フェルミガンマ線宇宙望遠鏡で見た銀河系内天体

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On Behalf of the Fermi LAT Collaboration

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- Fermi Large Area Telescope
- Supernova Remnants
  - GeV-Bright SNRs
  - TeV-Bright SNRs
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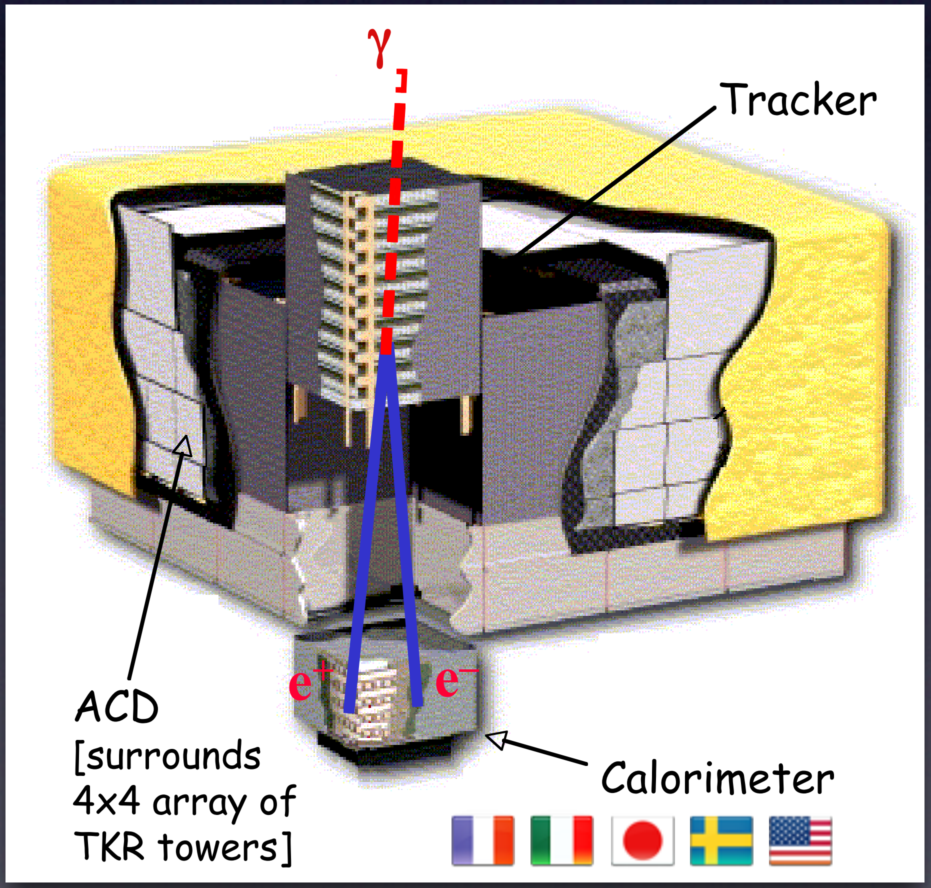
Fermi Large Area Telescope

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 (all-sky coverage in ~ 3 hr)



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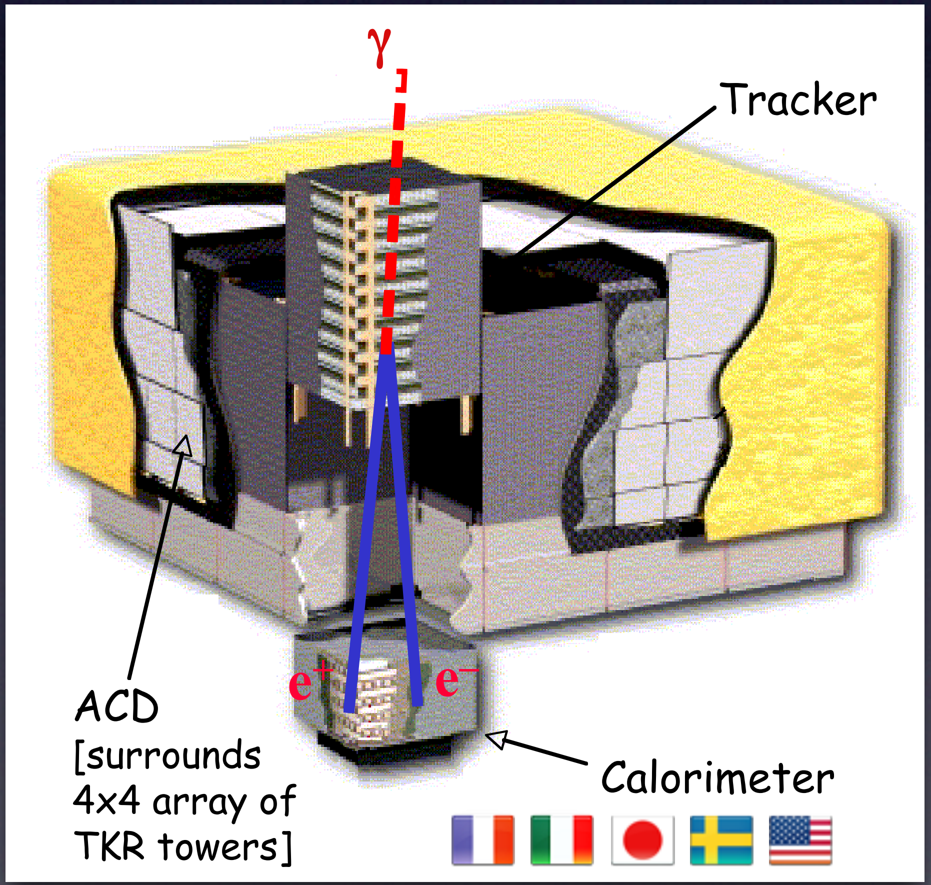
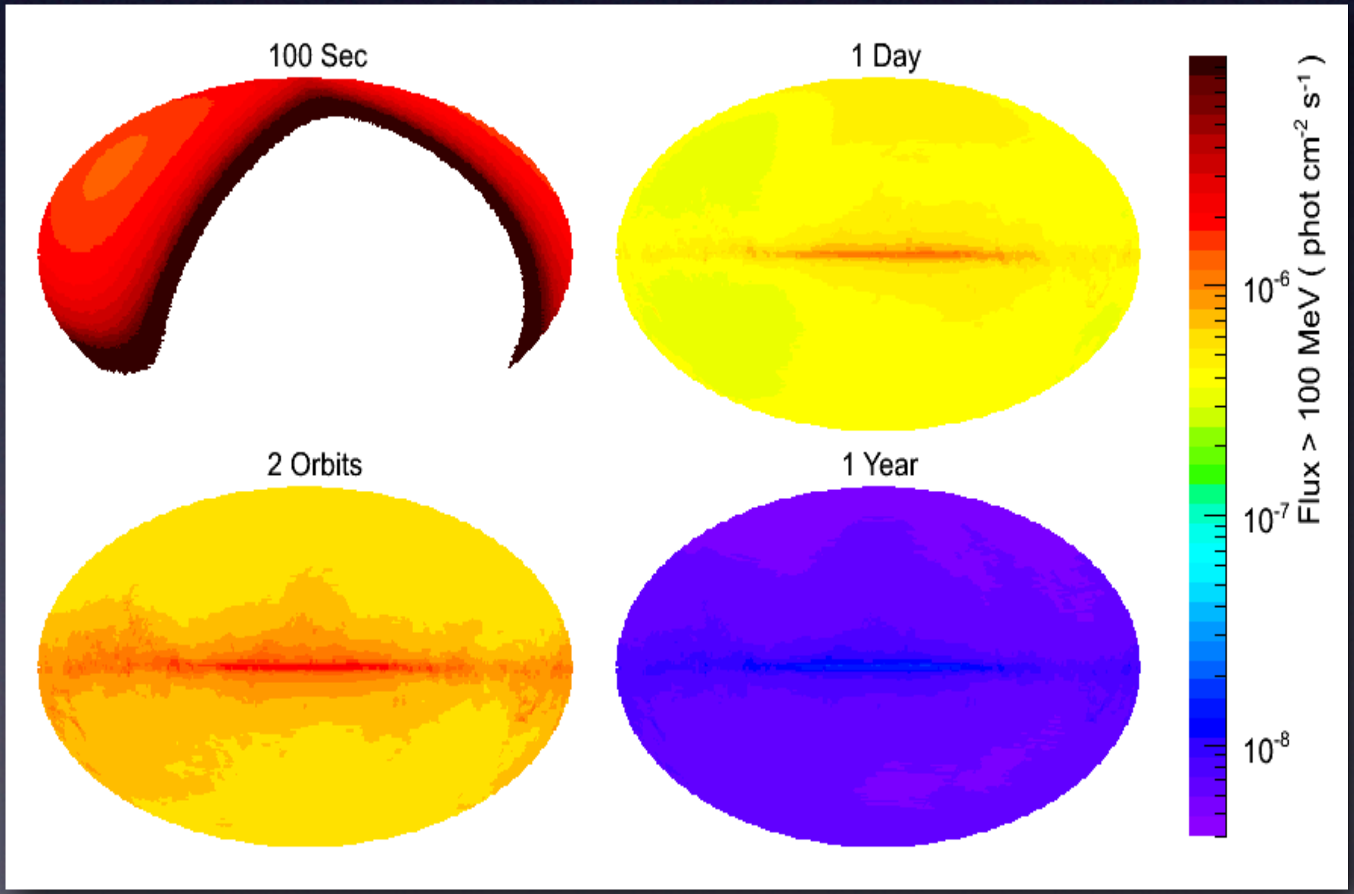




CGRO EGRET vs Fermi LAT

LAT Specifications & Performance

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area [1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution [2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution [3]	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination [4]	< 0.5'	15'
Point Source Sensitivity [5]	$< 6 \times 10^{-9}$ cm^{-2} s^{-1}	$\sim 10^{-7}$ cm^{-2} s^{-1}

[1] After background rejection

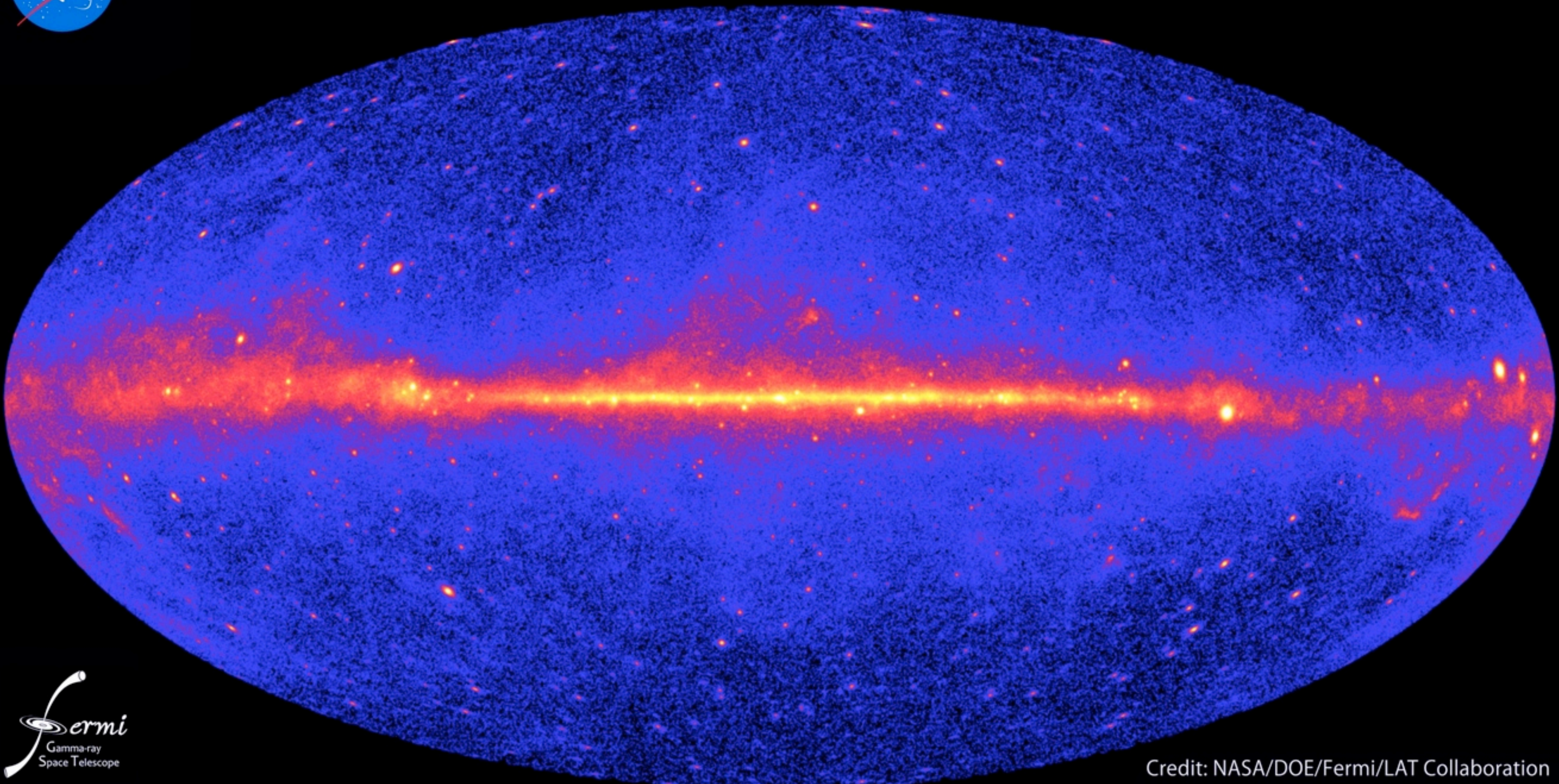
[2] Single photon, 68% containment, on-axis

[3] 1-σ, on-axis

[4] 1-σ radius, flux 10^{-7} cm^{-2} s^{-1} (>100 MeV), high |*b*|

[5] > 100 MeV, at high |*b*|, for exposure of one-year all sky survey, photon spectral index -2

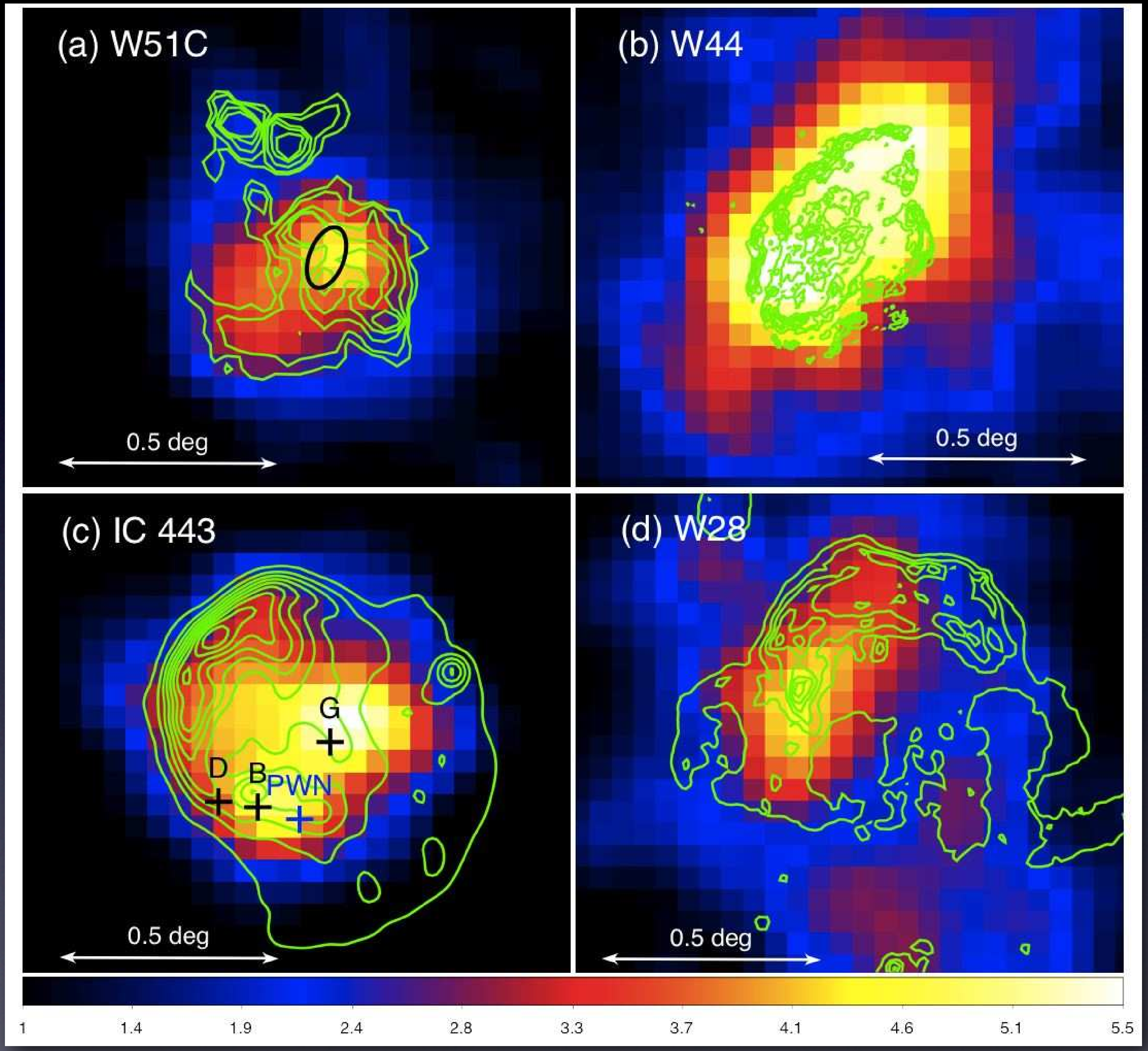
Fermi two-year all-sky map



2FGL catalog contains 1873 sources (cf. 271 sources for 3EG catalog)

