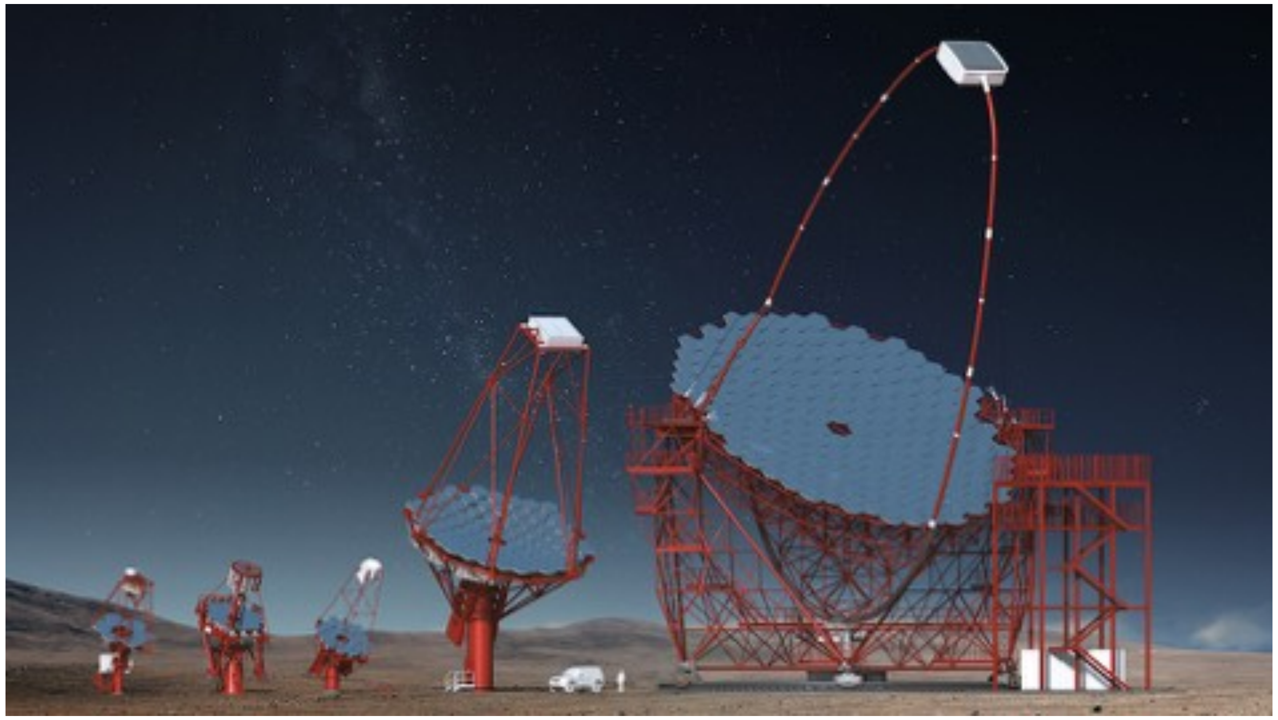
Quest for the Origin of Cosmic Rays with Gamma-Ray Observations

Hiroyasu Tajima
Institute for Space-Earth Environmental Research,
Nagoya University

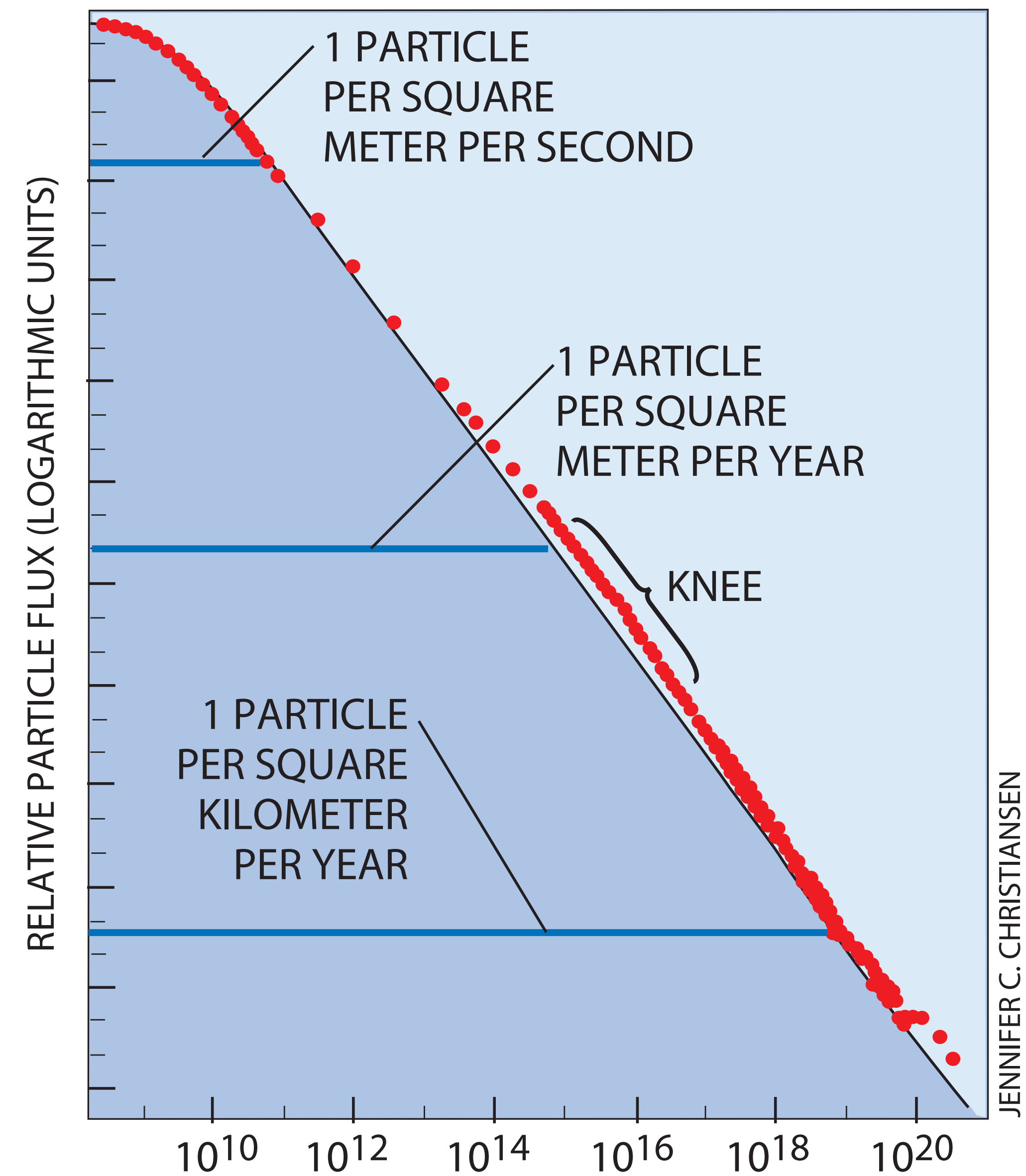

G. Pérez, IAC, SMM

January 5–7, 2017
The 3rd International Symposium
on "Quest for the Origin of Particles and the Universe"
Nagoya University, Japan

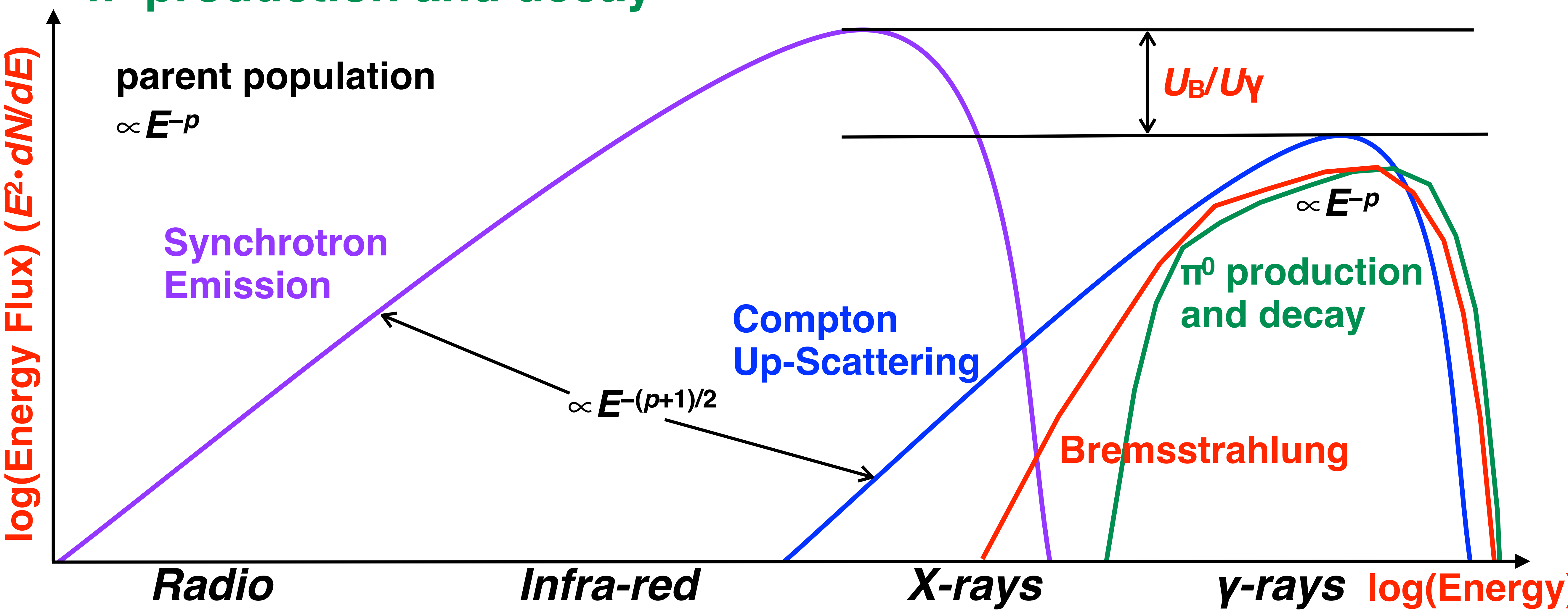
Cosmic-Ray (CR) Accelerators

- 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

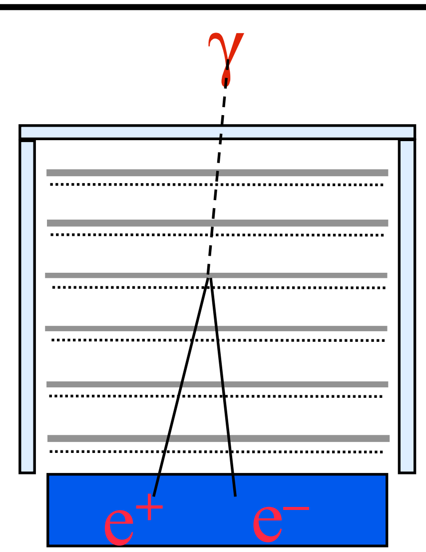


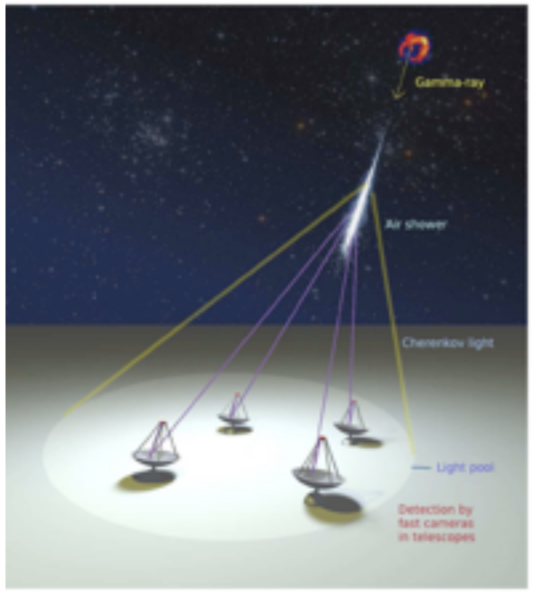
- Electron origins
  - Synchrotron radiation
  - Compton up-scattering (Inverse Compton)
  - Bremsstrahlung
- Hadron origins
  - π^0 production and decay



Gamma-ray Instruments

	Satellite based pair conversion telescope	Air shower array	Atmospheric Cherenkov telescope
Experiments	EGRET, Fermi	Milagro, HAWC	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%

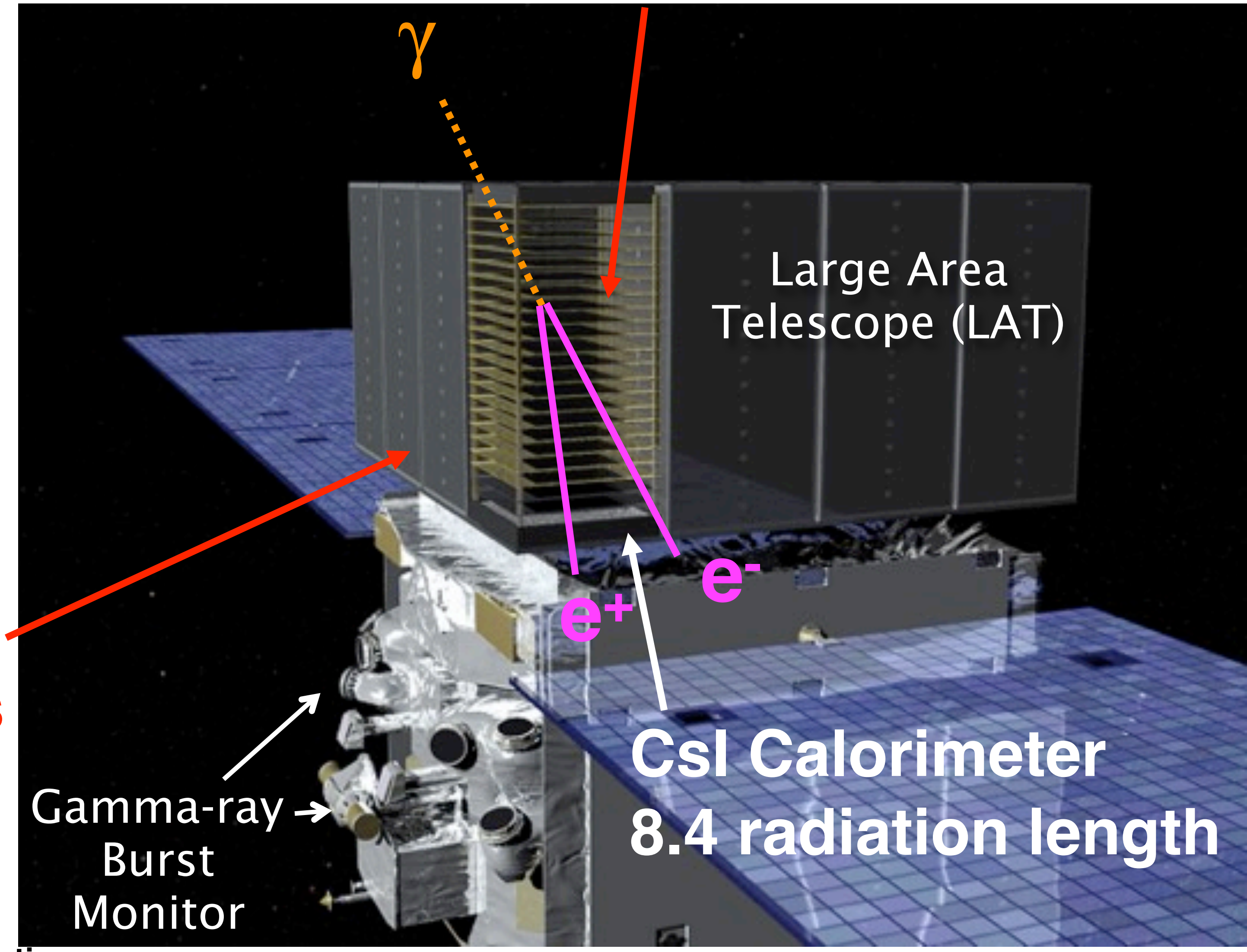




Pair–Conversion telescope

- **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

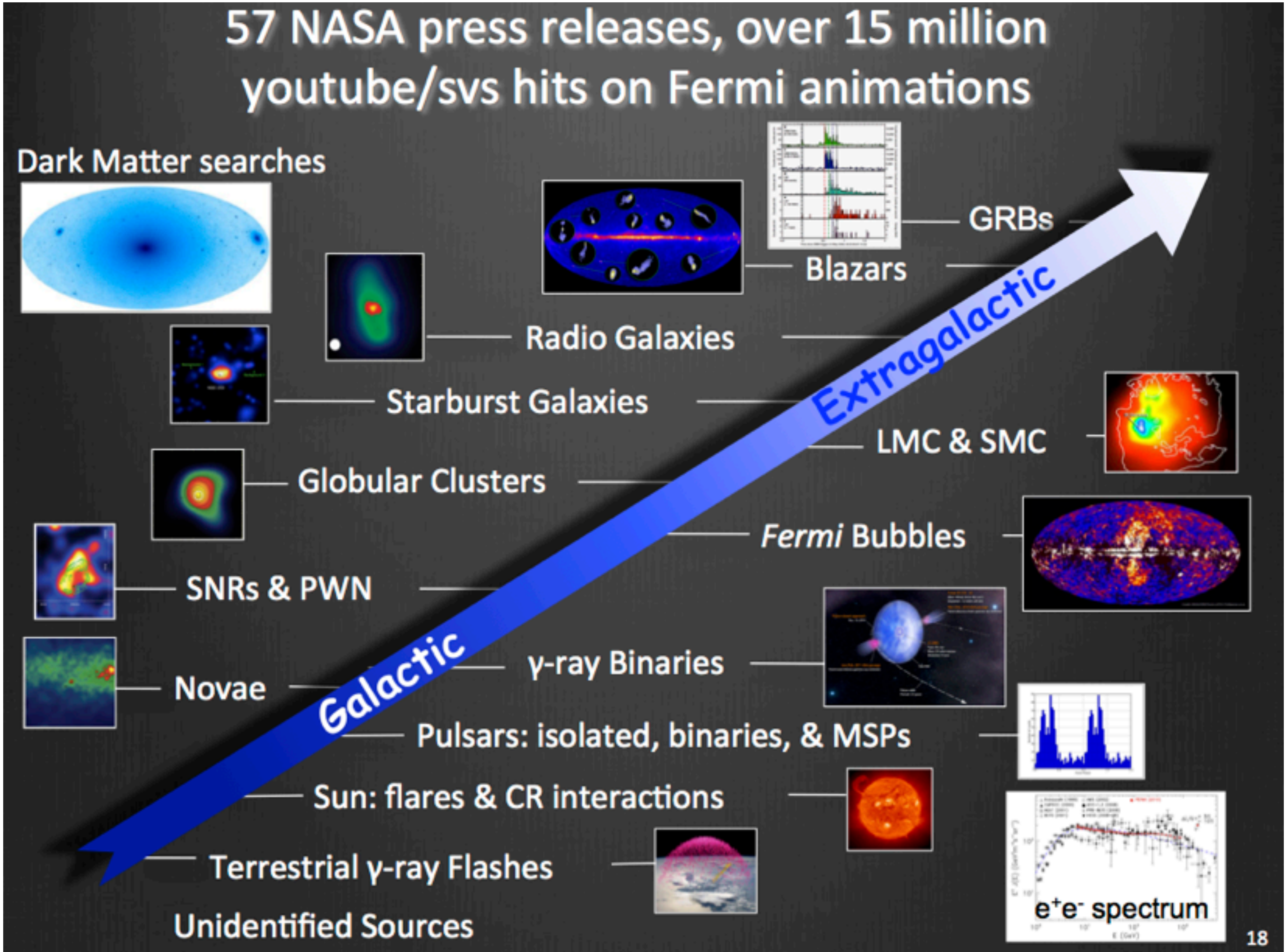
Si Tracker
70 m^2, 228 μm pitch
~0.9 million channels



