Unveiling
Origin of Galactic Cosmic Rays

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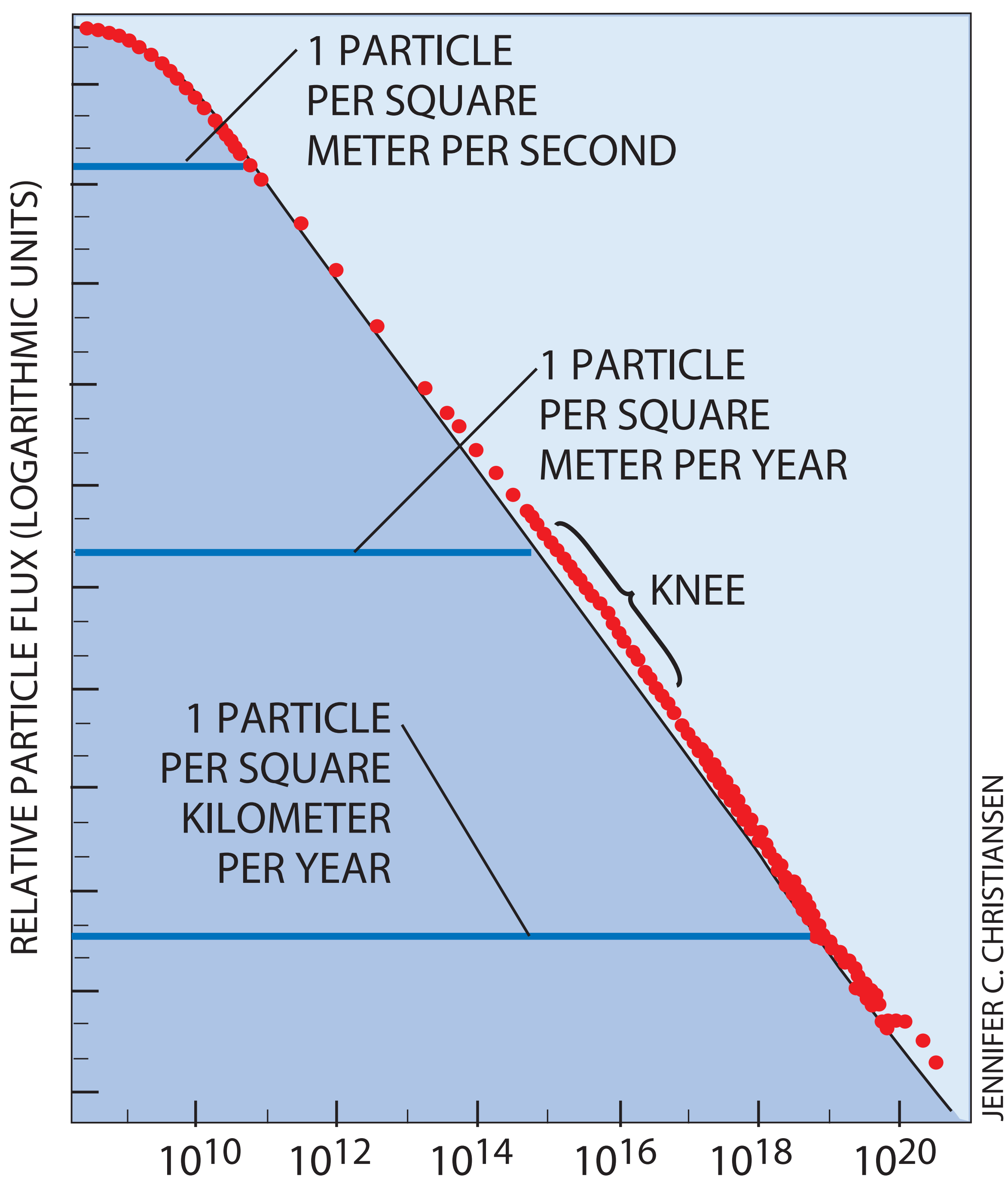
天文・天体物理若手 夏の学校
蔵王

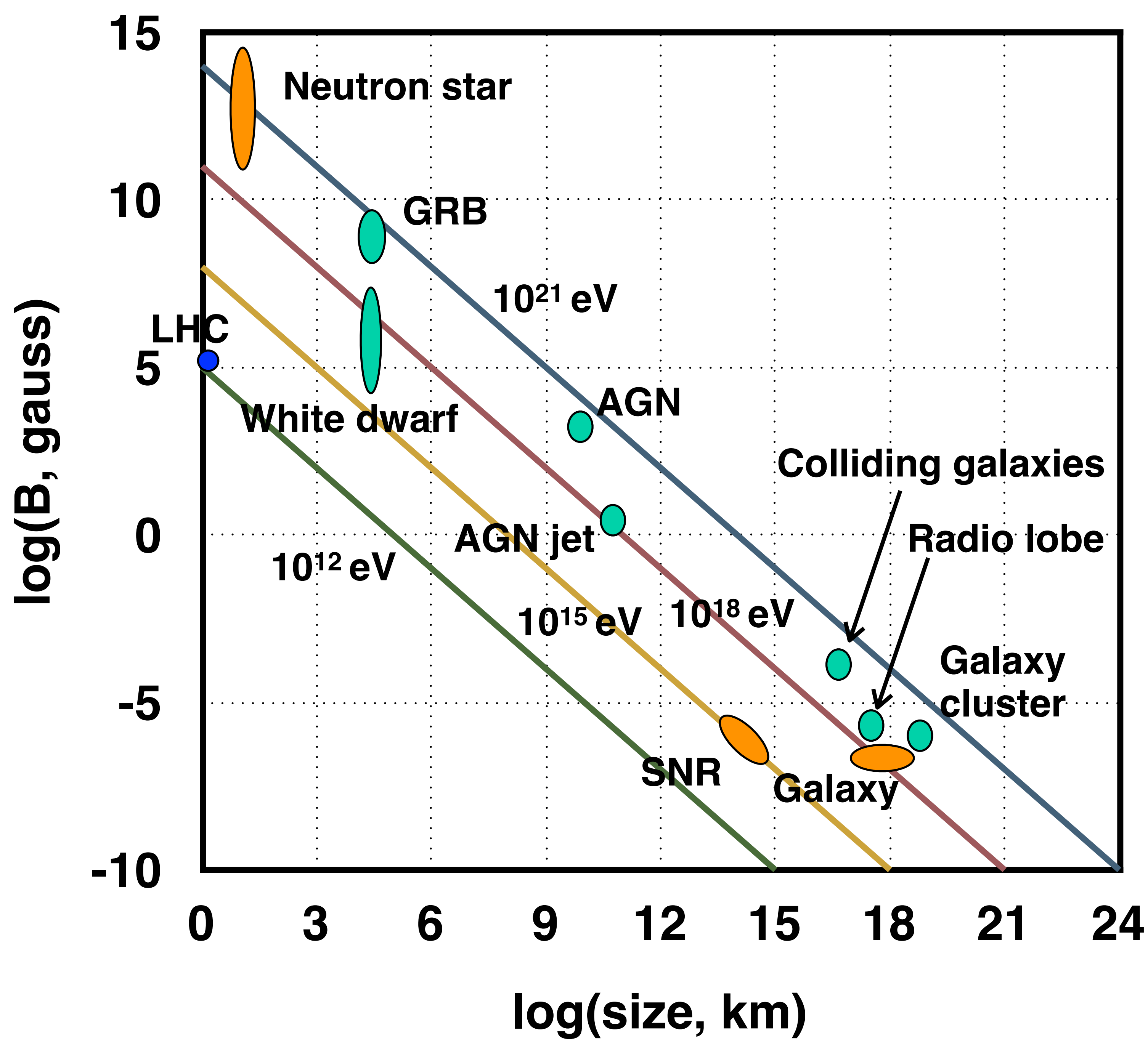
Outline

- Introduction
- Gamma-ray emissions from cosmic rays
- Cosmic gamma-ray experiments
  - Fermi Gamma-Ray Space Telescope
  - Imaging atmospheric Cherenkov telescopes
- Search for origin of cosmic rays
  - Galactic supernova remnants
- Future prospects

Cosmic Particle Accelerators

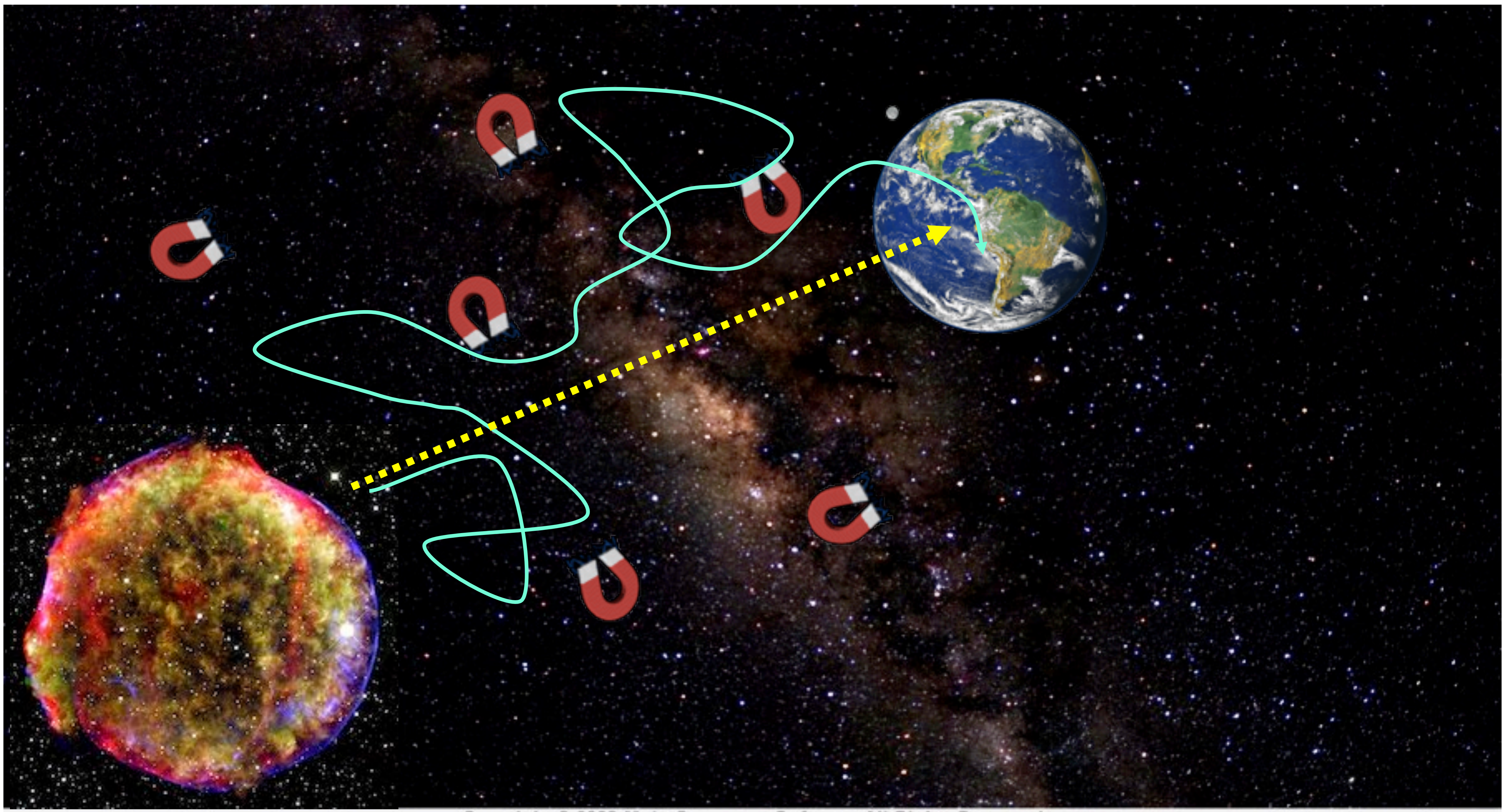
- Origin of cosmic ray is one of the biggest mysteries of astrophysics





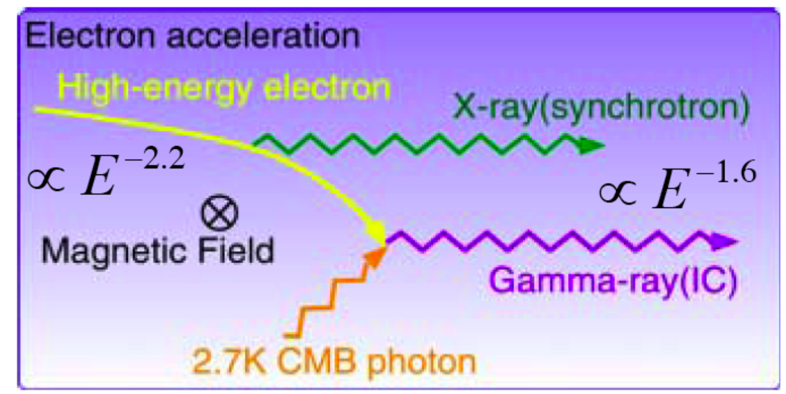
Deflection of Cosmic Rays

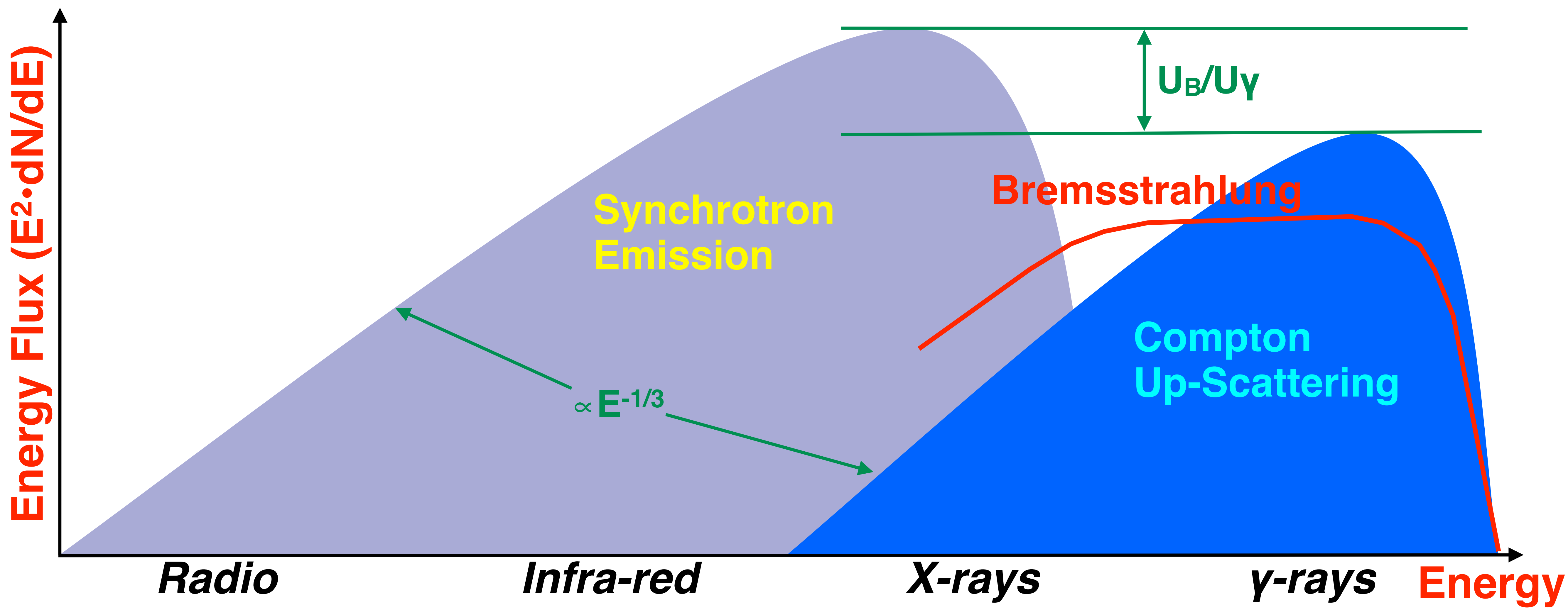
- Cosmic rays (charged particles) are deflected by (turbulent) Galactic magnetic field
- Neutral particles (Photons and neutrinos) come straight to us



Gamma-ray Emission from Electrons

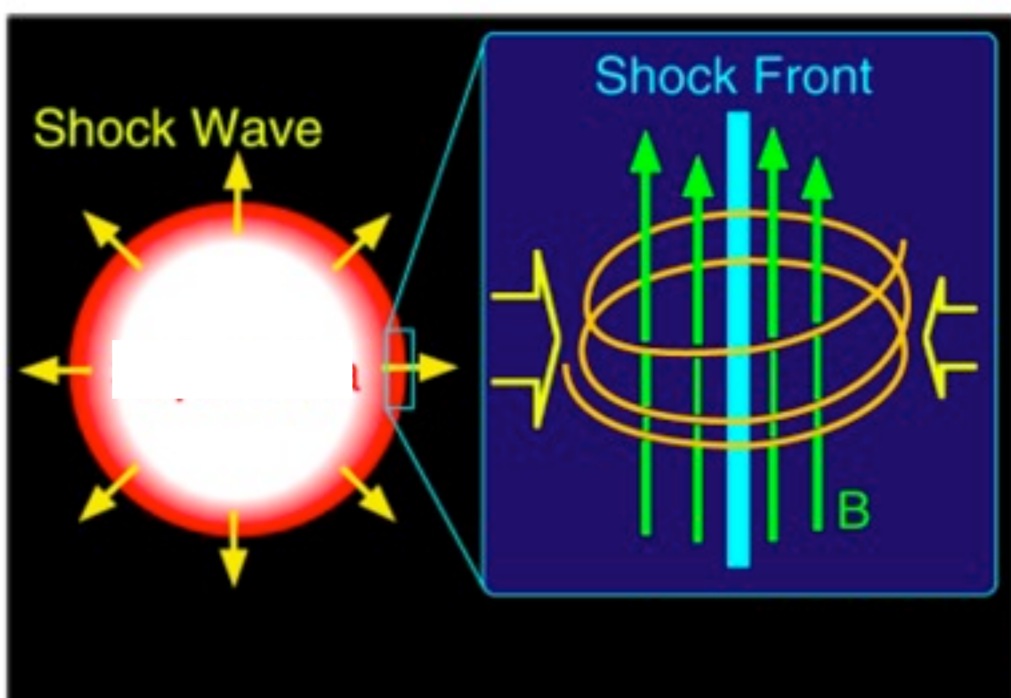
- Synchrotron radiation
- Compton up-scattering
  - CMB (Cosmic Microwave BG)
  - Synchrotron light
  - Interstellar light
- Bremsstrahlung

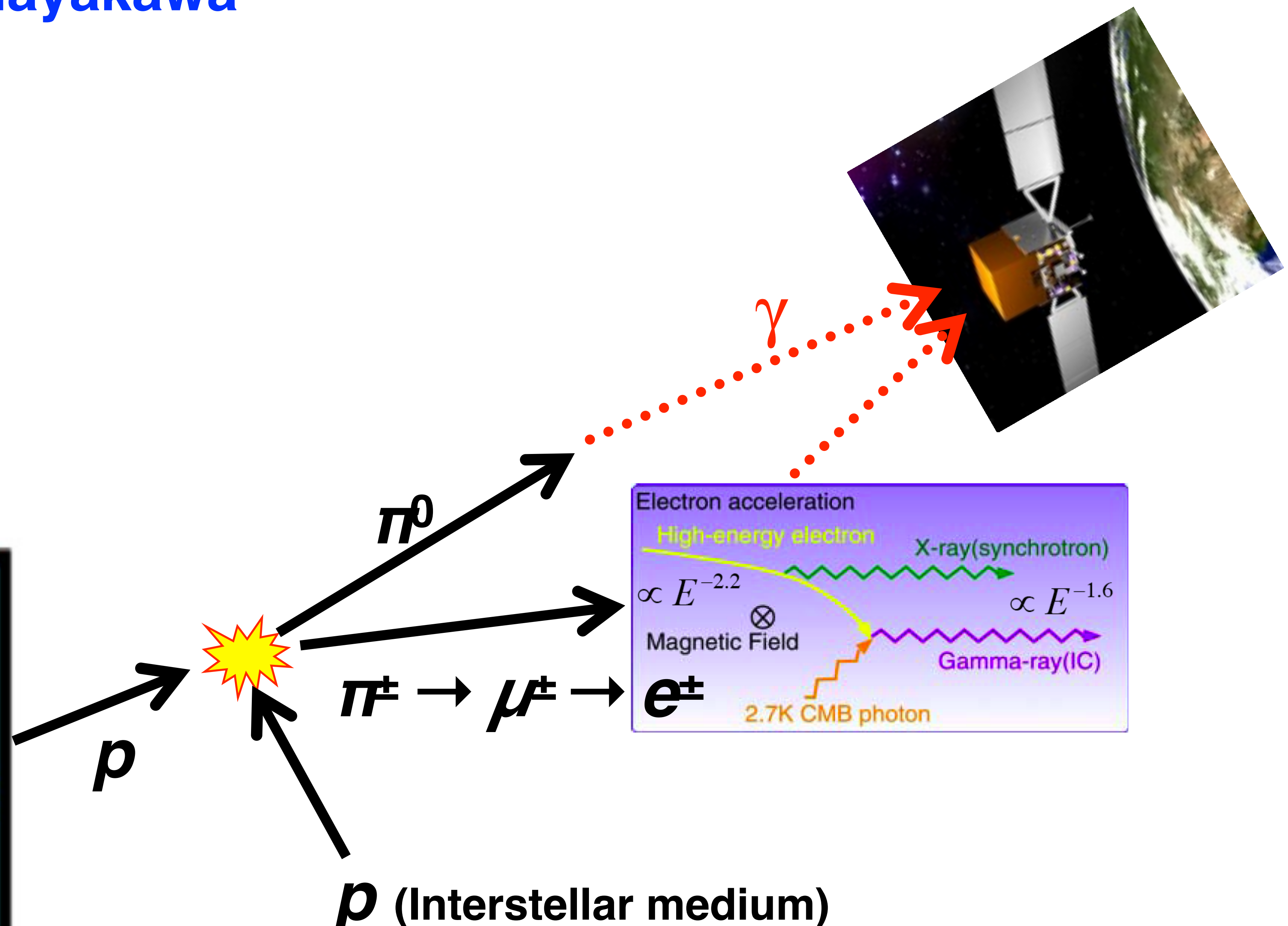




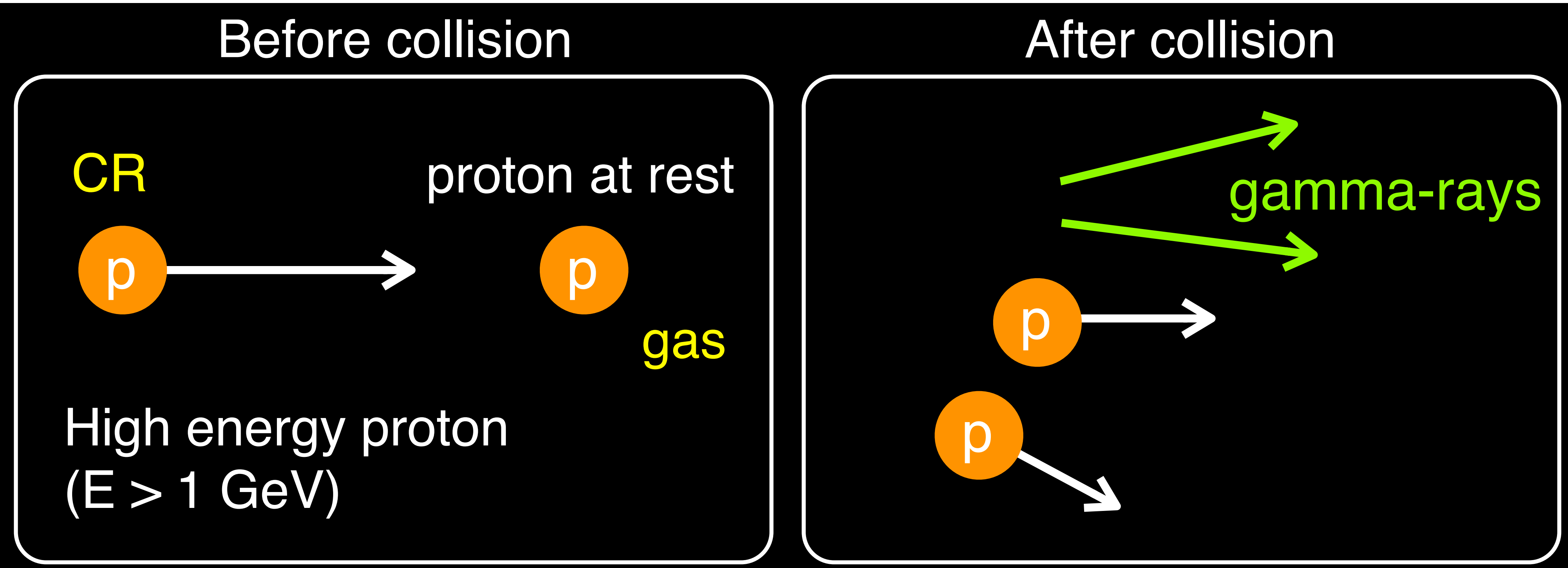
Gamma-ray Emission from Protons

- Nuclear interactions with interstellar medium
  - First suggested by S. Hayakawa





Gamma rays from π^0 decays



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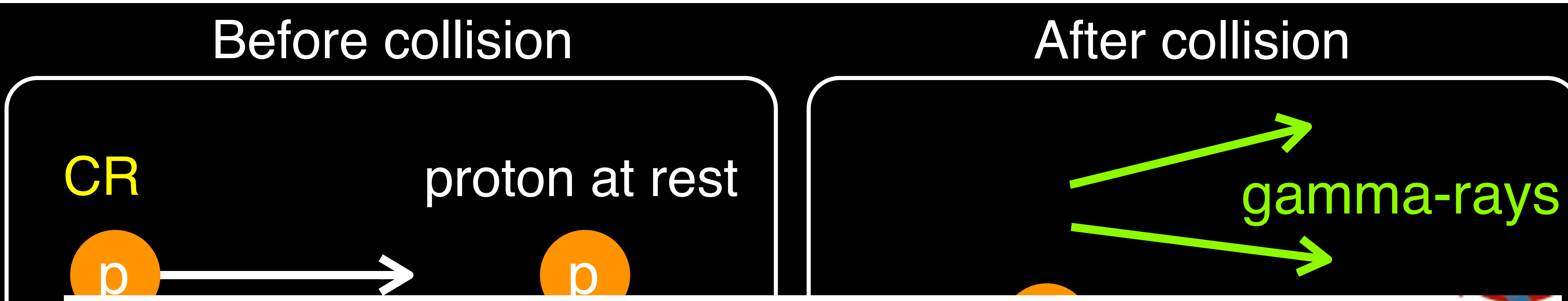
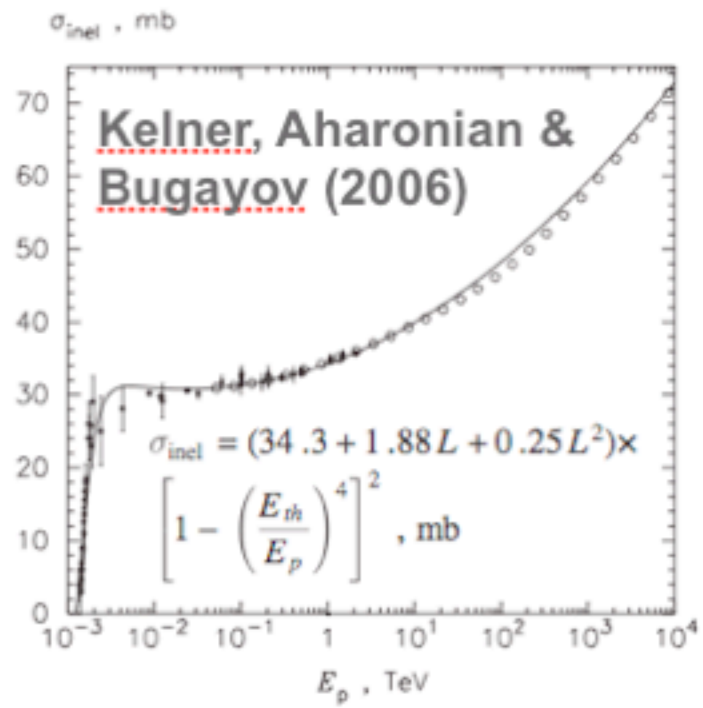


$p + p \rightarrow \pi^0 + X$

$\sigma \sim$ const
($\lesssim$ a factor 2 over 5 decades)



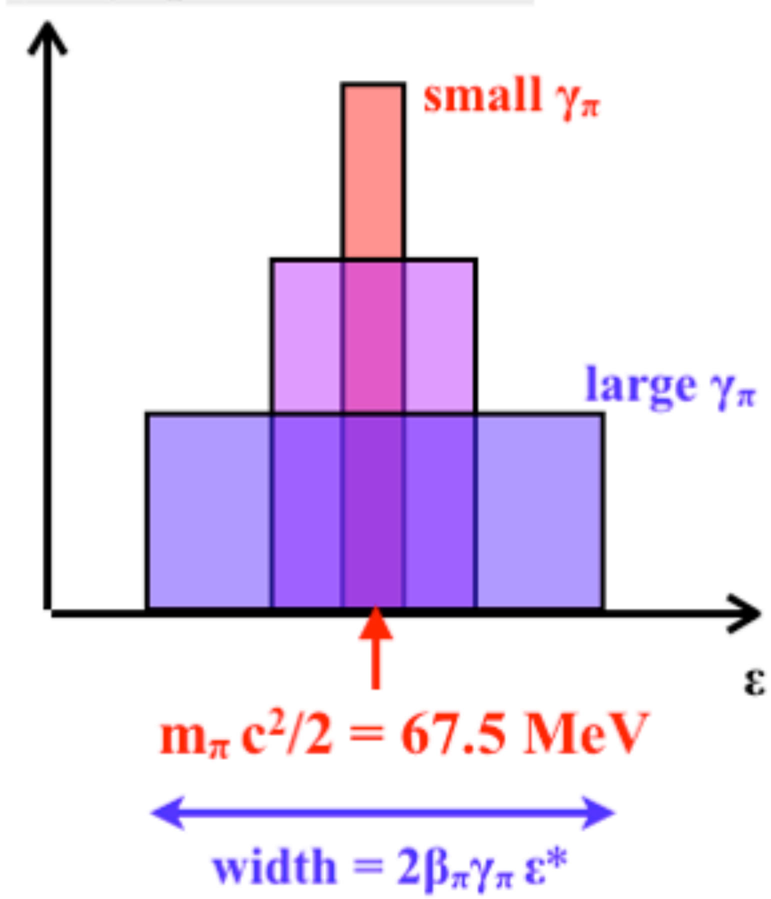
inelastic p-p collision cross section: σ_{inel}

threshold kinetic energy:

$$T_{th} = 2m_\pi c^2 (1 + m_\pi / 4m_p) = 279.6 \text{ MeV}$$

Two body decay: $\pi^0 \rightarrow 2\gamma$

γ-ray spectrum: $dN/d\varepsilon$



Symmetric about 67.5 MeV, irrespective of proton spectrum

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

- γ-ray spectral shape is determined solely by dN/dp (proton spectrum). $dN/dp \propto p^{-s} \exp(-p/p_m)$ s=1.5, 2.0, 2.5, cp_m = PeV ➜ $dN_\gamma/d\varepsilon$

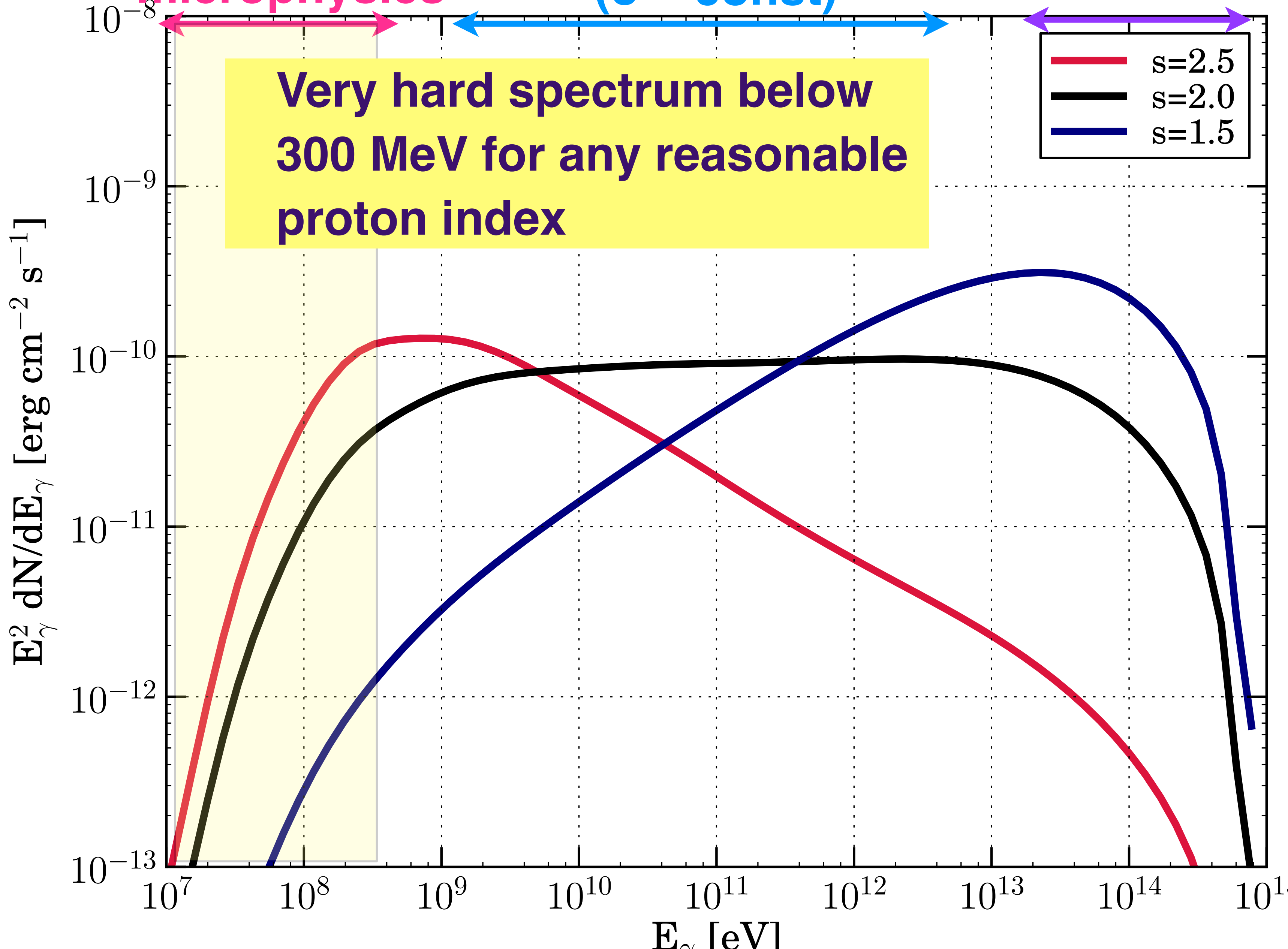
π^0 production microphysics

photon index $\Gamma \simeq s$ ($\sigma \sim$ const)

cutoff at $\varepsilon \sim 0.1\ cp_m$

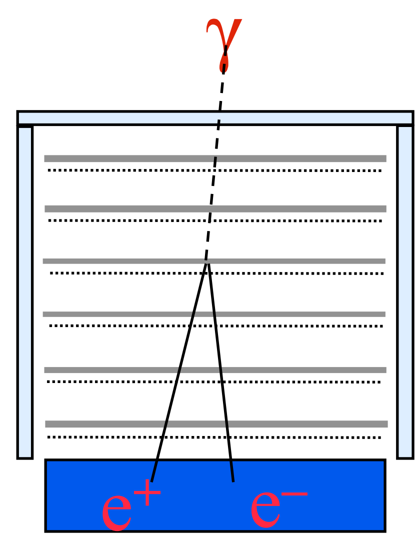
$dN_\gamma/d\varepsilon$: symmetric about 68 MeV

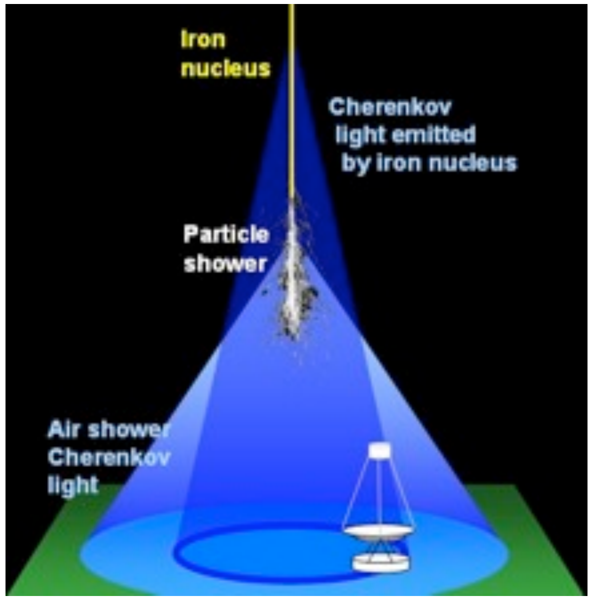
$\varepsilon^2\ dN_\gamma/d\varepsilon$: hard spectrum below 300 MeV



Gamma-ray Detectors

	Satellite-based pair conversion telescope	Ground atmospheric Cherenkov telescope
Experiments	EGRET, AGILE, Fermi	HESS, VERITAS MAGIC
Energy range	0.02 – 200 GeV	0.1 – 100 TeV
Angular res.	0.04 – 10 deg	~0.1 deg
Collection area	1 m^2	10^5 m^2
Field of view	2.4 sr	10^{-2} sr
Duty cycle	~95%	<10%





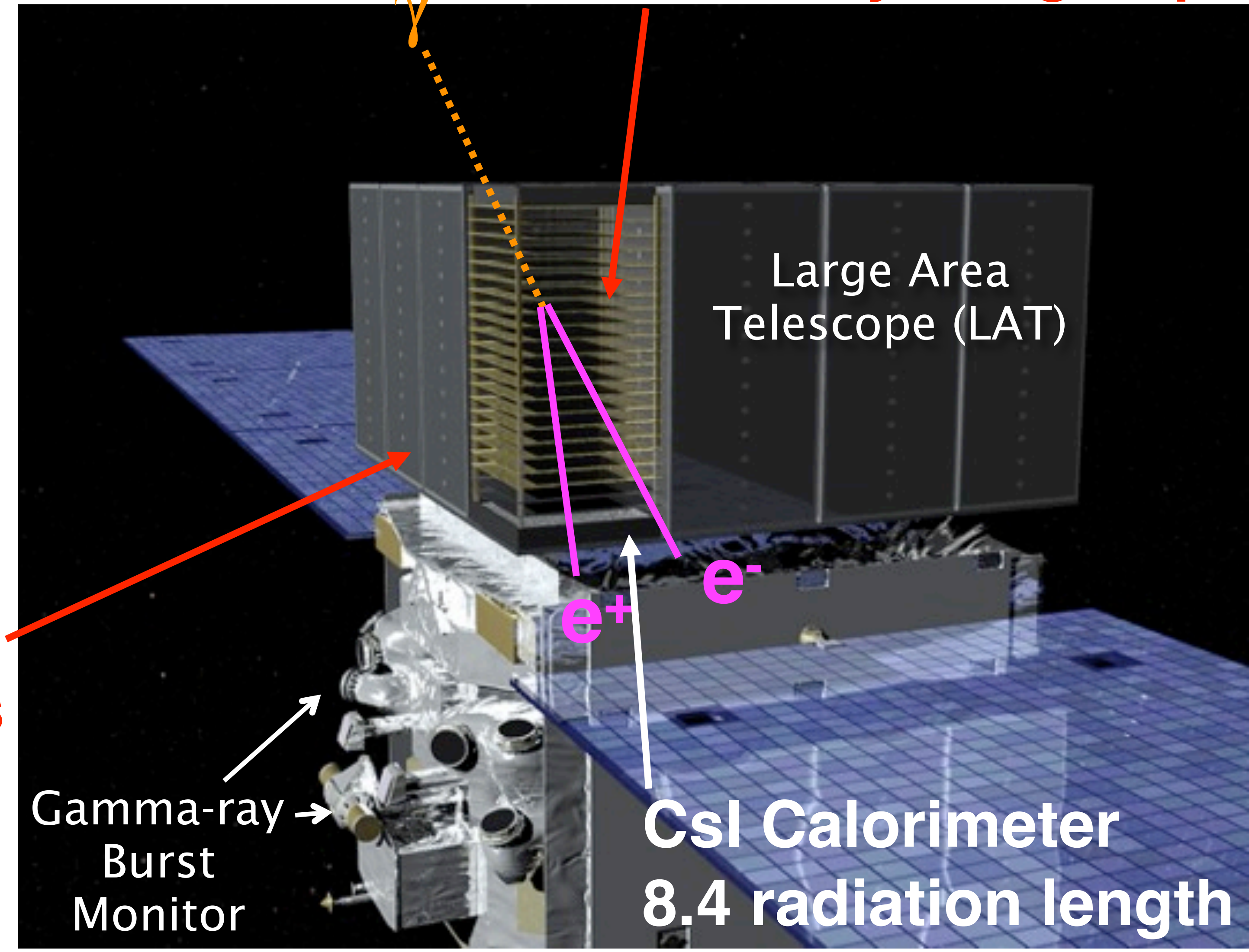
Fermi (GLAST)/LAT Overview

- **LAT (Large Area Telescope) on board Fermi Observatory**
- **Satellite experiment to observe cosmic gamma rays**
  - **Wide energy range: 20 MeV to >300 GeV**
  - **Large effective area: > 8000 cm^2 (~6xEGRET)**
  - **Wide field of view: > 2.4 sr (~5xEGRET)**

Si Tracker
70 m^2 , 228 μm pitch
~0.9 million channels
maintained by our group

- **Pair-conversion telescope**
  - **"Clear" signature**
  - **Background rejection**

Anti-coincidence Detector
Segmented scintillator tiles
99.97% efficiency



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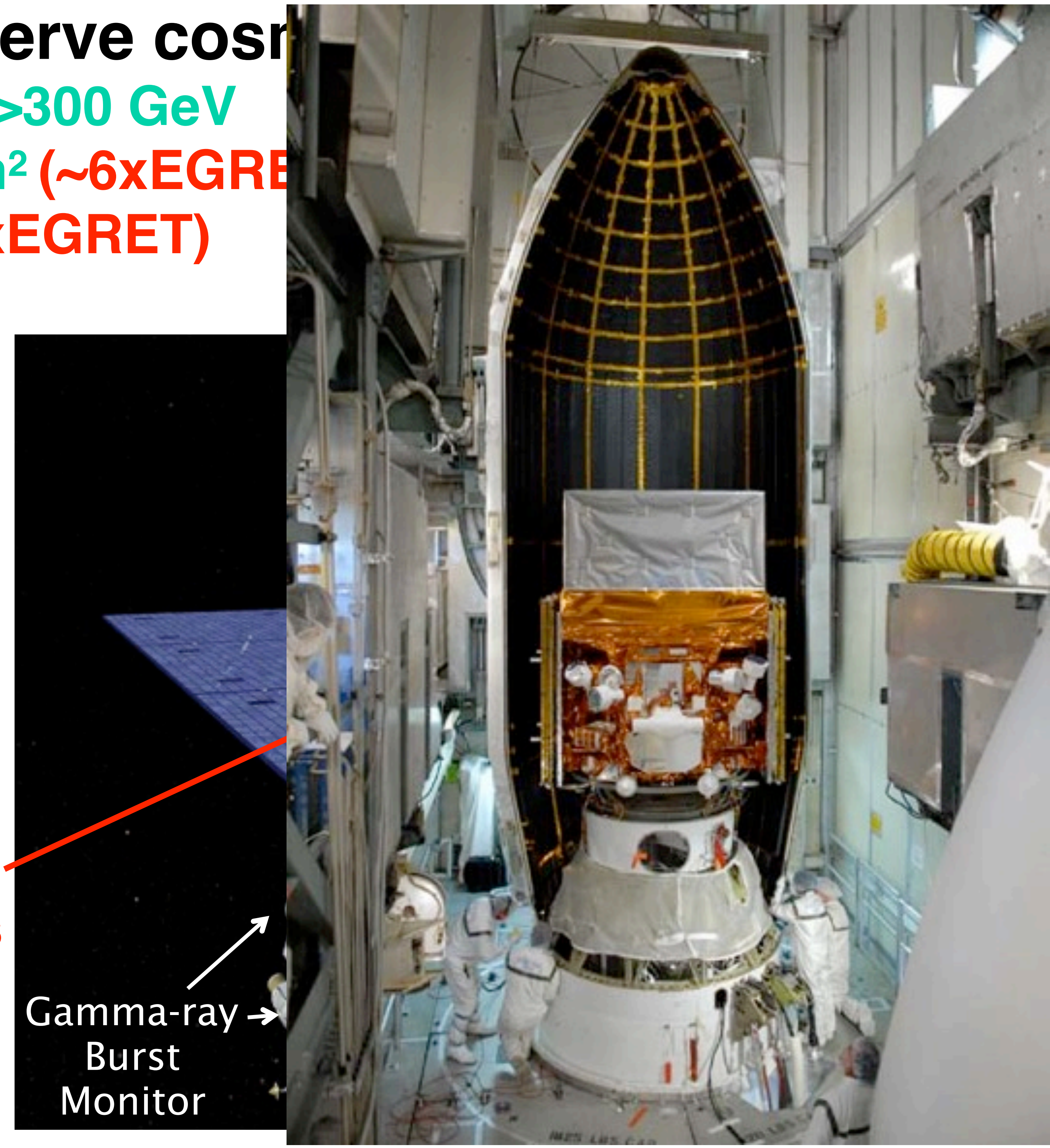

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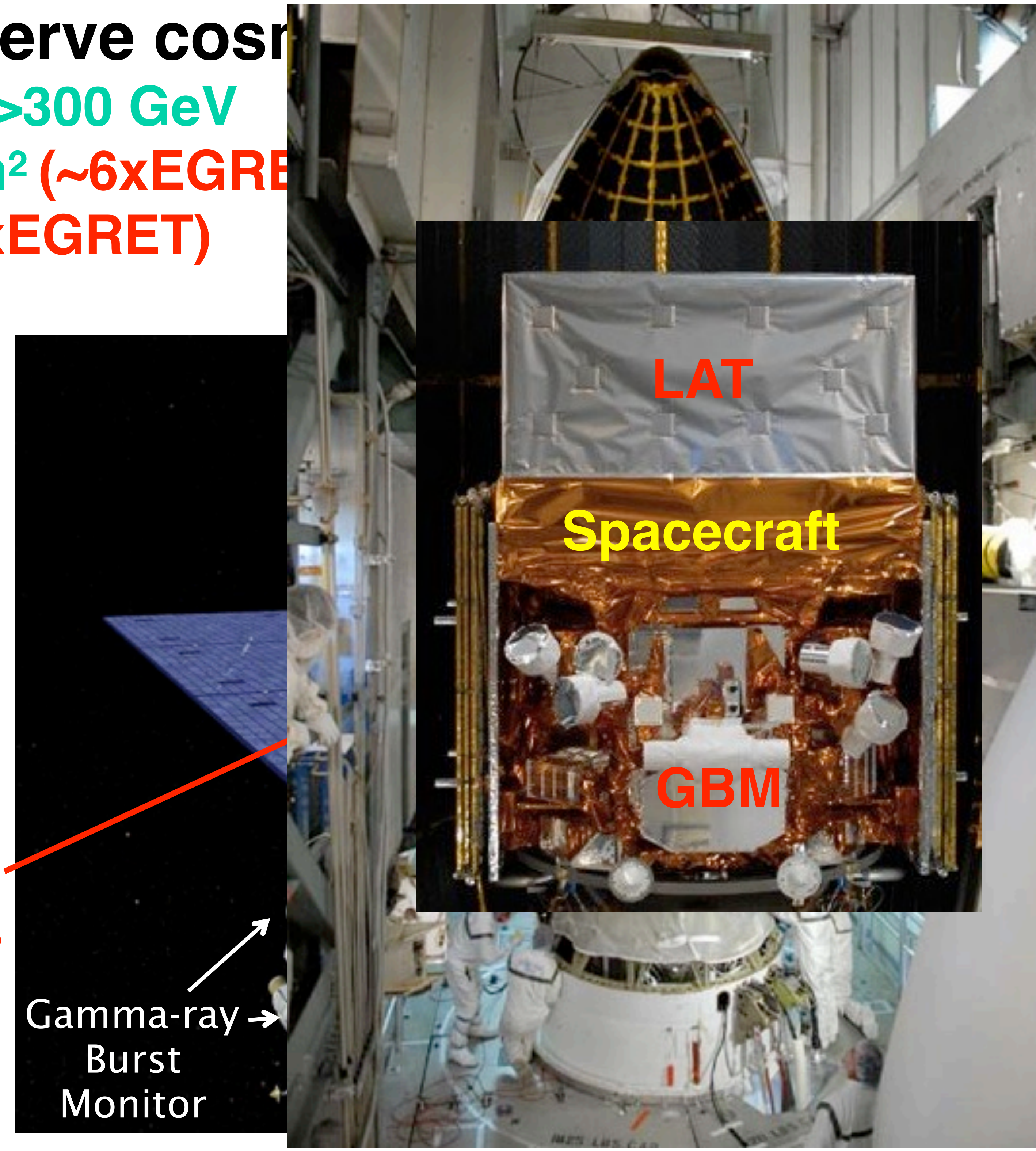
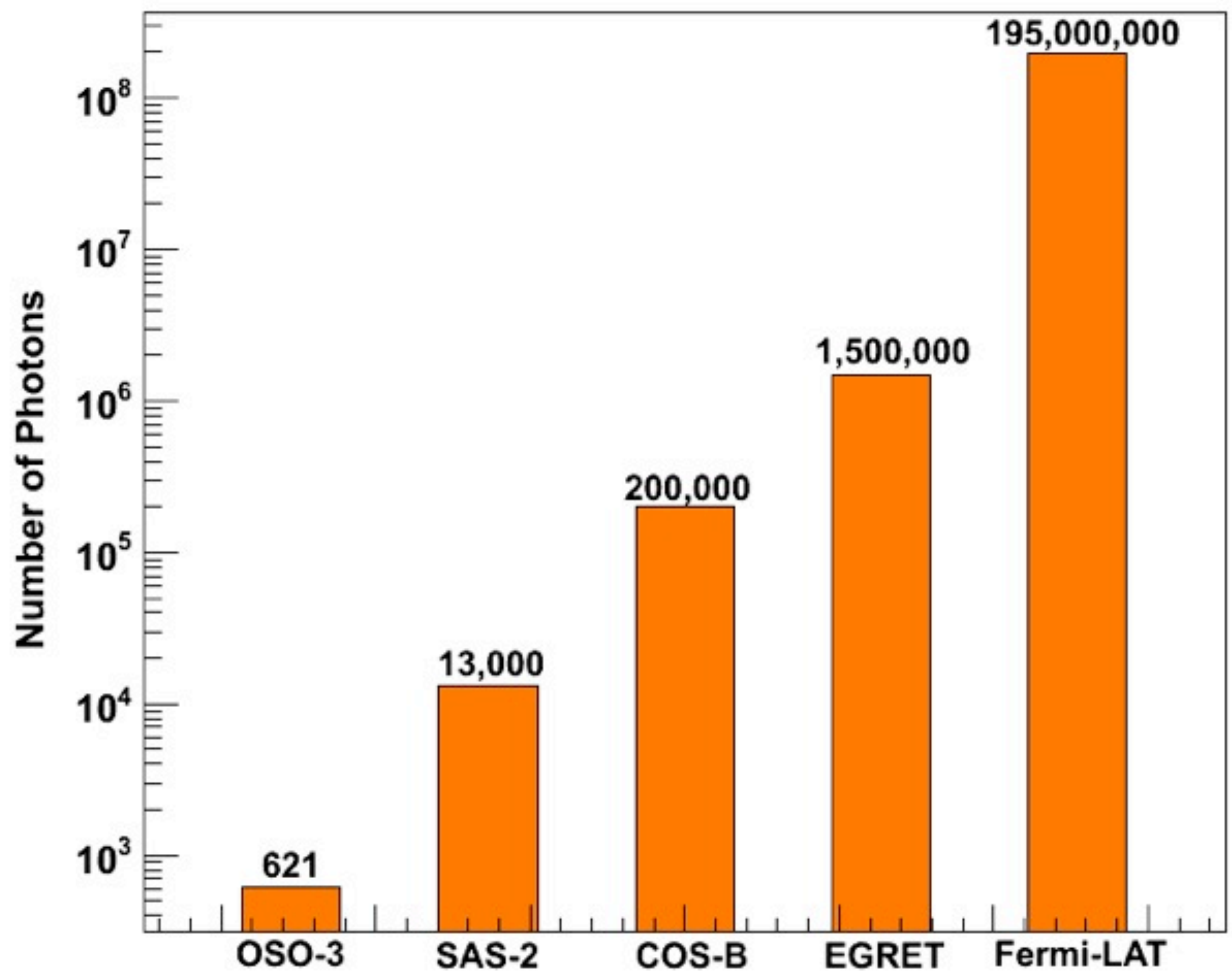


Comparison with Previous Missions

- Number of triggers way beyond 100 billion ($134x10^9$; $26x10^9$ downlinked)
- Number of photons in one year dwarfs previous missions
- Uptime: 99.1%
- All data public
  Processing time: typically 5-10 hours
- 5-year mission, no consumables



