MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

Selected Highlights of γ-ray Astronomy with Ground-Based Telescopes

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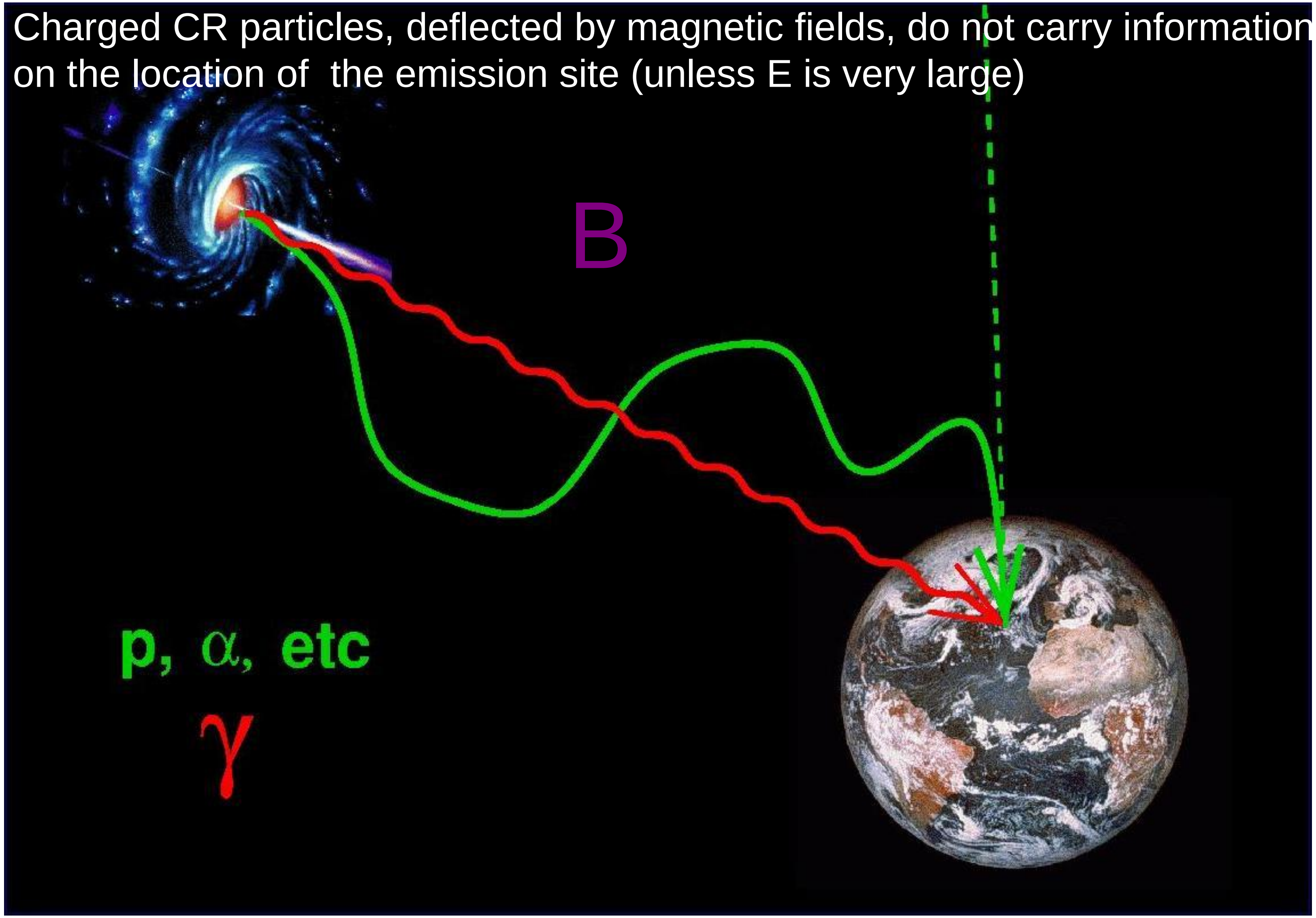
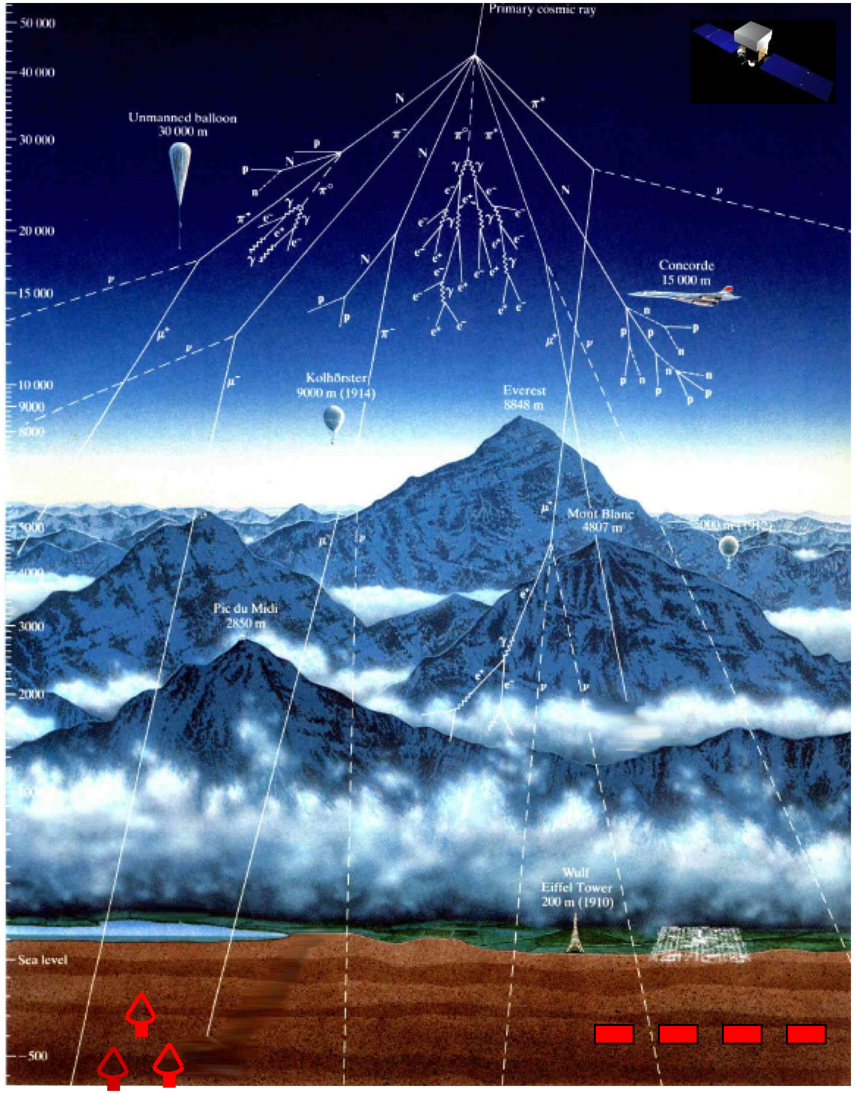
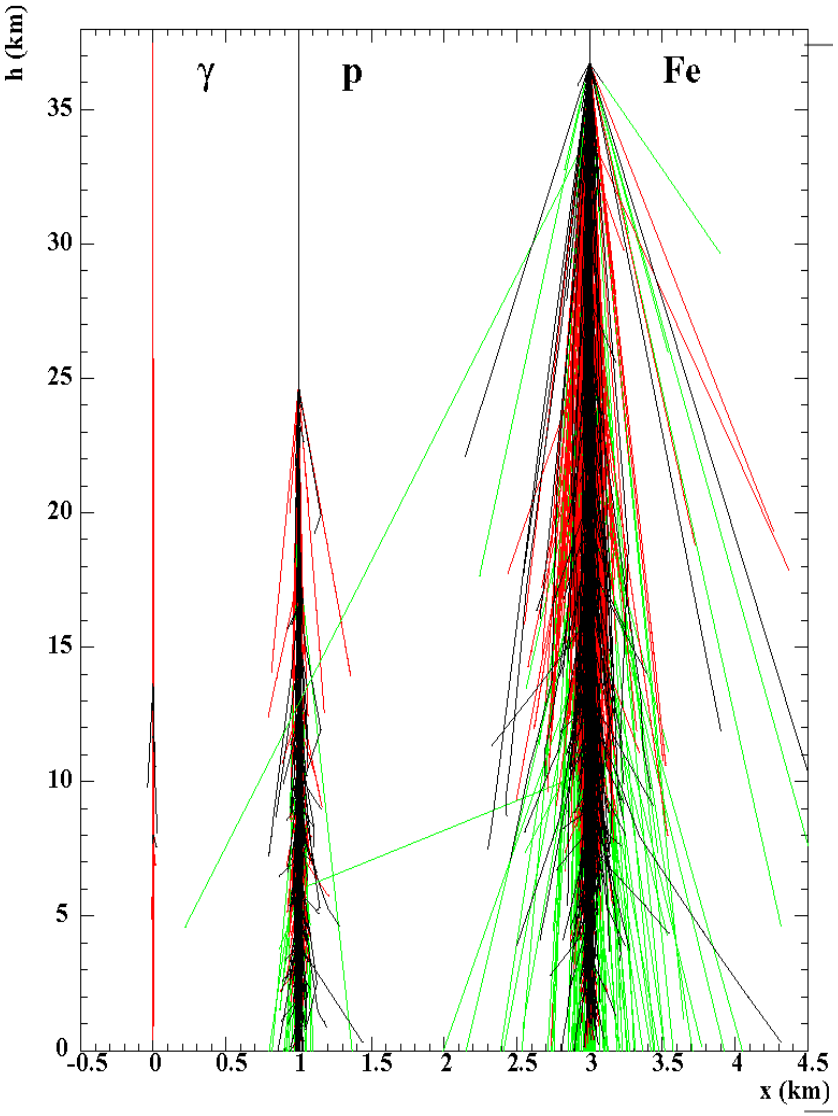
Why not charged CR astronomy?

