Recent results from HAWC and LHAASO

Heraus Meeting, 08.11.2022 Krakow

Sabrina Casanova, IFJ-PAN, Krakow

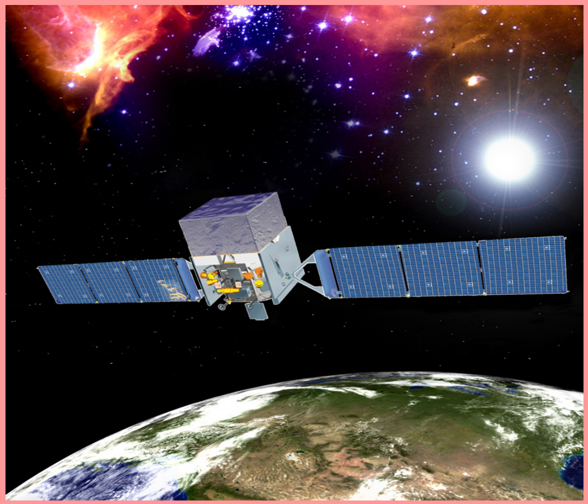
Outline

- HAWC and LHAASO Observatory
- VHE and UHE Sky Surveys
- The Variable Sky
- AGN Monitoring
- The Sun at TeV energies
- SFRs as Galactic PeVatrons ?
- The brightest sources in 0.1-1 PeV range
- PWNe and TeV halos
- Conclusions and Outlook

Wide FOV continuous operation

TeV sensitivity

Satellites



AGILE
EGRET
Fermi-LAT

EAS

Milagro
Tibet ASγ
ARGO-YBJ
HAWC, LHAASO

IACT

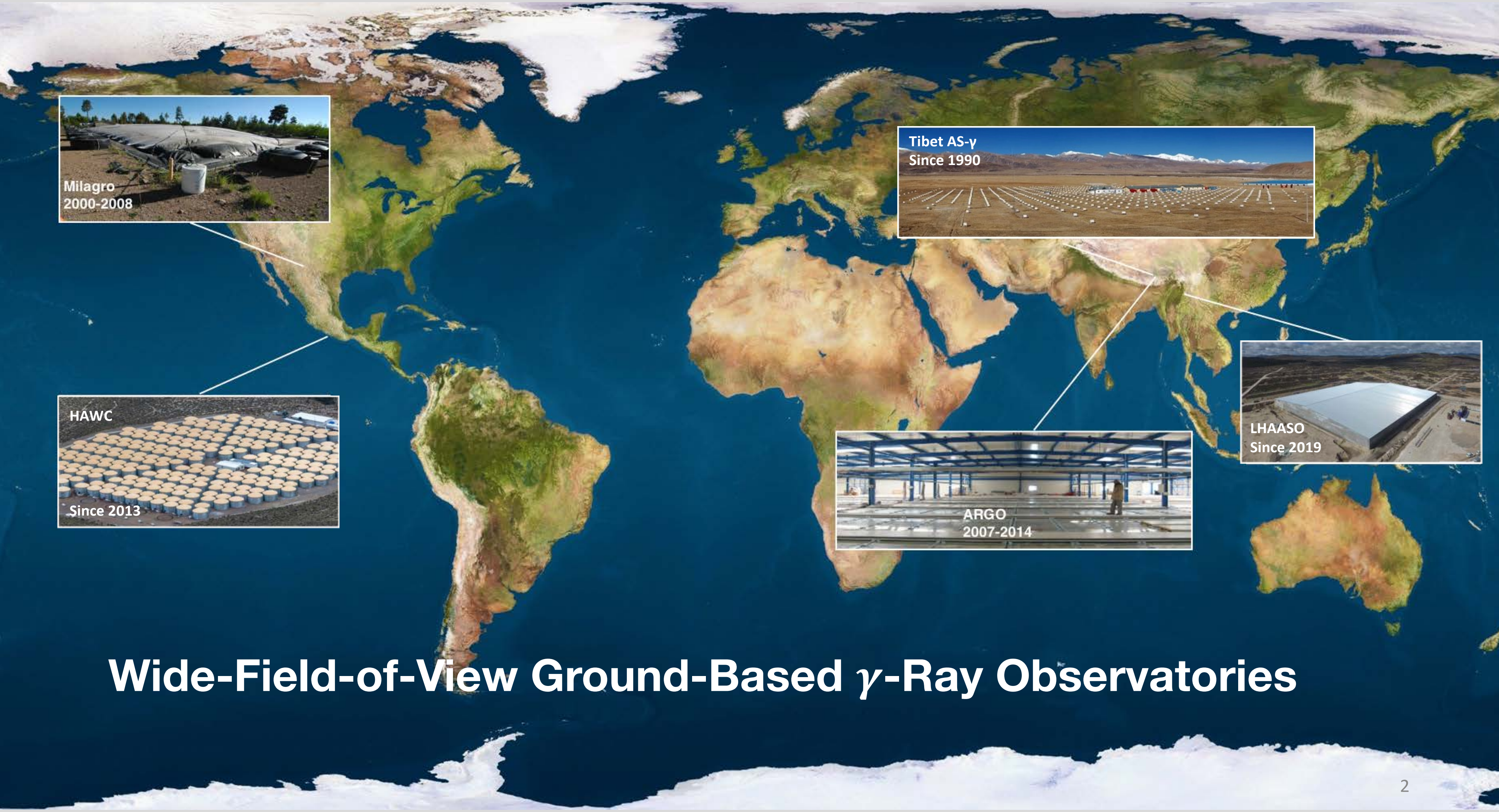
H.E.S.S.
MAGIC
VERITAS
CTA

Space-based

Ground-based

- **High Duty Cycle (> 95%)** Transients
- **Sensitivity & Angular Resolution > ~ 10 TeV** Highest Energy Accelerators
- **Wide field of view** Extended Emission, Surveys, Transients

Covering different time zones



The HAWC Collaboration

USA

Mexico

United States

Los Alamos National Laboratory
University of Wisconsin
University of Utah
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Michigan State University
University of Rochester

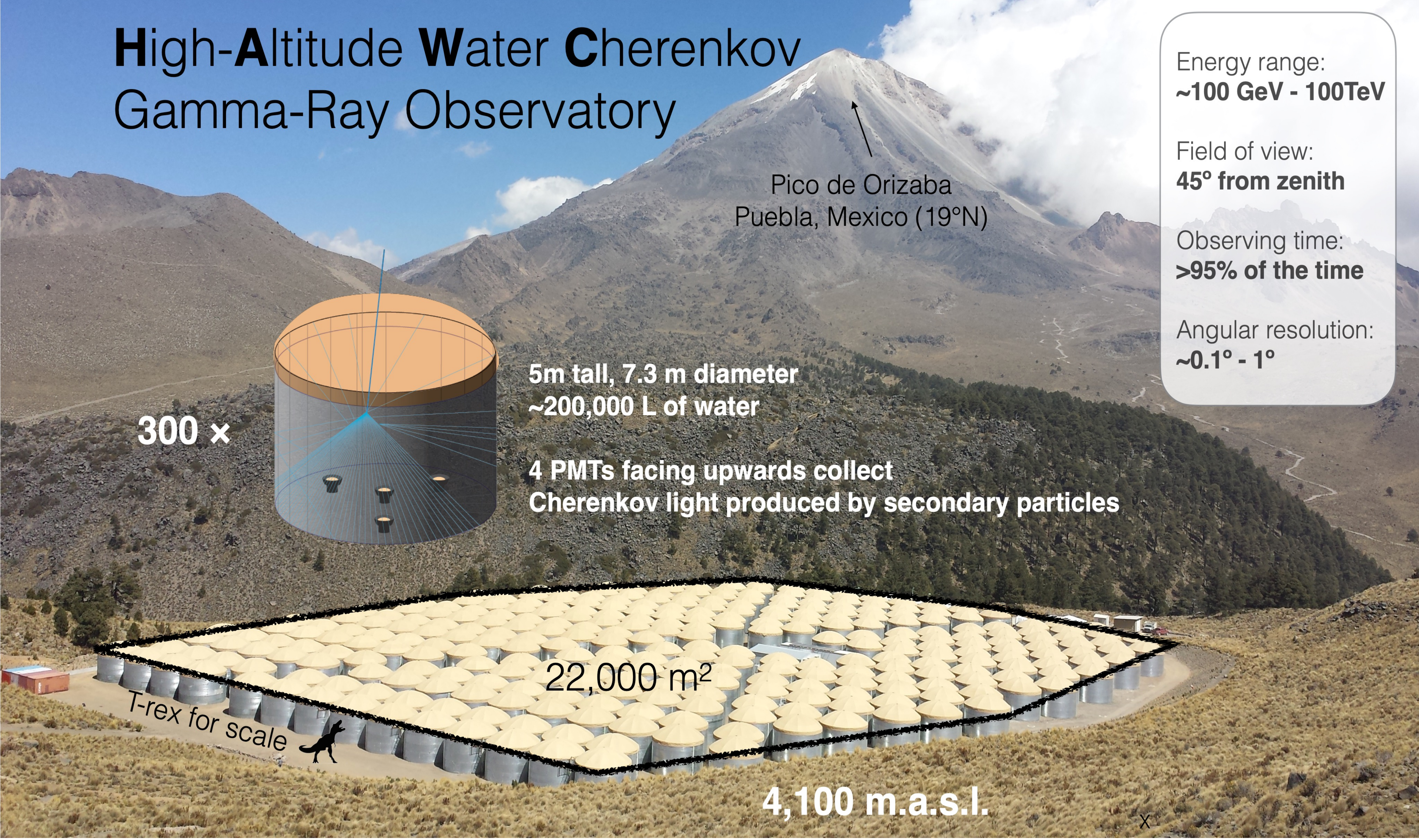
Mexico

Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapa
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación – IPN

Europe

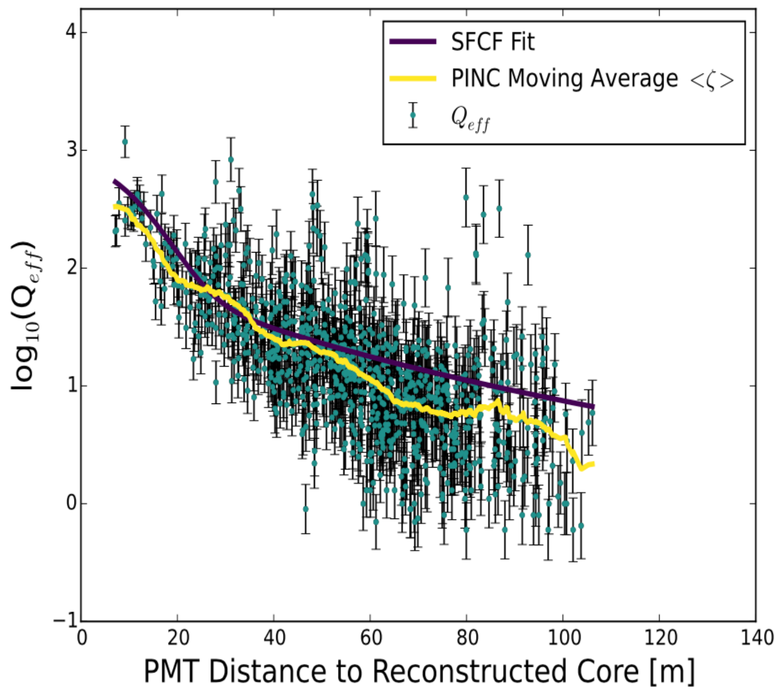
Max-Planck Institute for Nuclear Physics
IFJ-PAN, Krakow, Poland



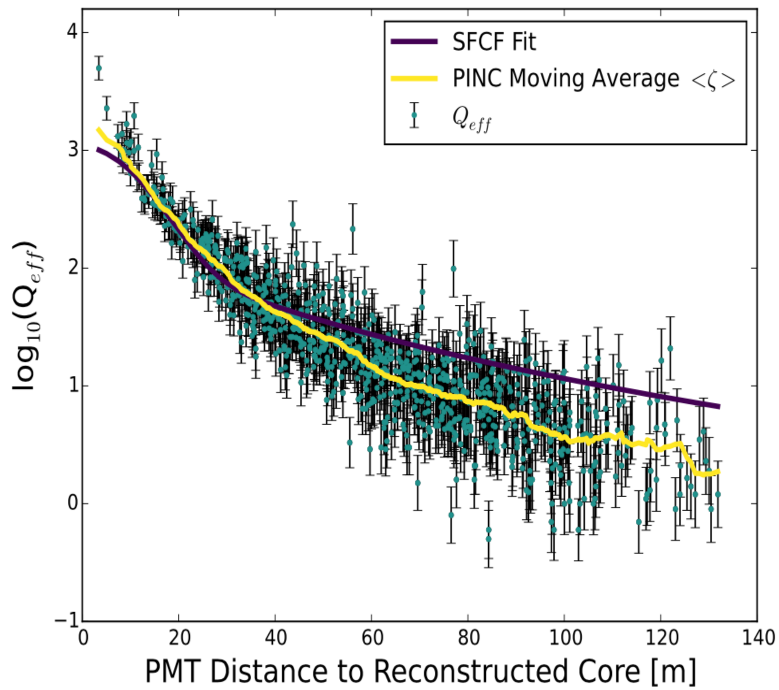
- Site: Sierra Negra, Mexico, 19° N, 4,100 m altitude.
- Inaugurated **March 2015**.
- **Instantaneous FOV 2sr. Daily 8sr (66% of the sky)**
- High energy extension: Outrigger array, since summer 2018
- Takes data with >95 on time
- ~5 trillion triggers to date - 7PB of data