Anti-coincidence Detector
Segmented scintillator tiles
99.97% efficiency

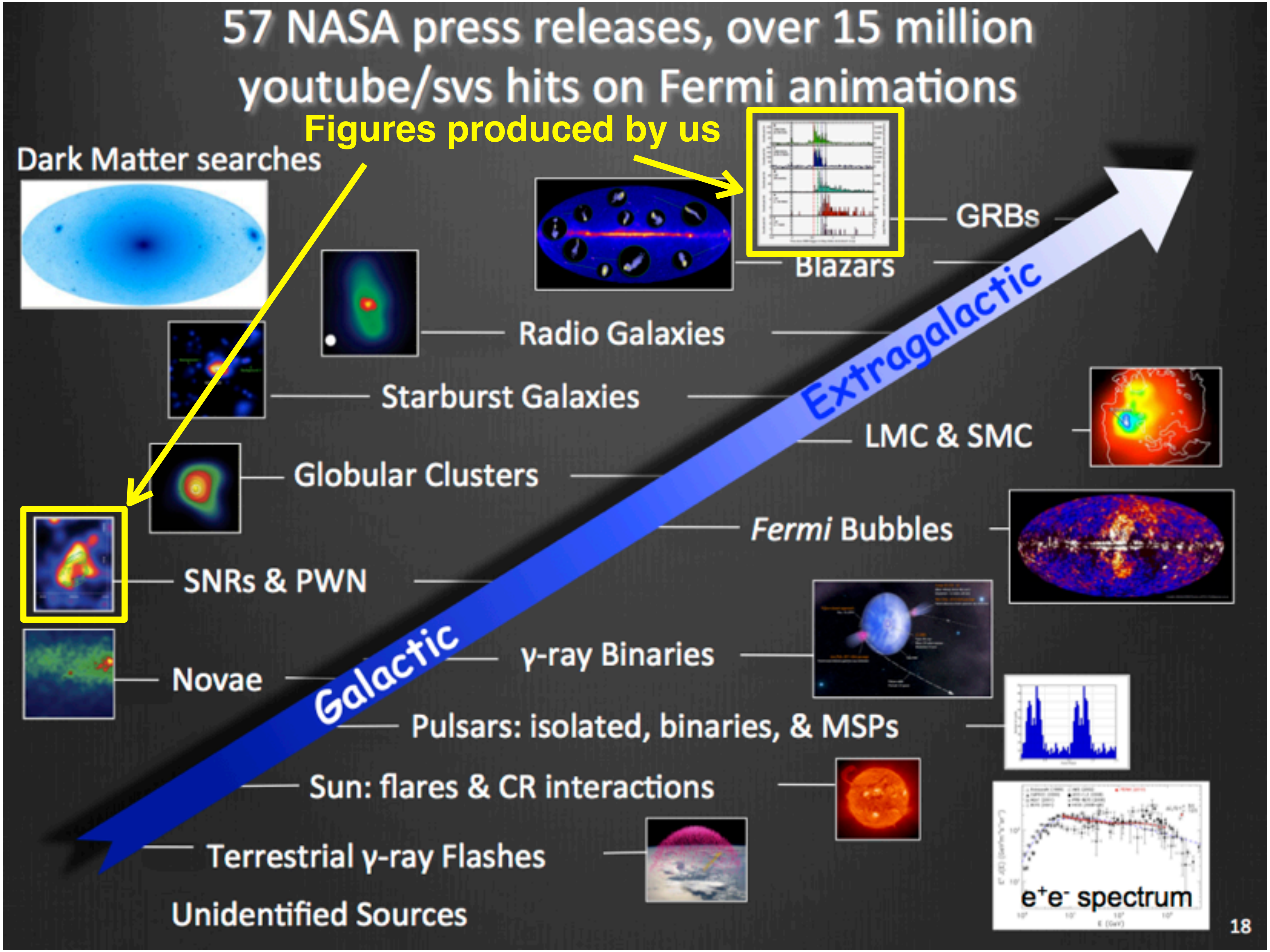
CsI Calorimeter
8.4 radiation length

Fermi Science Highlights



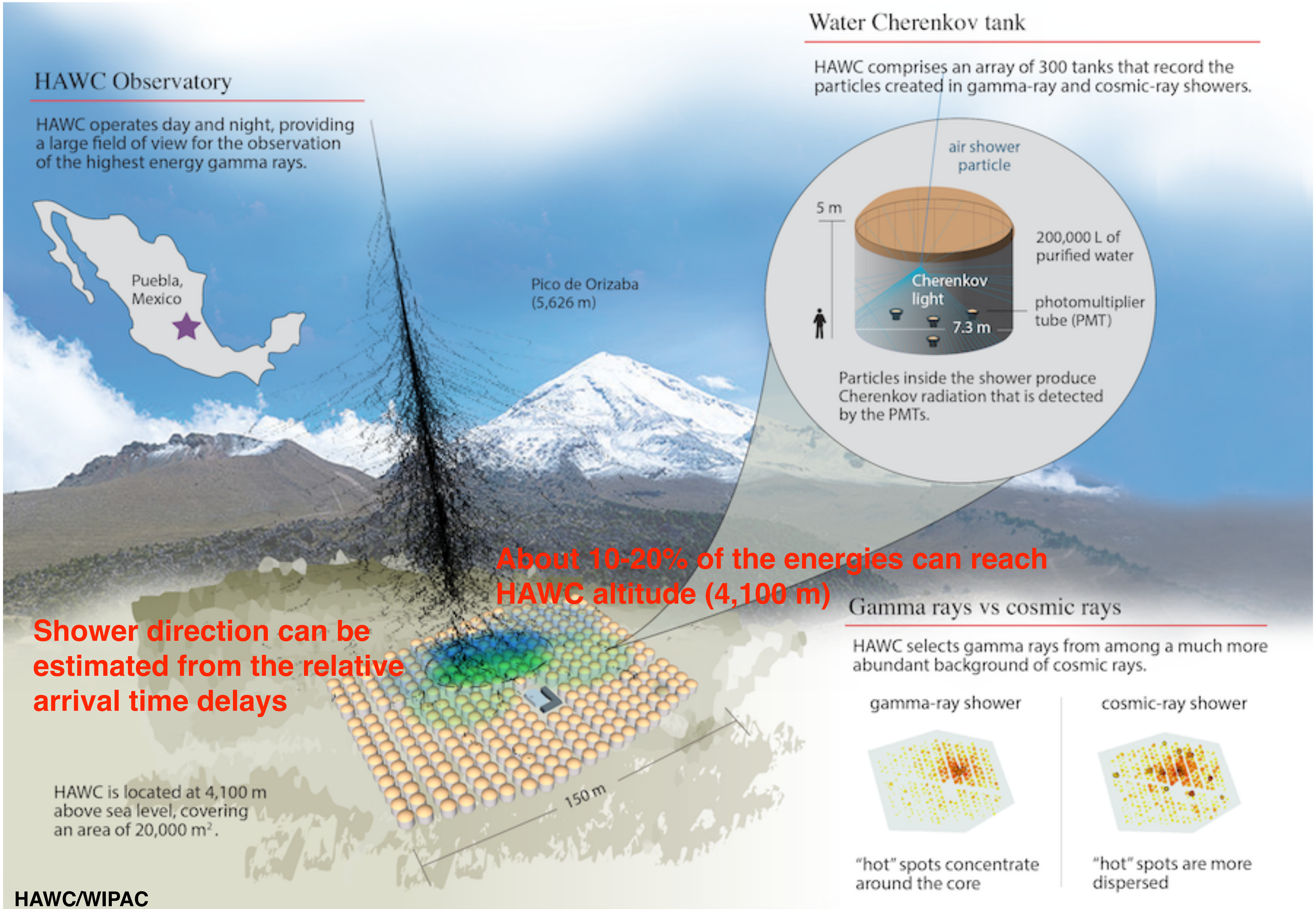
J. McEnery
5th Fermi Symposium

Fermi Science Highlights



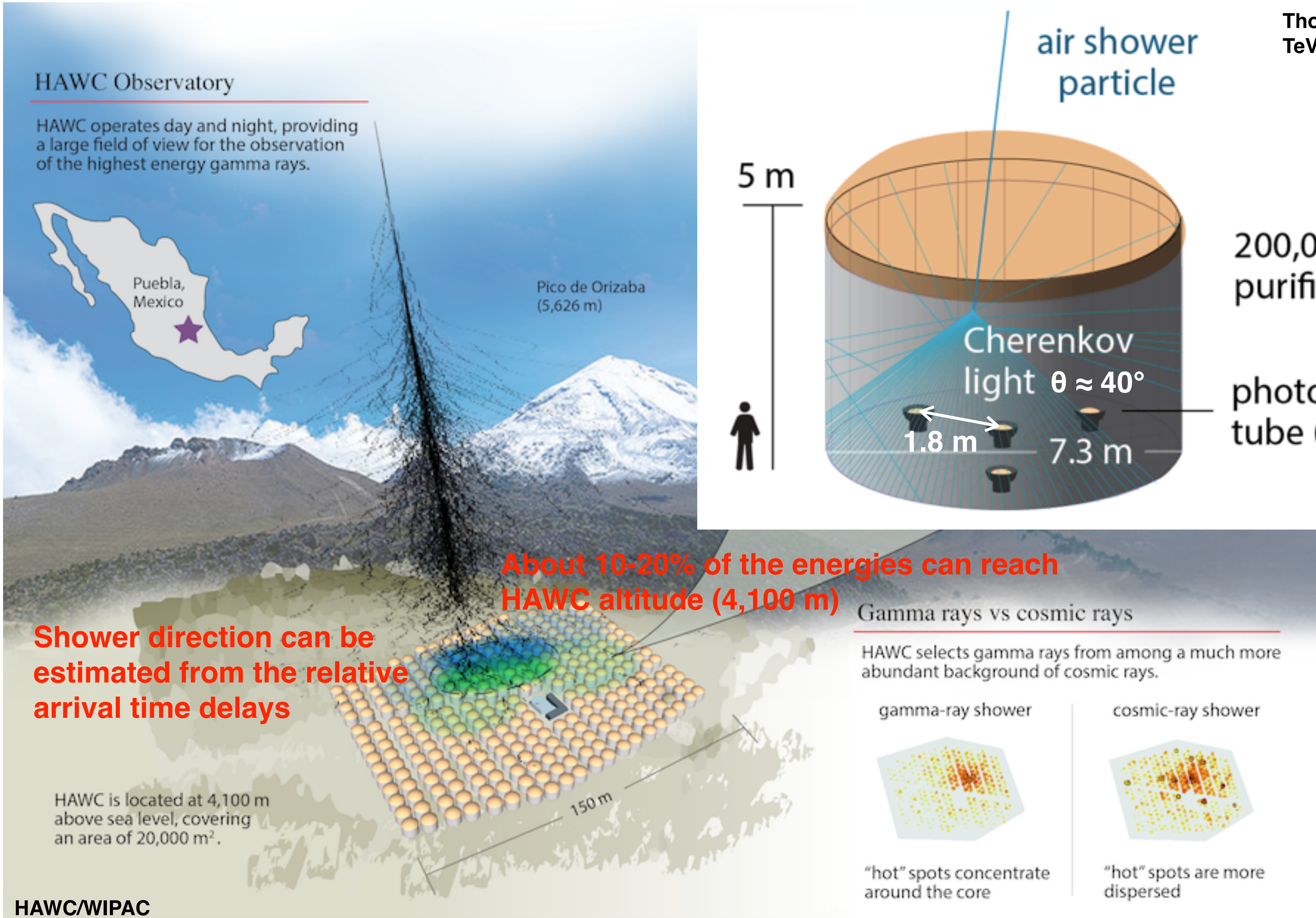
J. McEnery
5th Fermi Symposium

Air Shower Array



Air Shower Array

Thomas Weisgarber, TeVPA 2016

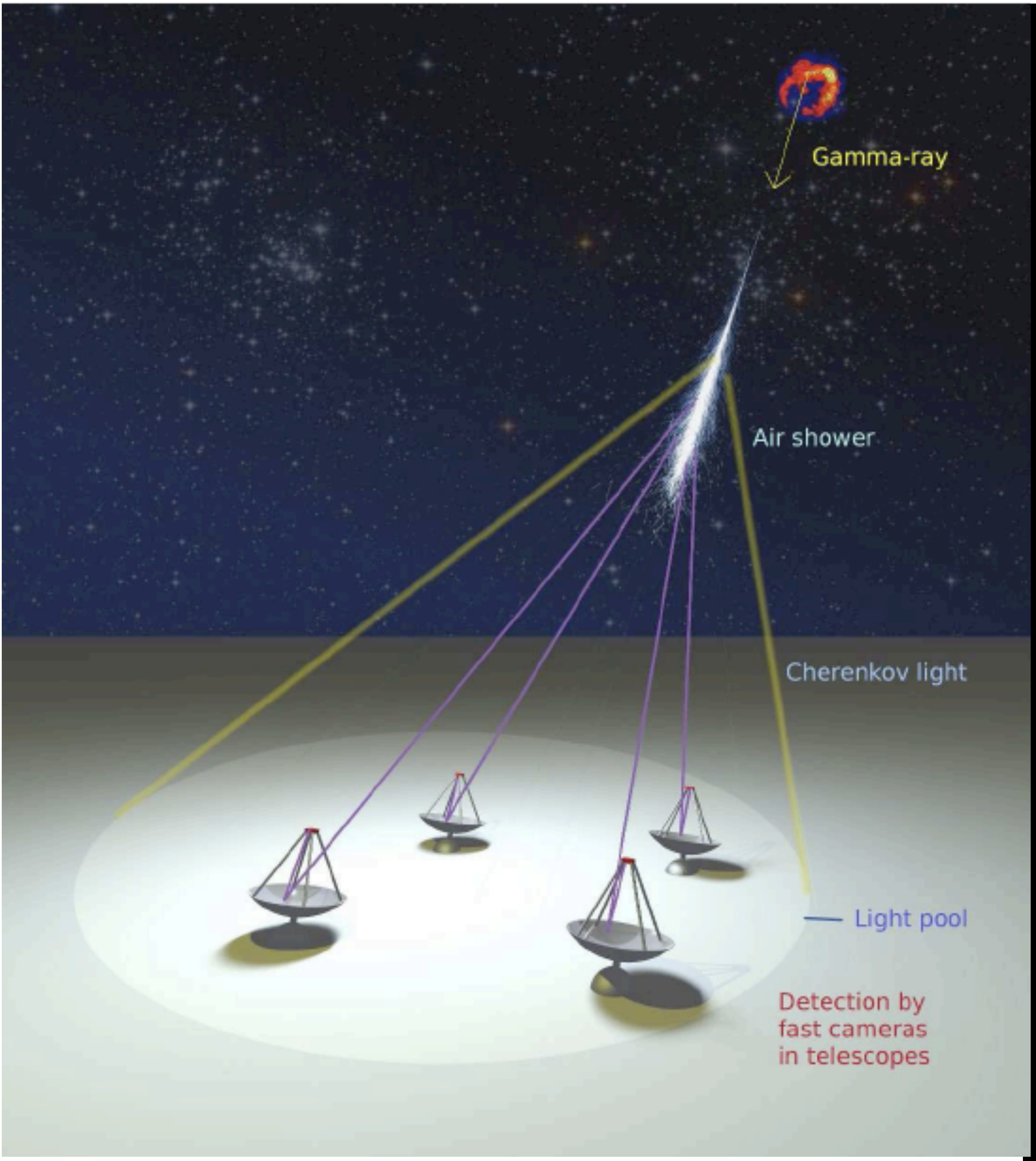


About 10-20% of the energies can reach HAWC altitude (4,100 m)

Shower direction can be estimated from the relative arrival time delays

HAWC/WIPAC

Imaging Atmospheric Cherenkov Telescope



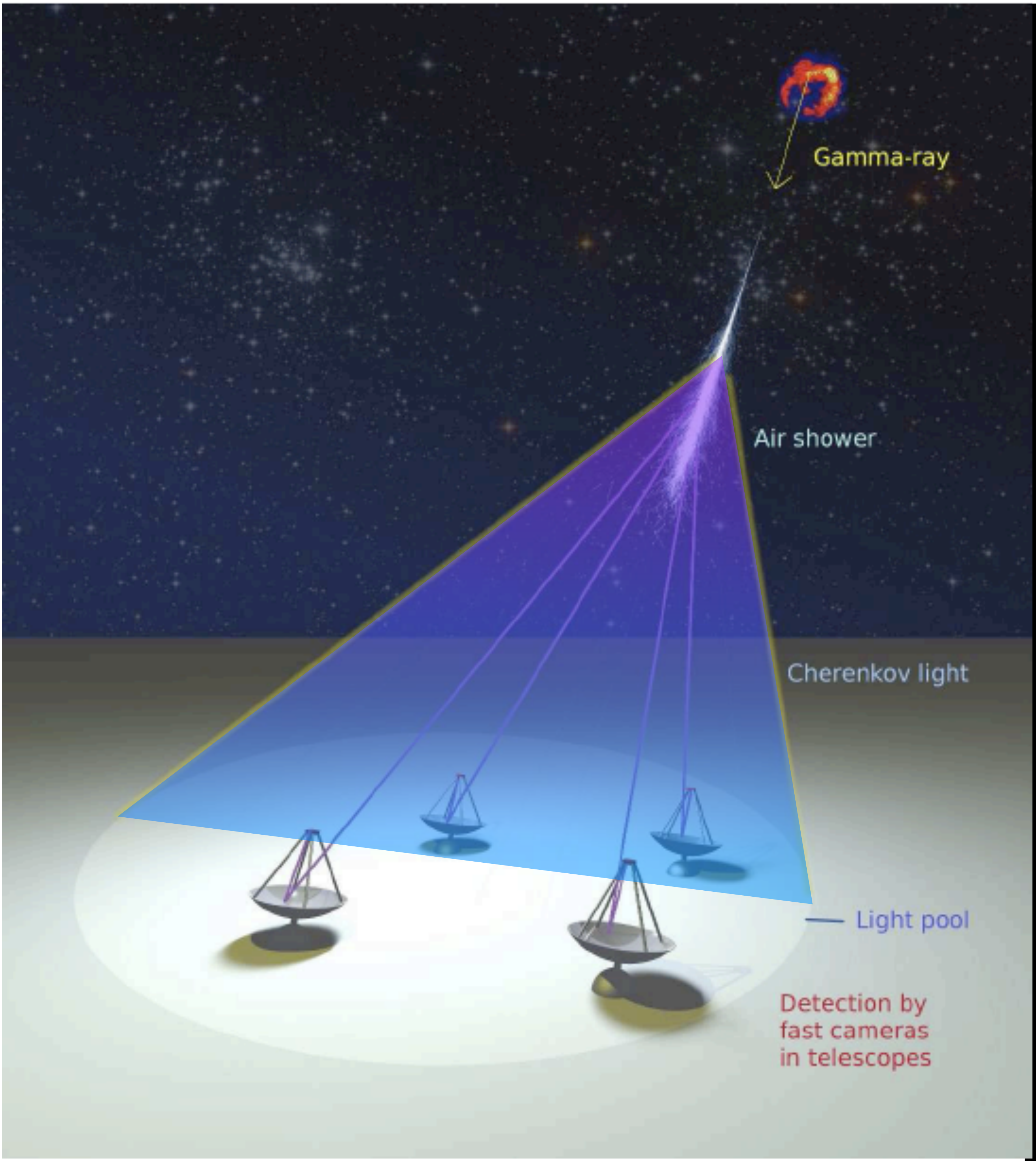
Cherenkov Light
50 photons/m^2 (5 pe/m^2) at 1 TeV

Typical parameters

Energy range	50GeV ~ 10TeV
CR rejection power	>99%
Angular resolution	~0.1 degrees
Energy resolution	~20%
Detection area	~10^{5}m^2

Sensitivity ~1% Crab Flux (10^{-13} erg/cm^{2}s)

Imaging Atmospheric Cherenkov Telescope



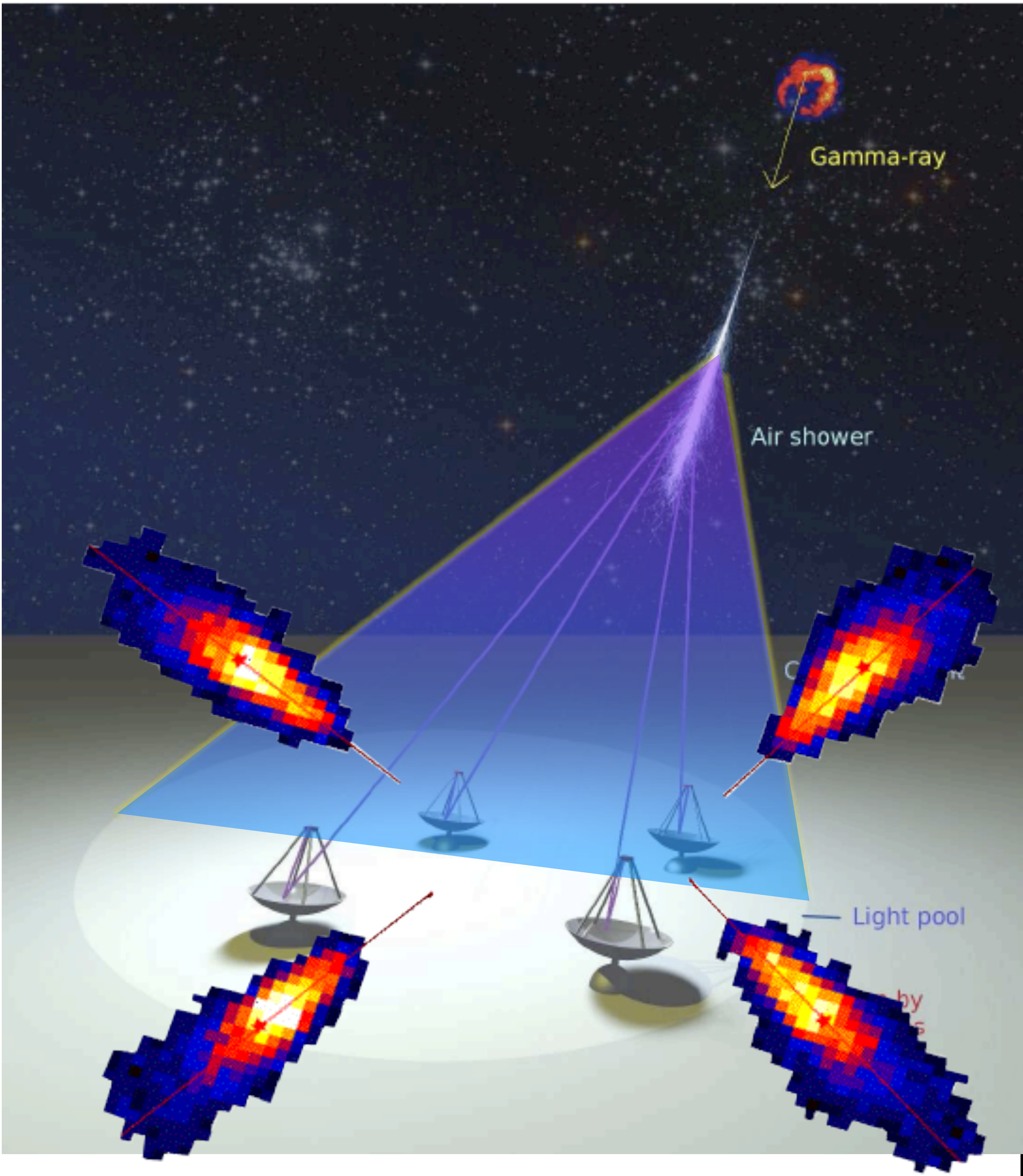
Cherenkov Light
50 photons/m² (5 pe/m²) at 1 TeV

Typical parameters

Energy range	50GeV ~ 10TeV
CR rejection power	>99%
Angular resolution	~0.1 degrees
Energy resolution	~20%
Detection area	~10^5m²

Sensitivity ~1% Crab Flux (10^{-13} erg/cm²s)

Imaging Atmospheric Cherenkov Telescope

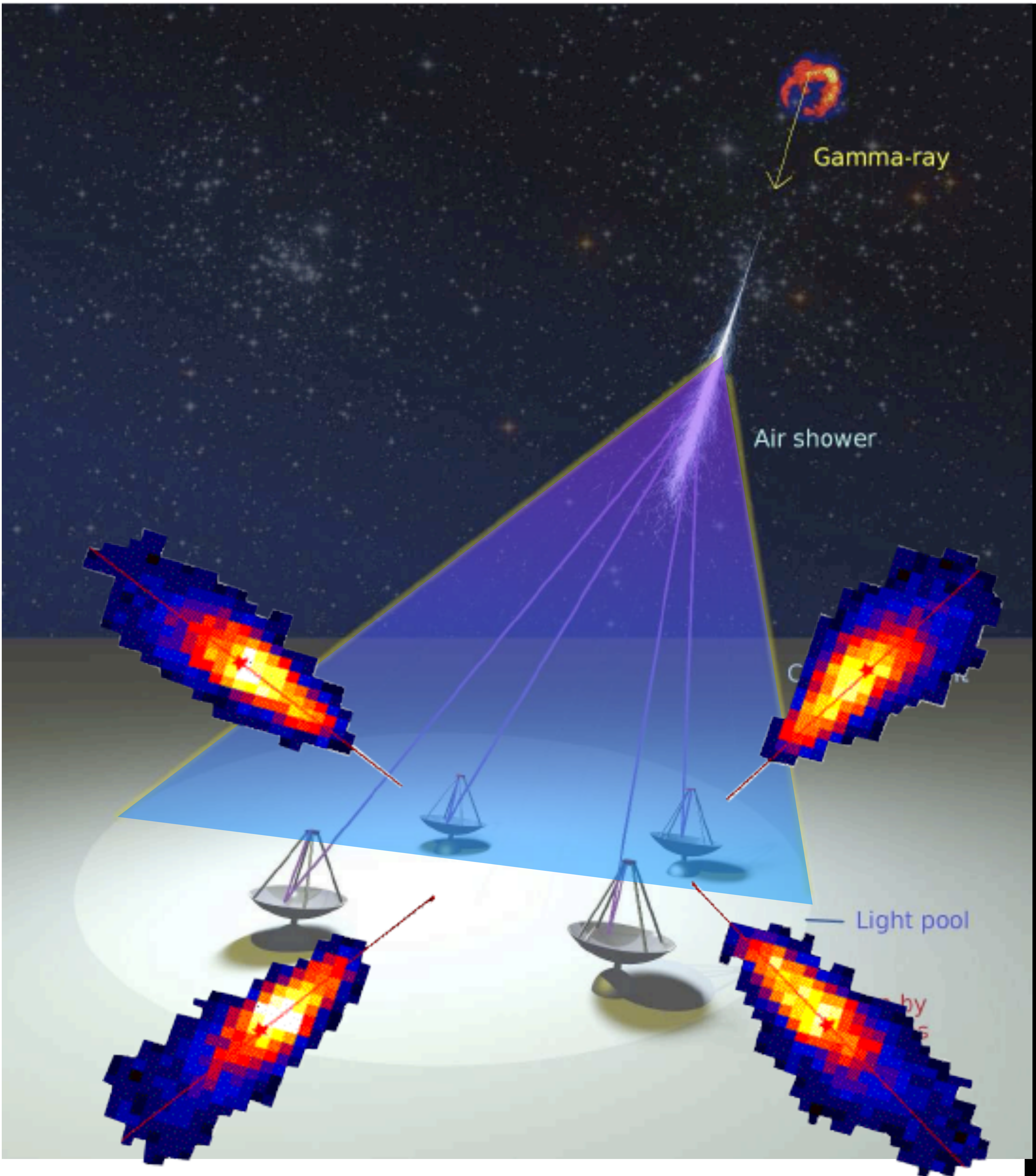


Cherenkov Light
50 photons/m^2 (5 pe/m^2) at 1 TeV

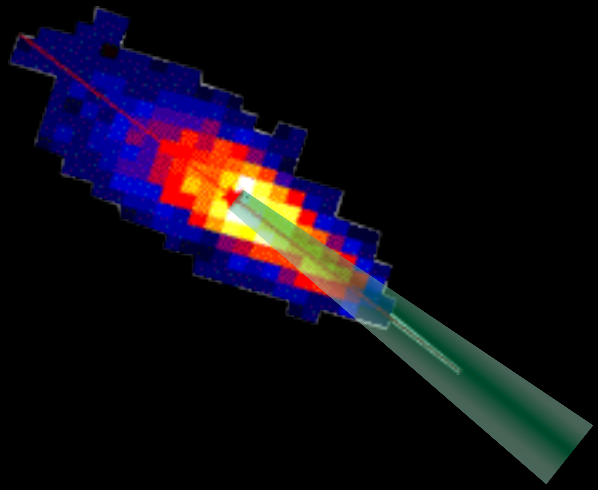
Typical parameters

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

Imaging Atmospheric Cherenkov Telescope



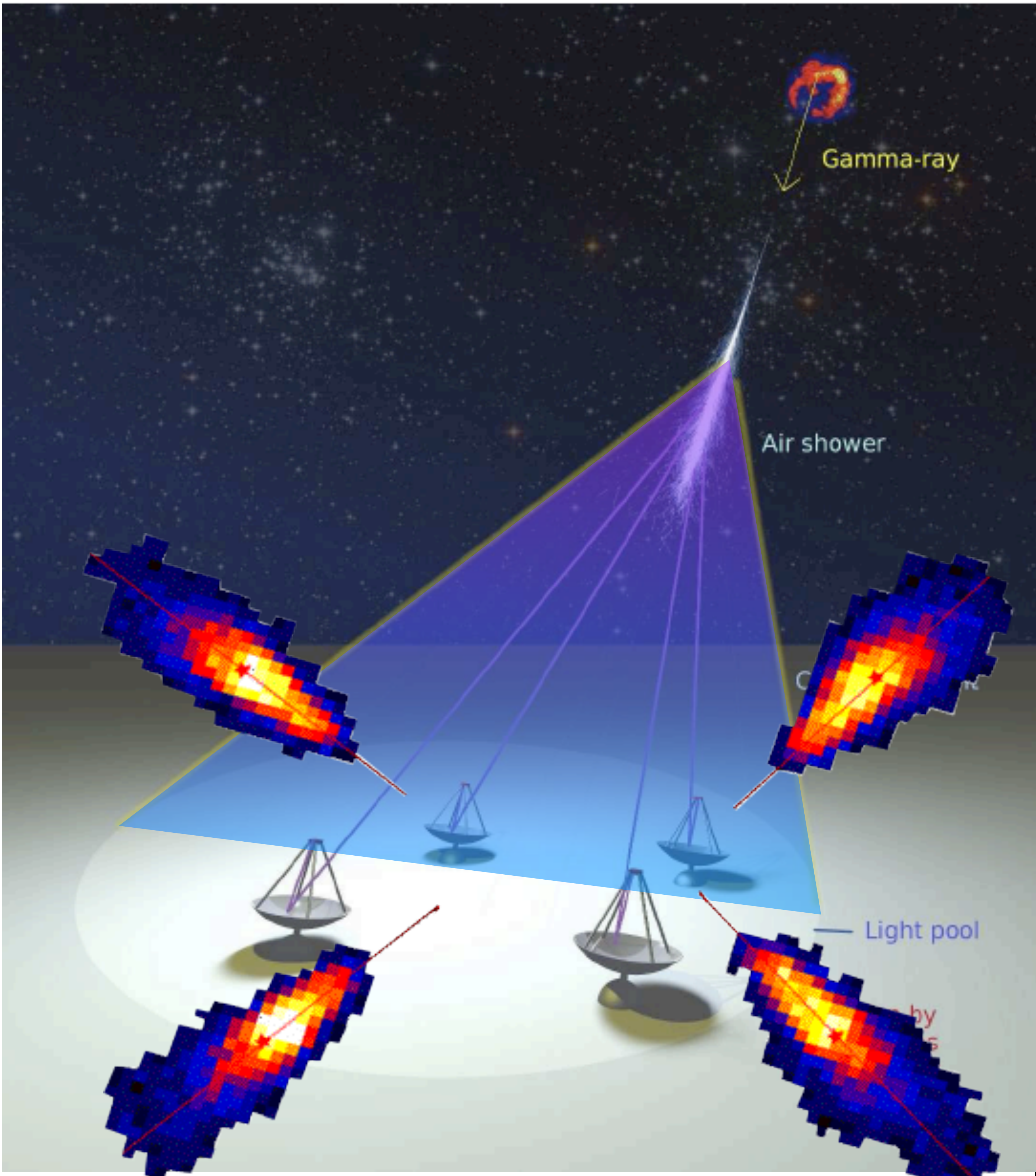
Cherenkov Light
50 photons/m² (5 pe/m²) at 1 TeV