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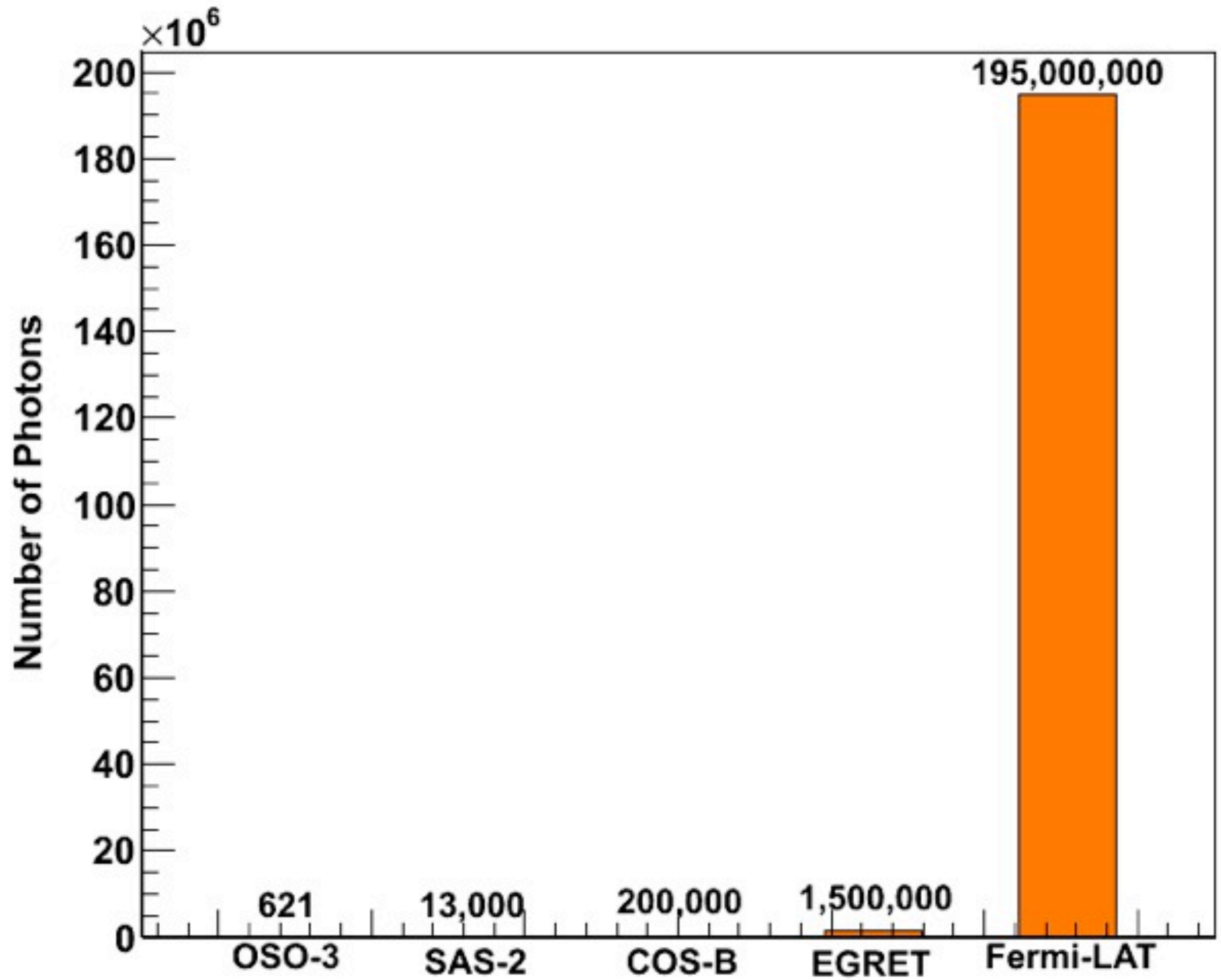
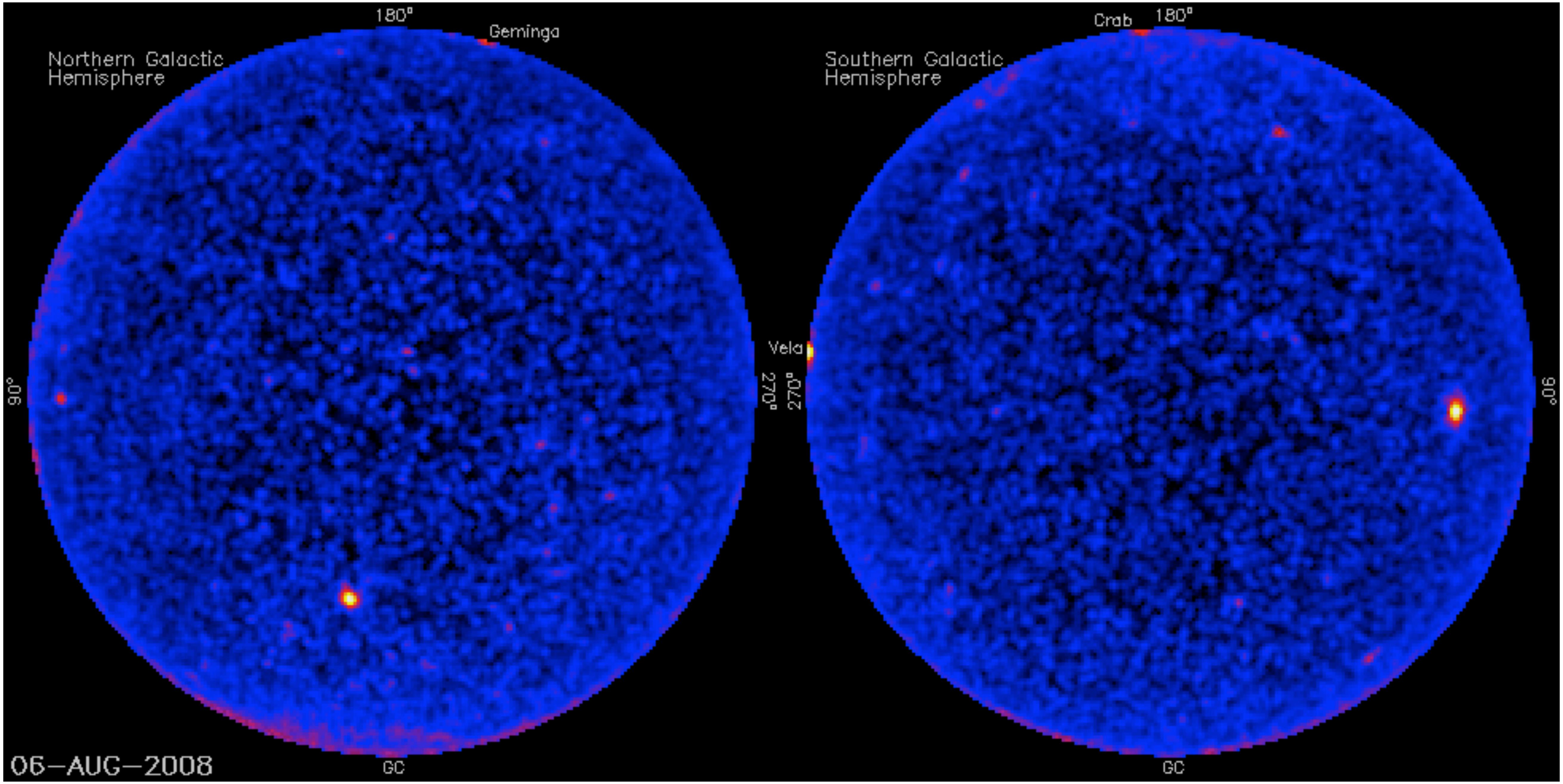
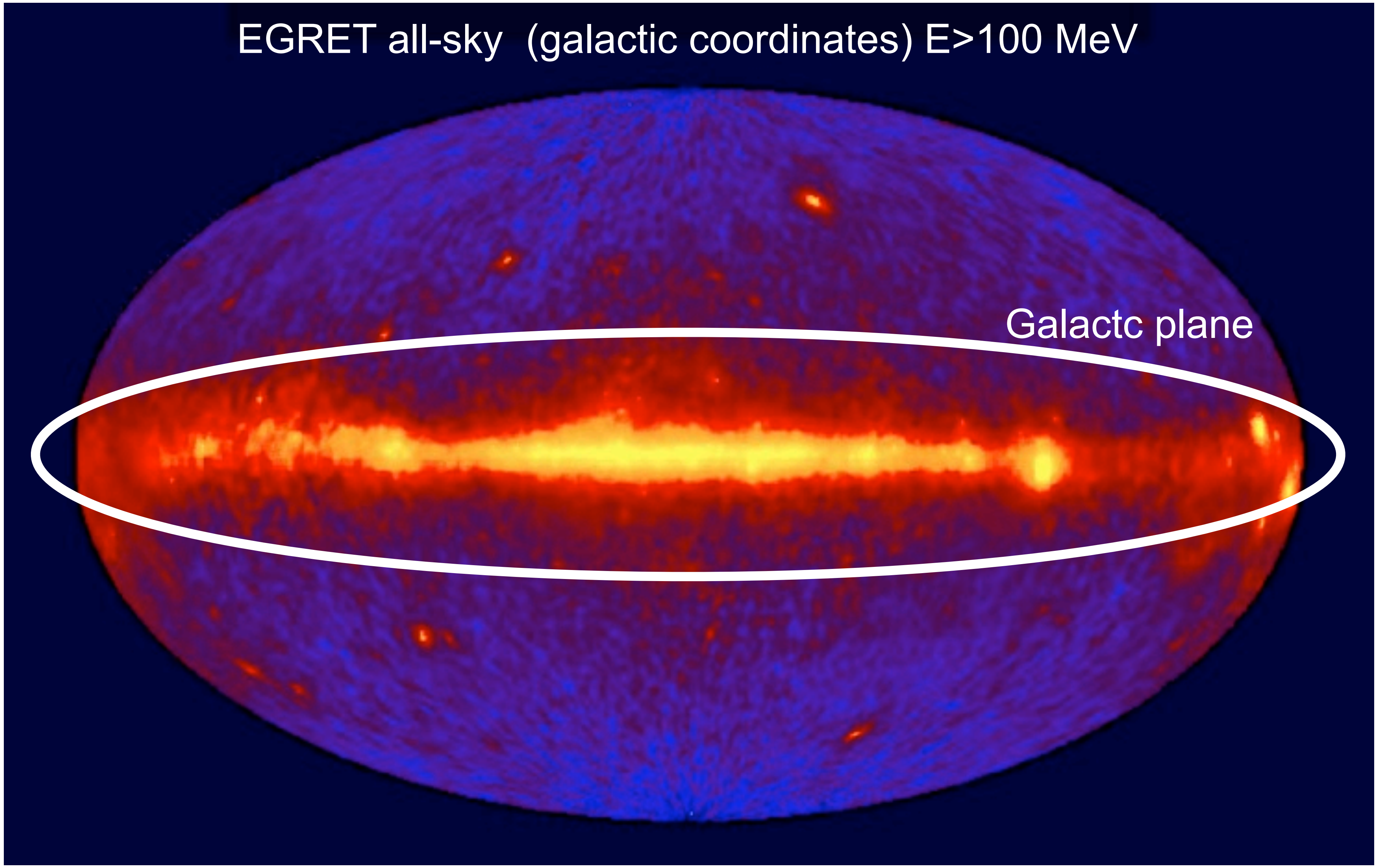


Variable Gamma-ray Sky

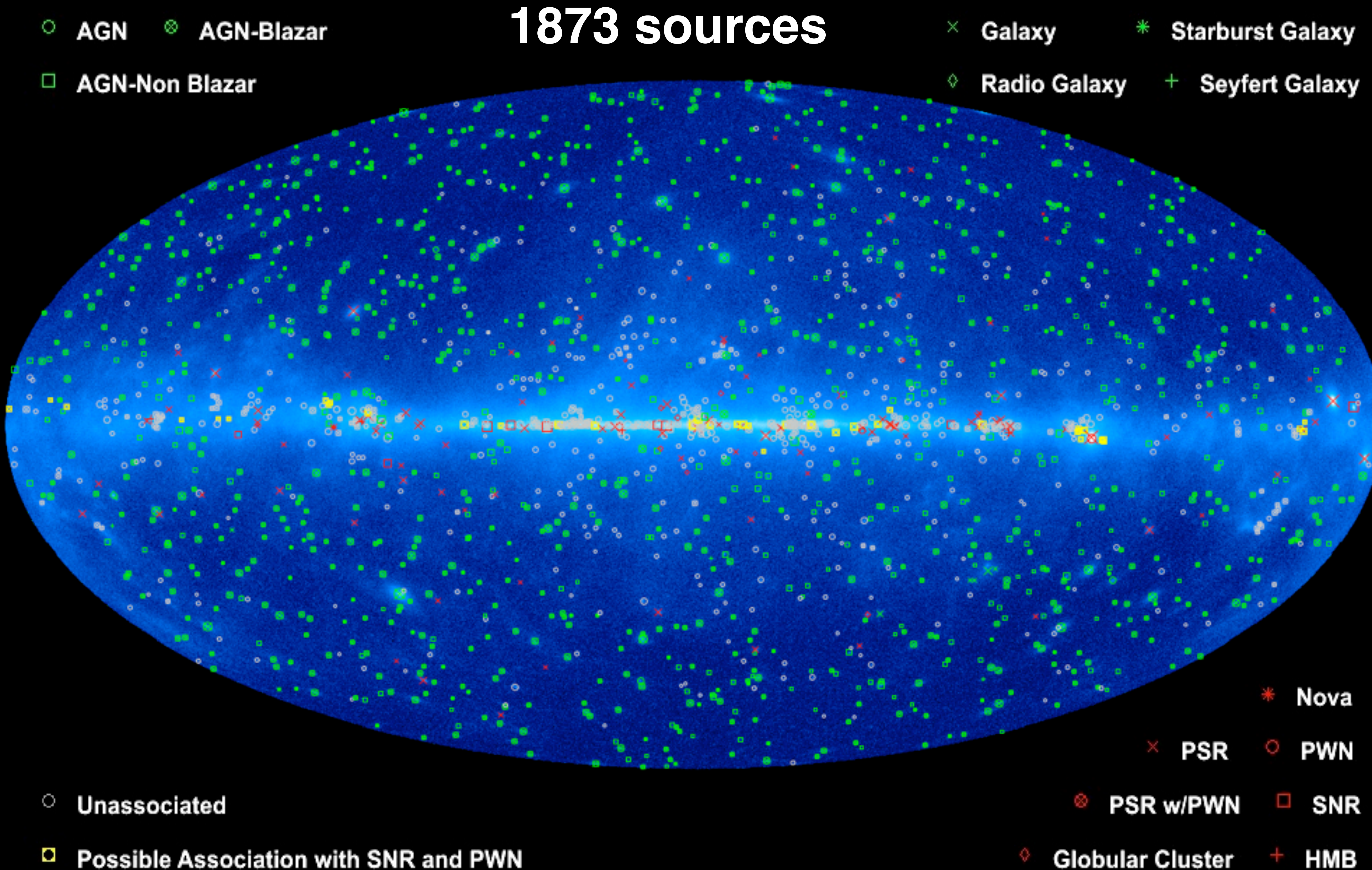


Predecessor, EGRET

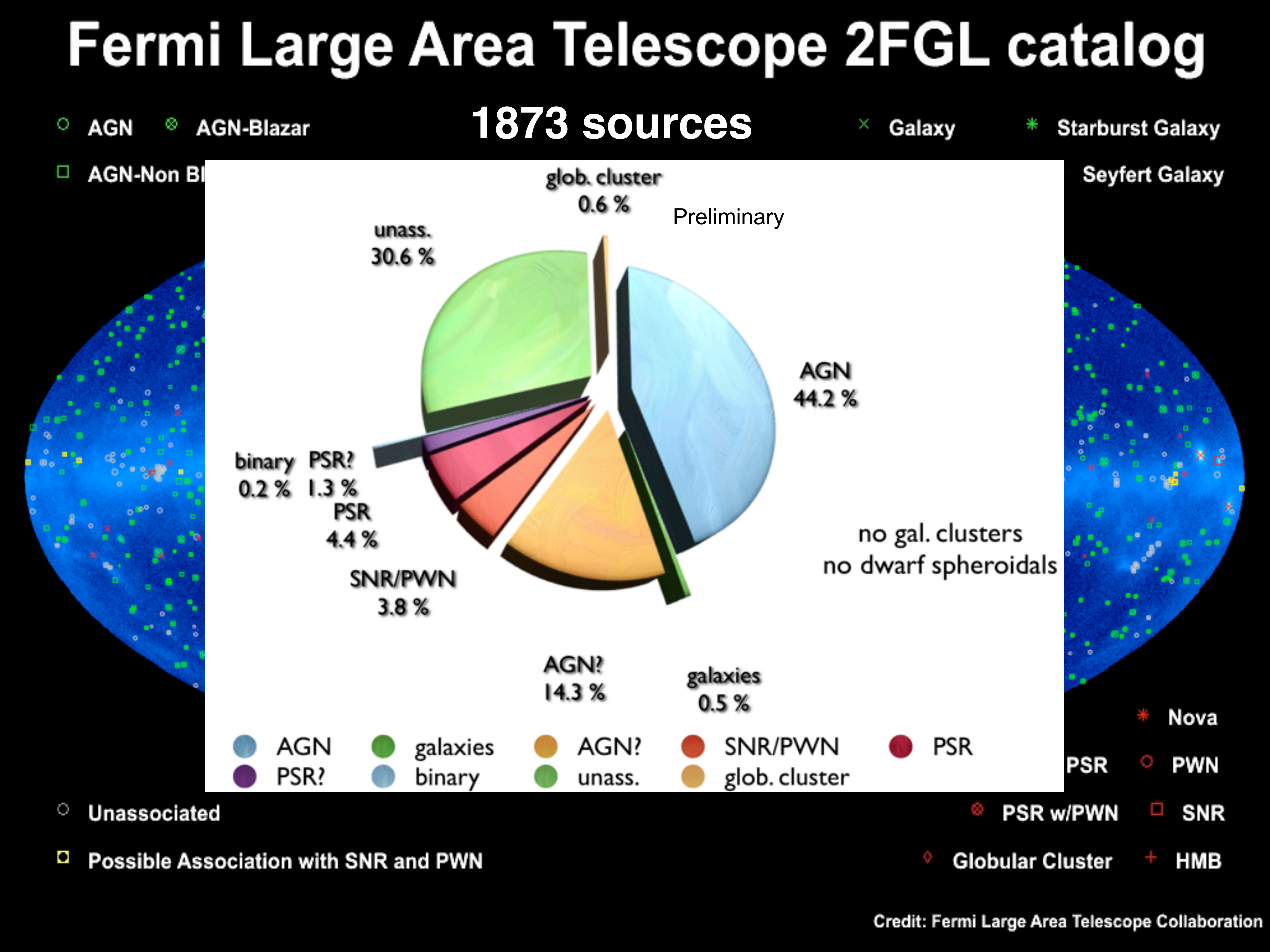
- EGRET: 1991–2000
  - 271 gamma-ray sources (Hartman et al. 1999)
    - Only 38% (101 sources) have clear “identifications”



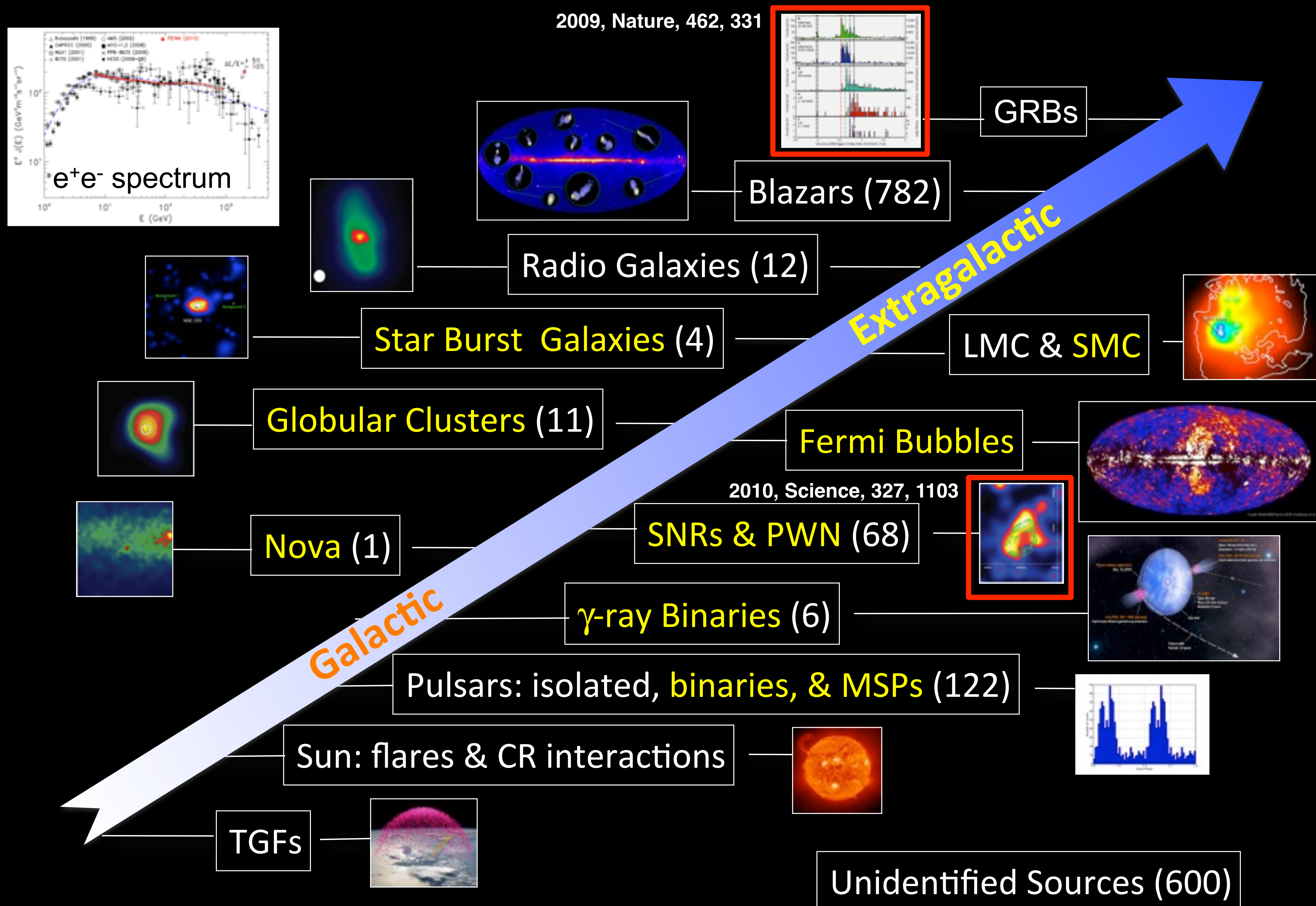
Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration


Fermi Large Area Telescope 2FGL catalog
1873 sources
AGN
AGN-Blazar
Galaxy
Starburst Galaxy
AGN-Non Bl
Seyfert Galaxy
glob. cluster
0.6 %
Preliminary
unass.
30.6 %
AGN
44.2 %
binary
0.2 %
PSR?
1.3 %
PSR
4.4 %
no gal. clusters
no dwarf spheroidals
SNR/PWN
3.8 %
AGN?
14.3 %
galaxies
0.5 %
AGN
galaxies
AGN?
SNR/PWN
PSR
PSR?
binary
unass.
glob. cluster
Nova
PSR
PWN
Unassociated
PSR w/PWN
SNR
Possible Association with SNR and PWN
Globular Cluster
HMB
Credit: Fermi Large Area Telescope Collaboration

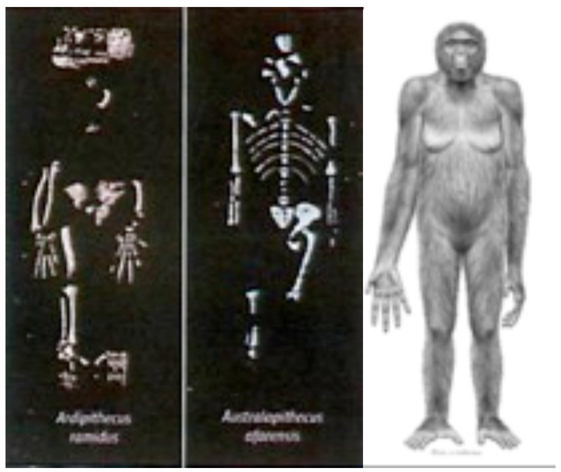
Fermi Highlights and Discoveries



Scientific Impacts of Fermi

- 225 publications (> 3300 citations for top 8 papers) as of 2013/03
- "Breakthrough of the Year" in 2009 selected by Science magazine

1. Ardipithecus Ramidus
2. Opening up the gamma-ray sky



- Bruno Rossi Prize 2011 awarded to W.B. Atwood, P. Michelson and Fermi LAT Team by High-Energy Astrophysics Division of AAS

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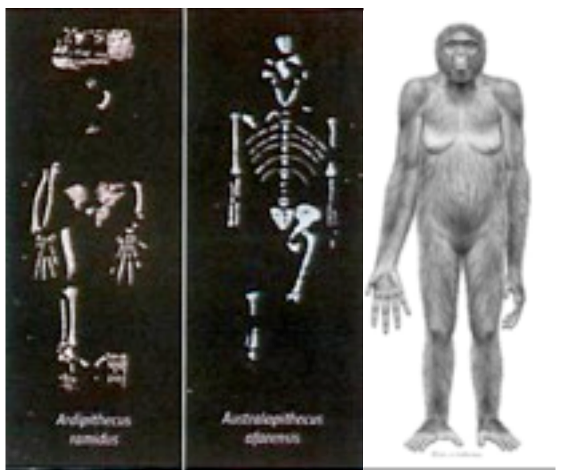

2. Opening up the gamma-ray sky

Nature: 3
Science: 15
(as of 2013/03)

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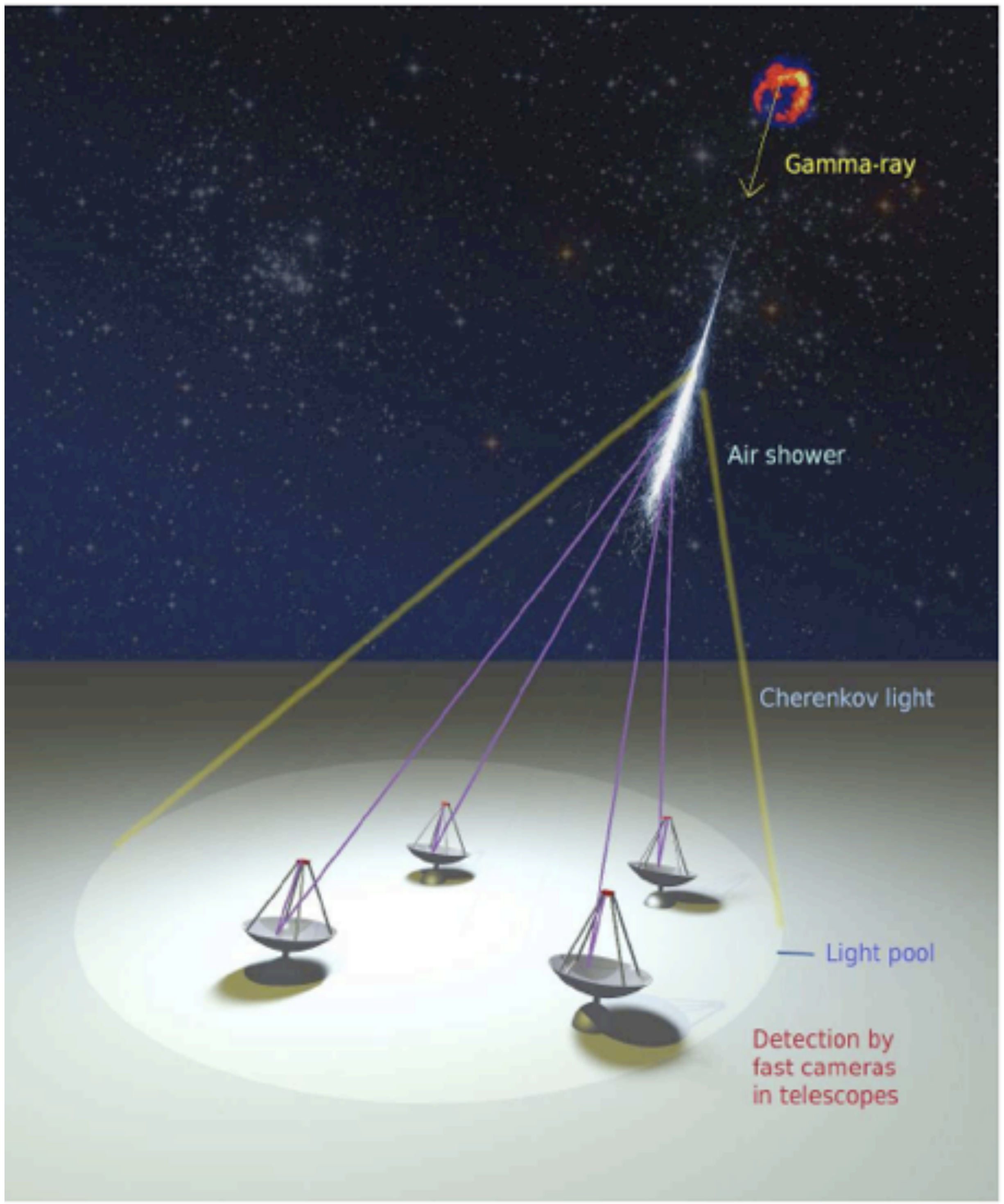
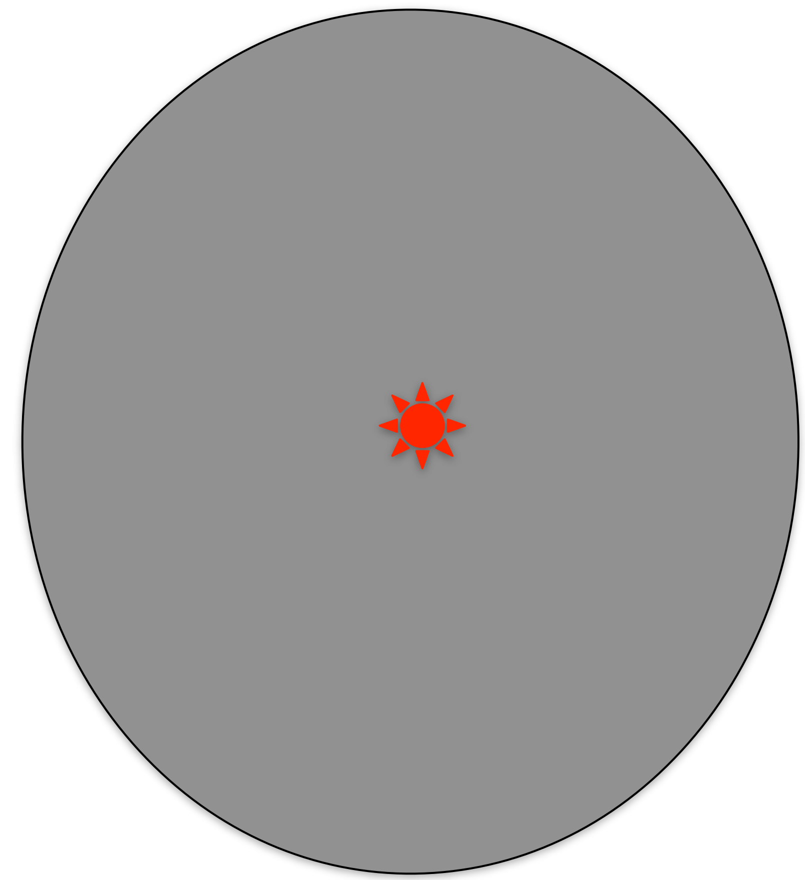
Imaging Atmospheric Cherenkov Telescope

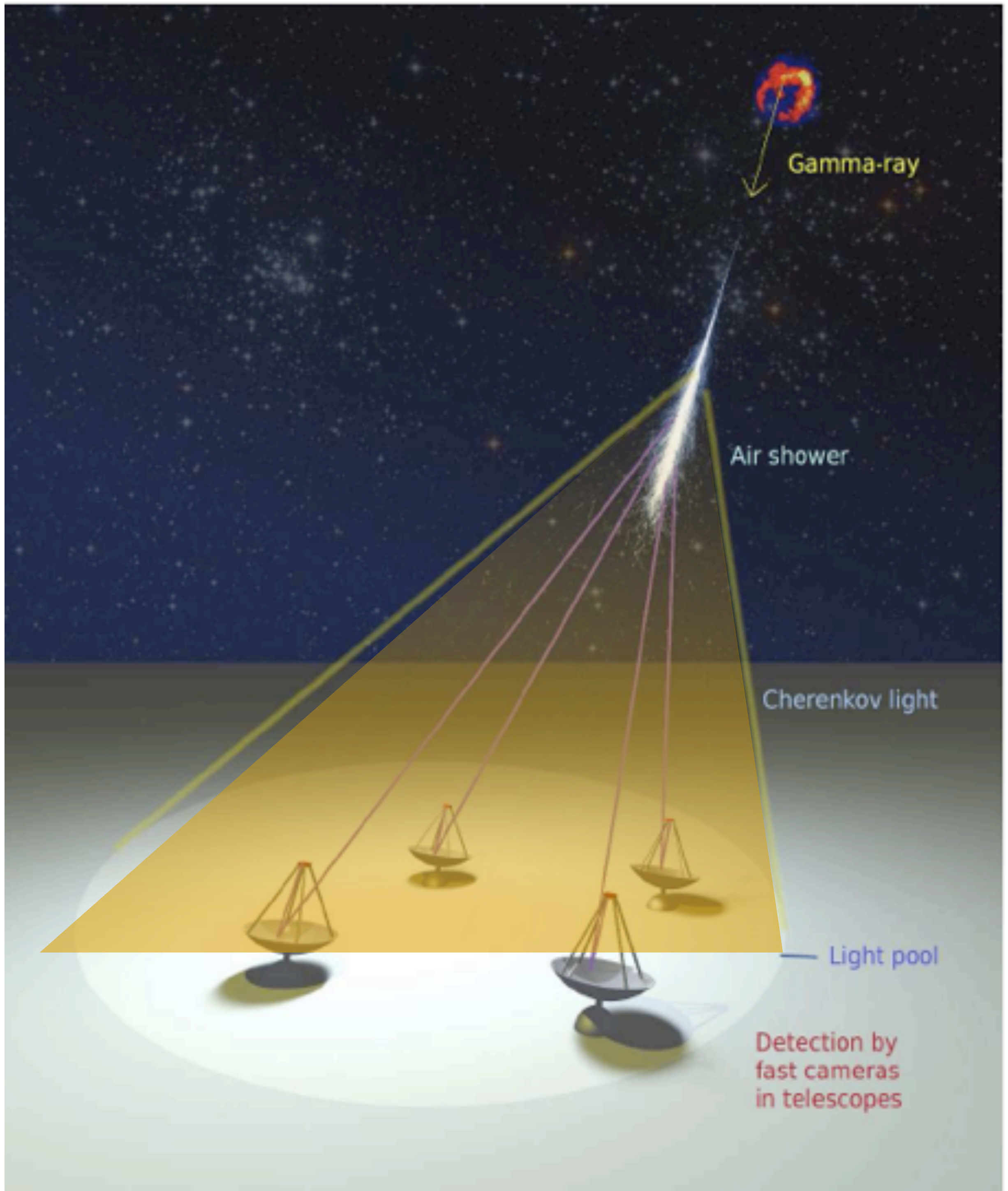


Cherenkov Light
50photons/m^2 (5 pe/m^2) at 1TeV



Typical parameters

Energy range 50GeV ~ 10TeV
CR rejection power >99%
Angular resolution ~0.1 degrees
Energy resolution ~20%
Detection area ~10^5m^2
Sensitivity ~1% Crab Flux (10^{-13} erg/cm^{2}s)



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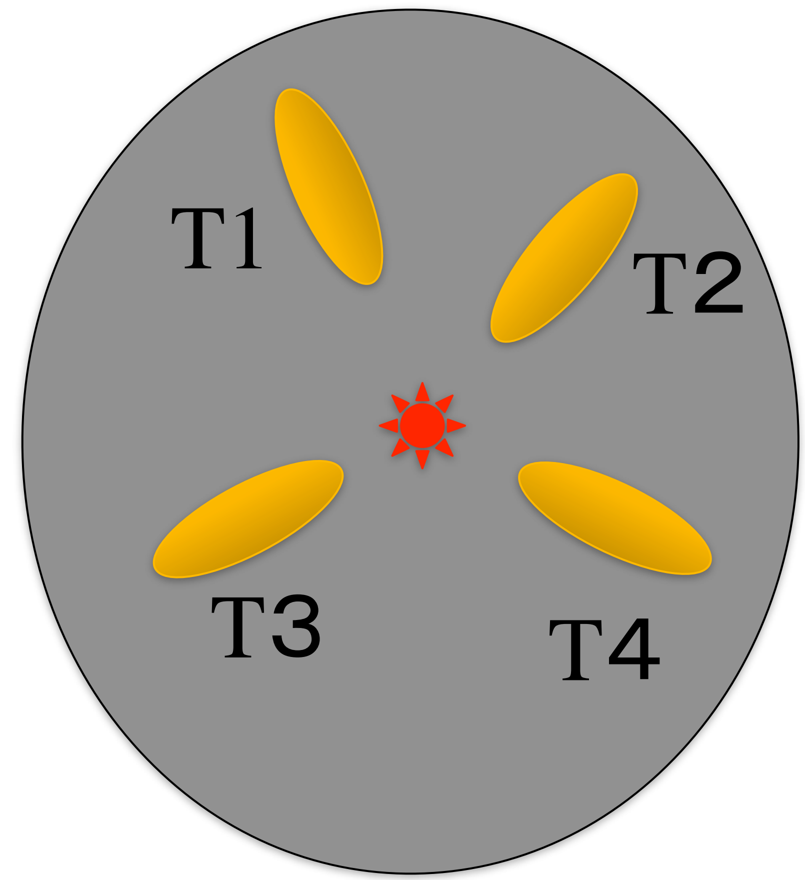

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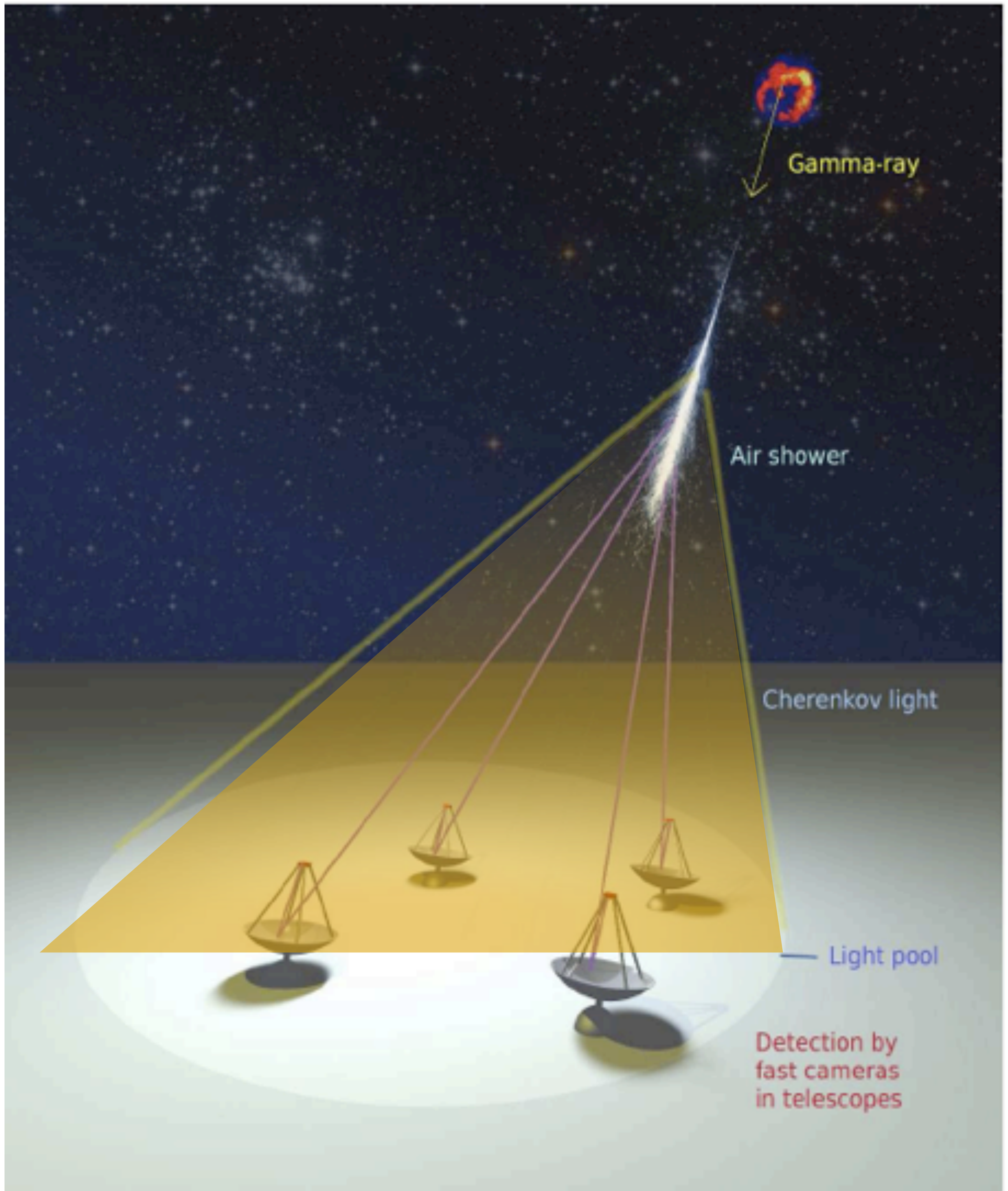

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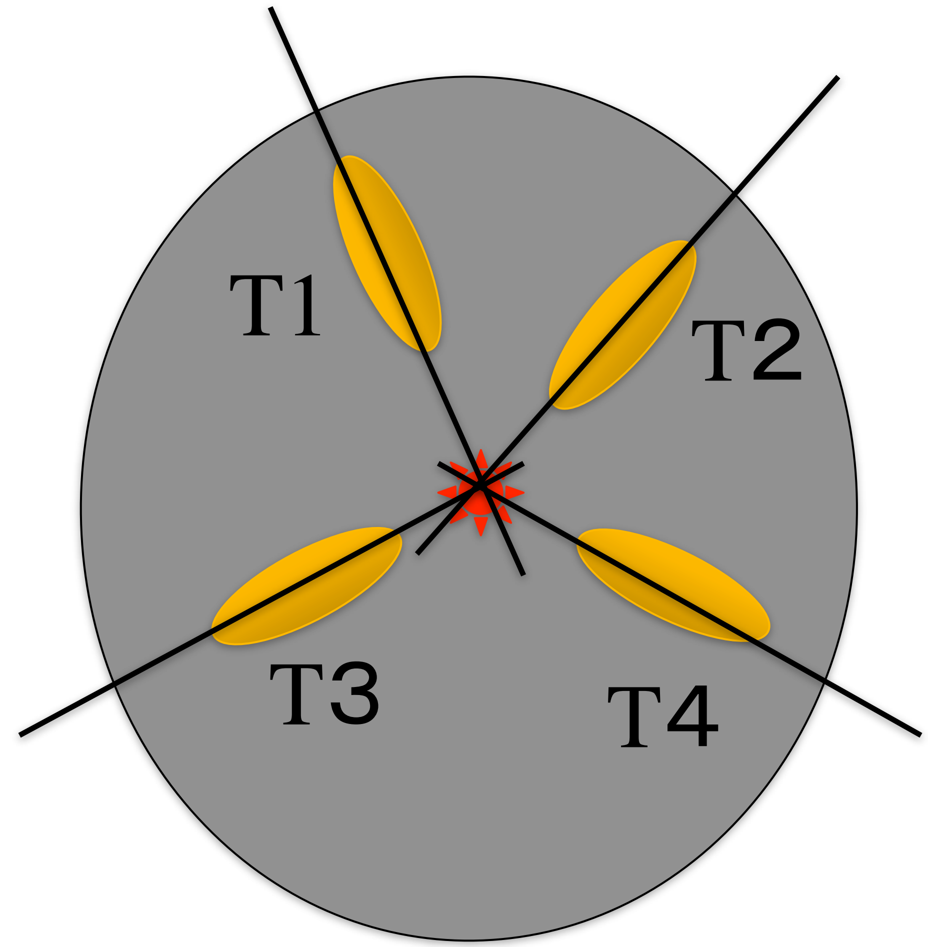

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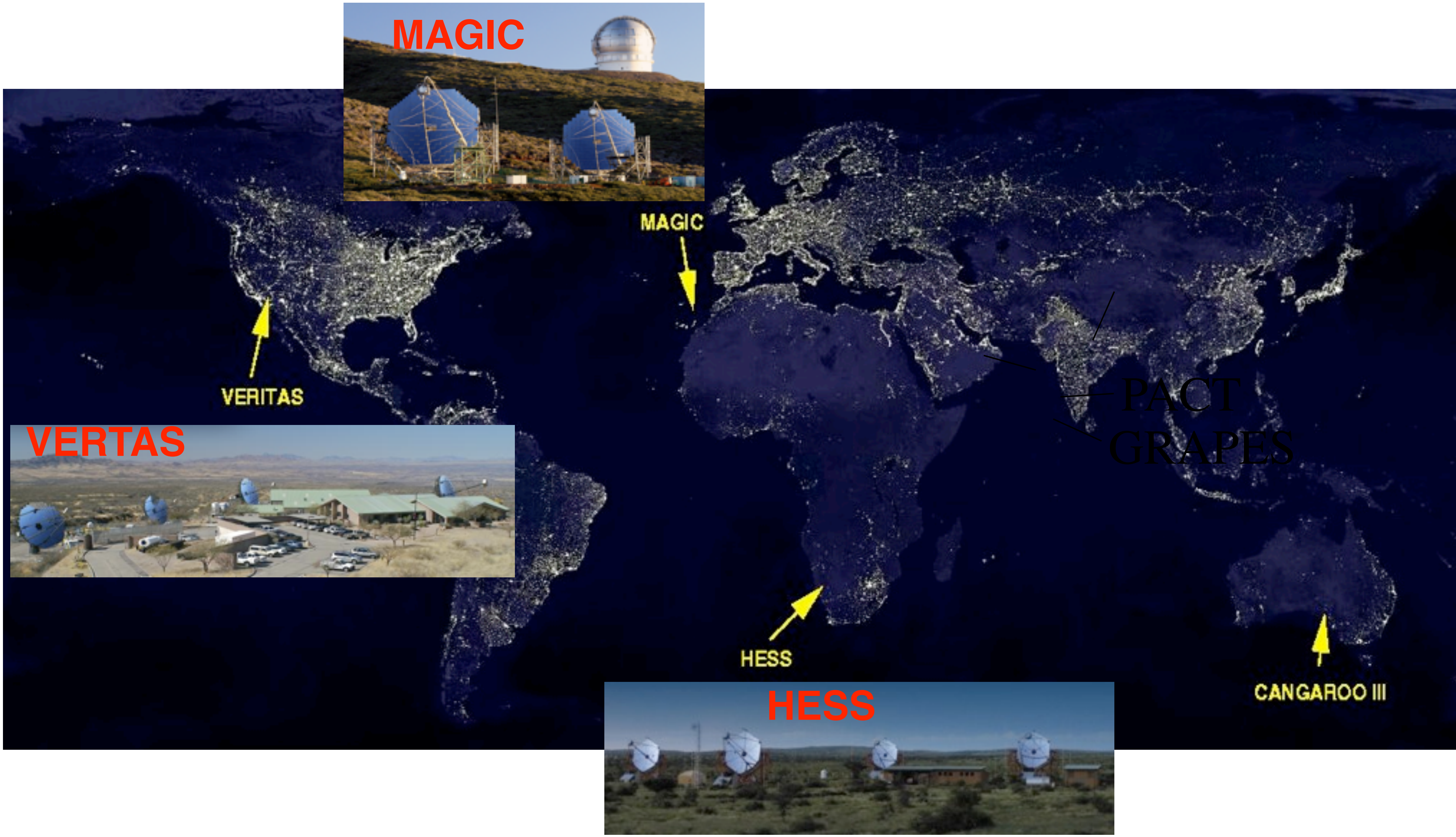
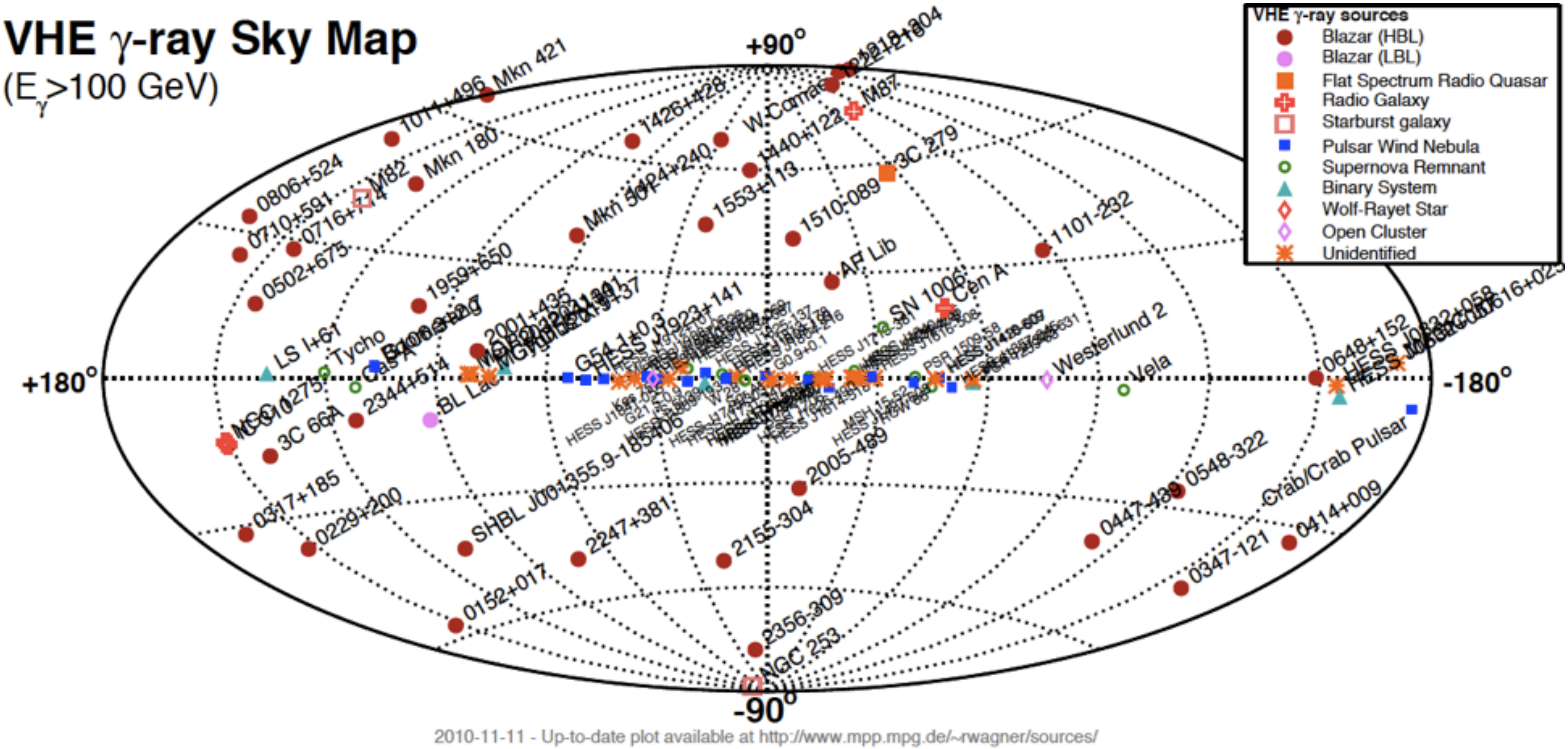
Currently Operating IACTs on Earth



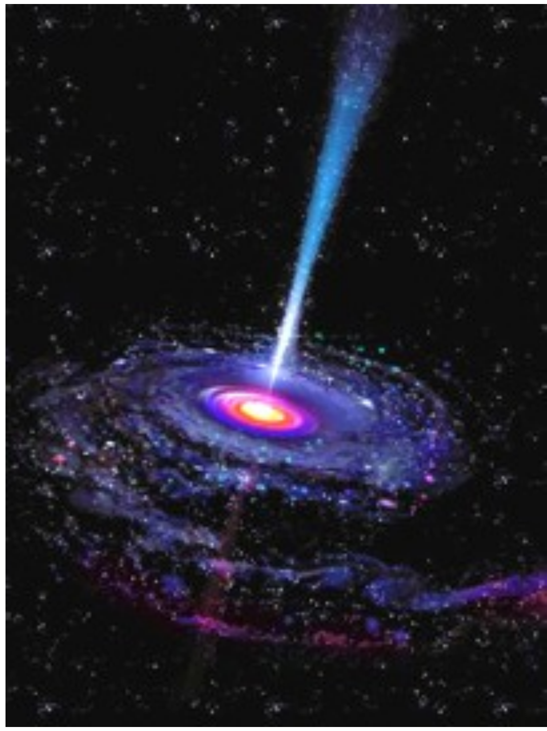
VHE Skymap



106 sources (45 Extragalactics + 61 Galactics) in Nov 2010
Blazars, FSRQs, FR-I, Starburst galaxies
SNRs, PWNe, Pulsar, Binaries, un-IDs

Origin of cosmic ray protons

- Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below “Knee”
  - Only circumstantial evidence
    - CR energy sum consistent with SNR kinetic energy (Ginzburg&Syrovatskii 1964)
    - Diffusive shock acceleration (Blanford&Eichler 1977)
    - Chemical Composition (Hayakawa 1956)
  - No observational evidence
  - Spectral index (~2.7) is difficult to explain
- Cosmic-rays above “Knee” are considered extragalactic
  - Gamma-ray bursts (GRB)
  - Active Galactic Nuclei (blazar)
  - Merging galaxy clusters



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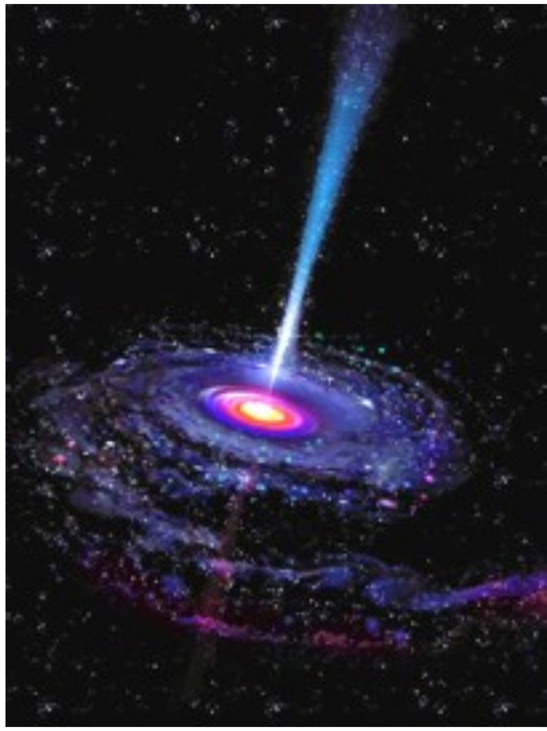

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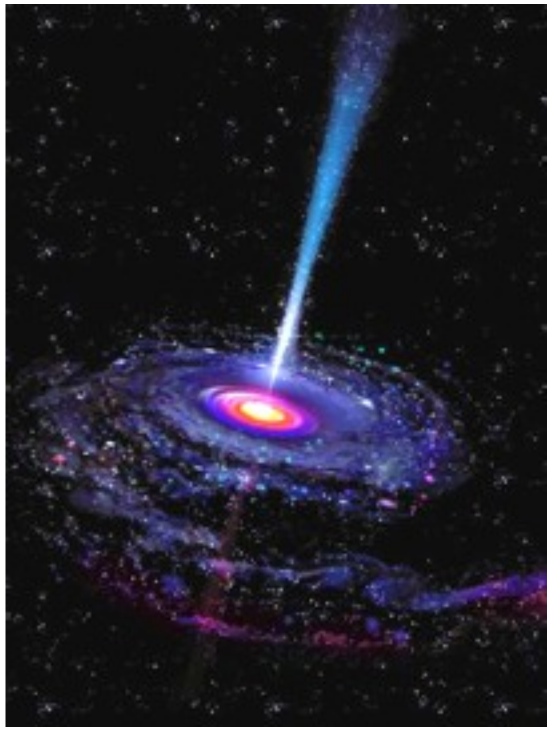
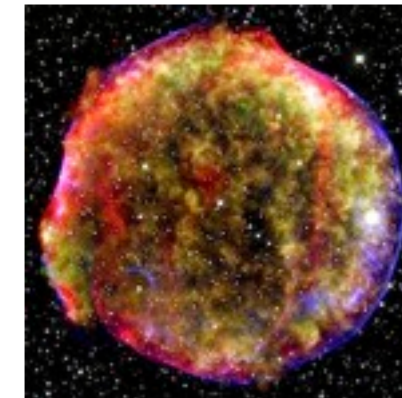


