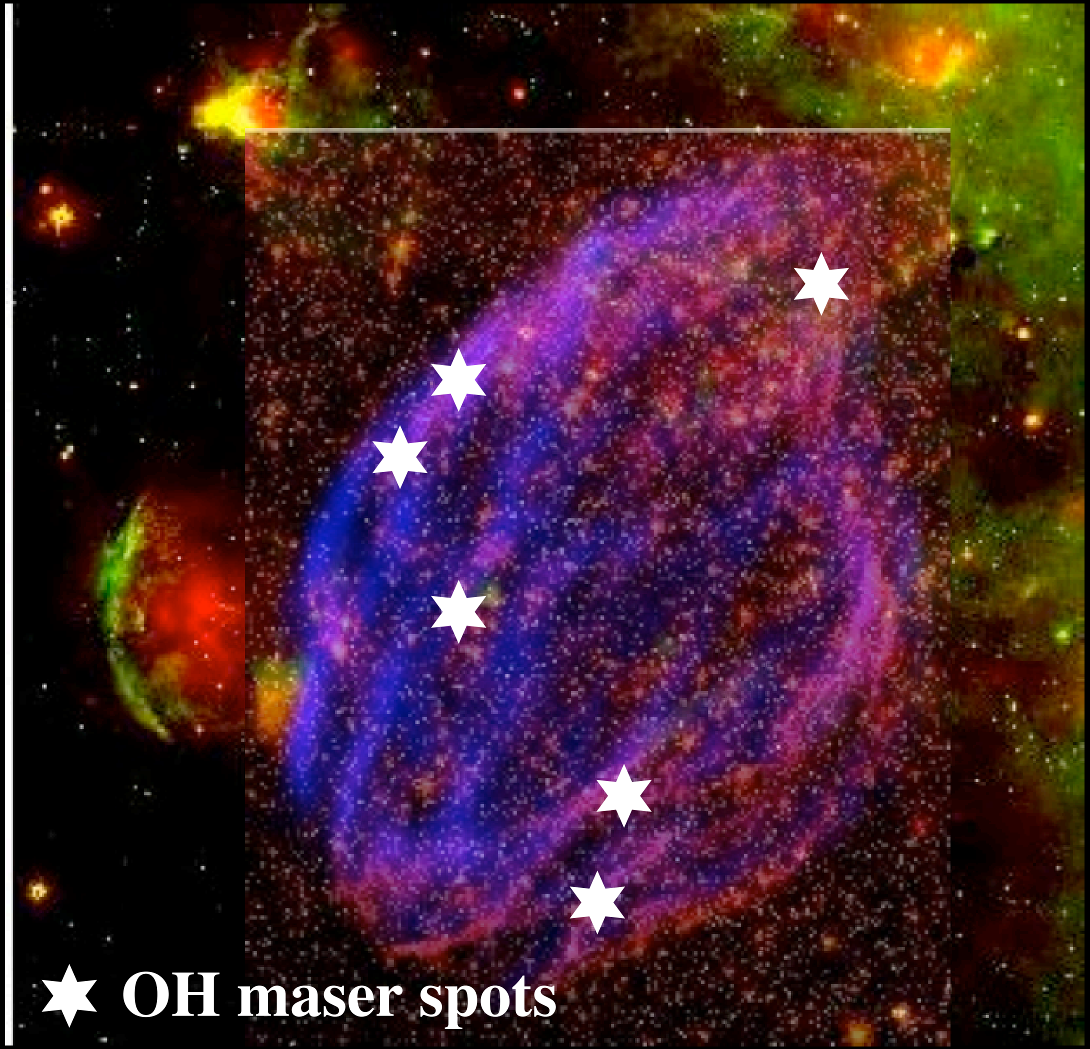
lines from H_2 gas (Spitzer)
radio synchrotron (VLA)

The remnant of a supernova exploded in a <u>molecular cloud</u> (Age ~10000 yr)

- Distance: ~ 3 kpc
- Mixed-morphology SNR
  - radio: shell
  - thermal X-ray: center filled
- **Interaction with a molecular cloud**

W44

Castelletti+2007



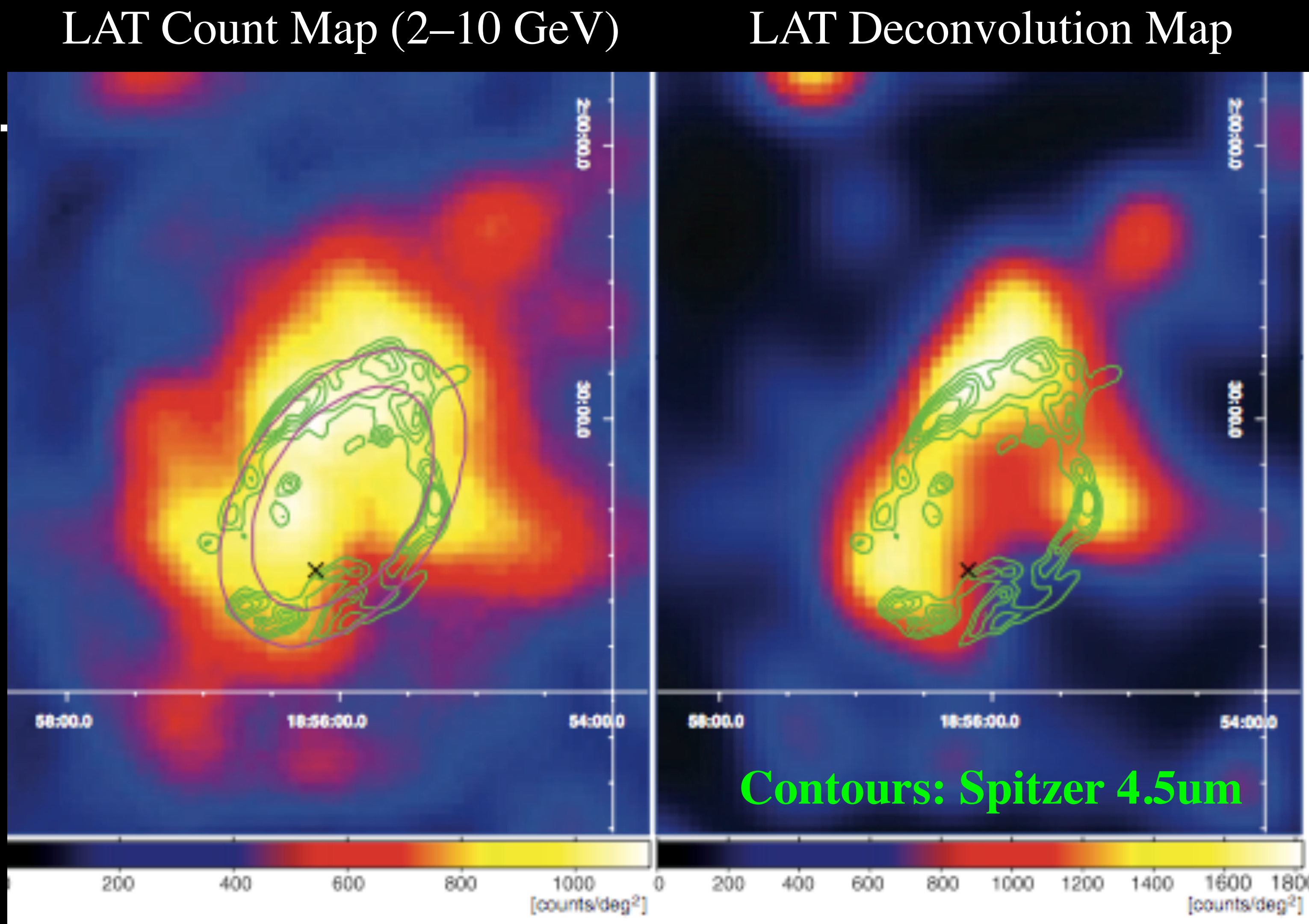
lines from H_2 gas (Spitzer)
radio synchrotron (VLA)

The remnant of a supernova exploded in a molecular cloud (Age ~10000 yr)

- Distance: ~ 3 kpc
- Mixed-morphology SNR
  - radio: shell
  - thermal X-ray: center filled
- **Interaction with a molecular cloud**

