Search for PeVatrons in Milky-way Galaxy by Cosmic Gamma-ray Observations

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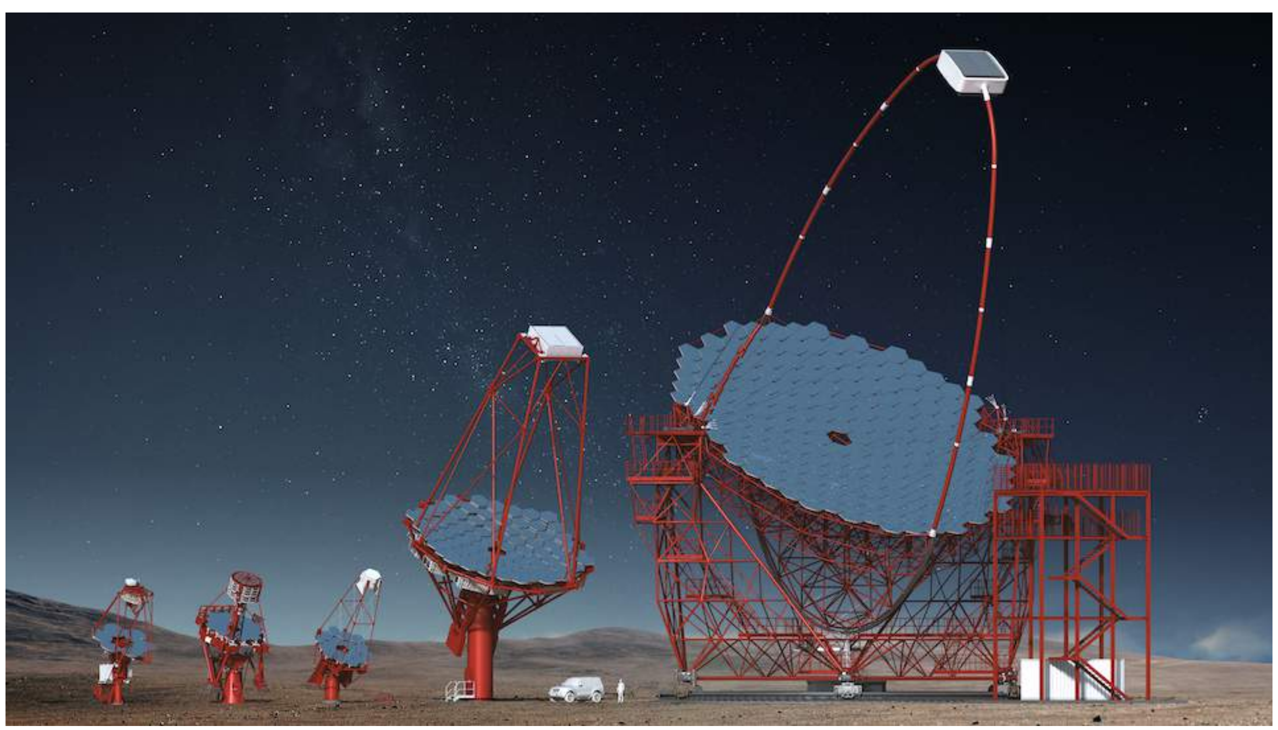


G. Pérez, IAC, SMM

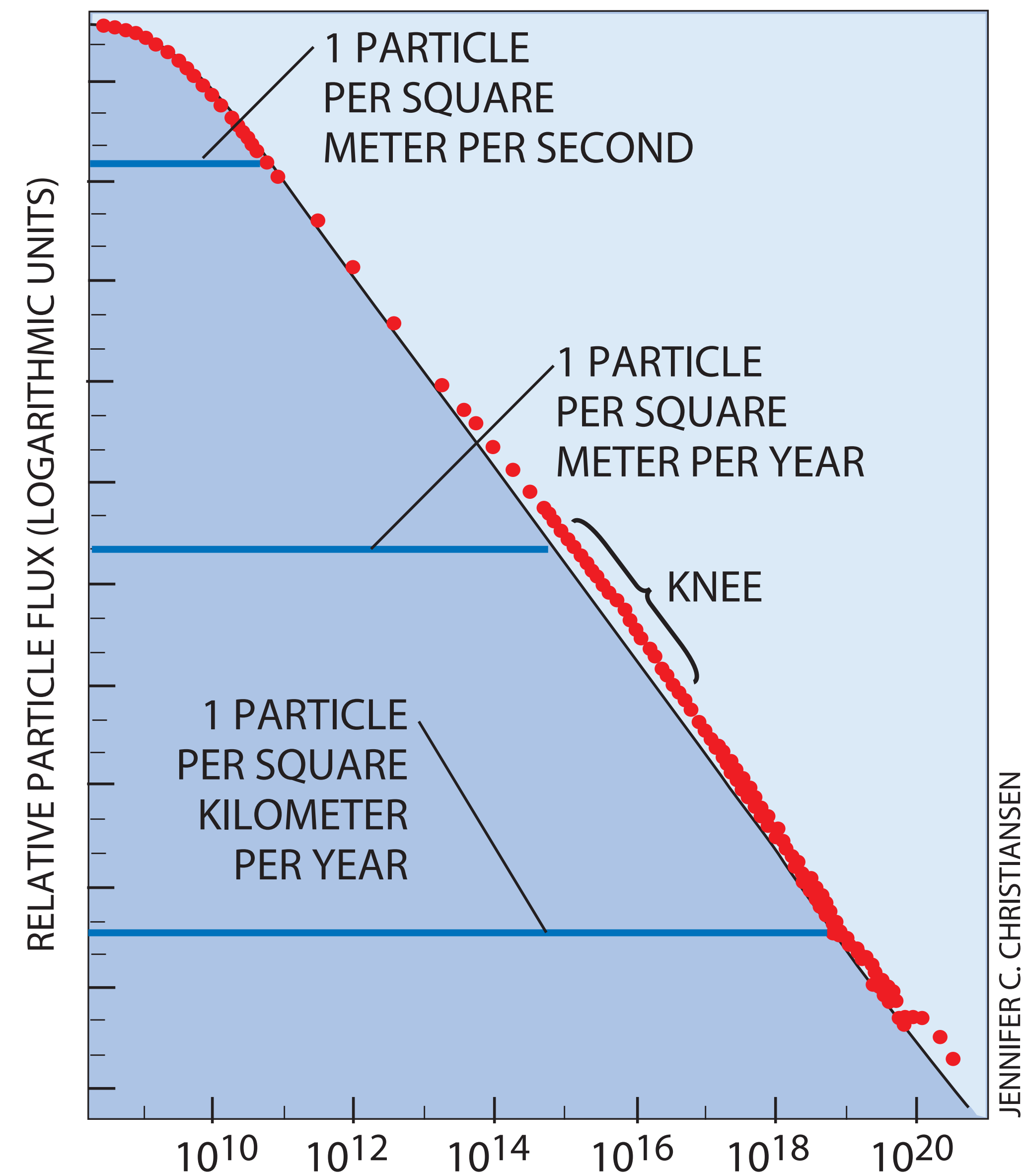
Institute for Space-Earth Environmental Research

May 8, 2019
KMI Seminar, Nagoya University

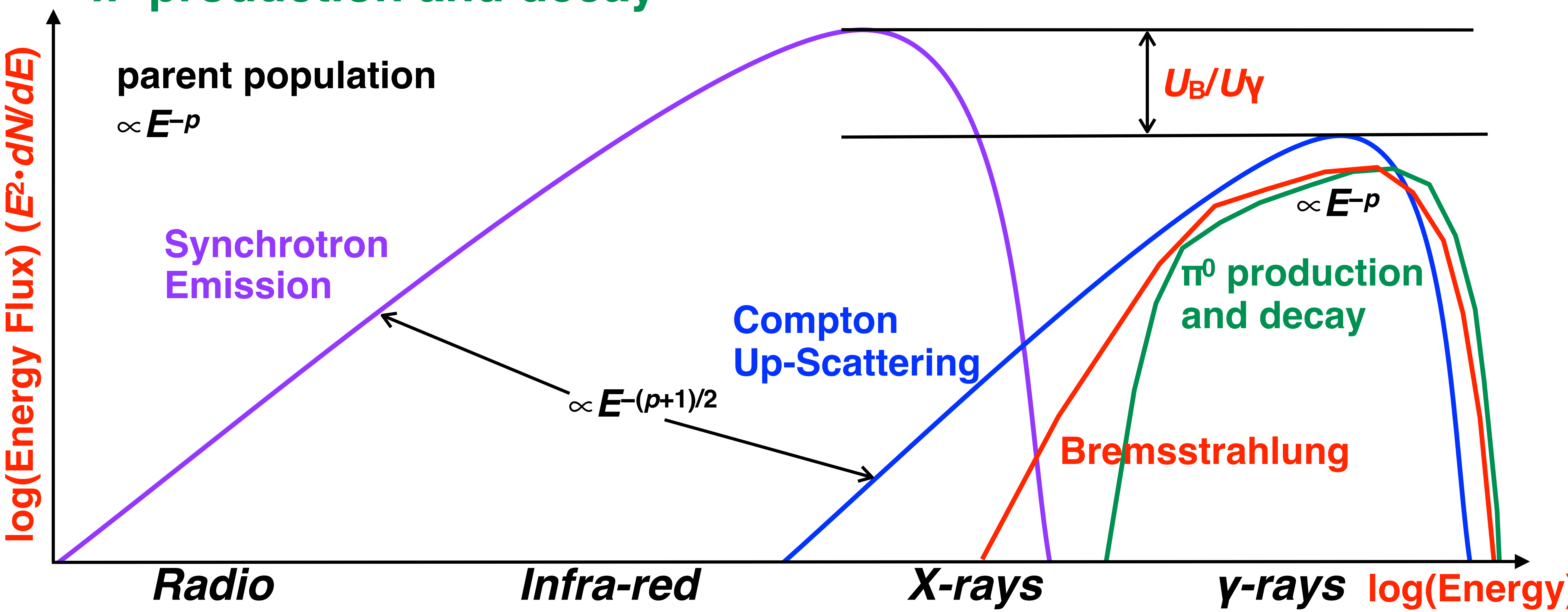
Cosmic-Ray (CR) Accelerators

- At least two CR accelerators may exist
  - Galactic accelerator
    - Knee implies acceleration limit: $P_{max} \propto B \times$ (size of accelerator)
    - Supernova remnants are the leading candidate
      - Energetics
      - Acceleration mechanism
  - Extragalactic accelerator
    - Milky way cannot hold cosmic rays above $P \approx 10^{17}$ eV
    - Cosmic rays above Ankle are considered to be extragalactic
- Gamma ray is an excellent messenger to study cosmic-ray accelerators
  - Neutral (not bent by magnetic field)
  - Produced by CRs interacting with interstellar matter
    - Electrons can also produce gamma rays via Compton up-scattering or Bremsstrahlung

Scientific American 1998

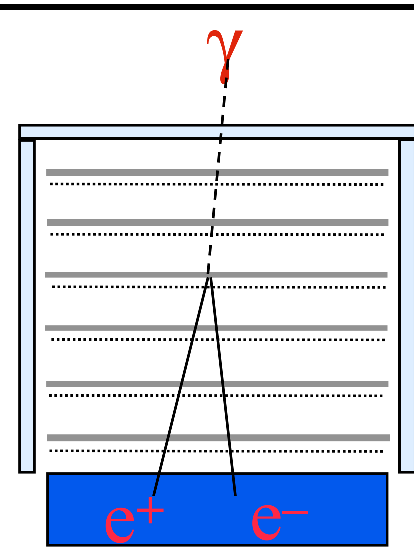


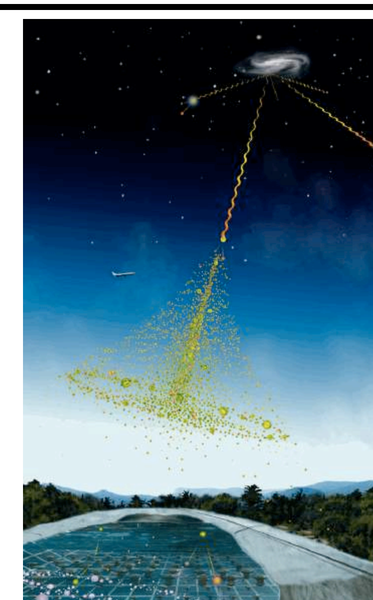
- Electron origins
  - Synchrotron radiation
  - Compton up-scattering (Inverse Compton)
  - Bremsstrahlung
- Hadron origins
  - π^0 production and decay

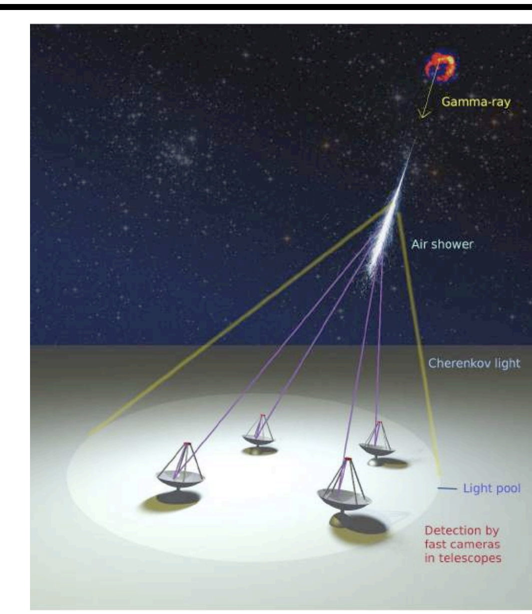


Gamma-ray Instruments

	Satellite based pair conversion telescope	Air shower array	Atmospheric Cherenkov telescope
Experiments	EGRET, Fermi	Milagro, HAWC, Tibet, ALPACA	HESS, VERITAS, MAGIC, CTA
Energy range	0.02 – 300 GeV	1 – 100 TeV	0.1 – 100 TeV
Energy resolution	5 – 15%	~100%	~10%
Angular resolution	0.1 – 10 deg	~1 deg	~0.1 deg
Collection area	~1 m^2	$10^3 – 10^4$ m^2	$10^5 – 10^6$ m^2
Field of view	2.4 sr	2 sr	10^{-2} sr
Duty cycle	~95%	>90%	<10%



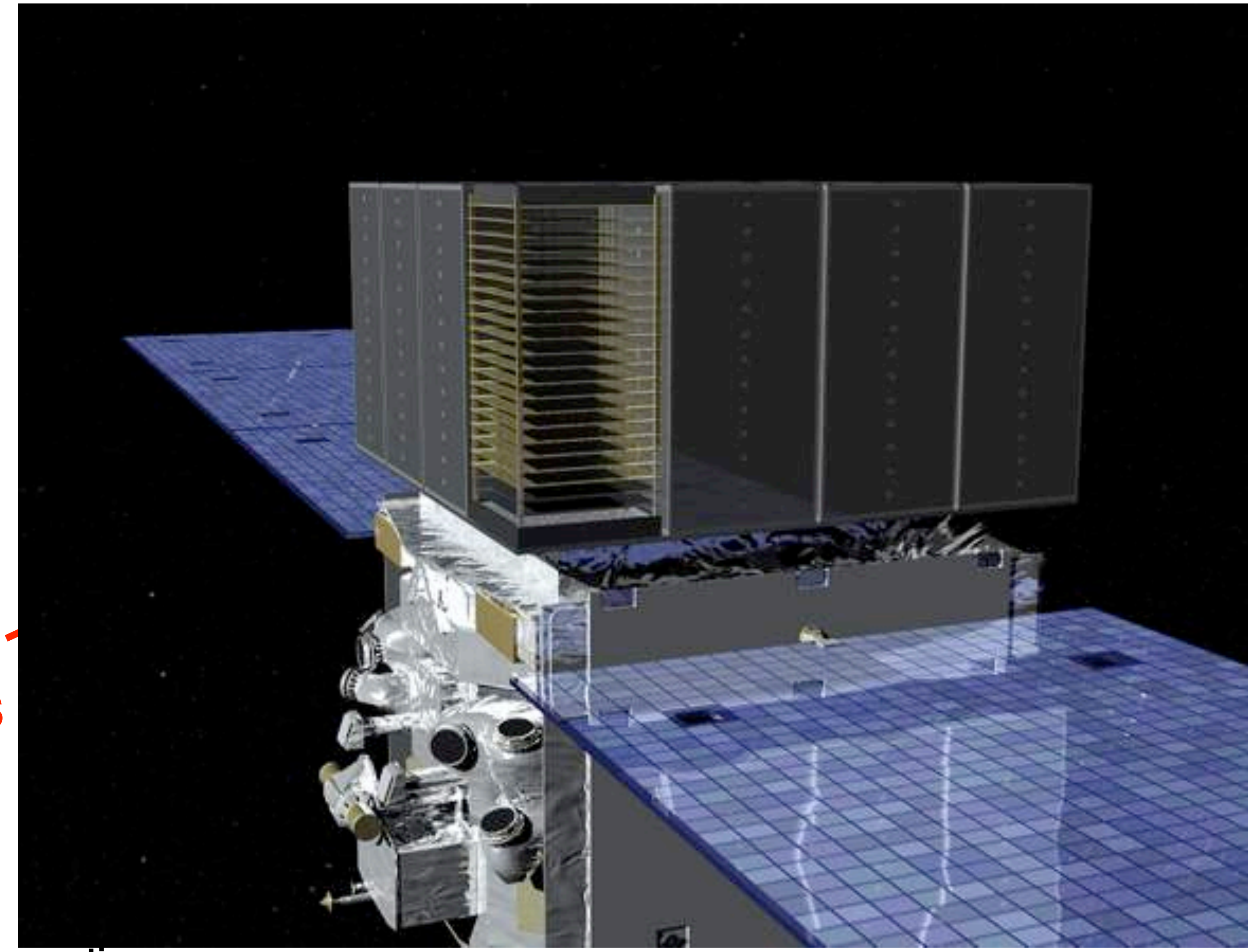




Pair–Conversion telescope

- 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 (~6×EGRET)
  - Wide field of view: > 2.4 sr (~5×EGRET)
  - Total mass: 3000 kg
  - Size: ~1.5 m (W) × 0.6 m (H)
  - Total Power: 650 W
- Pair conversion
  - "Clear" signature
  - Background rejection

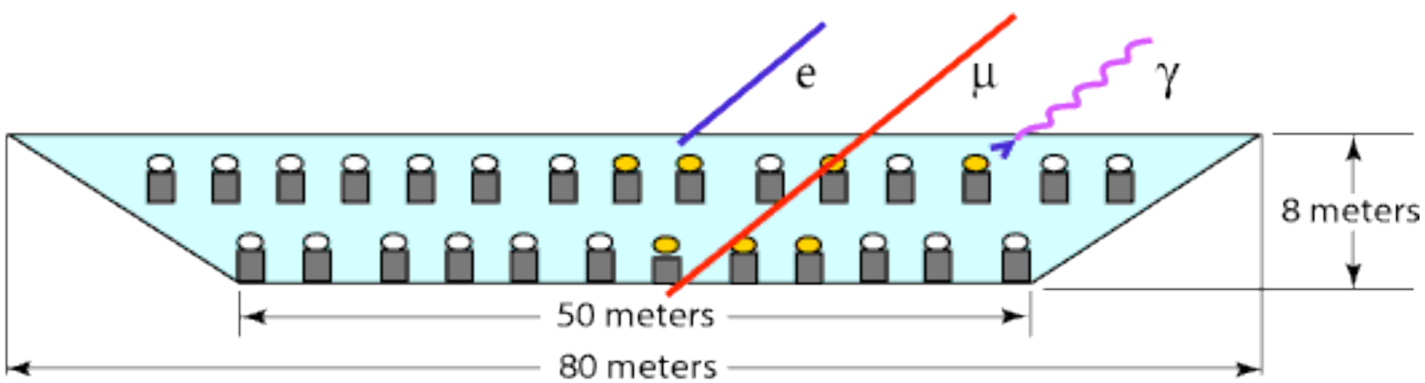
Si Tracker
70 m^2, 228 μm pitch
~0.9 million channels

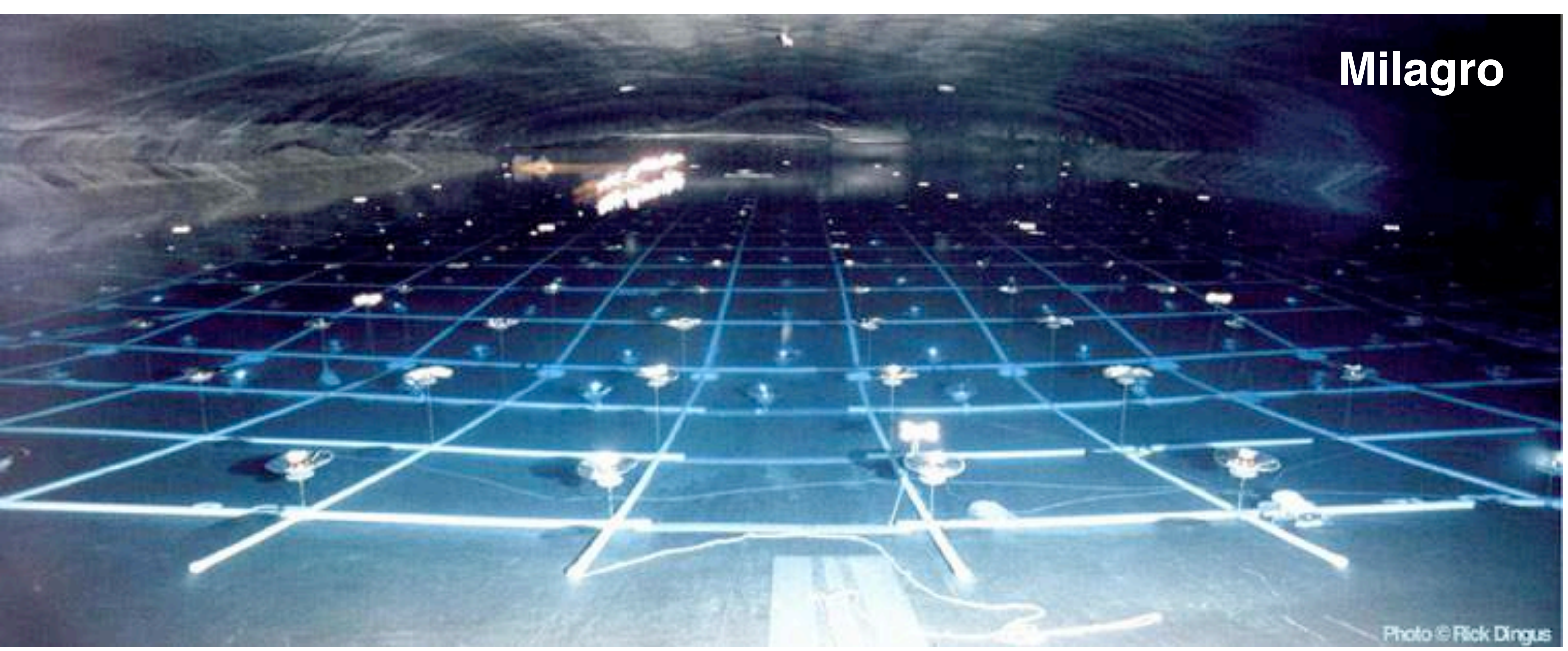


Anti-coincidence Detector
Segmented scintillator tiles
99.97% efficiency

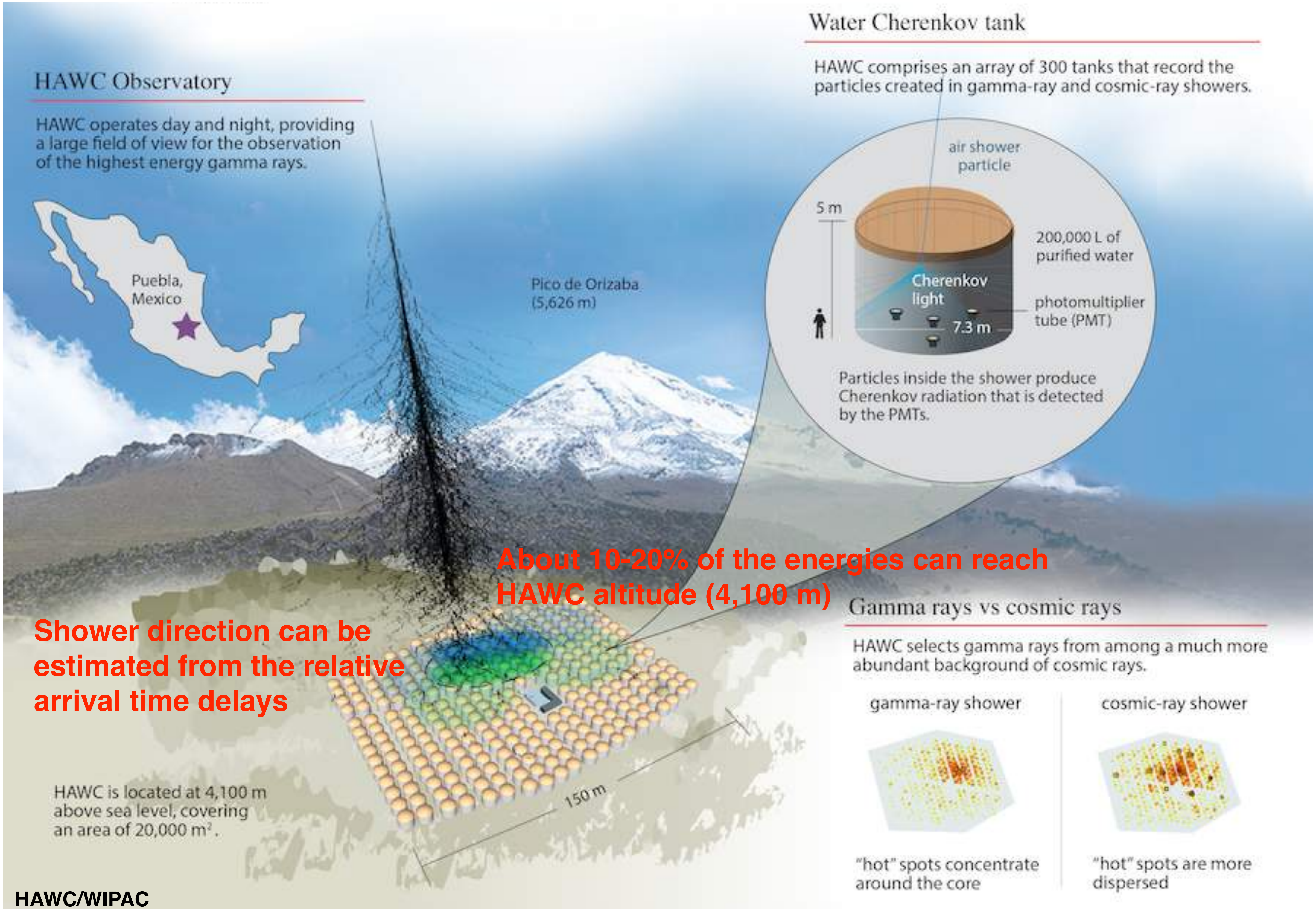
Water Cherenkov Air Shower array

- 900 PMTs with 3 m spacing
  - 60 m × 80 m × 8 m
  - ~100% coverage of all incoming particles
- Reconstruct shower direction from arrival time difference



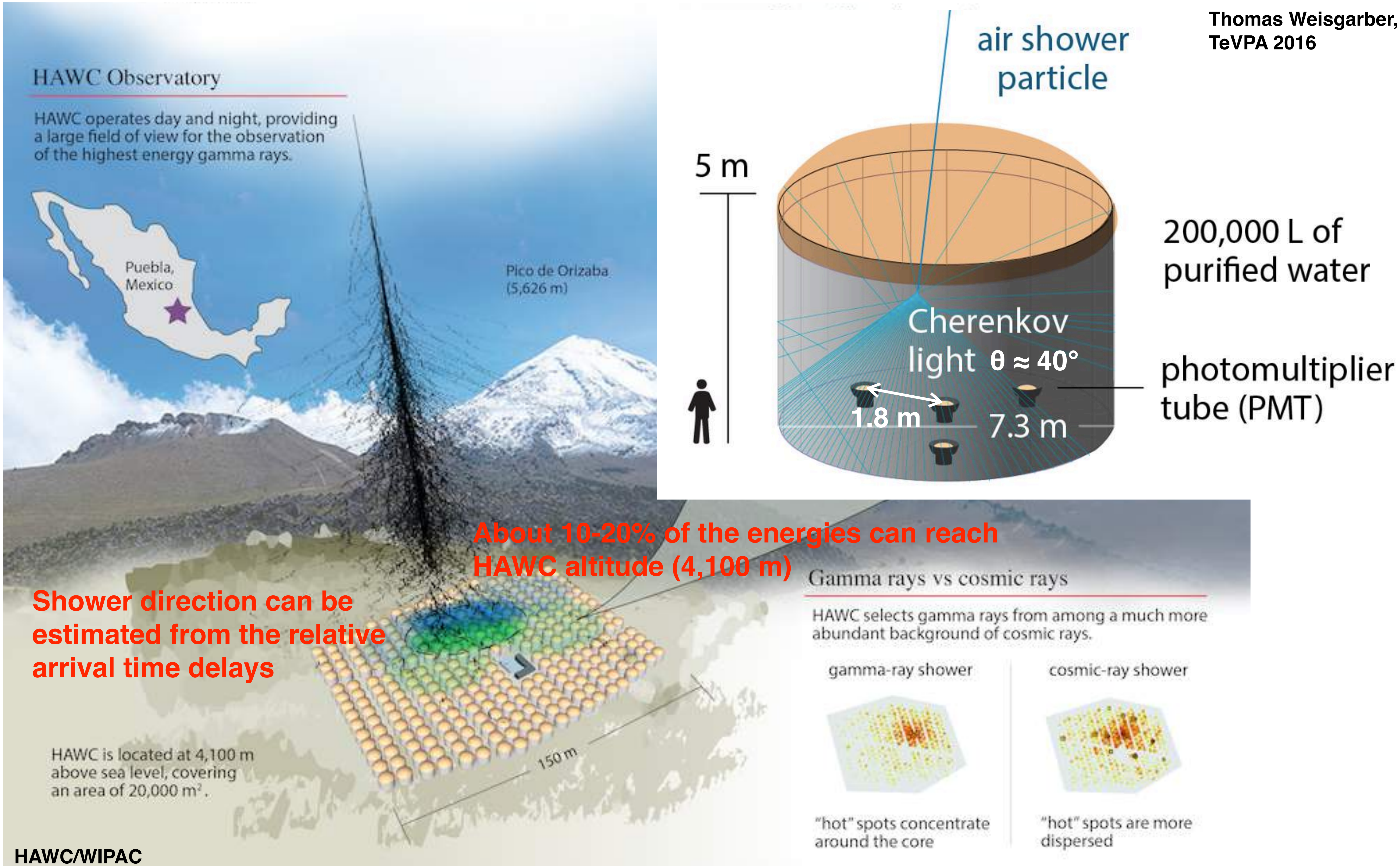


Air Shower Array



Air Shower Array

Thomas Weisgarber, TeVPA 2016



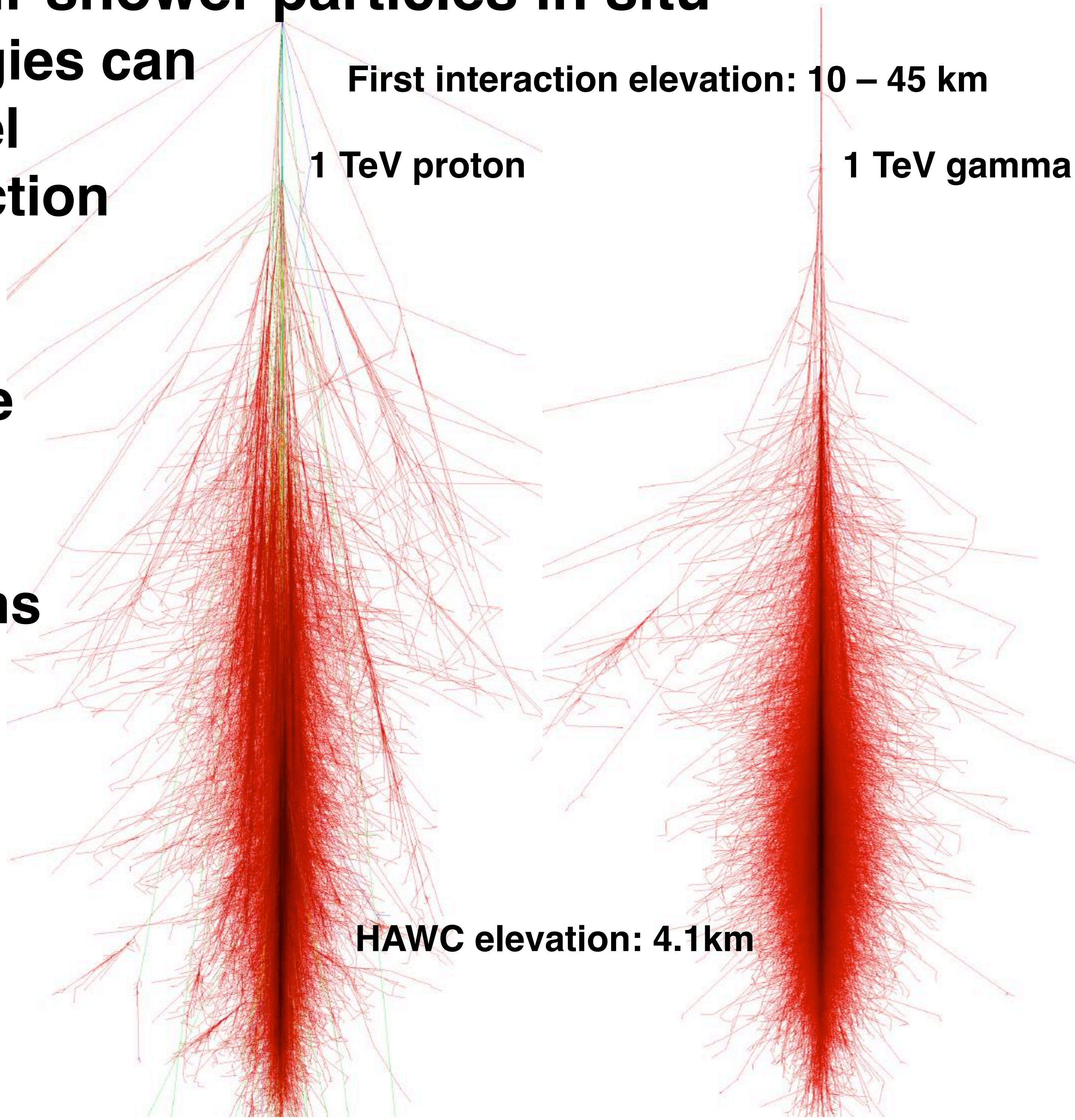
About 10-20% of the energies can reach HAWC altitude (4,100 m)