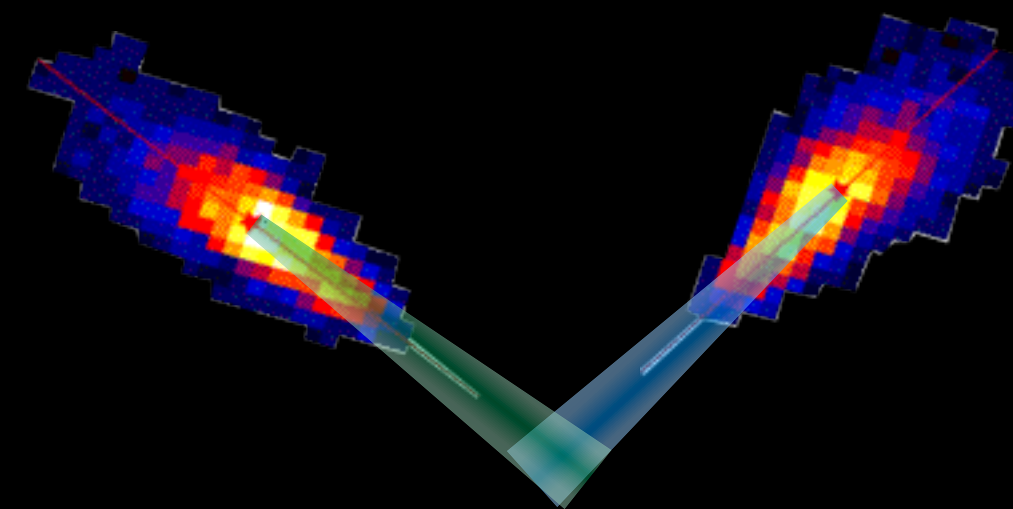
Typical parameters

Energy range 50GeV ~ 10TeV
CR rejection power >99%
Angular resolution ~0.1 degrees
Energy resolution ~20%
Detection area ~10^5m²
Sensitivity ~1% Crab Flux (10^{-13} erg/cm²s)

Imaging Atmospheric Cherenkov Telescope



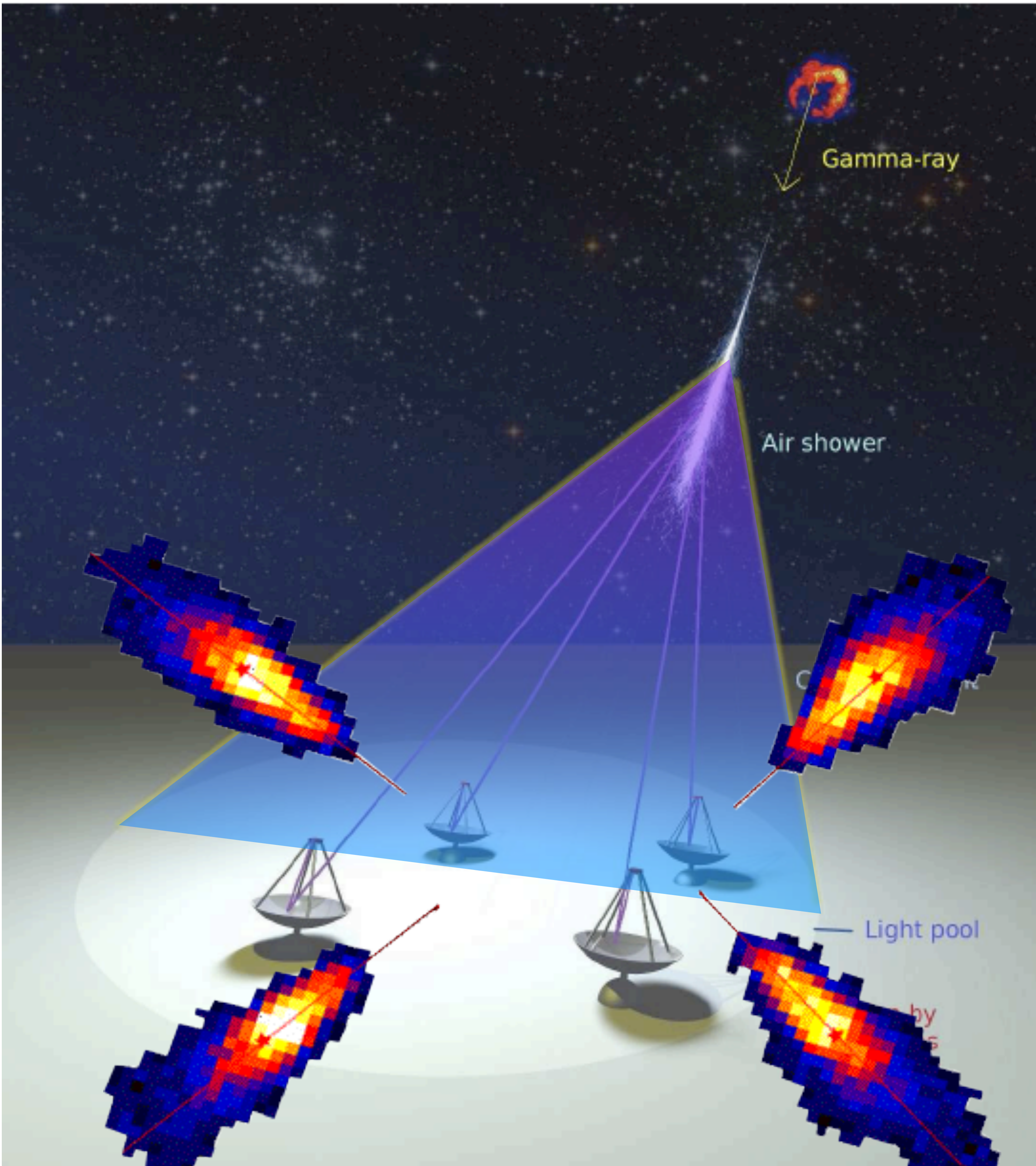
Cherenkov Light
50 photons/m² (5 pe/m²) at 1 TeV



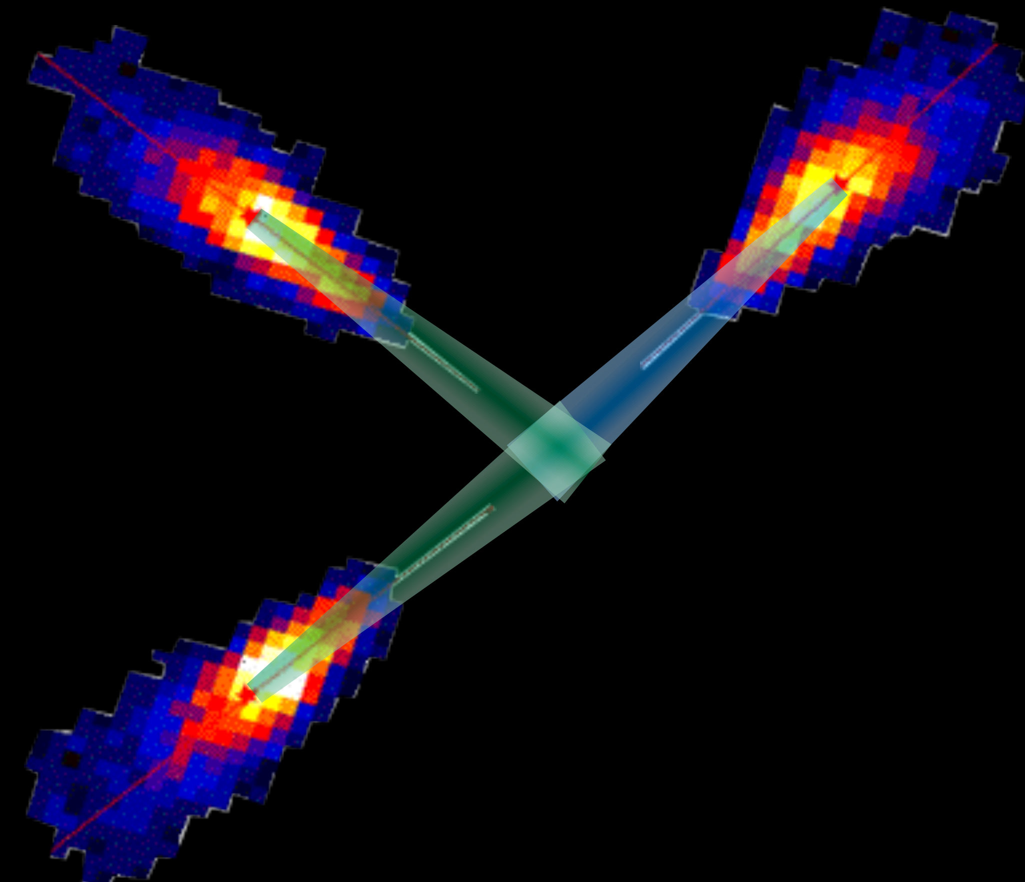
Typical parameters

- Energy range 50GeV ~ 10TeV
- CR rejection power >99%
- Angular resolution ~0.1 degrees
- Energy resolution ~20%
- Detection area ~10^5 m^2
- Sensitivity ~1% Crab Flux (10^{-13} erg/cm²s)

Imaging Atmospheric Cherenkov Telescope



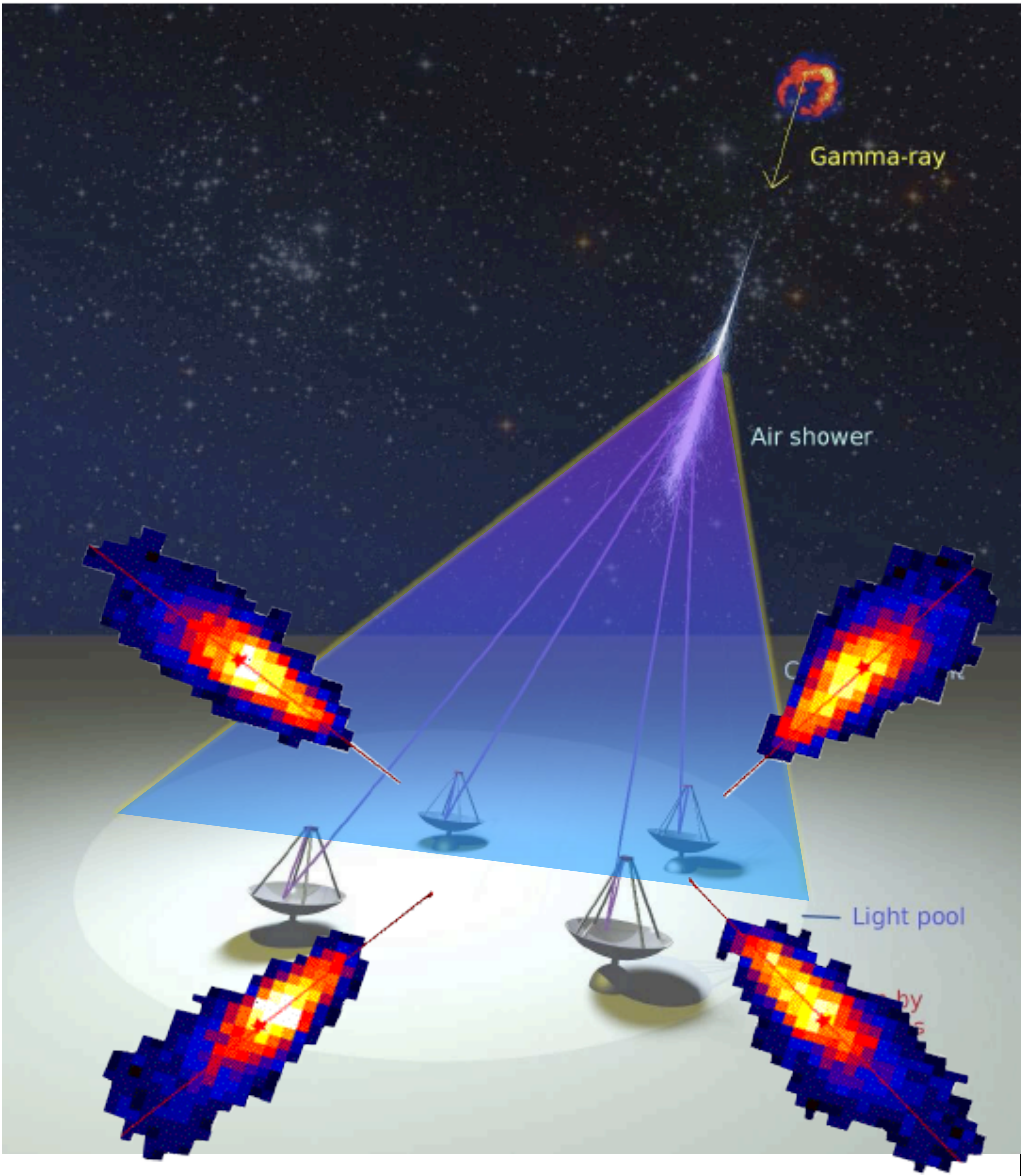
Cherenkov Light
50 photons/m² (5 pe/m²) at 1 TeV



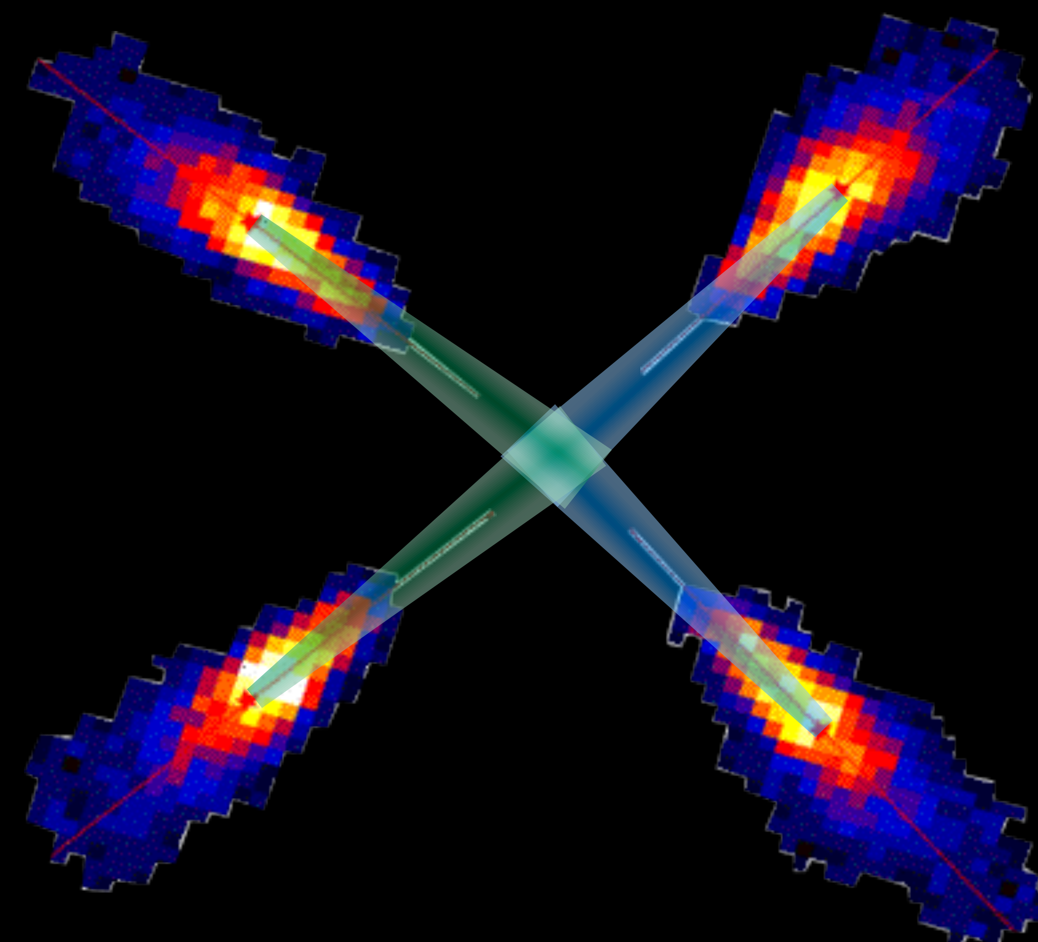
Typical parameters

Energy range	50GeV ~ 10TeV
CR rejection power	>99%
Angular resolution	~0.1 degrees
Energy resolution	~20%
Detection area	~10^5m²
Sensitivity	~1% Crab Flux (10^{-13} erg/cm²s)

Imaging Atmospheric Cherenkov Telescope



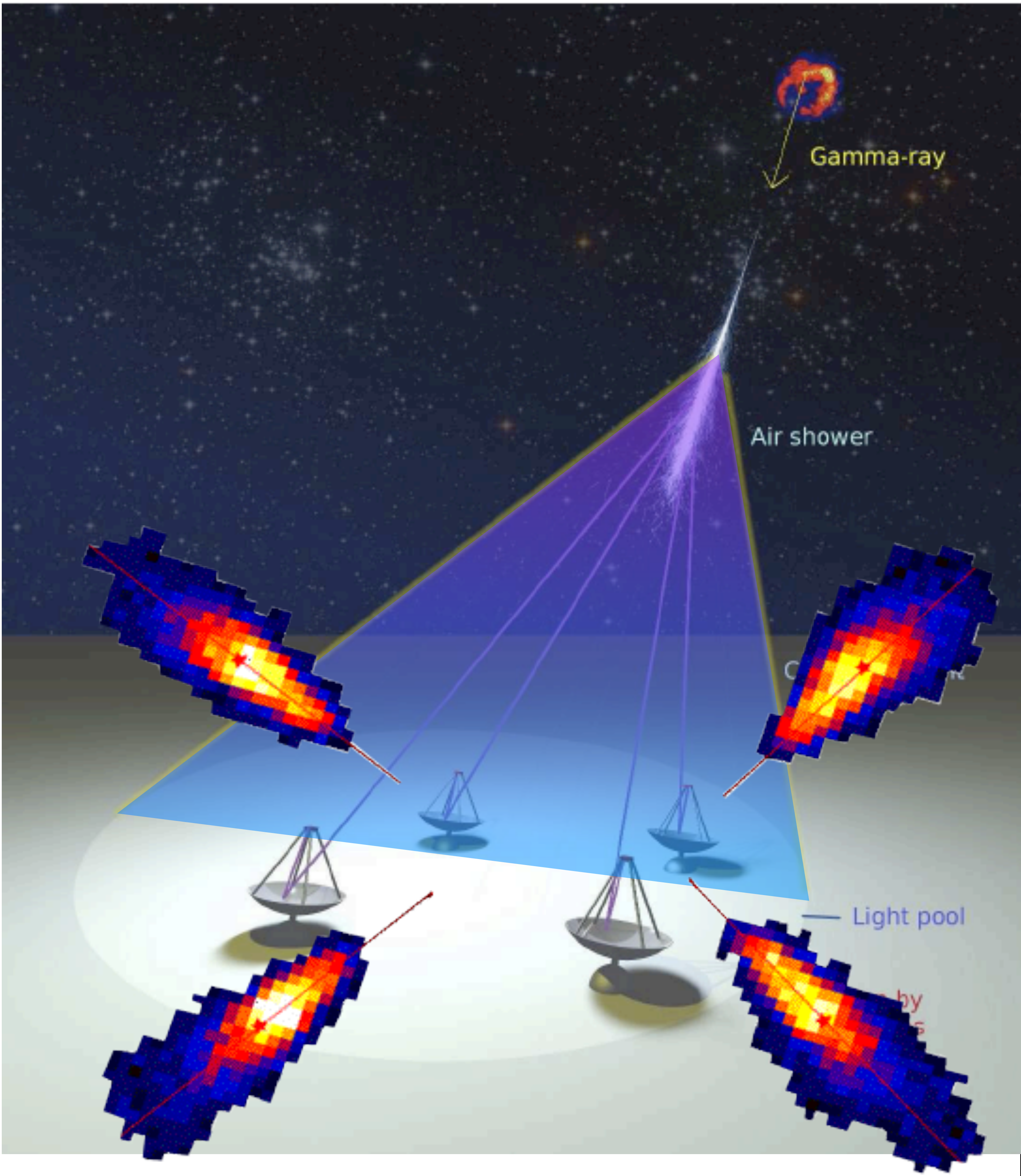
Cherenkov Light
50 photons/m^2 (5 pe/m^2) at 1 TeV



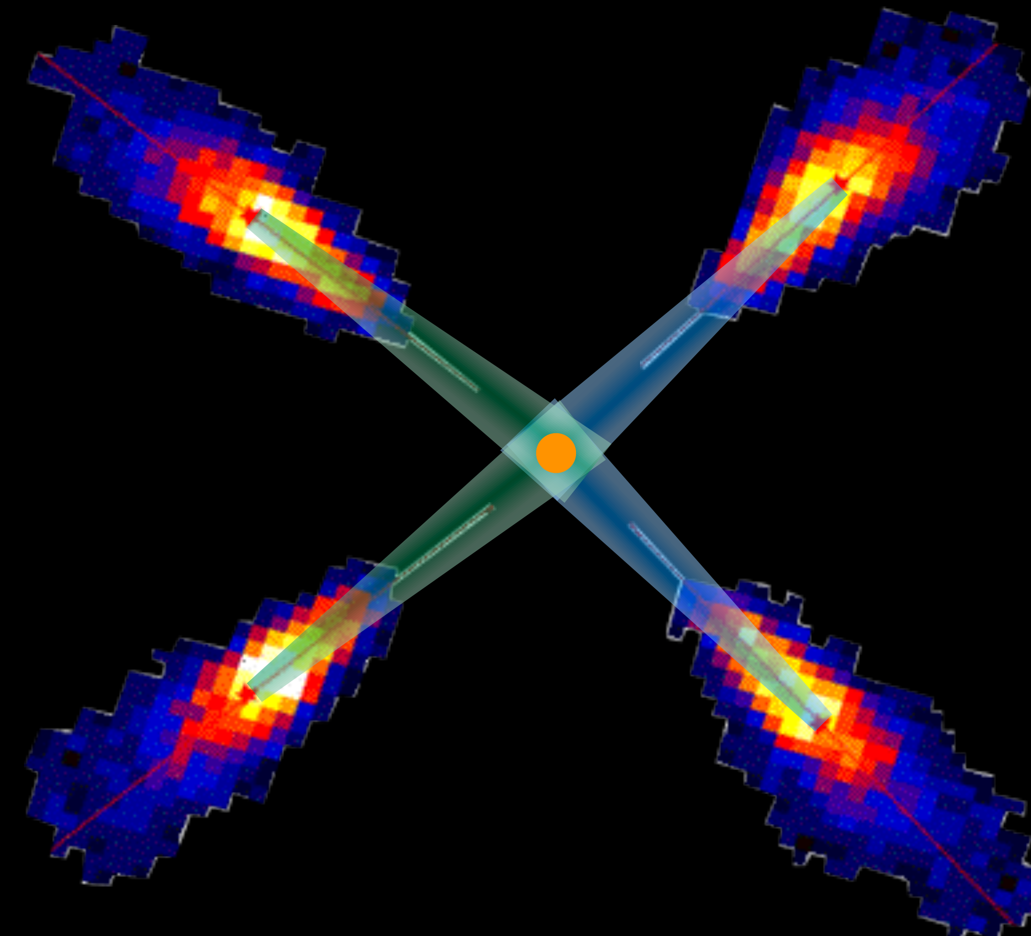
Typical parameters

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

Imaging Atmospheric Cherenkov Telescope



Cherenkov Light
50 photons/m² (5 pe/m²) at 1 TeV

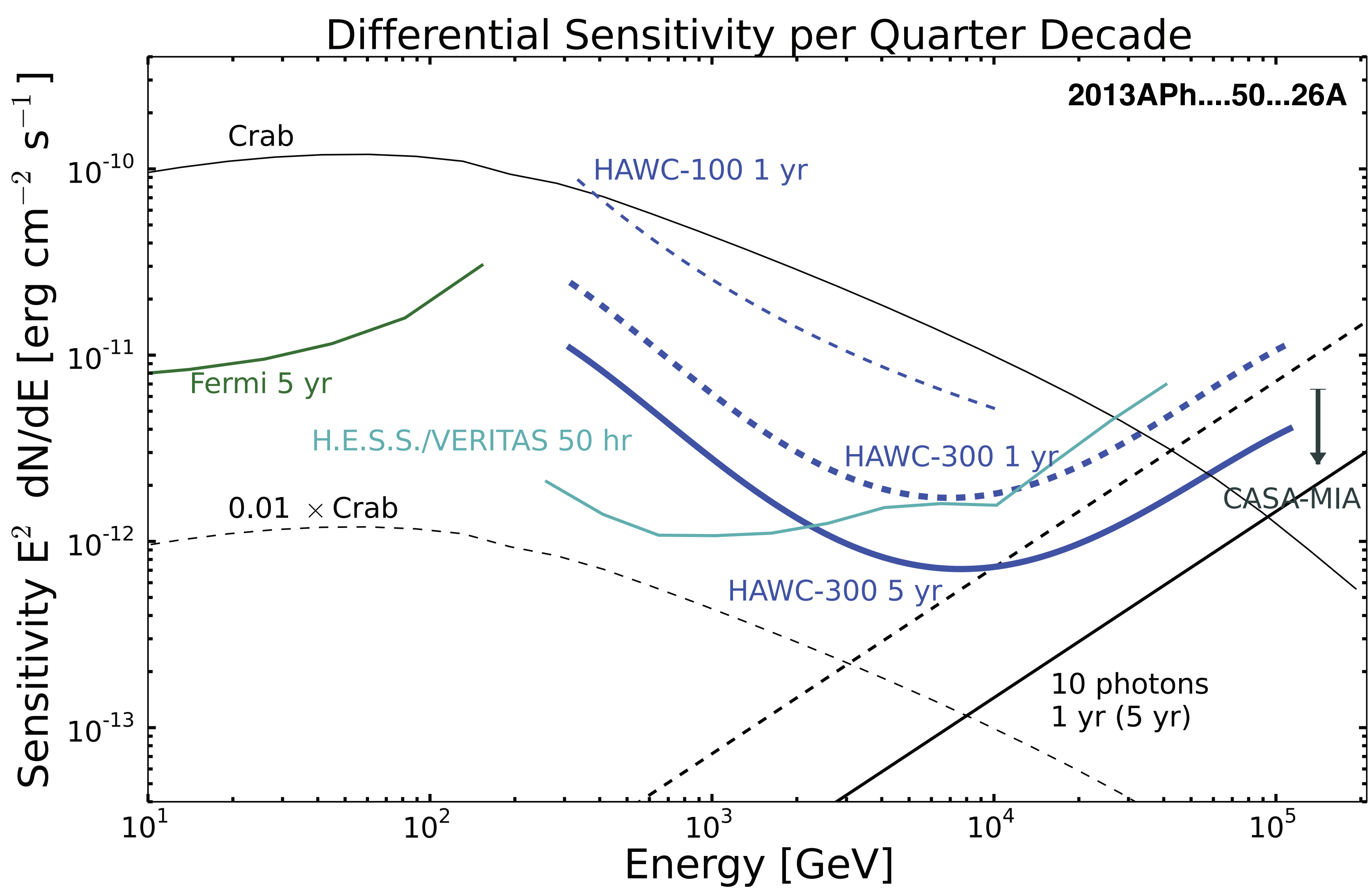


Typical parameters

- Energy range 50GeV ~ 10TeV
- CR rejection power >99%
- Angular resolution ~0.1 degrees
- Energy resolution ~20%
- Detection area ~10^5m²
- Sensitivity ~1% Crab Flux (10^{-13} erg/cm²s)