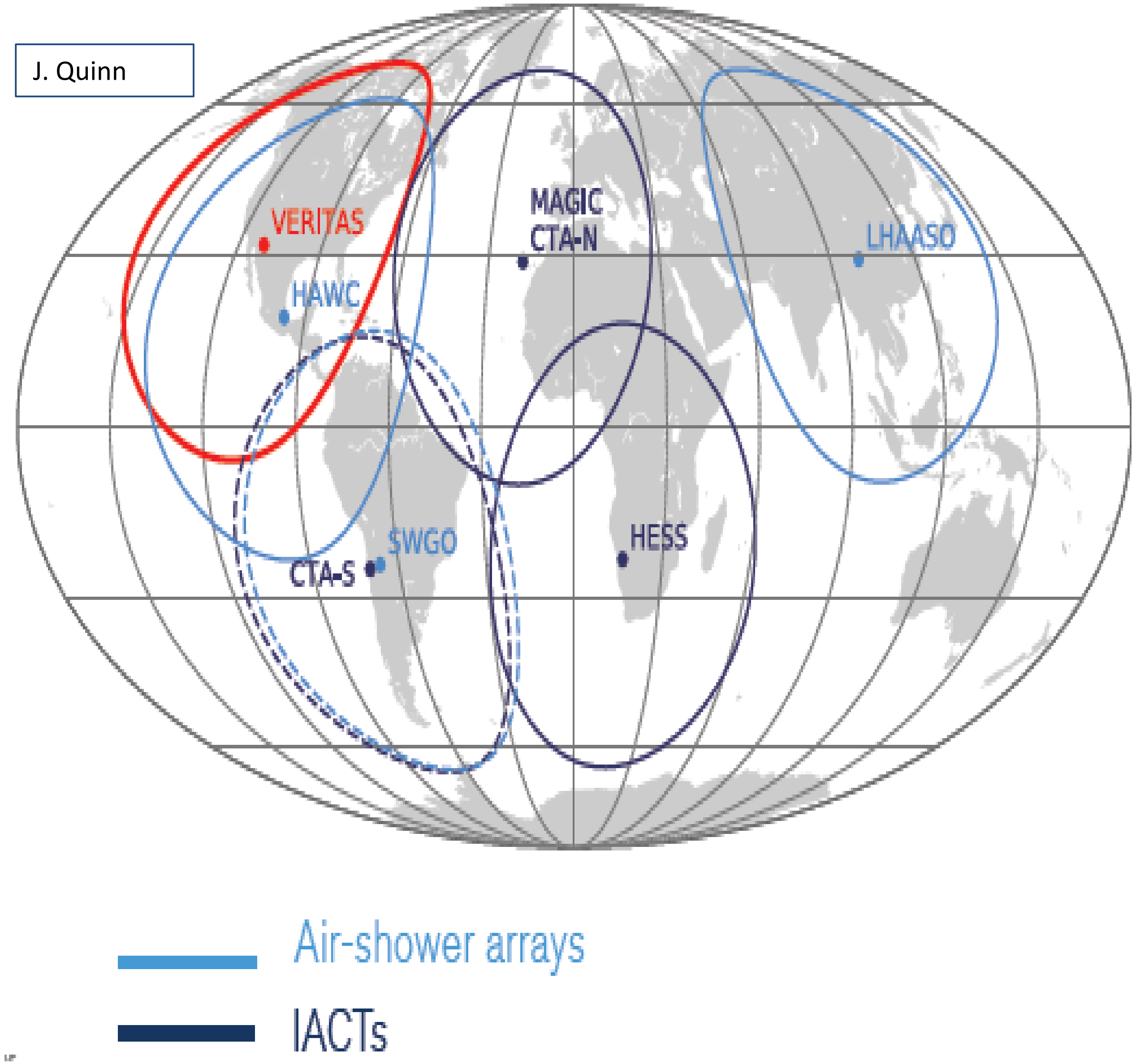


Charged CR particles, deflected by magnetic fields, do not carry information on the location of the emission site (unless E is very large)

Extensive Air Showers







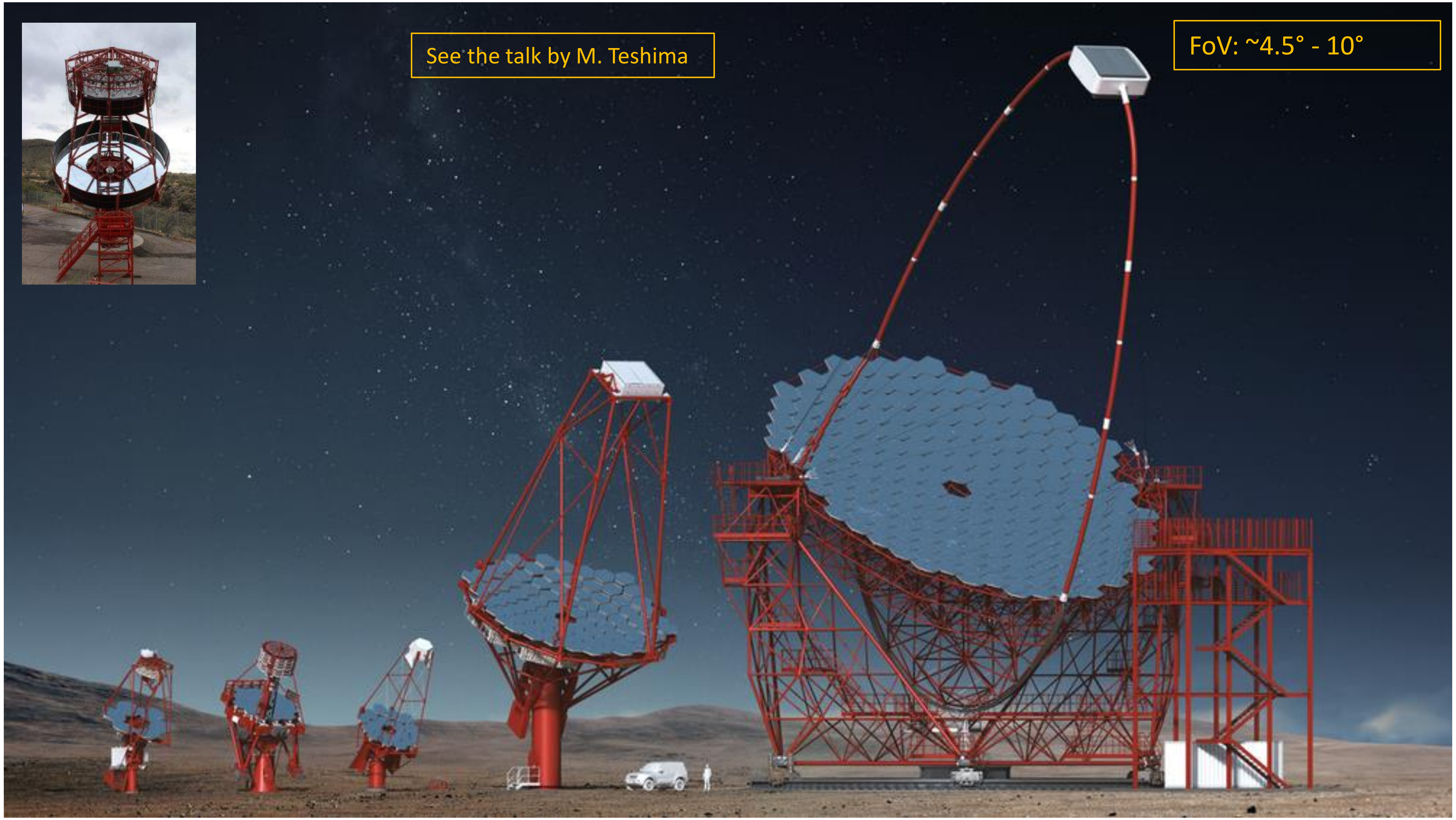
J. Quinn

Air shower array:
High-mountain altitude necessary, > 4 km a.s.l.
Measure particles from EAS, mostly $e^{\pm}$
Typical FoV: 1-2 srad
Operation time: > 90 % during a year
Sources can be observed 6-8 h every day
Threshold (optimistic): > 1 TeV
High sensitivity > few 10‘s of TeV to > 100 TeV
Angular resolution: ~0.3°
EAS collection area: can be as high as ~1 km^2

IACT arrays:
Moderate location altitude, ~2 km
Measure Cherenkov light from EAS
Typical FoV: 3.5° - 10°
Operation time: 10 % during a year
Threshold: can be as low as > 20 GeV
Best sensitivity: (0.2 – 1) TeV
Source can be observed for up to 400 h (incl. Moon)
Angular resolution: 0.03° - 0.08°
EAS collection area: can be as high as few km^2

VERITAS, H.E.S.S., MAGIC and since recently, the 1st 23m Ø CTA/LST: at the frontier of VHE γ-astro-physics