Fermi-LAT Image of W44

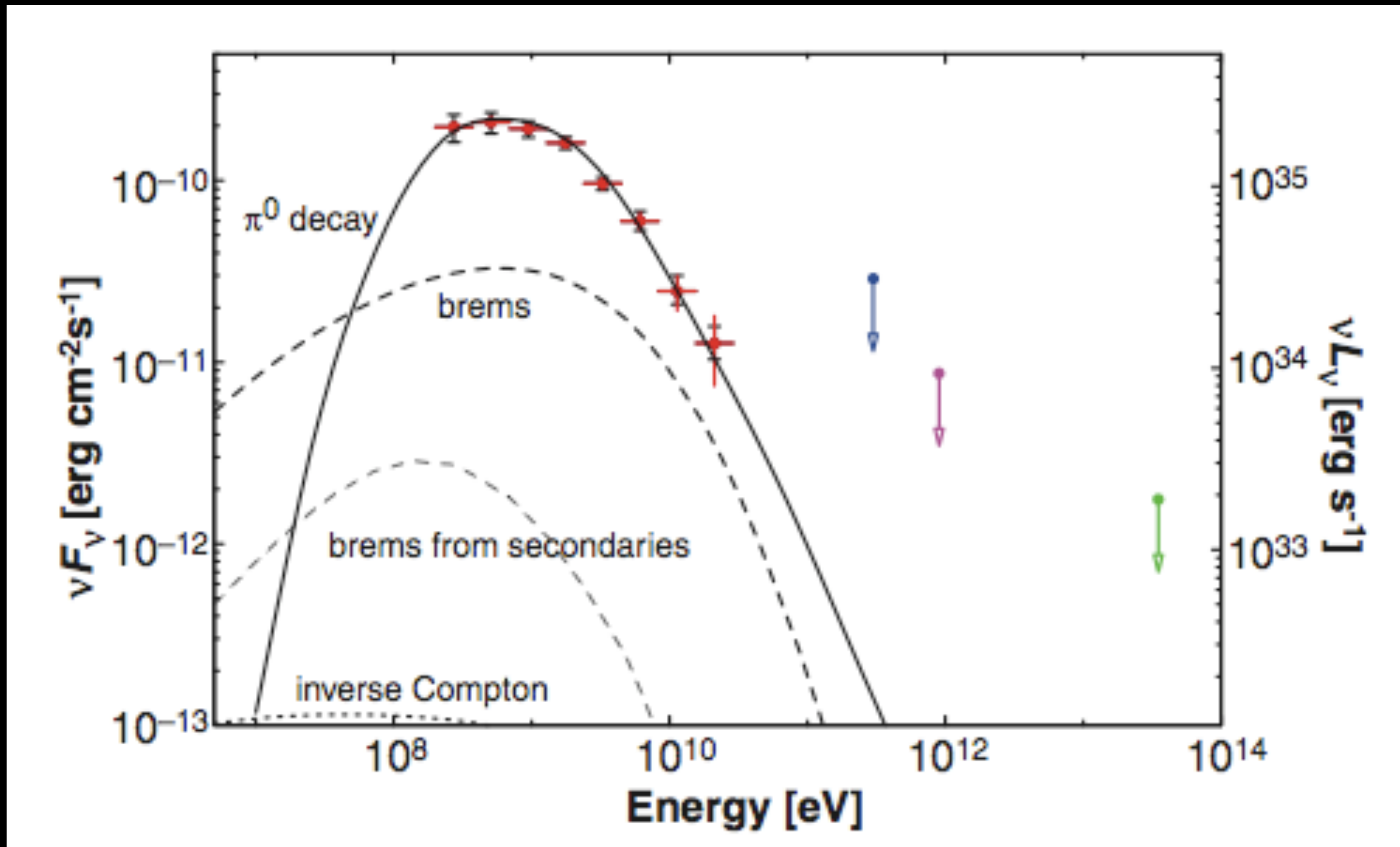
Abdo+ (2010)



Black cross: PSR B1853+01 (**No evidence of pulsed gamma-rays**)

Fermi-LAT Spectrum of W44

Abdo+ (2010)

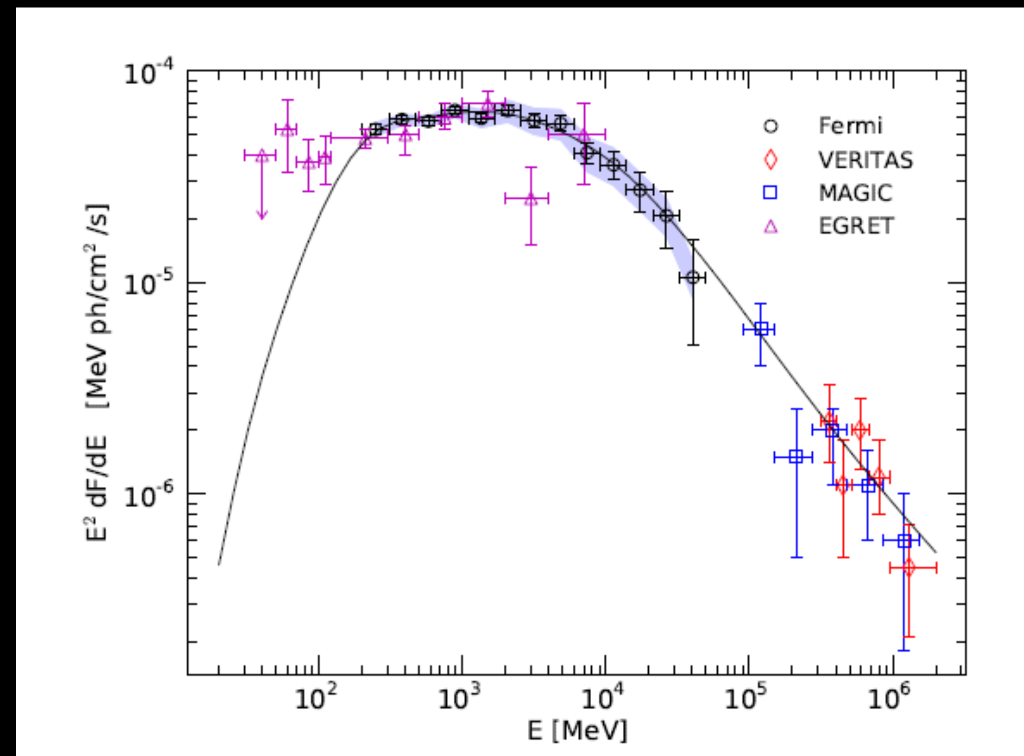


GeV gamma-rays: π^0 decay

Useful information: radio spectrum, [O I], H_2 lines, etc...