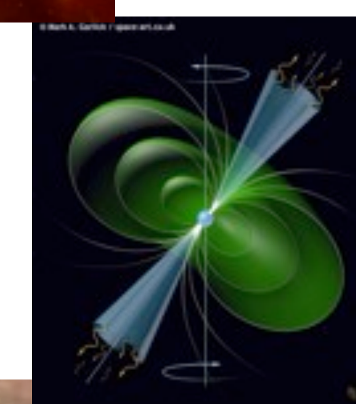
Energetics of Galactic Cosmic Rays

- Cosmic ray power in our Galaxy: ~ 5 x 10^{40} ergs/s
  - Supernovae: Q ~ 10^{42} ergs/s
    - Energy release (10^{51} ergs) x frequency (1/30 years)



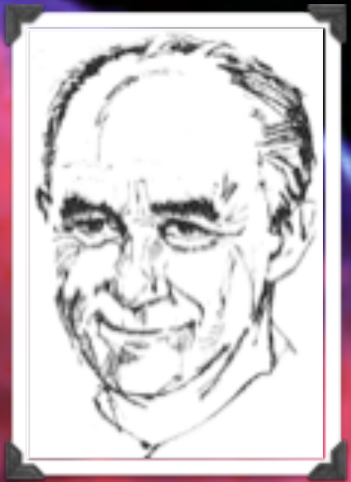
  - Novae: Q ~ 10^{42} ergs/s
    - Accretion of matter onto white dwarf
    - Energy release (10^{42} ergs) x frequency (100/year)

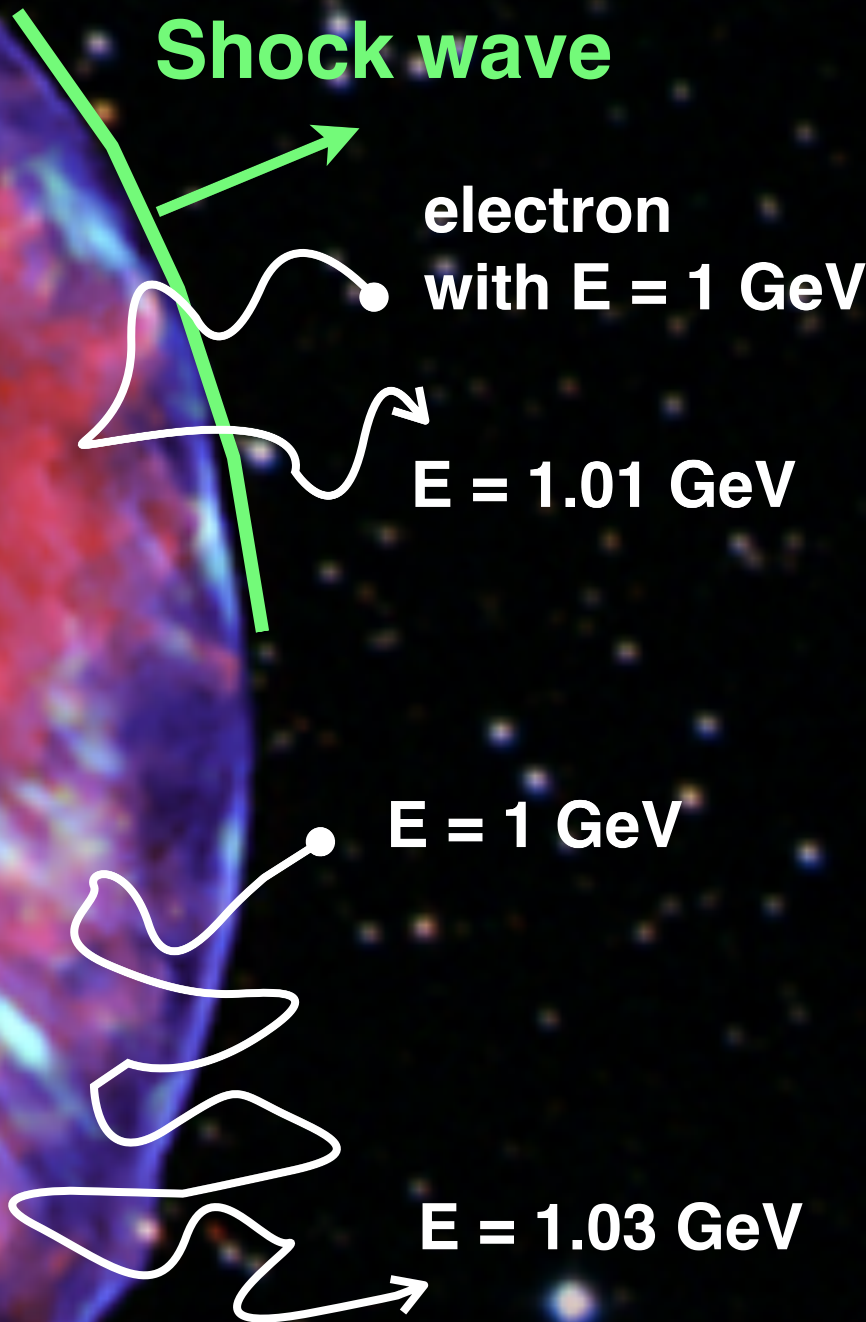
  - Rotating neutron stars: Q ~ 10^{41} ergs/s
    - Majority of Galactic Fermi-LAT sources



  - Stellar winds from hot O/B stars: Q ~ 10^{41} ergs/s
    - Strong winds from radiation pressure ($10^9 \dot{M}_\odot$)

"Fermi Acceleration" Mechanism





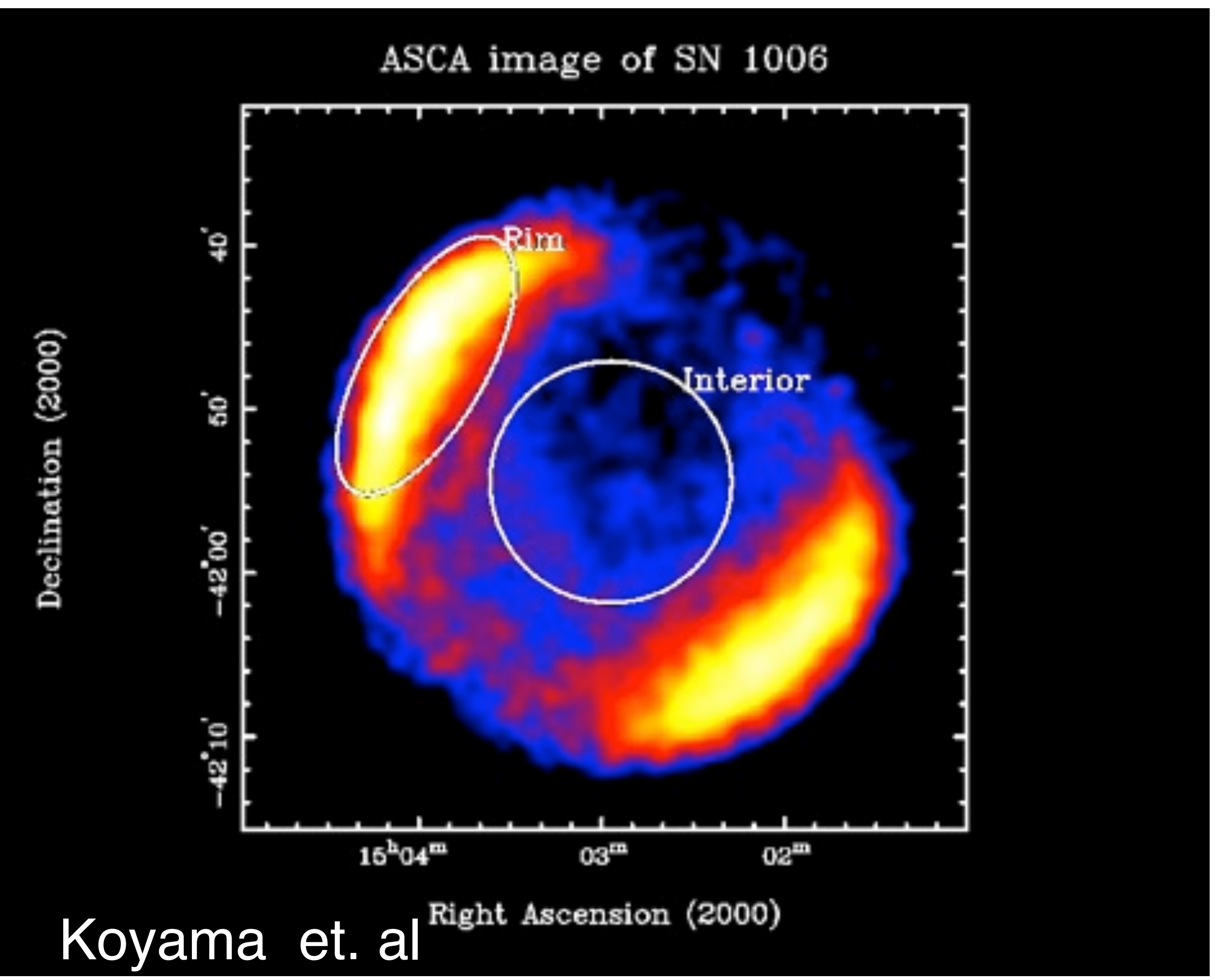
Energetic charged particles "random walk" in turbulent magnetic field.

Shock crossing
→ energy gain
Energy gain per one round trip: $\Delta E/E \sim v/c$
~ 1% of original energy
(for v = 3000 km/s)

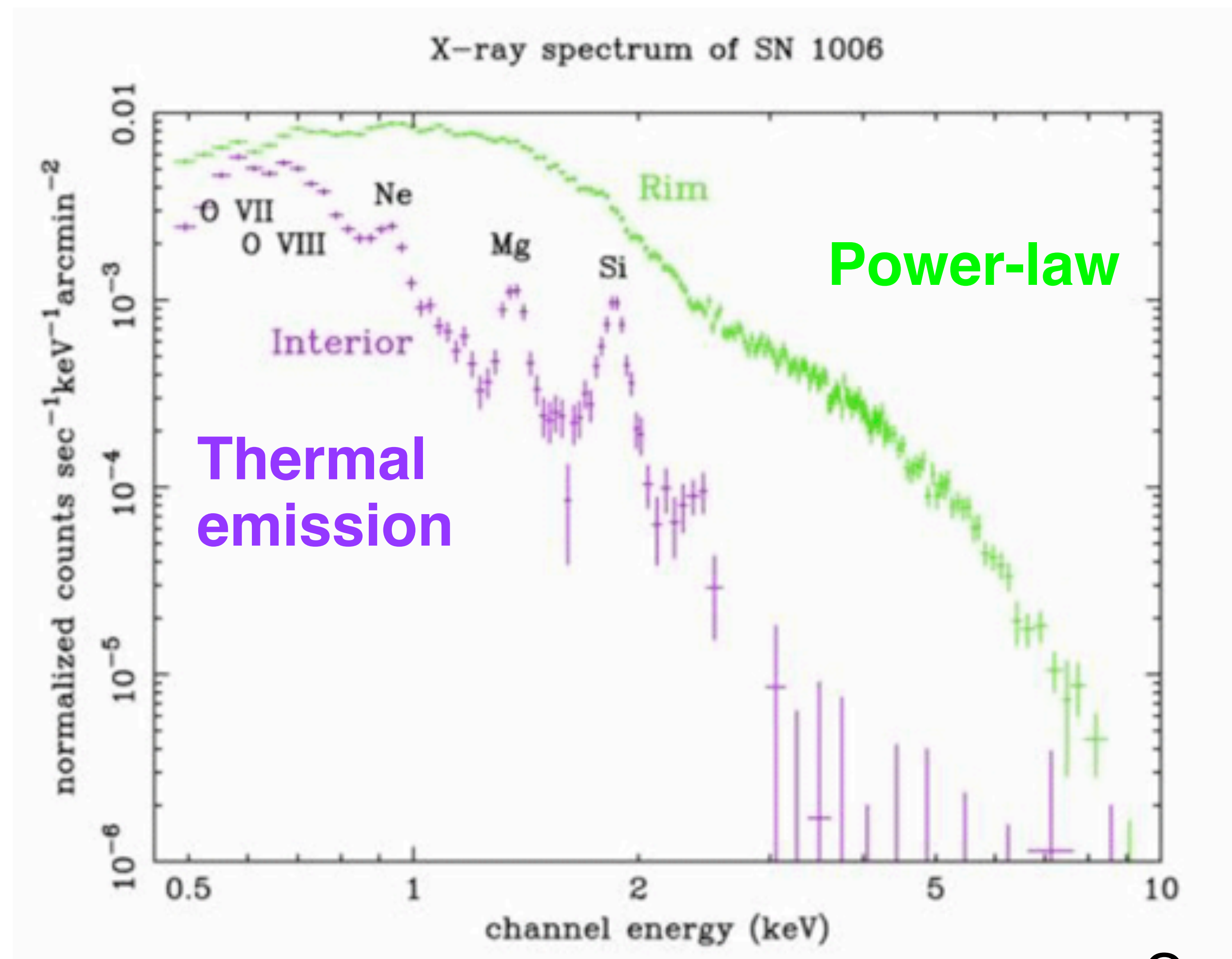
After 1000 round trips:
Energy: x20,000
(e.g. 1 GeV → 20 TeV)
But, very few particles can make 1000 trips
→ power law distribution

Particle Acceleration in SNR

- **Young shell-type supernova: SN1006**
  - **Power law spectrum from rim is best described by synchrotron emission by ultra-relativistic electrons**
  - **First evidence of particles accelerated to > 10^{14} eV**



Koyama et. al



Ozaki

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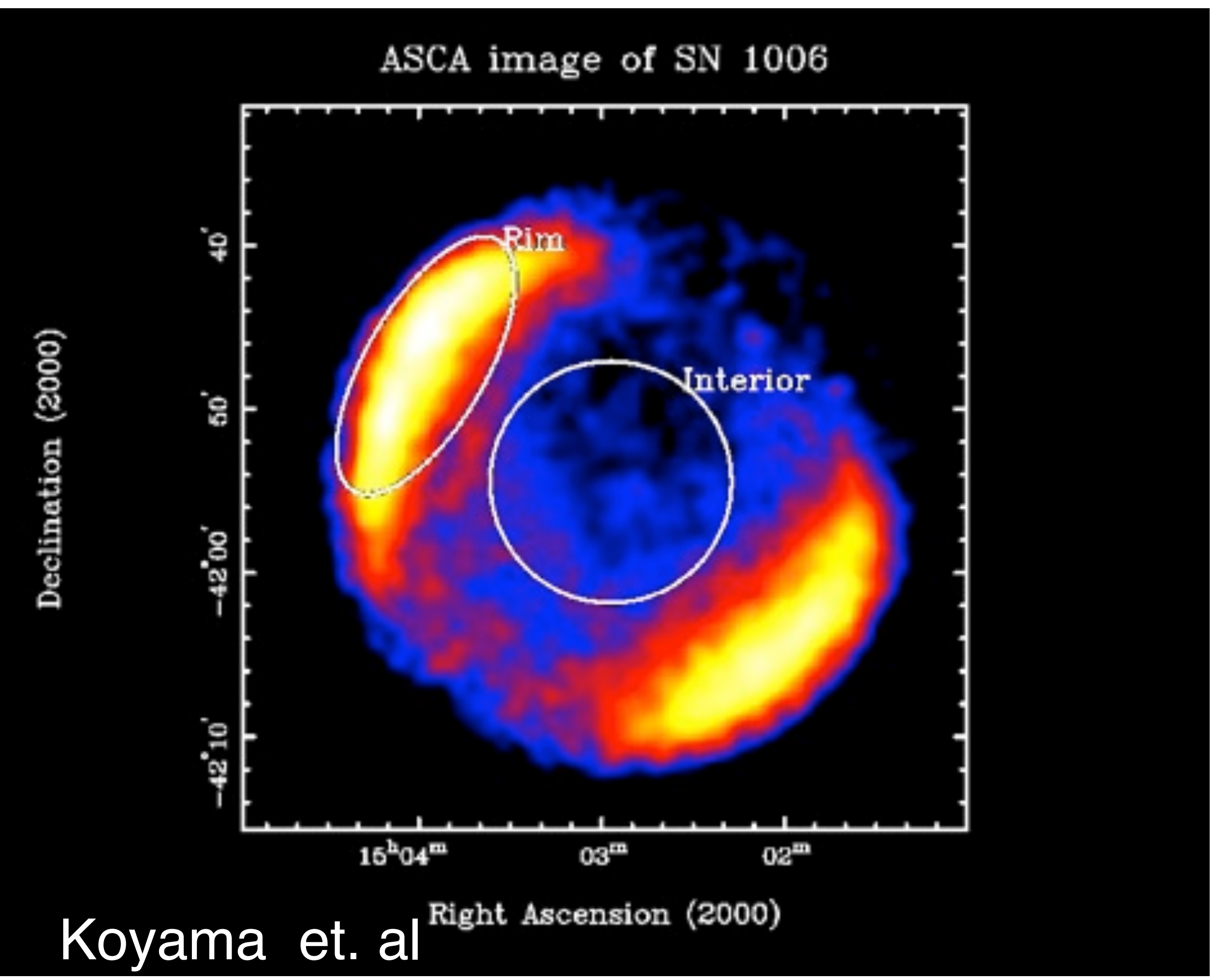

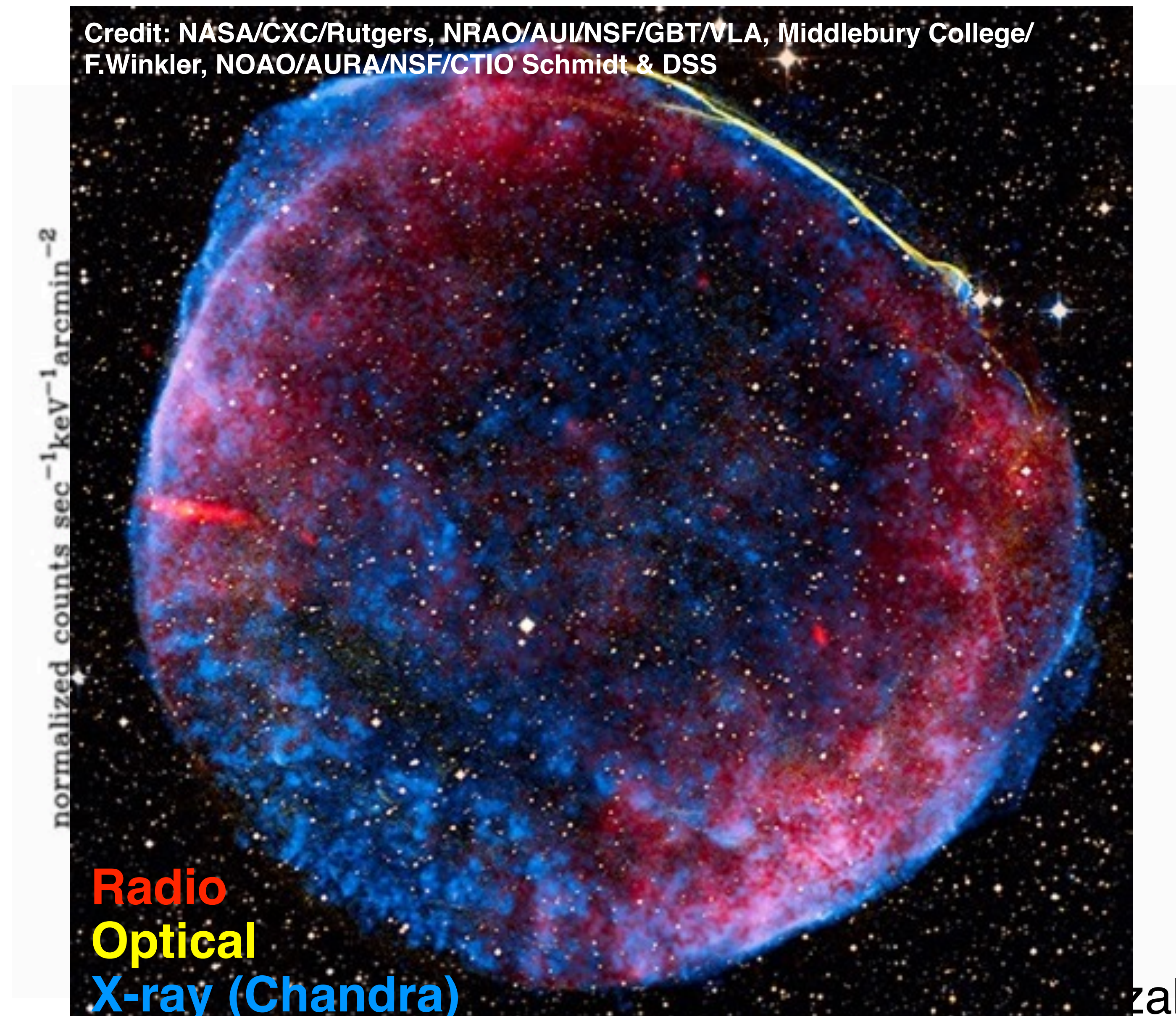

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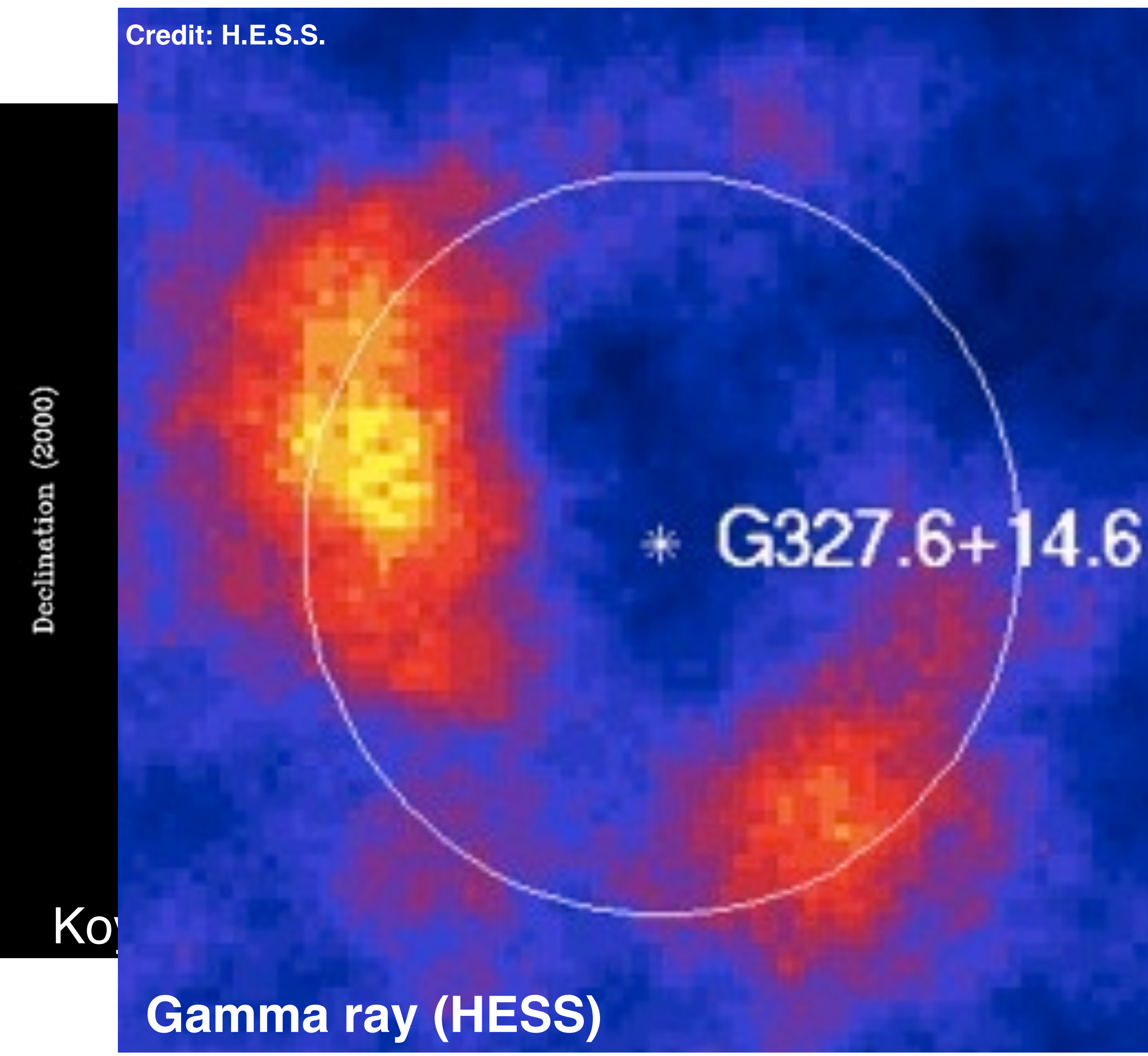
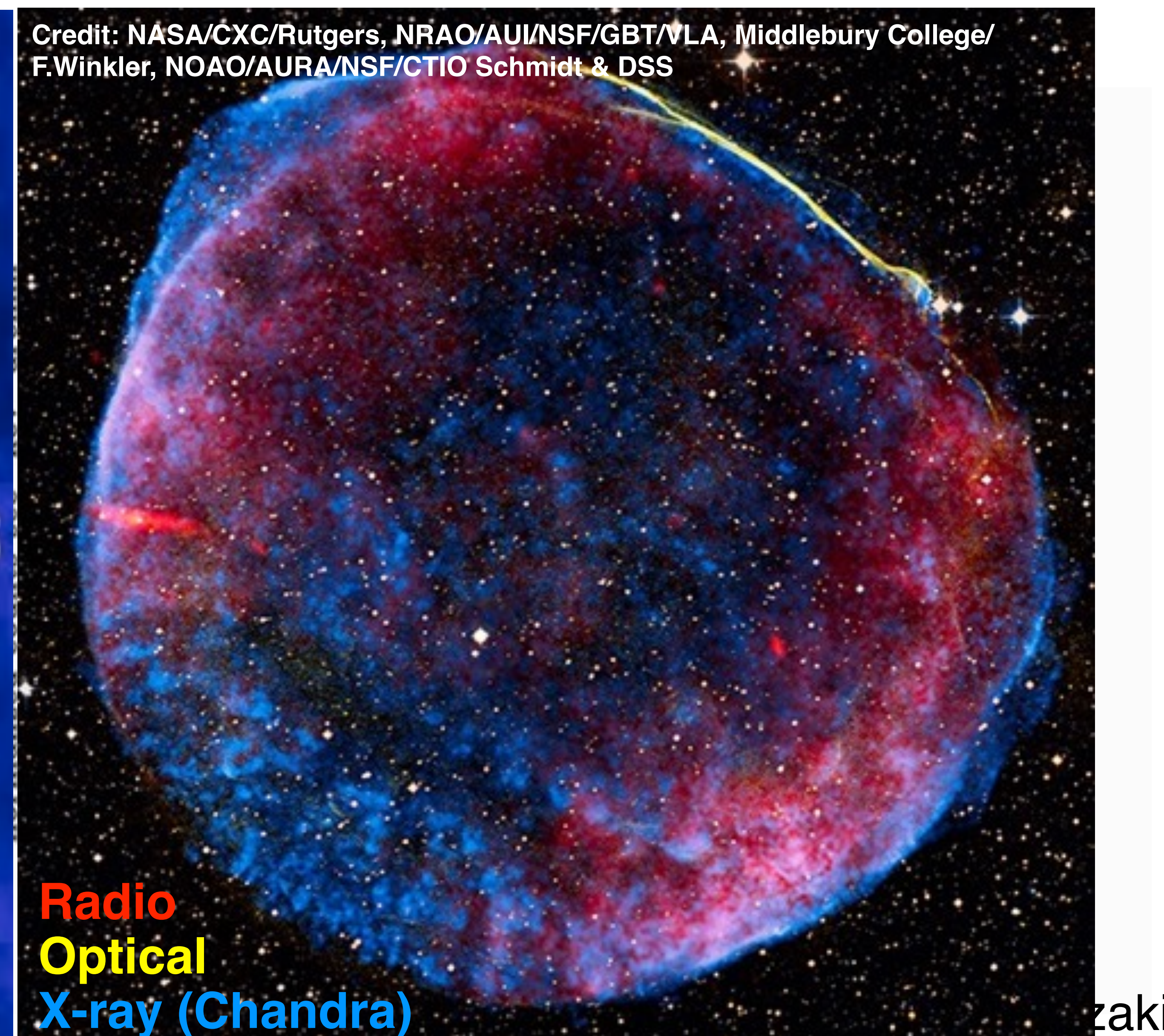
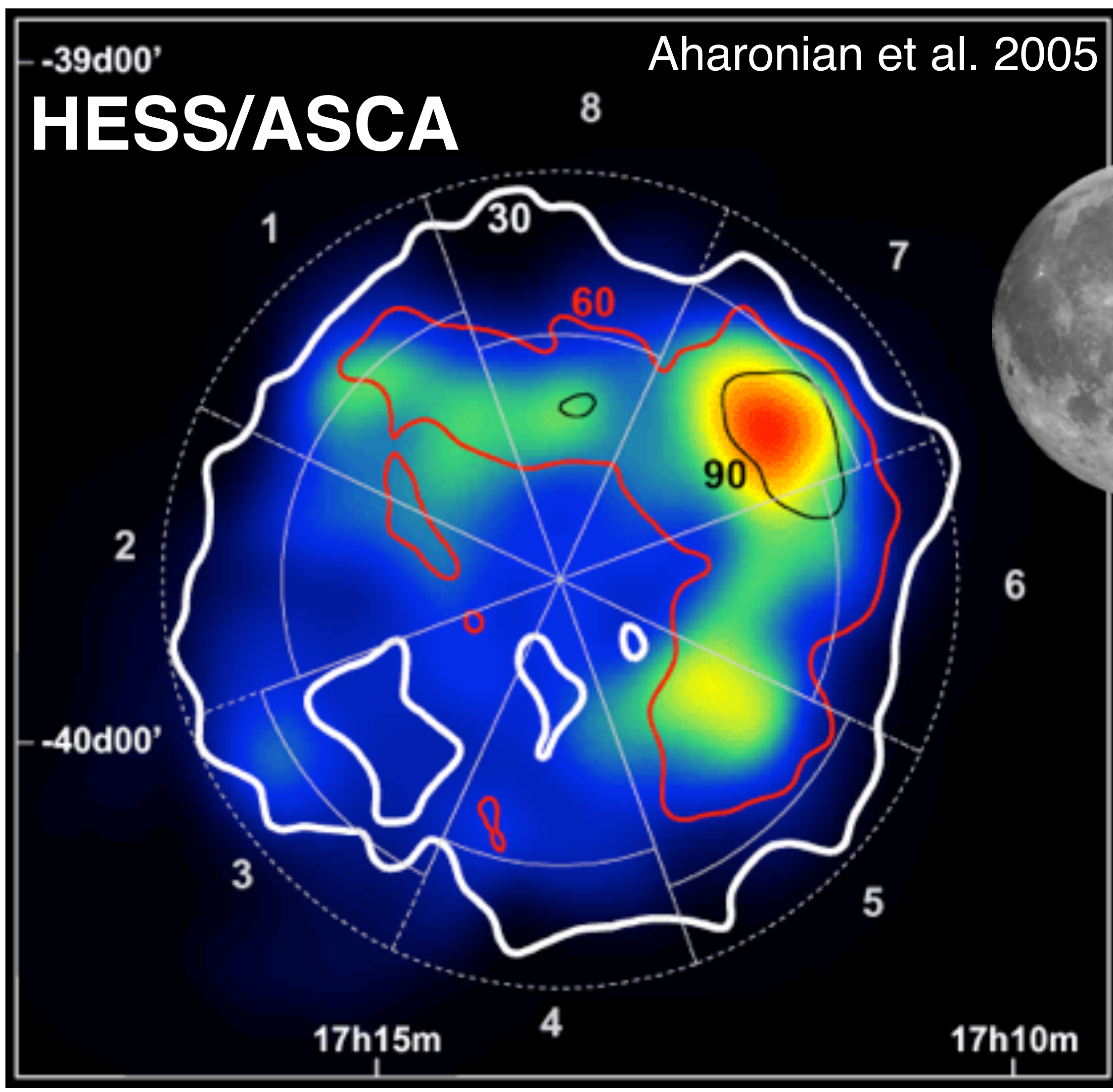


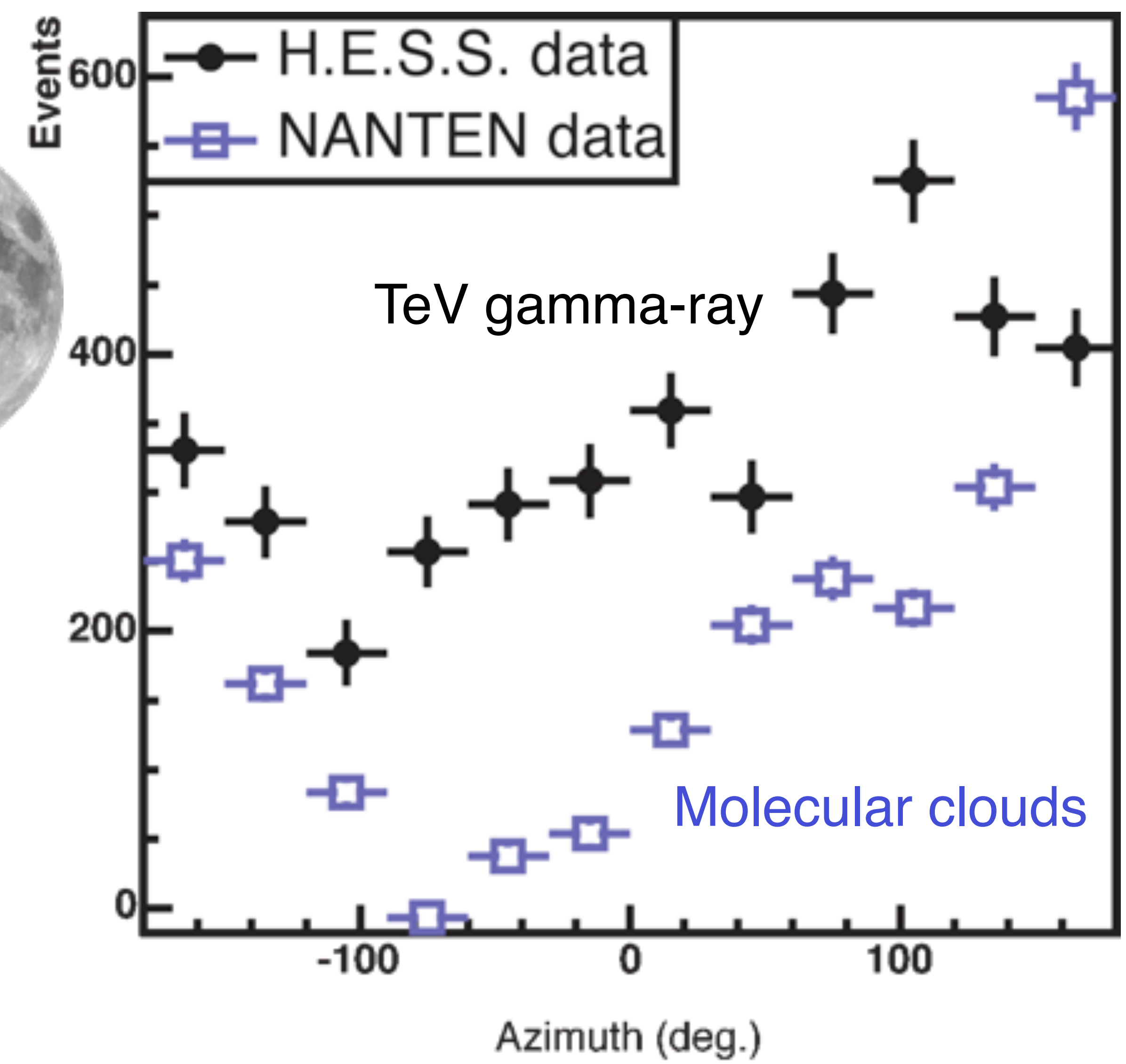


“Gold-Plated” Supernova Remnant

- **HESS TeV gamma-ray observation of RX J1713.7-3946**
  - **Evidence for particle acceleration > 10^{14} eV**
  - **Morphological similarity with X-ray observation**
  - **Spectral feature can not conclusively distinguish leptonic or hadronic origin of gamma rays**

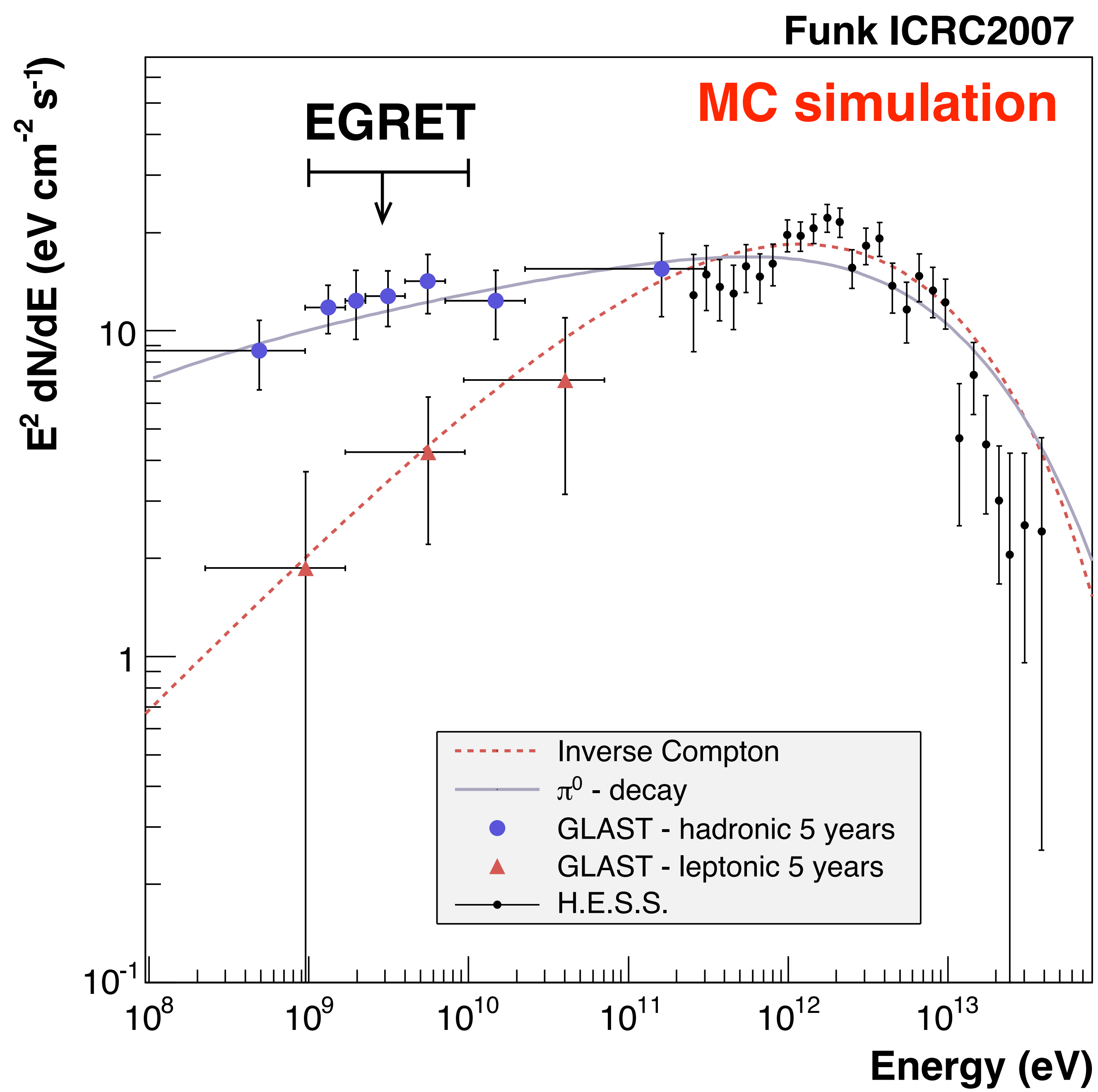


Aharonian et al. 2005



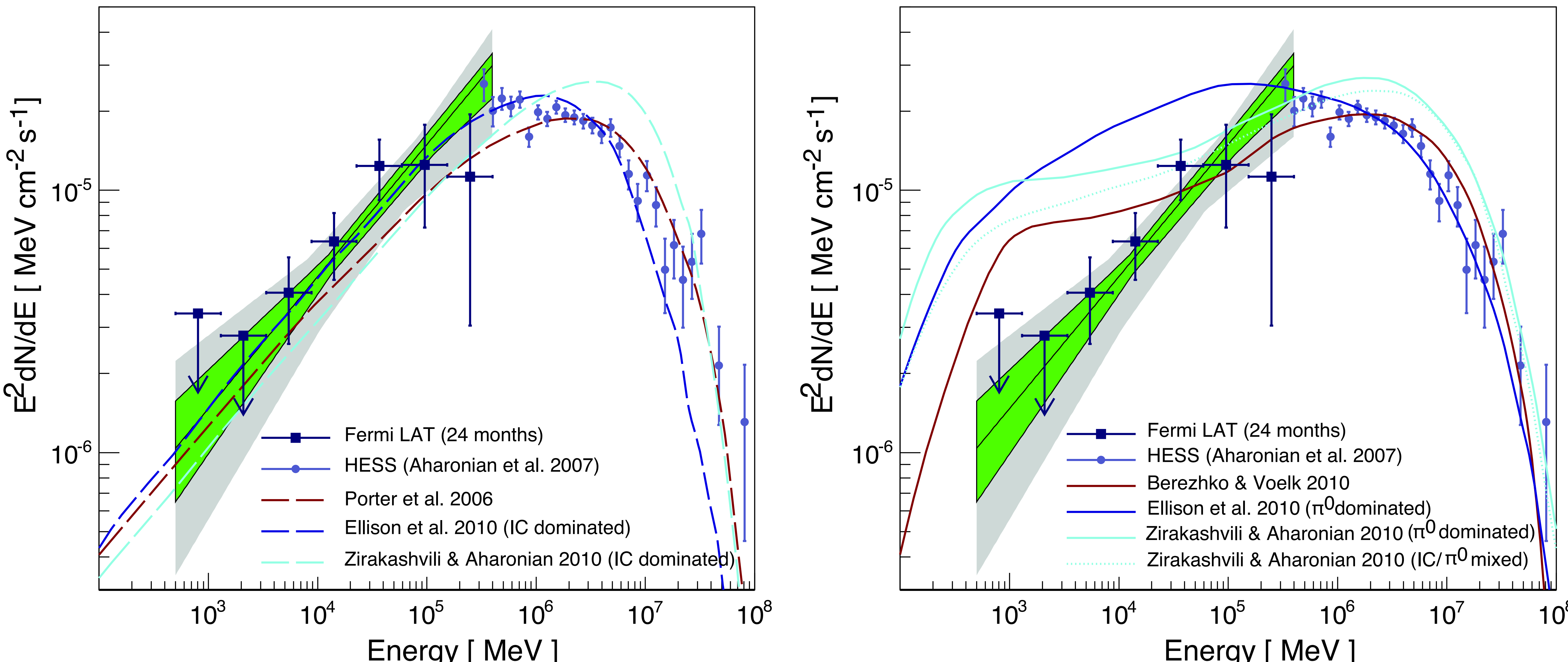
Expected Fermi Spectrum for J1713

- Simulated 5-year Fermi observation of RX J1713-3946
  - Fermi is expected to positively identify hadronic contribution



Fermi Observation of RX J1713.7-3946

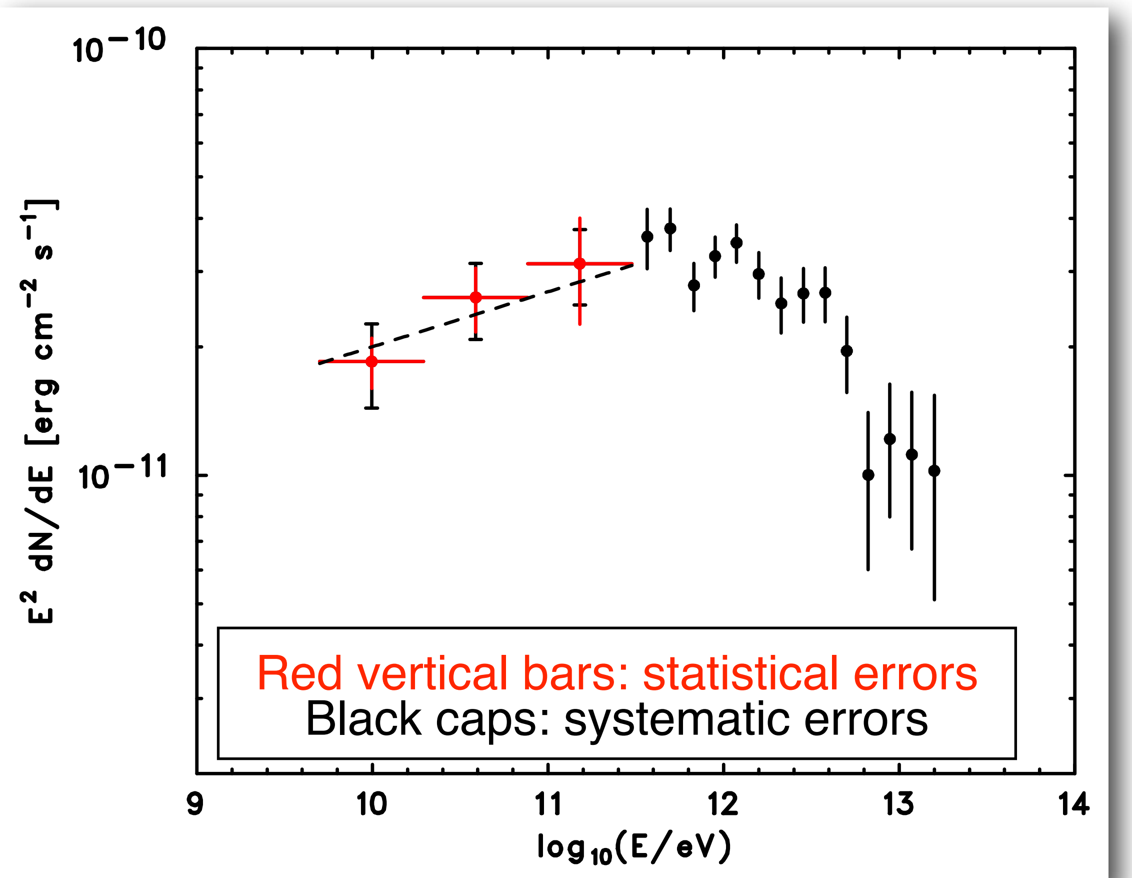
- Data from 2-year Fermi observation
  - Leptonic model may explain the Fermi spectrum better
  - Requires more statistics to distinguish hadronic or leptonic nature of gamma-ray emissions

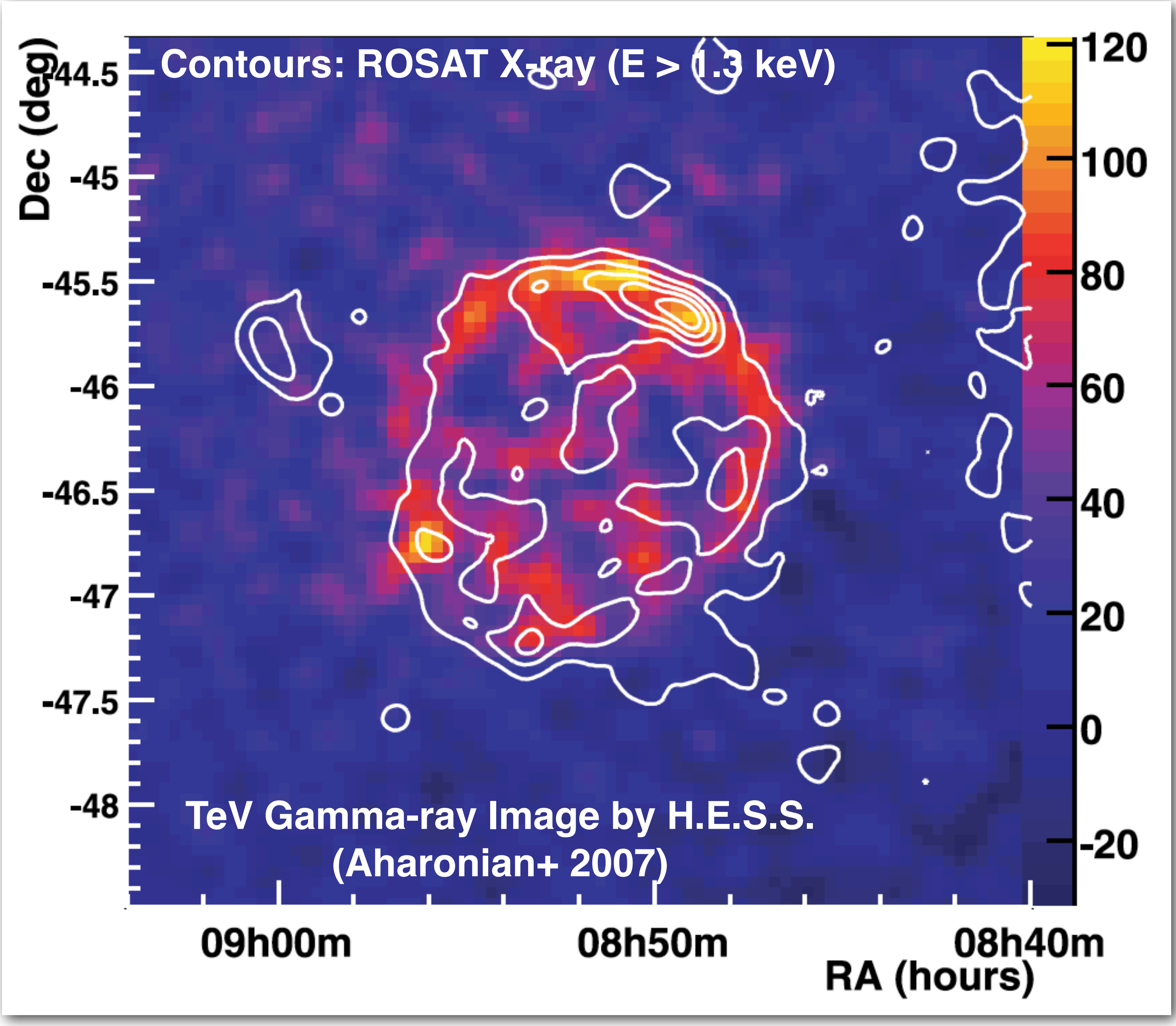


2011, ApJ, 734, 28

RX J0852.0–4622: Another TeV SNR

- **B = 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}**





2011, ApJL, 740, L51

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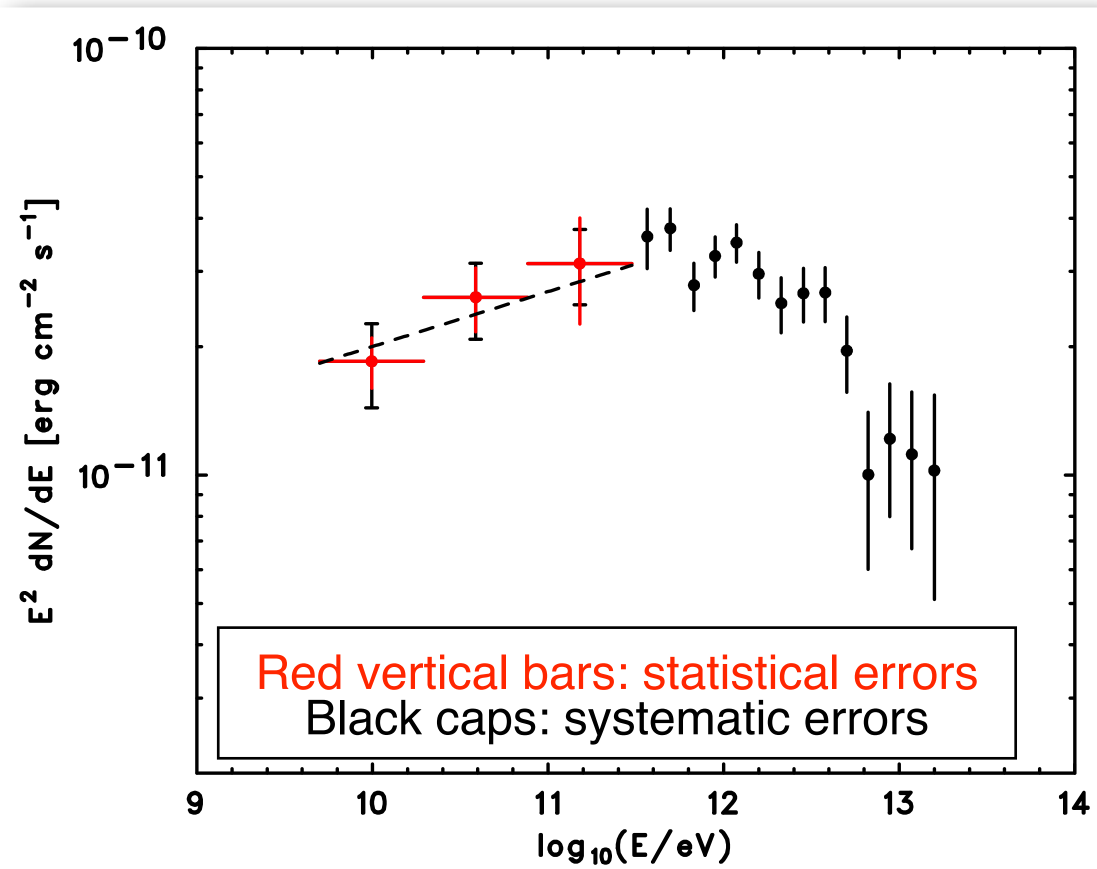
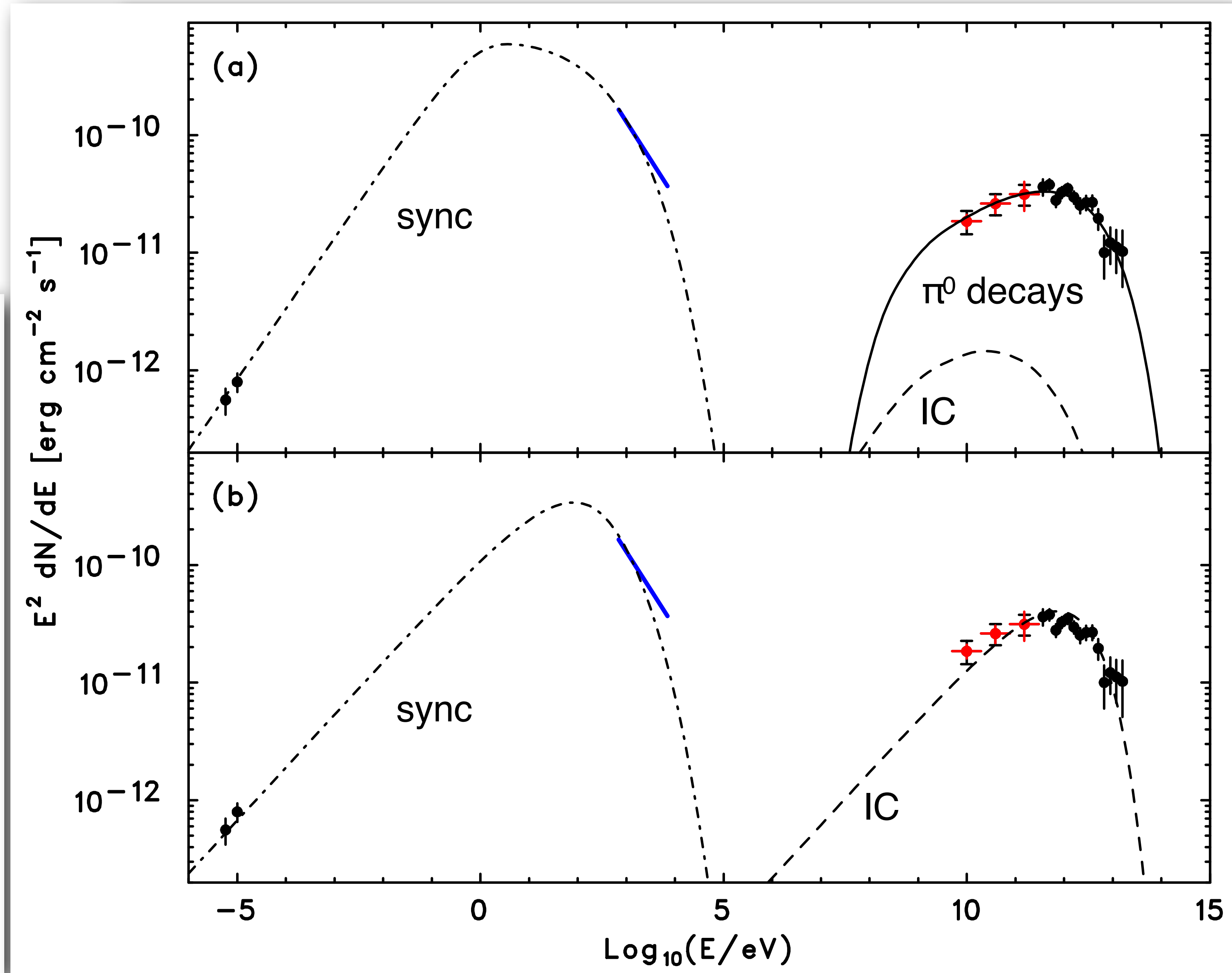
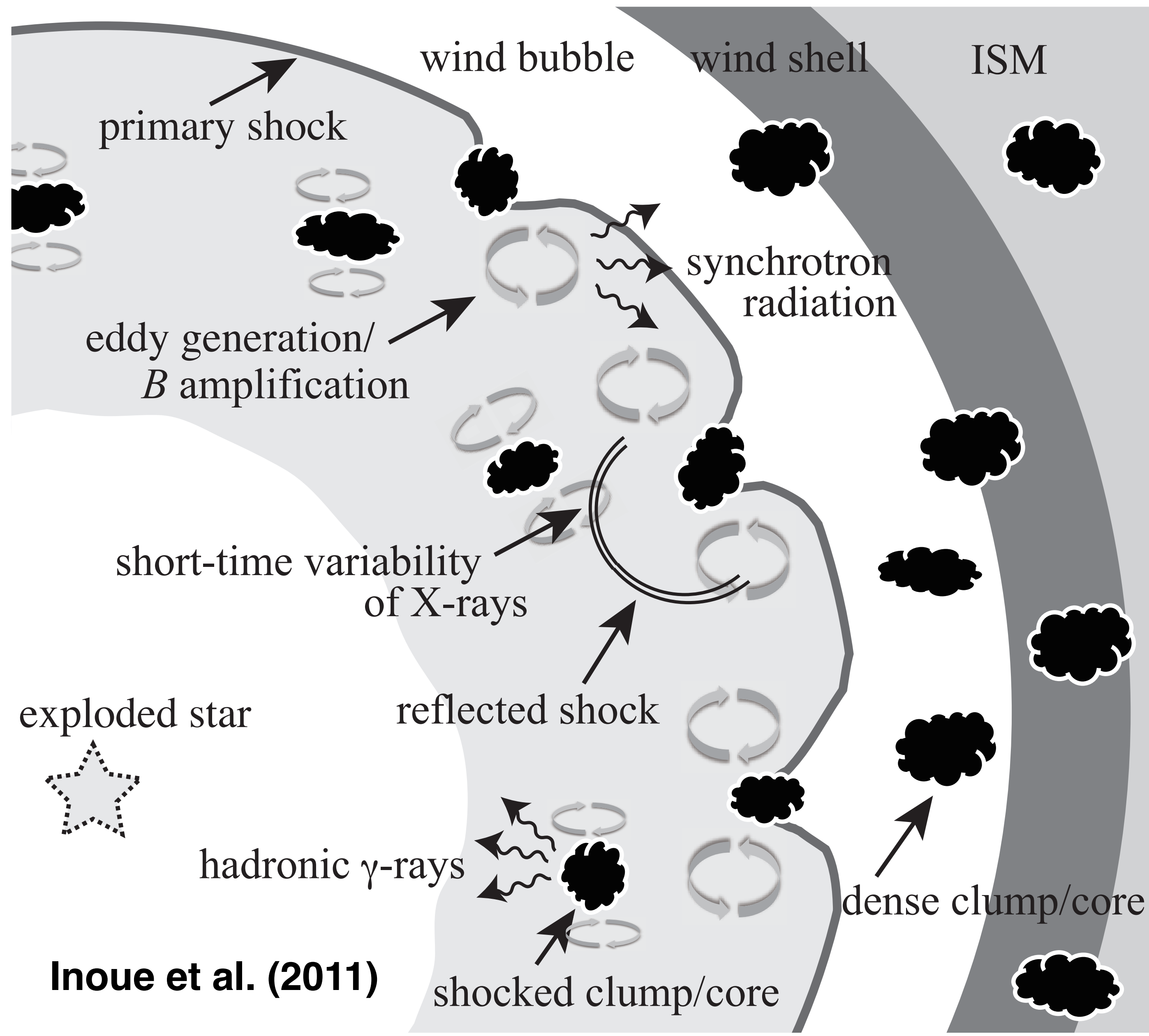