Shower direction can be estimated from the relative arrival time delays

HAWC/WIPAC

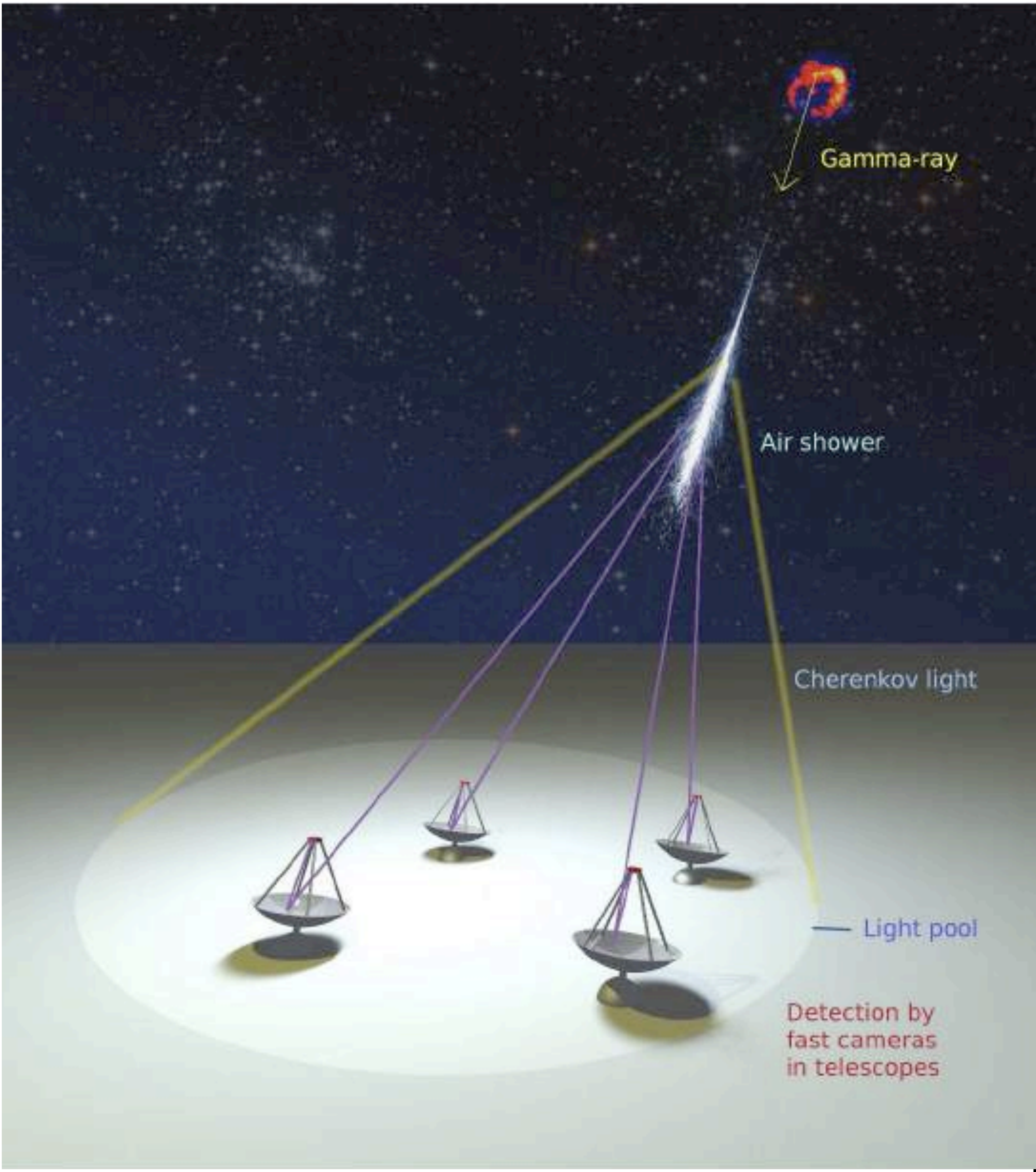
Air Shower Array

- Air Shower Array detect air shower particles in situ
  - About 10-20% of the energies can reach 4 km above sea level (depending on first interaction elevation)
  - Shower direction can be estimated from the relative arrival time delays
  - Gamma rays can be distinguished from hadrons using shower shapes



http://www.ast.leeds.ac.uk/~fs/photon-showers.html

Imaging Atmospheric Cherenkov Telescope



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

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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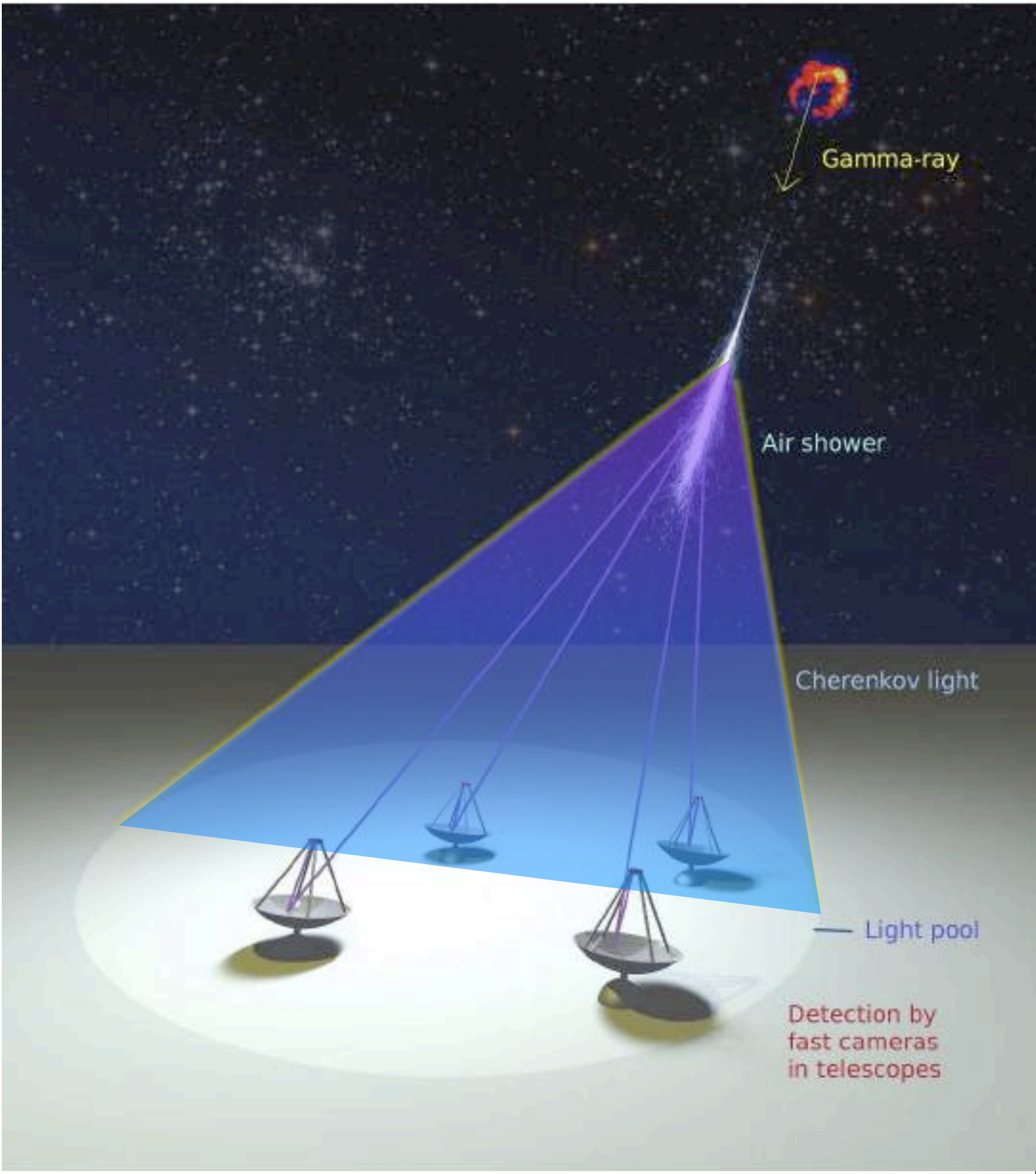

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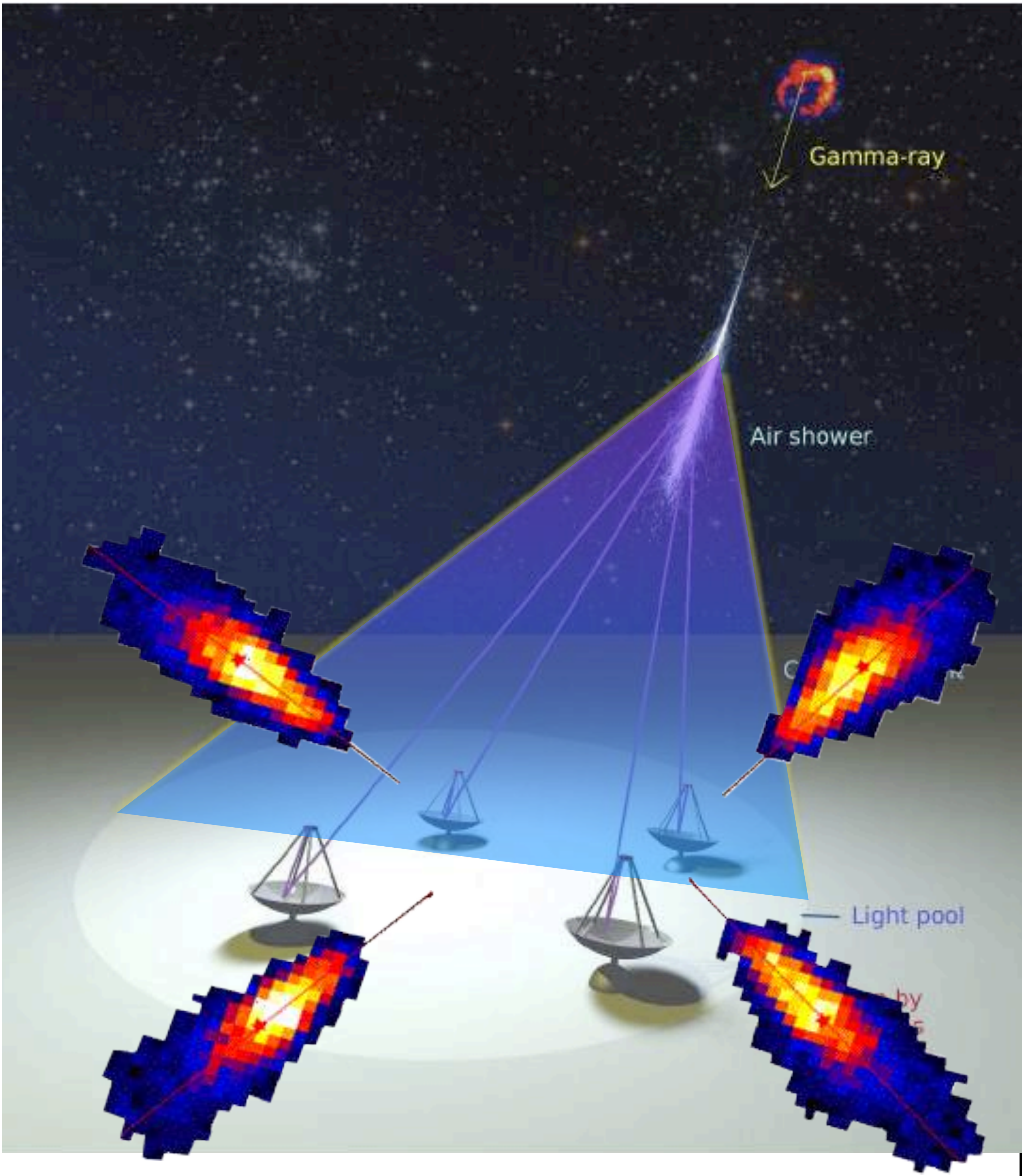

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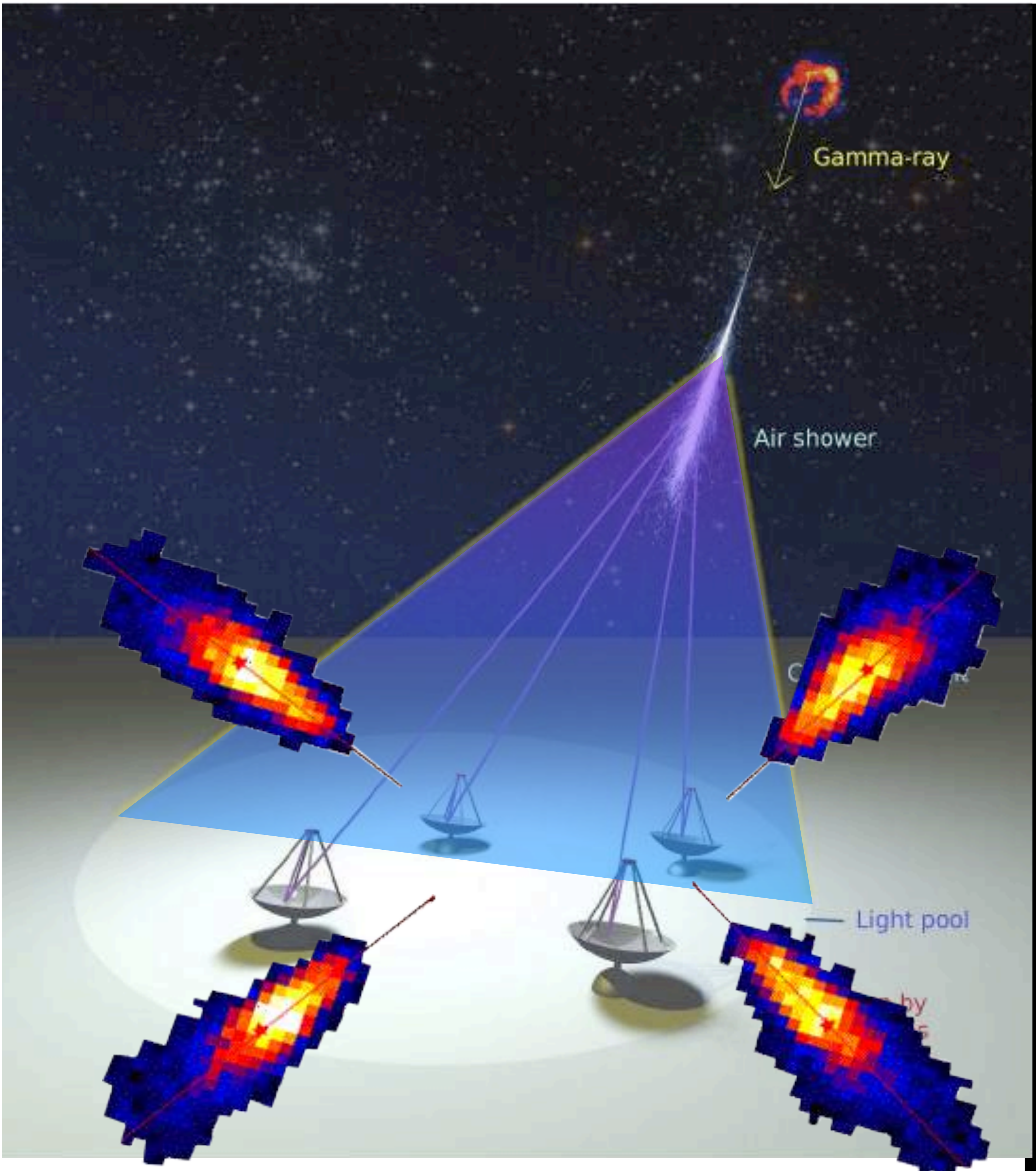

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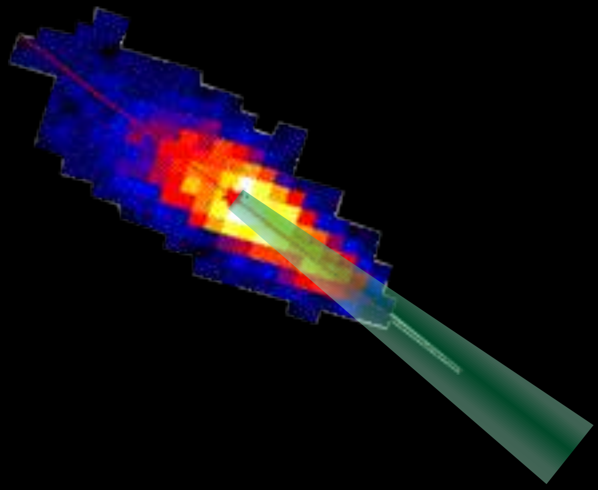

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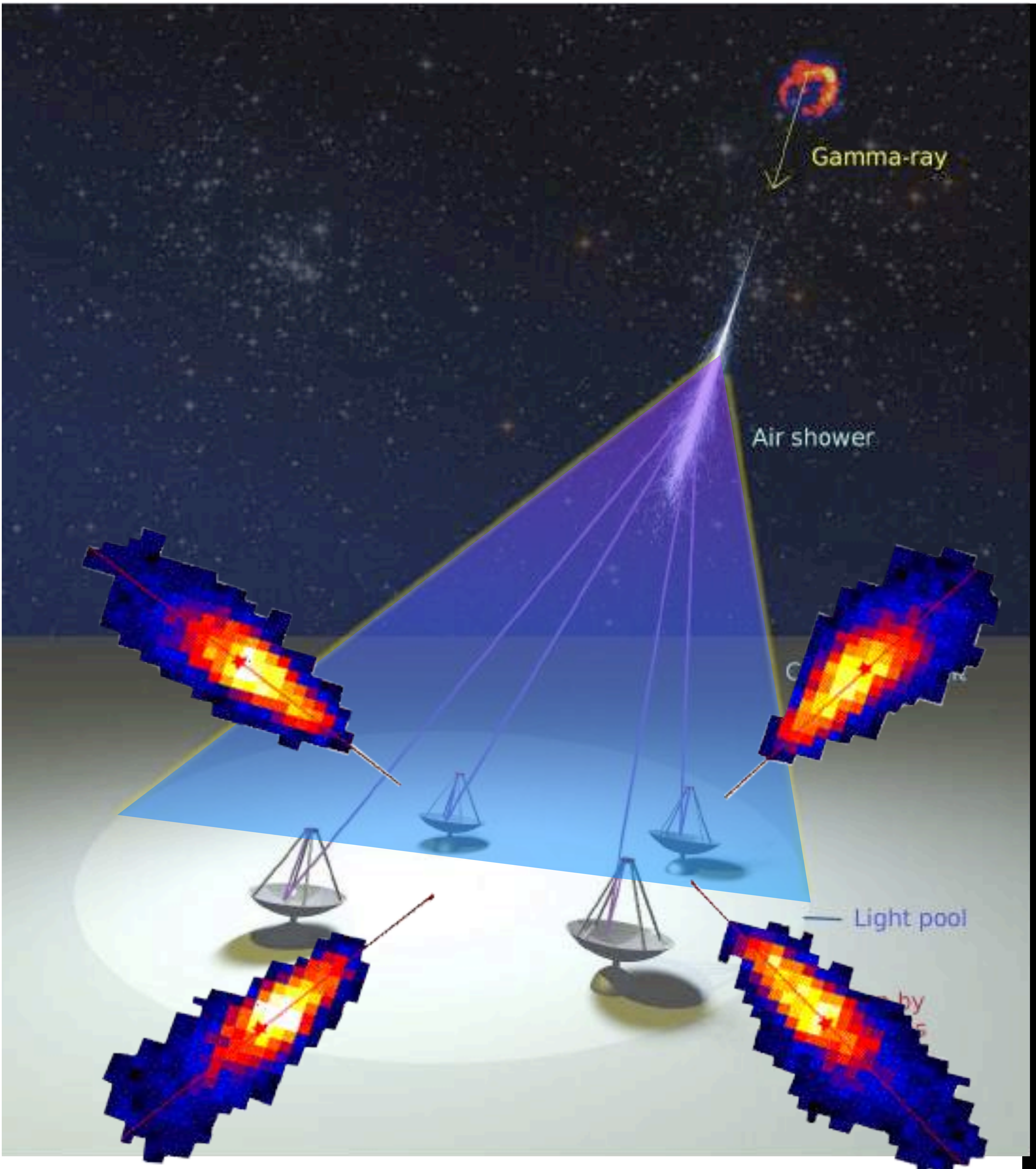

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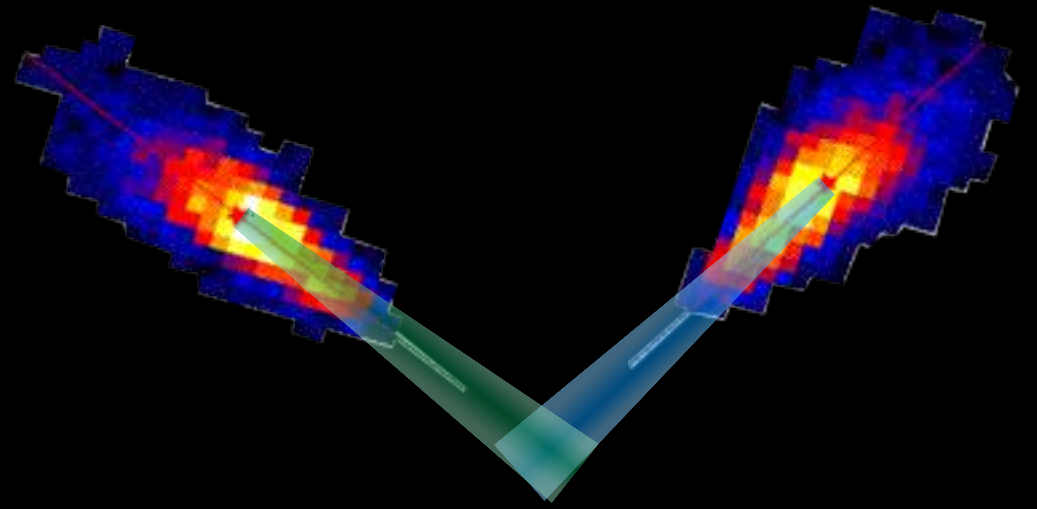

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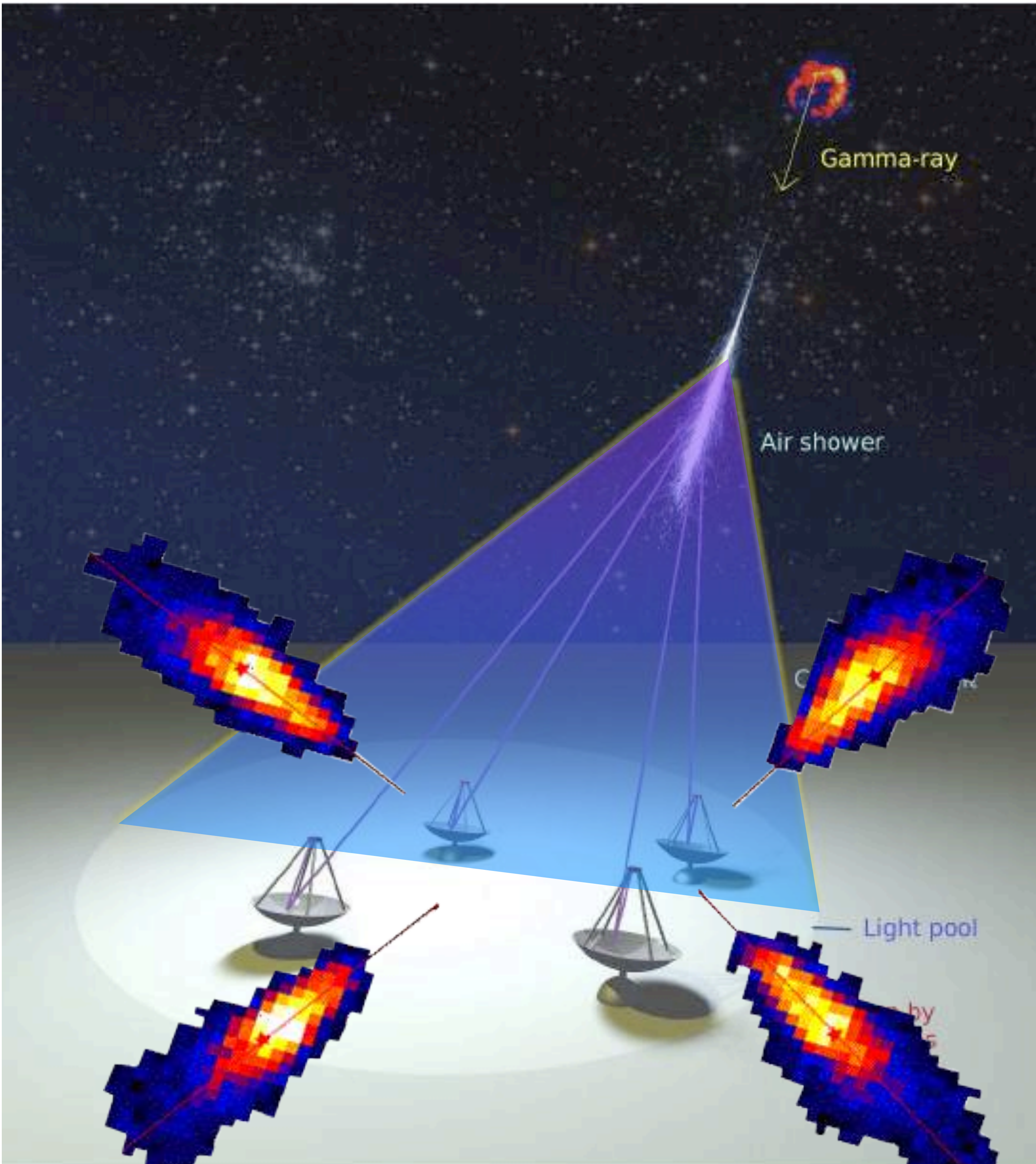

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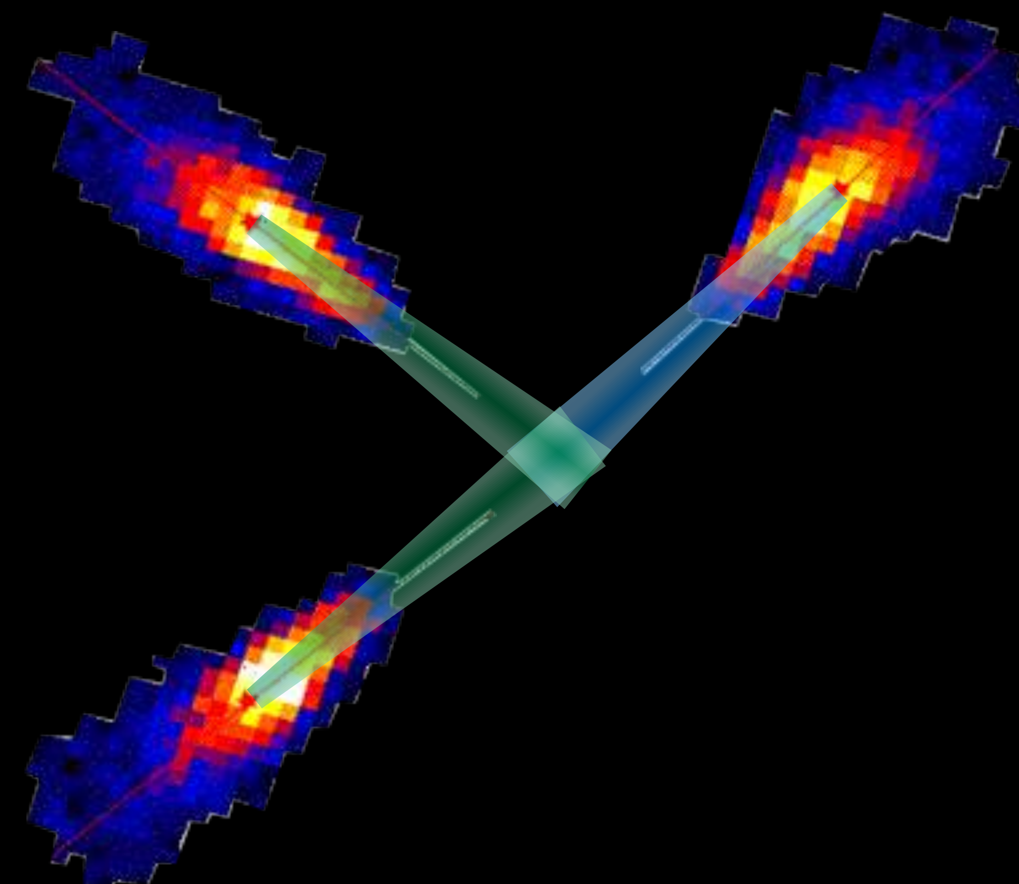

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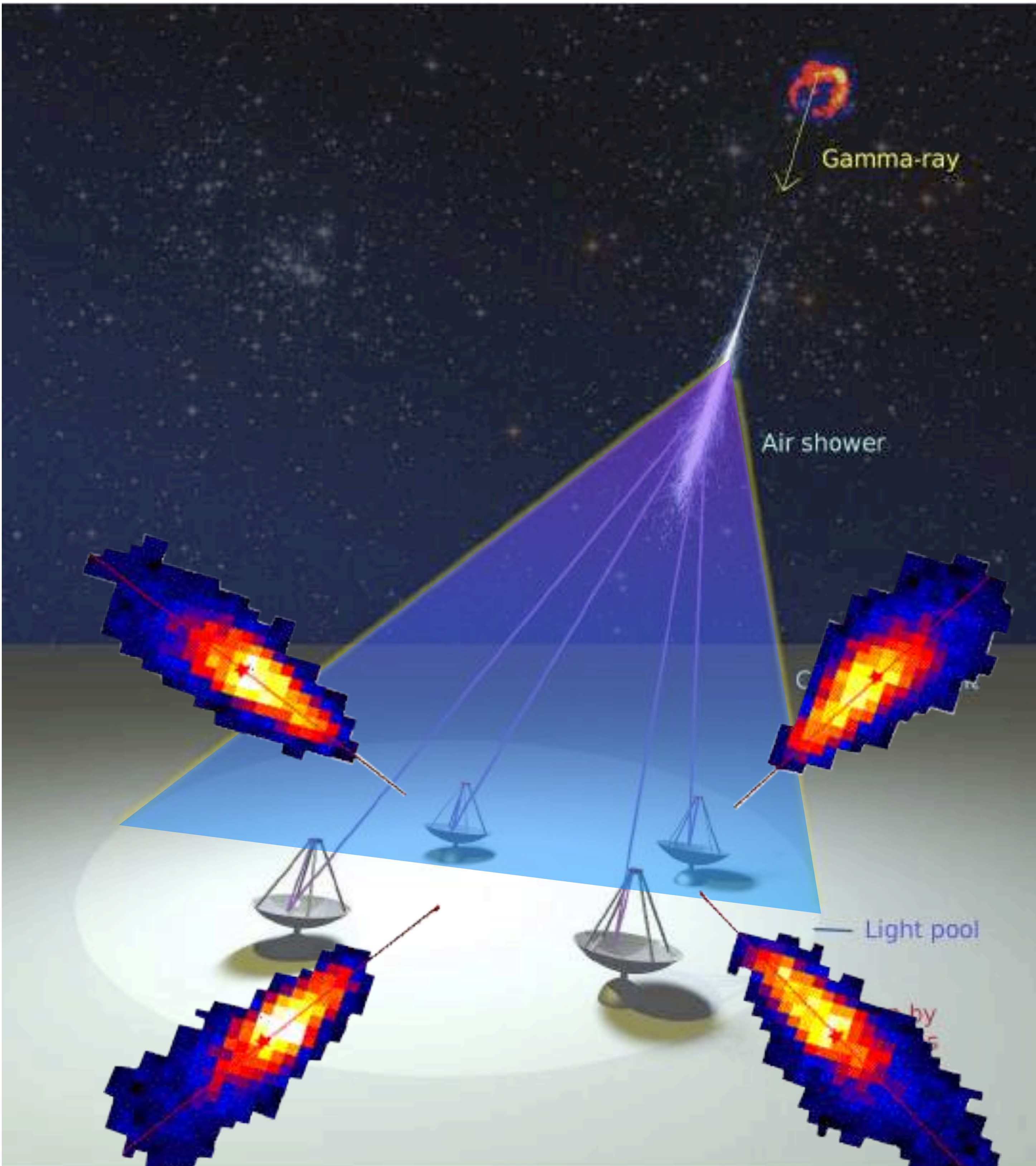

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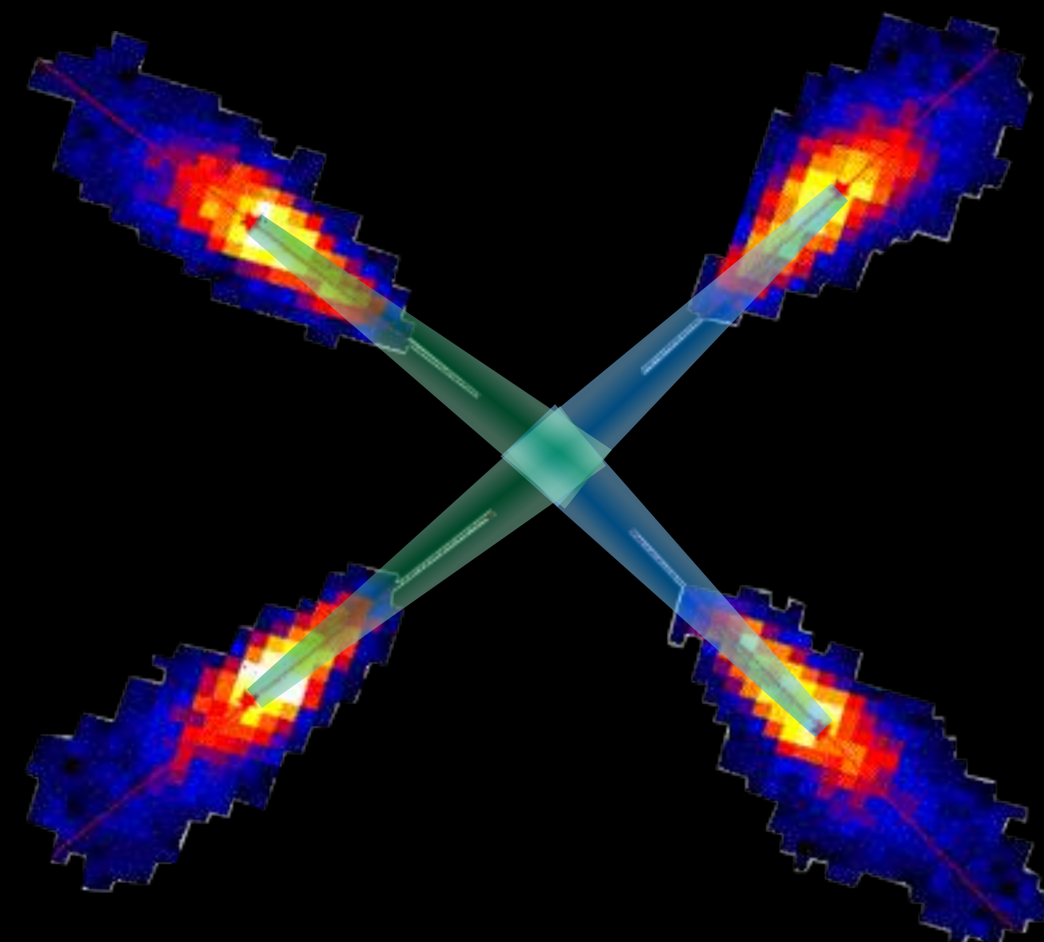

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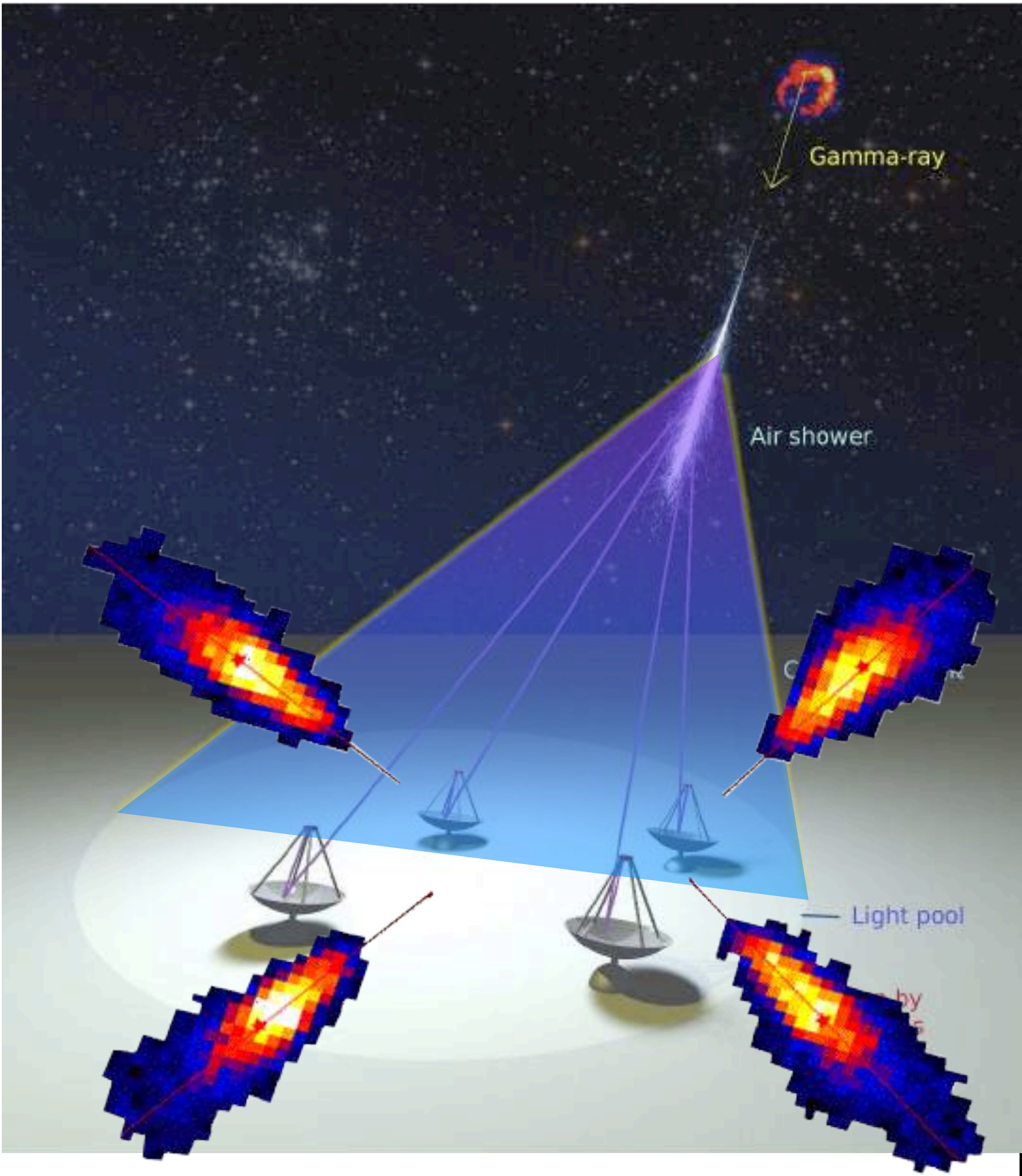

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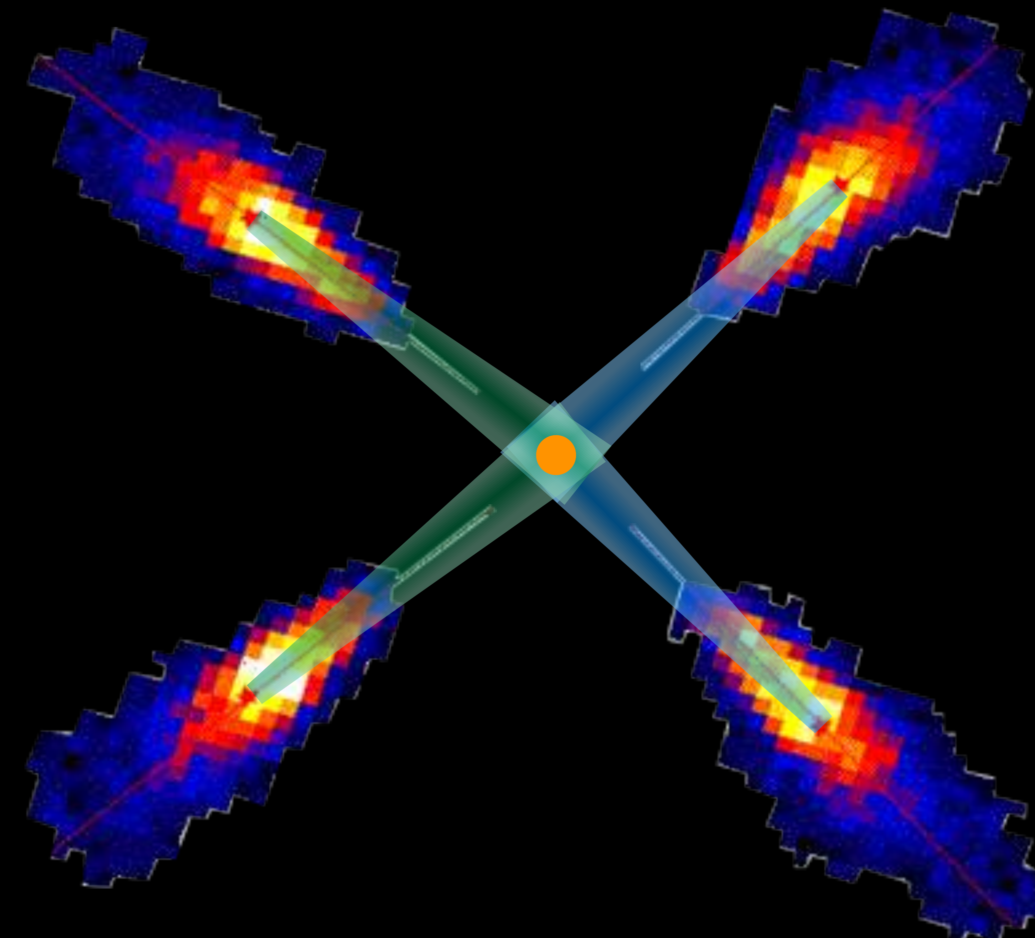

