Recent Developments on Very-High-Energy Gamma-Ray Astronomy

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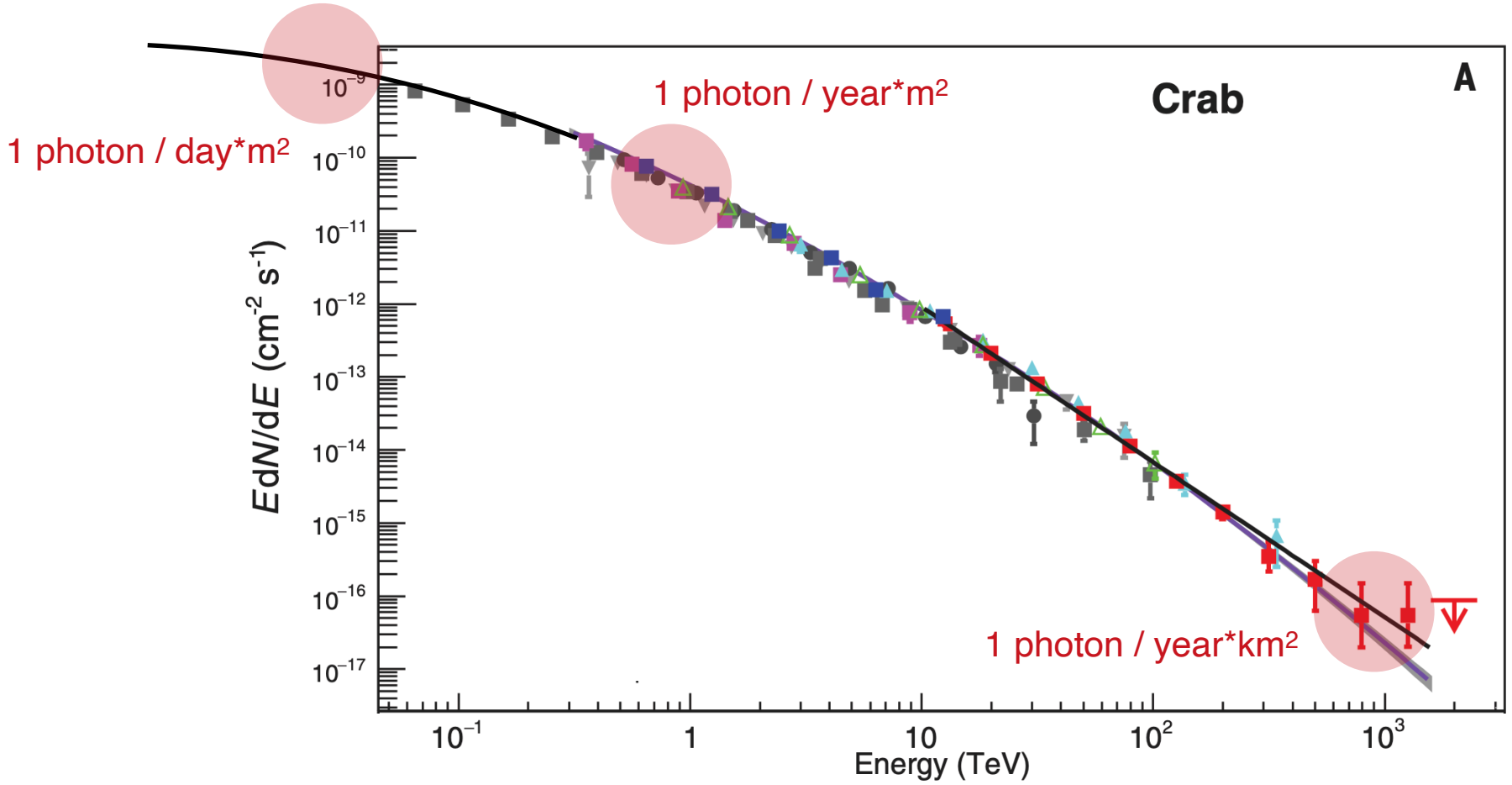
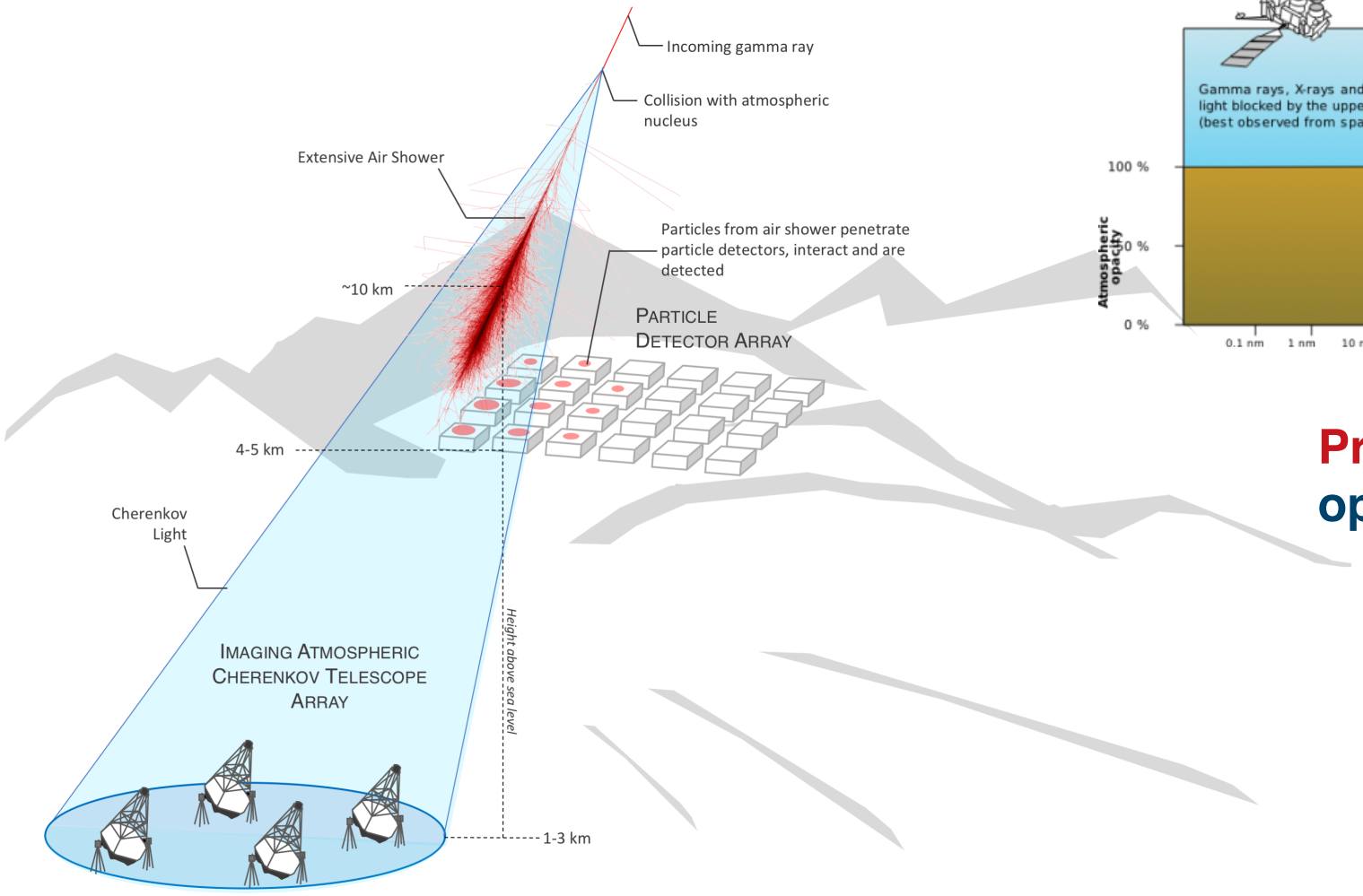
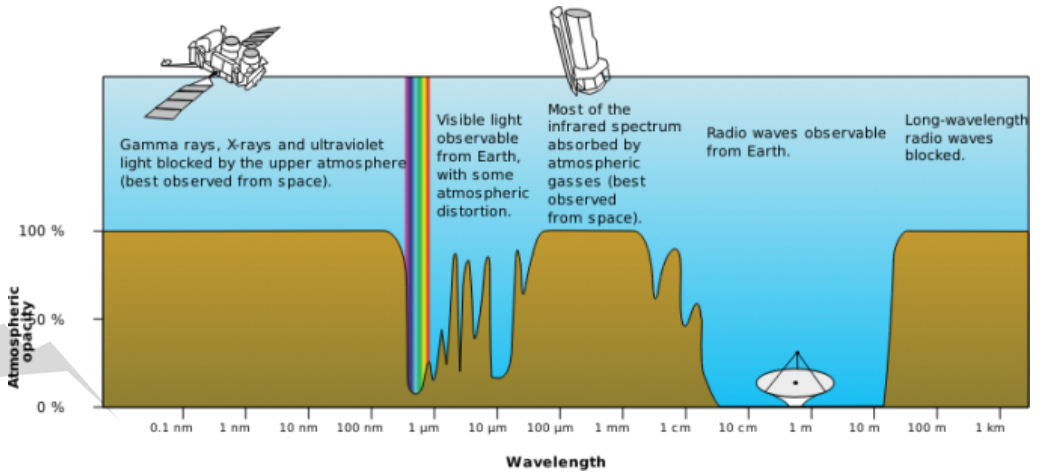
~~Very-High-Energy~~ Gamma-Ray Astronomy

Ground-Based



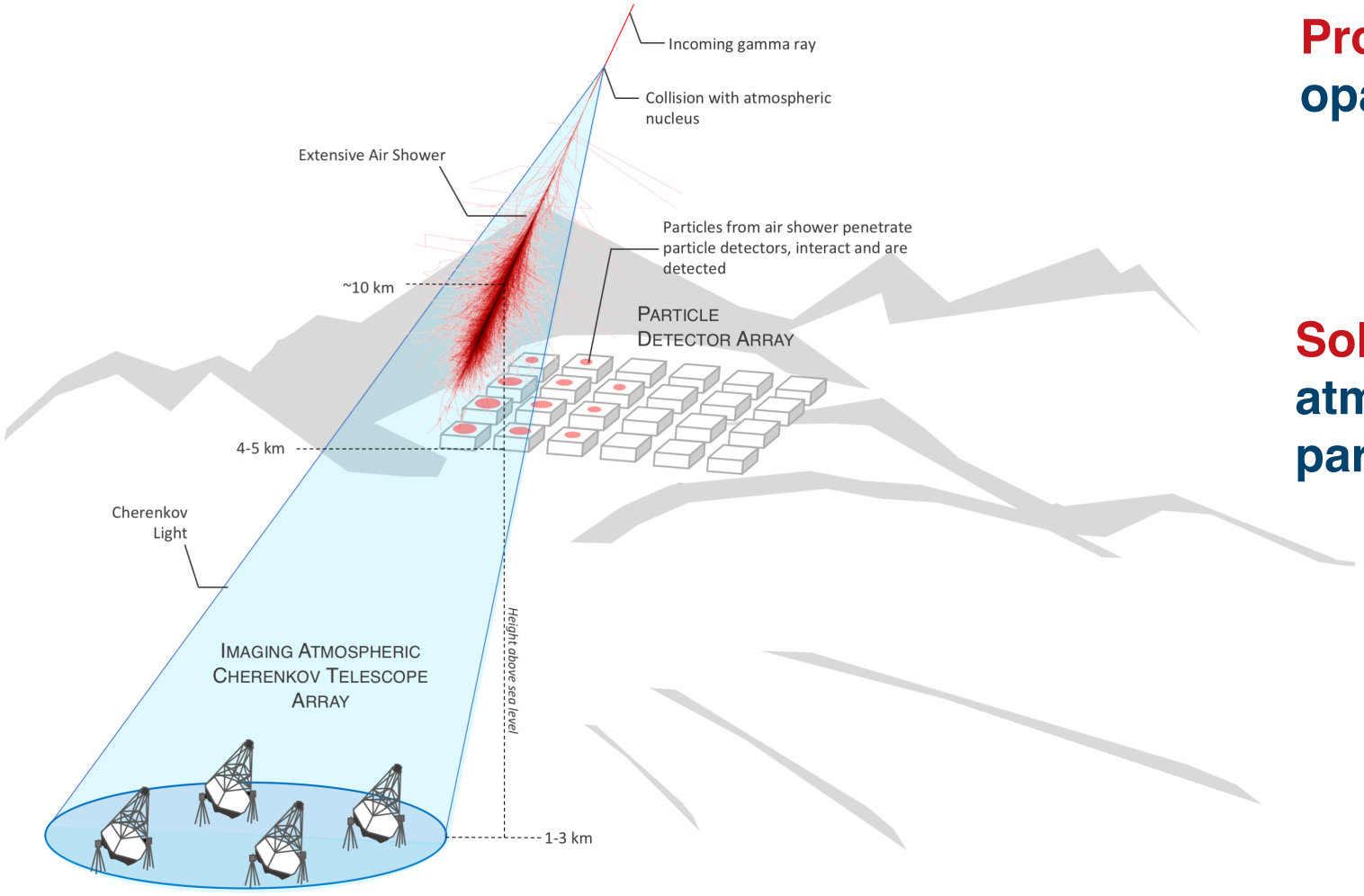
How to detect gamma rays?





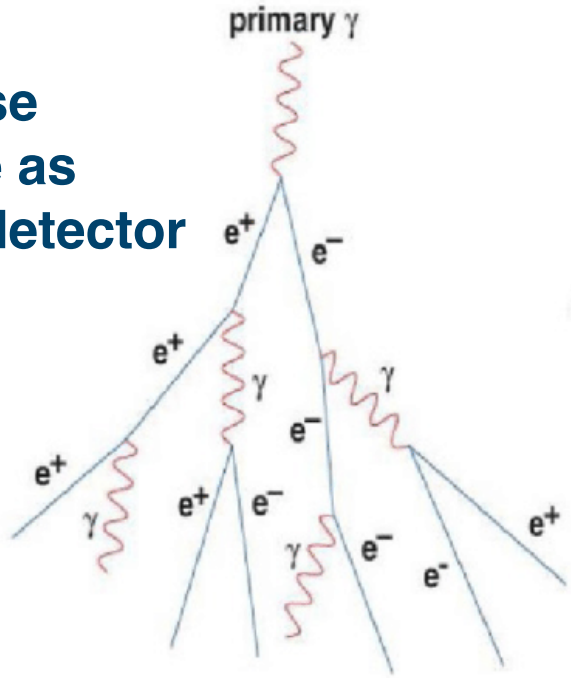
Problem: Our atmosphere is opaque to gamma rays.

How to detect gamma rays?



