1st August 2013
at RIKEN (Nagataki Group)

Gamma-ray Observations of Supernova Remnants with Fermi

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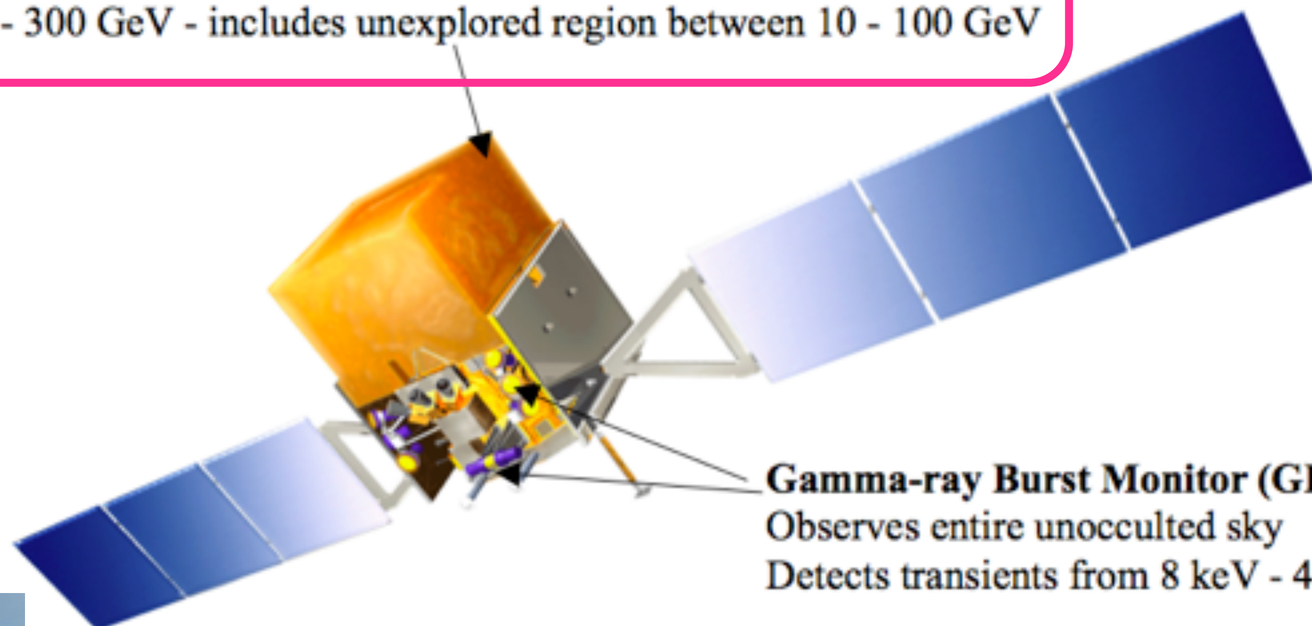
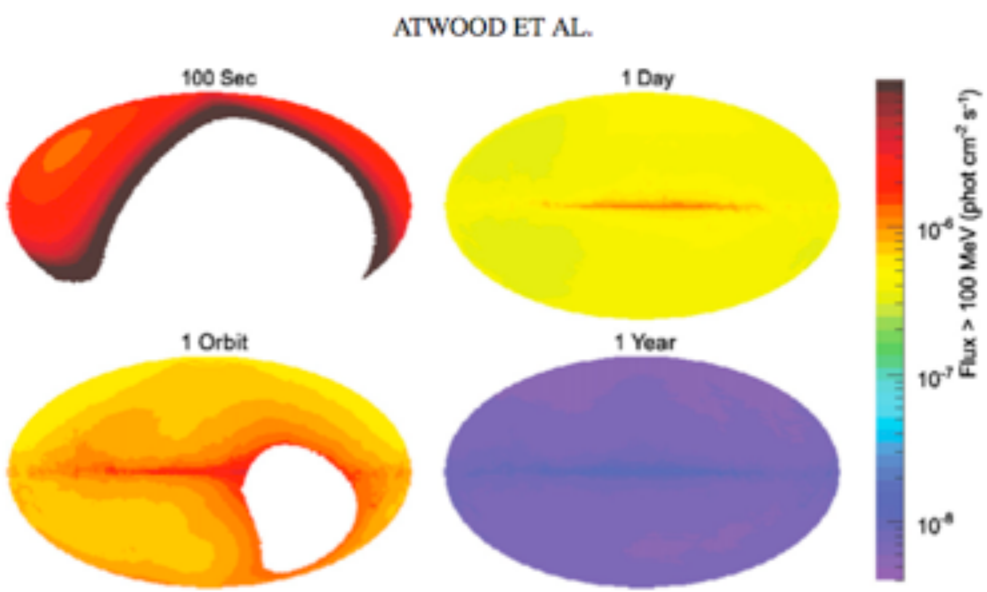
Fermi Gamma-ray Space Telescope

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV



Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

Launch in 2008

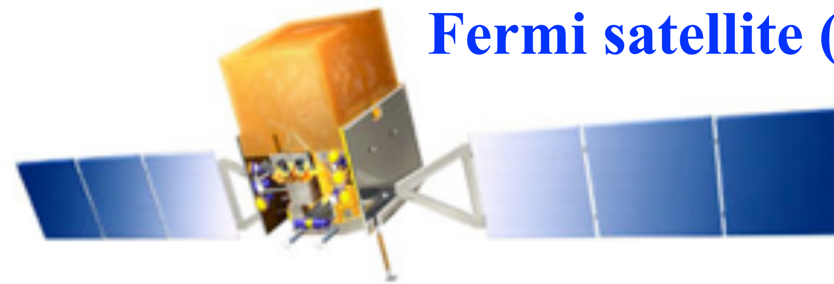


⬅ LAT sensitivity

for various exposures

Large Area Telescope (LAT) onboard Fermi

Fermi satellite (2008-)

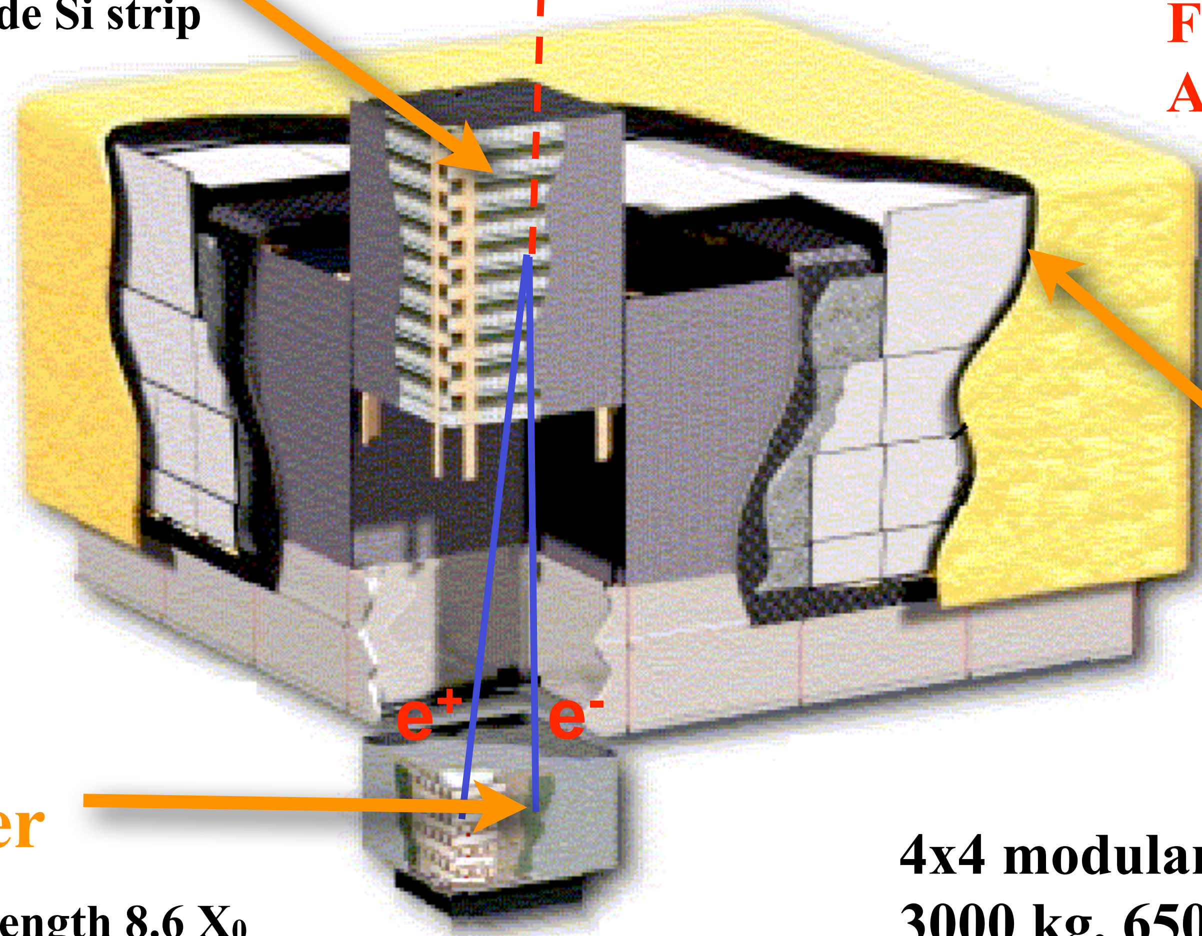


Gamma-ray (20 MeV - 300 GeV)

Field of view: 2.4 str
Angular resolution:
~ 1 deg at 1 GeV
~0.1 deg > 10 GeV

Si Tracker
(18 planes)

converter: tungsten
tracker: single-side Si strip



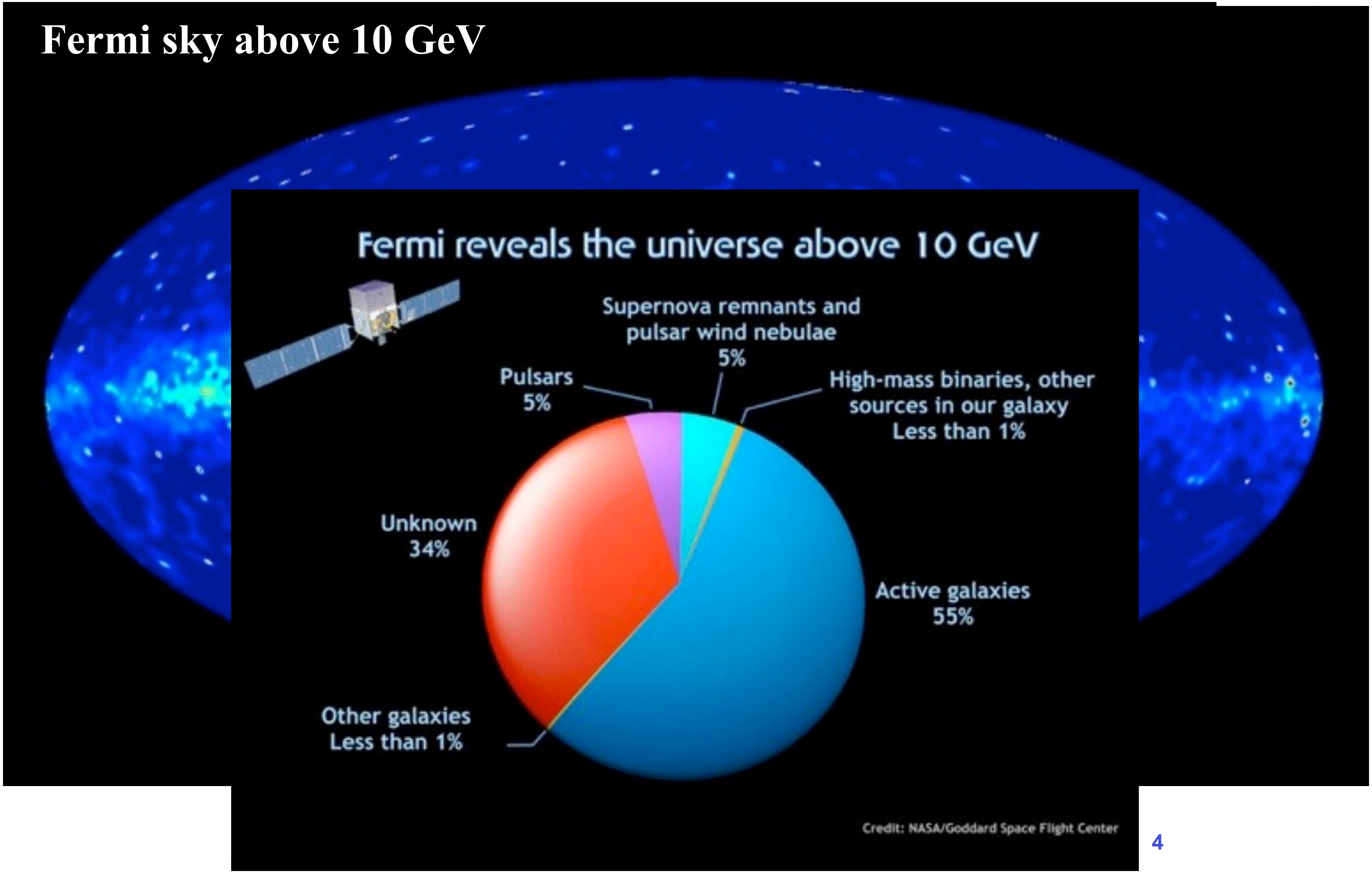
Anti Coincidence Detector

CsI Calorimeter

total radiation length 8.6 X_0

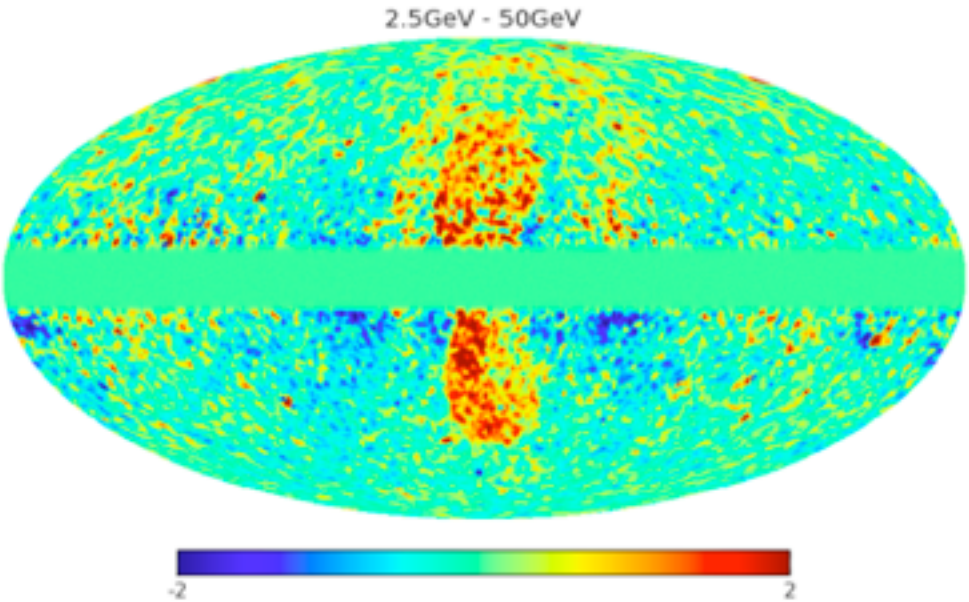
4x4 modular array
3000 kg, 650 W

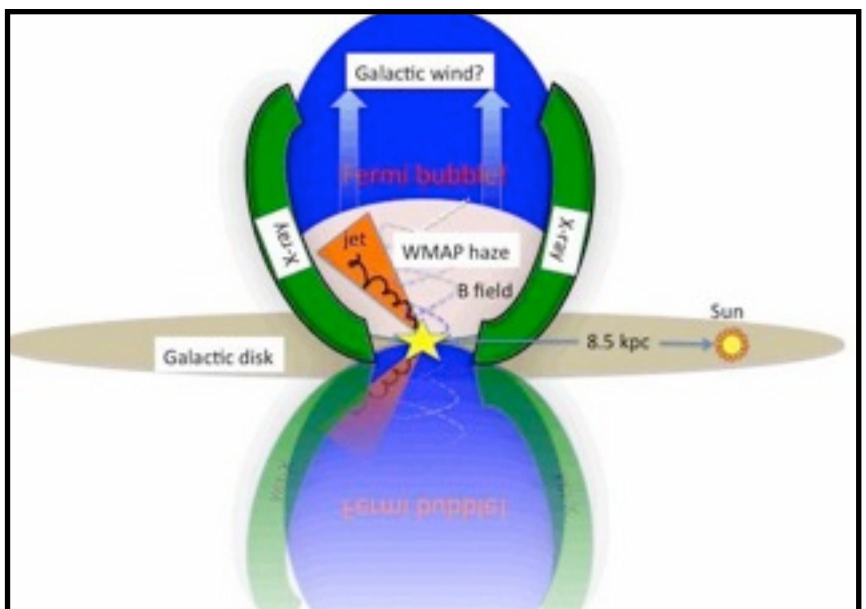
Gamma-ray Sky with Fermi-LAT



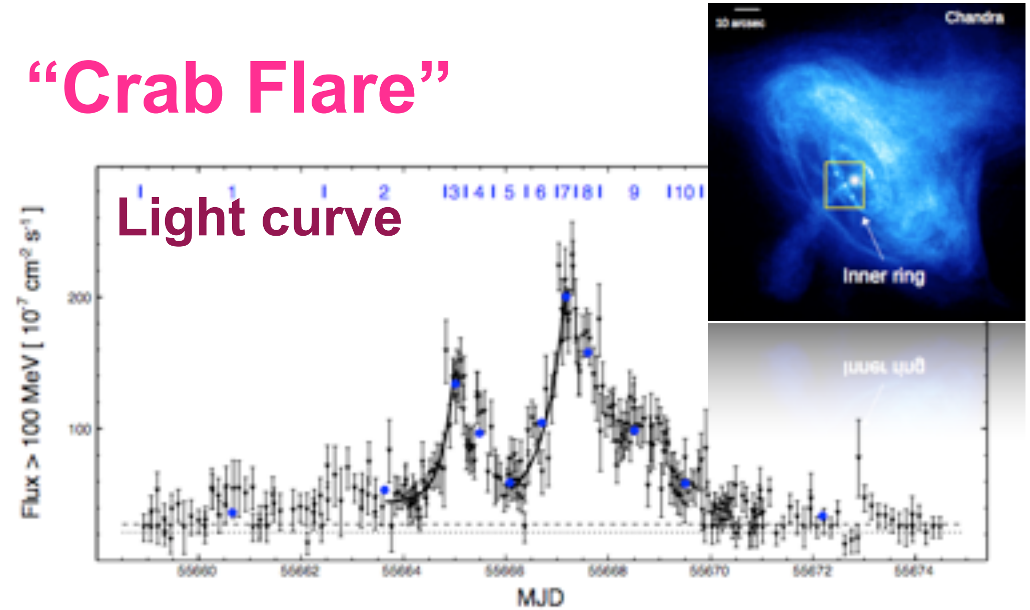
Recent Highlights of Fermi Observations

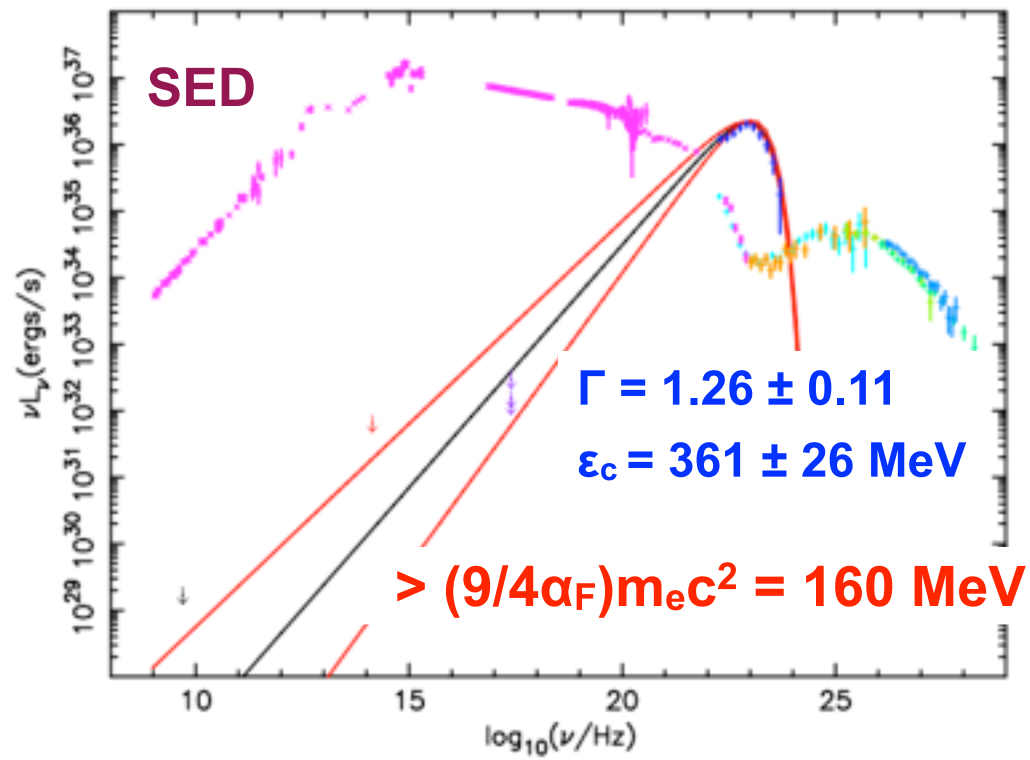
"Fermi Bubble"