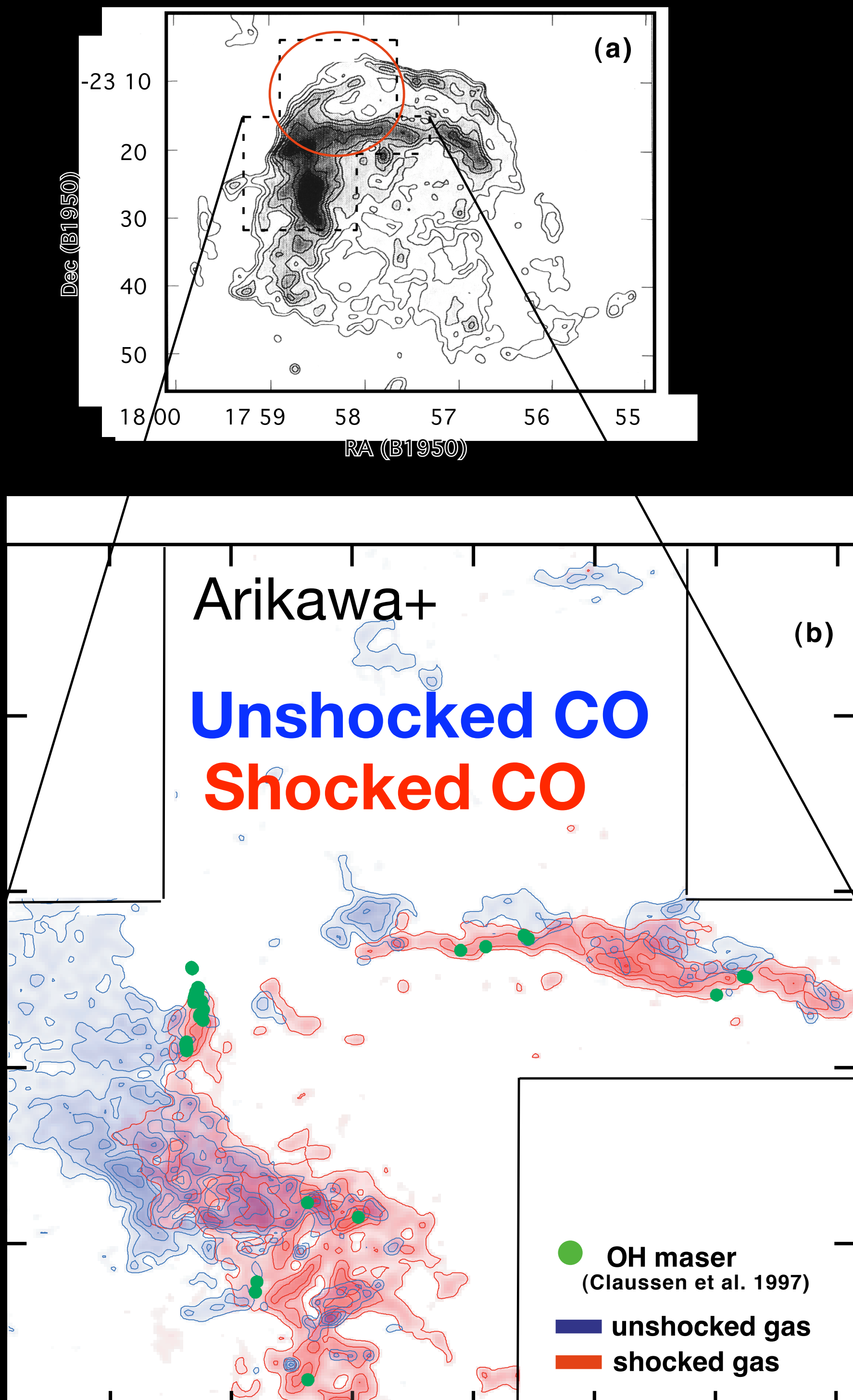
IC 443

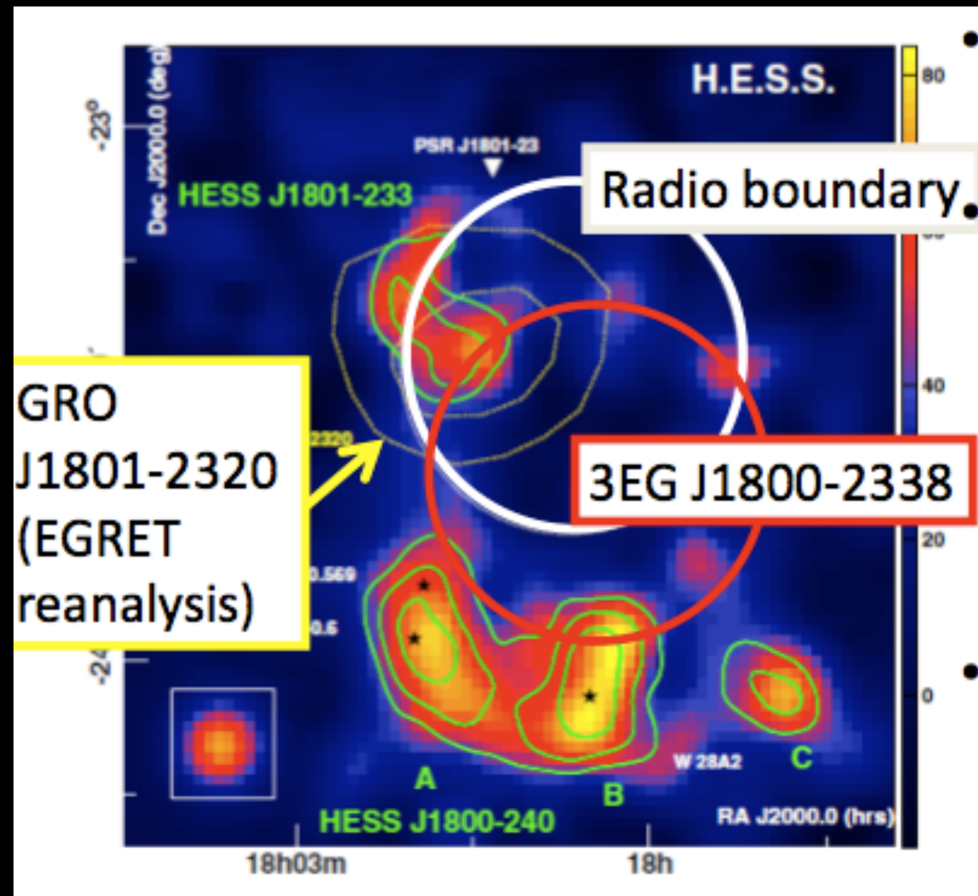
Abdo+ (2010)



W28

Synchrotron Radio





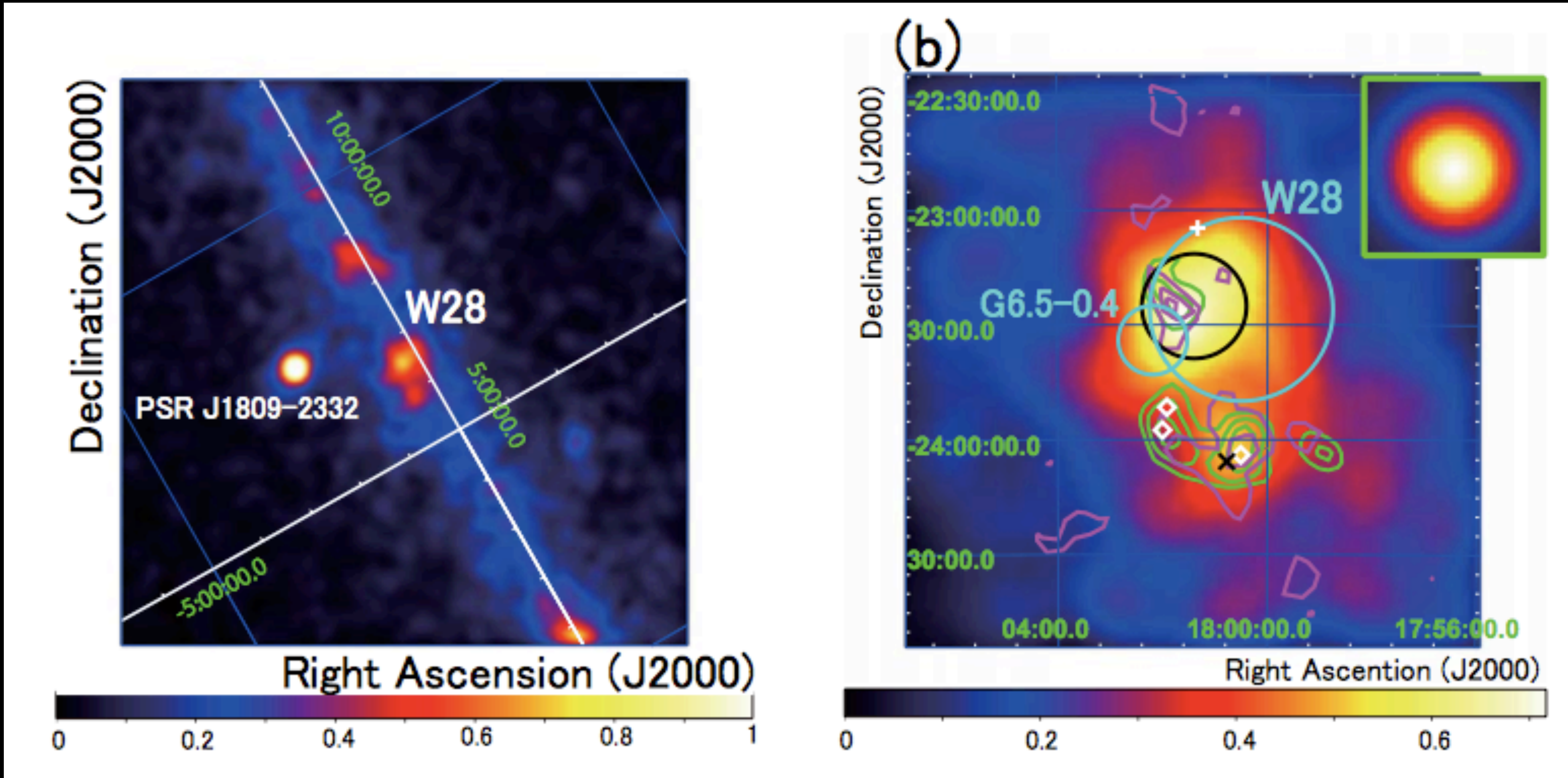
TeV gamma-rays associated with a molecular cloud

→ **π^0-decay gamma-rays**

W28

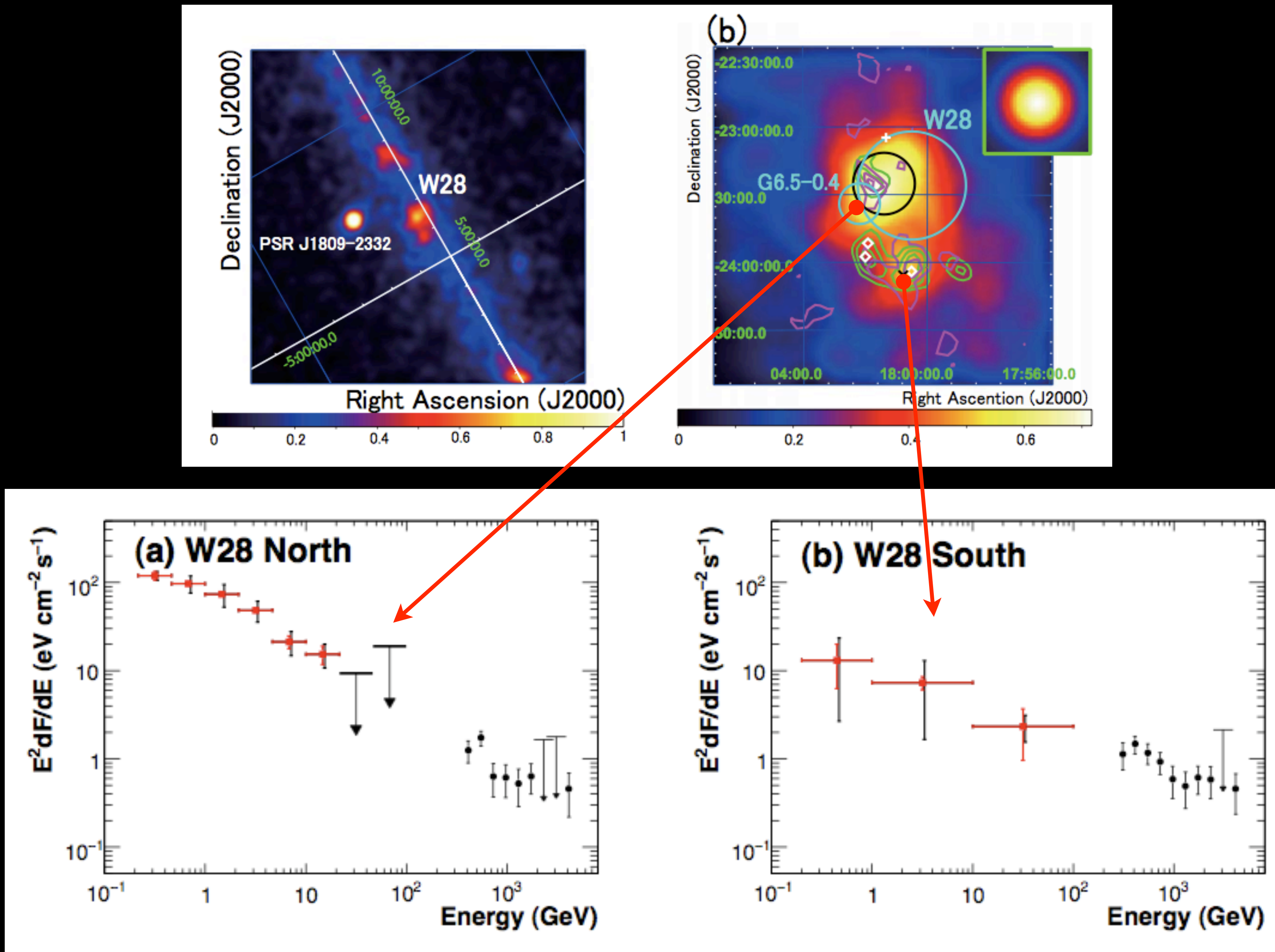
Abdo+ (2010)