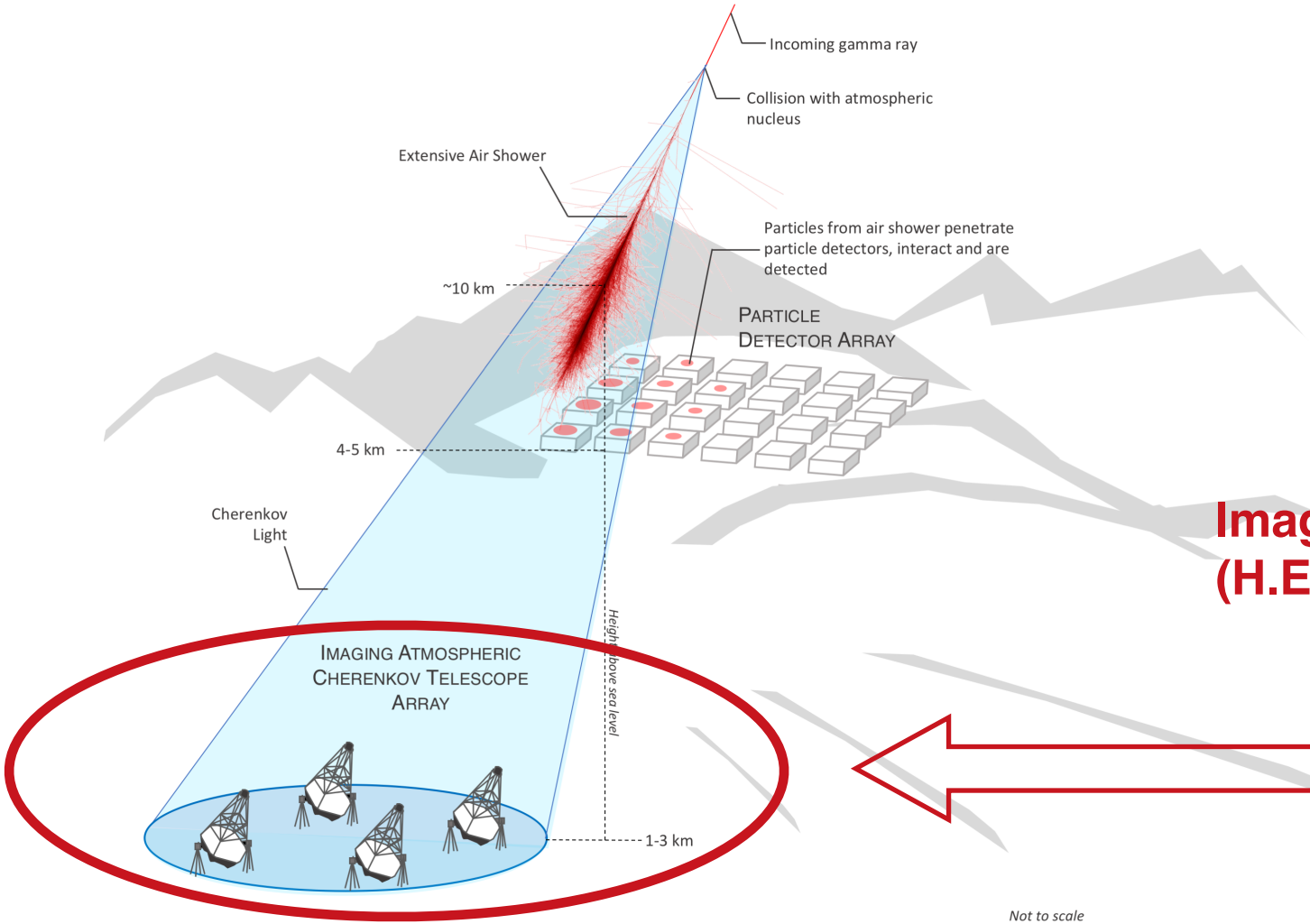
Problem: Our atmosphere is opaque to gamma rays.

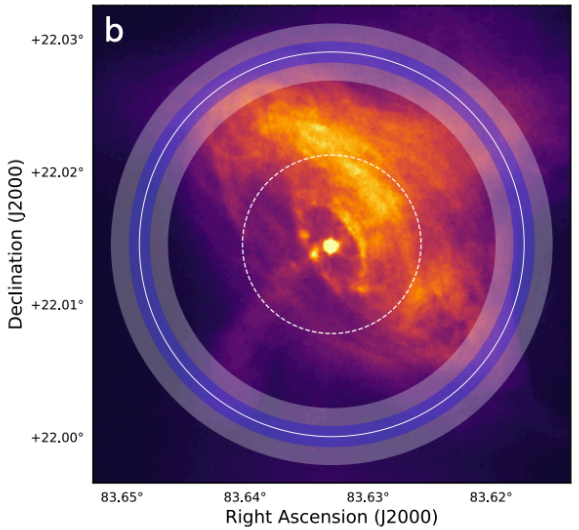
Solution: use atmosphere as part of the detector



Two Major Techniques

The H.E.S.S. Collaboration, *Nature Astronomy* 4, 167 (2020)

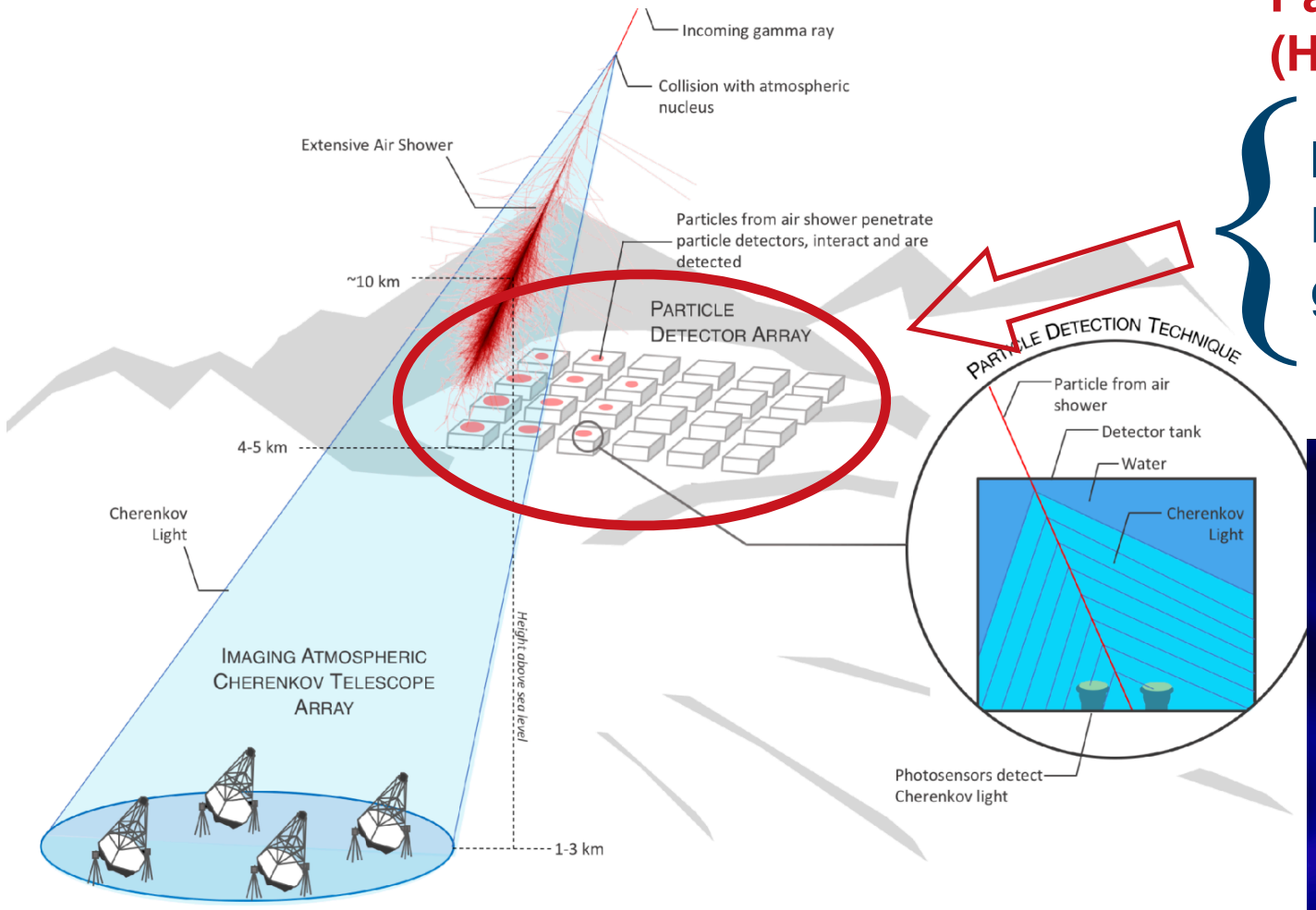




Imaging Atmospheric Cherenkov Telescope (H.E.S.S., MAGIC, VERITAS)

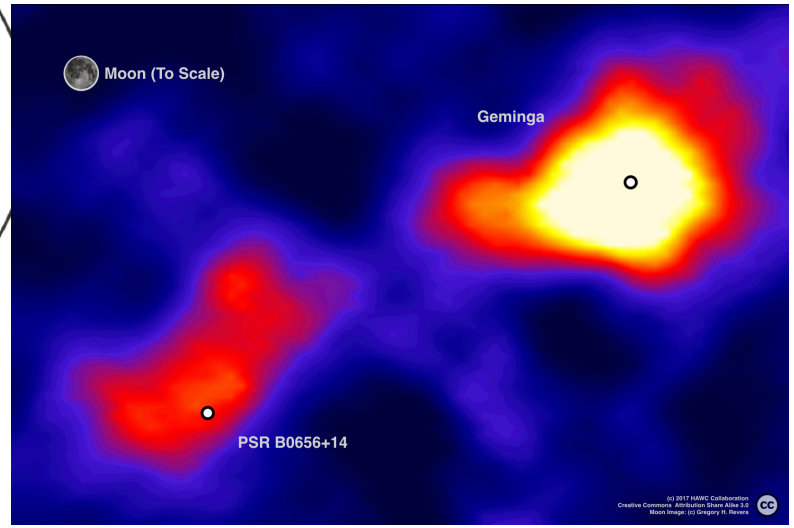
- good angular resolution
- good energy resolution
- small FOV (<5°)
- low (~10%) duty cycle

Two Major Techniques



Particle Detector Array (HAWC, LHAASO, Tibet-ASγ)

- large FOV (2 sr)
- high (~100%) duty cycle
- good sensitivity on higher energies



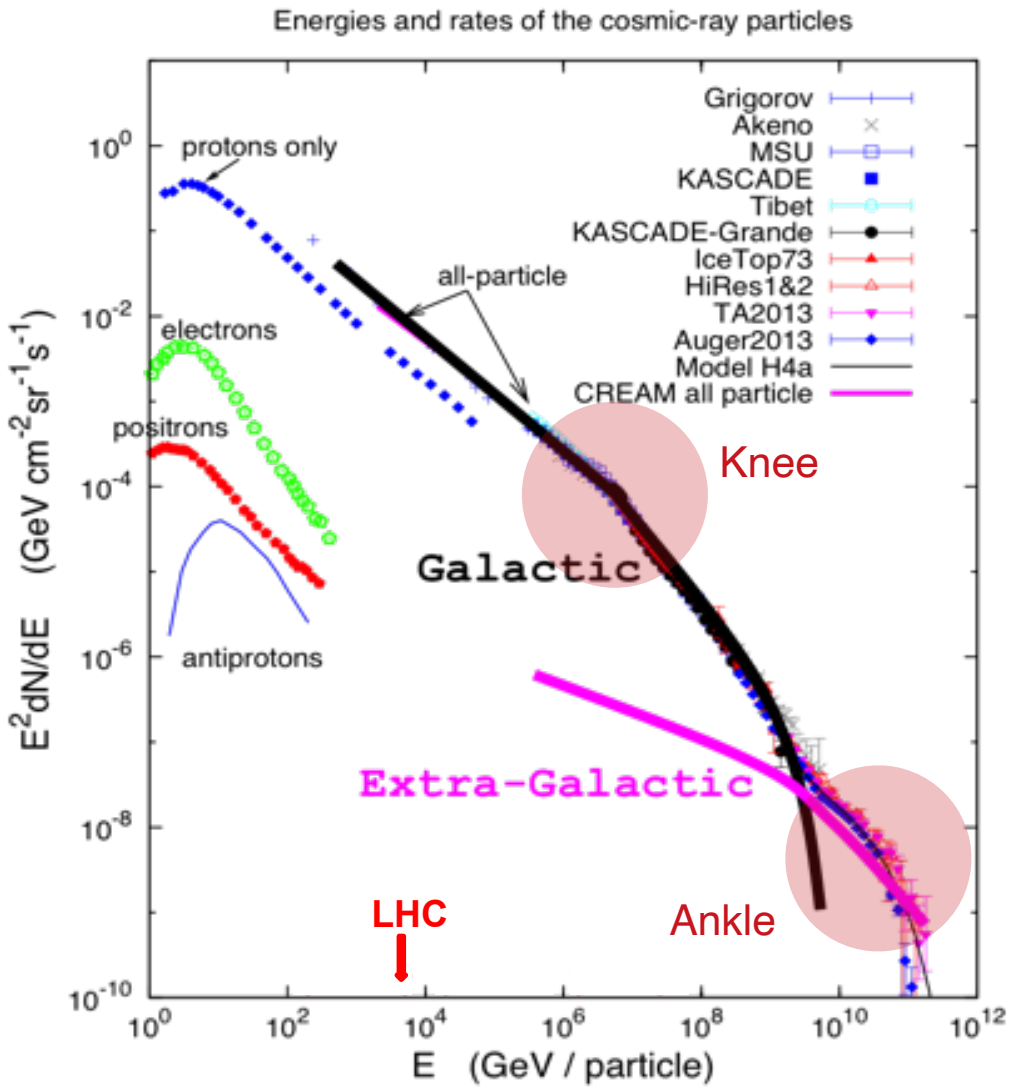
The HAWC Collaboration, *Science* 358, 911 (2017)

Origin of Galactic Cosmic Ray

- Galactic CR contribute beyond the knee
- Cannot point back to the source with CR
- Gamma rays provide unambiguous evidence of CR acceleration and propagation

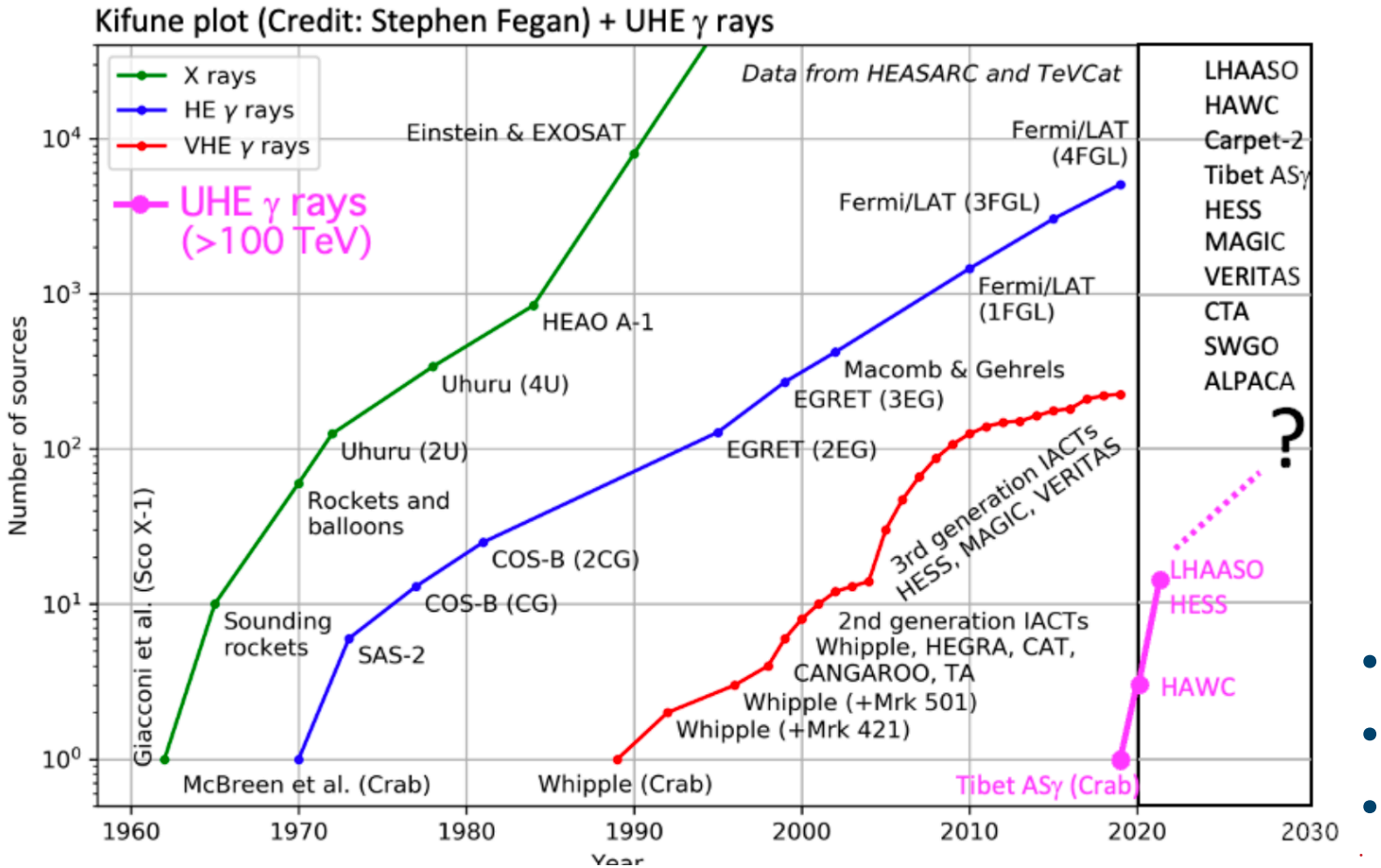
Search for Galactic PeVatrons

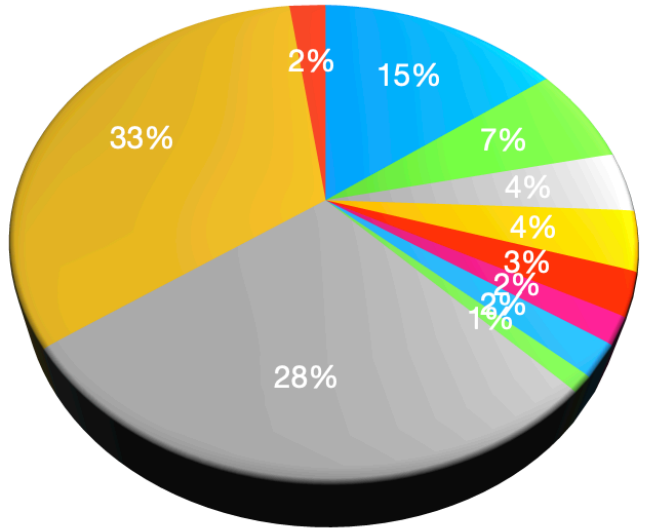
Accelerators of particles (hadronic or leptonic) to beyond 1PeV



What we have seen so far?