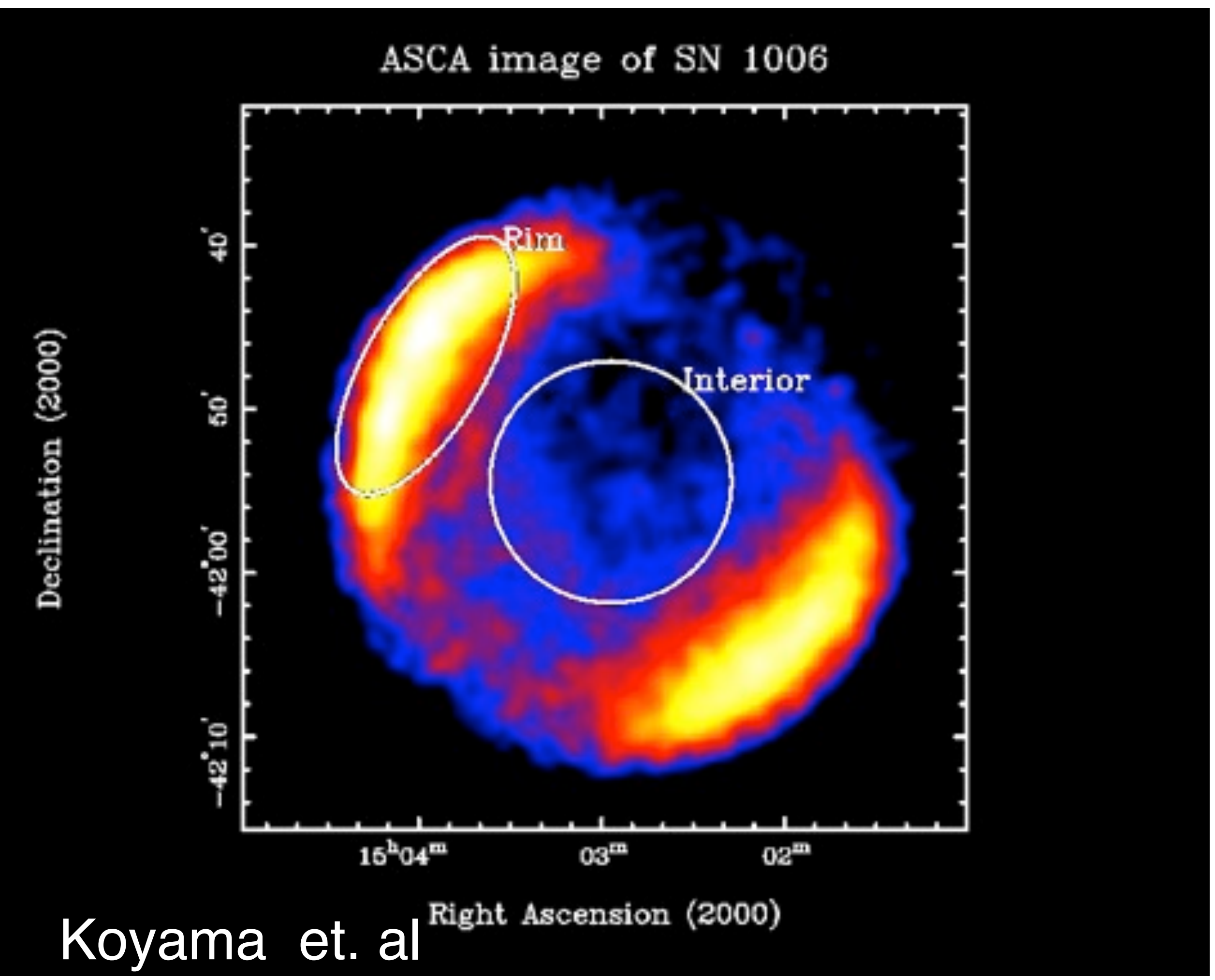
Performance Comparisons

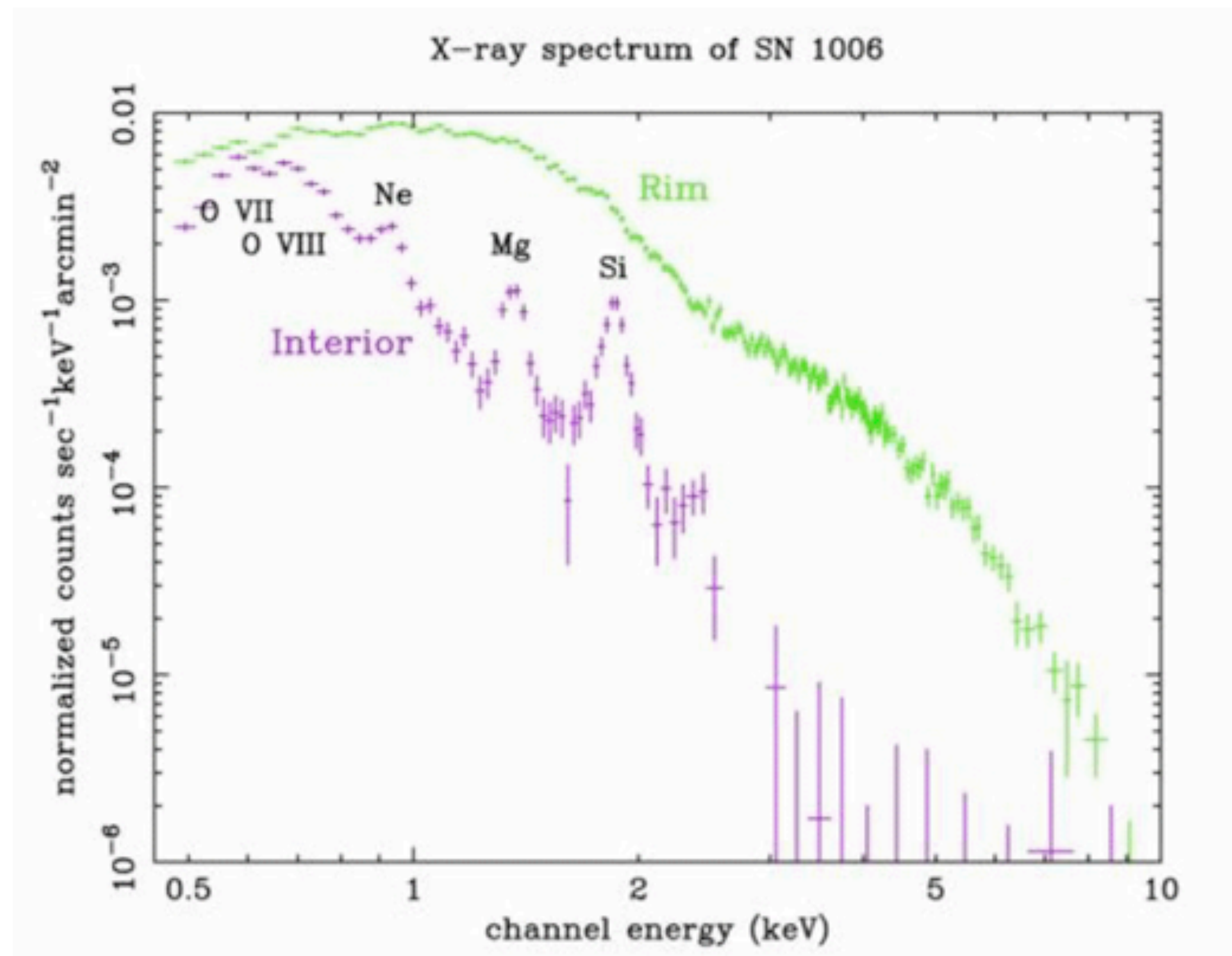
- Fermi, HAWC and IACTs are complimentary
  - Fermi and HAWC provide survey of unknown sources and long-term temporal monitoring
  - Fermi and IACTs provide good spectral information
  - IACTs provide better imaging and short variability measurements