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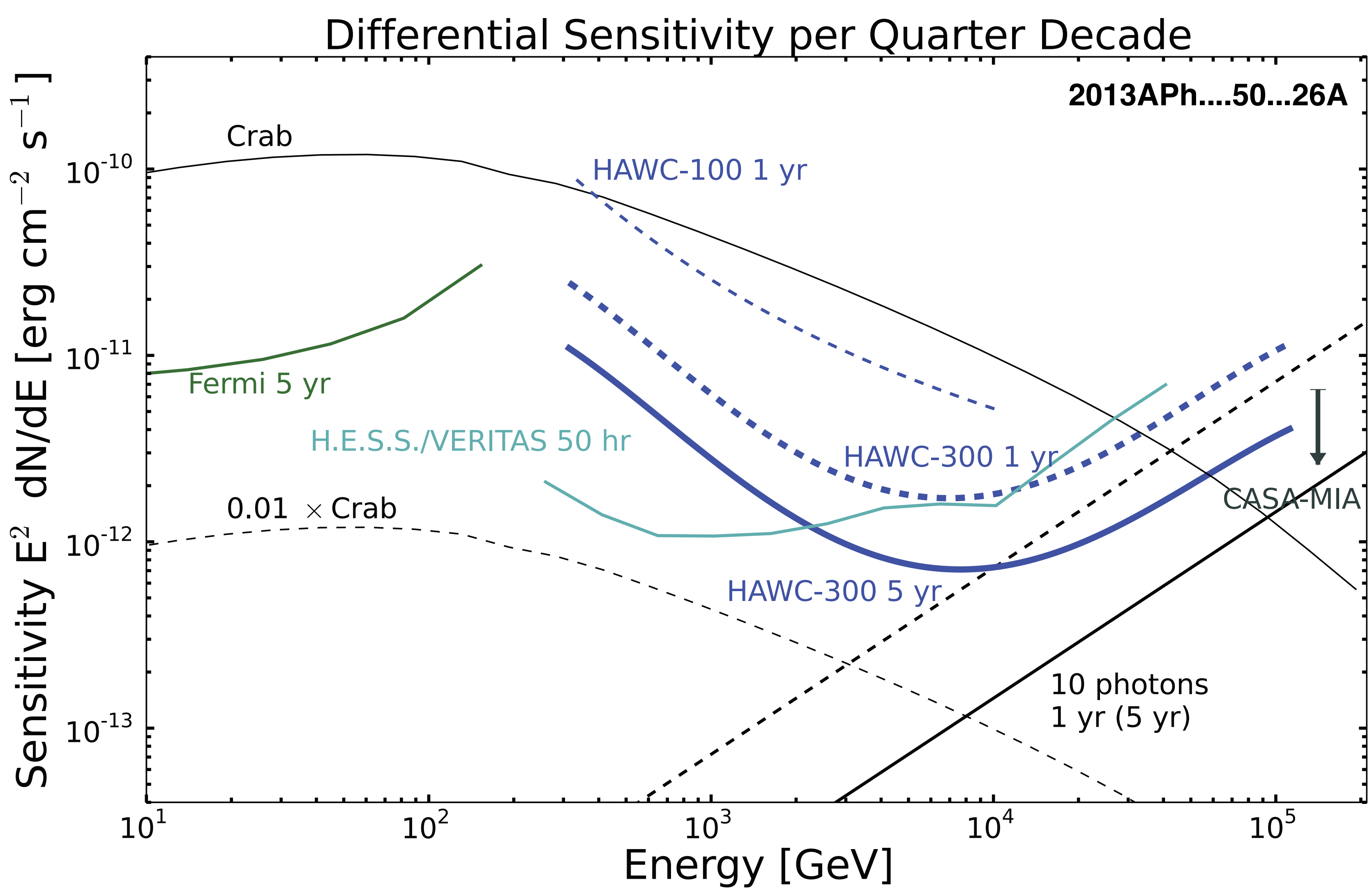
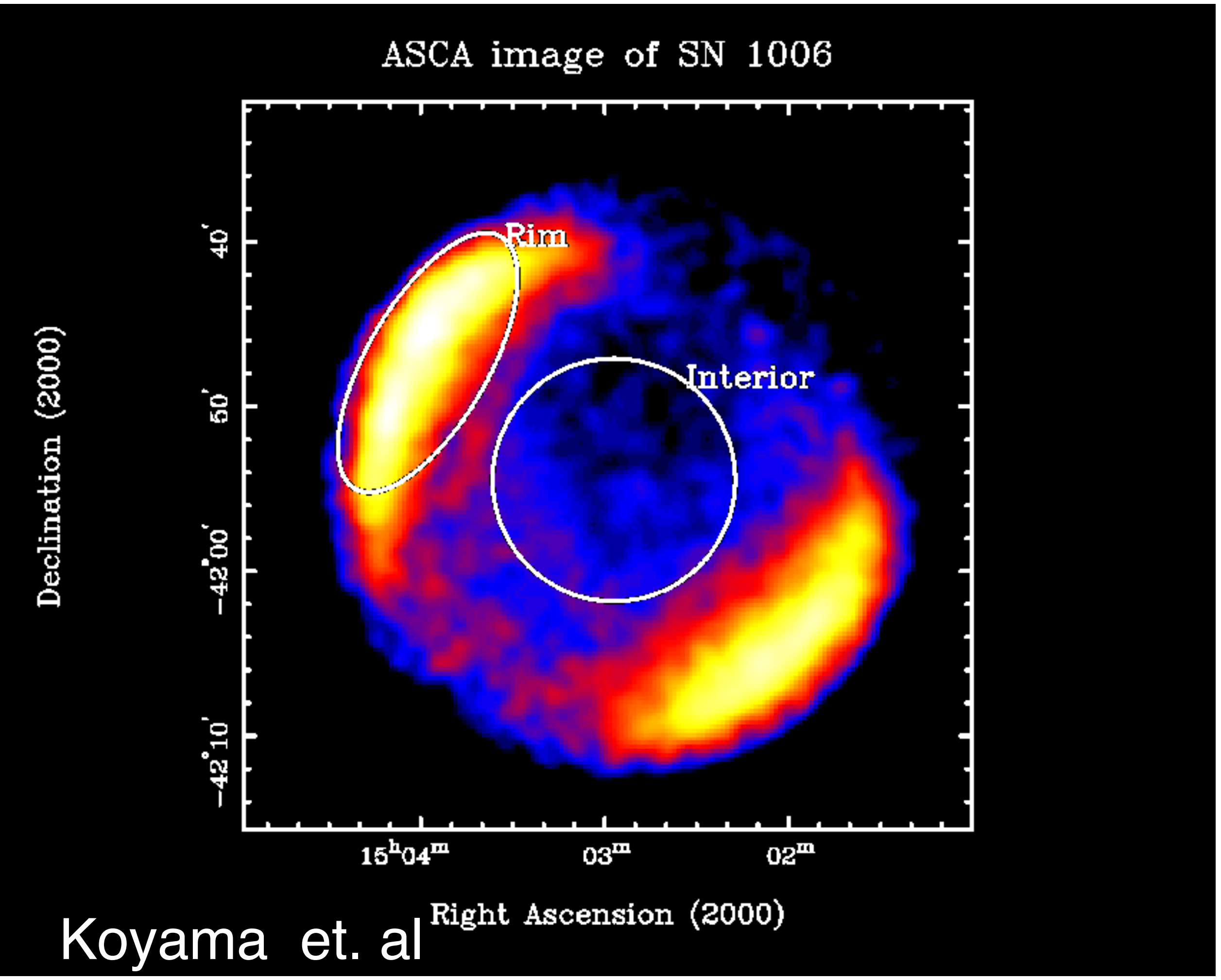
Comparisons of Gamma-ray Instruments

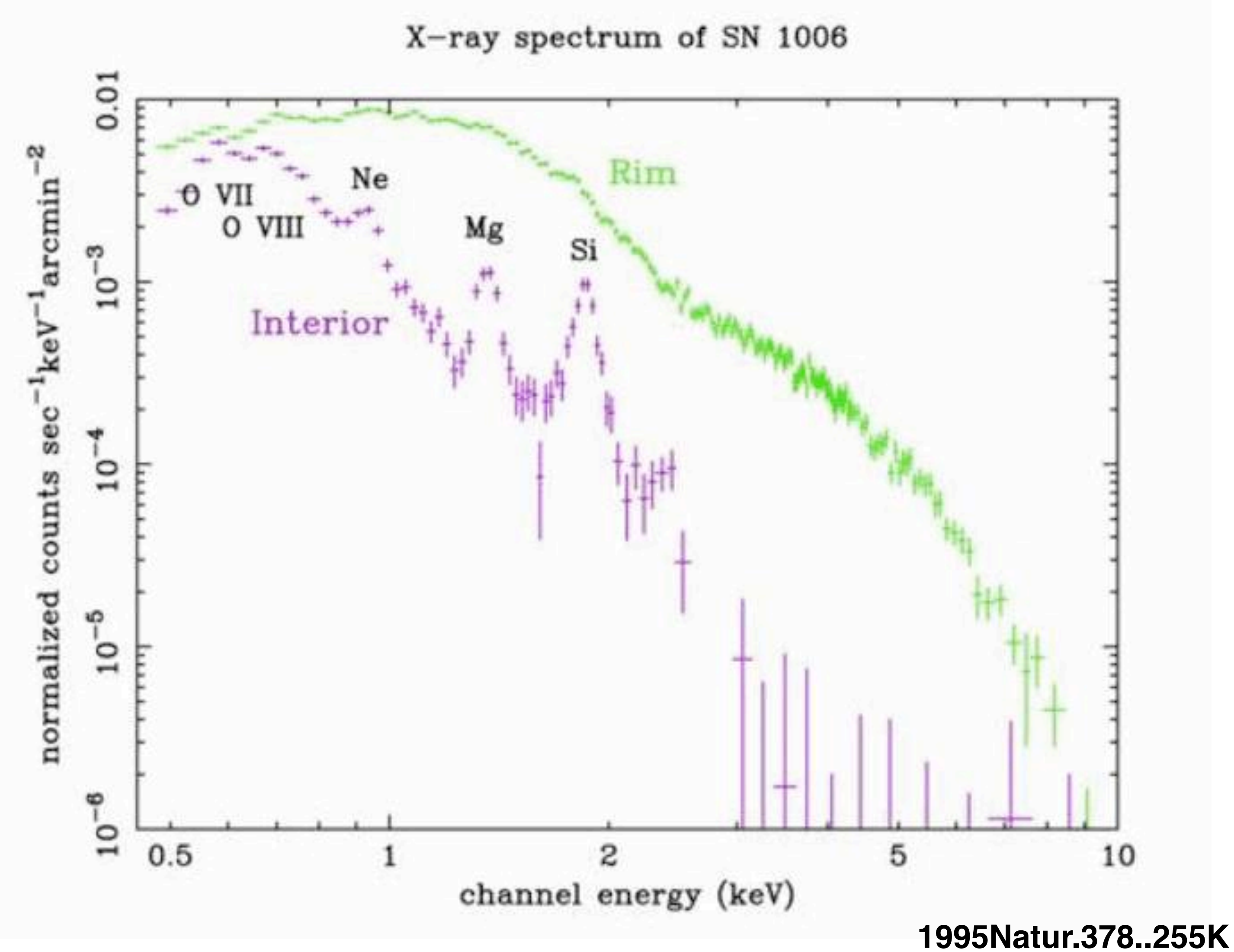
- Fermi, HAWC and IACTs are complimentary
  - Fermi and HAWC provide **survey** of unknown sources and long-term temporal monitoring
  - Fermi and IACTs provide good **spectral** information
  - IACTs provide better **imaging** and short variability measurements



- Young shell-type supernova remnant: 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



1995Natur.378..255K

Particle Acceleration in SNR

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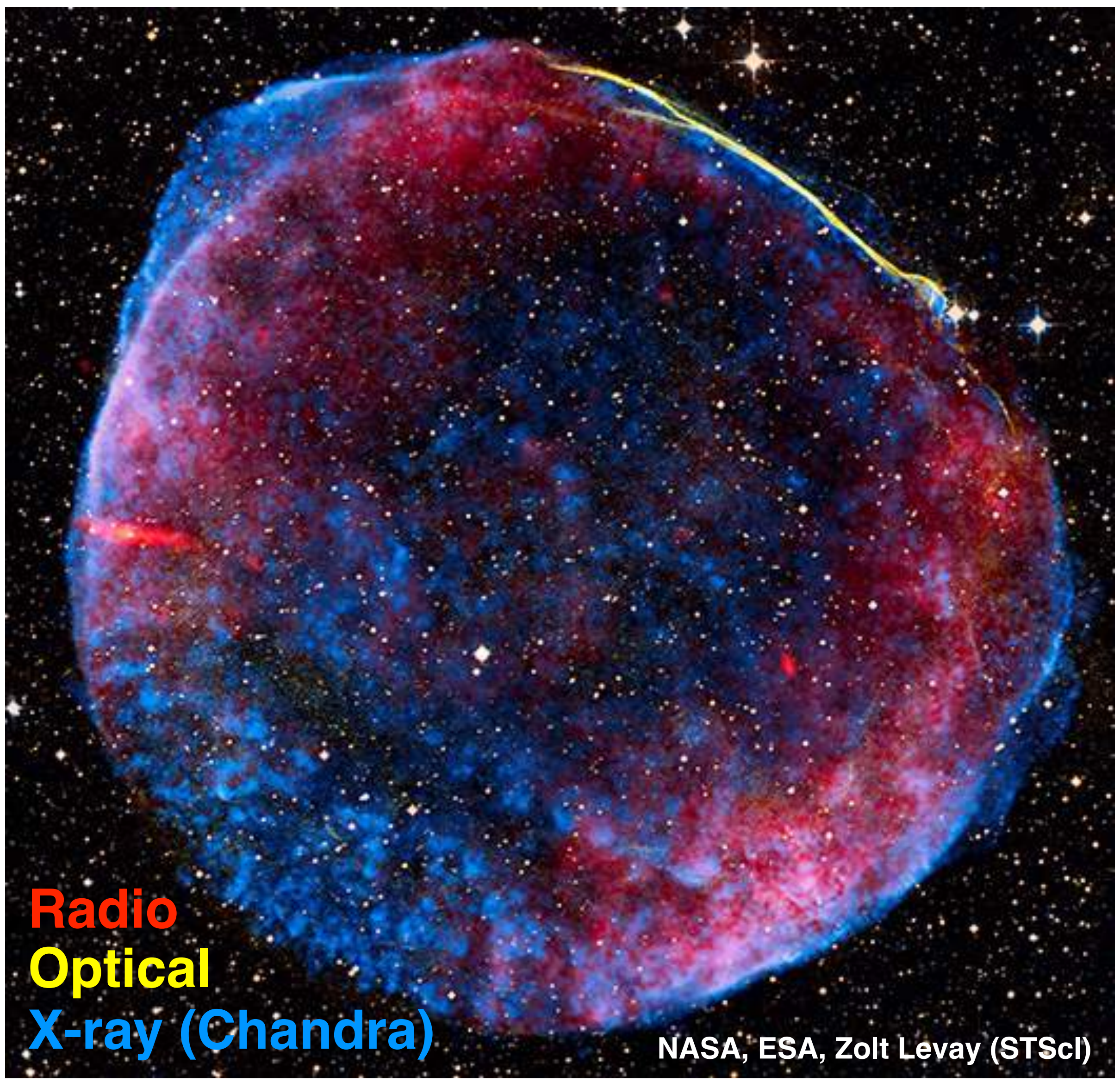
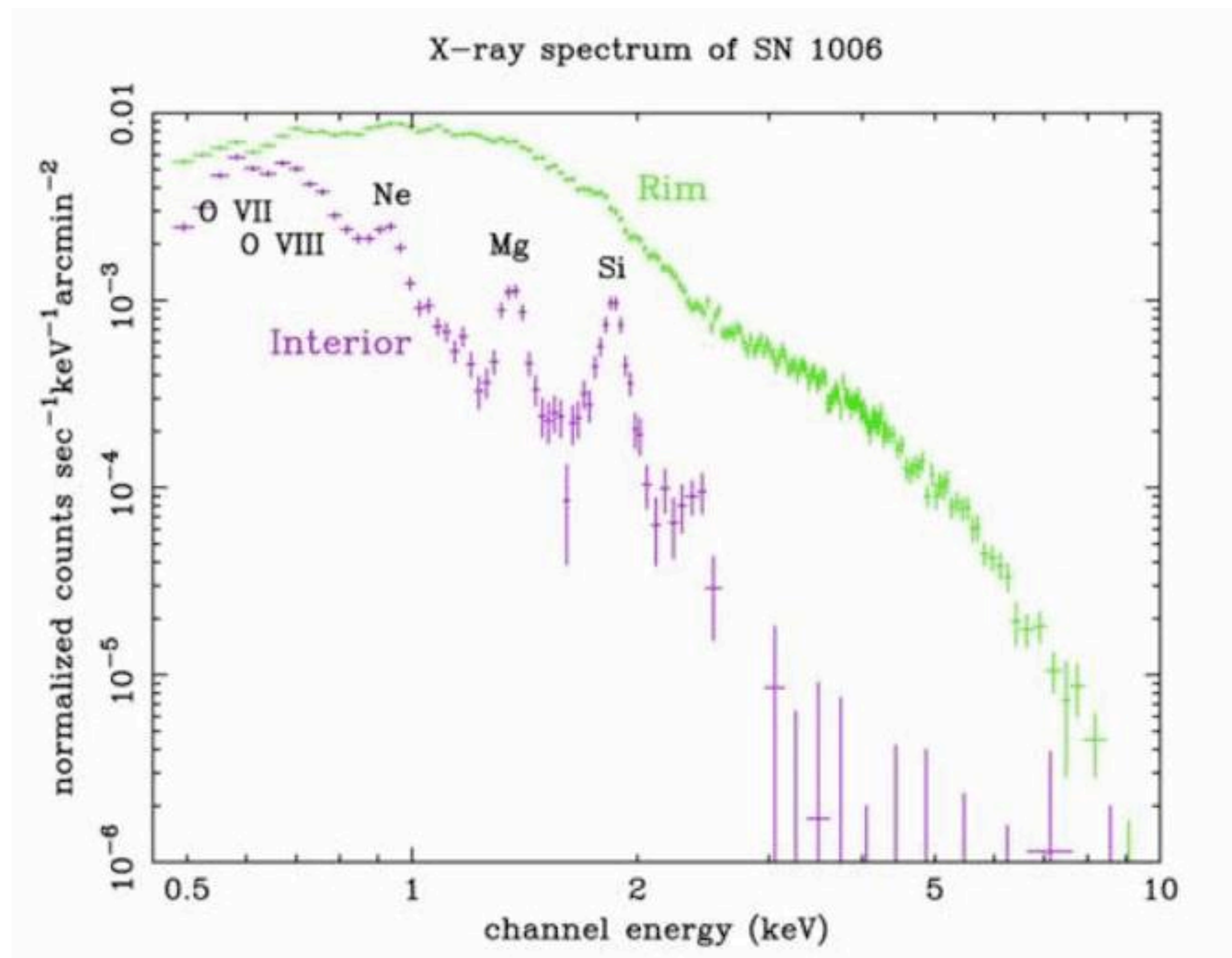
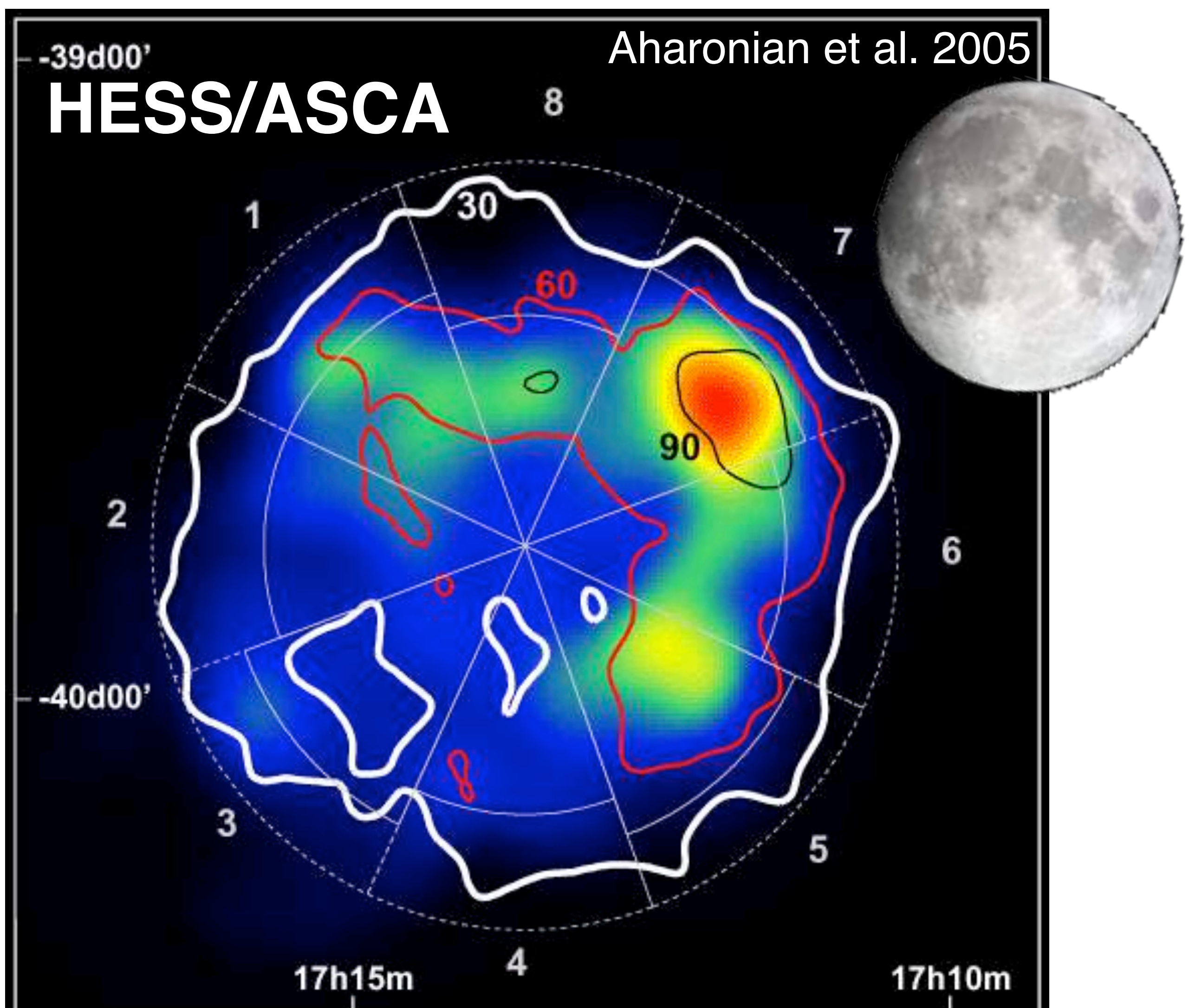




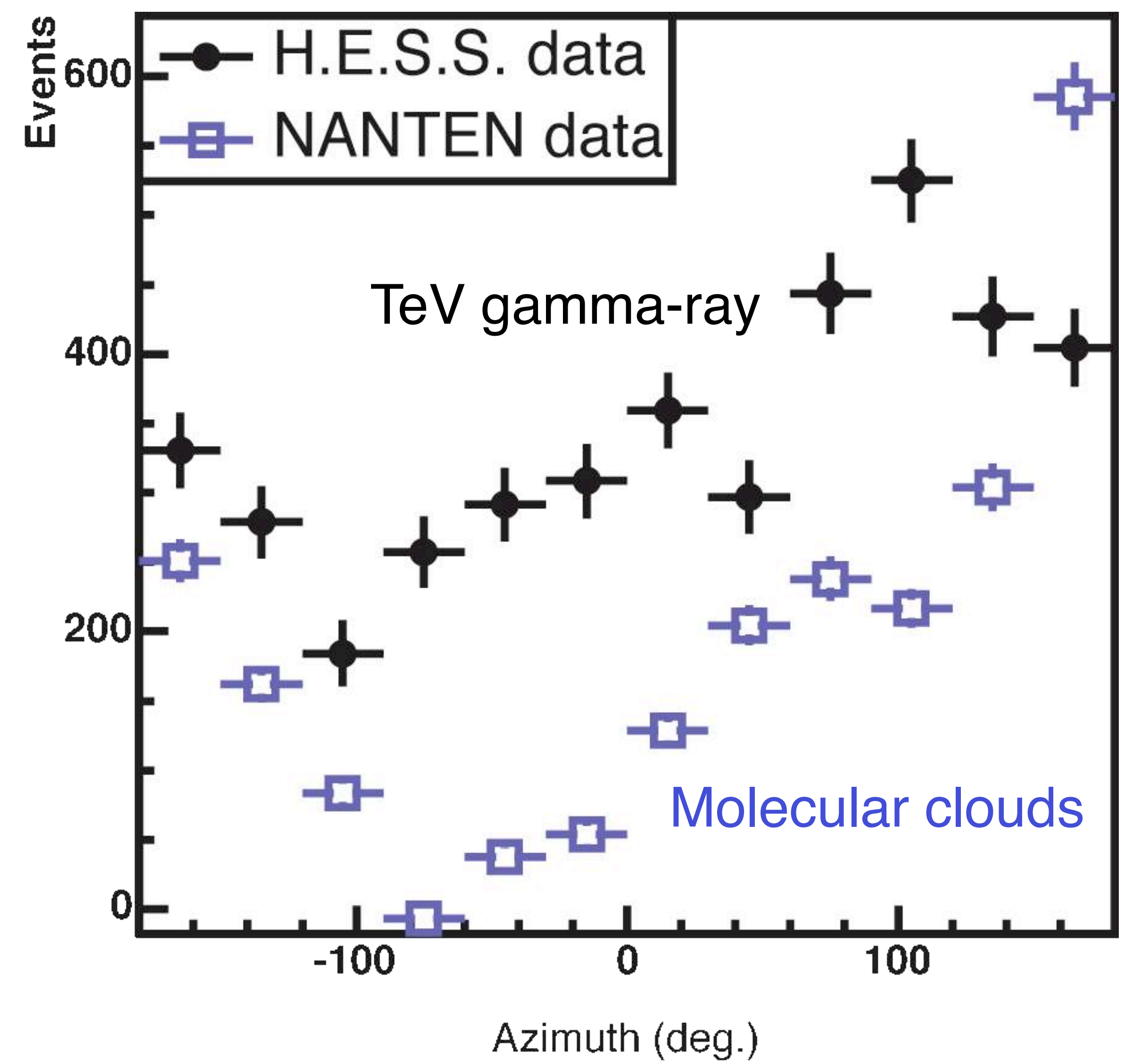
1995Natur.378..255K

TeV Gamma Ray from SNR

- H.E.S.S. observation of TeV gamma rays from 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



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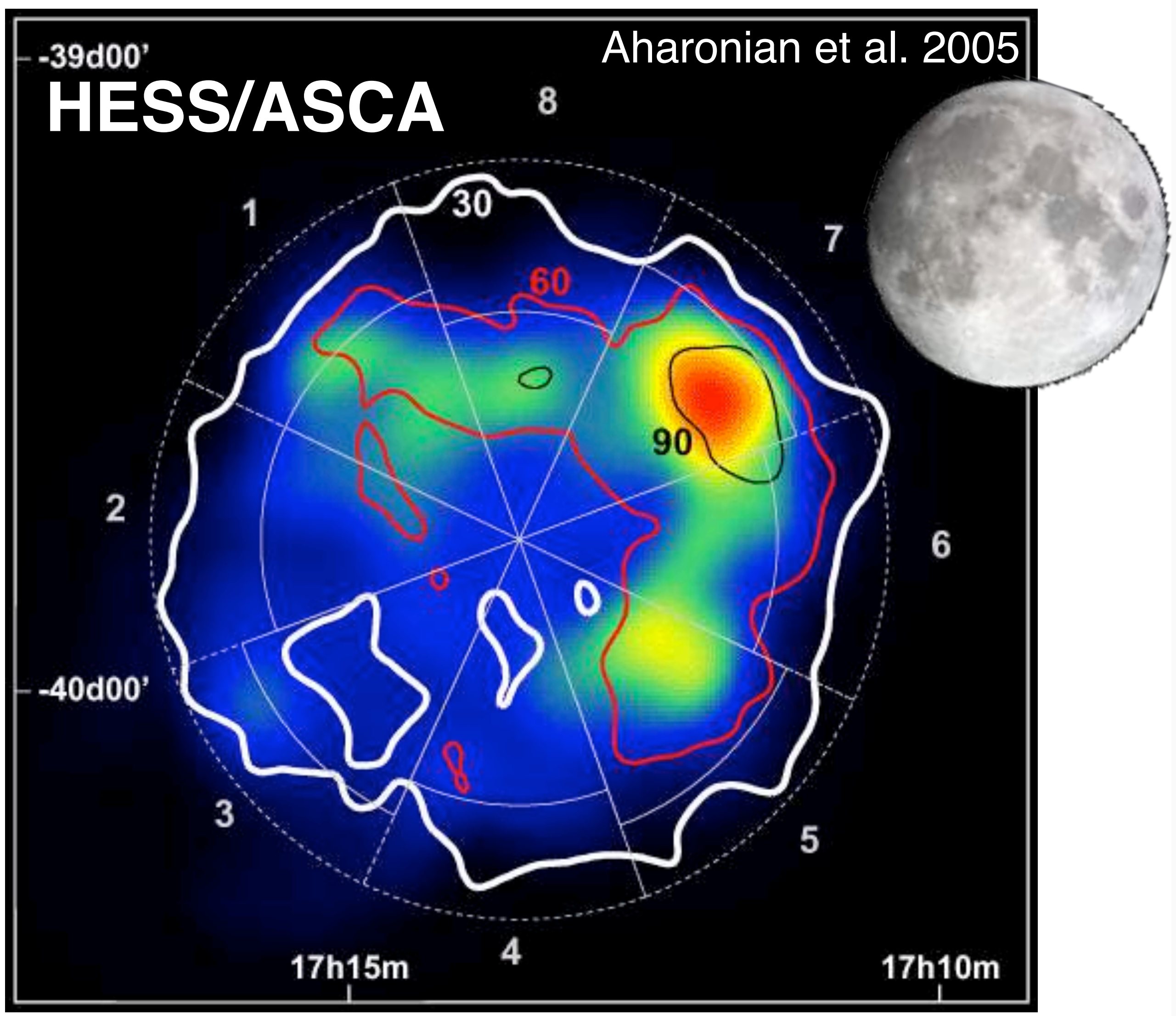
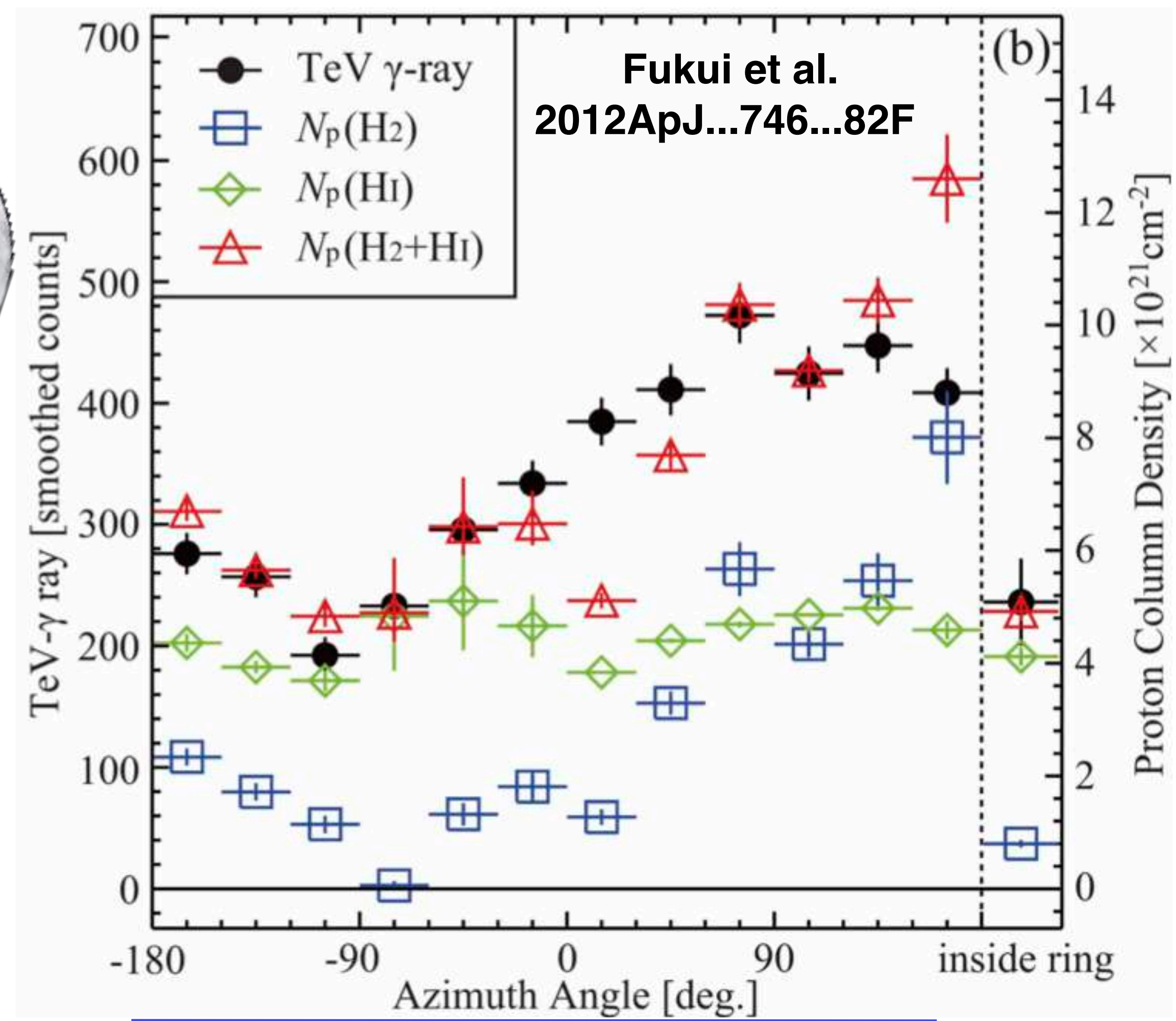
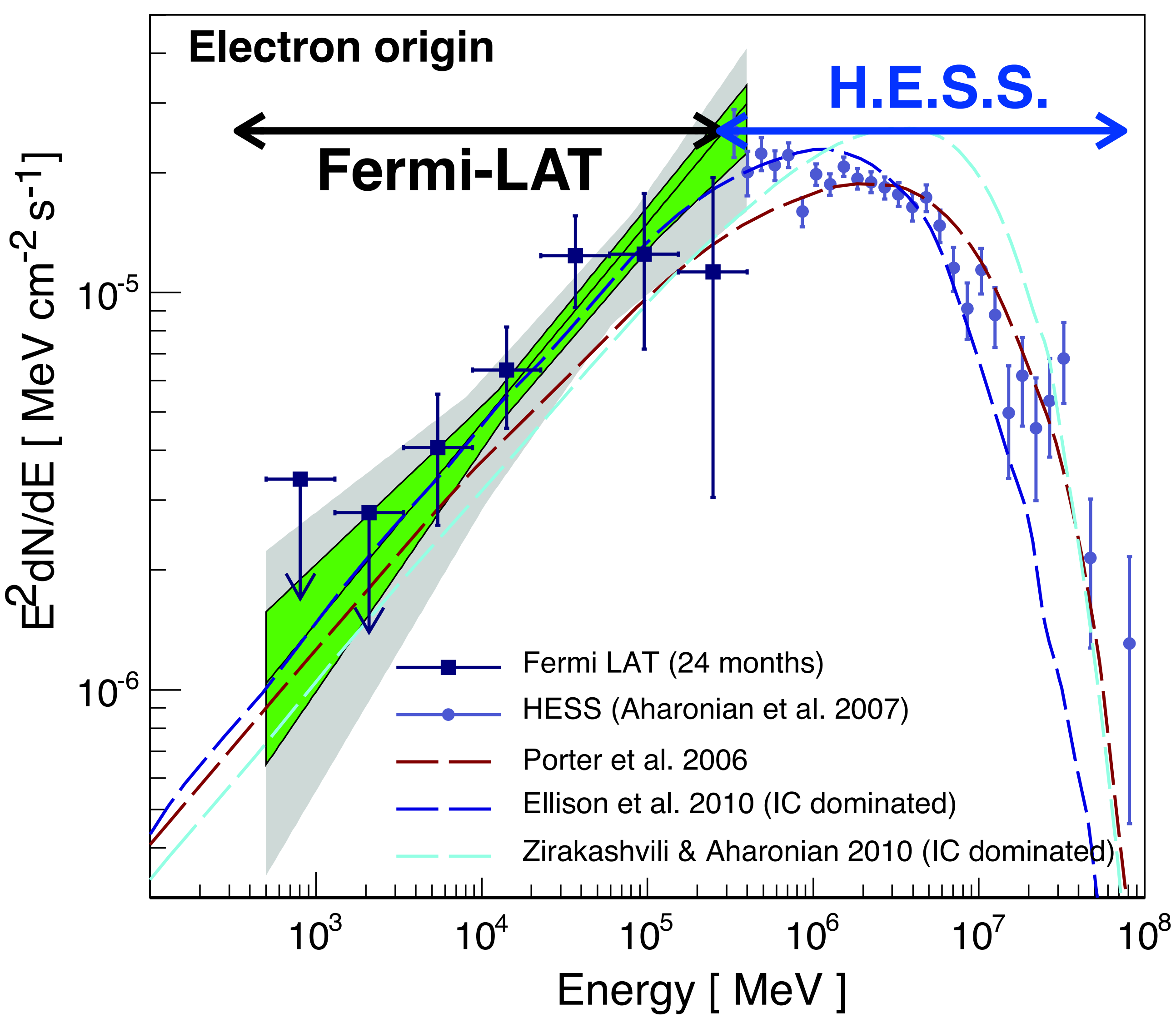


