X-Ray and Gamma-Ray Studies of Particle Acceleration in Supernova Remnants

Takaaki Tanaka (KIPAC, Stanford University)

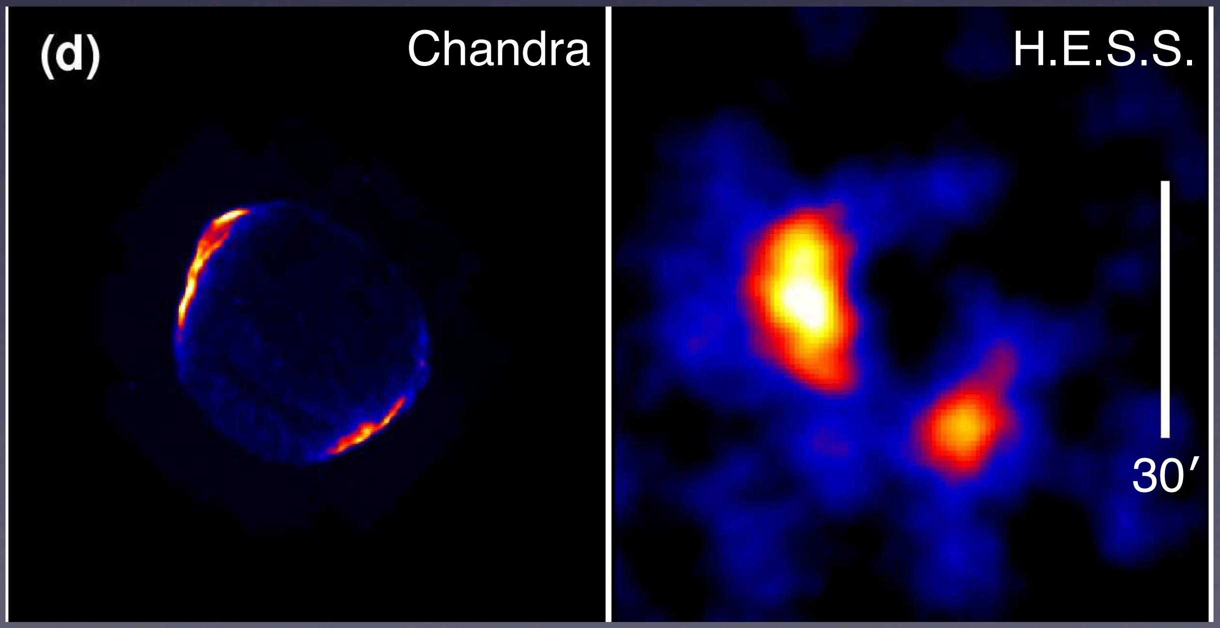
Fermi LAT results presented on behalf of the Fermi LAT collaboration

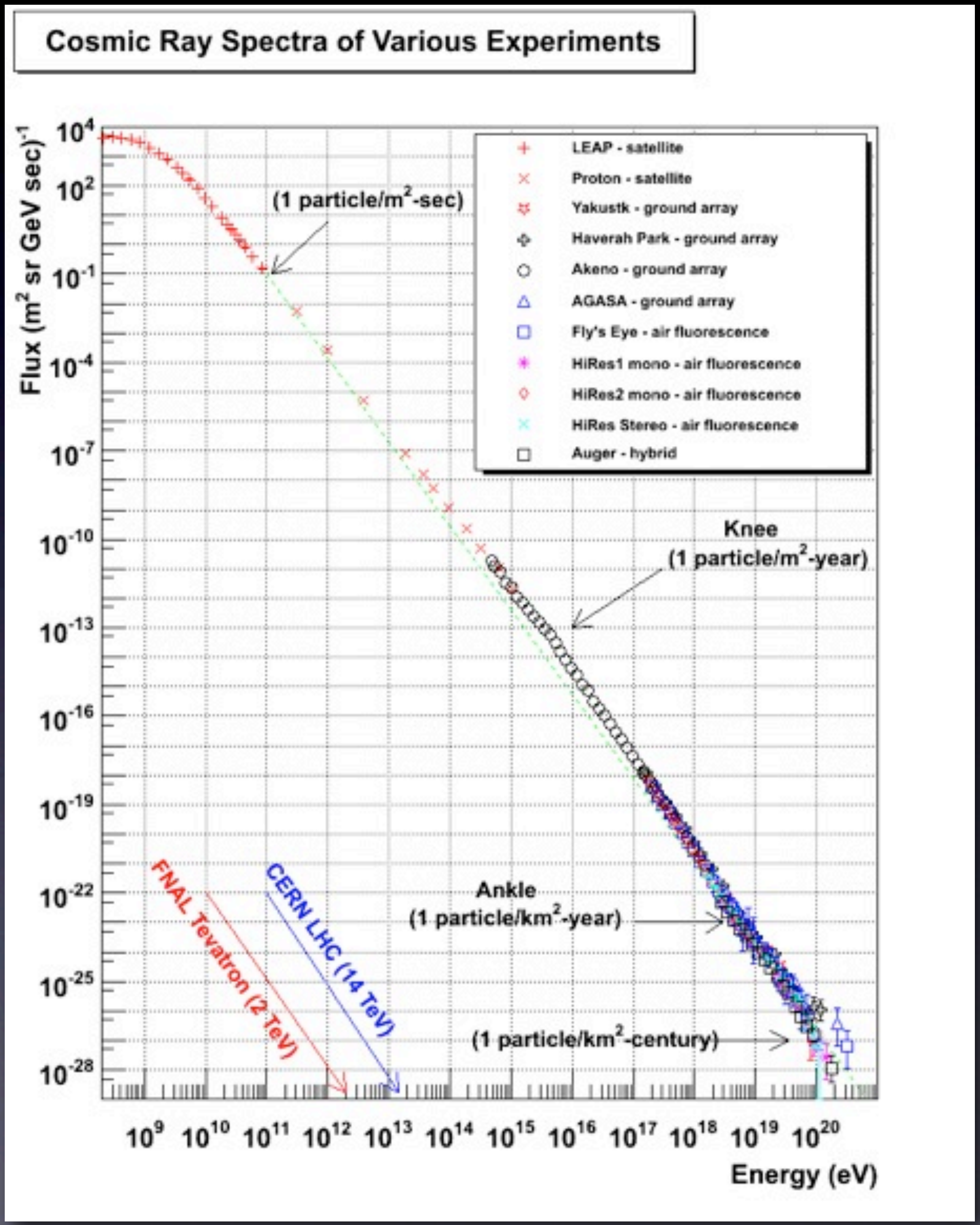
SNRs = Cosmic-Ray Sources?

Supernova remnants have been thought to be accelerating cosmic rays up to the knee (PeV) thorough the diffusive shock acceleration mechanism

Synchrotron X-rays and TeV gamma rays from SNRs = Evidence of acceleration up to TeV energies

SN 1006





Suzaku (XIS + HXD) Results

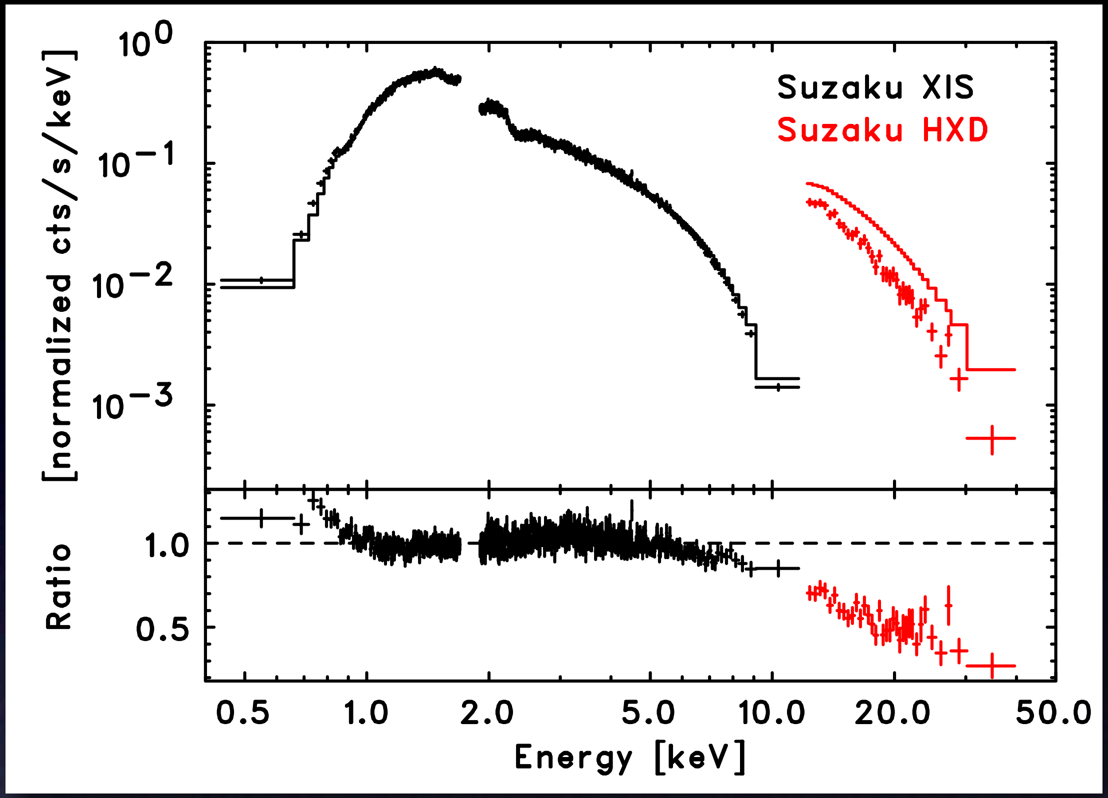
Suzaku has been probing electrons accelerated in SNRs through XIS + HXD measurements of synchrotron X-rays

① RX J1713.7–3946 (Takahashi+ 2008; Tanaka+ 2008)

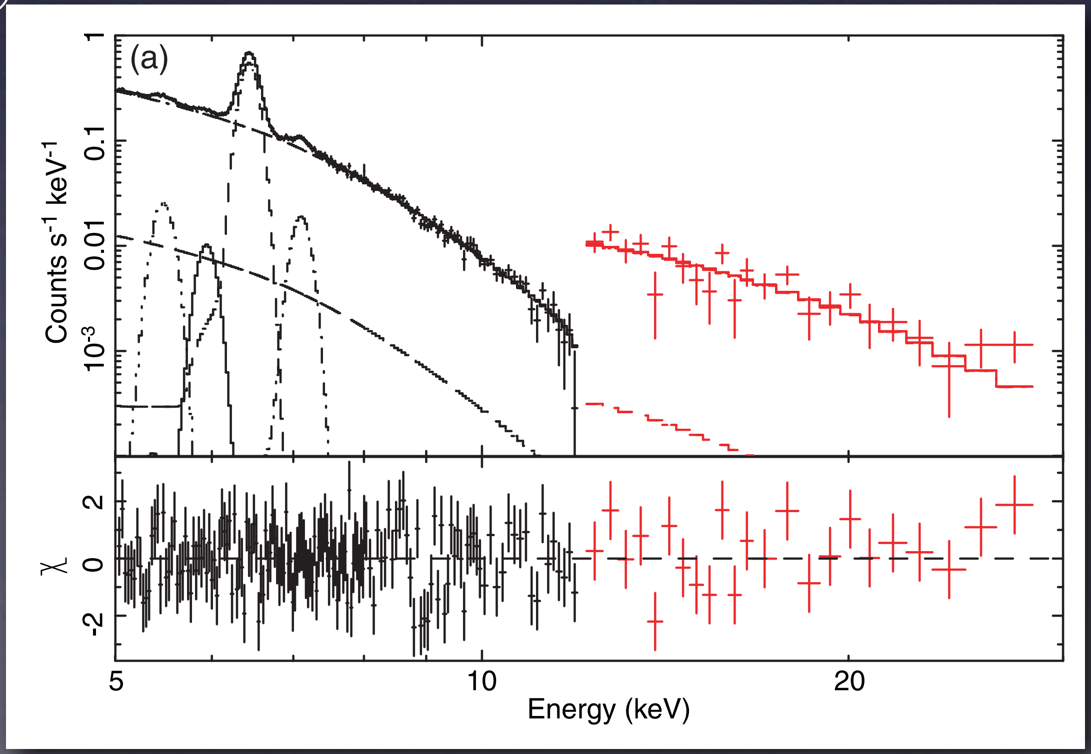
② Tycho (Tamagawa+ 2009)

③ Cassiopeia A (Maeda+ 2009)