Particle Acceleration in SNR

- 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

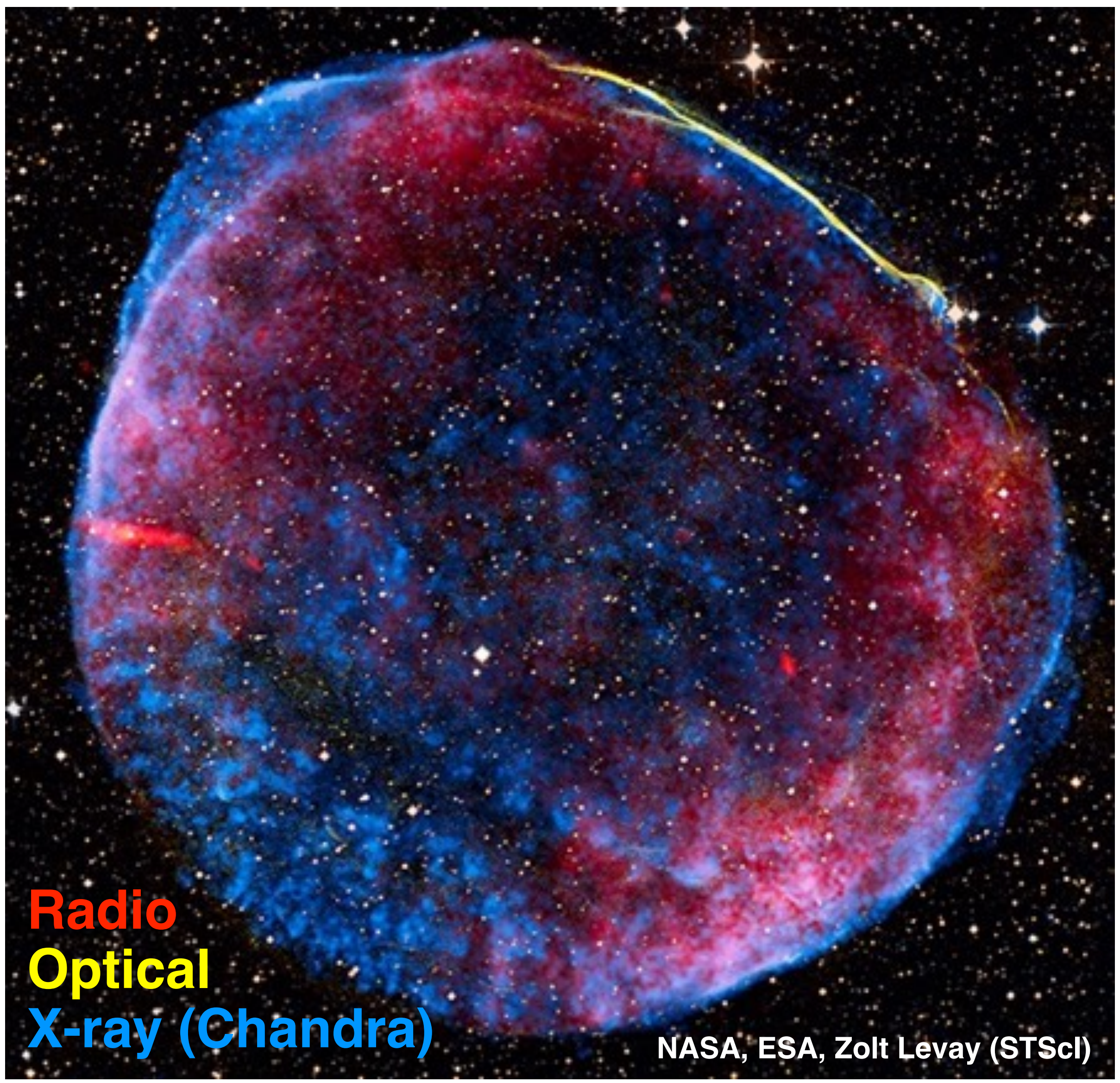


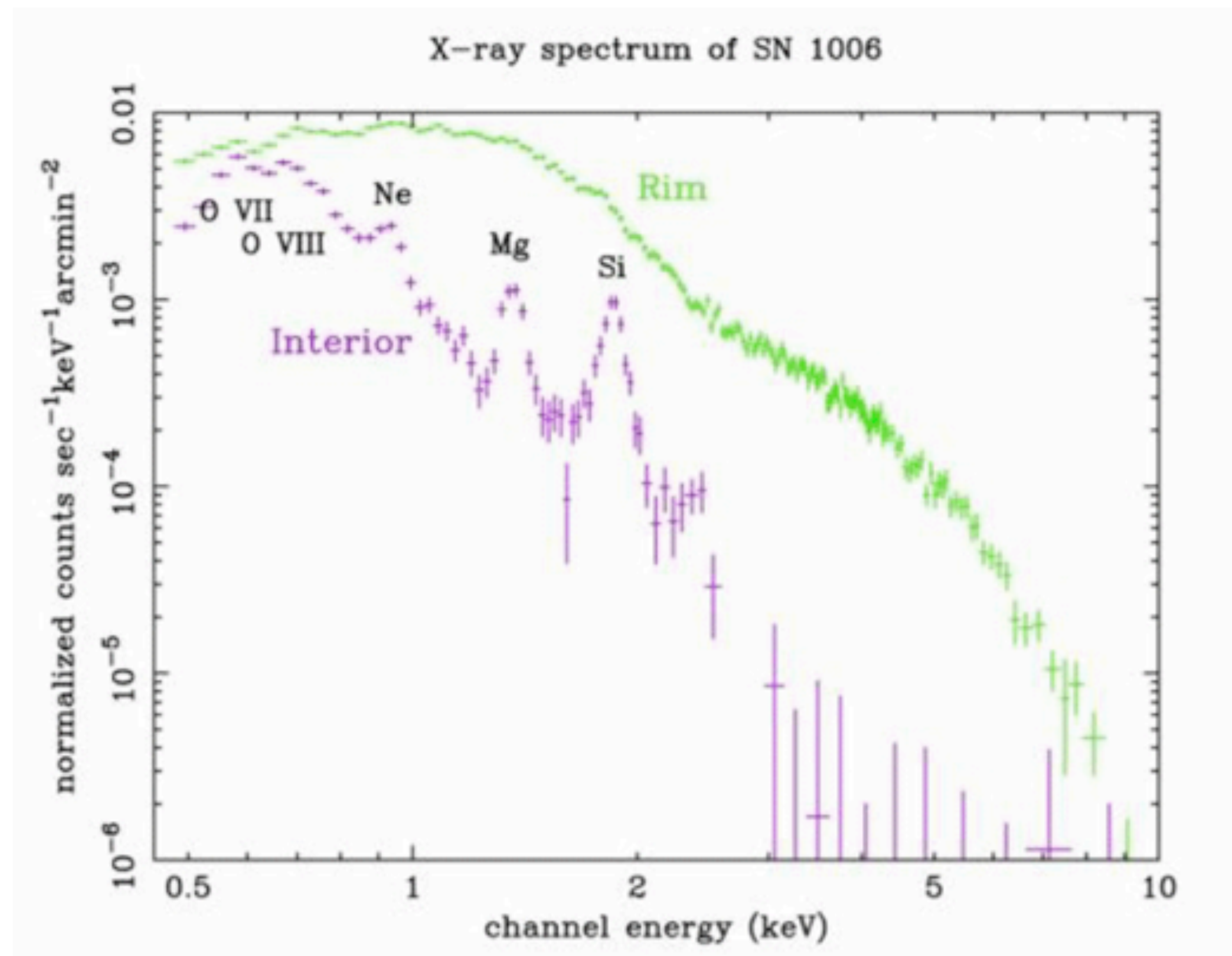


1995Natur.378..255K

Particle Acceleration in SNR

- 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

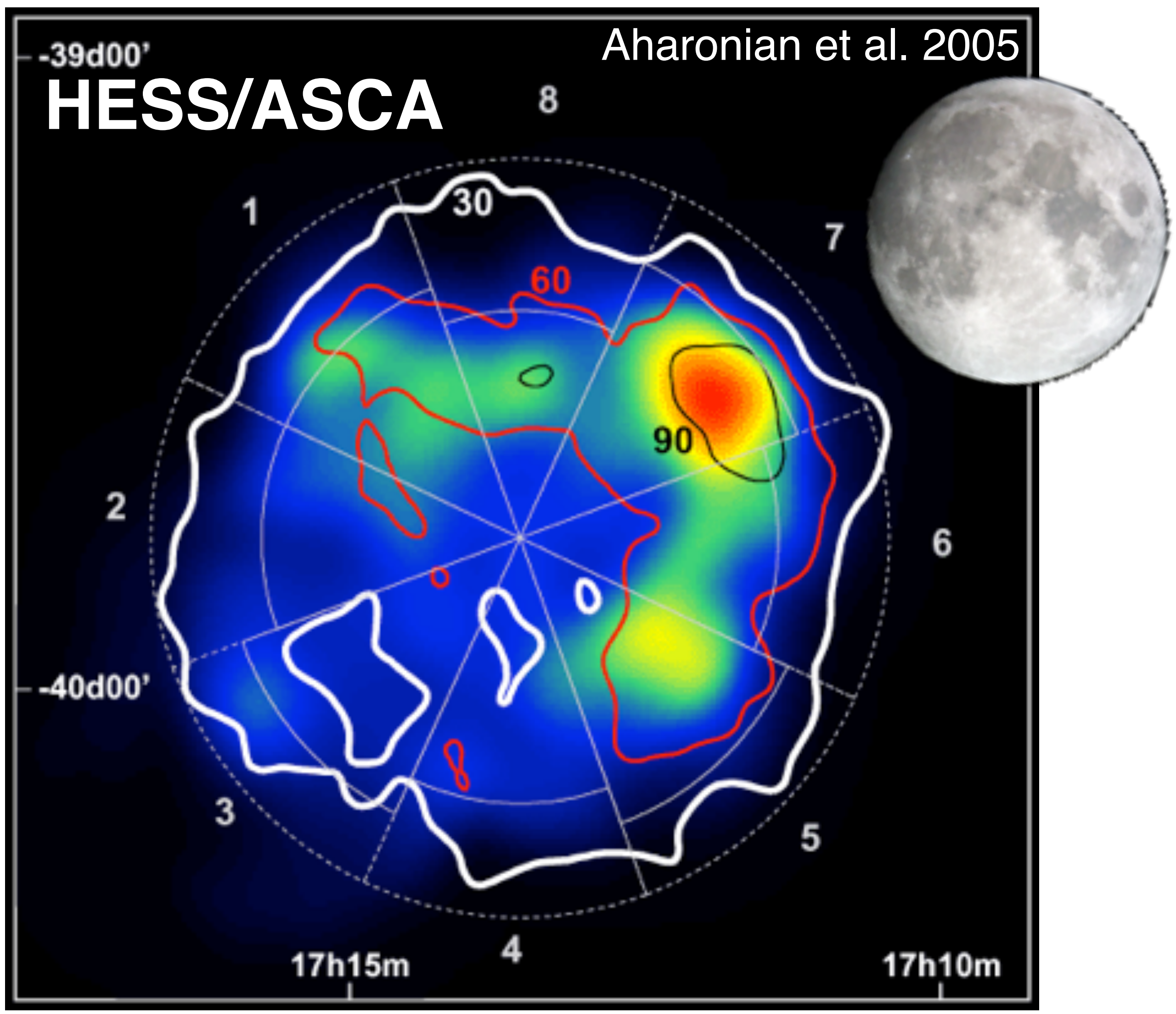




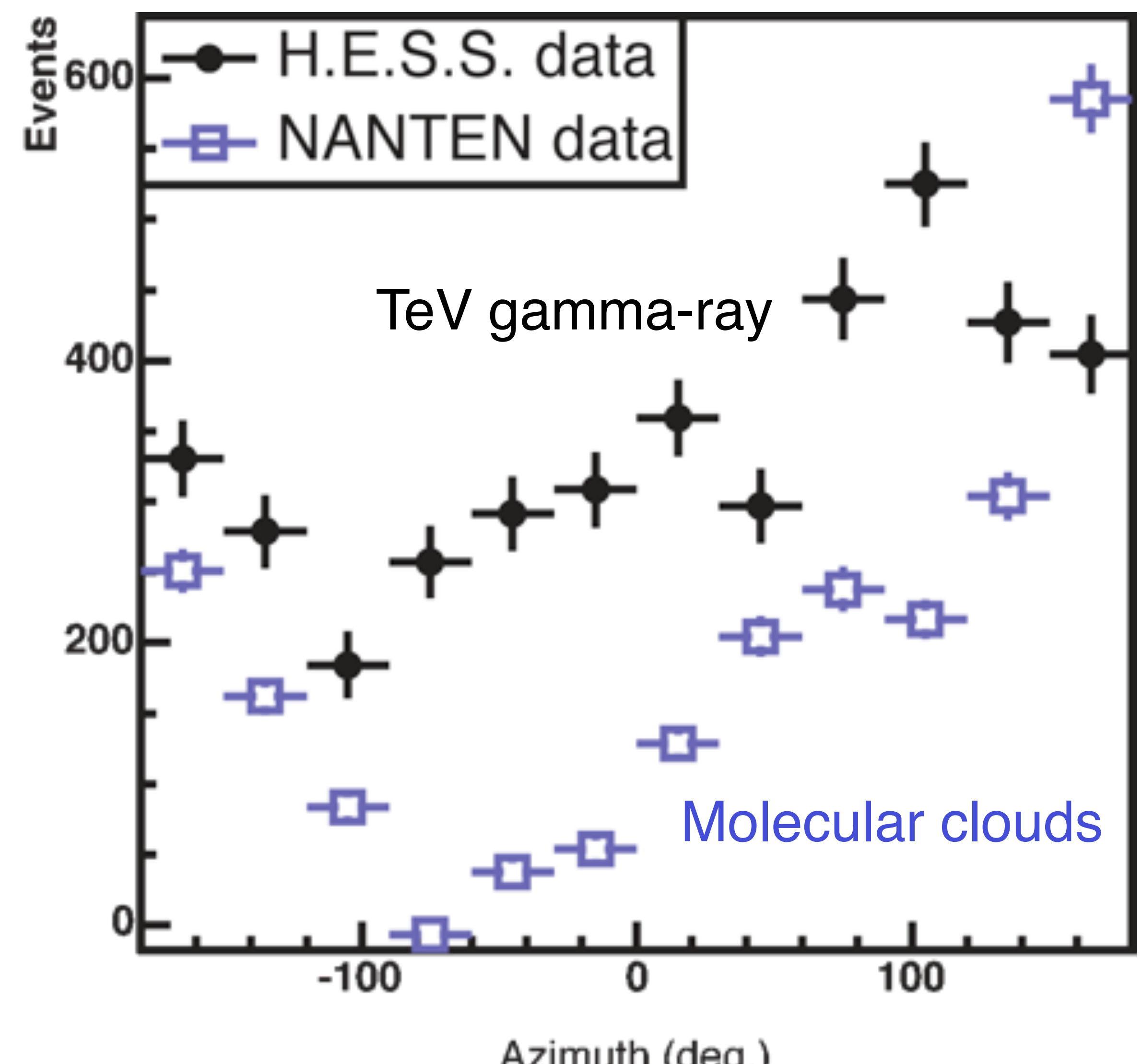
1995Natur.378..255K

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

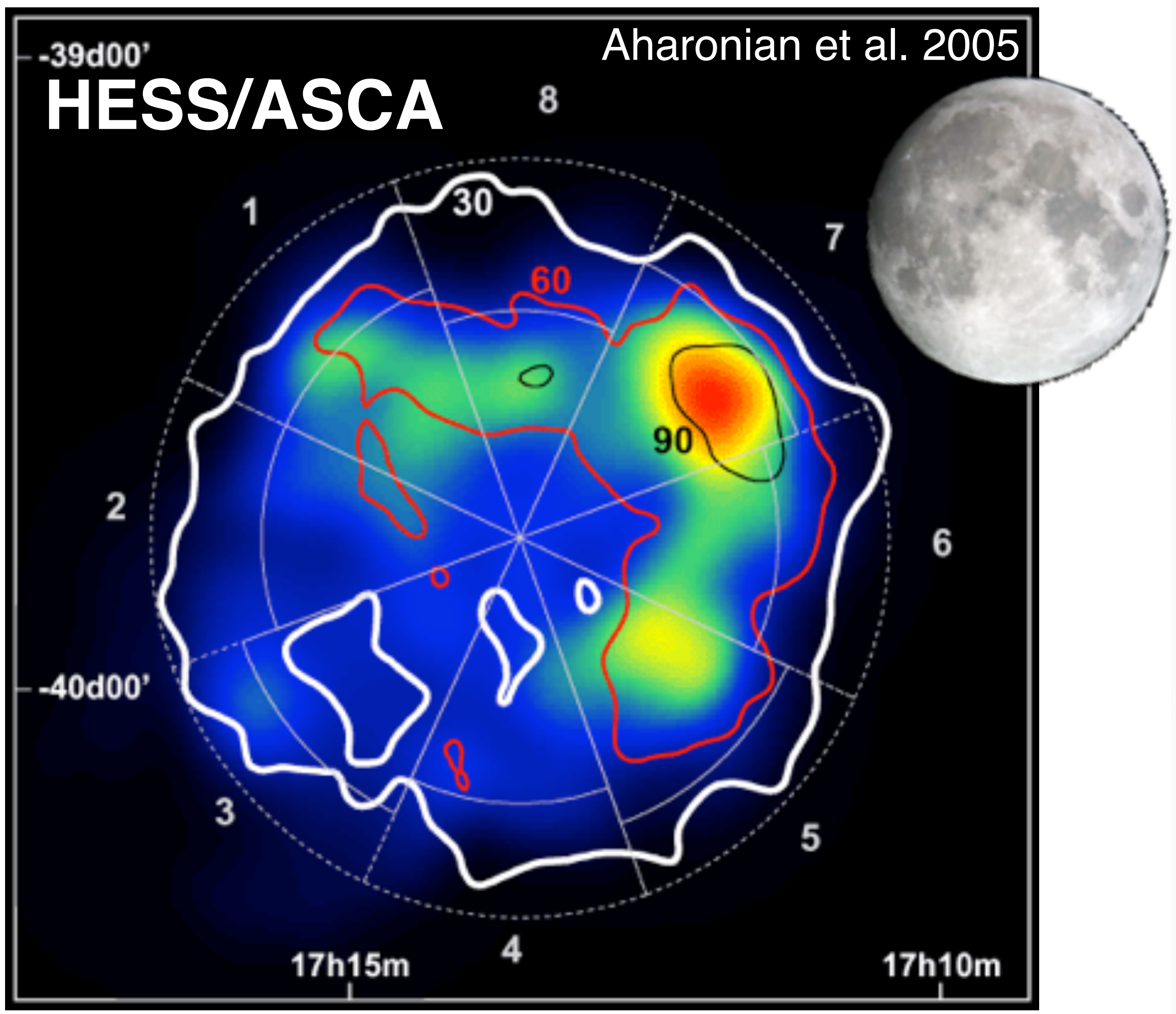


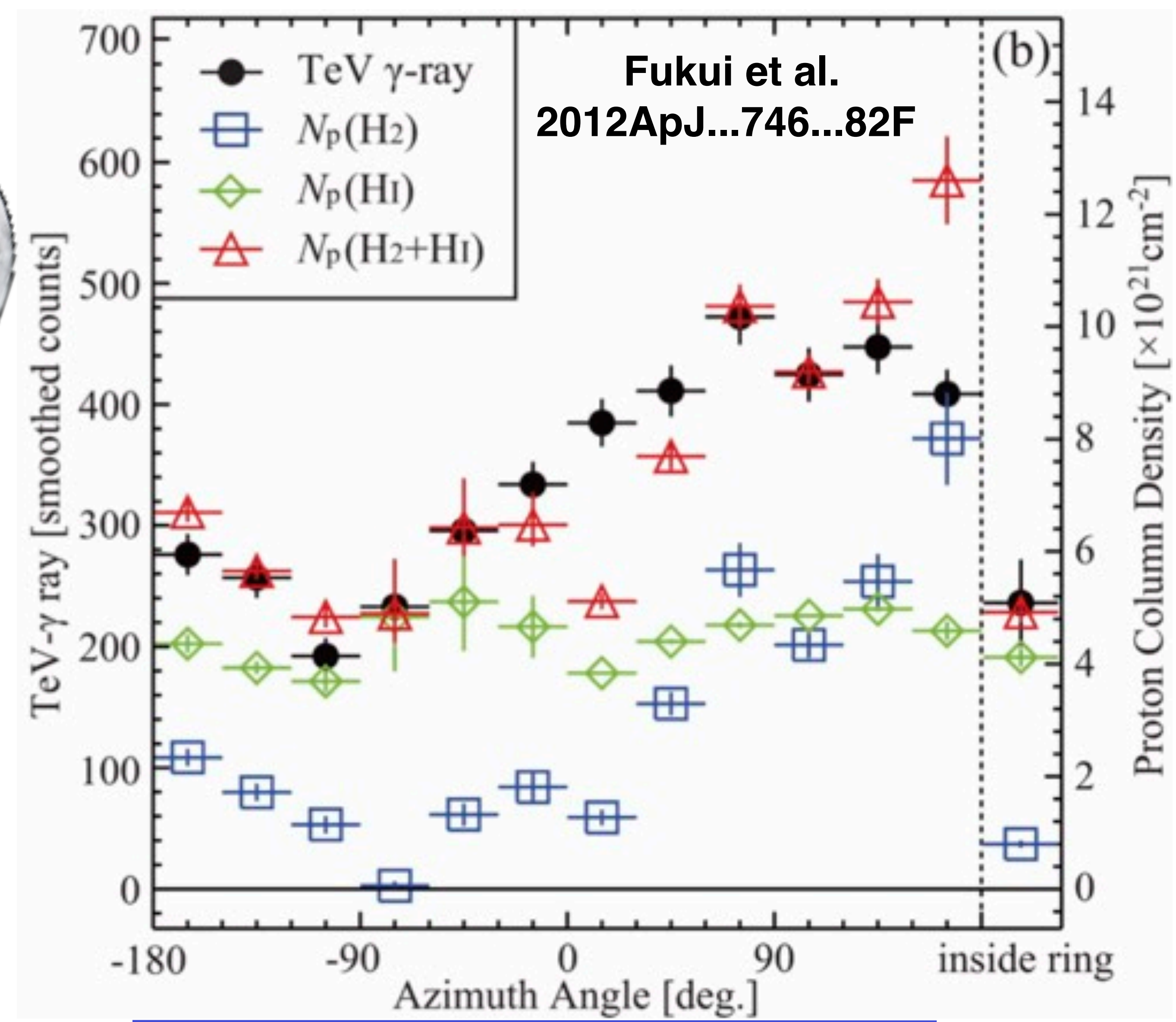
Aharonian et al. 2005



TeV Gamma Ray from SNR

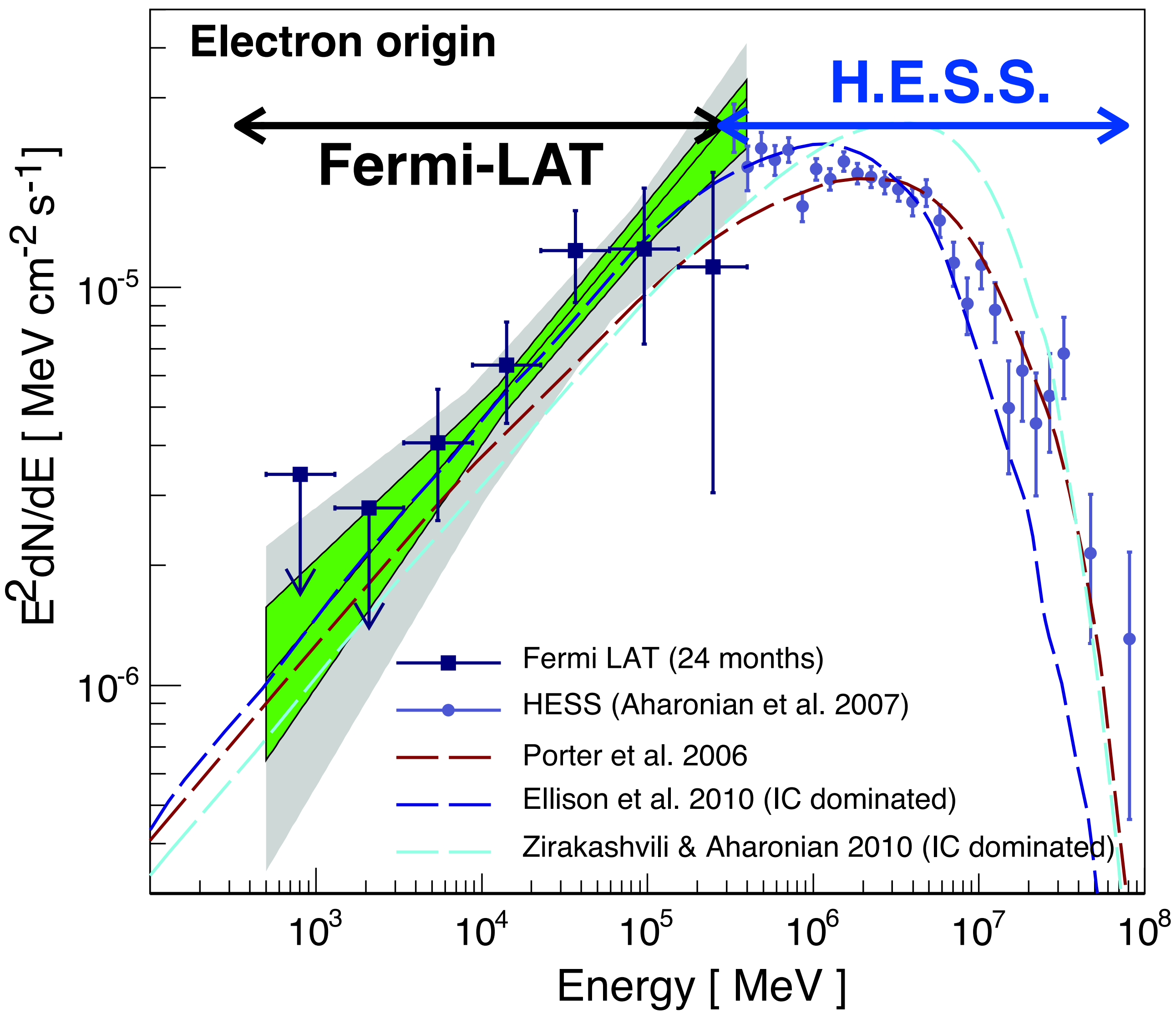
- H.E.S.S. observation of TeV gamma rays from RX J1713.7-3946
  - Evidence for “particle” acceleration > 10^{14} eV
  - Morphological similarity with X-ray observation
  - Spectral feature can not conclusively distinguish leptonic or hadronic origin of gamma rays

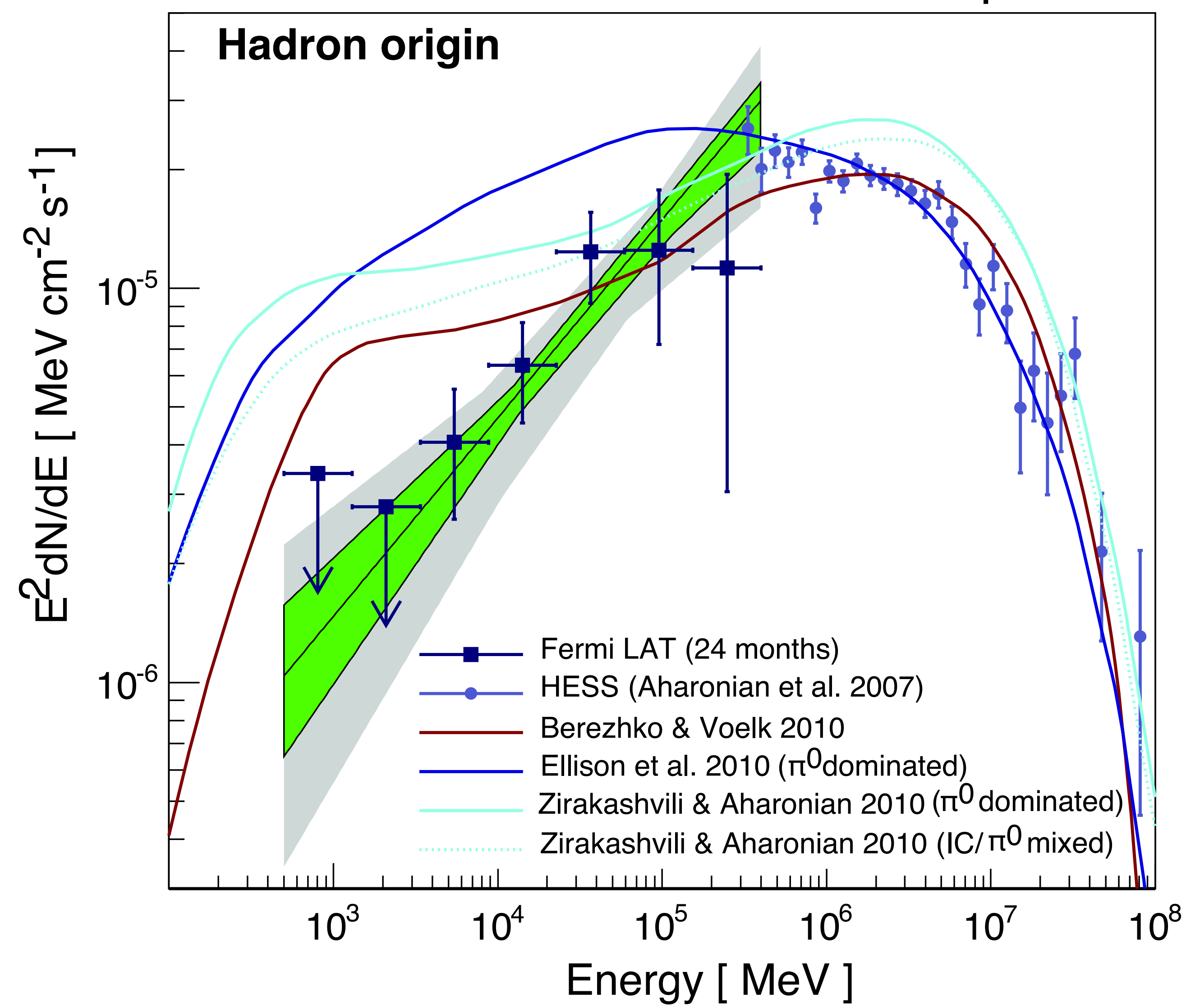




- Both models have issues describing Fermi and H.E.S.S. spectra at the same time
  - Requires further investigations to distinguish hadronic or leptonic nature of gamma-ray emissions

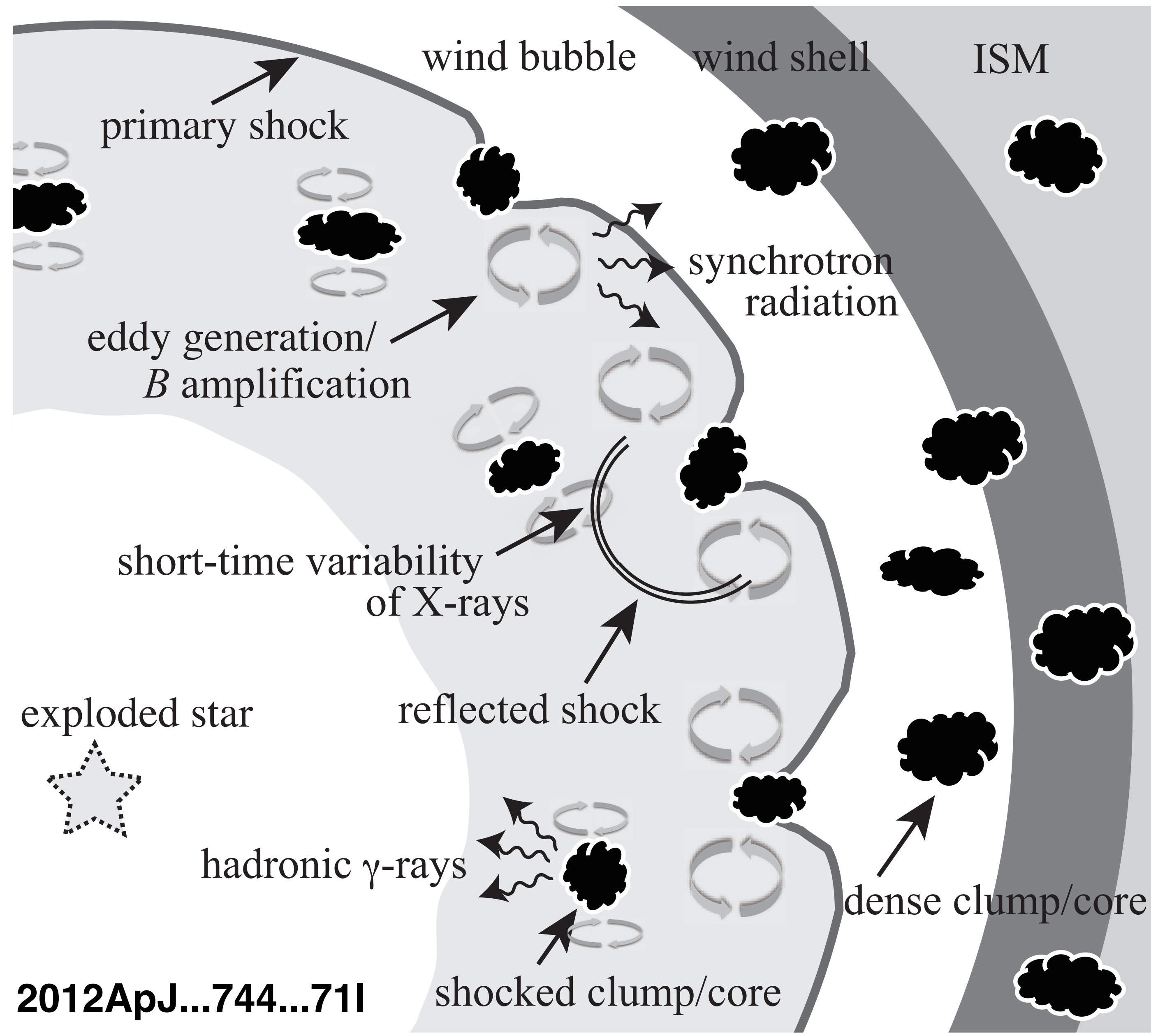
2011ApJ...734...28A





“Hard” Gamma-Ray Spectra

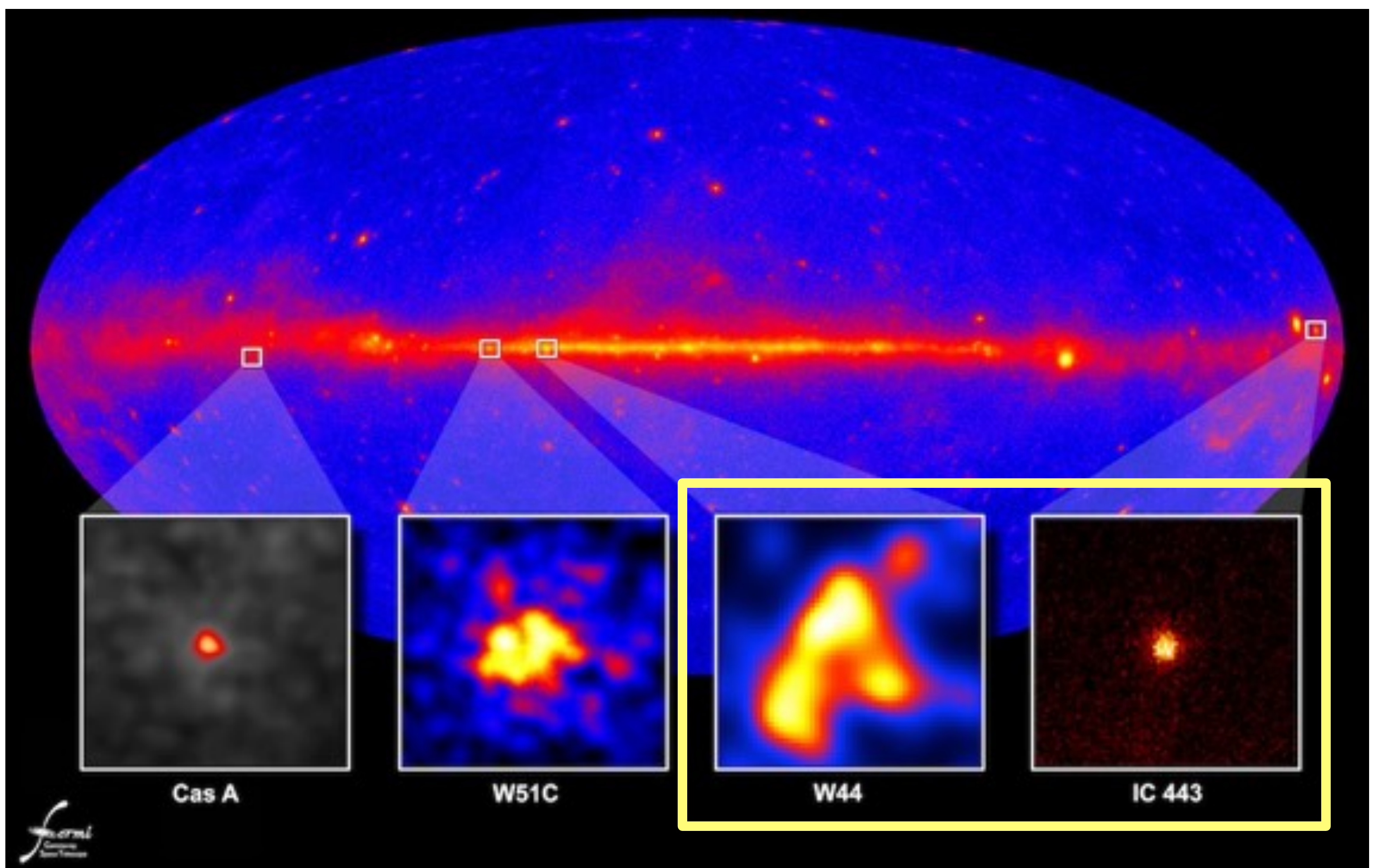
- “Hard” gamma-ray can be explained by higher target density for higher energy particles
  - Highly inhomogeneous molecular clouds interacting with SNR
  - Higher energy protons can penetrate into the cloud core where target gas density is high



2012ApJ...744...71I

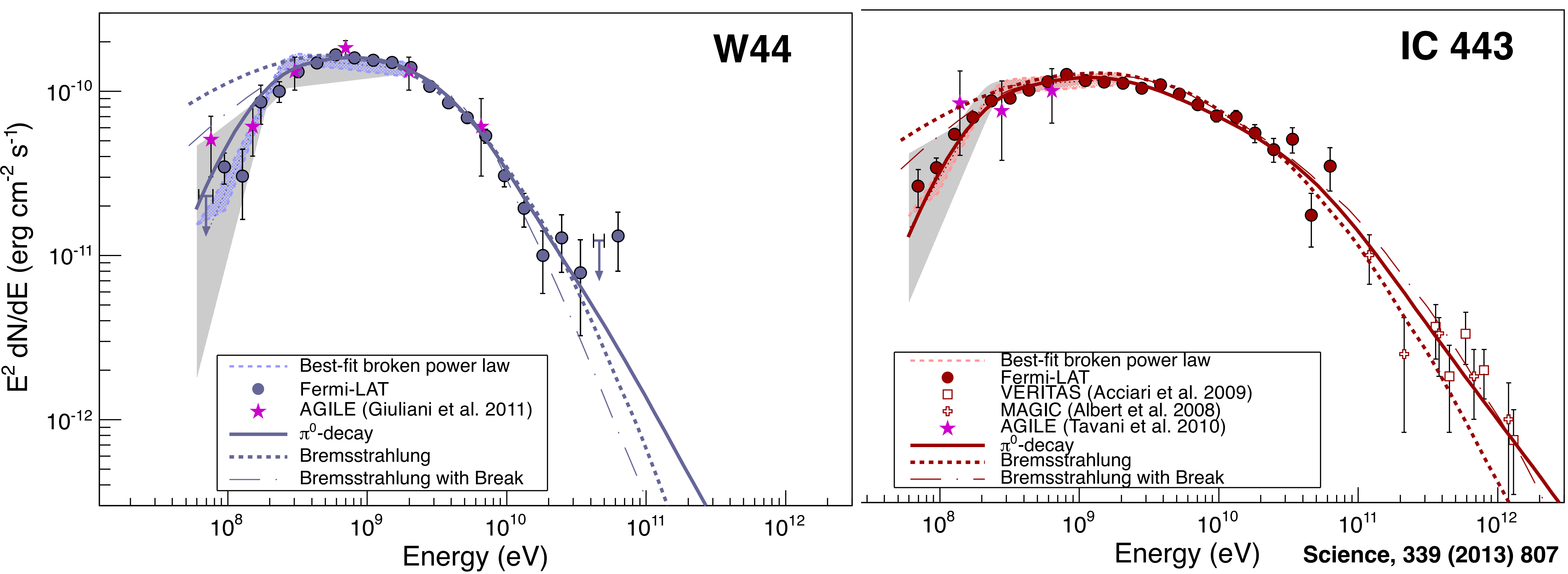
“Smoking gun” Signature of π^0-decay γ-rays