Number of sources vs. Time

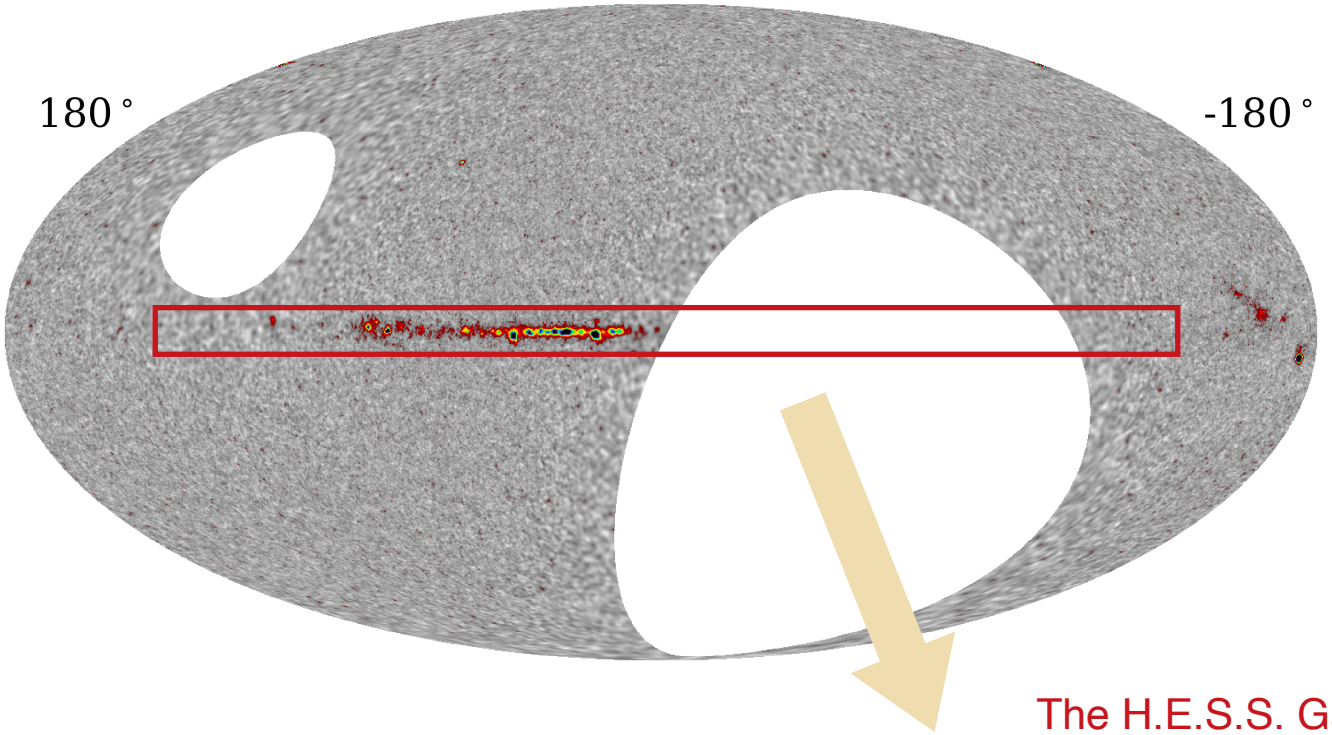




- Particle acceleration at the source
- Particle escaping from their sources
- Propagation of CRs across the Galaxy

What we have seen so far?

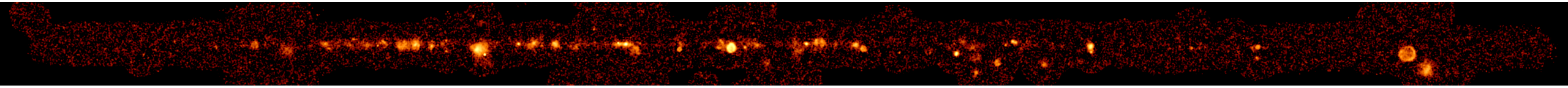
The 3HWC Catalog (1523 days), The HAWC Collaboration, ApJS, 905(1), 76



Two detection techniques are complimentary

- unbiased sky survey with particle array
- deep observations with IACTs

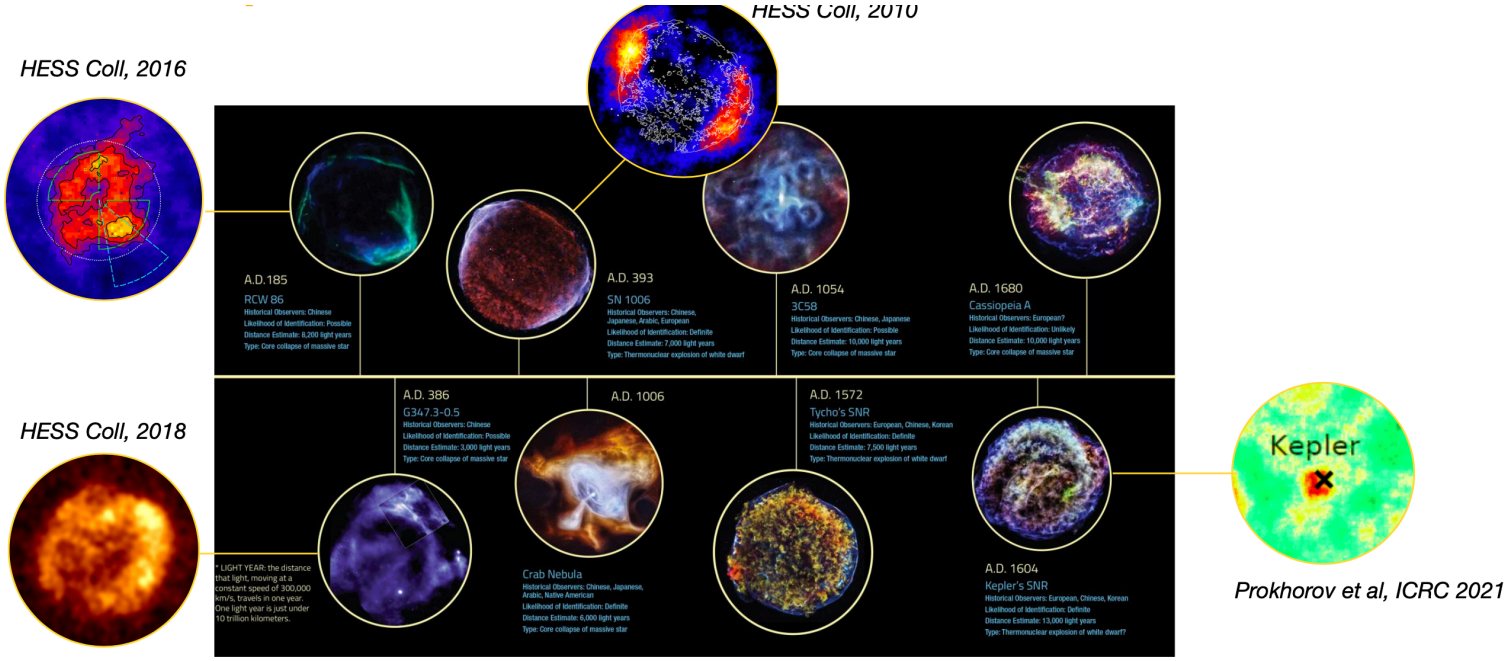
The H.E.S.S. Galactic Plane Survey, The H.E.S.S. Collaboration, A&A, 612



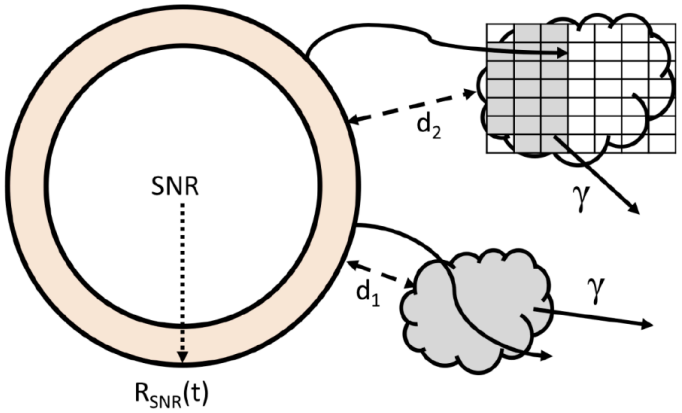
SNRs (Supernova Remnants)

SNRs have been postulated as origin of GCRs due to energy arguments.

- However, only work when very young (<1k year)
- Low surface brightness (mostly detected by IACTs)
- Unless, there are nearby molecular clouds interacting with SNRs



Prokhorov et al, ICRC 2021



Credit: Emma de Oña Wilhelmi

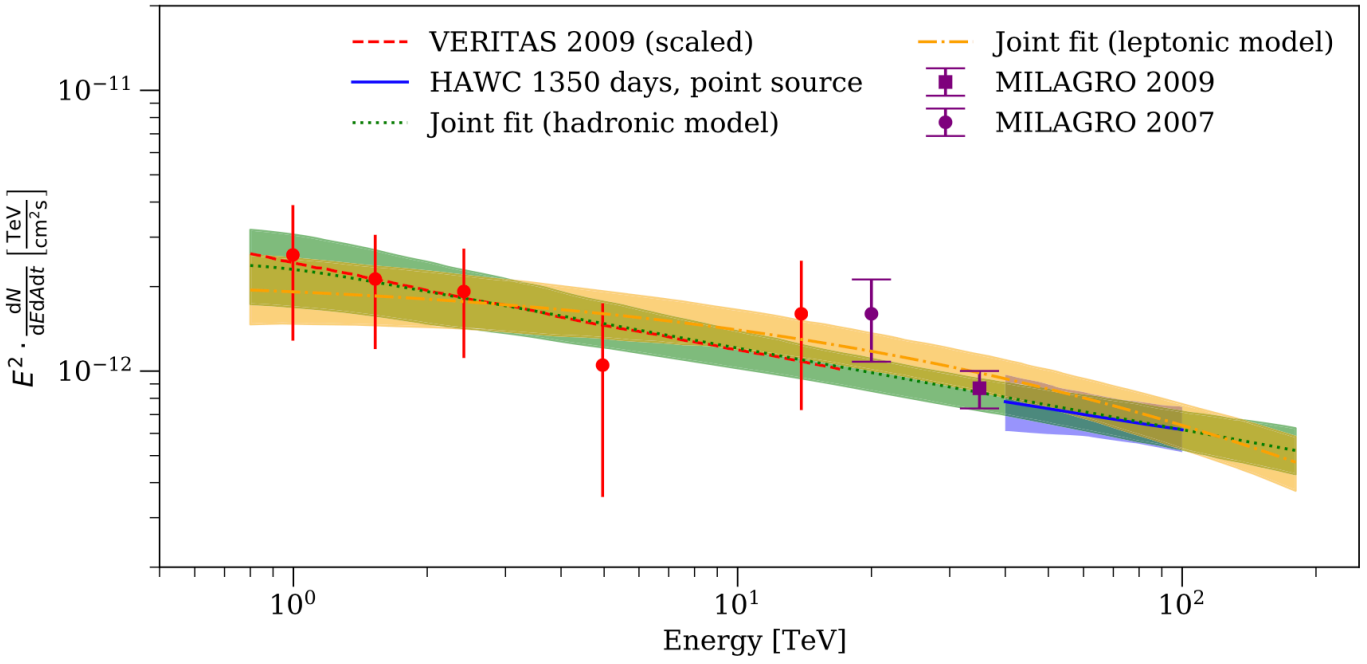
A. Mitchell et al., MNRAS, 503, 3522

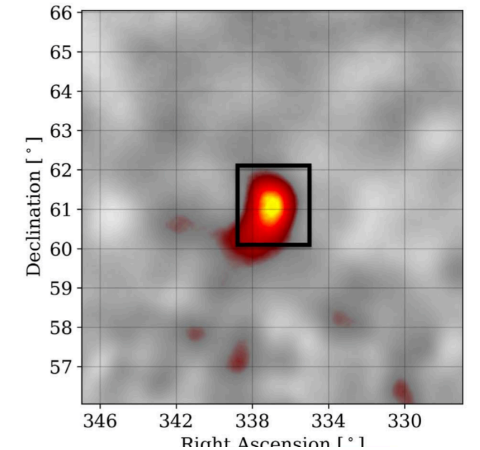
SNRs (Supernova Remnants)

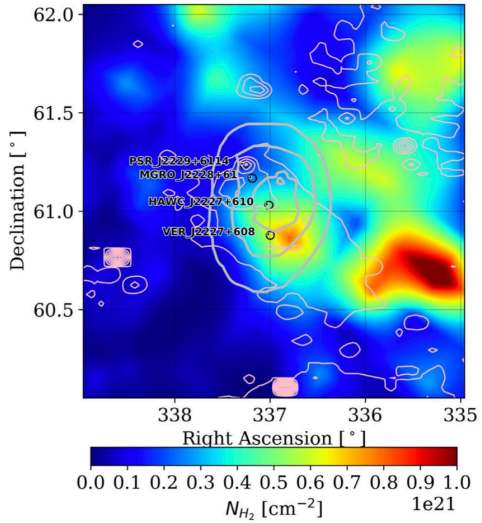
HAWC J2227+610: a candidate Galactic PeVatron

- Possible association with SNR G106.3+2.7
- However, a purely leptonic origin cannot be ruled out.