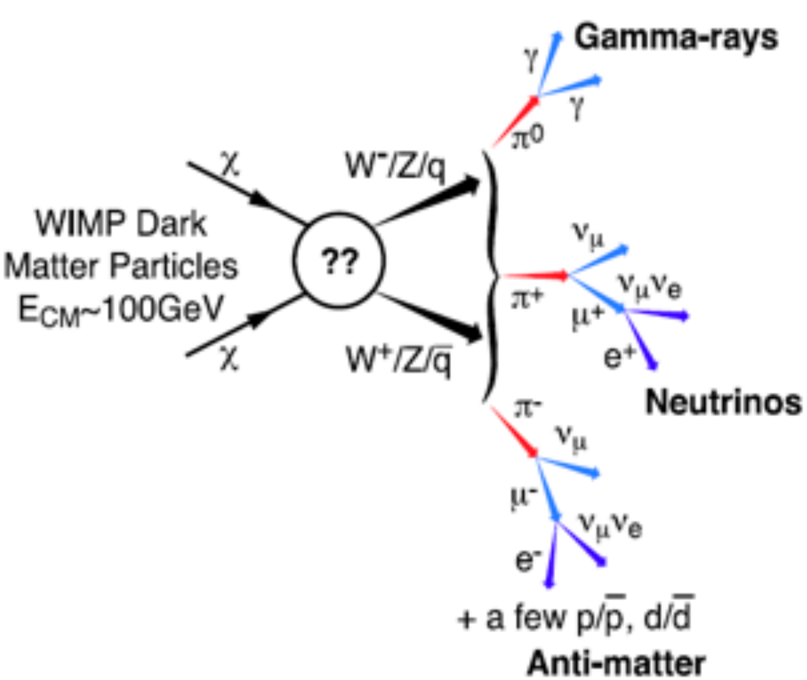
"Crab Flare"

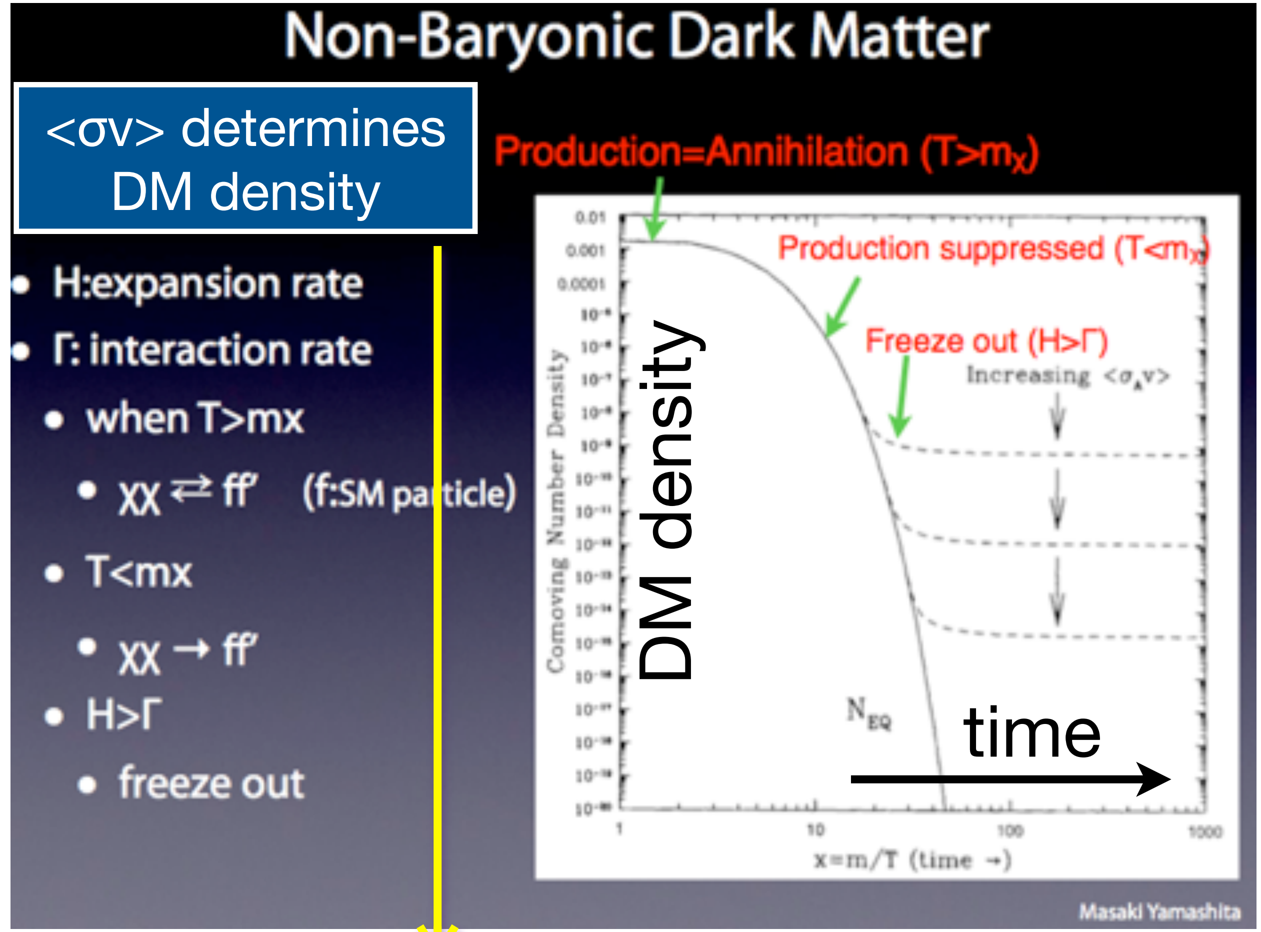




Dark Matter Indirect Searches

WIMP: DM top candidate

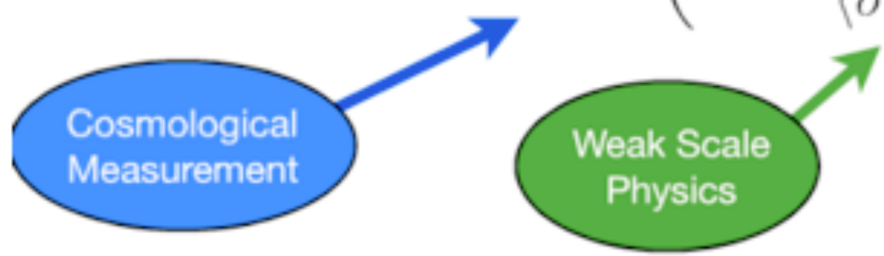




“WIMP miracle”

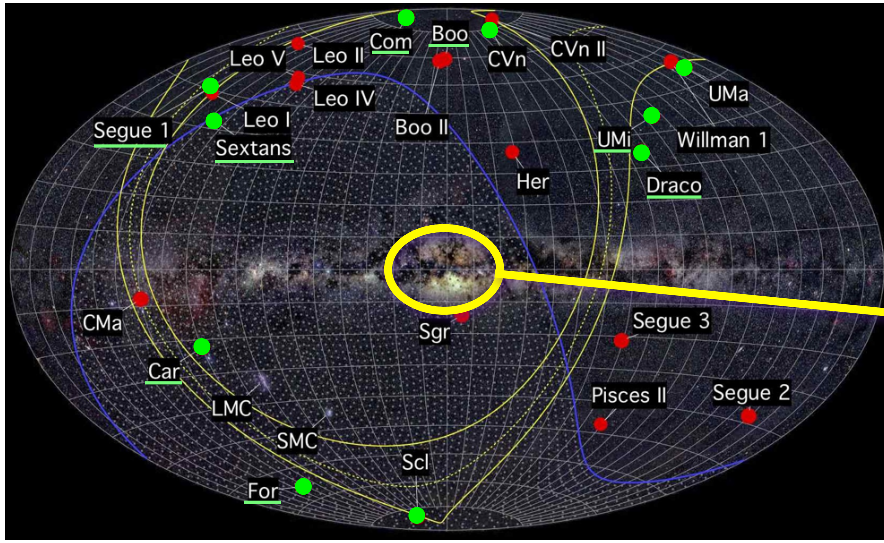
Dark Matter Abundance from Thermal Production

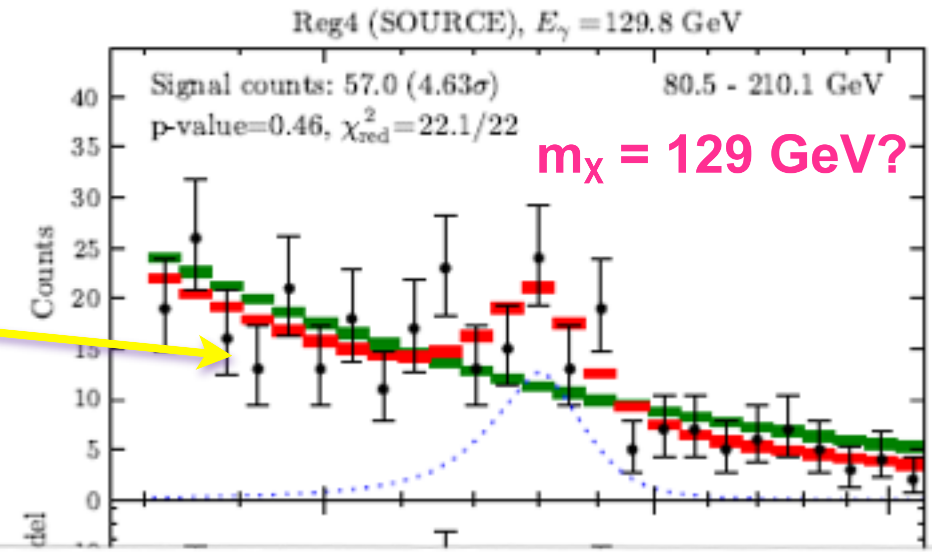
$$\Omega_{dm} = 0.23 \times \left(\frac{10^{-26}\ \mathrm{cm}^3 \cdot \mathrm{s}^{-1}}{\langle \sigma v \rangle}\right)$$

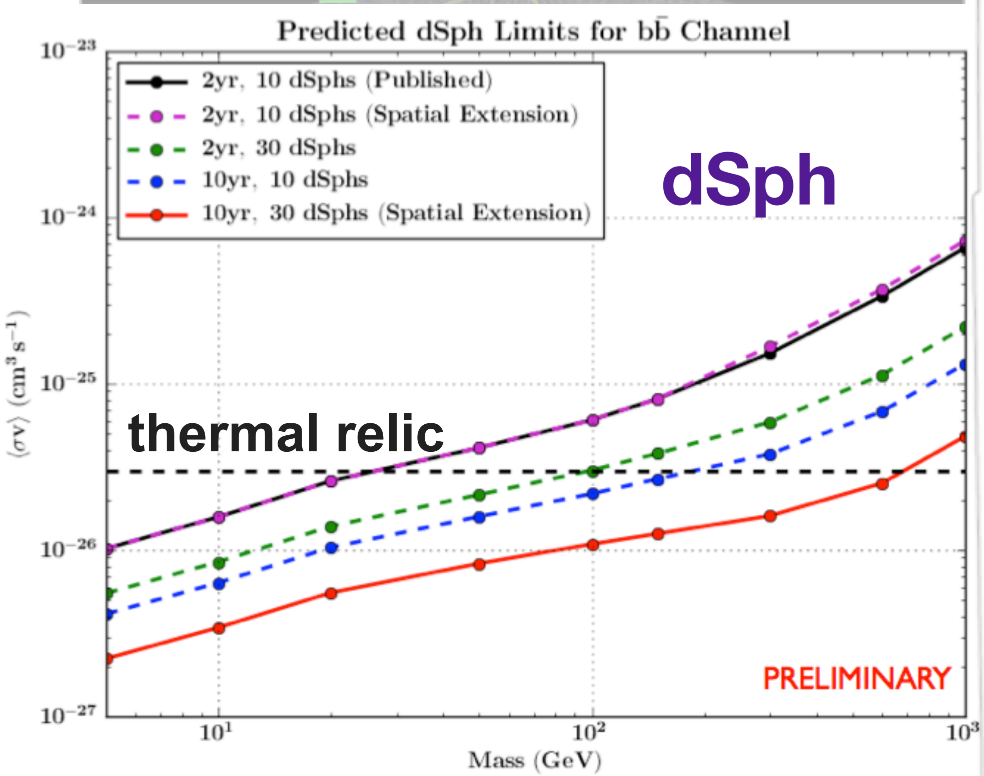


As anticipated from particle theory

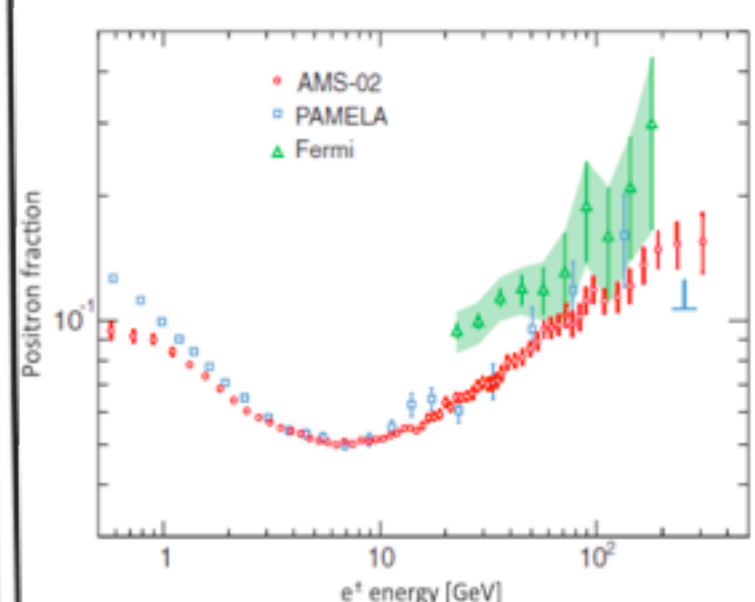
Dark Matter Searches with Fermi







$e^+/(e^- + e^+)$ by AMS, PAMELA & Fermi



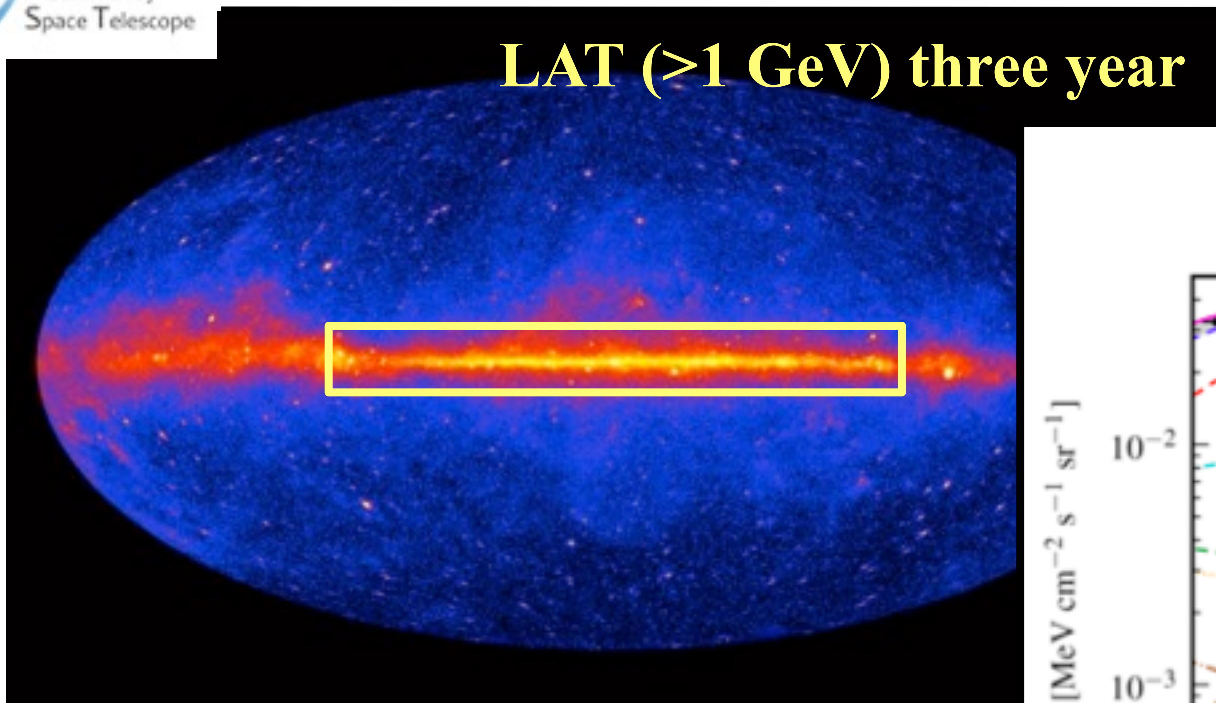
AMS-2 results

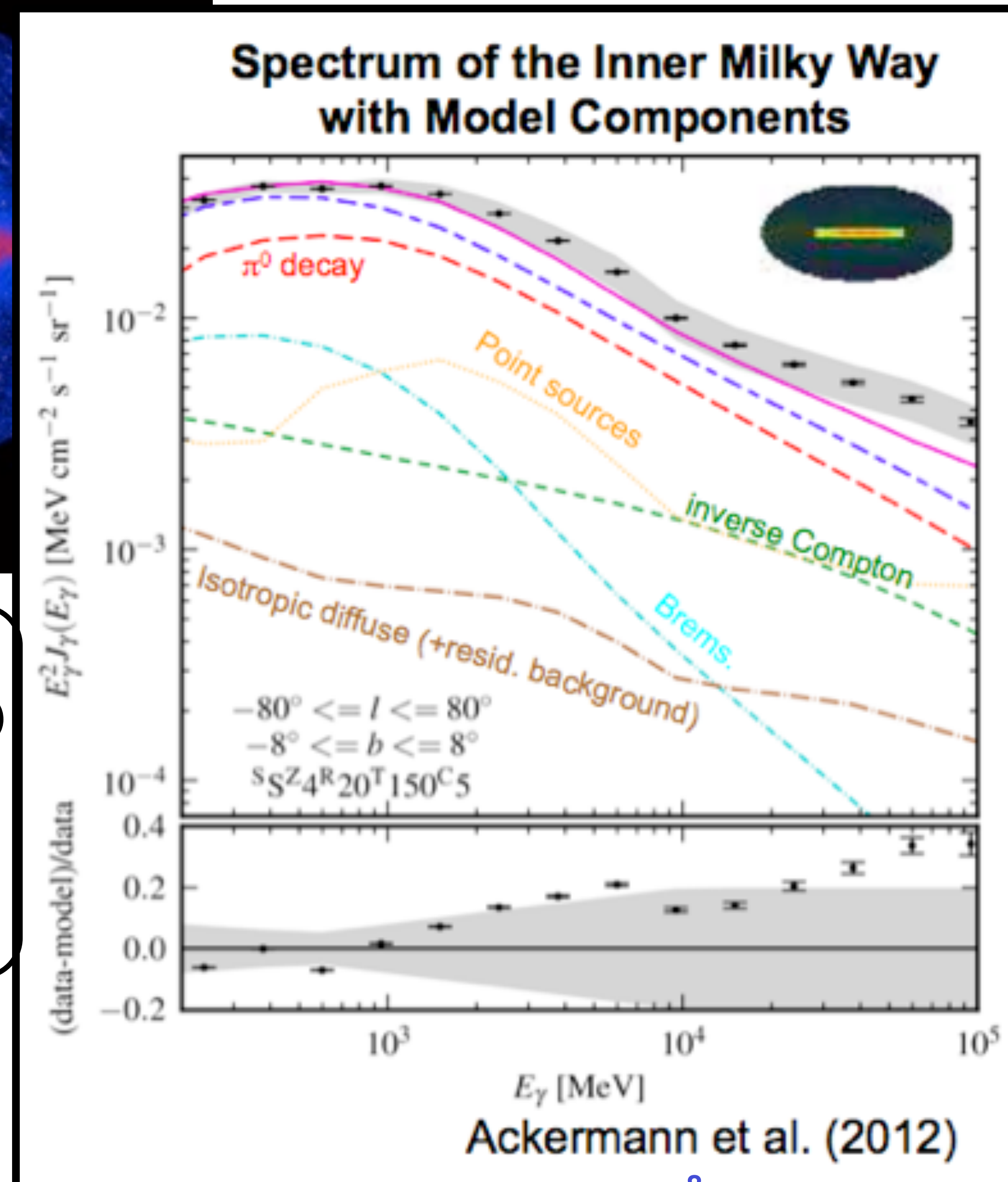
- Extends to ~300GeV
- Highest precision
- Agree with PAMELA