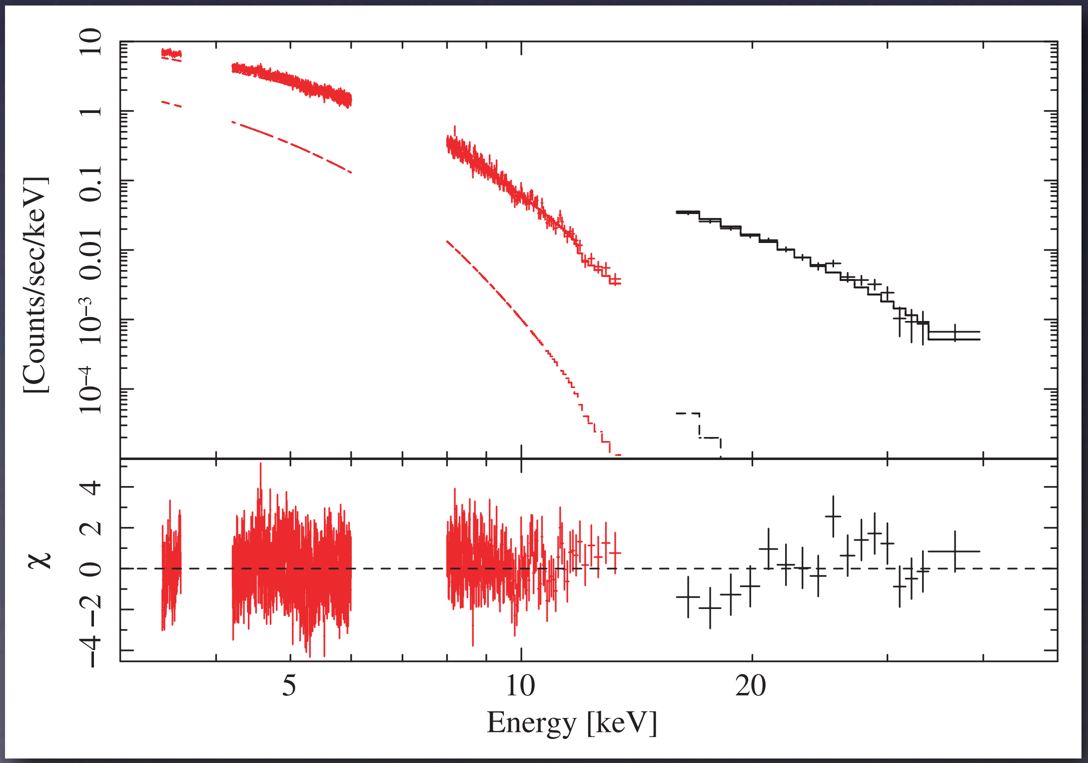
①



②



③

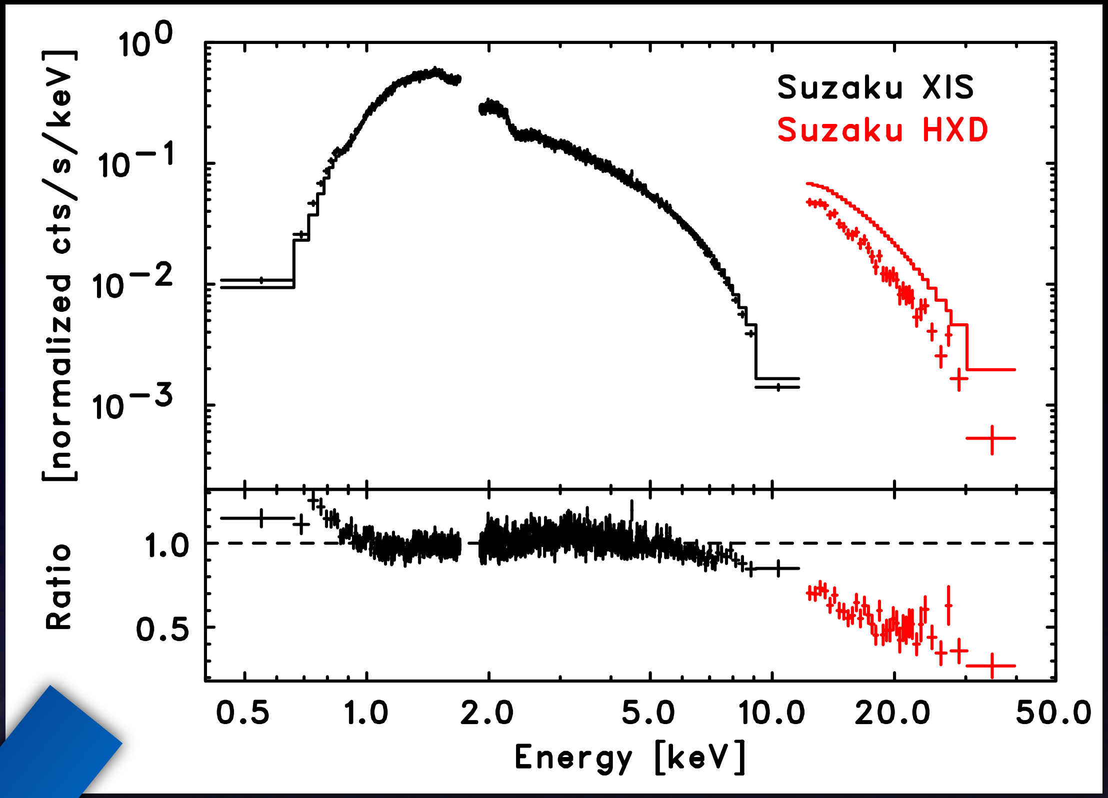


Suzaku (XIS + HXD) Results

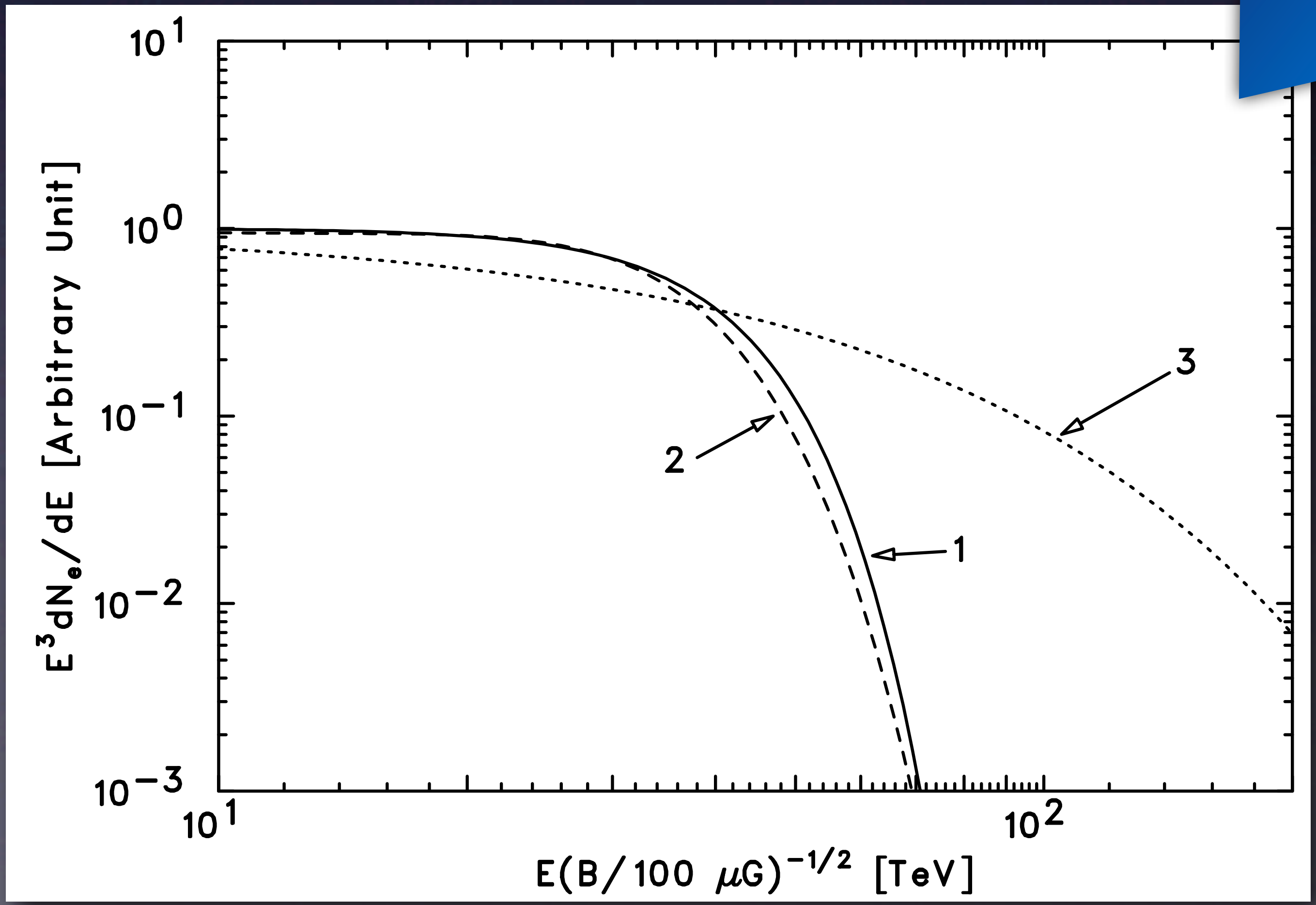
Suzaku has been probing electrons accelerated in SNRs through XIS + HXD measurements of synchrotron X-rays

① RX J1713.7–3946 (Takahashi+ 2008; Tanaka+ 2008)

①



Parent Electron Spectrum



1. Derived from Suzaku spectrum
2. Zirakashvili & Aharonian (2007)
3. Exponential Cutoff Power Law

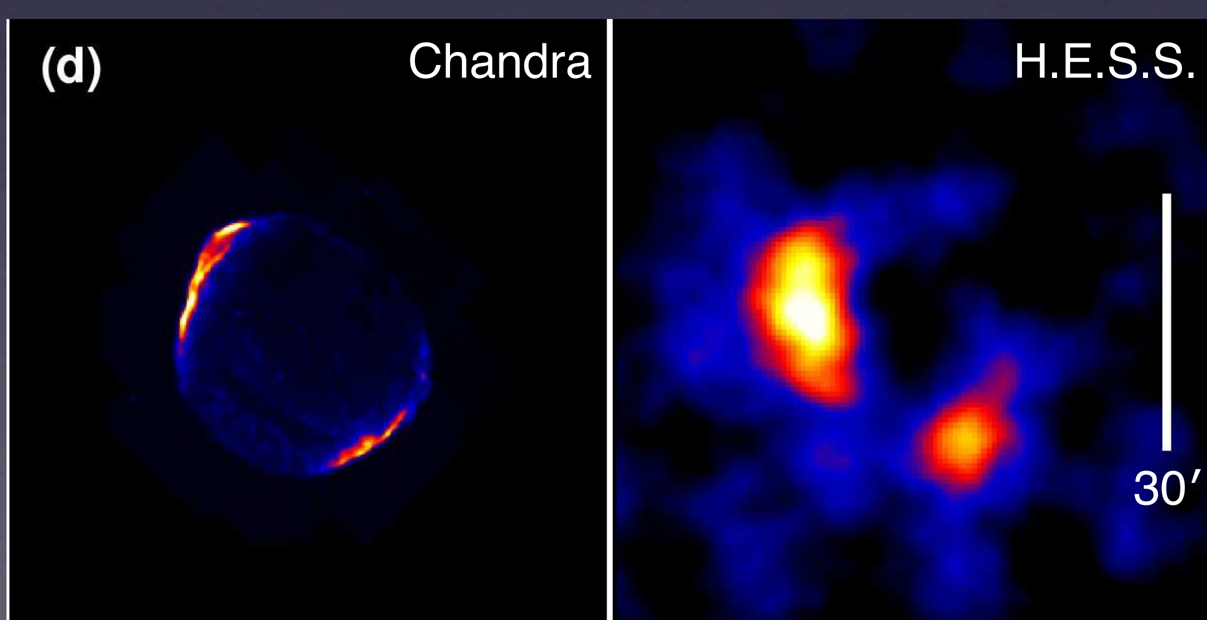
SNRs = Cosmic-Ray Sources?

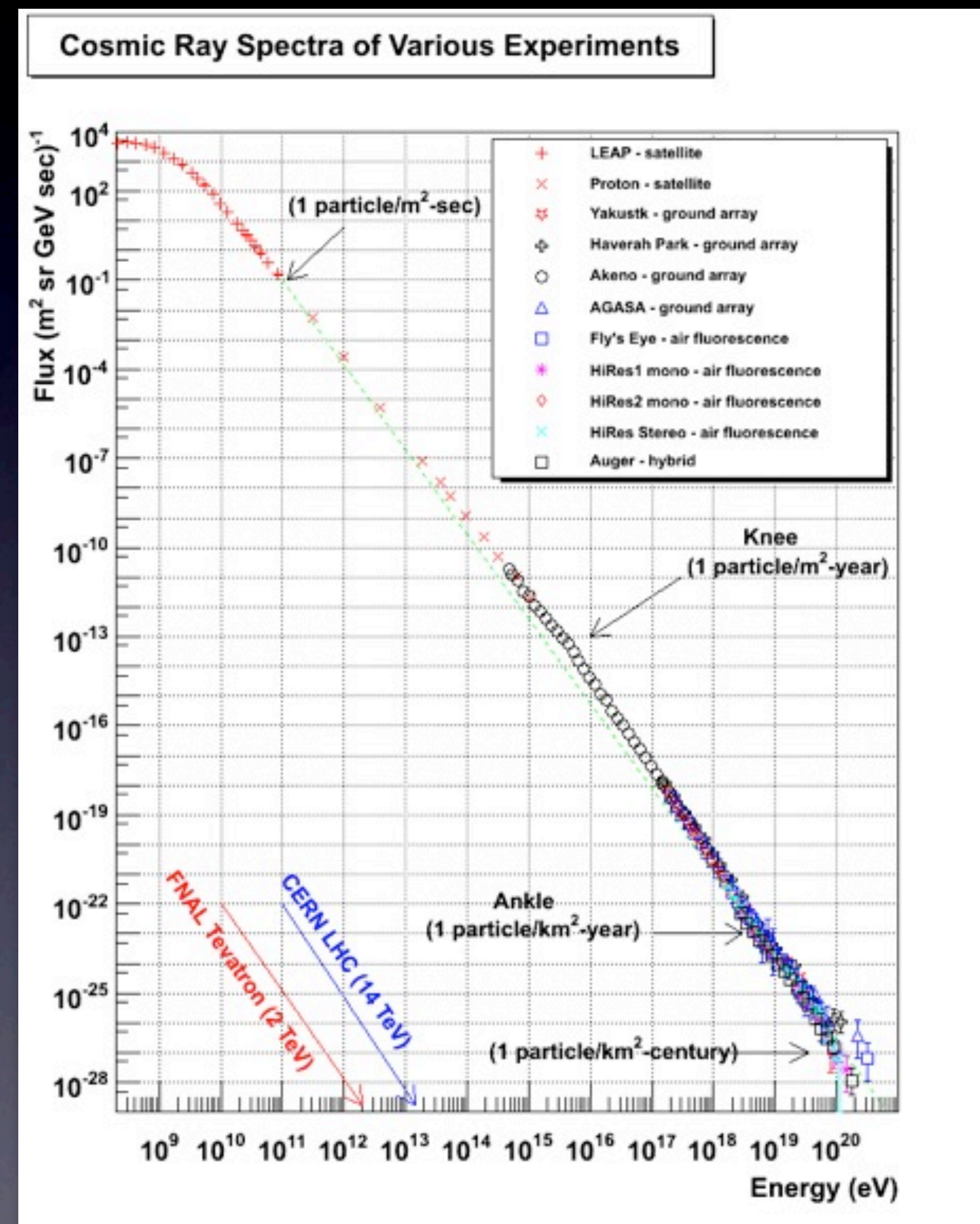
Supernova remnants have been thought to be accelerating cosmic rays up to the knee (PeV) thorough the diffusive shock acceleration mechanism

Synchrotron X-rays and TeV gamma rays from SNRs = Evidence of acceleration up to TeV energies

We still need evidence of
1. Acceleration of protons/ions in SNRs
2. Acceleration up to PeV energies

SN 1006





Magnetic Field Amplification

RX J1713.7–3946

Uchiyama+ 2007

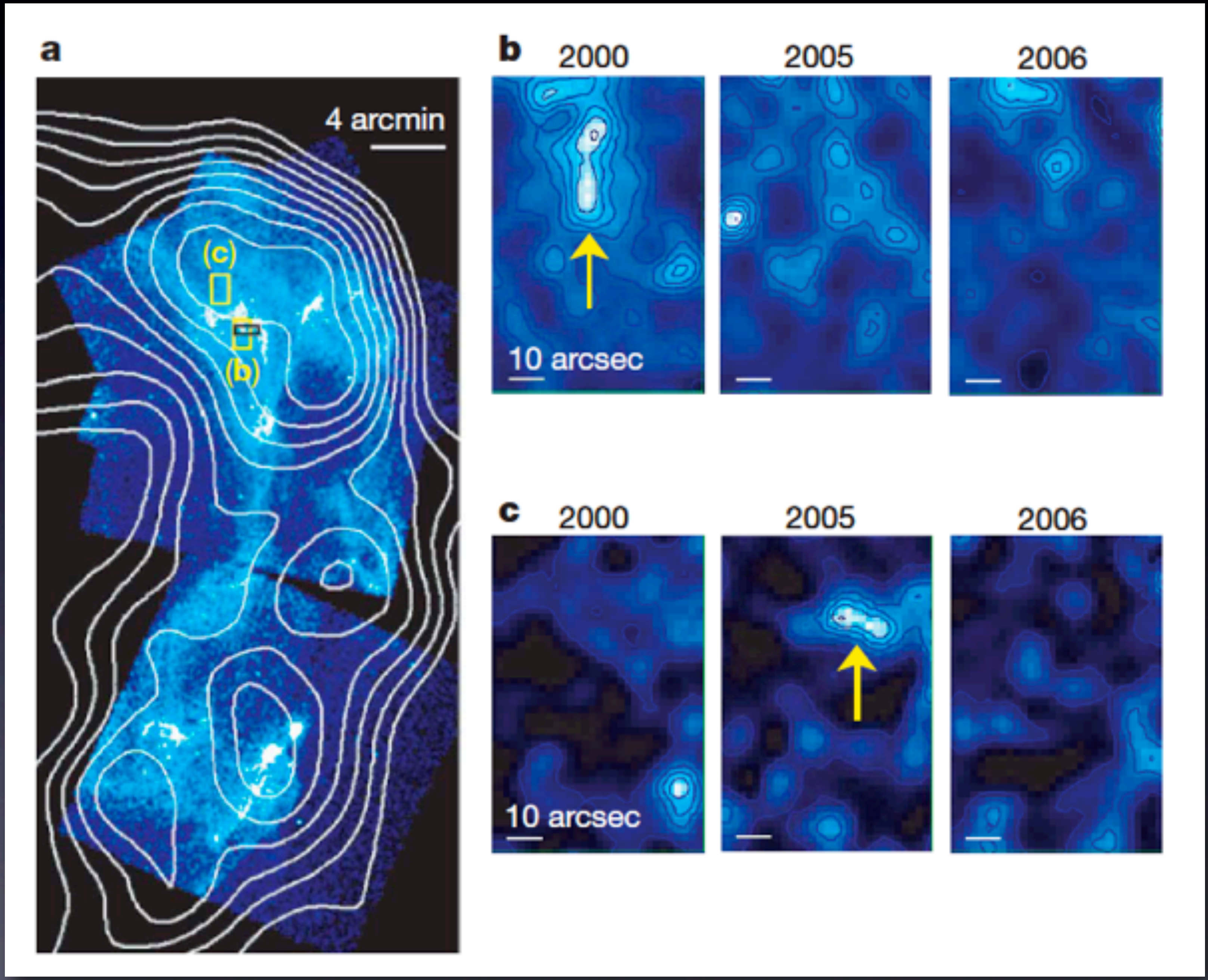
Year-scale variability of X-ray flux from filamentary structures