Shower reconstruction

Clumpy: hadron-like



Smooth: gamma-like

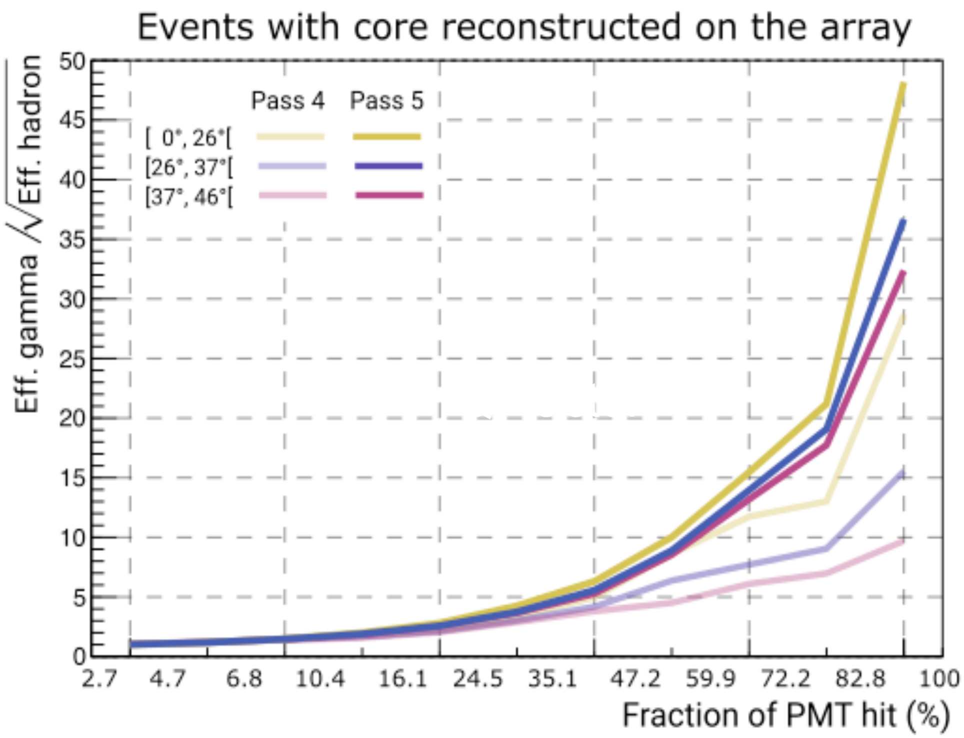


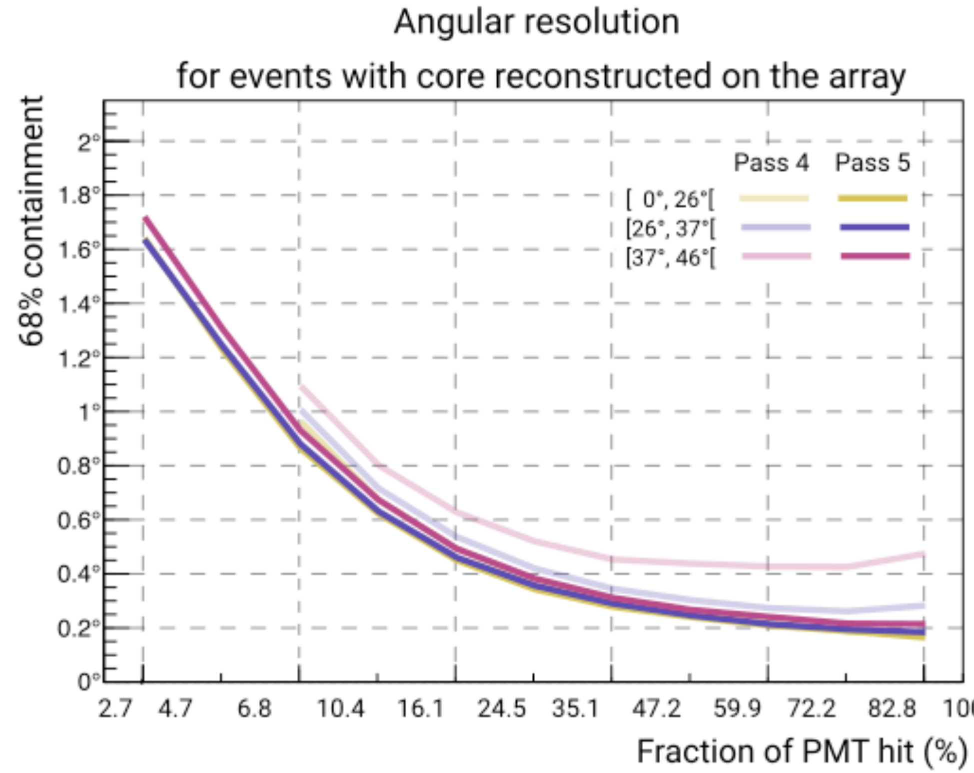
Measure: time and light level in each PMT.

Reconstruct: direction, location, energy, and background rejection.

Reference: Crab paper, ApJ 843 (2017), 39.

Pass 5 reconstruction





PRELIMINARY

$$Q = \frac{\text{Efficiency}_{\text{gammas}}}{\sqrt{\text{Efficiency}_{\text{hadrons}}}}$$

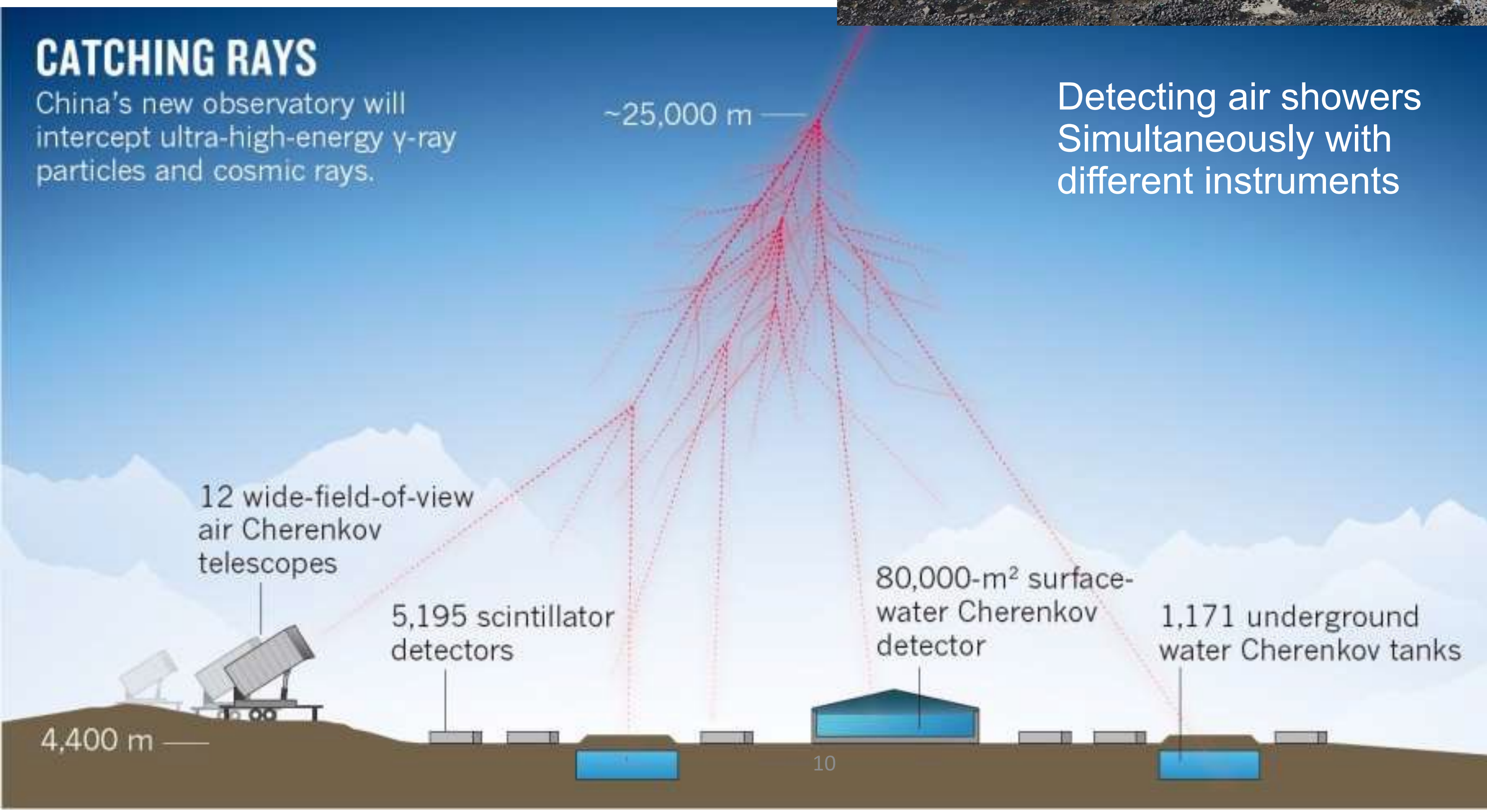
Large Events - Much improved background rejection