- 300GeVまで拡張
- 高精度
- PAMELAと合っている

PRL 110, 141102 (201

Galactic Diffuse Background





Hadronic:

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

Leptonic:

bremsstrahlung (CR e + H → γ)

Inverse Compton (CR e + γ → γ)

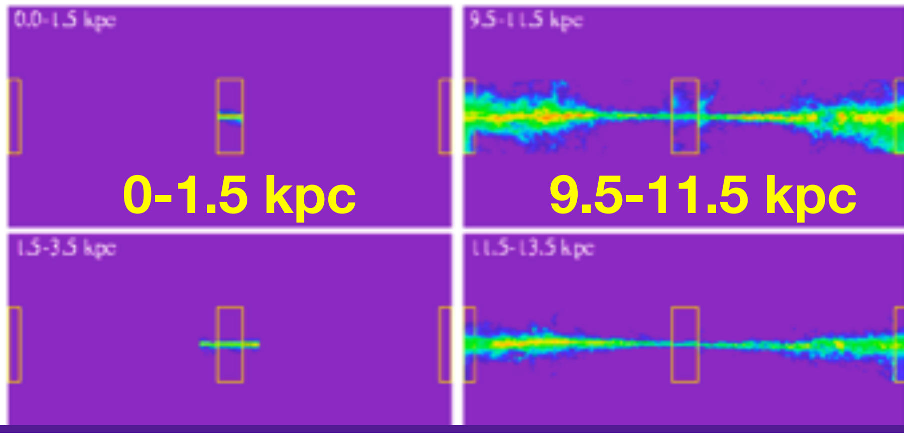
Galactic diffuse emission

– the distribution of interstellar gas; and

– the distribution of Galactic cosmic rays

Modeling Diffuse Background

All-sky H I ‘Ring’ maps*



The diffuse gamma-ray emission is modeled as a linear combination of templates of gas tracers and other diffuse components

$$N_{pred}(l,b) = \iint d\Omega_k \Big(\sum_{i=rings} [q_{HI,i} N_{HI}(r_i,l_k,b_k) + q_{CO,i} W_{CO}(r_i,l_k,b_k)]$$
$$+ q_{EBV} E(B-V)_{res}(l_k,b_k) + q_{IC} I_{IC}(l_k,b_k) + I_{iso}(l_k,b_k) \Big) \epsilon(l_k,b_k)\, PSF(l,b,l_k,b_k)$$
$$+ \sum_{j=sources} F_j\, \epsilon(l_j,b_j)\, PSF(l_j,b_j,l,b)$$

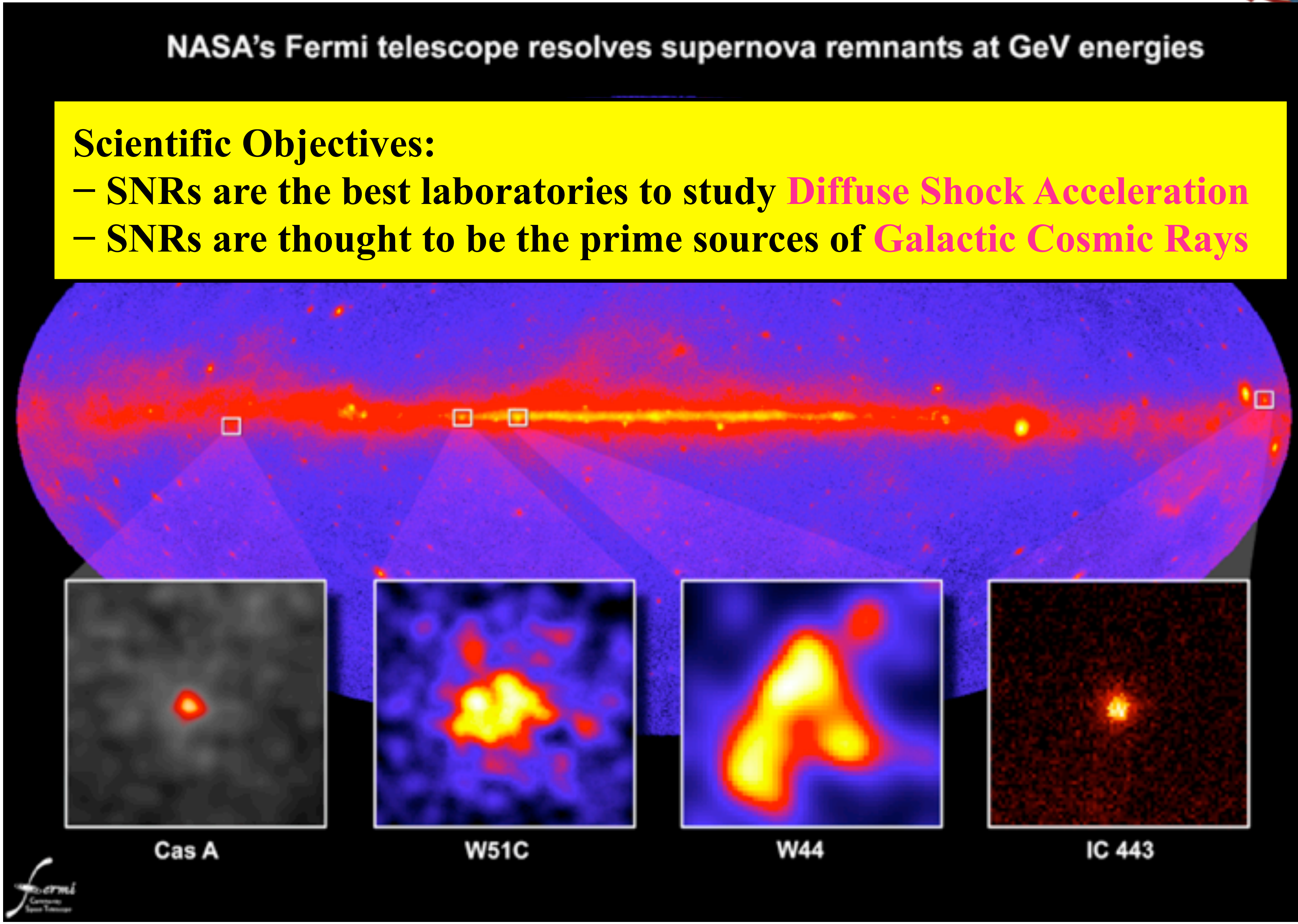
Model for diffuse gamma-ray intensity (q_{HI} is the emissivity, related to cosmic-ray intensities)

Point sources

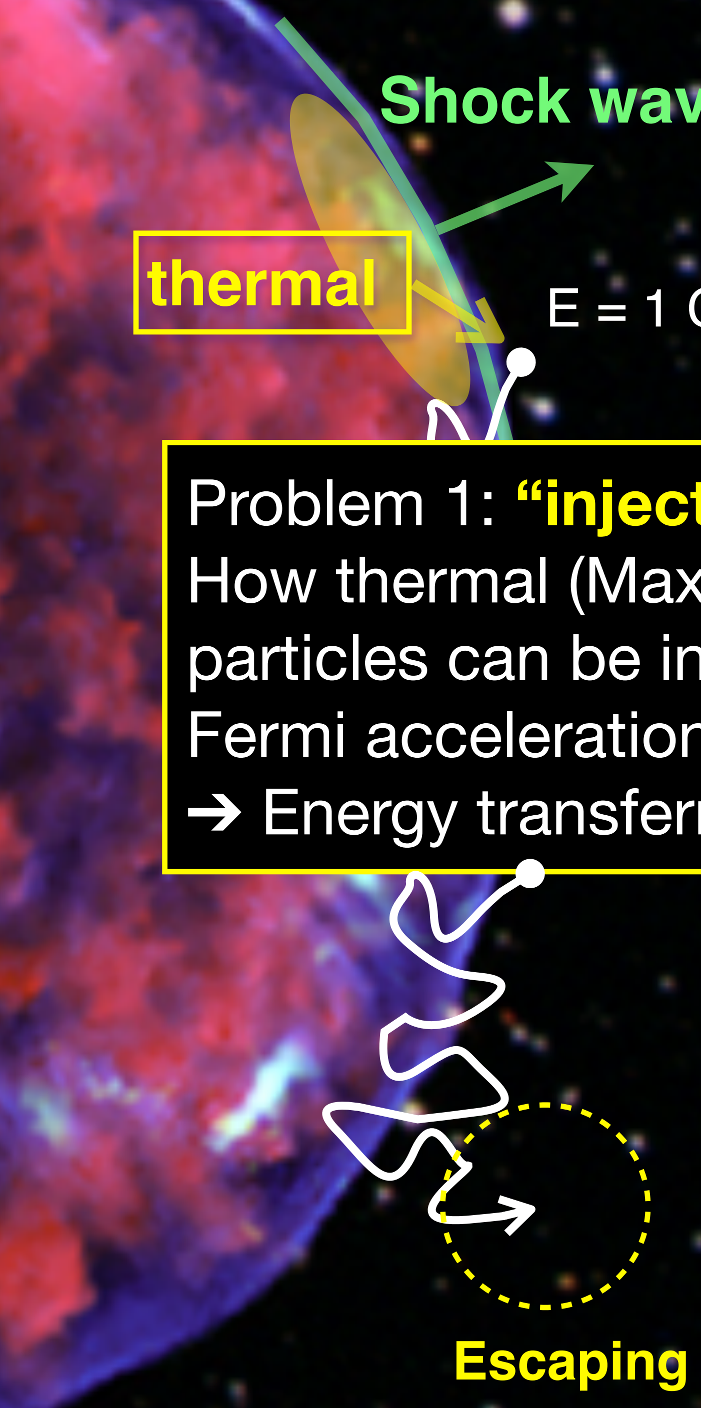
Exposure

Effective point-spread function

Fermi Observations of SNRs



Diffusive Shock Acceleration



Problem 1: **“injection”**
How thermal (Maxwellian) particles can be injected into Fermi acceleration?
➔ Energy transferred to CRs

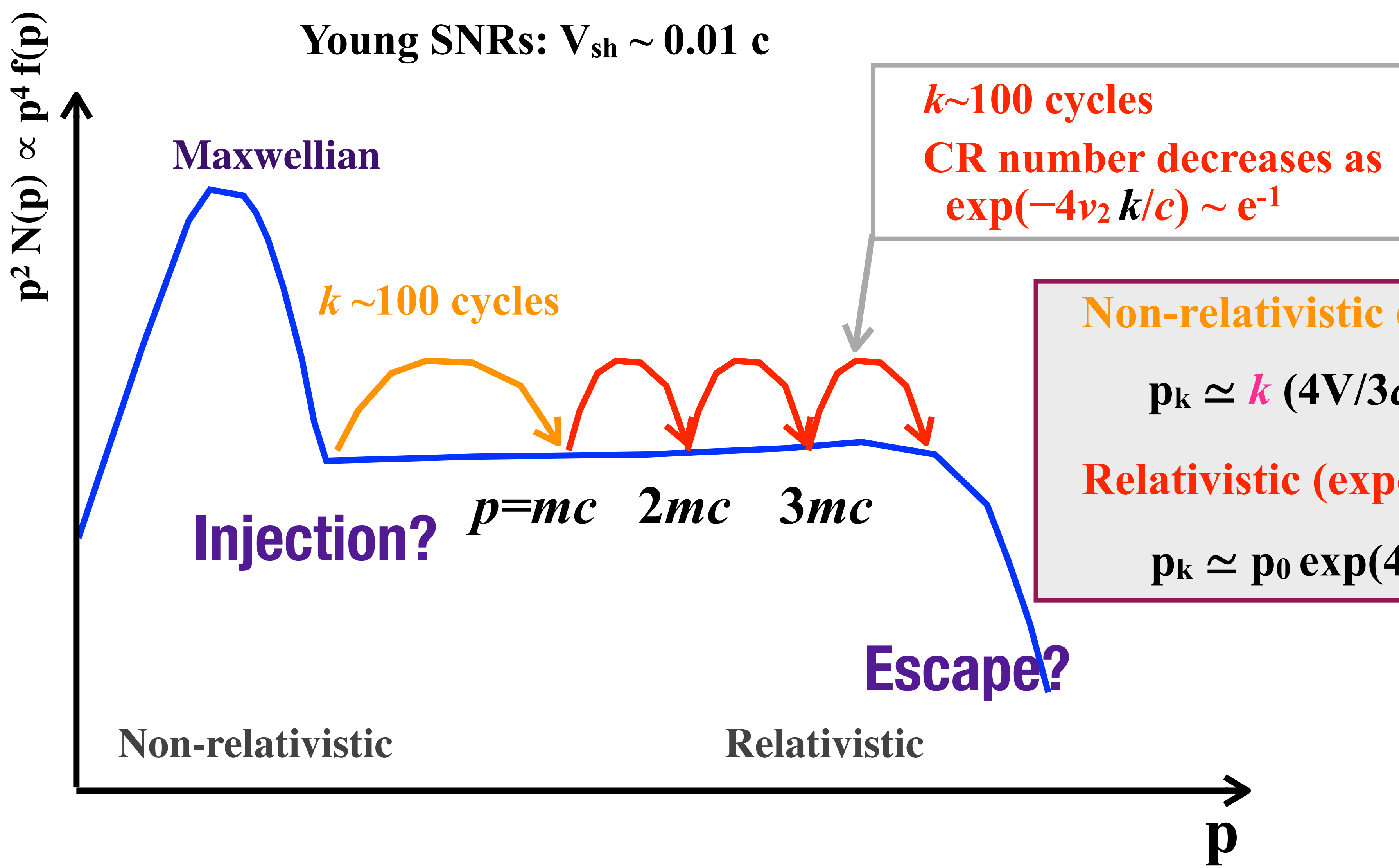
Problem 2: **“escape”**
How highest energy particles escape from a shock?
➔ Maximum attainable energy

Shock crossing ➔ energy gain
Energy gain per one round trip:
$\Delta E/E \sim V/c$ ~ 1% for young SNRs. After 1000 round trips:
e.g. 1 GeV ➔ 20 TeV
Energy distribution (test particle approximation):
$N(E)dE \propto E^{-2}\,dE$

NB:
- ✔ **Non-linear effects**
- ✔ **Magnetic field amplification**

Diffusive Shock Acceleration

Young SNRs: $V_{sh} \sim 0.01$ c



Non-relativistic (linear)

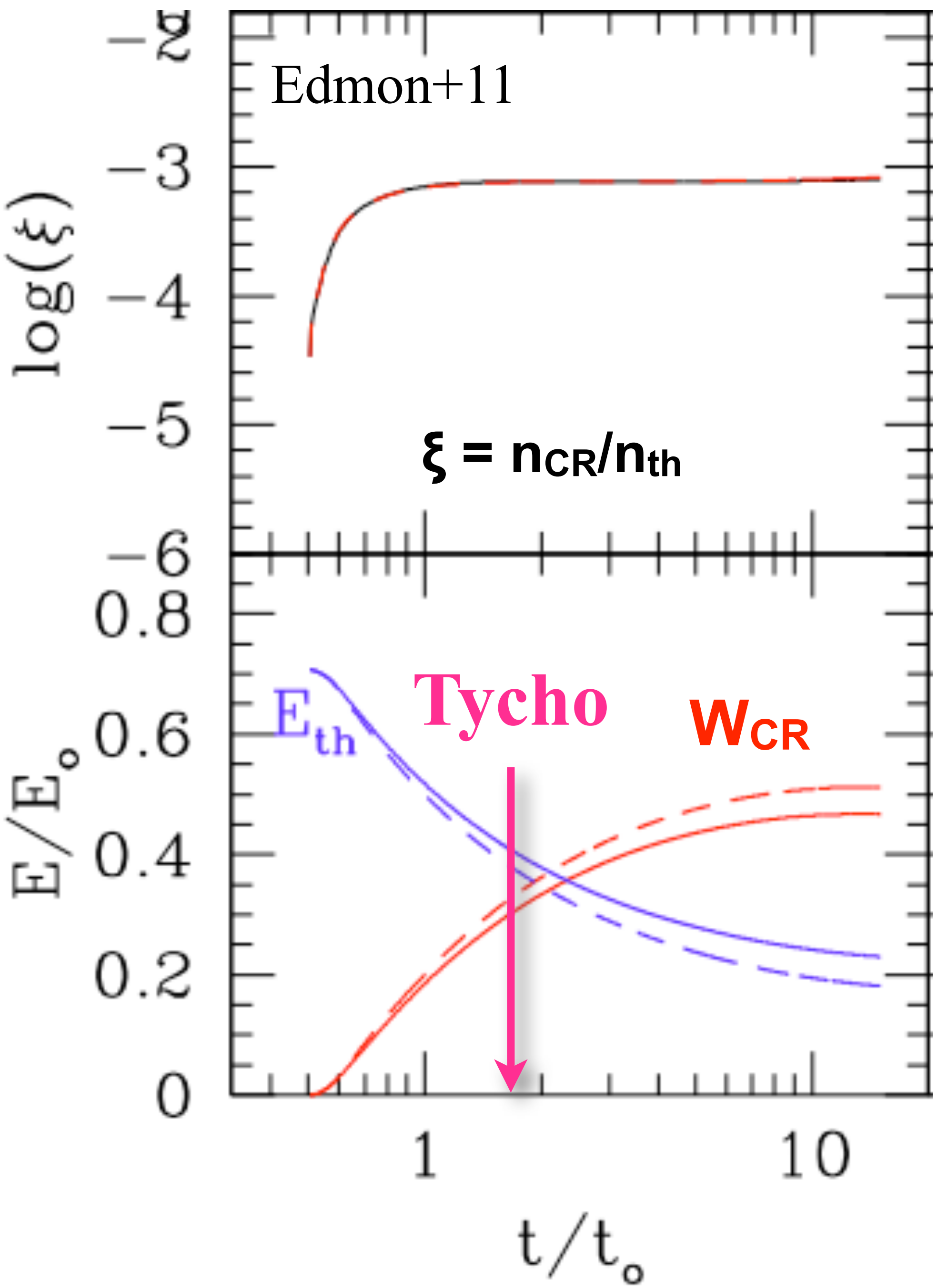
$p_k \simeq k\,(4V/3c)\,mc$

Relativistic (exponential)

$p_k \simeq p_0 \exp(4kV/3c)$

$N(p) \propto p^{-s}$ with s = 2 for strong shock

How to determine normalization (1)?