LAT Count Map (2–10 GeV)



W28

Abdo+ (2010)



Fermi-LAT Detections of SNRs

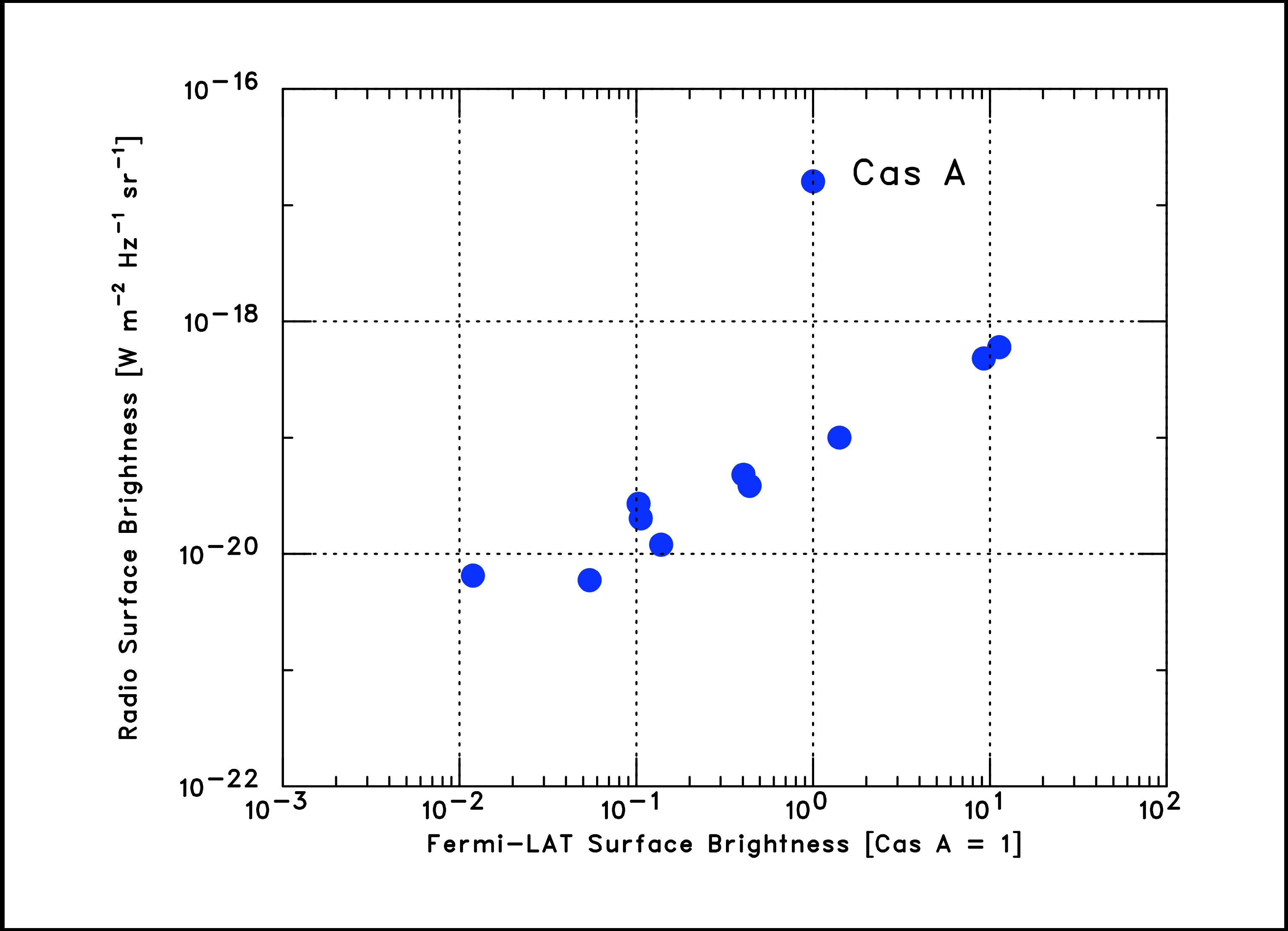
Object	Diameter	Age	Cloud Interaction	L_γ 1-100 GeV
Cas A	5 pc	330 yr	No	4×10^{34} erg/s
W49B	10 pc	~3000 yr	Yes	9×10^{35} erg/s
3C 391	15 pc	~6000 yr	Yes	6×10^{34} erg/s
G349.7+0.2	17 pc	~6000 yr	Yes	9×10^{34} erg/s
IC 443	20 pc	~10000 yr	Yes	8×10^{34} erg/s
W44	25 pc	~10000 yr	Yes	3×10^{35} erg/s
W28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

Characteristics of LAT-Detected SNRs

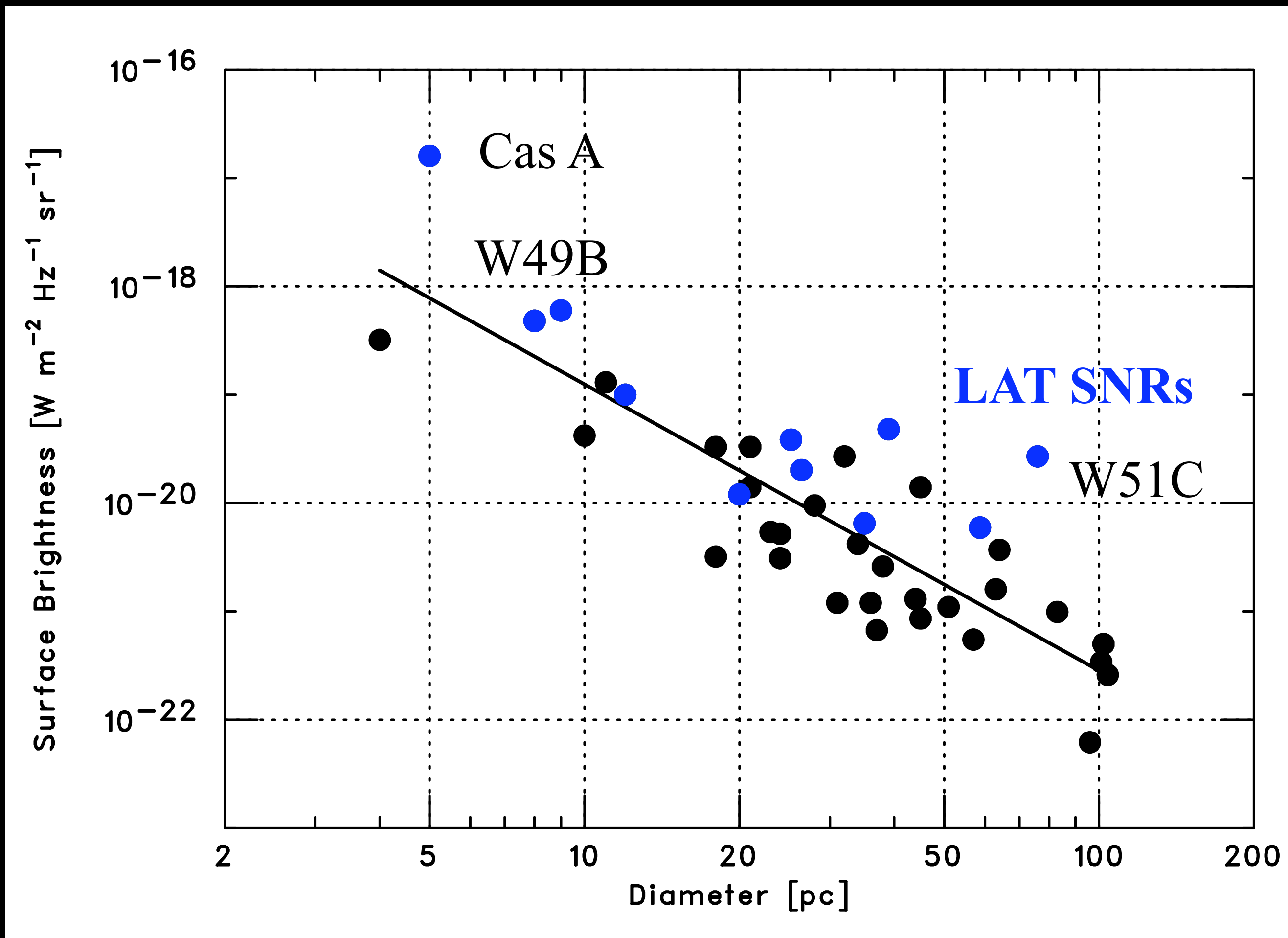
Surface Brightness Diagram (d-independent)