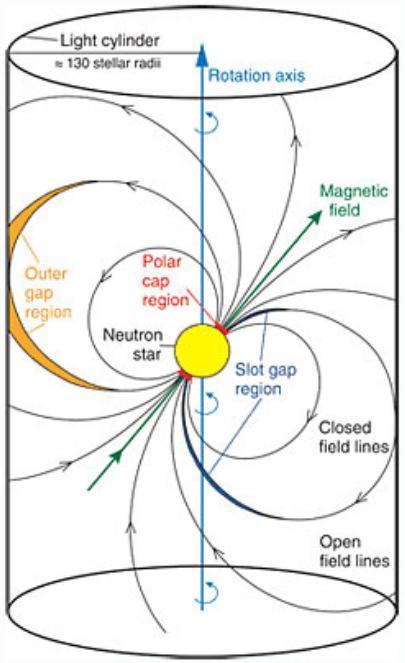
The HAWC Collaboration, ApJL, 896:L29







The Pulsar Complex

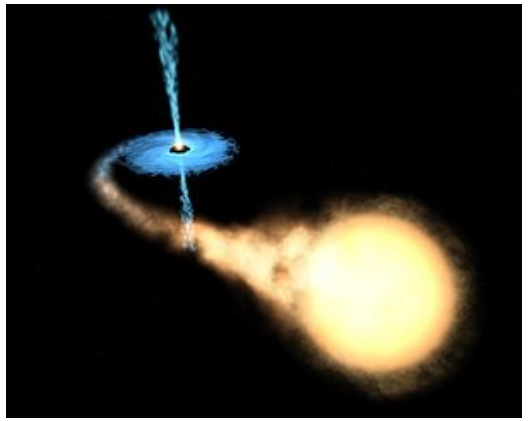


Pulsar

PWN (pulsar wind nebula)

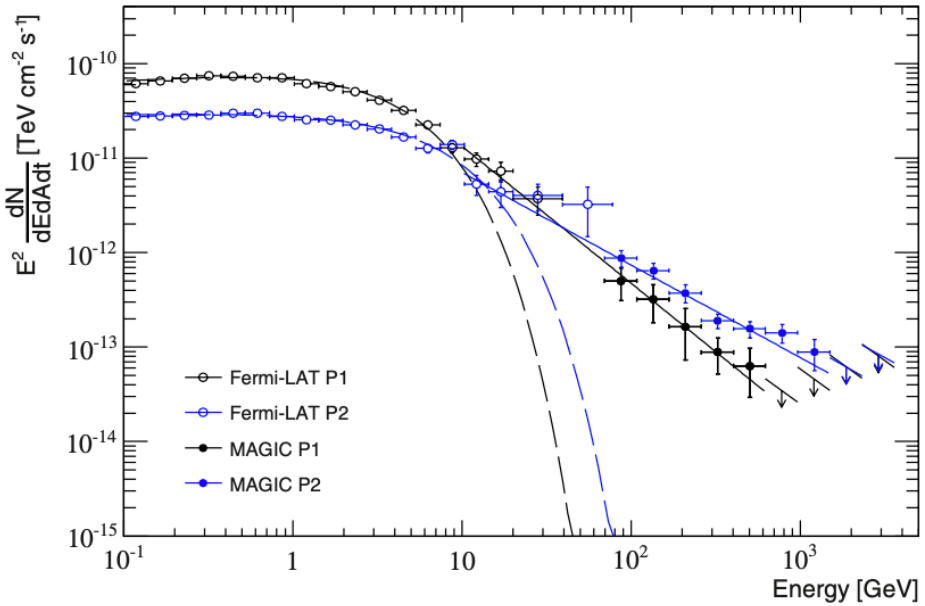
Pulsar Halo

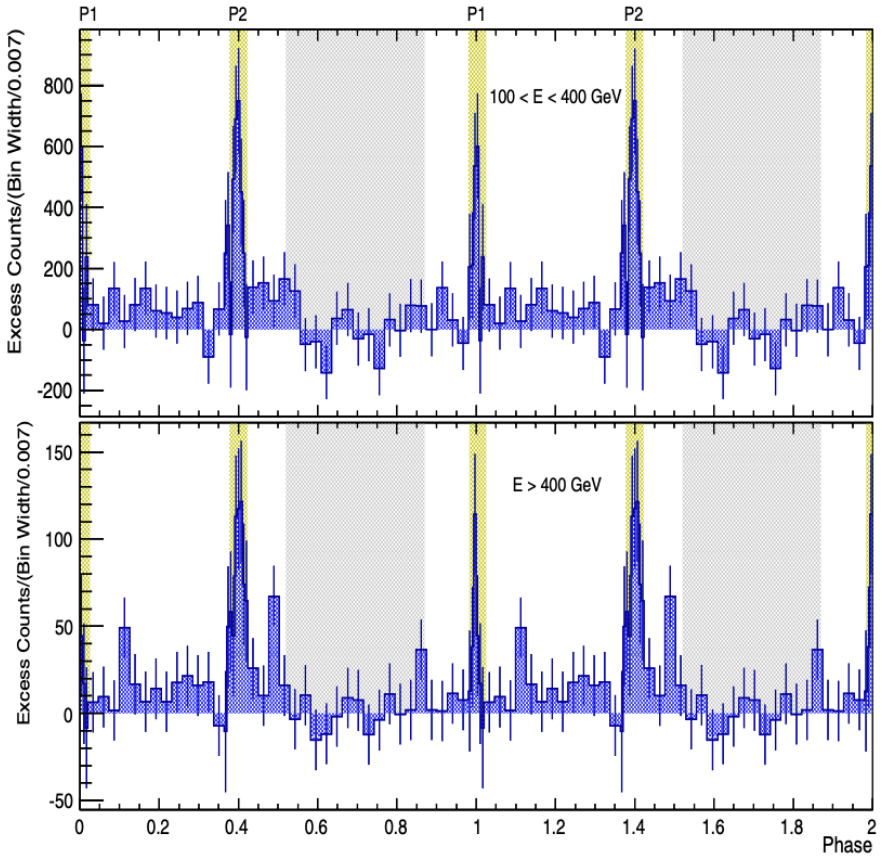
Binary/Microquasar



Pulsars

- Pulsed emission has been detected from four pulsars
  - Crab, Vela, PSR B1706-44, Geminga
  - MAGIC's detection of pulsations from Crab up to 1.5 TeV

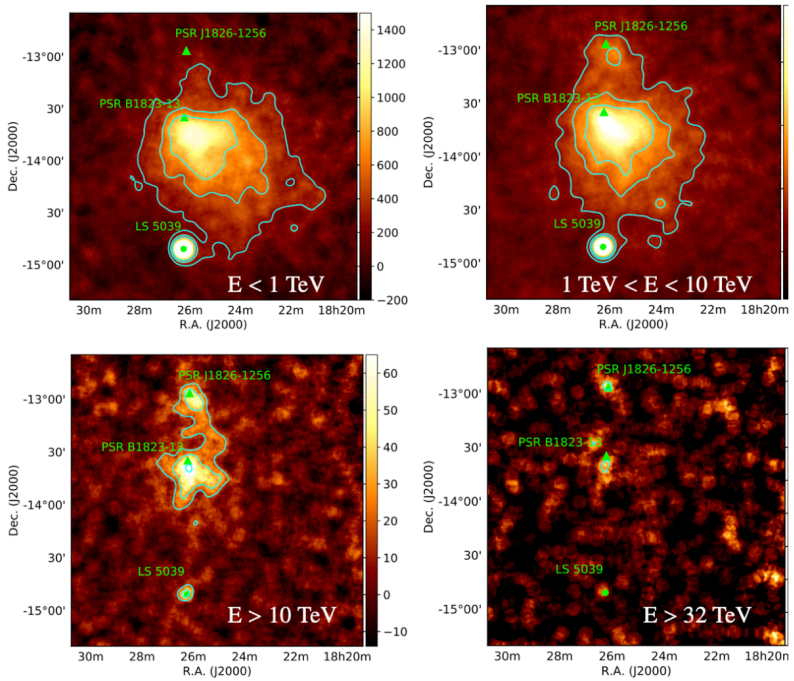


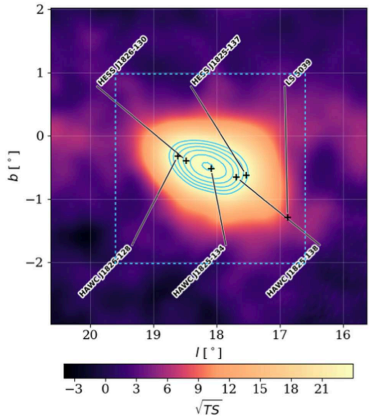


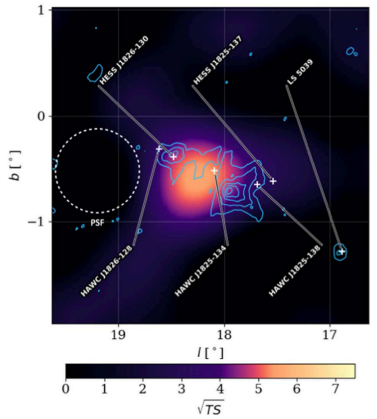
The MAGIC Collaboration, A&A, 585, A133

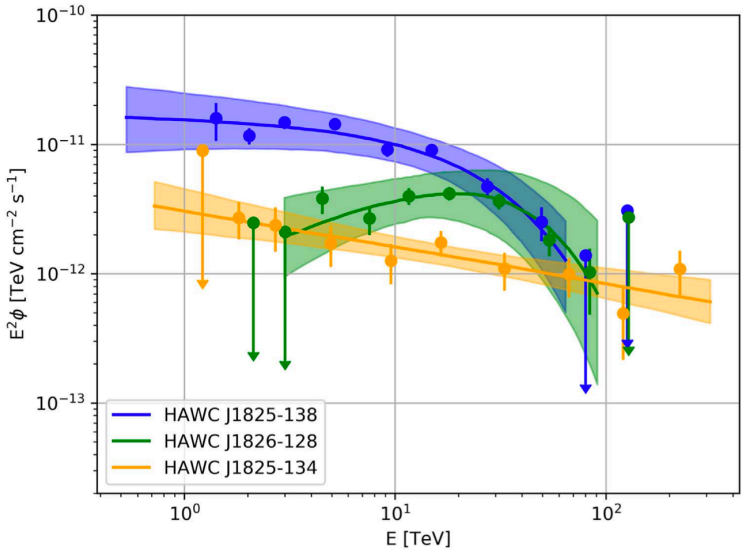
PWN (Pulsar Wind Nebula)

- Gamma-ray centroid moves closer to the pulsar at higher energies.
  - consistent with a leptonic scenario
- A complex region with three sources









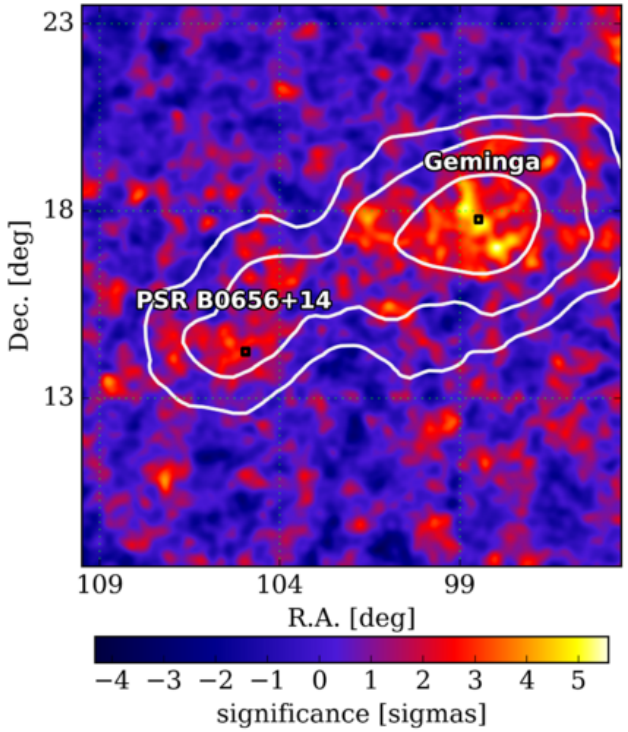
The H.E.S.S. Collaboration, A&A, 621, A116

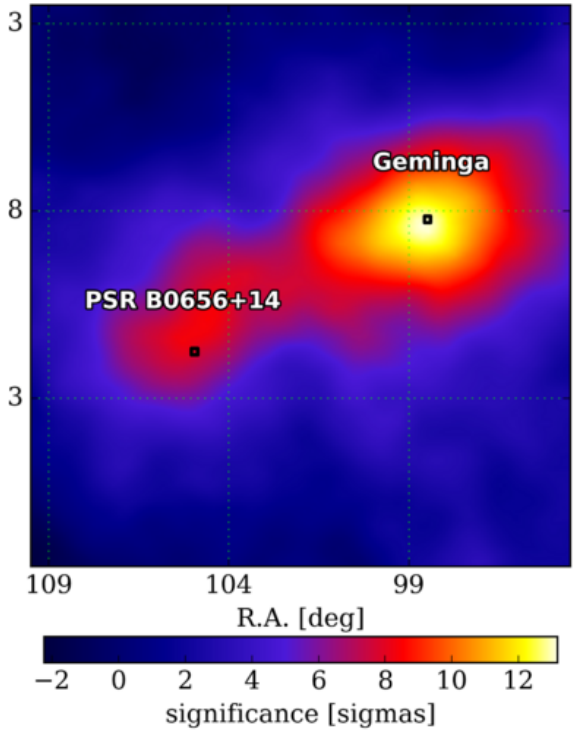
The HAWC Collaboration, ApJL, 907, L30

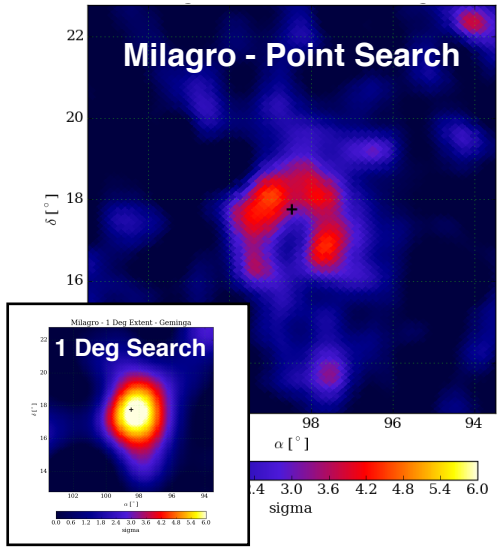
Pulsar Halo

- A relatively new source class that was separated from PWNe
- The first pulsar halo was discovered by HAWC (with a hint already from Milagro)

The HAWC Collaboration, *Science* 358, 911 (2017)



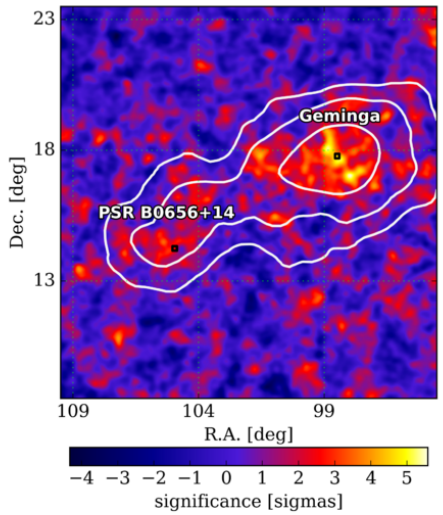


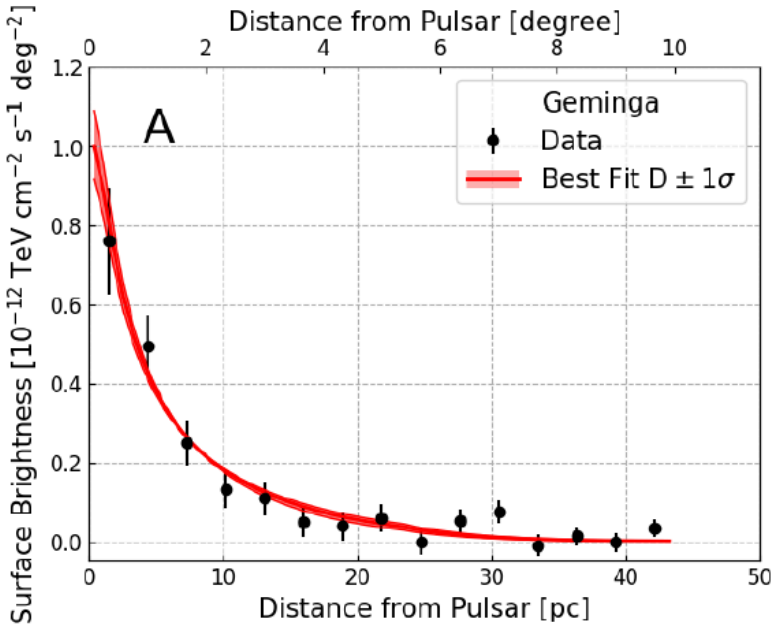


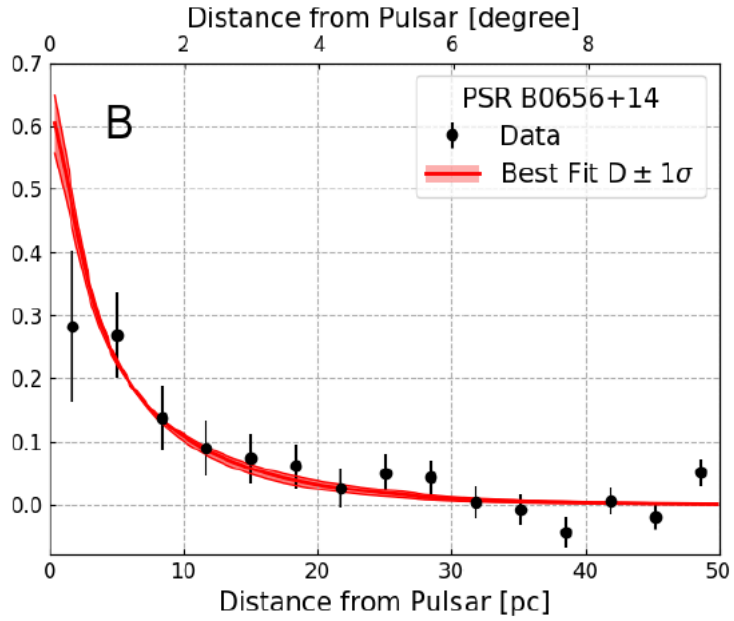
Pulsar Halo

- The gamma-ray profile match the scenario that $e^{\pm}$ diffuse away from their source.
- Diffusion coefficient, directly measured by HAWC, is 100x lower than that indirectly derived from cosmic ray primary/secondary ratio.