$\xi = n_{CR}/n_{th} = \frac{\text{CR particles}}{\text{thermal particles}}$

ξ is assumed to be constant

From the gamma-ray data, the amount of CRs in Tycho's SNR at its age of t = 439 yr is:

$W_{CR} \sim 7\%$ of E_{SN}

W_{CR} will reach 14% of E_{SN}

Supporting SNR origin of Galactic CRs

How to determine normalization (2)?

the rate at which kinetic energy is swept up from the ISM

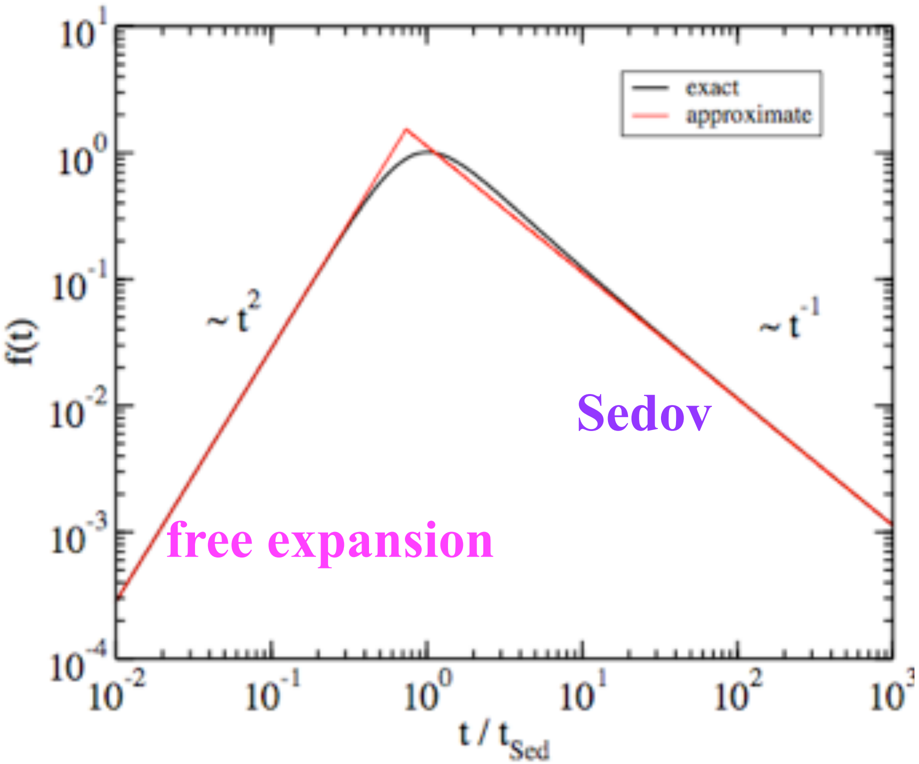
$$mc^2 \int d\gamma \gamma Q(\gamma, t) = \xi \cdot 4\pi R^2 n_{\rm H} v_{\rm sh} \left(\frac{1}{2} m_{\rm H} v_{\rm sh}^2 \right)$$

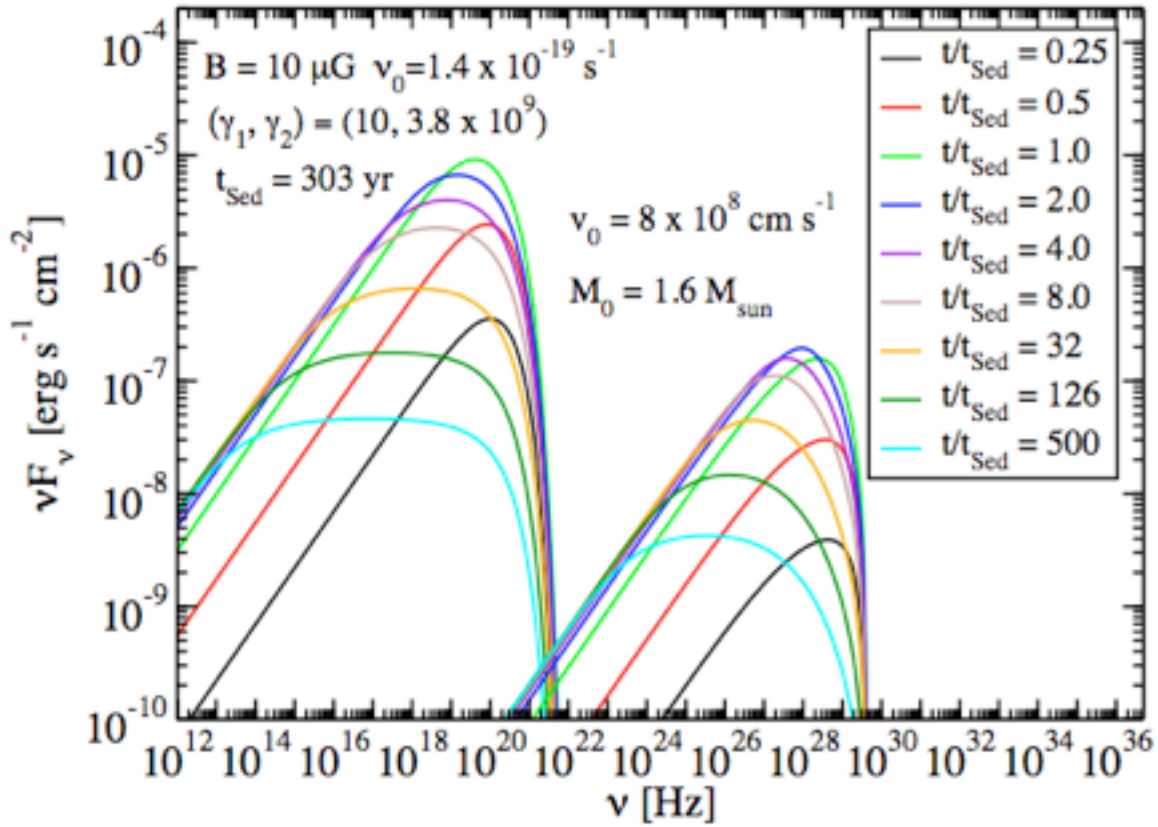
CR power

$\xi < 1$ is assumed to be constant

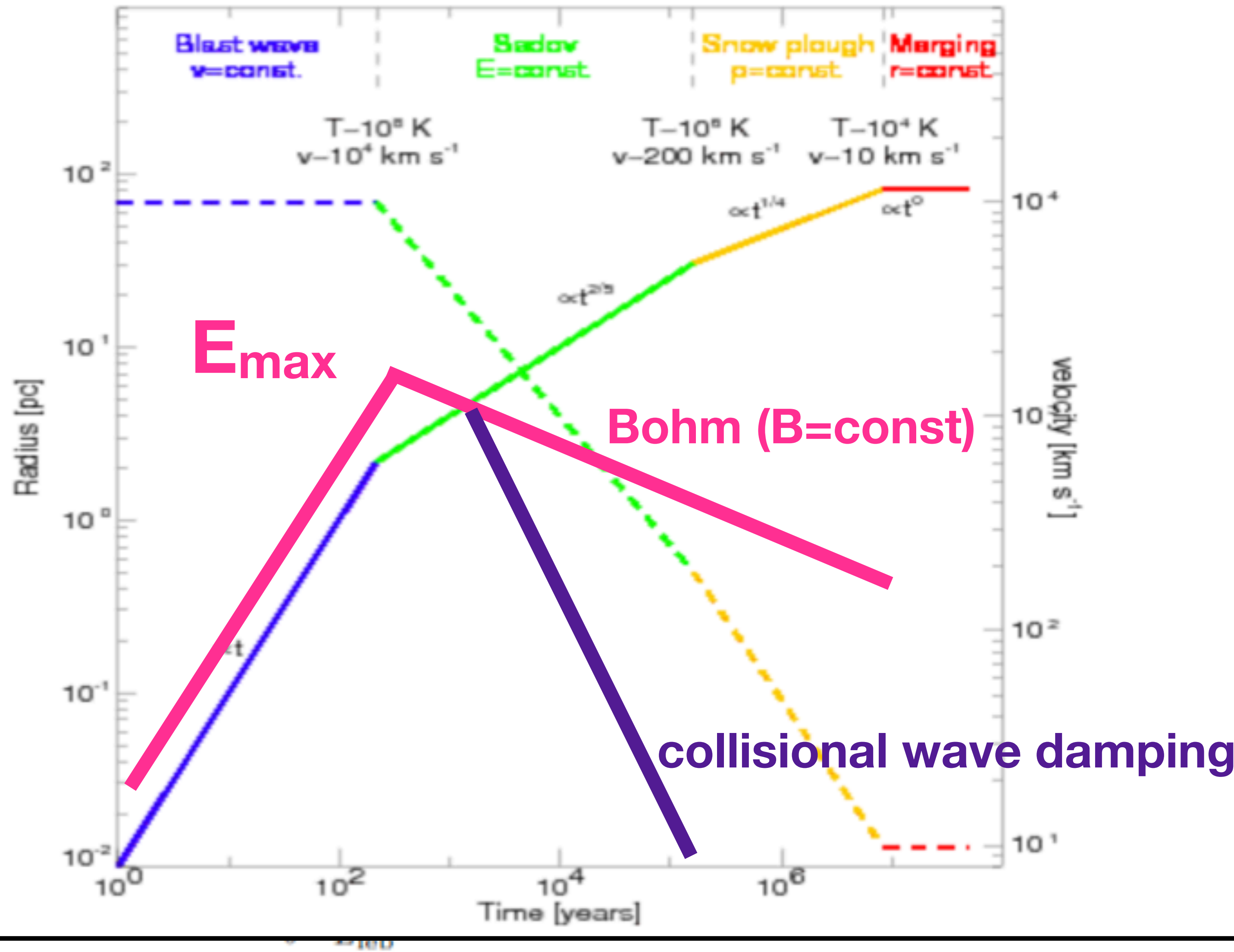
Finke & Dermer (2012)

$Q(\gamma=1, t)$





E_{max} limited by CR escaping due to wave damping



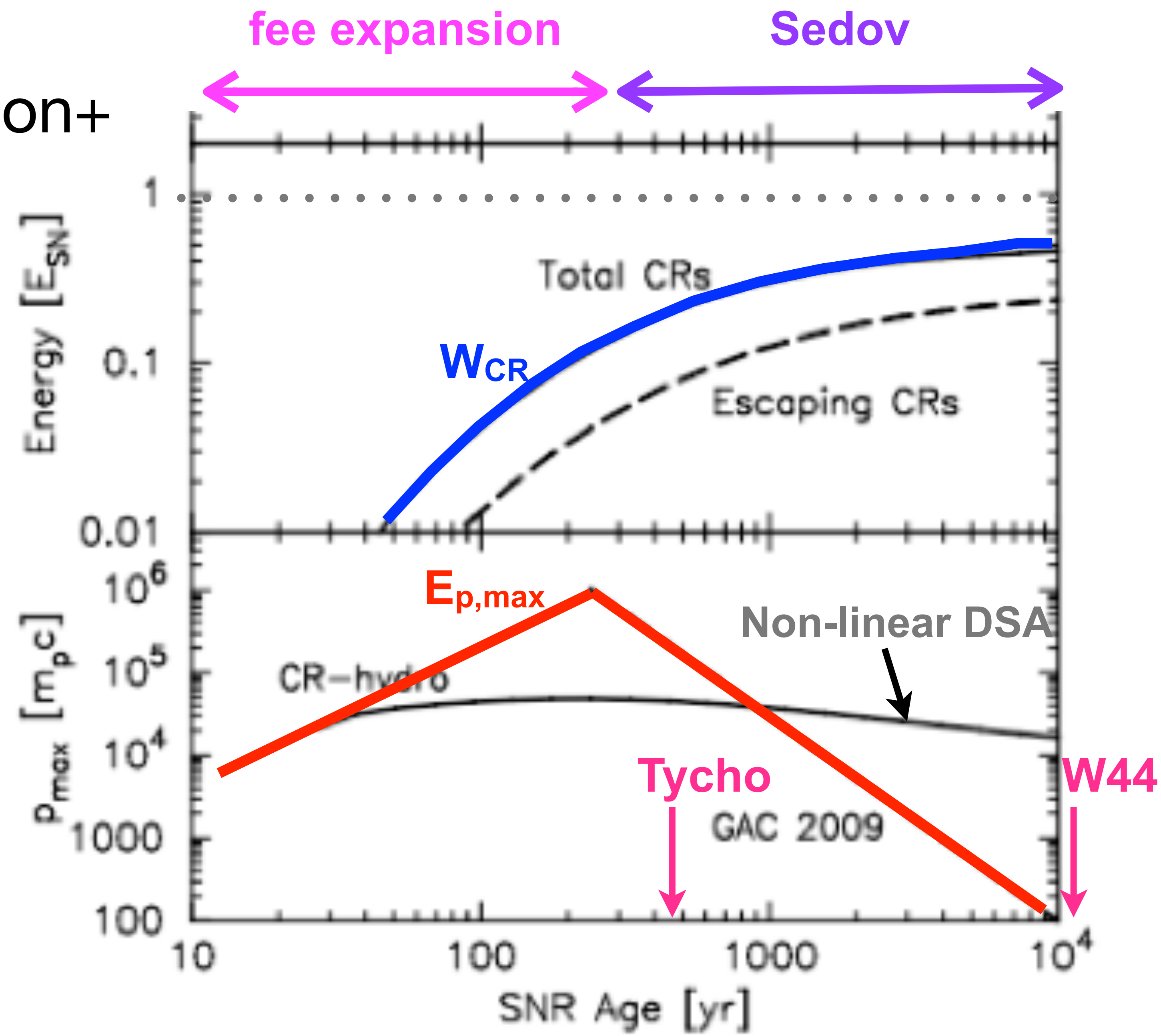
Cutoff from ion-neutral wave damping (e.g. Drury+ 1996)

$$E_{\rm max} \approx u_{0,7}^3 T_4^{-0.4} n_n^{-1} n_i^{0.5} \xi_{\rm CR,-1}\,{\rm GeV}$$

Origin: loss of CR trapping power
→ enhanced escape in partially ionized medium

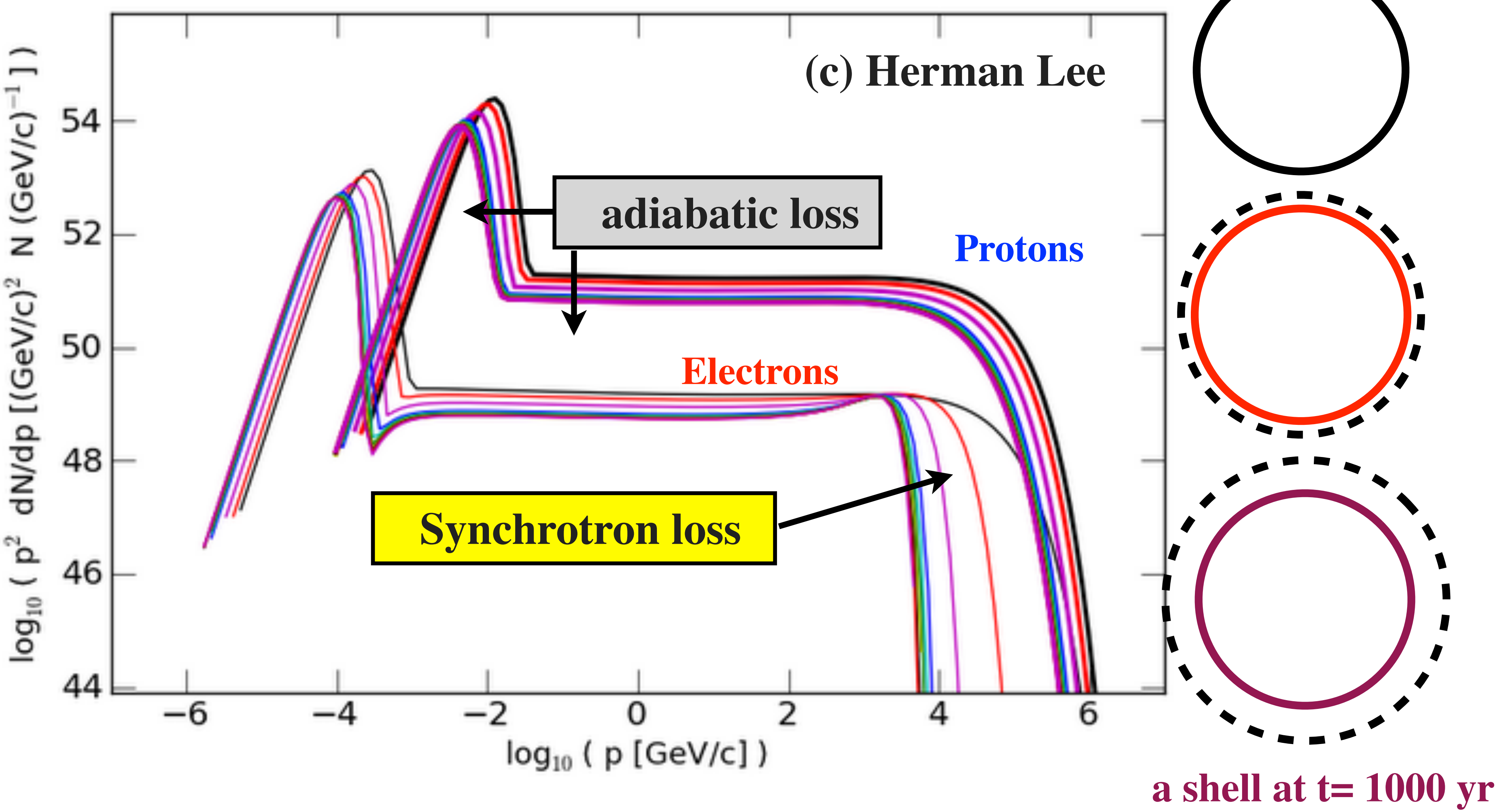
CR Content and Maximum Energy as Function of SNR Age

c: Ellison+

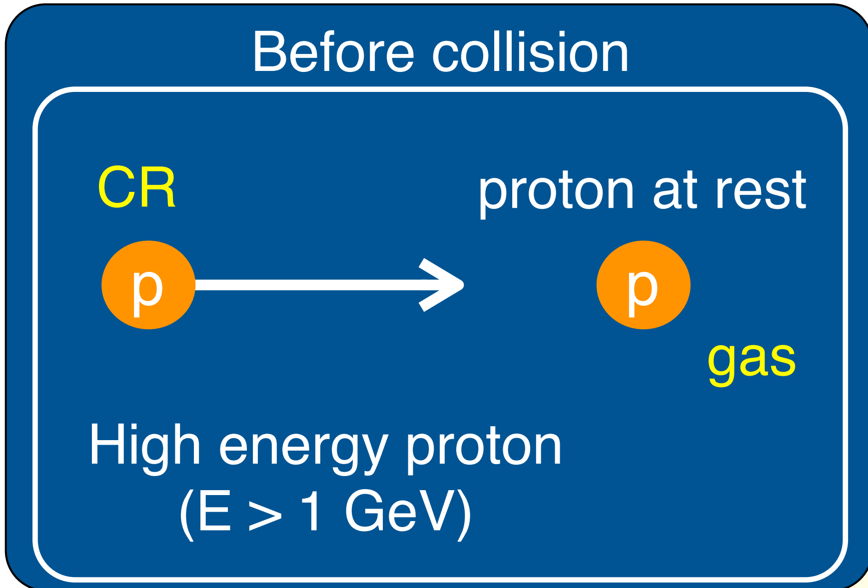


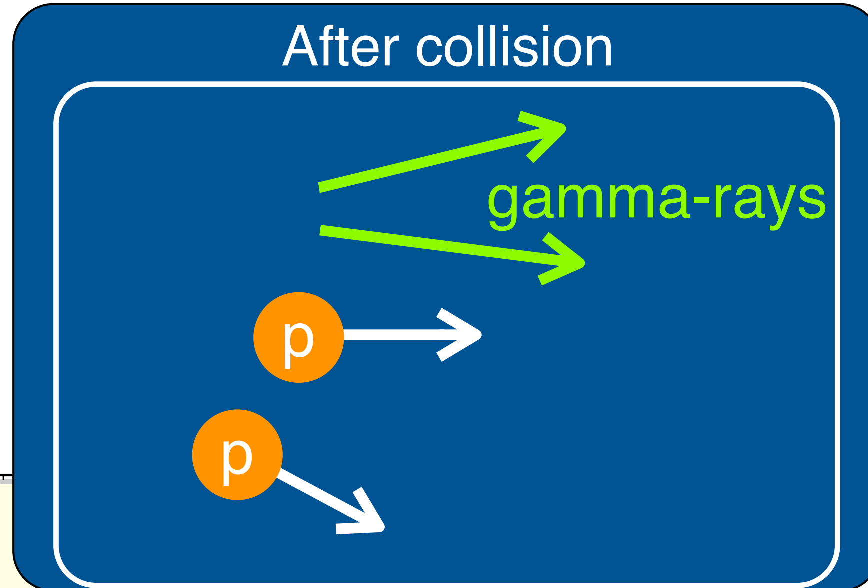
Time Evolution of Particle Distribution behind Shock