LAT (1-100 GeV) vs Radio (1 GHz)



Characteristics of LAT-Detected SNRs

Σ-D relation of Galactic SNRs



SNR Diameter vs Radio Surface Brightness

LAT SNRs (excl. Cas A)

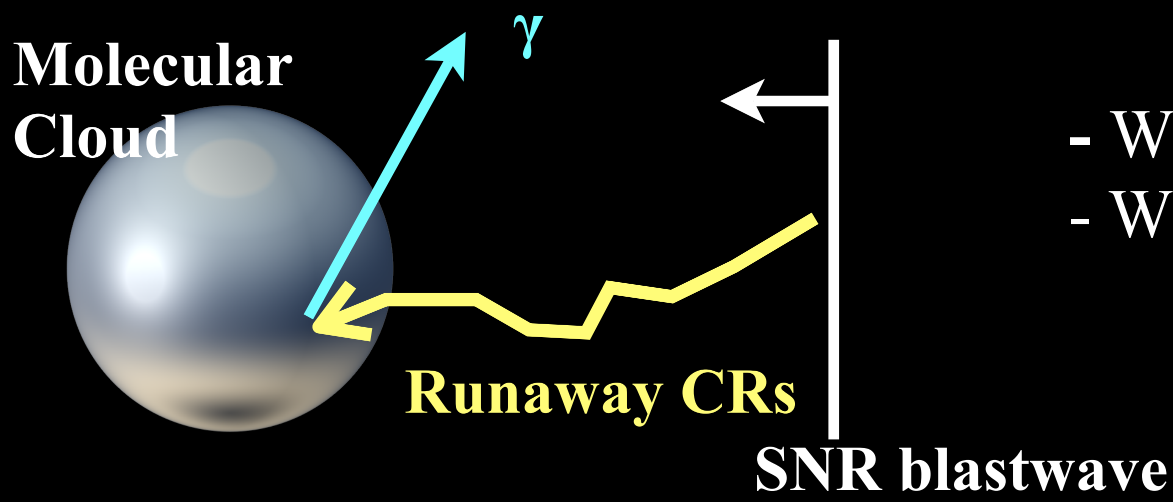
- Radio-bright
- Radio-GeV correlation
- Flat radio spectrum (α = 0.3-0.4) for W51C,W44, W28, IC 443
- Cloud-interacting
- GeV flux >> TeV flux
- $L\gamma = 10^{35\text{-}36}$ erg/s

Two Different Models

“Aharonian-type” Scenario:

e.g., Fujita+10, Ohira+10

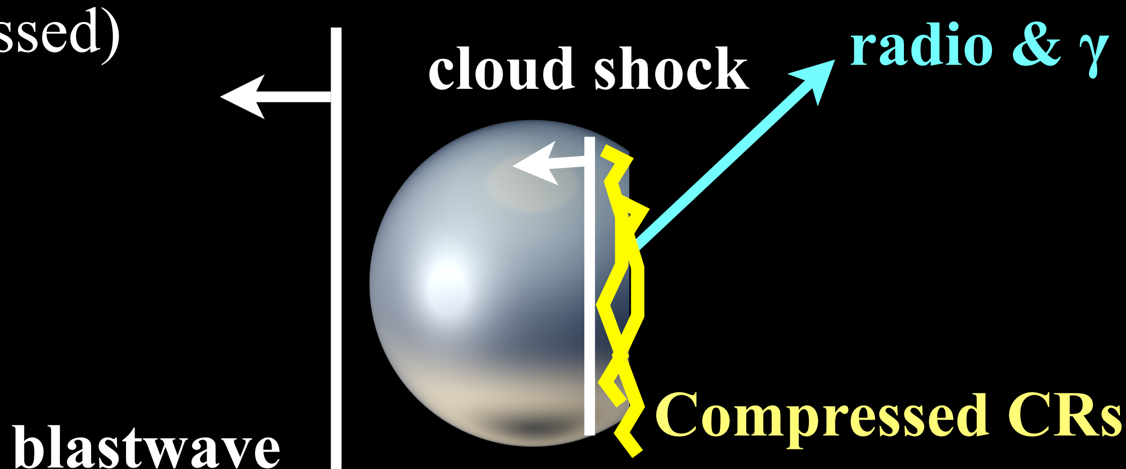
CRs escaping from SNR and colliding with nearby MCs



- Why radio-GeV correlation?
- Why radio-bright SNRs?

Our Scenario (Uchiyama+10):

γ-ray coming from “cloud shock” (CRs and MC simultaneously compressed)



A key point:
a large compression ratio
due to radiative cooling

Examples of Aharonian-type Model

Ohira+ (2010)

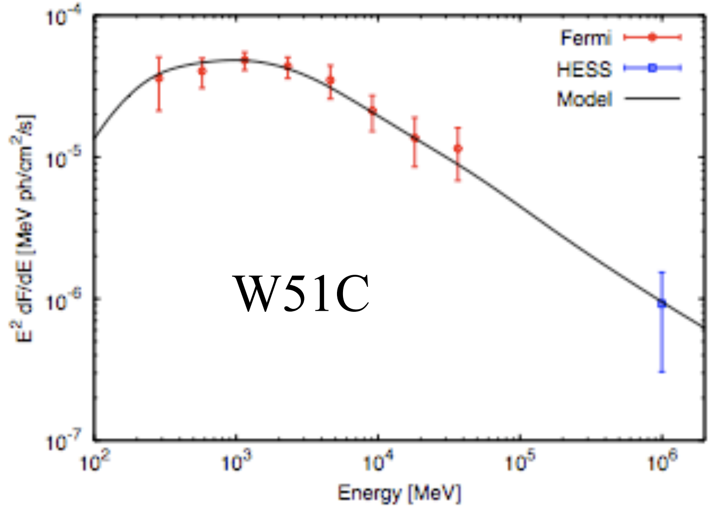


Figure 1. Comparison of the model results (solid line) with *Fermi* (red) (Abdo et al. 2009b) and HESS (blue) (Fiasson et al. 2009) observations for SNR W51C.

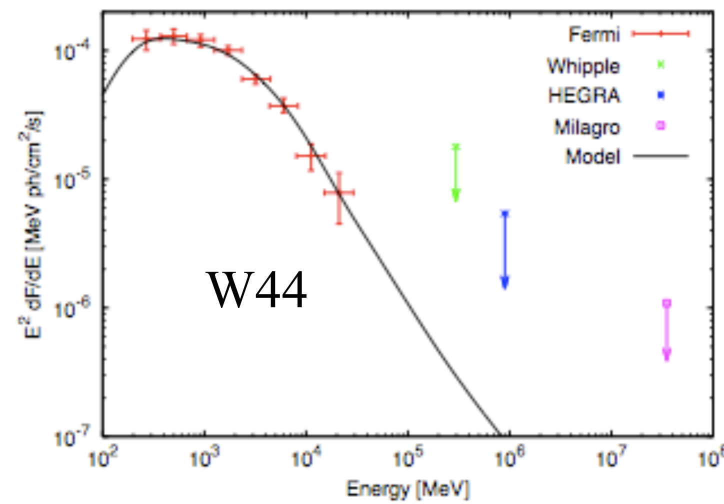
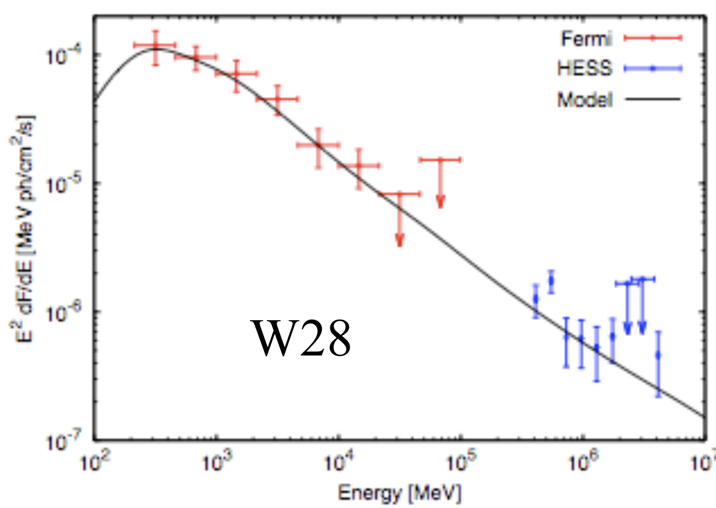
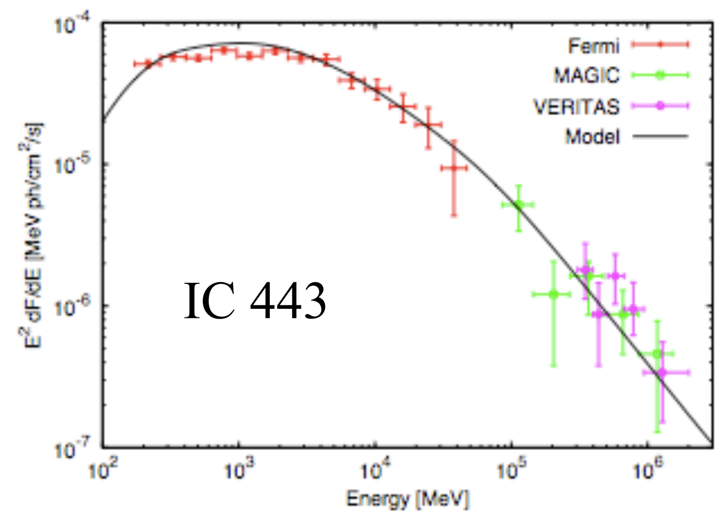