Explained by rapid acceleration and synchrotron cooling of electrons

Required *B* field strength ~ 1 mG

Magnetic Field Amplification

essential to reach PeV energies



Locations of BW and CD

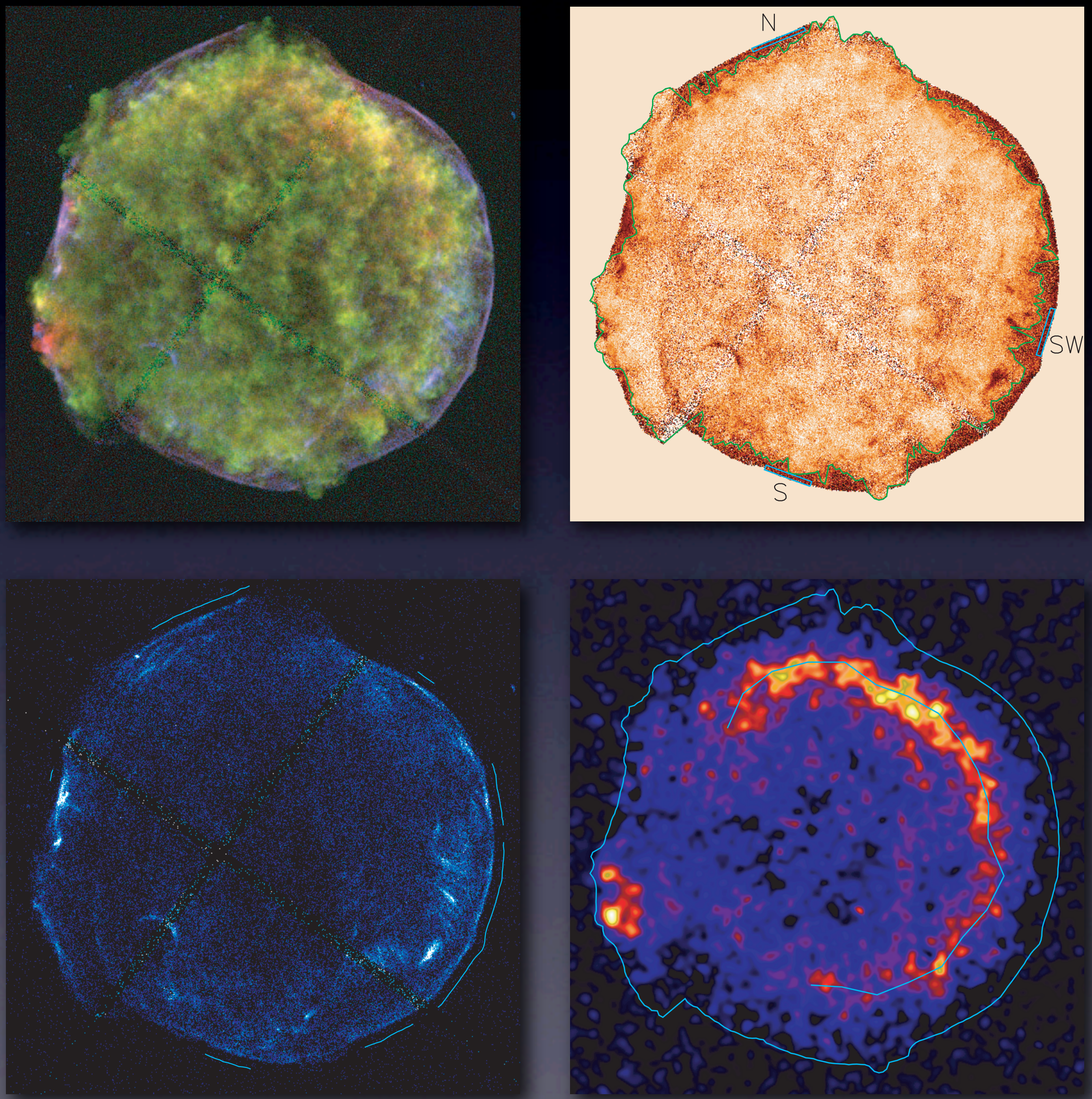
Narrow gap between the contact discontinuity (CD) and the blast wave (BW) observed in Tycho's SNR

Inconsistent with adiabatic hydrodynamic models of SNR evolution

Can be explained if ***ions*** are accelerated at the forward shock

Tycho

Warren+ 2005



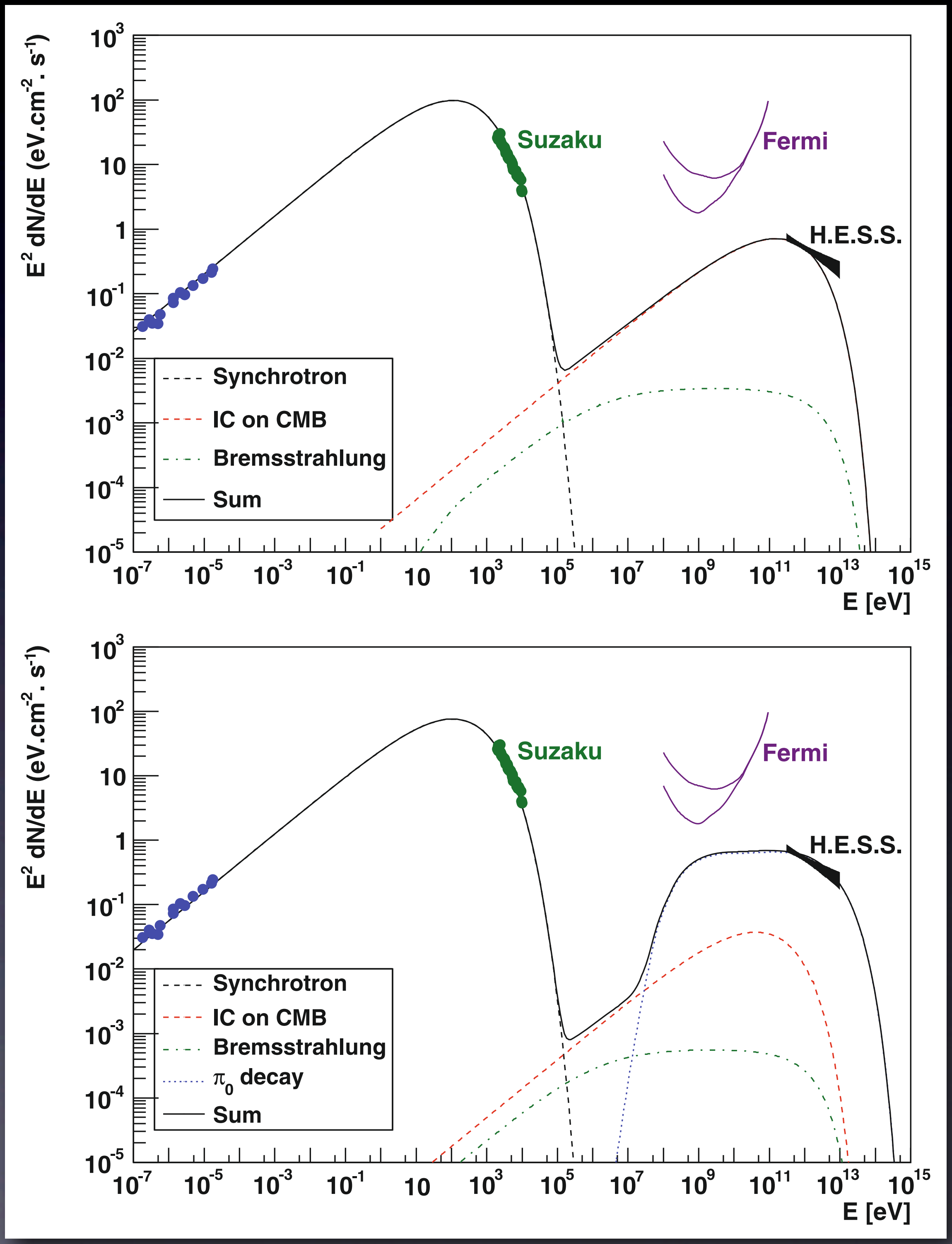
Gamma-Ray Spectrum

One of the few channels to probe hadronic component of cosmic rays
= Gamma rays from decays of π^0 mesons

$$pp \rightarrow pp\pi^0$$
$$\pi^0 \rightarrow 2\gamma$$

TeV gamma-ray spectra can be fit by π^0-decay emission (hadronic model)
but also by leptonic emission such as inverse Compton scattering or bremsstrahlung (leptonic model)

SN 1006

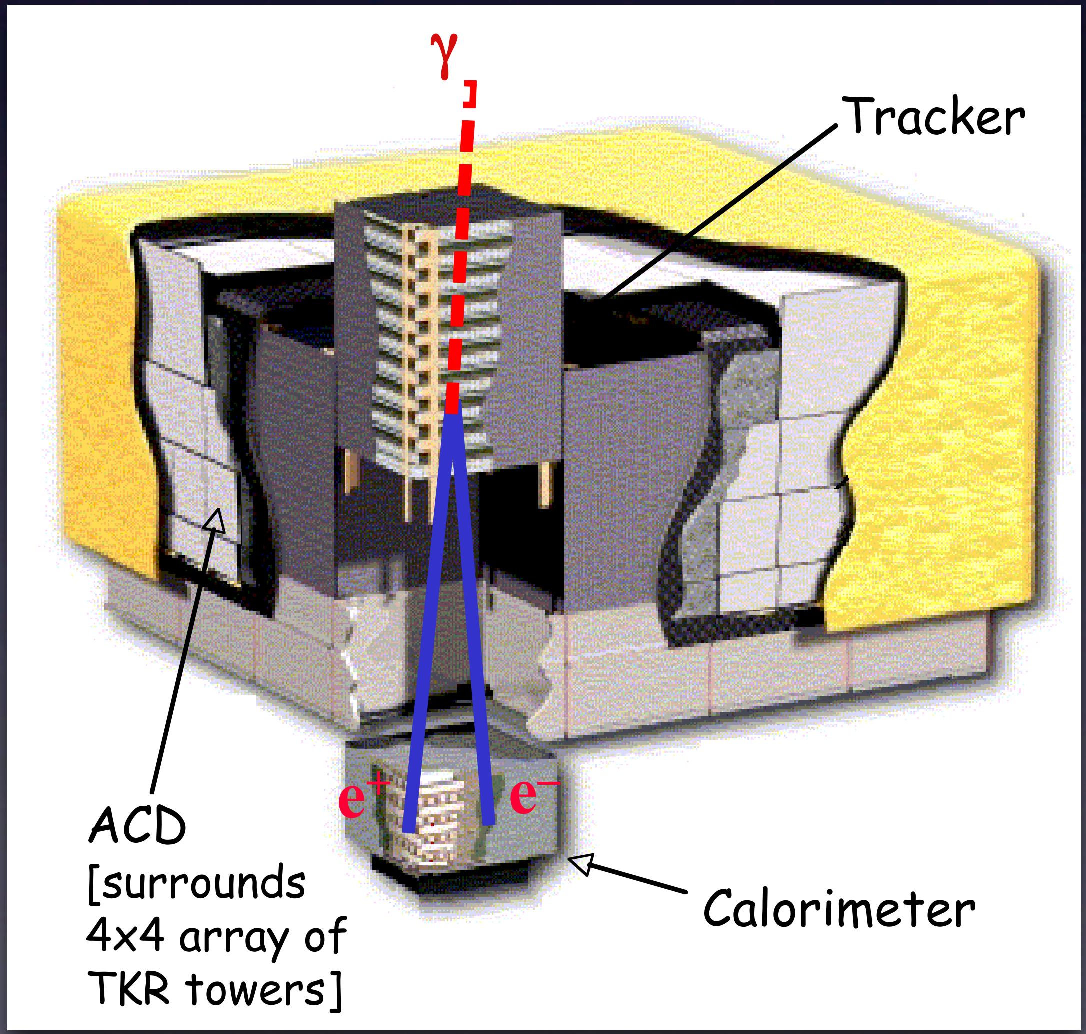


Acero+ 2010

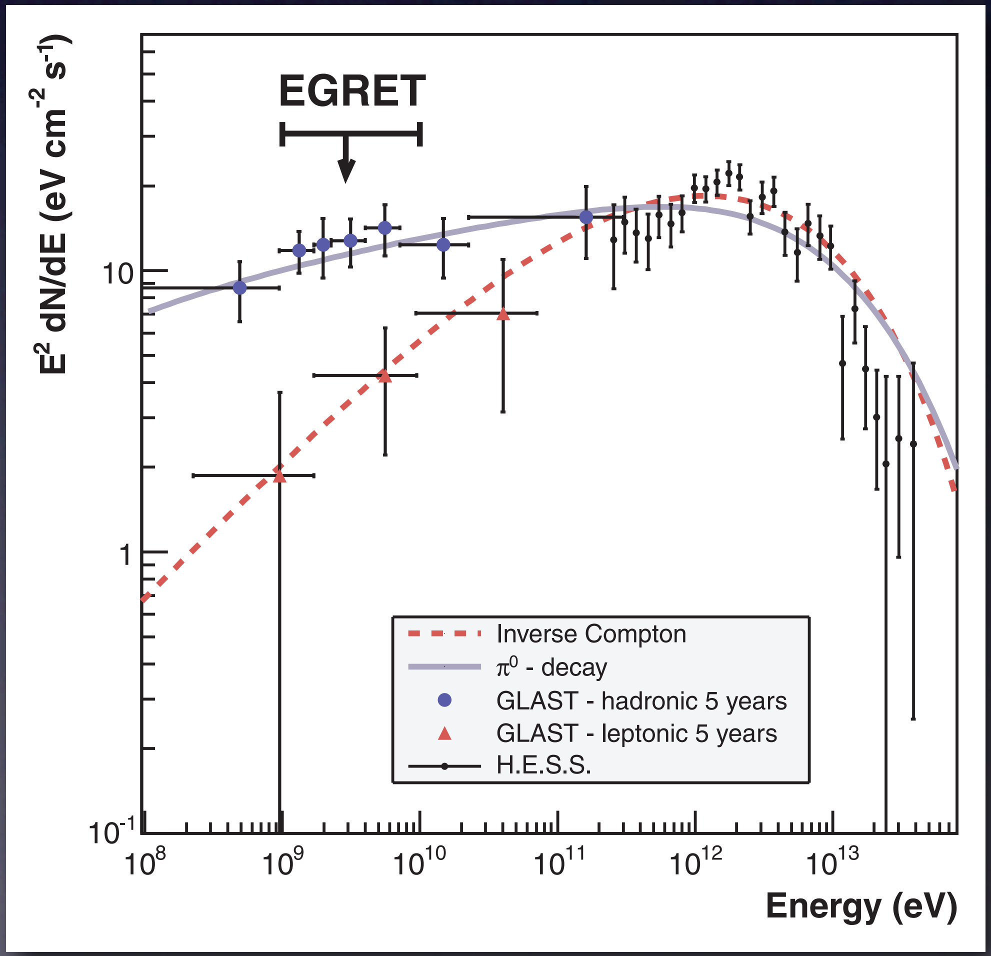
Fermi Large Area Telescope

Pair-production telescope launched in June, 2008
Energy Range: from 20 MeV to > 300 GeV
Angler Resolution: < 1° (68% containment at 1 GeV)
Effective Area: 8000 cm^2 (on axis at 1 GeV)
Field of View: 2.4 sr

Covers the key energy range to study SNRs



Prelaunch Simulation (RX J1713.7–3946)



Funk+ 2008

Young TeV-Bright SNRs

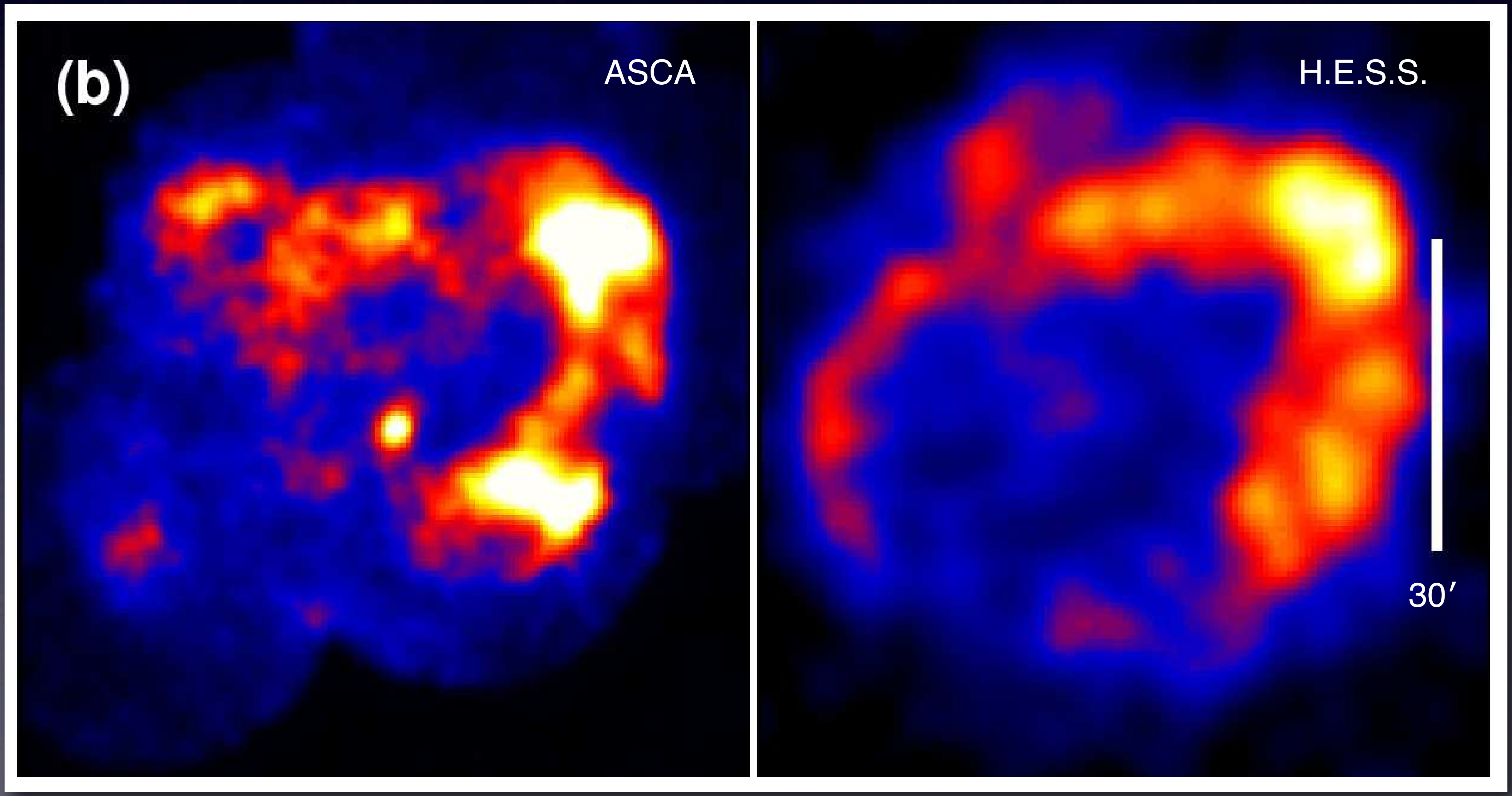
RX J1713.7–3946

One of the well studied TeV-bright SNRs

Age ~ 1600 yr,   Distance ~ 1 kpc

X-rays dominated by non-thermal emission (e.g. Takahashi+ 2008)