Evolution (t= 100 yr to 1000 yr) of CRs in a shocked shell (Lagrangian sense)



π^0-decay γ-rays: Direct Probe of Accelerated Protons

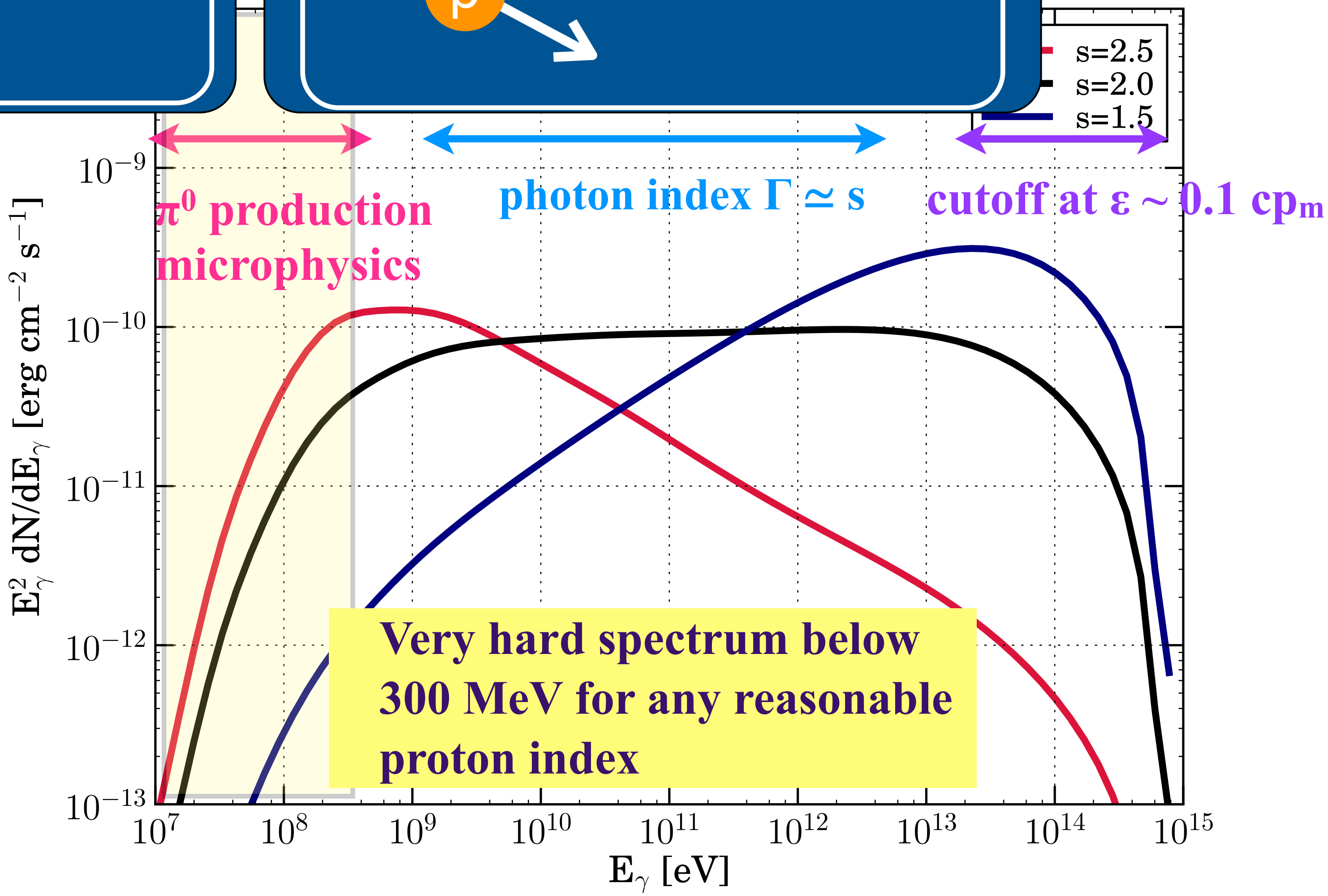




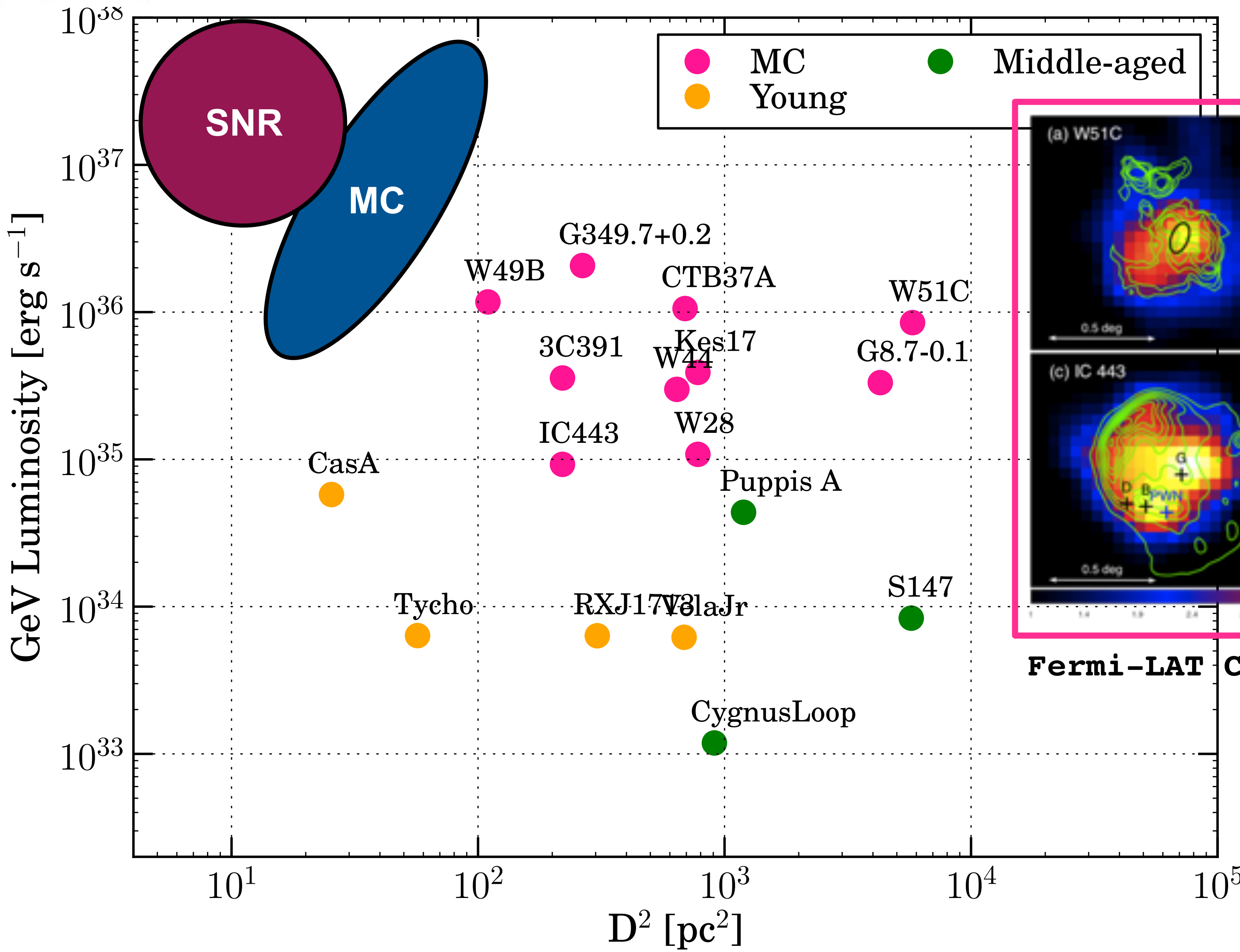
$dN_\gamma/d\varepsilon$: symmetric about 68 MeV

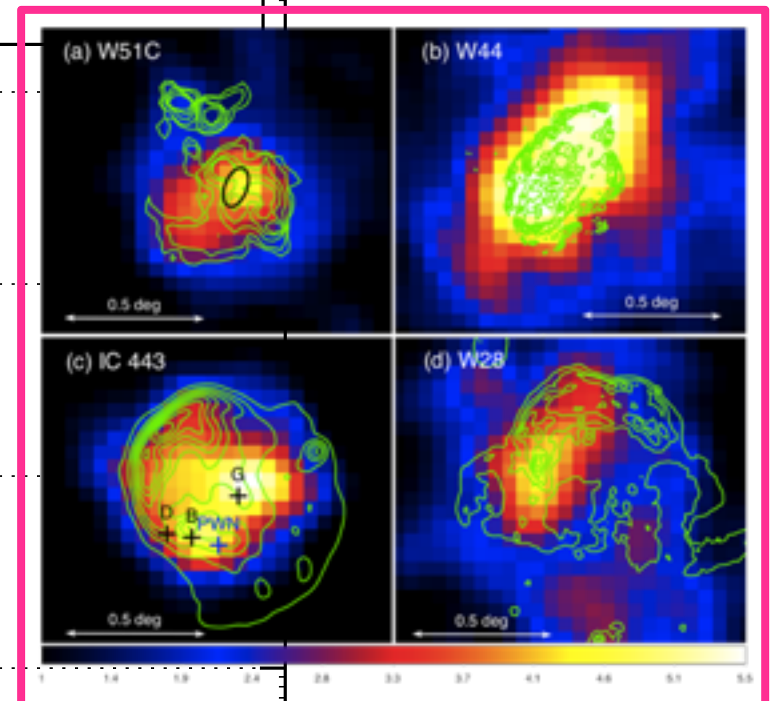
↓

$\varepsilon^2\, dN_\gamma/d\varepsilon$: hard spectrum below 300 MeV



SNRs Detections with Fermi

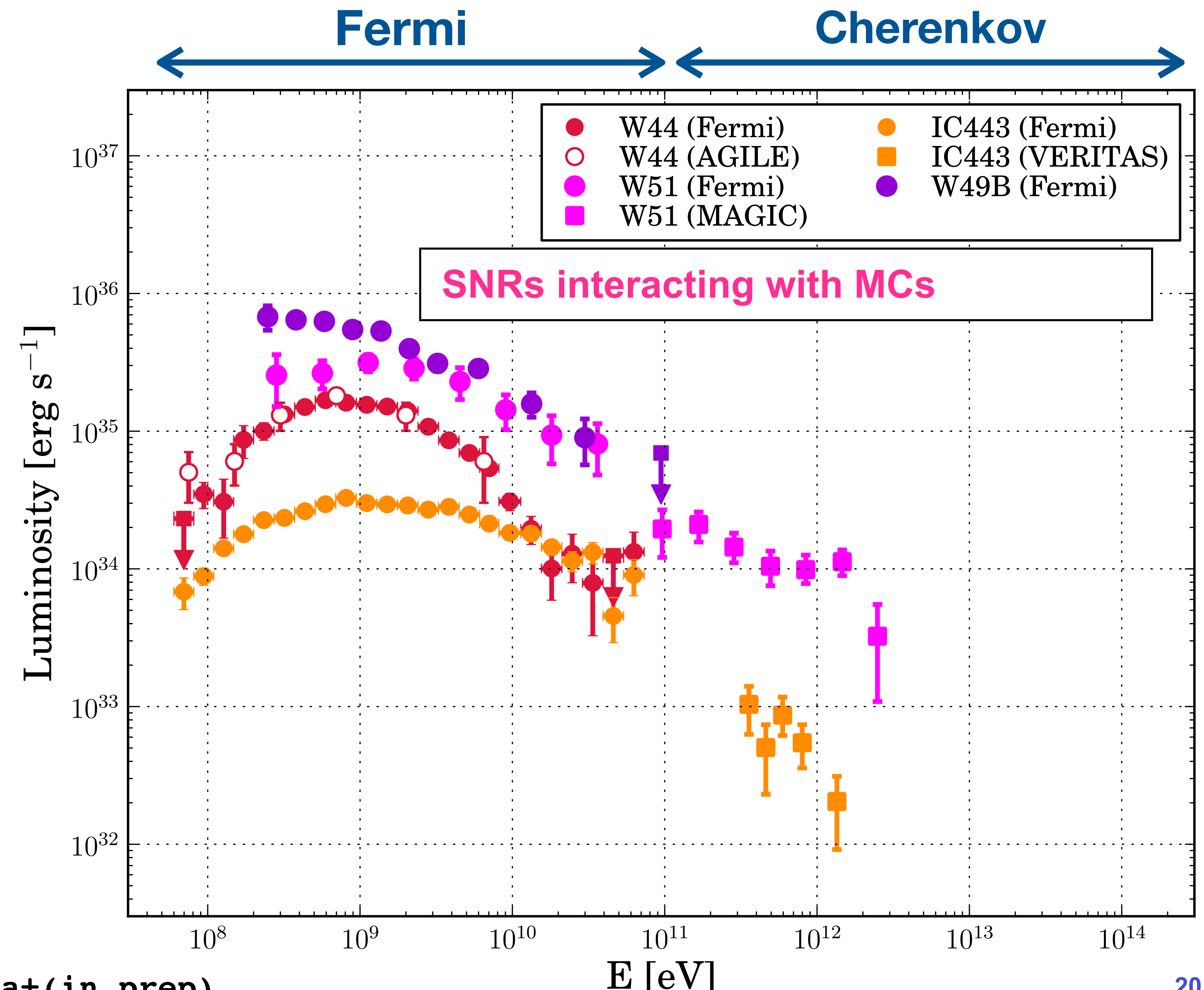




Fermi-LAT Coll(Uchiyama+)2011

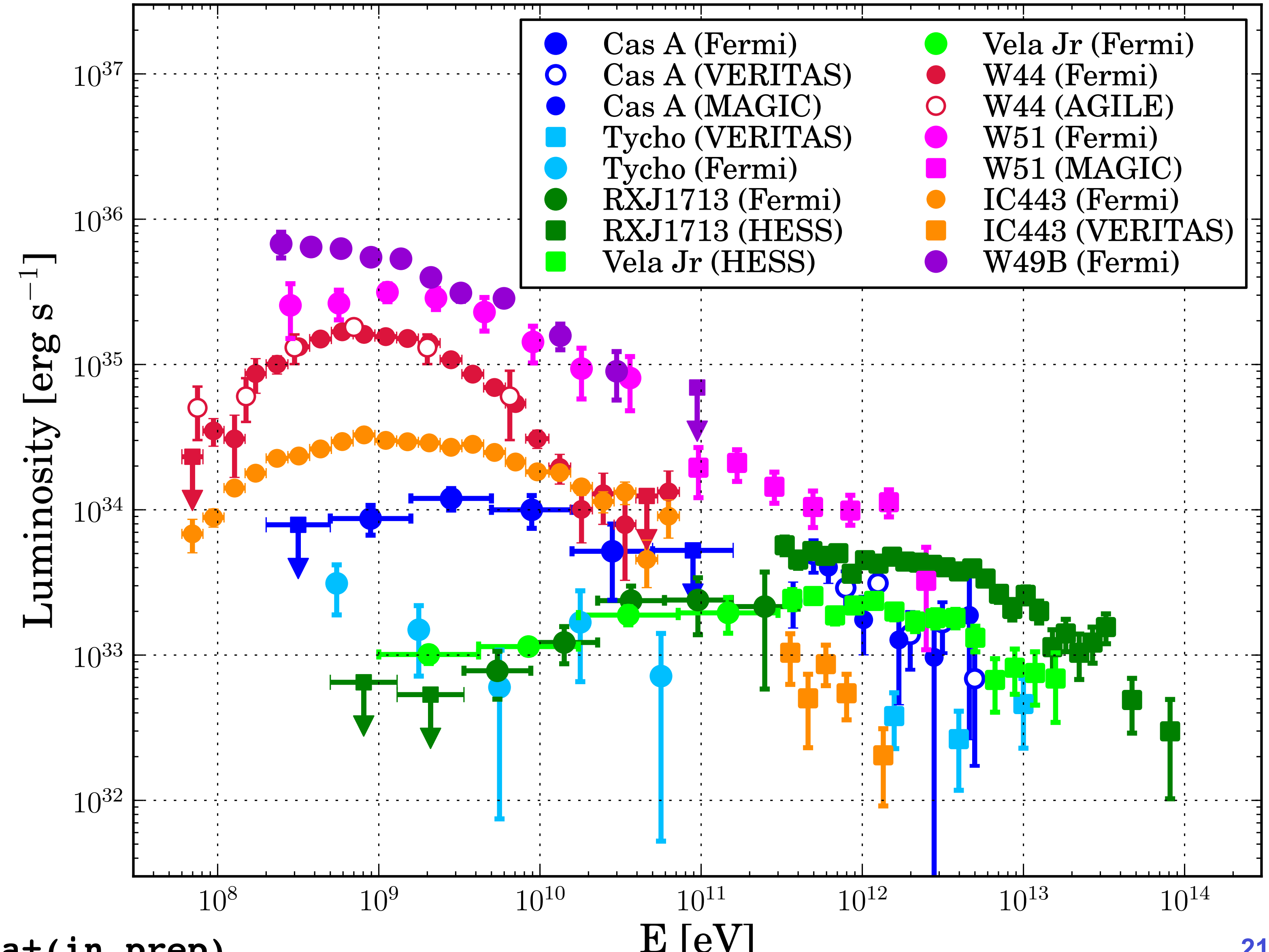
Updated from Thompson,Baldini,Uchiyama(2012)

Gamma-ray Spectra of Fermi-Detected SNRs



Uchiyama+(in prep)

Gamma-ray Spectra of Fermi-Detected SNRs



Uchiyama+(in prep)

Young SNR: Tycho's SNR

Fermi-LAT Detection (5σ)