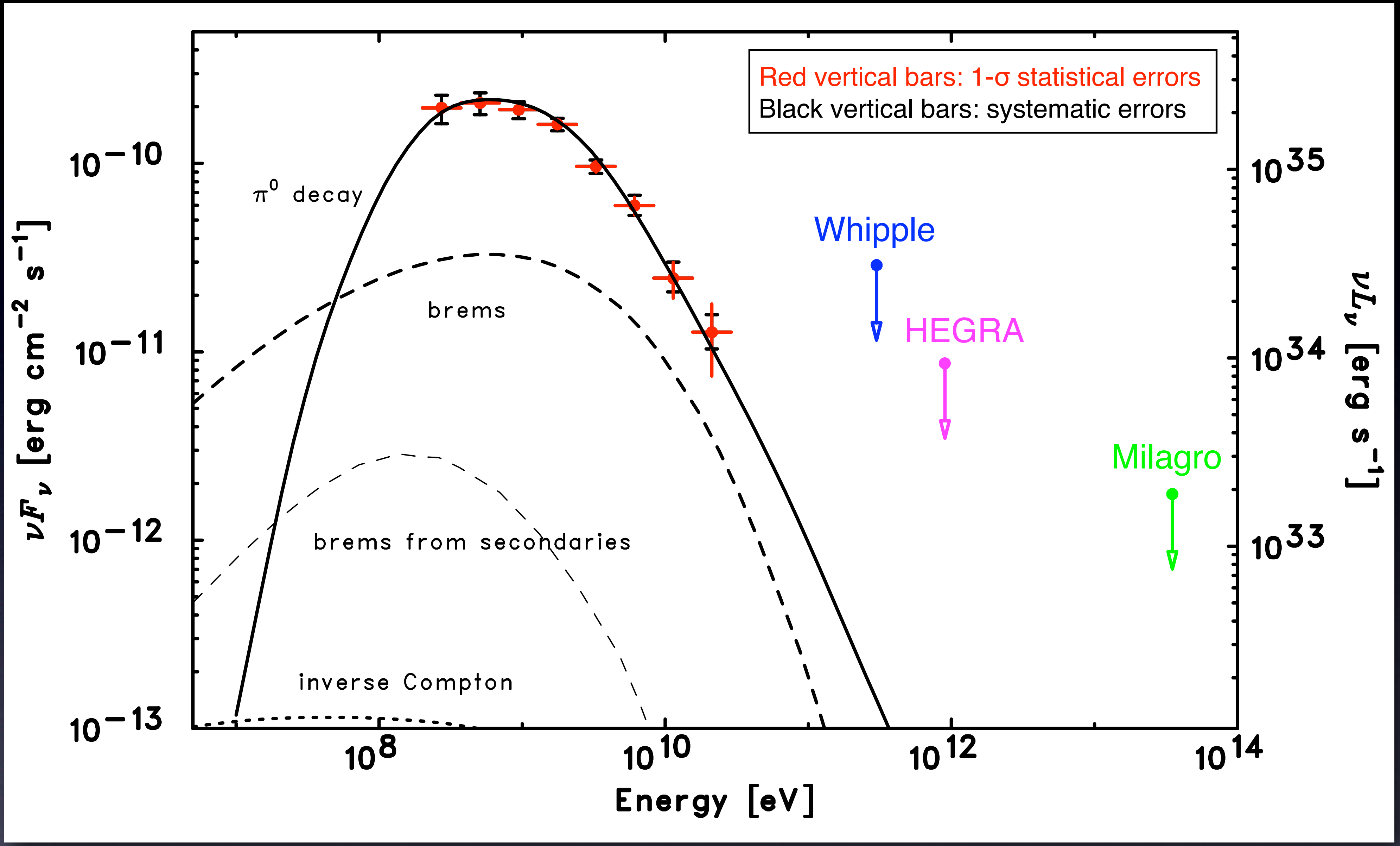
超新星残骸

GeV-Bright SNRs



Color: Gamma Rays by Fermi LAT
Contours: Radio Continuum by VLA

W44: Fermi LAT Spectrum



Abdo+ 2010

Spectral break at a few GeV

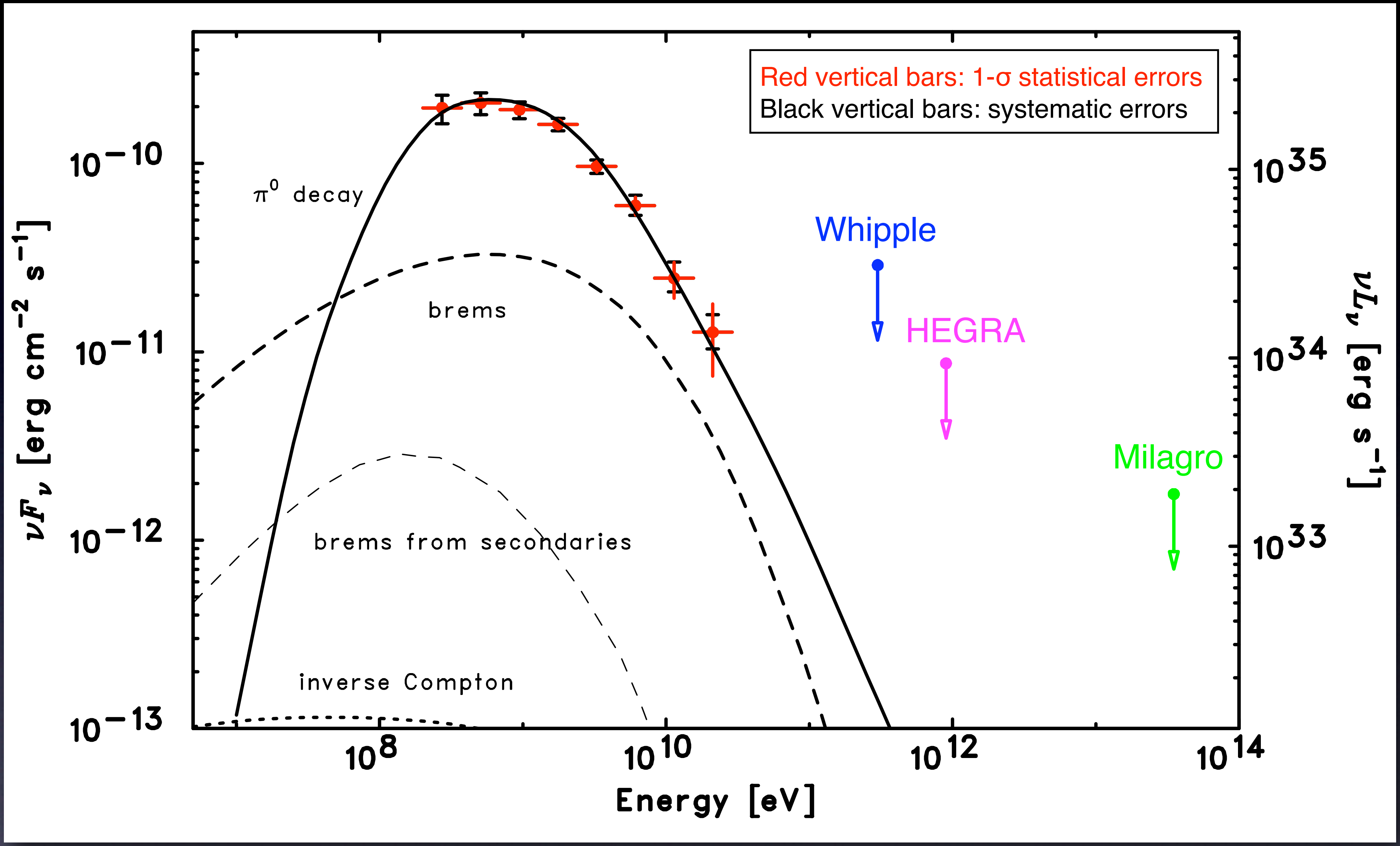
π^0-decay model can explain the data well

Leptonic scenarios have similar difficulties

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

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

W44: Fermi LAT Spectrum



Abdo+ 2010

Proton Spectrum: Broken PL

$s_1 = 1.74$, $s_2 = 3.7$, $E_b = 8$ GeV

$W_p = 6 \times 10^{49}$ (n/100 cm^{-3})$^{-1}$ (d/3 kpc)^2 erg

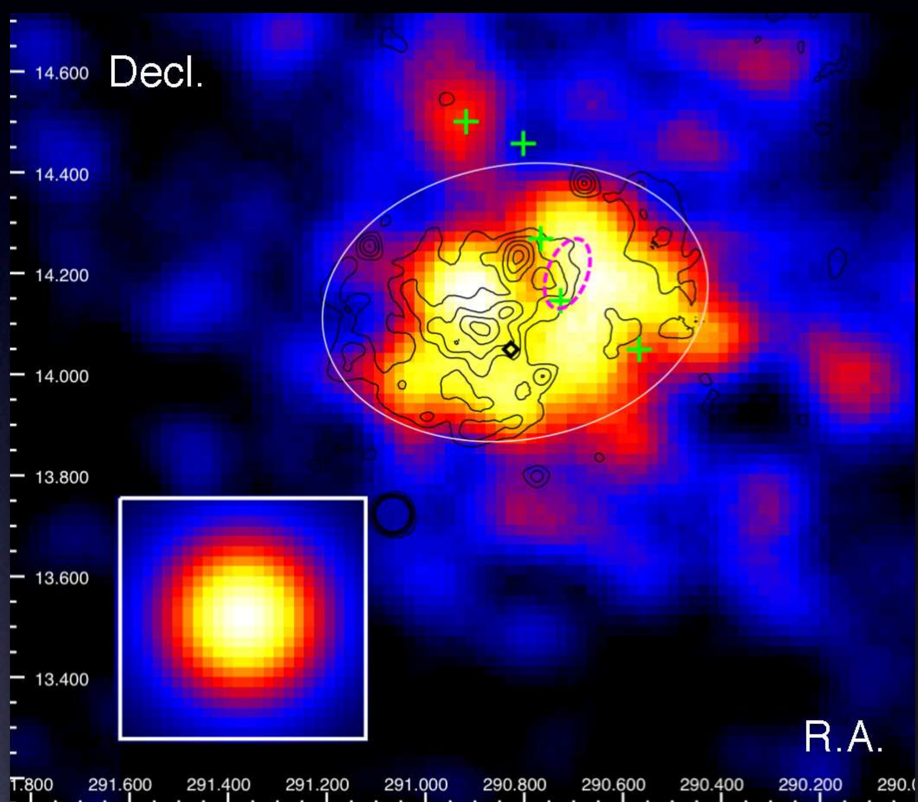
$K_{ep} = 0.01$

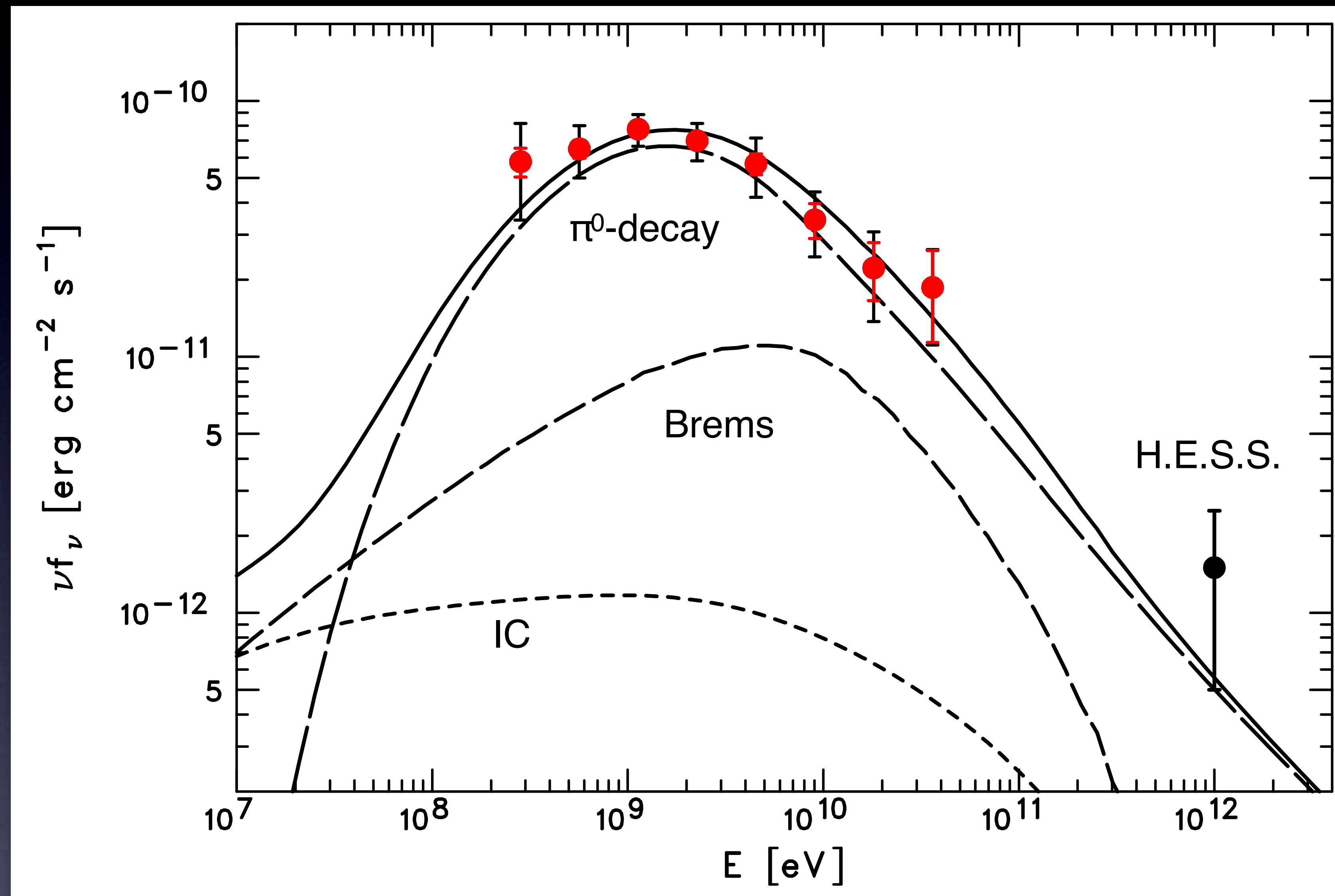
Similar Case: W51C

Age: 3.0 × 10^4 yr, Distance: 6 kpc

Abdo+ 2009

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)

One of the most luminous gamma-ray sources L = 1 × 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: W51C

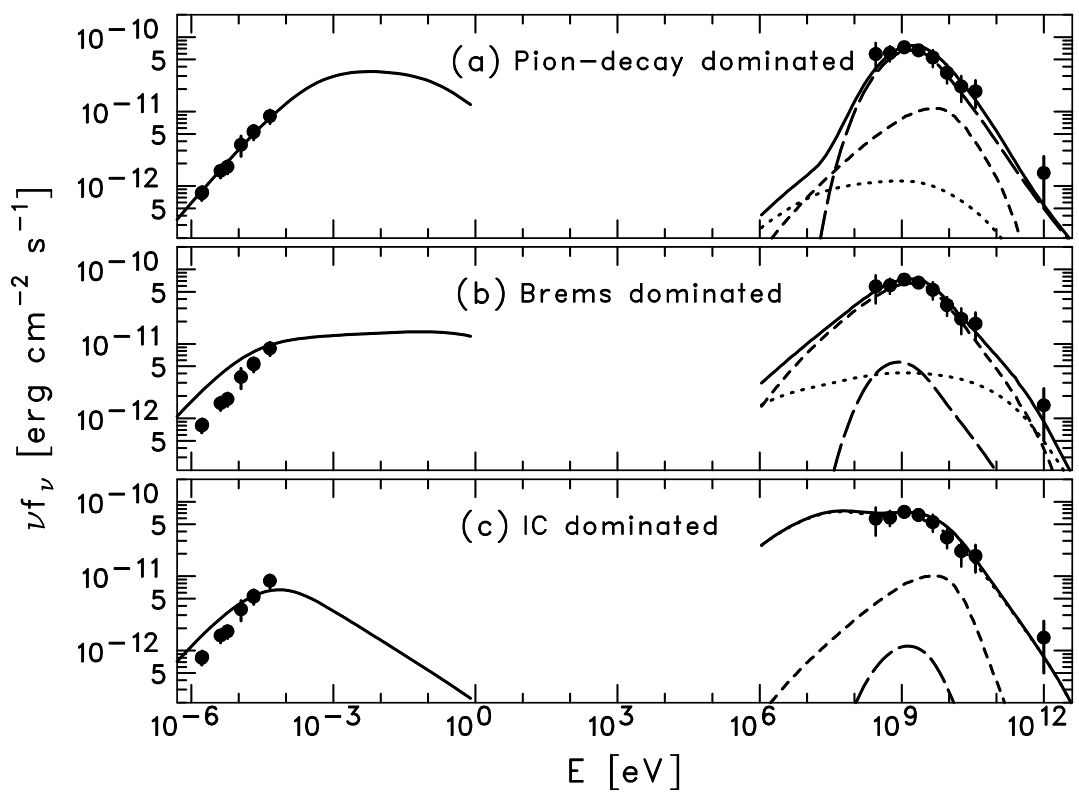


Figure 4. Three different scenarios for the multiwavelength modeling (see Table 1). The radio emission (from Moon & Koo 1994) is explained by synchrotron radiation, while the gamma-ray emission is modeled by different combinations of π^0 decay (long-dashed curve), bremsstrahlung (dashed curve), and IC scattering (dotted curve). The sum of the three component is shown as a solid curve.