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



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

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

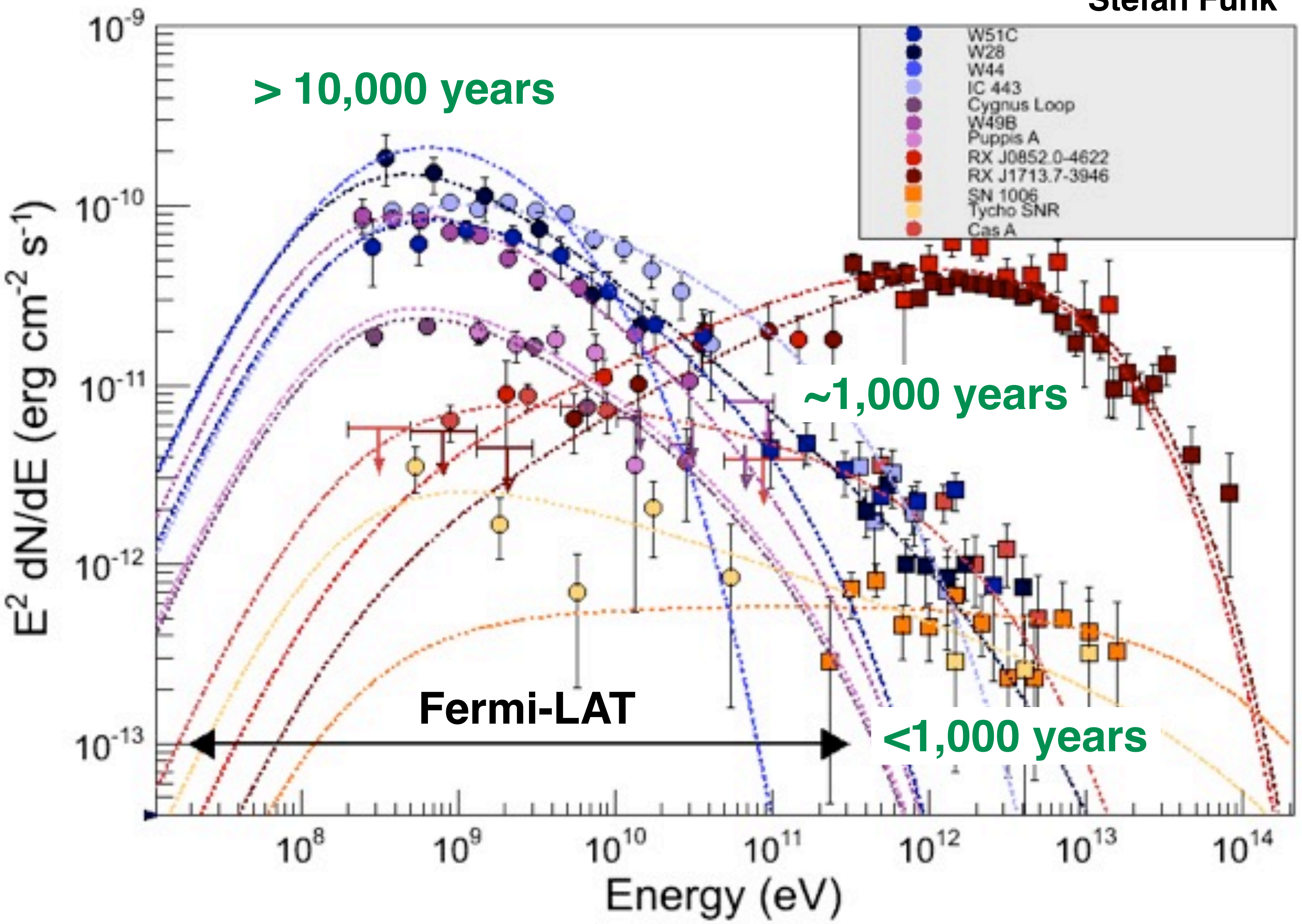


Science, 339 (2013) 807

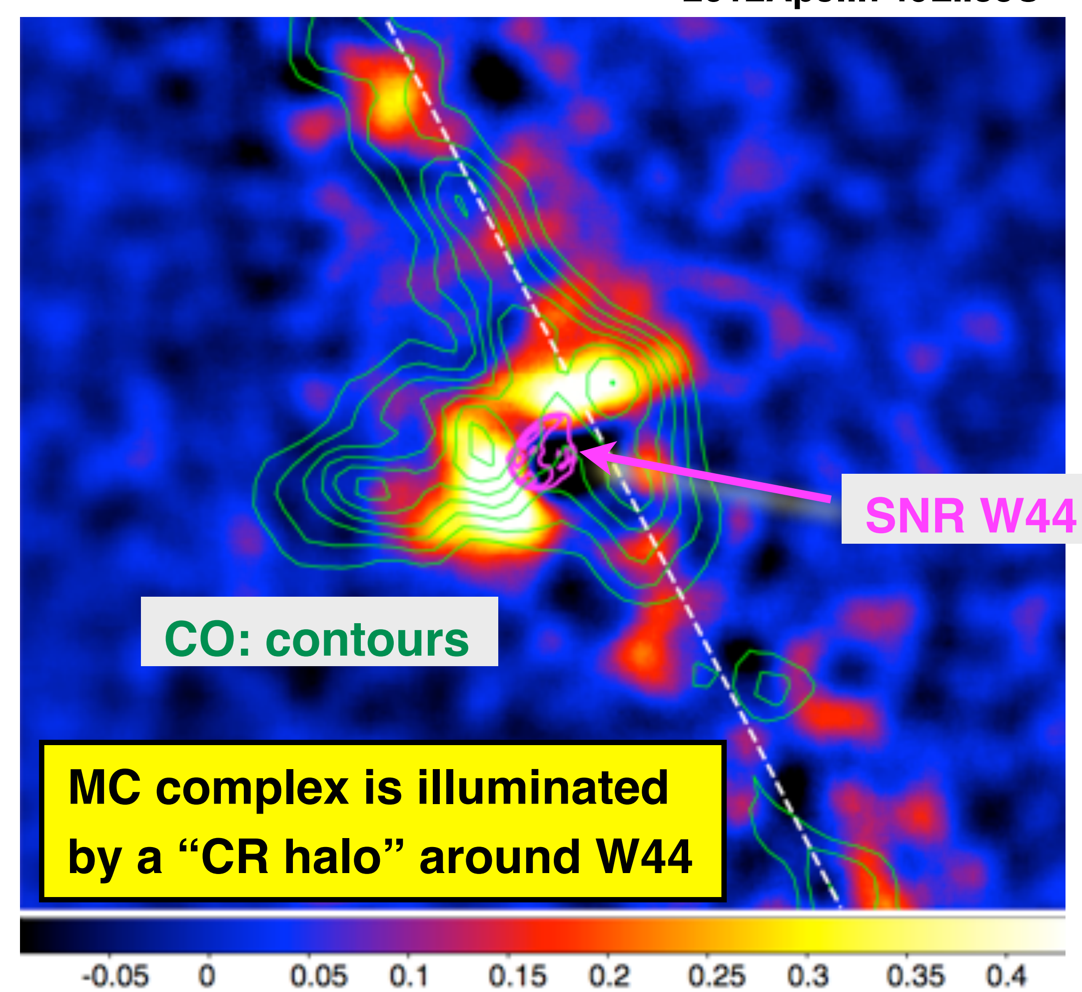
Remaining Issues

- We have not found SNRs which can accelerate CRs up to Knee energies (gamma-ray energy > 100 TeV): **PeVatrons**
  - Evolution with SNR age
  - Escape of CR from SNRs
- **We need to find more multi-TeV gamma-ray sources**

Stefan Funk

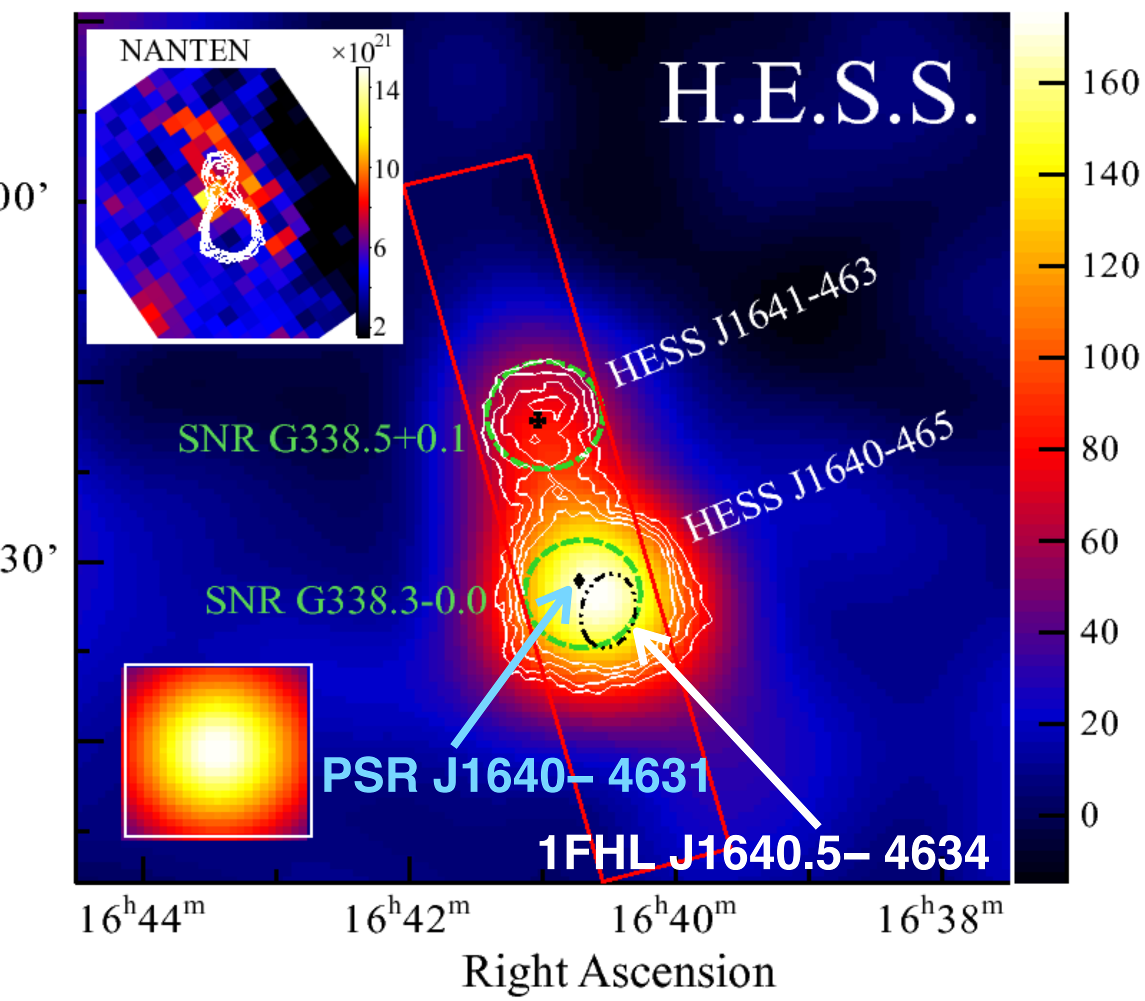


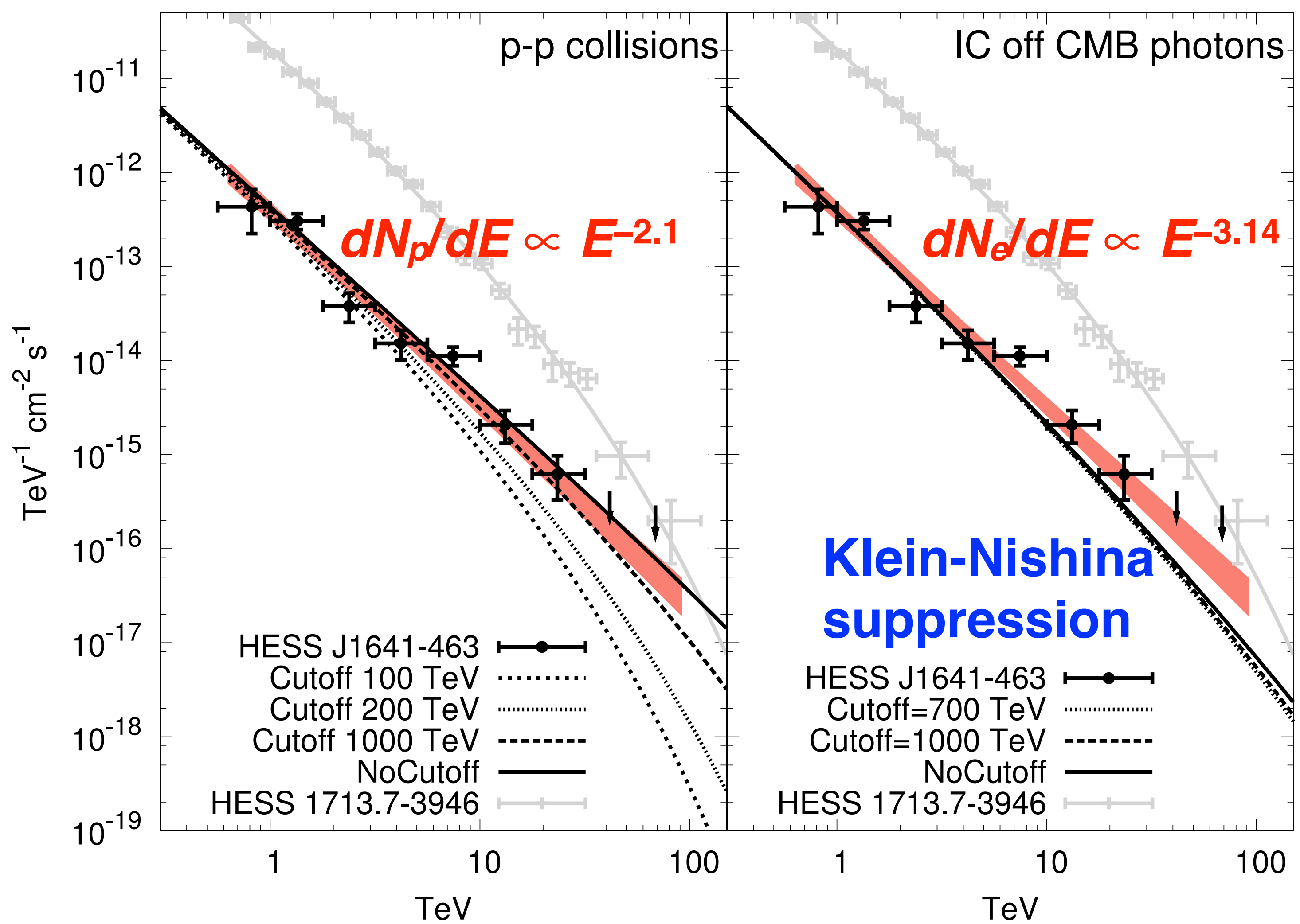
2012ApJ...749L..35U



- 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

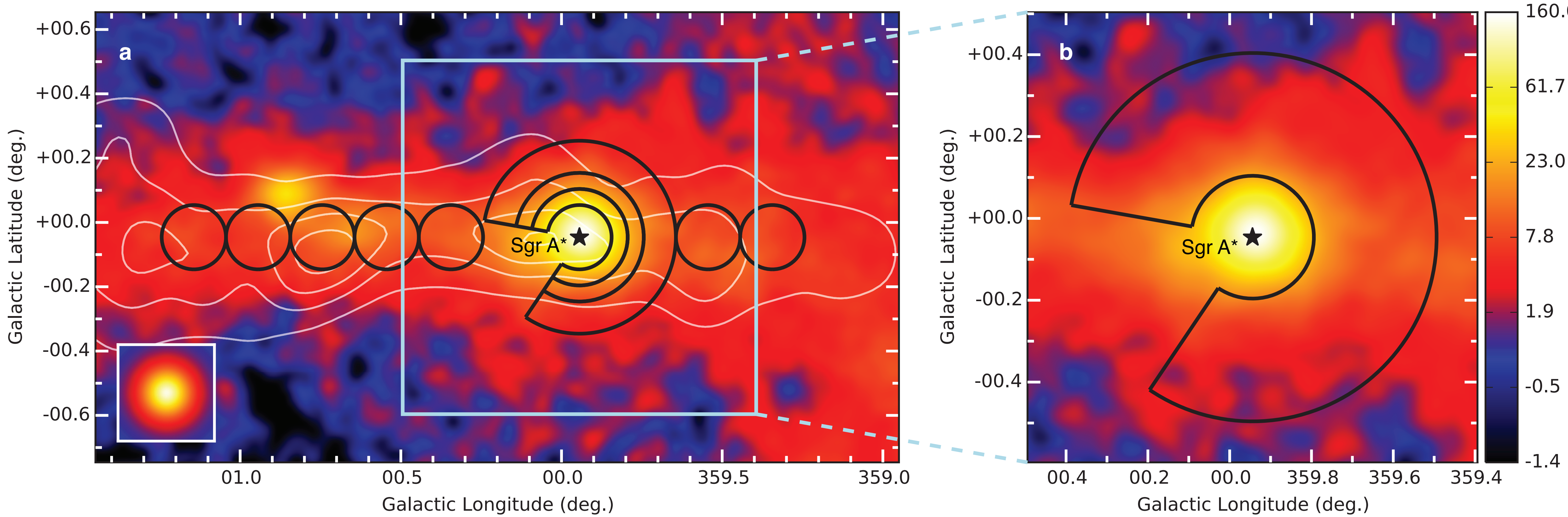




Another PeVatron Candidate

- H.E.S.S. found a PeVatron candidate in the Galactic center region
  - Diffuse gamma-ray emission correlate with interstellar matter
    - TeV electrons cannot propagate long distance
  - CR density shows 1/*r* dependence
    - Implies continuous injection from a source and propagation by diffusion
  - CR source can be Sgr A* (supermassive blackhole in GC) or SNR G359.95–0.04
    - Both can explain total proton energy of 1.0×10^{49} erg
- Spectrum implies hadronic origin with E_{max} > 3 PeV

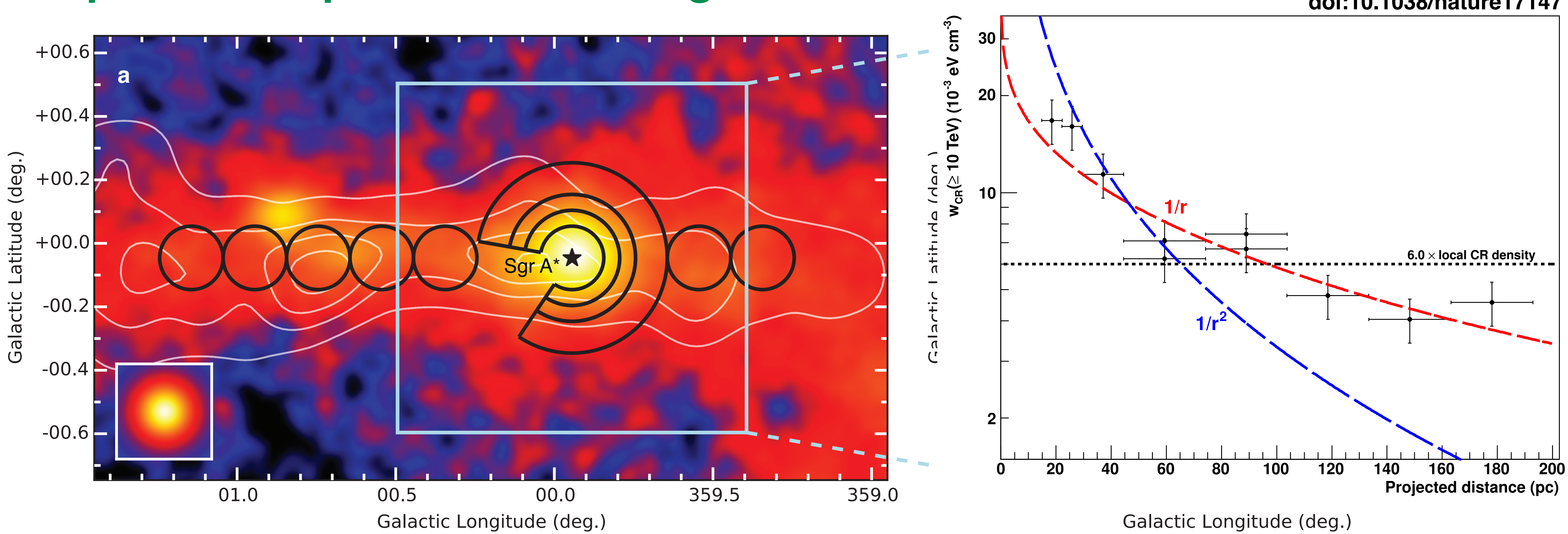
doi:10.1038/nature17147



Another PeVatron Candidate

- H.E.S.S. found a PeVatron candidate in the Galactic center region
  - Diffuse gamma-ray emission correlate with interstellar matter
    - TeV electrons cannot propagate long distance
  - CR density shows 1/*r* dependence
    - Implies continuous injection from a source and propagation by diffusion
  - CR source can be Sgr A* (supermassive blackhole in GC) or SNR G359.95–0.04
    - Both can explain total proton energy of 1.0×10^{49} erg
- Spectrum implies hadronic origin with E_{max} > 3 PeV

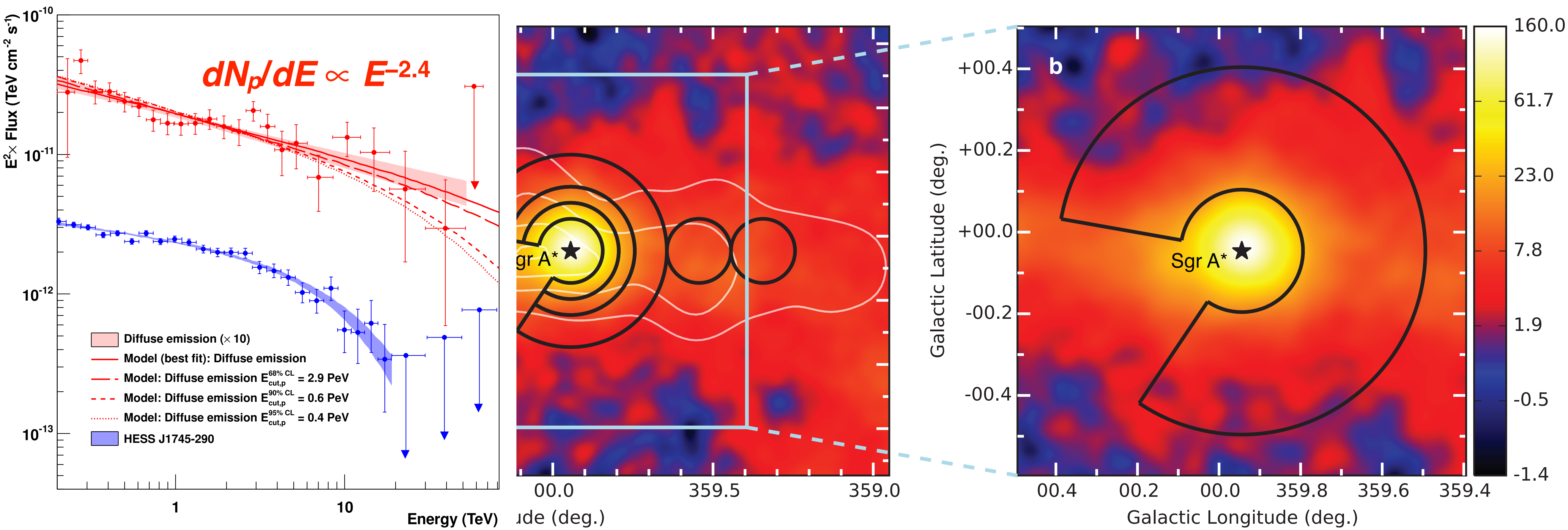
doi:10.1038/nature17147



Another PeVatron Candidate

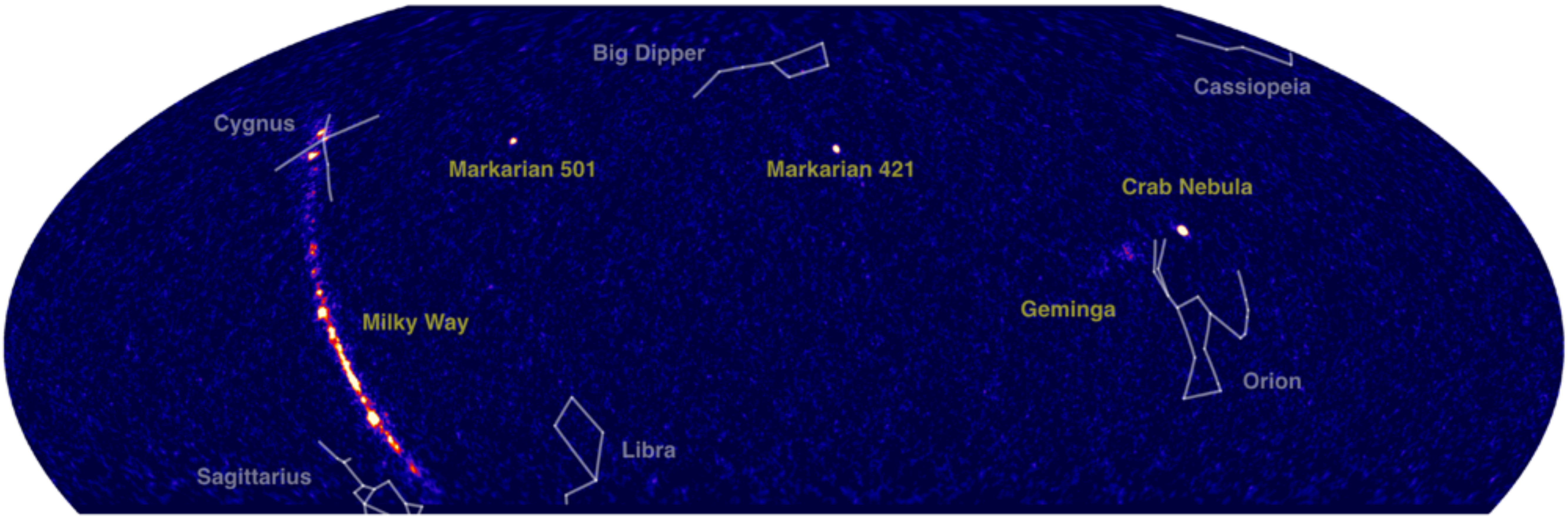
- H.E.S.S. found a PeVatron candidate in the Galactic center region
  - Diffuse gamma-ray emission correlate with interstellar matter
    - TeV electrons cannot propagate long distance
  - CR density shows 1/*r* dependence
    - Implies continuous injection from a source and propagation by diffusion
  - CR source can be Sgr A* (supermassive blackhole in GC) or SNR G359.95–0.04
    - Both can explain total proton energy of 1.0×10^{49} erg
- Spectrum implies hadronic origin with $E_{max} > 3$ PeV

doi:10.1038/nature17147



HAWC View of Northern Sky

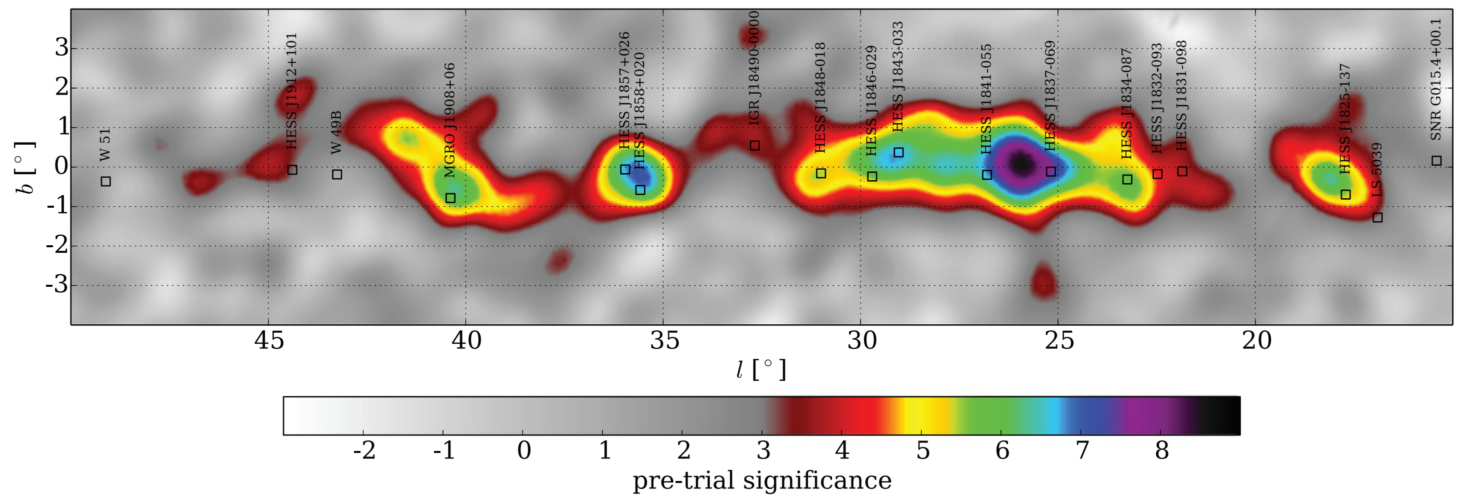
- HAWC found many multi-TeV gamma-ray sources along Galactic plane in the first year of operation with partial array