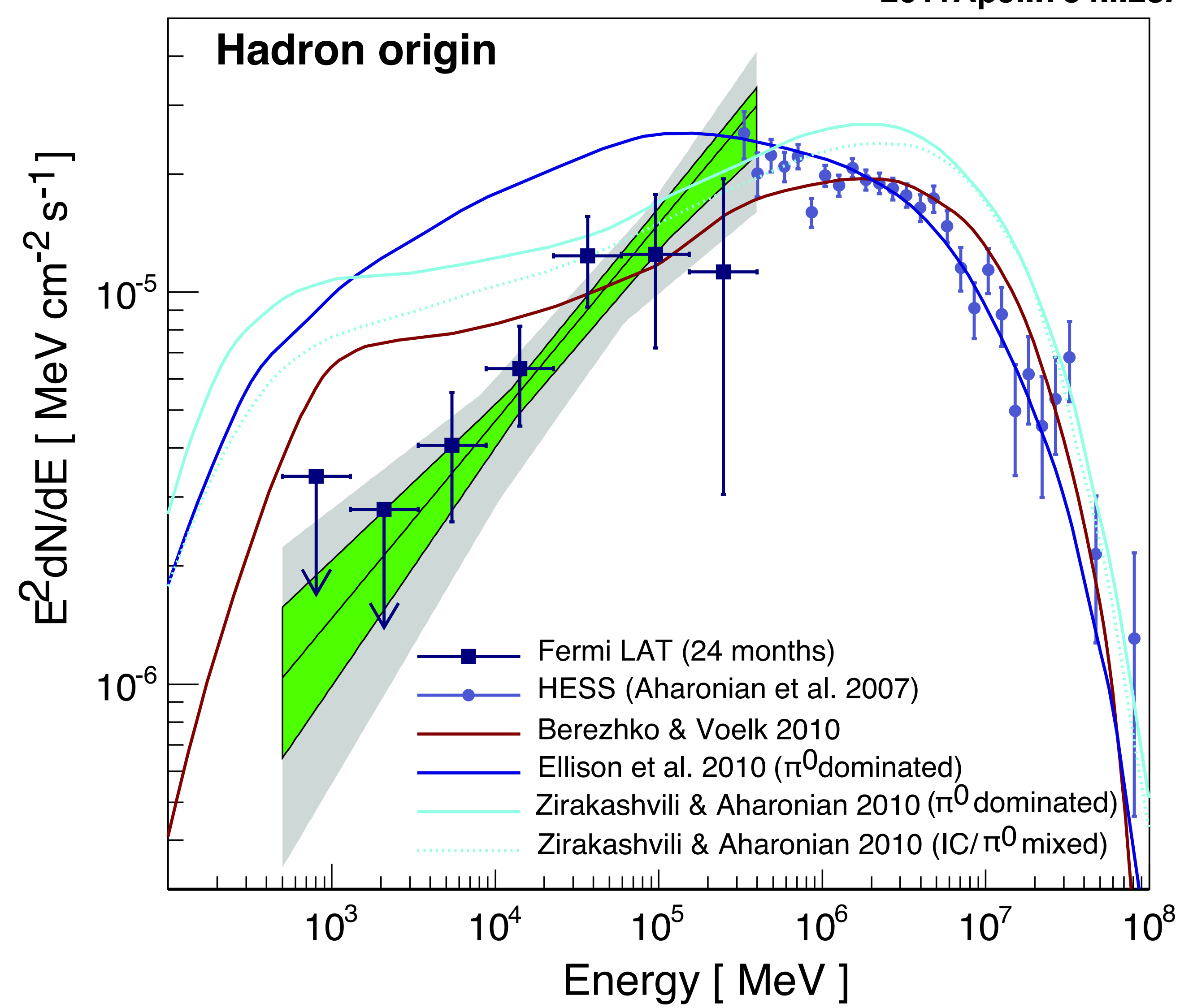


RX J1713.7-3946 Spectra

- **Both models have issues describing Fermi and H.E.S.S. spectra at the same time**
  - **Requires further investigations to distinguish hadronic or leptonic nature of gamma-ray emissions**

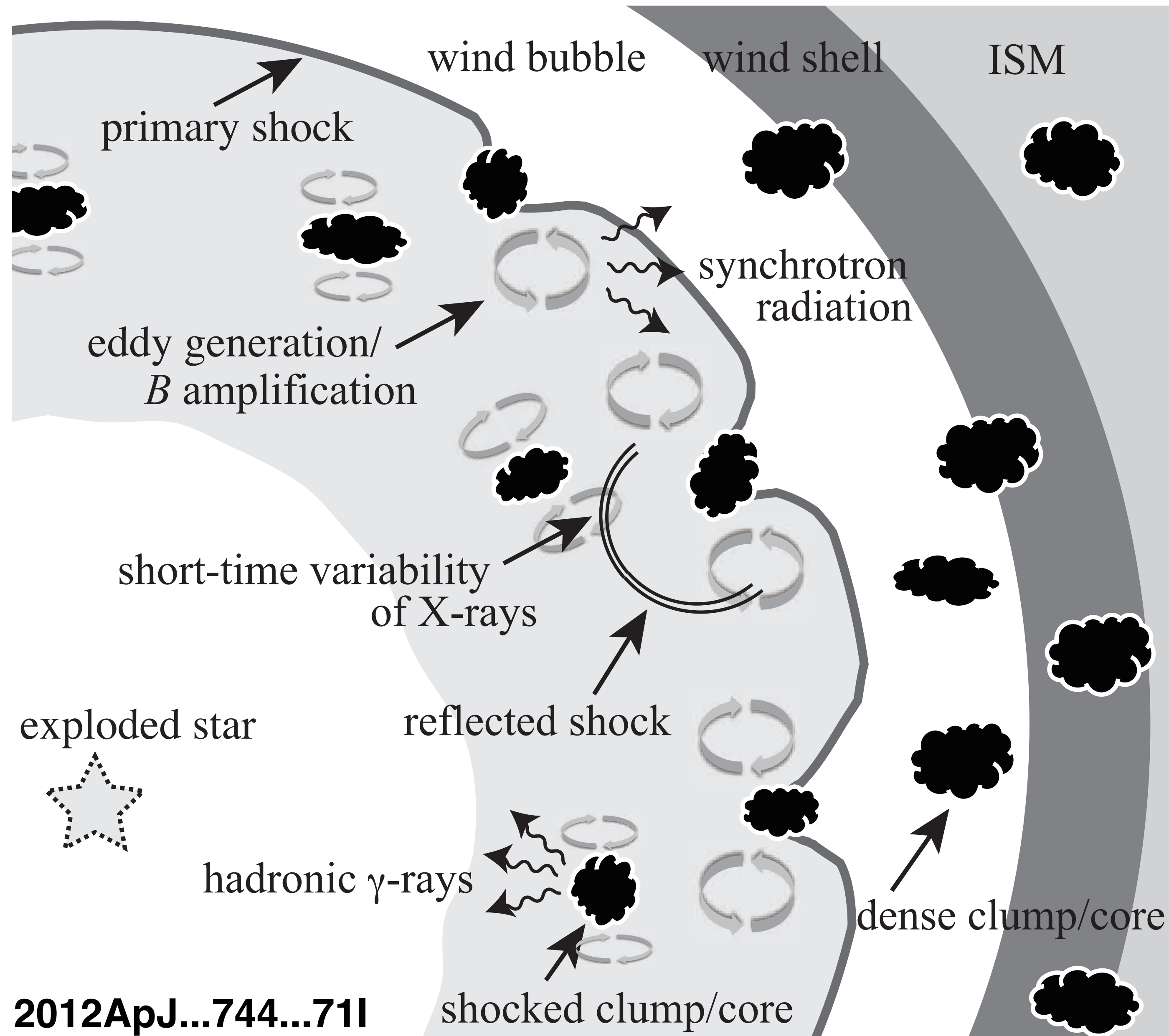
2011ApJ...734...28A





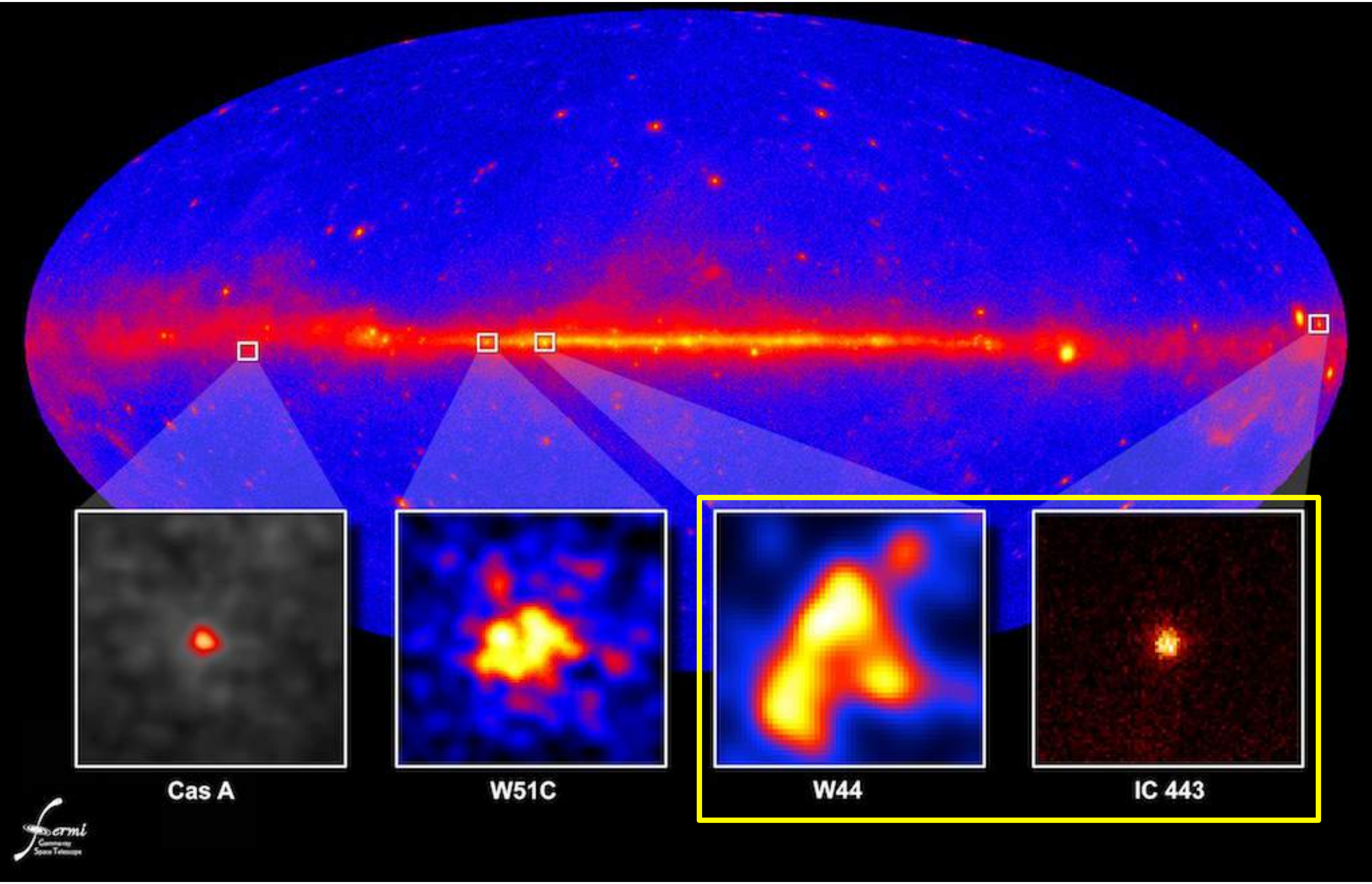
“Hard” Gamma-Ray Spectra

- “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



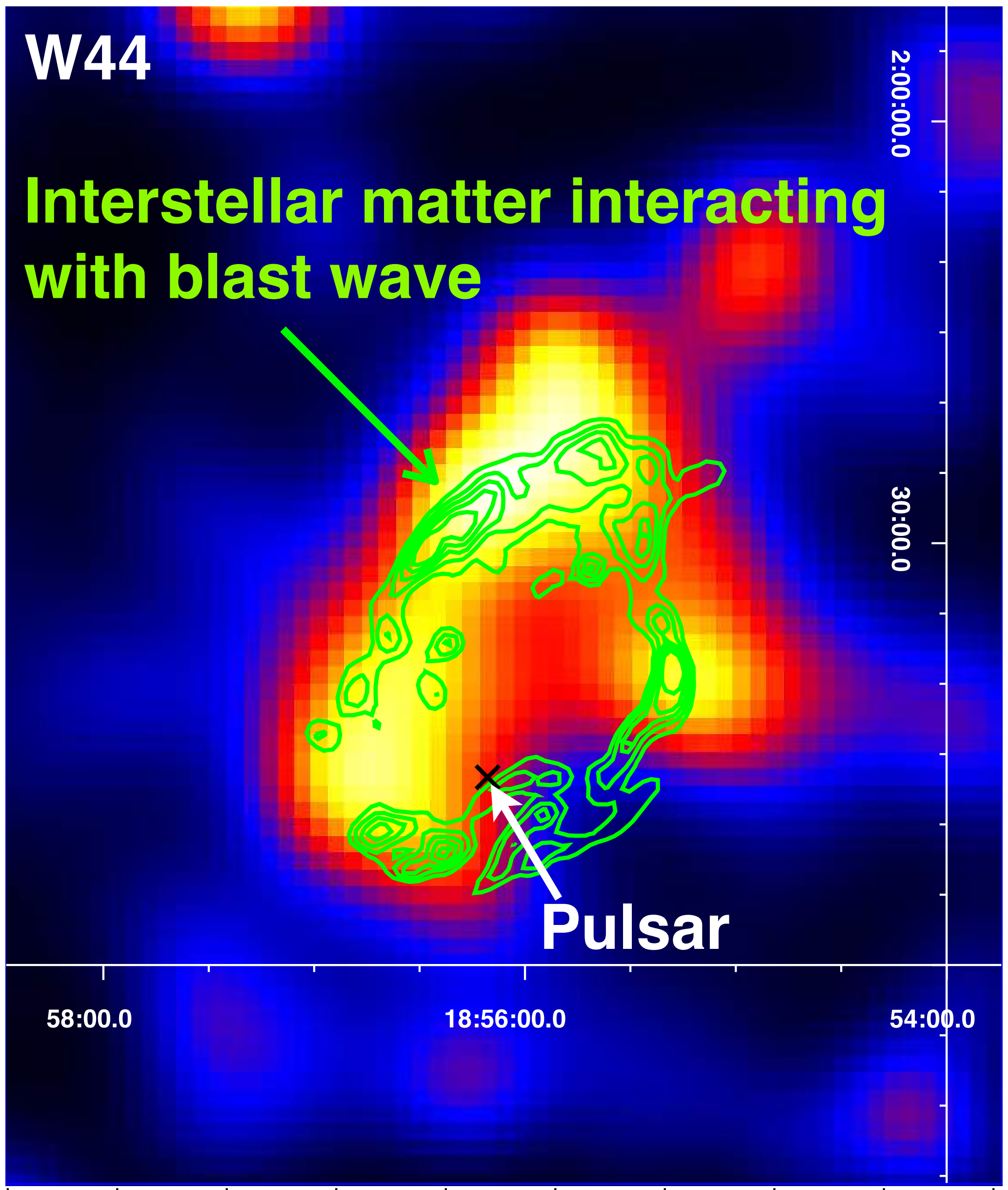
2012ApJ...744...71I

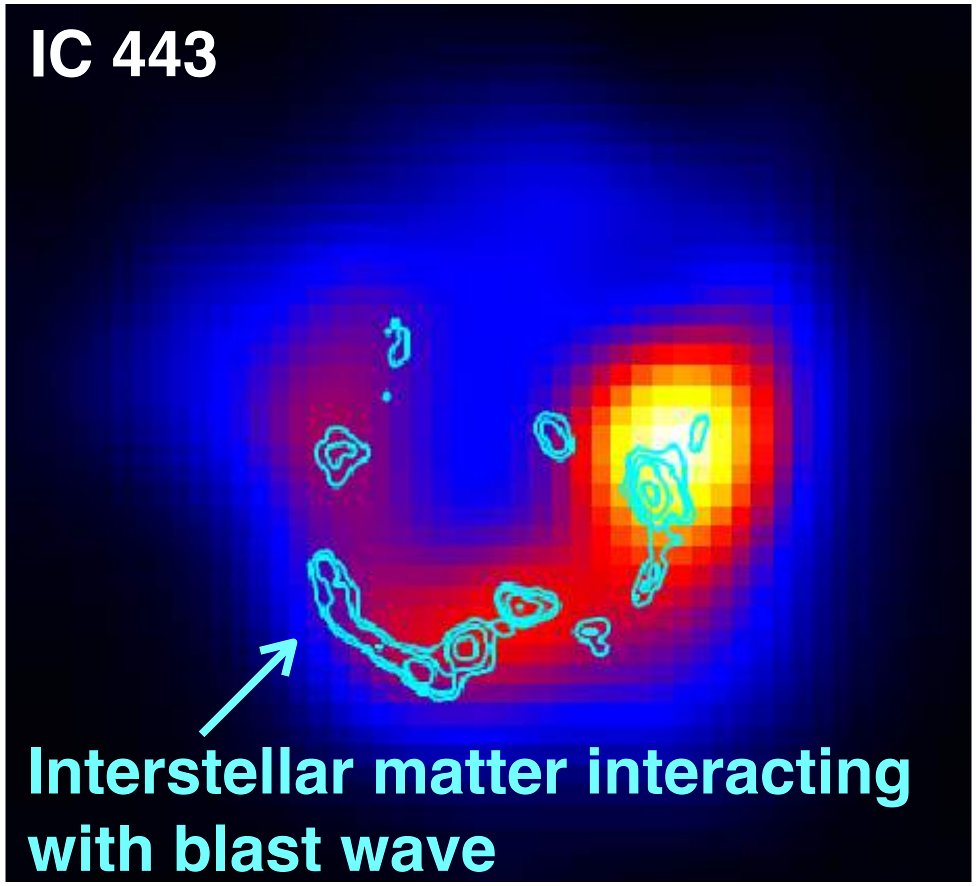
Supernova Remnants Seen by Fermi



Gamma-ray Images of Supernova Remnants

- Gamma rays originate from the region where blast wave and interstellar matte are interacting





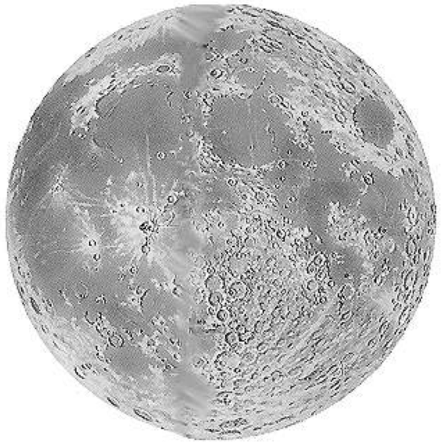
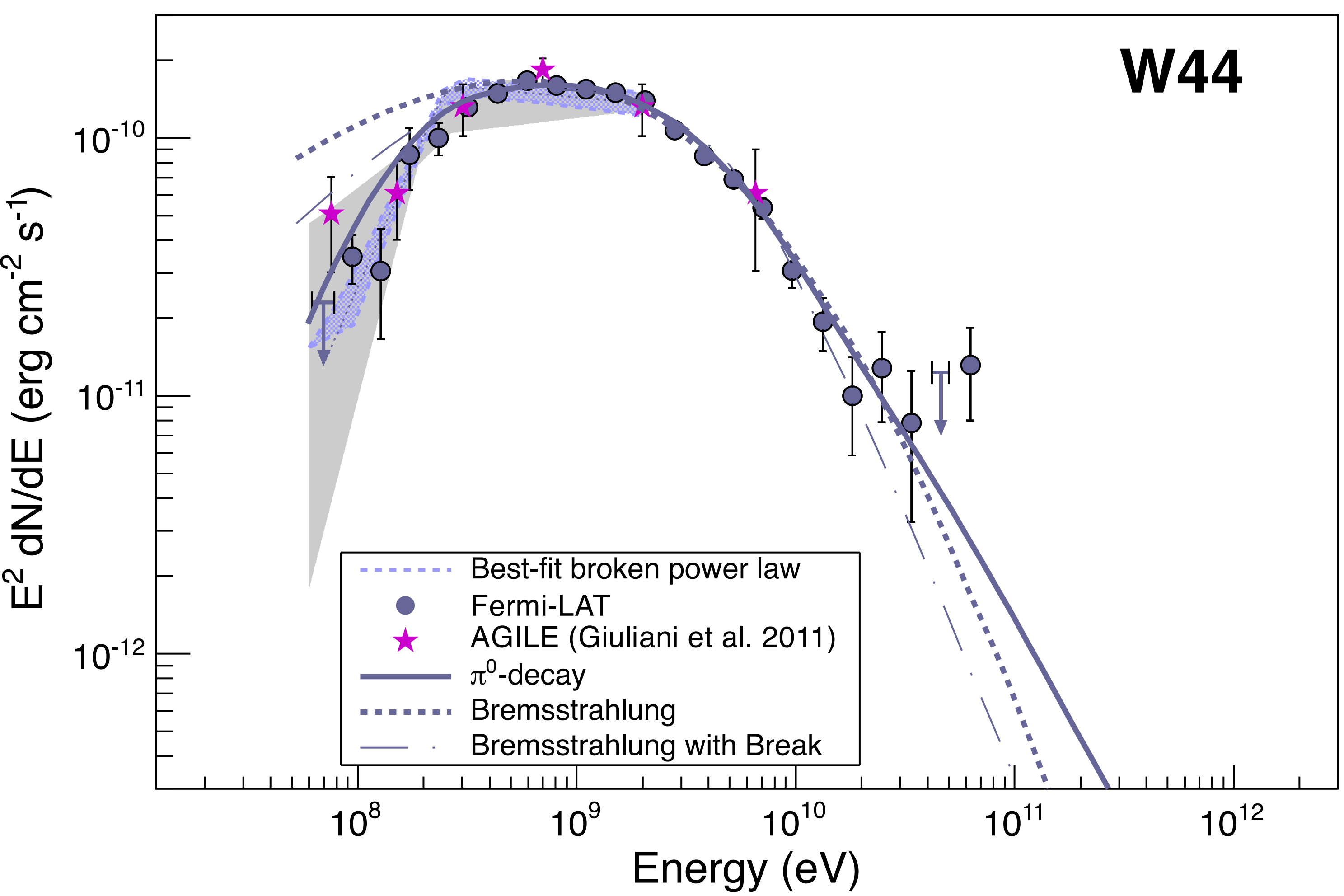
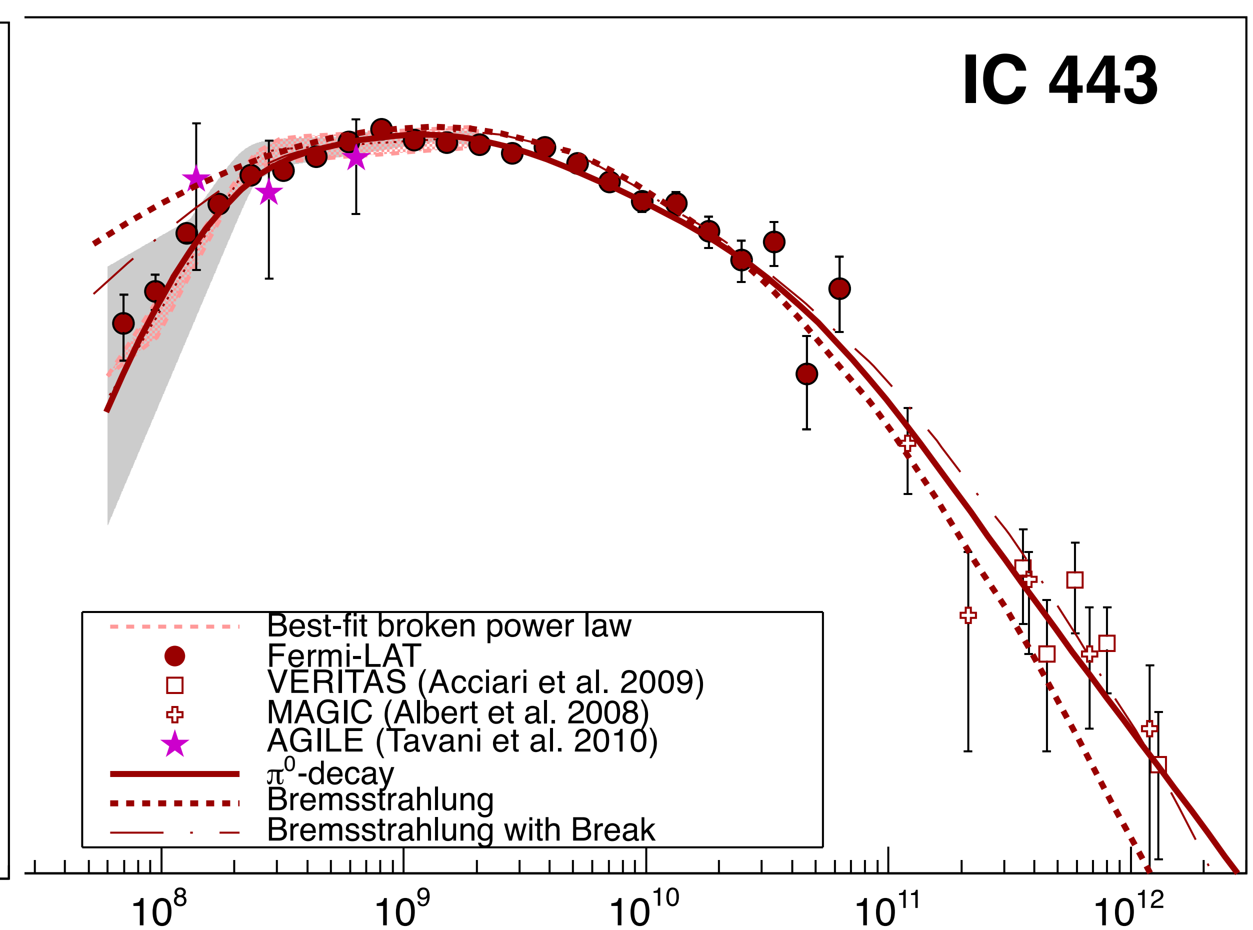


Image processing technique developed by Japanese group

- Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra
- Lepton models cannot describe the spectrum very well
  - Compton up-scattering
    - Energetically completely disfavored (×100 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





Science, 339 (2013) 807

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NEWSFOCUS

Science Breakthrough of the year

2013 Runners-Up

Cosmic Particle Accelerators Identified

For decades, physicists thought they knew where many of the immensely energetic protons and atomic nuclei that whiz in from space as cosmic rays get their start: in the wreckage of exploded stars, or supernovas. Now they're sure. This year, researchers with NASA's orbiting Fermi Gamma-ray Space Telescope produced the first direct evidence of such particles revving up in cloudlike supernova remnants within our galaxy.

When a star explodes, material ejected from it crashes into a tenuous sea of gas between the stars. That interstellar medium is so thin that few particles collide directly. However, particles from the supernova can rebound off magnetic fields in space, twisting them up to form a lingering collisionless shock that slingshots other particles to higher energies. In the late 1970s, theorists realized that as protons and nuclei circulate repeatedly through such a shock, they may accelerate to colossal energies—hundreds of times higher than particle accelerators have reached.

But tracing cosmic rays to supernova remnants

Boom! Supernova remnants such as the Jellyfish Nebula can boost particles to enormous energies.

E^2 dN/dE (erg cm^{-2} s^{-1})

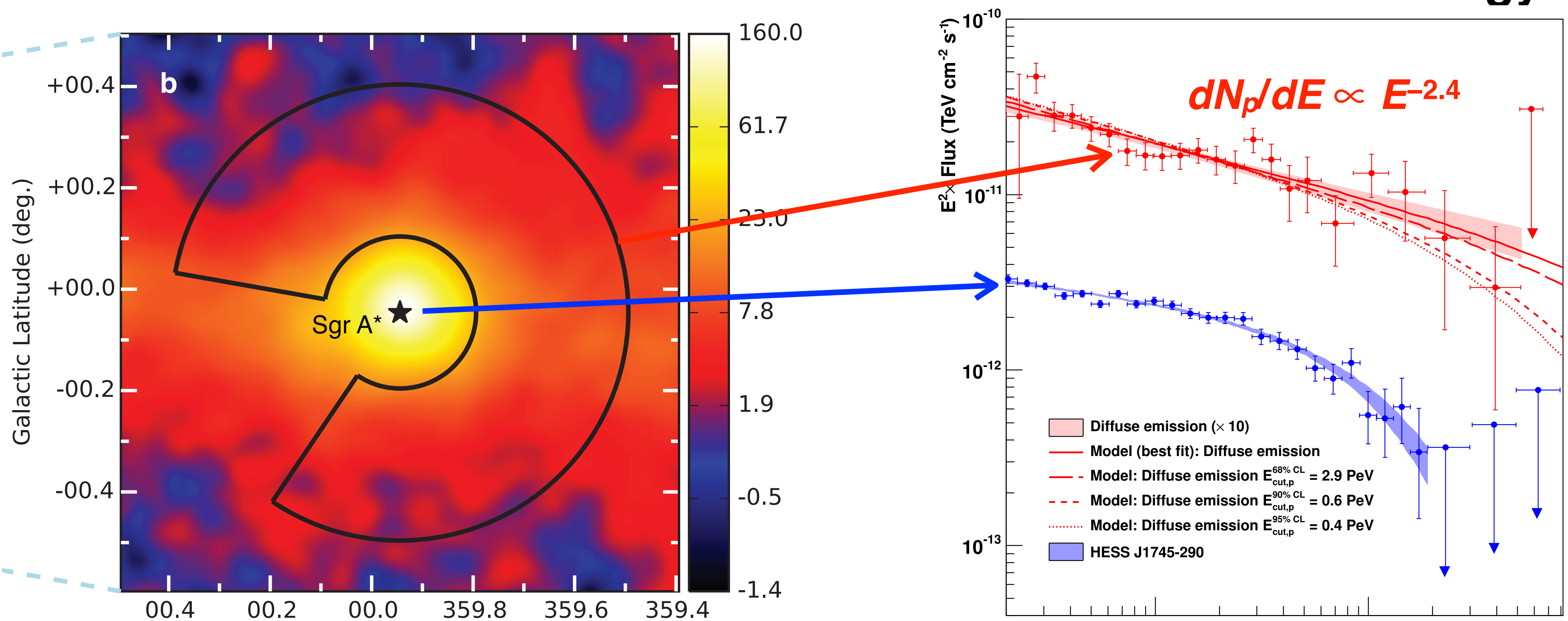
10^{-10}

10^{-11}

10^{-12}

PeVatron Candidate in Galactic Center

- **Spectrum implies hadronic origin with E_{max} > 3 PeV**
  - **Sgr A* (supermassive blackhole in GC) is a plausible CR source**
    - **Sgr A* is known to be active in the past**
    - **Sgr A*'s cutoff may be due to attenuation due to infrared field**
  - **SNR G359.95–0.04 is another possible CR source**
    - **Hard to explain 10^4 years of injection**
  - **Both source can explain total proton energy of 1.0×10^{49} erg**
    - **This is not still sufficient to account for entire Galactic CR energy**

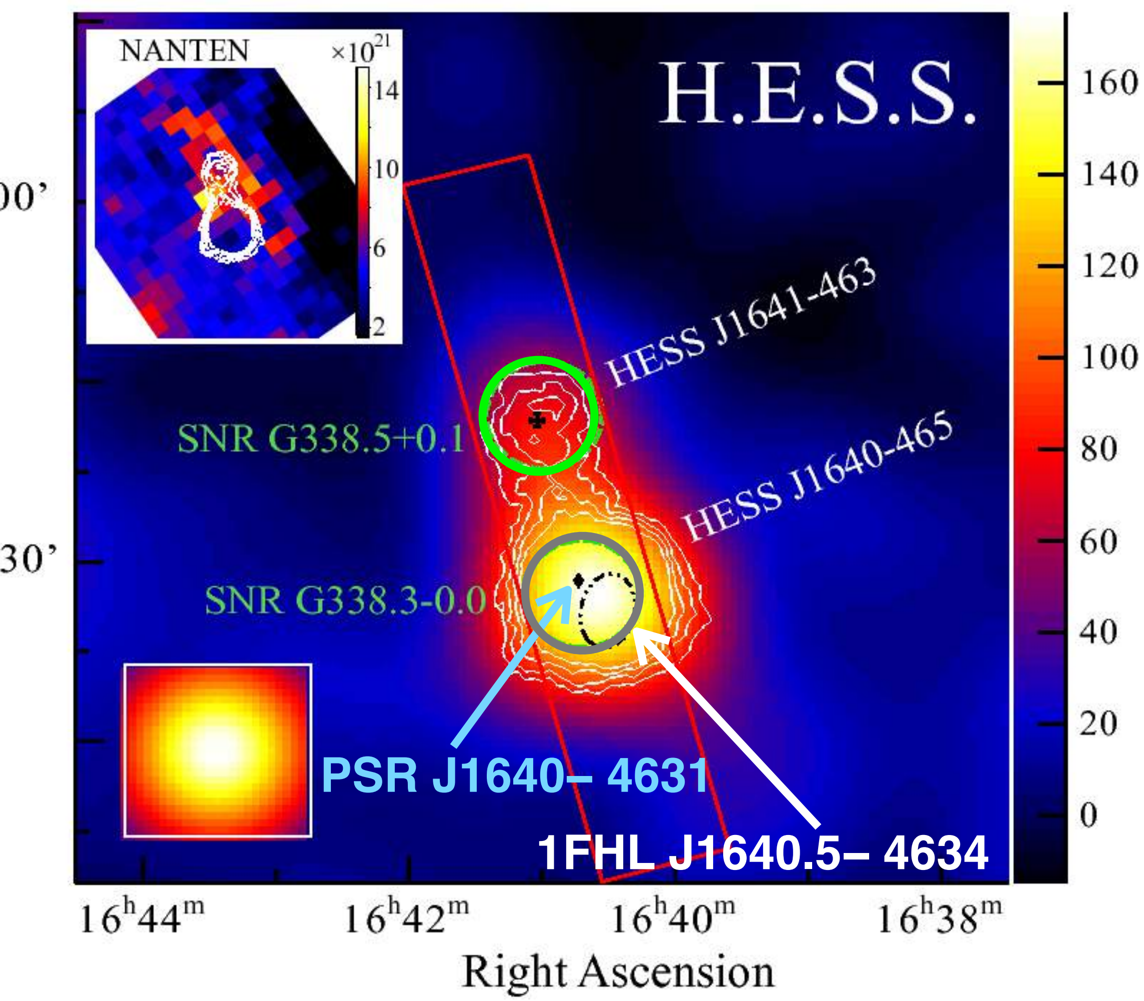


doi:10.1038/nature17147

PeVatron Candidate in Galactic Plane

- H.E.S.S. found a PeVatron candidate, HESS J1641–463 within a boundary of SNR G338.5+0.1
  - Estimated age of 1.1 – 1.7 kyr, estimated distance of ~11 kpc
  - No X-ray counterpart found by Chandra/XMM-Newton
  - Fermi-LAT found both sources
- Spectrum implies hadronic origin with E_{max} > 1 PeV