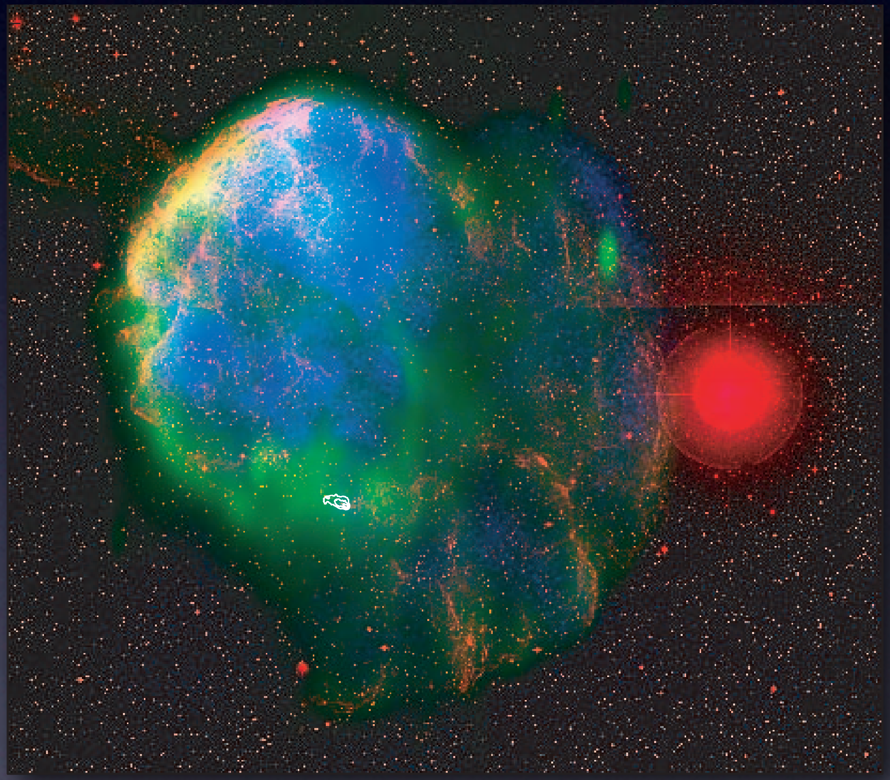
Table 1
Parameters of Multiwavelength Models

Model	Parameters					Energetics	
	a_e/a_p	Δs	p_{br} (GeV c^{-1})	B (μG)	$\bar{n}_H$ (cm^{-3})	W_p (10^{50} erg)	W_e (10^{50} erg)
(a) π^0 decay	0.02	1.4	15	40	10	5.2	0.13
(b) Bremsstrahlung	1.0	1.4	5	15	10	0.54	0.87
(c) Inverse Compton	1.0	2.3	20	2	0.1	8.4	11

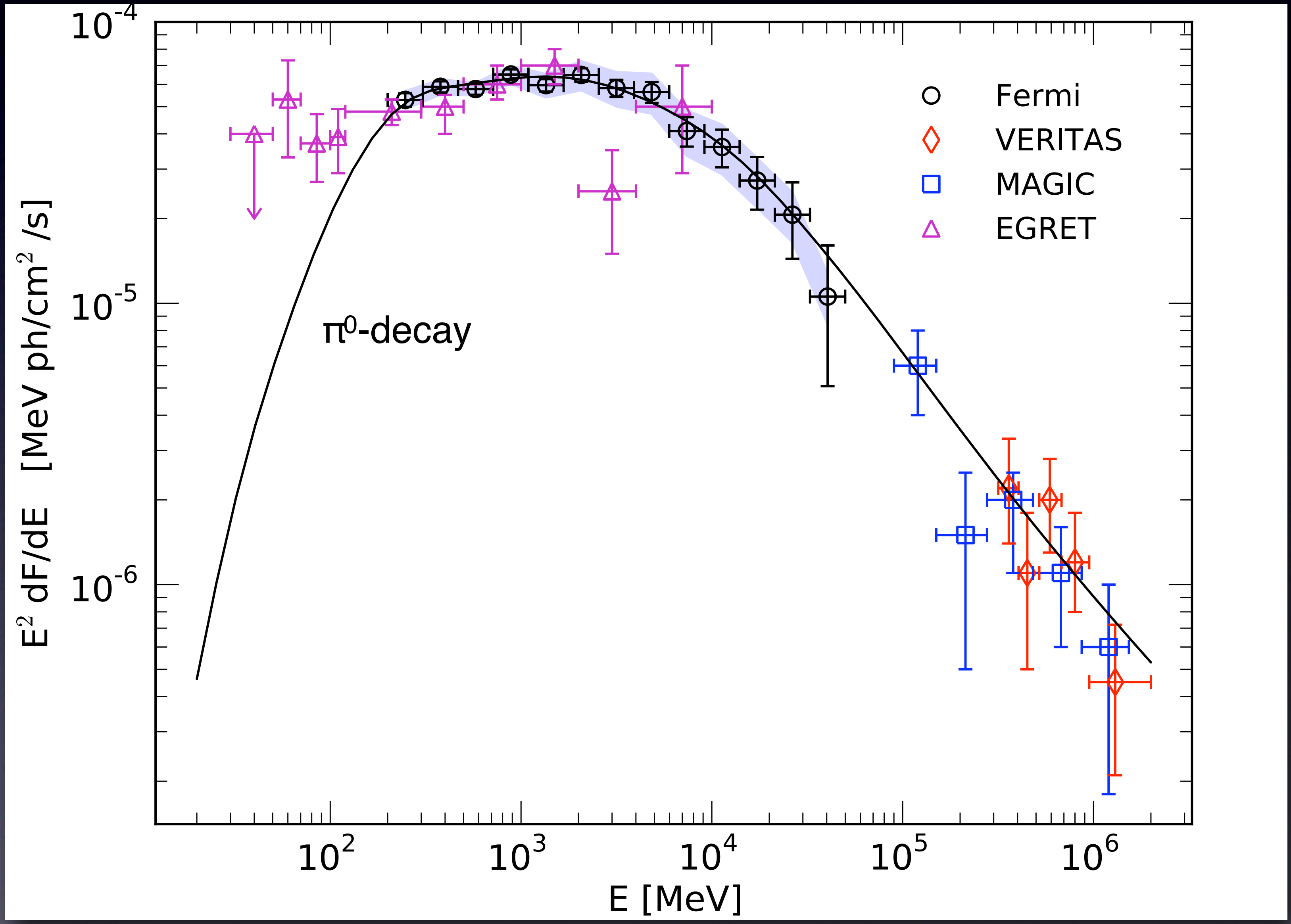
Notes. Seed photons for IC include the CMB ($kT_{CMB} = 2.3 \times 10^{-4}$ eV, $U_{CMB} = 0.26$ eV cm^{-3}), infrared ($kT_{IR} = 3 \times 10^{-3}$ eV, $U_{IR} = 0.90$ eV cm^{-3}), and optical ($kT_{opt} = 0.25$ eV, $U_{opt} = 0.84$ eV cm^{-3}). The total energy content of radiating particles, $W_{e,p}$, is calculated for $p > 10$ MeV c^{-1}.

Similar Case: IC 443

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

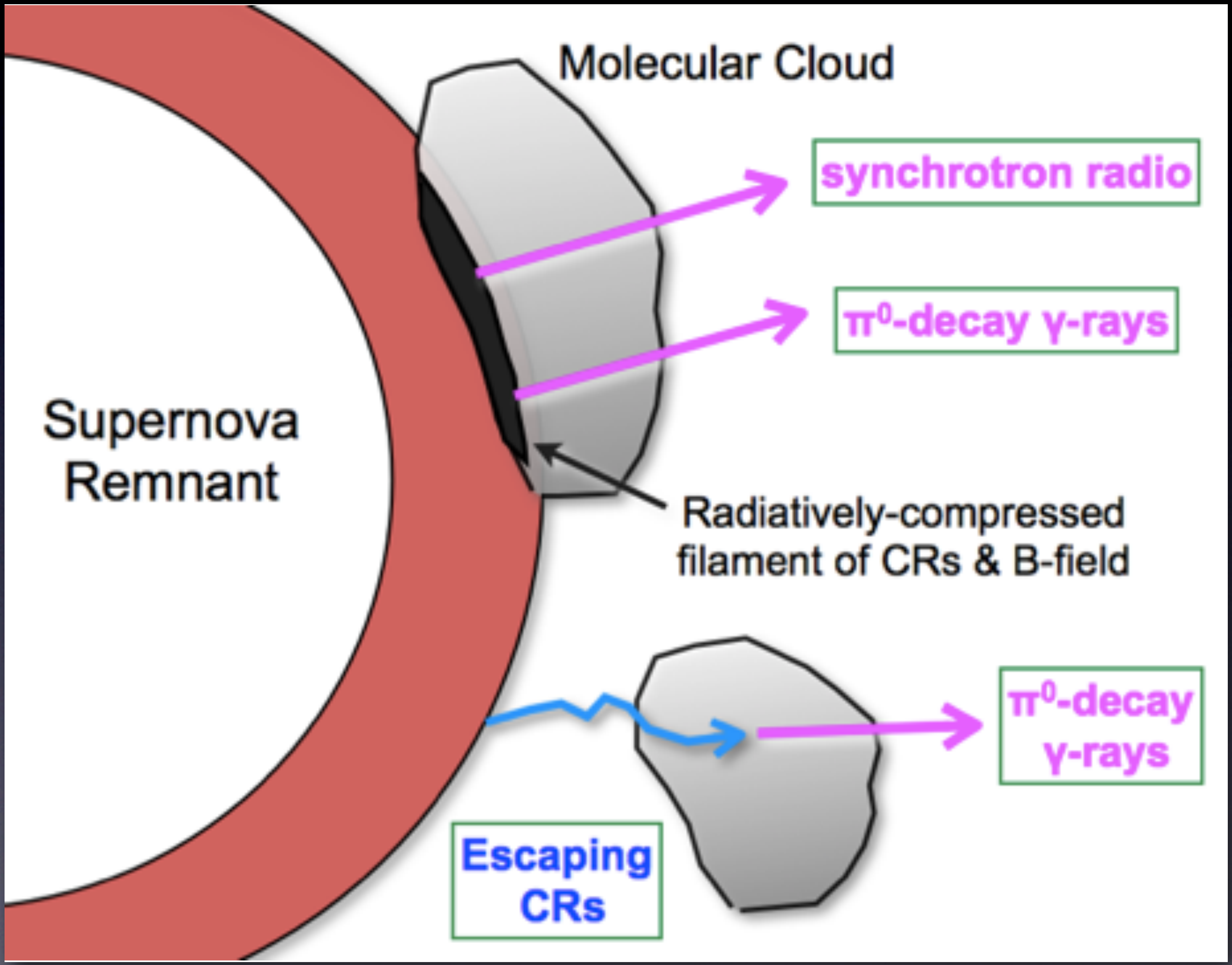


Gaensler+ 2006



Abdo+ 2009

Gamma-Ray Production Site



Uchiyama+ 2010

e.g. Ohira+ 2010

Emission from the Vicinity of W44

Uchiyama+ 2012

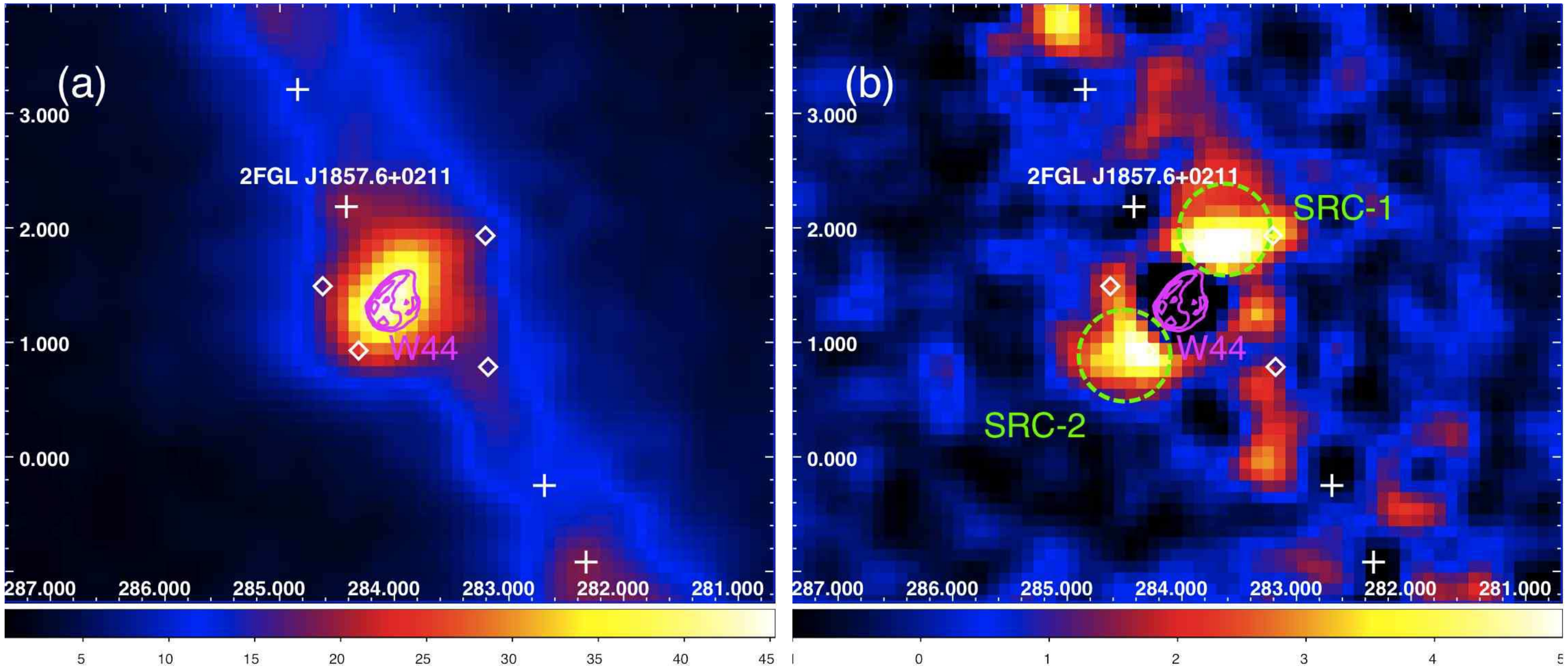


FIG. 1.— (a) *Fermi* LAT γ-ray count map for 2–100 GeV around SNR W44 in units of counts per pixel ($0.^\circ1 \times 0.^\circ1$) in celestial coordinates (J2000). Gaussian smoothing with a kernel $\sigma = 0.^\circ3$ is applied to the count maps. Green contours represent a 10 GHz radio map of SNR W44 (Handa et al. 1987). 2FGL sources included in the maximum likelihood model are shown as crosses, while those removed from the model are indicated by diamonds. (b) The difference between the count map in (a) and the best-fit (maximum likelihood) model consisting of the Galactic diffuse emission, the isotropic model, 2FGL sources (crosses), and SNR W44 represented by the radio map. Excess γ-rays in the vicinity of W44 are referred to as SRC-1 and SRC-2.