2011, ApJL, 740, L51

Hard Gamma-Ray Spectra

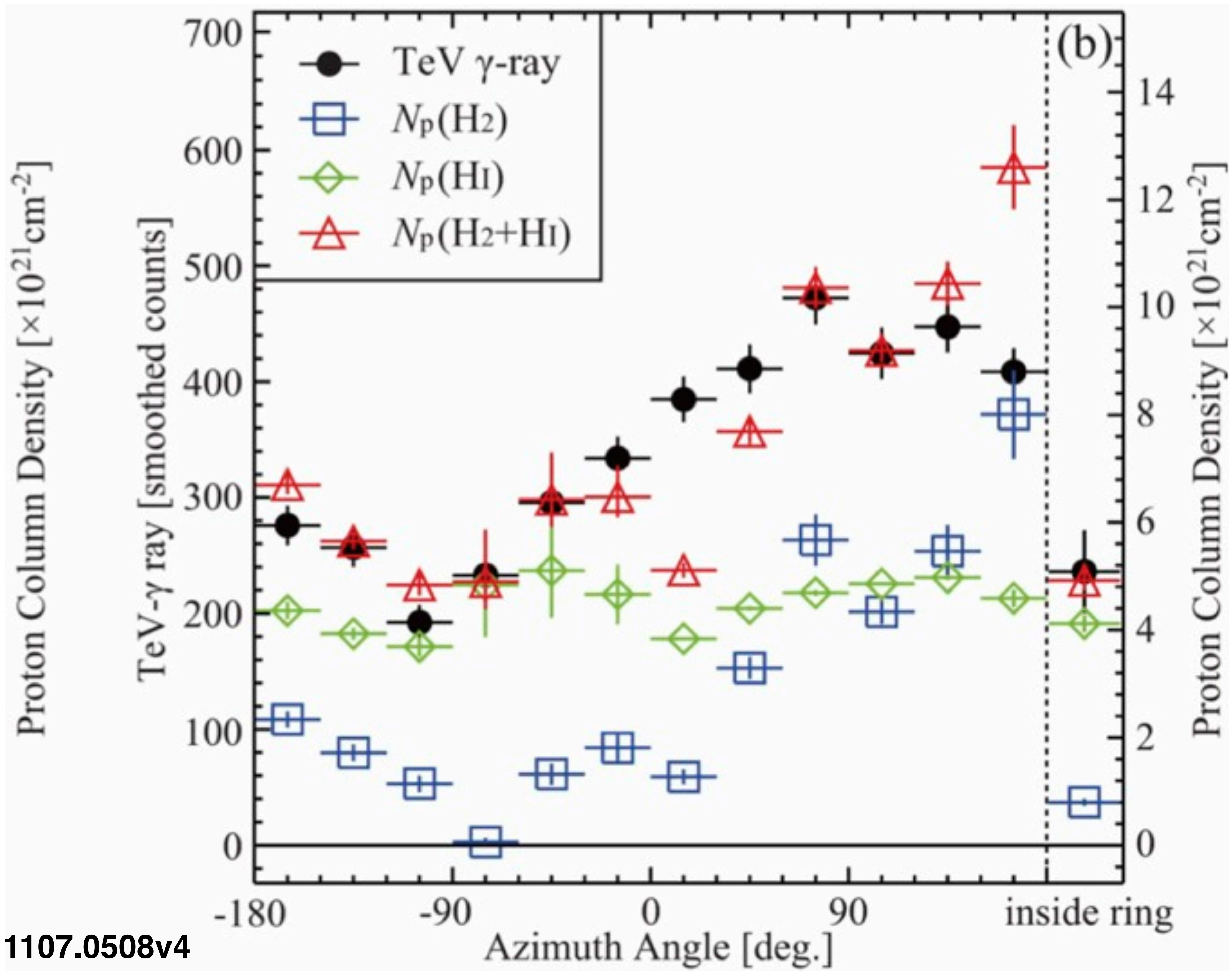
- Hard gamma-ray can be explained by higher target density for higher energy particles
  - Highly inhomogeneous molecular clouds interacting with SNR
  - Higher energy protons can penetrate into the cloud core where target gas density is high



Inoue et al. (2011)

Correlation with Matter Density

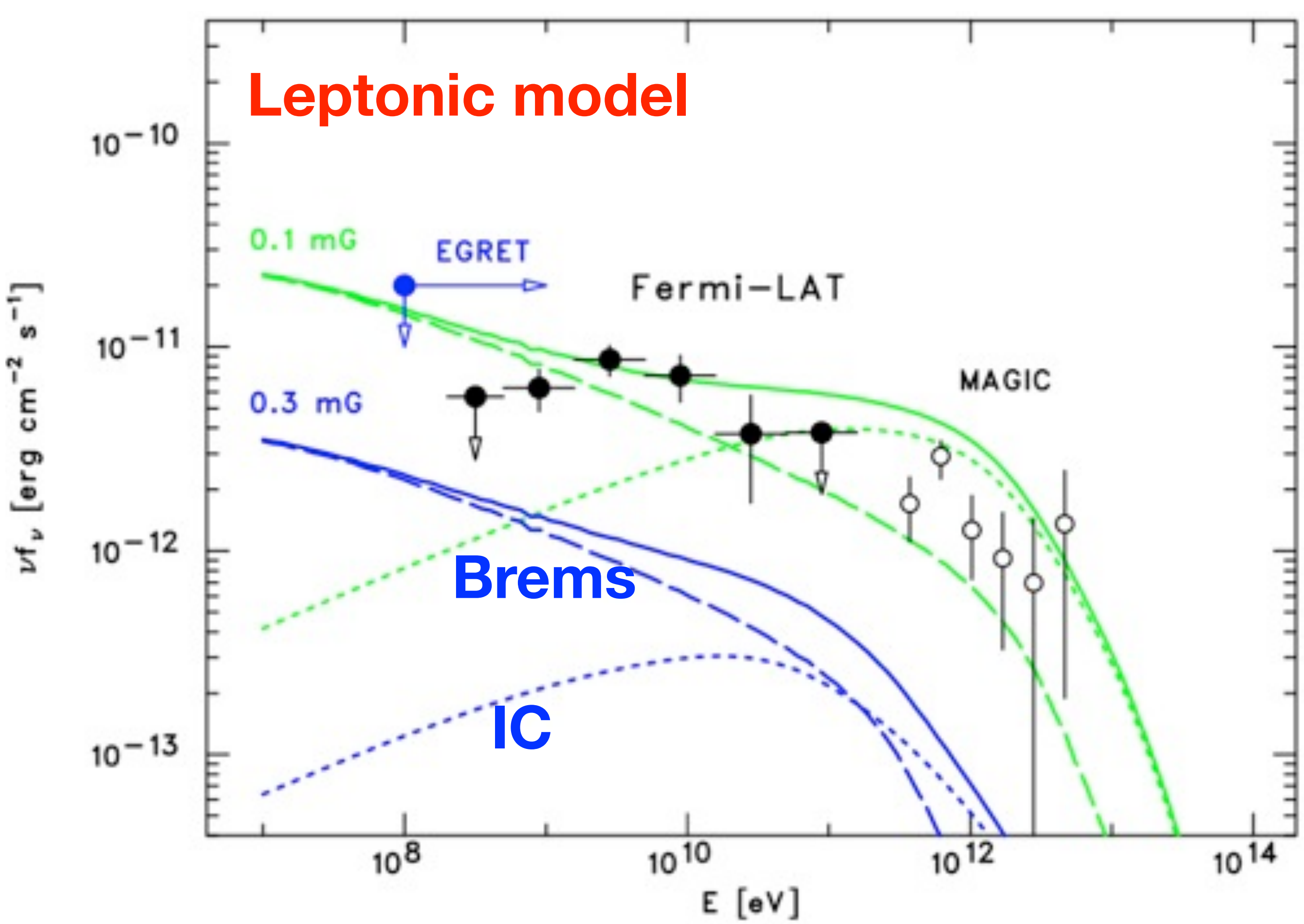
- Sum of molecular and atomic hydrogen gives good correlation with TeV gamma-ray intensity

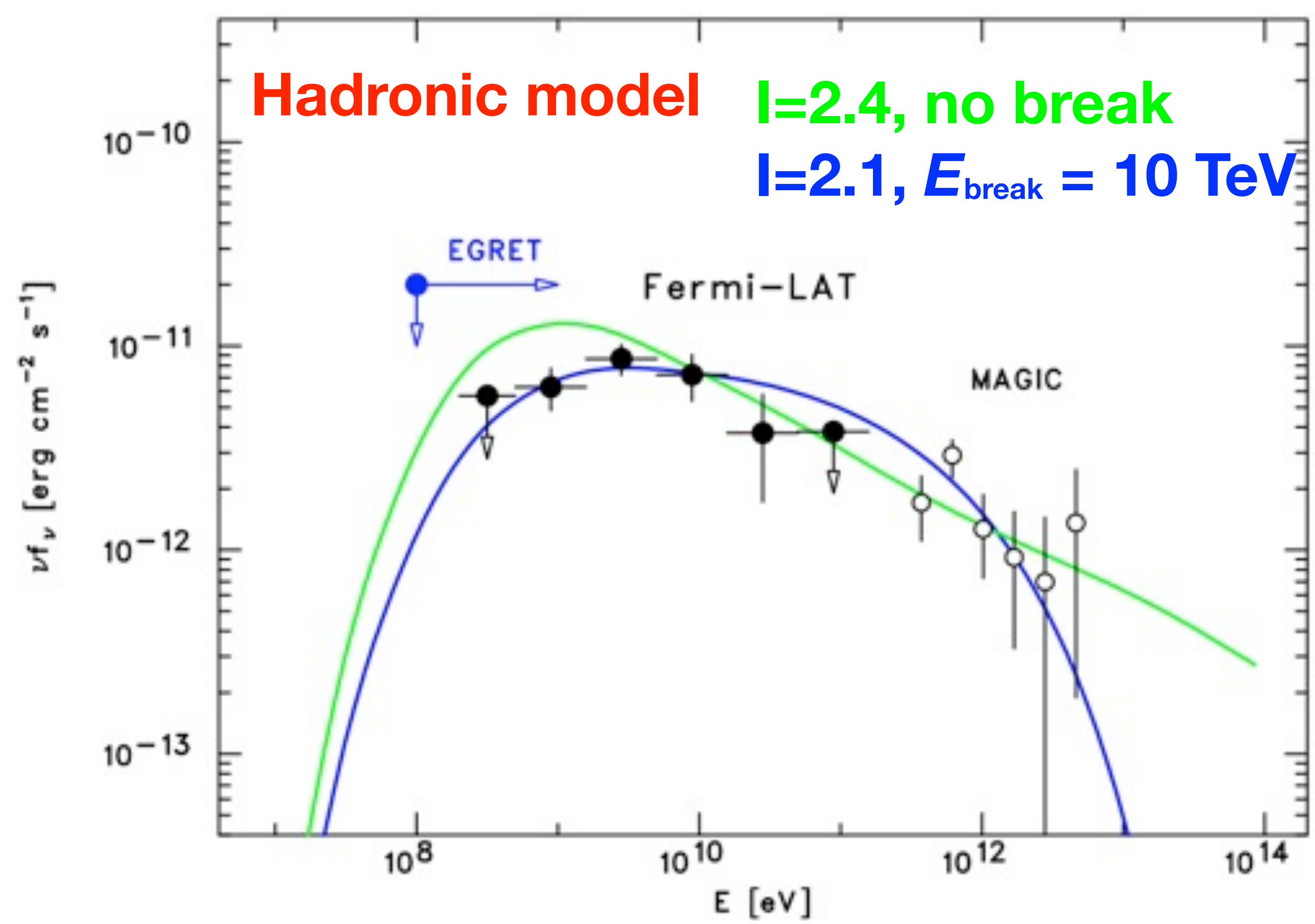


Fukui et al. arXiv 1107.0508v4

Young SNR Cassiopeia A

- Last SNR witnessed by human (AD 1680)
- Both leptonic and hadronic interpretation possible
  - Leptonic (Bremsstrahlung + IC)
    - B ~ 0.12 mG, W_e ~ 1×10^{49} erg
    - Not consistent with X-ray variability (B ~ 0.5 mG)
  - Hadronic (π^0 decay)
    - B > 0.12 mG, W_p ~ 5×10^{49} erg





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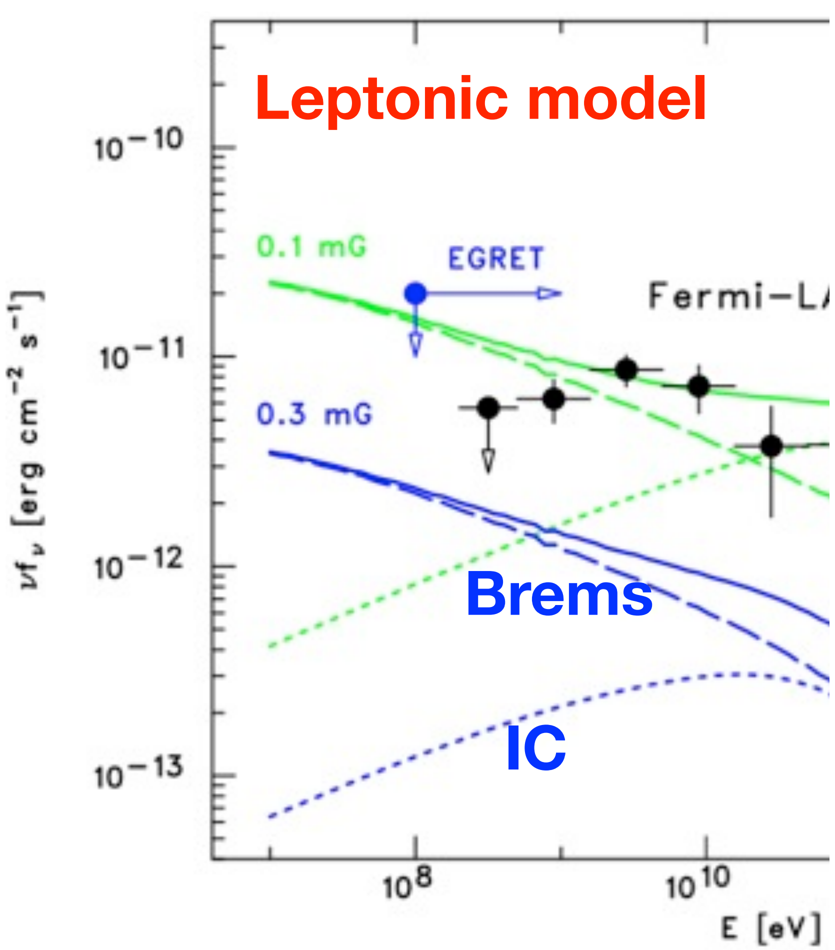
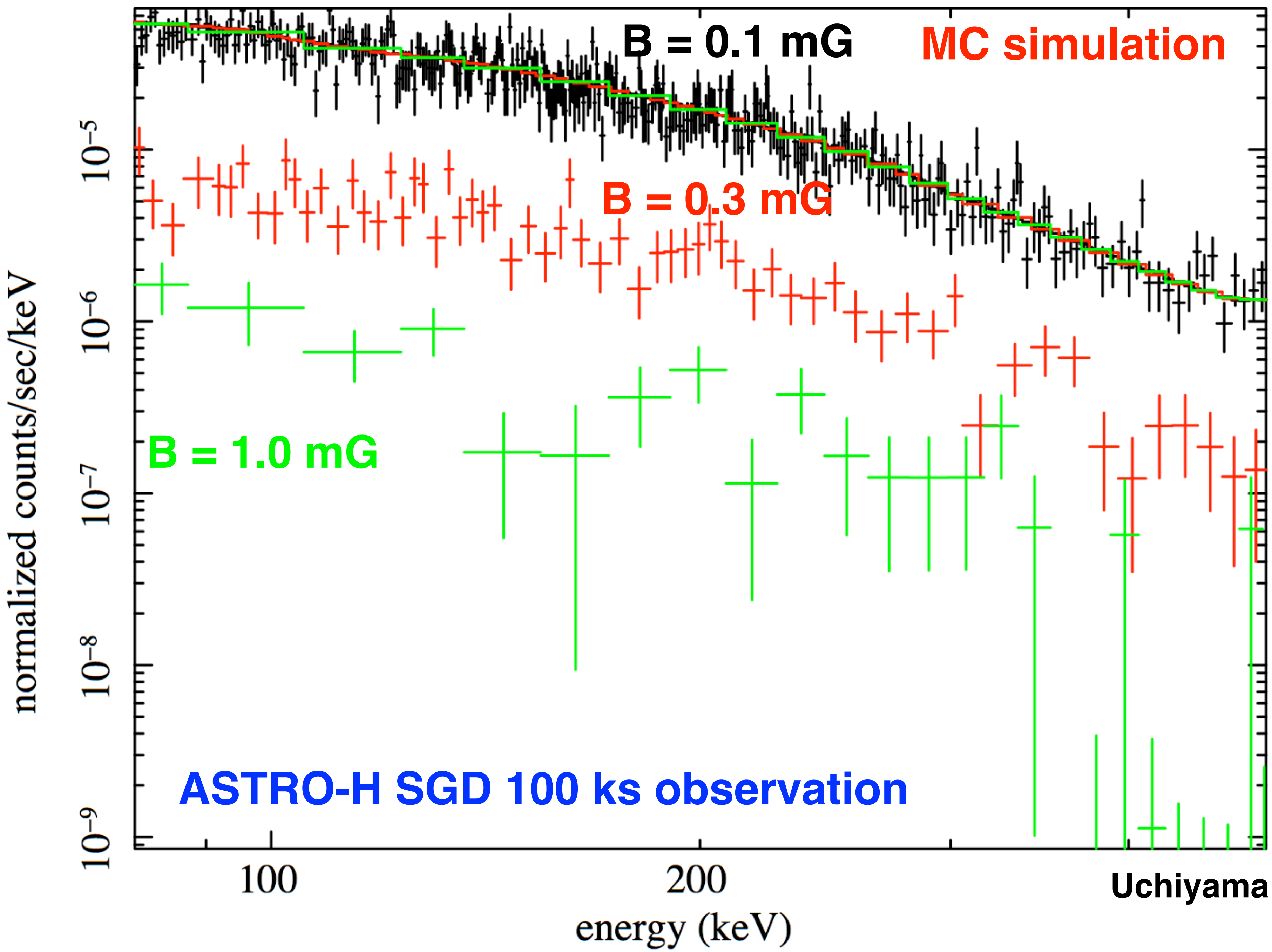
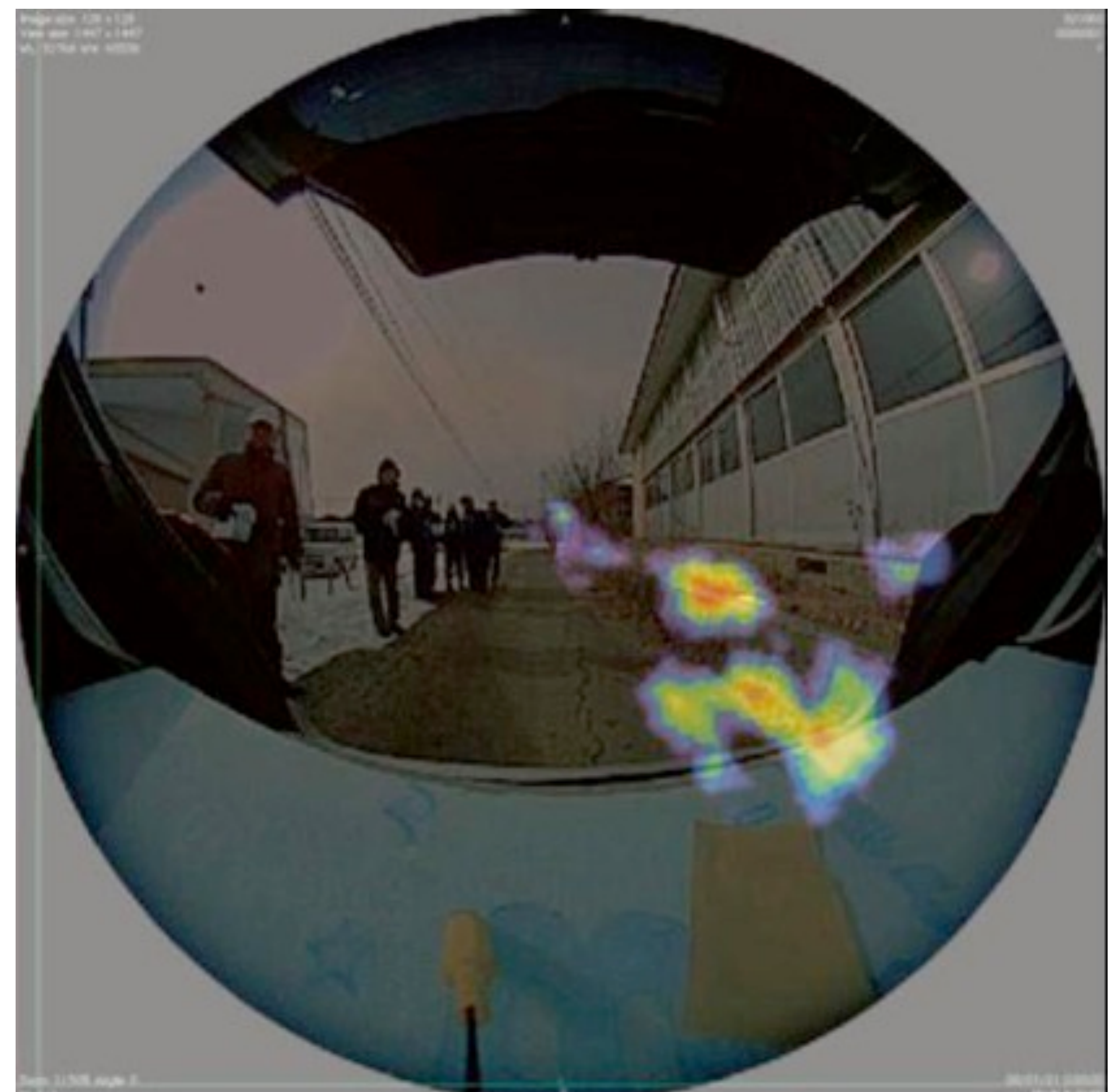




Uchiyama

ASTRO-H Soft Gamma-ray Detector

- Taking advantage of Japanese semiconductor detector technologies and space technologies
  - Silicon sensors by Hamamatsu photonics
  - Space instrument assembly (Mitsubishi Heavy Industries)
  - Visualization of gamma-ray sources such as radio isotopes
    - Technology transfer to accelerate removal of Cs hotspots in Fukushima



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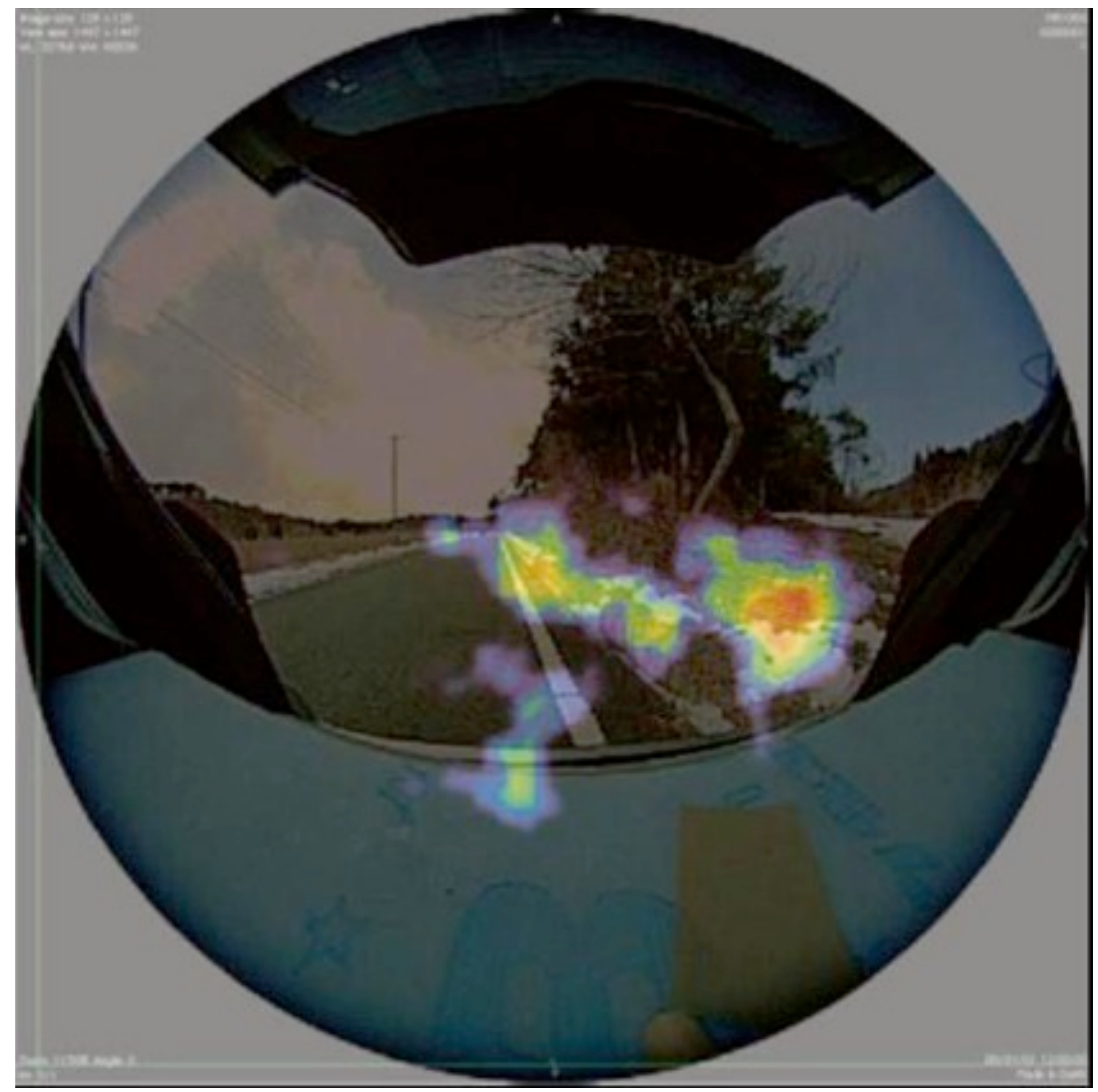
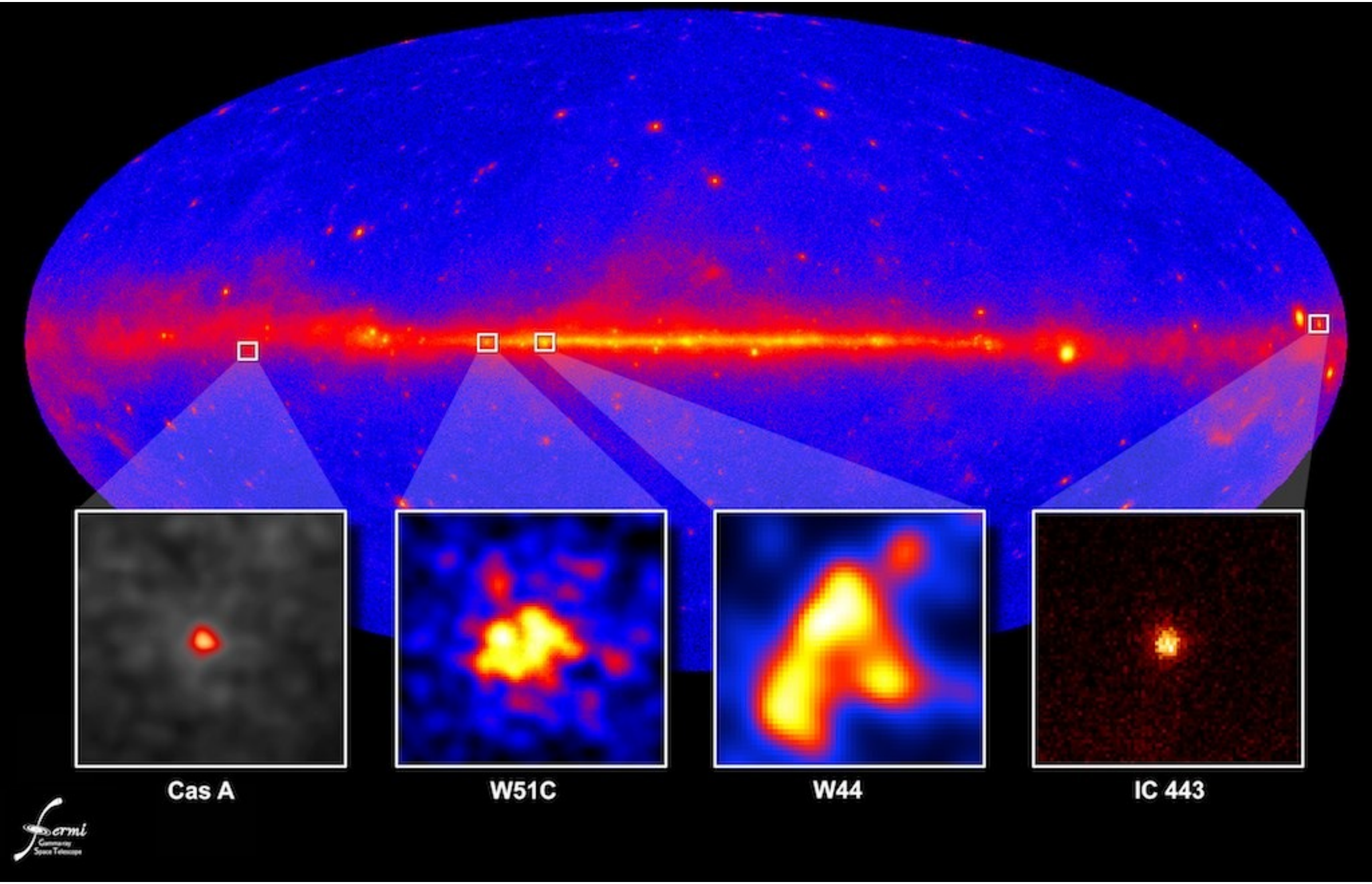


Fermi Observations of middle-aged SNRs



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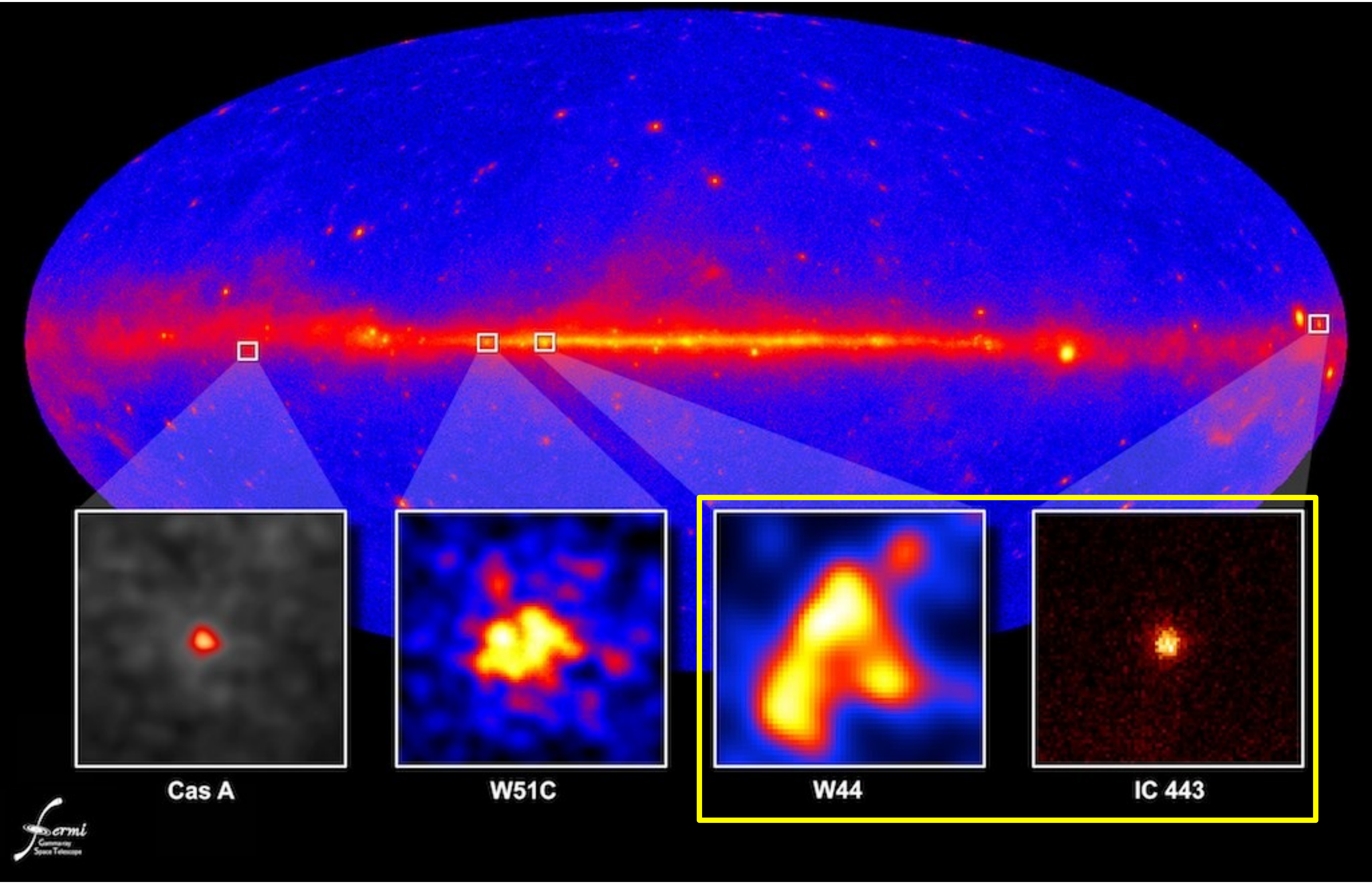
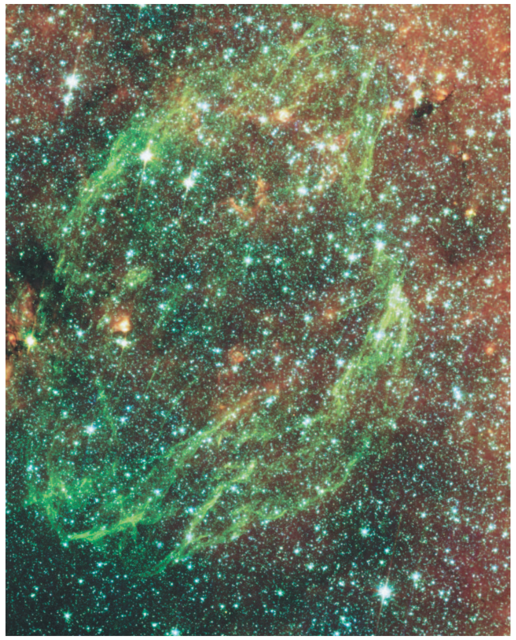


W44 Gamma-ray Image

- **Deconvolved image indicates shell-like gamma-ray emission**
- **Maximum likelihood analysis prefer ring-like morphology rather than disk-like morphology (> 8 σ)**

Middle-aged (~ 2.0×10^4 yr)
mixed-morphology SNR
(radio: shell, thermal X-ray: centrally filled)
Distance: ~ 3 kpc

Cloud-shell interactions
CO (Seta et al. 2004)
OH maser (Hoffman et al. 2005)



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

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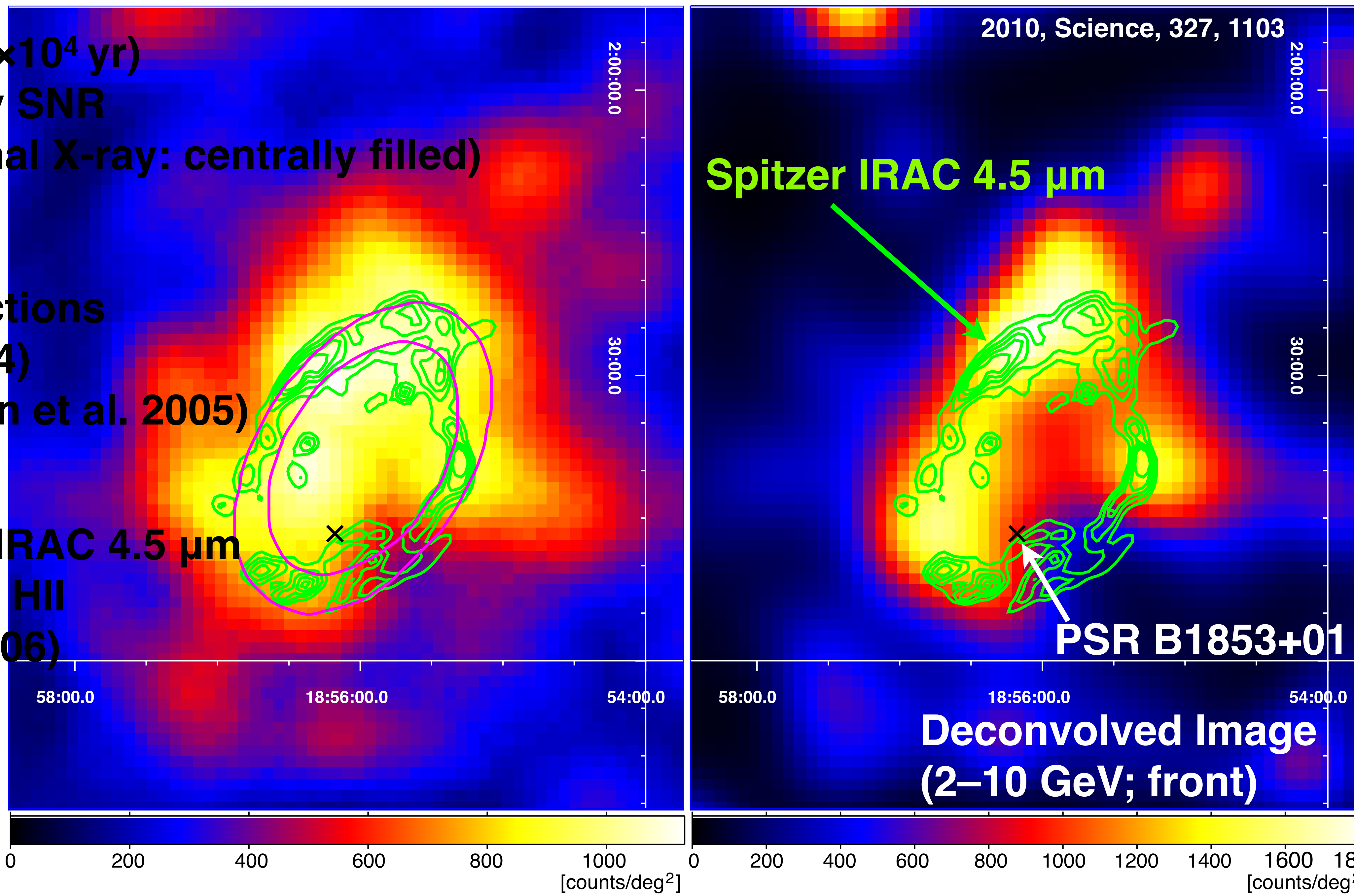

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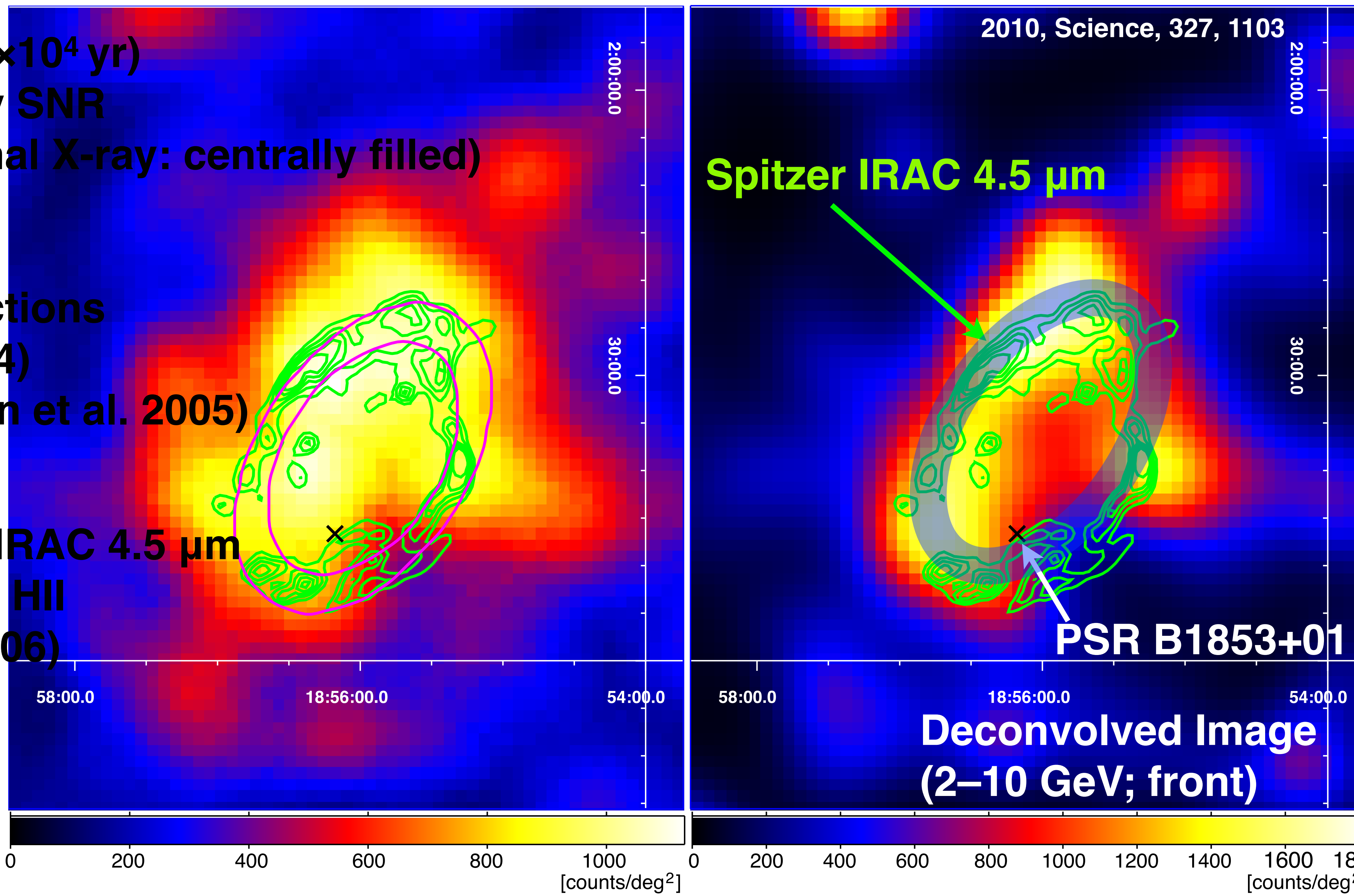
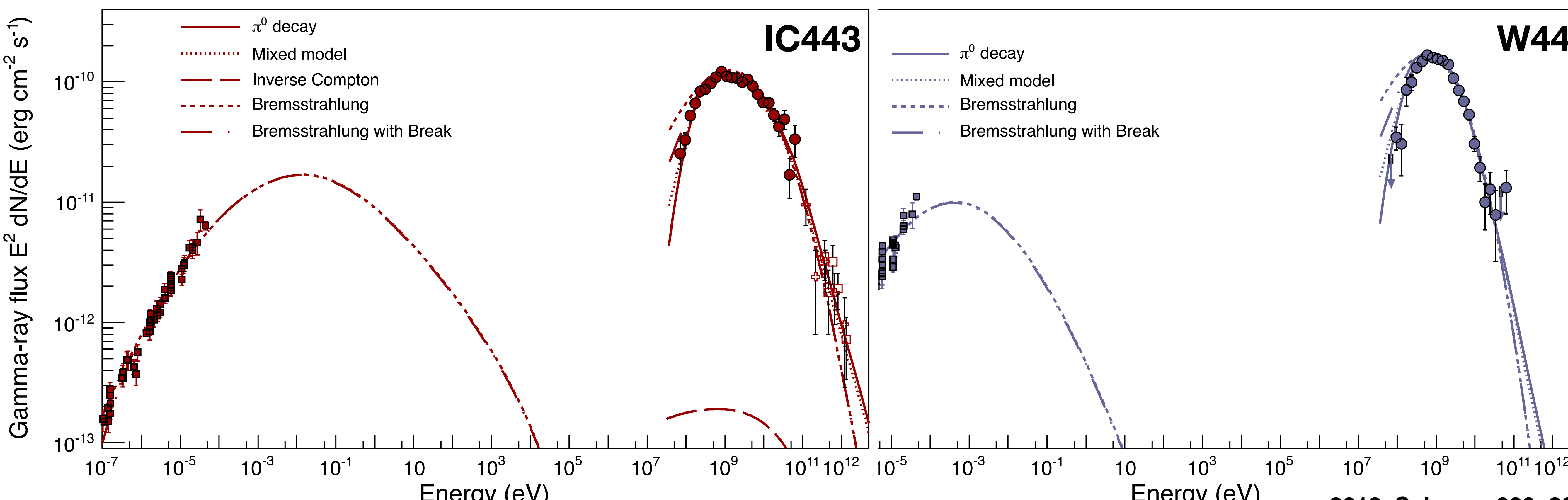


“Smoking gun” Signature of π^0-decay γ-rays

- Compton up-scattering
  - Energetically completely disfavored (x100 higher radiation fields)
  - Shape not consistent with Compton up-scattering
- Best-fit Bremsstrahlung model shows less steep decline
  - Even with abrupt cutoff at 300 MeV in electron spectrum
  - Mixed model requires $N_e/N_p = 0.01$ (@ $p = 1$ GeV/c)
- Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra



2013, Science, 339, 807

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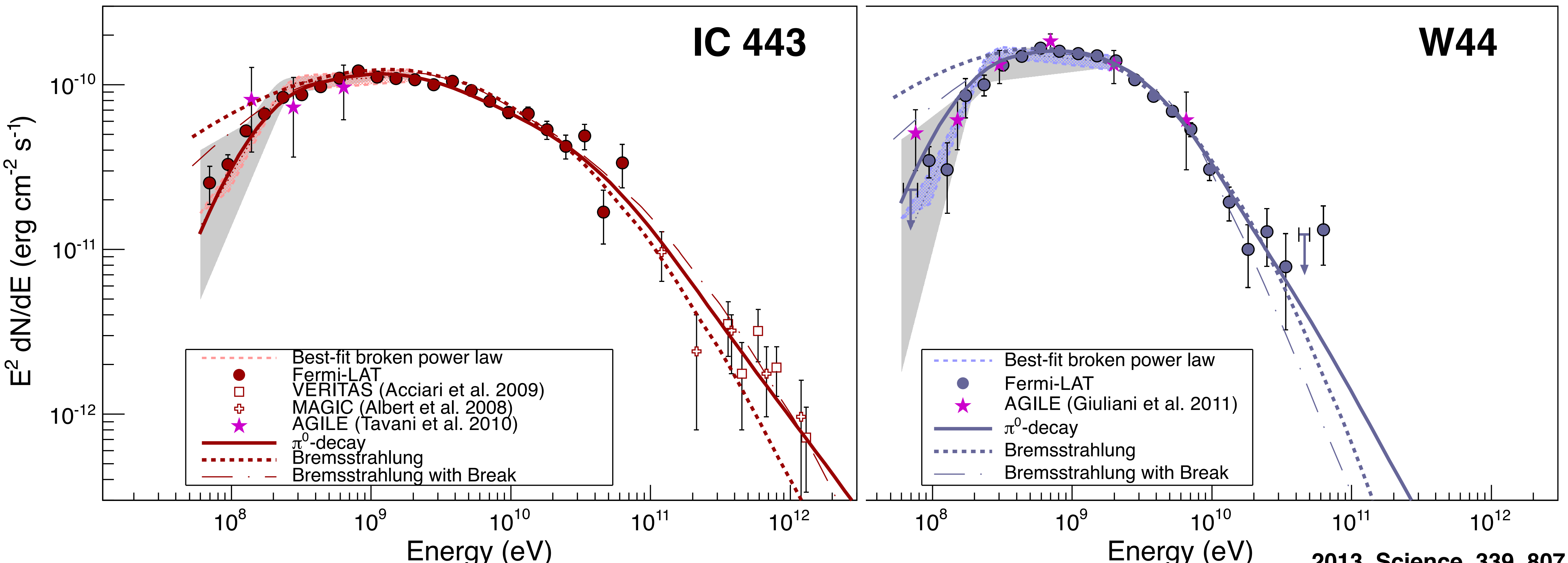
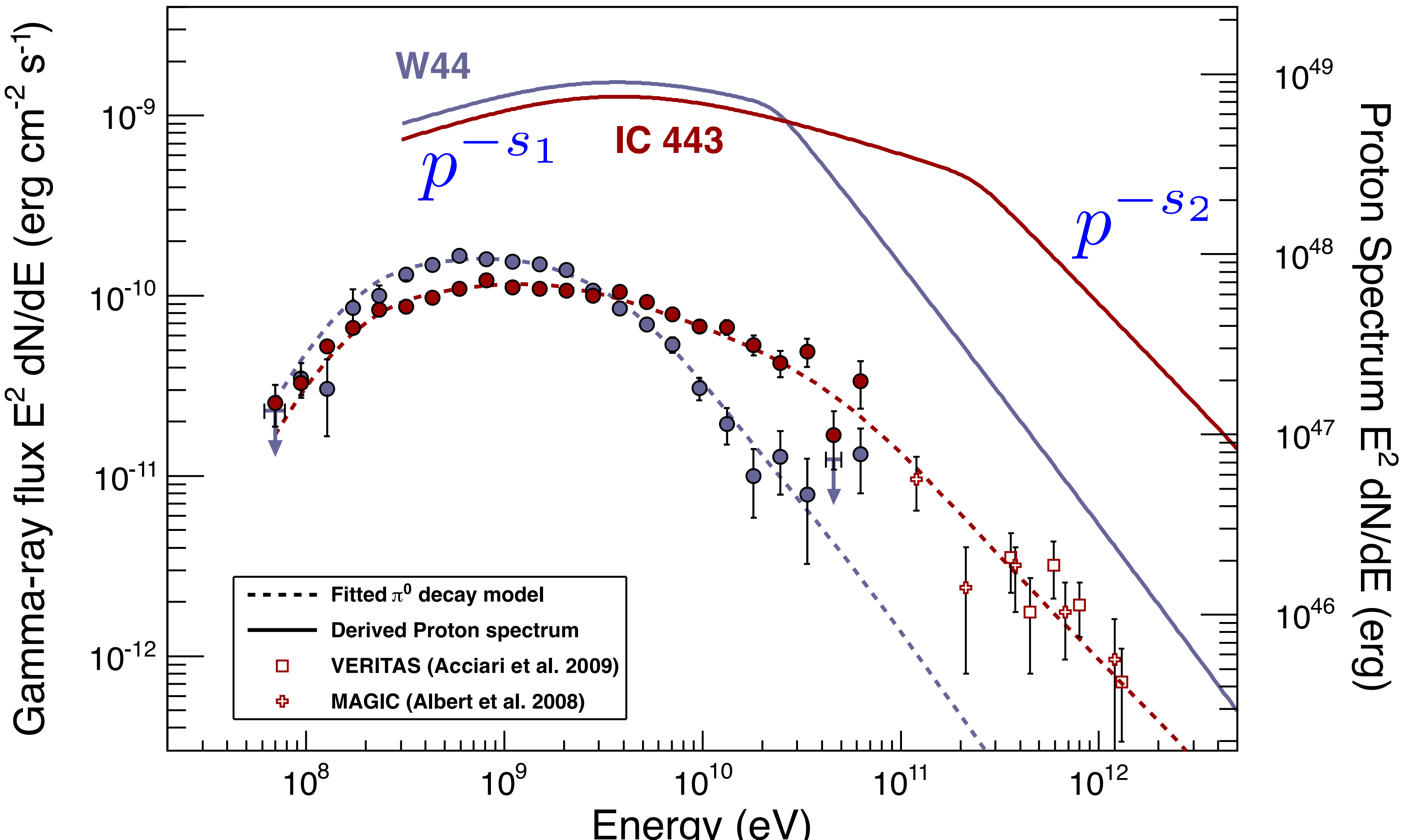