The HAWC Collaboration, *Science* 358, 911 (2017)

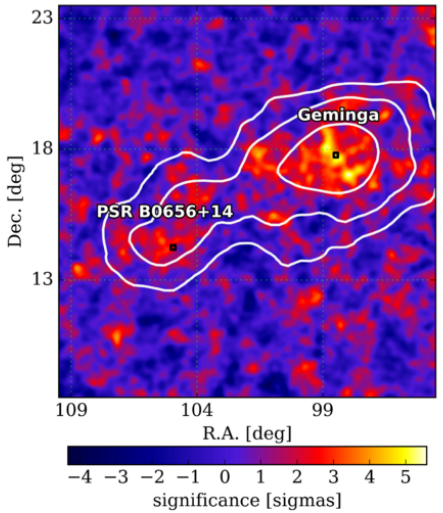


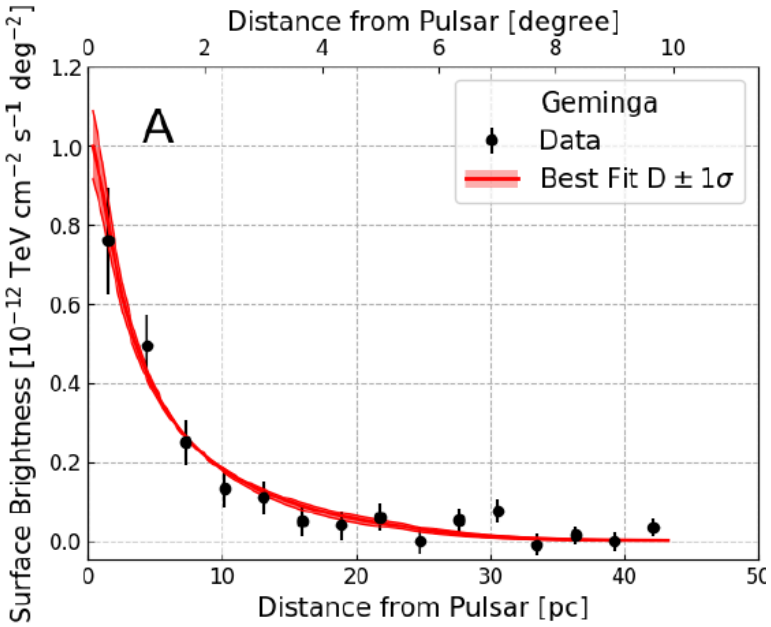


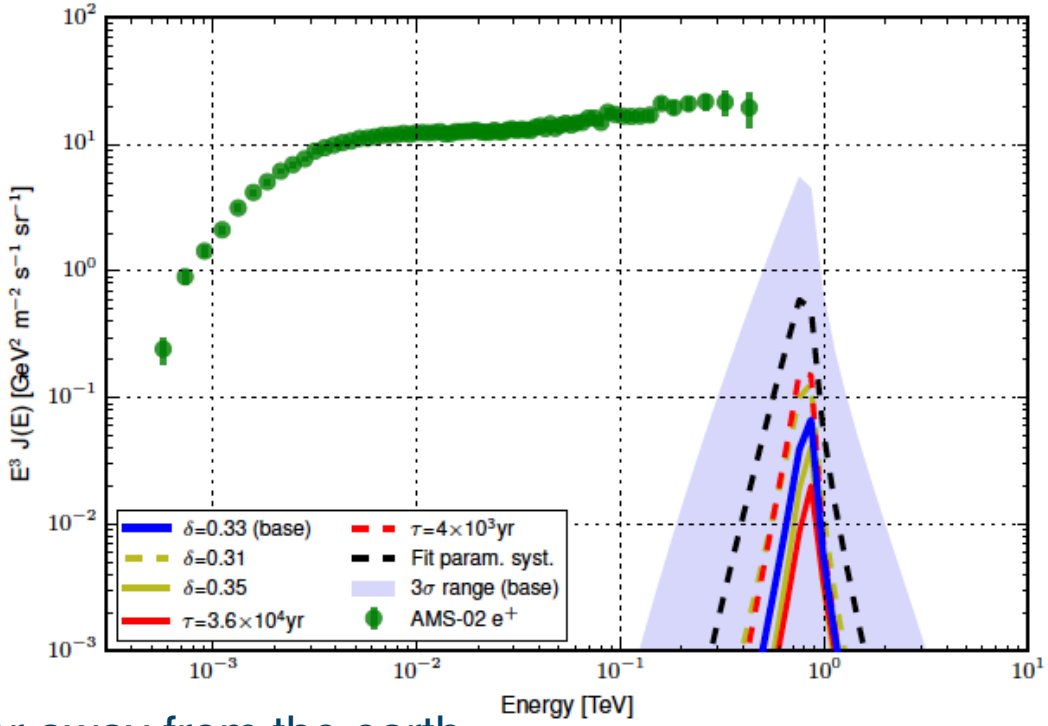


Pulsar Halo and Positron Excess

- Assuming the HAWC measured diffusion coefficient, the positrons from Geminga or Monogem contribute negligibly to the positron flux measured by satellite detectors like AMS-02.





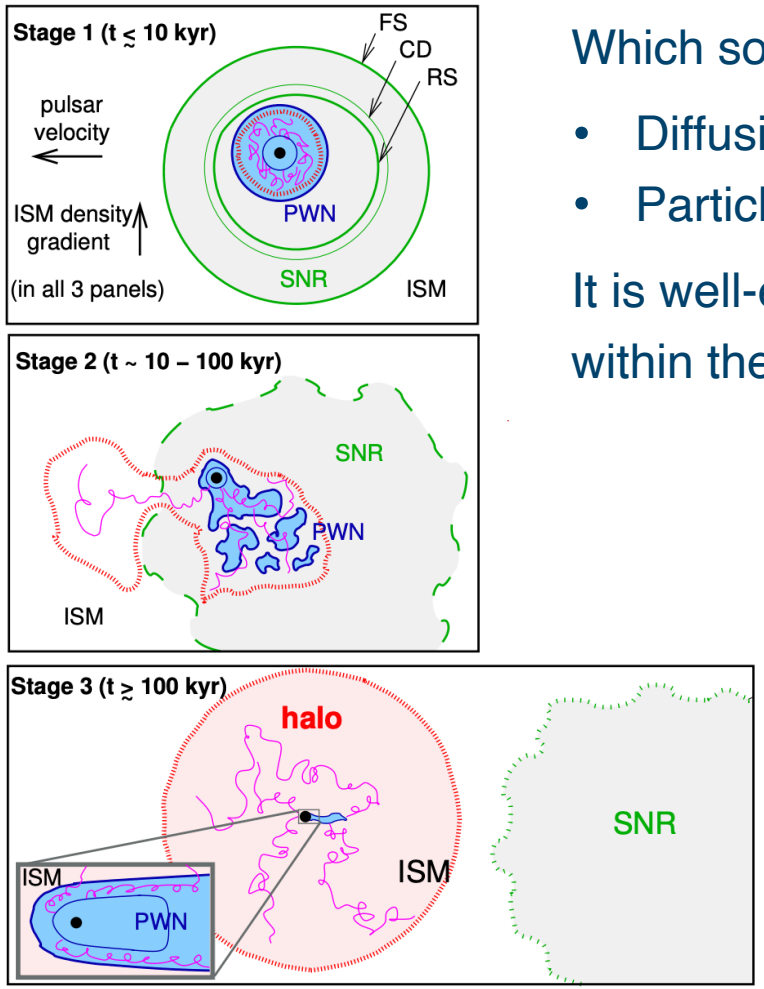


Recchia et al., arxiv.org/pdf/2106.02275

- Observations on pulsar halos probe the CR propagation far away from the earth
- However, it is worth noting that a quasi-ballistic particle propagation may explain the observed profile without low diffusion.

More Pulsar Halos

Giacinti et al., A&A, Volume 636, id.A113

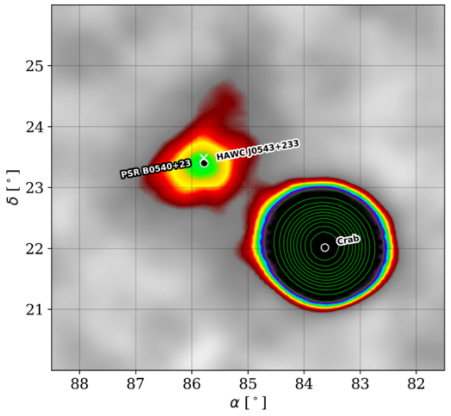


Which sources should be classified as either PWN or halo remains a point of debate

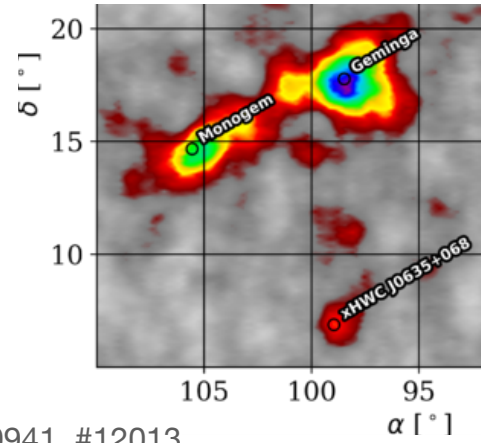
- Diffusive particle transport over advection
- Particle energy density far below the level of ISM

It is well-established that diffusive particle transport may dominate over advection within the PWN or escaped into the ISM

HAWC J0543+233

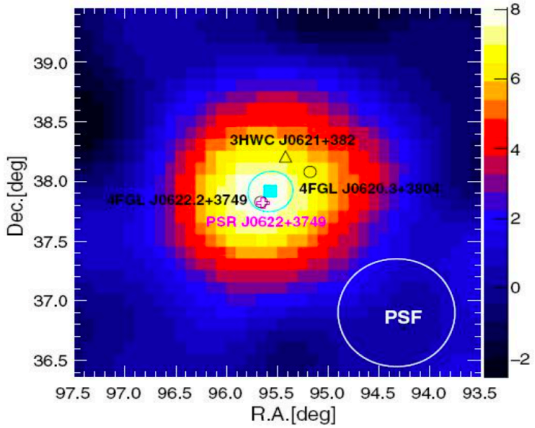


HAWC J0635+070



HAWC, ATel #10941, #12013

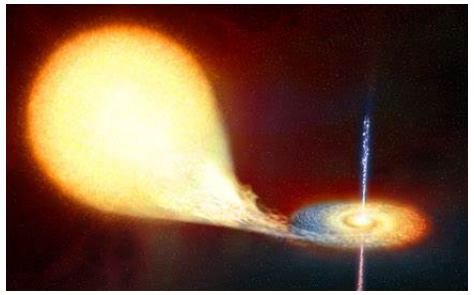
LHAASO J0621+3755



LHAASO, PRL, 126:241103

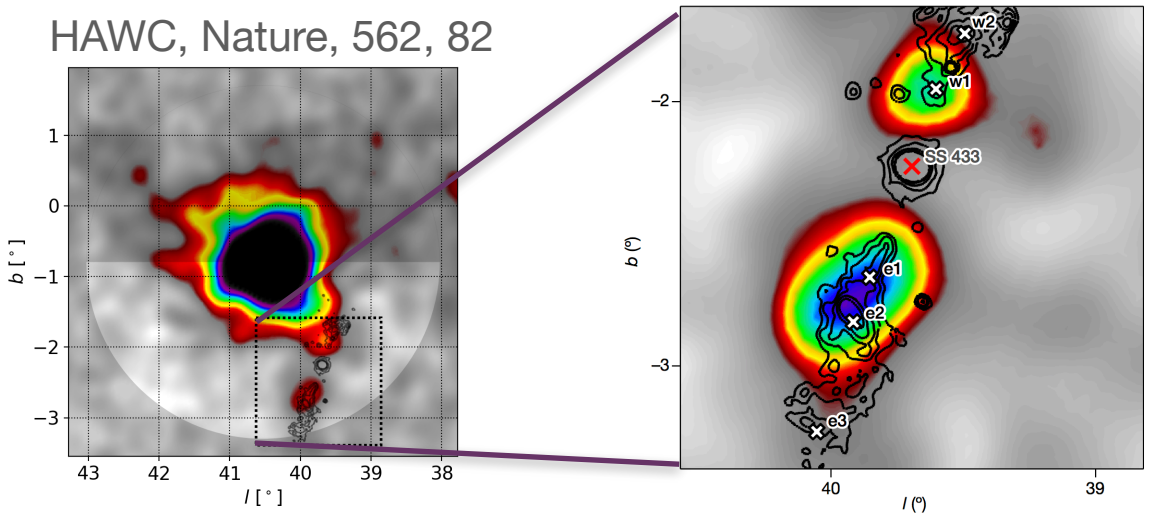
Discovery of TeV Microquasar SS433

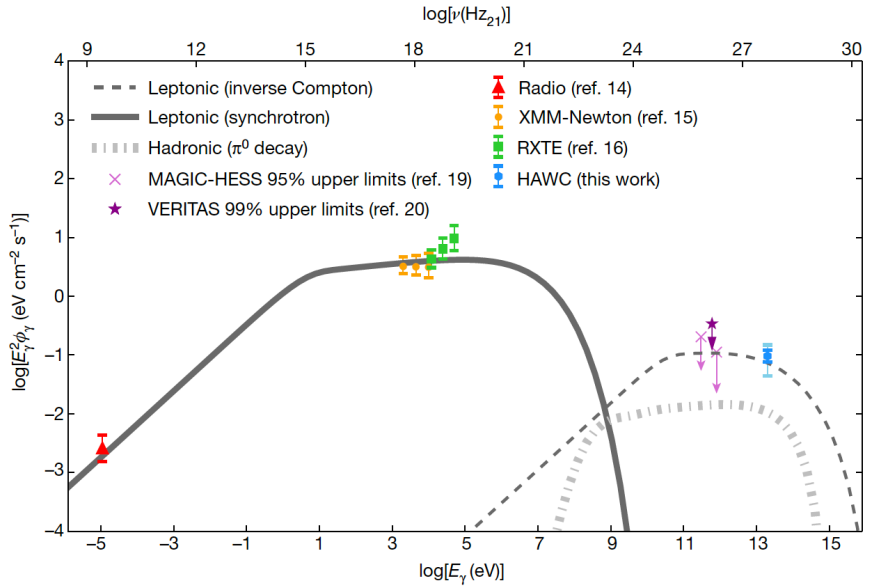
HAWC observation of SS433 is the first direct evidence of particle acceleration to ~PeV in jets



- Microqusars are scaled models of Active Galactic Nuclei
- This is the first time astrophysical jets have been spatially resolved at TeV energies
- Hadronic acceleration disfavored due to extreme energetics required
- Particle acceleration occurs in the jet termination regions, not in the central binary