1509.08310v2



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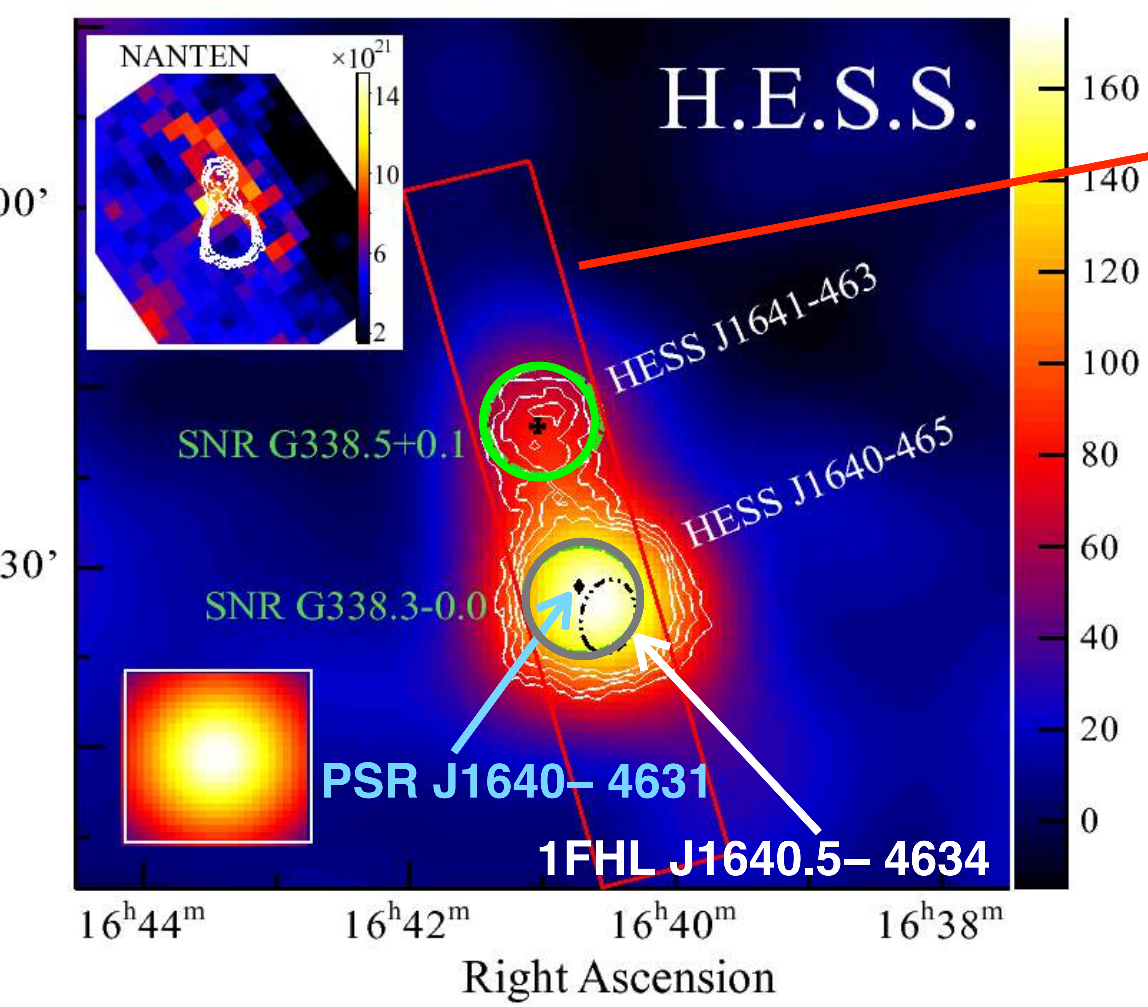
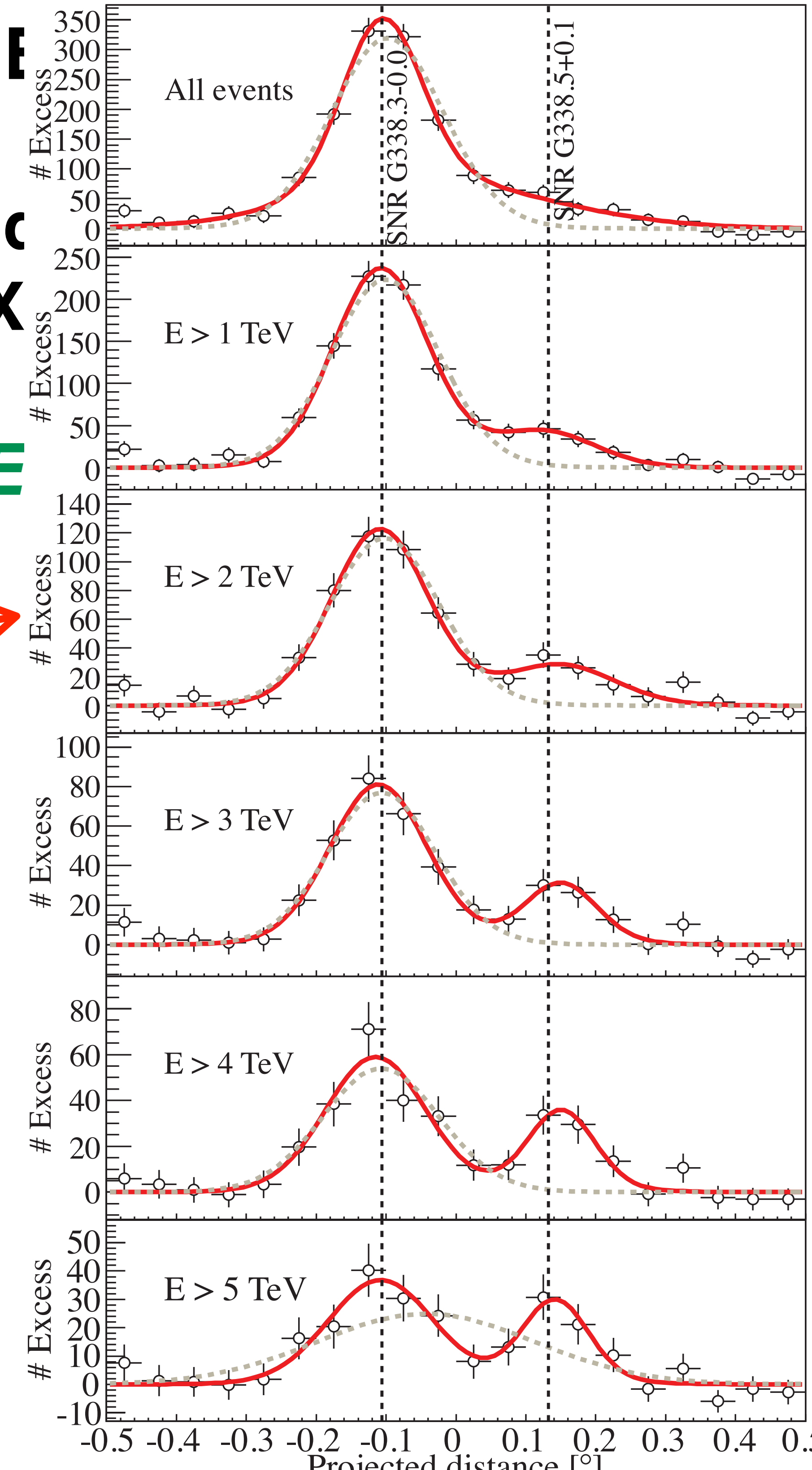
1509.08310v2





PeVatron Candidate in Galactic Plane

- H.E.S.S. found a PeVatron candidate, HESS J1641–463 within a boundary of SNR G338.5+0.1
  - Estimated age of 1.1 – 1.7 kyr, estimated distance of ~11 kpc
  - No X-ray counterpart found by Chandra/XMM-Newton
  - Fermi-LAT found both sources
- Spectrum implies hadronic origin with E_{max} > 1 PeV

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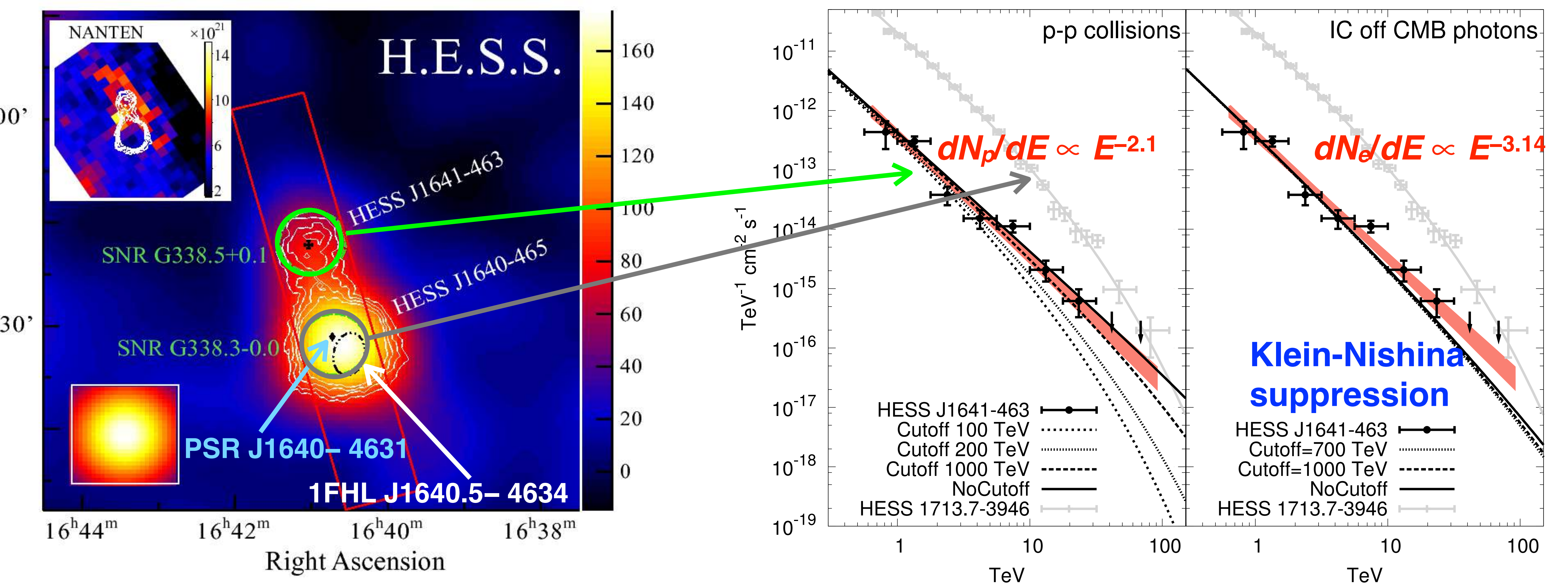
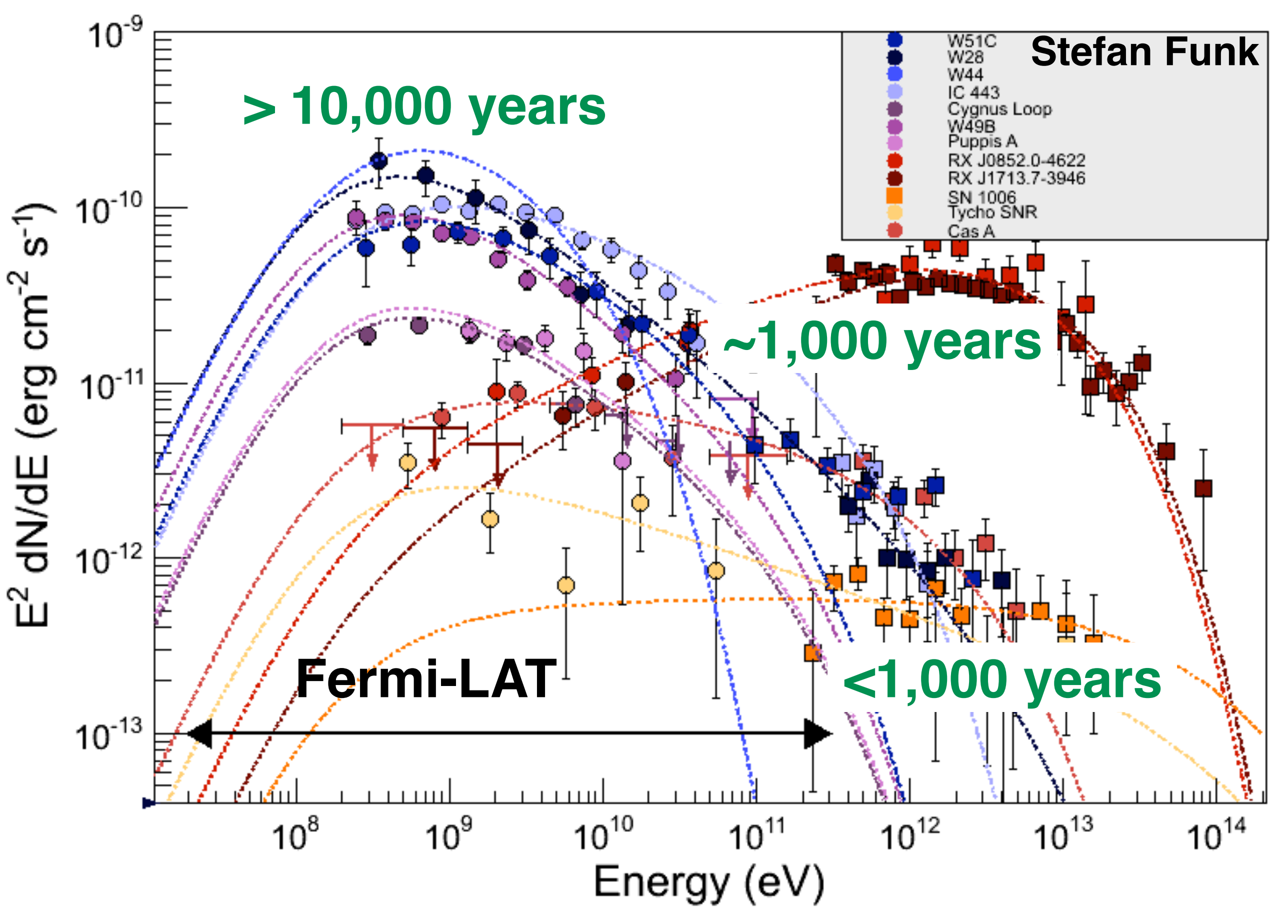
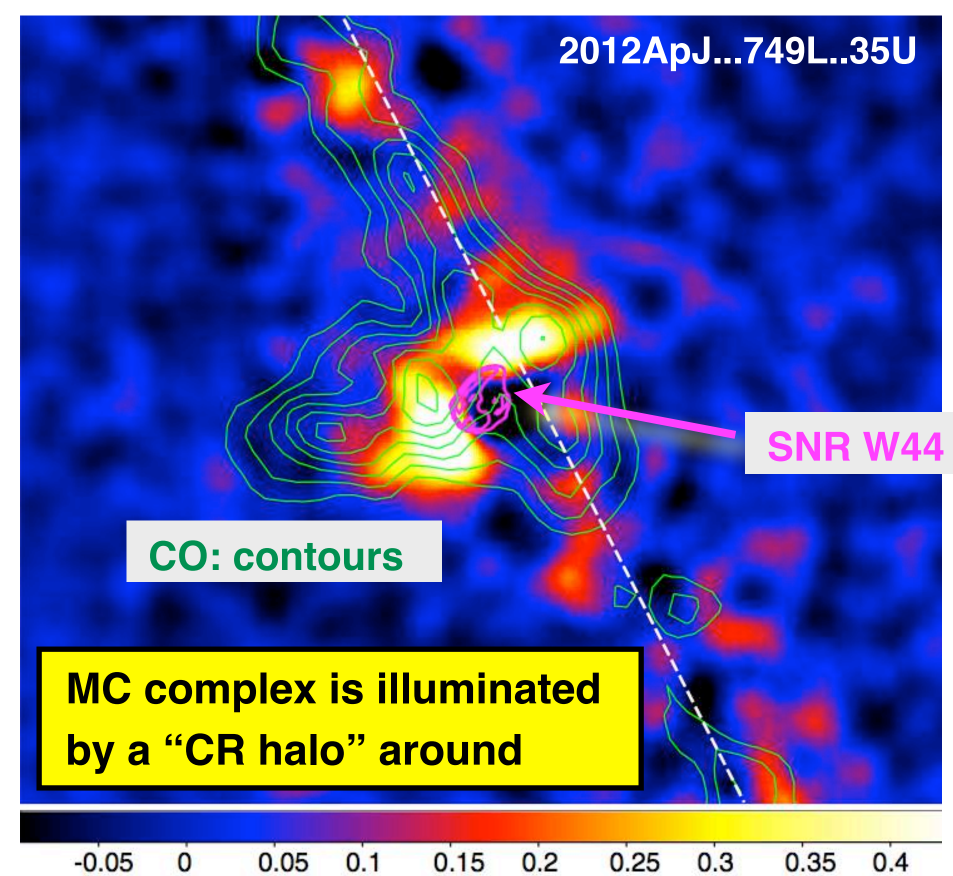


Is SNR a PeVatron?

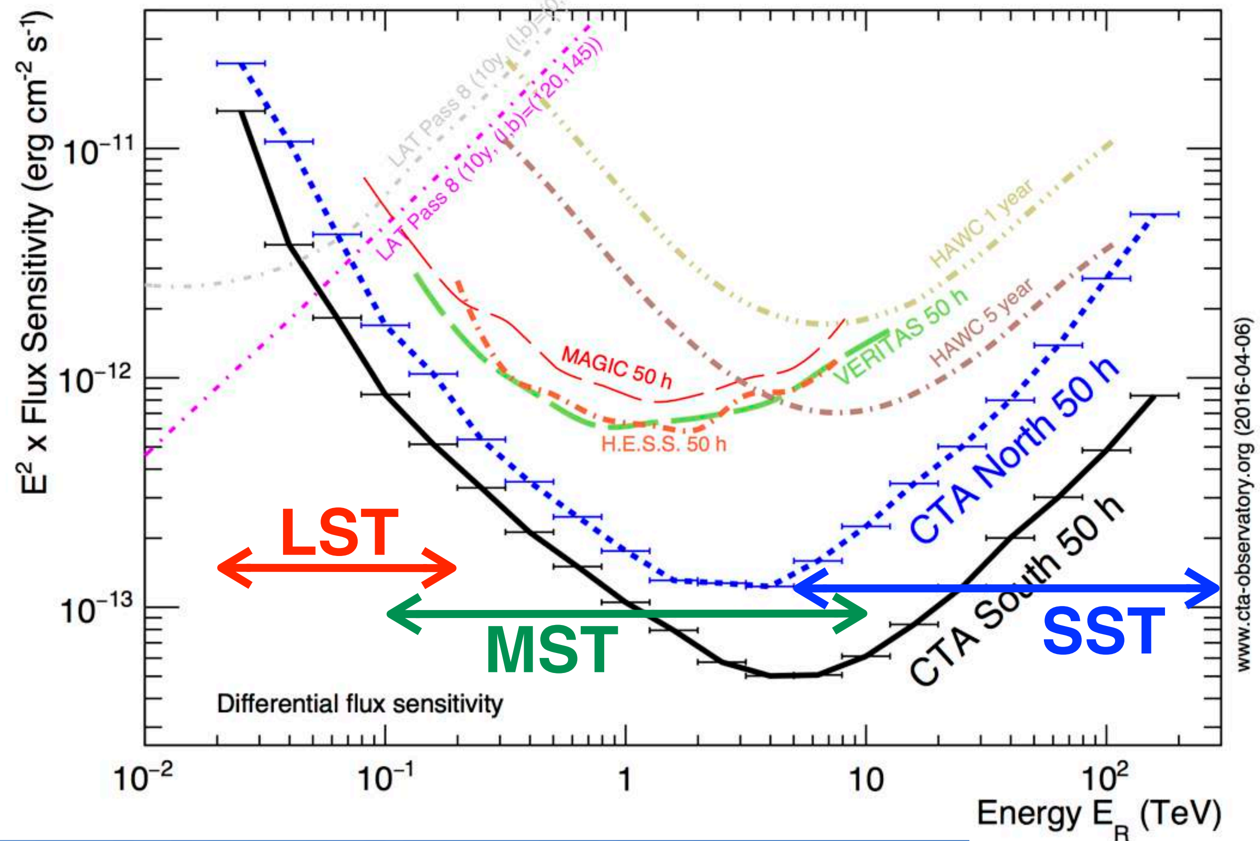
- We have not identified PeVatrons, CR sources with maximum CR energy around Knee (gamma-ray energy ≈ 100 TeV)
- We need to survey more multi-TeV gamma-ray sources
  - Evolution with SNR age: SNR can be a PeVatron for < 100 years
    - We expect only a few such SNRs in Milky Way Galaxy
  - Escape of CRs from SNRs: ~ a few 100 pc in 1,000 years
  - Air shower array will be useful to find PeVatron candidates
- Currently operating IACTs do not have sufficient sensitivities



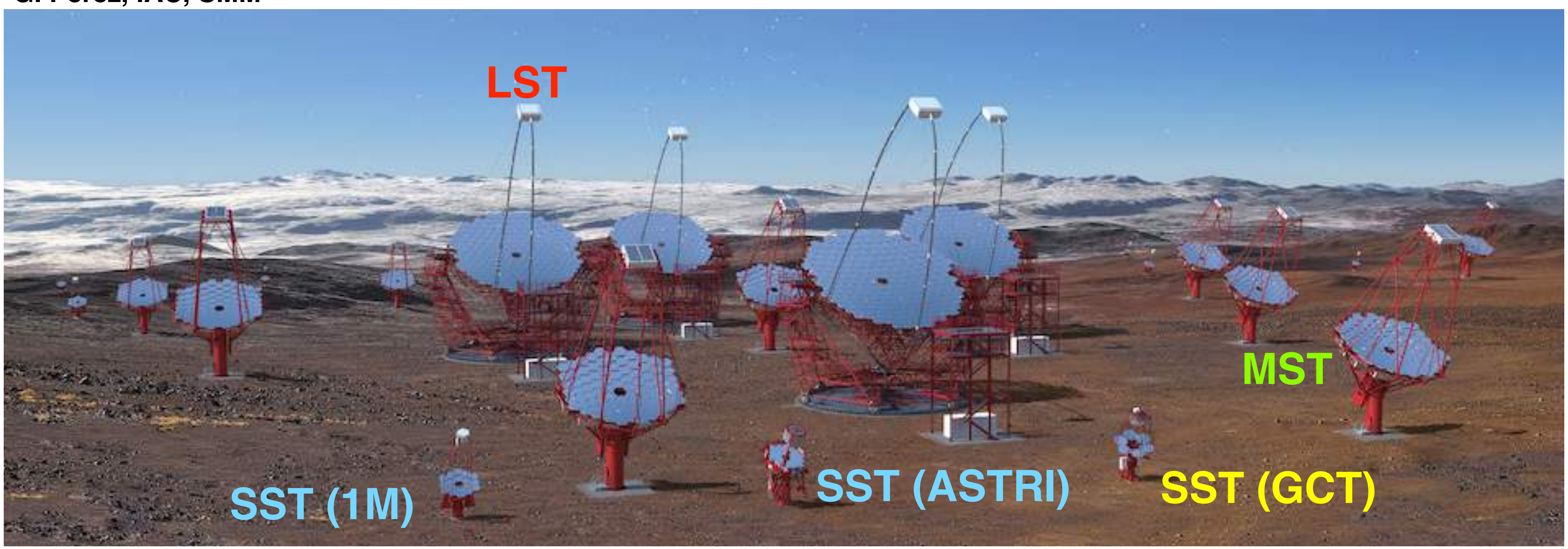


Cherenkov Telescope Array

- Large number of telescopes
  - Large collection area (×~30)
  - Better angular resolution (0.03°)
- Optimized telescope configuration
  - LST: ~23 m ϕ × 4, ~20 GeV – 200 GeV
  - MST: ~12 m ϕ × 20, ~100 GeV – 10 TeV
  - SST: ~4 m ϕ × 70, ~5 TeV – 300 TeV
- SST is essential to study PeVatrons

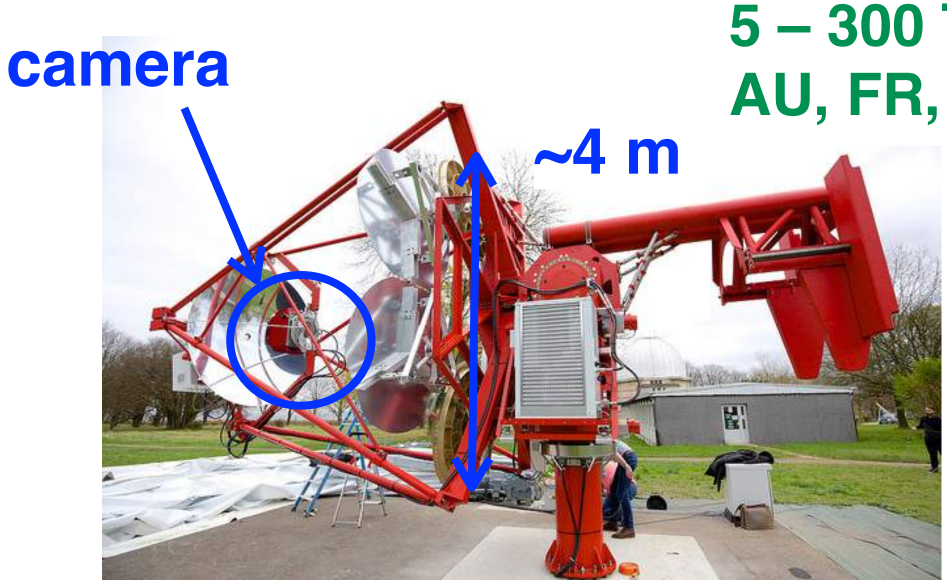


G. Pérez, IAC, SMM

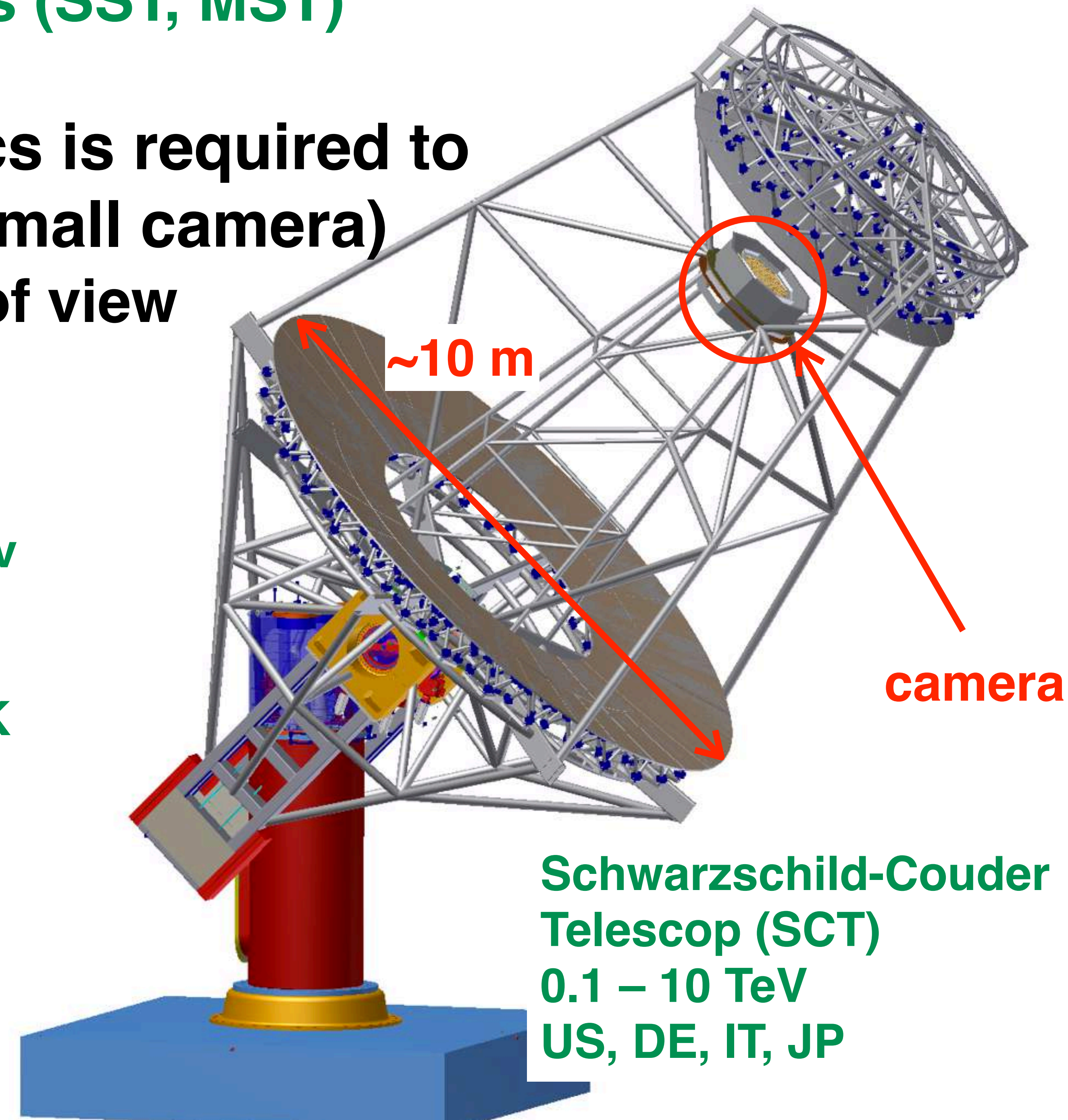


Nagoya Involvements with CTA

- Silicon photomultiplier (SiPM) camera for dual-mirror telescopes
  - SiPM: low cost, durable, high photon detection efficiency (SST)
  - High-density front-end electronics (SST, MST)
  - Camera software (SST)
- Schwarzschild-Couder (SC) optics is required to achieve short focal length (and small camera)
  - SC optics also realize large field of view
    - Sparse telescope spacing (Larger collection area)



Gamma-ray Cherenkov Telescope (GCT)
5 – 300 TeV
AU, FR, DE, JP, NL, UK

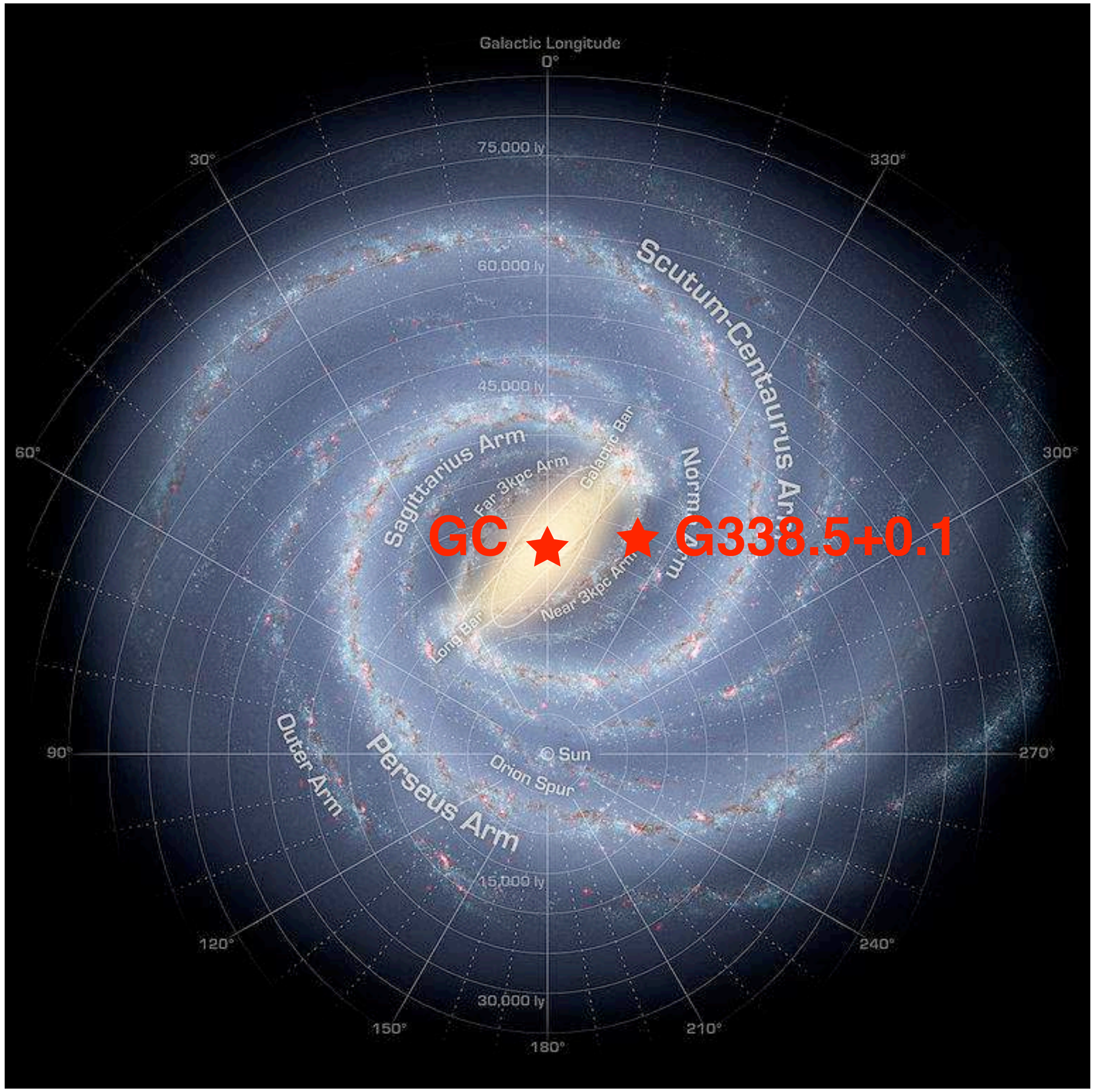


Schwarzschild-Couder Telescop (SCT)
0.1 – 10 TeV
US, DE, IT, JP

CTA collaboration

Galactic Plane Survey by CTA

- CTA plans to spend 1,600 hours for Galactic Plane Survey
  - 0.2–0.3% Crab sensitivity is expected
  - H.E.S.S. Galactic plane survey: 2–3% Crab sensitivity with 250 Hours
  - Survey entire Milky Way Galaxy for sources like G338.5+0.1 (2% Crab)



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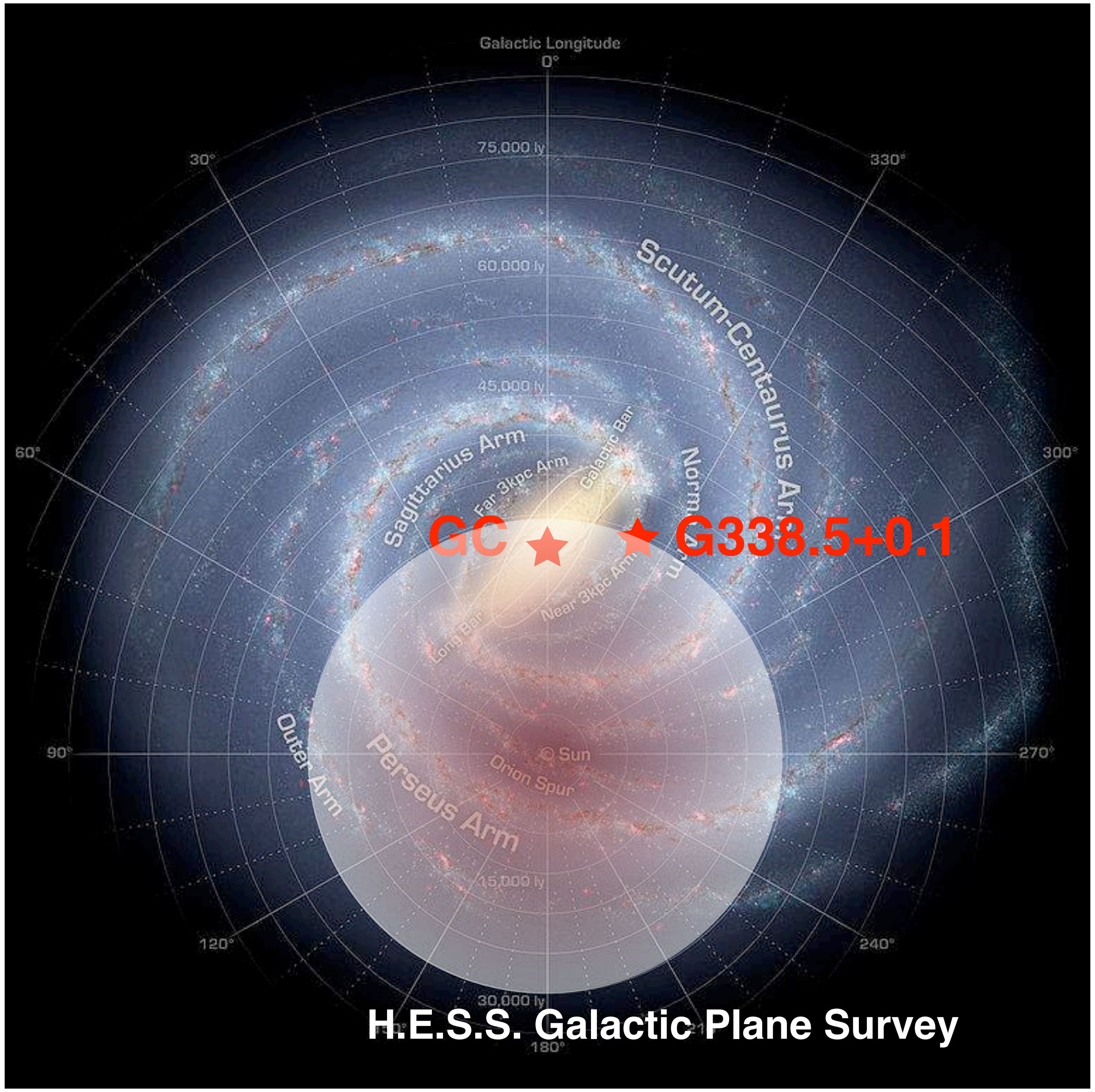

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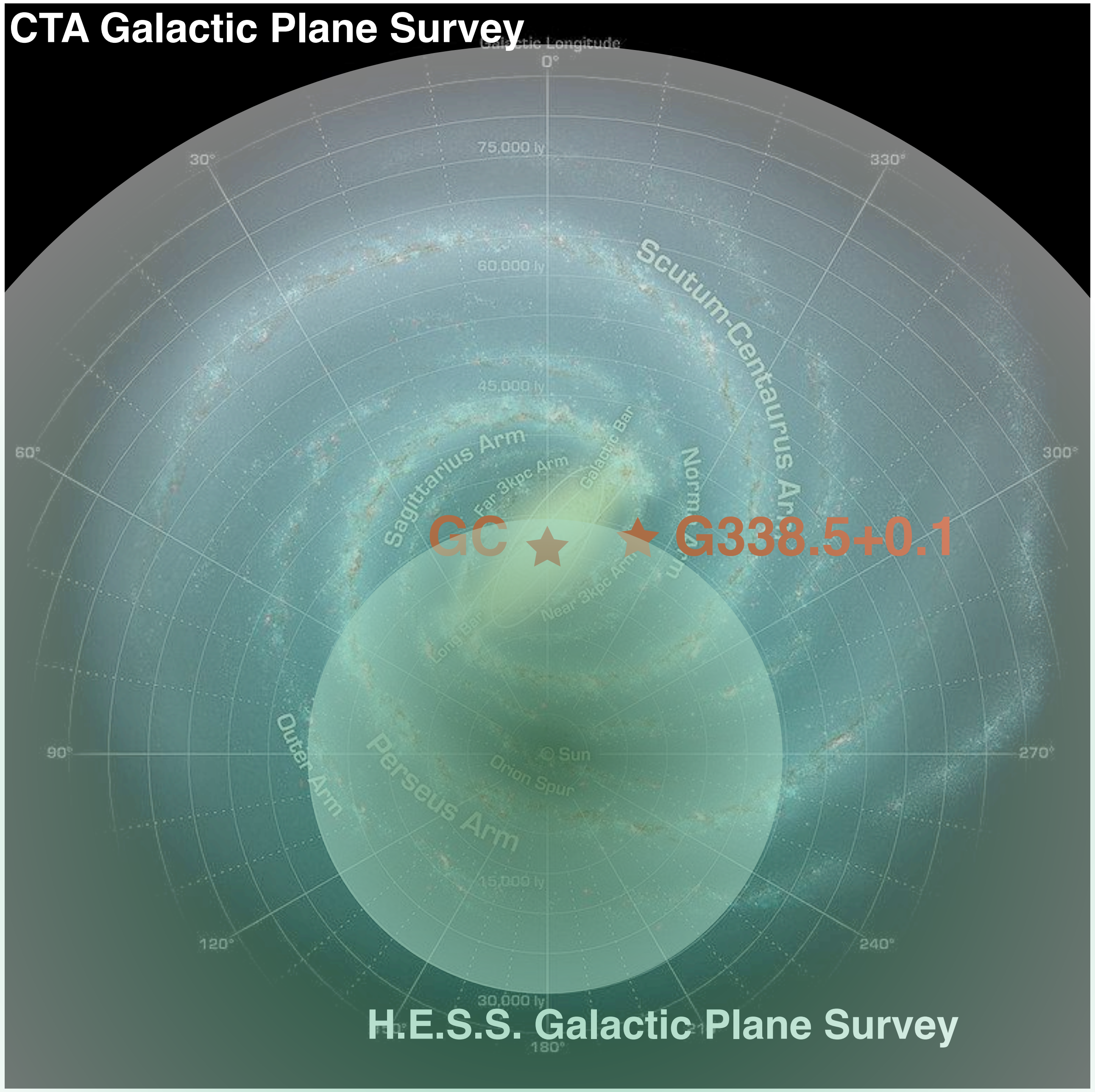