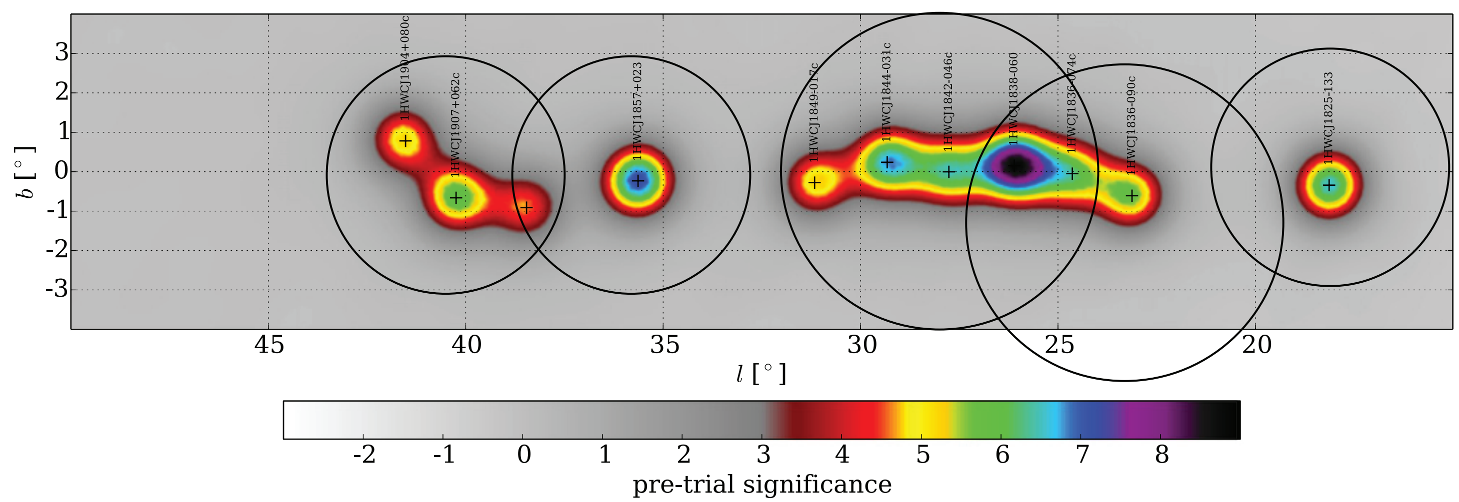
http://www.hawc-observatory.org

Significance Map of Galactic Plane

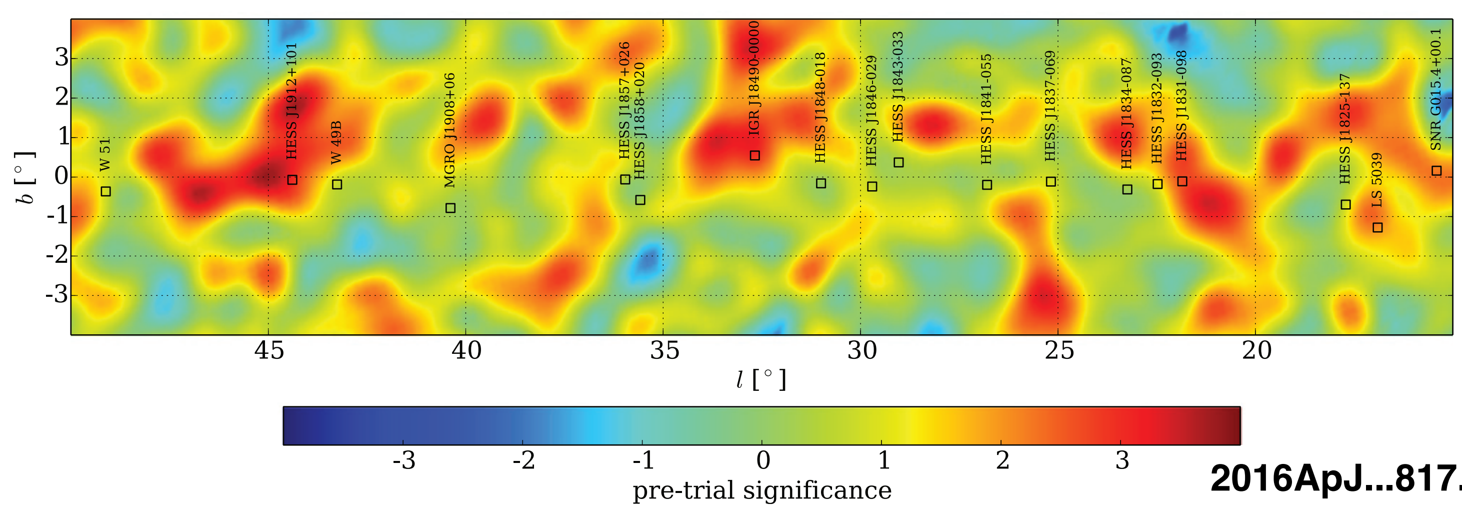
Significance map
with uniform diffuse gamma ray



Significance map for 11 seed sources



Residual



2016ApJ...817....3A

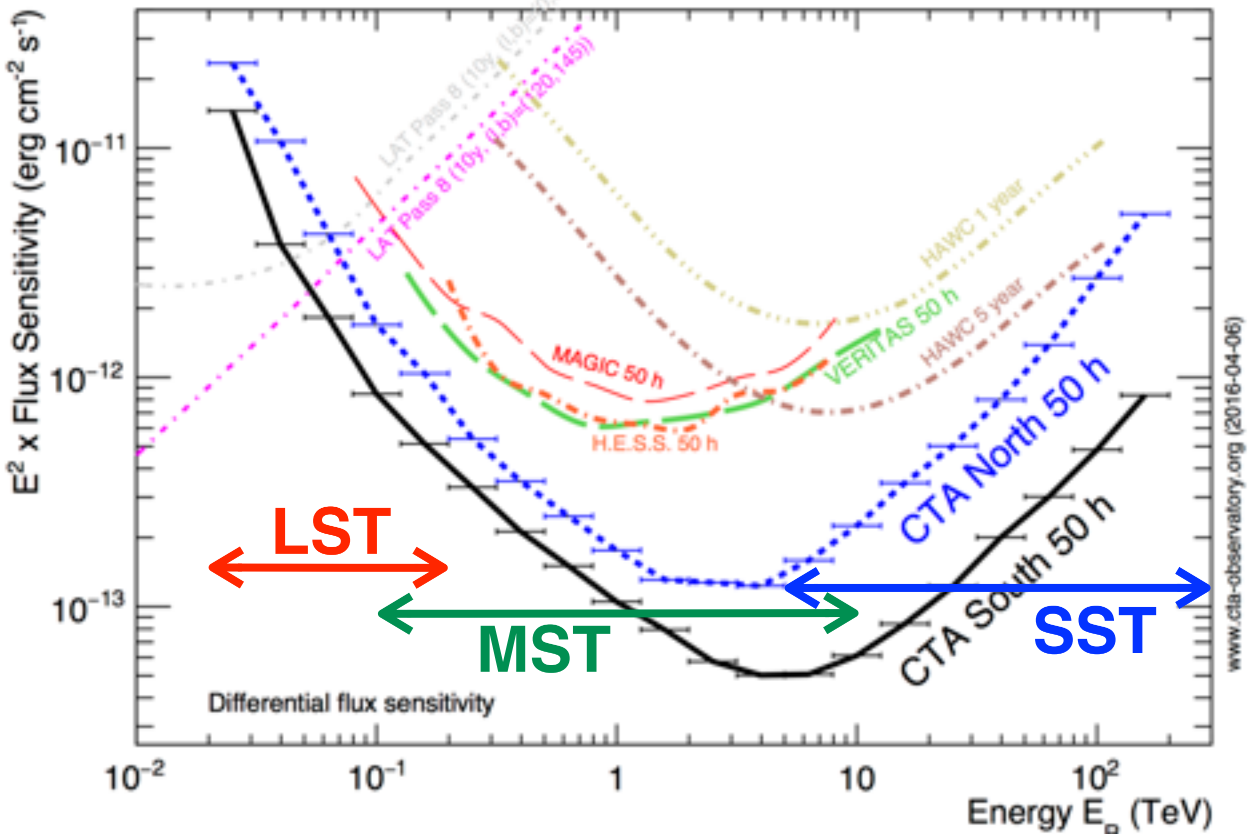
HAWC Galactic Source Candidates

Source	*l* (deg)	*b* (deg)	Flux (10^{-14} TeV/cm²/s)	Post-trial significance	Counterpart
1HWC J1907+062	40.2±0.2	–0.7±0.2	22.0±4.6 @4 TeV	4.6σ	HESS
1HWC J1904+080	41.5±0.2	0.8±0.2	19.0±4.4 @4 TeV	3.9σ	—
—	38.5±0.4	–0.9±0.4	—	2.5σ	—
1HWC J1857+023	35.6±0.2	–0.2±0.2	18.0±3.0 @5 TeV	6.2σ	HESS, MAGIC
1HWC J1838–060	26.1±0.3	0.2±0.3	11.3±1.2 @7 TeV	6.1σ	HESS
1HWC J1844–031	29.3±0.2	0.2±0.2	11.8±2.4 @6 TeV	4.7σ	HESS
1HWC J1849–017	31.2±0.3	–0.3±0.3	9.1±2.2 @6 TeV	3.7σ	HESS
1HWC J1842–046	27.8±0.3	0.0±0.3	7.0±1.6 @7 TeV	3.4σ	HESS
1HWC J1836–090	23.1±0.3	–0.6±0.3	5.8±1.3 @8 TeV	3.2σ	HESS
1HWC J1836–074	24.6±0.3	0.0±0.3	6.9±1.4 @7 TeV	3.2σ	HESS
1HWC J1825–133	18.1±0.2	–0.3±0.2	7.3±1.4 @9 TeV	5.4σ	HESS

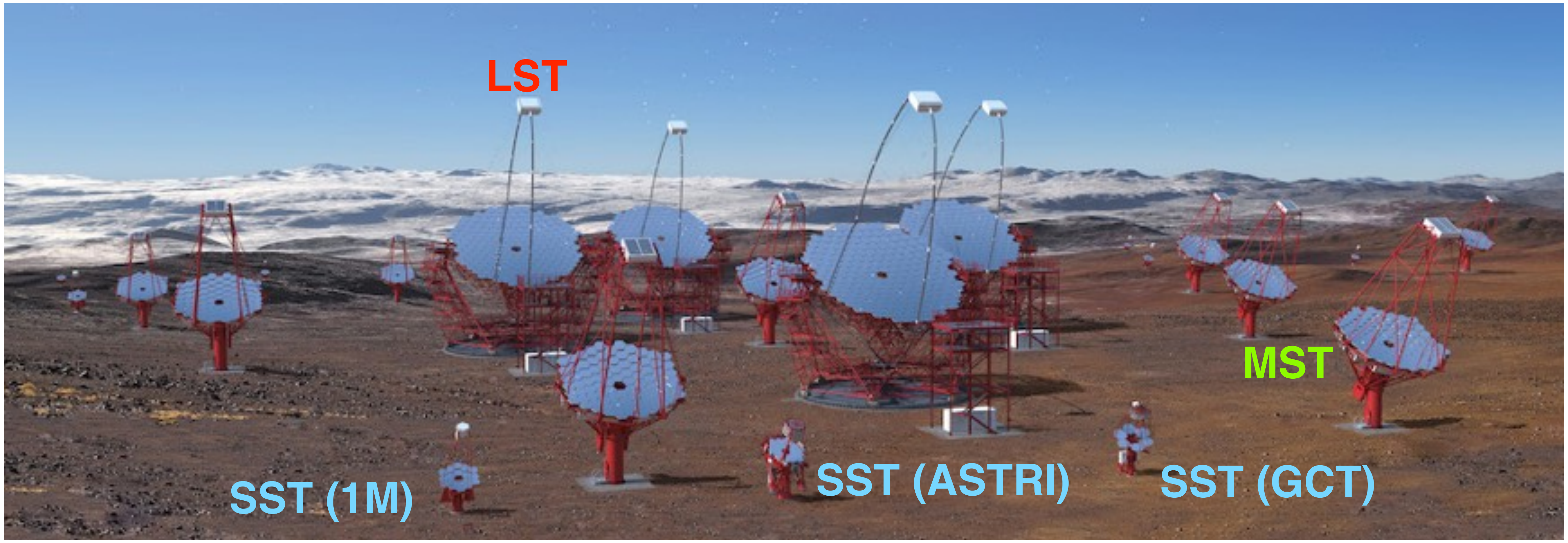
2016ApJ...817....3A

Future Gamma-ray Observatory

- Cherenkov Telescope Array (CTA)
  - 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
  - ~1000 of TeV gamma-ray sources



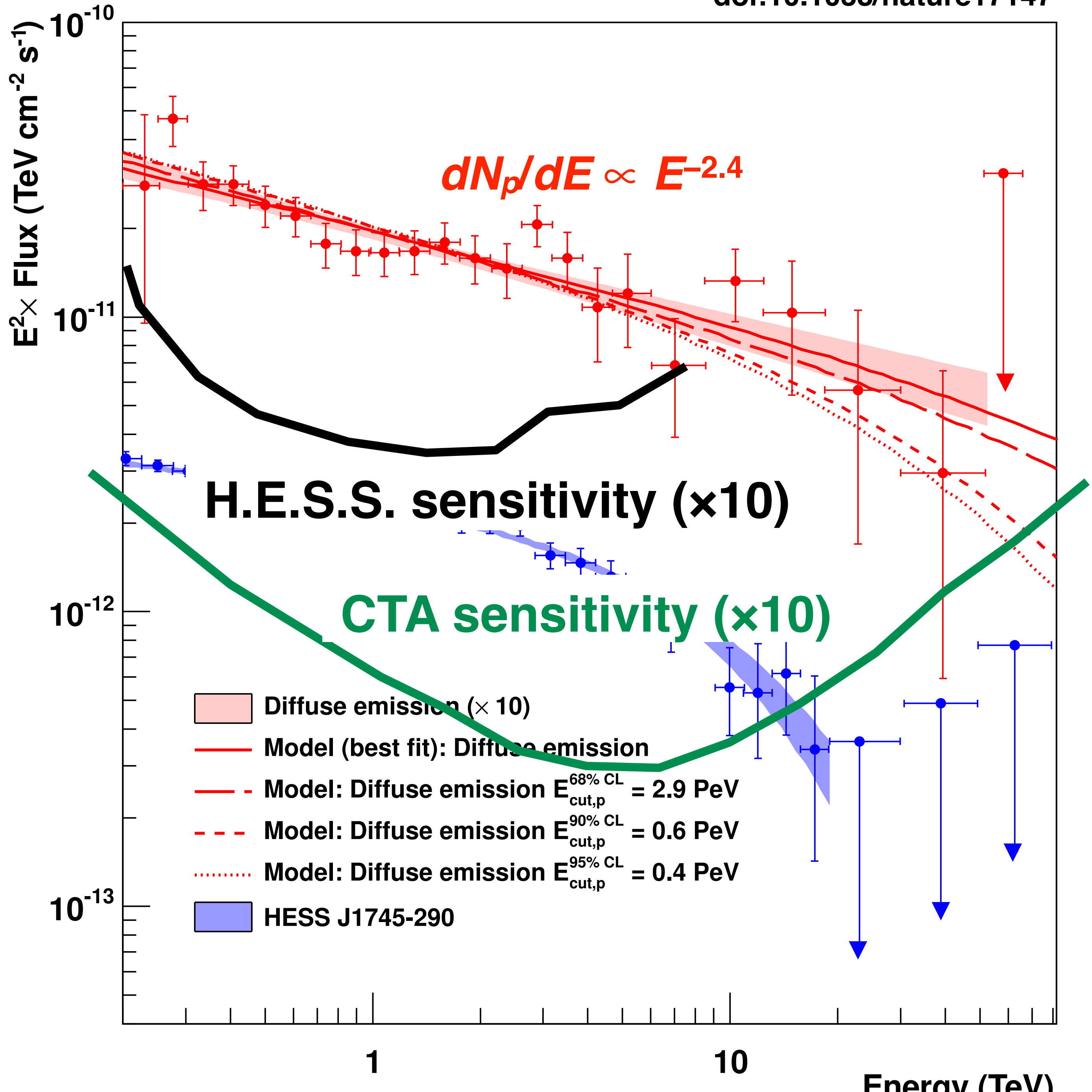
G. Pérez, IAC, SMM



Expected CTA Performance

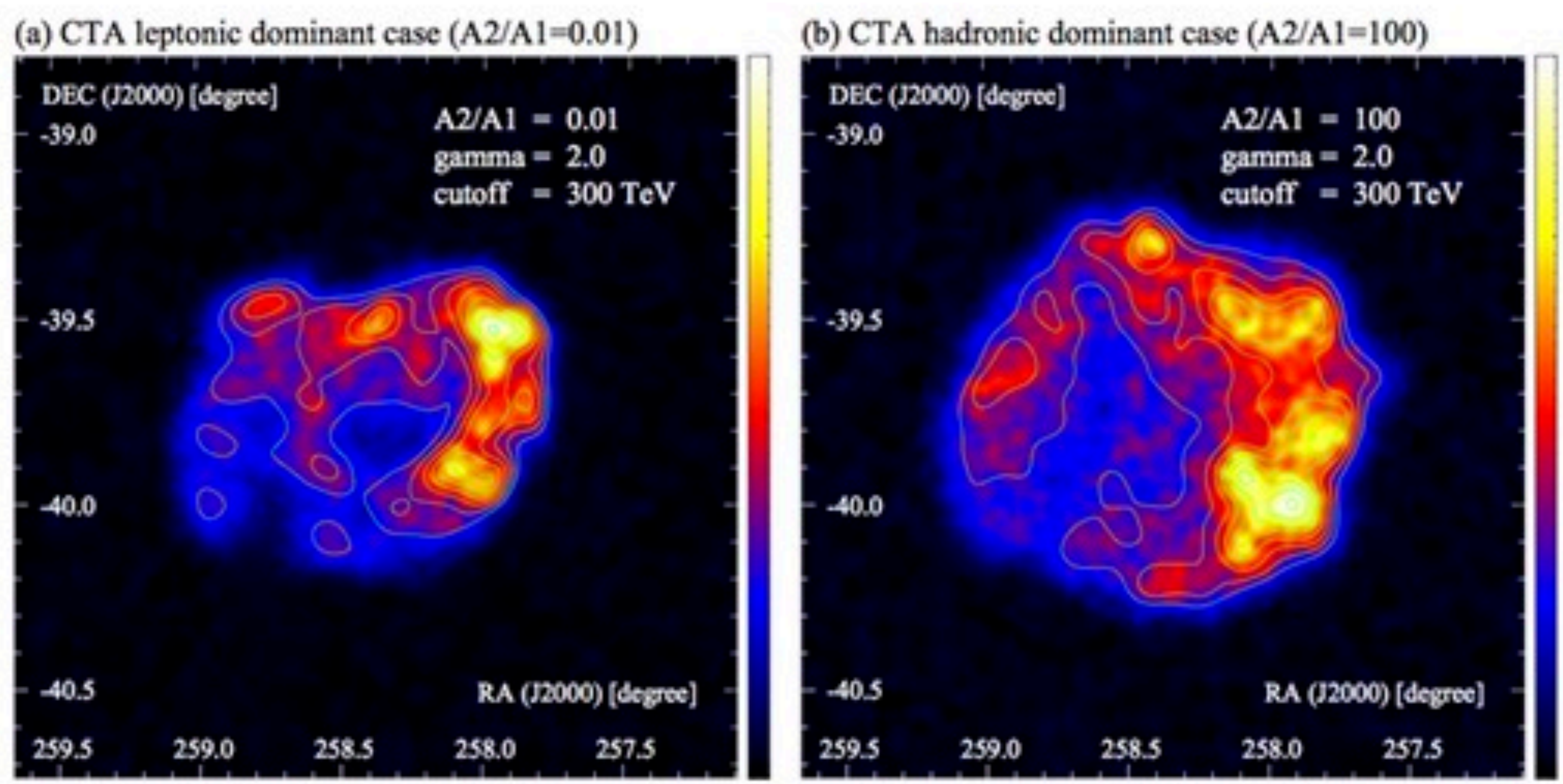
- CTA will provide precise spectral measurements up to 100 TeV
- CTA will provide better imaging of TeV gamma-ray sources

doi:10.1038/nature17147



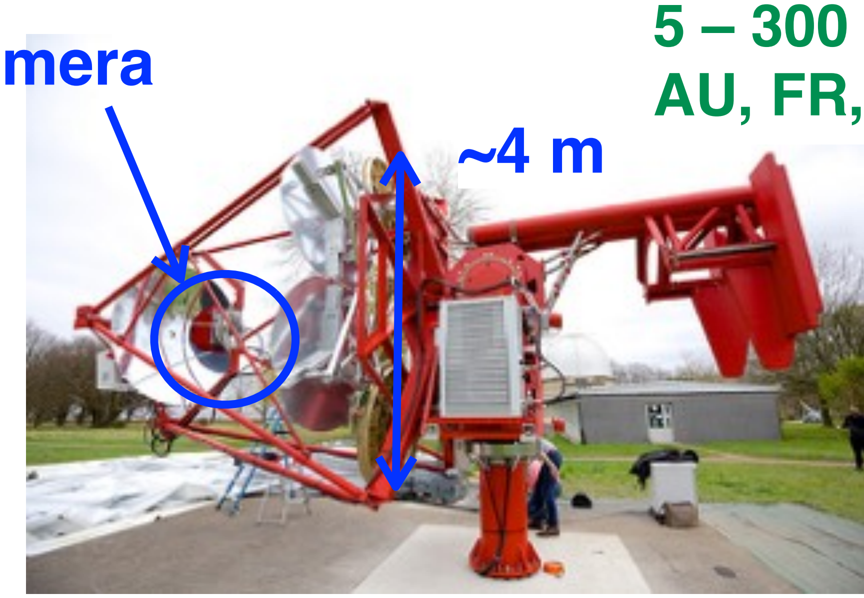
Expected CTA Performance

- CTA will provide precise spectral measurements up to 100 TeV
- CTA will provide better imaging of TeV gamma-ray sources

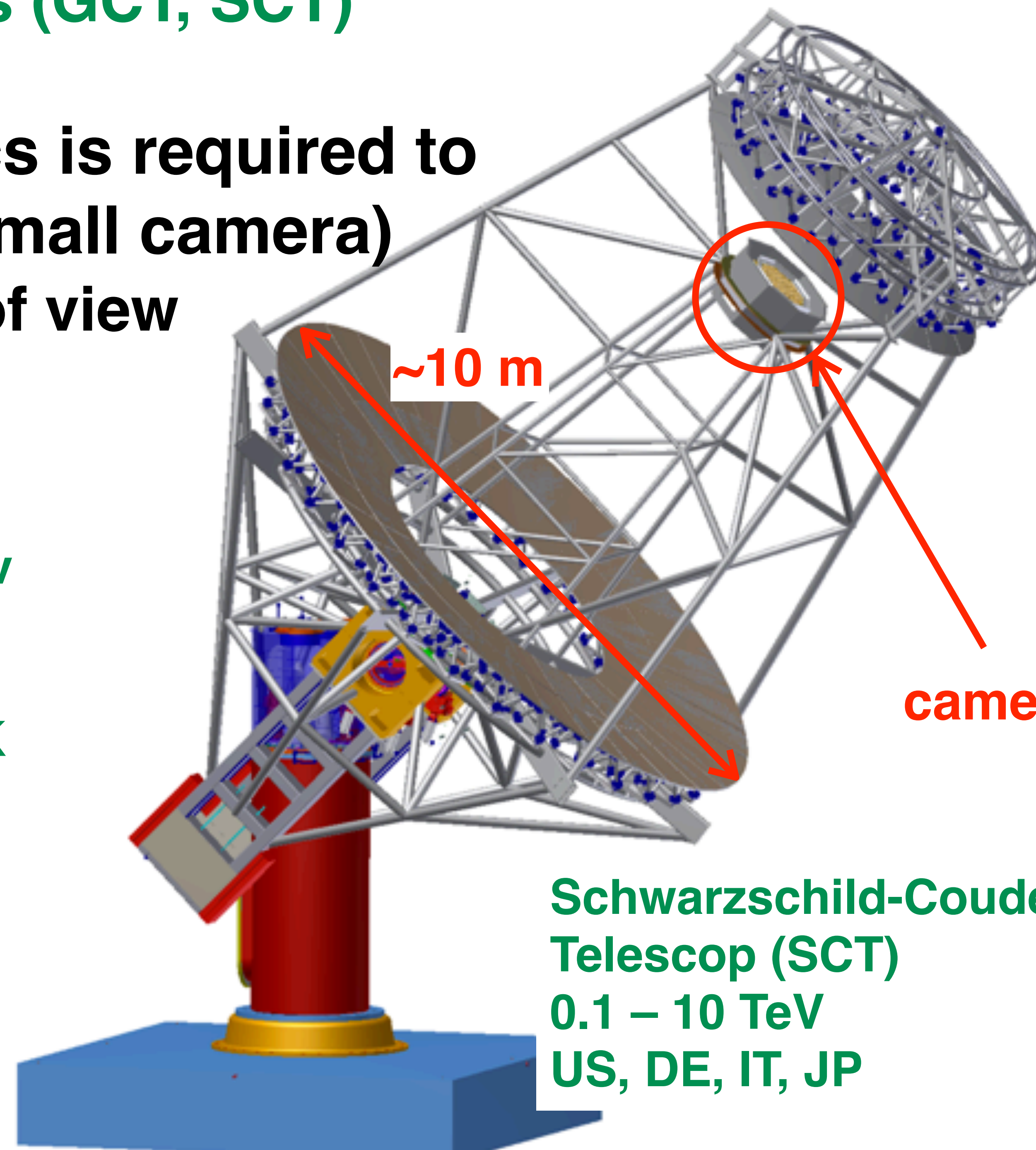


Nagoya Involvements with CTA

- Silicon photomultiplier (SiPM) camera for dual-mirror telescopes
  - SiPM: low cost, durable, high photon detection efficiency (GCT)
  - High-density front-end electronics (GCT, SCT)
  - Camera software (GCT)
- 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