Emission from the Vicinity of W44

Kinetic energy of the escaped cosmic rays (W_{esc}) can be estimated

$$W_{esc} = (0.3\text{–}3) \times 10^{50} \text{ erg}$$

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

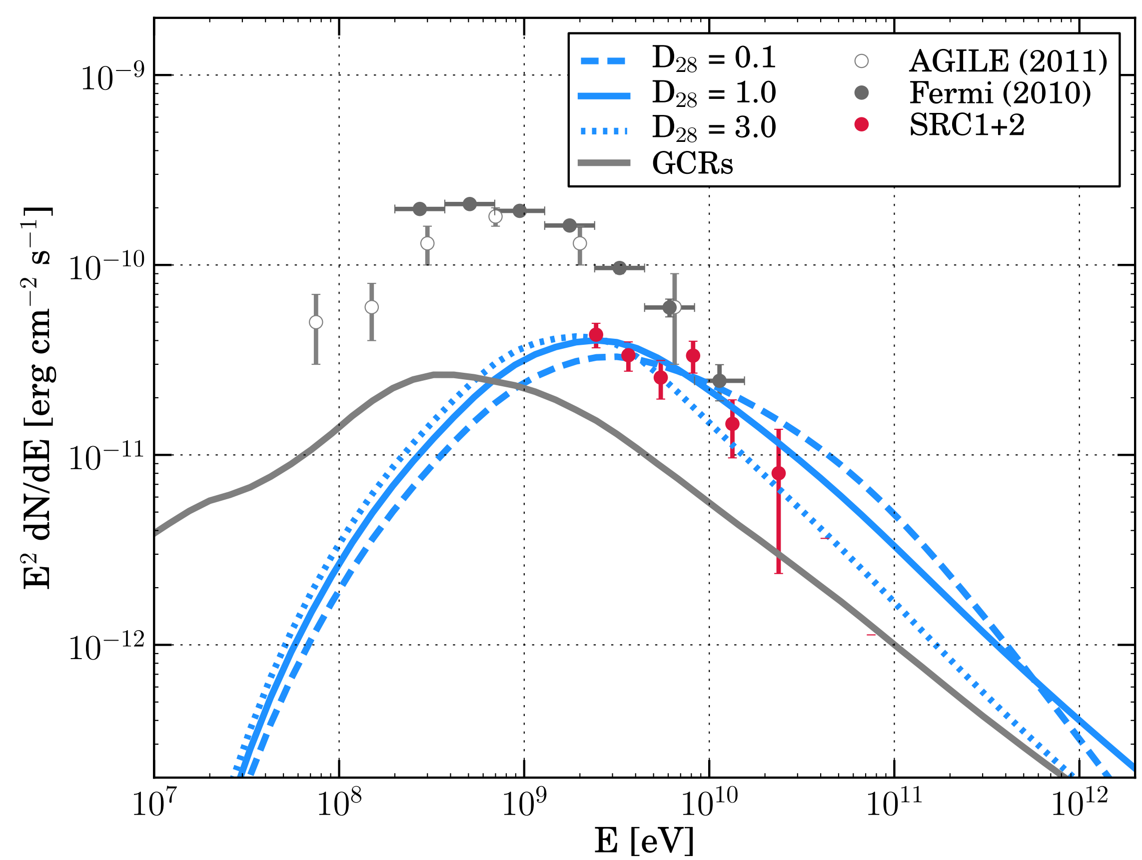
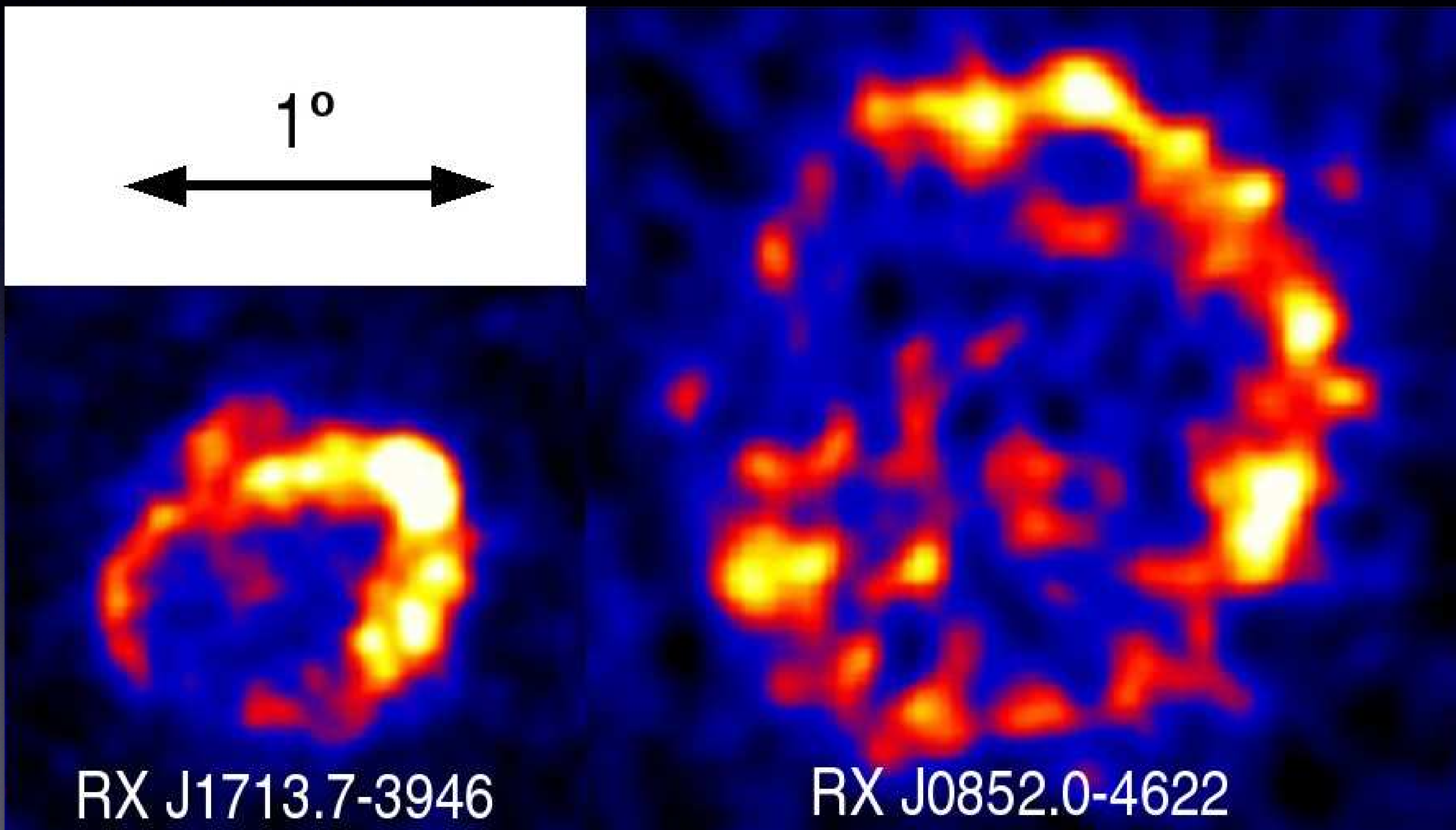


FIG. 4.— Modeling of the γ-ray emission from the molecular cloud complex that surrounds W44. Data points are from Fig. 2, but SRC-1 and SRC-2 are co-added. The SRC-1+2 spectrum (red points with statistical errors) is attributable to the π^0-decay γ-rays from the cloud complex illuminated by the CRs that have escaped from W44 (blue curves). Three cases of diffuse coefficient, $D_{28} = 0.1, 1, 3$, are shown. A gray curve indicates the γ-ray spectrum produced by the sea of GCRs in the same CR-illuminated clouds.

Uchiyama+ 2012

TeV-Bright SNRs

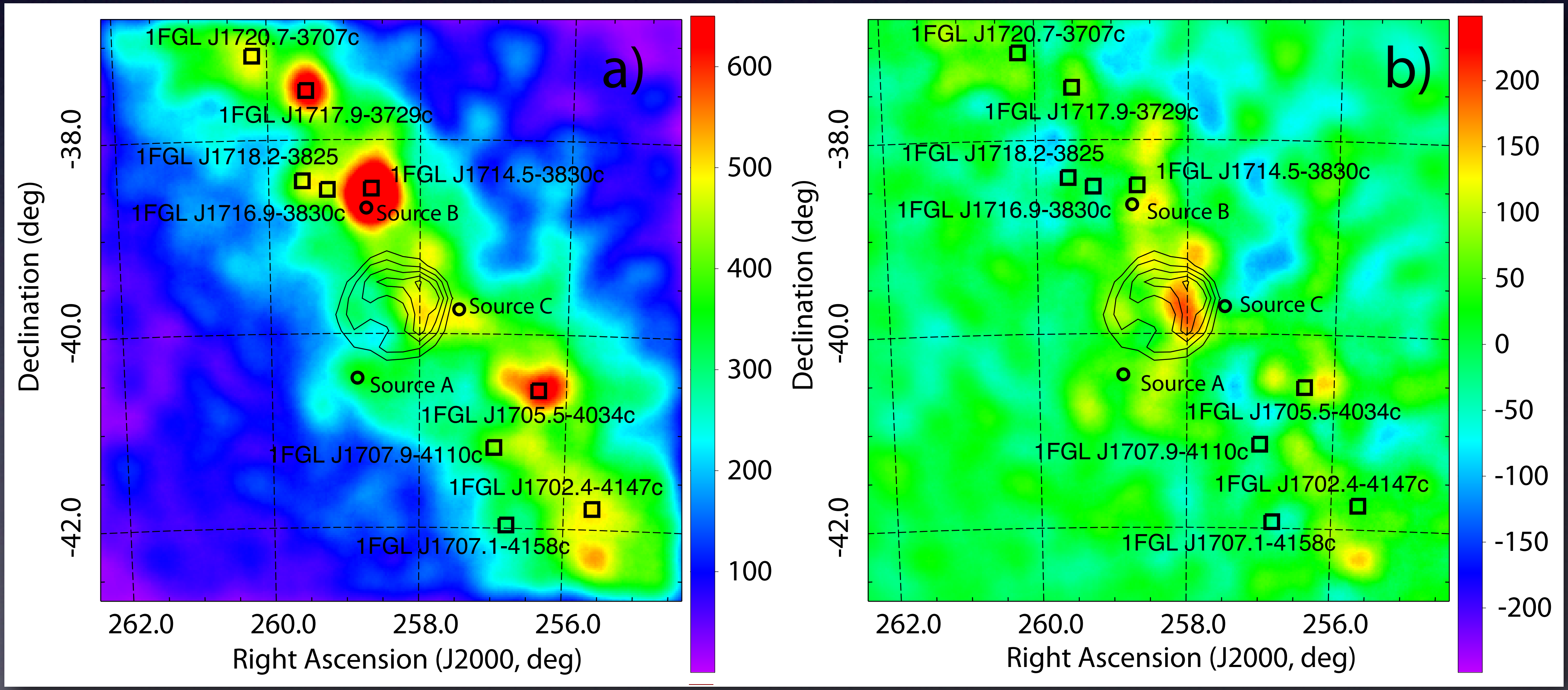
H.E.S.S. Images



RX J1713.7−3946

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)

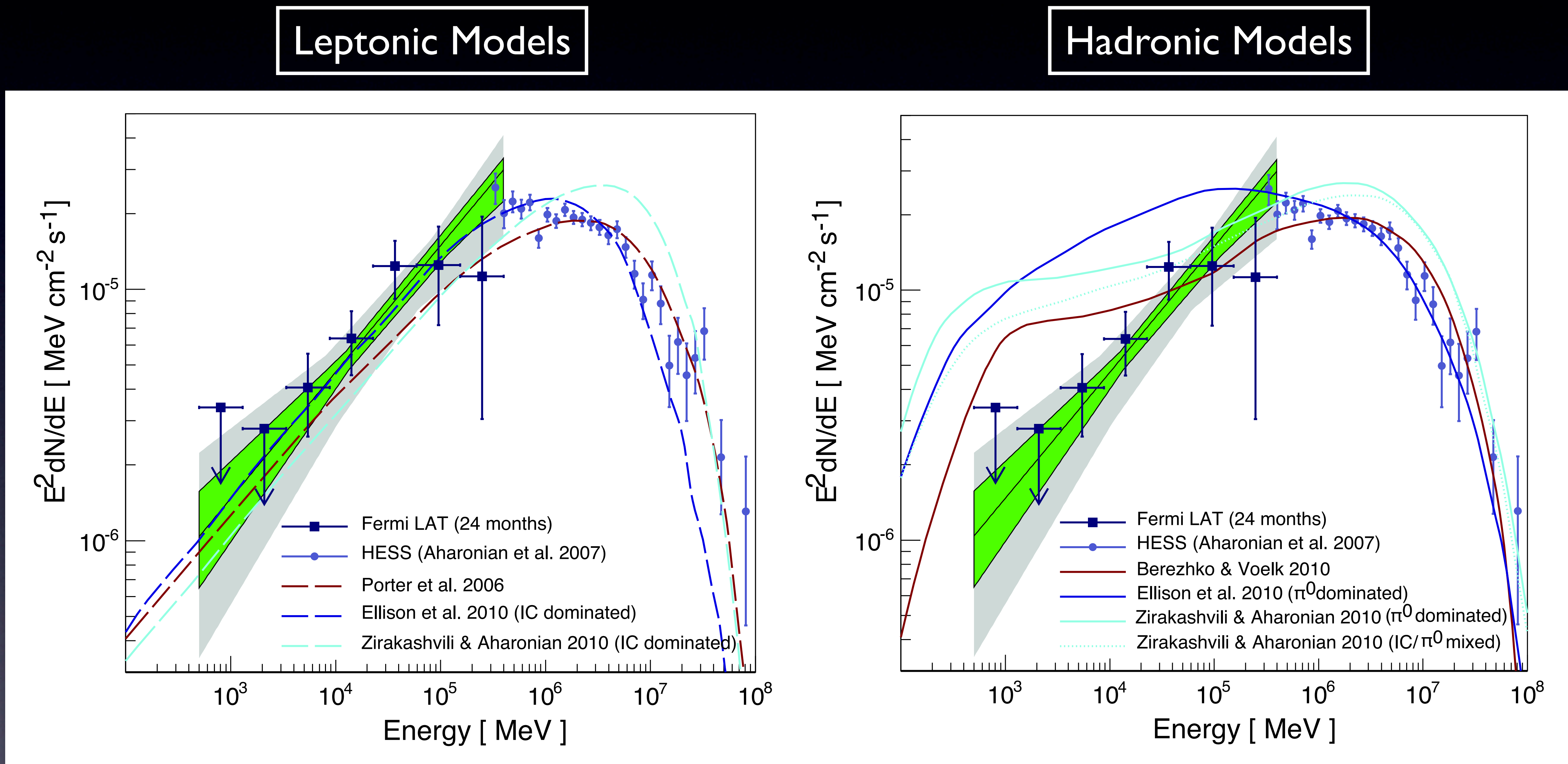


Before background subtraction

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

RX J1713.7−3946

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



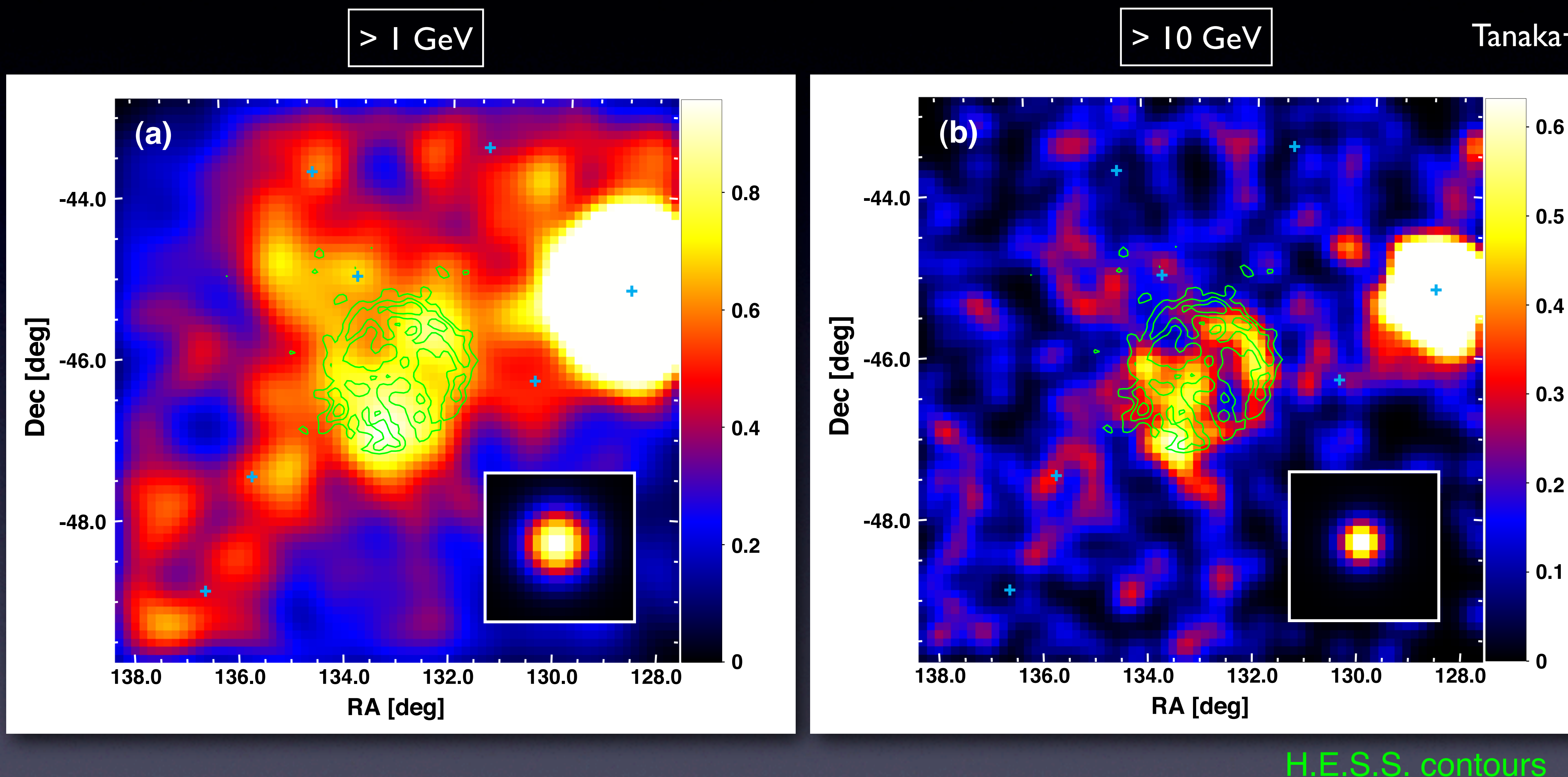
The Fermi LAT + H.E.S.S. spectrum can be fit well with leptonic models

How to reconcile with the large magnetic field?