Similar morphologies between X-rays and TeV gamma rays



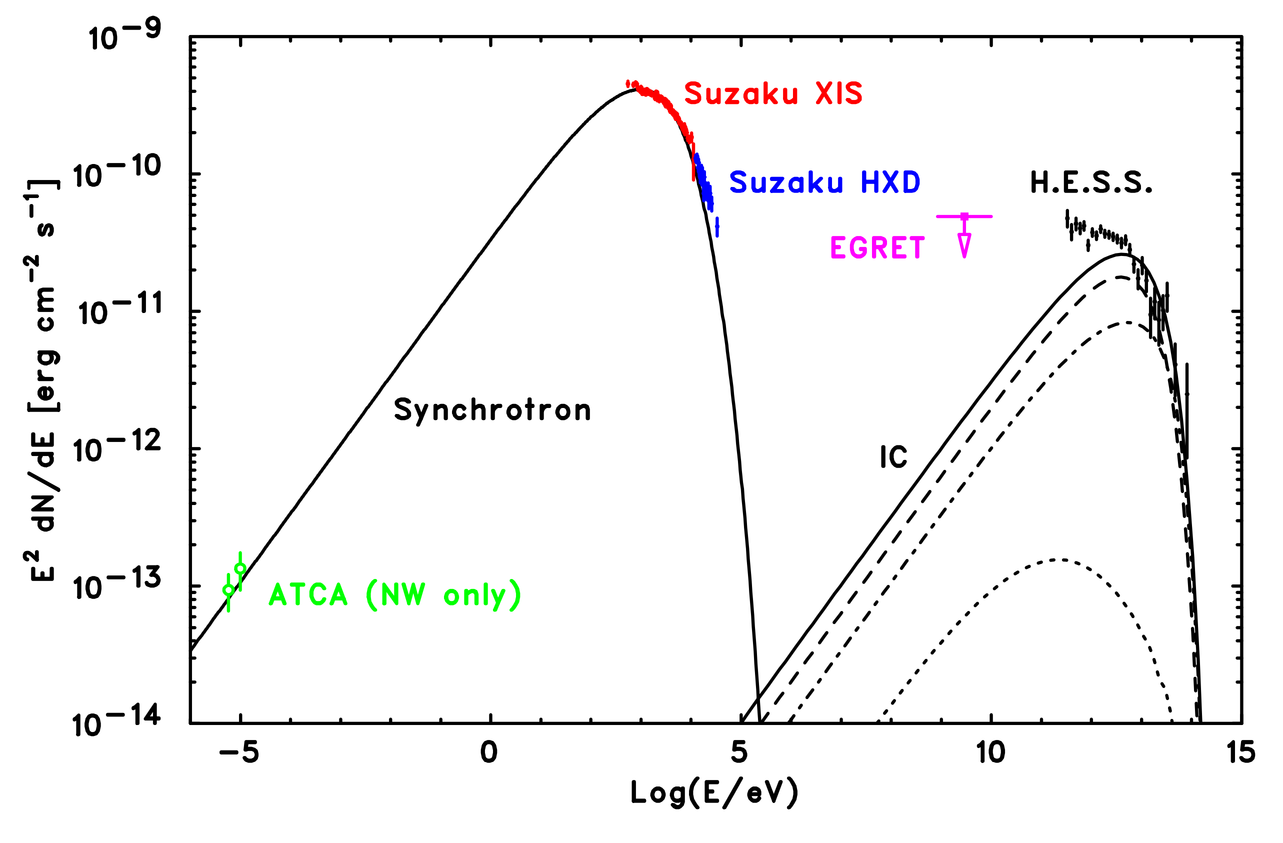
Leptonic or Hadronic ?

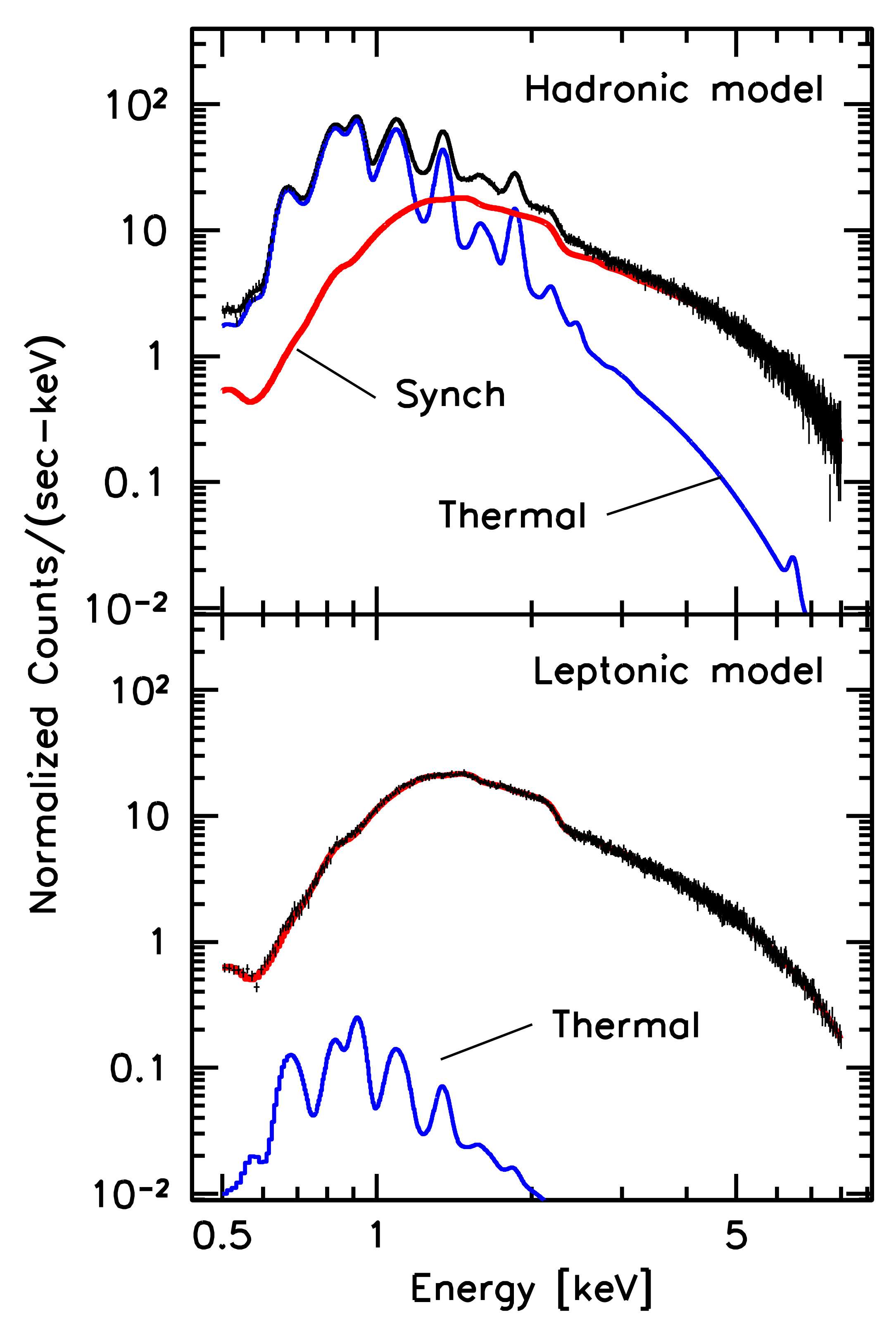
Difficult to explain Suzaku and H.E.S.S. spectra with leptonic emission from the same electron population

(Tanaka+ 2008)

However, if the gamma rays are of hadronic origin, Suzaku would have detected thermal emission (Note that they assumed uniform CSM)

(Ellison+ 2010)

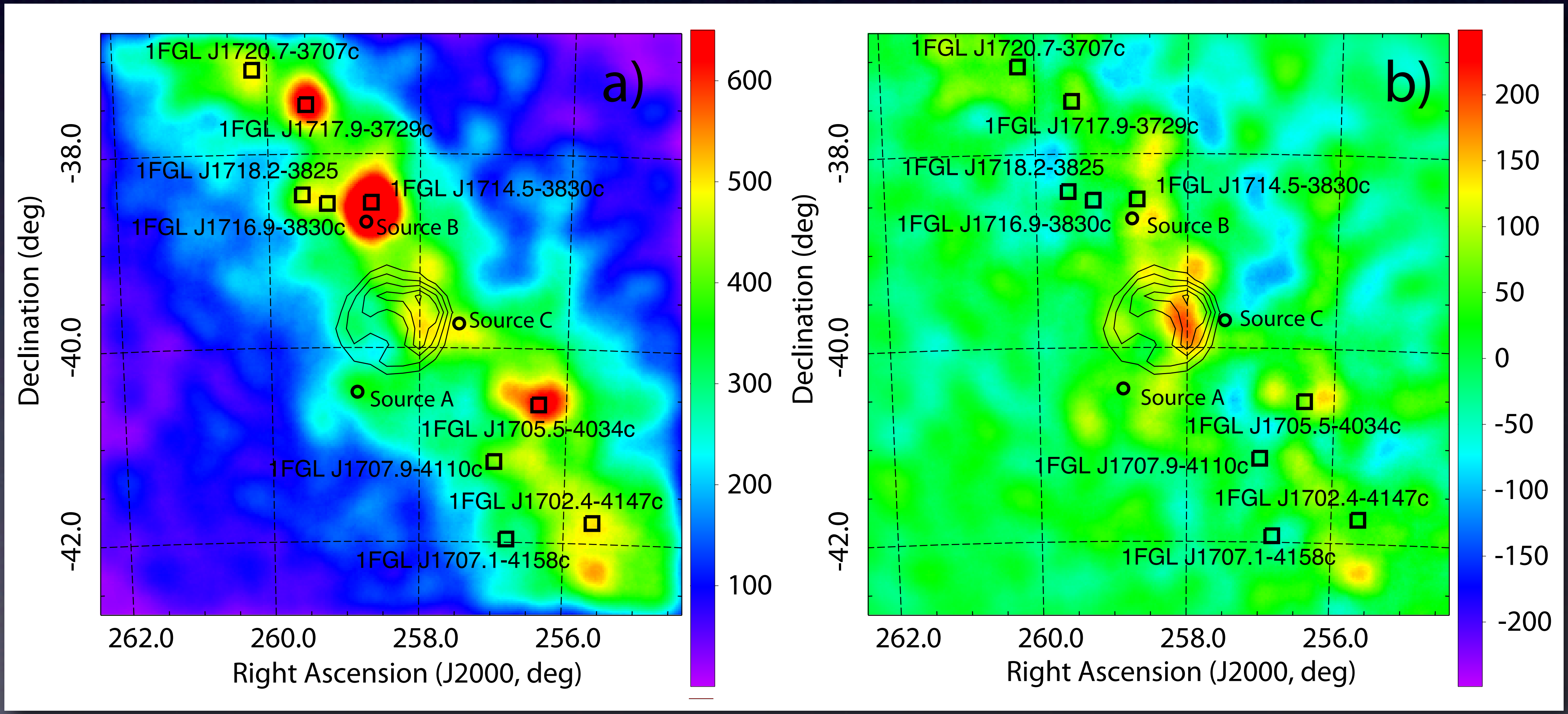




RX J1713: Fermi LAT Image

The Fermi LAT collaboration recently published the results (Abdo+ 2011)
Spatially extended source at the location of the SNR
The extent determined by a maximum likelihood fit is consistent with that of the SNR observed in other wavelengths

Fermi LAT count maps (> 3 GeV)

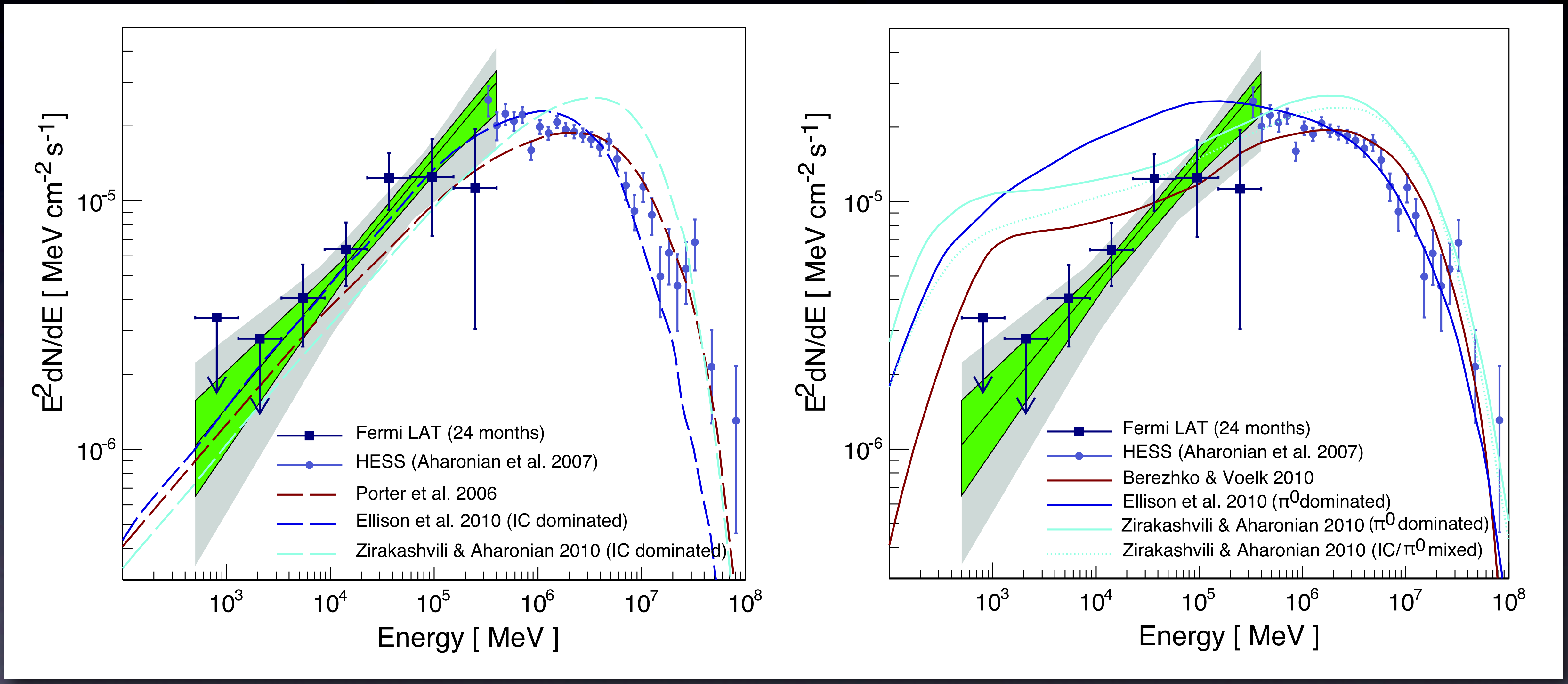


Before background subtraction

After background (contributions from diffuse backgrounds + other sources) subtraction

RX J1713: Fermi LAT Spectrum

Fermi LAT spectrum: Very hard with $\Gamma = 1.5 \pm 0.1$ (stat) ± 0.1 (sys)



The Fermi LAT + H.E.S.S. spectrum can be fit well with leptonic models
How to reconcile with the large magnetic field?
If interpreted with hadronic models, extremely hard proton spectrum is required to fit the data
(proton index must be $s_p \sim 1.5$ to fit the Fermi LAT spectrum)

Hard Gamma-Ray Spectrum

An interesting paper by Inoue+ (2011)

They considered highly inhomogeneous structure of the molecular cloud interacting with RX J1713.7–3946 (Fukui+ 2004)

SN explosion in a bubble created by stellar wind from the massive progenitor

Dense clumps stay inside the bubble because of their high density

Higher energy protons can penetrate into the cloud core where target gas density is high

Photon index of π^0-decay gamma rays can be $s_p - 0.5 = 1.5$ for $s_p = 2$, where s_p is index of the proton acceleration spectrum

Simple discussion based solely on gamma-ray spectral shape may not be correct!!