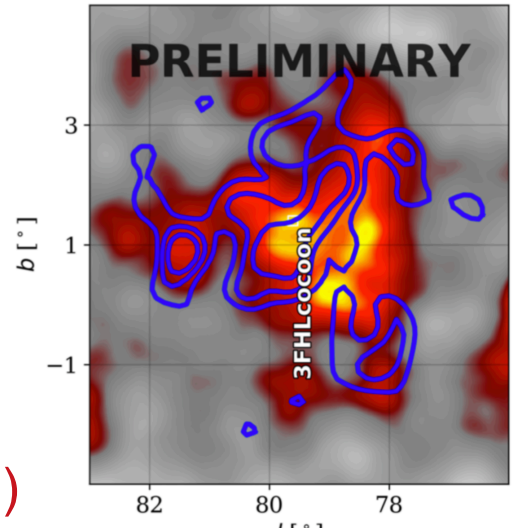
HAWC, Nature, 562, 82



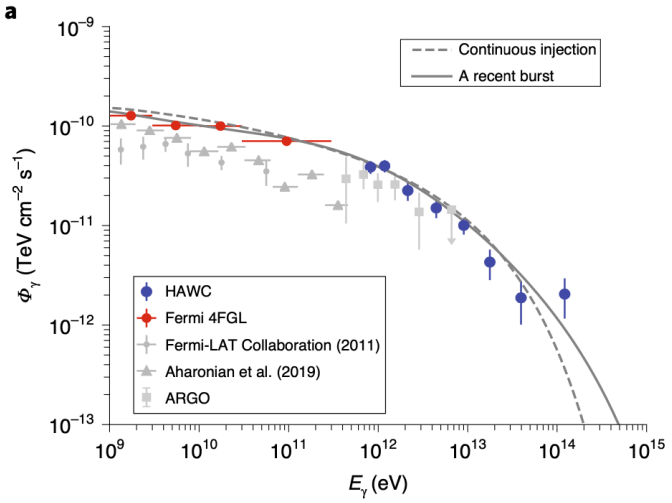


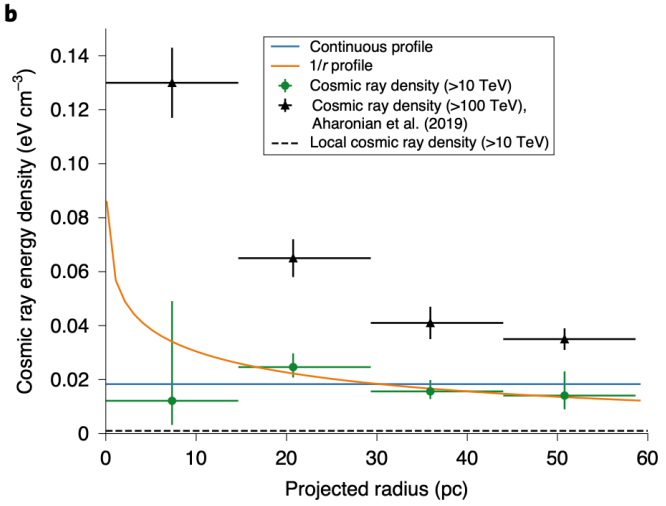
Star Forming Region - The Cygnus Cocoon

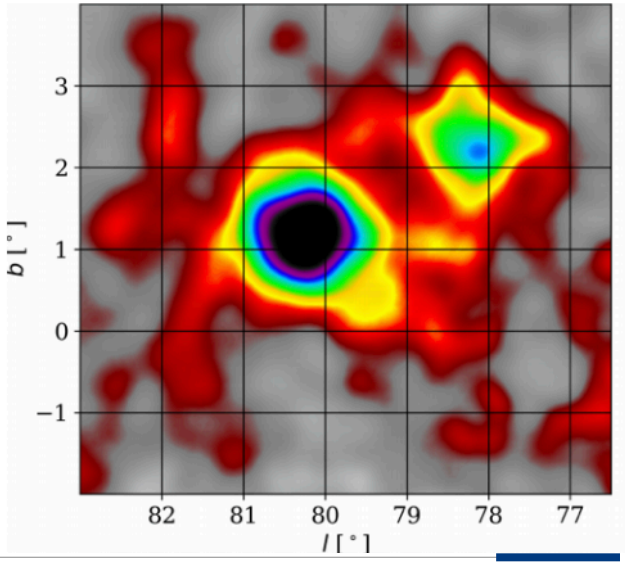
- Can Star Forming Regions accelerate particles to high energies?
- Candidate: OB2 association in Cygnus Region
  - Fermi detection at GeV “Cygnus Cocoon”
  - HAWC and ARGO detection of a likely TeV counterpart
  - LHAASO detection of a 1.42±0.13 PeV photon from this region
  - However, complex region with multiple sources (Cocoon, PWN, SNR, …)



HAWC, Nature Astronomy, 5(5):465

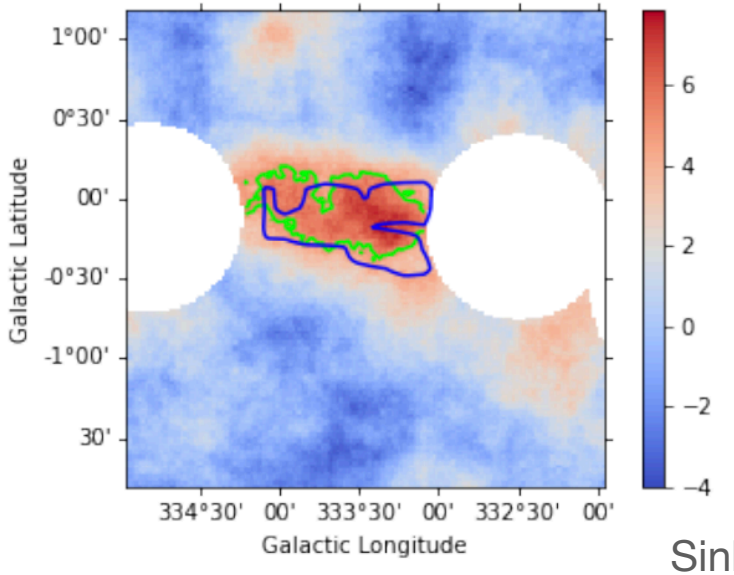


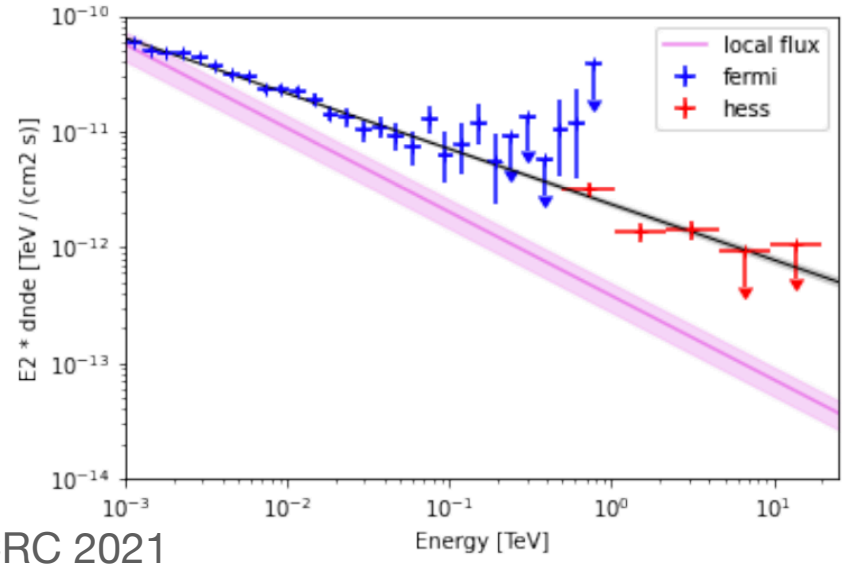




Galactic Cosmic Ray Tracer - Giant Molecular Cloud

- CR interactions with dense gas produce neutral pions, then gamma rays
- “Passive” molecular cloud can probe the level of the “sea” of GCR
- Cloud 877 from H.E.S.S. observation: 5-6 times of the local CR density

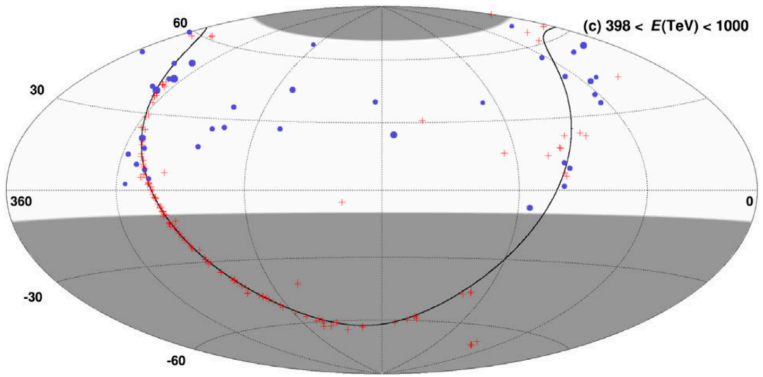


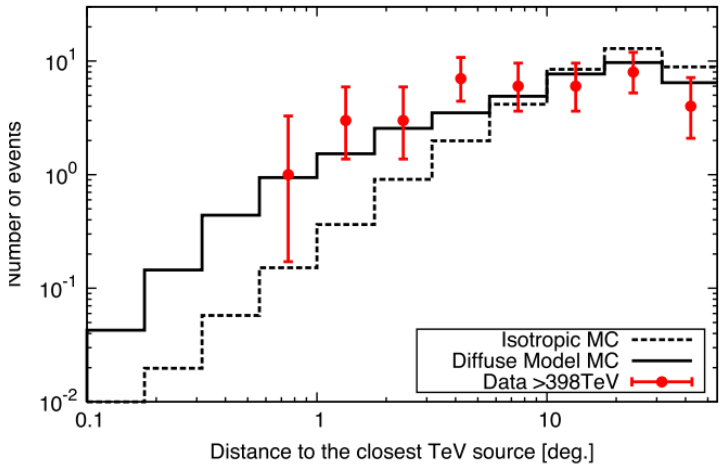


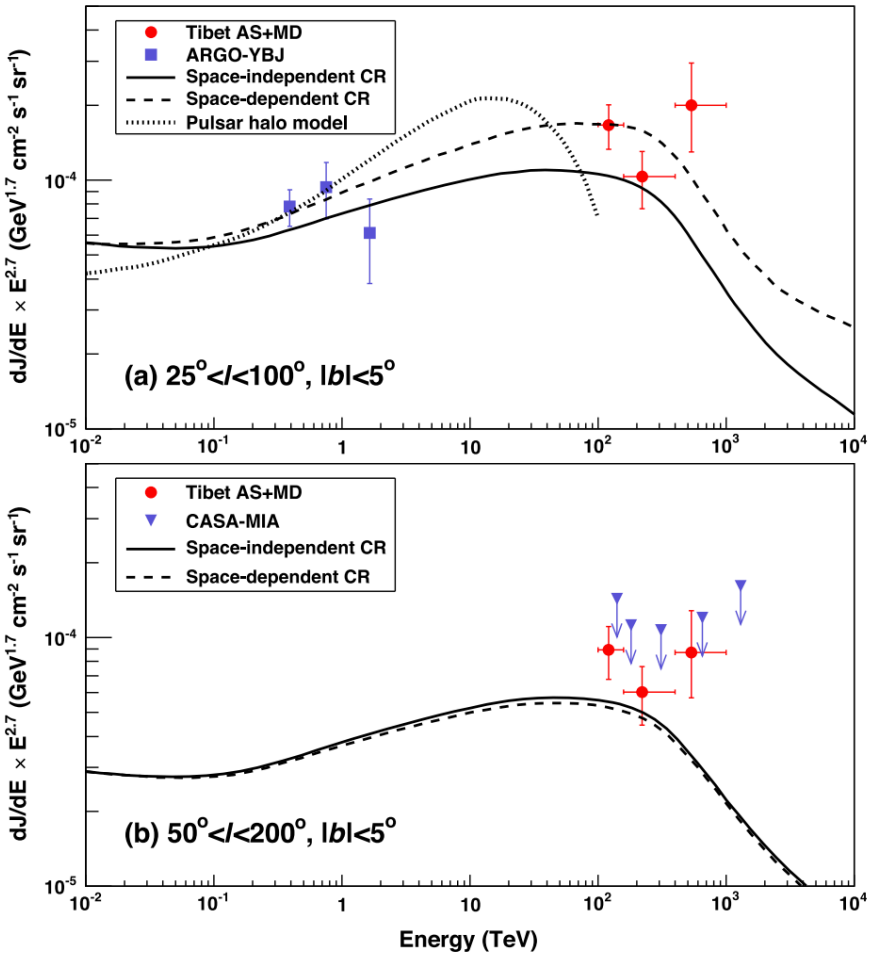
Sinha et al., ICRC 2021

Galactic Cosmic Ray Tracer - Diffuse Emission

- Tibet ASγ detected 38 events from 0.4 to 1 PeV.
- Arrival directions do not associate with known sources.
- Observed flux higher than model prediction
  - unresolved sources?
  - space-dependent CR?



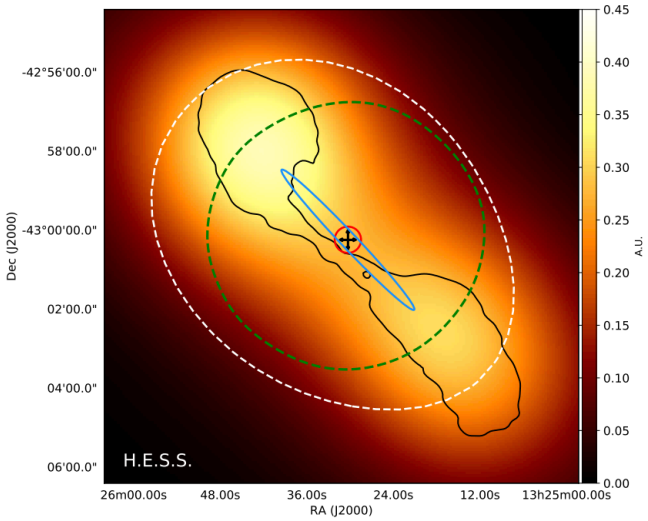




The Tibet Asγ Collaboration, PRL 126, 141101

Pushing the Boundaries

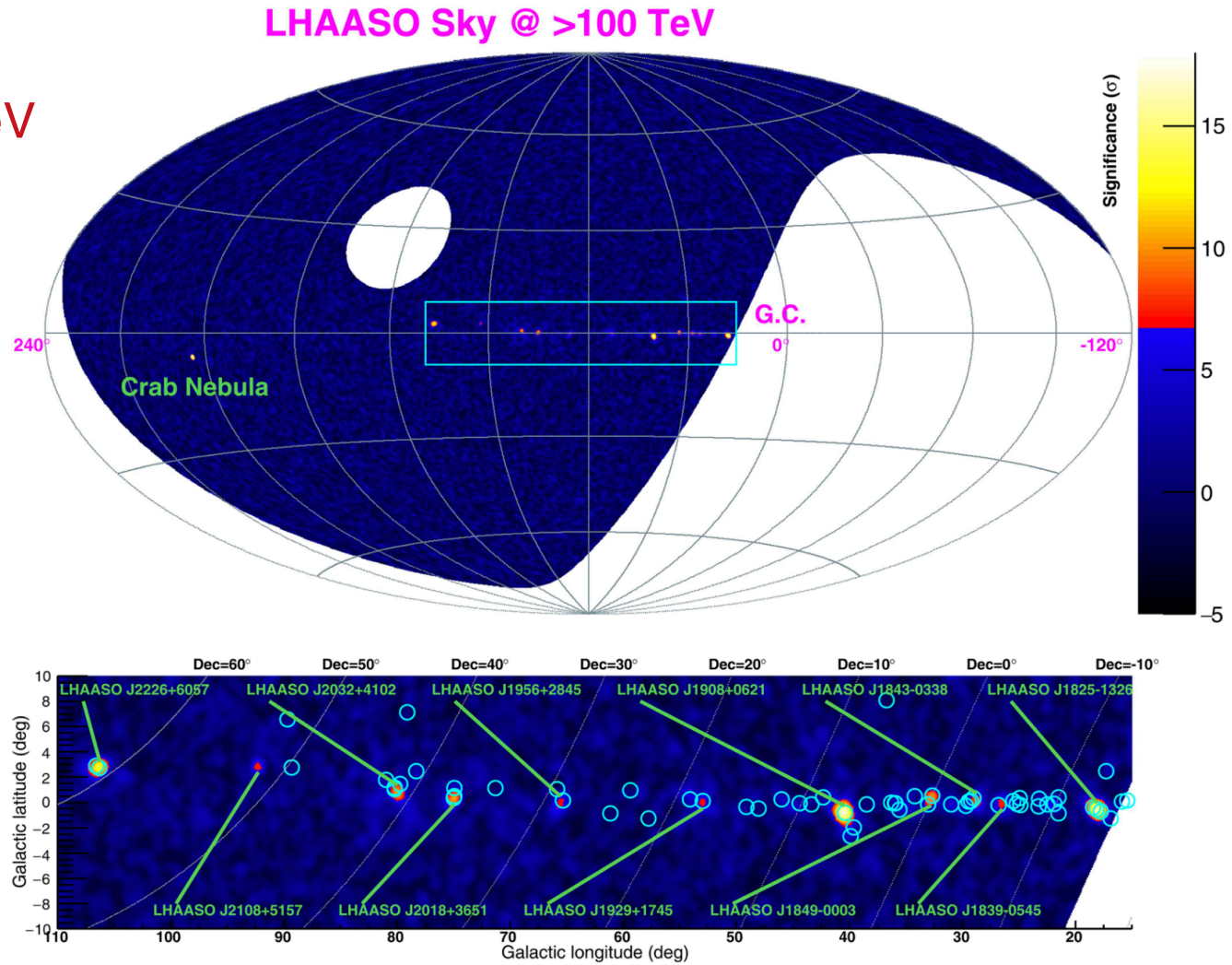
- Higher energies: large collection area -> LHAASO-KM2A
- Lower energies (pointing observation): IACTs
  - pulsars, GRBs, distant AGNs
- Lower energies (surveying observation): higher altitude and larger PMTs -> LHAASO-WCDA
  - GRB prompt emission
- Better angular resolution
  - Crab extent, jet of Centaurus A
- Fast repositioning: IACTs
  - GRB afterglow



The H.E.S.S Collaboration, Nature, 582, 7812

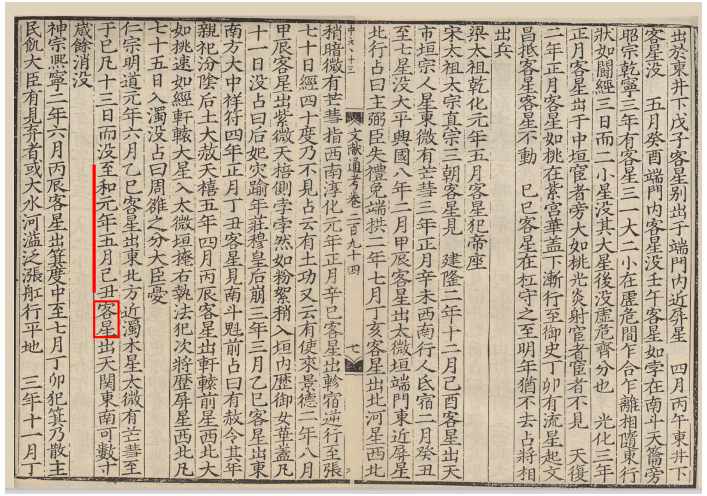
Higher Energies - PeV Gamma-Ray Astronomy

- With unprecedented area of 1.3km^2,
- LHAASO detected 530 photons > 0.1PeV
  - the highest energy: 1.42±0.13 PeV
- from 12 PeV Galactic sources
  - PWN, SNR, Star forming regions…
- which are clearly Galactic PeVatrons
  - leptonic or hadronic?