If interpreted with hadronic models, extremely efficient particle acceleration is required to fit the data (proton index must be $s_p \sim 1.5$ to fit the Fermi LAT spectrum)

RX J0852.0−4622

Fermi LAT count maps



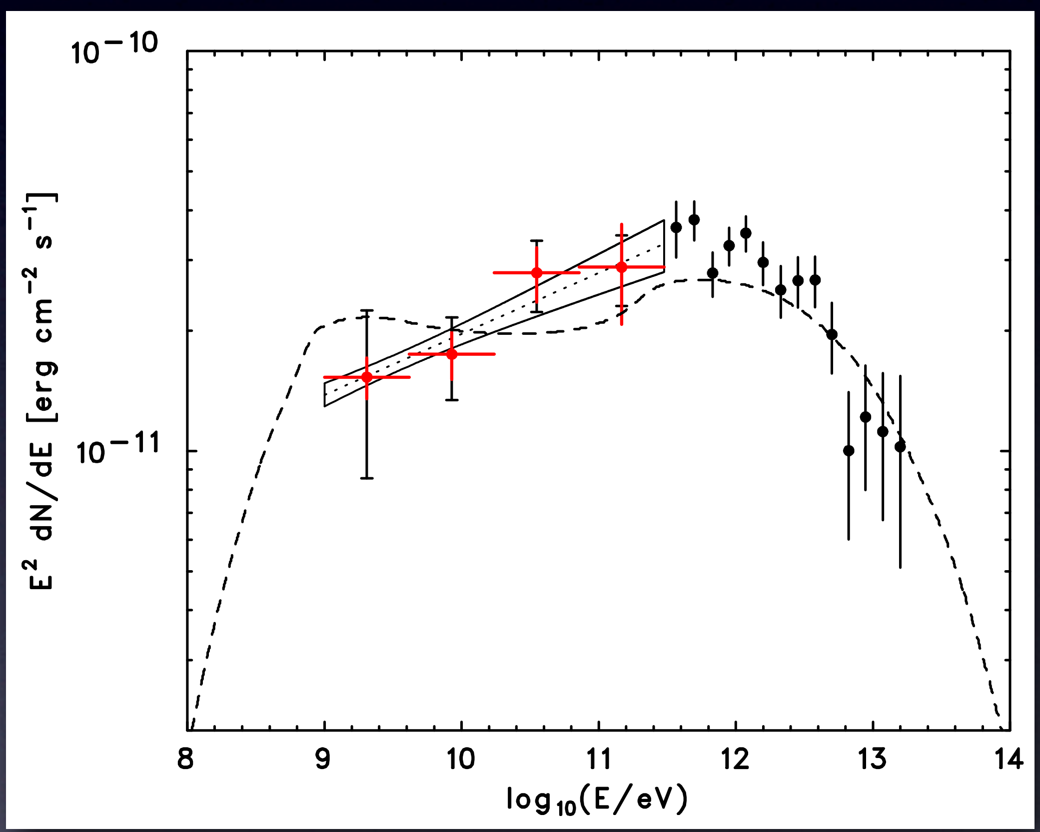
Spatially extended source at the location of the SNR RX J0852.0–4622

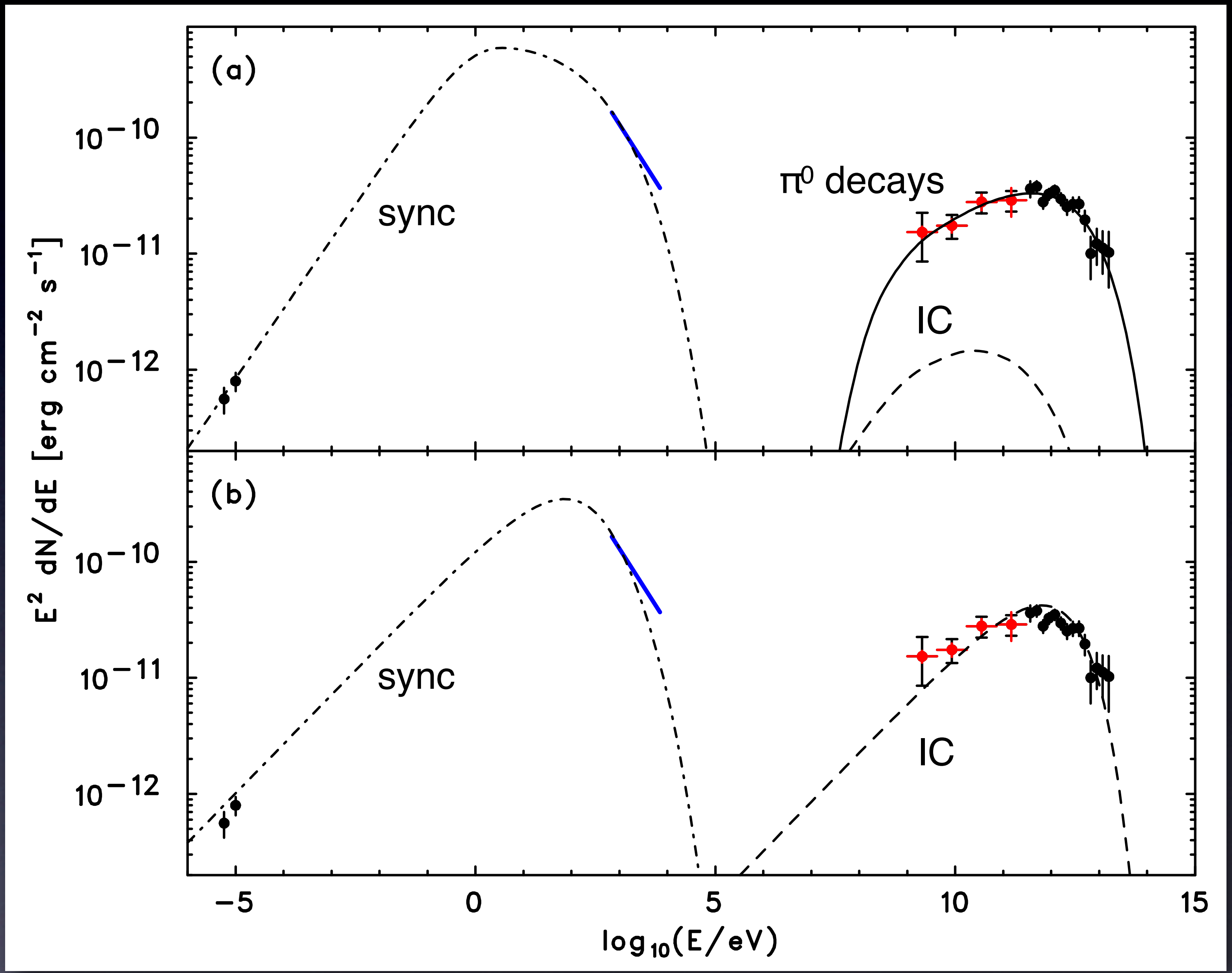
The emission clearly detected in the high energy region (Hereafter we show results with events > 5 GeV)

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 J0852.0−4622

Tanaka+ 2011





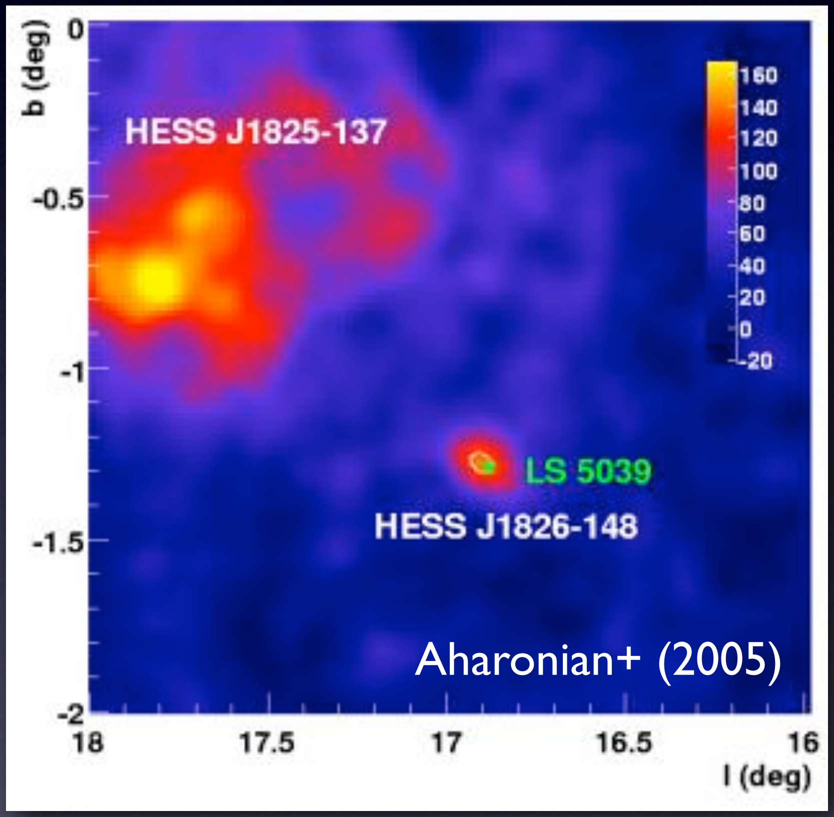
Power-law fit to the Fermi LAT spectrum yields Γ = 1.85 ± 0.05 (stat) ± 0.17 (sys)
The hadronic model requires a large amount of protons (5×10^{50} erg for n = 0.1 cm^{-3})
How to reconcile the weak magnetic field with X-ray filaments in the case of the leptonic model

ガンマ線連星

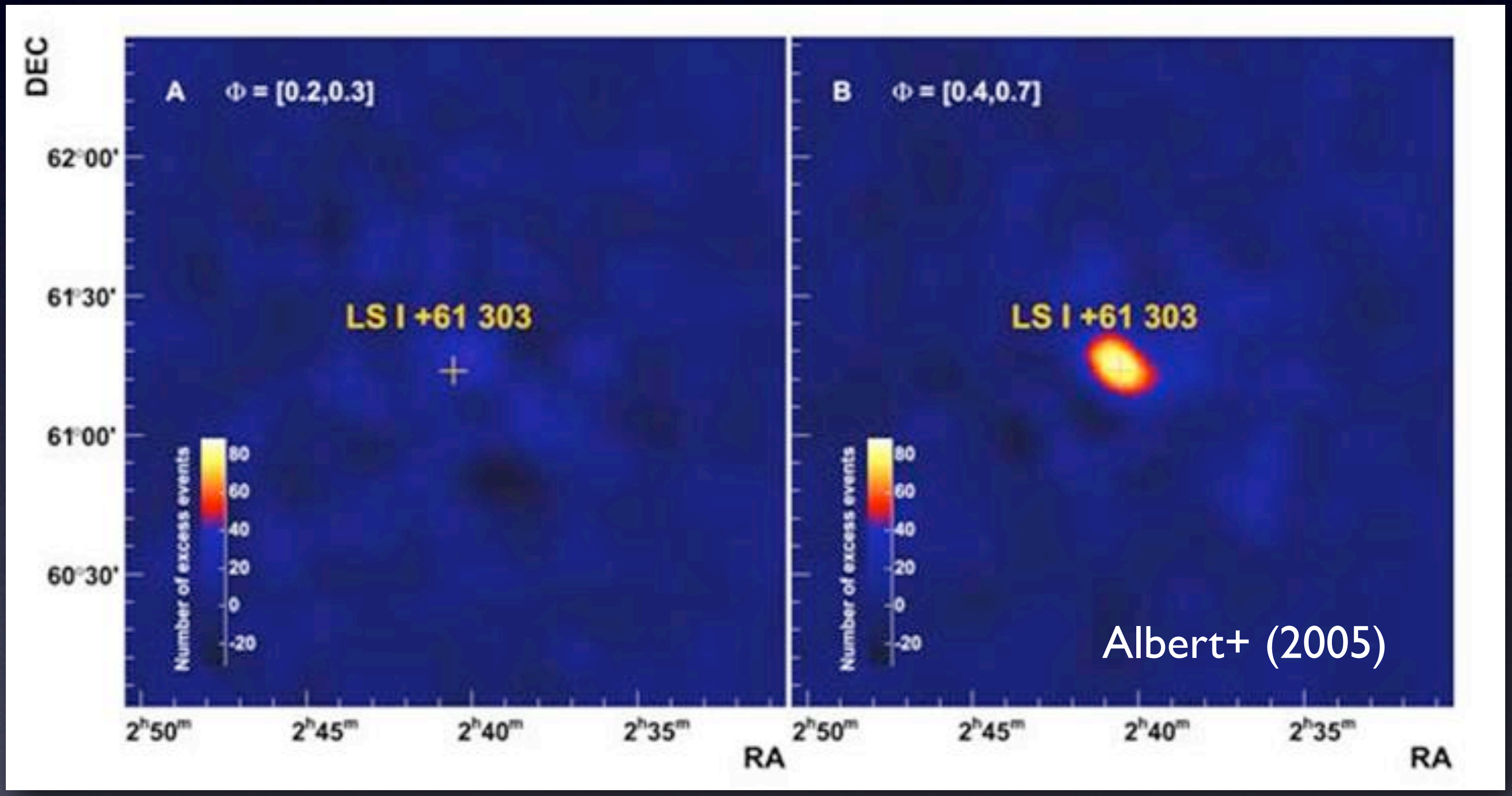
Gamma-ray Binaries

Gamma-ray emitting X-ray binaries
First discovered by air Cherenkov telescopes

LS 5039



LS I +61° 303

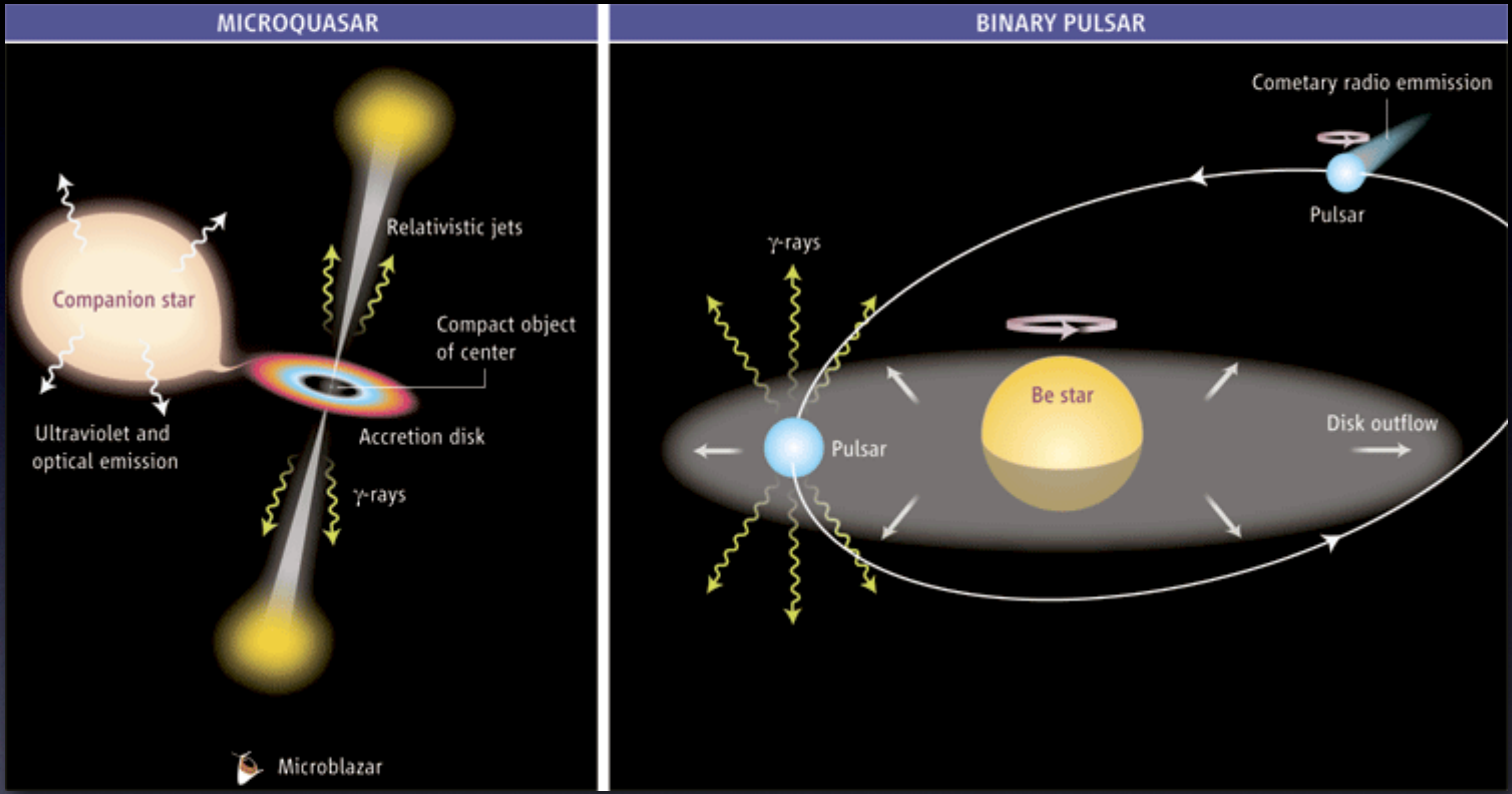


O star + ?
H.E.S.S. detected
Periodicity (3.9 days)