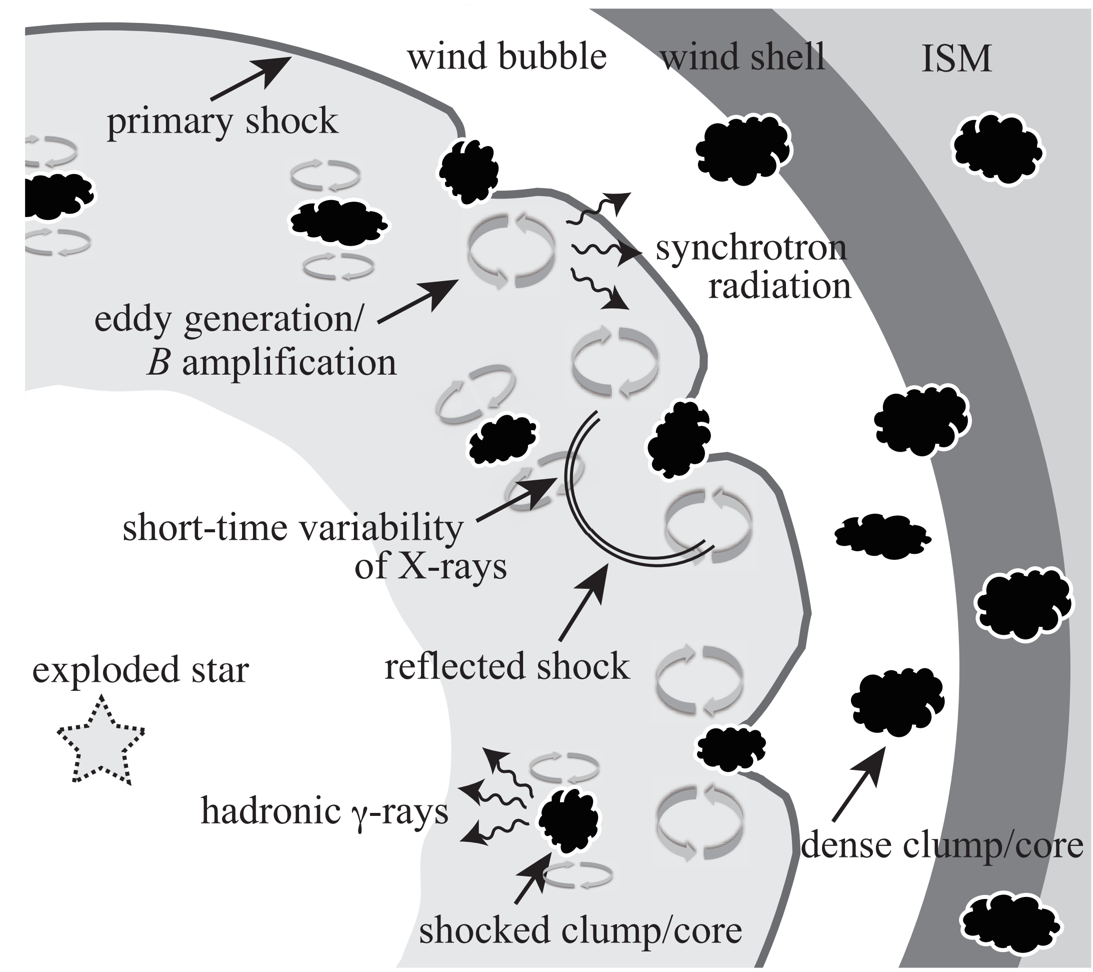


FIG. 10.— Schematic picture of the shock-cloud interaction model. Primary forward shock wave propagates through the cloudy wind bubble, where particle acceleration operates. Transmitted shock waves in clouds are stalled, which suppresses thermal X-ray line emission and particle acceleration in clouds. Shock-cloud interactions induce shock deformations and turbulent eddies. The turbulent dynamo effect amplifies the magnetic field that enhances synchrotron emissions. Secondary reflected shock waves are generated when the primary shock hits clouds that induce the short-time variability of synchrotron X rays where magnetic field strength is ~ 1 mG around shocked clouds. Hadronic gamma rays are emitted from dense clouds illuminated by accelerated protons whose photon index can be $p - 1/2 = 1.5$ for $p = 2$.

RX J0852.0–4622 (Vela Jr.)

Another TeV-bright young SNR

Discovered by ROSAT (Aschenbach 1998)

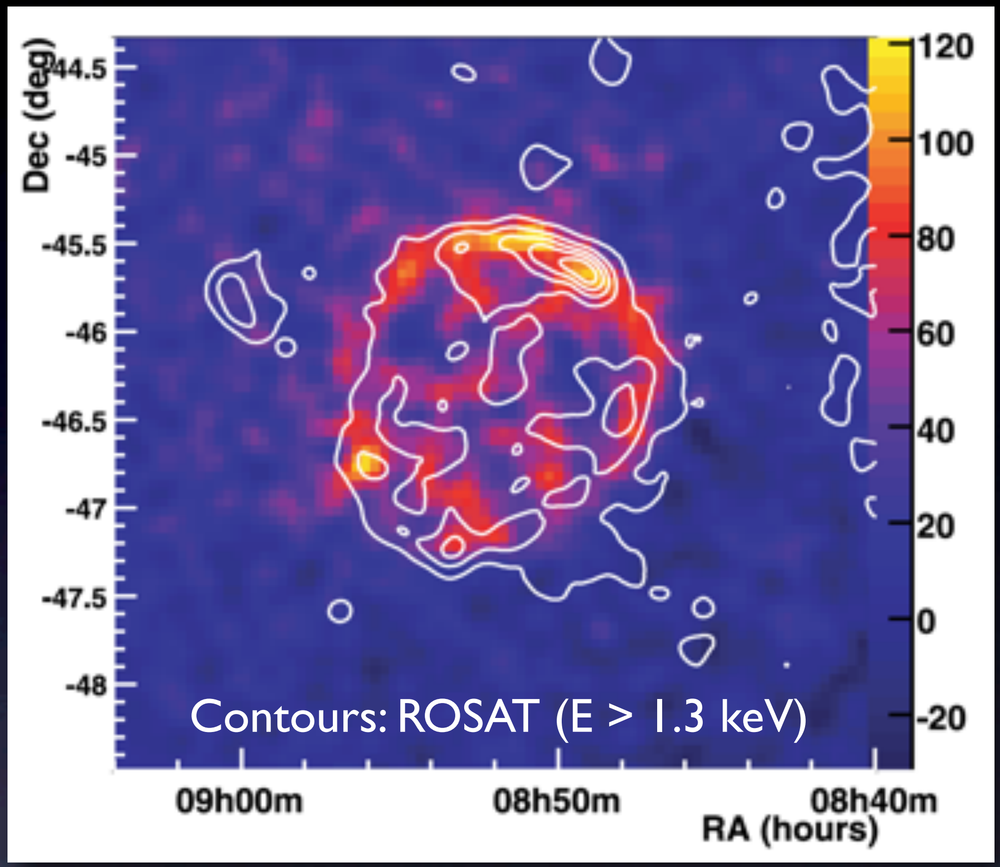
Non-thermal X-rays (Slane+ 2001)

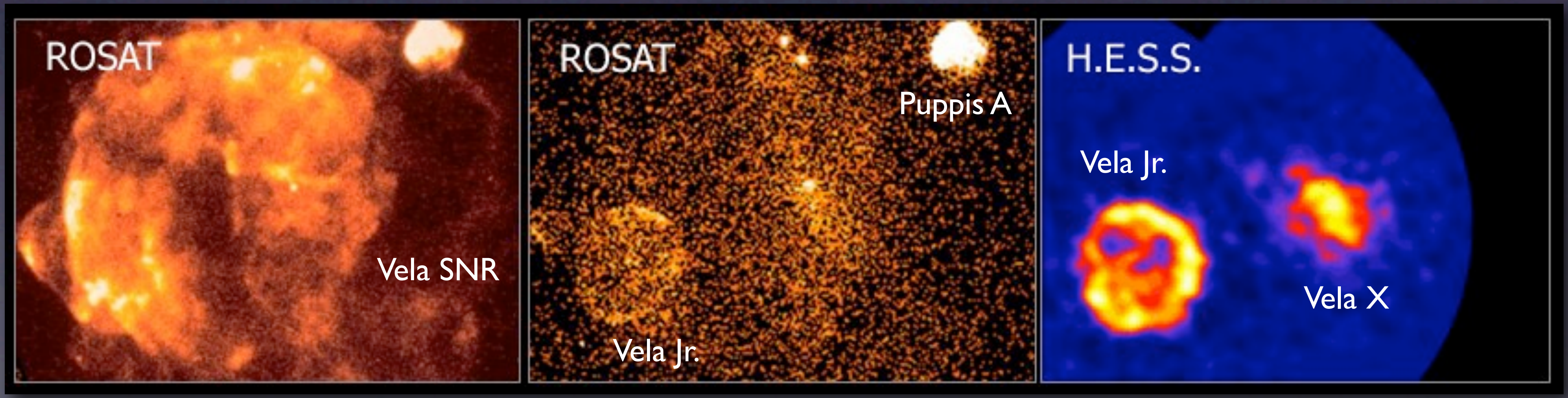
Detected in TeV
CANGAROO: Katagiri+ (2005)

Spatially resolved image by H.E.S.S.
(Aharonian+ 2005, 2007)

Latest estimate of age & distance (Katsuda+ 2008):
τ = 1700–4300 yr, D ~ 750 pc
(Further away than the Vela SNR)

TeV Gamma-ray Image by H.E.S.S.
(Aharonian+ 2007)





0.1 keV < E < 2.4 keV

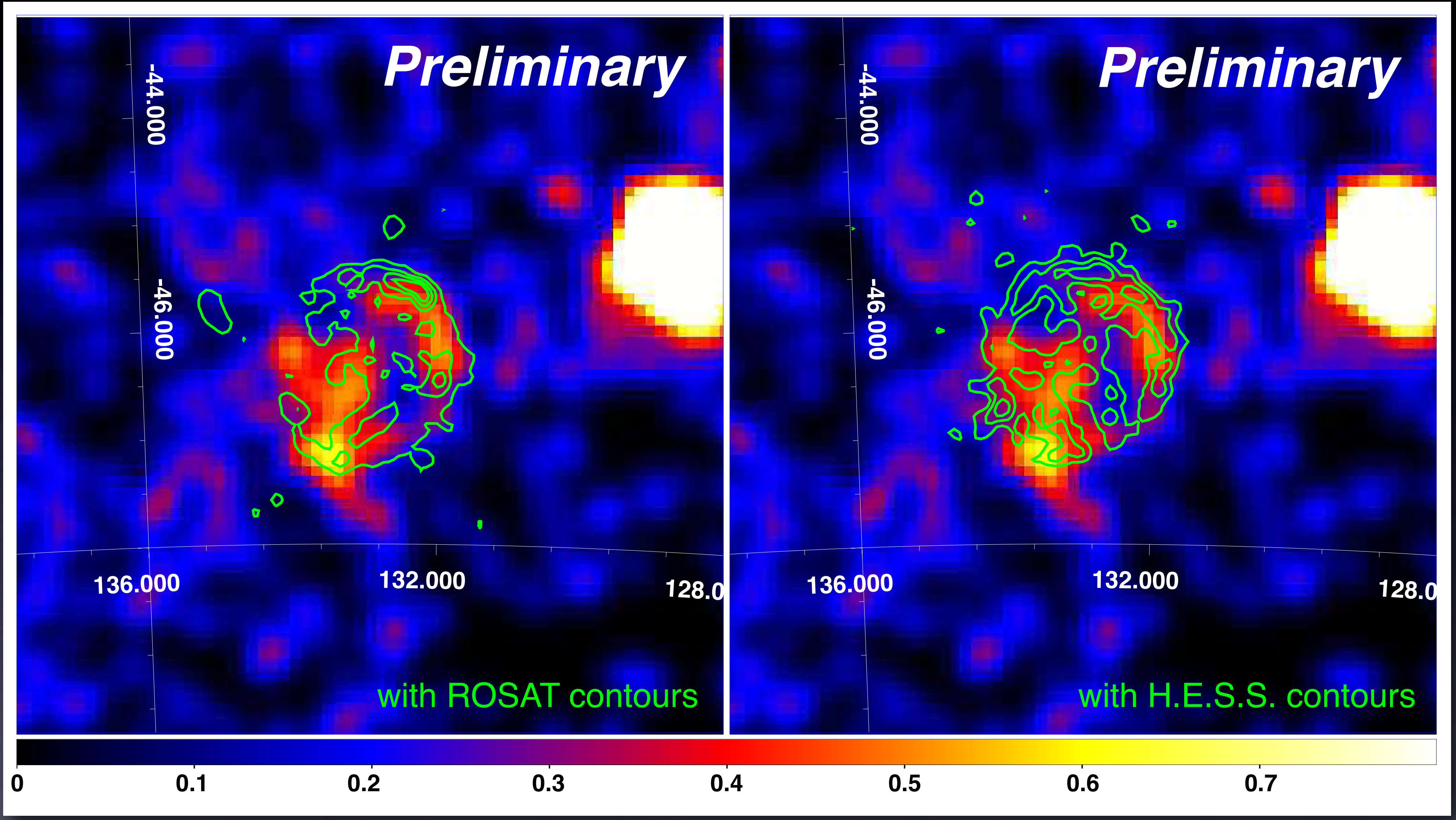
E > 1.3 keV

TeV

RX J0852: Fermi LAT Image

Fermi LAT count maps (> 10 GeV)

Tanaka+ 2011 in prep.