2013, Science, 339, 807

Cosmic-ray Proton Spectrum

- s_1 = 2.36±0.05, s_2 = 3.1±0.1 (3.5±0.1) p_{br} =239±74 (22±8) GeV/c (for IC 443)
  - Below the break: proton spectrum softer than electron spectrum ($s_{1,e}$ = 1.72)
- CR efficiency 1-4%. Strongly depends on assumed density

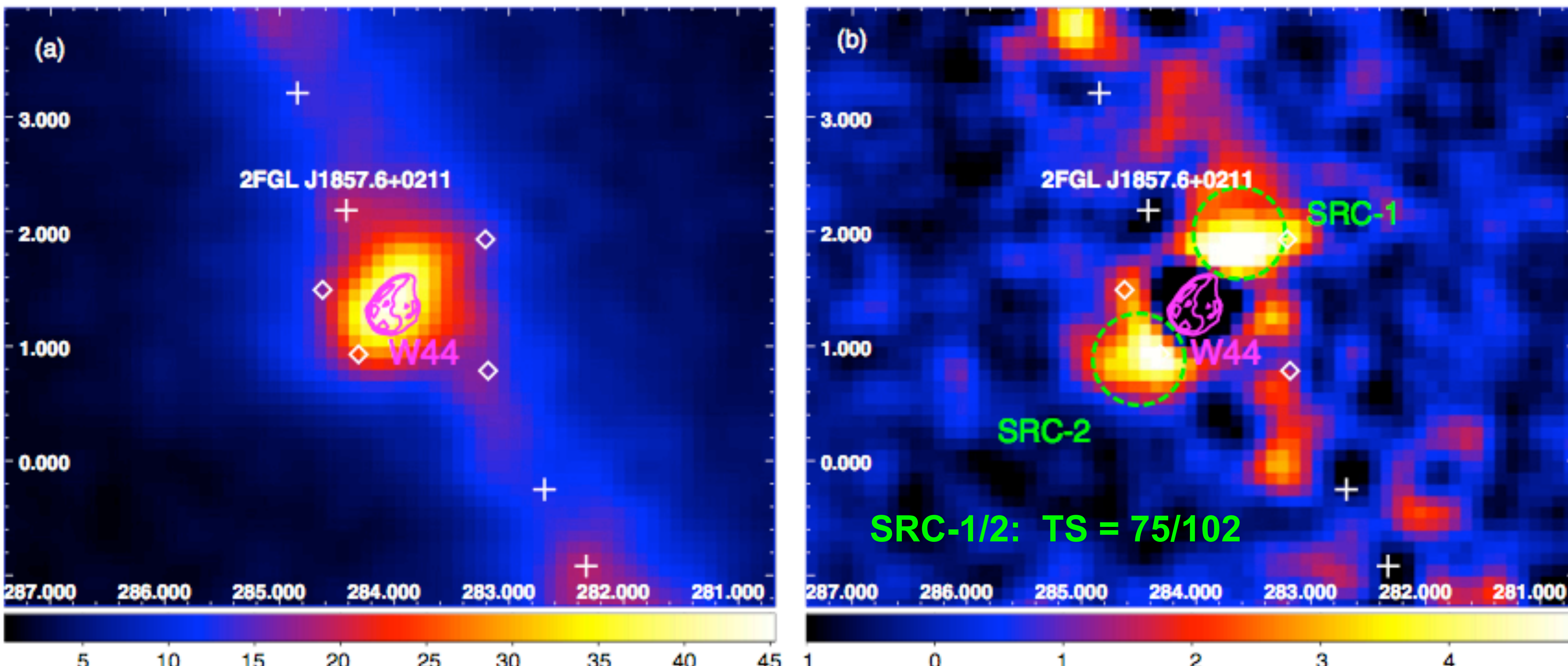


2013, Science, 339, 807

Cosmic-ray Escape from W44

- Large-scale GeV emission was found in the vicinity of W44

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



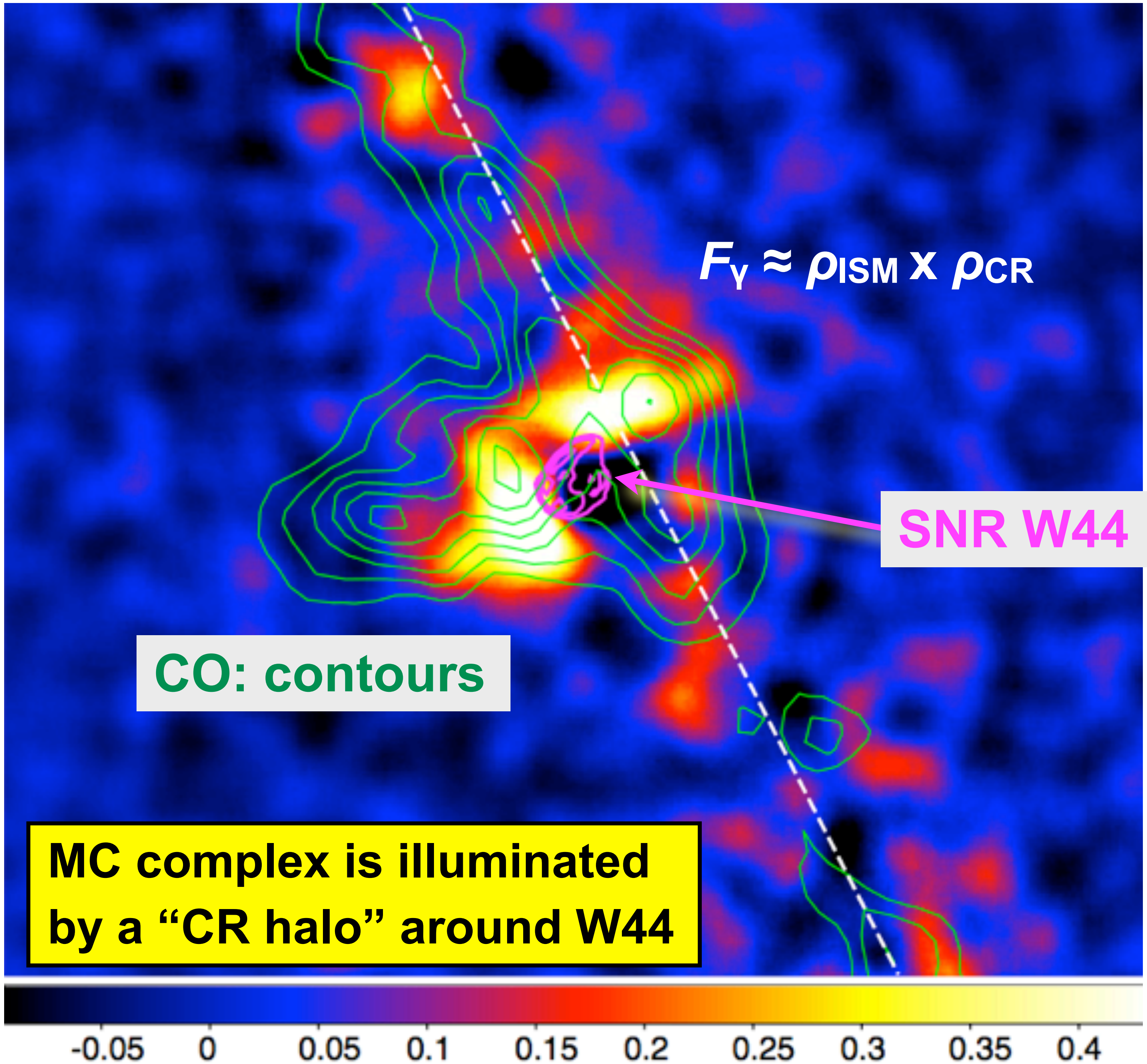
Subtraction of W44

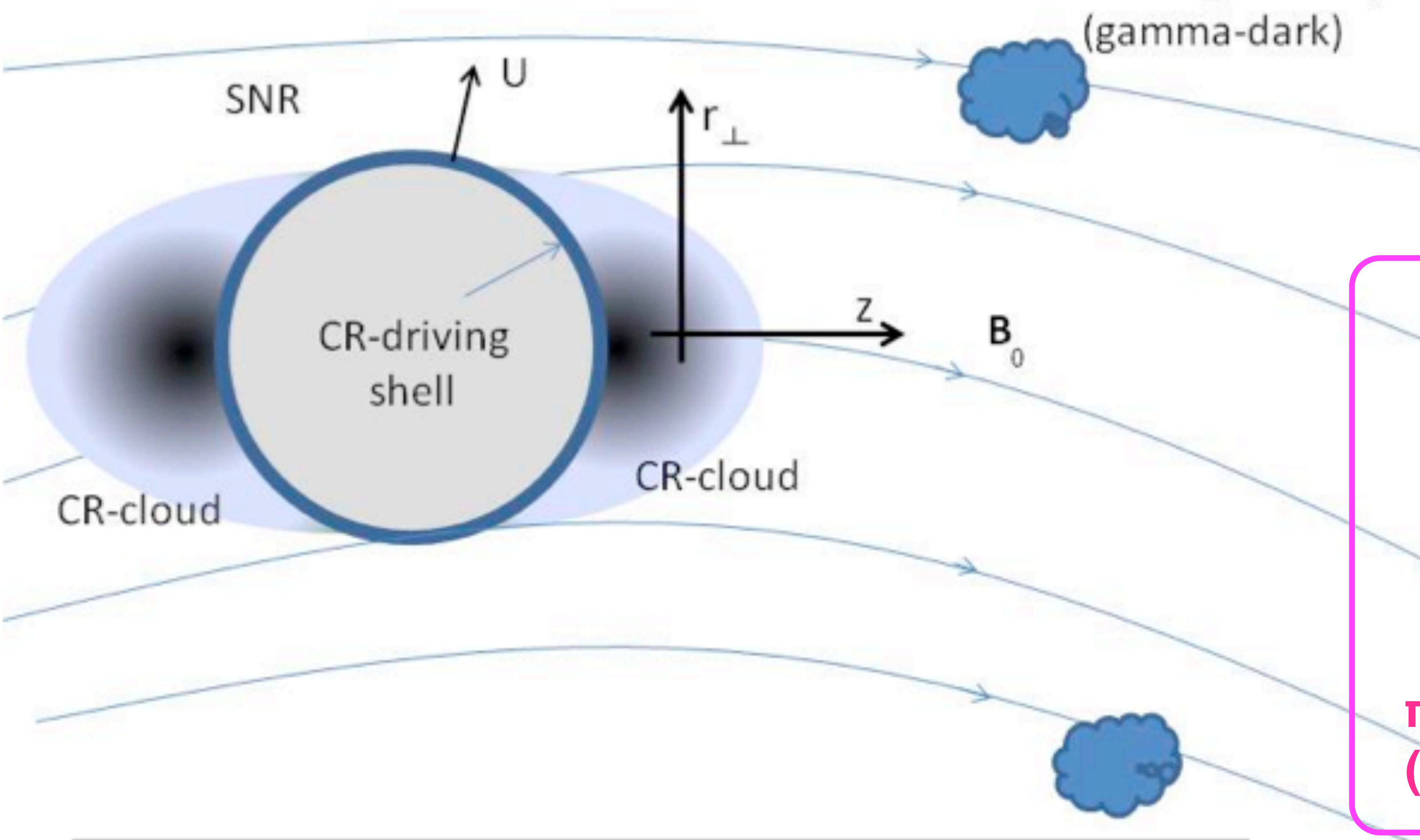
Gamma-rays from W44 itself are subtracted, assuming "radio map = gamma-ray map"

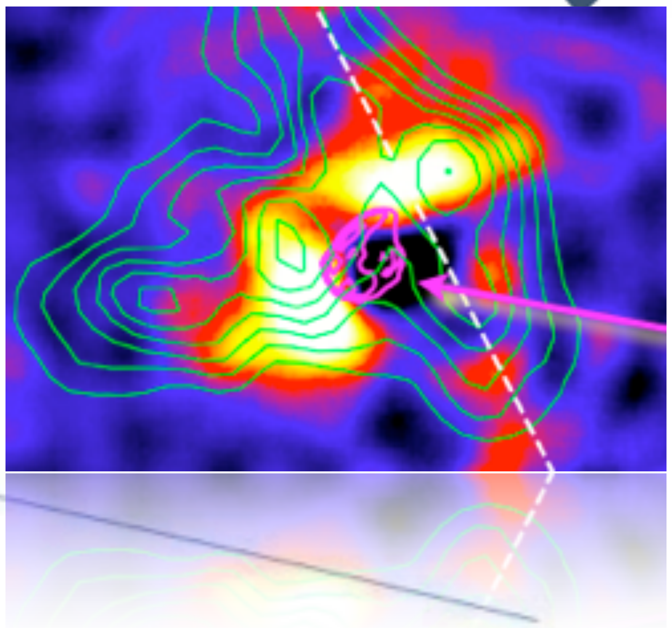
Uchiyama et al. (2012)

Large-scale GeV γ-rays vs CO map

- W44 is known to be surrounded by a complex of molecular clouds (CO)
- Size ~100 pc, Mass ~10^6 $M_\odot$ (Dame+1986)
- Amount of CRs escaped
  - W_{esc} = (0.3 – 3)×10^{50} erg depending on diffusion coefficient



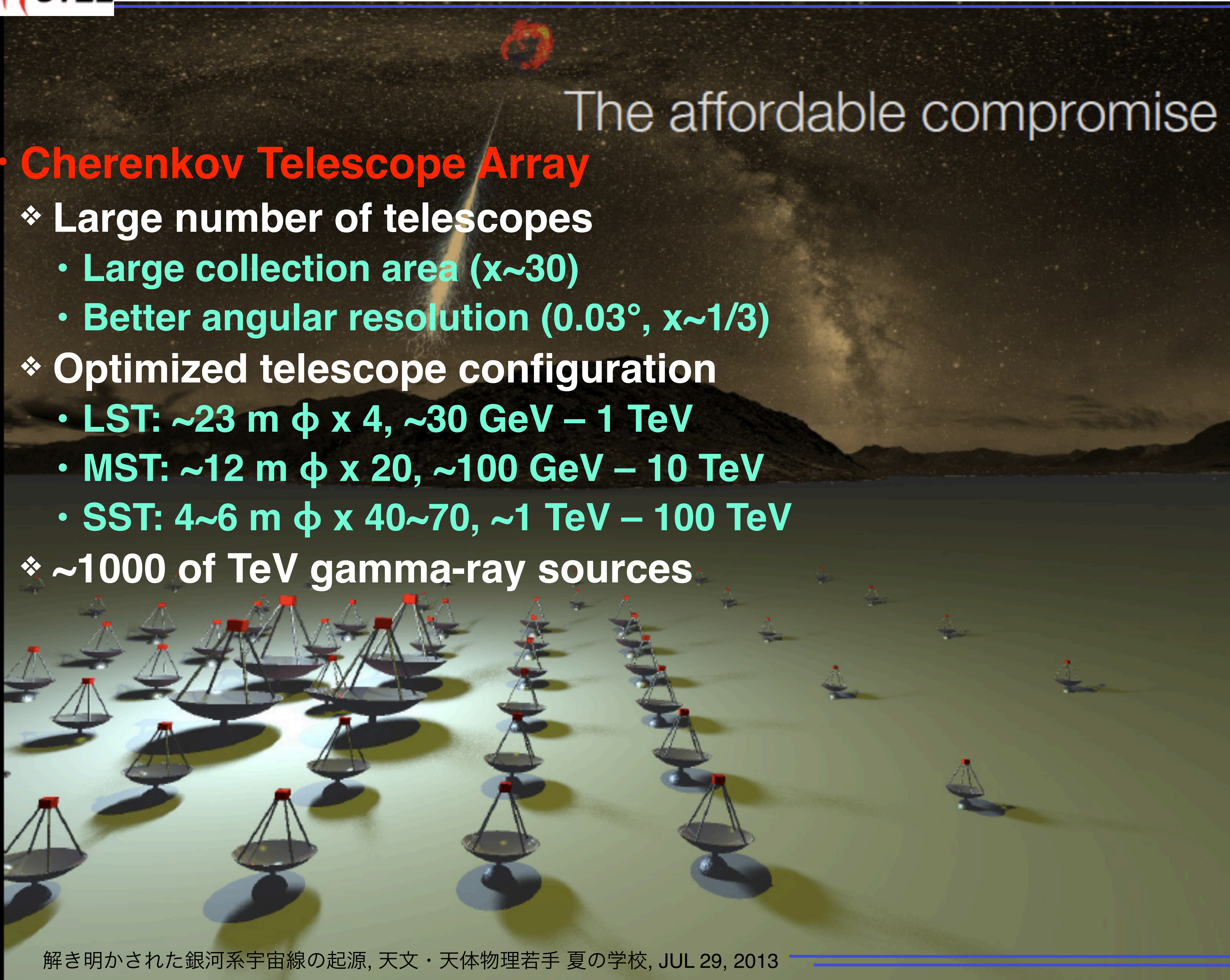




π^0-decay γ-ray
(and bremsstrahlung)

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

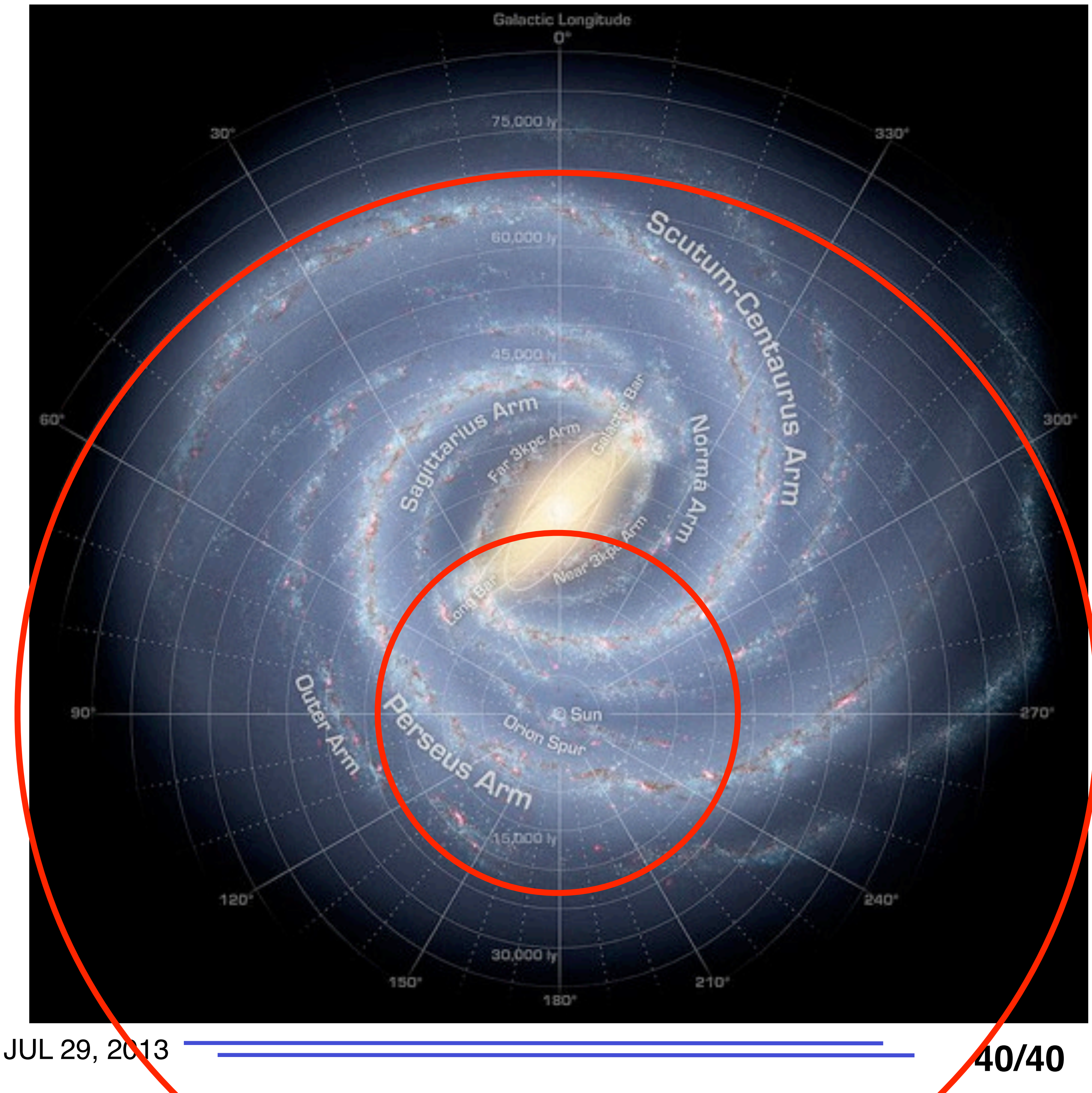
Future Gamma-ray Observatory



- **Cherenkov Telescope Array**
  - **Large number of telescopes**
    - Large collection area (x~30)
    - Better angular resolution (0.03°, x~1/3)
  - **Optimized telescope configuration**
    - LST: ~23 m ϕ x 4, ~30 GeV – 1 TeV
    - MST: ~12 m ϕ x 20, ~100 GeV – 10 TeV
    - SST: 4~6 m ϕ x 40~70, ~1 TeV – 100 TeV
  - **~1000 of TeV gamma-ray sources**

Future Prospect

- CTA will be x10 more sensitive with x3 better angular resolution
  - finer morphological comparison with X-ray (*e*) and interstellar gas
  - detect more RX J1713-like SNRs in entire Galaxy
- CTA can be sensitive up to >100 TeV
  - corresponding to CR spectra in “knee” region
  - Gamma-ray spectra beyond Klein-Nishina regime of Compton up-scattering
- Explore extragalactic CR sources
  - Active galactic nuclei
  - Gamma-ray bursts
    - 10,000x more sensitive than Fermi at ~30 GeV



Supplemental Slides

Fermi/LAT Collaboration

Stanford University & SLAC
NASA Goddard Space Flight Center
Naval Research Laboratory
University of California at Santa Cruz
Sonoma State University
University of Washington
Purdue Univeristy-Calumet
Ohio State University
University of Denver

~400 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Commissariat a l'Energie Atomique, Saclay
CNRS/IN2P3 (CENBG-Bordeaux, LLR-Ecole polytechnique, LPTA-Montpellier)

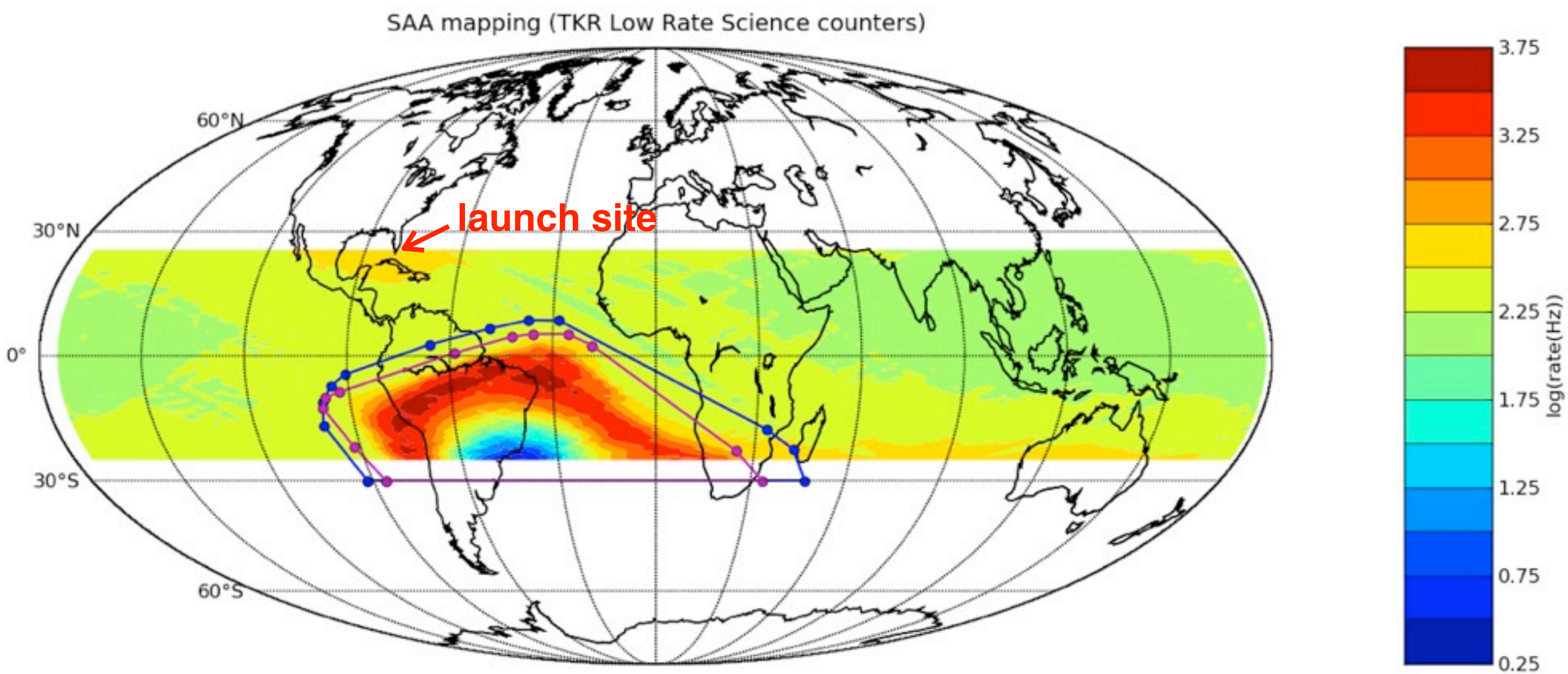
Hiroshima University
Institute of Space and Astronautical Science
Tokyo Institute of Technology
RIKEN

Instituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana
Istituto di Astrofisica Spaziale e Fisica Cosmica

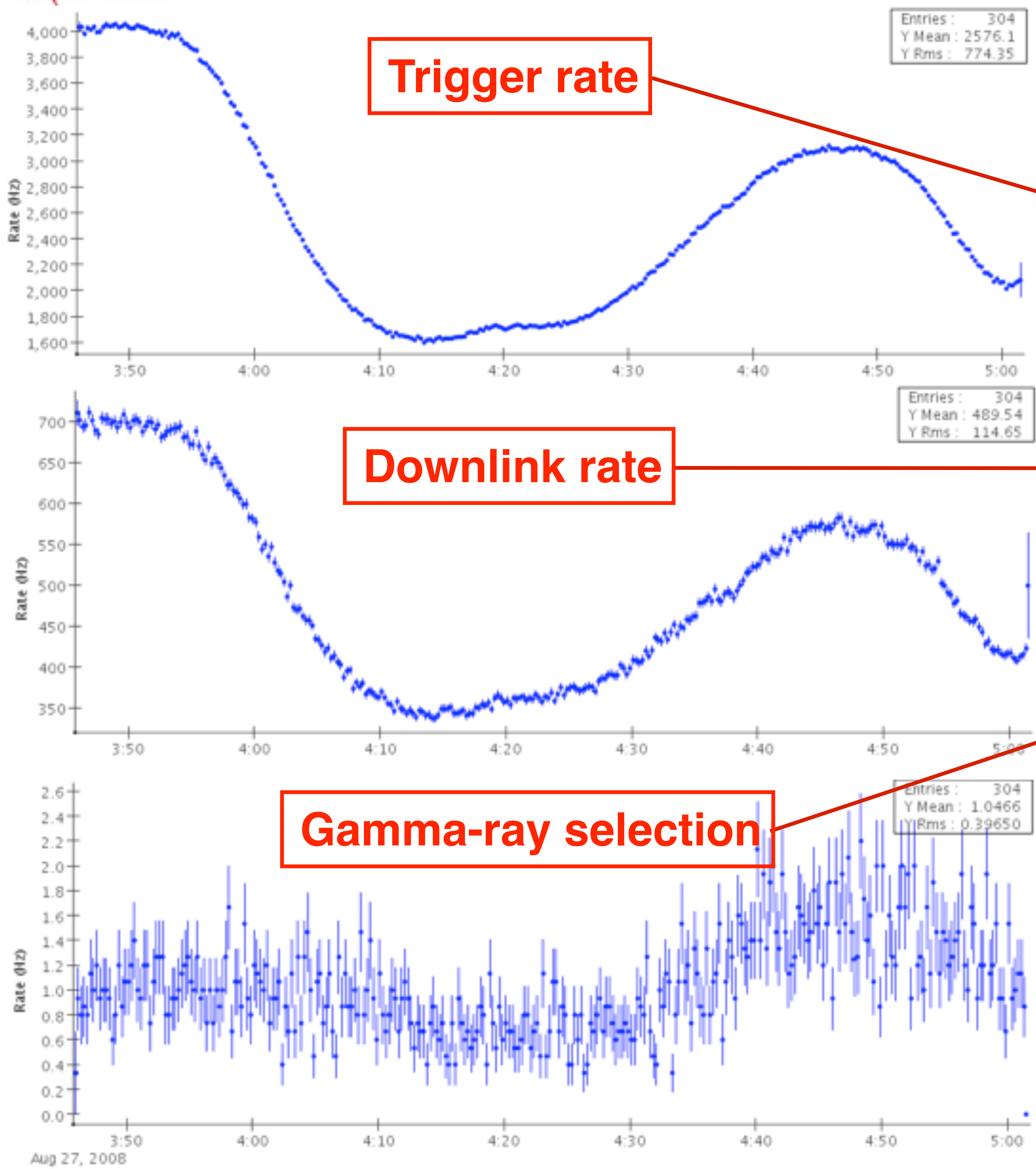
Royal Institute of Technology, Stockholm
Stockholms Universitet

Particle Background Environment

- TKR trigger rate is monitored throughout South Atlantic Anomaly
  - Trigger rate saturates above ~3.7 kHz/layer



Event Rates



- ✓ Overall trigger rate: ~1–4 kHz
  - ✓ Huge variations due to orbital effects.

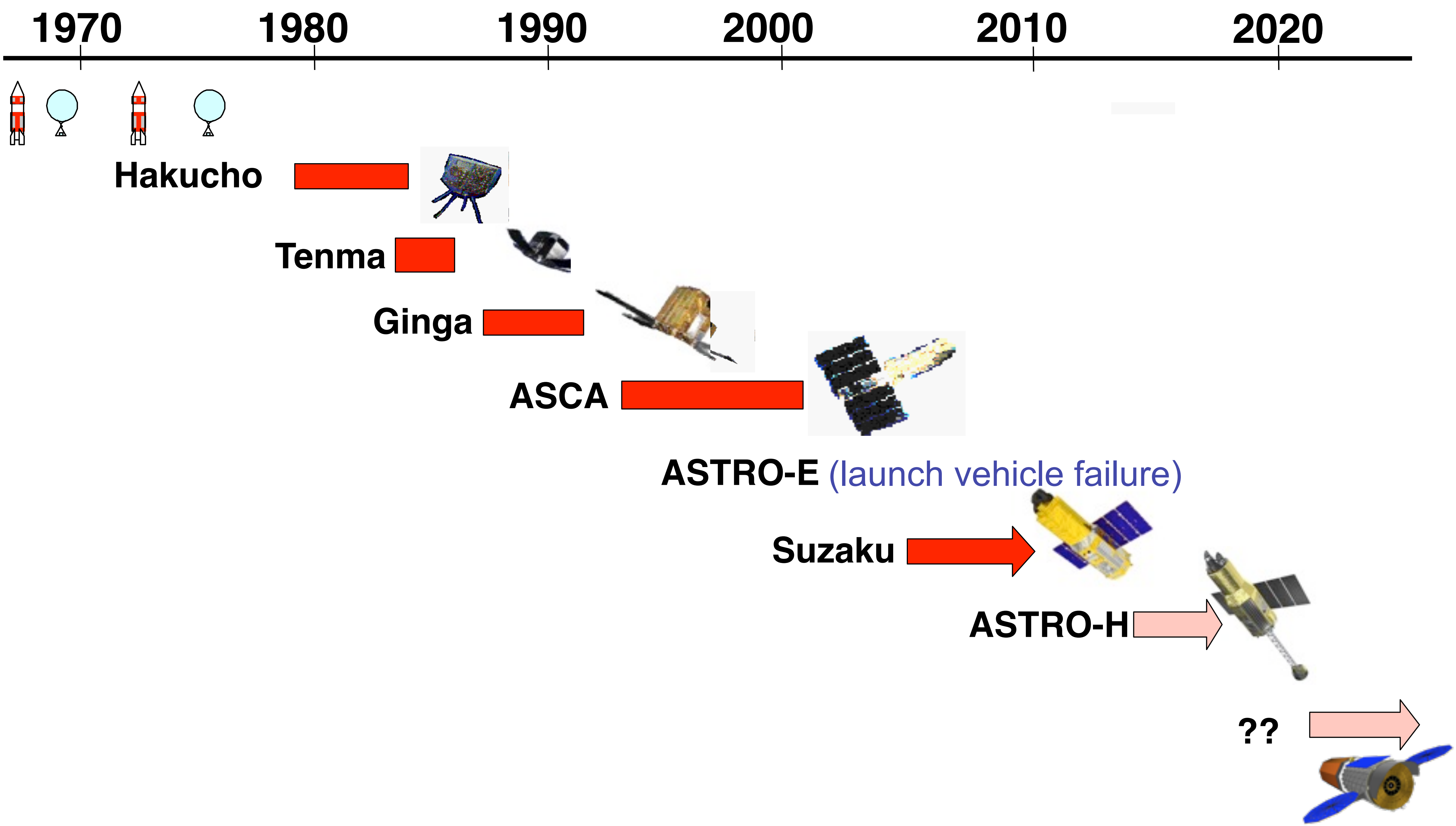
- ✓ Downlink rate: ~0.3–0.7 kHz
  - ✓ ~90% from GAMMA filter
  - ✓ ~30 Hz from minimum bias filter
  - ✓ ~5 Hz from heavy ion filter

- ✓ Rate of photons after the standard background rejection cuts for source study: ~1 Hz

- ✓ Most of the downlinked events are in fact background, final ~ 1000:1 rejection is done in ground processing.

JAXA ASTRO-H

✤ History of Japanese X-ray satellite



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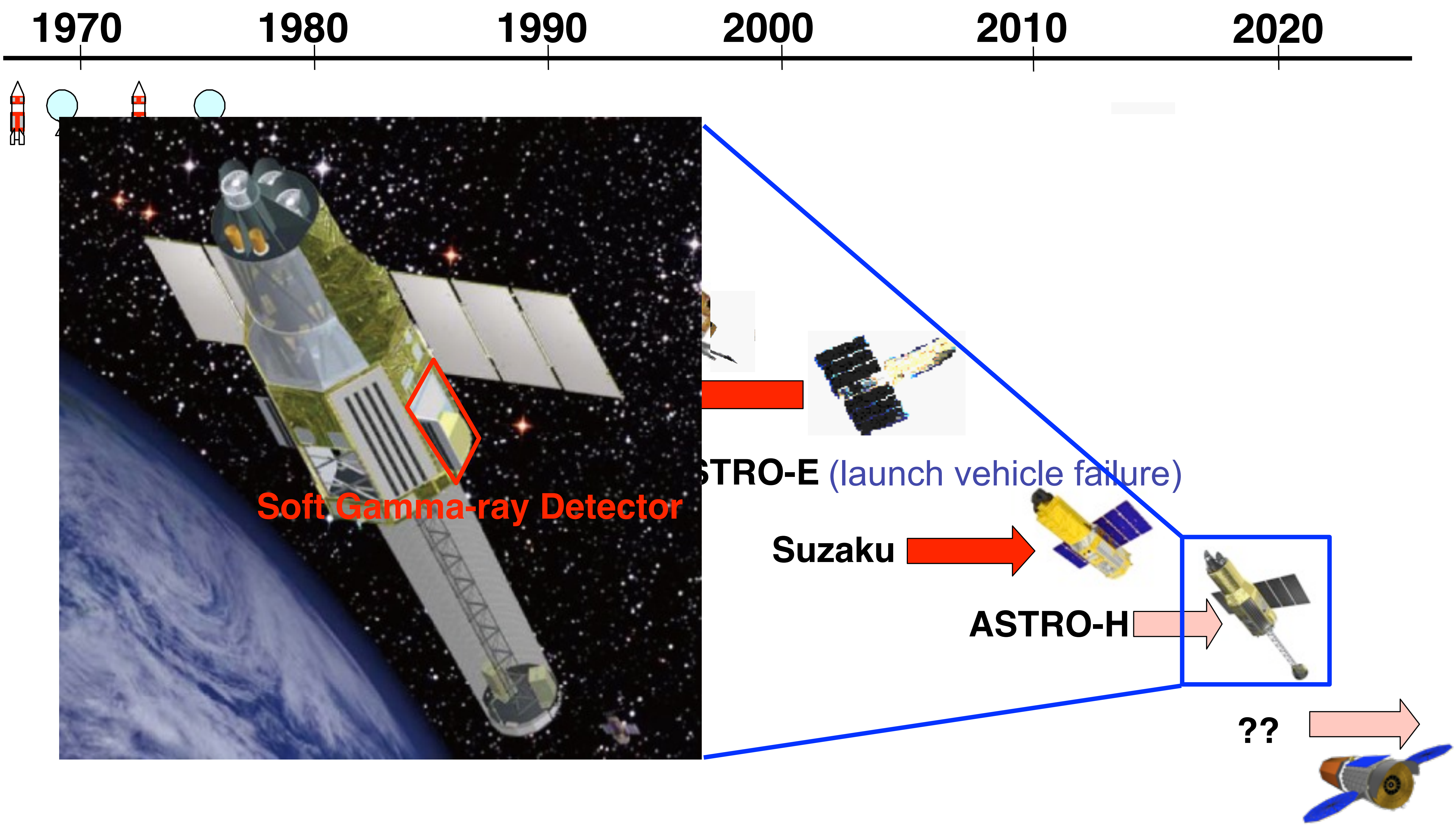
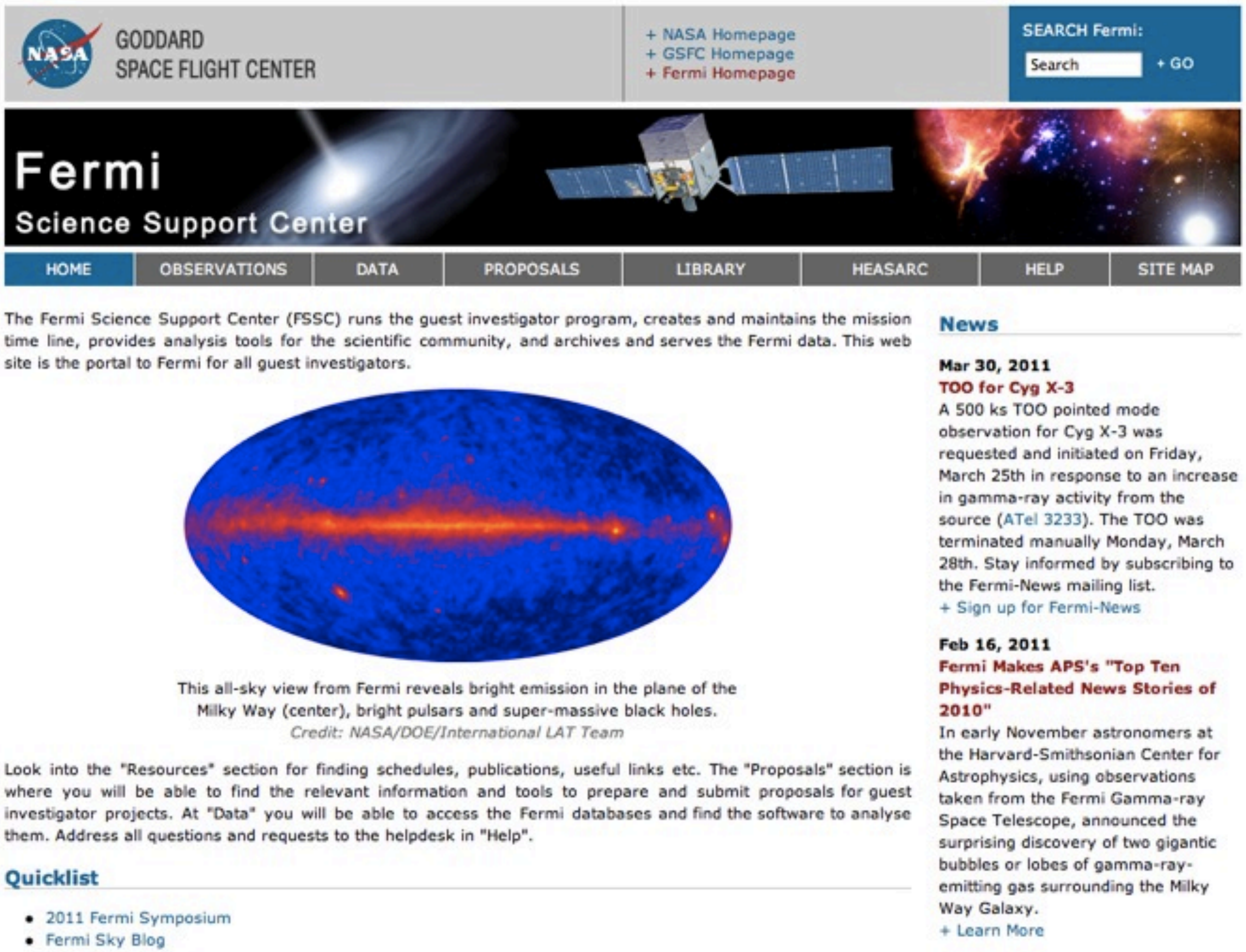


Credit: ISAS/JAXA

Fermi Science Support Center

- Fermi data have been public since 2009 August
  - data access: http://fermi.gsfc.nasa.gov/ssc/data/access/
  - analysis tool: http://fermi.gsfc.nasa.gov/ssc/data/analysis/



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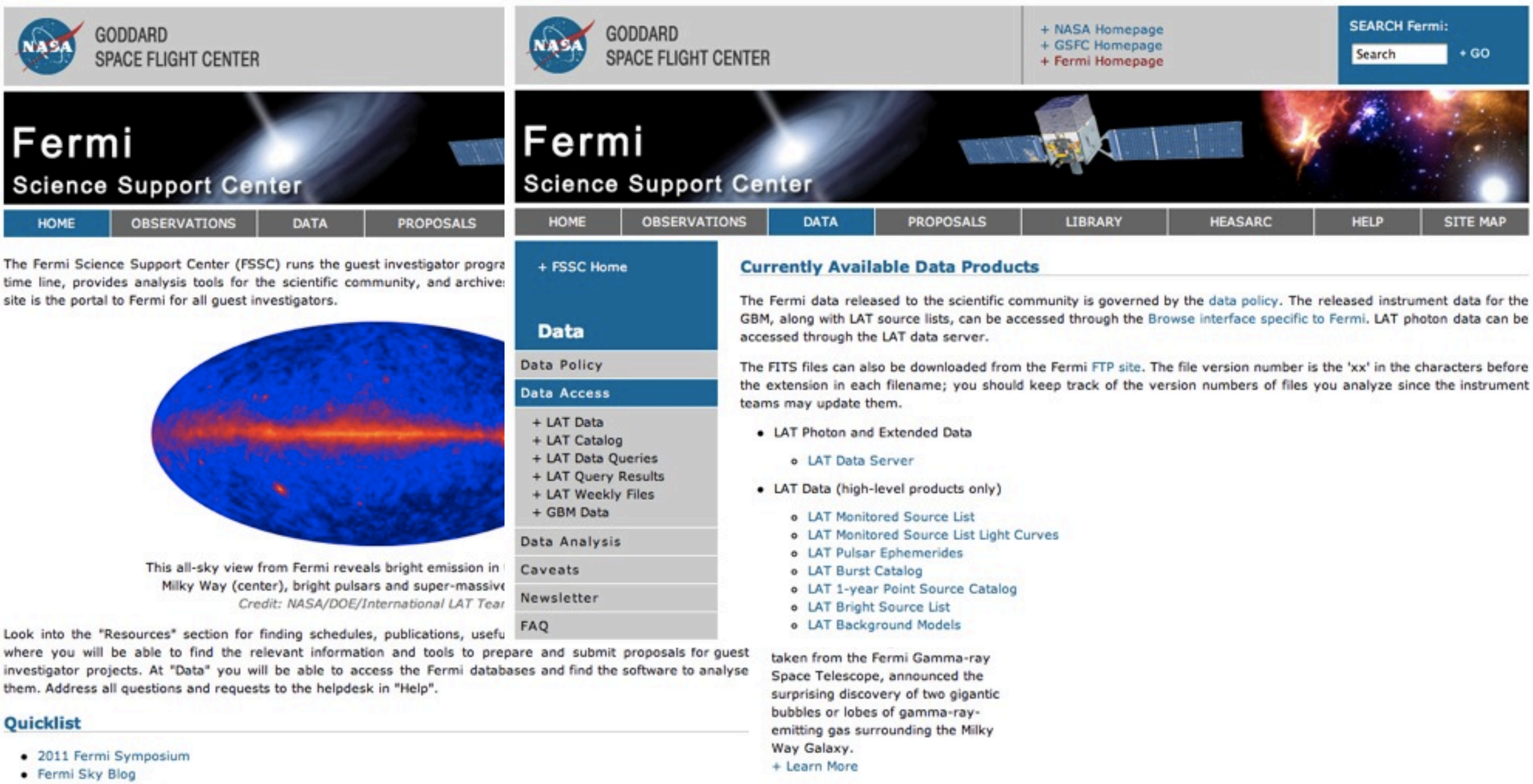
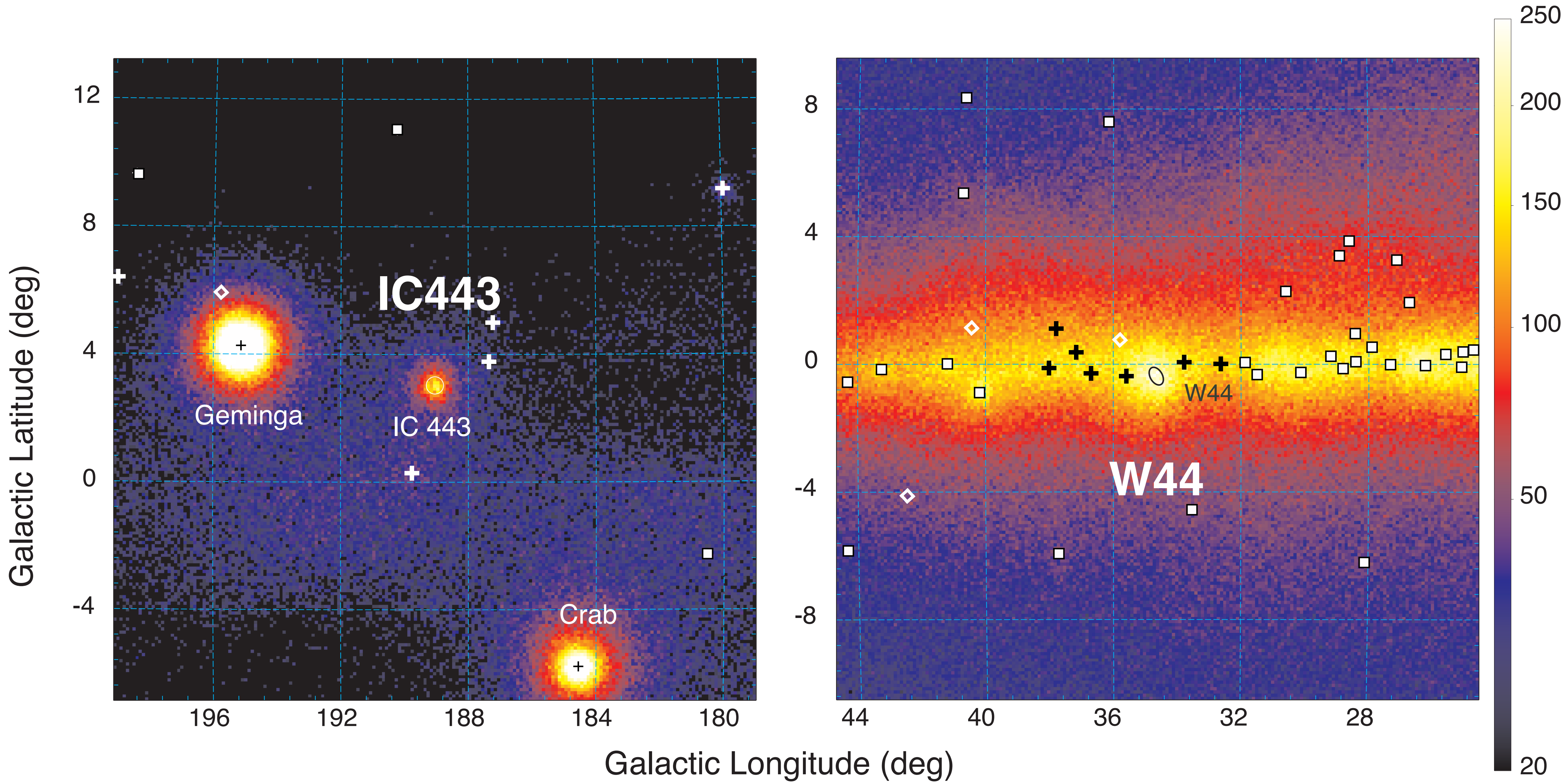


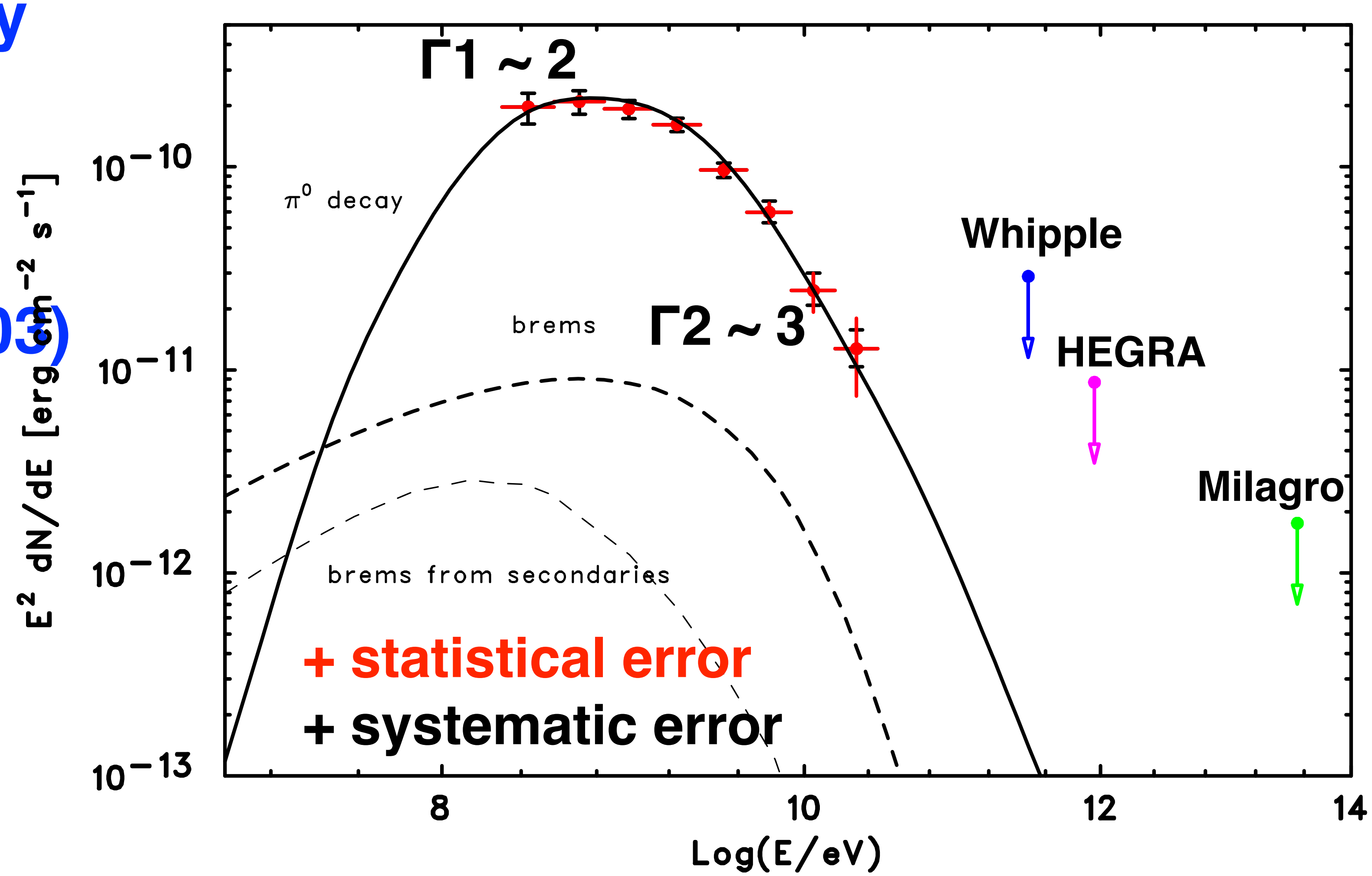
Pion-decay cutoff in SNRs

- IC 443 and W44: two “brightest” SNRs in the Fermi-LAT range
  - 2FGL: IC 443: 132σ, W44: 57σ, W51C: 50σ, W28: 49σ
  - Energy range: 60 MeV - 2 GeV (energy range of main interest)