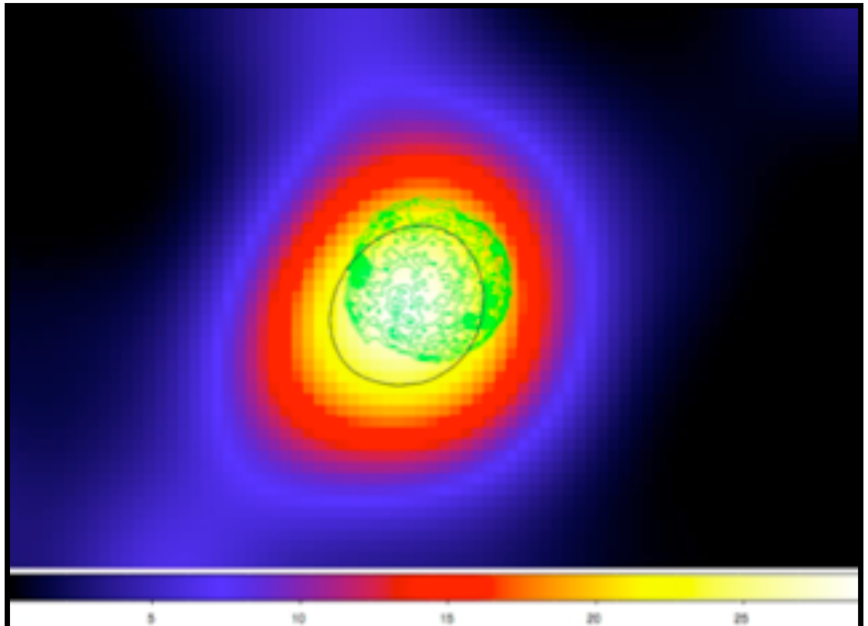
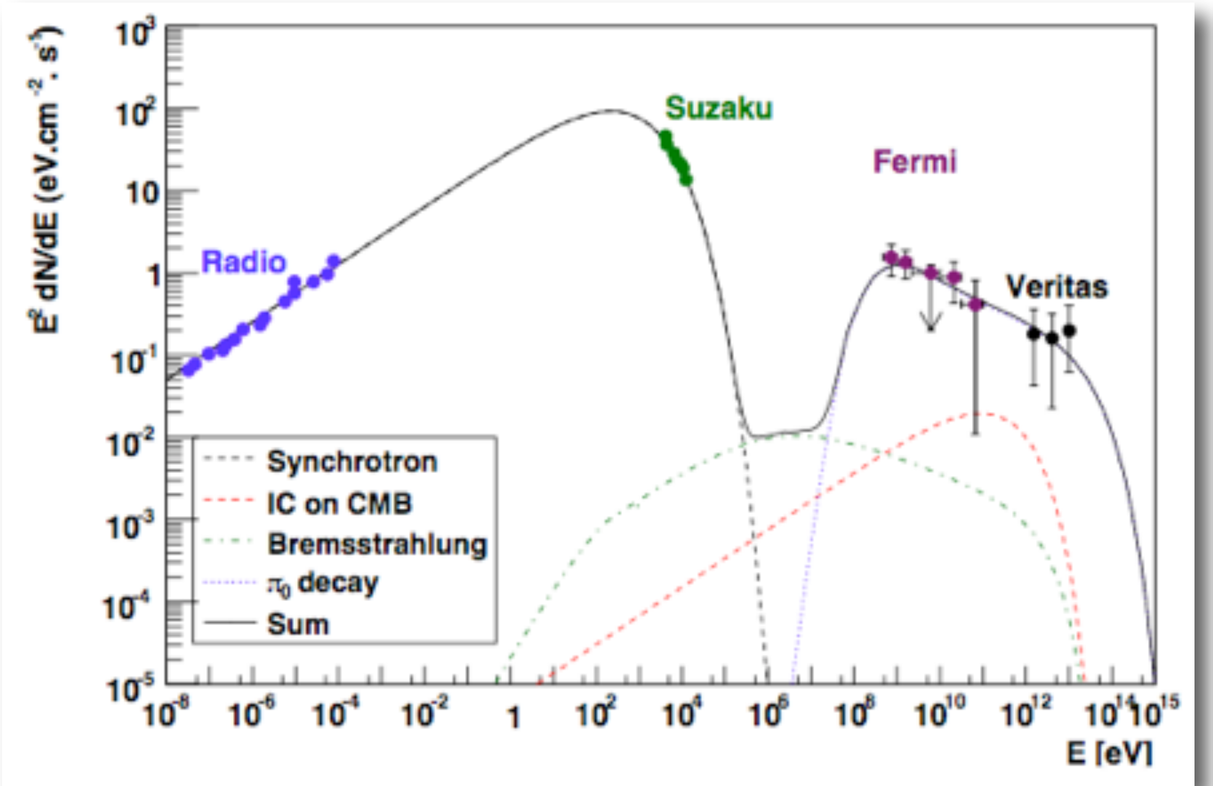


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*



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}

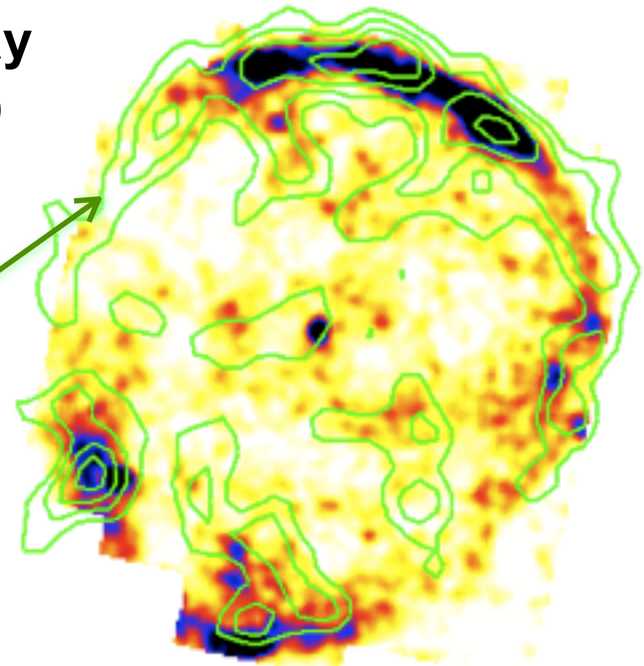
Photon index = 2.3 ± 0.1 (favors hadronic origin)

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

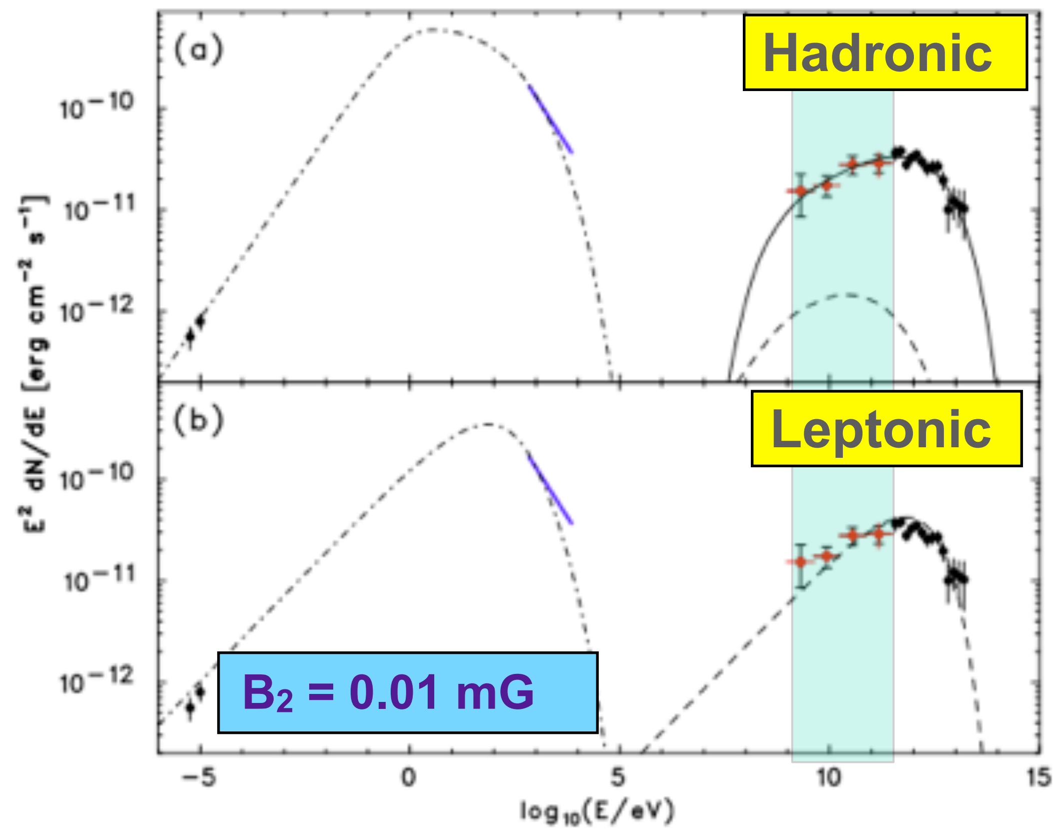
Synchrotron-dominated SNR: Vela Jr.

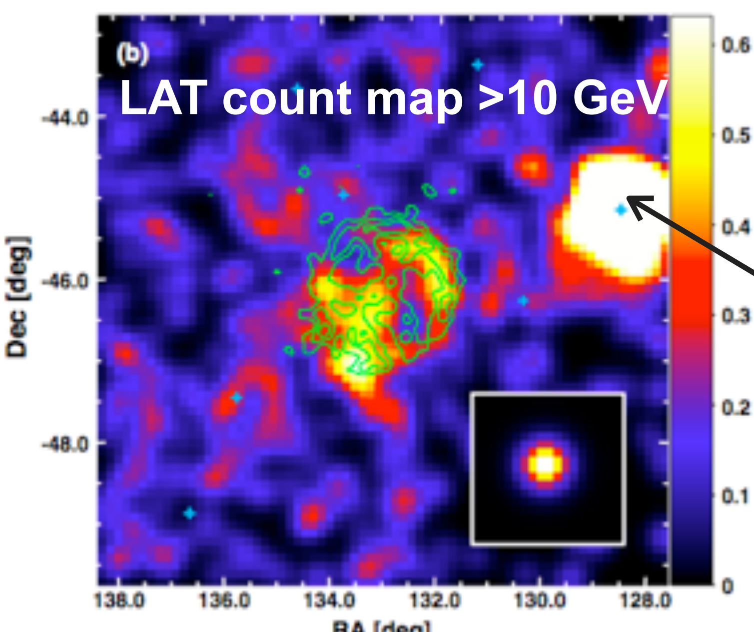
Suzaku X-ray
(Y. Uchiyama)

TeV (H.E.S.S.)



Tanaka+2011





Vela pulsar

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

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})

Middle-Aged SNR: Puppis A

Hewitt+2012

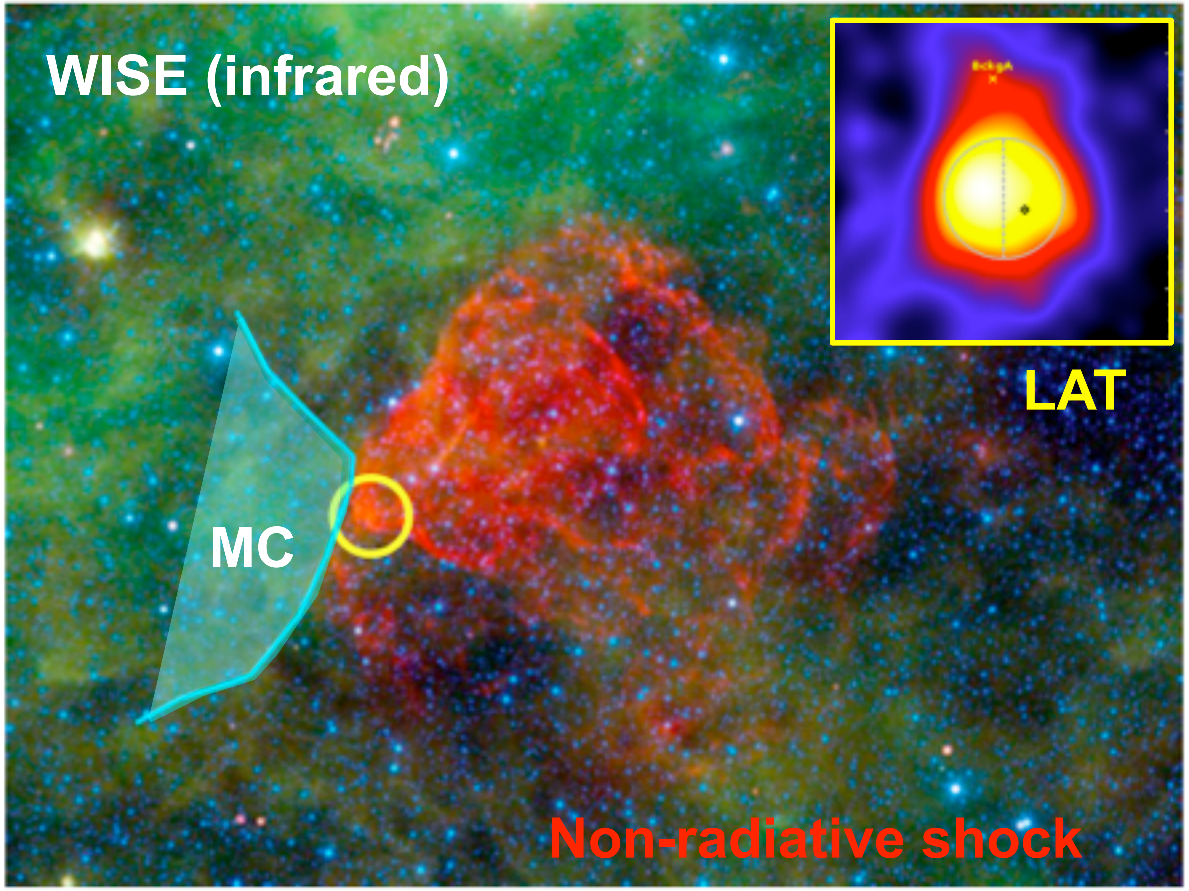
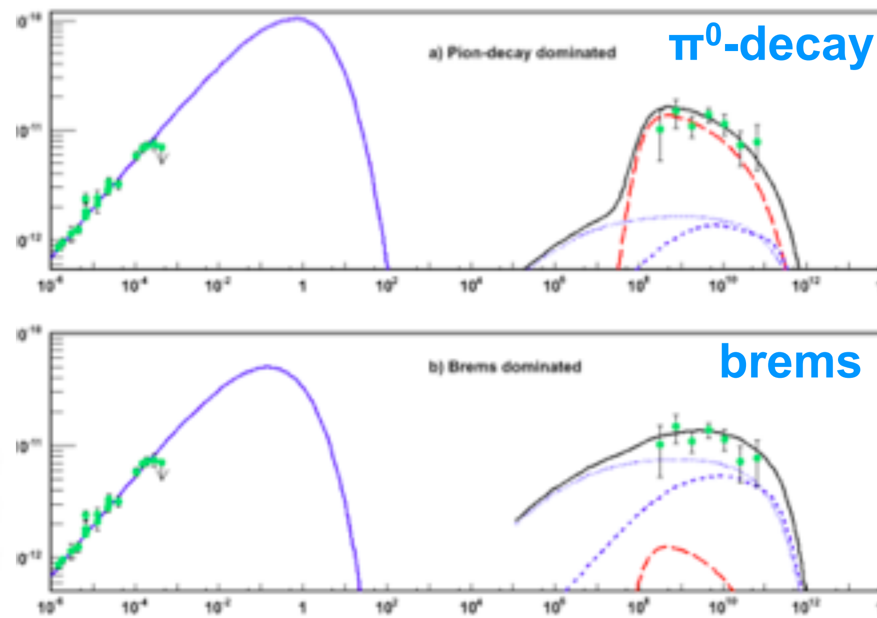


Figure 1: *Infrared emission from dust heated by the expanding shock-wave of Puppis A (courtesy WISE). Yellow circle indicates where the shock has encountered a small cloud. Cyan contours highlight the adjacent molecular cloud, just beyond the SNR.*

Diameter: 30 pc
Age: ~40,000 yr (Sedov phase)
ISM Density: 1 cm^{-3}

LAT Detection at ~13σ level
Γ_{LAT} = 2.10 ± 0.07(sta)
± 0.10(sys)



The gamma-ray emission can be modeled either by bremsstrahlung with $W_e = 1\times10^{49}$ erg or by hadronic (π^0-decay) with $W_p = 4\times10^{49}$ erg

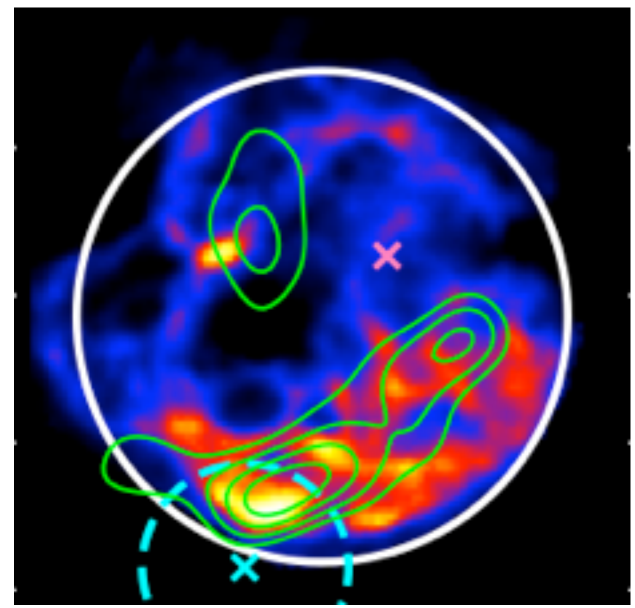
Old SNR: S147

Katsuta, Uchiyama+2012

Hα image (radiative shock)

Diameter: 76 pc (d=1.3 kpc)
Age: ~30,000 yr
ISM Density (2 phases): 4 cm^{-3} / 0.1 cm^{-3}
➜ compression ➜ 400 cm^{-3} / 0.4 cm^{-3}

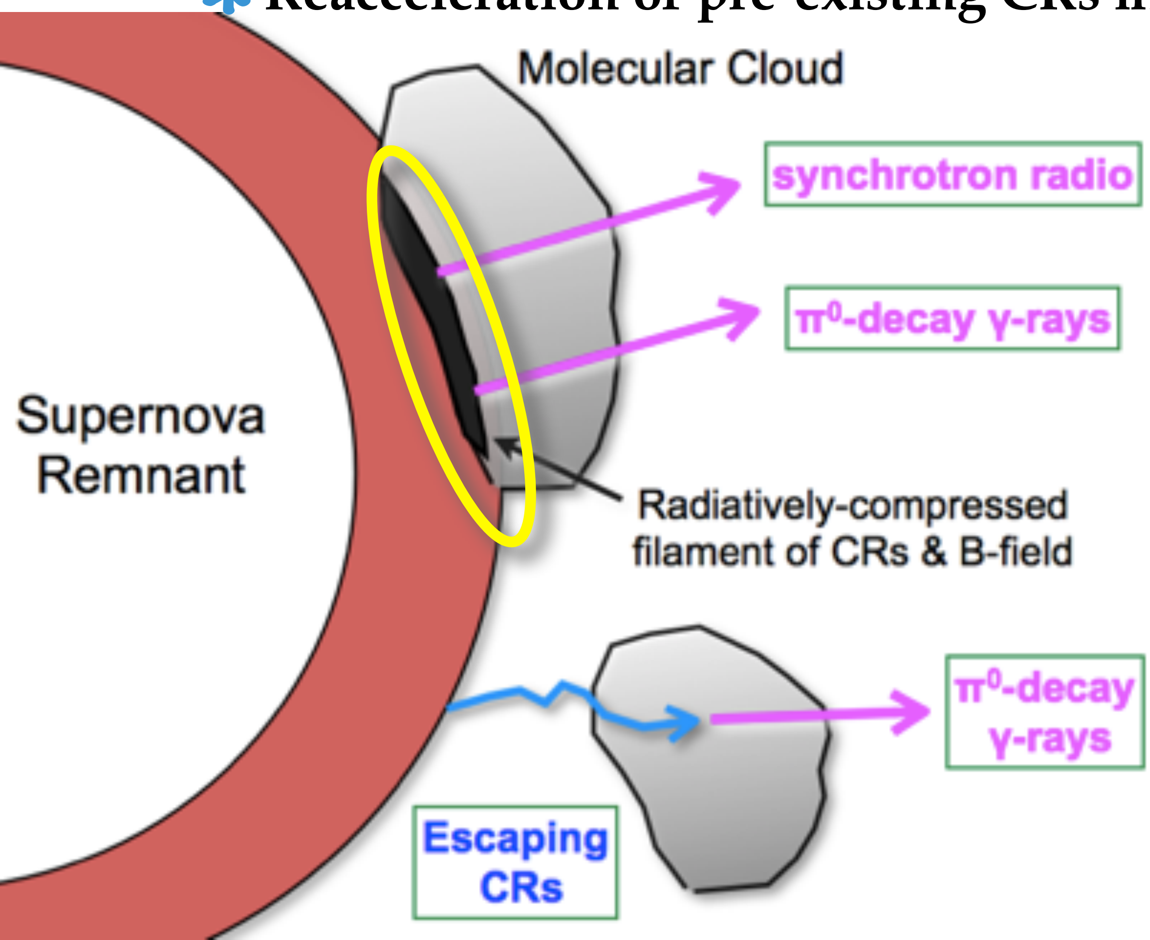
Fermi vs Hα



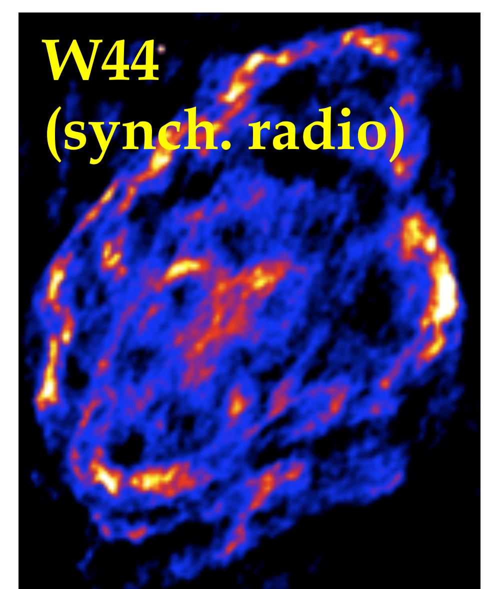
The gamma-ray emission can be explained by re-acceleration of Galactic CRs in optical filaments (Uchiyama+2010).