Be star + ?
MAGIC & VERITAS detected
Periodicity (26.5 days)

Possible Scenarios

Mirabel (2006)



Particles accelerated at a jet from the compact object

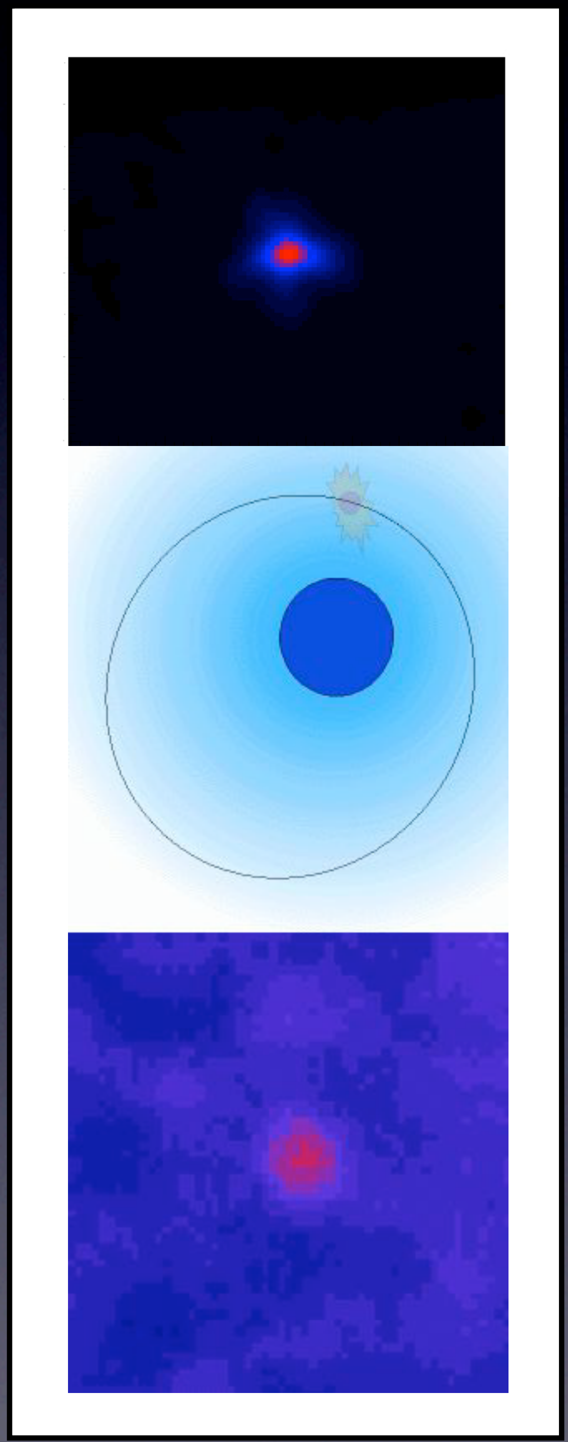
or

at a shock generated by interaction between stellar wind and pulsar wind

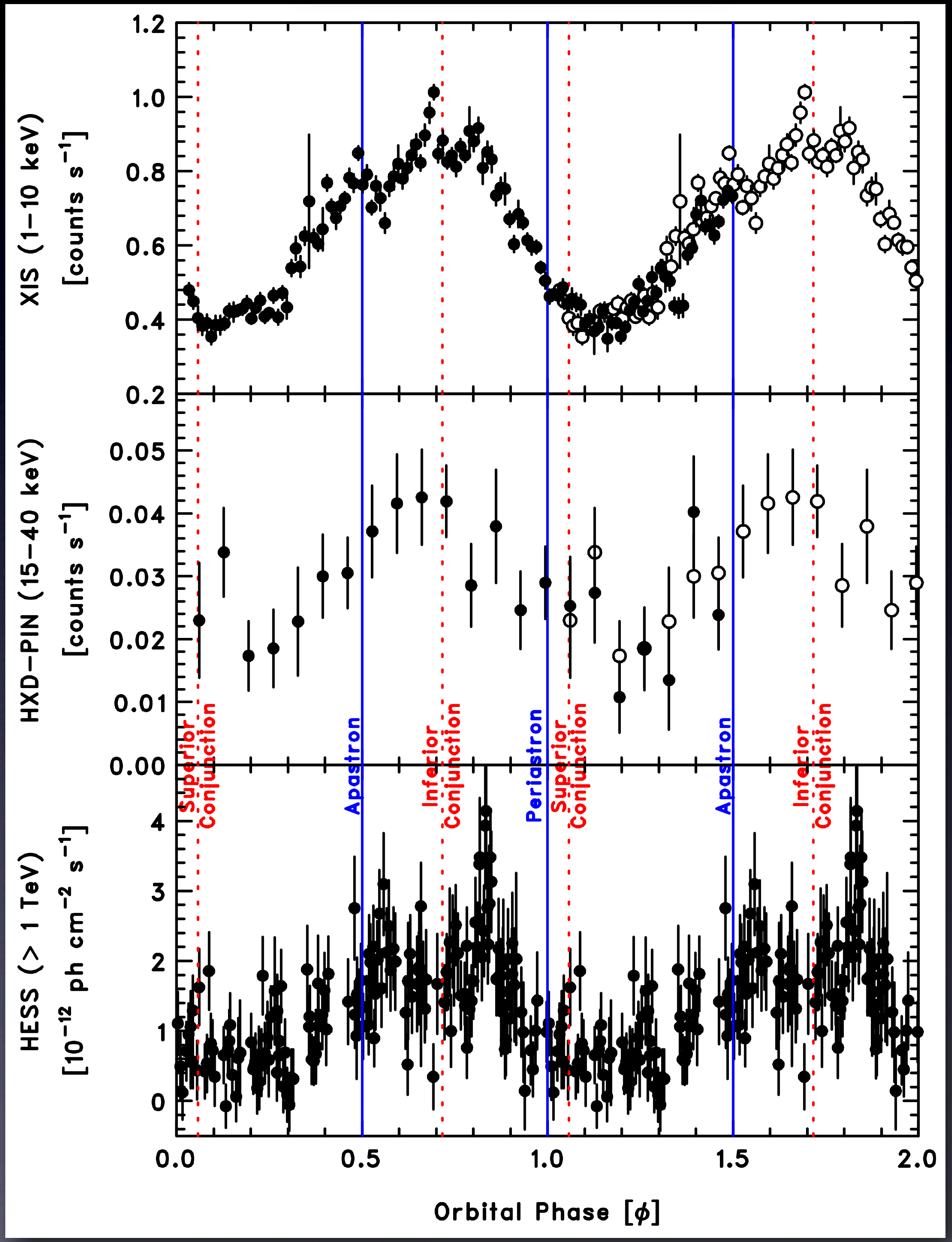
LS 5039 in X and TeV

Suzaku XIS
X-ray

HESS
TeV Gamma

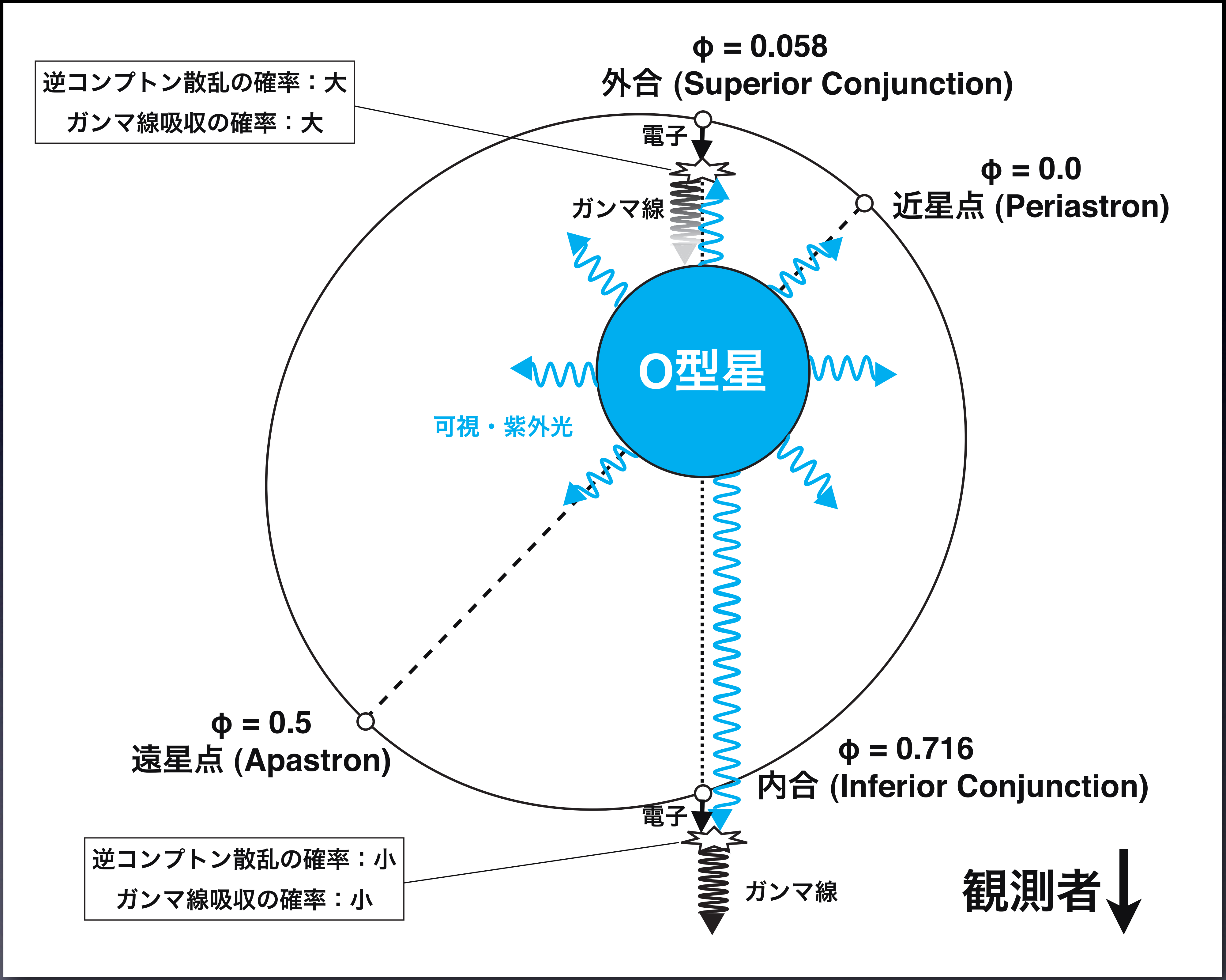


Folded Lightcurves



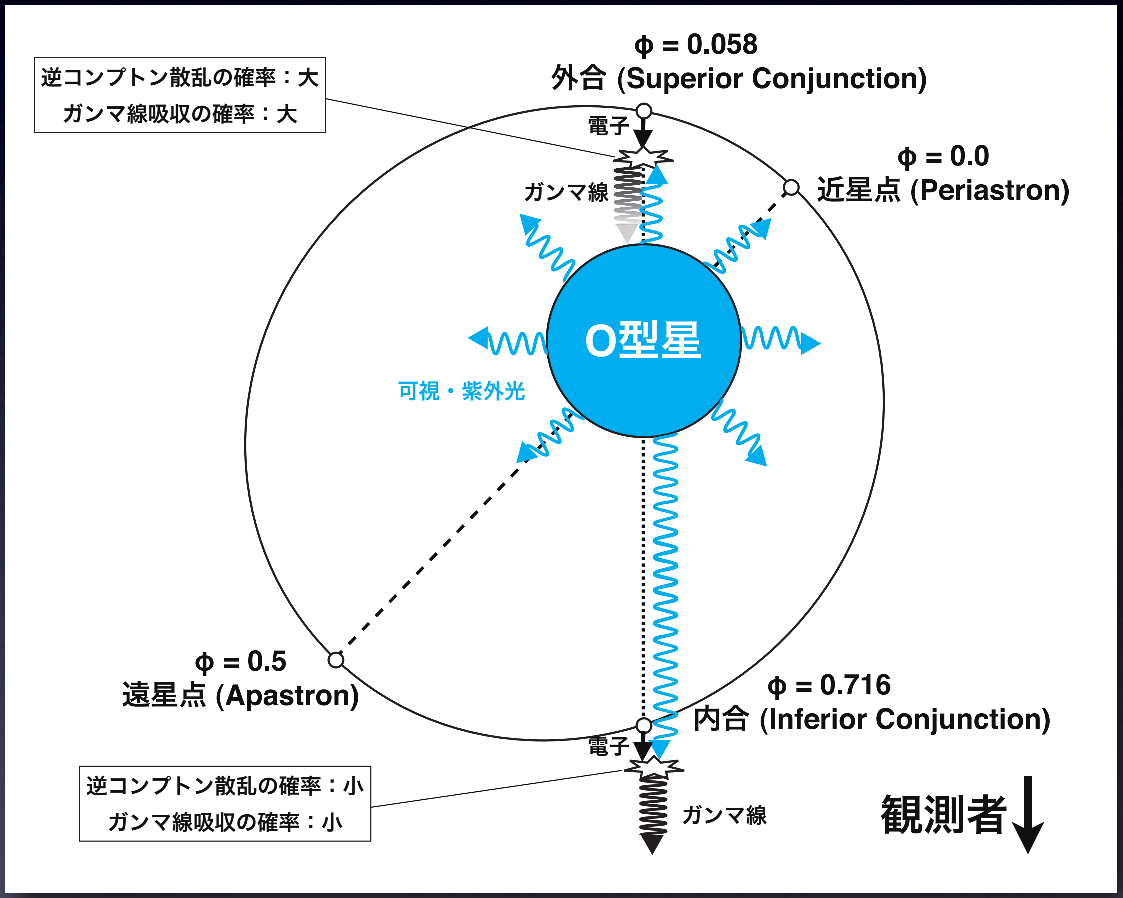
Aharonian+ 2006, Takahashi+ 2007

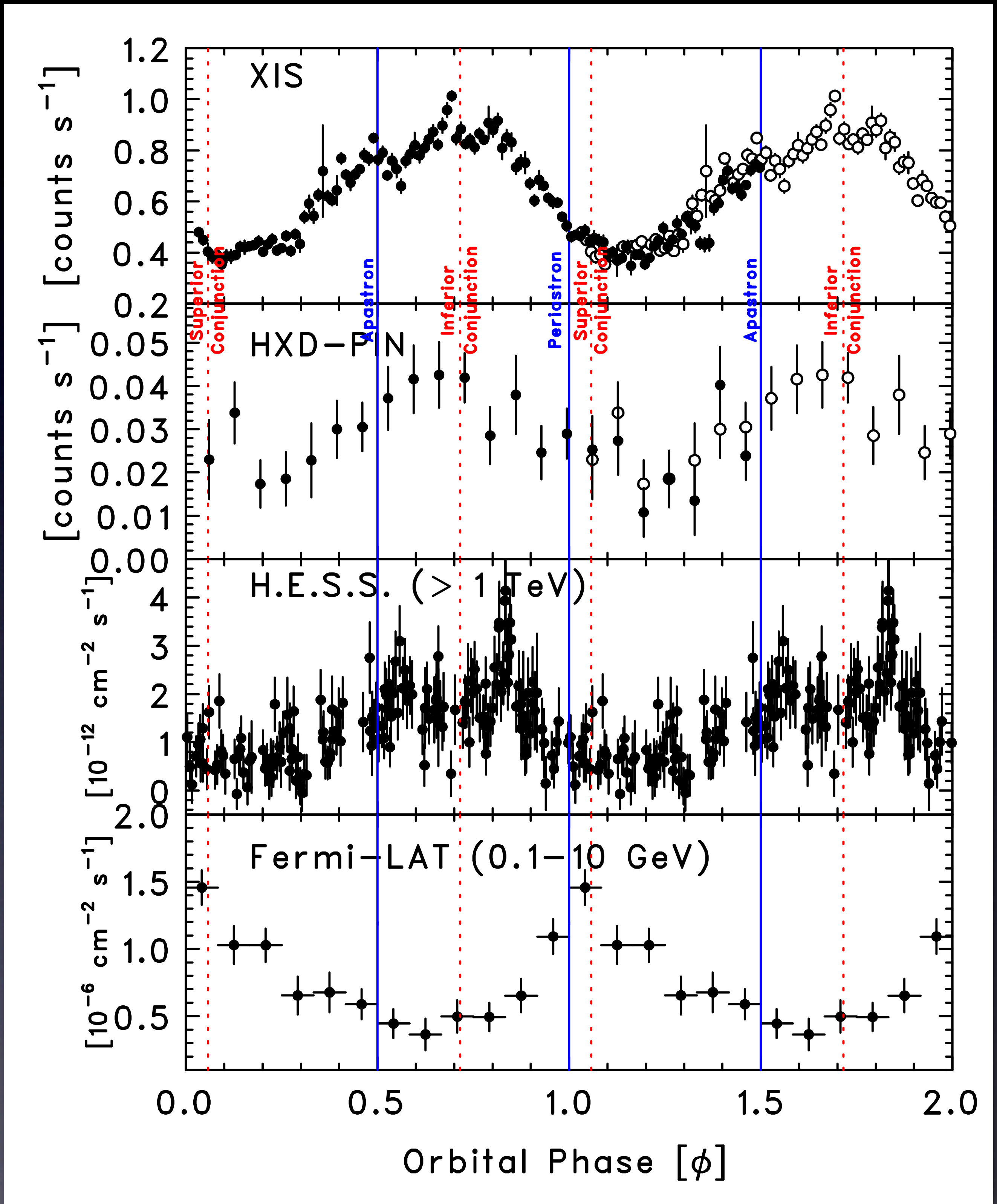
Geometry of LS 5039