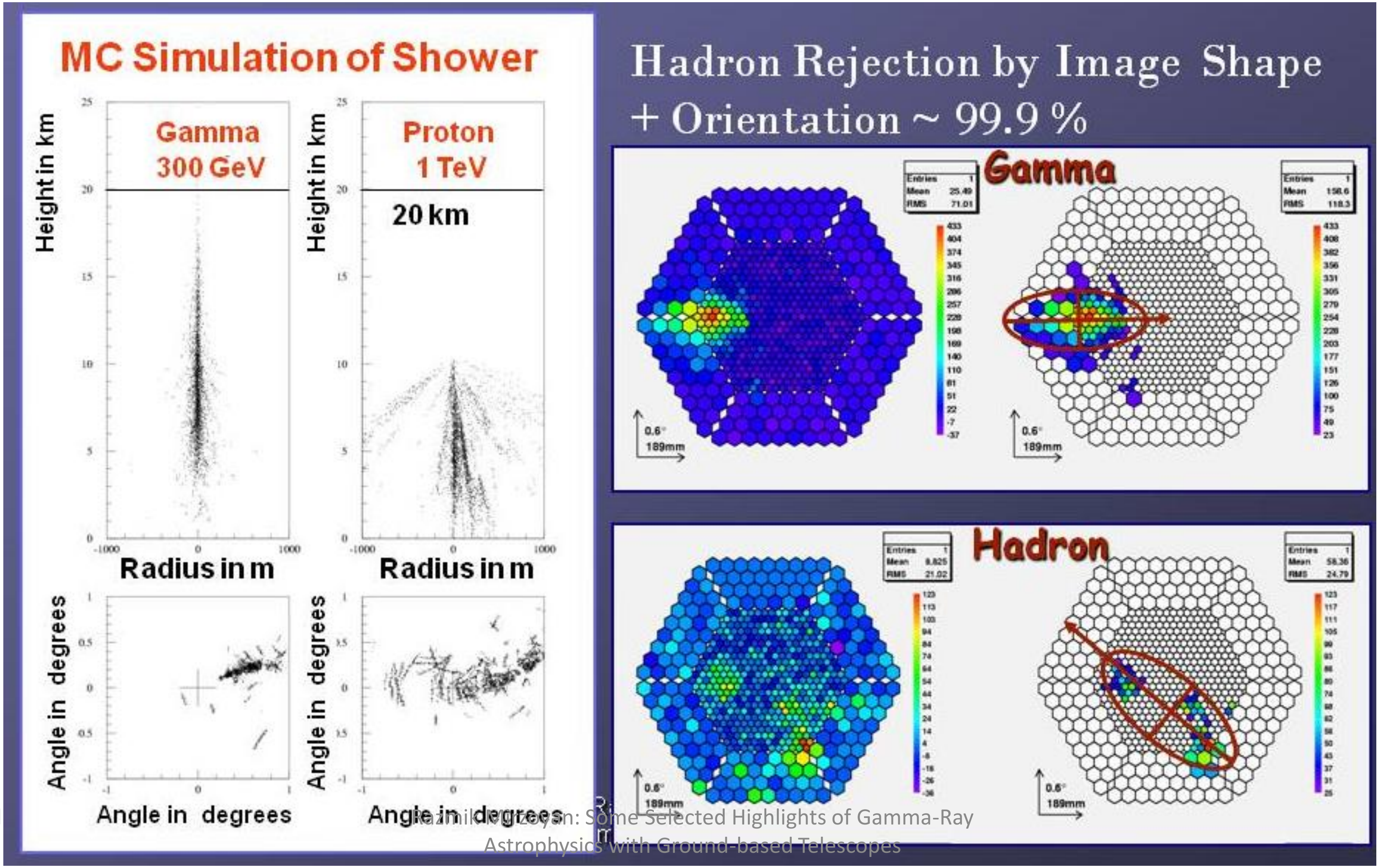
Cherenkov Telescope Array



See the talk by M. Teshima

FoV: ~4.5° - 10°

γ-ray and hadron images and their separation

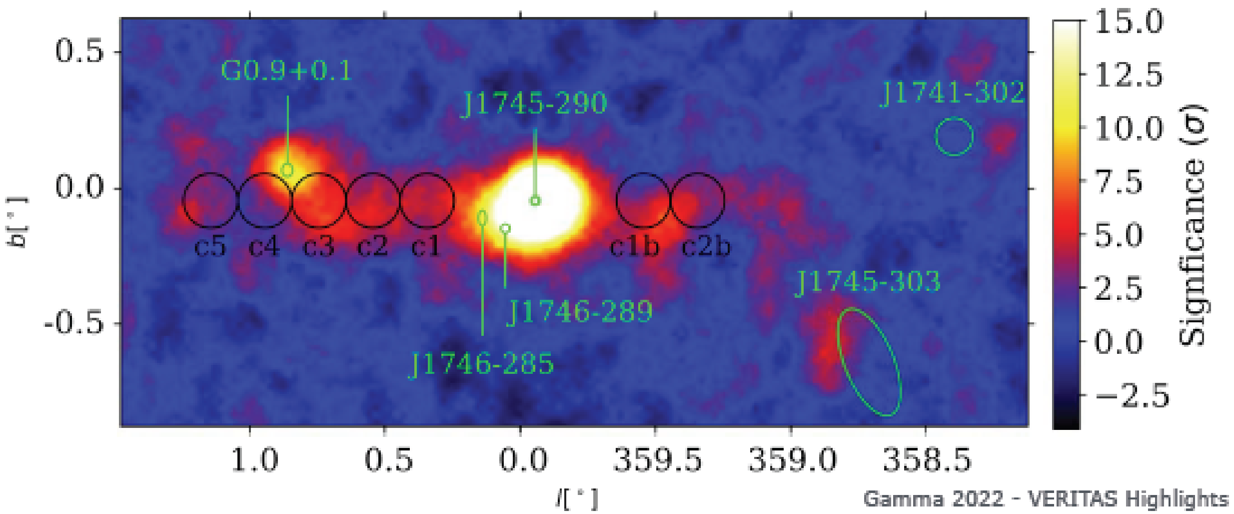


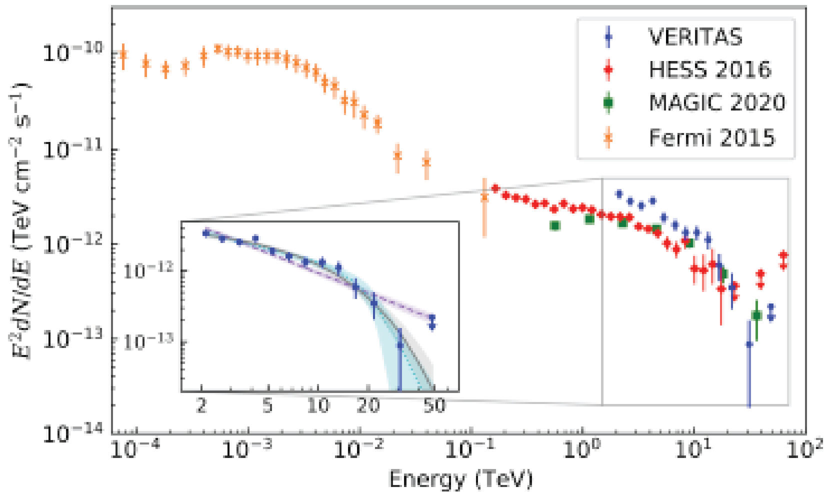
MC Simulation of Shower

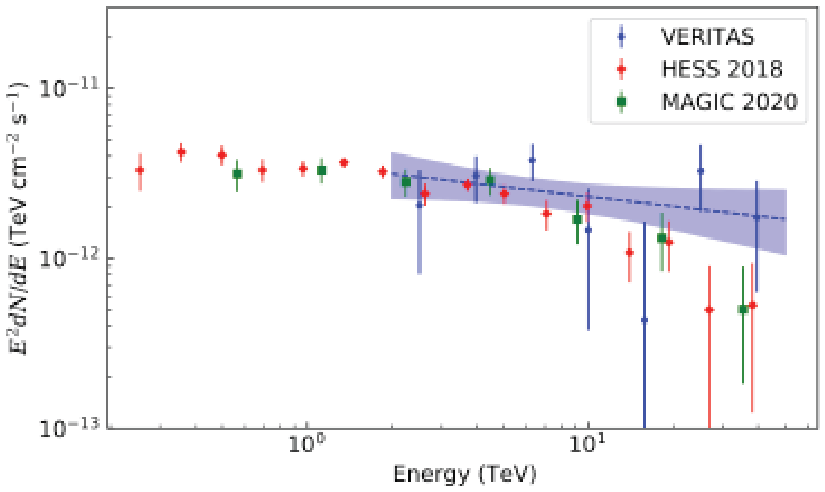
Hadron Rejection by Image Shape + Orientation ~ 99.9 %

A recent study of Veritas of the Galactic Center region

- VERITAS observations (*Adams et al., ApJ 913, 115 (2021)*):
  - 125 hours at zenith angle ~60° - 65° yielding E > 2 TeV
  - **Sagittarius A***:
    - Detected at 38σ,
    - Spectrum: PL Exp. Cutoff, $\Gamma = 2.12^{+0.22}_{-0.17}$, $E_c = 10$ TeV
    - Variability? no
  - **Diffuse Emission:**
    - Detected at 9.5σ
    - Spectrum: power law $\Gamma = 2.2 \pm 0.2$, no cutoff up to 40 TeV

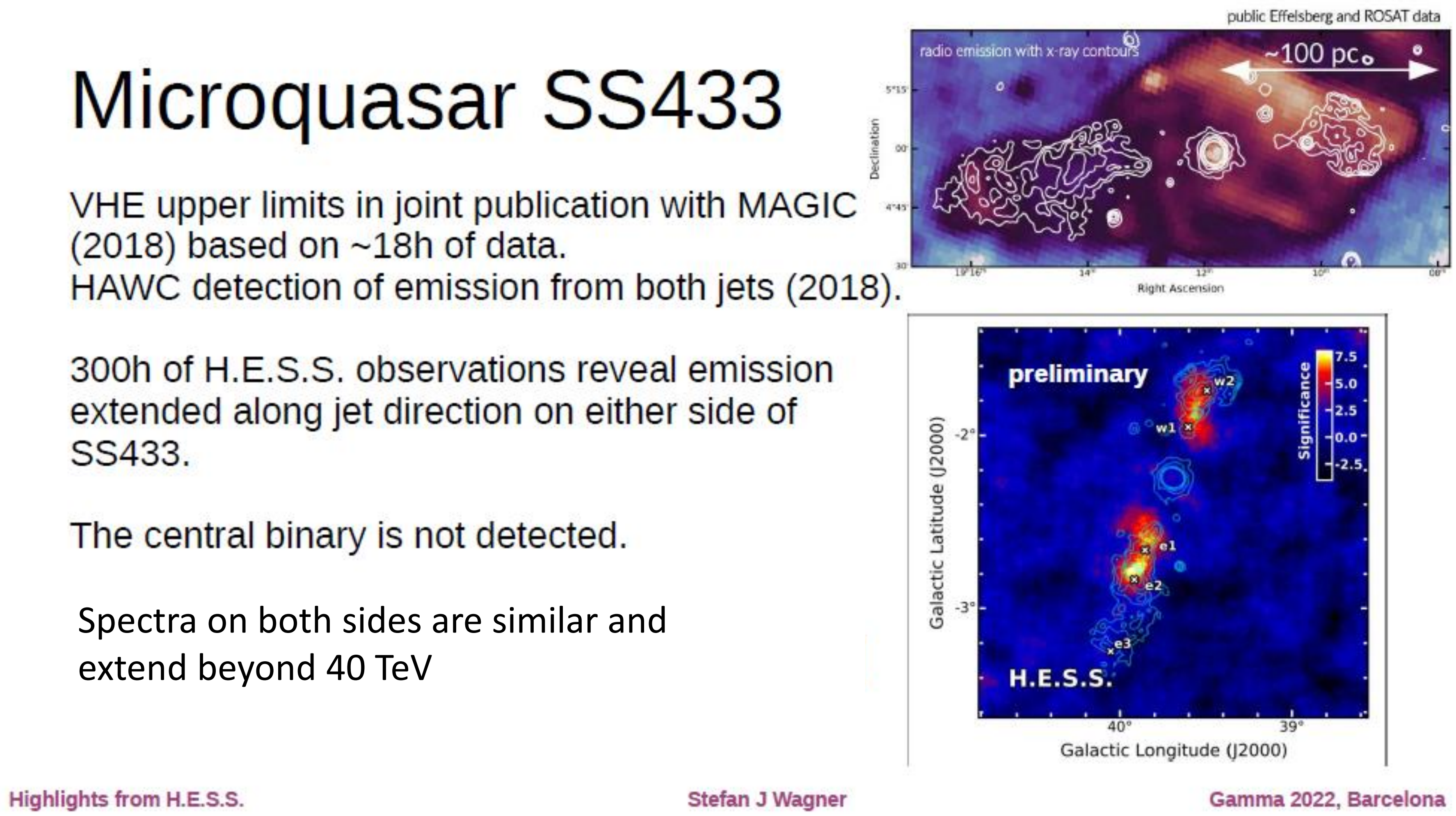






Gamma 2022 - VERITAS Highlights - Quinn

A recent interesting study by H.E.S.S.



Microquasar SS433

VHE upper limits in joint publication with MAGIC (2018) based on ~18h of data.
HAWC detection of emission from both jets (2018).

300h of H.E.S.S. observations reveal emission extended along jet direction on either side of SS433.