Better Angular Resolution - doesn't degrade at high zenith angles

Wider FOV - Previous 45° now 60°

LHAASO
高海拔宇宙线观测站

LHAASO Observatory



LHAASO Observatory: 1.3 km^2 EAS array

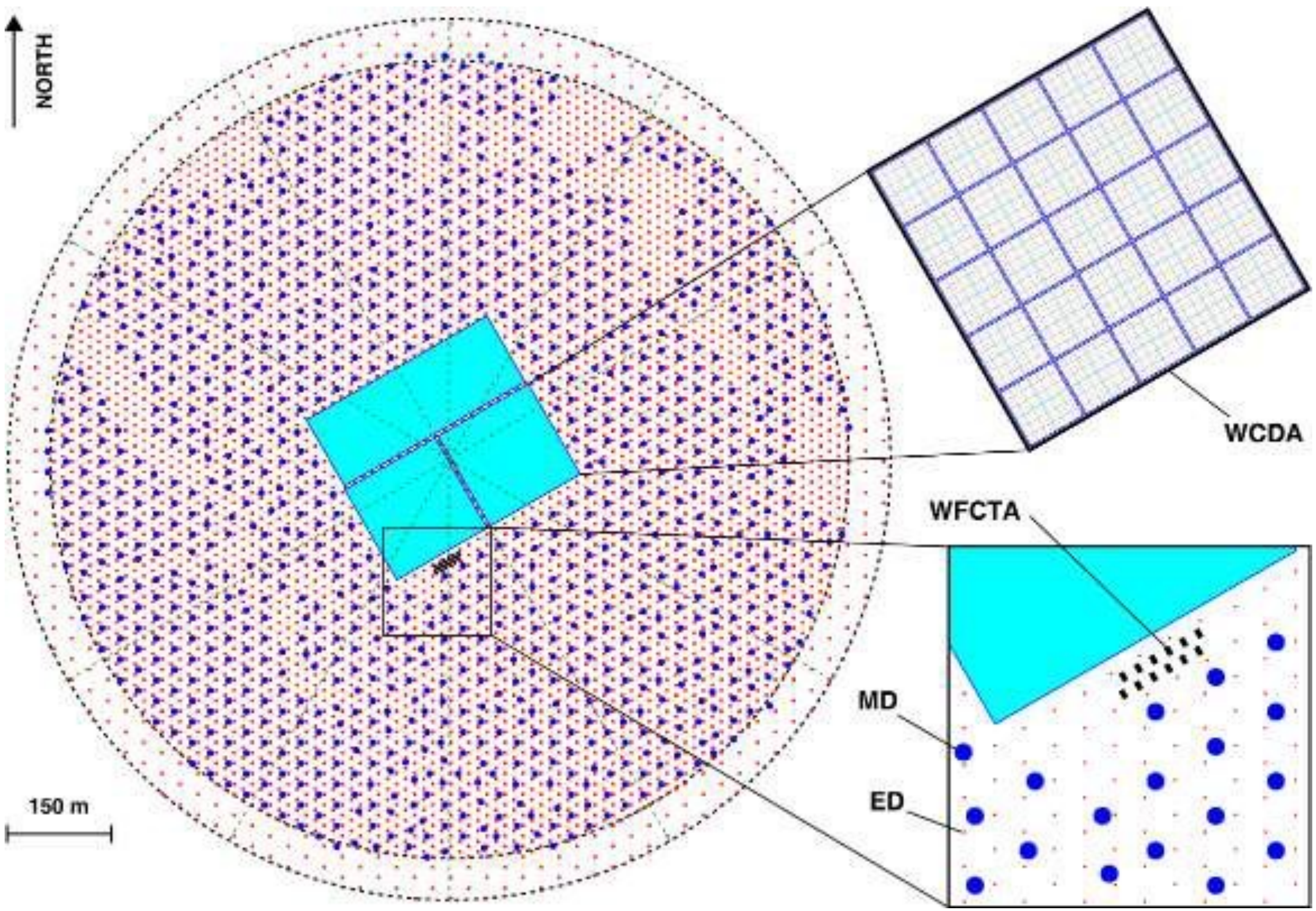
LHAASO
高海拔宇宙线观测站

- 5242 Electron Detectors (ED)s
  - 1 m^2 each
  - 15 m spacing

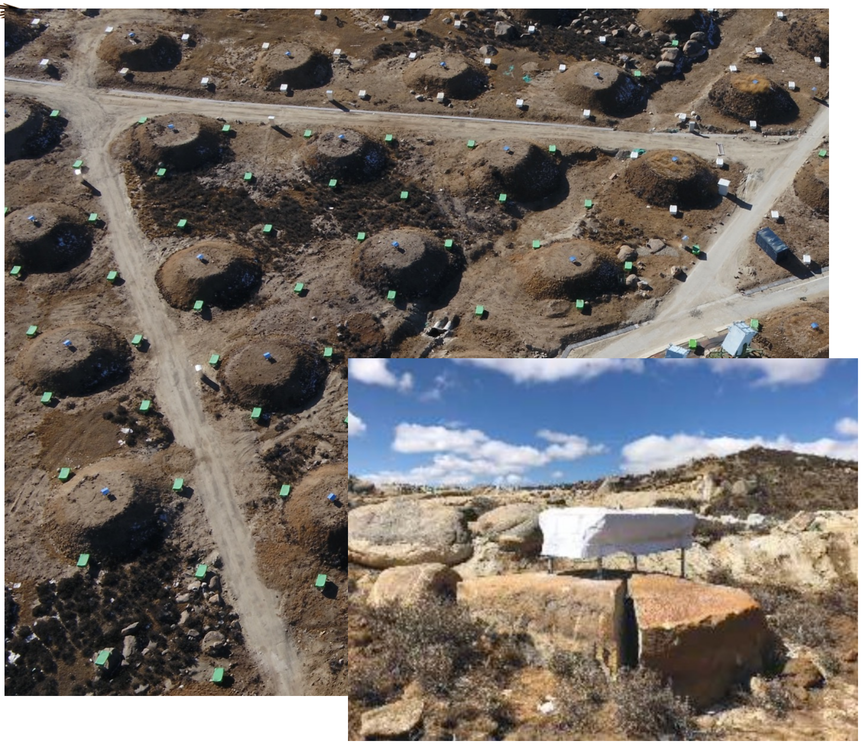
  1188 Muon Detectors (MD)s
  - 36 m^2 each
  - 30 m spacing

  3120 Water Cherenkov Det. WCDs
  - 25 m^2 each

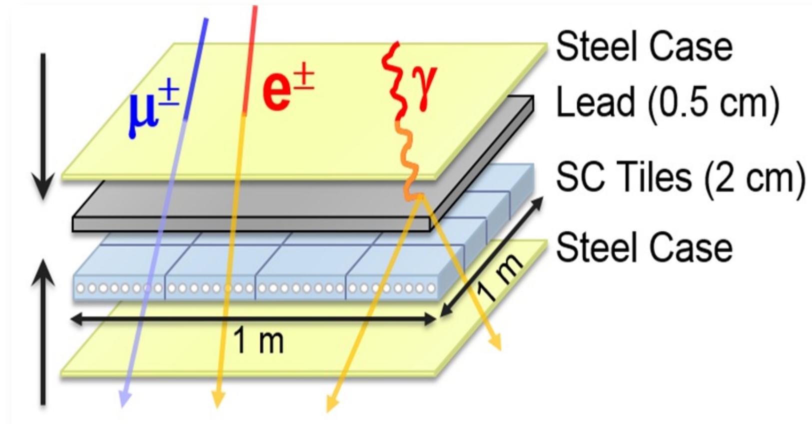
  18 Wide Field Cherenkov Telescopes WFCTs

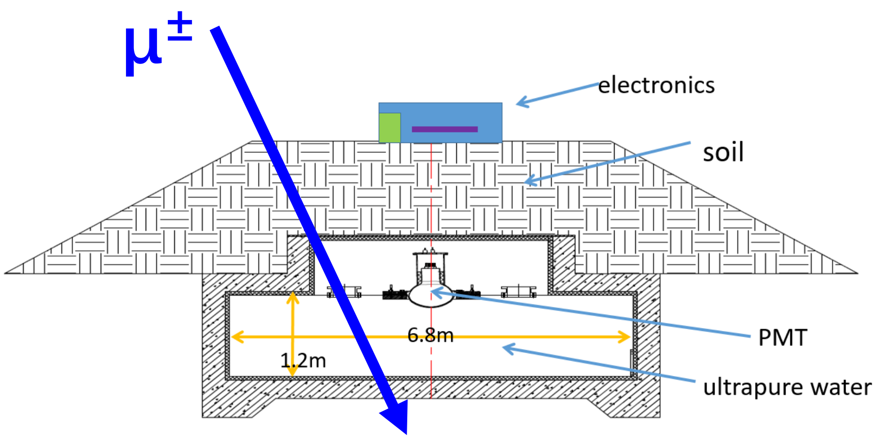


KM2A: 1.36 $(km)^2$

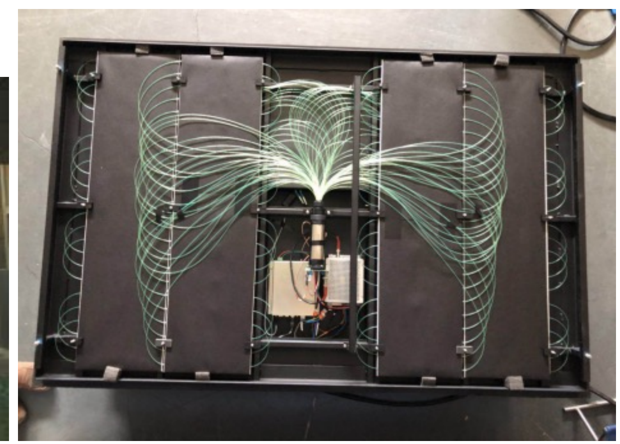


- ➢ **5195 EDs**
  - **1 m^2 each**
  - **15 m spacing**
- ➢ **1188 MDs**
  - **36 m^2 each**
  - **30 m spacing**





Inner View of one ED



LHAASO
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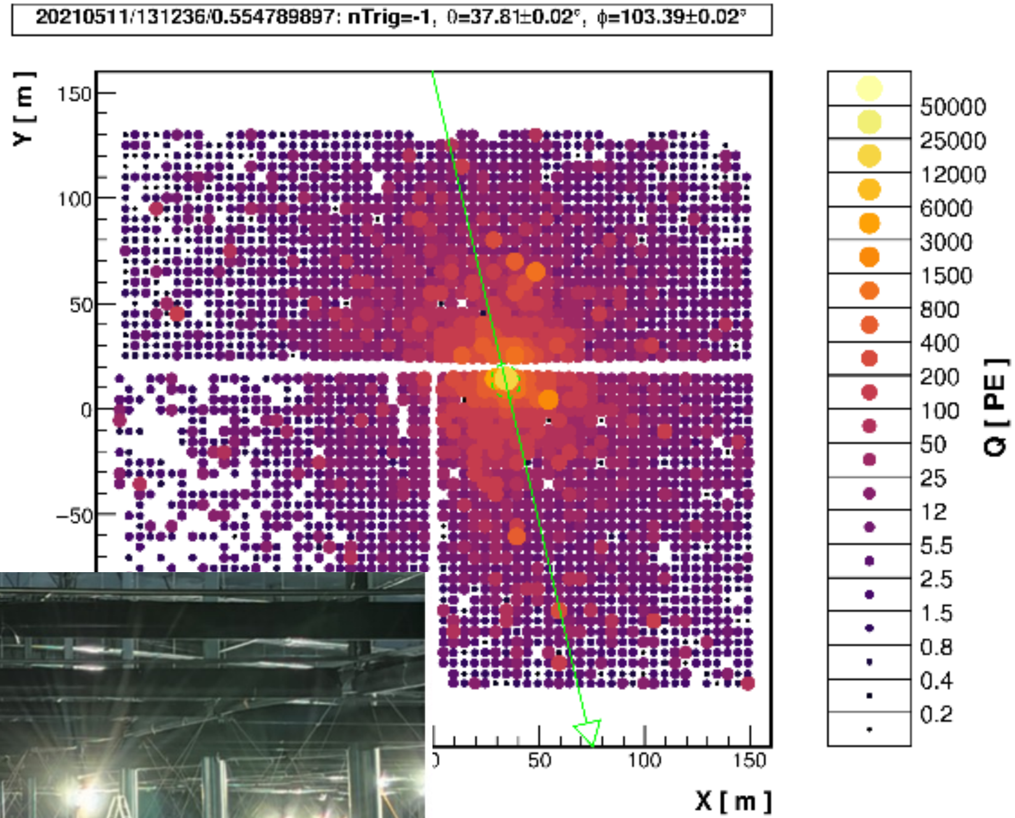
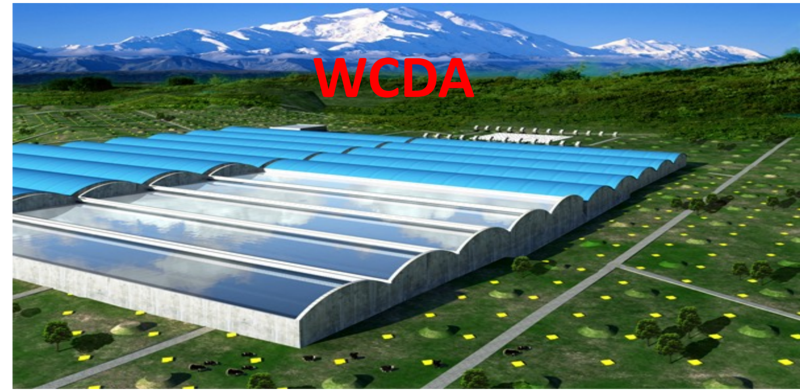
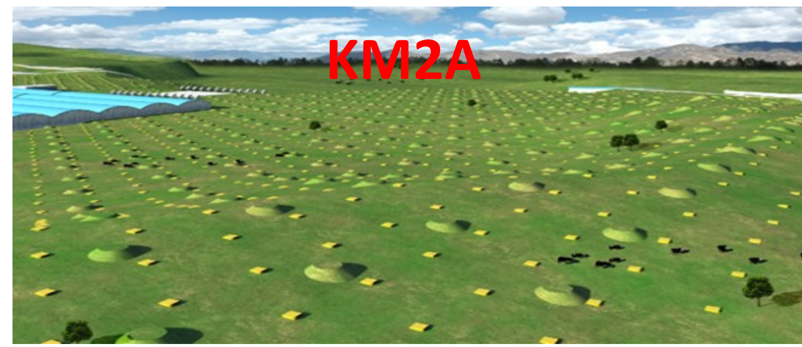
WCDA-3



LHAASO
高海拔宇宙线观测站

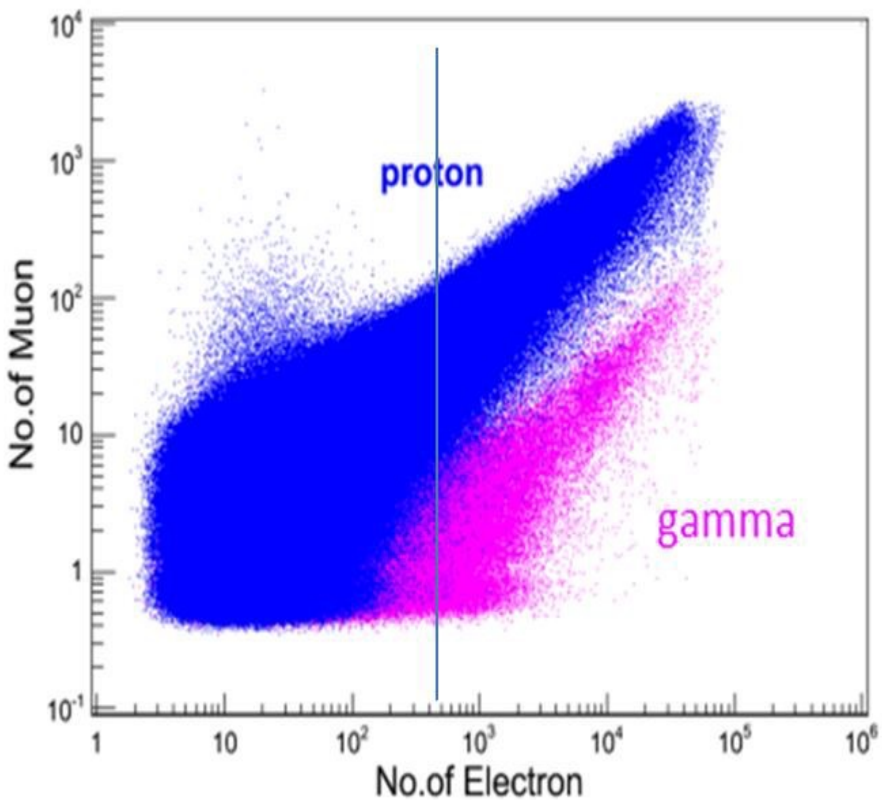
- TeV gamma-ray survey → WCDA (100 GeV-30 TeV)
  - AGN, GRB, survey new source, …
- >20 TeV gamma-ray survey →KM2A (10TeV-1PeV)
  - SNR, PWN, Superbubble, diffuse around 100TeV, …
- Individual nuclei spectra →WFCTA (10TeV to EeV)