Figure 3. Comparison of the model results (solid line) with *Fermi* (red) (Abdo et al. 2010c), *Whipple* (green) (Buckley et al. 1998), *HEGRA* (blue) (Aharonian et al. 2002), *Milagro* (purple) (Abdo et al. 2009a) observations for SNR W44. The data of *Whipple*, *HEGRA* and *Milagro* are upper limits.



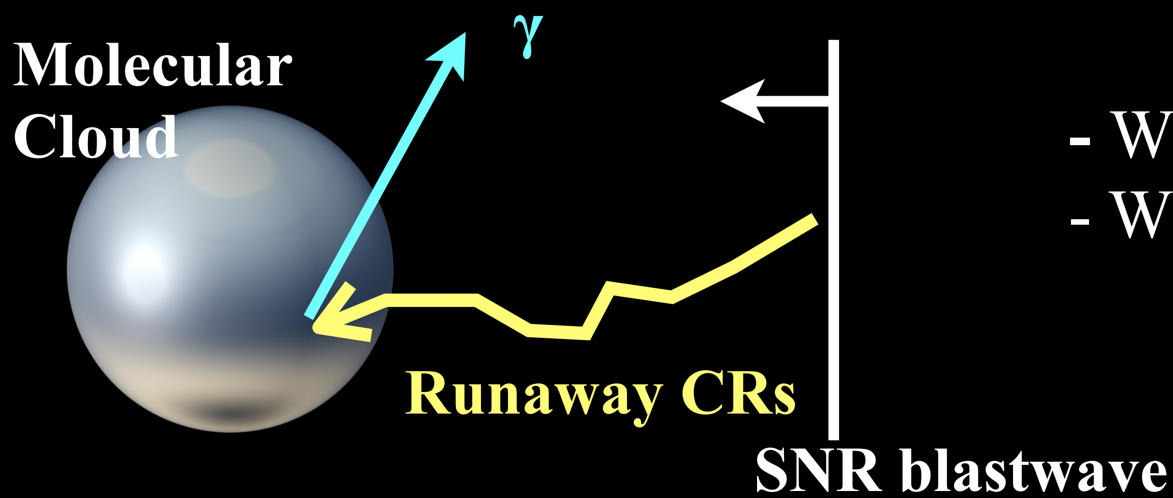


Two Different Models

"Aharonian-type" Scenario:

e.g., Fujita+10, Ohira+10

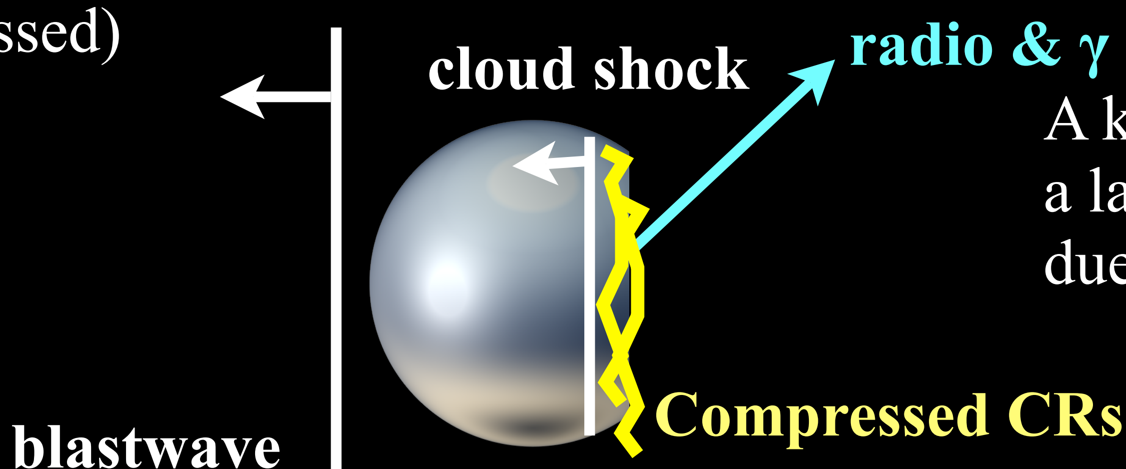
CRs escaping from SNR and colliding with nearby MCs



- Why radio-GeV correlation?
- Why radio-bright SNRs?

Our Scenario (Uchiyama+10):

γ-ray coming from "cloud shock" (CRs and MC simultaneously compressed)