The central binary is not detected.

public Effelsberg and ROSAT data

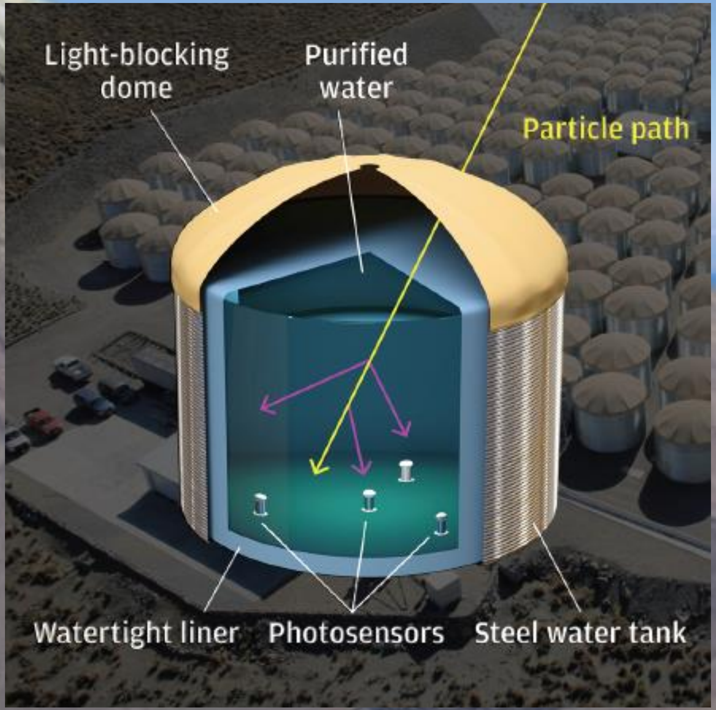
Highlights from H.E.S.S.   Stefan J Wagner   Gamma 2022, Barcelona

Spectra on both sides are similar and extend beyond 40 TeV

High Altitude Water Cherenkov (HAWC) detector

Pico de Orizaba
5636 m a.s.l.

FoV: ~2 sr



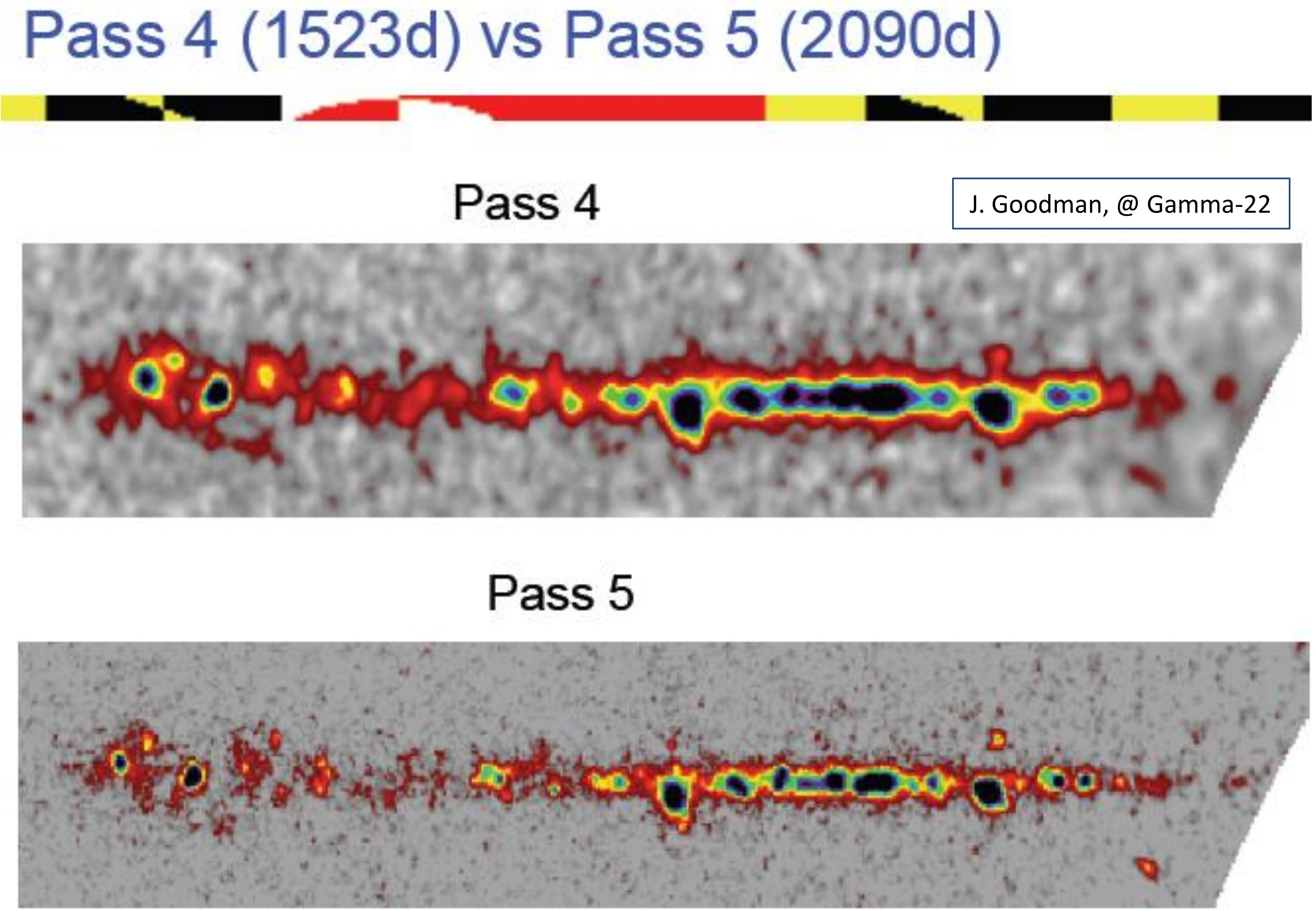
Sierra Negra
Alfonso Serrano
Large Millimetric Telescope
4640 m a.s.l.

HAWC
4100 m a.s.l.

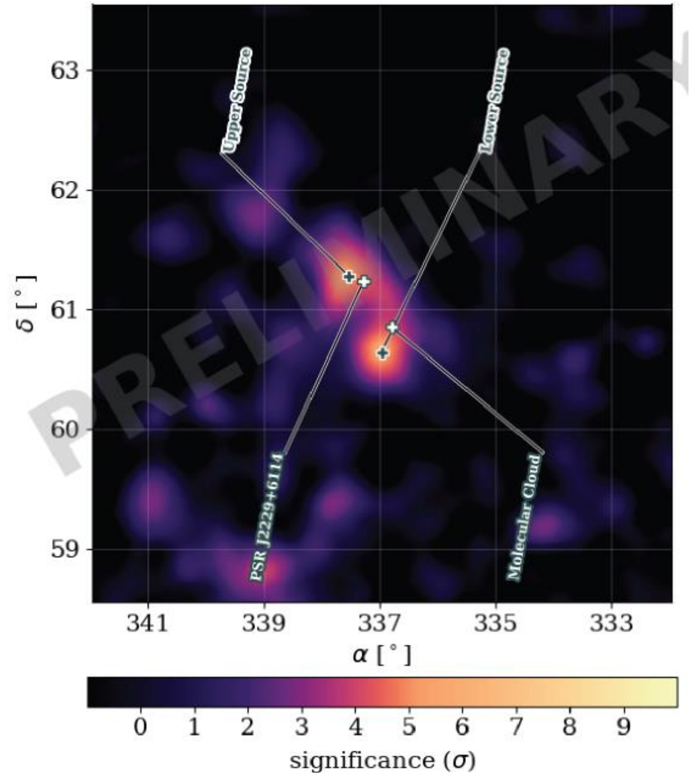
~24000 m²

- 300 close-packed optically isolated water Cherenkov detectors
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, since summer 2018
- Takes data with >95 on time
- ~5 trillion triggers to date - 7PB of data

Recently HAWC has improved its sensitivity

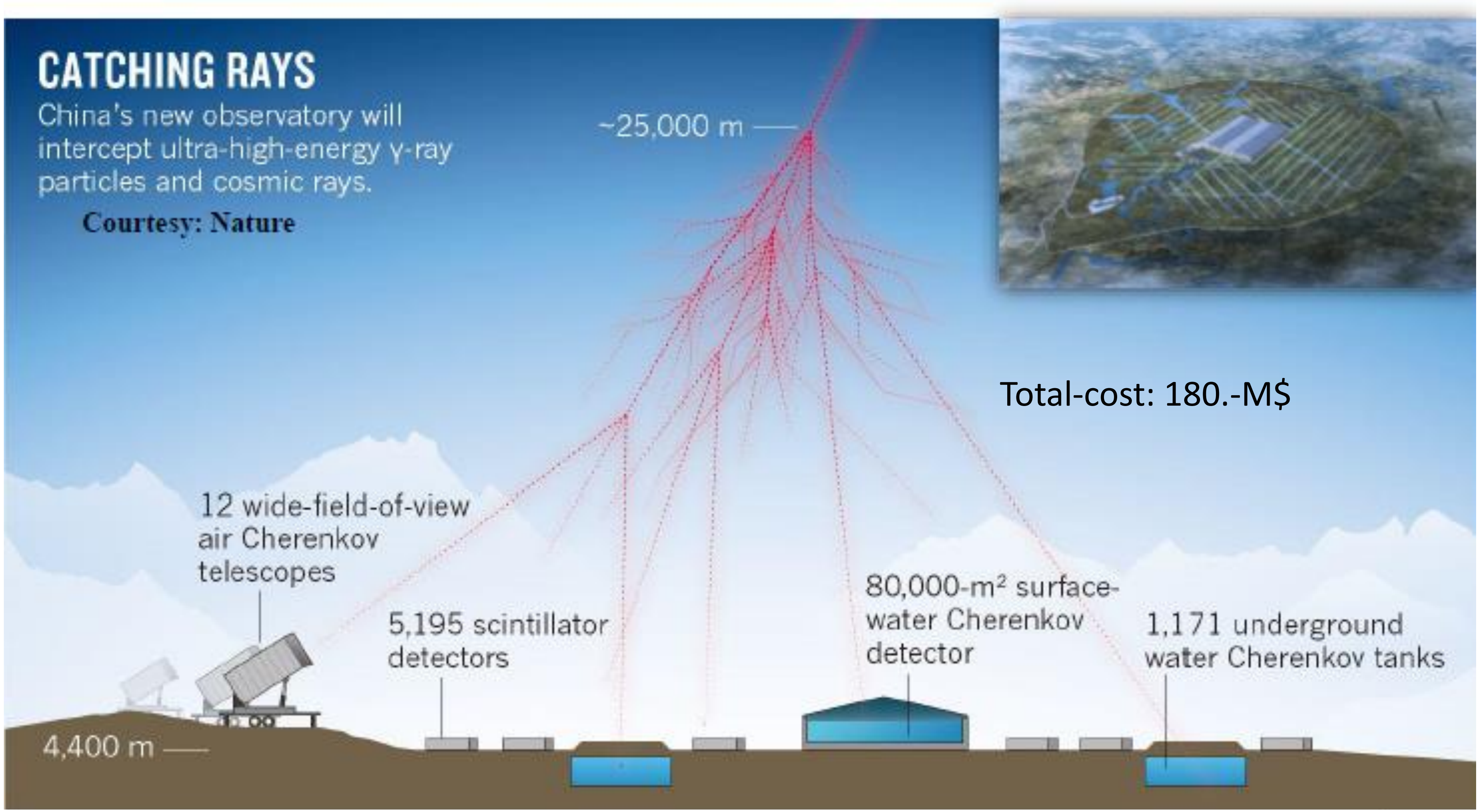


J. Goodman, @ Gamma-22



An example; galactic PeVatron candidate Boomerang. HAWC & MAGIC see 2 sources, upper: IC scattering in PWN, lower: nearby molecular cloud. Both $\pi^0 \text{-->} 2\gamma$ and IC possible