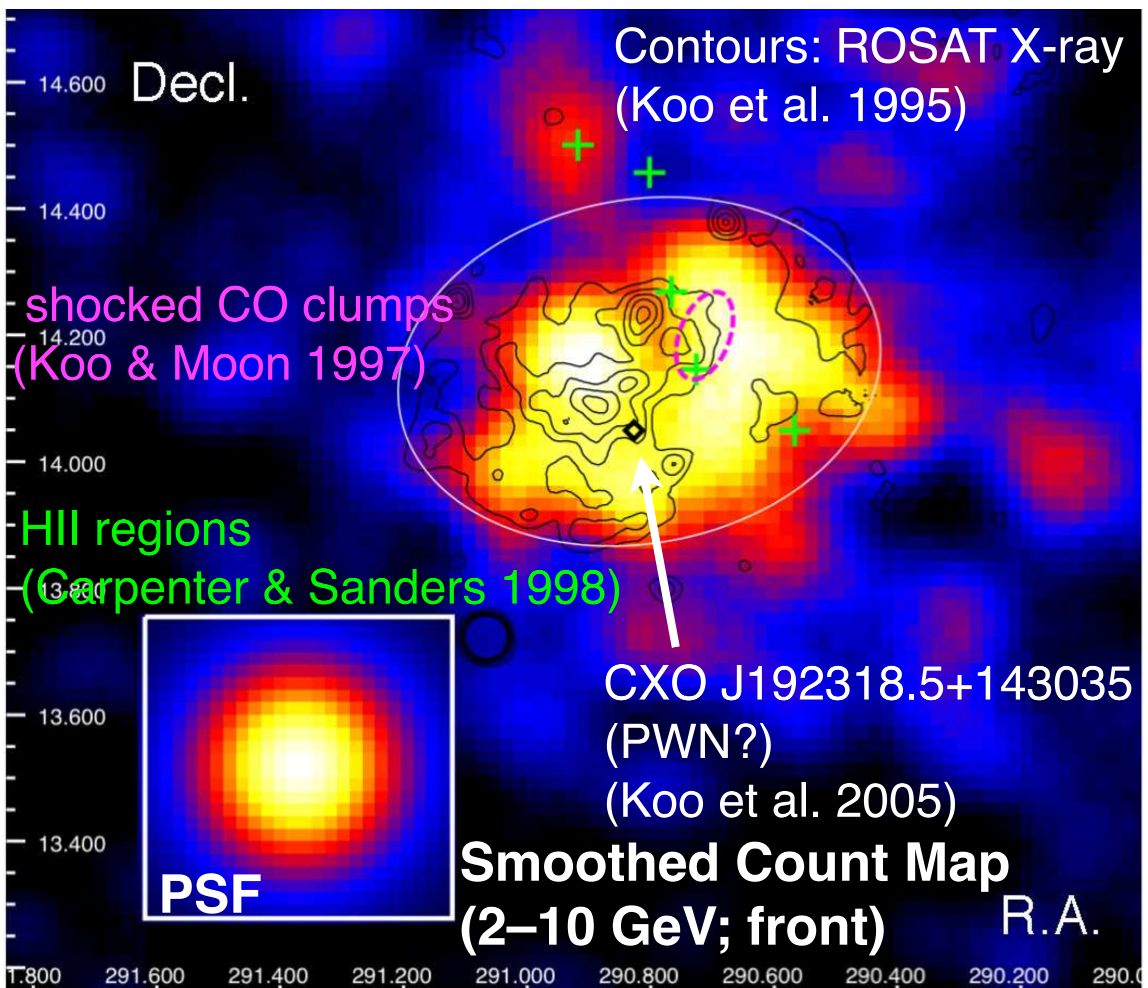
W44 Spectrum

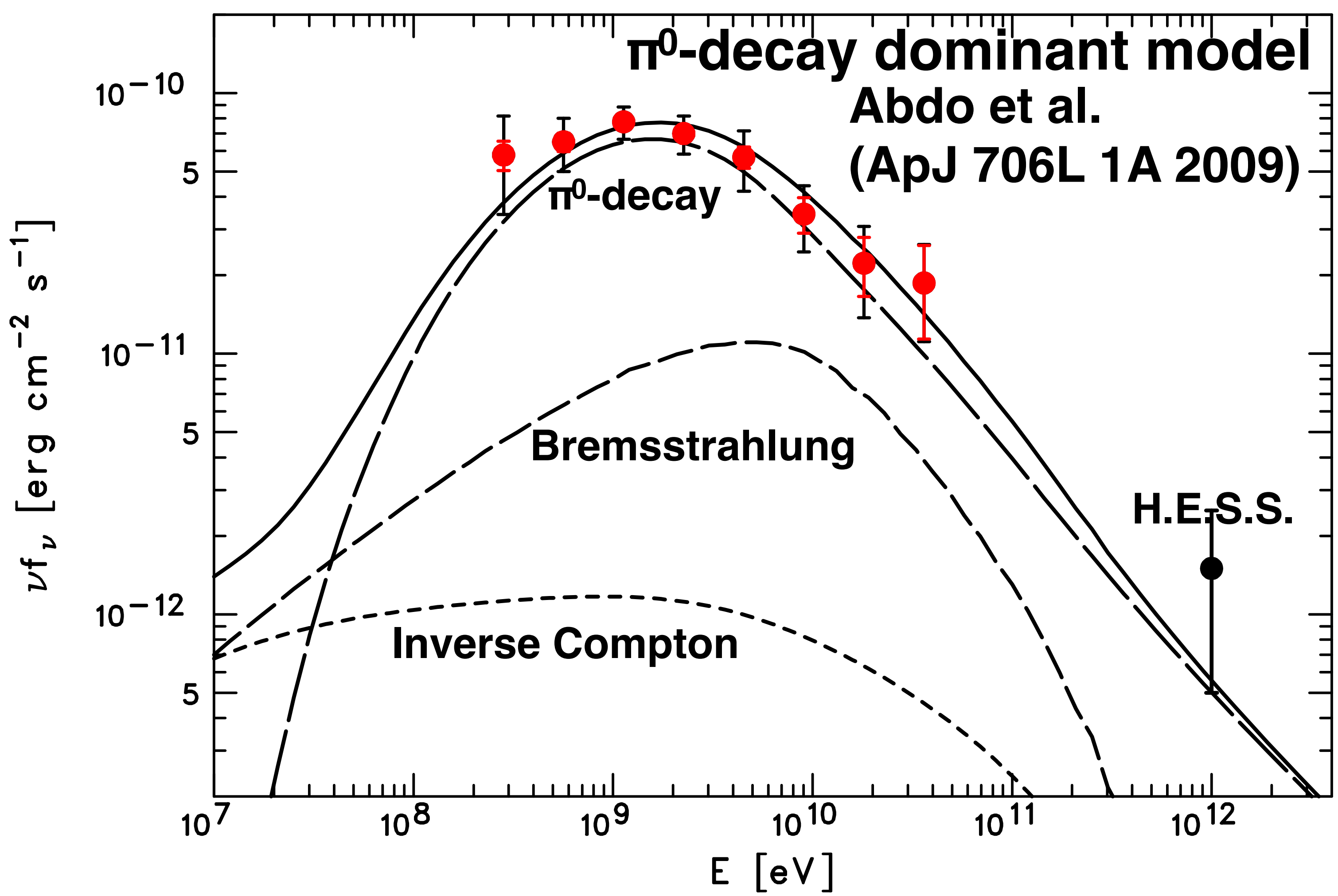
- Simple power-law function is rejected with 14σ
- π^0-decay dominant model is most natural explanation
- Electron bremsstrahlung cannot completely be ruled out
  - Brems: amount of electrons should be comparable to protons
  - Inverse Compton: $W_e \sim 10^{51}$ erg or quite intense photon field needed
- Protons need to have a spectral break at ~ 10 GeV/*c*
  - Fast escape of high energy particles with damping of magnetic turbulence due to the dense environment (Ptuskin & Zirakashvili 2003)



SNR W51C

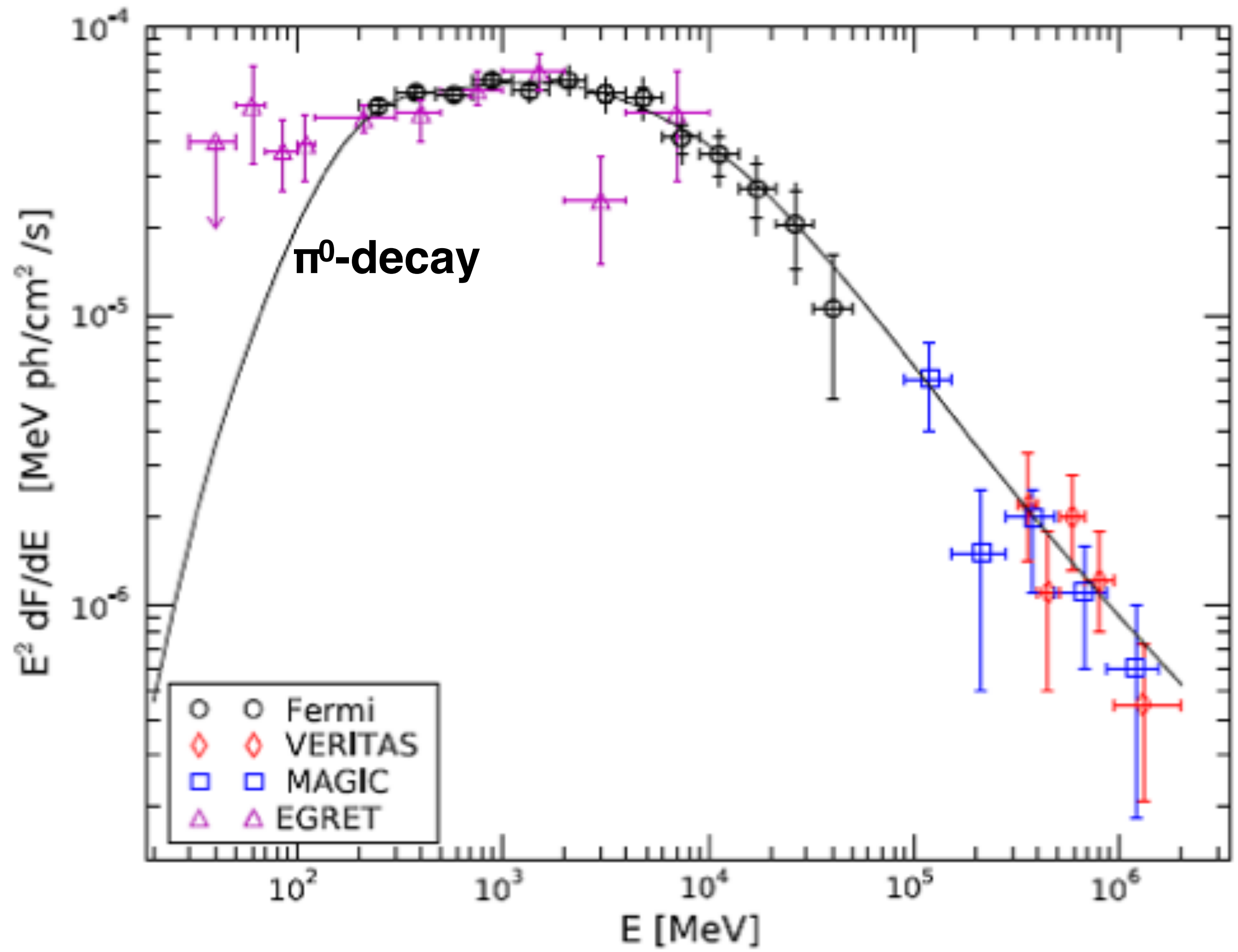
- Another Fermi-LAT SNR interacting with molecular clouds
  - Middle age: 3×10^4 yr, Distance: 6 kpc
- Most luminous gamma-ray source: $L = 10^{36}$ (D/6 kpc)^2 erg s^{-1}
- Spectral steepening similar to the W44 spectrum
  - π^0-decay model can reasonably explain the data
  - Leptonic scenarios have similar difficulties as W44





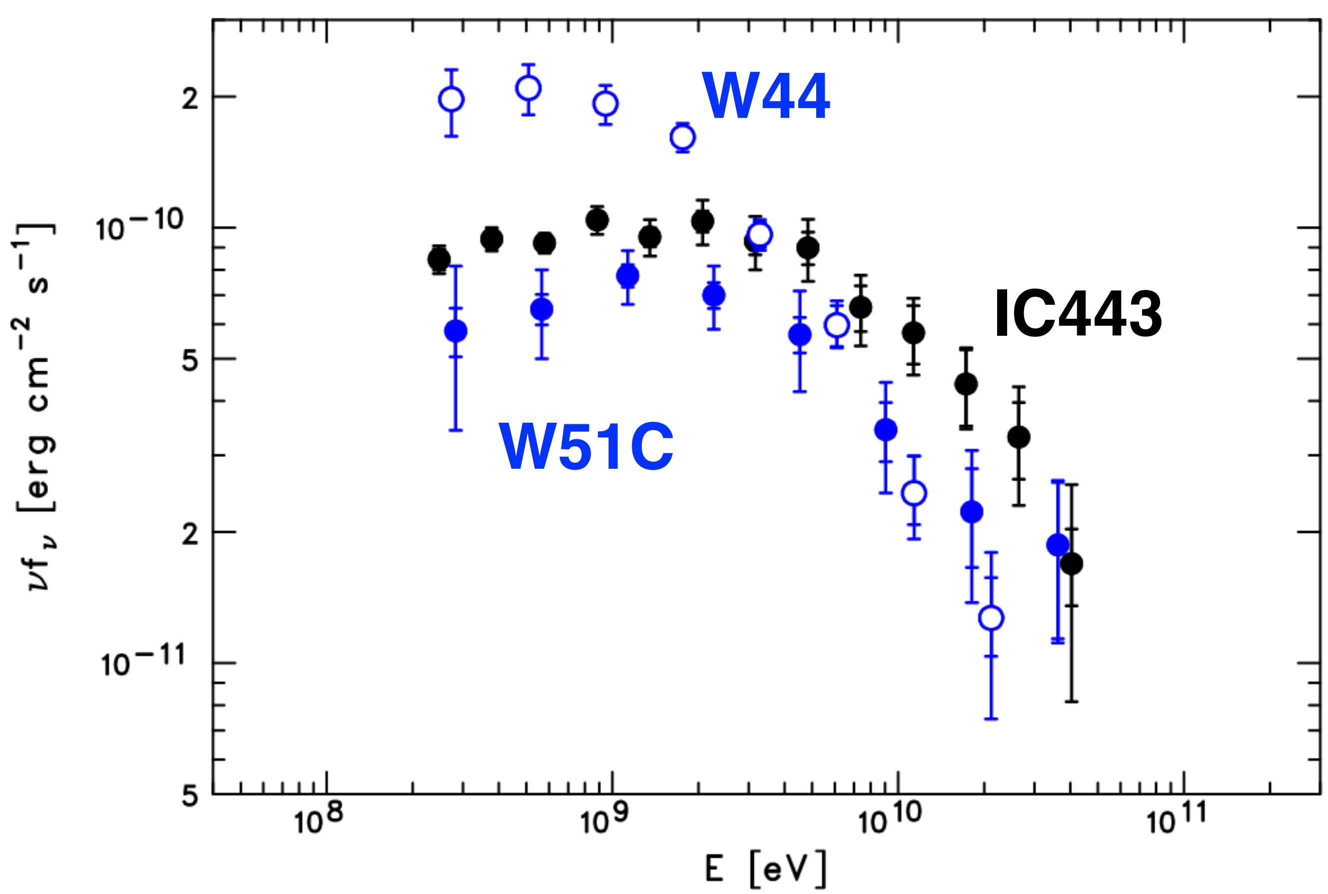
SNR IC443

- SNR interacting with molecular clouds
  - Middle age: $(3\sim30)\times10^4$ yr, Distance: 1.5 kpc
- IC 443 is an extended source against a point-source at >17σ significance in the LAT band
- π^0-decay dominant model is most natural explanation
  - Proton spectral break at ~ 70 GeV/*c*



Fermi Observations of Middle-Aged SNR

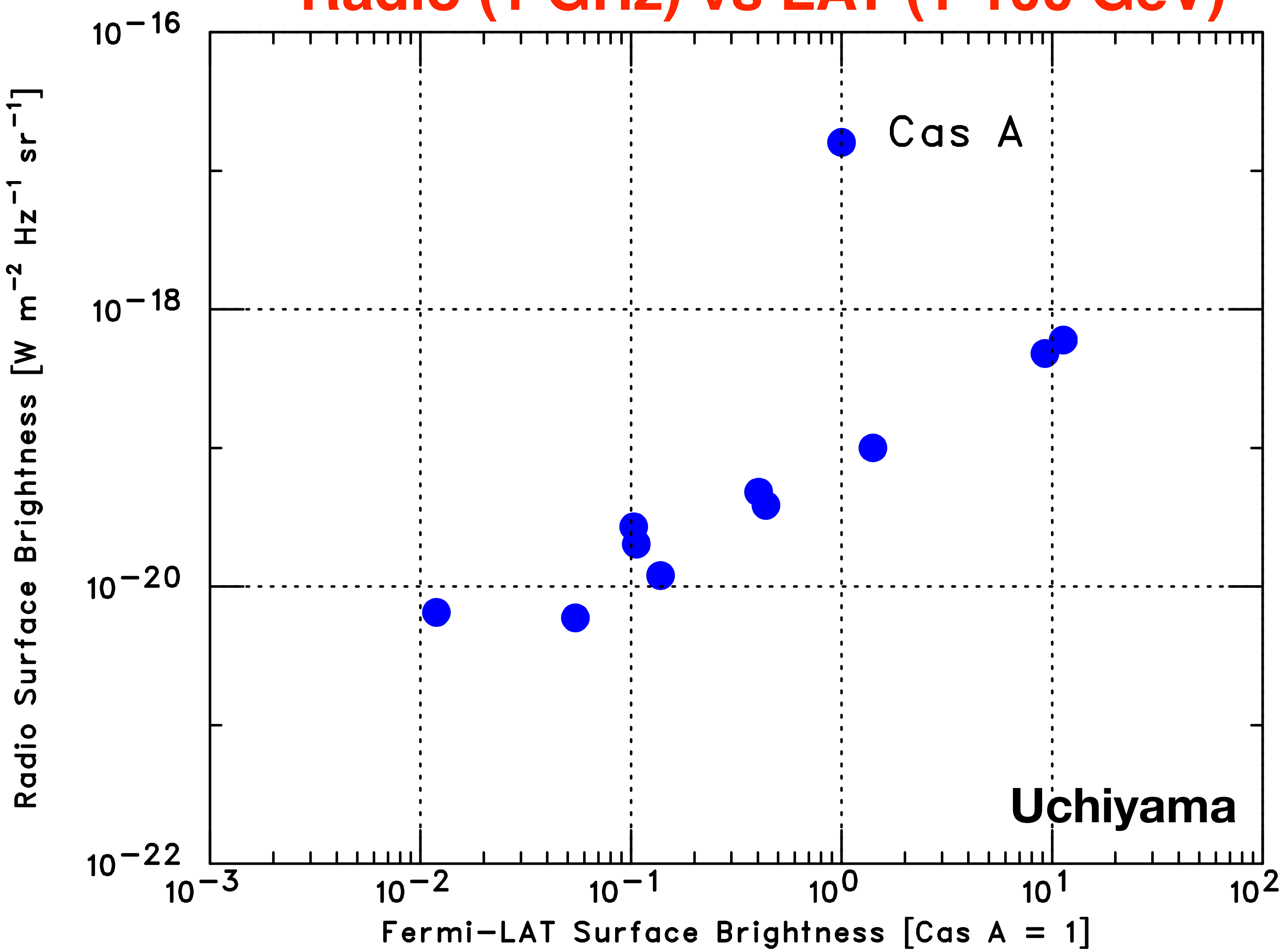
- Common feature of middle-aged SNRs observed by Fermi
  - Interacting with molecular clouds
  - Spectrum steepening between GeV and TeV
- SNR observed by Fermi may give new clues on
  - Effect on cosmic ray acceleration from interacting molecular clouds
- Ensemble of SNRs with different cutoff may explain cosmic-ray spectral index of ~2.7
  - Shock acceleration @ ~2.0
  - Softening of spectral index by propagation effect is not sufficient to describe differences
  - Note: #(middle aged SNRs) >> #(young SNR)



Implications of LAT-Detected SNRs

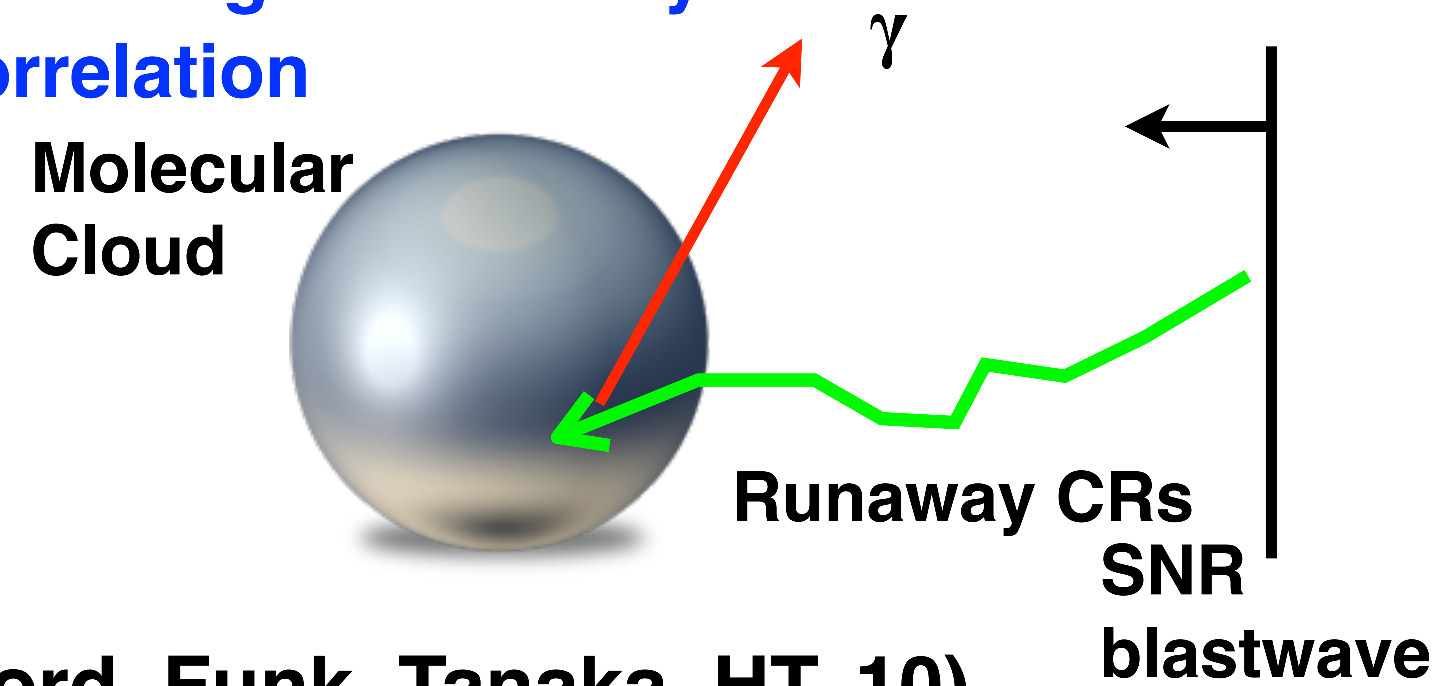
- Common features of LAT-detected SNRs (except for Cas A)
  - Radio-bright
    - Flat radio spectrum (α = 0.3 – 0.4) for W51C,W44, W28, IC 443
    - Radio-GeV correlation
  - Interacting with molecular clouds
  - Break in GeV region

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

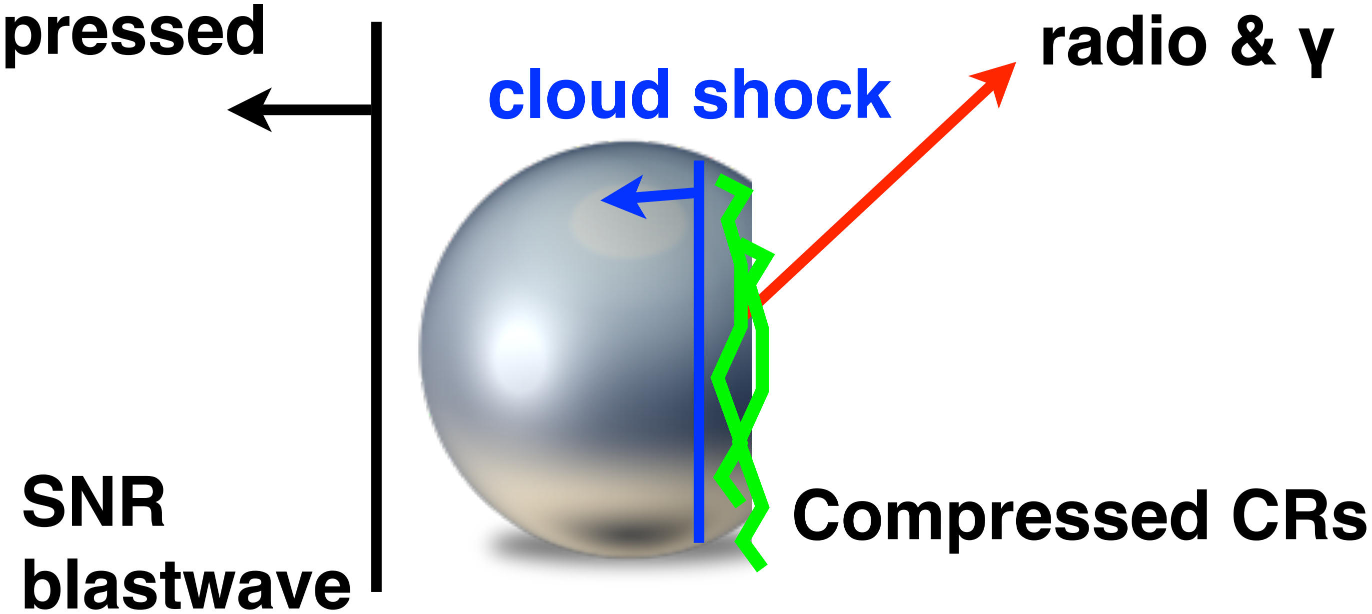


Models for SNRs with Molecular Could

- “Aharonian-type” model
  - CRs escaping from SNR and colliding with nearby MCs
  - Does not explain radio-GeV correlation



- Our model (Uchiyama, Blandford, Funk, Tanaka, HT, 10)
  - γ-ray coming from “cloud shock”
    - CRs and MC simultaneously compressed

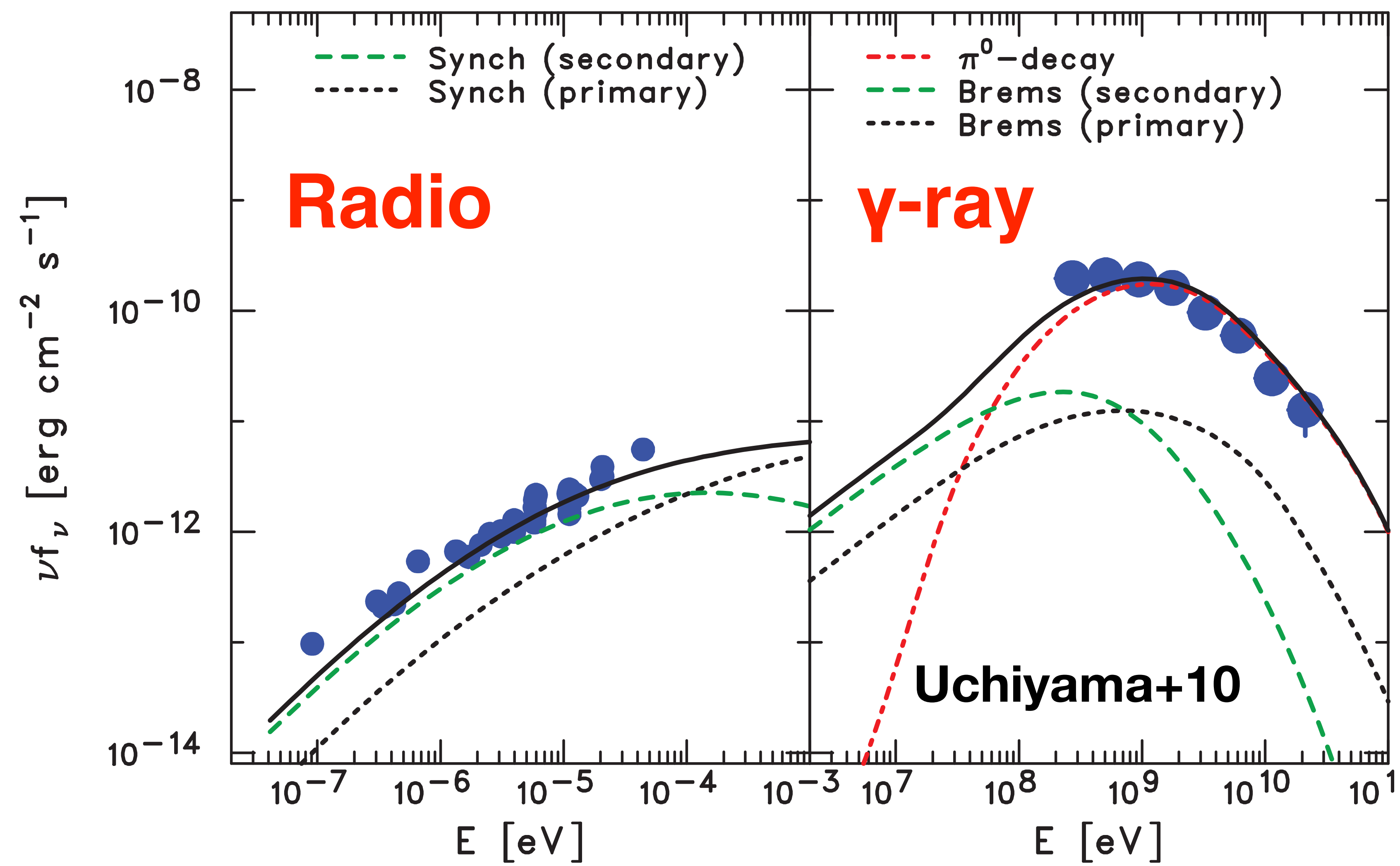


“Prediction” for W44

- Re-acceleration of the pre-existing Galactic CRs results in
  - Flat radio index (α=0.37) & correlation between radio & γ-ray fluxes

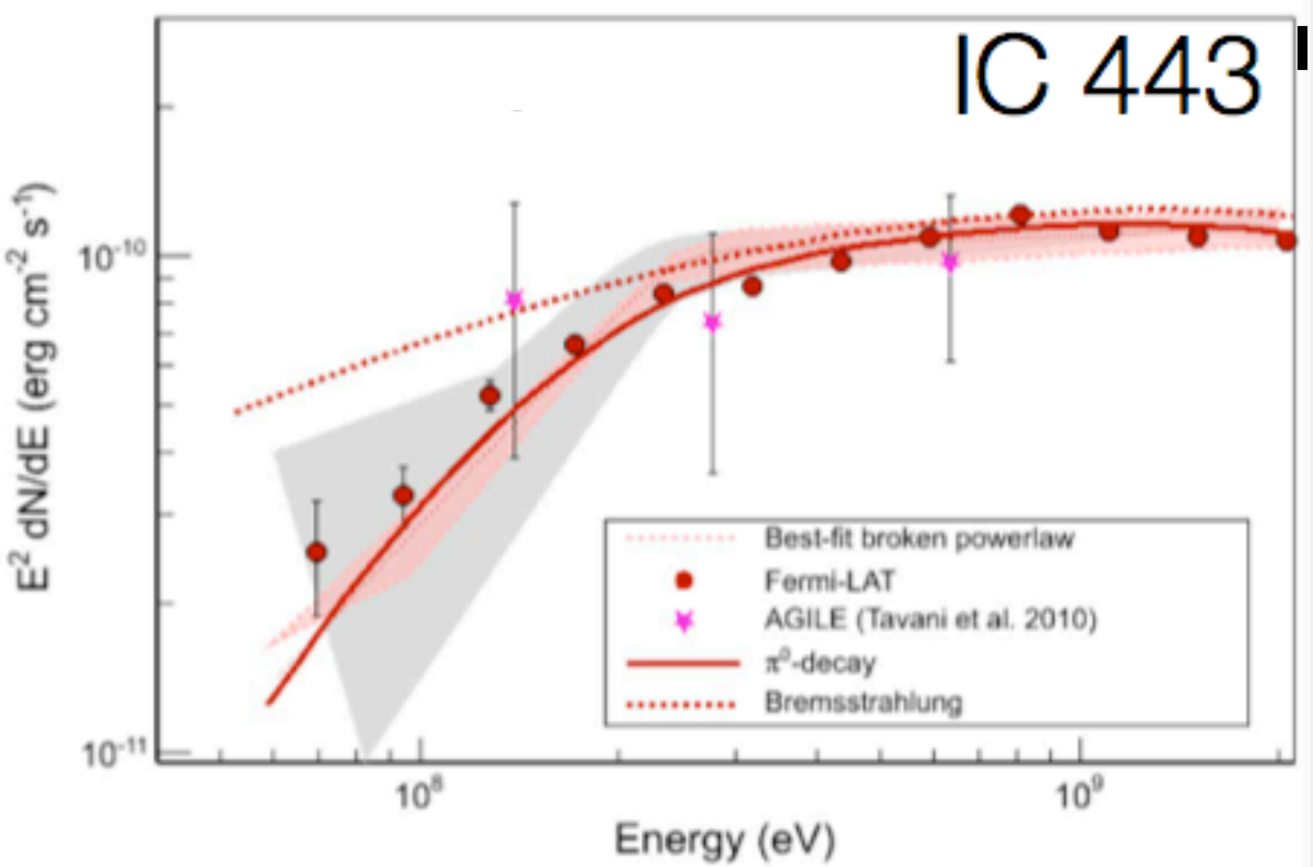
Blandford & Cowie (1982)

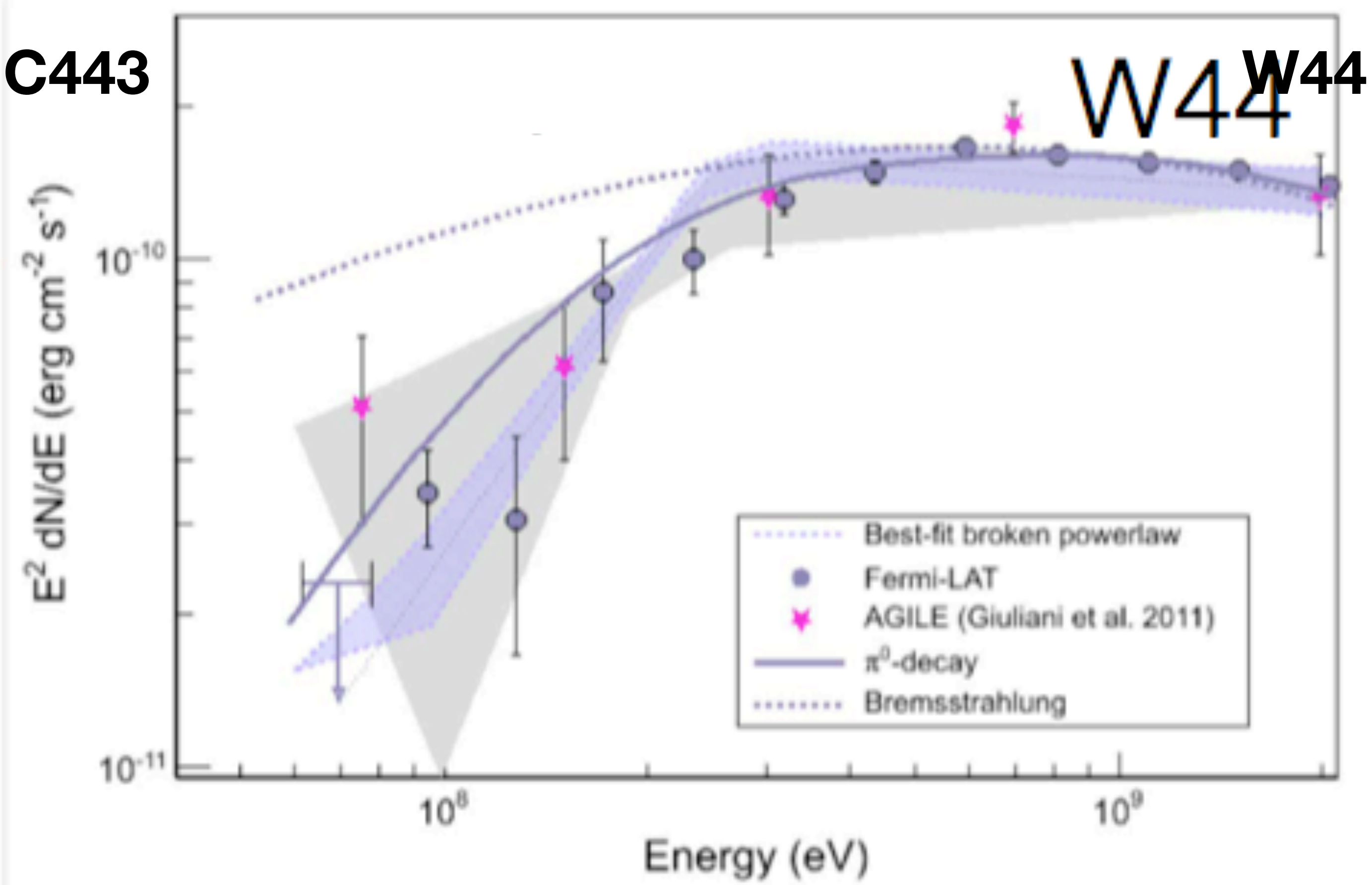
- GeV break as a result of Alfvén wave evanescence (damping) (Malkov+2010)
  - Spectral steepening by one power at $cp_{br} = 2eBV_A/v_{i-n}$
- Three free parameters for pre-shock cloud conditions
  - Density
  - Filling factor
  - Magnetic field



Comparison with Model Predictions

- Inverse Compton
  - Energetically completely disfavored (x100 higher radiation fields)
  - Shape not consistent with IC
- Best-fit Bremsstrahlung model shows less steep decline
  - Even with abrupt cutoff at 300 MeV in electron spectrum
  - Mixed model requires K_{ep}= 0.01 (@ p = 1 GeV/c)
- Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra





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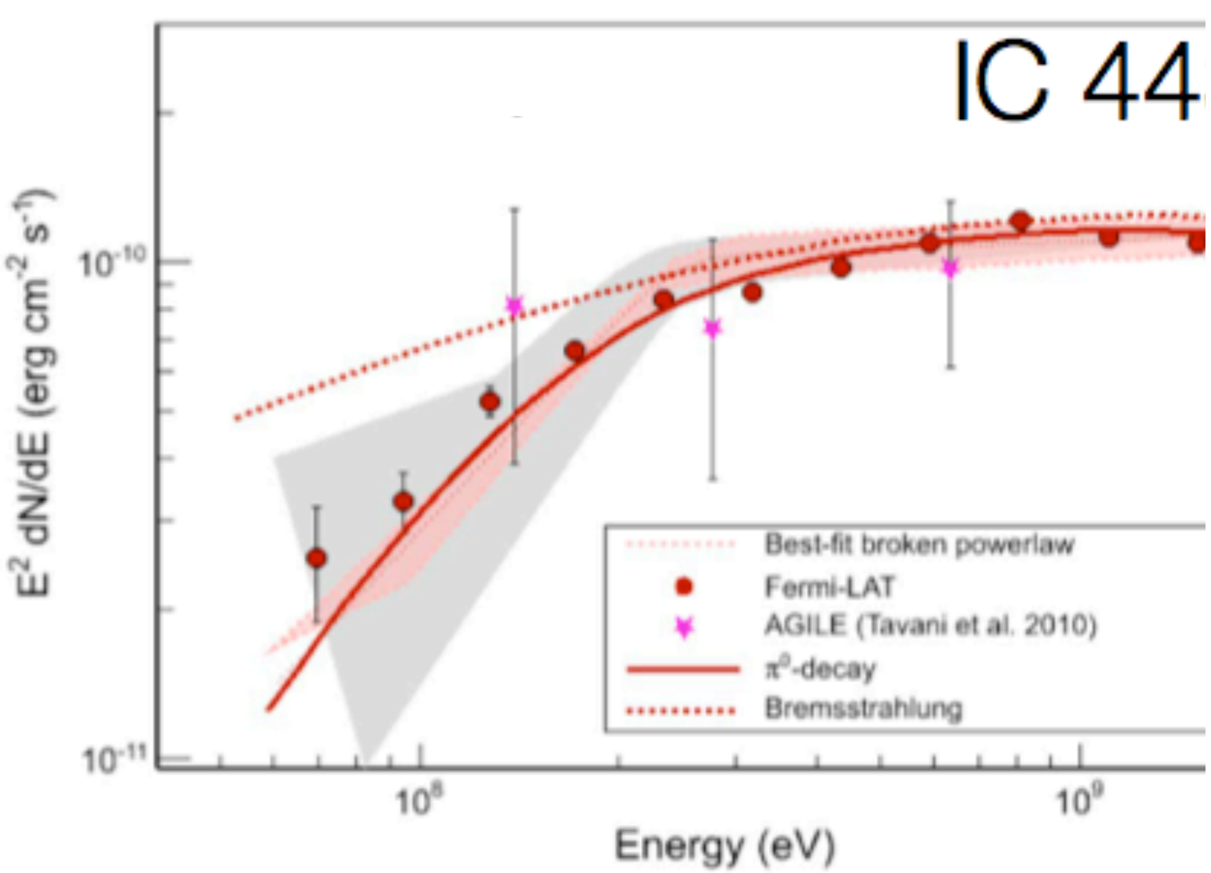

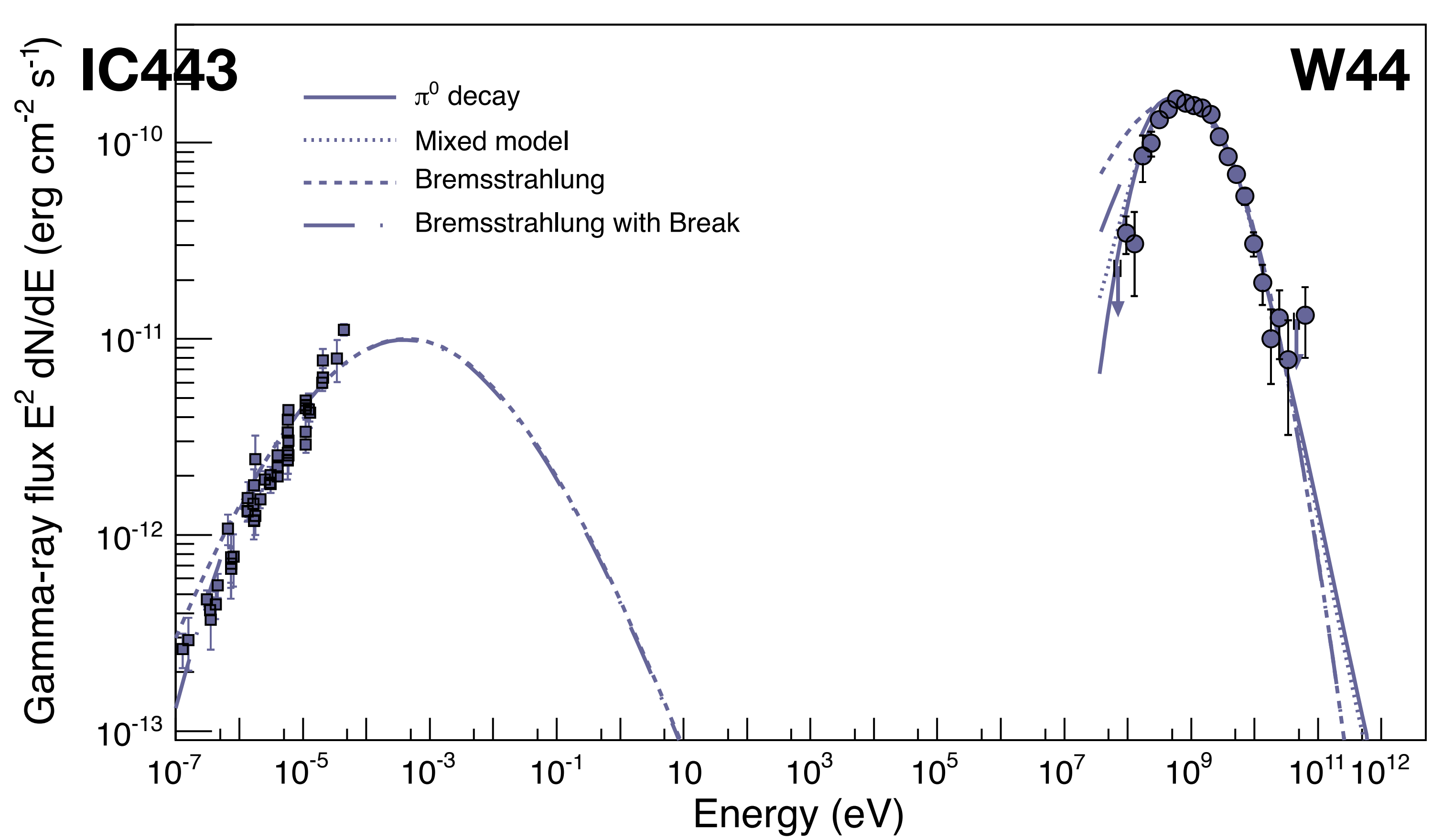

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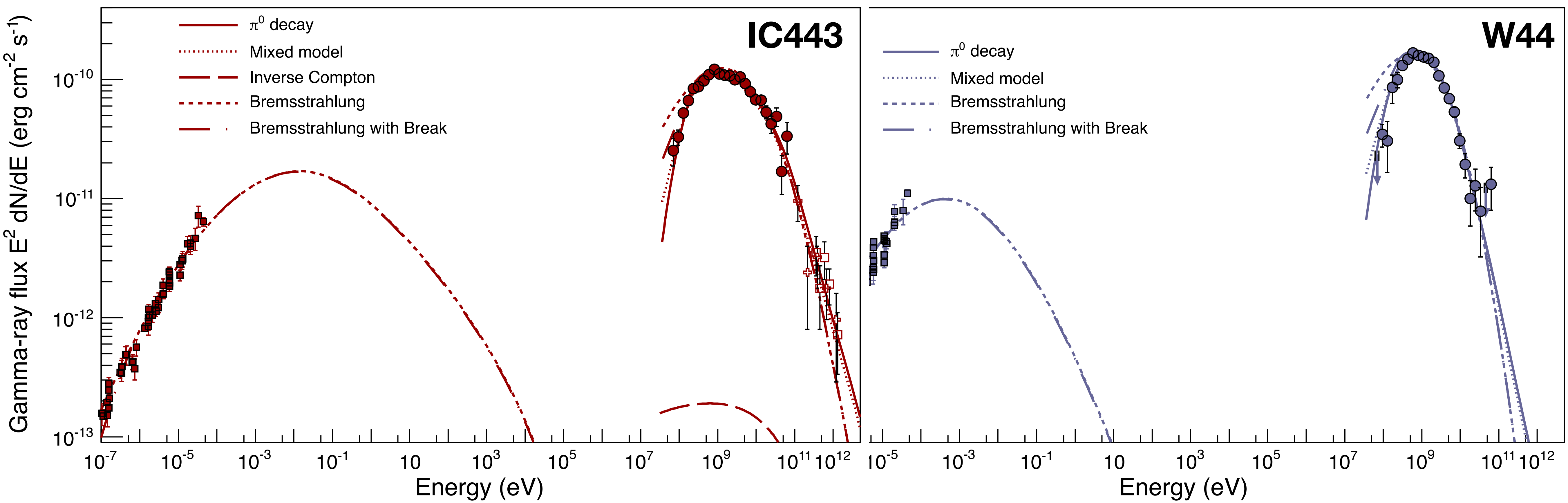
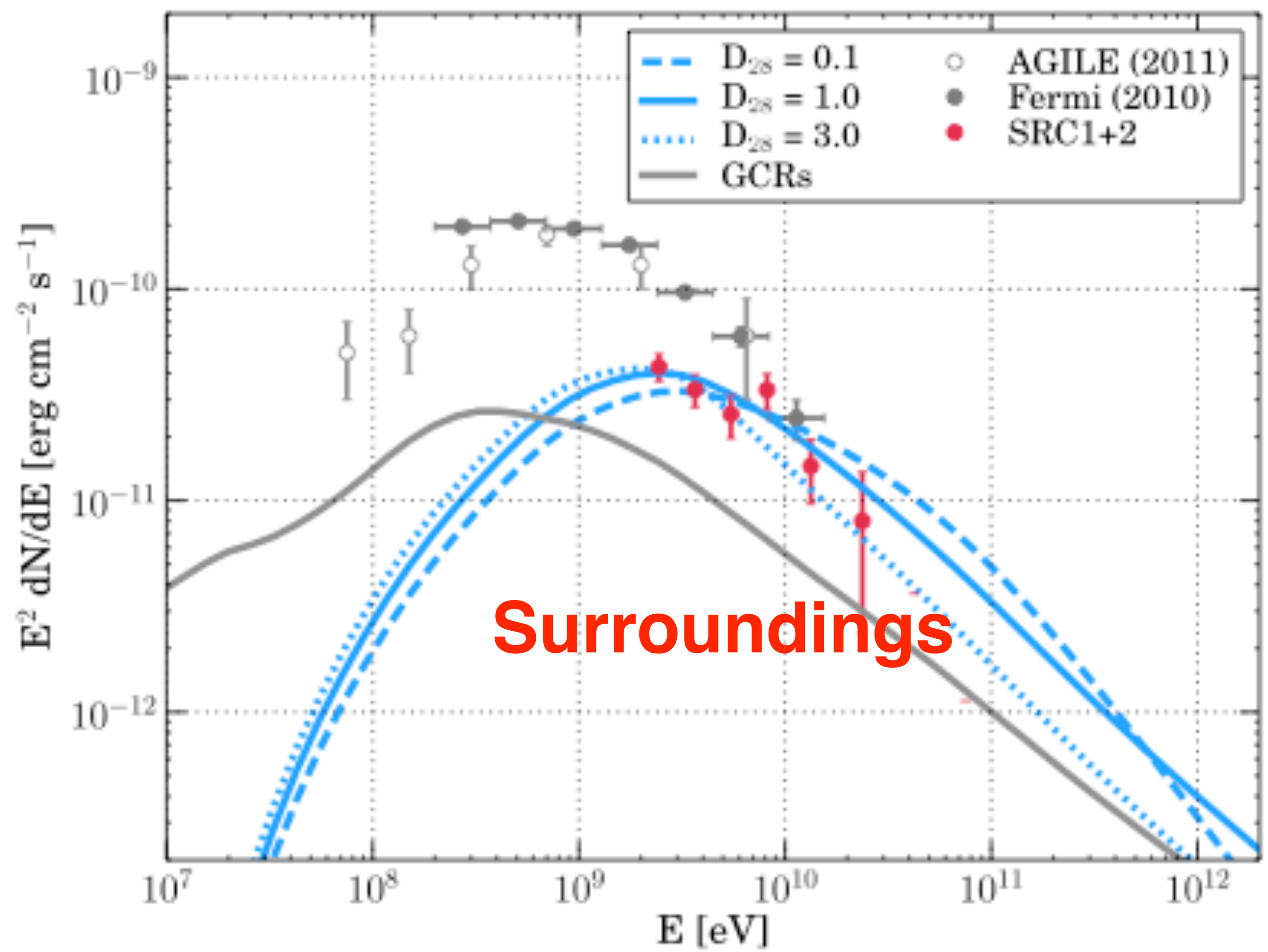
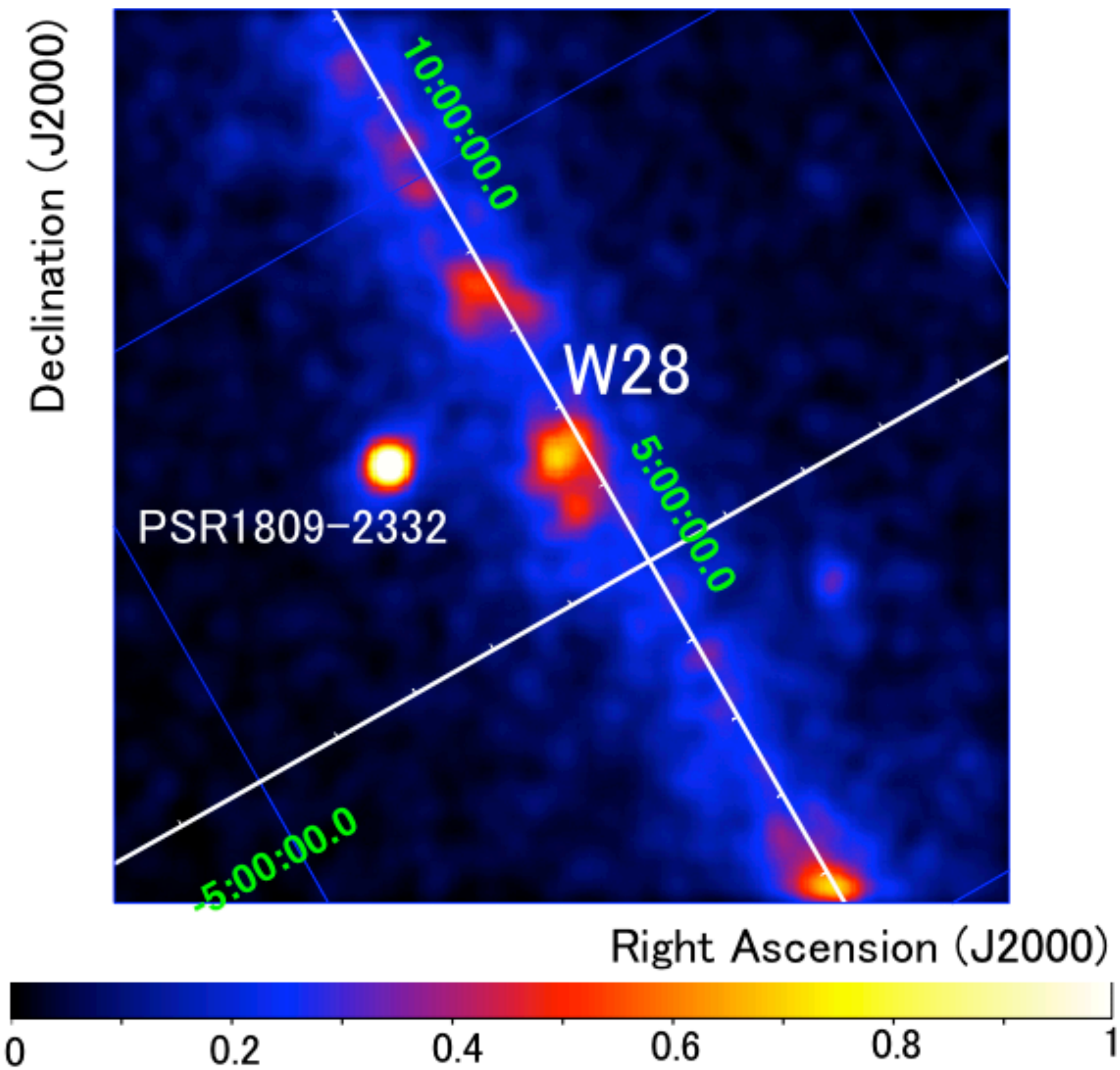