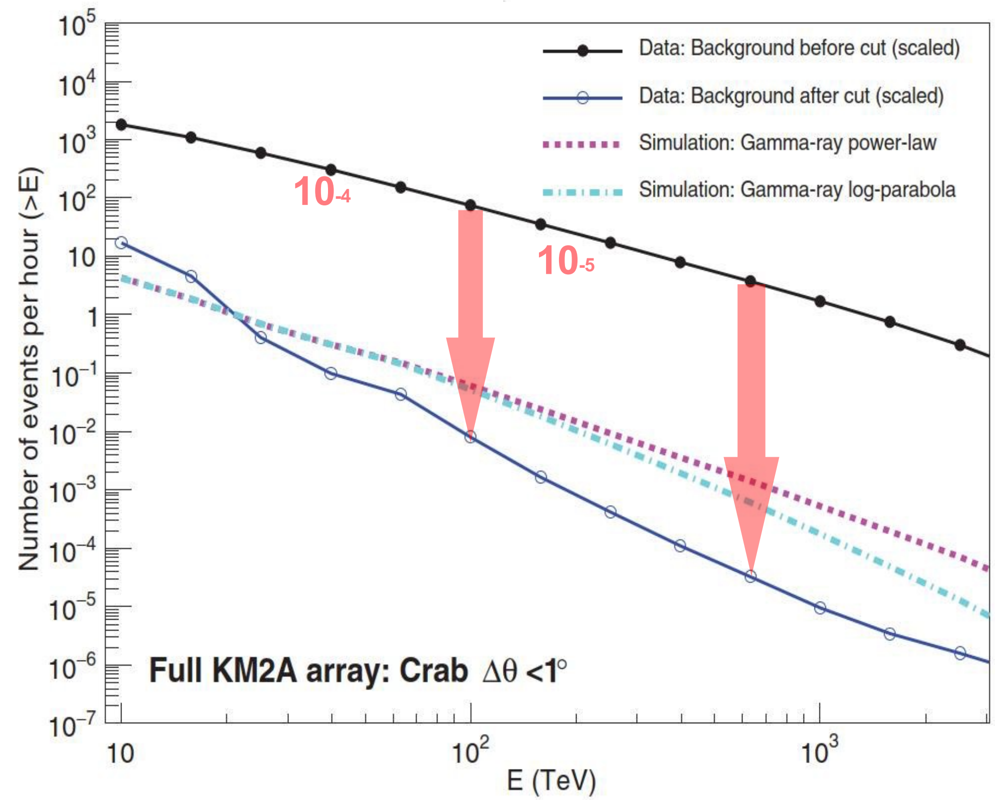




Background rejection in LHAASO

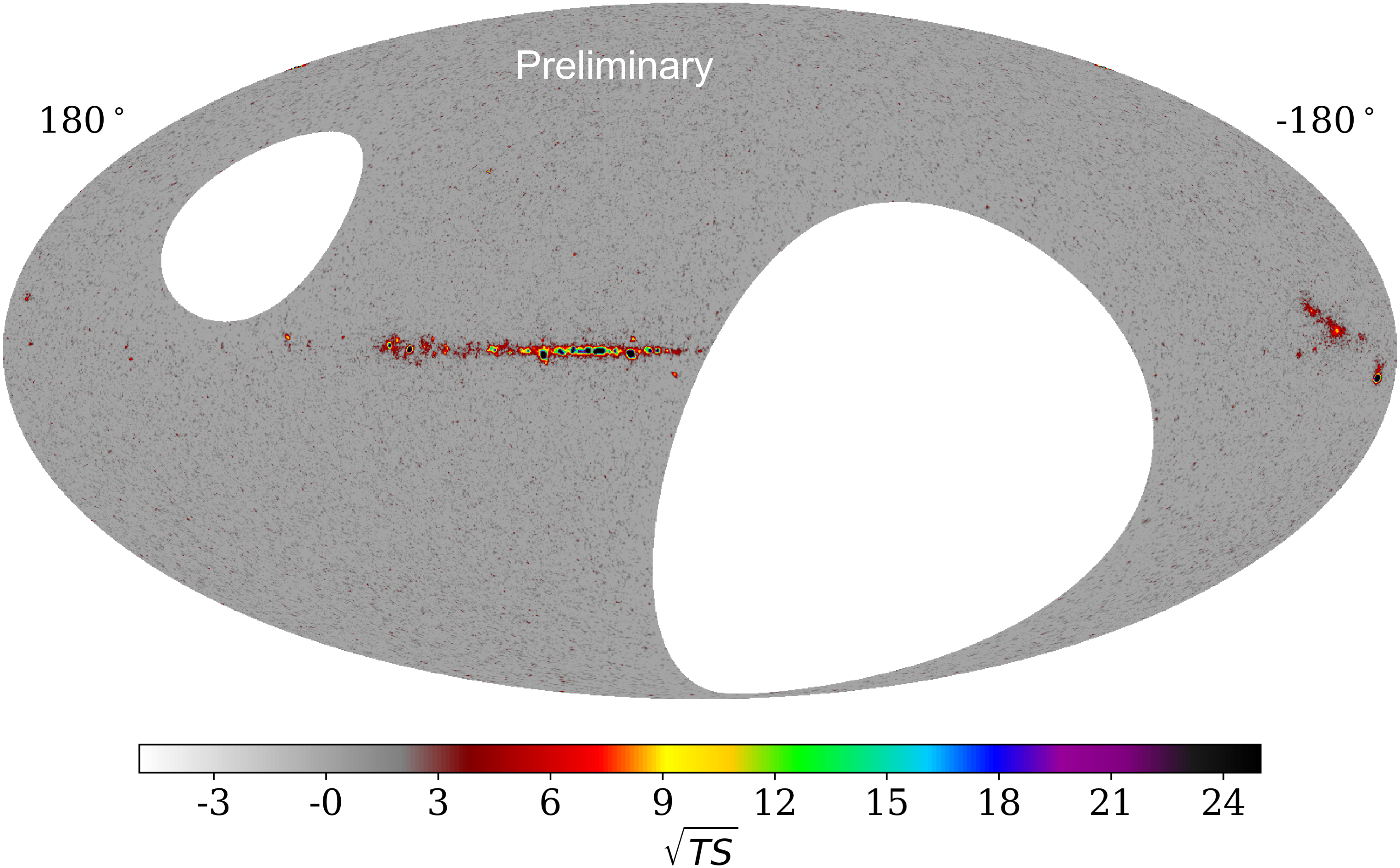
- Counting number of measured muons in a shower
- Cutting on ratio N_{μ}/N_e<**1/230**
- BG-free (N_{γ}>10N_{CR}) Photon Counting for showers E>100 TeV from the Crab



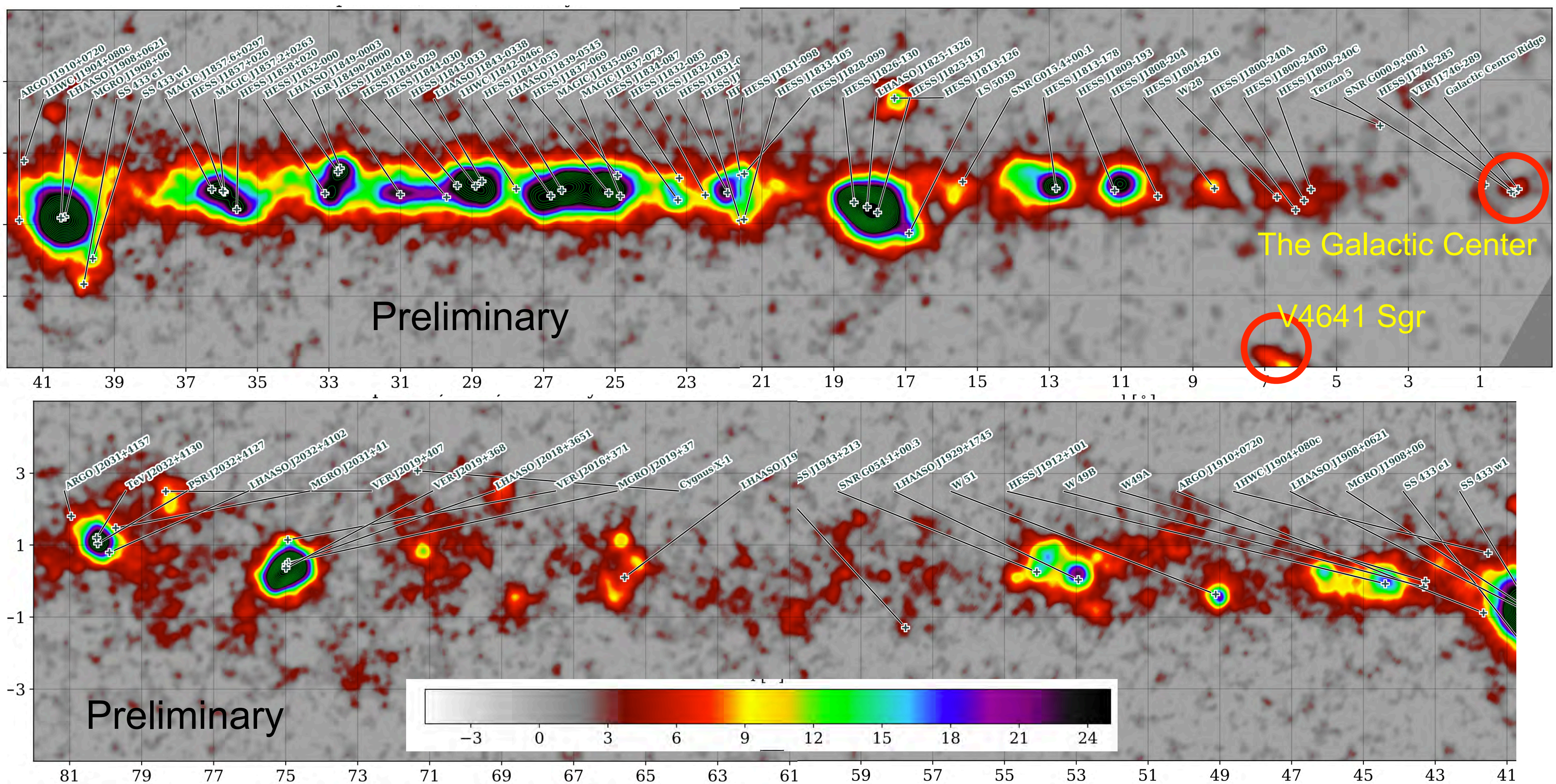


SKY SURVEYS AT VHE AND UHE

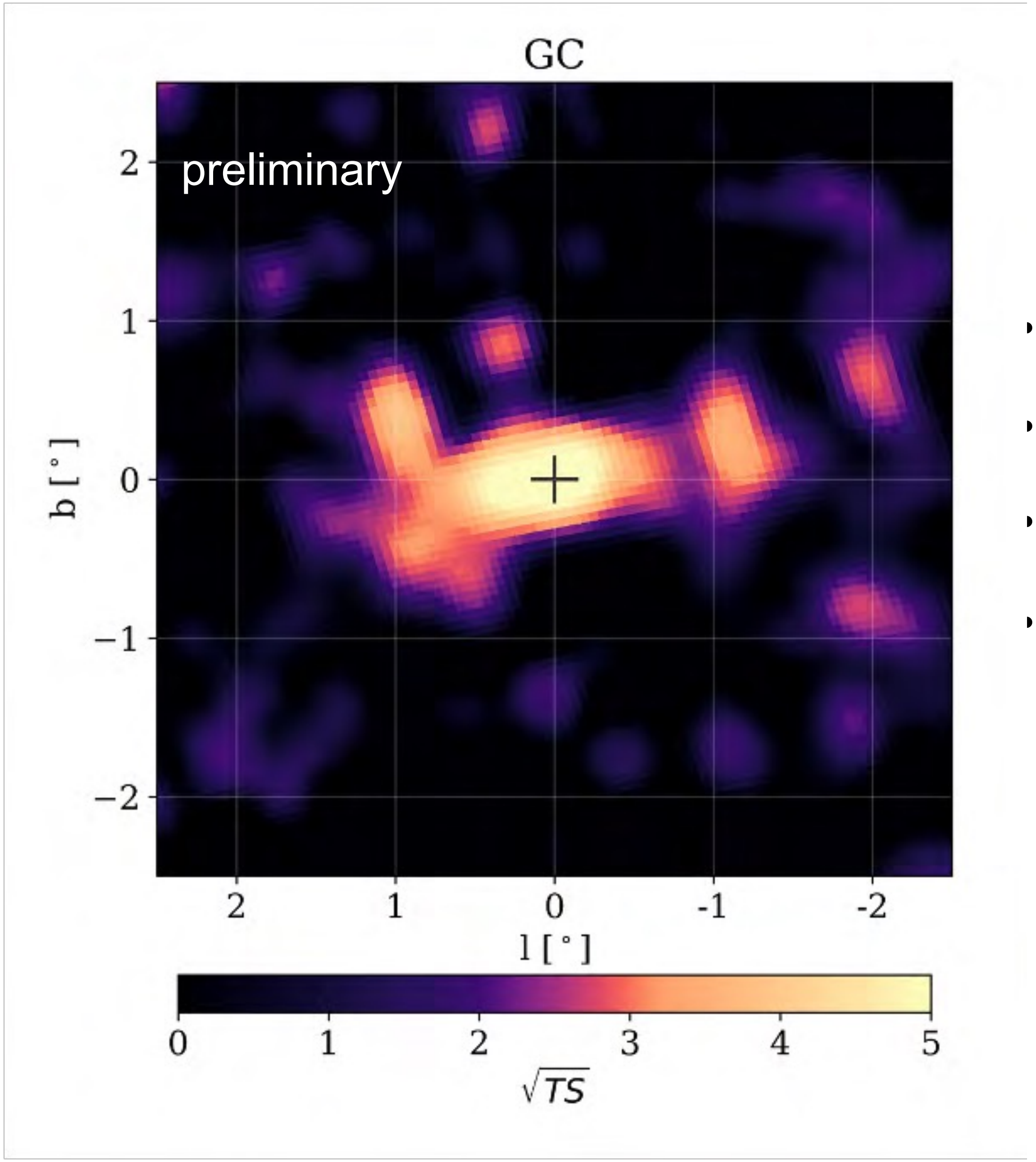
HAWC 2321-Day TeV Sky Survey Pass 5



HAWC Pass 5 – 2090 days maps



HAWC View of the Galactic Centre Ridge



- 6 σ detection in Pass 5
- HAWC and HESS fluxes compatible
- **No spectral cutoff**
- Maximum γ energy detected in HAWC