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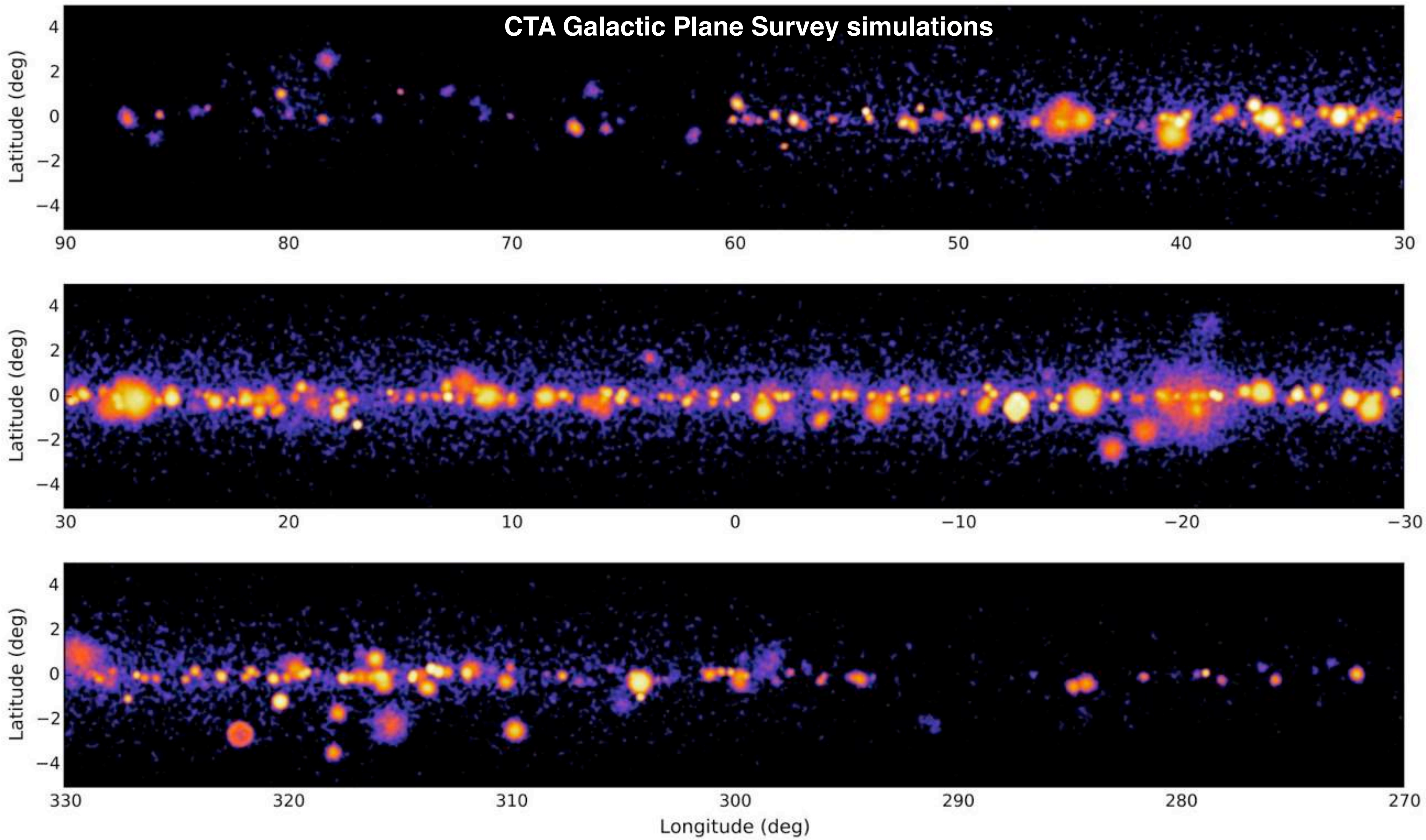
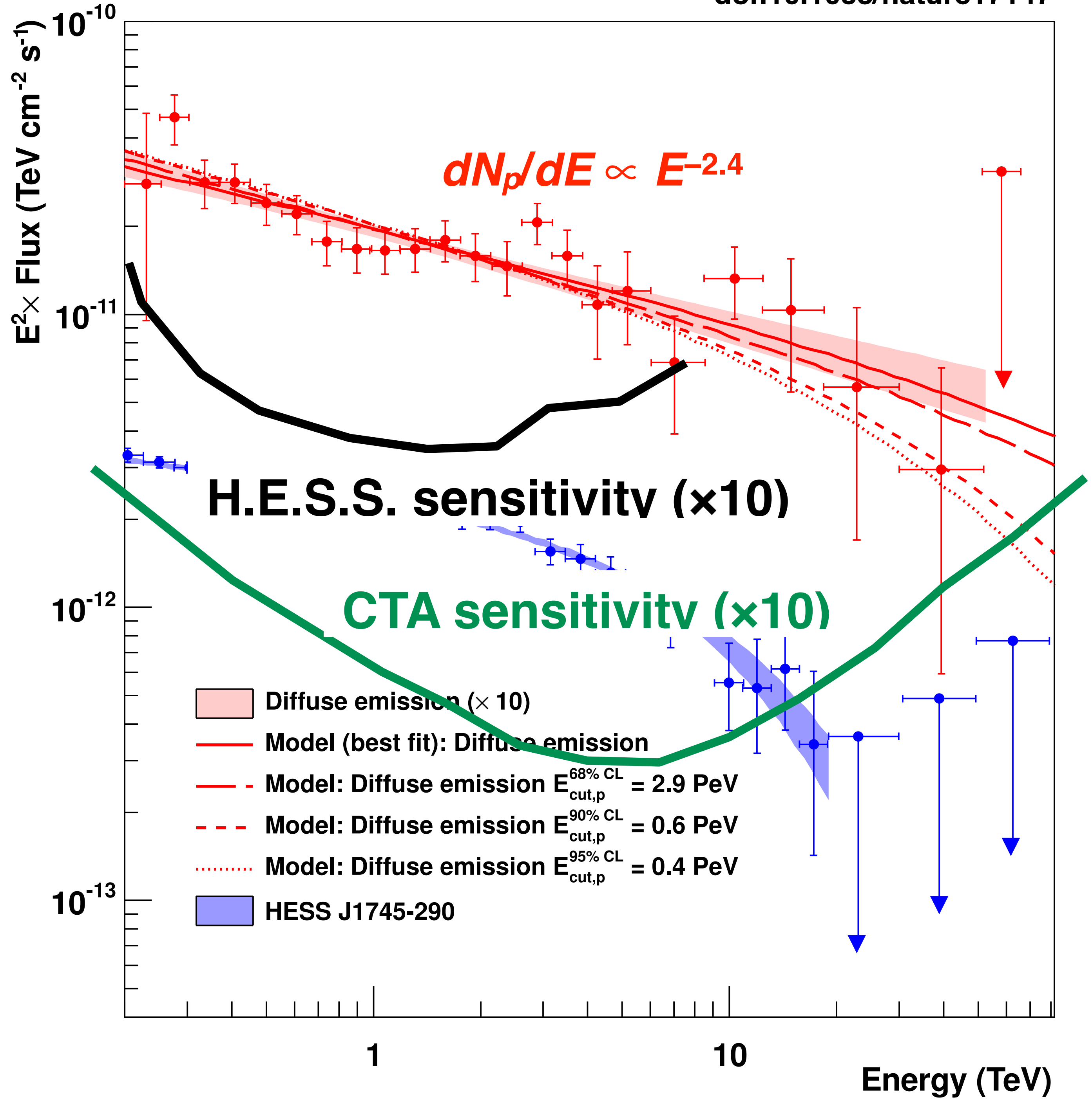


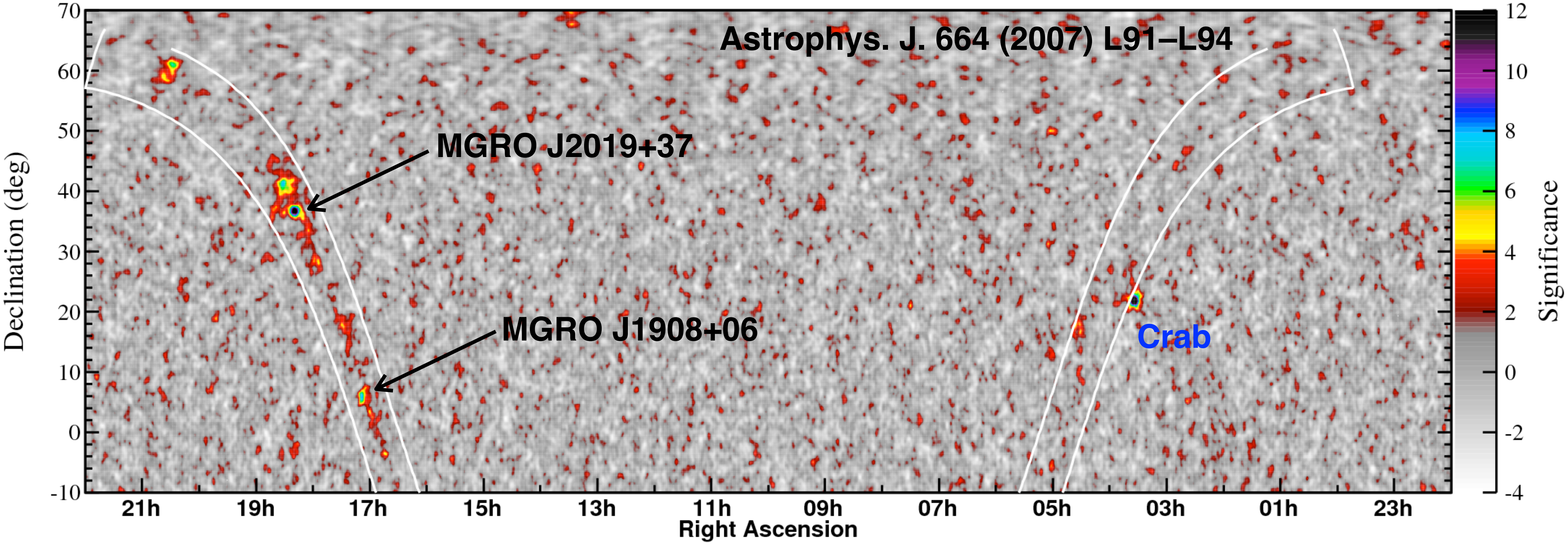
CTA Spectral Performance

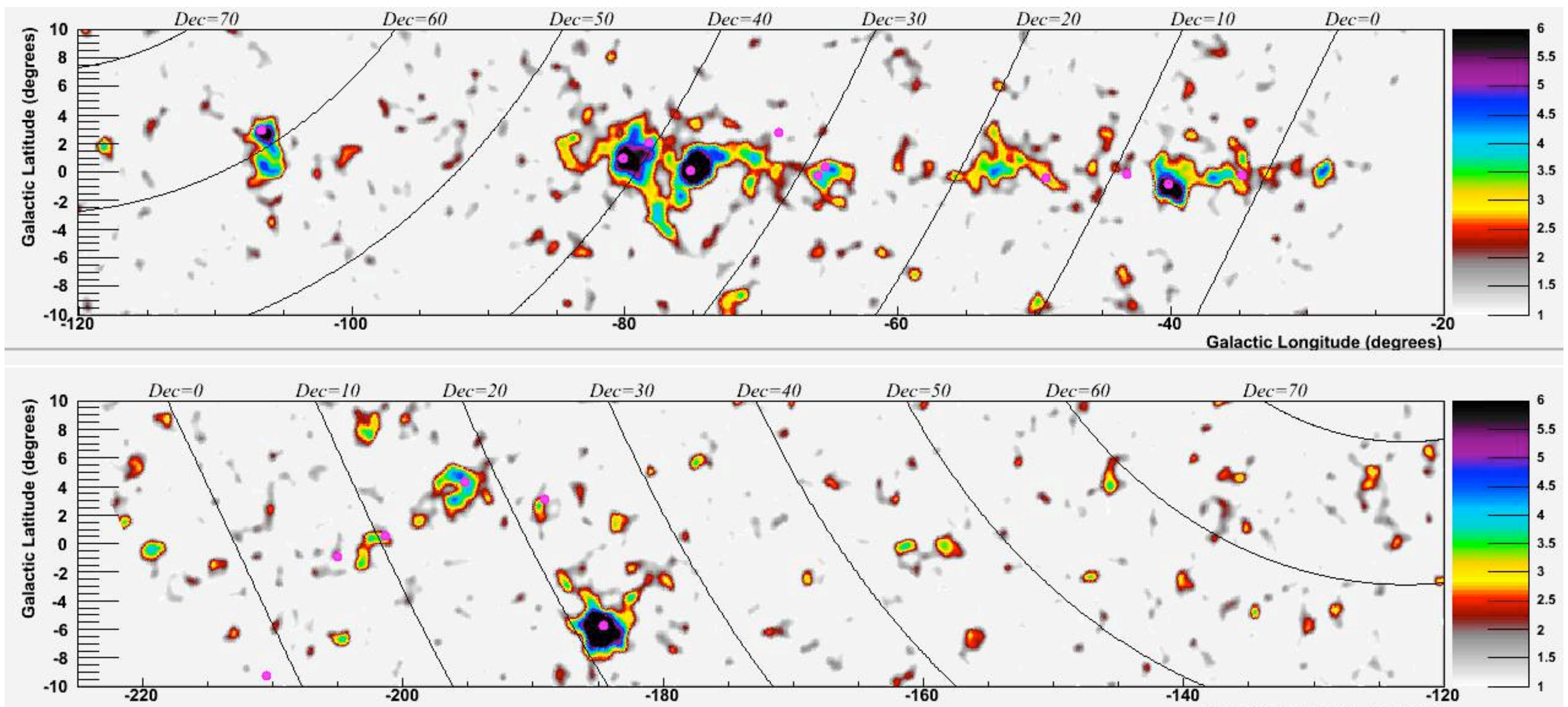
- CTA will provide precise spectral measurements up to 100 TeV
  - 500 hours of GC observation is planned (10× of nominal observation time)
- Determine the maximum energy of GC source

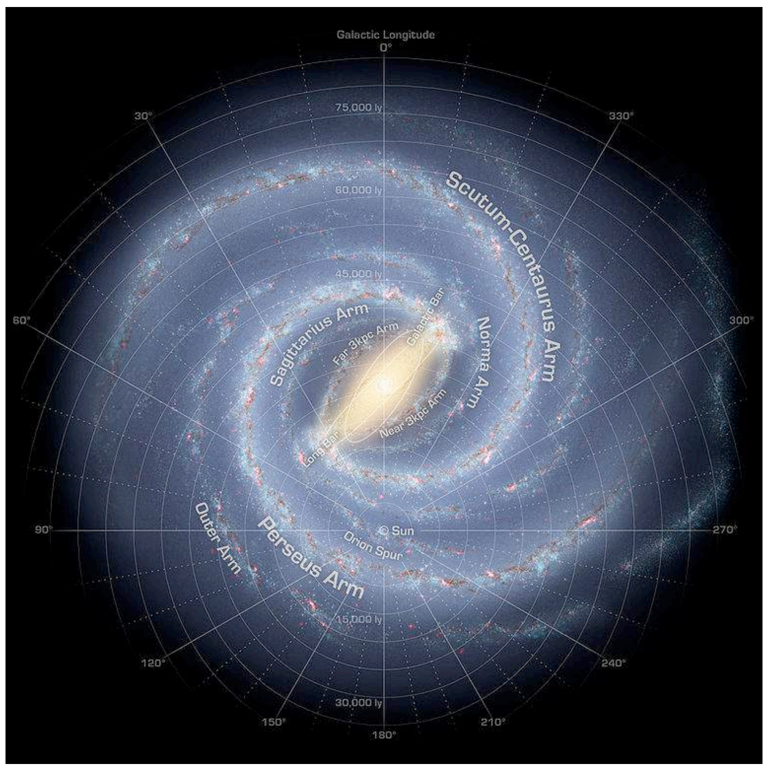
doi:10.1038/nature17147



TeV Gamma-ray Sources Observed by Milagro







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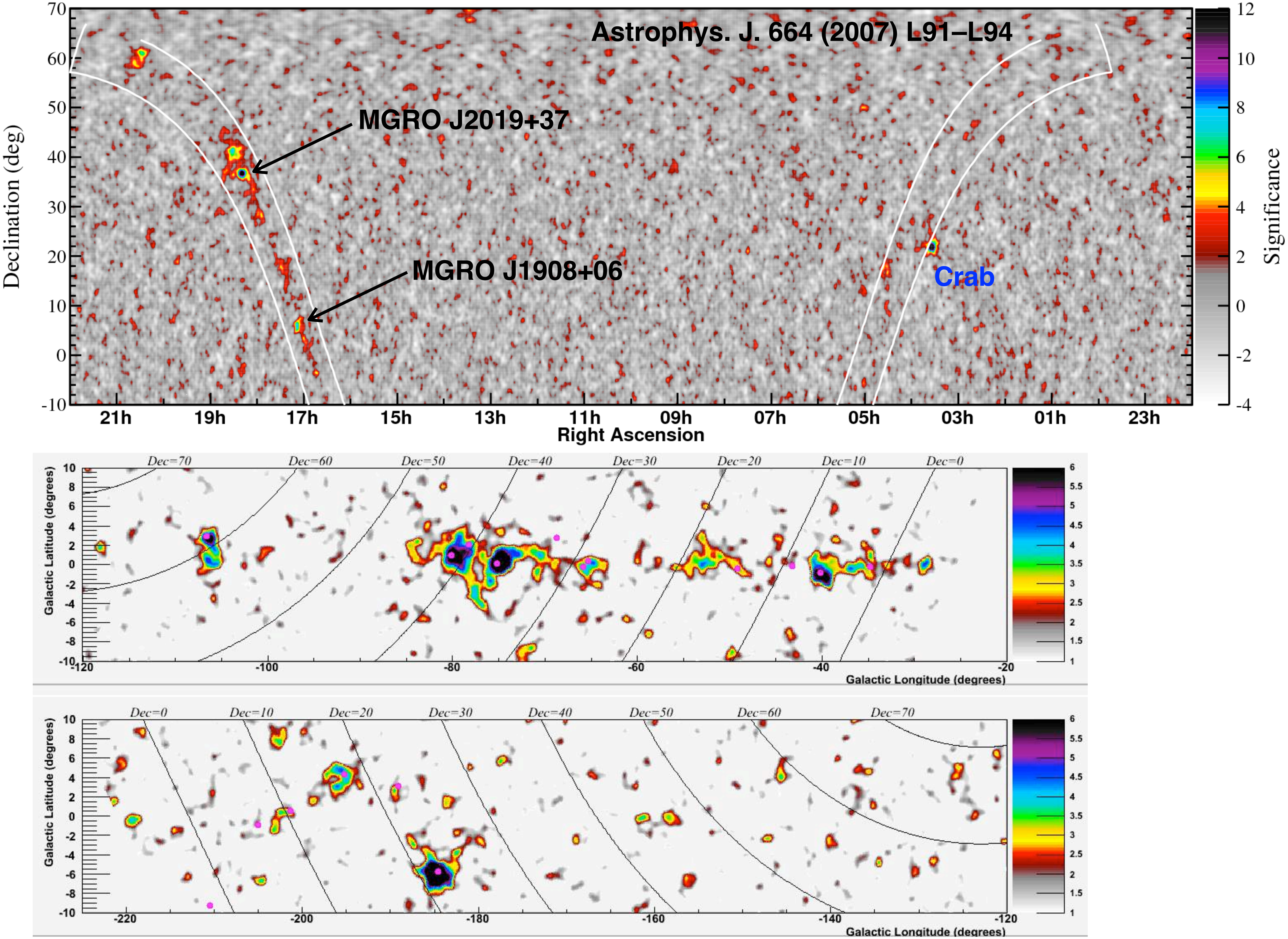
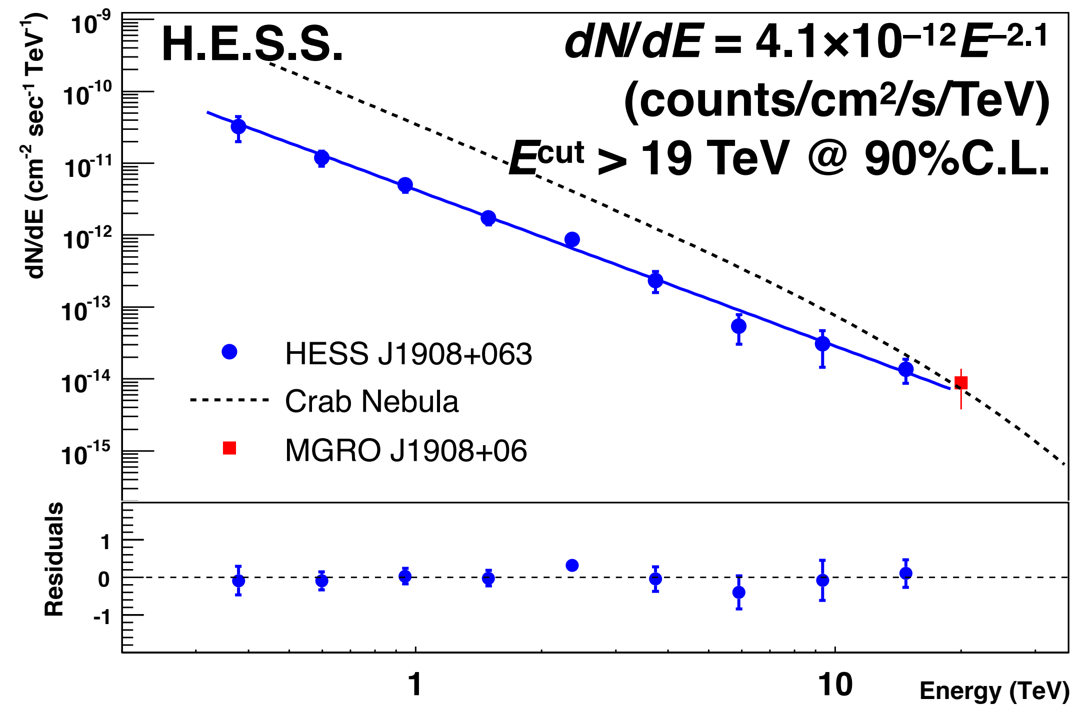
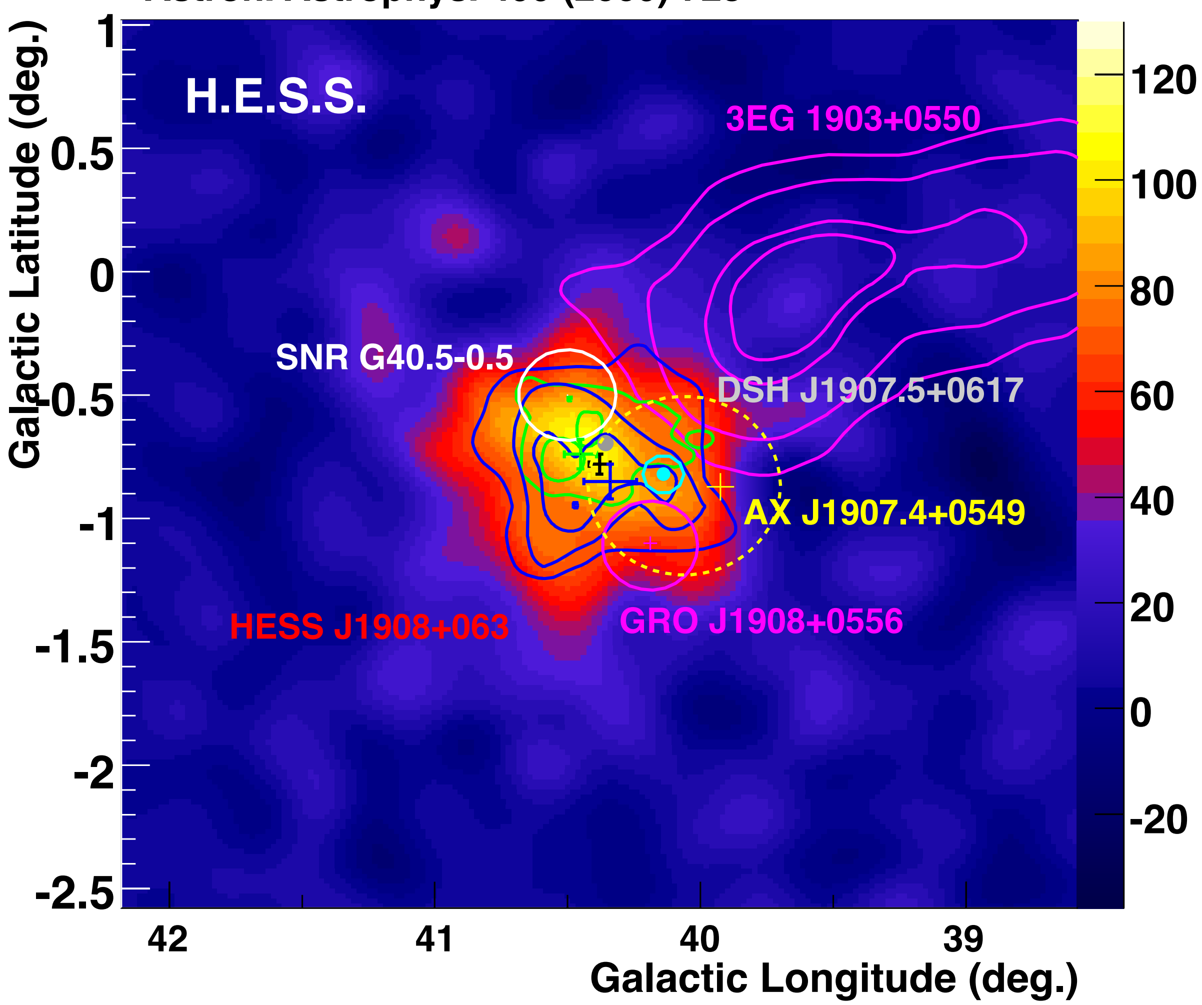


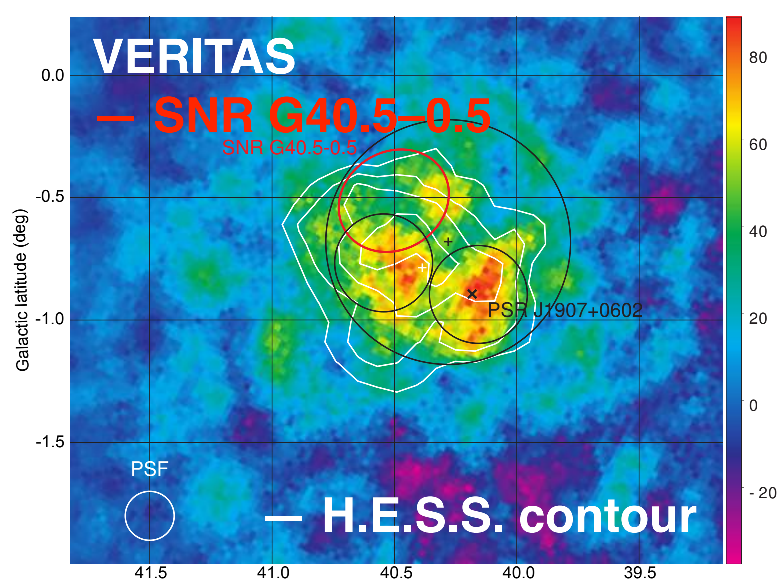
- MGRO J1908+06 is also observed by HAWC, H.E.S.S. and VERITAS
- No cutoff was observed up to ~20 TeV



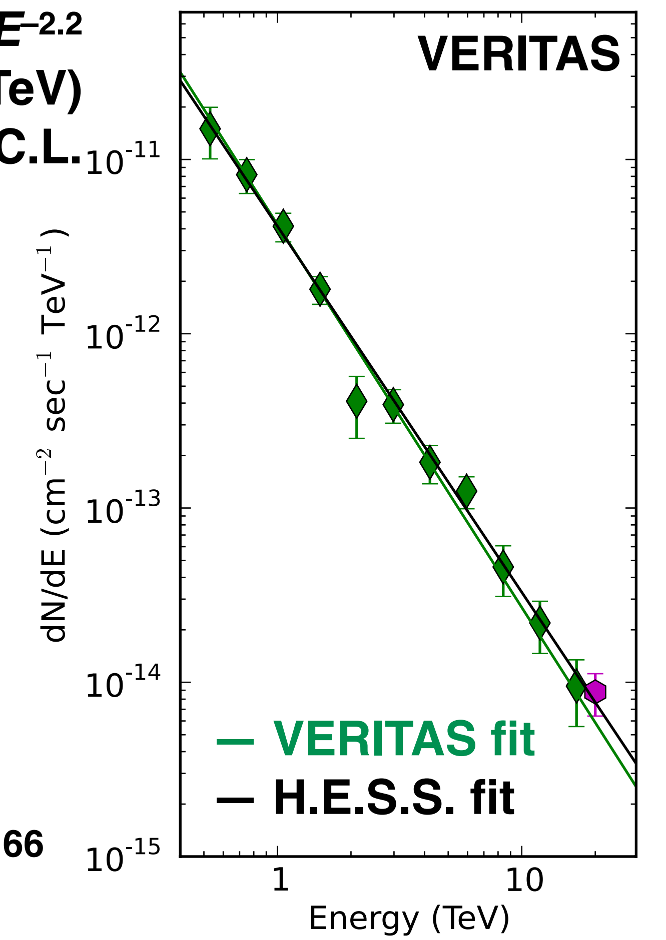
Astron. Astrophys. 499 (2009) 723



$dN/dE = 4.2\times10^{-12}E^{-2.2}$ (counts/cm²/s/TeV)
E_{cut} > 18 TeV @ 90%C.L.



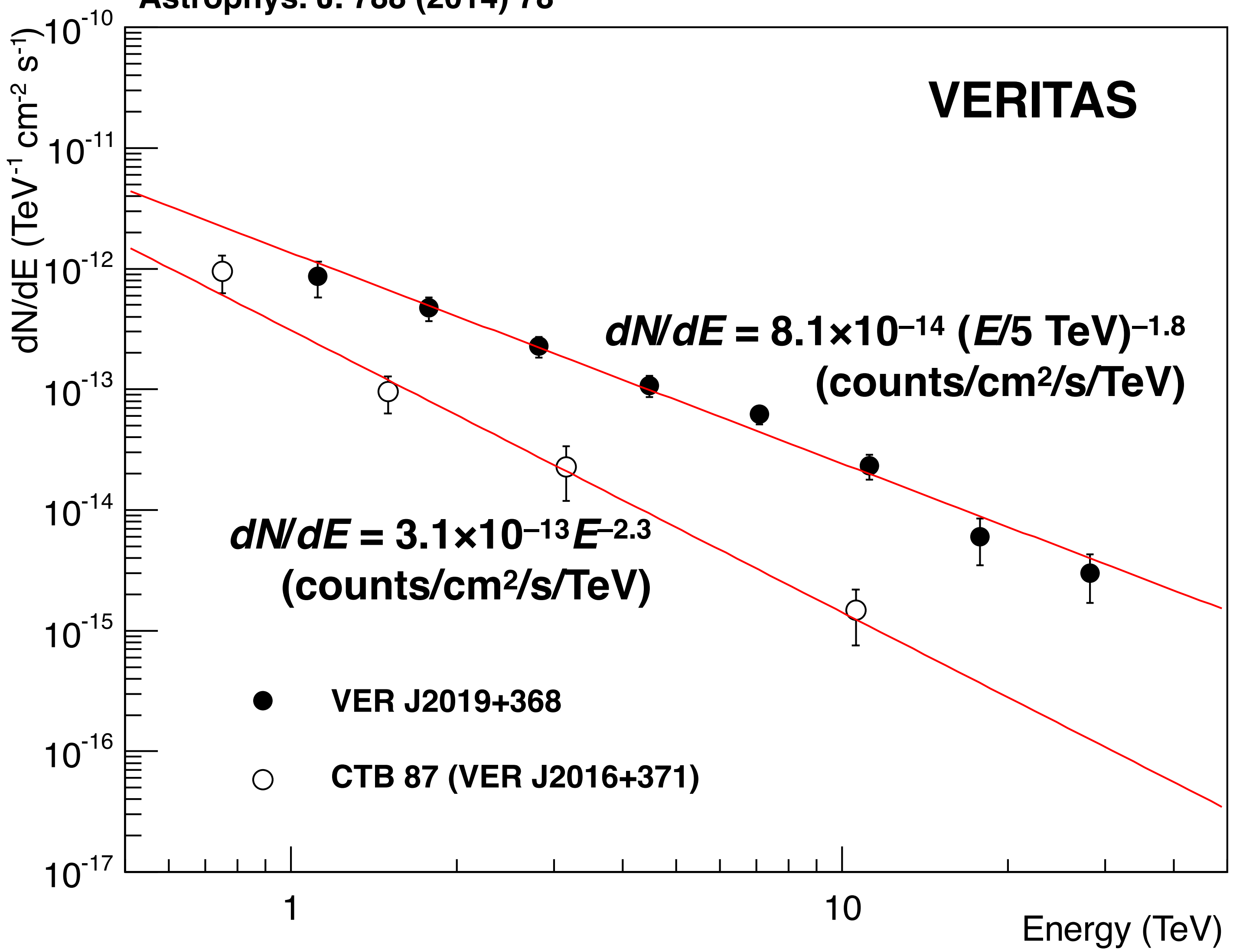
Astrophys. J. 787 (2014) 166

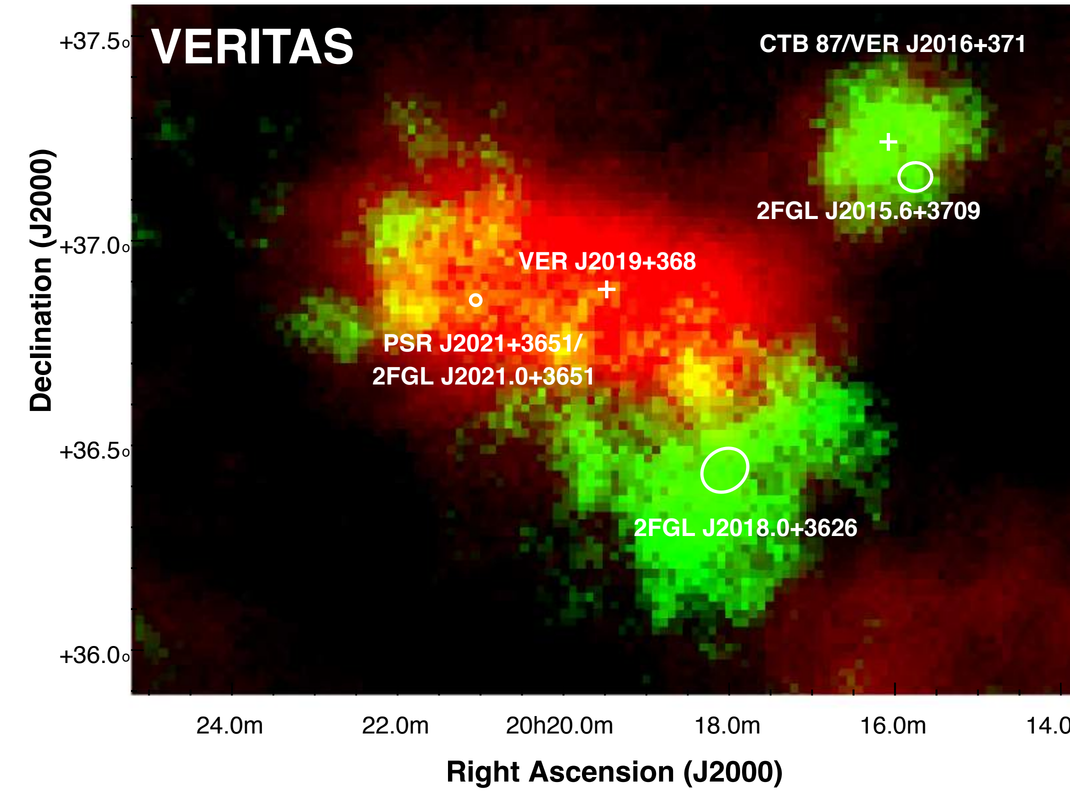


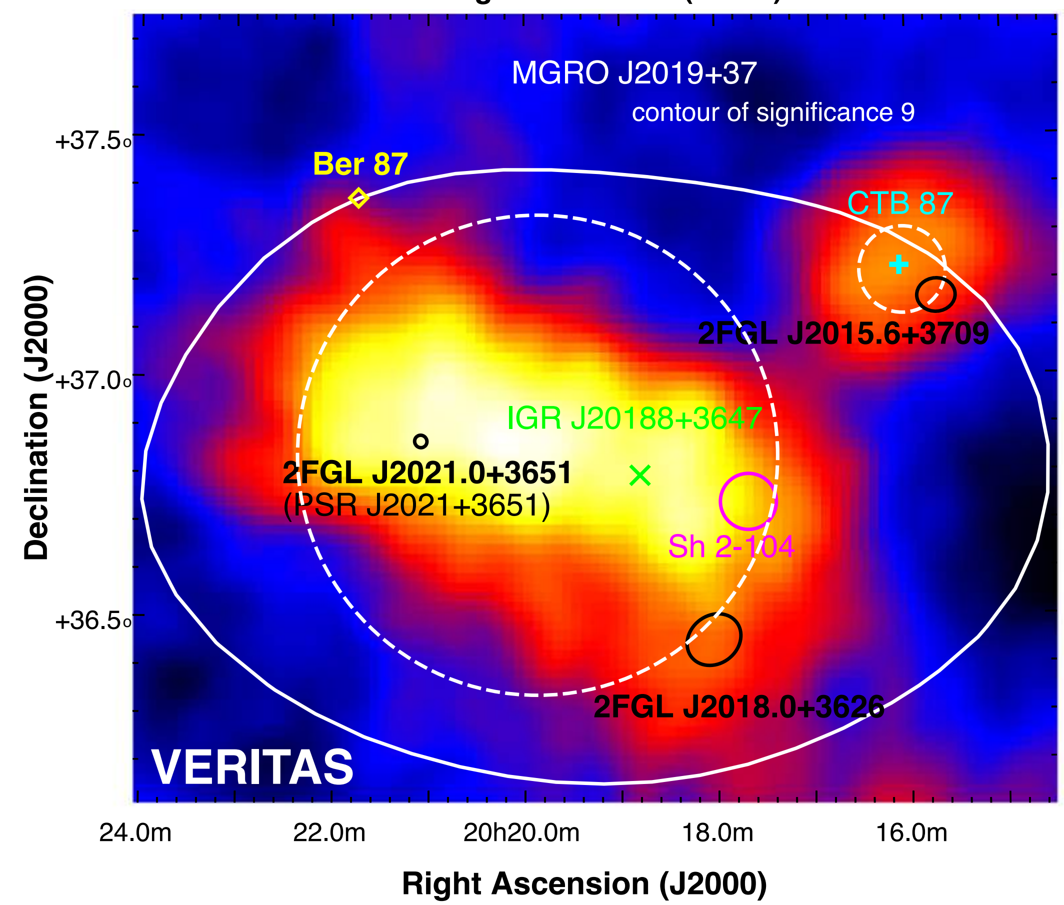
Gamma-ray Observations of MGRO J2019+37

- MGRO J2019+37 is also observed by HAWC and VERITAS
- VERITAS shows very hard spectrum up to 30 TeV