田中 他　天文月報より

LS 5039 by Fermi LAT

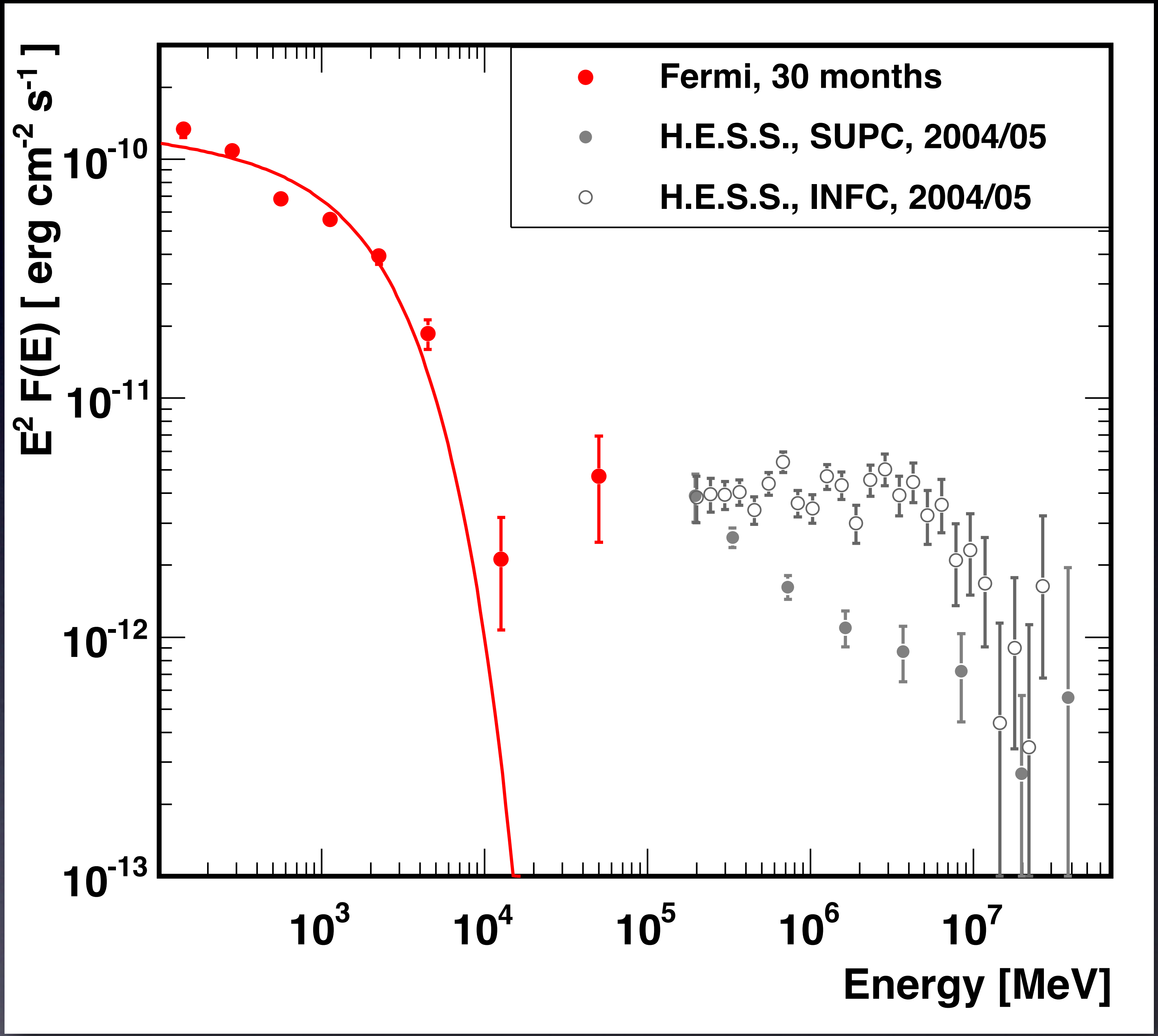




Anti-correlation between GeV and TeV flux as predicted Abdo+ (2007)

LS 5039 Gamma-ray Spectrum

Hadasch+ (2012)



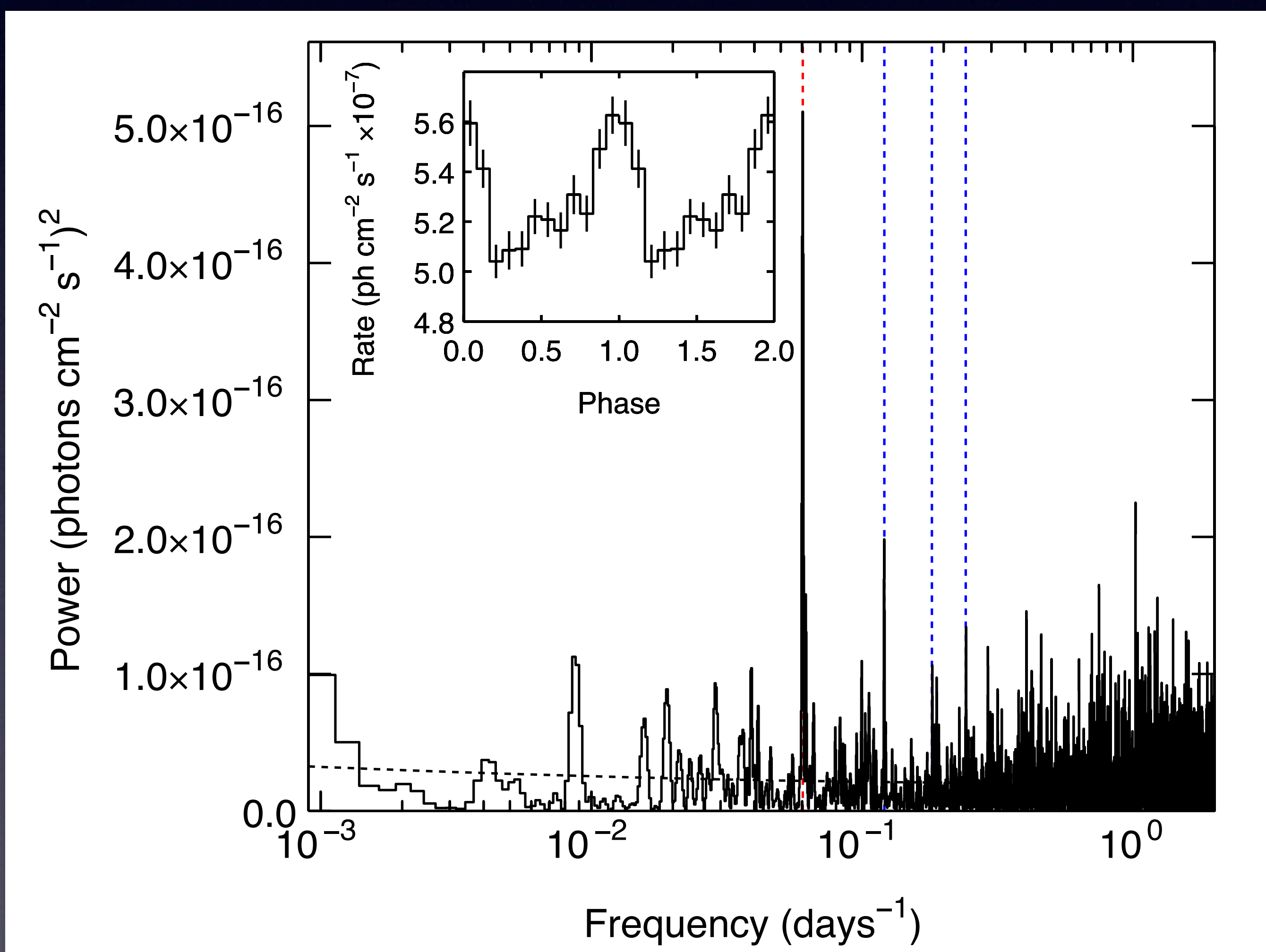
Cutoff energy of 2.2 GeV is too low compared to that expected from γγ absorption (> 30 GeV)

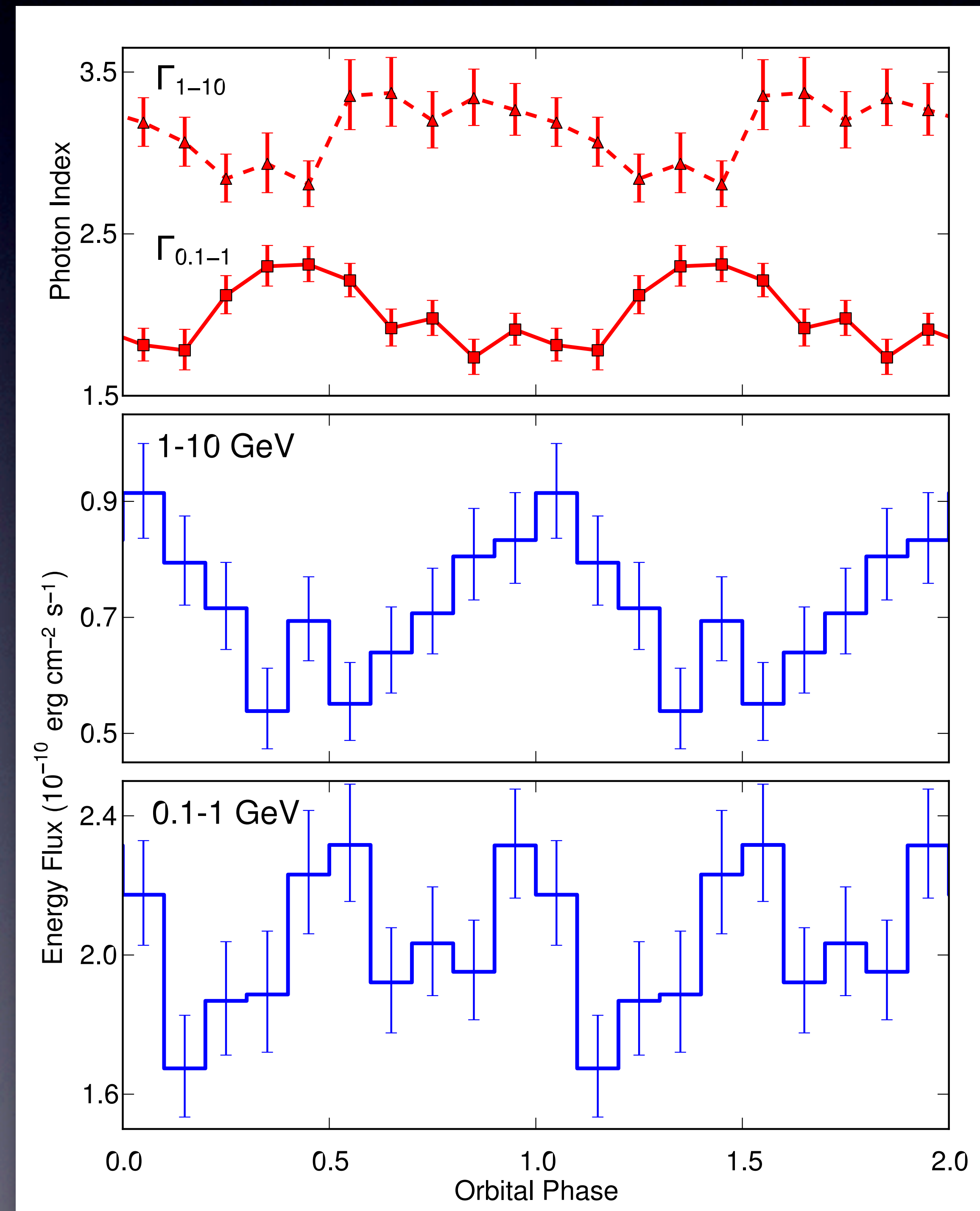
1FGL J1018.6−5856

Periodic source (P = 16.6 days) found in 1FGL catalog

Follow-up observations confirmed this source is a X-ray binary

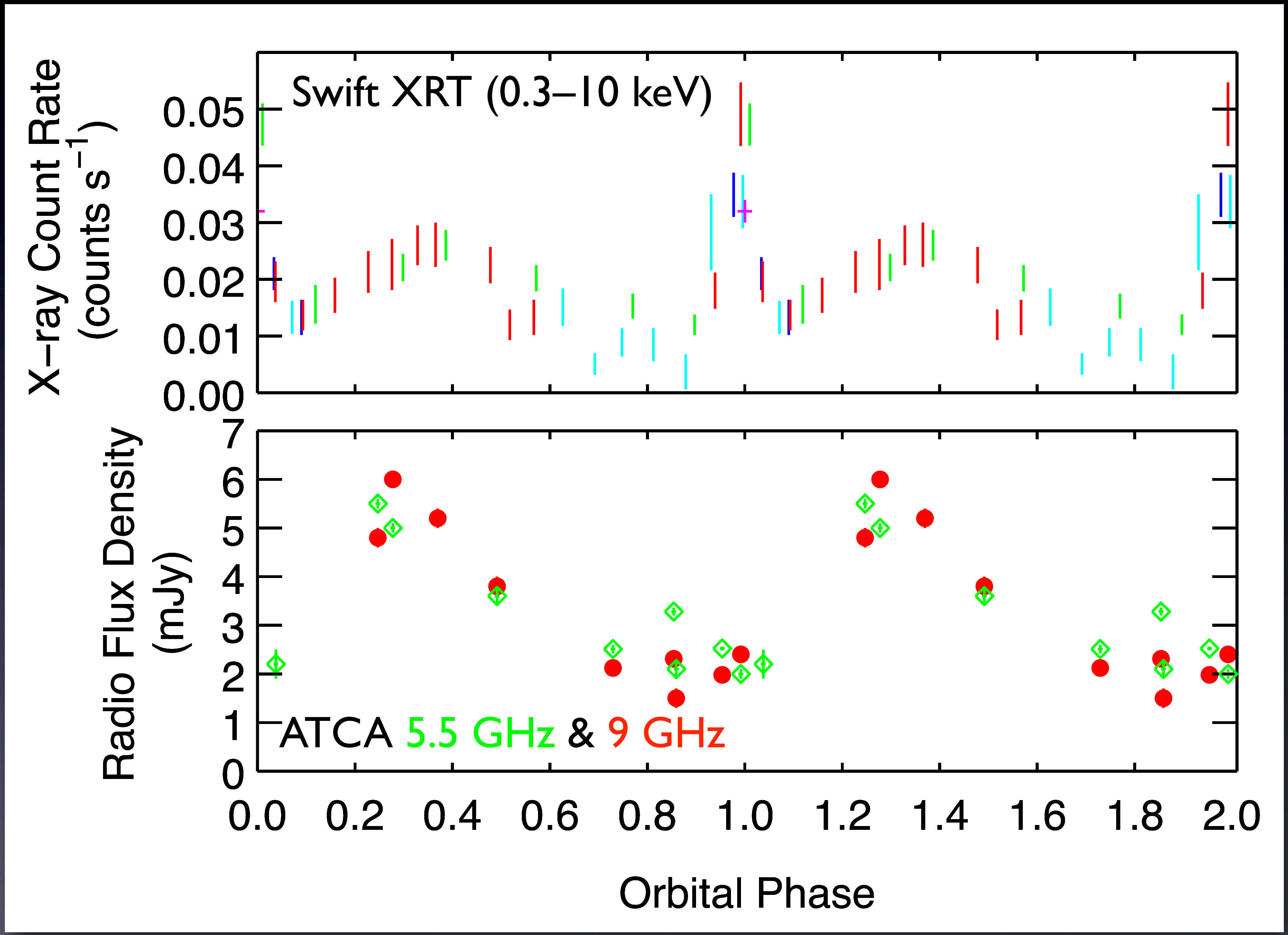
Ackermann+ (2012)