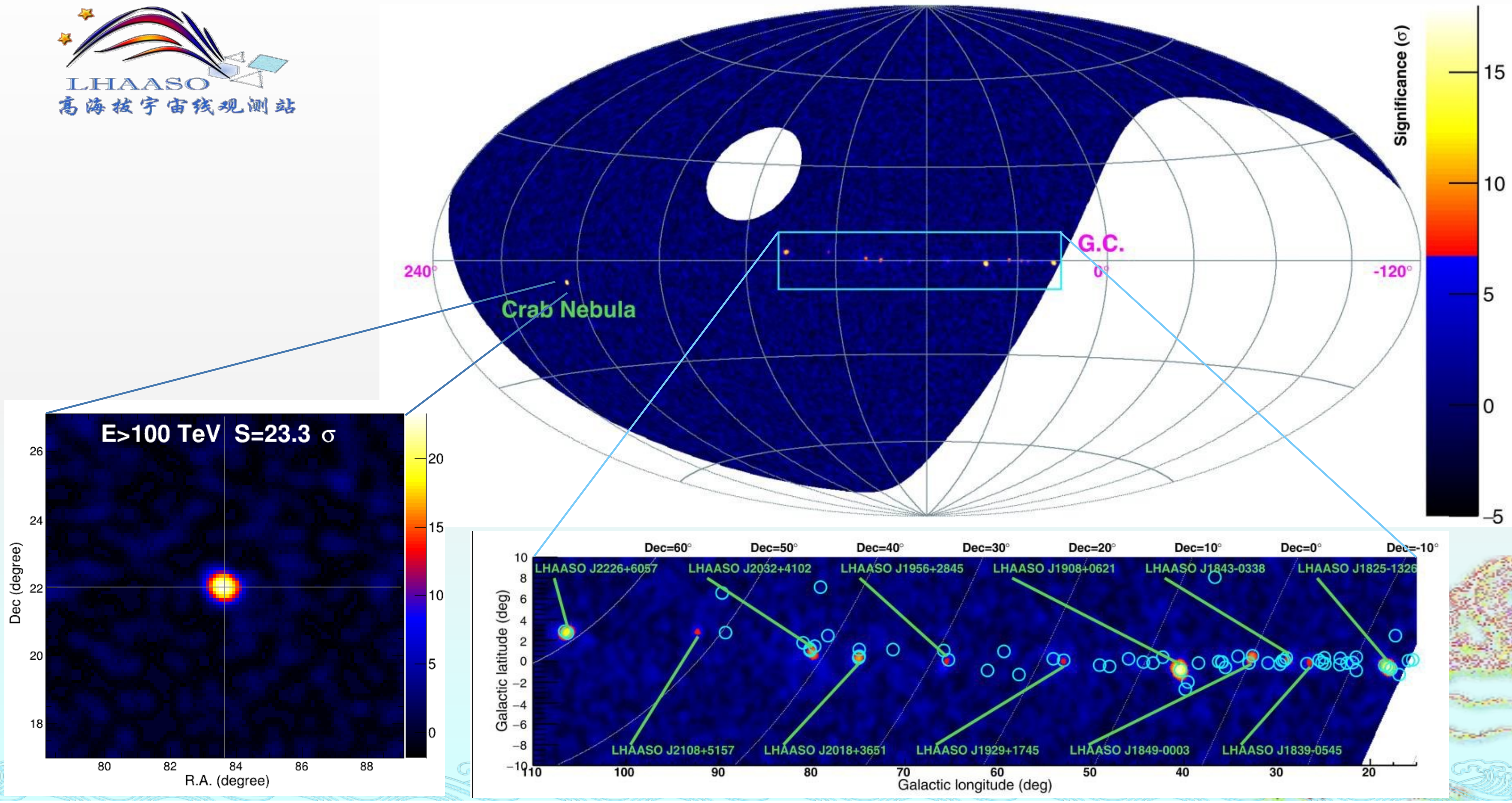
1 sigma: 69.57 TeV

2 sigma: 50.17 TeV

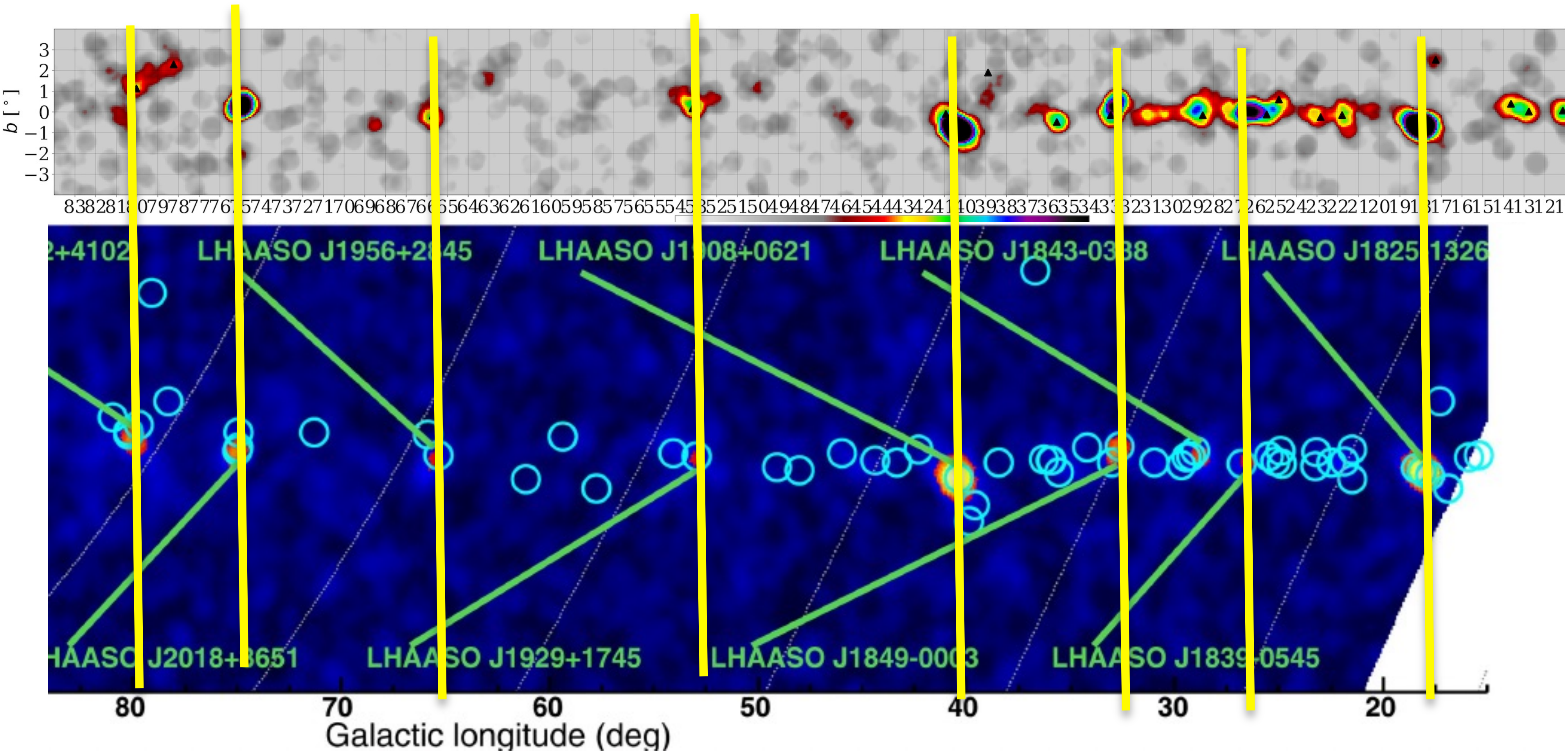
3 sigma: 34.24 TeV

UHE γ-ray (0.1-1 PeV) Sky Map

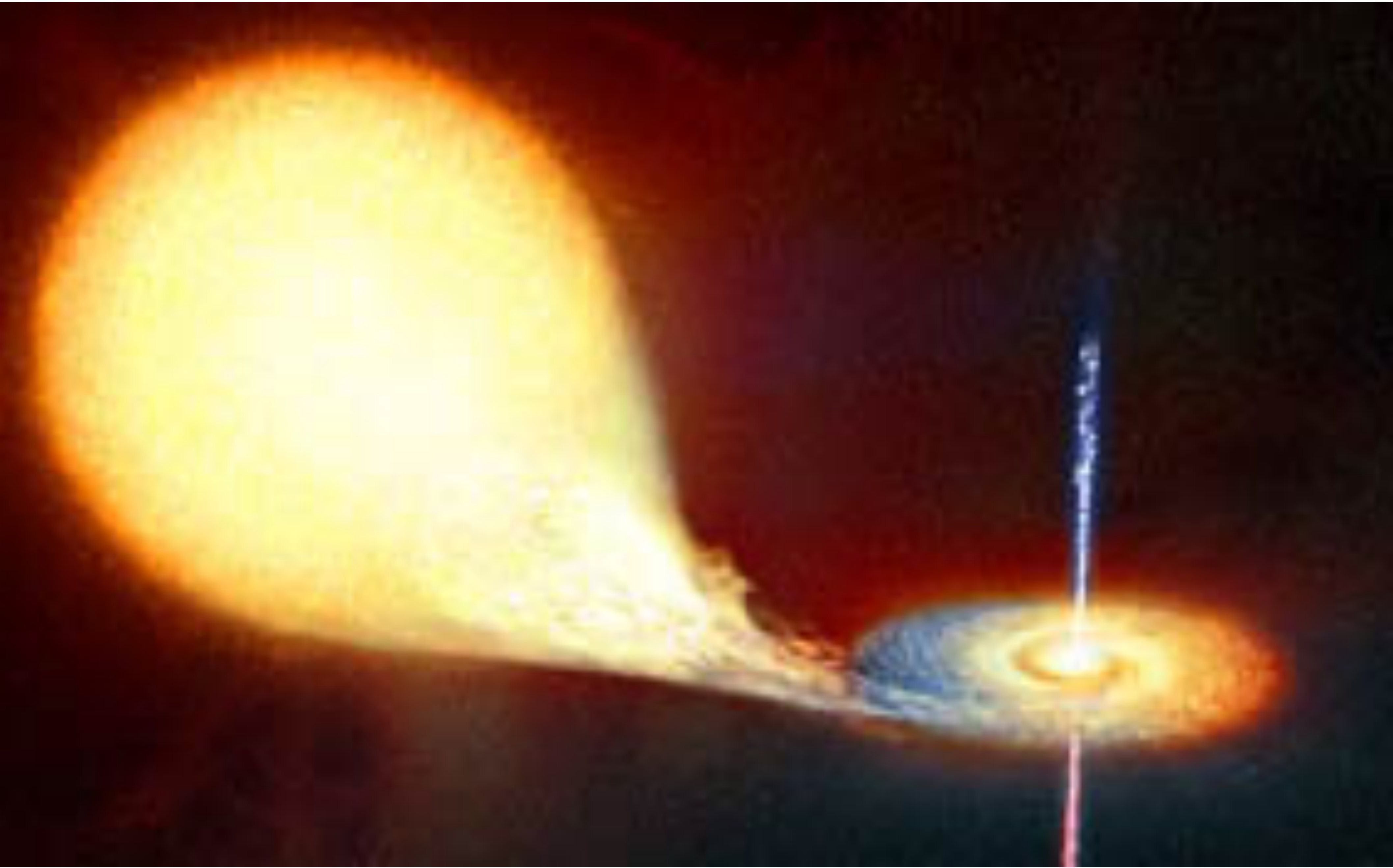
LHAASO
高海拔宇宙线观测站



HAWC - LHAASO Comparison



HAWC Observations of Variable Sources



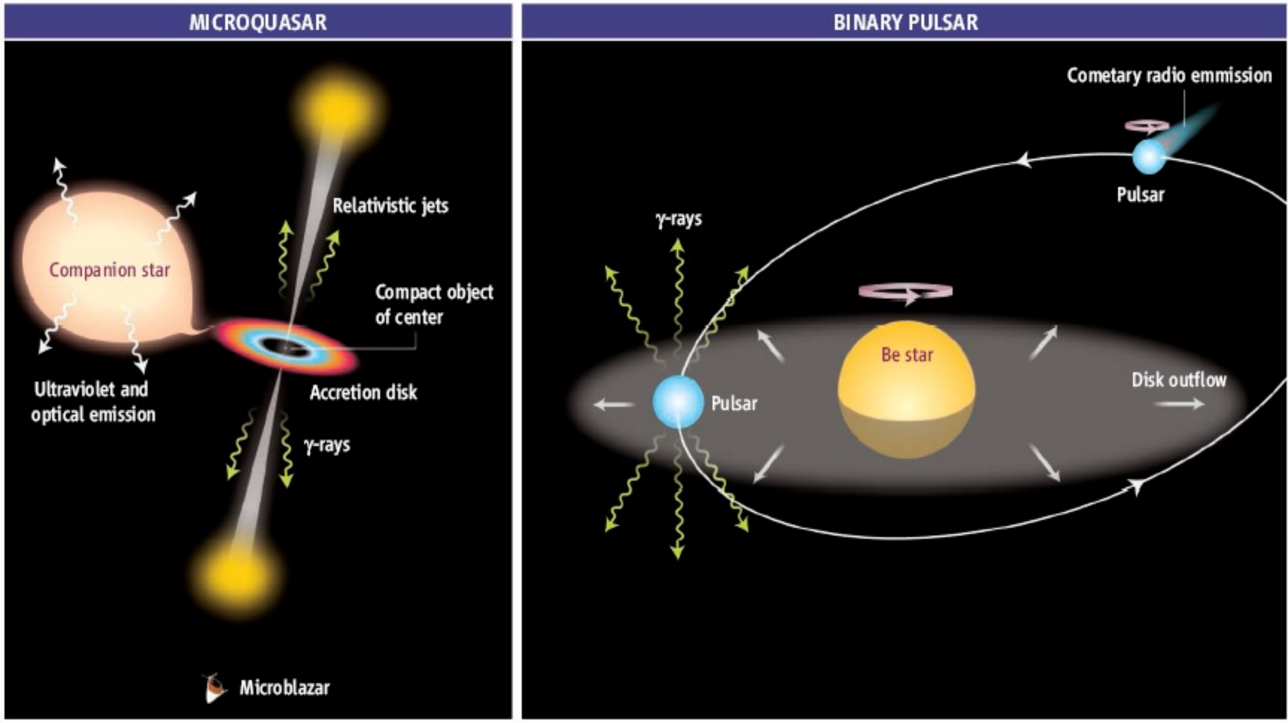
Common Features

Microquasars, binaries with non-accreting pulsars, massive stars binaries

Compactness → dynamical and radiation timescales short → high luminosities → high energies

Powerful Outflows from the compact object (a jet or pulsar wind or even stellar wind) + Stellar wind

Non thermal emission

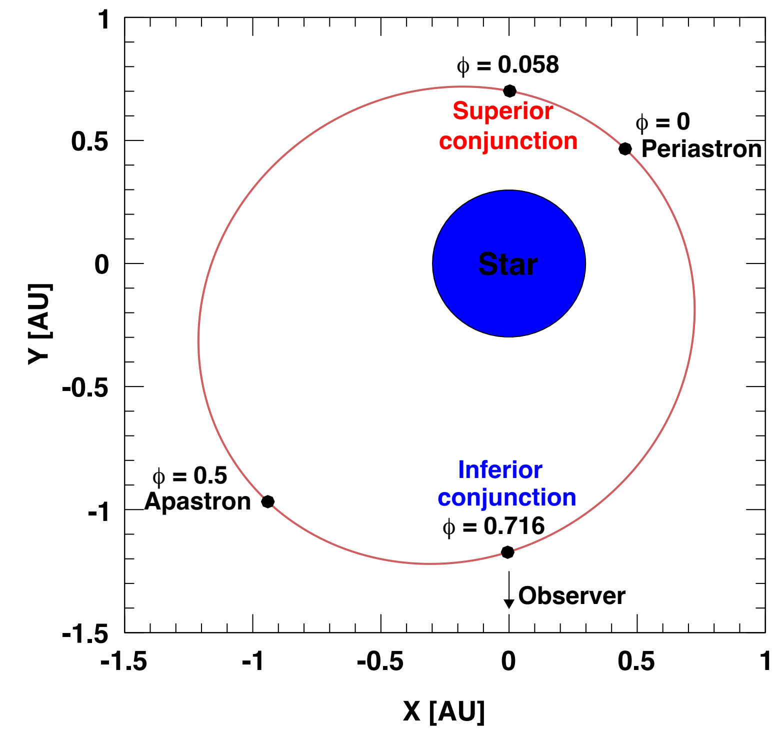


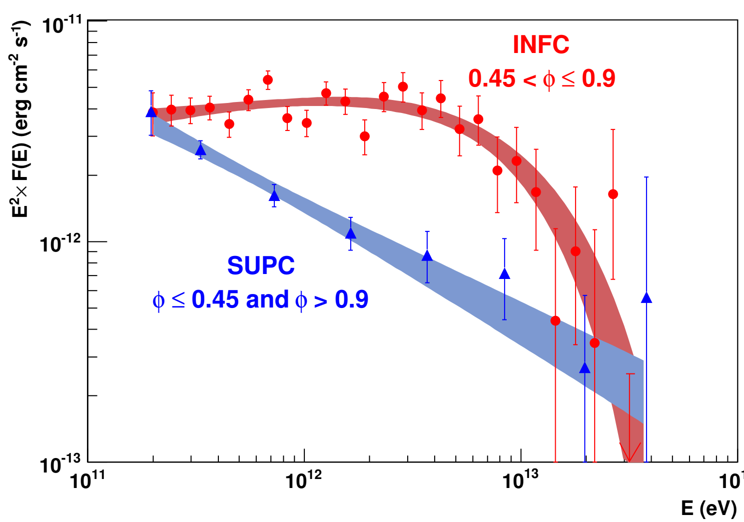