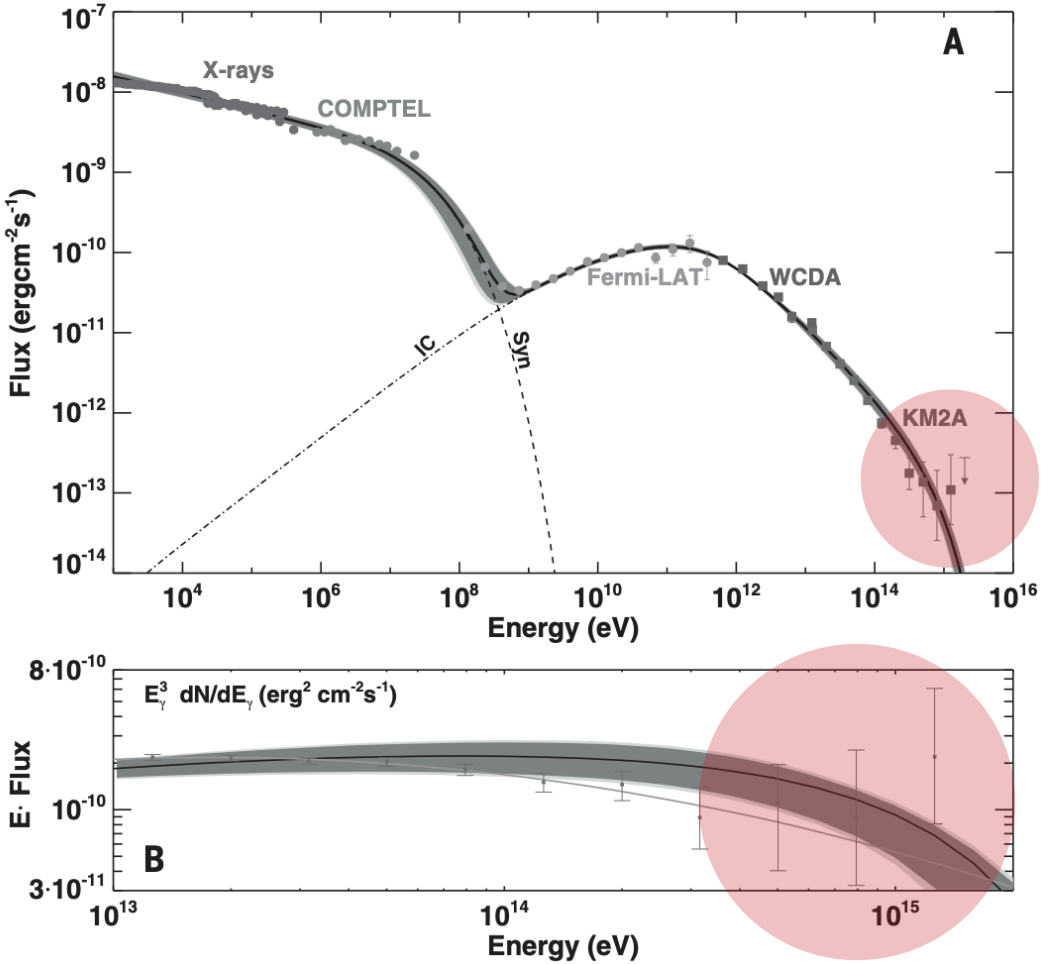


The LHAASO Collaboration, Nature, 2021

Higher Energies - the Crab Nebula



- A “guest star” on 7 July 1054
- LHAASO detected photons up to 1.12±0.09 PeV
- PWNs are known to be lepton accelerators
  - 1.12 PeV γ -> 2.3 PeV $e^{\pm}$ challenge current acceleration mechanisms
  - need an extra hadronic component?



The LHAASO Collaboration, Science, 2021

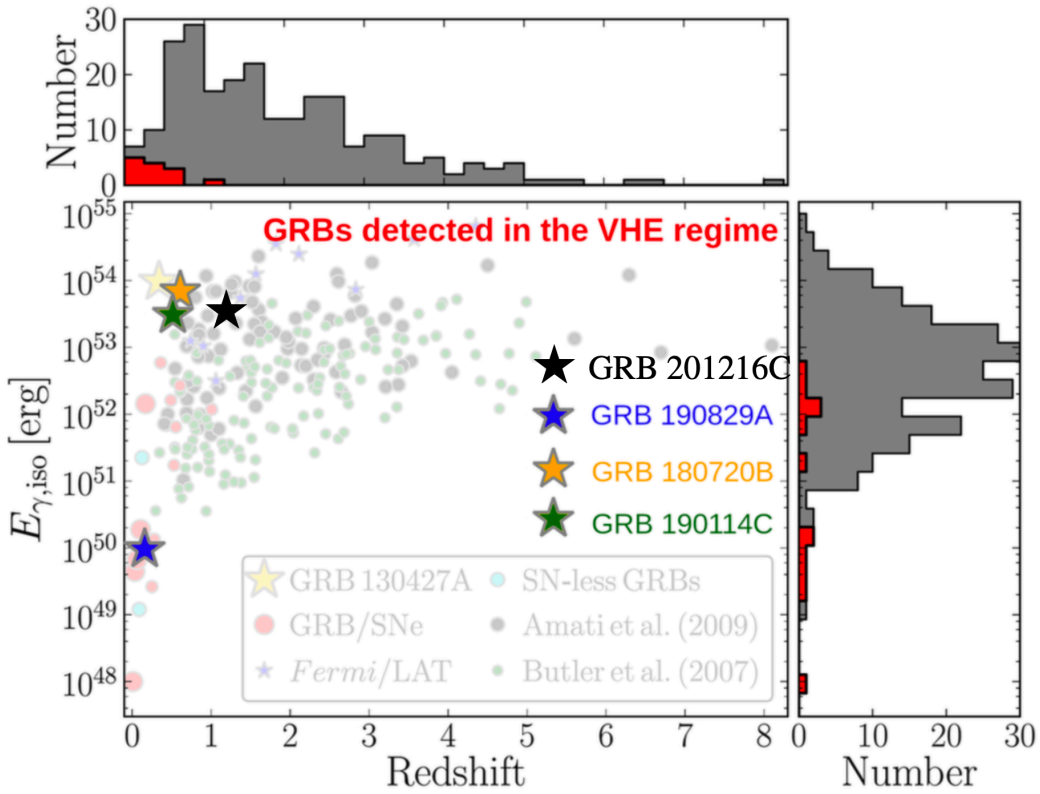
Lower Energies - Expend the Horizon

- Four Gamma-Ray Bursts detected by MAGIC and H.E.S.S.: paid off after years of search
  - GRB 190114C, GRB 180720B, GRB 190829A, GRB 201216C
  - the furthest one: z=1.1

First GRB detected by MAGIC:
Long GRB 190114C

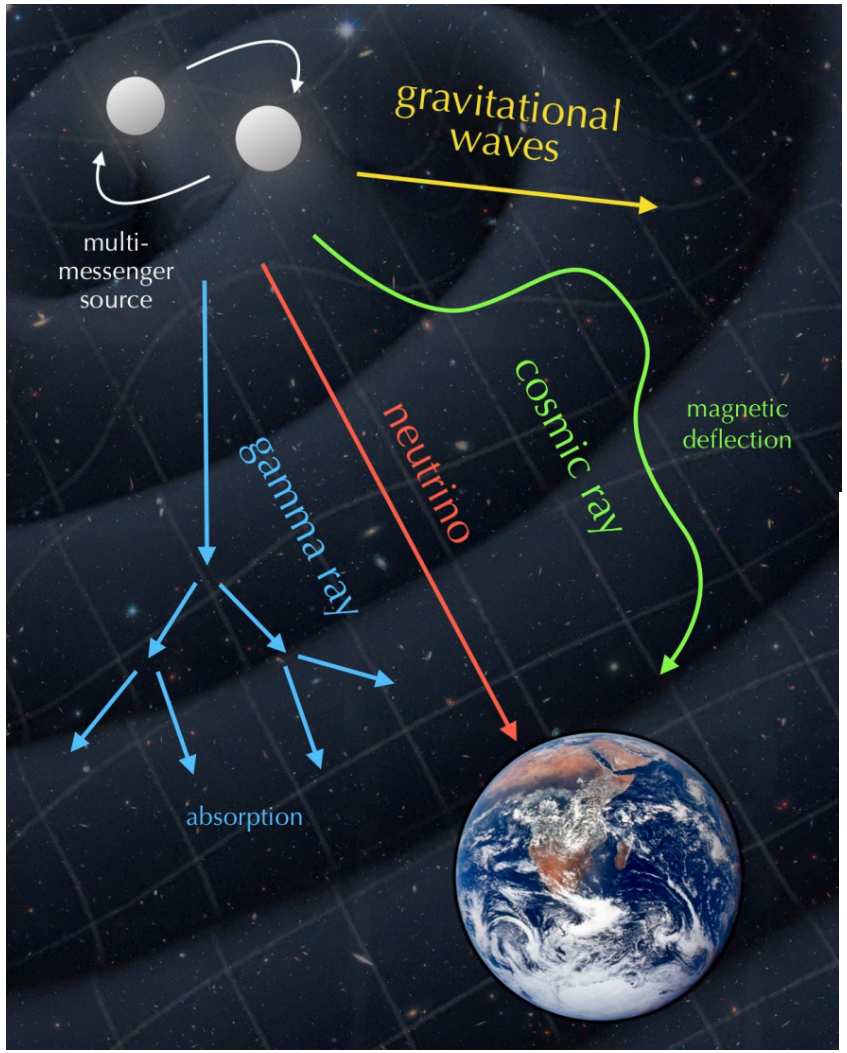
T_0 = 20:57:03 UT : Swift-BAT and Fermi-GBM triggered on GRB190114C
T_0 + 22s: MAGIC received the alert
T_0 + 50s: MAGIC started tracking
T_0 + 57s: MAGIC started data acquisition (35s after the alert)
T_0 + 62s: MAGIC data acquisition stabilised

Credit: Marina Manganaro



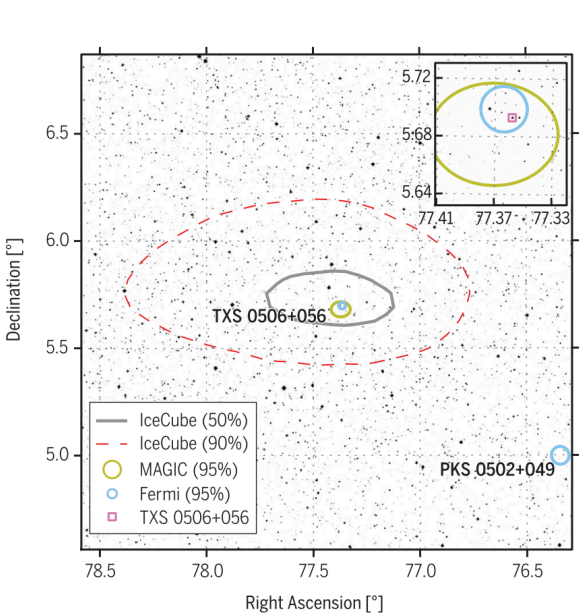
A. Mitchell, ICRC 2021

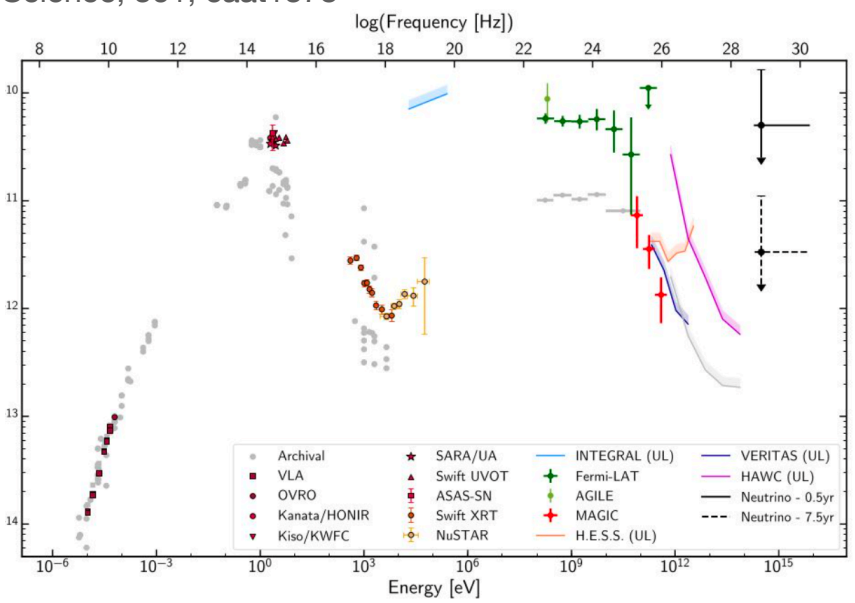
Multi-Messenger Astronomy



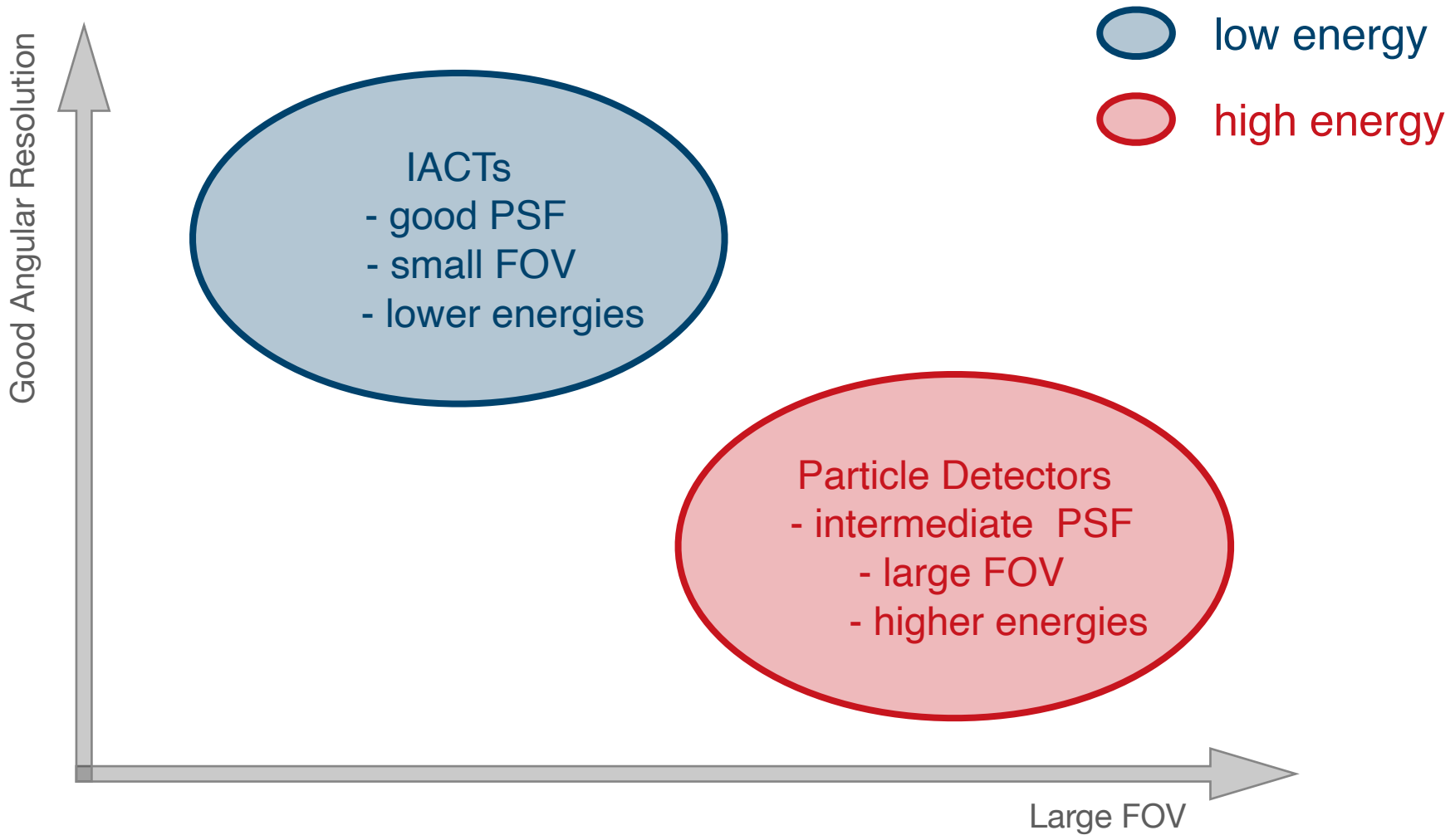
- First time coincidence between VHE gamma rays and high energy neutrino
- Firm detection of the blazer TXS 0506+056