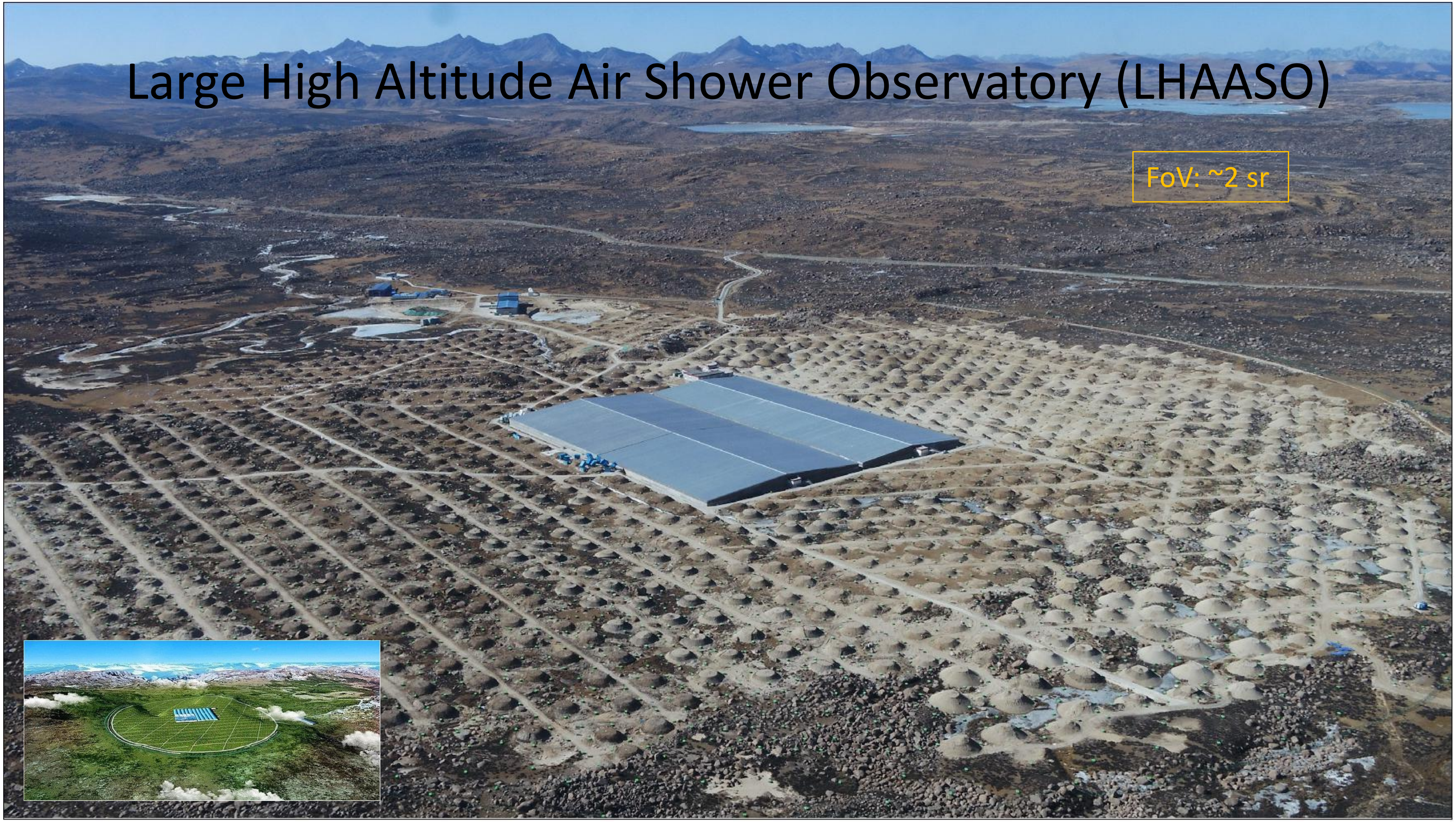
Hybrid Detection of EASs by LHAASO



Courtesy: Nature

Total-cost: 180.-M$

Large High Altitude Air Shower Observatory (LHAASO)



FoV: ~2 sr

Discovery of 12 PeVatrons by LHAASO

Zhen Cao, et al., Nature, May 2021

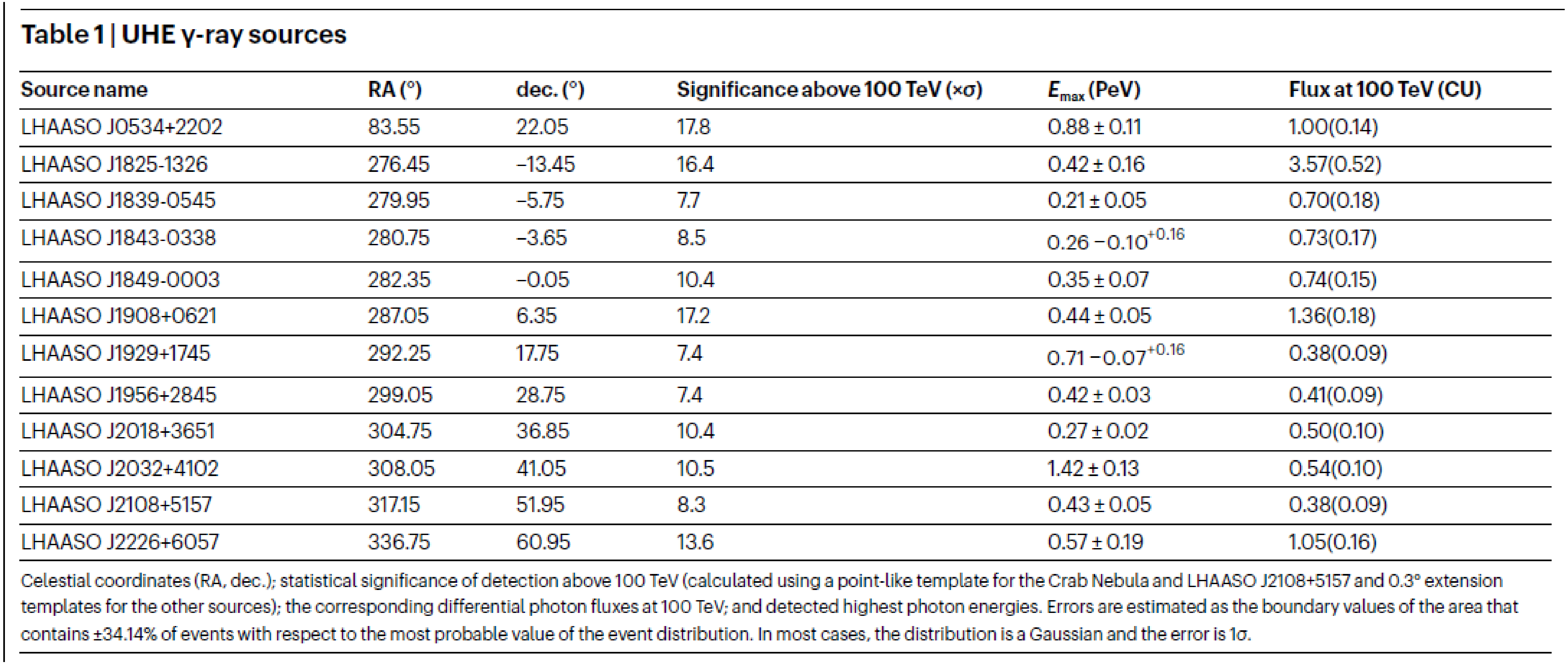


Table 1 | UHE γ-ray sources

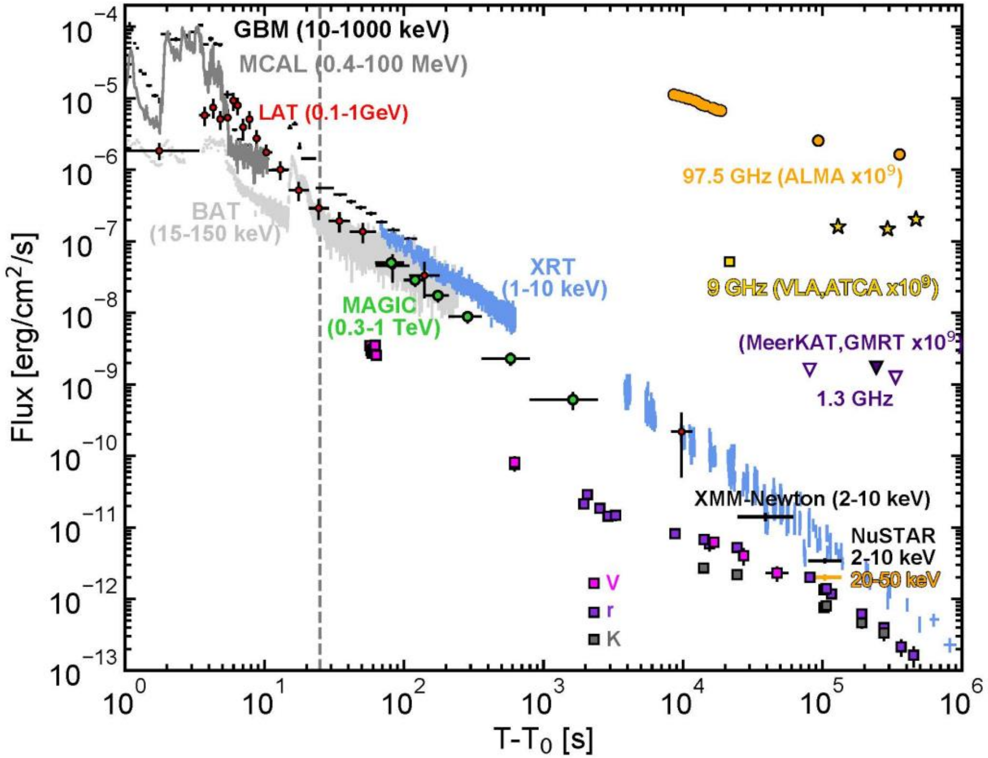
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