LS5039 with HESS

Either microquasar with relativistiv jet formation through matter accretion onto the compact object or acceleration resulting from the interaction between pulsar and star winds

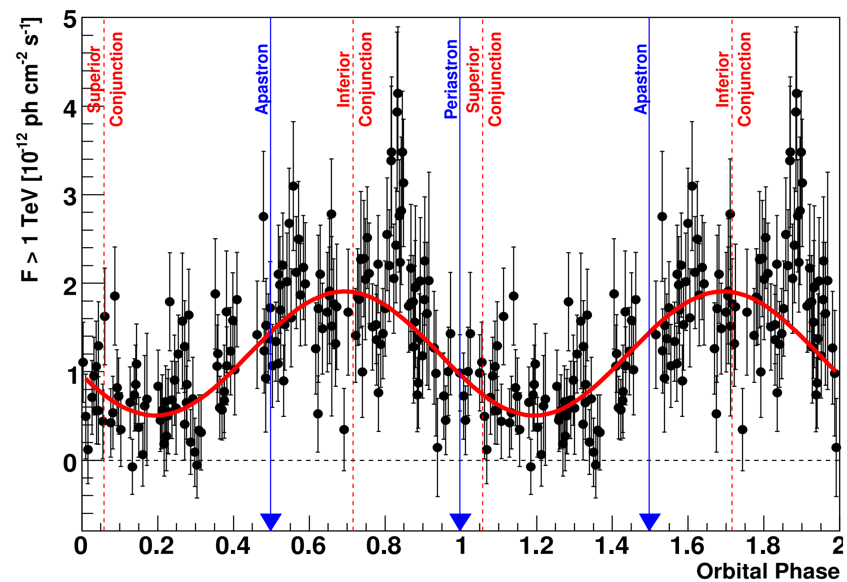
Distance = 3.5 kpc , O6.5V star and compact object with a mildly eccentric 3.9 day orbit. Mass companion star 23 M, mass compact object = 3.7 M

From radio to TeV energies. Flux and spectral modulation as a function of its orbital period. **Properties and location of accelerator(s) and emitter(s) in the source not understood**



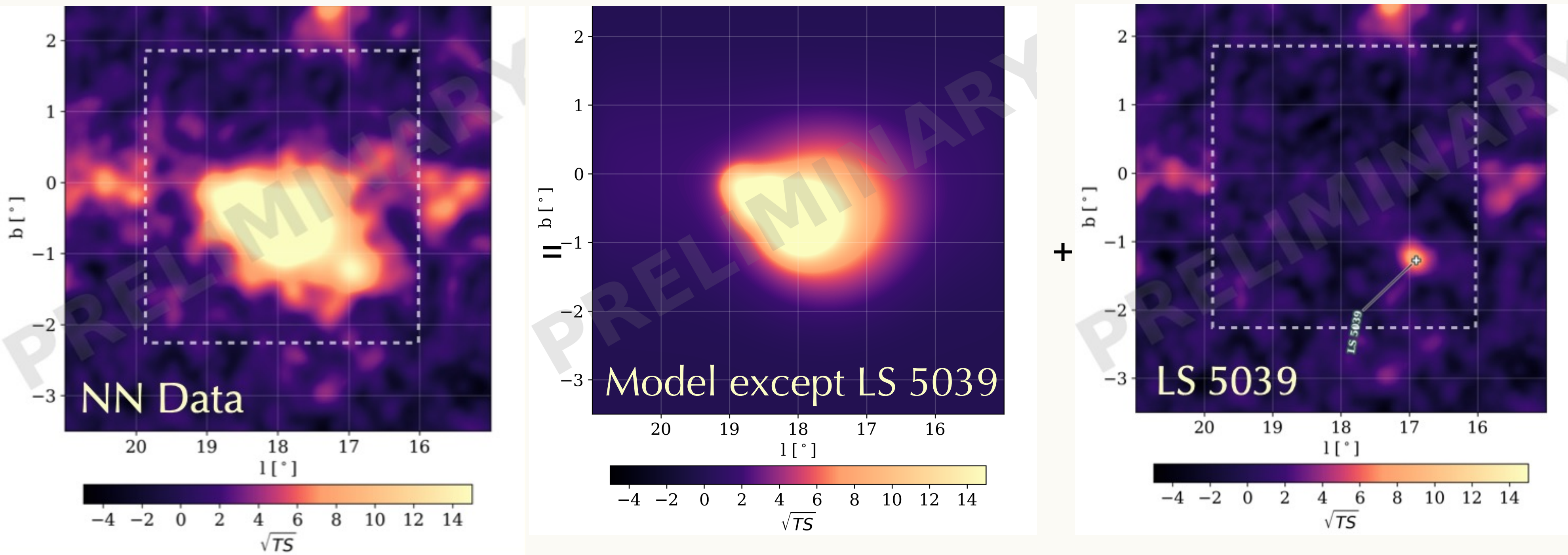


(Aharonian et al. 2005)



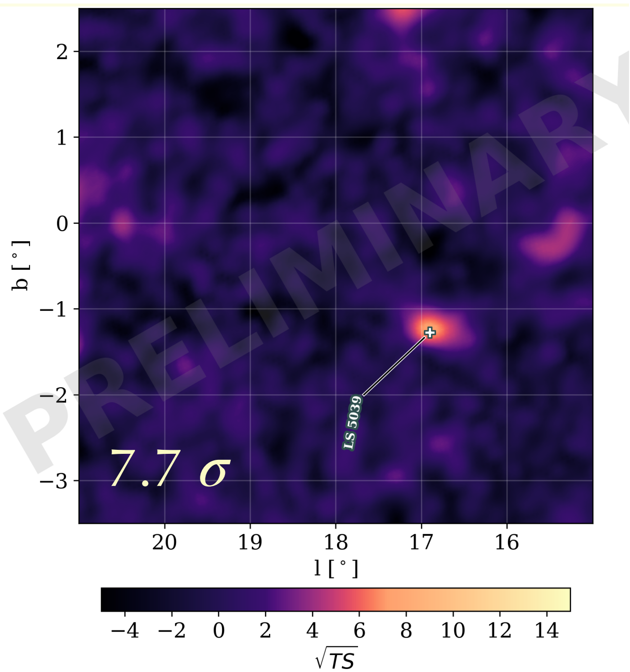
(Aharonian et al. 2005)