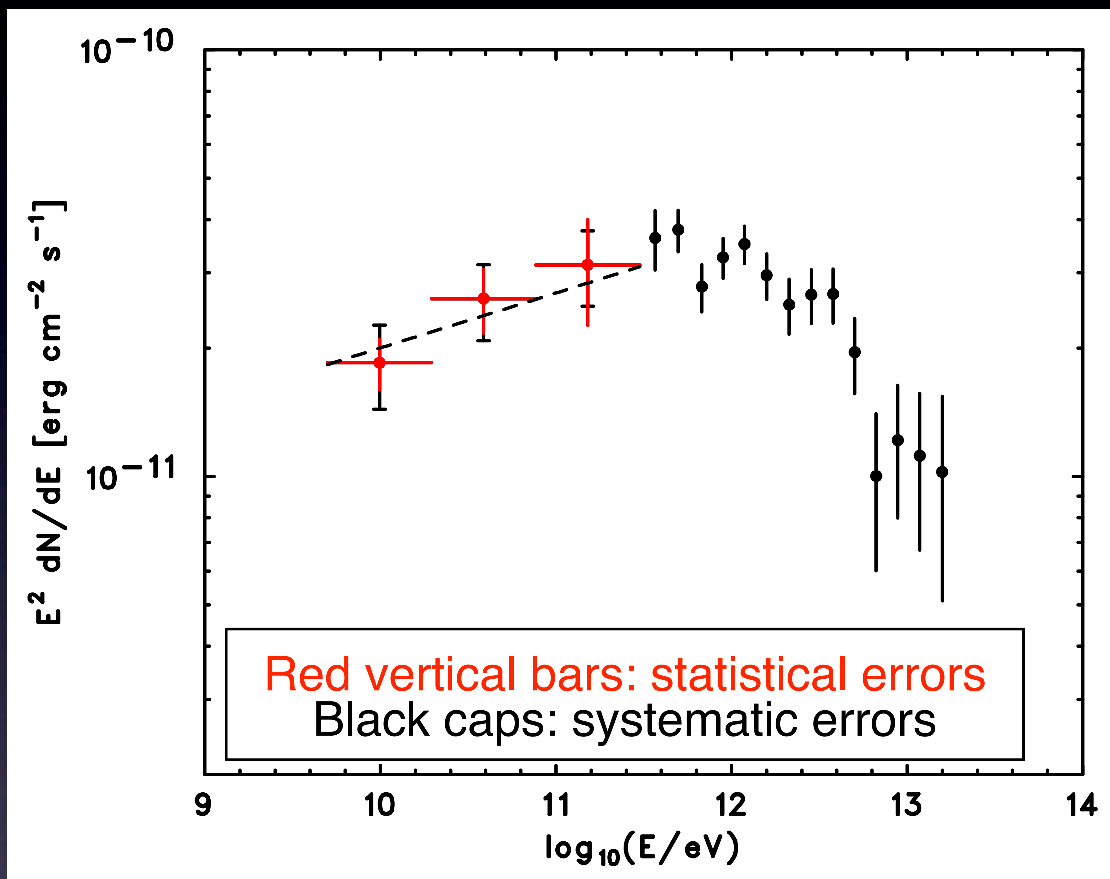
Spatially extended source at the location of the SNR RX J0852.0–4622

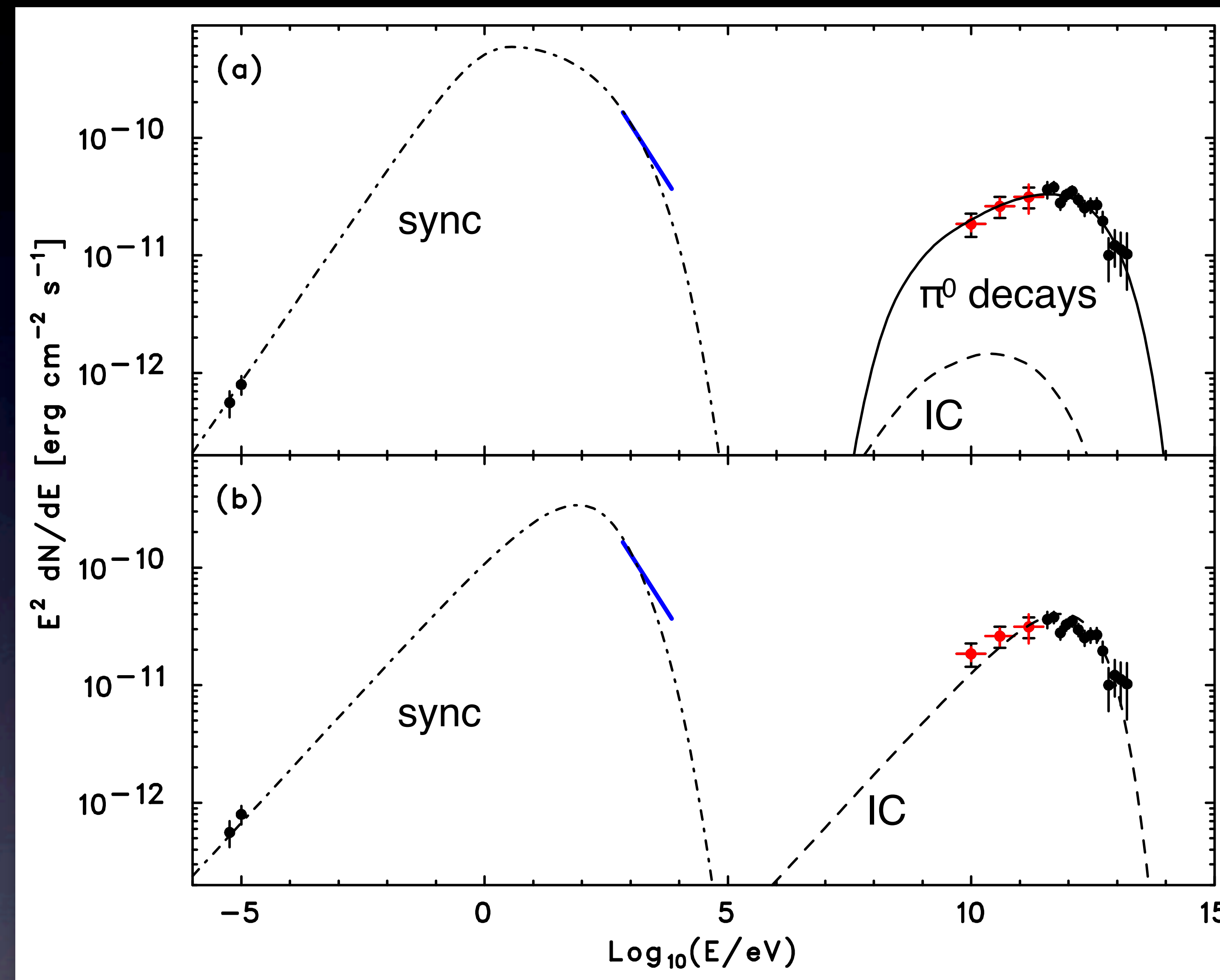
The emission clearly detected in the high energy region (Hereafter we show results with events > 5 GeV)

Using a uniform disk as a spatial template, we obtain a radius of 1.12 (+0.07, –0.06) deg, which is consistent with the extent observed in radio, X-rays, and TeV gamma rays

RX J0852: Fermi LAT Spectrum

Tanaka+ 2011 in prep.





Power-law fit to the Fermi LAT spectrum yields $\Gamma = 1.87 \pm 0.08$ (stat) $\pm\ 0.17$ (sys)

The hadronic model requires a large amount of protons (5×10^{50} erg for $n = 0.1$ cm^{-3})

How to reconcile the weak magnetic field with X-ray filaments in the case of the leptonic model

Middle-Aged SNRs with Shock-Cloud Interactions

SNRs Interacting with Molecular Clouds

Interaction with molecular clouds → higher gas density
→ we can expect brighter π^0-decay emission

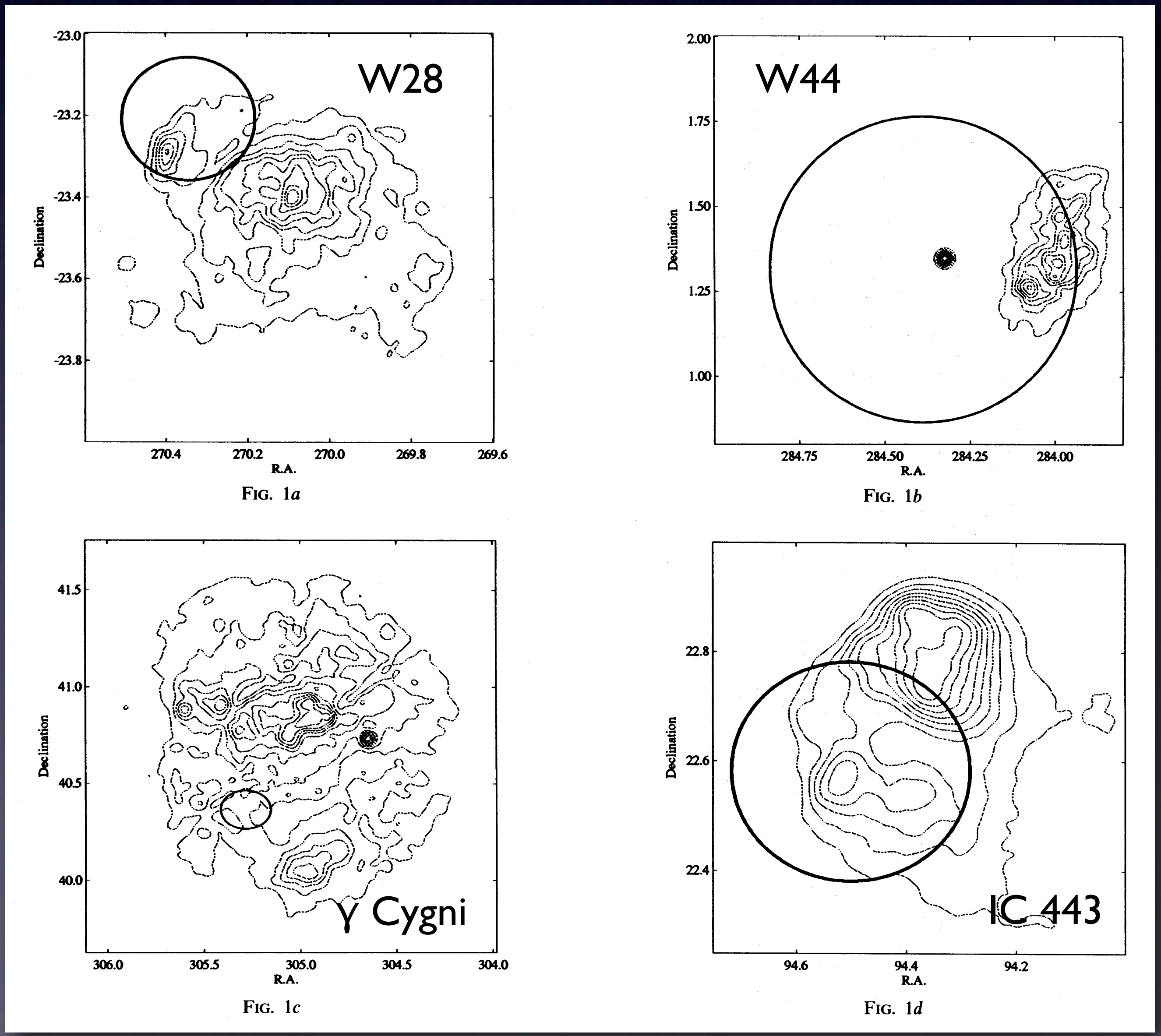
$$F \propto \frac{W_p n}{d^2}$$

W_p: total energy in accelerated protons,
n: target gas density,
d: distance to the SNR

EGRET found gamma-ray sources around SNRs interacting with molecular clouds

However, no firm association of the sources with the SNRs

EGRET error circles on ROSAT X-ray contours
(Esposito+ 1996)



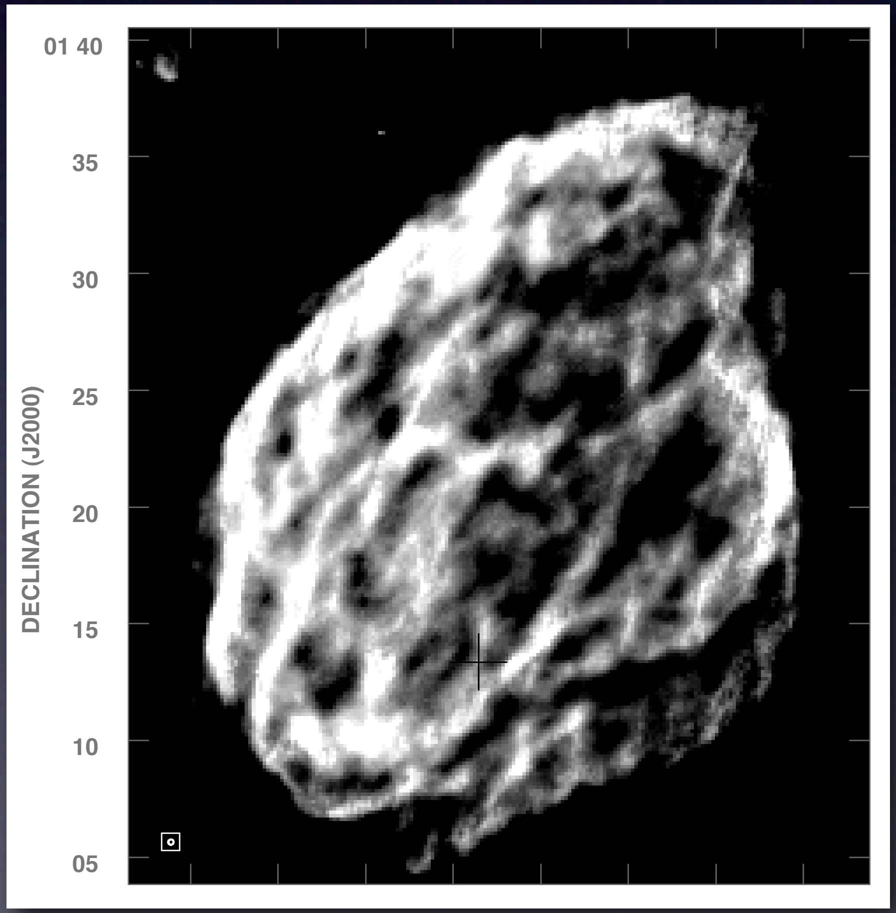
W44

Age: 2.0×10^4 yr, Distance: 3kpc
Spatial extent: ~ 35 arcmin × 26 arcmin
Spatially coincident with 3EG J1856+0114

Cloud-shell interactions
CO (Seta et al. 2004),
OH maser (1720 MHz: Hoffman et al. 2005),
mid-IR (traces shocked H_2; Reach et al. 2006)

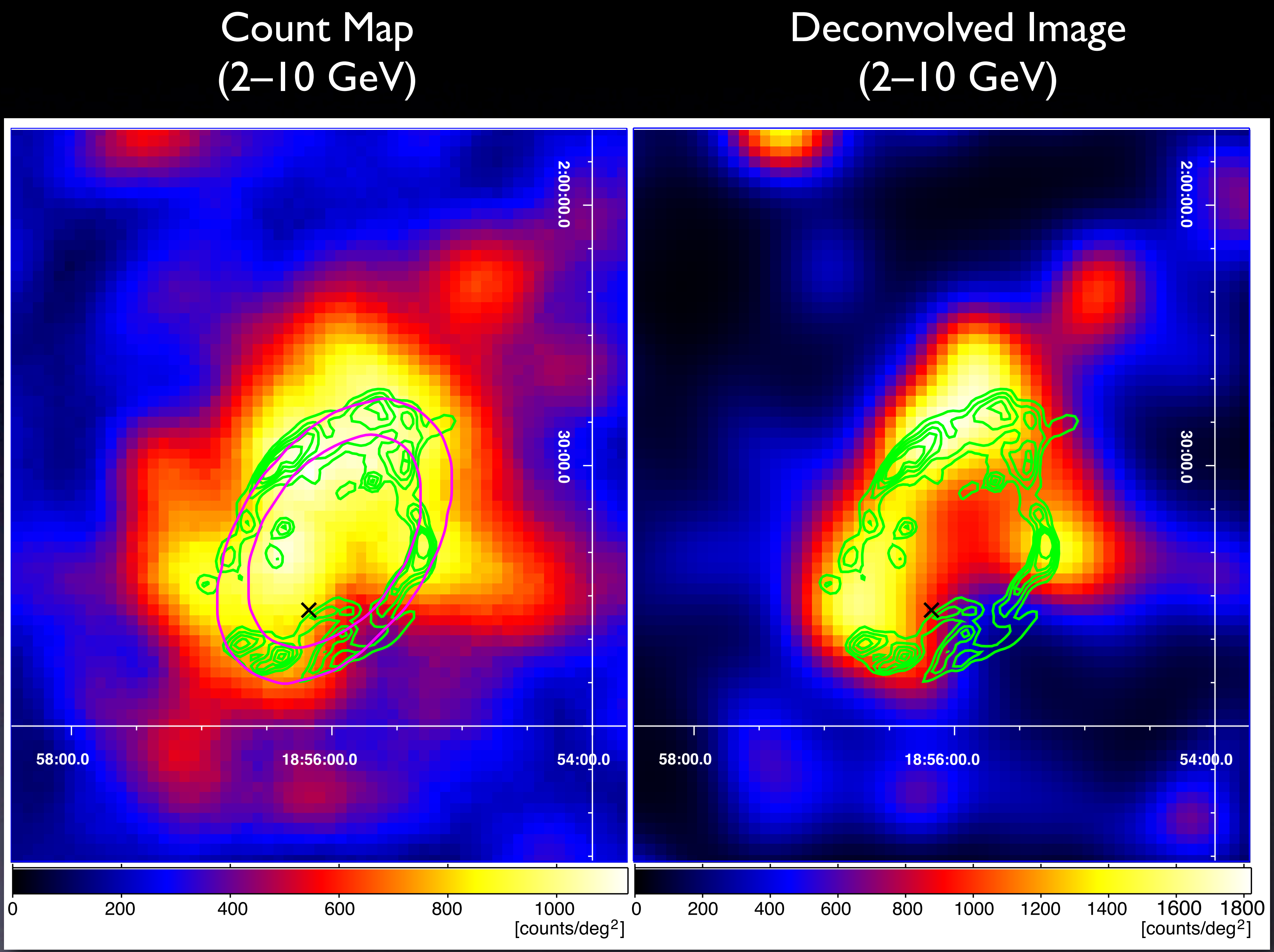
Green: Spitzer IRAC 4.5 μm
Reach et al. (2006)

Bright radio source (S_{1GHz} ~ 230 Jy)
Filamentary shell structures



VLA 324 MHz
Castelletti et al. (2007)