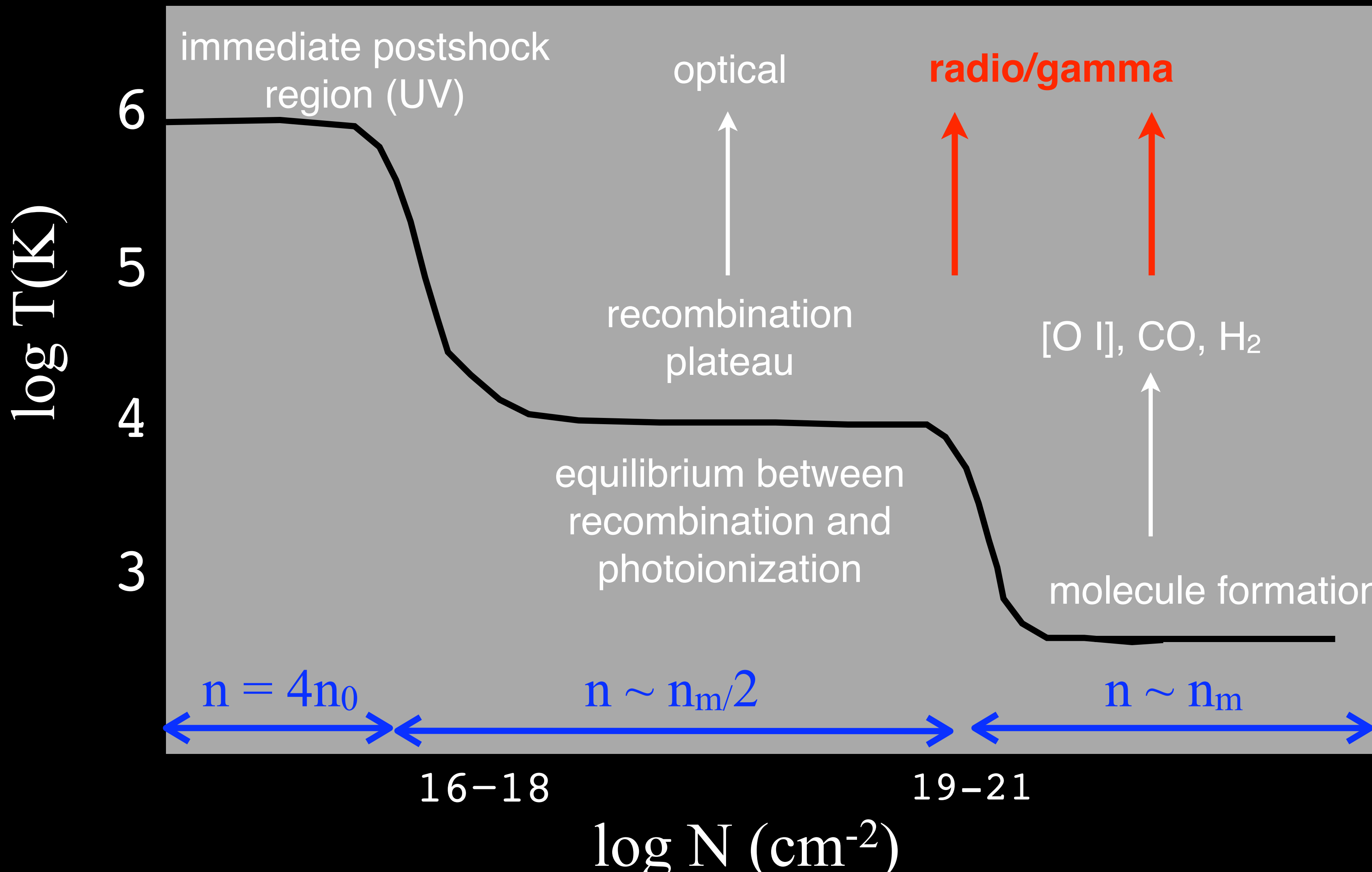


A key point:
a large compression ratio
due to radiative cooling

Shocked Molecular Cloud

Postshock structure of a fast (>50 km/s) molecular shock

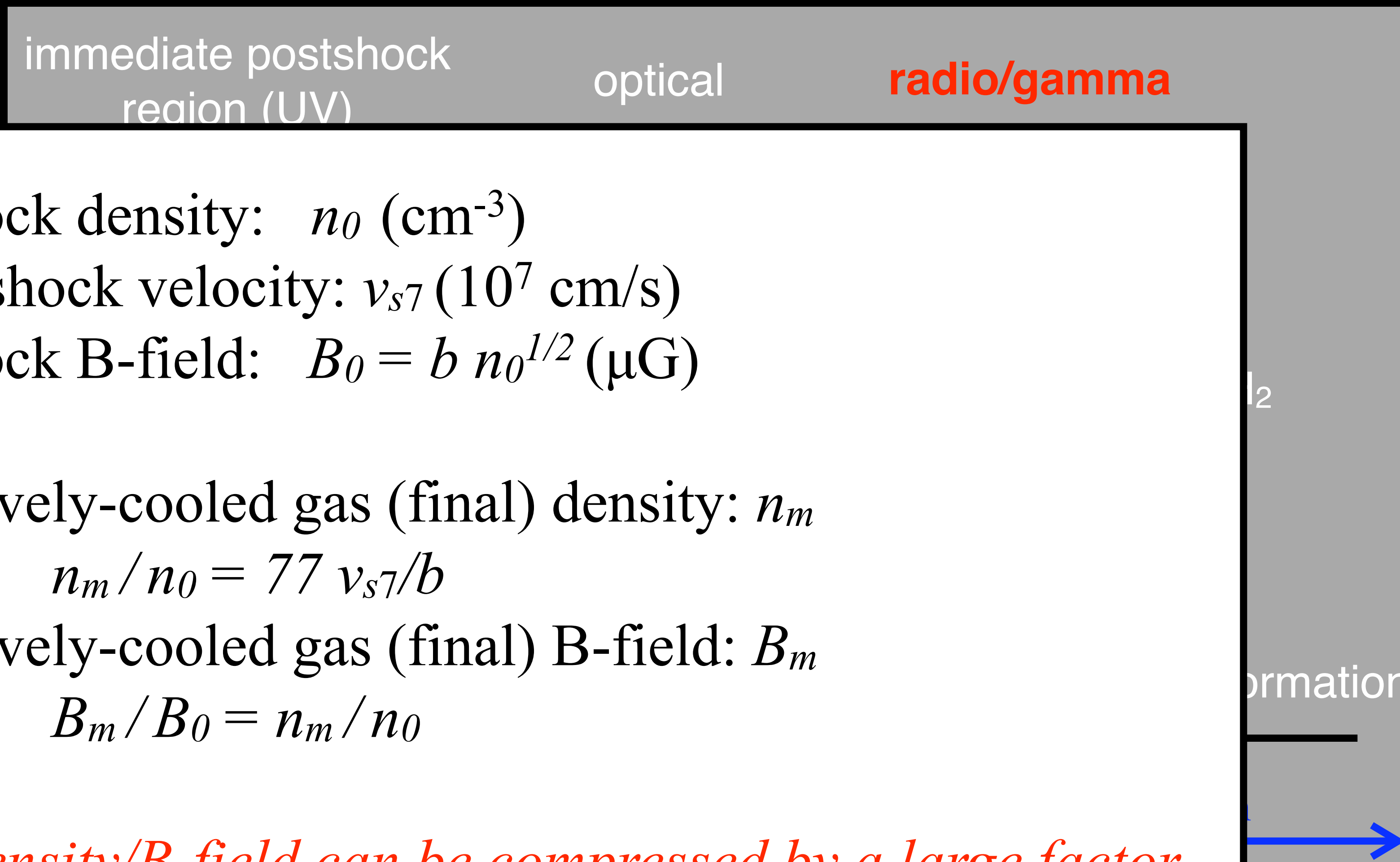
Hollenbach & McKee (1989)



Shocked Molecular Cloud

Postshock structure of a fast (>50 km/s) molecular shock

Hollenbach & McKee (1989)



Pre-shock density: n_0 (cm^{-3})

Cloud shock velocity: v_{s7} (10^7 cm/s)

Pre-shock B-field: $B_0 = b\, n_0^{1/2}$ (μG)

Radiatively-cooled gas (final) density: n_m

$$n_m / n_0 = 77\, v_{s7}/b$$

Radiatively-cooled gas (final) B-field: B_m

$$B_m / B_0 = n_m / n_0$$

Both density/B-field can be compressed by a large factor (10-100).

CR Acceleration at Cloud Shock

Diffusive shock acceleration:

Since $v \sim 100$ km/s, a conservative assumption is

Seed = the "pool" of Galactic CRs (Namely, Re-acceleration)

(if this is not enough, seed = thermal particles)

Spectral break:

Ion-neutral collision → Alfvén wave evanescence (Malkov+2010)

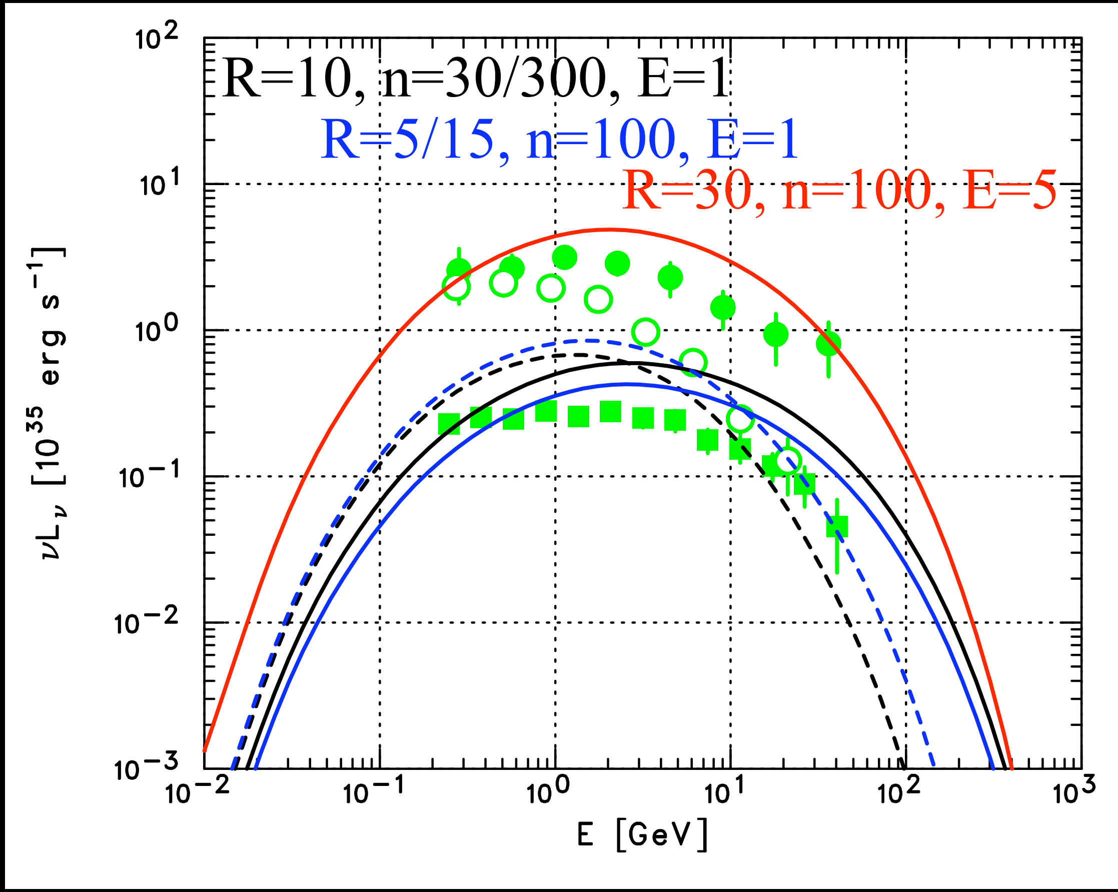
Spectral steepening by one power at $cp_{\rm br} = 2eBV_{\rm A}/\nu_{\rm i\text{-}n}$

Maximum energy:

Age-limited at $cp_{\rm max} = 500\, v_{s7}^2 B_{-5}\, t_4 / \eta$ GeV

Expected Gamma-ray Luminosity

$L_\gamma \propto f\, n\, R\, E^{2/3}\, B^{-4/3}$
$\rightarrow L_\gamma \sim f \times 10^{36}$ erg/s