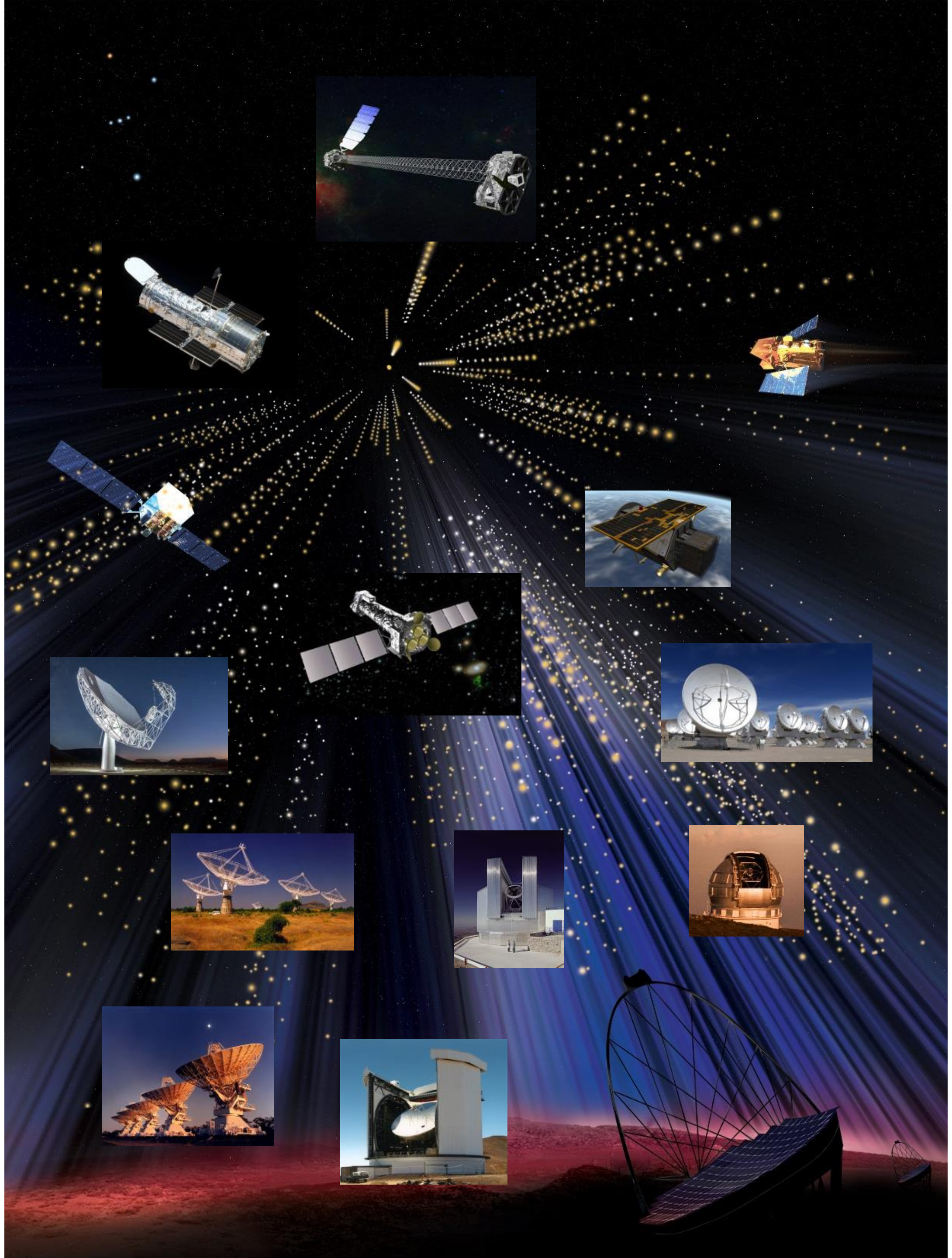
Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

For the 1st time MAGIC discovered extreme γ-ray emission from a GRB; GRB190114C was measured by 2 dozens of space-born and ground-based instruments

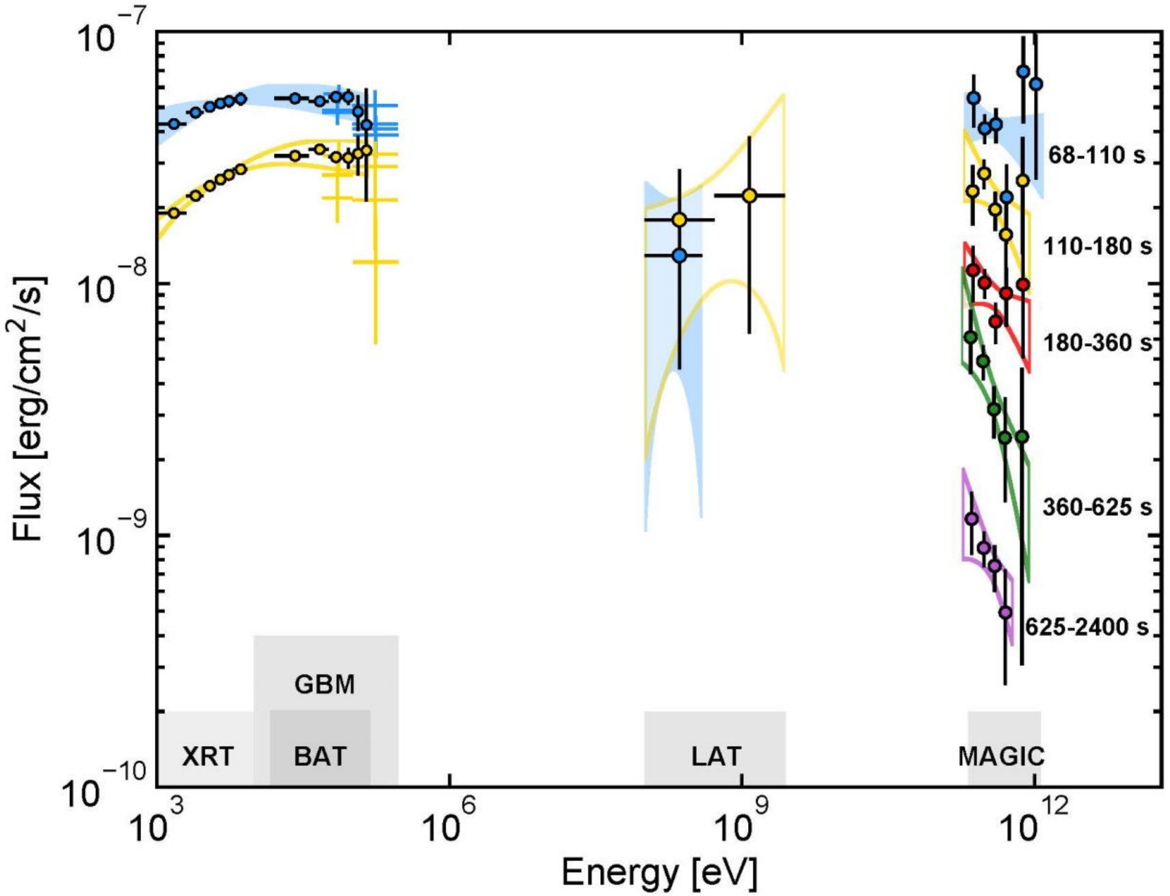
MAGIC published 2-papers in
Nature, 575 Nov. 2019

- MAGIC discovered a gigantic emission from a GRB starting 58 s after its onset – afterglow emission
- 60 σ
- 130 Crab intensity in the first 30 s
- A significant share of GRB energy is emitted in the TeV energy range





Dynamics of multi-wavelength spectra of GRB 190114C; afterglow emission can be well described by the SSC model