GCT Development Status

- “First light” of GCT prototype achieved with cosmic-ray showers
  - Contributions from Nagoya group
    - Front-end electronics (Tajima)
    - Camera software (Okumura)

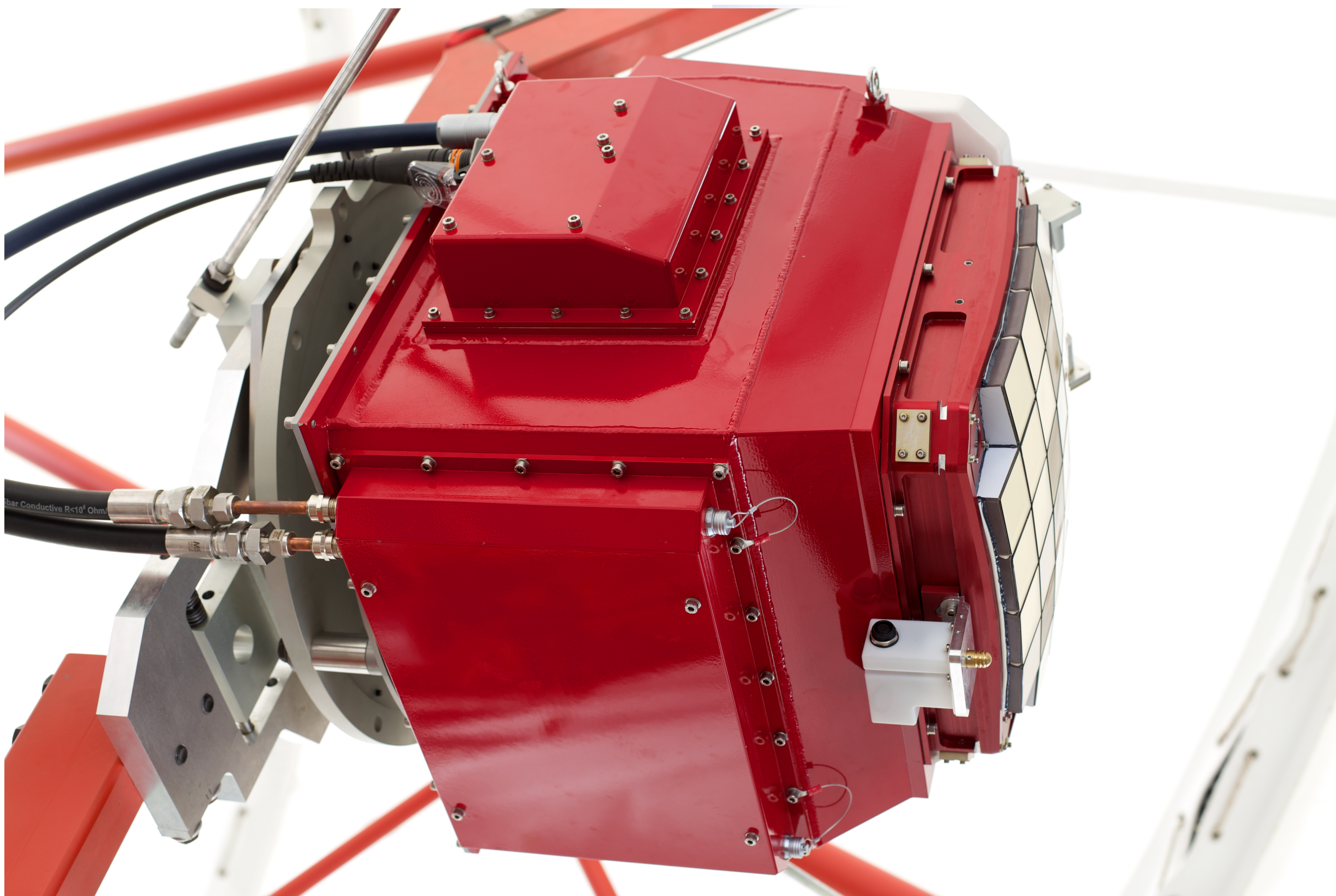
photo taken by Okumura

CTA collaboration

GCT Development Status

- "First light" of GCT prototype achieved with cosmic-ray showers
  - Contributions from Nagoya group
    - Front-end electronics (Tajima)
    - Camera software (Okumura)

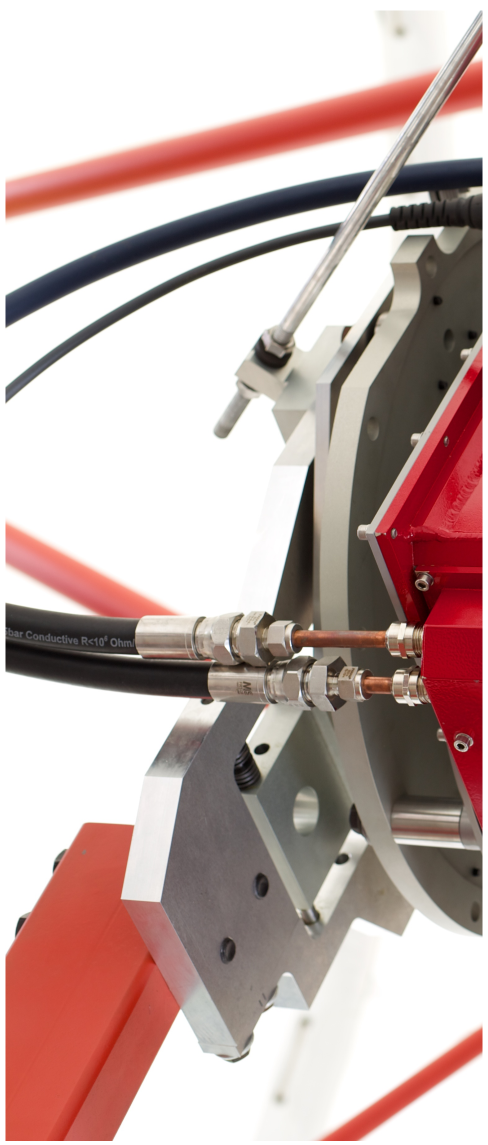
photo taken by Okumura



CTA collaboration

GCT Development Status

- “First light” of GCT prototype achieved with cosmic-ray showers
  - Contributions from Nagoya group
    - Front-end electronics (Tajima)
    - Camera software (Okumura)



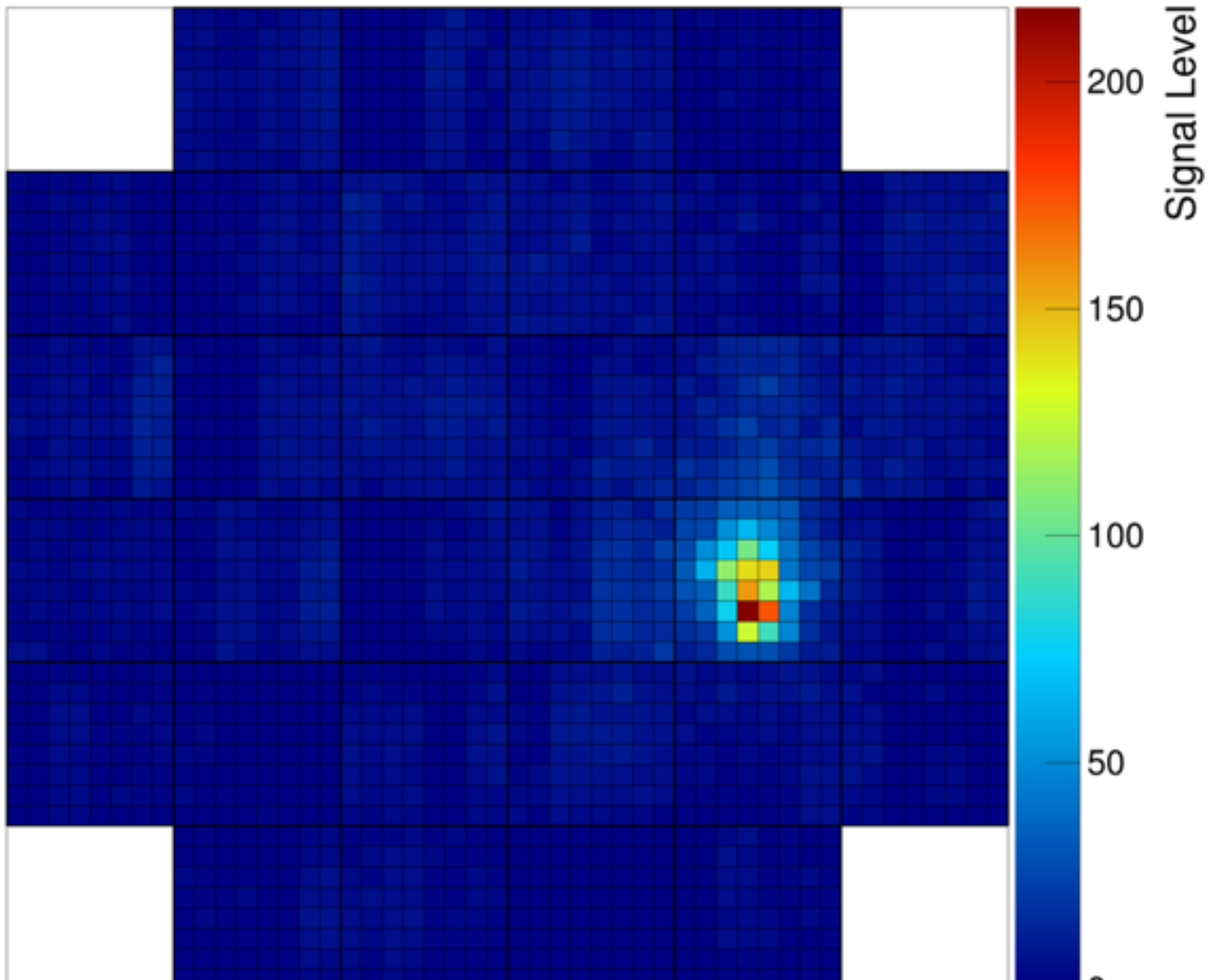
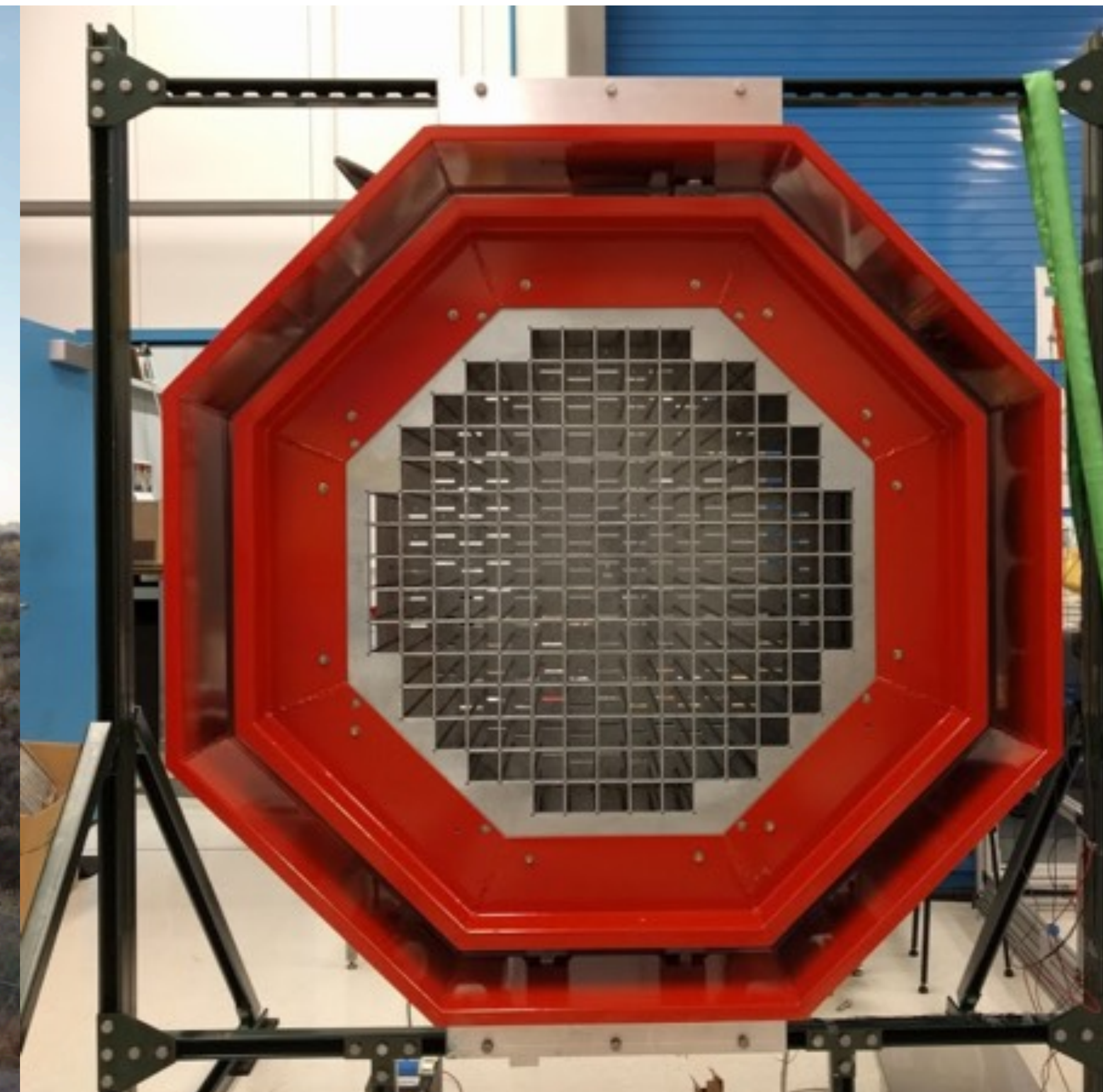


photo taken by Okumura

CTA collaboration

SCT Development Status

- Prototype is being constructed at Arizona
  - Test performance of SC optics and SiPM camera



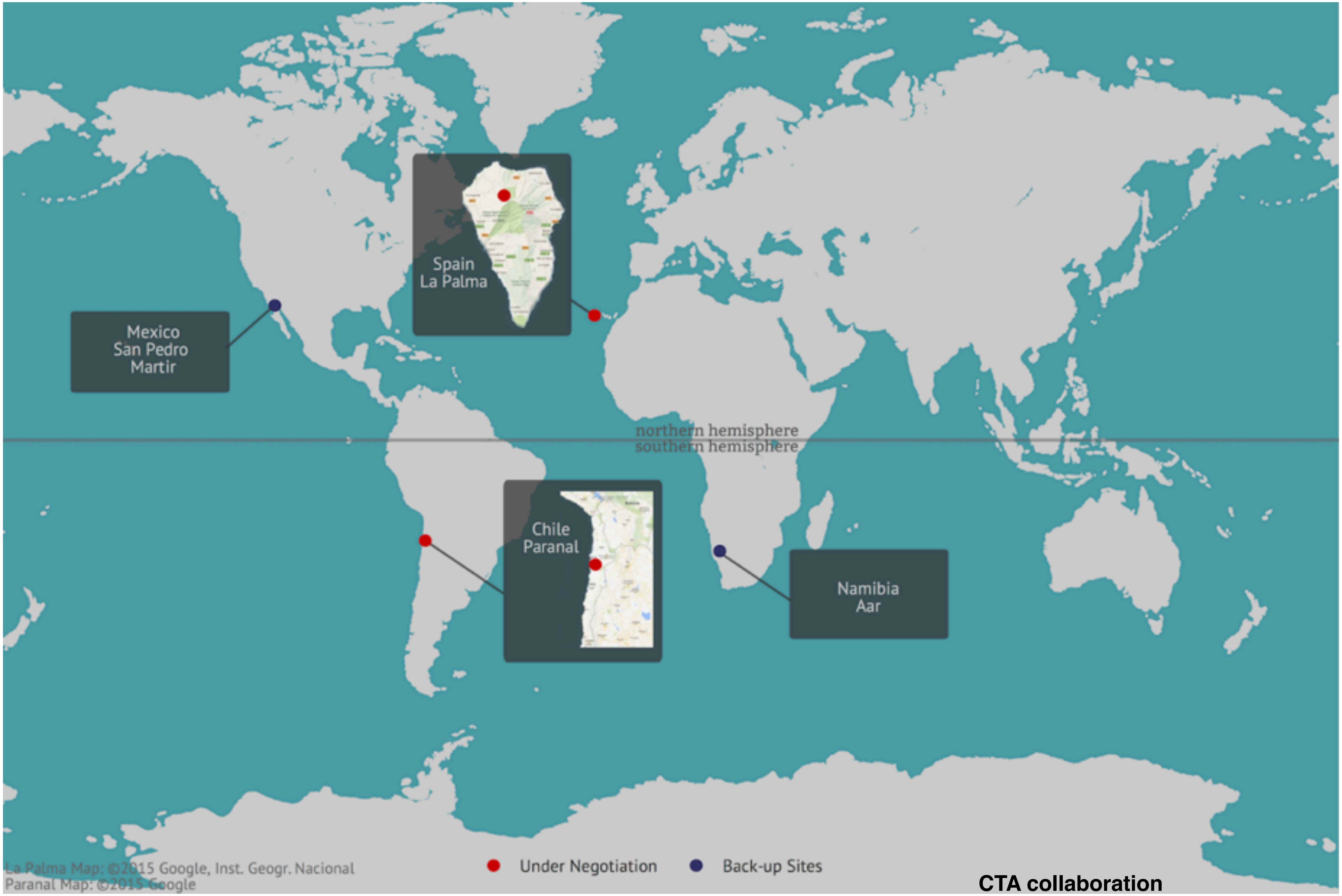
CTA collaboration

Summary

- At least two origins are expected for cosmic rays
  - Galactic origin may have acceleration limit at a few PeV (PeVatron)
  - Extragalactic origin may be dominant above ~10^{17} eV
- Supernova remnants (SNRs) are the leading candidate for Galactic cosmic rays
  - 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 my be an SNR, the other may be a supermassive blackhole
  - HAWC is expected to find more PeVatron candidates in northern sky with longer operations of the full array
  - CTA is expected to provide more insights into the nature of those PeVatron candidates

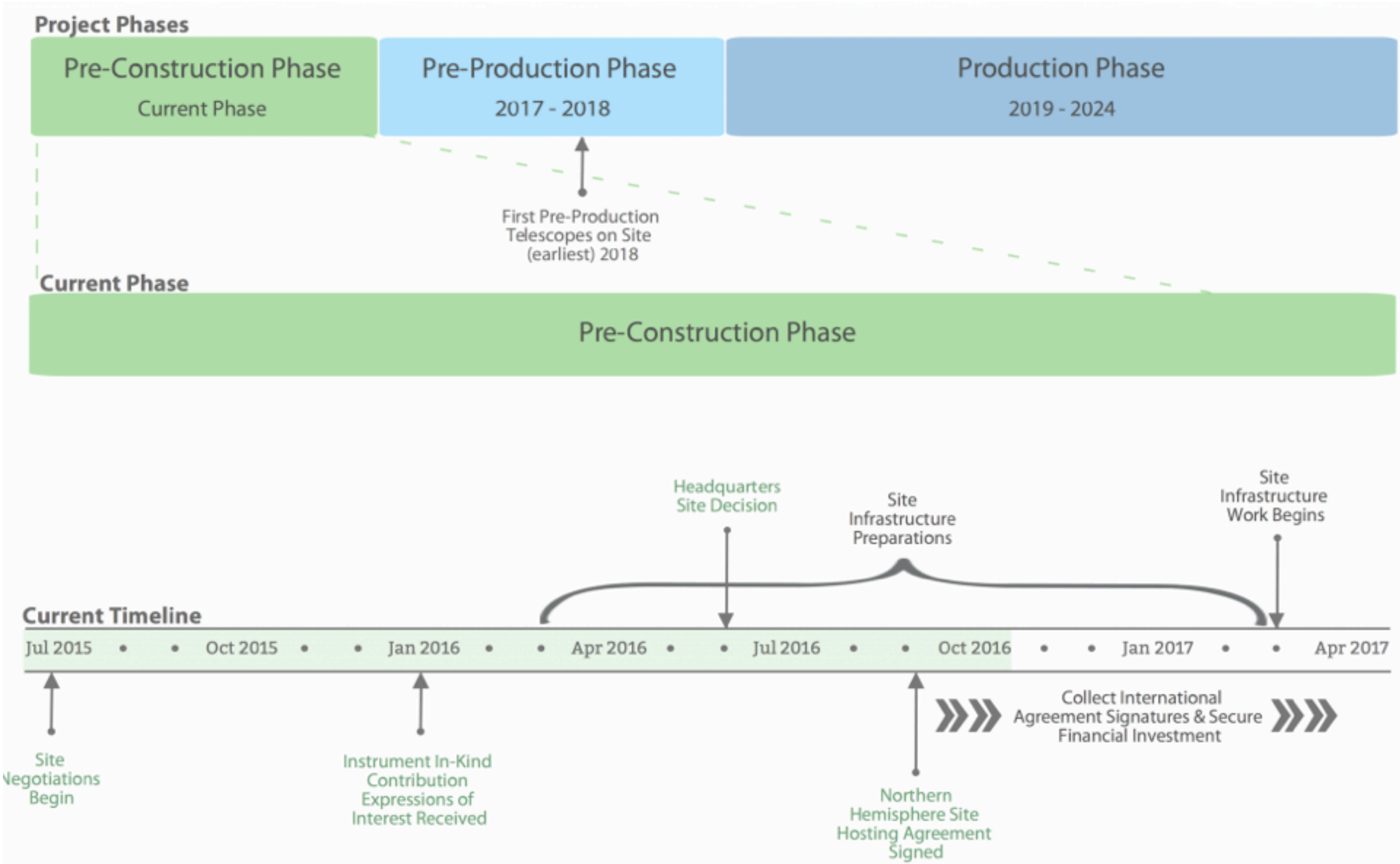
Supplemental Slides

CTA Sites



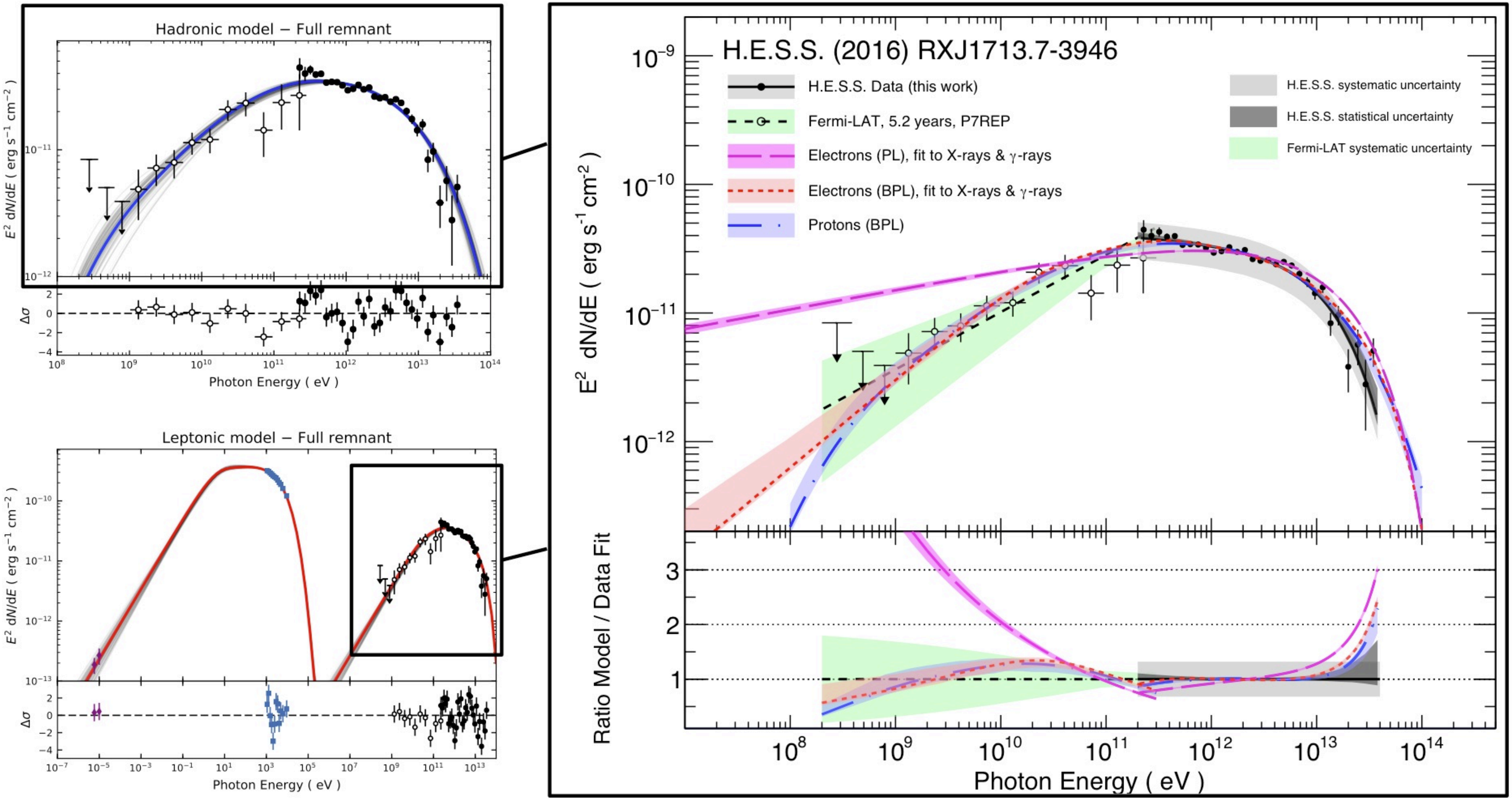
CTA collaboration

CTA Project Timeline



CTA collaboration (as of Oct, 2016)

Latest Results on RX J1713.7-3946



1609.08671v1