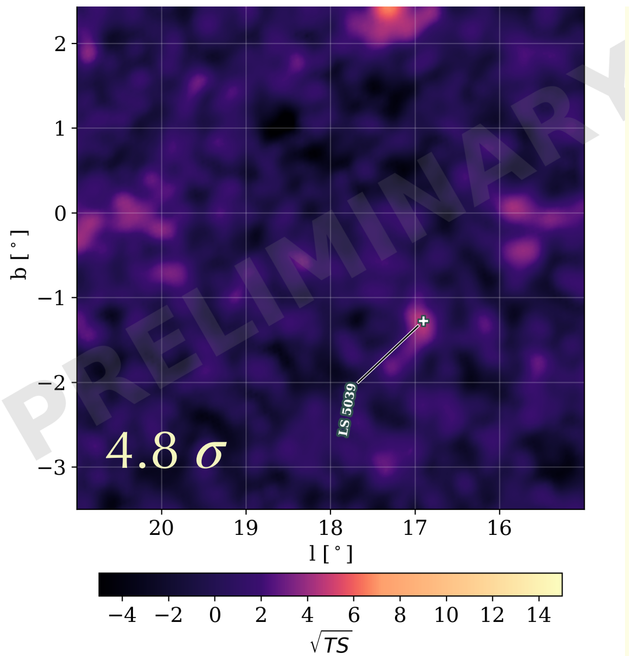
LS5039 with HAWC



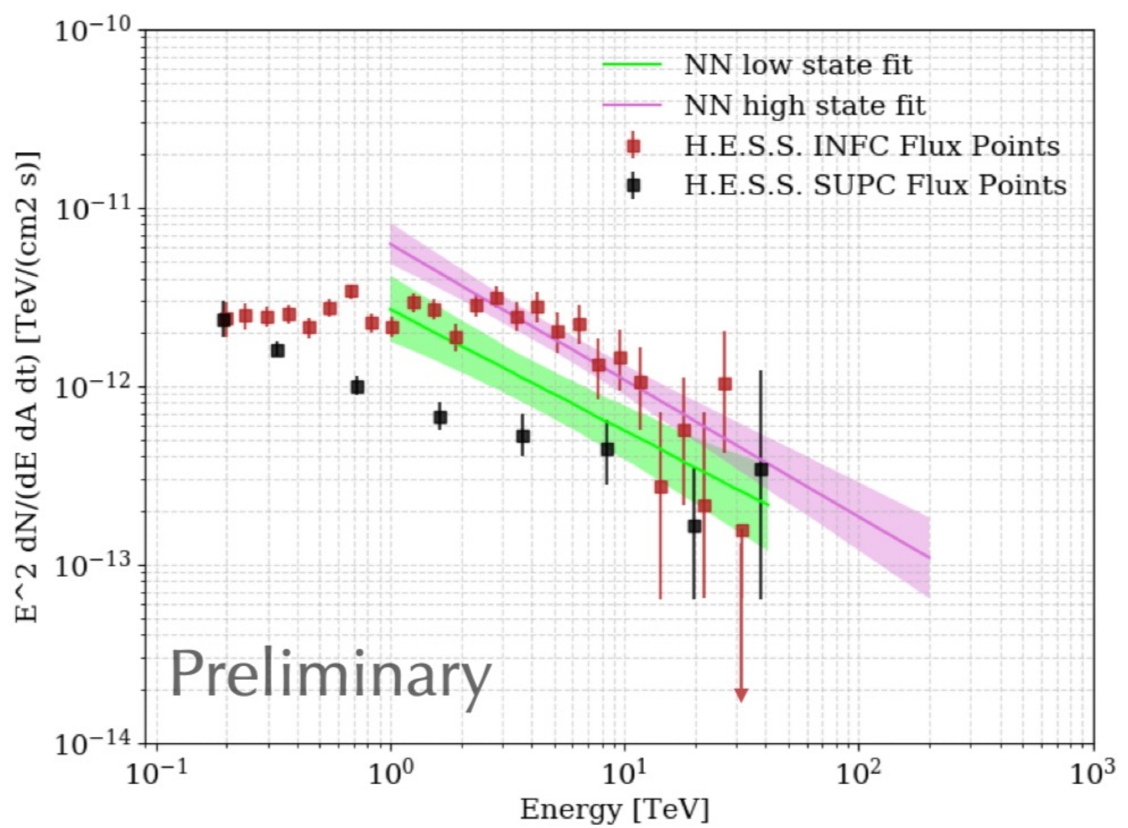
- Simultaneously likelihood fit performed inside the region of interest
- Model includes diffuse background emission and all background sources

Modulation in HAWC data

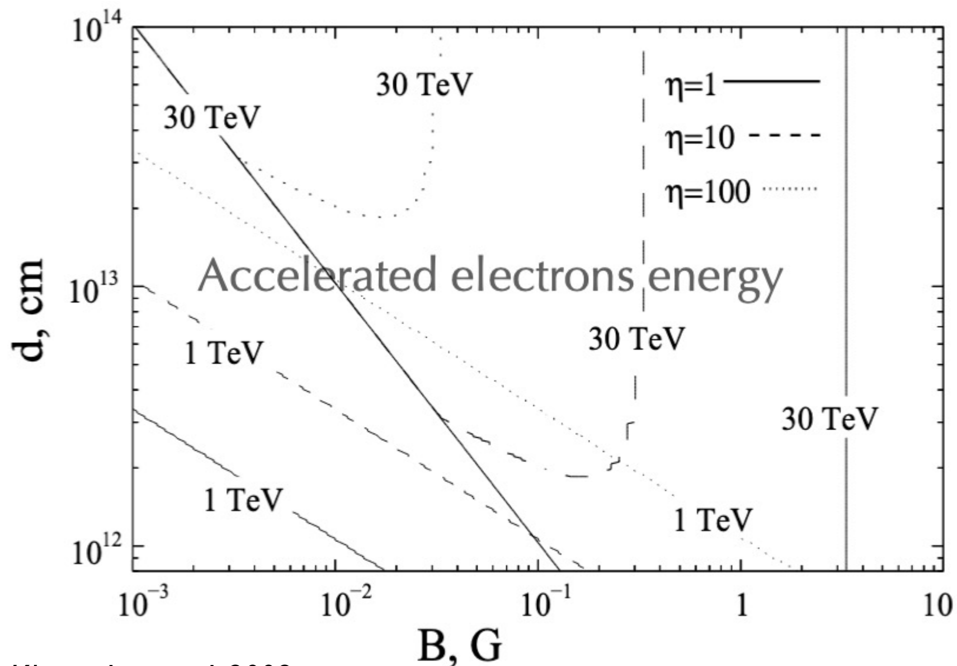




- HAWC see flux modulation at LS5039
- High state flux have a factor of two higher than low state flux
- High and low state have similar powerlaw index .No cutoff found in both low state and high state maps yet

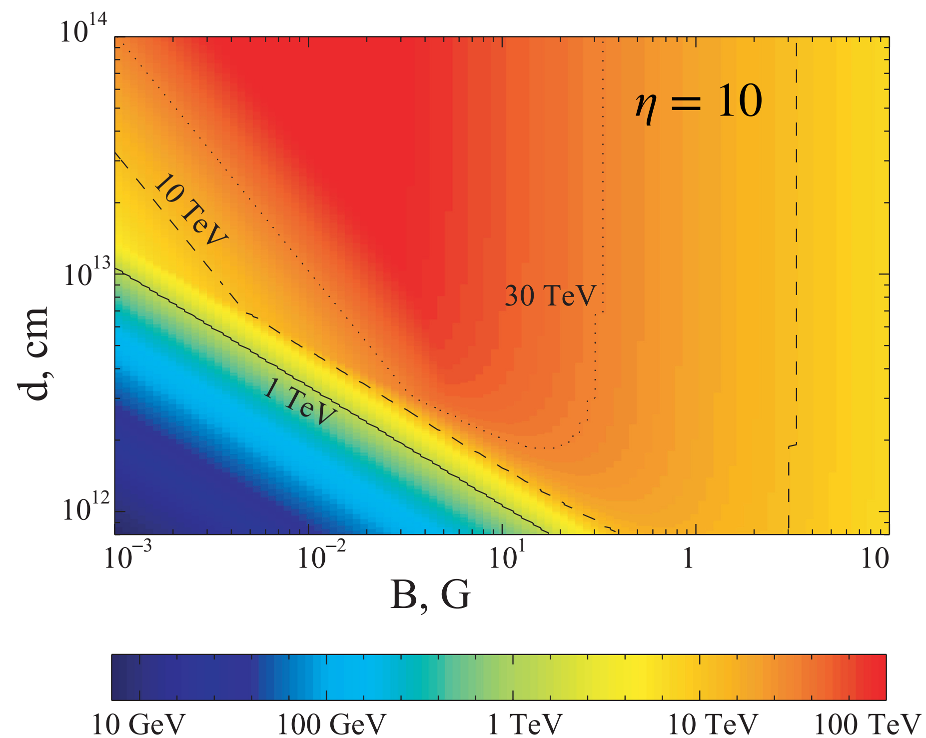


Constraints on the acceleration mechanism from HAWC maximum detected energy



Khangulian et al, 2008

Khangulian et al, 2008



How efficient the accelerator is
Very efficiently with η even < 10

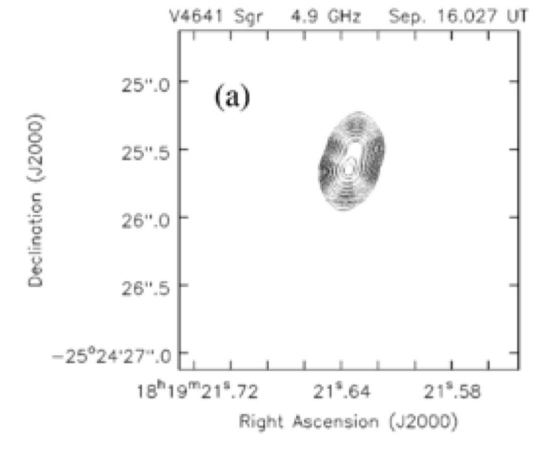
Where is γ-ray produced
May not be located deep inside the binary unless $\eta = 1$

What is the magnetic field
B < 0.1 G unless $\eta = 1$

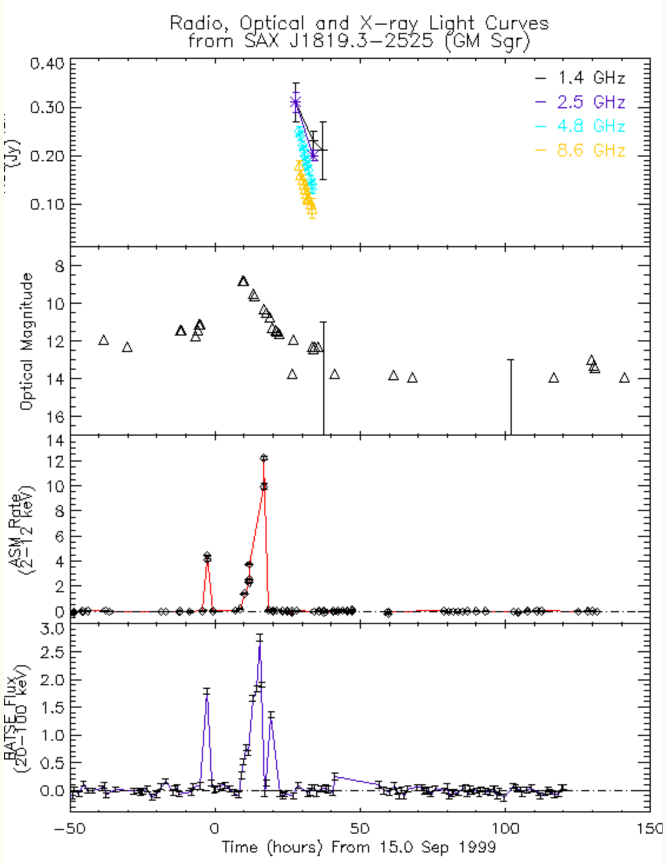
V4641 Sgr

- Transient X-ray binary
- First detected flares in 1999
- Arcsec radio jets
- Mass of the compact object : $6.4 \pm 0.6\ M_\odot$: black-hole (MacDonald+2014)
- The B-star secondary is among the most massive, the hottest, and the most luminous secondary among confirmed transient black hole binaries, $2.9 \pm 0.4\ M_\odot$
- Mass of the system largest among the dynamically confirmed black hole binaries
- Distance : 6.2 ± 0.7 kpc
- V4641 Sgr possibly the most superluminal galactic source known with an apparent expansion velocity of 9.5c and a bulk Lorentz factor of $\Gamma = 9.5$
- L_{Edd}/d^2 ($L_{Edd} \simeq 1.3 \times 10^{38}(M/M_\odot)$ erg/s $\sim 10^{39}/d^2$ erg/s - the Eddington luminosity gives an idea of the potential power available in the system