W44: Fermi LAT Image

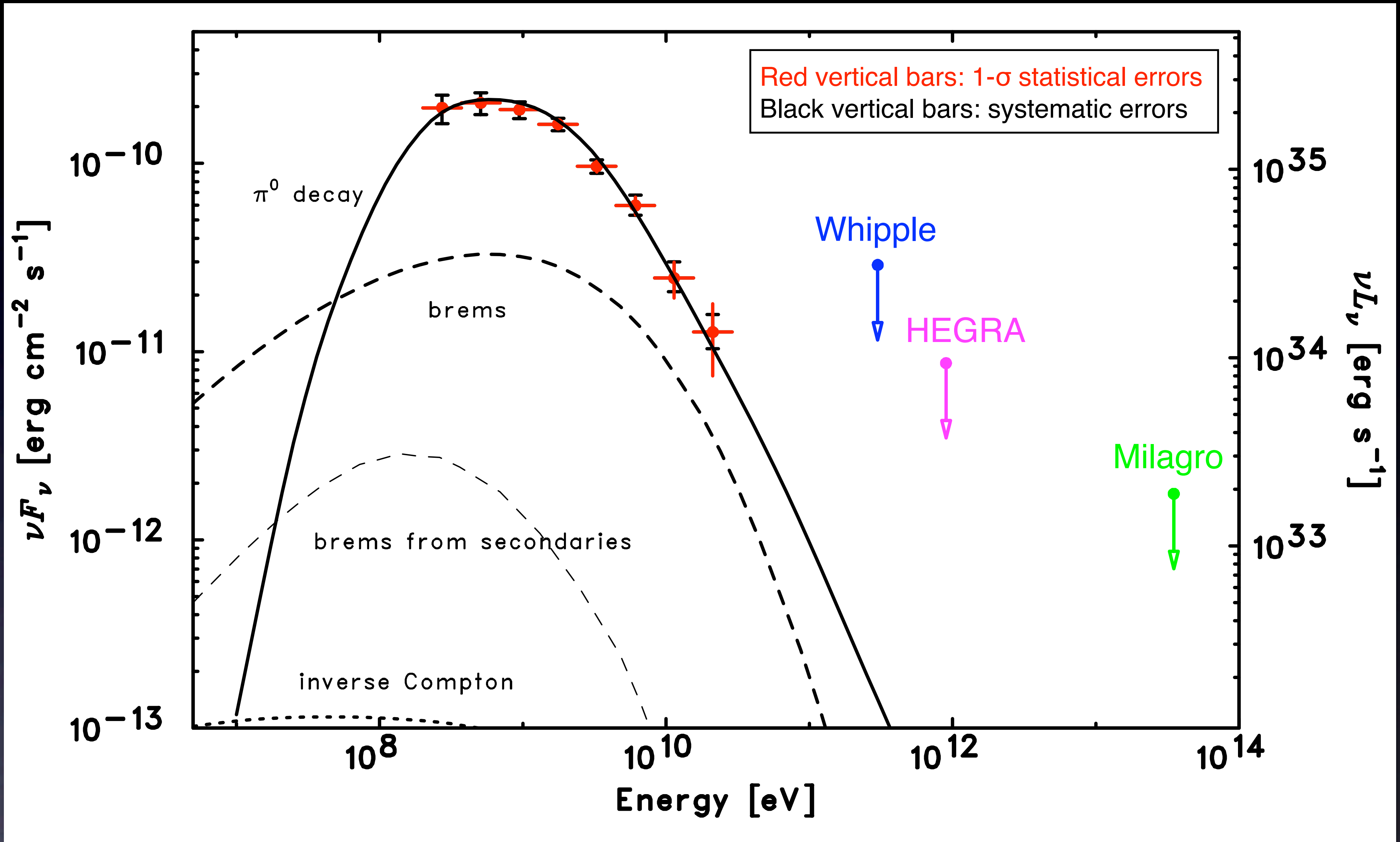


Abdo+ 2010

Black cross: location of PSR B1853+01, Green contours: Spitzer IRAC 4.5 μm

Results of maximum likelihood analysis also prefer ring-like morphology rather than centrally filled morphology (> 8 σ)

W44: Fermi LAT Spectrum



Abdo+ 2010

Spectral break at a few GeV

π^0-decay model can explain the data well

Leptonic scenarios have difficulties

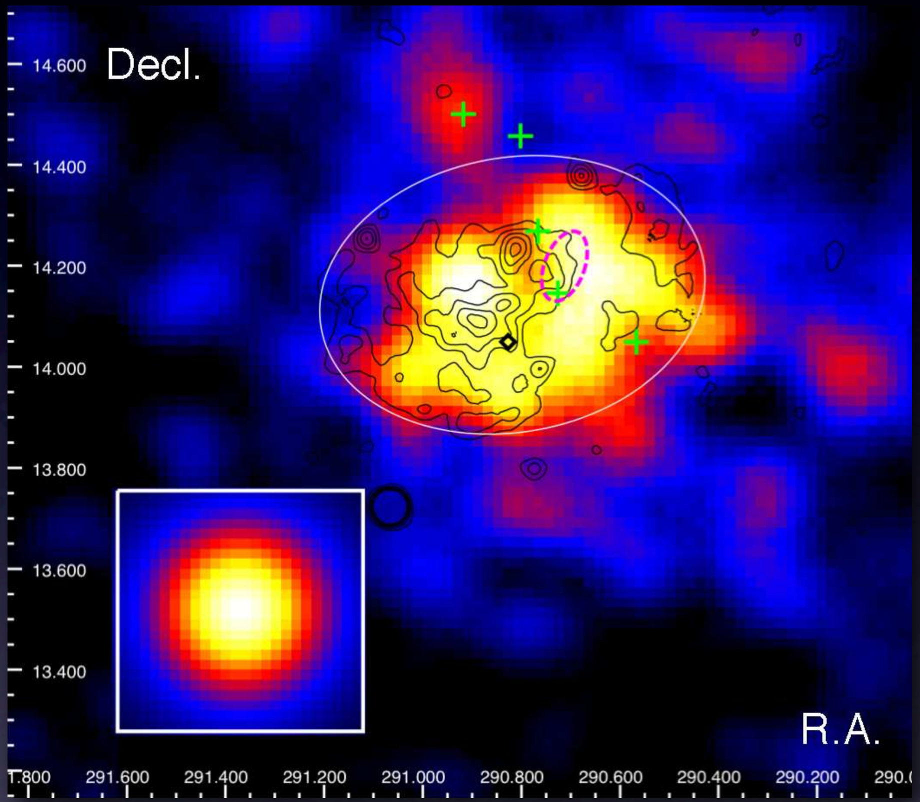
Bremsstrahlung: difficult to fit the radio and GeV data at the same time

IC: requires large amount of electrons (~ 10^{51} erg)

Similar Case: W51C

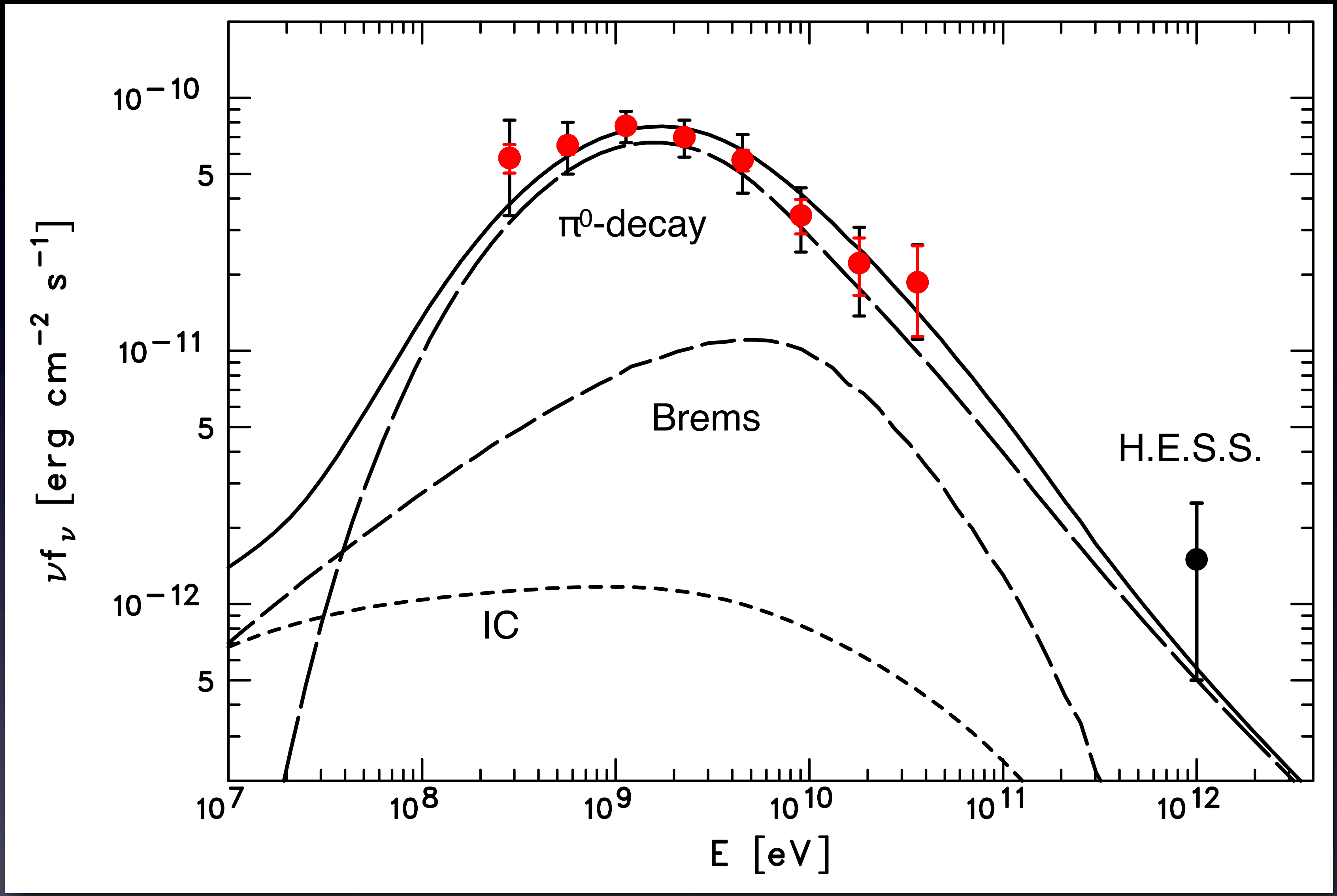
Age: 3.0×10^4 yr, Distance: 6 kpc

Count Map
(2–10 GeV)



Contours: ROSAT X-ray (Koo+ 1995)
Dashed magenta ellipse: shocked CO clumps (Koo & Moon 1997)
Green crossed: HII regions (Carpenter & Sanders 1998)
Diamond: CXO J192318.5+143035 (PWN?) (Koo+ 2005)

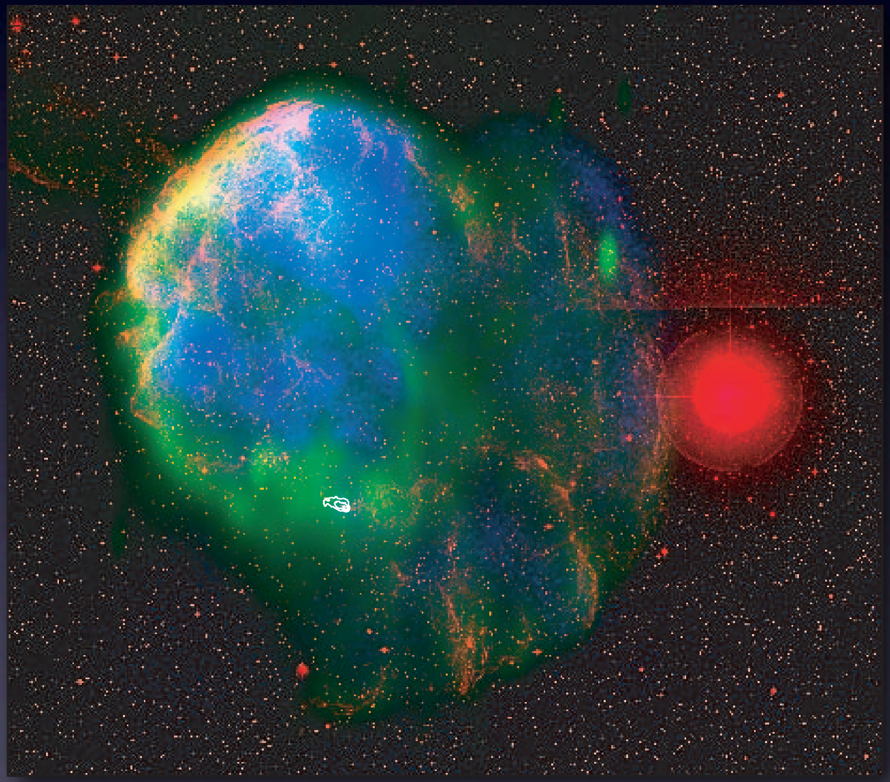
Abdo+ 2009



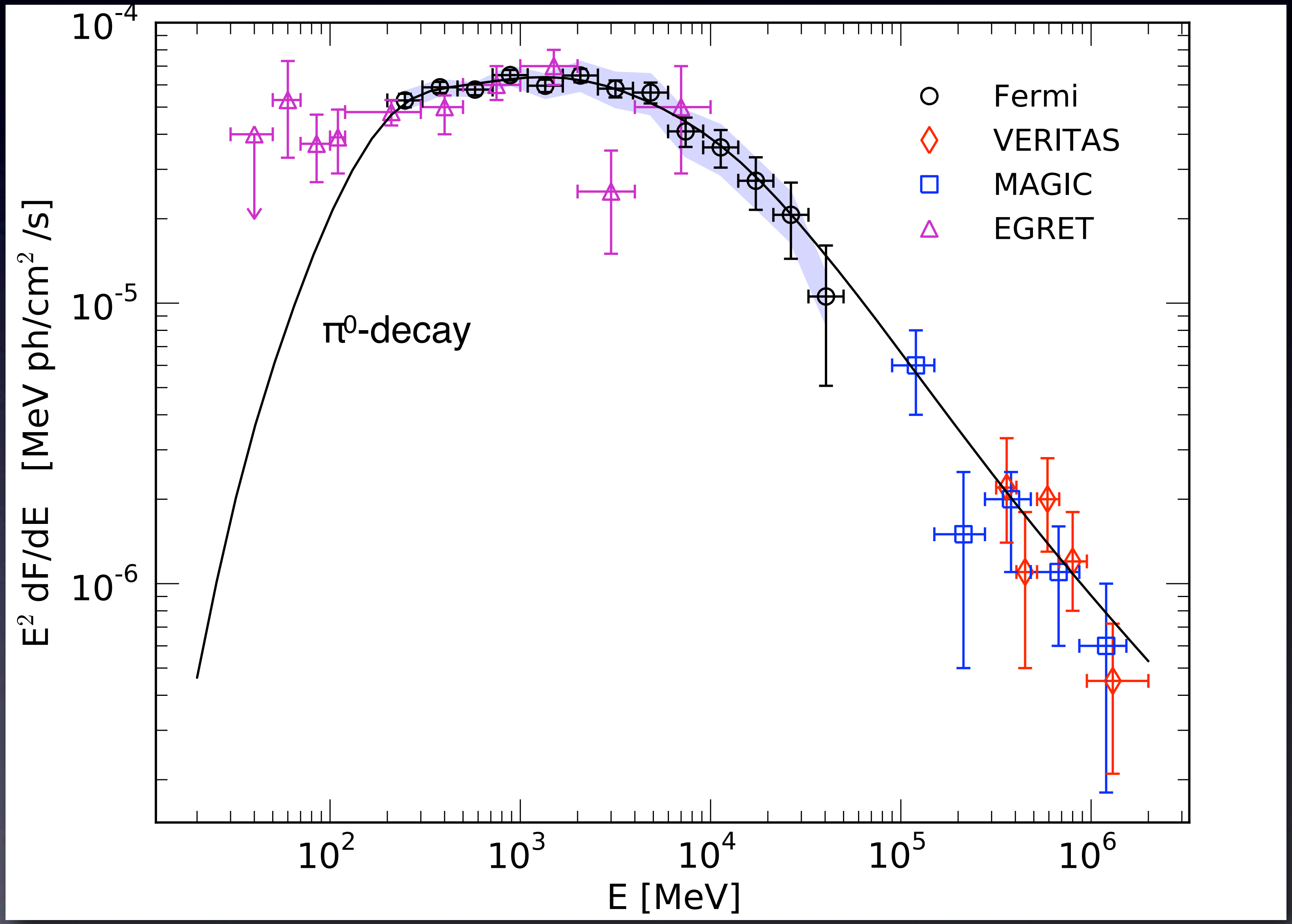
One of the most luminous gamma-ray sources $L = 1 \times 10^{36}$ (D/6 kpc)^2 erg s^{-1}
Spectral steepening
π^0-decay model can reasonably explain the data
Leptonic scenarios have difficulties similar to those for W44