Amount of CRs Escaped from W44

- Solving the diffusion equation in the vicinity of W44, we can estimate the energy spectrum of escaping CRs
  - Uniform molecular clouds illuminated by escaping CRs (within r<L)
    - L ~100 pc, Mass = 0.5×10^5 M⊙
  - Diffusion coefficient of the interstellar medium (isotropic)
    - $D(p) = D_{28}\ (cp/10\ \mathrm{GeV})^{0.6}\ 10^{28}\ \mathrm{cm^2/s}$
  - 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

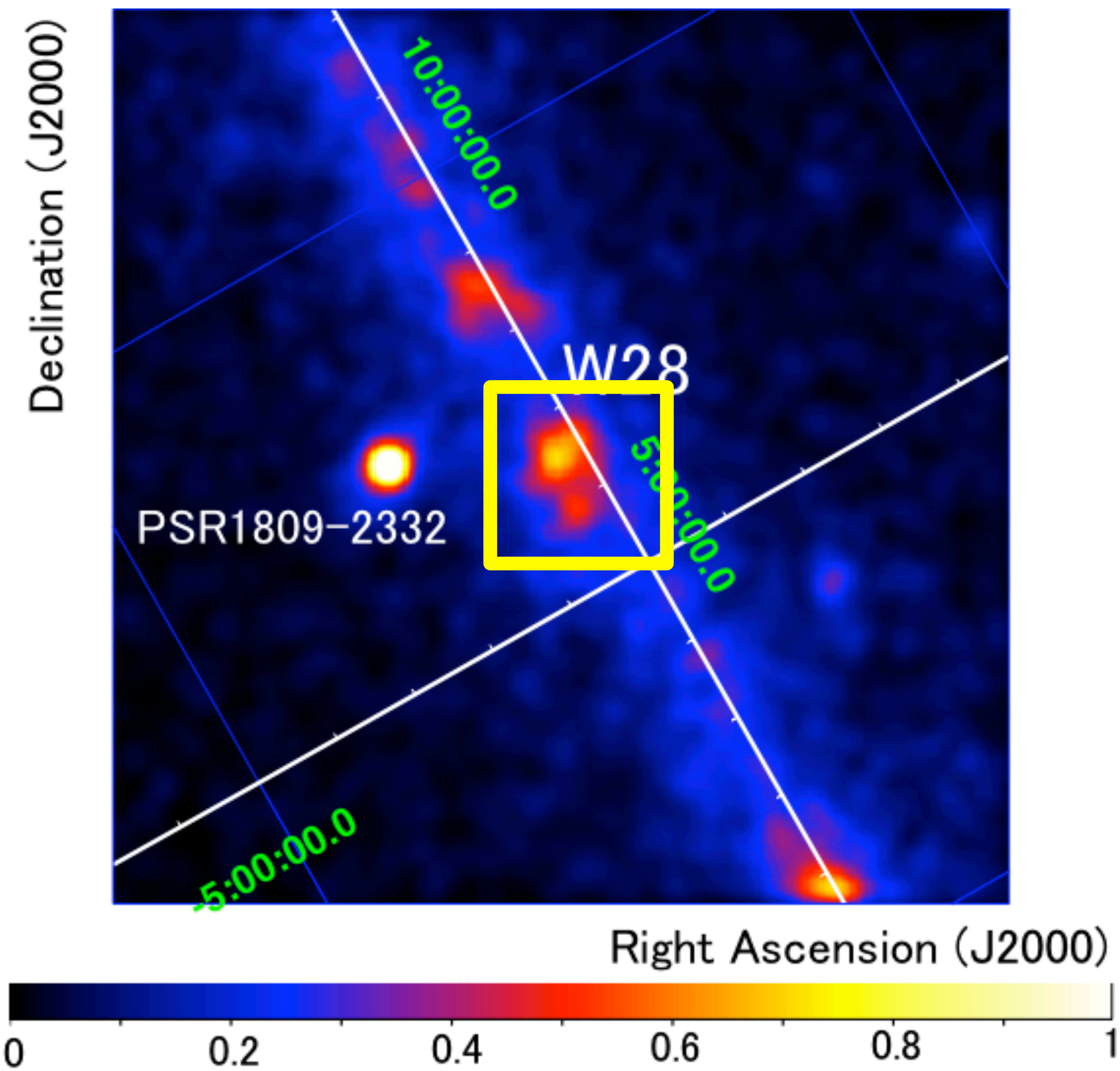


SNR W28

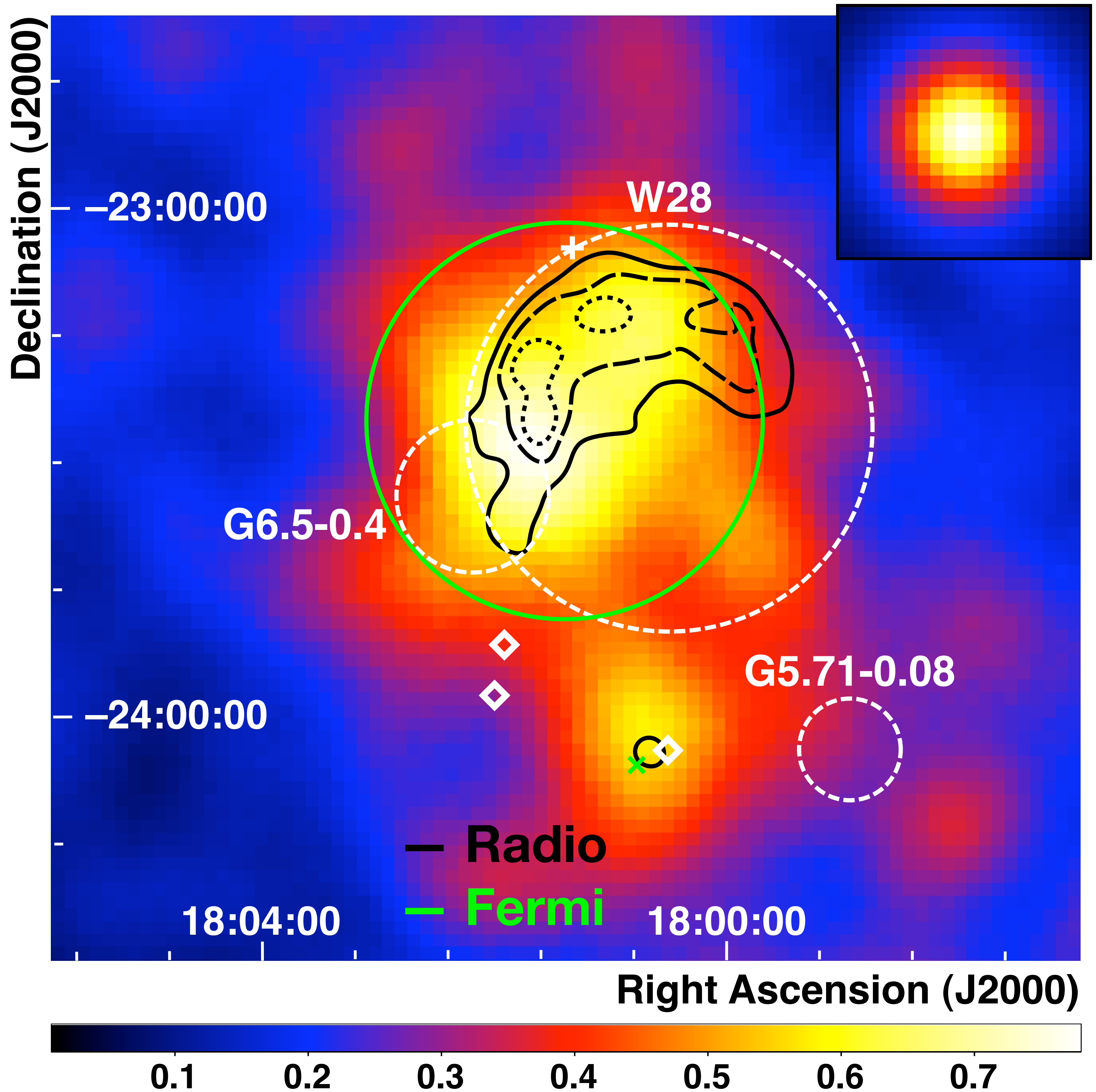


10:00:00.0
W28
5:00:00.0
PSR1809-2332
-5:00:00.0
Declination (J2000)
Right Ascension (J2000)
0
0.2
0.4
0.6
0.8
1

SNR W28

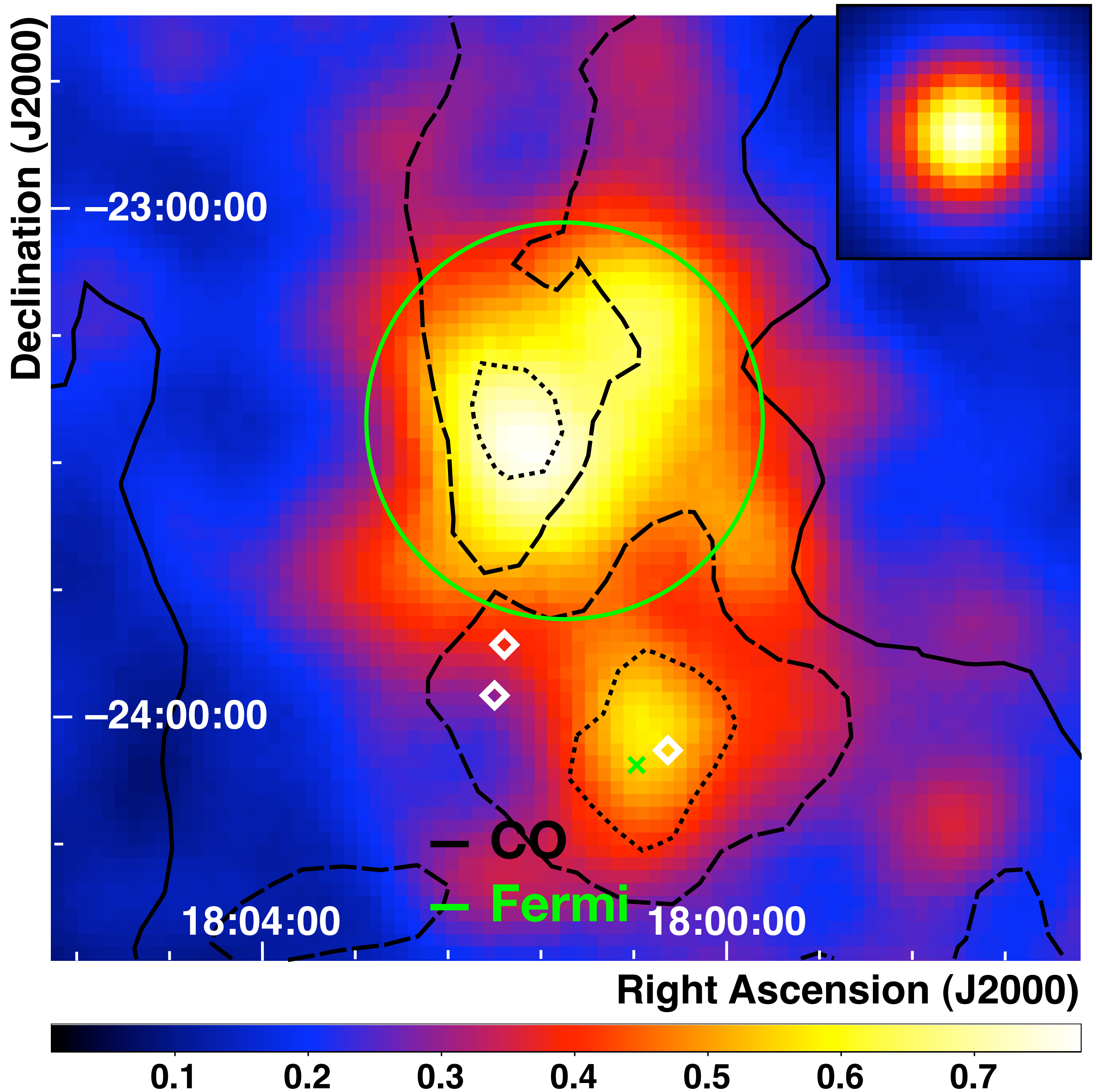

Declination (J2000)
10:00:00.0
W28
5:00:00.0
PSR1809−2332
-5:00:00.0
Right Ascension (J2000)
0
0.2
0.4
0.6
0.8
1

SNR W28

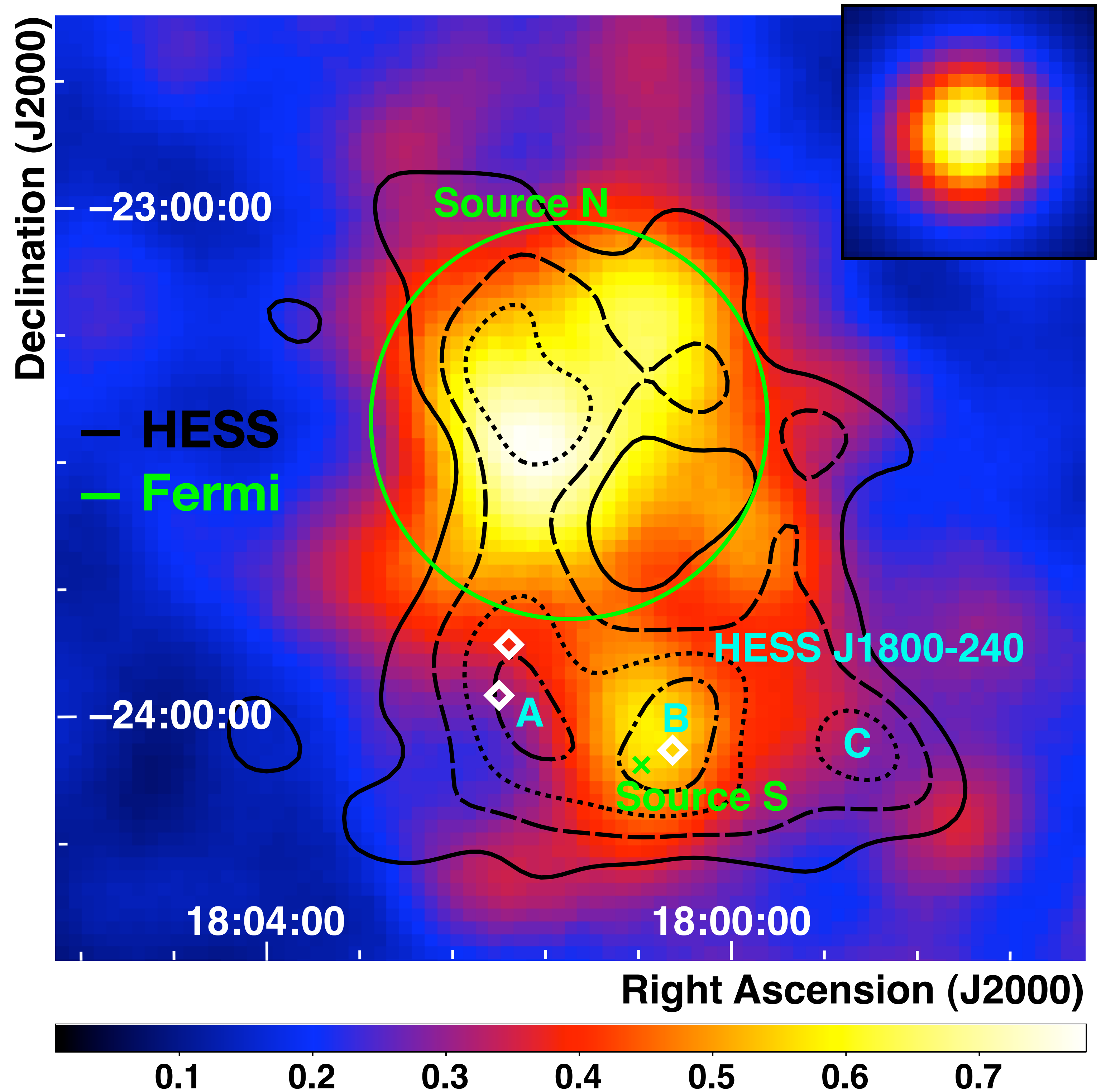


Declination (J2000)
−23:00:00
−24:00:00
W28
G6.5-0.4
G5.71-0.08
Radio
Fermi
18:04:00
18:00:00
Right Ascension (J2000)
0.1
0.2
0.3
0.4
0.5
0.6
0.7

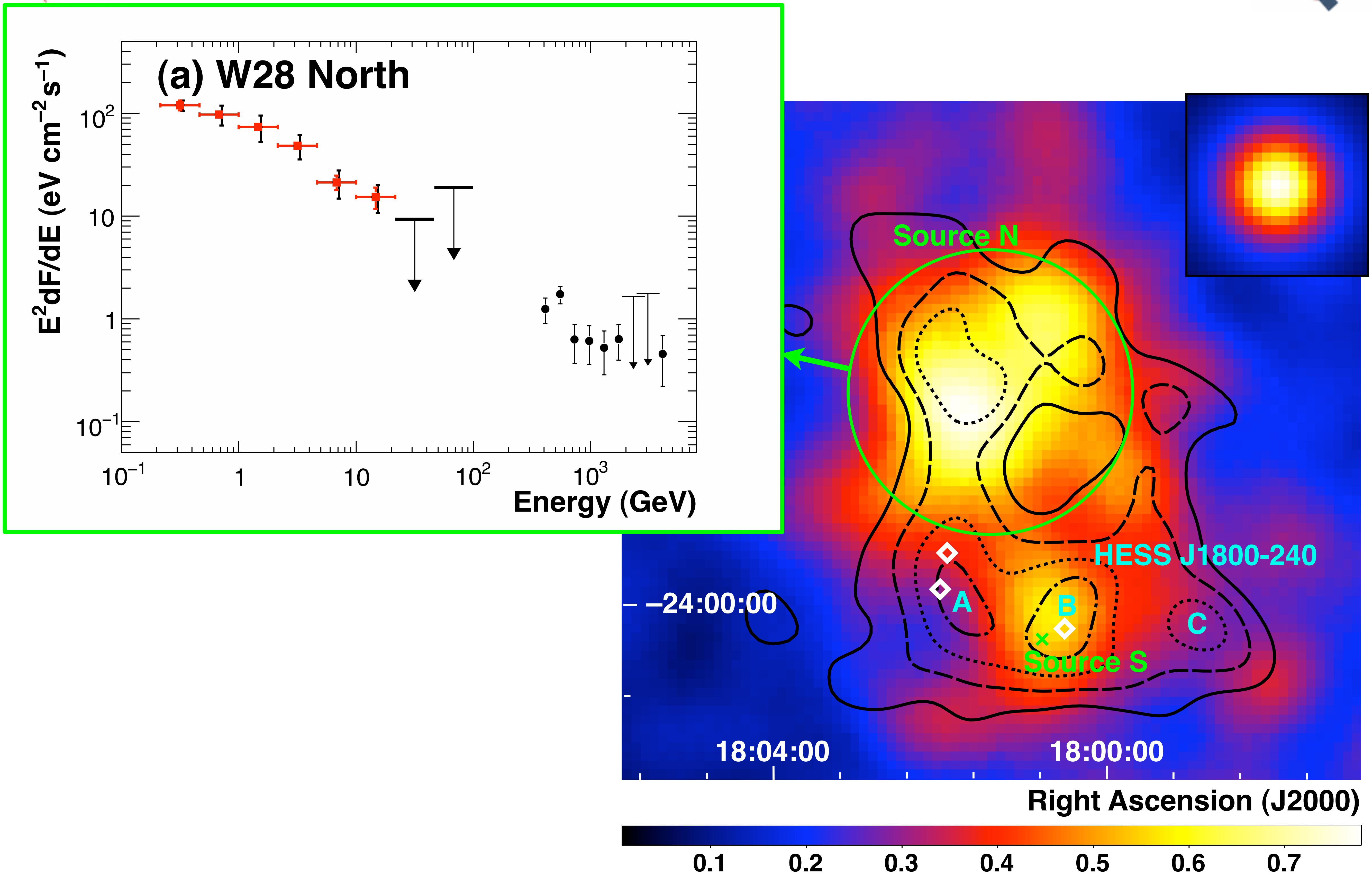
SNR W28



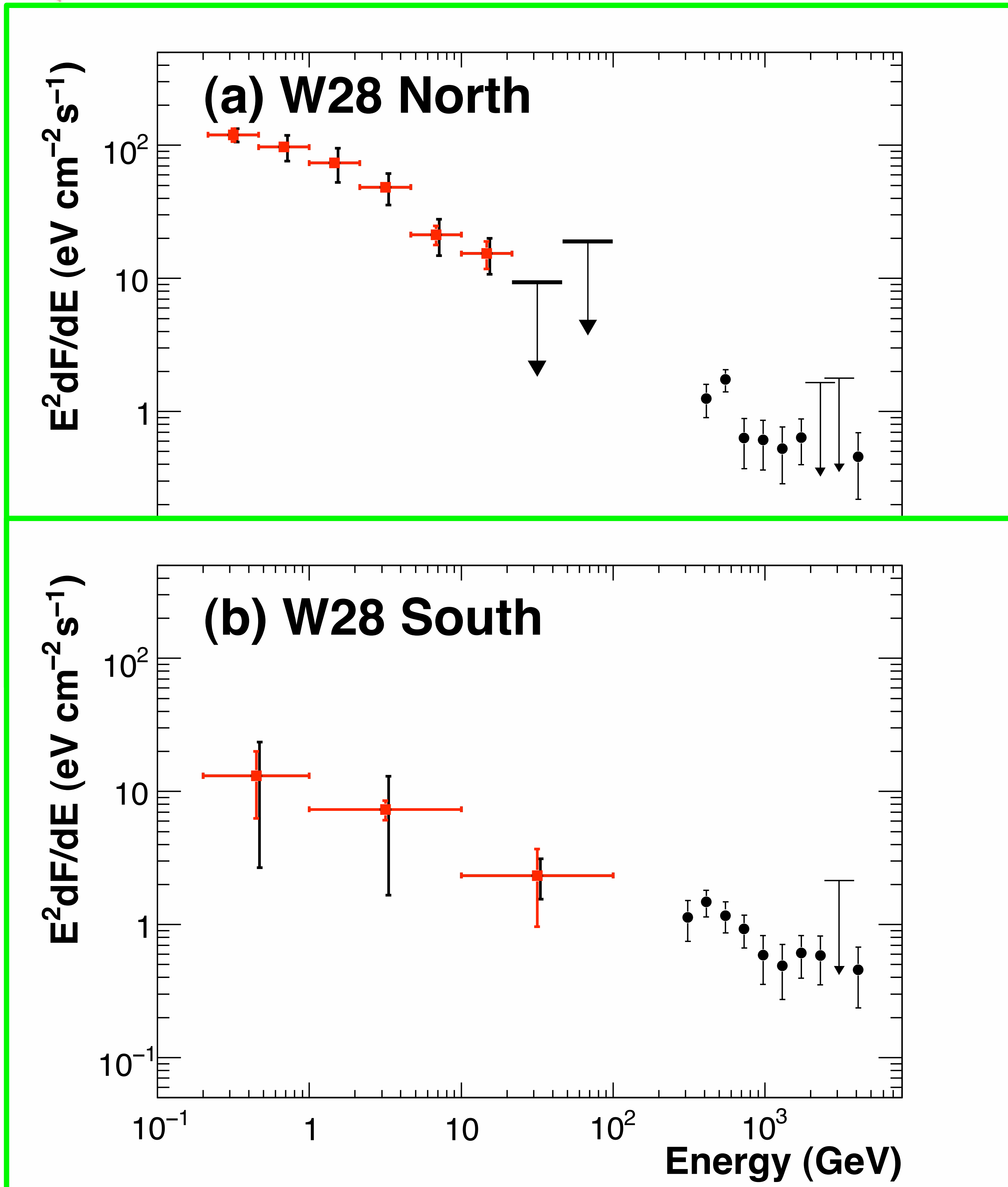
Declination (J2000)
–23:00:00
–24:00:00
18:04:00
18:00:00
Right Ascension (J2000)
— CO
— Fermi
0.1
0.2
0.3
0.4
0.5
0.6
0.7


Declination (J2000)
−23:00:00
−24:00:00
— HESS
— Fermi
Source N
HESS J1800-240
A
B
C
Source S
18:04:00
18:00:00
Right Ascension (J2000)
0.1
0.2
0.3
0.4
0.5
0.6
0.7

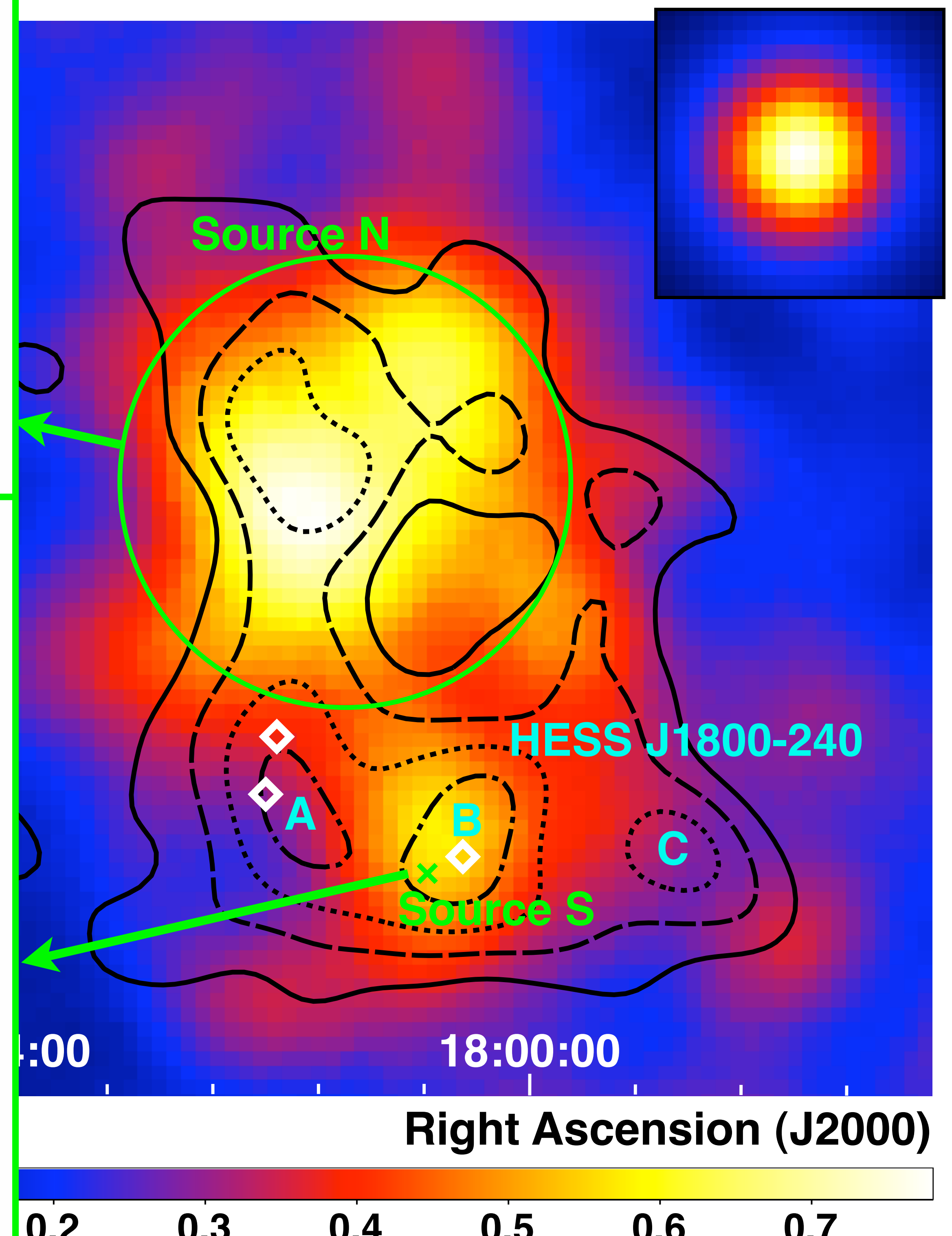
SNR W28


(a) W28 North
E^2dF/dE (eV cm^{-2}s^{-1})
Energy (GeV)
10^{-1}
1
10
10^2
10^3
Source N
Source S
HESS J1800-240
A
B
C
–24:00:00
18:04:00
18:00:00
Right Ascension (J2000)
0.1
0.2
0.3
0.4
0.5
0.6
0.7

SNR W28

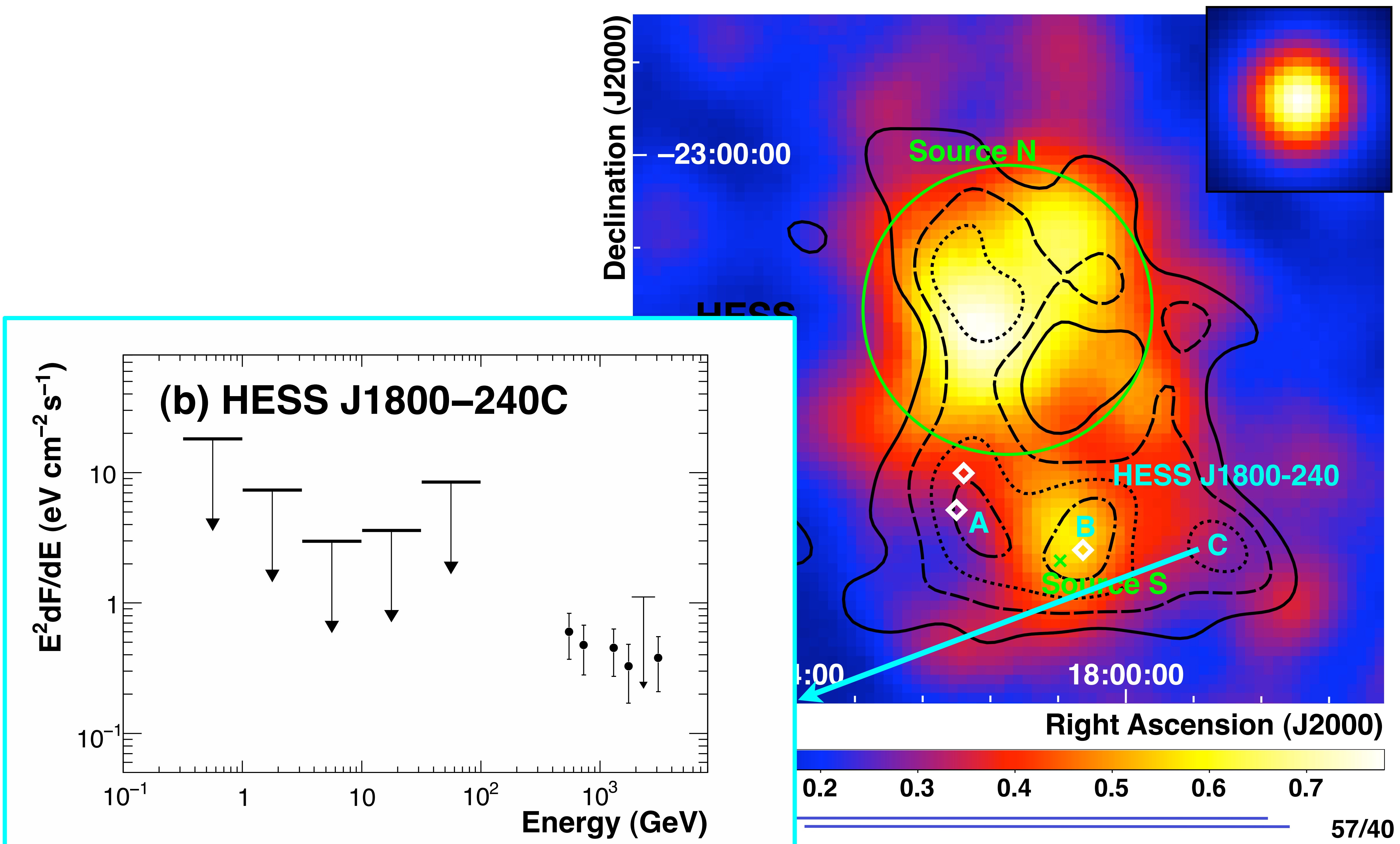


(a) W28 North
(b) W28 South
E^{2}dF/dE (eV cm^{-2}s^{-1})
Energy (GeV)

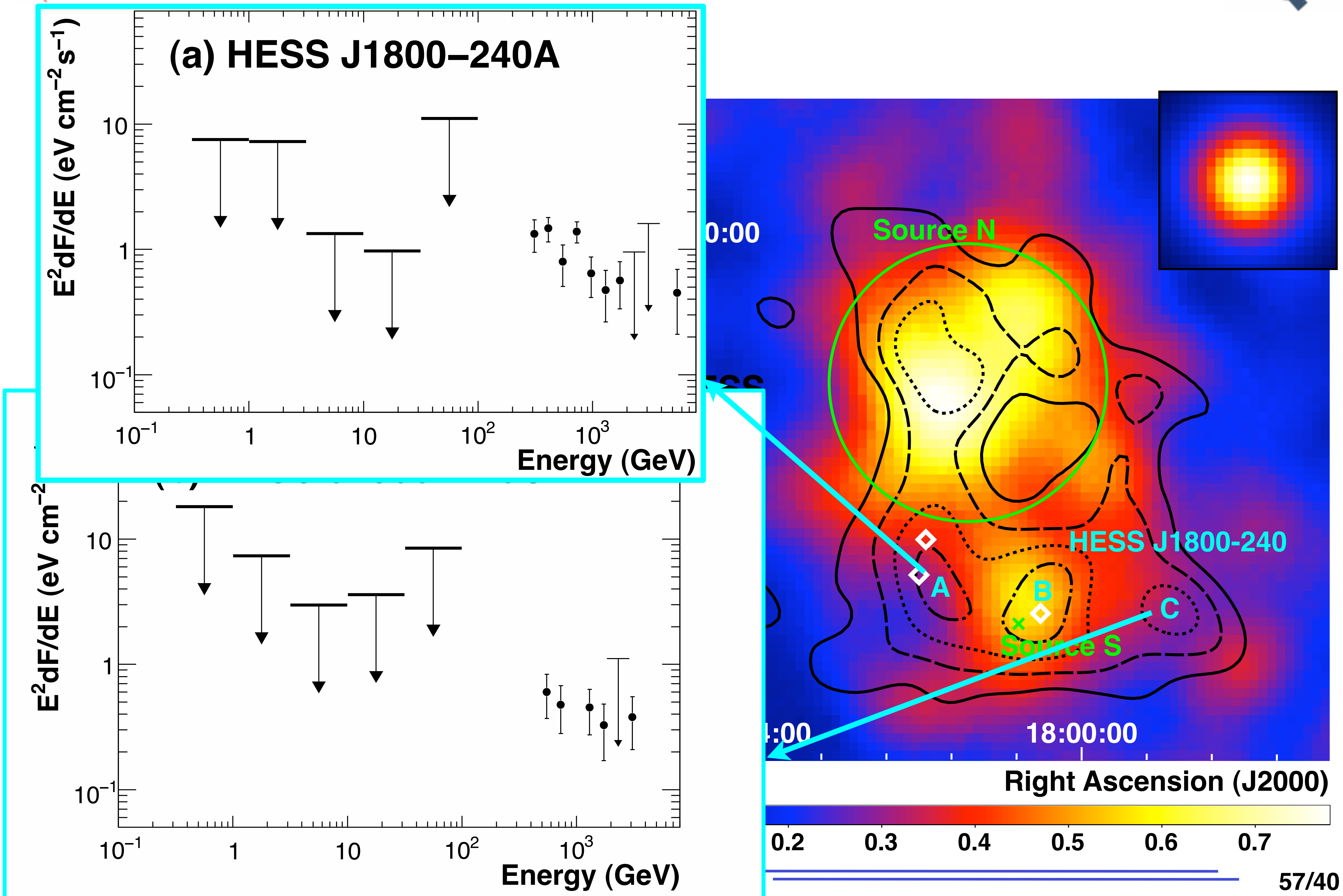


Source N
HESS J1800-240
A
B
C
Source S
18:00:00
Right Ascension (J2000)
0.2
0.3
0.4
0.5
0.6
0.7

SNR W28

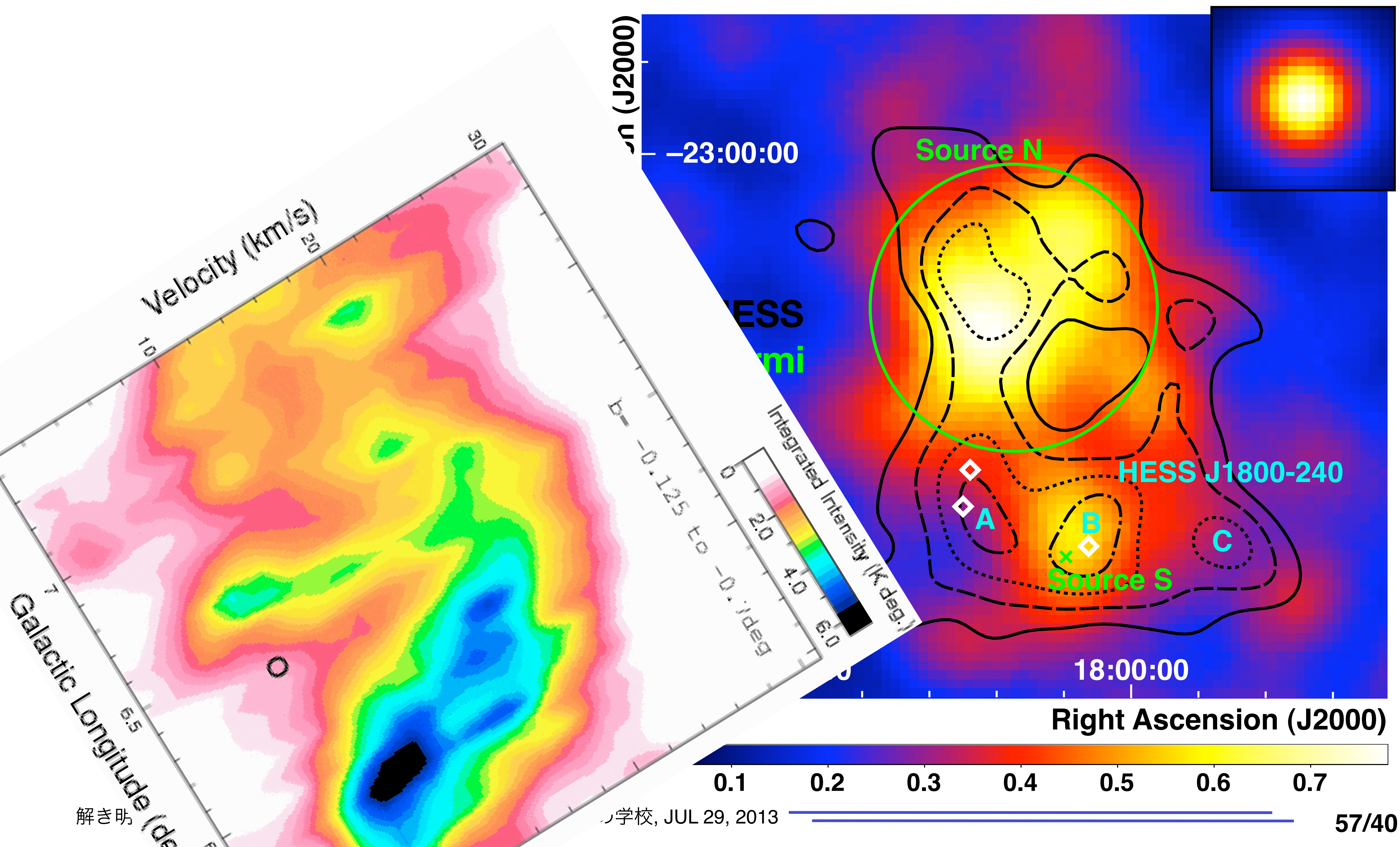

Declination (J2000)
−23:00:00
Source N
HESS J1800-240
A
B
C
Source S
18:00:00
Right Ascension (J2000)
0.2
0.3
0.4
0.5
0.6
0.7
(b) HESS J1800−240C
E^2dF/dE (eV cm^{-2}s^{-1})
10
1
10^{-1}
1
10
10^2
10^3
Energy (GeV)

SNR W28



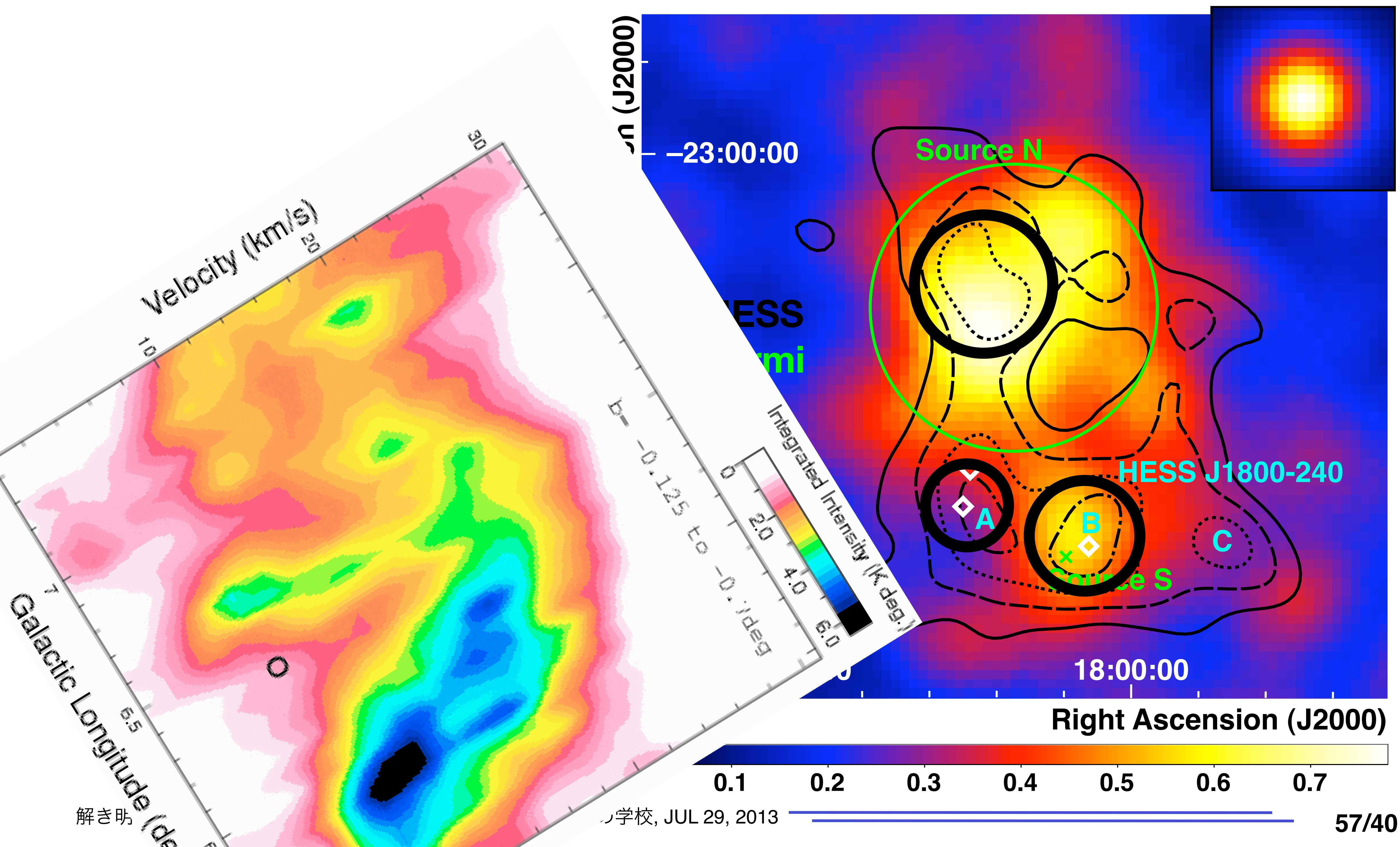
(a) HESS J1800−240A
E^2dF/dE (eV cm^{-2}s^{-1})
Energy (GeV)
Source N
HESS J1800-240
A
B
C
Source S
18:00:00
Right Ascension (J2000)
0.2
0.3
0.4
0.5
0.6
0.7

SNR W28

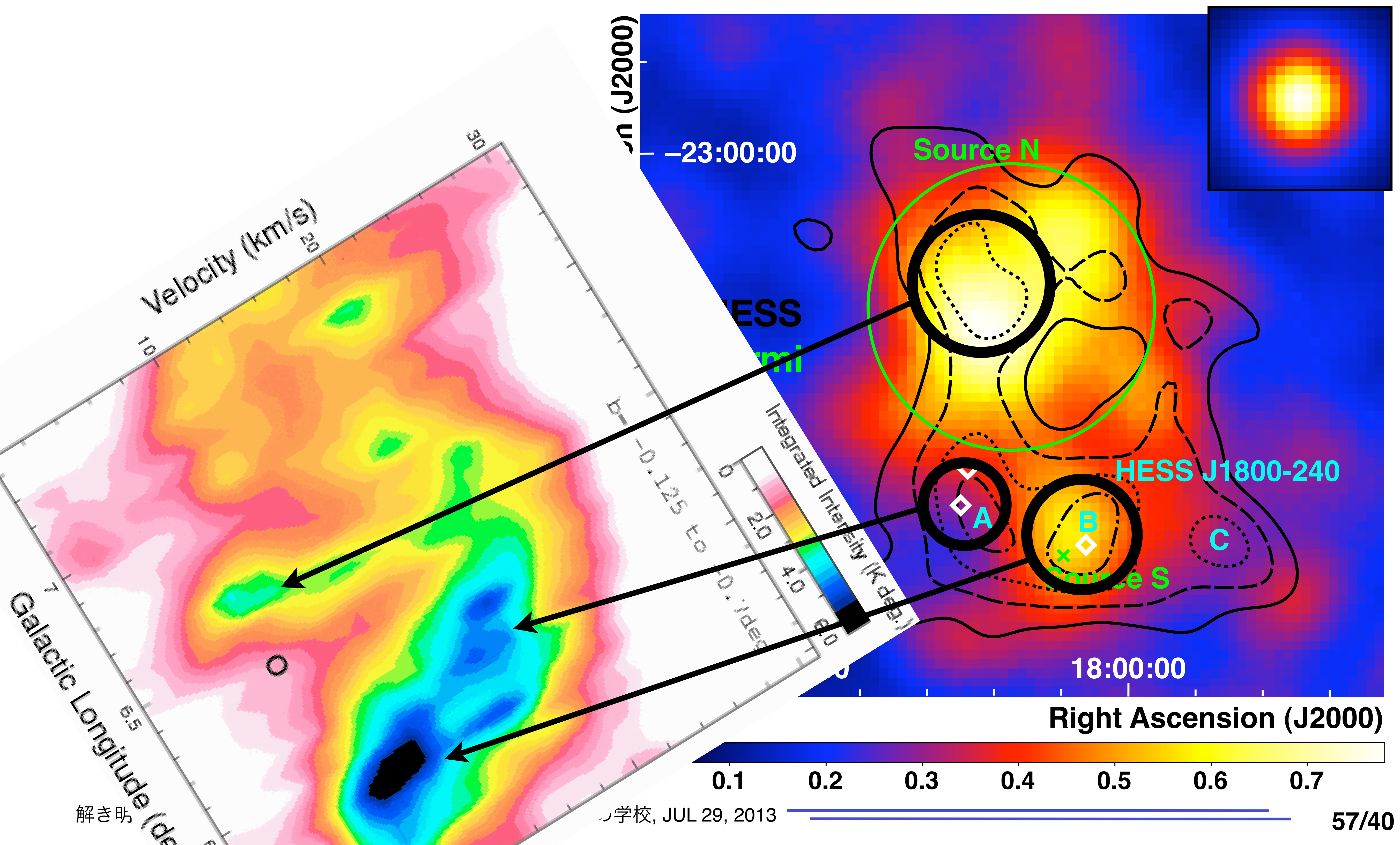


Source N
HESS J1800-240
A
B
C
Source S
−23:00:00
18:00:00
Right Ascension (J2000)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Velocity (km/s)
10
20
30
Galactic Longitude (de
7
6.5
b= -0.125 to -0.1/deg
Integrated Intensity (K deg.)
0
2.0
4.0
6.0

SNR W28


Source N
HESS J1800-240
A
B
C
–23:00:00
18:00:00
Right Ascension (J2000)
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Velocity (km/s)
10
20
30
7
6.5
0
2.0
4.0
6.0
Integrated Intensity (K deg.)