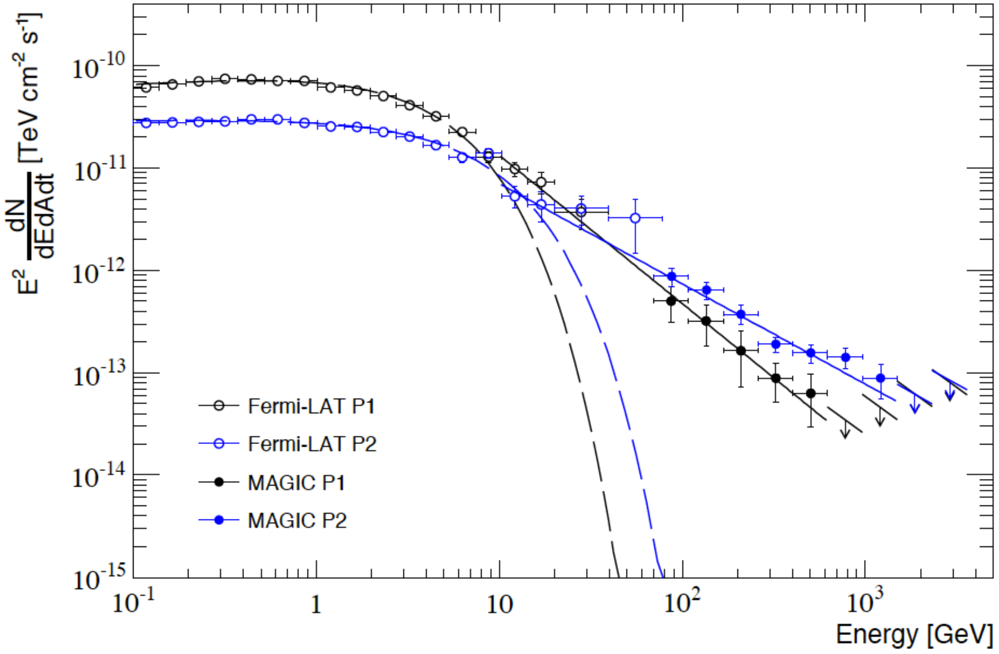


A really unique event; the spectra have been measured during the

- 1st time bin for only 42 s,
- 2nd time bin for 70 s
- 3rd time bin 180 s

MAGIC measured pulsed γ-rays from the Crab pulsar up to ~2 TeV

Ansoldi, et al, 2016

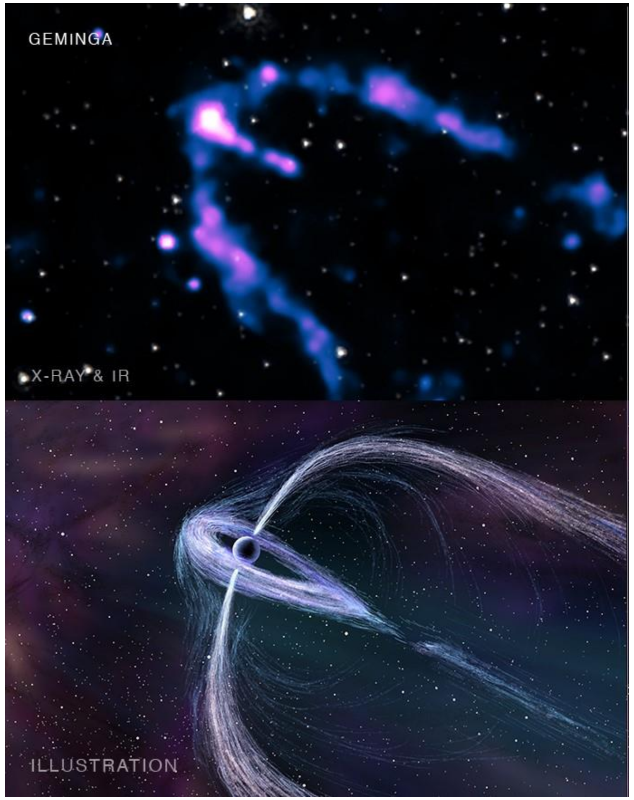


Detected pulsed emission up to ~2 TeV; no cutoff observed

- Power law fit to MAGIC + Fermi data favors the IC emission mechanism for the E range ~ 10 GeV – 1 TeV
- Emission from the neighborhood of Light Cylinder (r ~ 1600 km); confirming that pulsars are the most compact particle accelerators
- TeV pulsation is used to put a very competitive quadratic limit for the Lorentz Invariance Violation (LIV)

Pulsed γ-ray signal measured by MAGIC @ 6.3σ from Geminga pulsar at **E ≥ 15 GeV**

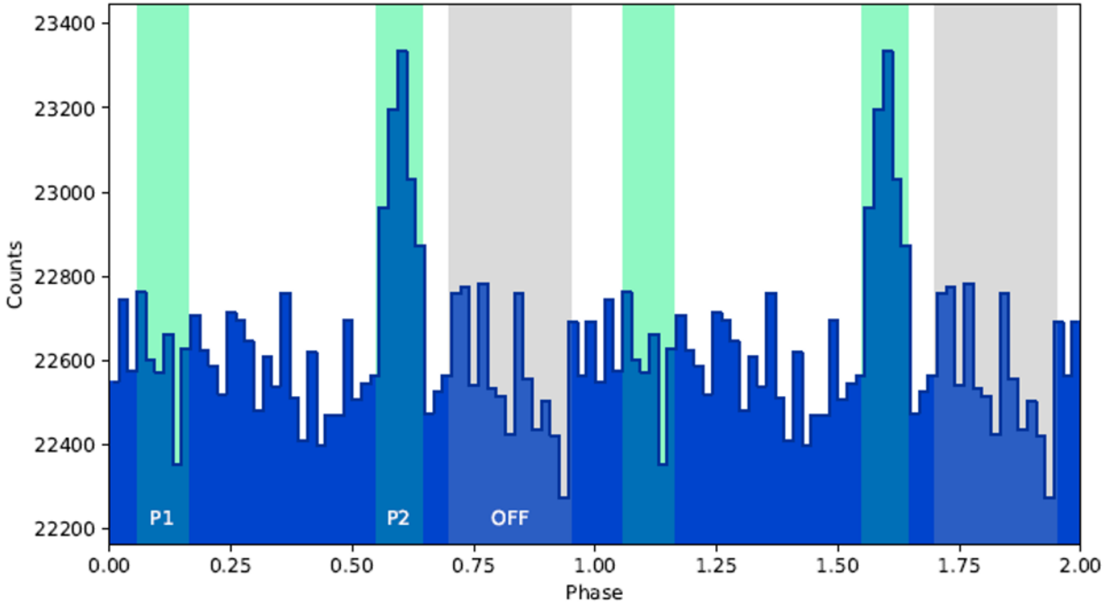
(the 3rd pulsar revealed in the VHE domain)