Similar Case: IC 443

Spatially extended emission detected with the Fermi LAT
Similar spectral steepening to W51C and W44

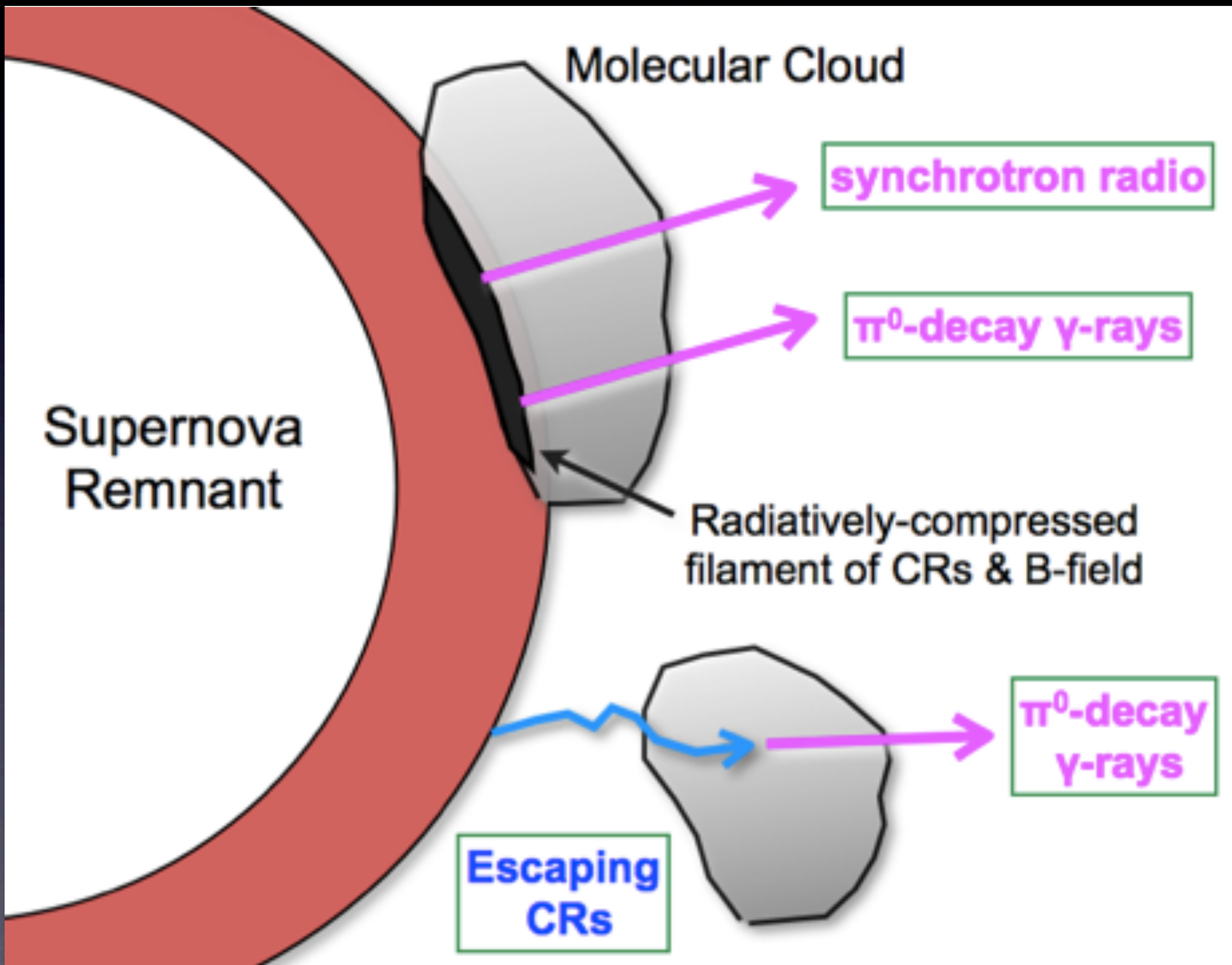


Gaensler+ 2006



Abdo+ 2009

Gamma-Ray Production Site

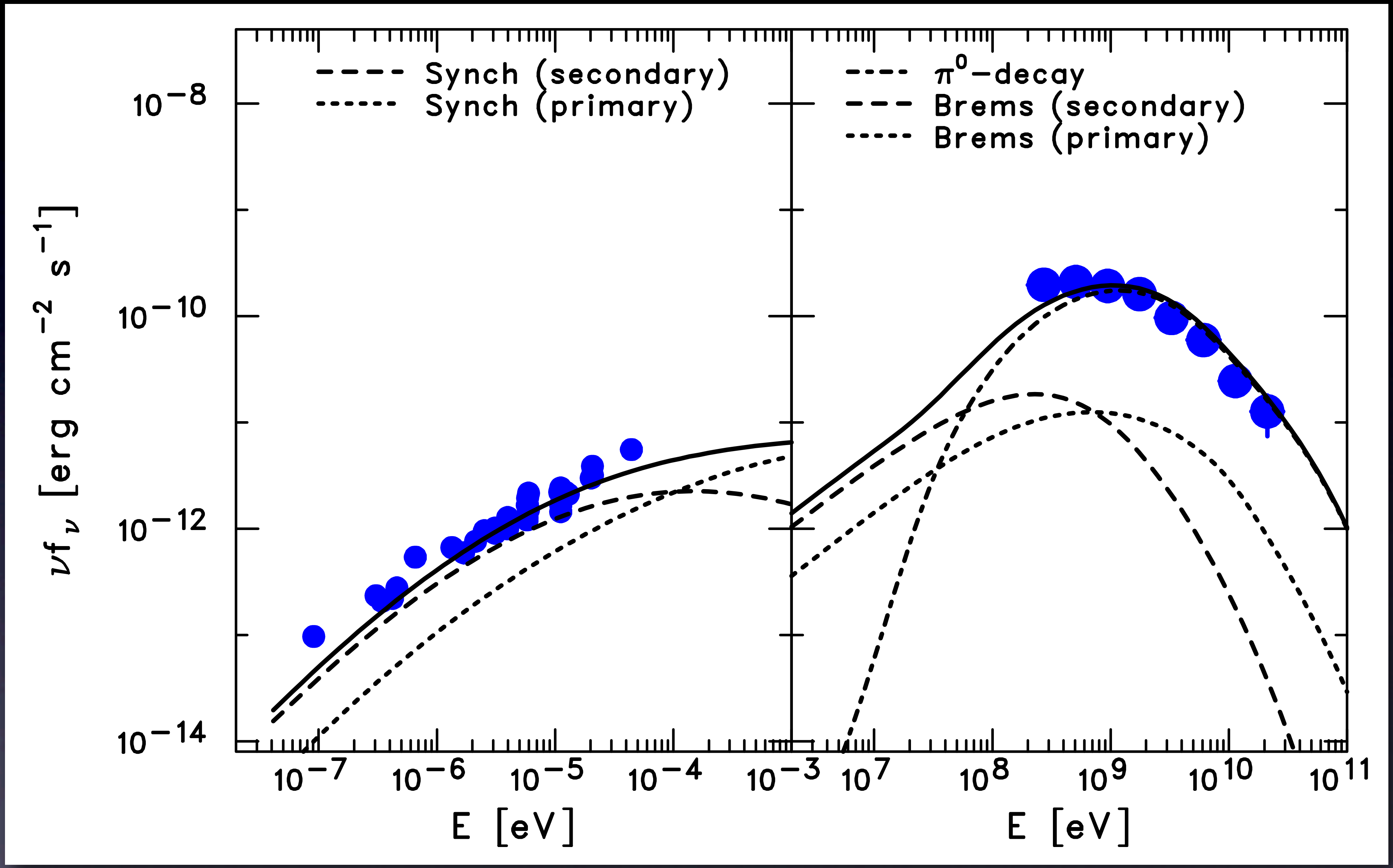


Uchiyama+ 2010

e.g. Ohira+ 2010

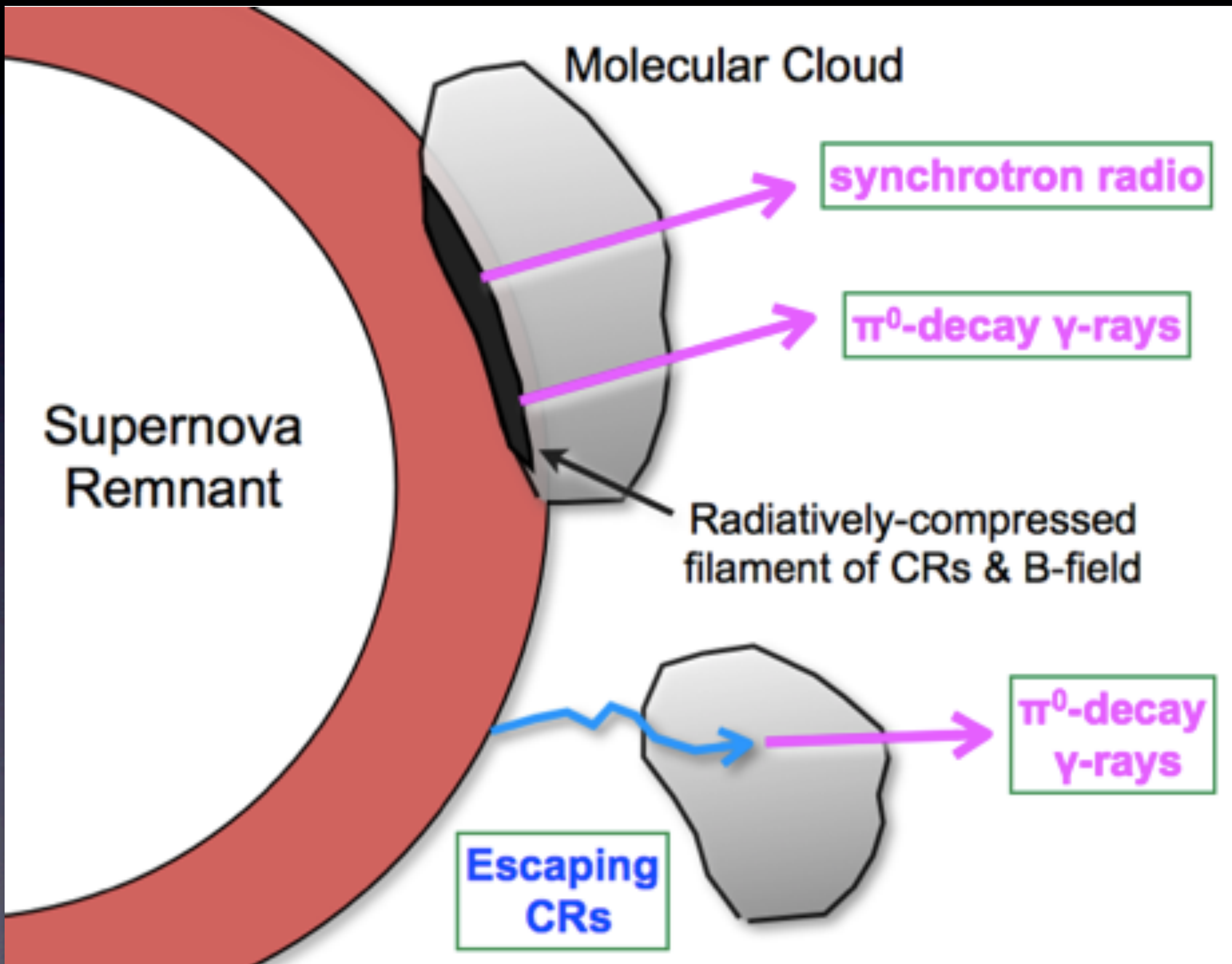
Crushed Cloud Model

Results for W44 Uchiyama+ 2010



Reacceleration of pre-exsiting Galactic cosmic rays at cloud radiative shocks
Naturally explain the large gamma-ray luminosity of ~ 10^{35} erg s^{-1}
and the flat (α = 0.37) radio spectrum

Gamma-Ray Production Site



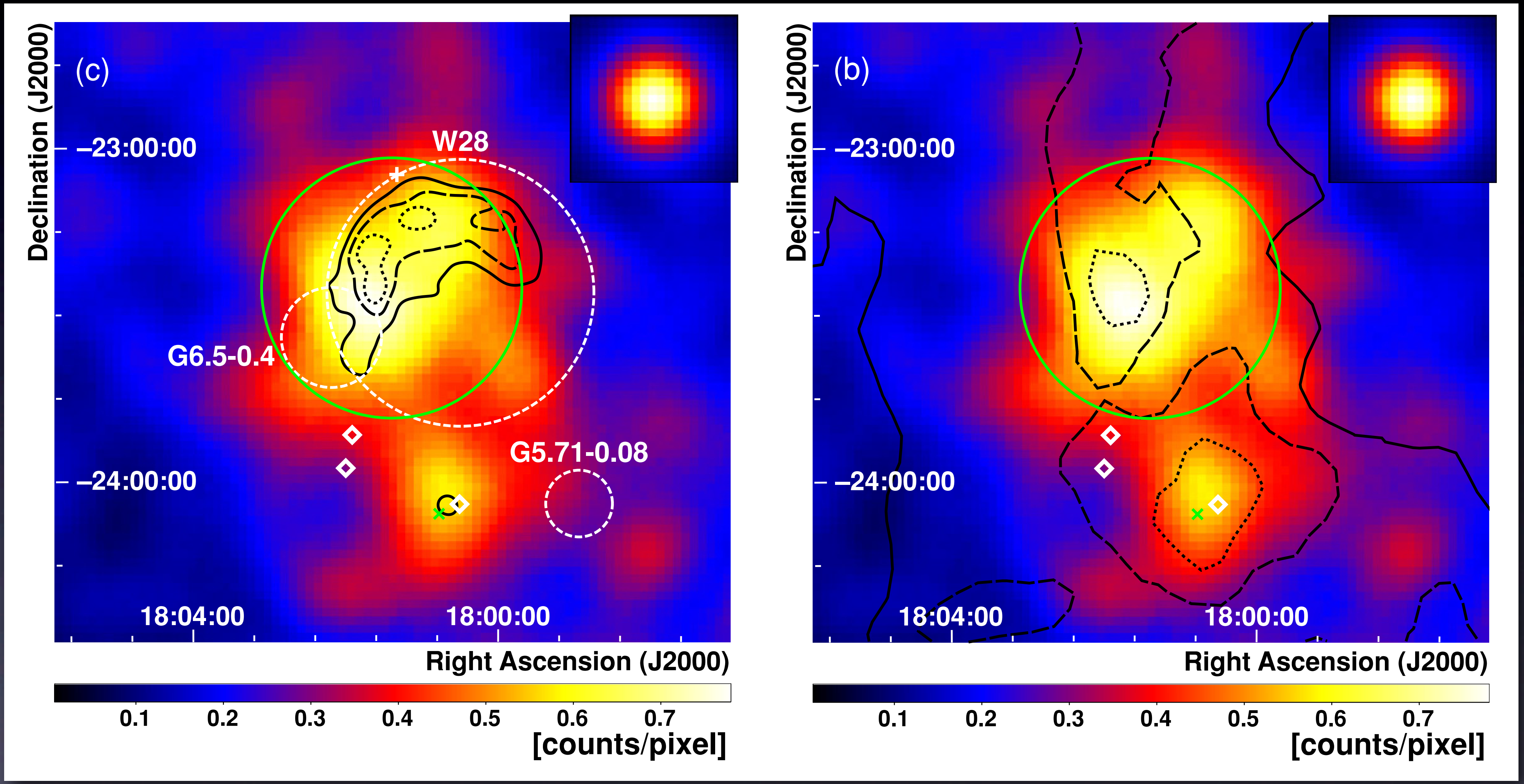
Uchiyama+ 2010

e.g. Ohira+ 2010

A Escape Model Case?: W28

Fermi LAT Count Map
(2–10 GeV)

Abdo+ 2010



with Radio contours

with CO contours

Gamma-ray emission from a molecular cloud outside the SNR

Summary

- X-ray and TeV gamma-ray observations have been providing evidence for cosmic-ray acceleration in SNRs
- GeV observations by the Fermi LAT opened up a new window to study particle acceleration in SNRs
- Fermi LAT detected gamma rays from two major TeV-bright SNRs, RX J1713.7–3946 and RX J0852.0–4622 (Vela Jr.)
- Bright GeV emission from SNRs interacting with molecular clouds
- New observational results triggered theoretical studies to explain multiwavelength spectra of SNRs