SNR W28

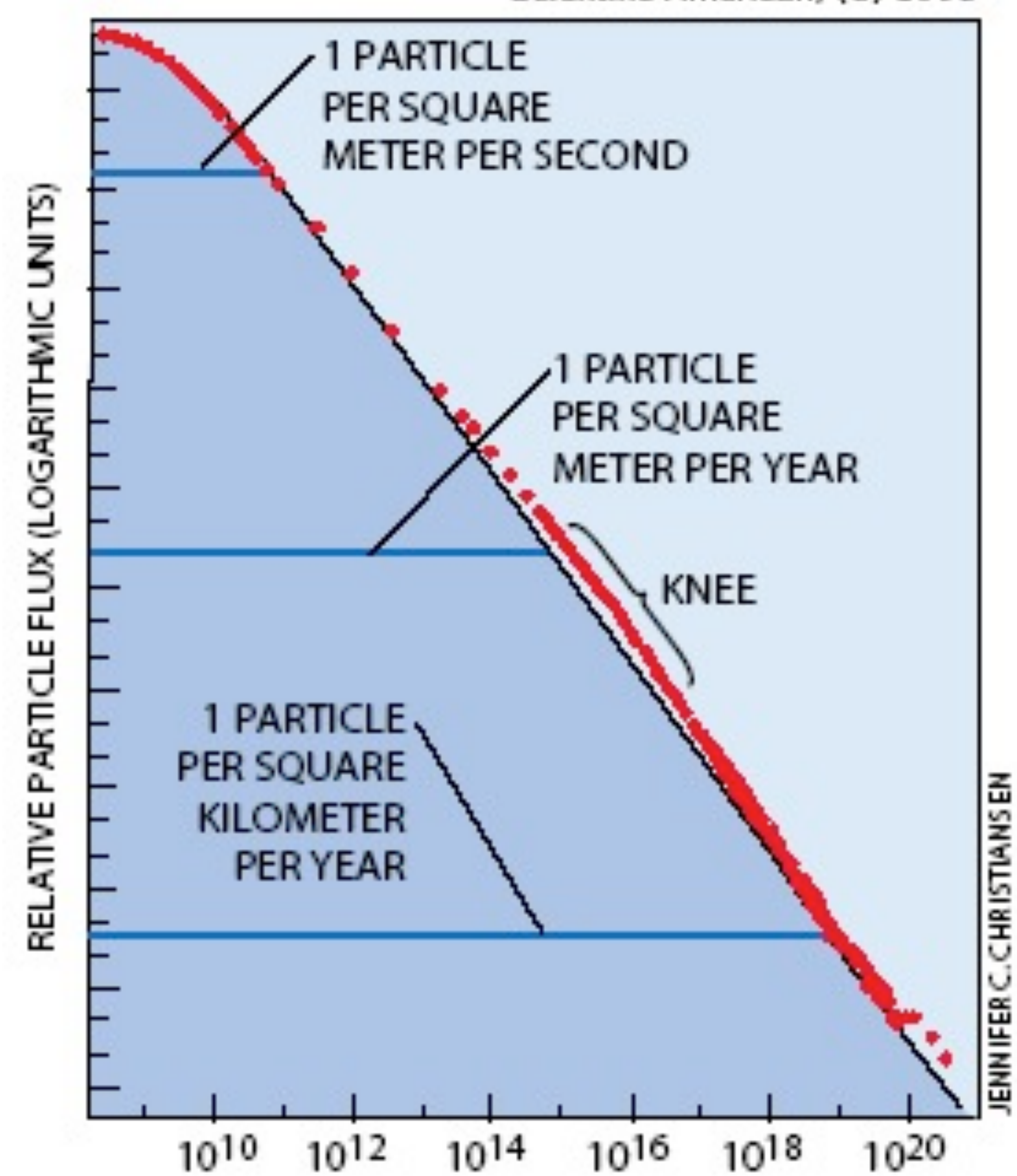


Velocity (km/s)
30
20
10
7
6.5
Integrated Intensity (K deg.)
2.0
4.0
6.0
−23:00:00
Source N
HESS J1800-240
A
B
C
18:00:00
Right Ascension (J2000)
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Cosmic Particle Accelerators

- **Origin of cosmic ray protons?**
  - **Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below "Knee"**
    - Only circumstantial evidence
      - CR energy sum consistent with SNR kinetic energy (Ginzburg&Syrovatskii 1964)
      - Diffusive shock acceleration (Blanford&Eichler 1977)
    - No observational evidence for hadronic acceleration
    - Spectral index (~2.7) is difficult to explain
  - **Cosmic-rays above "Knee" are considered extragalactic**
    - Gamma-ray bursts (GRB)
    - Active Galactic Nuclei (blazar)
    - Merging galaxy clusters

Scientific American, (c) 1998



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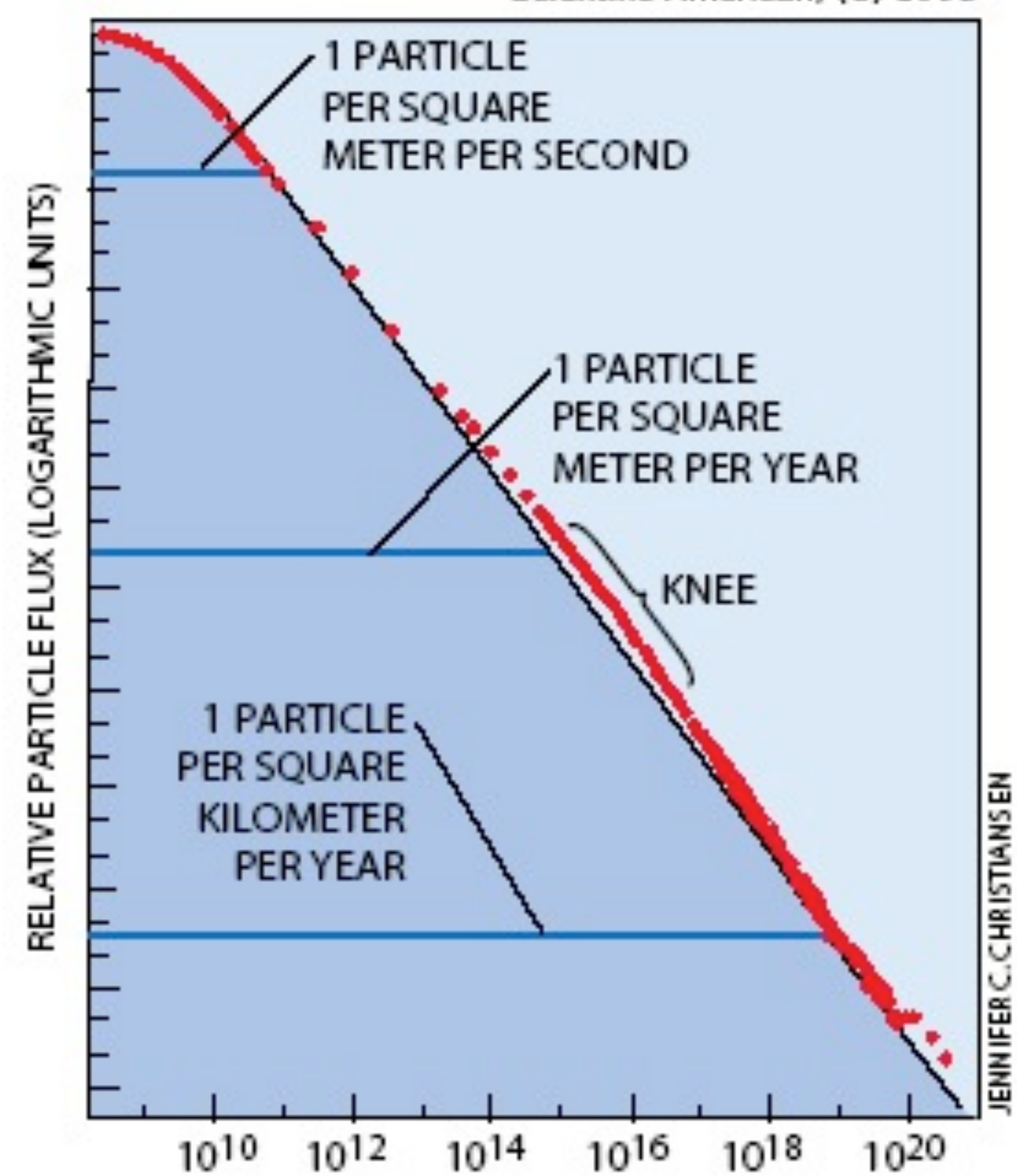
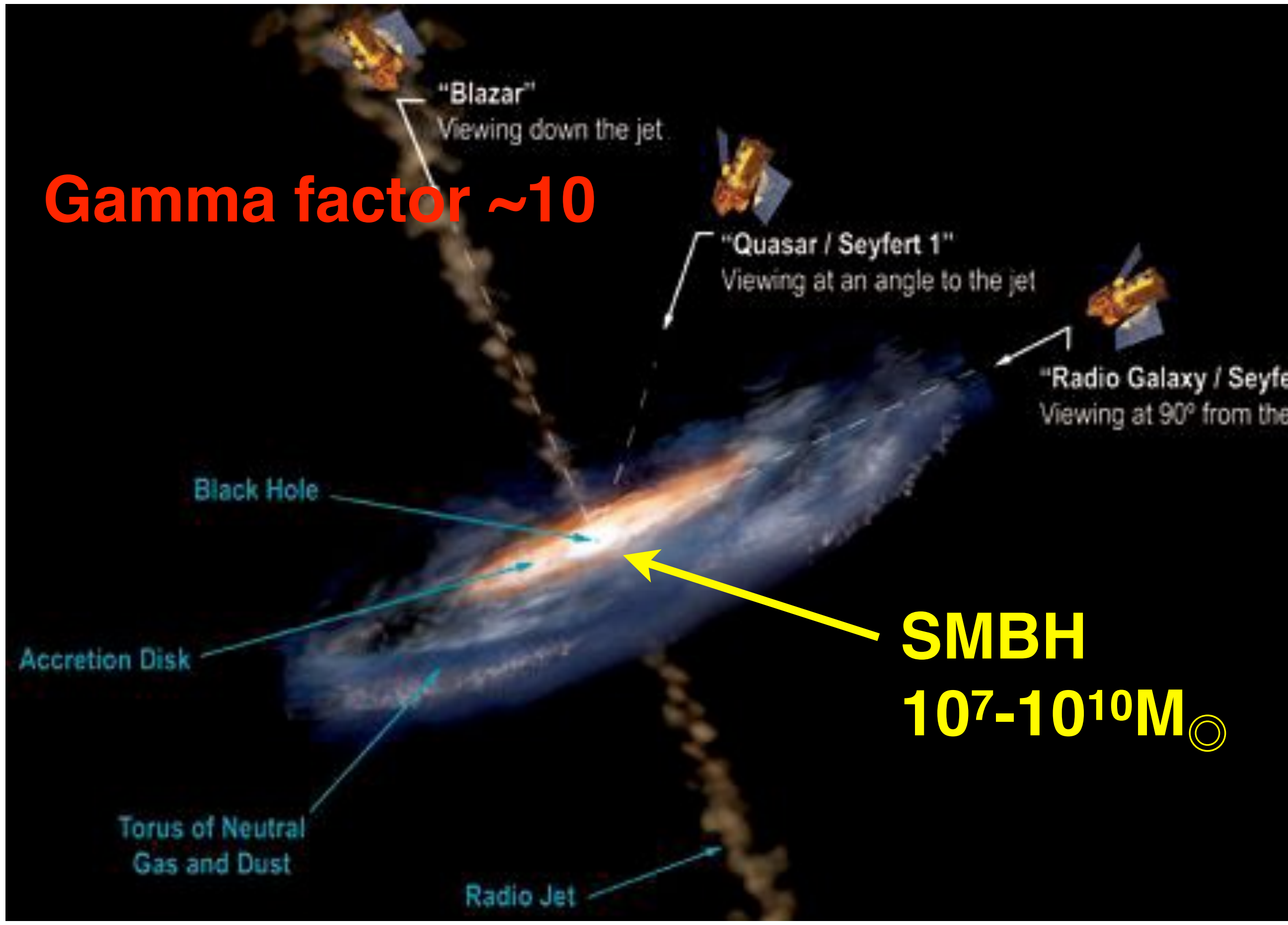


Blazars (AGN)

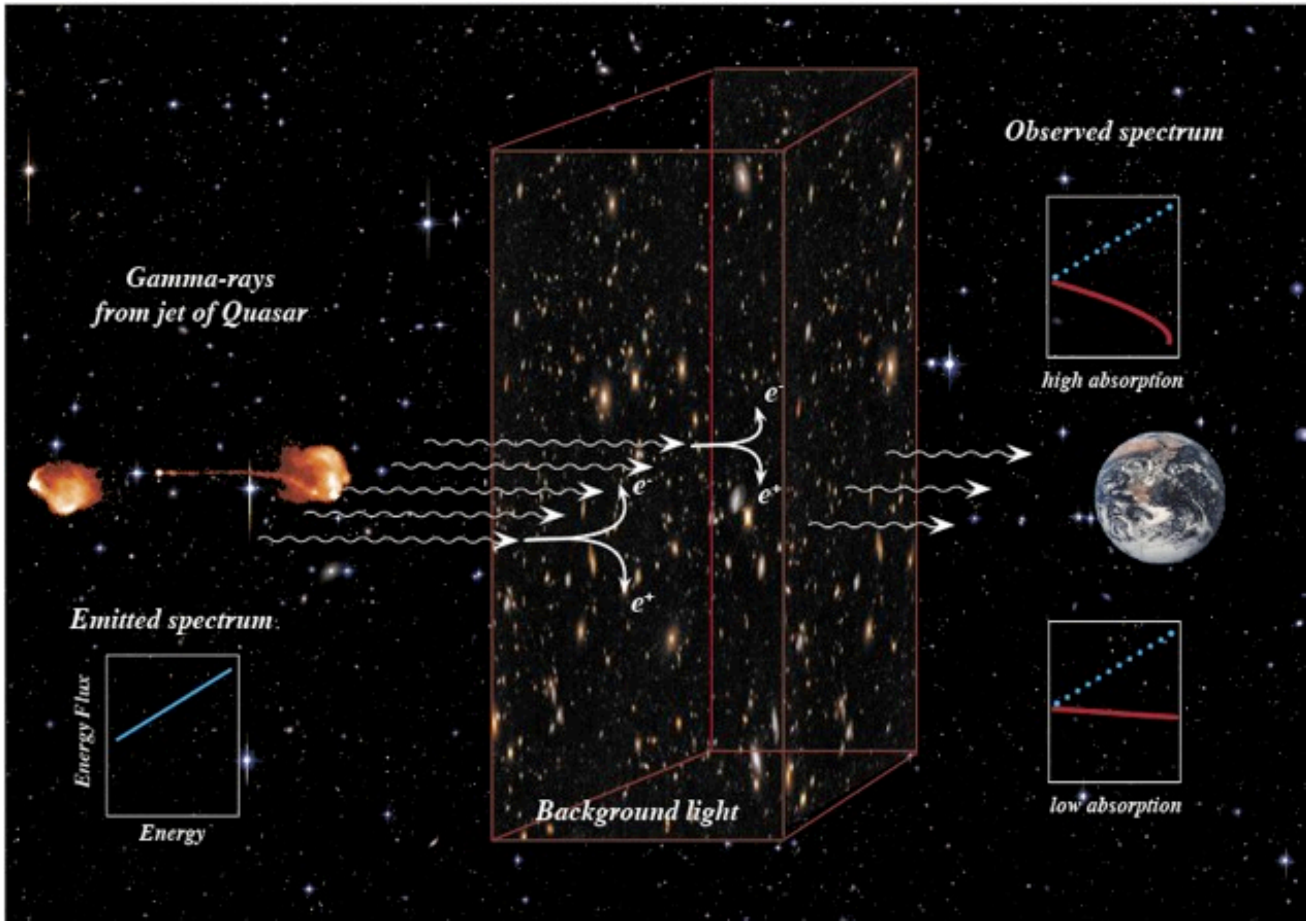
- Emission mechanisms (for HE component)
  - Leptonic (IC of synchrotron or external photons) vs hadronic ($\pi 0 \rightarrow \gamma\gamma$, proton synchrotron)
- Emission location
  - Single zone for all wavebands?
- Particle acceleration mechanisms
  - Shocks, magnetic reconnection, turbulence acceleration
- Jet composition
  - Poynting flux, leptonic, ions
- FSRQ/BLLac dichotomy
- Jet confinement
  - External pressure, magnetic stresses
- Accretion disk—black hole—jet connection
- Effect of blazar emission on host galaxies and galaxy clusters
- Blazars as probes of the extragalactic background light (EBL)



Pair Creation

- **Interaction with ambient photons**
  - **Cross section peaks at**

$$E_1^\gamma E_2^\gamma (1-\cos\theta) \approx 2(m_e c^2)^2$$
$$E_2^\gamma \approx 500\ [\mathrm{eV}]\ \text{for}\ E_1^\gamma = 1\ [\mathrm{GeV}]$$
$$E_2^\gamma \approx 0.5\ [\mathrm{eV}]\ \text{for}\ E_1^\gamma = 1\ [\mathrm{TeV}]$$



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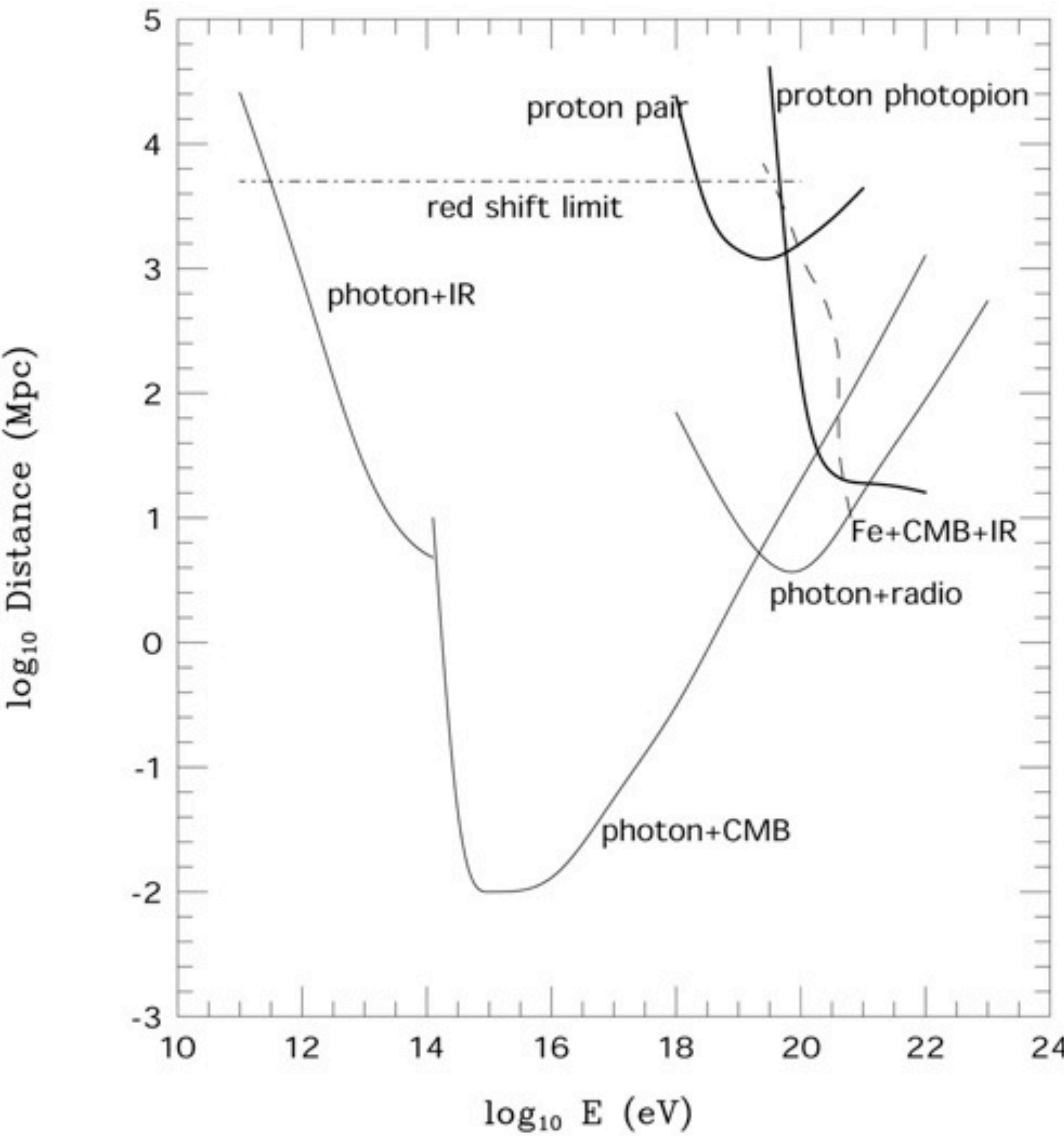
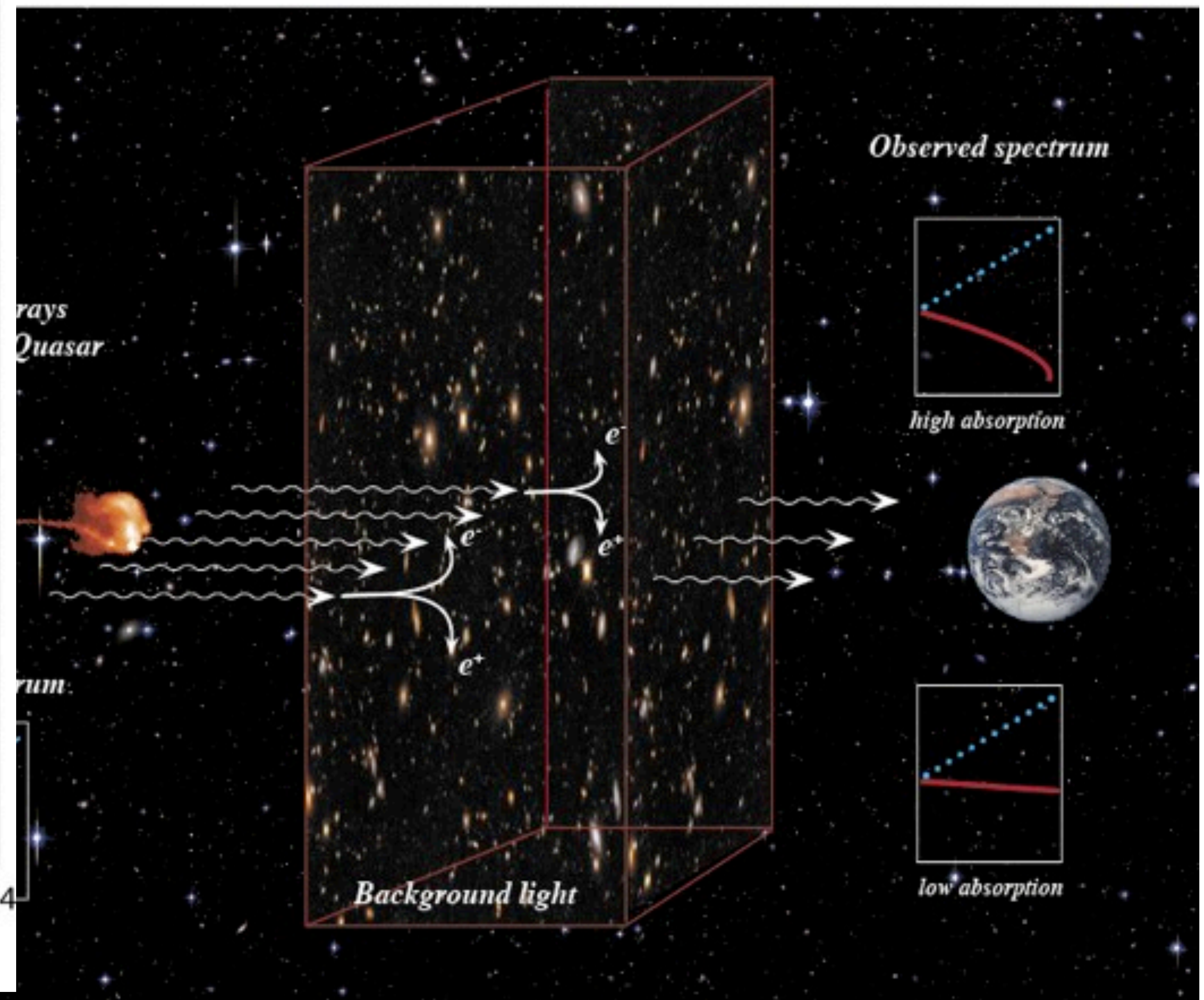
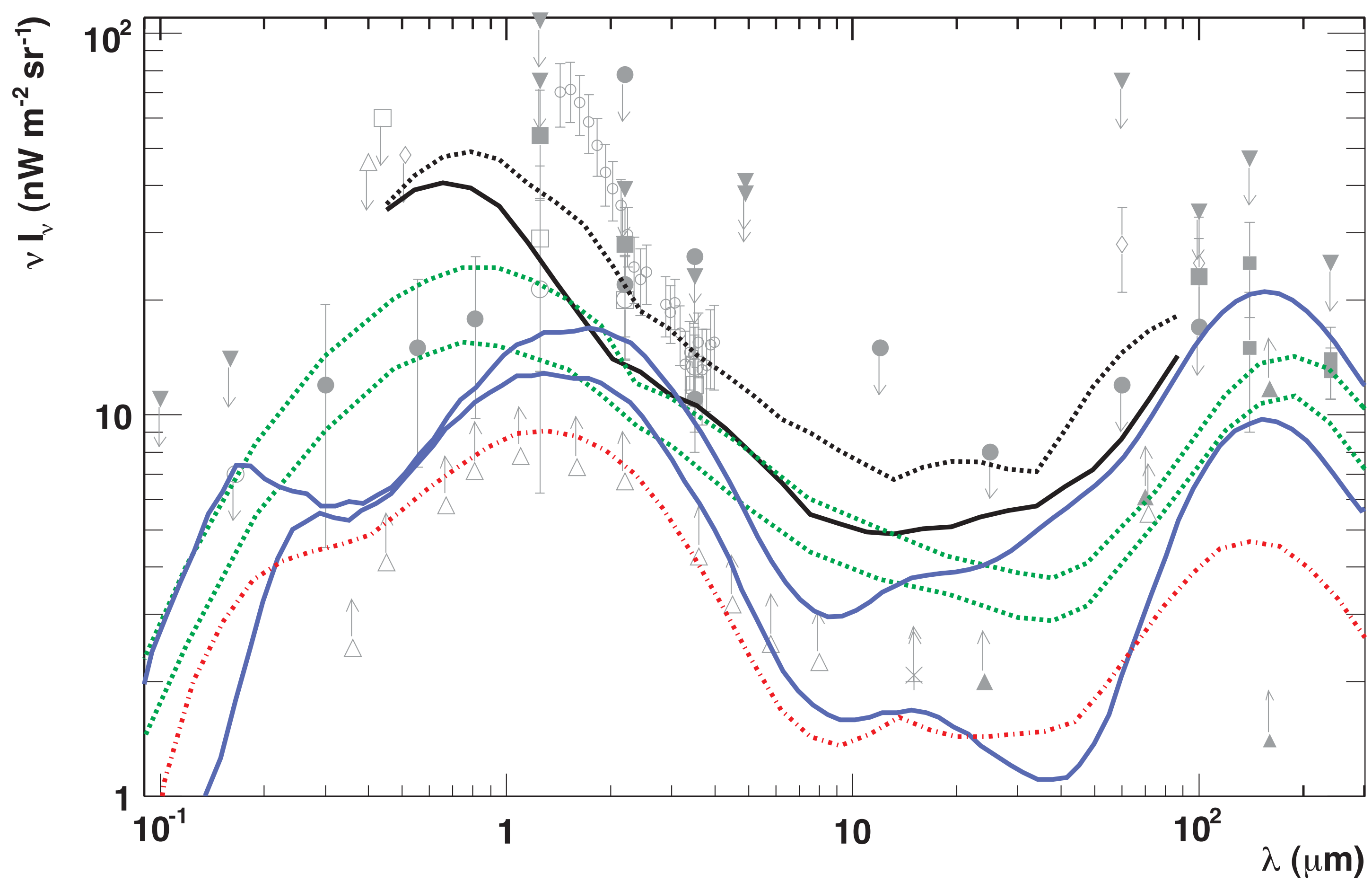




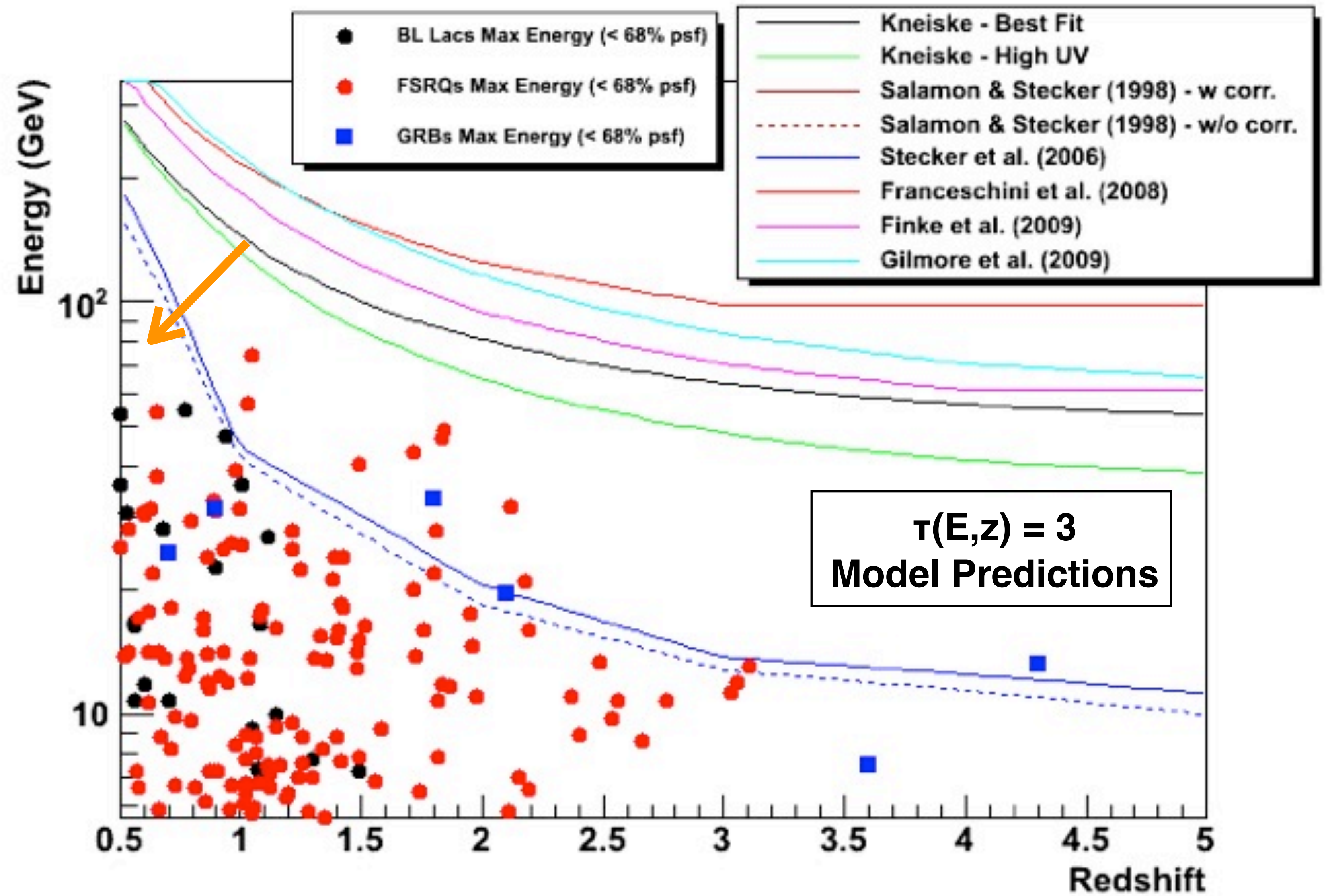
Extragalactic Background Light

- EBL is sensitive to star formation history, dust extinction, light absorption and re-emission by dust
  - Direct measurements of the IR-UV EBL are very difficult because of foreground subtraction
- ~TeV gamma rays are sensitive to EBL in IR to UV band via $\gamma\gamma \rightarrow e^+e^-$ process
  - EBL will steepen AGN/GRB spectra above > 10 GeV



Probing EBL with AGN and GRB

- 10–100 GeV gamma rays can probe EBL in early universe
  - Information on intrinsic spectrum
- Requires many sources at various redshifts to untangle EBL effect and intrinsic spectra
  - Fermi has ~100 of blazars and ~10 of GRBs with redshift



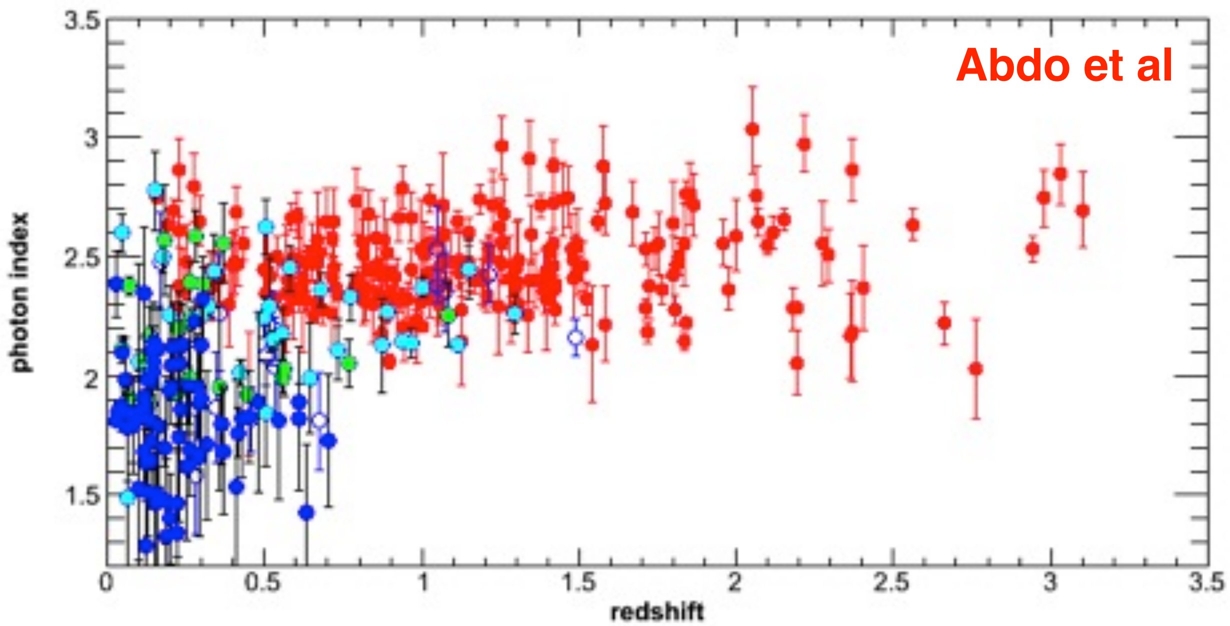
EBL - TeV Gamma-ray Crisis

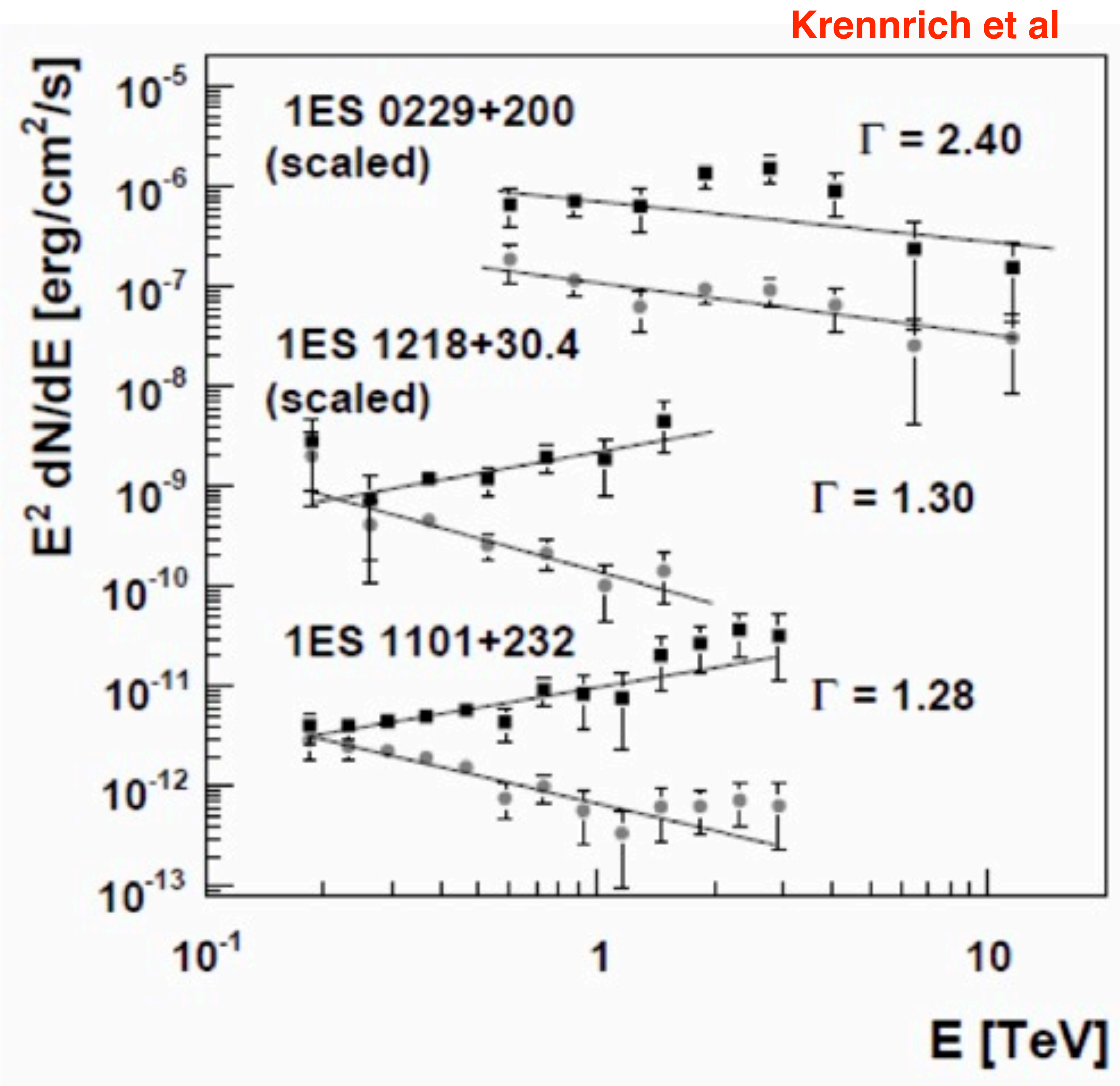
- **Observed TeV spectrum is too "hard"**

$$\frac{dN}{dE} = N_0 E^{-\Gamma_{\rm int}} \times e^{-\tau(E)}$$

Intrinsic spectrum — EBL attenuation

- **Even lowest EBL still often yields $\Gamma_{int} < 1.5$ as low as 0.5**
- **Blazars at redshifts z > 0.1 have particularly hard spectra**
- **Fermi observed softer spectra at ~GeV region**





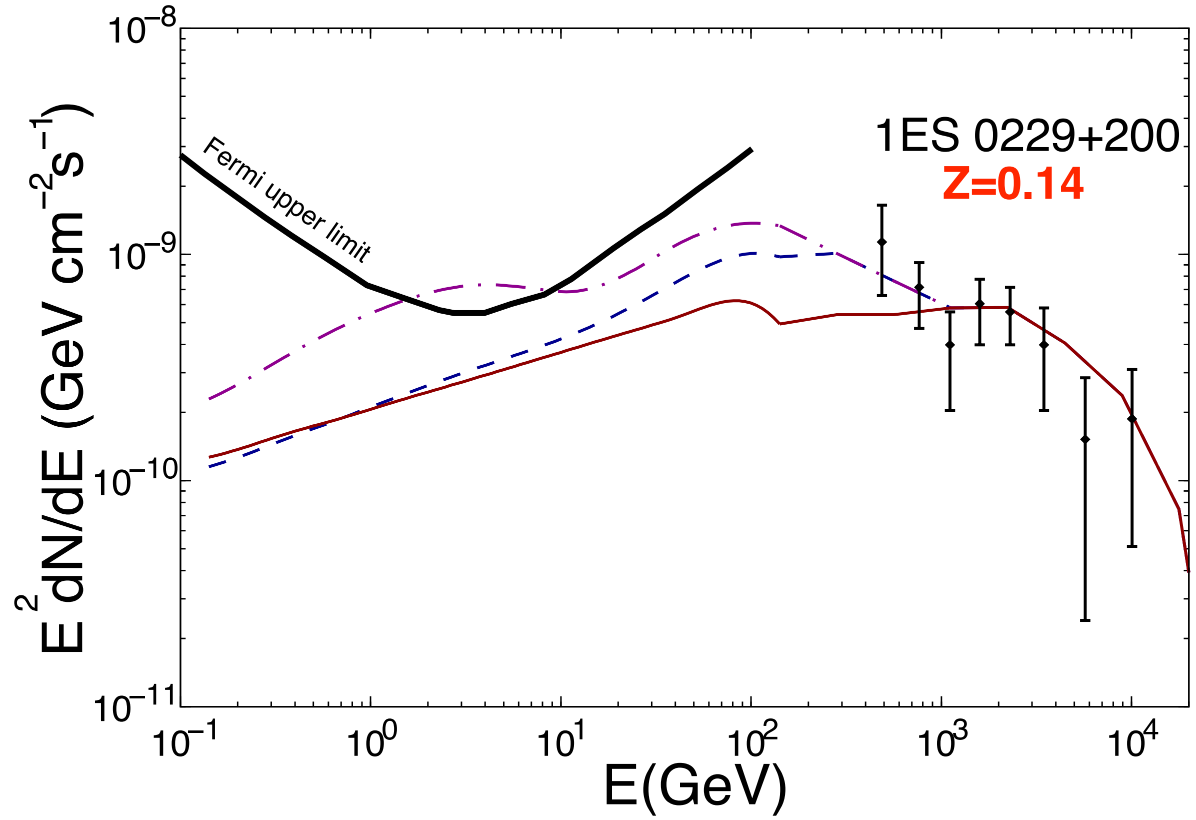
New Approach

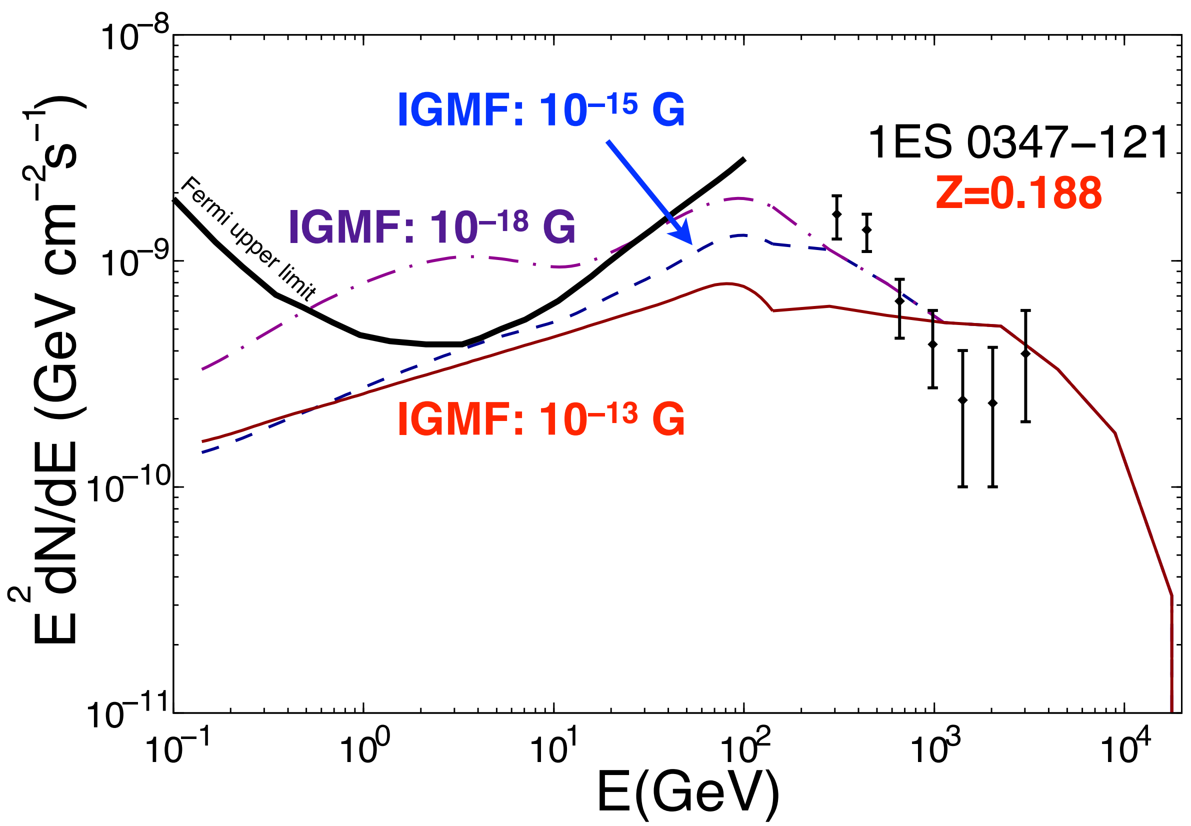
- Take into account secondary photons from UHE gamma rays to explain “hard” spectra of distant blazars
  - Use Monte Carlo to track individual photons and all secondary particles (instead of analytical parametric approaches)
  - EBL models considered in this study
    - “High”: based on observed luminosity functions (Stecker et al)
    - "Low": based on lower limits from galaxy counts
    - EBL models include evolution with redshift
  - Include effects from Intergalactic magnetic field (IGMF)
    - Only upper limits exist for IGMF
      - 10^{-6} – 10^{-12} G depending on model (Dolag et al 2004)
    - Strong IGMF will deflect secondaries and produce halo beyond the PSF of Fermi or Cherenkov telescopes

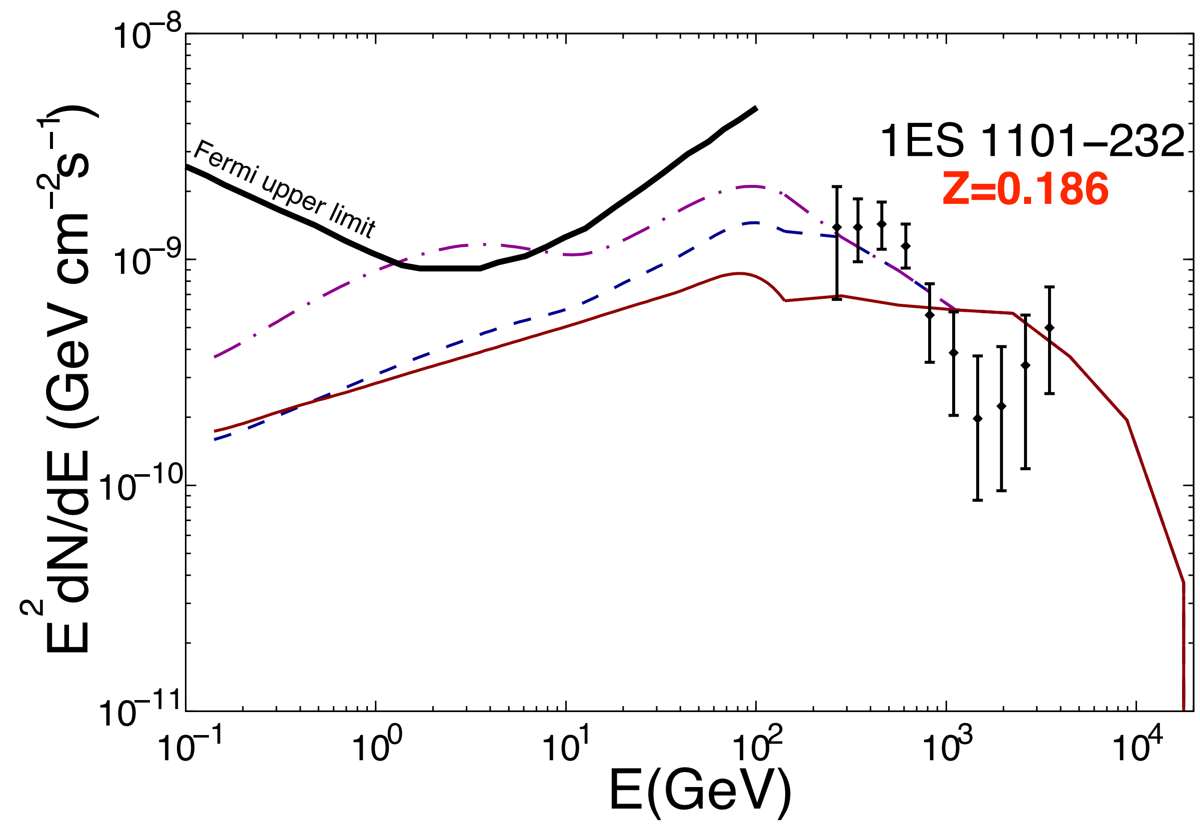
$$\Delta\theta \approx 0.1^\circ \left(\frac{B}{10^{-14}\mathrm{G}}\right)\left(\frac{4\times10^{16}\mathrm{eV}}{E}\right)\left(\frac{D_s}{1\mathrm{Gpc}}\right)^{1/2}\left(\frac{l_c}{1\mathrm{Mpc}}\right)^{1/2}$$

Spectral Fit

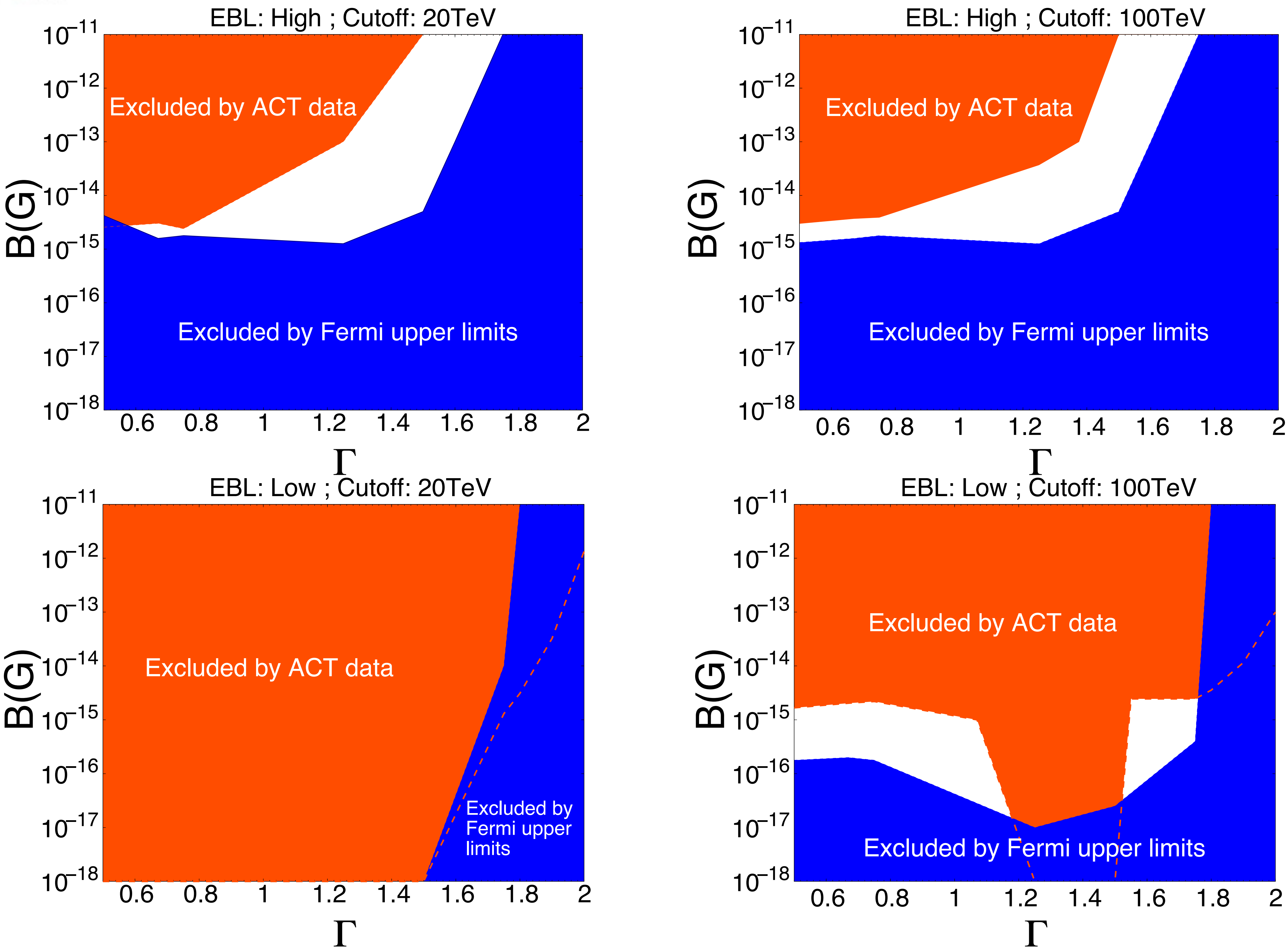
- Γ_{int} = 1.75, E_{max}=100 TeV assumed







Parameter Scan



Gamma rays from Cosmic-Ray Cascades

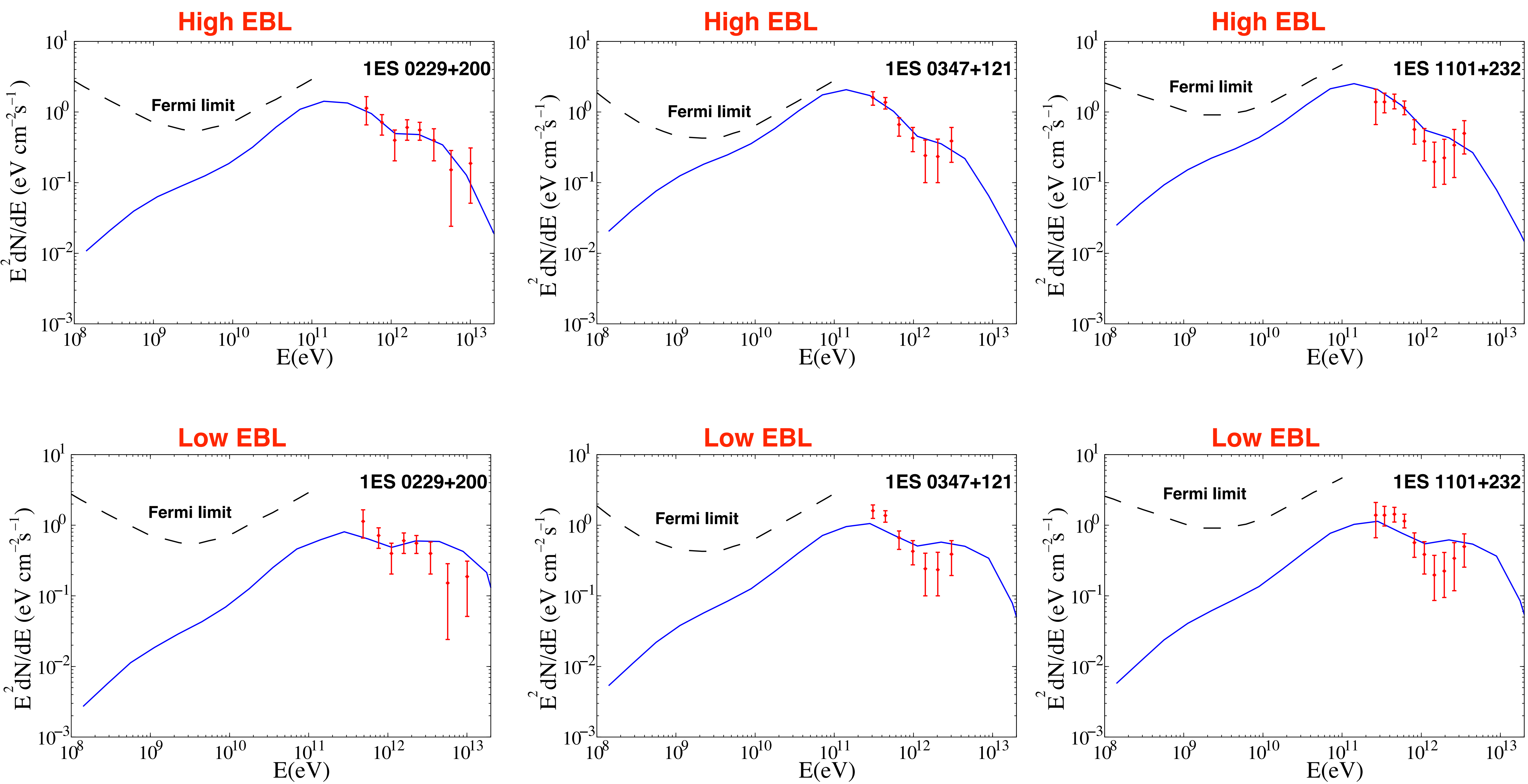
- **Proton interaction with CMB photons**

$$p + \gamma_{\rm CMB} \rightarrow p + e^+ + e^-$$
$$p + \gamma_{\rm CMB} \rightarrow N + n\pi \rightarrow m\gamma + k\nu$$

  - **Secondary electrons up-scatter CMB photons producing VHE gamma rays**
- **Remainder is similar to previous study**

Spectral Fit with CR Origin

B = 10^{-15} G, E_{max} = 10^{20} eV, Γ_{int}= 2, and θ_{jet} = 6°



Summary of CR Origin Fit

- 95% CL limit on IGMF found to be
  - 2×10^{-16} G < B < 3×10^{-14} G ("High" EBL)
  - 1×10^{-17} G < B < 8×10^{-16} G ("Low" EBL)

$\ell_{\mathrm{UHECR}} \approx 3 \times 10^{36}$ egs/s/Mpc^3

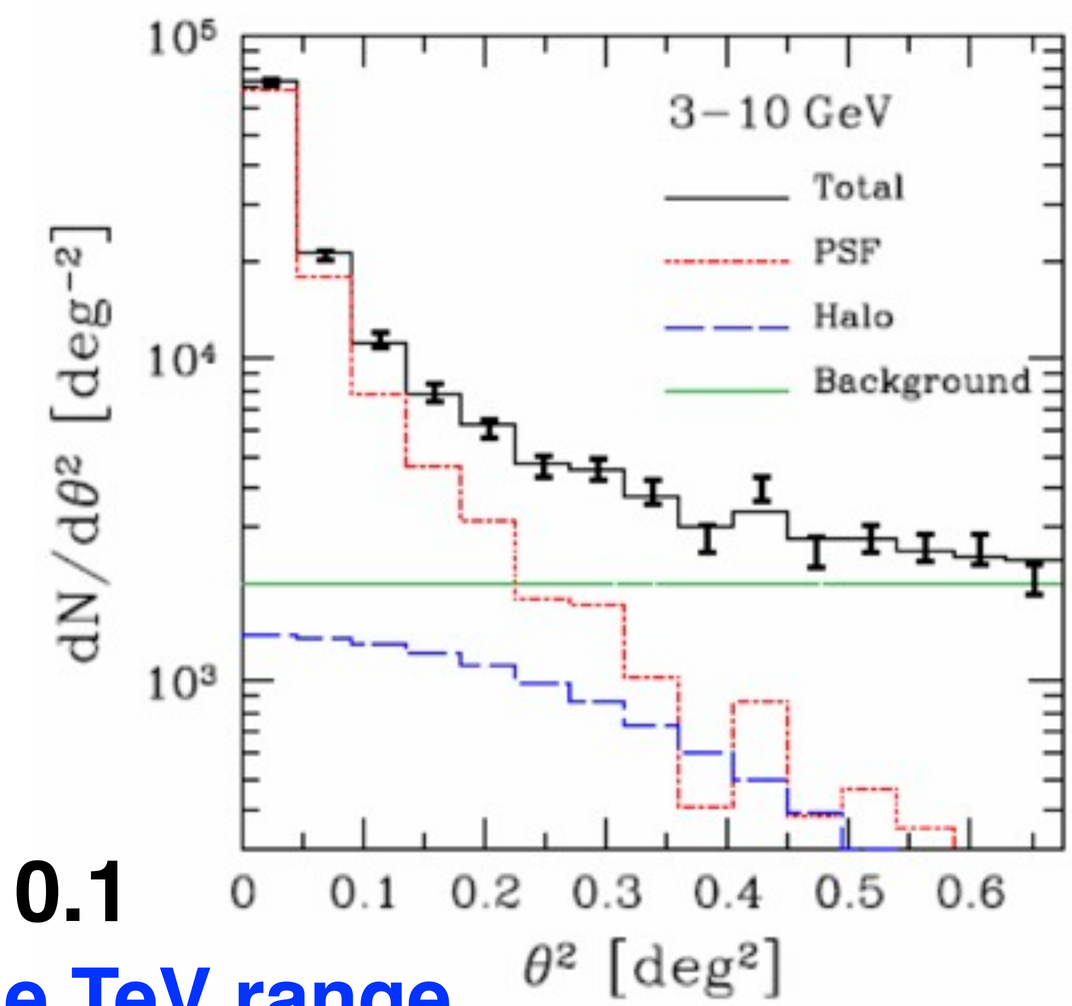
$n_{\mathrm{BLZR}} \approx 4 \times 10^{-6}$ Mpc^{-3}

Source	Redshift	EBL model	L_p ($\times 10^{43}$ erg/s)	χ^2/D.o.F.
1ES0229+200	0.14	Low	1.3	6.4 / 7
		High	3.1	1.8 / 7
1ES0347-121	0.188	Low	2.7	16.1 / 6
		High	5.2	3.4 / 6
1ES1101-232	0.186	Low	3.0	16.1 / 9
		High	6.3	4.9 / 9

$B = 10^{-15}$ G, $E_{\mathrm{max}} = 10^{20}$ eV, $\Gamma_{\mathrm{int}} = 2$, and $\theta_{\mathrm{jet}} = 6°$

Test of CR Origin Model

- **Secondary gamma rays with low IGMF have some testable consequences:**
  - **For $B > 10^{-15}$ G halos will be present around source, more significant for cosmic rays**
  - **Recent Fermi analysis consistent with $B \sim 10^{-15}$ G**



Essey, Ando, Kusenko 2010

- **Gamma-ray spectrum continues beyond Klein-Nishina regime**
- **No short scale time variability for z > 0.1**
  - **No variability has been observed in the TeV range**
  - **Some variability below 200 GeV**
- **High energy neutrino signal should accompany gamma rays**

CTA Membership

- 25 countries
- 132 Institutions
- 734 Scientists