SNR-MC System

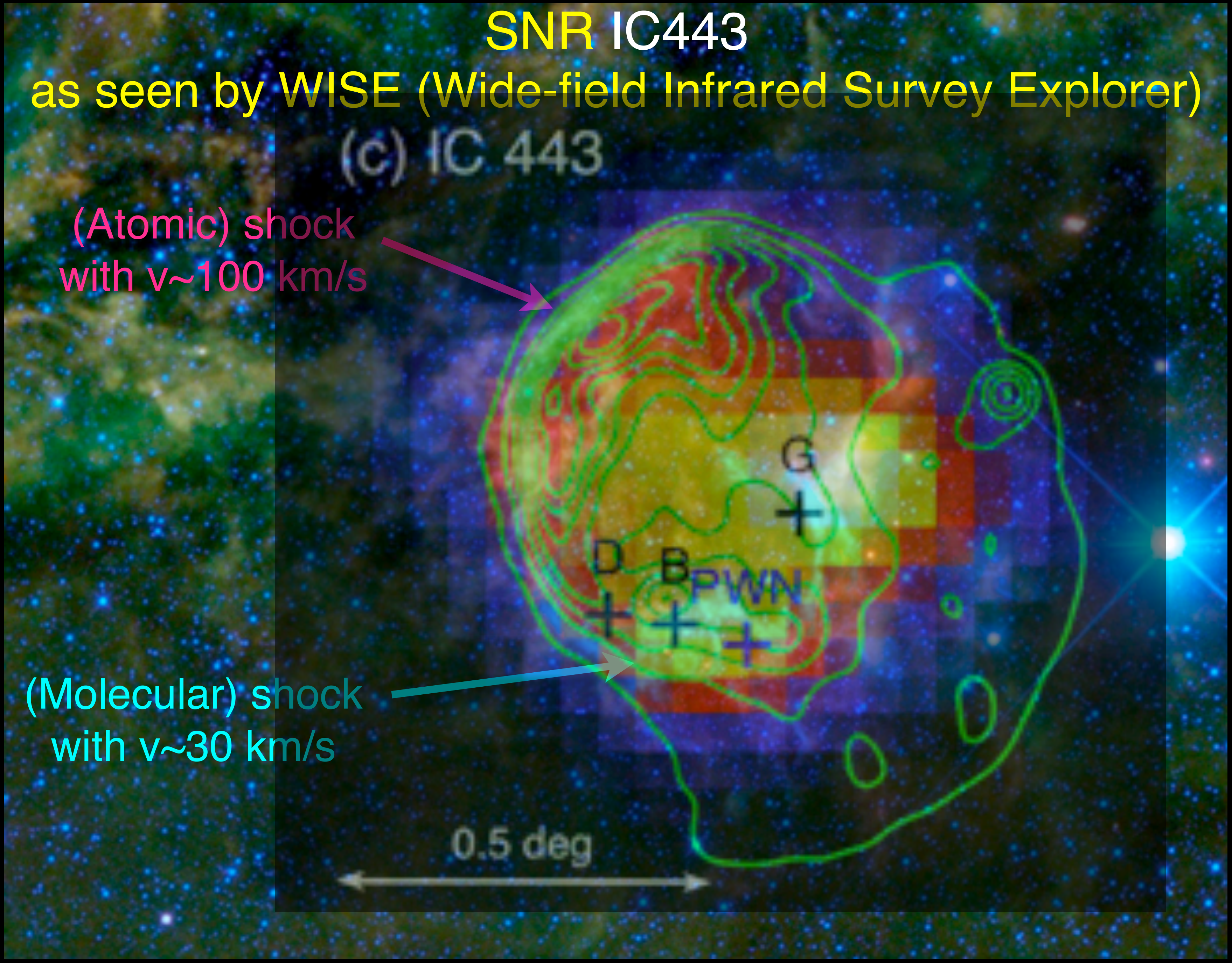
- Crushed Cloud model: π^0-decay γ-rays come from shocked molecular clouds Blandford & Cowie (1982), Uchiyama et al. (2010)
  - Radiative shock ➜ high compression ➜ high CR & gas density
  - Shock: slow (~100 km/s), partially ionized ➜ Maximum energy < TeV
  - Thin filaments or sheets ➜ Hard to confine CRs at high energies
  - Reacceleration of pre-existing CRs may be important



- The Case of W44:
  - Shocked MC mass of 5000 $M_\odot$
  - Synchrotron radiation correlated with shocked H_2 gas (infrared lines)



Fermi Telescope Revealed Cosmic-ray Protons



Detection of the Characteristic Pion-Decay Signature in Supernova Remnants

CA: Funk, Tanaka, Uchiyama

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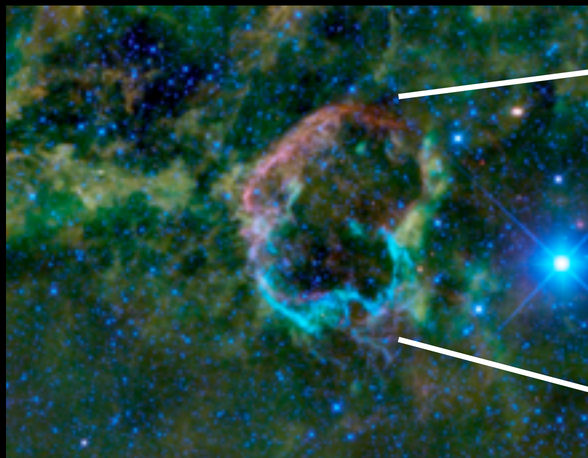
Cosmic rays are particles (mostly protons) accelerated to relativistic speeds. Despite wide agreement that supernova remnants (SNRs) are the sources of galactic cosmic rays, unequivocal evidence for the acceleration of protons in these objects is still lacking. When accelerated protons encounter interstellar material, they produce neutral pions, which in turn decay into gamma rays. This offers a compelling way to detect the acceleration sites of protons. The identification of pion-decay gamma rays has been difficult because high-energy electrons also produce gamma rays via bremsstrahlung and inverse Compton scattering. We detected the characteristic pion-decay feature in the gamma-ray spectra of two SNRs, IC 443 and W44, with the Fermi Large Area Telescope. This detection provides direct evidence that cosmic-ray

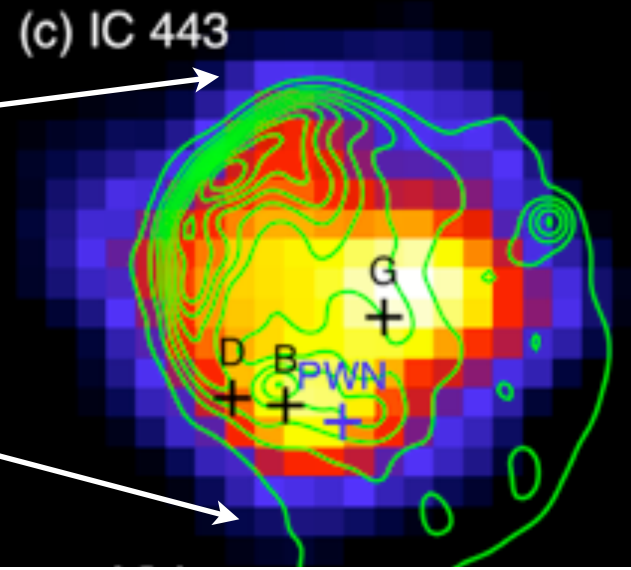
ejecta and is then transferred to kinetic and thermal energies of shocked interstellar gas and relativistic particles. The shocked gas and relativistic ...hermal ...). The ... (DSA) can explain the production of relativistic particles in SNRs (*1*). DSA generally predicts that a substantial fraction of the shock energy is transferred to relativistic protons. Indeed, if SNRs are the main sites of acceleration of the galactic cosmic rays, then 3 to 30% of the supernova kinetic energy must end up transferred to relativistic protons. However, the presence of relativistic protons in SNRs has been mostly inferred from indirect arguments (*2*–*5*).

A direct signature of high-energy protons is provided by gamma rays generated in the decay of neutral pions (π^0); proton-proton (more generally nuclear-nuclear) collisions create π^0 mesons, which usually quickly decay into two gamma rays (*6*–*8*) (schematically written as $p + p \rightarrow \pi^0$ + other products, followed by $\pi^0 \rightarrow 2\gamma$), each having an energy of $m_{\pi^0}c^2/2$ = 67.5 MeV in the rest frame of the neutral pion (where m_{π^0} is the rest mass of the neutral pion and c is the speed of light). The gamma-ray number spectrum, $F(\varepsilon)$, is thus symmetric about 67.5 MeV in a log-log representation (*9*). The π^0-decay spectrum in the usual $\varepsilon^2F(\varepsilon)$ representation rises steeply below ~200 MeV and approximately traces the energy distribution of parent protons at energies greater than a few GeV. This characteristic spectral feature (often referred to as the "pion-decay bump") uniquely identifies π^0-decay gamma rays and thereby high-energy protons, allowing a measurement of the source spectrum of cosmic rays.

Massive stars are short-lived and end their lives with core-collapse supernova explosions. These explosions typically occur in the vicinity of molecular clouds with which they in-

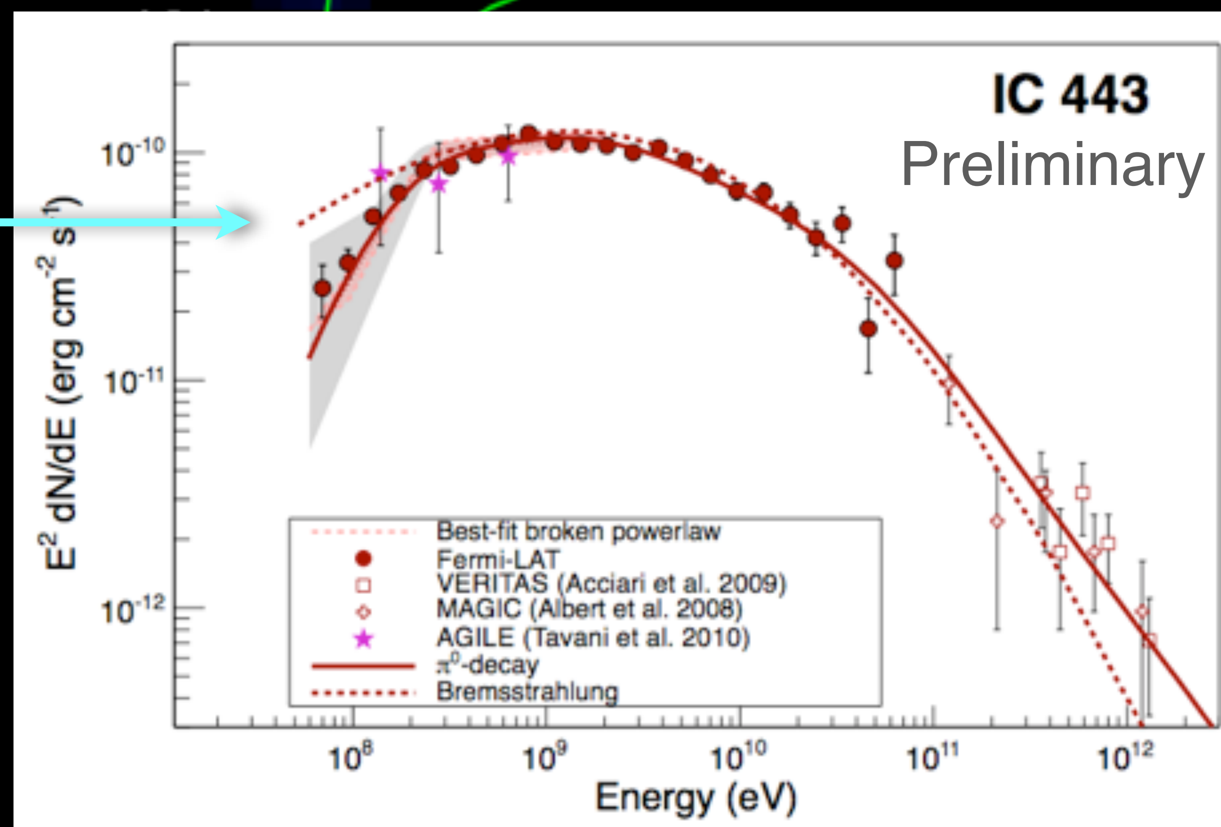
Fermi Telescope Revealed Cosmic-ray Protons



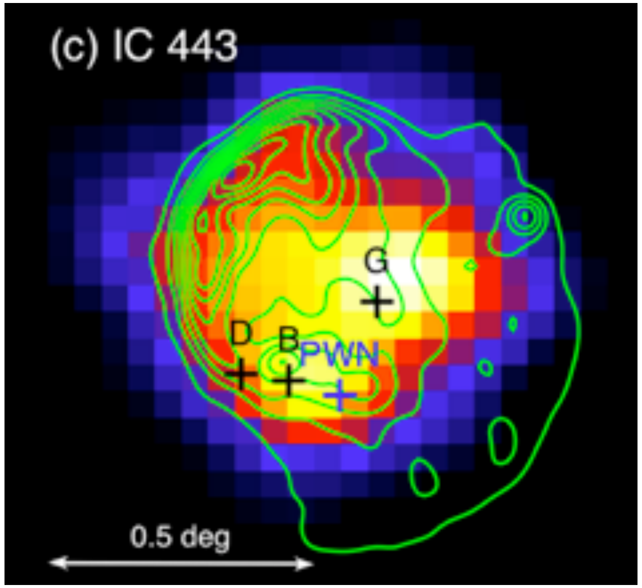


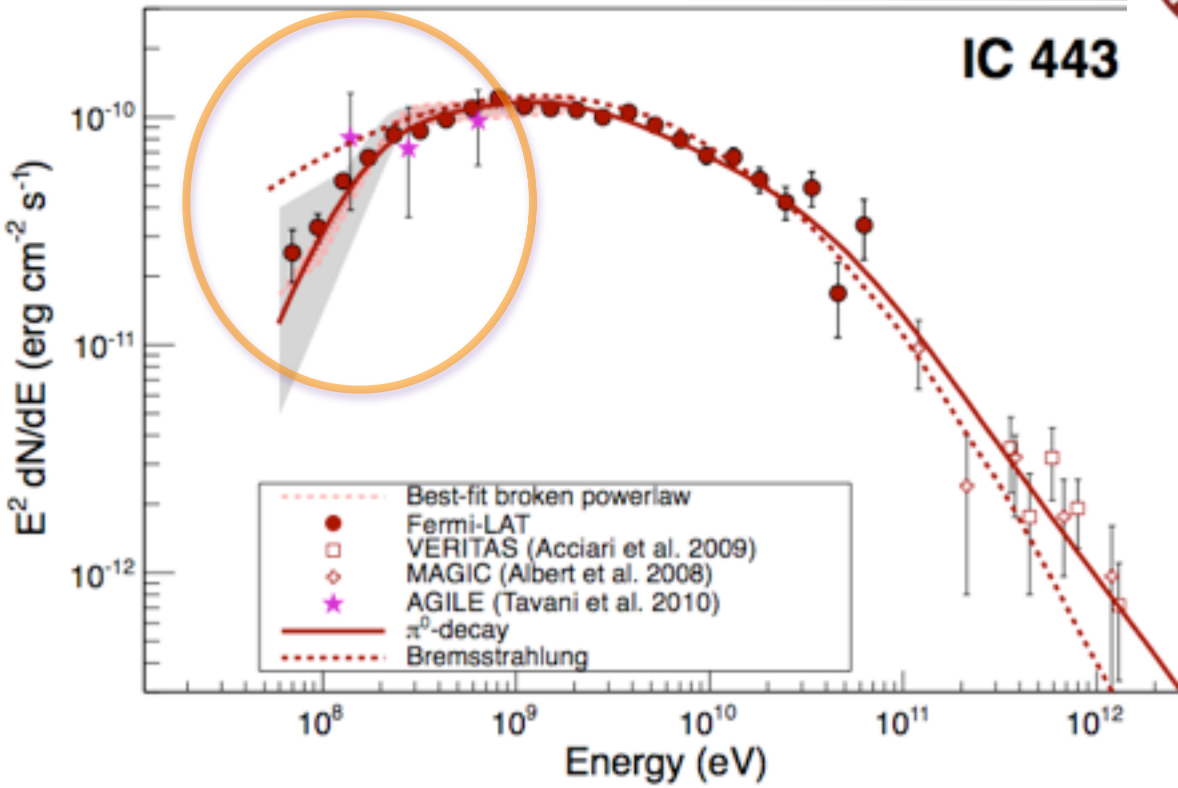
Gamma-ray map measured with Fermi Large Area Telescope

Gamma-ray spectrum measured with Fermi ➜ consistent with π^0 decay



Signature of π^0-decay Gamma-rays





- Our previous papers reported spectra only >200 MeV.
- Here we report spectra down to 60 MeV thanks to:
  - Recent update ("Pass-7") of event reconstruction, which largely improved effective area at low energies.
  - Increased exposure time: 1 yr ➜ 4 yr

Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra.