X-ray: NASA/CXC/GWU/N.Klingler et al;
IR: NASA/JPL-Caltech; Illst: Nahks TrEhnl

Age ~340ky; estimated distance ~ (175 – 250) pc

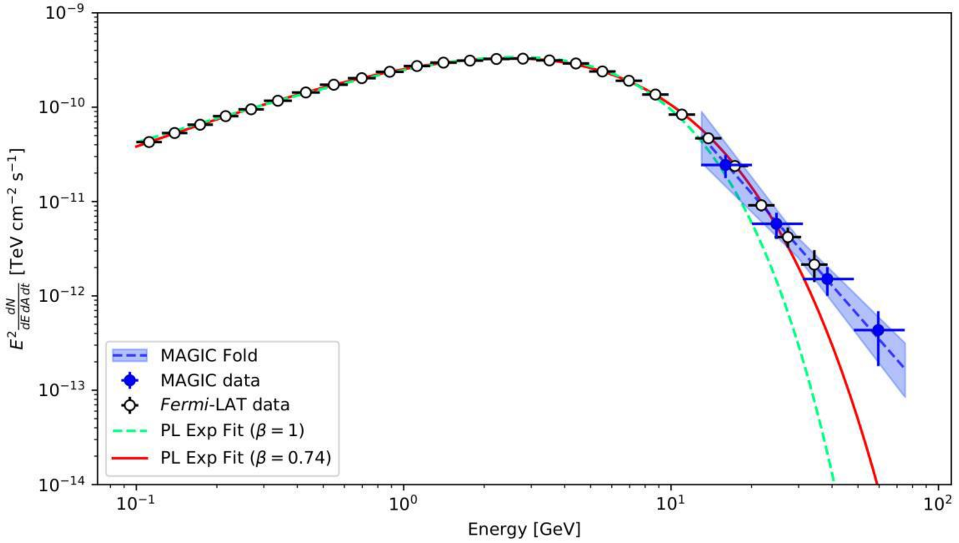
Acciari et al, A&A 2020

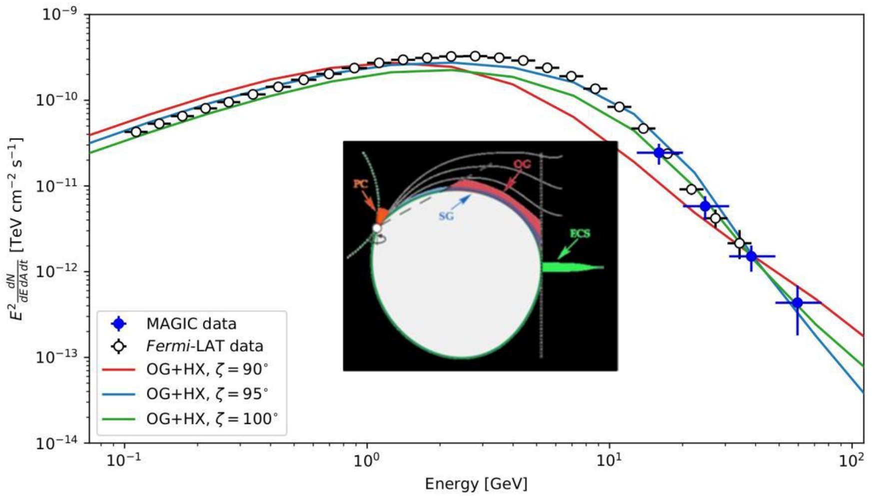


80h of data taken under *Sum-Trigger-II* low-energy trigger

MAGIC + Fermi Spectrum of Geminga

Acciari et al, A&A, 2020; **Highlight Letter**

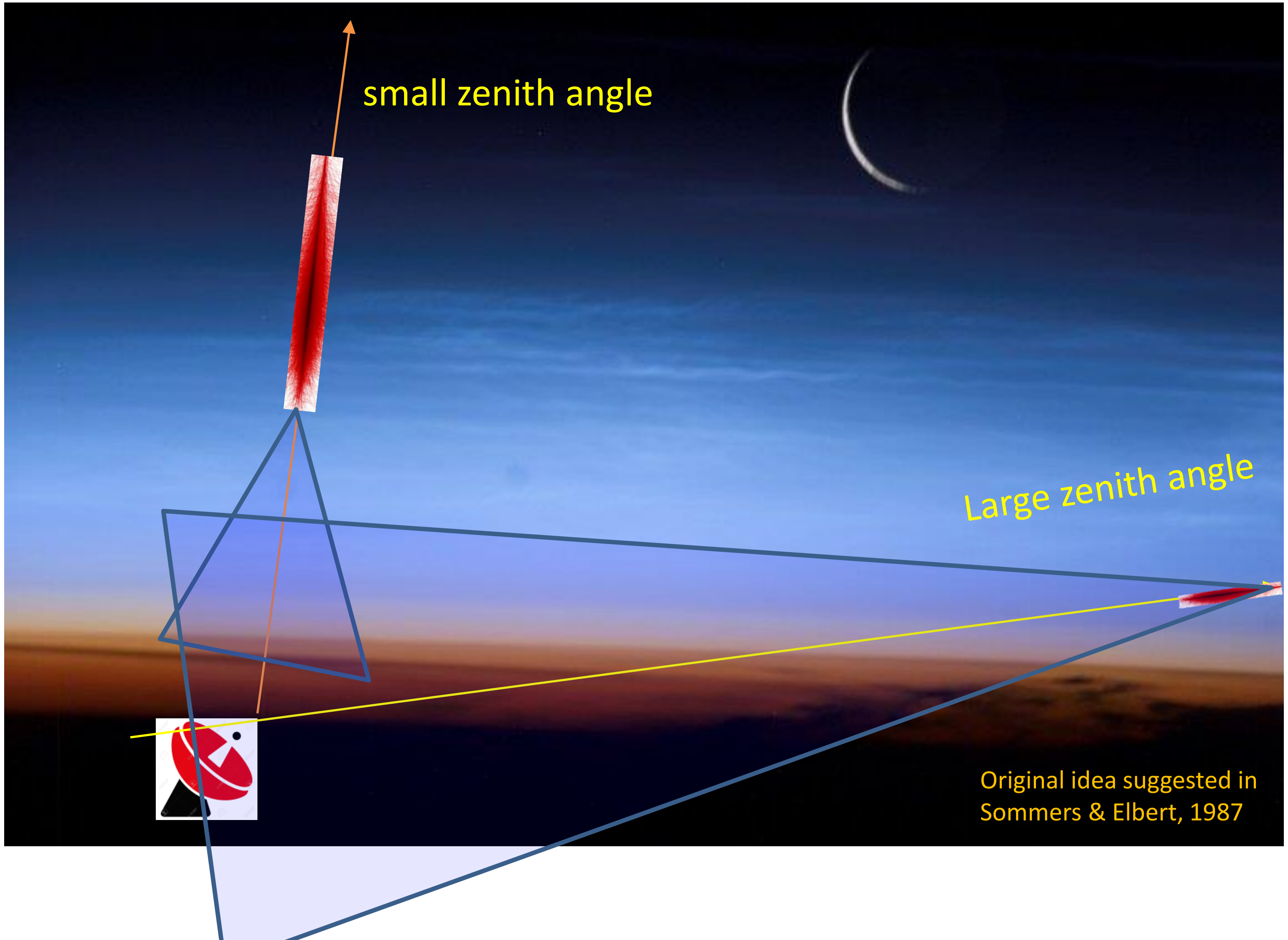




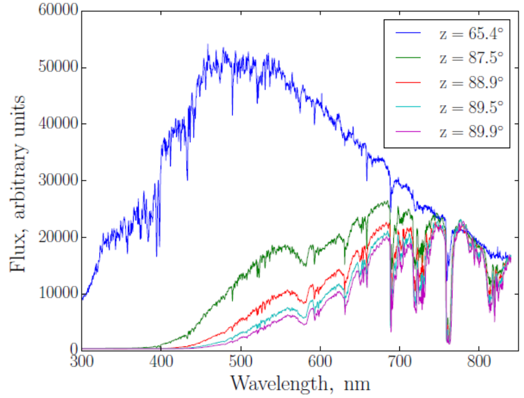
- Power law spectrum @ (15 – 75) GeV with $\Gamma = -5.2$
- MAGIC & Fermi data overlap for $E \leq 40$ GeV
- No cutoff observed
  - Exponential cutoff ruled out
  - Sub-exponential disfavored @ 3.5 σ level
  - Power law behavior compatible with IC

- Modeling with Outer Gap
  - IC with inward-going e^-
- Observation challenges the model
  - Contribution from Heated Polar Cap (Caraveo, 2004)
- A recent paper states that the spectrum is an extension of Fermi and can be explained as primary SC emission - no need to invoke ICS (A. Harding, et al, arXiv:2110.09412v12021)

Cartoon on larger collection area for EAS measured by IACT @ large zenith angles



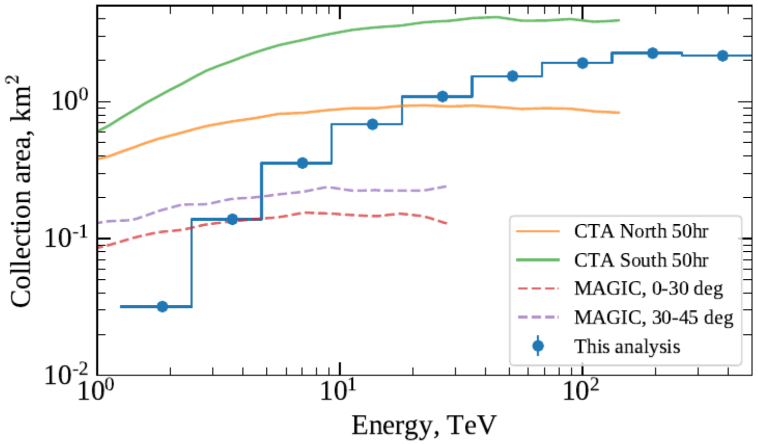
Original idea suggested in Sommers & Elbert, 1987



Sunset @ ORM
2200 m a.s.l.
La Palma

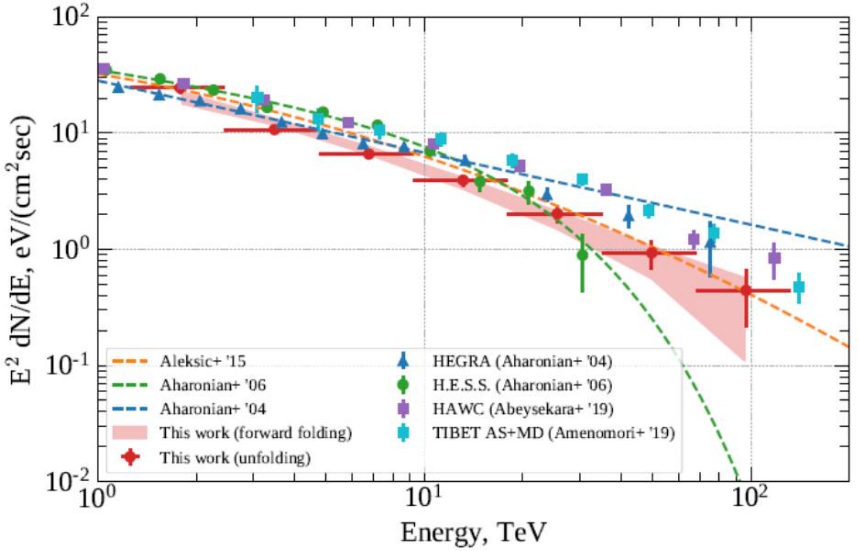
VLZA Crab Nebula spectrumup to 100 TeV in 50h VLZA obs.

Mirzoyan, et al, NIM A, 2018



- Collection area at VLZA observations (~2 km²) for E ≥ 100 TeV comparable with that of planned CTA array (~4 km²) ~ 20° zenith angle
- VLZA observations enable **high sensitivity to Galactic PeVatrons**

Acciari, et al., A&A, 2020



Tested models from Bednarek & Protheroe (1997) and Amato + (2003). No obvious contribution from hadronic component. Observations for E ≥ 100 TeV were reported by *Tibet*, *HAWC* and recently *by LHAASO, up to ~0.8 PeV*; can constrain the Nebula PeV electron population and magnetic field.

First association of a ~300 TeV neutrino to a γ-ray source

MAGIC
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See talk by T. Montaruli

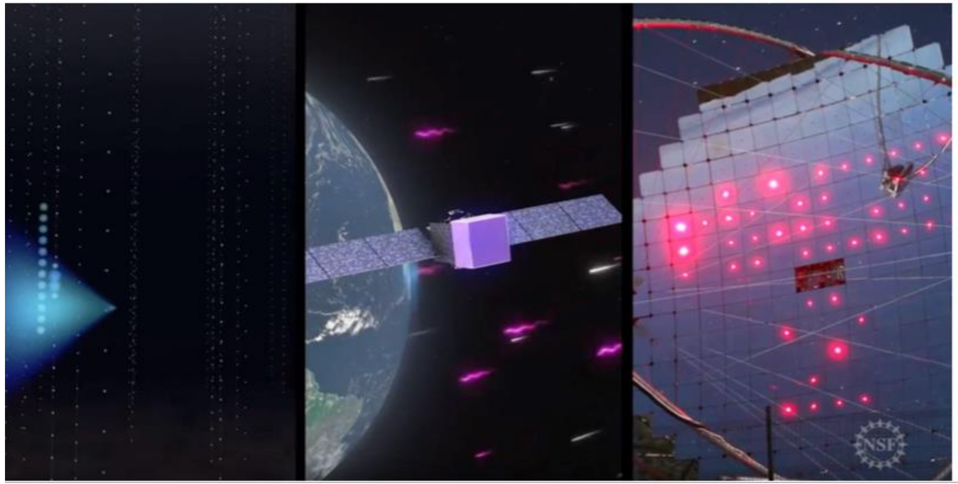
Science 361, July 2018

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

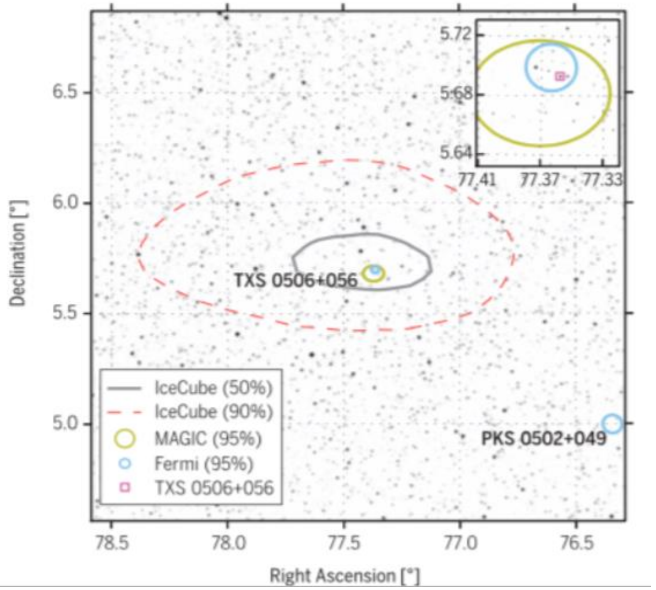
The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†



evaluated below, associating neutrino and γ-ray production.

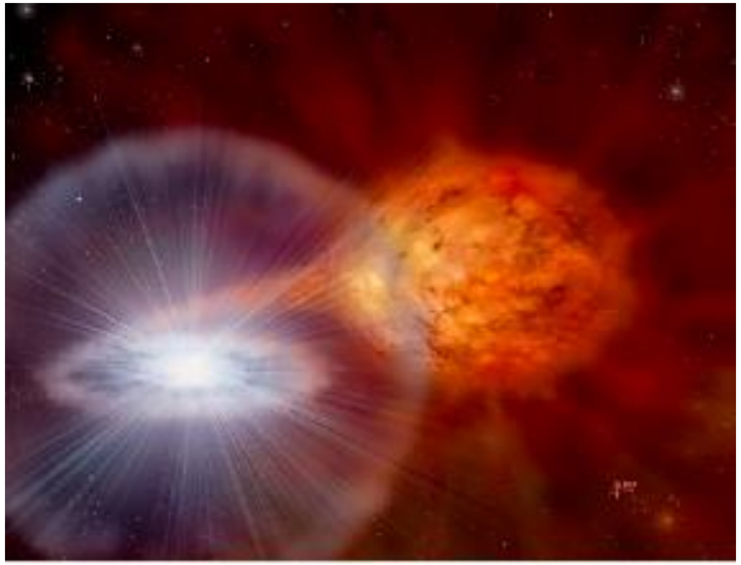
The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced moving through



MAGIC coll., Nature Astronomy, 2022
H.E.S.S. coll., Science, 2022

RS Oph detected and characterised over its peak emission by MAGIC & H.E.S.S.



- Recurrent nova in a symbiotic binary
- Outbursts once every 15-20 years
- Previous outburst in 2006 (no gamma-satellite in orbit)
- Distance under debate, from 1.4 - 4.3 kpc in literature
- Used value 2.45 kpc

Proton Acceleration

- The proton acceleration is the preferred option because
  - These can be injected with the natural -2 spectrum, while electrons need an ad-hoc spectral brake in the injection spectrum
  - The chi² of the fit is better for protons
  - There is a hint of spectral hardening in the energy for protons
  - Optical and high-energy emission decay similar → while IC emission should decay faster because of the photosphere expansion

MAGIC coll., Nature Astronomy, 2022