Astrophys. J. 788 (2014) 78







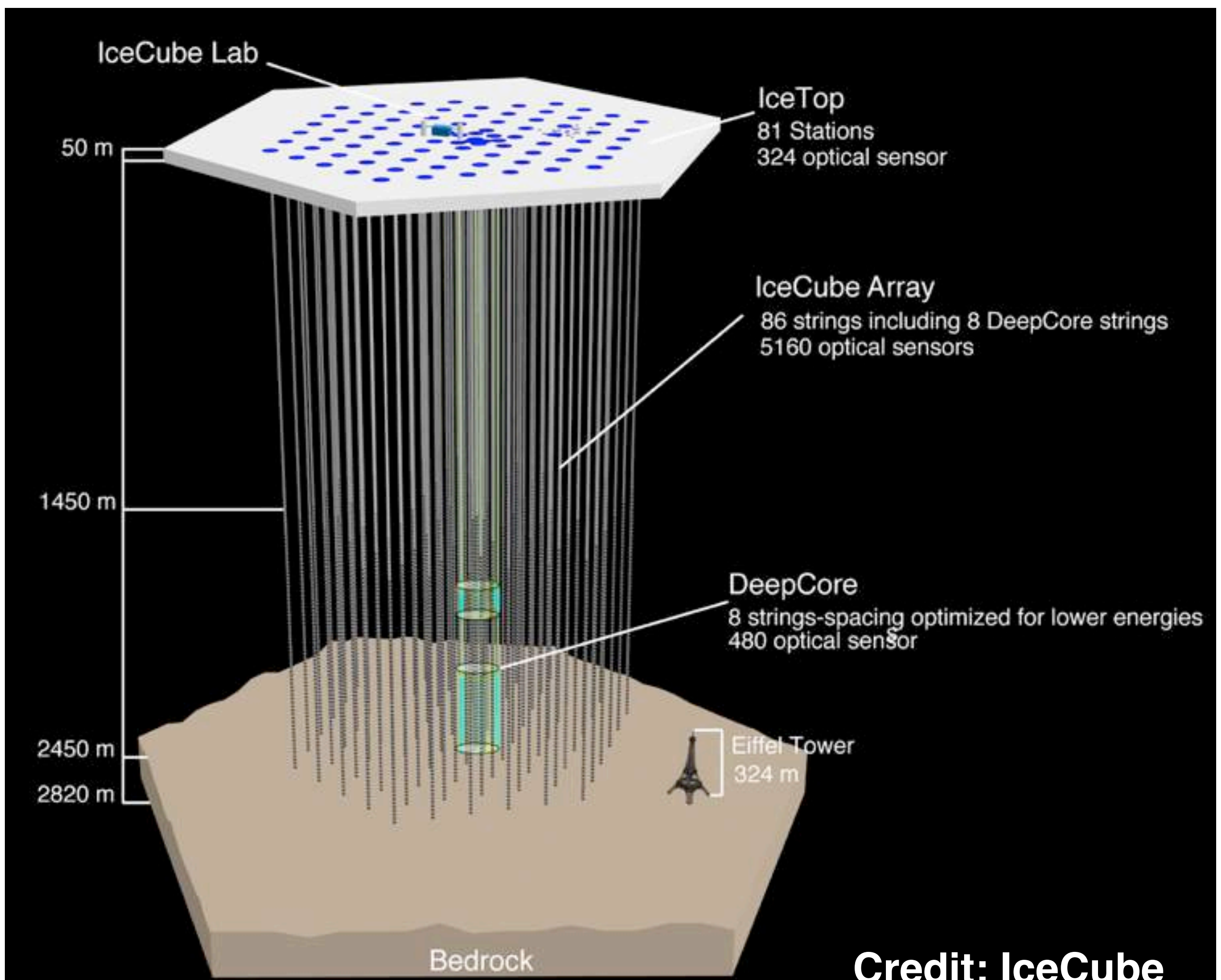
Summary

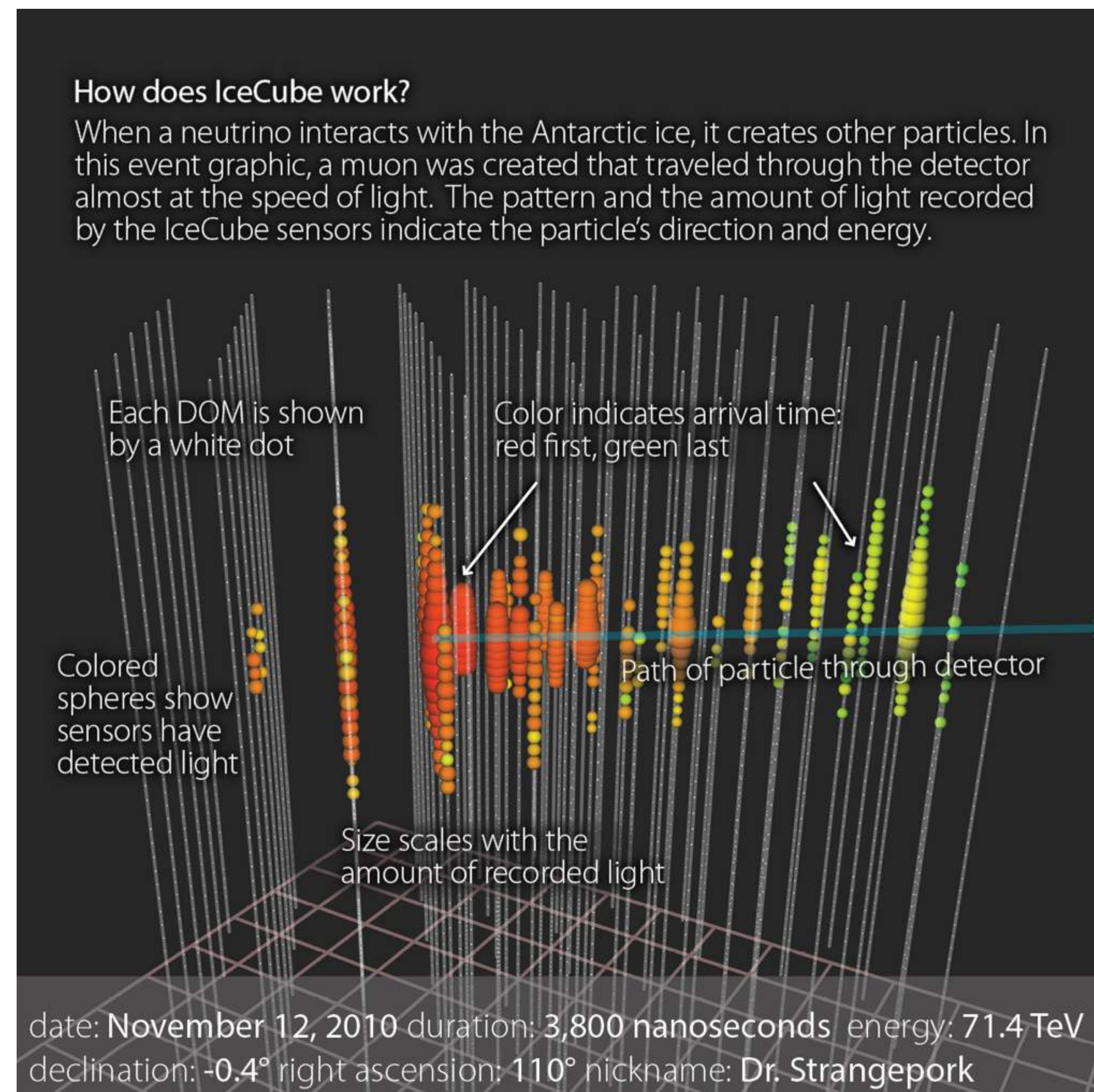
- Supernova remnants (SNRs) are the leading candidate for the origin of Galactic cosmic rays (PeVatron)
  - Fermi-LAT provided the first conclusive evidence that hadrons are accelerated in SNRs from the spectral features of W44 and IC 443
- SNRs are not proven to be PeVatrons yet
  - H.E.S.S. found two PeVatron candidates, one may be a supermassive blackhole, the other could be an SNR
  - Maximum energy could not be determined due to insufficient sensitivities at > 10 TeV
- CTA (SST) is expected to play critical roles to uncover the nature of those PeVatron candidates
- All sky survey instruments like Milagro, HAWC may be useful for finding more PeVatron candidates
  - Two Milagro sources are very promising according to follow-up observations by H.E.S.S. and VERITAS
  - IceCube may be also useful, but it will take 10–15 years to detect those sources

Supplemental Slides

IceCube Neutrino Observatory

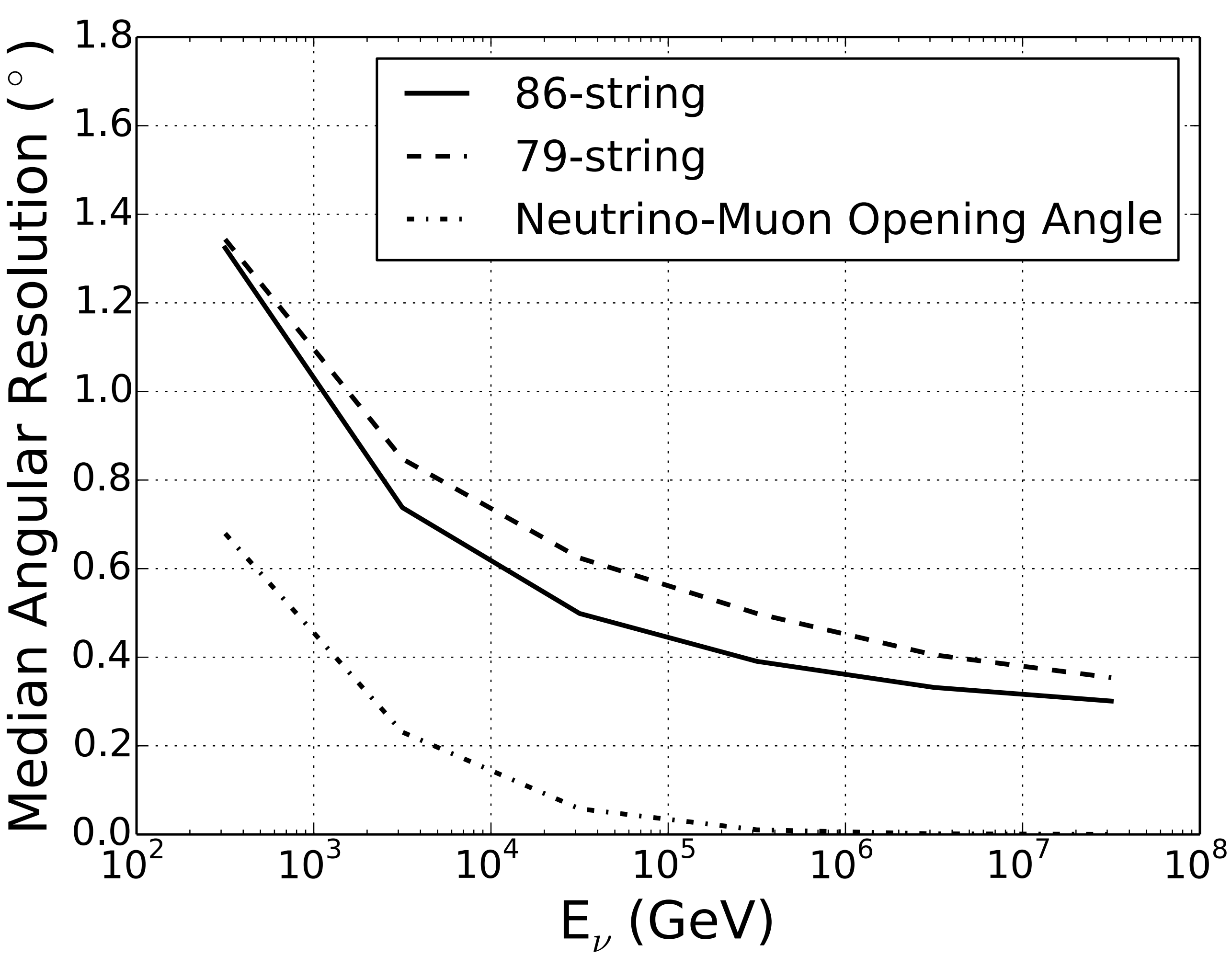
- Neutrinos are produced only by hadronic interactions
- Detect Cherenkov light produced in ice by secondary particles from UHE neutrino interactions
  - Massive instrumented volume of ~1 km^3
  - 86 strings of 60 Optical Modules spaced by 17 m.



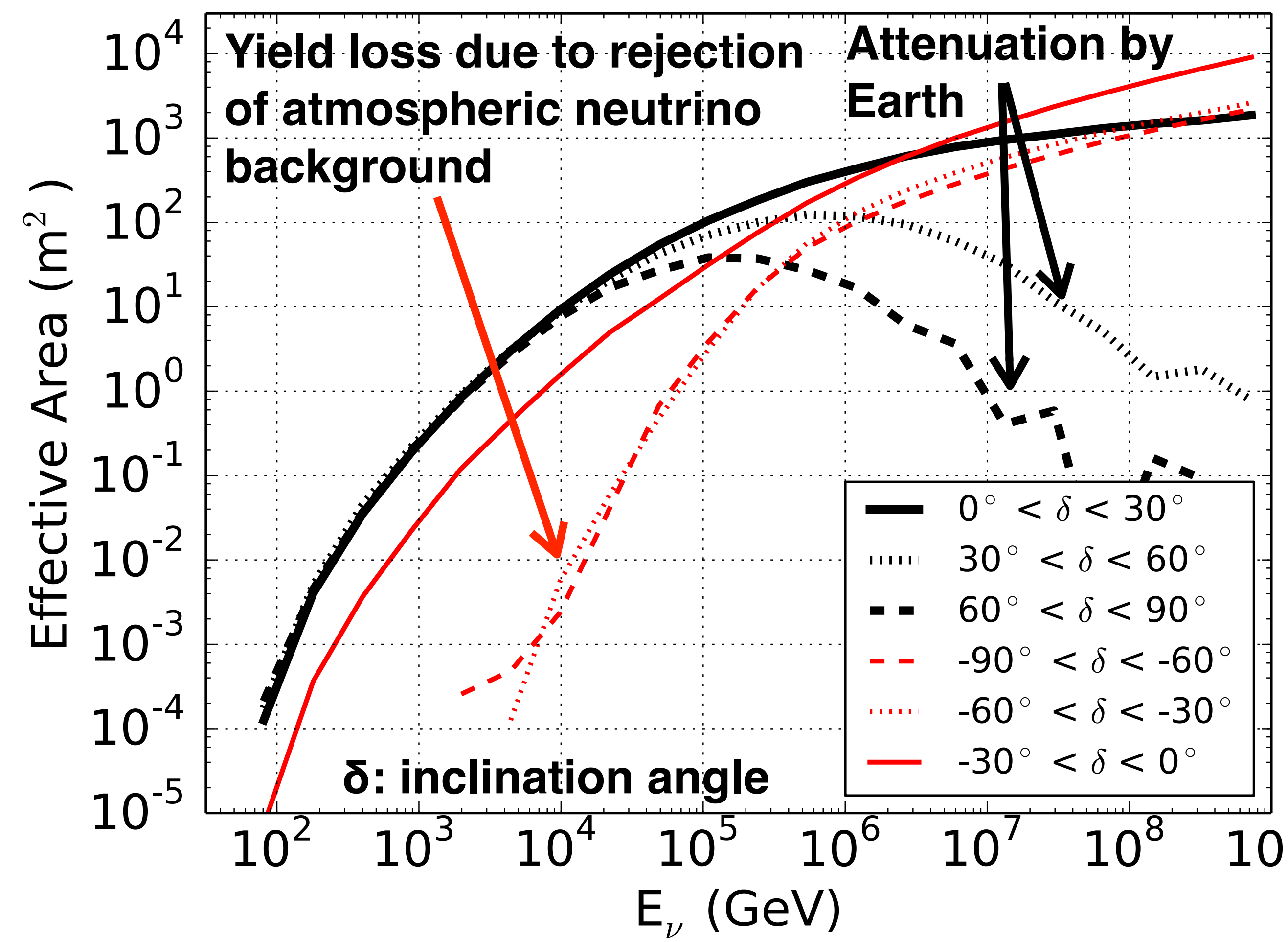


Expected Performance

- Effective area > 1000 m³ for E>100 TeV.
  - Low effective area for downward-going neutrino (southern sky) in TeV due to tight background rejection criteria for atmospheric neutrino
- Angular resolution better than 1° for E>1 TeV.



ArXiv: 1406.6757



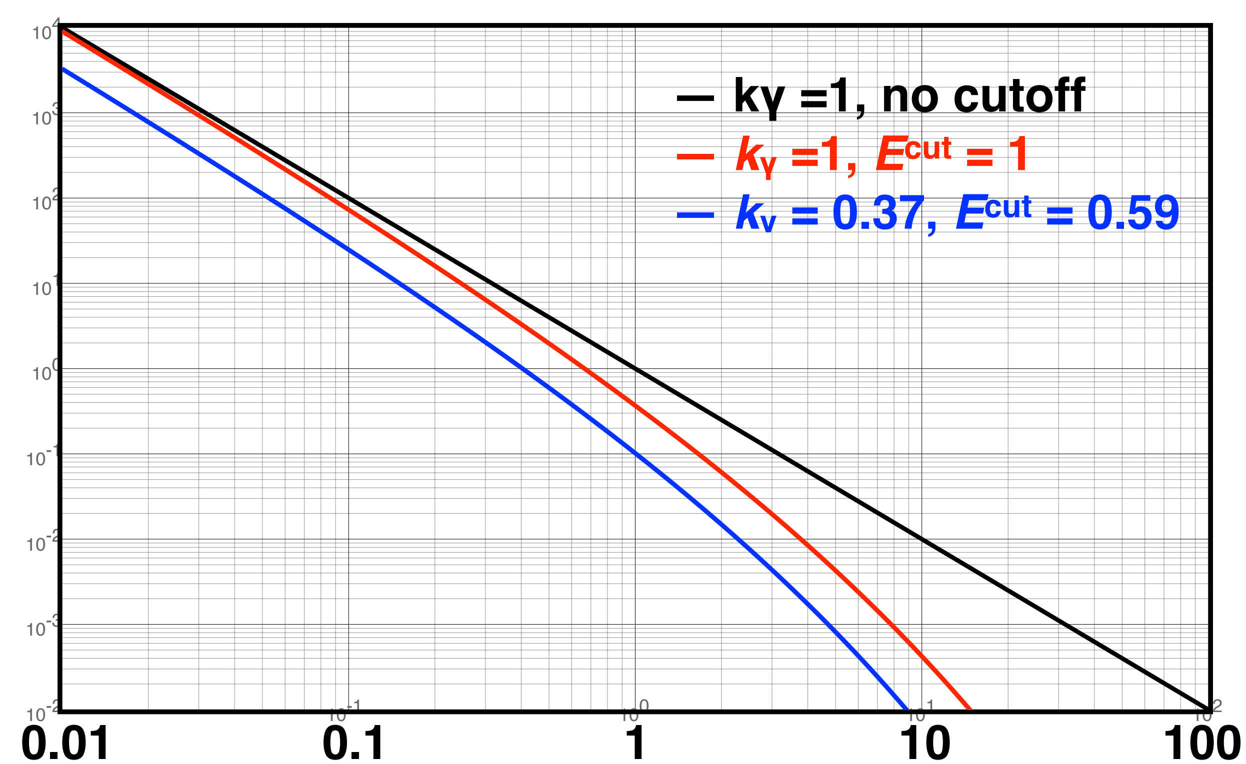
Neutrino and Gamma-ray Spectrum

- **Almost same numbers of muon neutrinos and gamma rays are produced by cosmic-ray interactions with interstellar gas**

$$p + p \to m\pi^{\pm} + n\pi^0 + X \ (m : n \approx 1 : 1)$$
$$\pi^0 \to 2\gamma$$
$$\pi^+ \to \mu^+ + \nu_\mu, \ \mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$

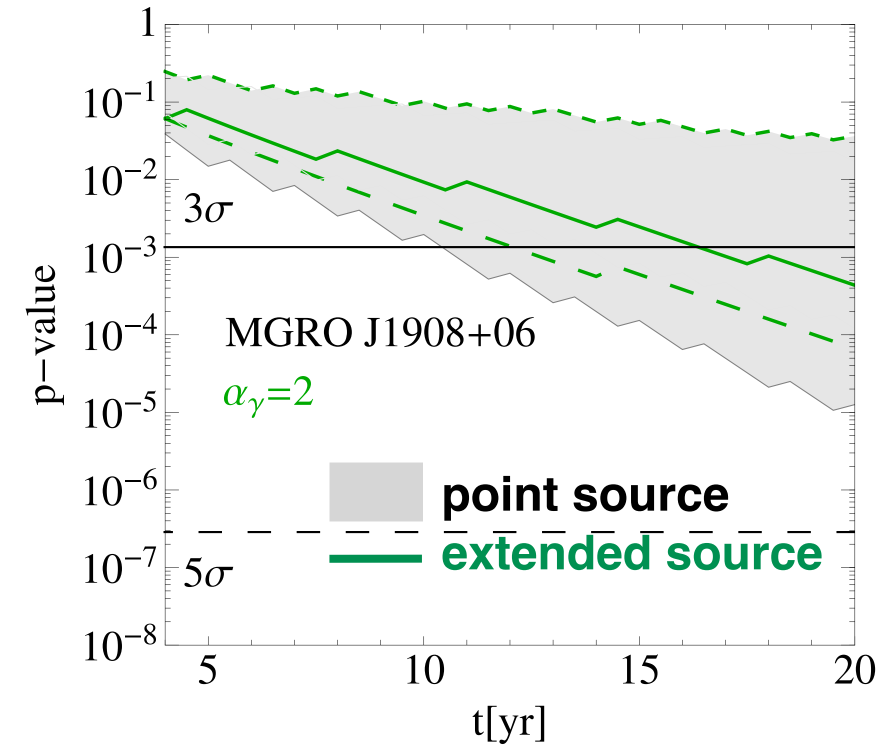
- **Neutrino spectrum can be related with gamma-ray spectrum**

$$\frac{dN_\gamma(E_\gamma)}{dE_\gamma} = k_\gamma \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{-\alpha_\gamma} \exp\left(-\sqrt{\frac{E_\gamma}{E_\gamma^{\mathrm{cut}}}}\right),$$
$$\frac{dN_{\nu_\mu+\overline{\nu}_\mu}(E_\nu)}{dE_\nu} = k_\nu \left(\frac{E_\nu}{\mathrm{TeV}}\right)^{-\alpha_\nu} \exp\left(-\sqrt{\frac{E_\nu}{E_\nu^{\mathrm{cut}}}}\right),$$
$$k_\nu = (0.694 - 0.16\alpha_\gamma)k_\gamma,$$
$$\alpha_\nu \approx \alpha_\gamma,$$
$$E_\nu^{\mathrm{cut}} = 0.59 E_\gamma^{\mathrm{cut}}$$



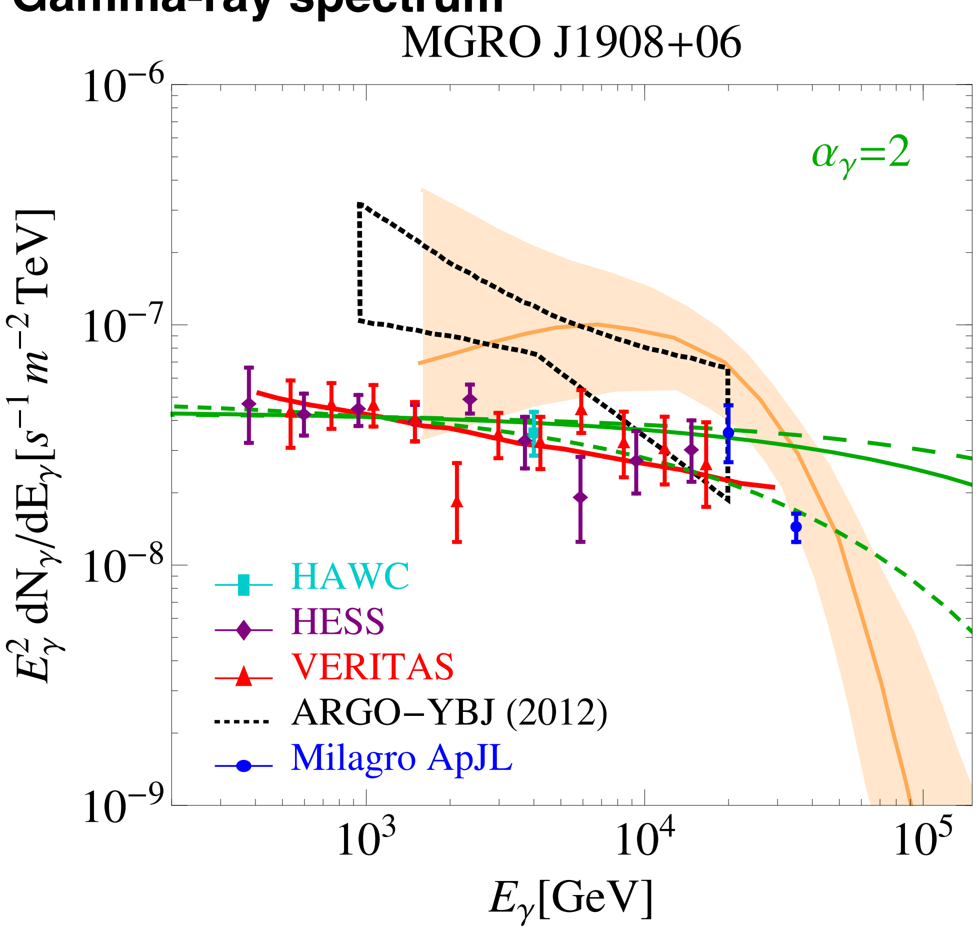
IceCube Sensitivity for MGRO J1908+06

- It will take more than 10 years of IceCube observations unless the source is very hard
  - Assuming α ≈ 2 is already optimistic compared with H.E.S.S. or VERITAS measurements



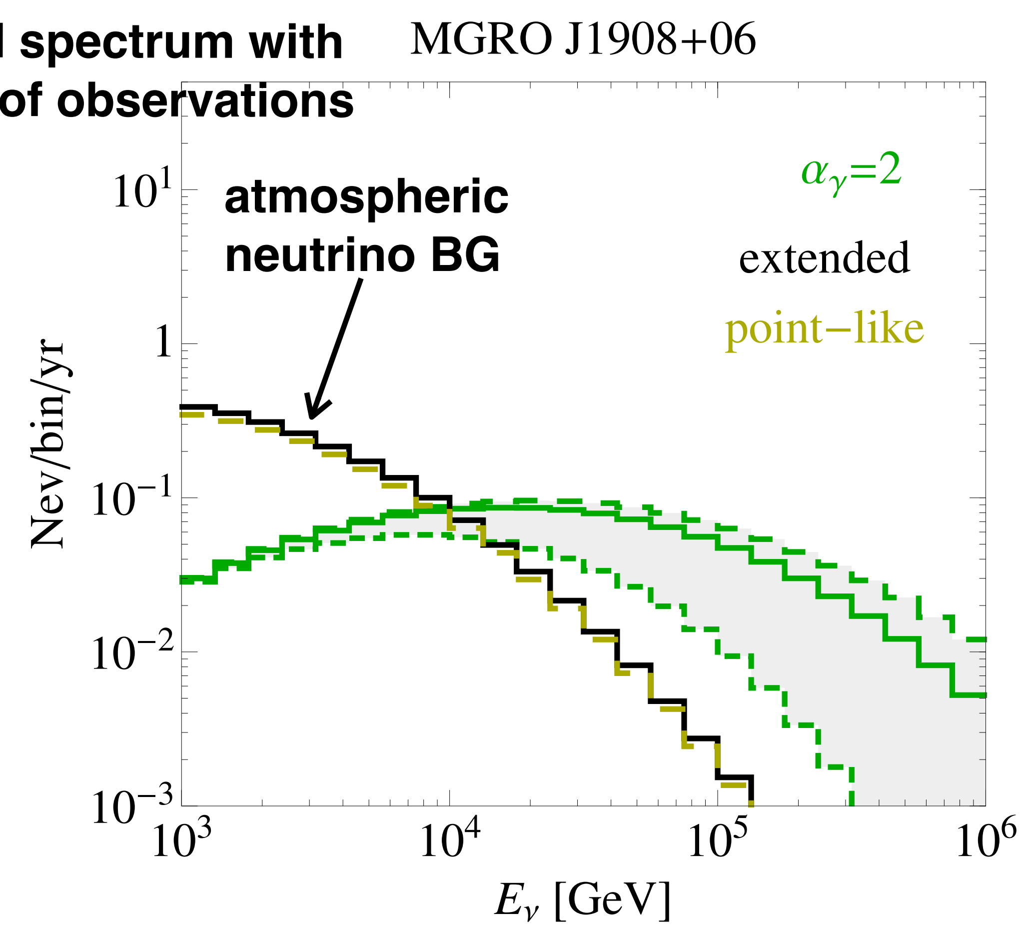
Astroparticle Physics, 86 (2017) 46-56

Gamma-ray spectrum



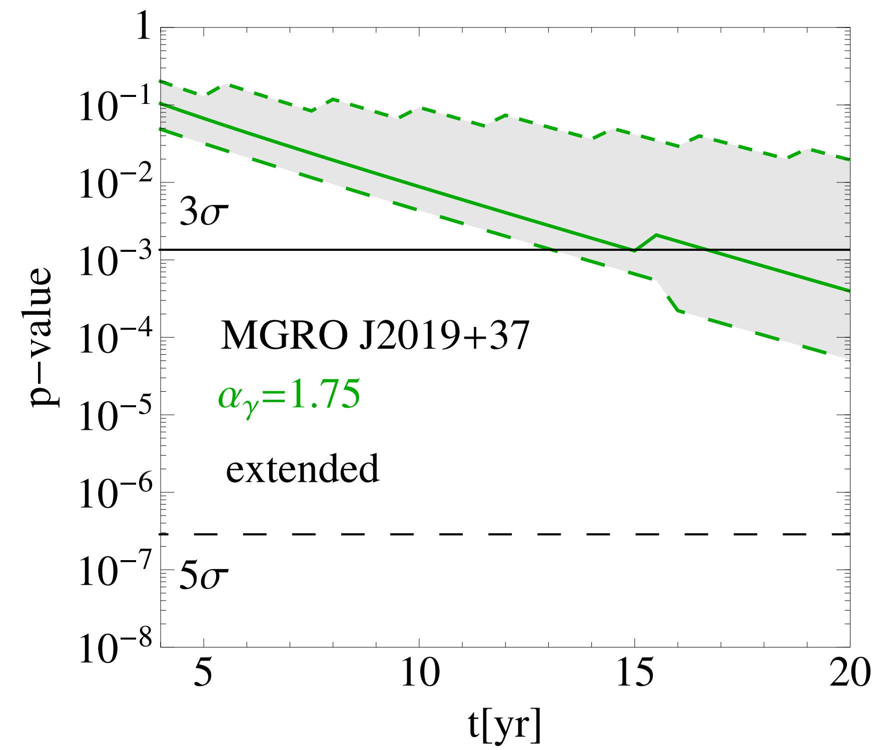
E_{cut} = 30 TeV
E_{cut} = 300 TeV
E_{cut} = 800 TeV

Expected spectrum with 15 years of observations

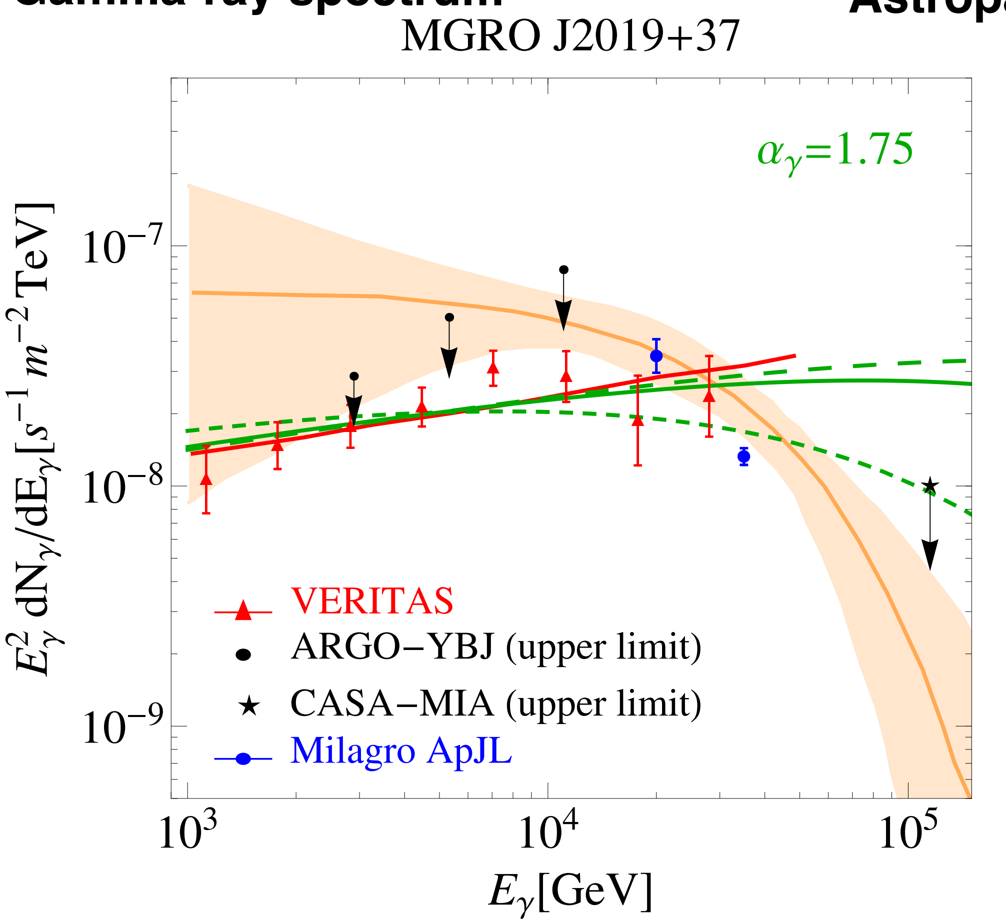


IceCube Sensitivity for MGRO J2019+37

- It will take more than 15 years of IceCube observations even though the source is hard
  - Inclination angle is not favorable for IceCube