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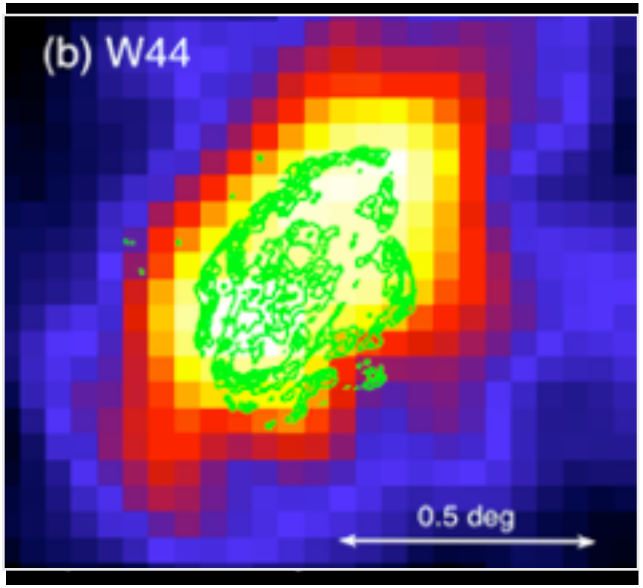

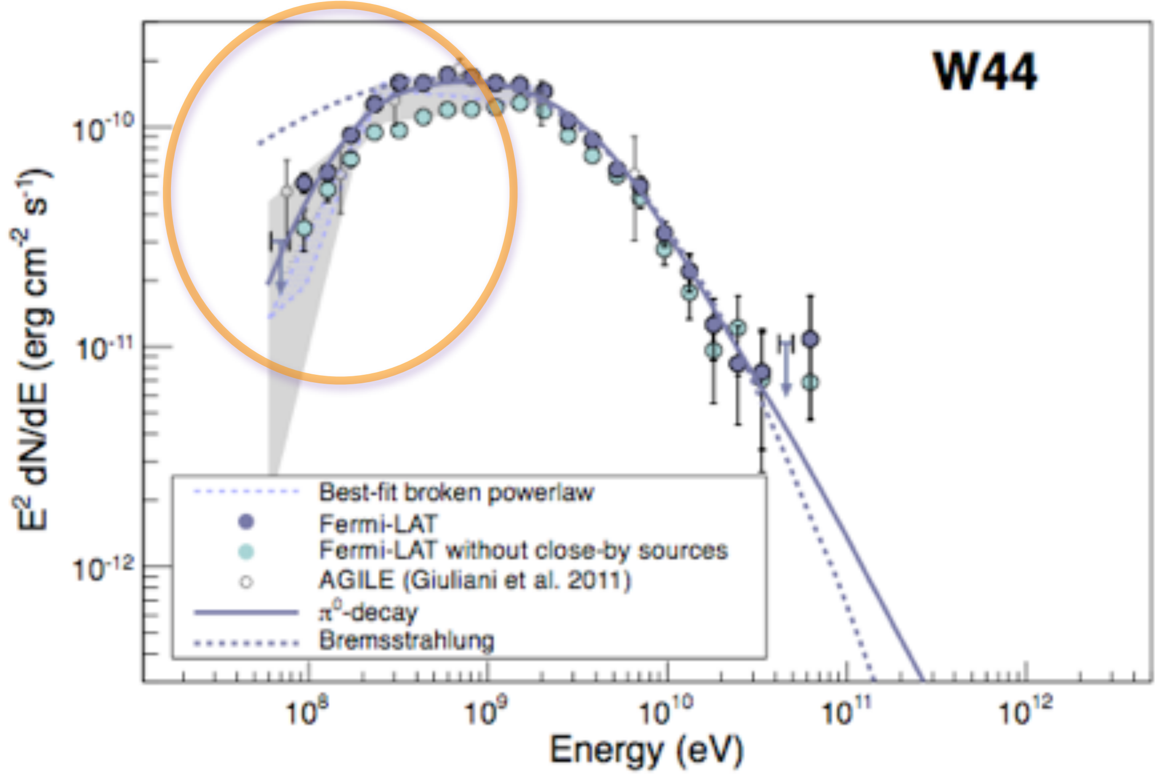

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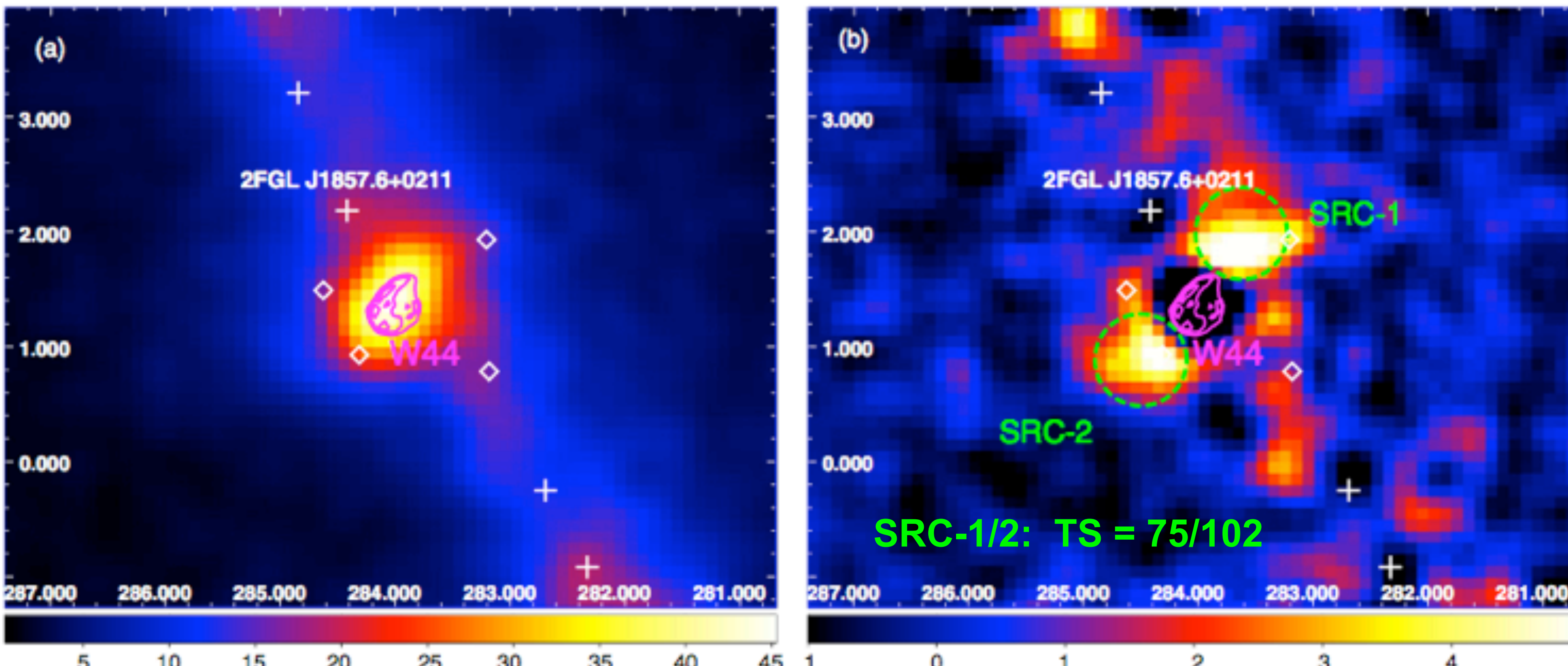
Fermi-LAT Detection of W44 Surroundings

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

Uchiyama et al. (2012)

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

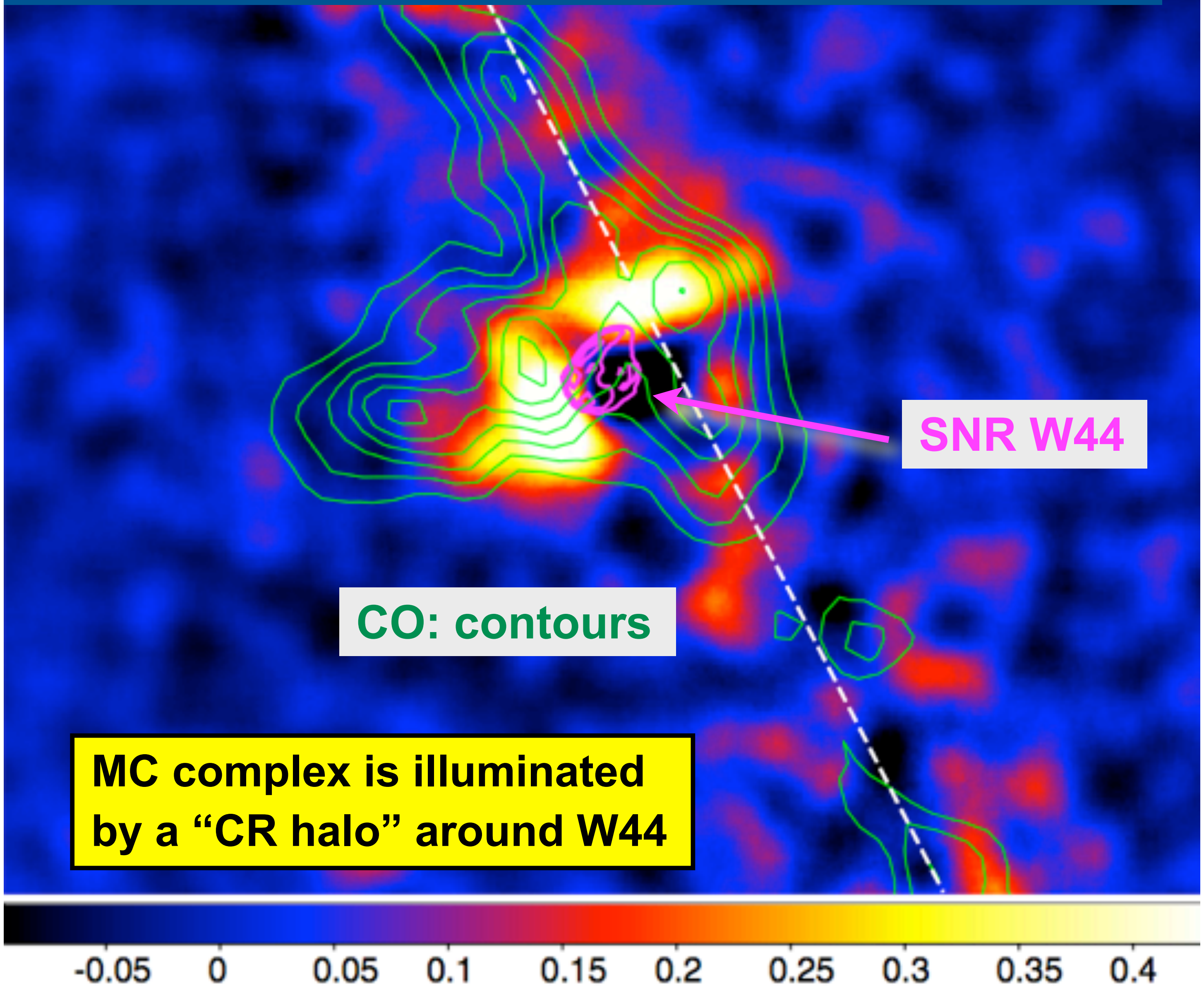


Subtraction of W44

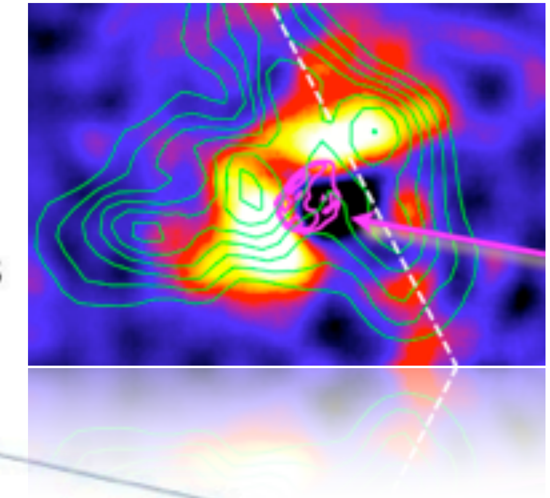
Gamma-rays from W44 itself are subtracted, assuming "radio map = gamma-ray map"

Large-scale GeV γ-rays vs CO map

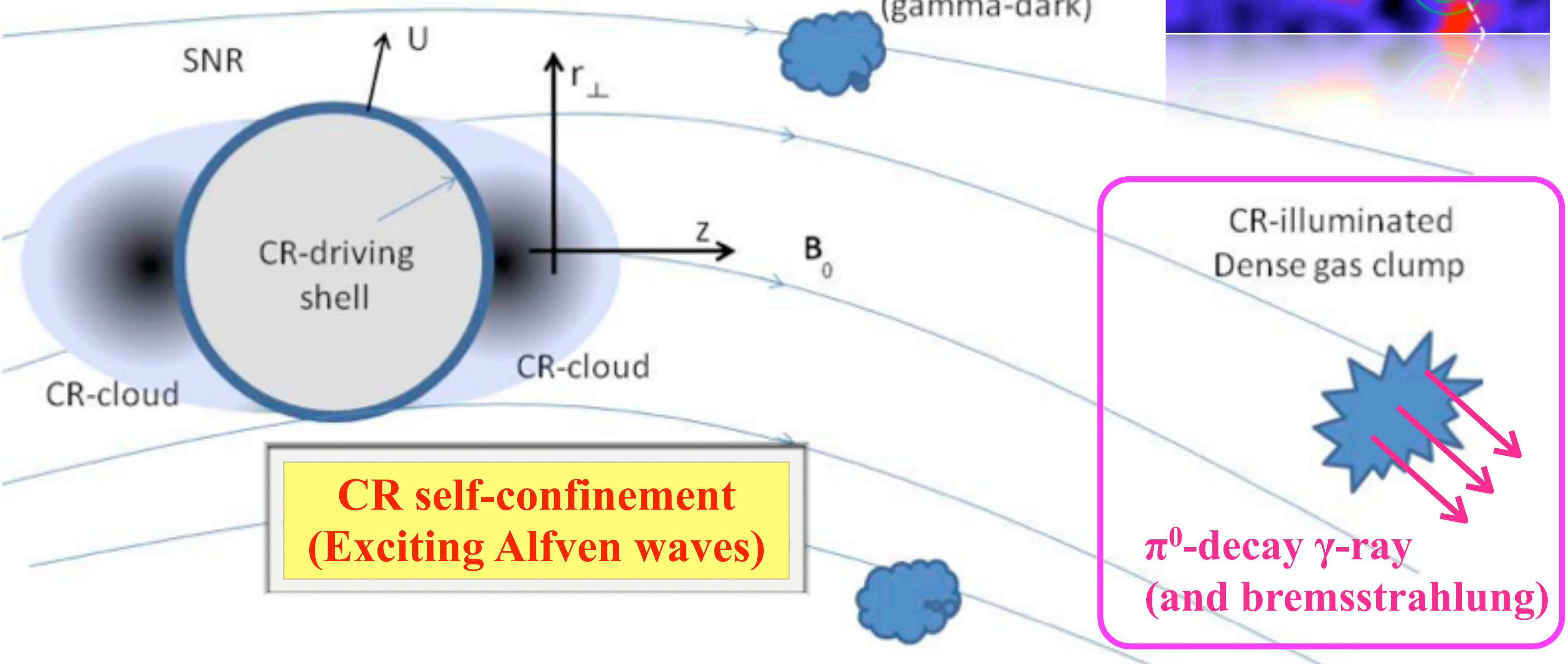
W44 is known to be surrounded by a complex of MCs.
Size ~100 pc, Mass ~10^6 M_{sun} (Dame+1986)



Gamma-ray Evidence for Leaking CRs



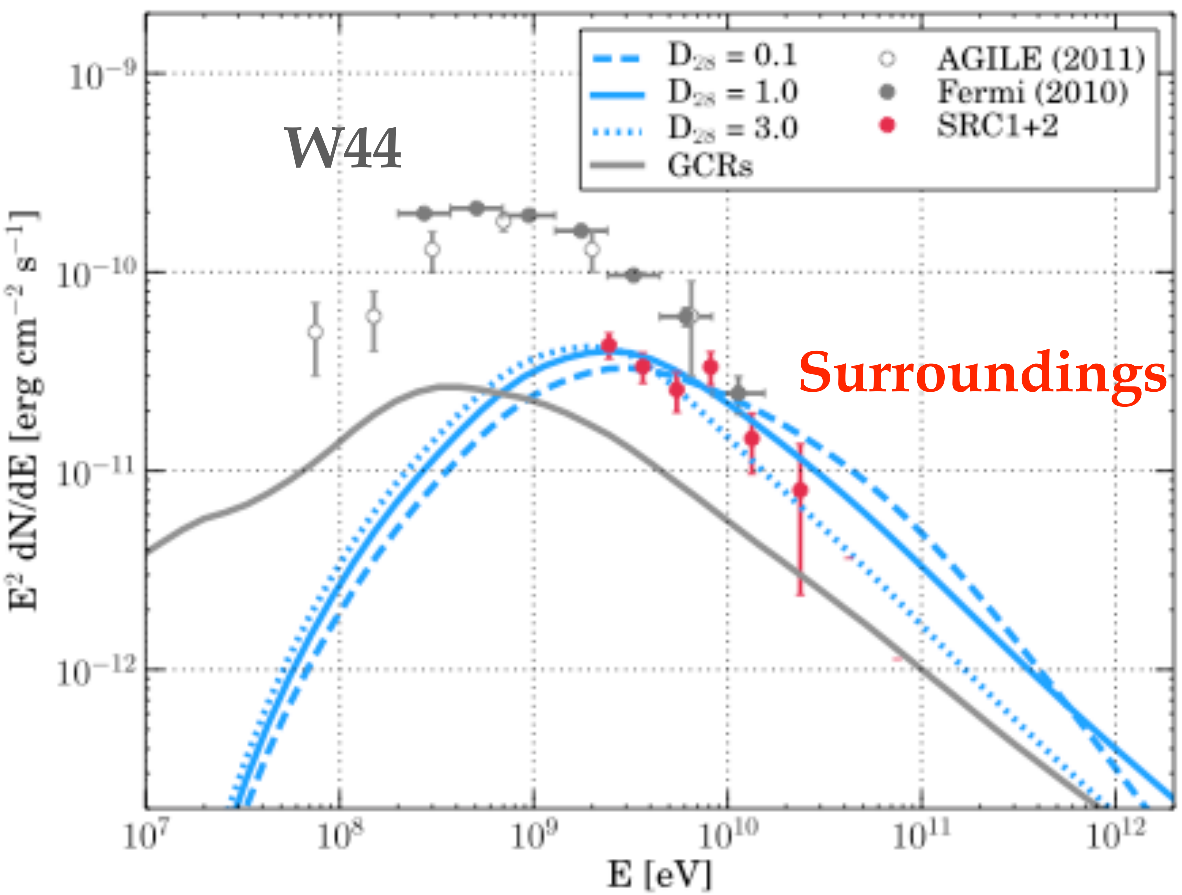
(c) M. Malkov (2012)



After leaving SNR W44, CRs diffuse along the external B-field direction ➜ bipolar morphology

Amount of CRs Escaped from W44

- Molecular clouds illuminated by escaping CRs (assumed to be uniform within r<L)
  - ✱ L ~100 pc, Mass = $0.5\times10^5\ M_\odot$
- Diffusion coefficient of the ISM (isotropic)
  - ✱ $D(p) = D_{28}\ (cp/10\ \mathrm{GeV})^{0.6}\ 10^{28}\ \mathrm{cm^2/s}$



Solving the diffusion equation in the vicinity of W44, we can estimate the energy spectrum of escaping CRs.

✱ Case 1:

Slow diffusion ($D_{28} = 0.1$)

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

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

✱ Case 2:

$D_{28} = 1$

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

$W_{esc} = 1.1\times10^{50}$ 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? (B-field too low?)
- SNRs interacting with molecular clouds
  - W51C, W44, IC443, W28, W49B, W30, CTB37A, ...
  - Direct evidence for hadronic origin (IC443, W44)
  - Evidence for Runaway CRs
- Evolved SNRs without molecular cloud interactions
  - Cygnus Loop, Pup A, S147
  - Hadronic origin?
  - Blast wave region? (X-ray) or Radiative shock? (Hα)