1FGL J1018.6−5856

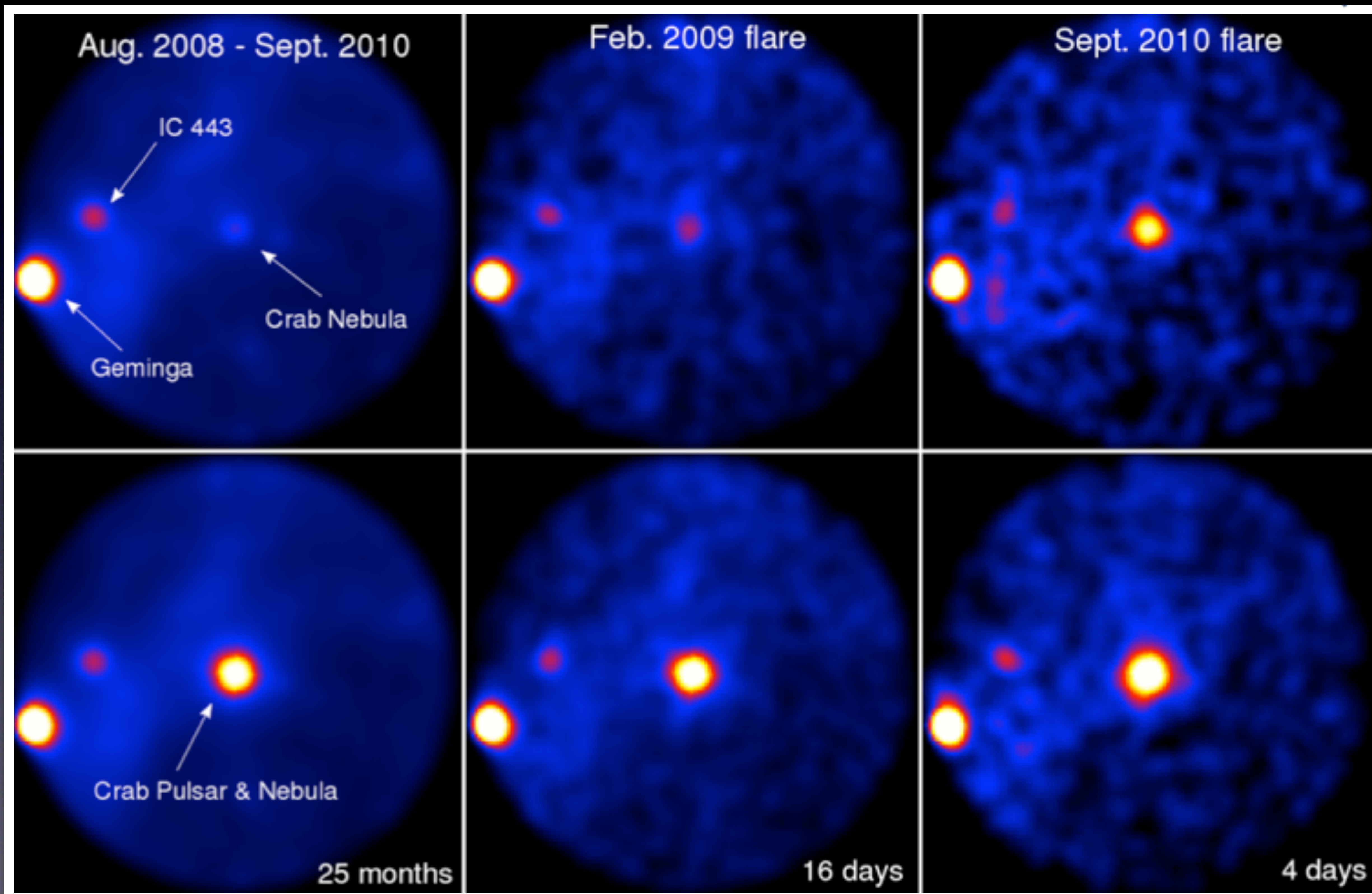
X-ray & Radio Lightcurve



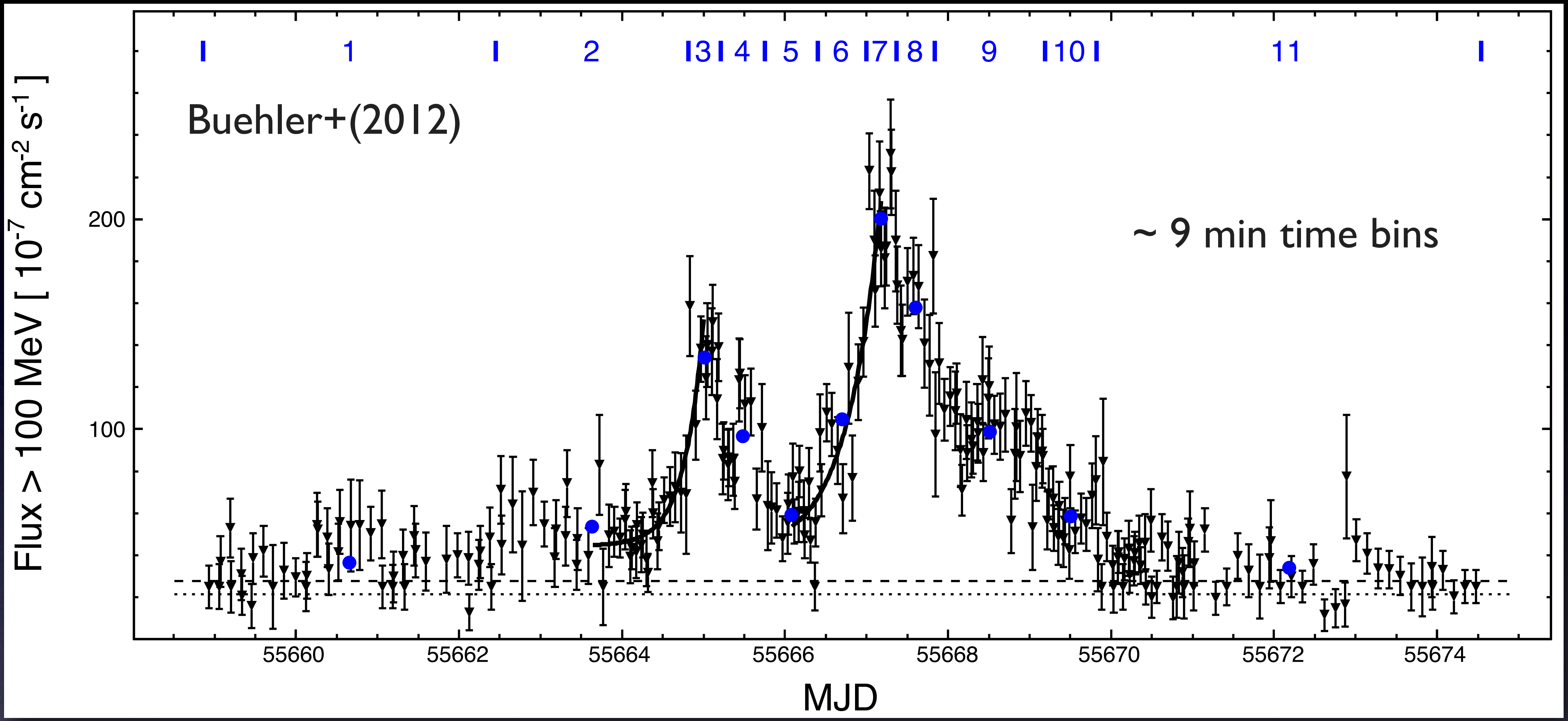
Suzaku observation during last summer (PI: Tanaka)

かに星雲からの
ガンマ線フレア

Fermi LAT Images

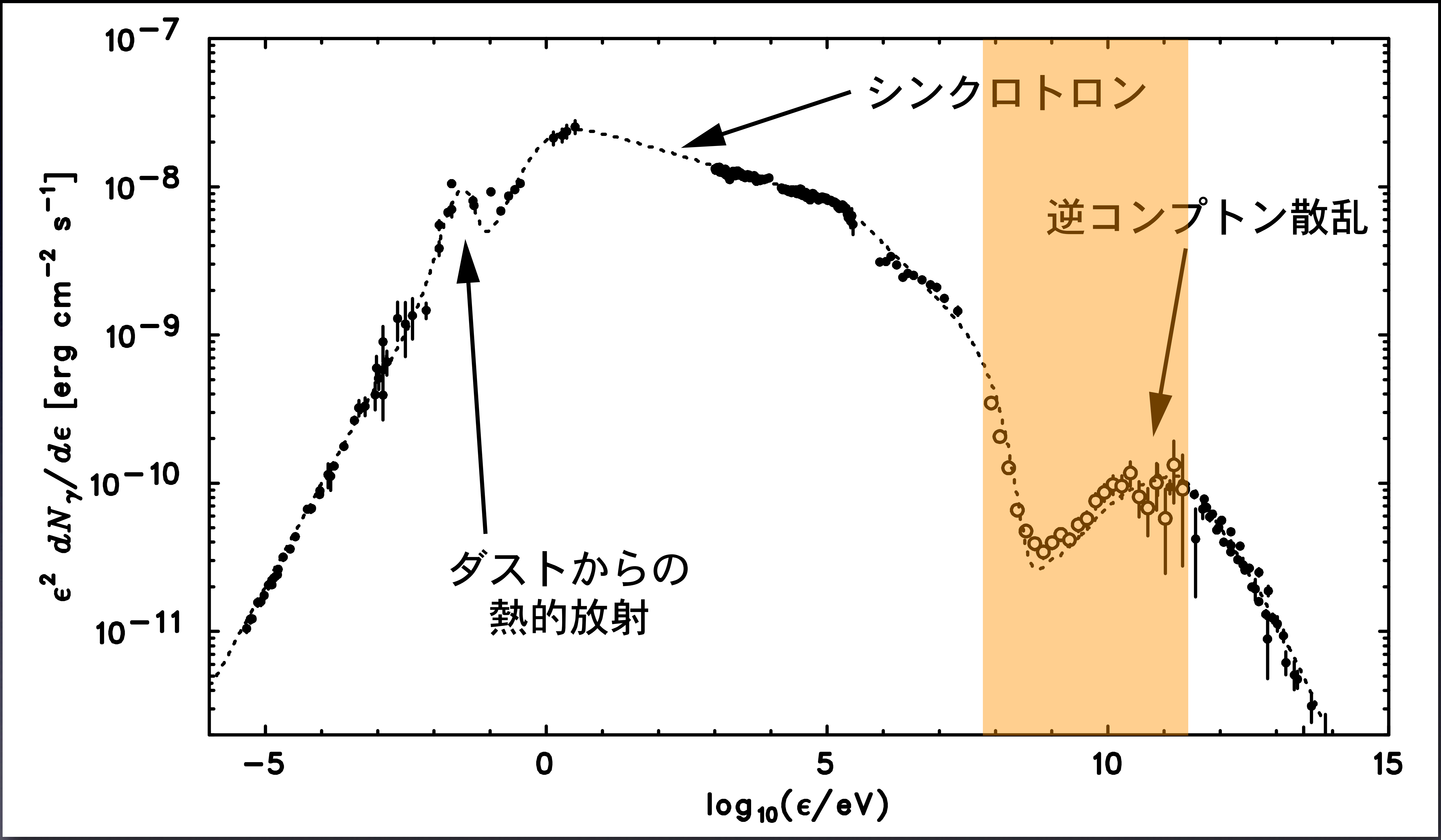


The April 2011 Flare



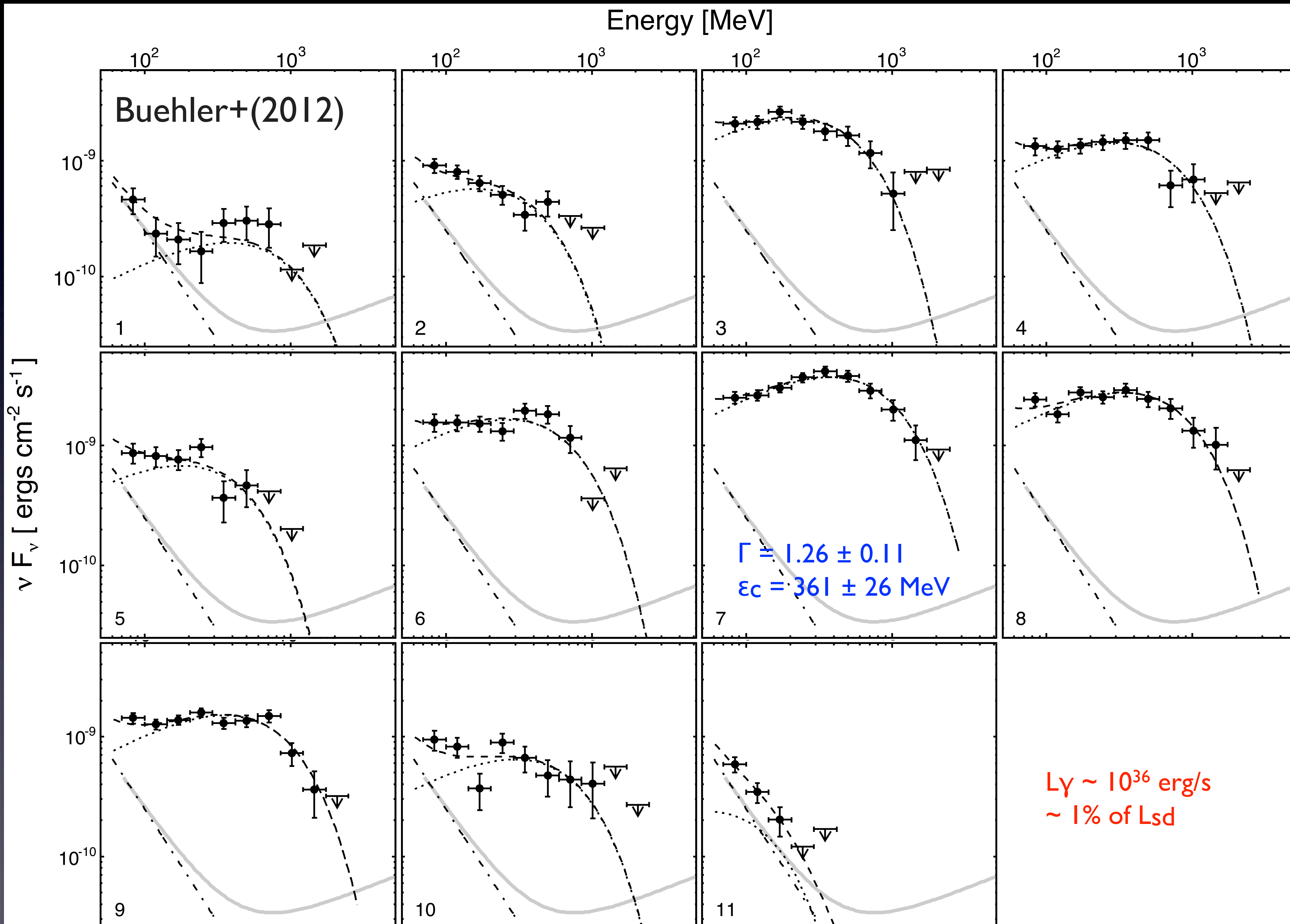
- Synchrotron nebula brightened by a factor of ~30
- Flux doubling time : 4–8 hours
- No change in pulsar flux and phase

Crab SED



シンクロトロン
逆コンプトン散乱
ダストからの
熱的放射
$\epsilon^2 \, dN_\gamma/d\epsilon$ [erg cm^{-2} s^{-1}]
$\log_{10}(\epsilon/\mathrm{eV})$
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
−5
0
5
10
15

Spectral Evolution



Why Puzzling?

✚ Compactness

Doubling time t ~ 4-8 hours ➜ Emission region < ct ~ 3×10^{-4} pc (Inner ring ~ 0.1 pc)

Large luminosity (~ 1% of spindown power) from a compact region

✚ Spectrum

$\Gamma = 1.26 \pm 0.11$: Flare energy is carried by the highest energy electrons $\varepsilon_c = 361 \pm 26$ MeV: Appears to violate the radiation reaction limit

synchrotron cooling time = gyroradius/c

➜ Cutoff of synchrotron spectrum must be:

$\varepsilon_c < (9/4\alpha_F)\, m_e c^2 = 160$ MeV

Summary

- Fermi LAT は順調に全天観測を進めている
- いくつかの超新星残骸のスペクトルは中性パイ粒子の崩壊でうまく説明できる
- 今後の低エネルギー帯域のデータ解析に期待
- TeV ガンマ線源の連星系の他、新たなガンマ線連星からも GeV ガンマ線を検出
- かに星雲からフレアを観測
- このフレアは既存の理論では説明が困難