Gamma-ray spectrum



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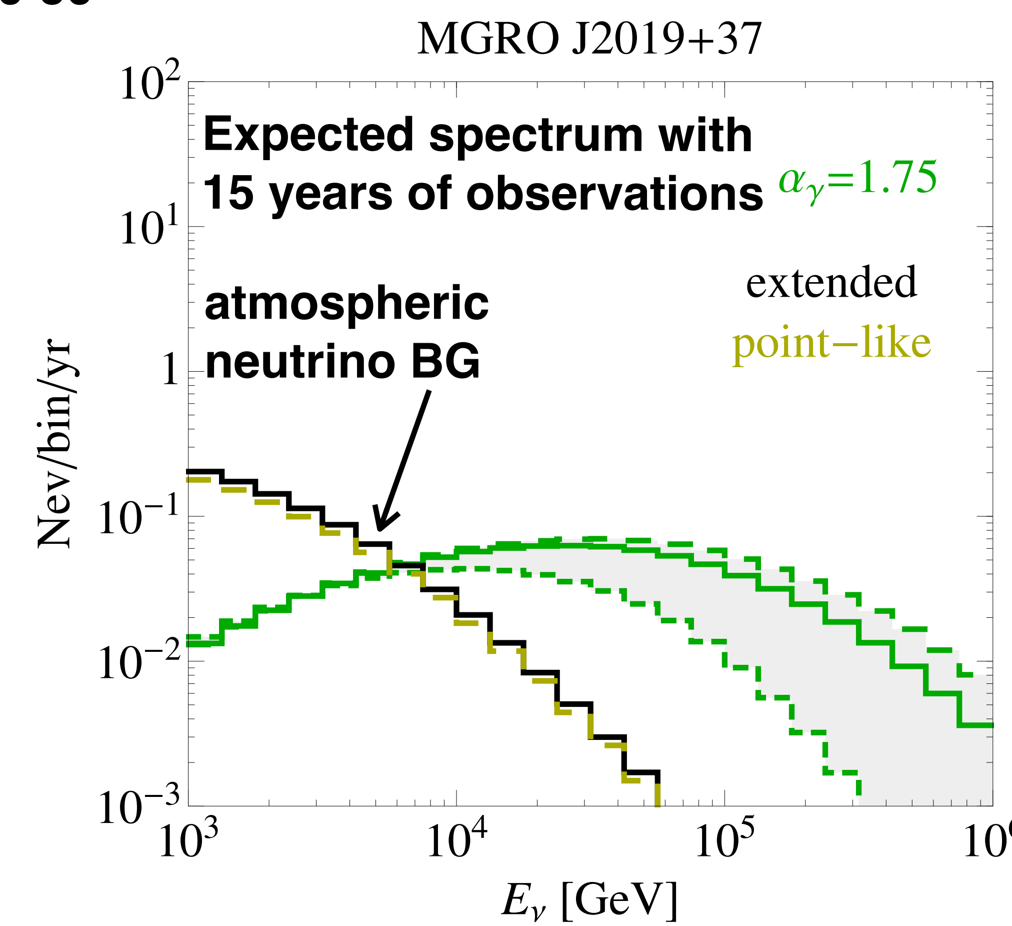
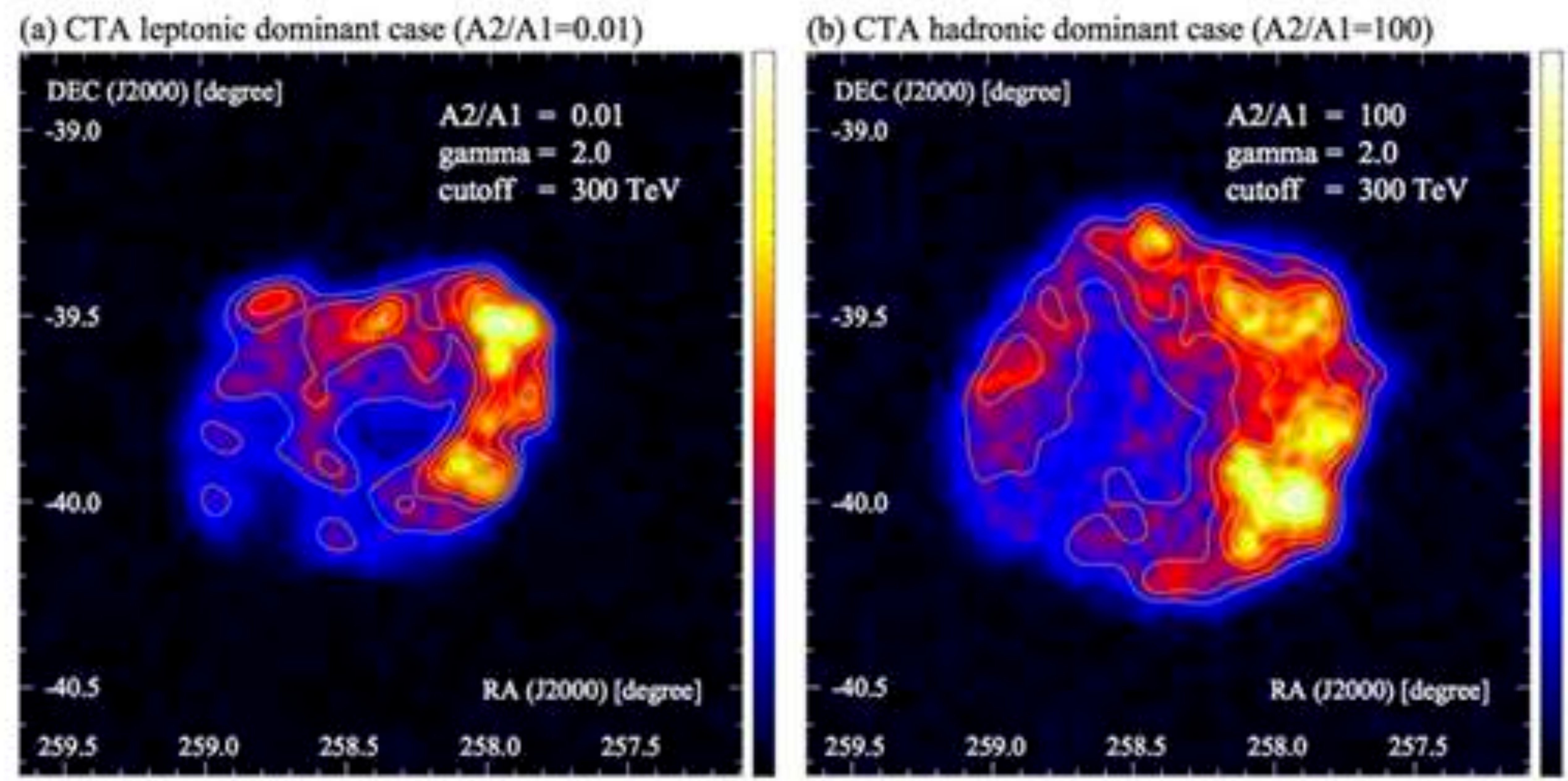


CTA Sites

CTA collaboration

CTA Imaging Performance

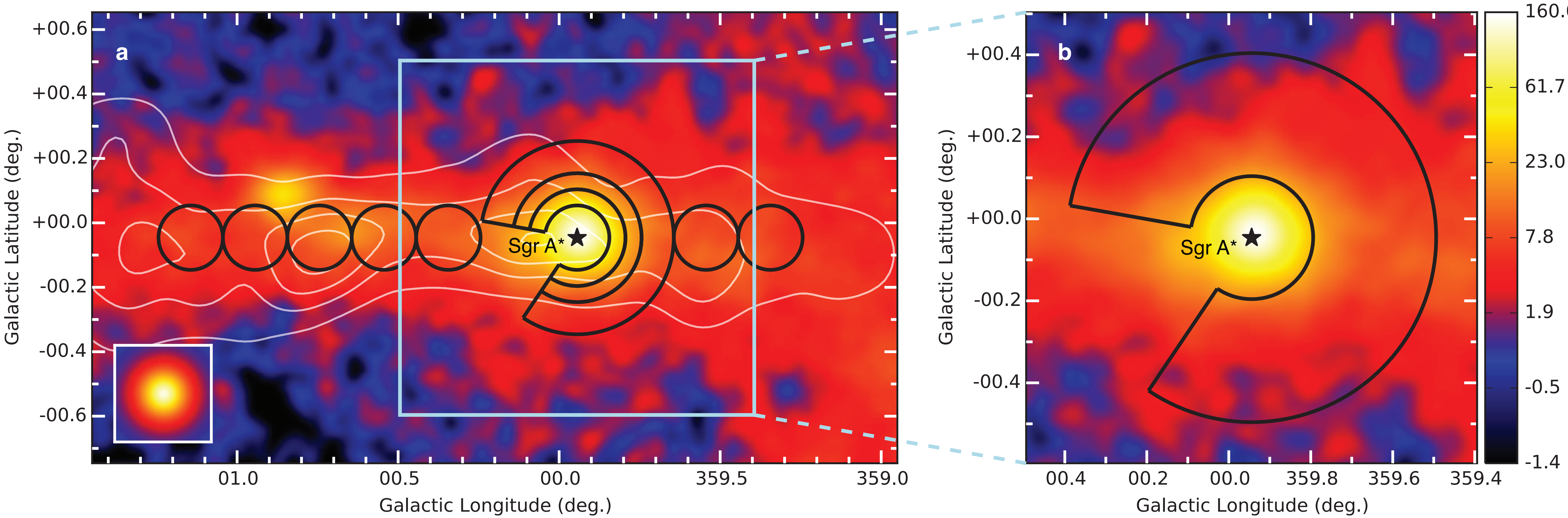
- CTA will provide better imaging of TeV gamma-ray sources



Diffuse Gamma Ray in Galactic Center

- H.E.S.S. observations of diffuse gamma-ray emission in the Galactic center region indicate a strong CR proton source
  - Diffuse gamma-ray emission correlate with interstellar matter
    - TeV electrons cannot propagate long distance
  - CR density shows $1/r$ dependence
    - Implies continuous ($>10^4$ years) injection and diffusive propagation
    - Homogeneous: impulsive injection
    - $1/r^2$: wind driven

doi:10.1038/nature17147



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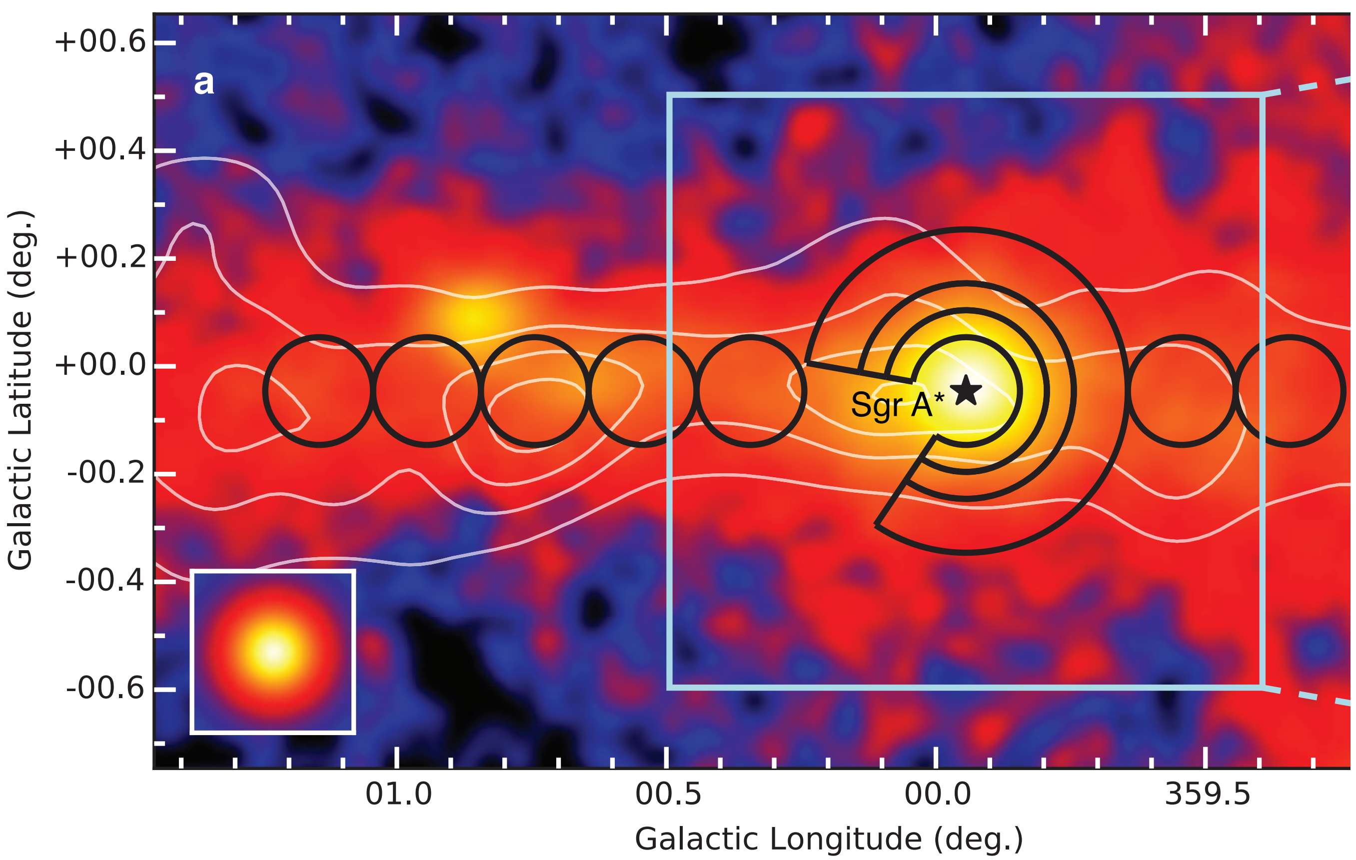

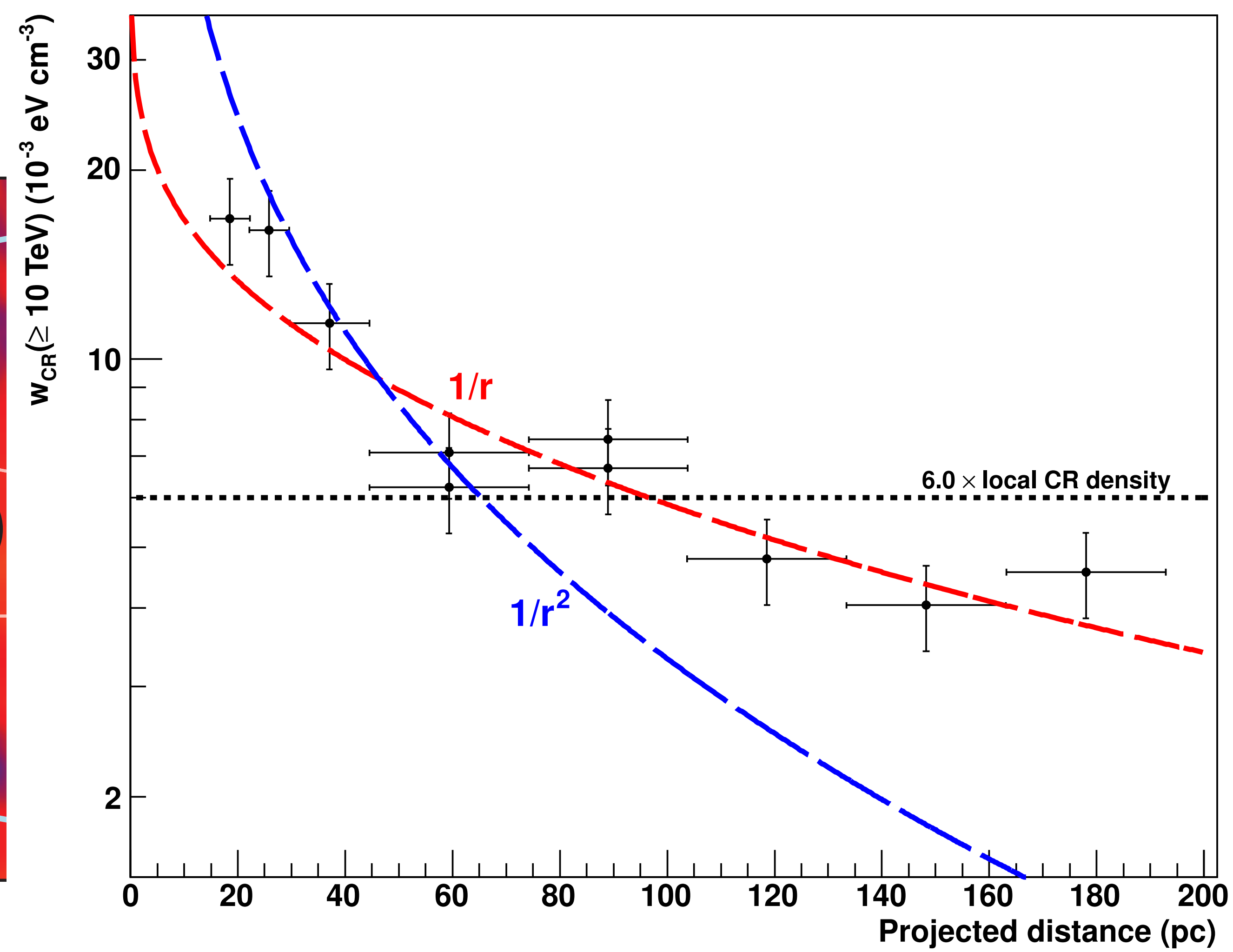

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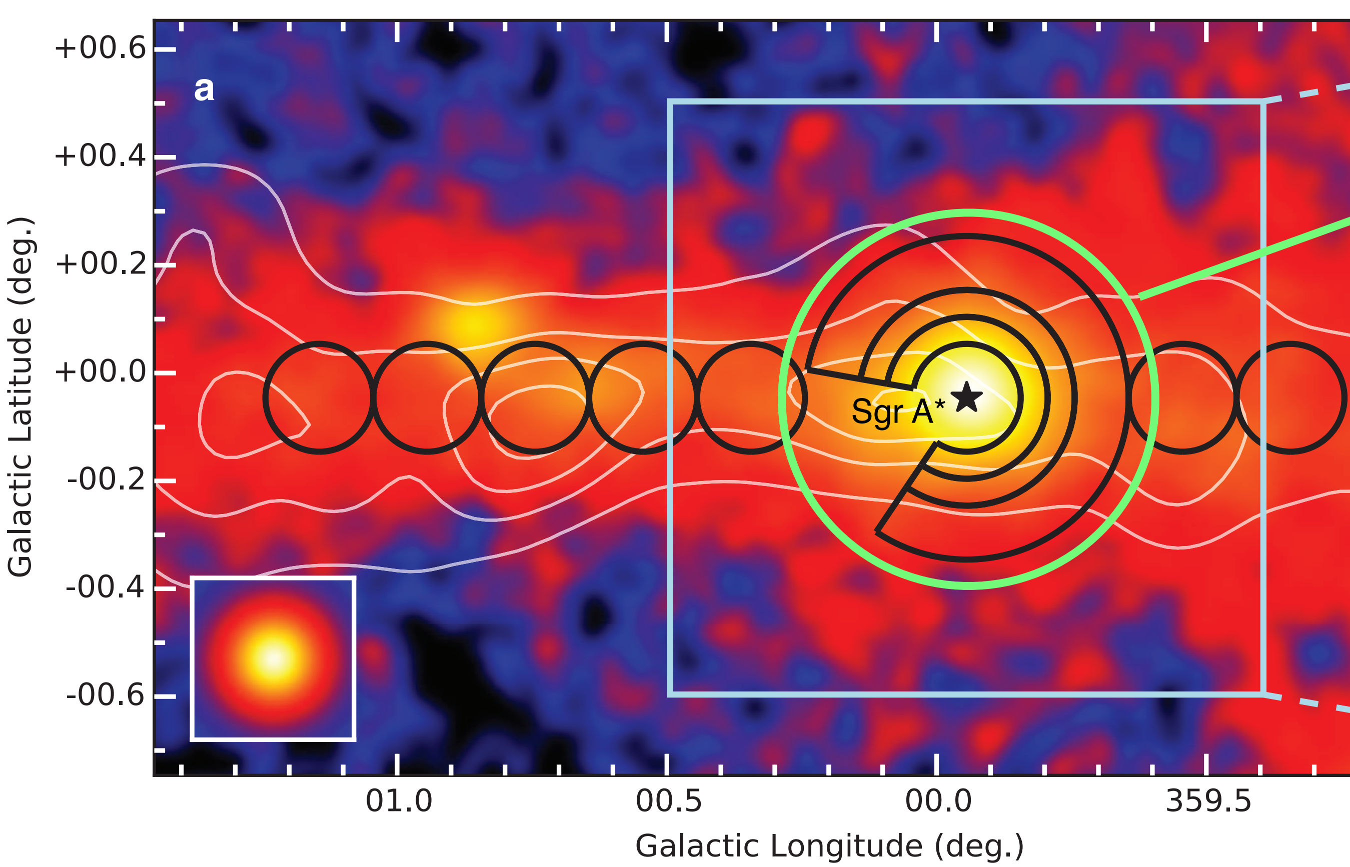

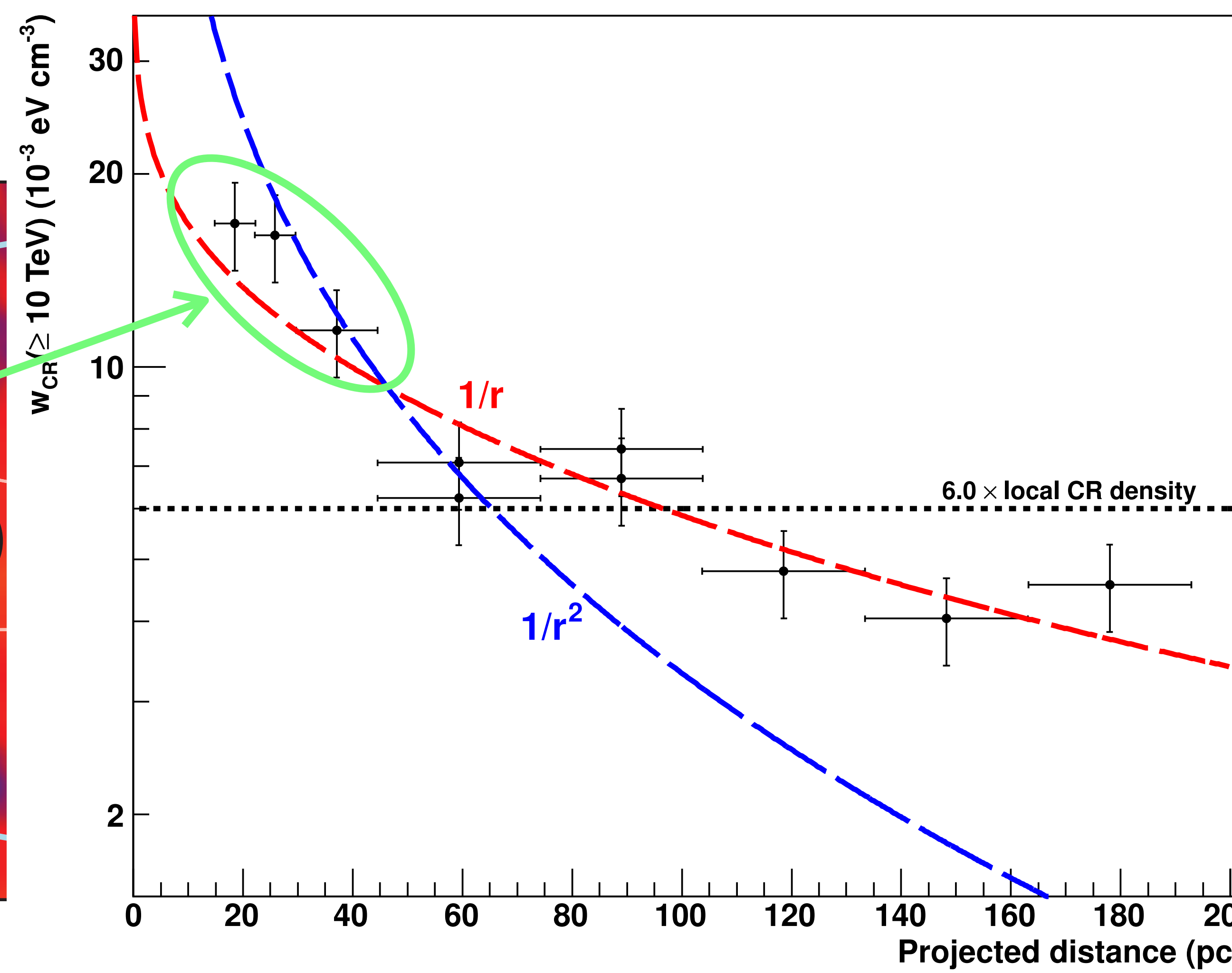

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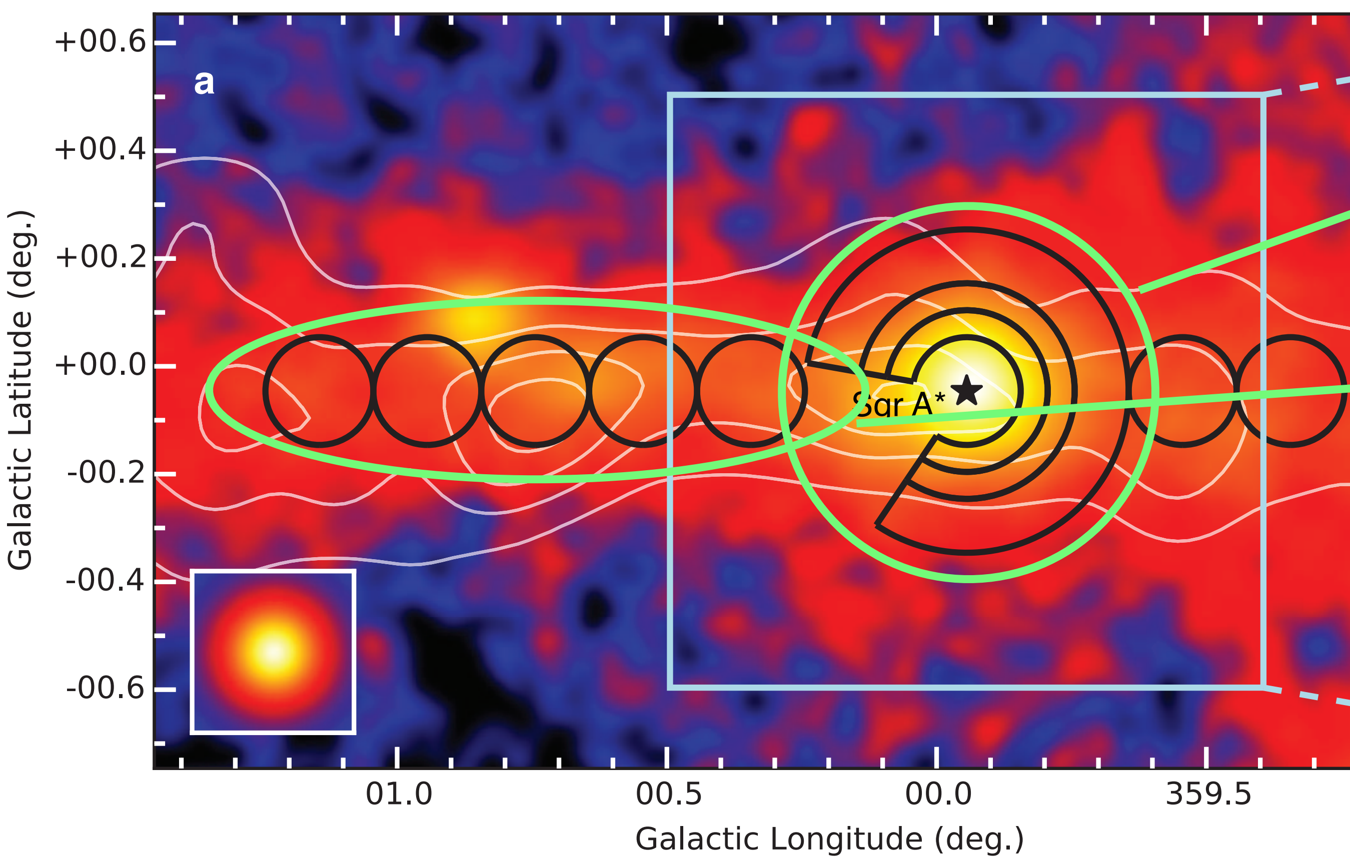
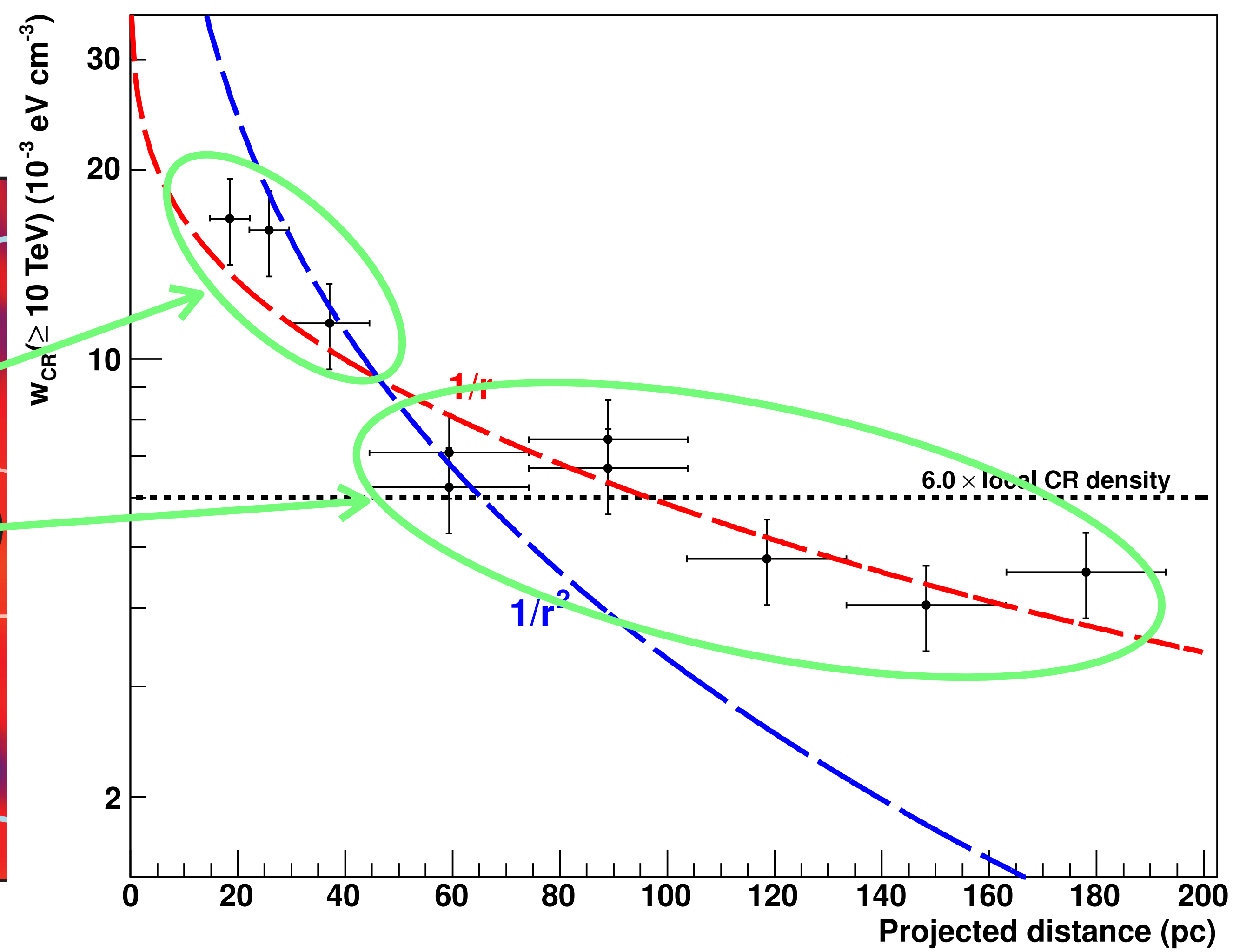
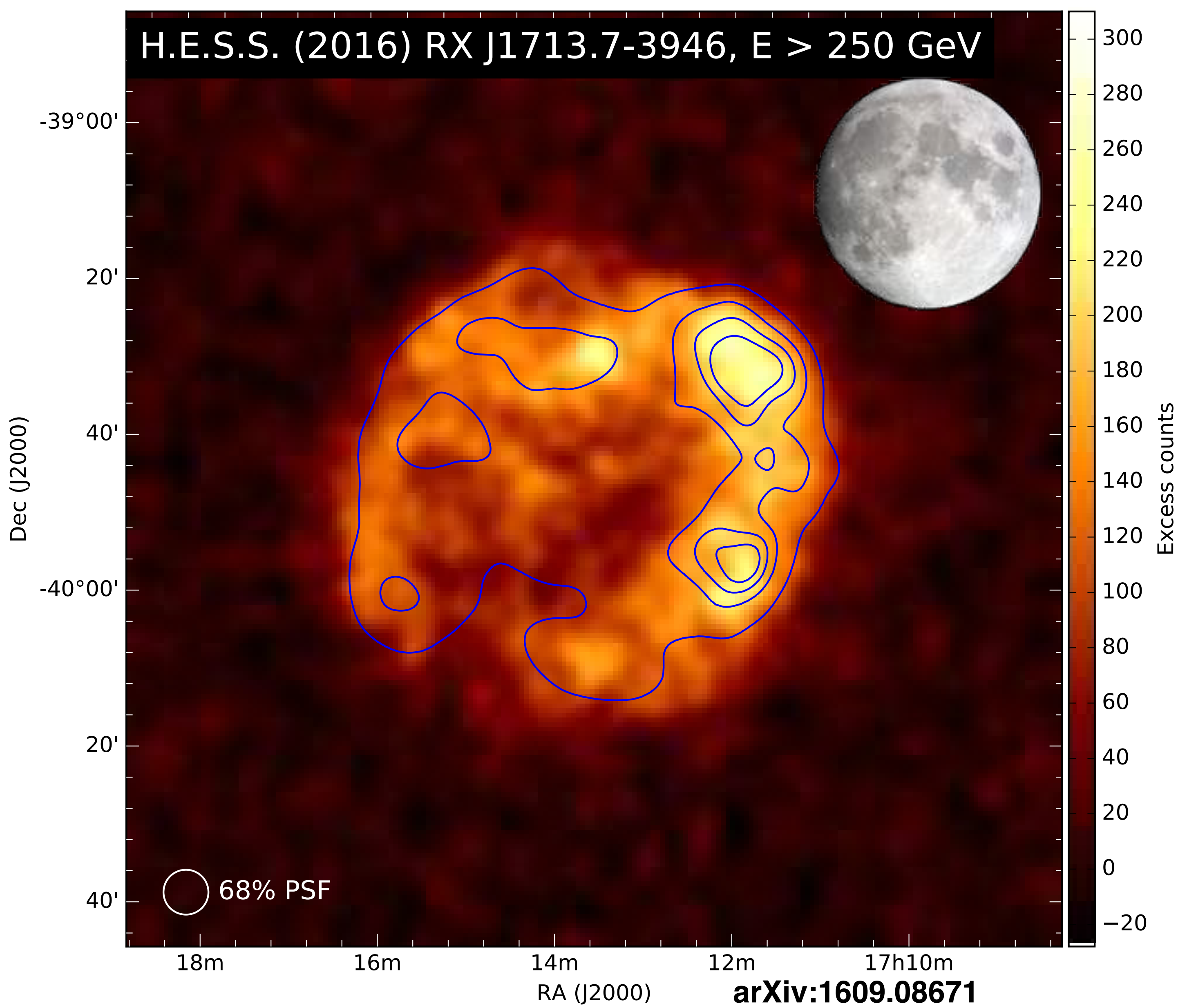




TeV Gamma Ray from SNR

- H.E.S.S. observation of TeV gamma rays from RX J1713.7-3946
  - Evidence for "particle" acceleration > 10^{14} eV
  - Spectral feature can not conclusively distinguish leptonic or hadronic origin of gamma rays even with wide band observations



arXiv:1609.08671

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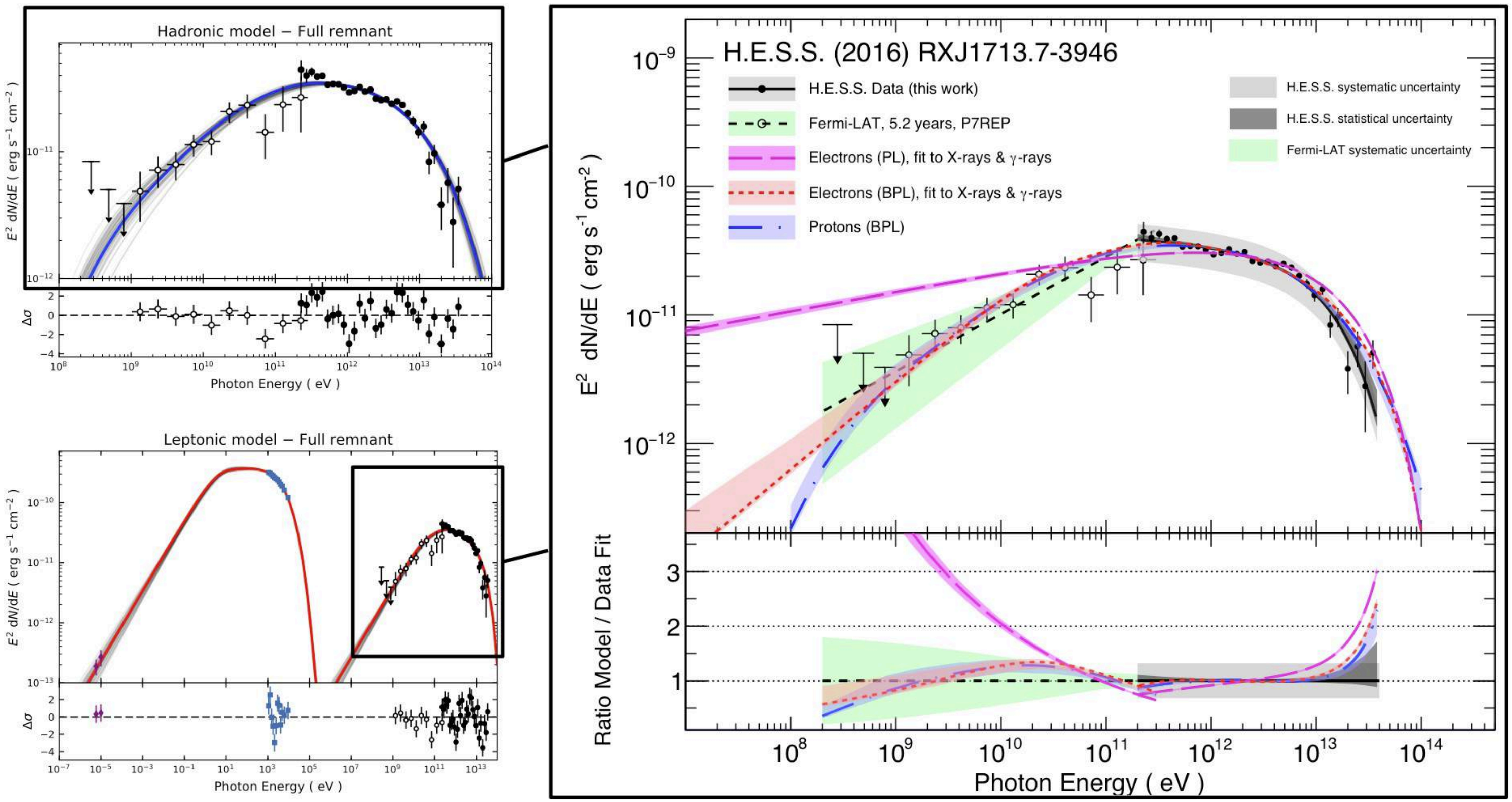

arXiv:1609.08671