Uchiyama+10

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

Parameters for W44 & IC 443

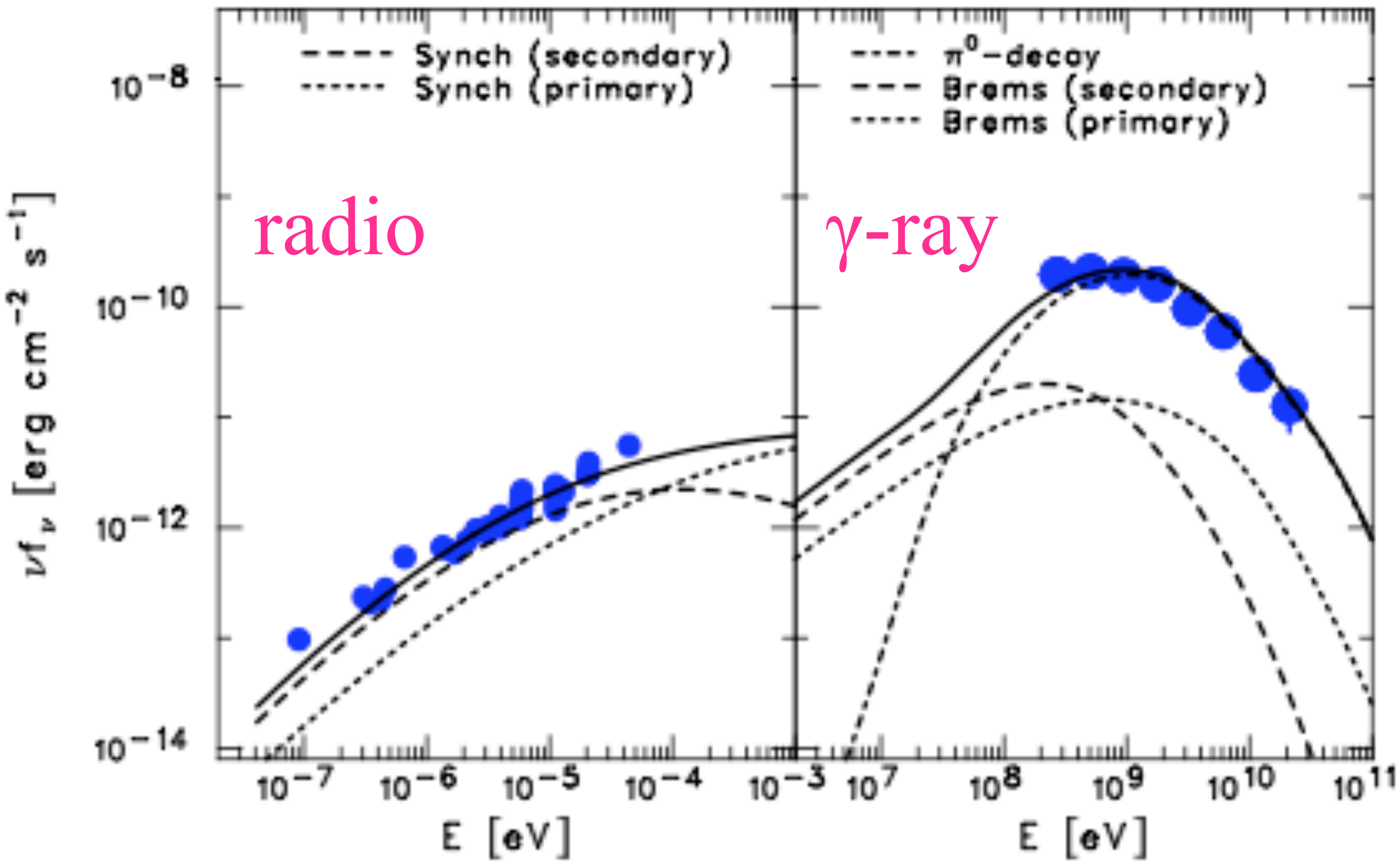
TABLE 1
MODEL PARAMETERS

Parameters	W44	IC 443
Assumed SNR Dynamics		
Distance: D	2.9 kpc[a]	1.5 kpc
Radius: R	12.5 pc[a] ($\theta = 15'$)	10 pc ($\theta = 23'$)
Age: t	10000 yr[a]	10000 yr
Explosion energy: E_{51}	5[a]	1
Preshock Cloud Parameters (Free Parameters)		
Density: n_0	200 cm^{-3}[a]	150 cm^{-3}
Filling factor: f	0.22	0.05
Magnetic field: B_0	20 μG	20 μG
Dependent Parameters		
Cloud shock velocity[b]: v_s	100 km s^{-1}[a]	80 km s^{-1}
Break momentum: p_{br}	6 GeV/c	42 GeV/c
Maximum momentum: p_{max}	96 GeV/c	60 GeV/c

Free parameters

Results for W44

Uchiyama+10



- radio & γ-ray fluxes can be explained by **re-acceleration of the pre-existing GCRs**
- **flat radio index (α=0.37) is naturally predicted**
- GeV break may be explained by Alfvén wave evanescence

Comments

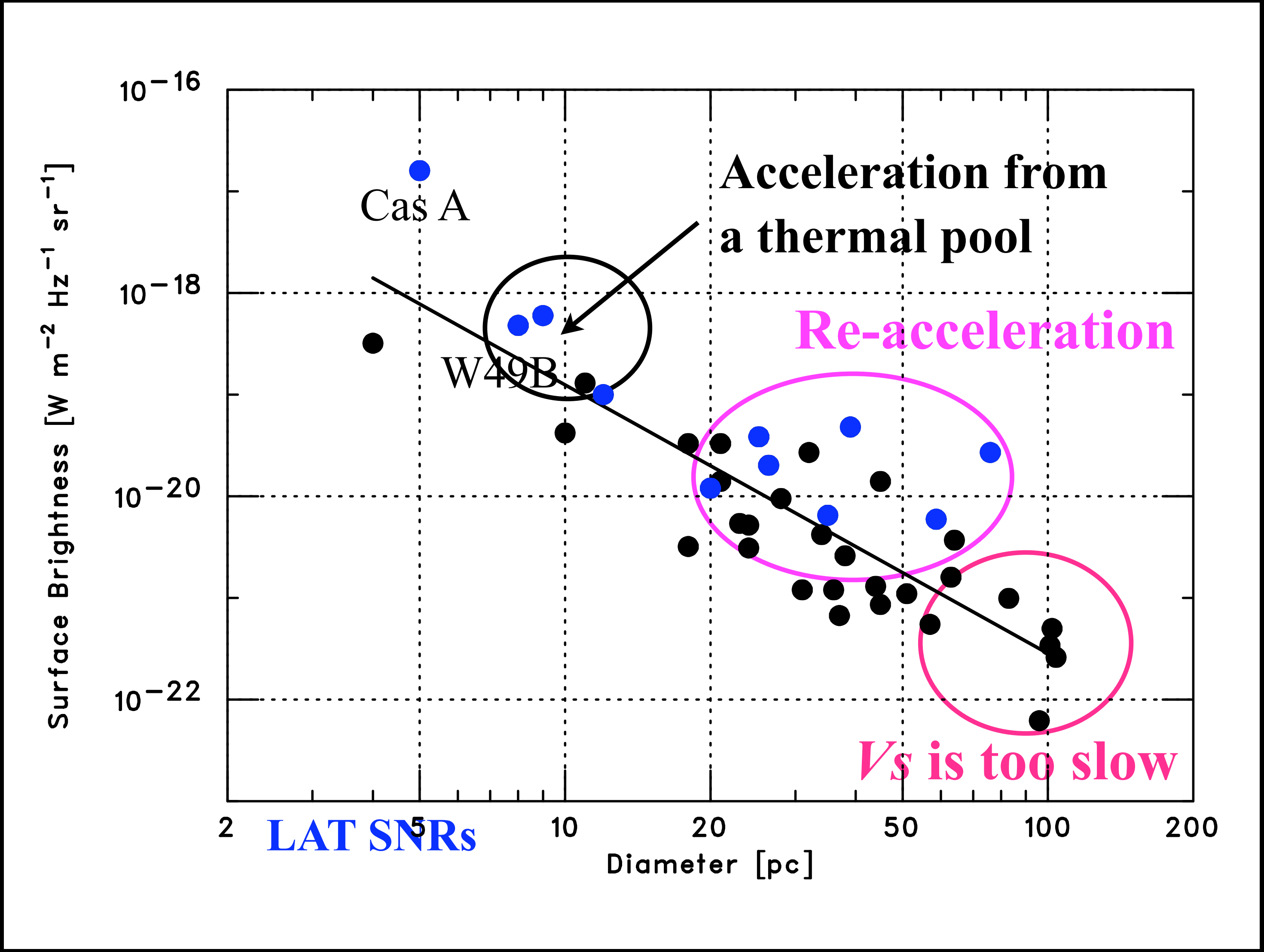
F. Aharonian

"Although I need more time to understand the details – generally I find this **a very good idea!** ....
Anyway, my opinion about **your paper is very positive**."

H. Völk

"Altogether I found this a very interesting piece of work, **congratulations**!
And I think that the basic point of dominant re-acceleration and adiabatic energization in shocks that compress dense clouds in a supernova remnant comes out **quite convincingly**. I am sure that Roger Blandford is happy to see his old idea so successfully be confronted with reality."

Summary



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