Science, 361, eaat1378

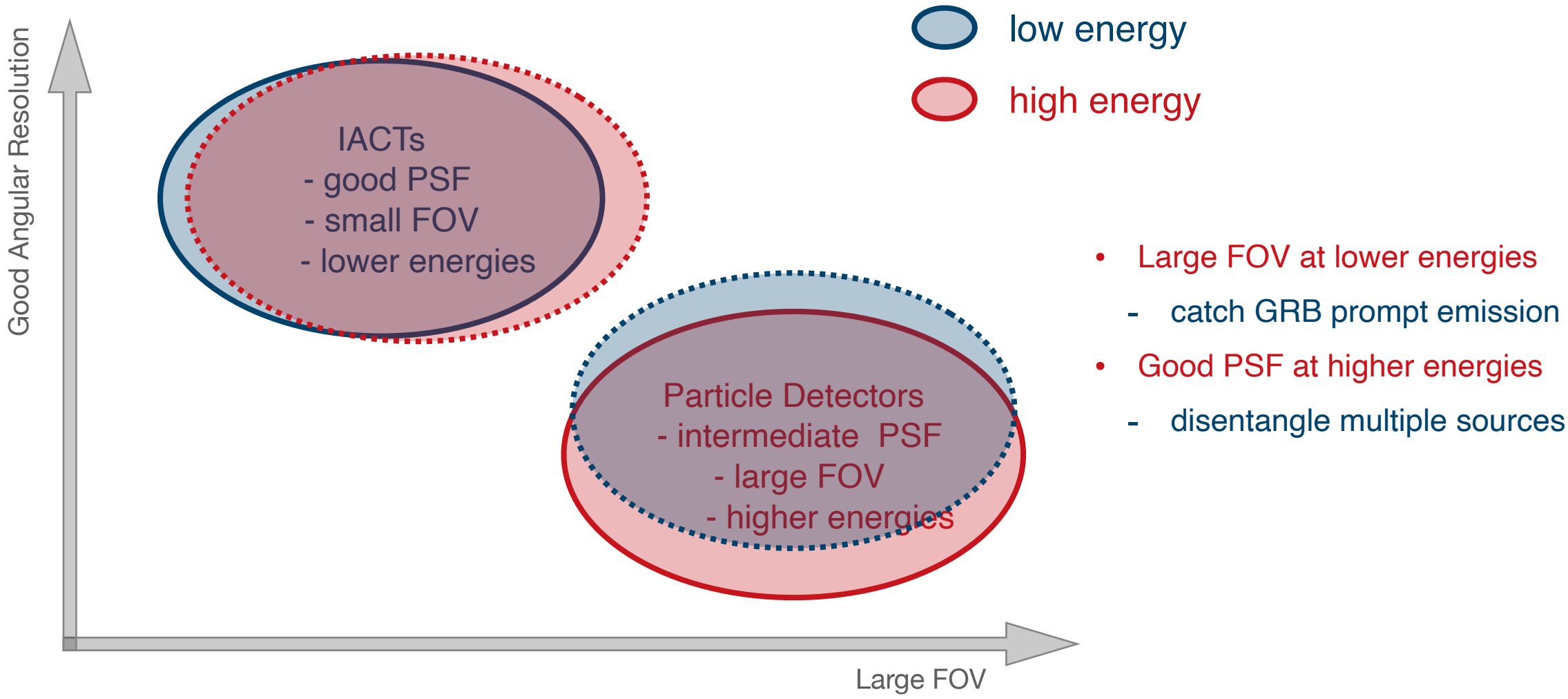




What we still missing?

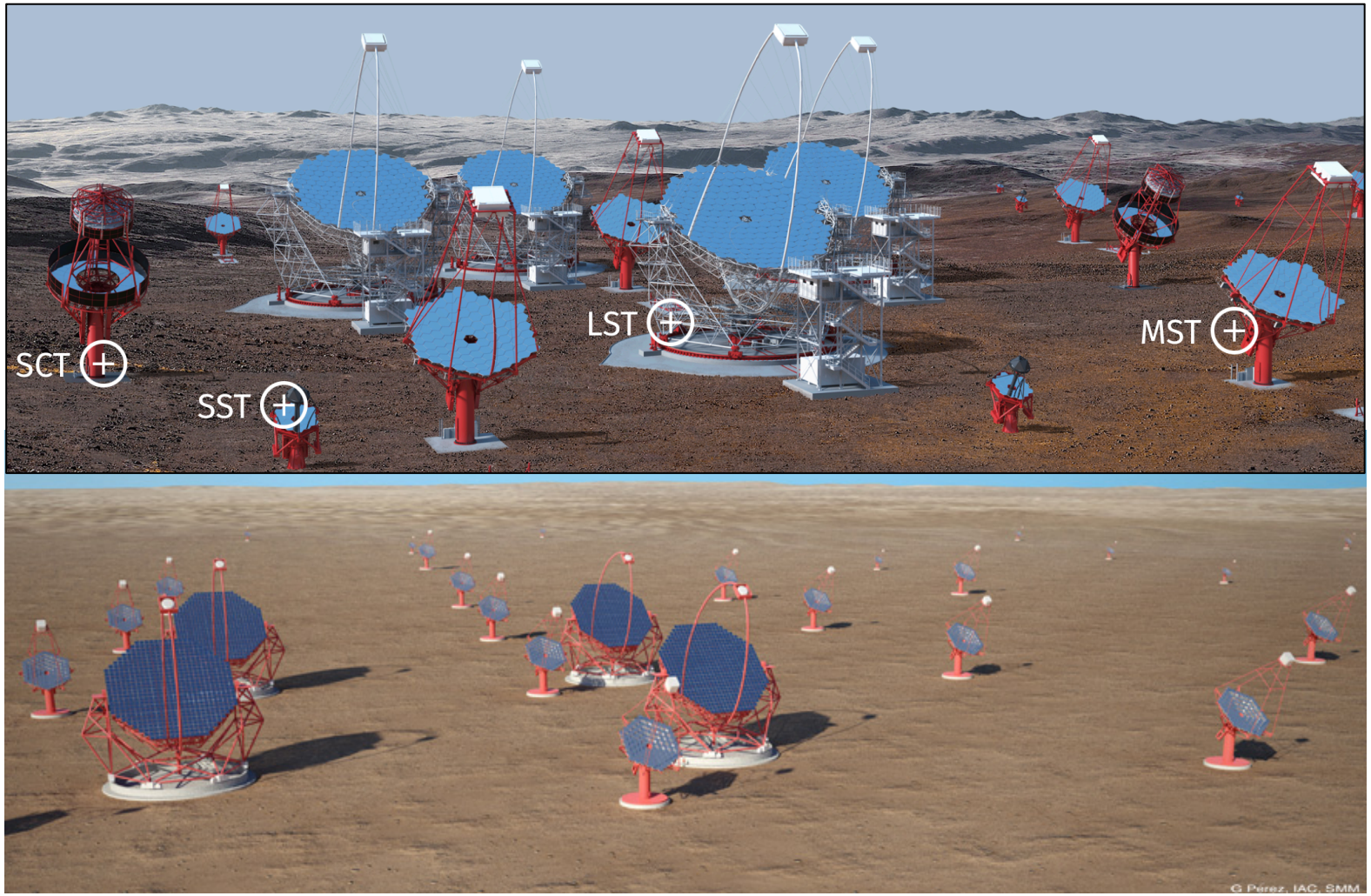


What we still missing?



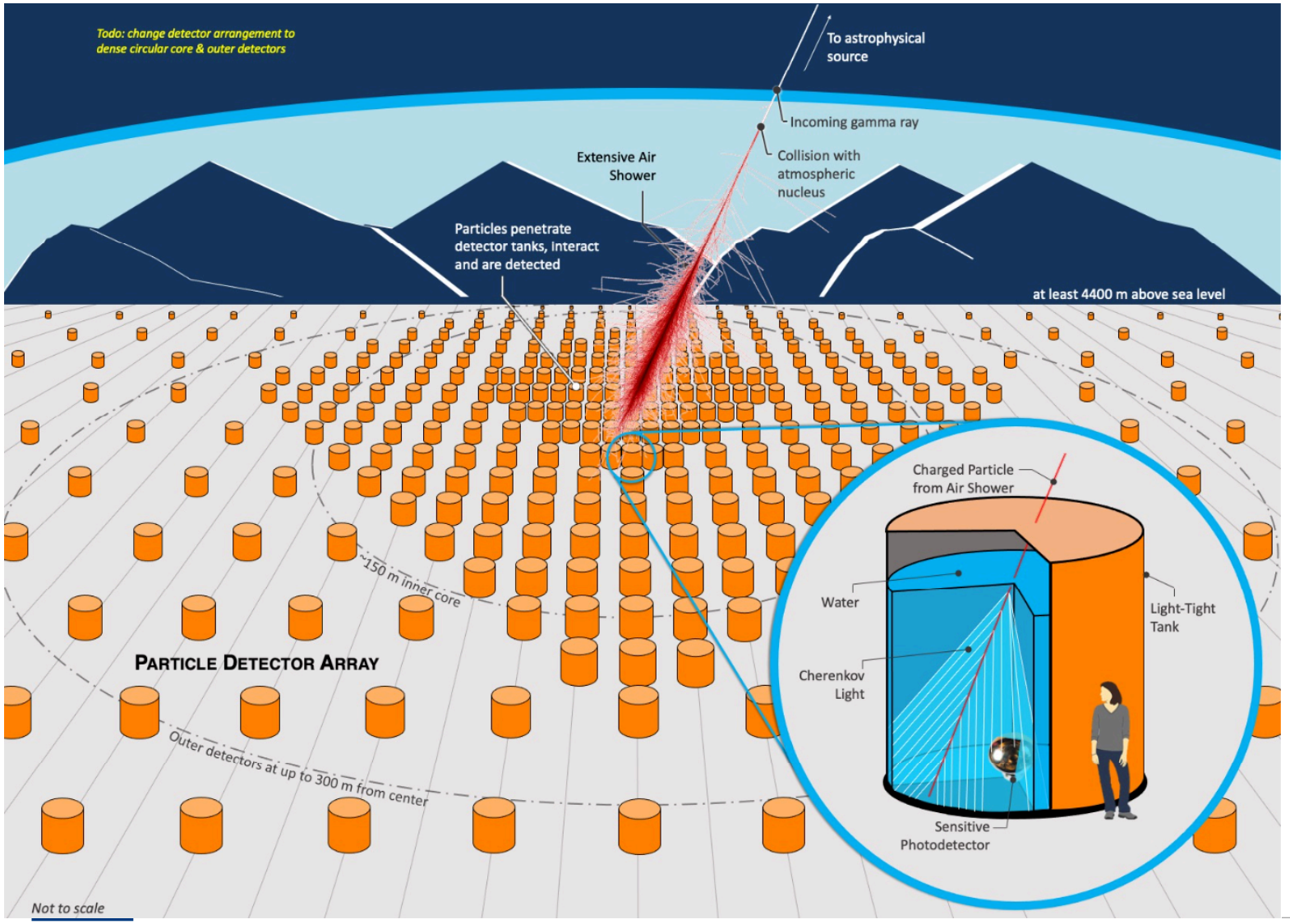
- Large FOV at lower energies
  - catch GRB prompt emission
- Good PSF at higher energies
  - disentangle multiple sources

Future Experiment: CTA

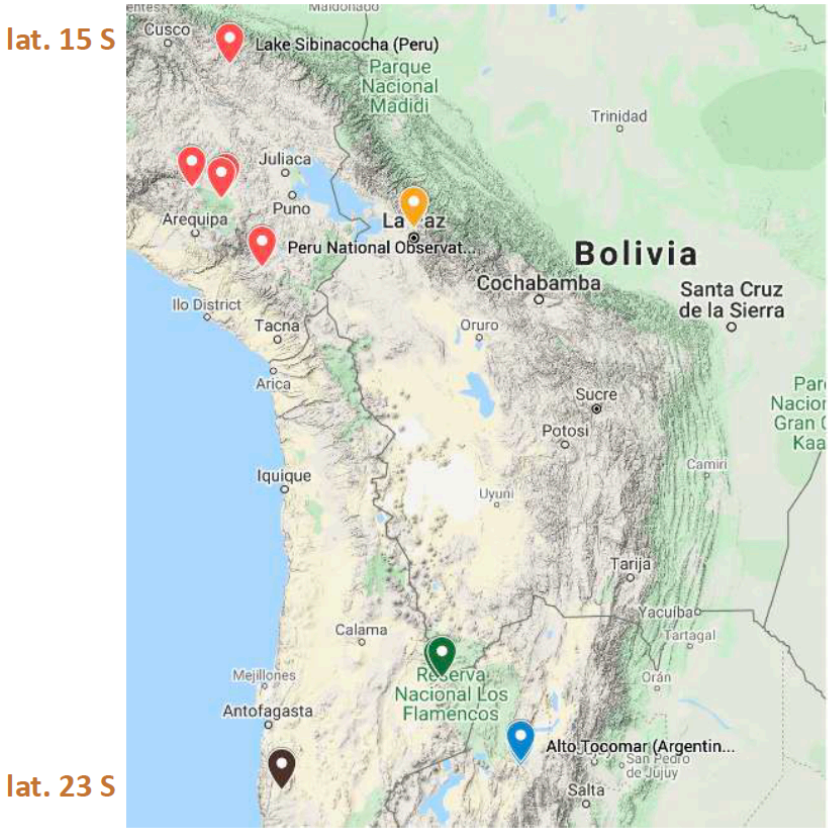


- Layout
  - 4 LSTs + 9 MSTs in the north
  - 14 MSTs + 37 SSTs in the south
- The two arrays should be completed in around 5 years
- LST: Energy threshold ~20 GeV, well in overlap with satellite but with 10^4 times larger collection area
- Fast repositioning: within 20s to any place in the sky
- First LST at La Palma has been operational since 2018

Future Experiment: SWGO



Credit: J. Hinton



Summary

- Very-high-energy gamma-ray directly probe particle acceleration and propagation at the highest energies.
- There are many important recent results that I did not cover
  - Galactic center, nova, jets of Centaurus A, distant FSRQs (z=0.99)
- Not covered either: search for new physics with very-high-energy gamma ray observations
  - LIV, dart matter…
- More discovery space for current and future experiments
  - LHAASO, CTA, SWGO…

谢谢