Radio observation



https://iopscience.iop.org/article/10.1086/317255/pdf



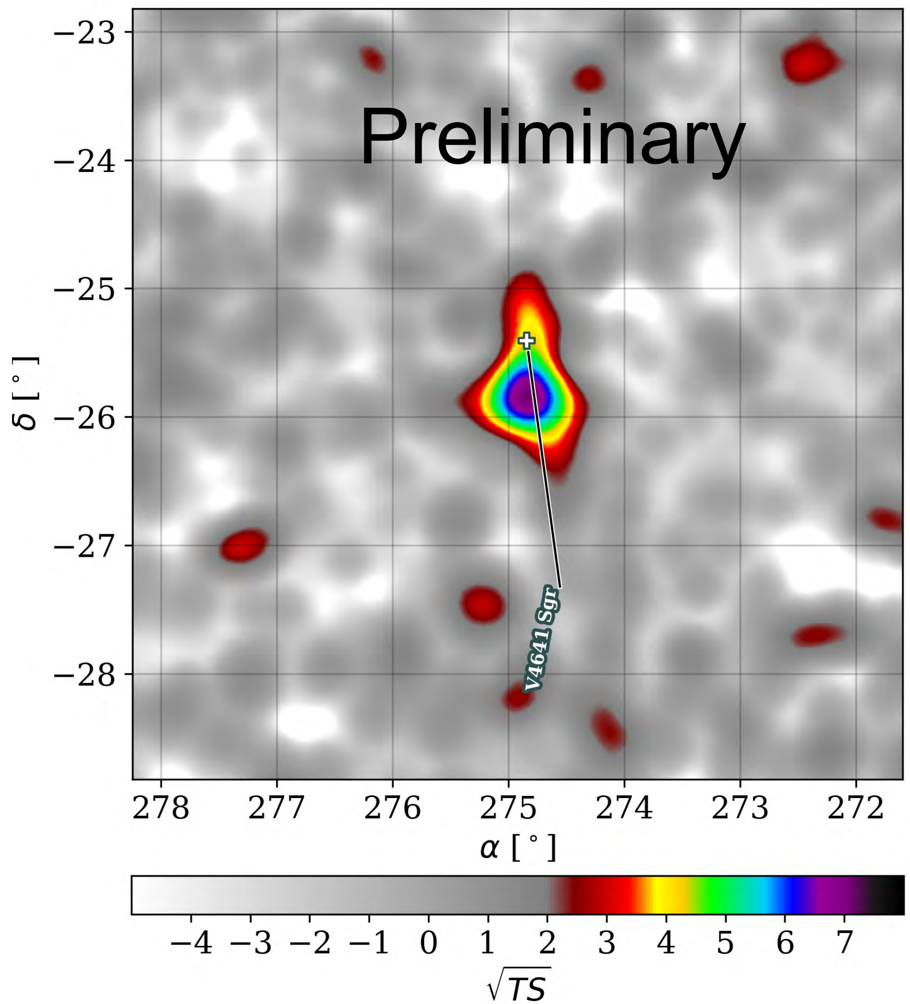
V4641 Sagitarii with HAWC

Newly discovered TeV microquasar

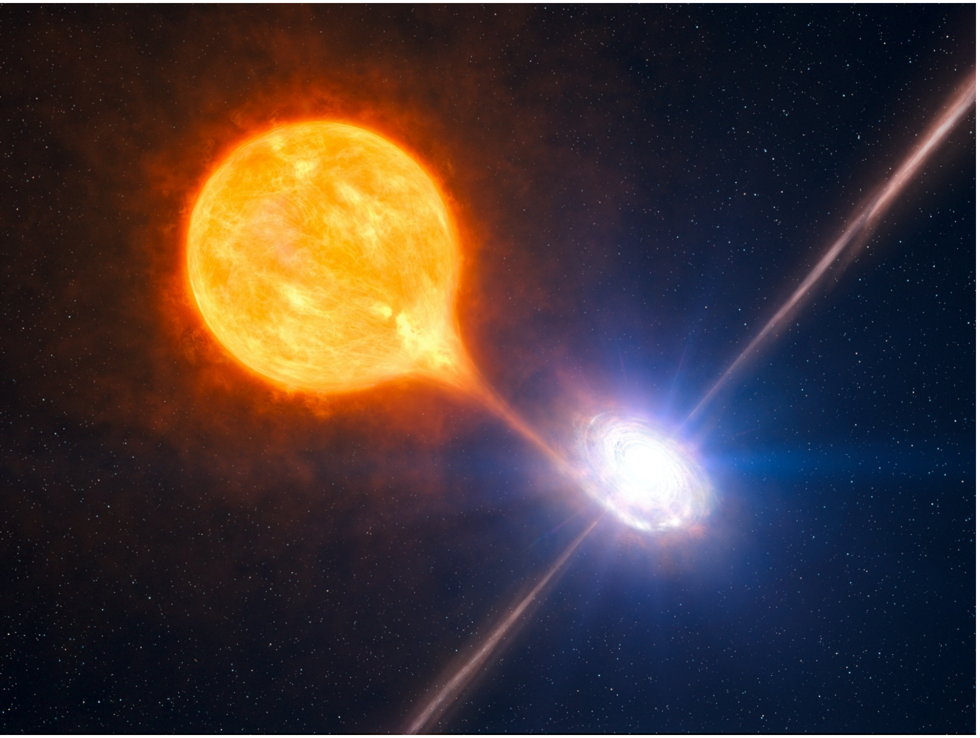
One of the fastest superluminal jets in the Milky Way galaxy
– Implies jet point toward us – but radio jet is very small

9.7σ in Pass 5 Median E~25 TeV
High zenith angle for HAWC
– 45° off zenith
– Extent appears <0.25°

Highest energy measured 180 TeV



Microquasars as gamma-ray sources: SS433 Lobes



- SS 433 is a Galactic micro-quasar observed in radio-X-rays.
- SS433 is a binary system formed by a Supergiant 30 solar masses star and a compact object, either a neutron star or a black hole
- Two jets, the most powerful known in the Galaxy, extend perpendicular to the line of sight and terminate in W50 nebula and produce western and eastern X-ray lobes
- SS433 jet : $10^{39\text{-}40}$ erg/s
- SS433 jet speed roughly c/4
- Baryon loaded
- Particle acceleration is believed to occur at the lobes

The lobes of the microquasar SS-433

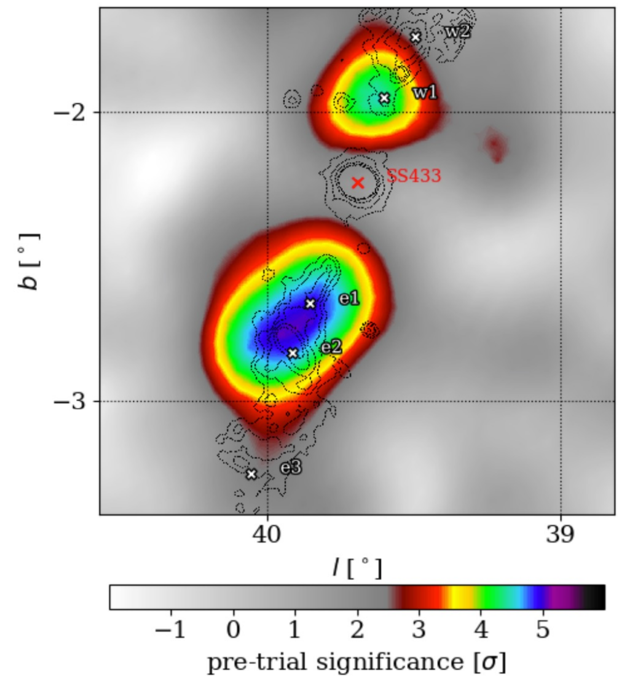
HAWC observation of SS433 is the first direct

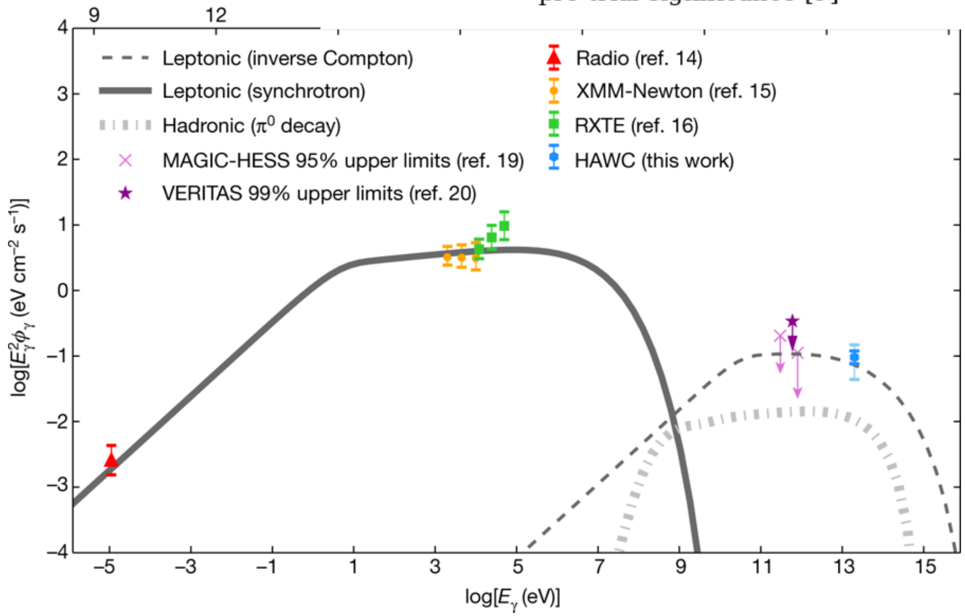
evidence of particle acceleration to ~PeV in jets

- Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities

- Leptonic mechanism explains the emission However, radiation from protons cannot be excluded

- Acceleration does not happen at the black hole

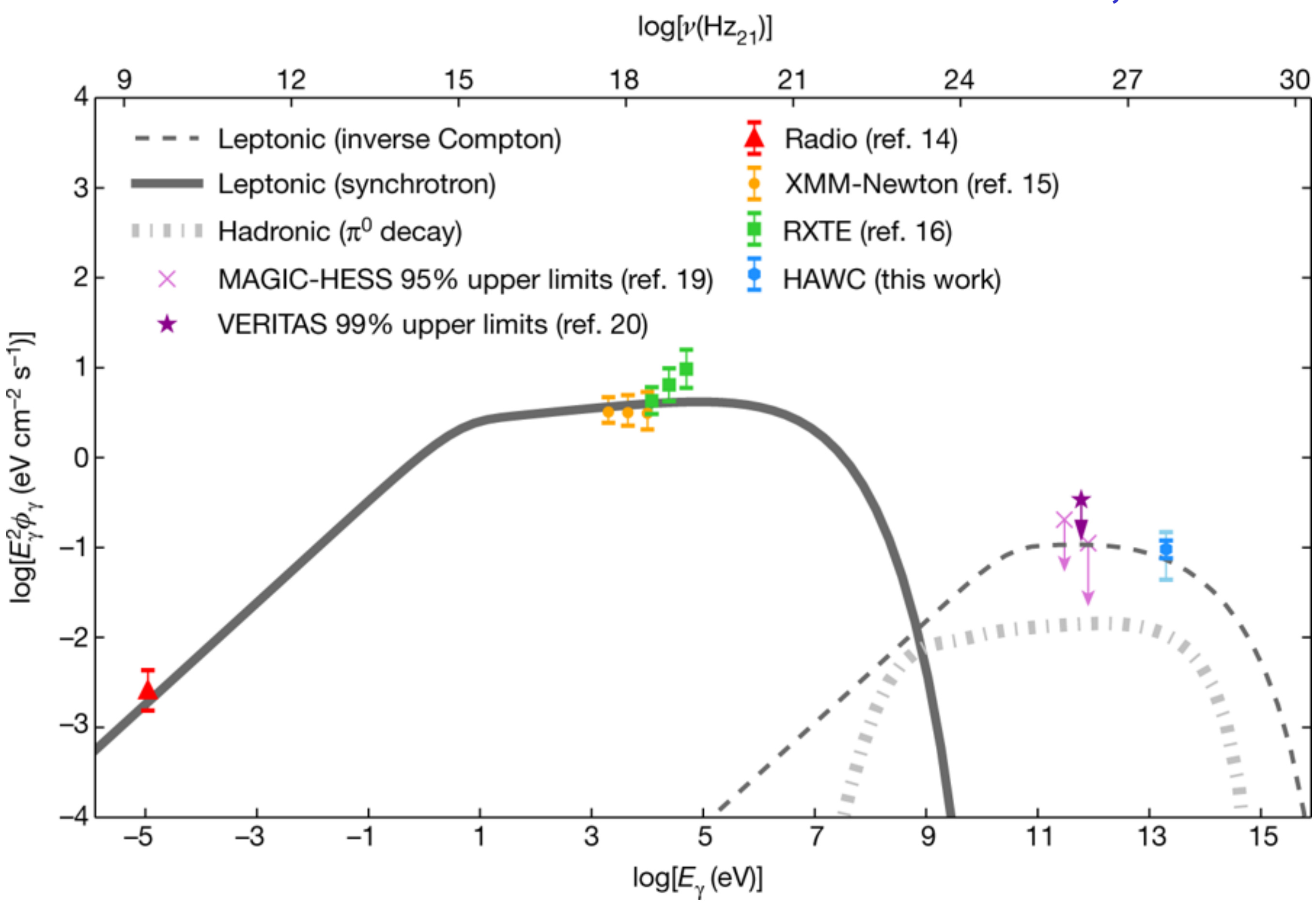




Nature, HAWC Coll 2018

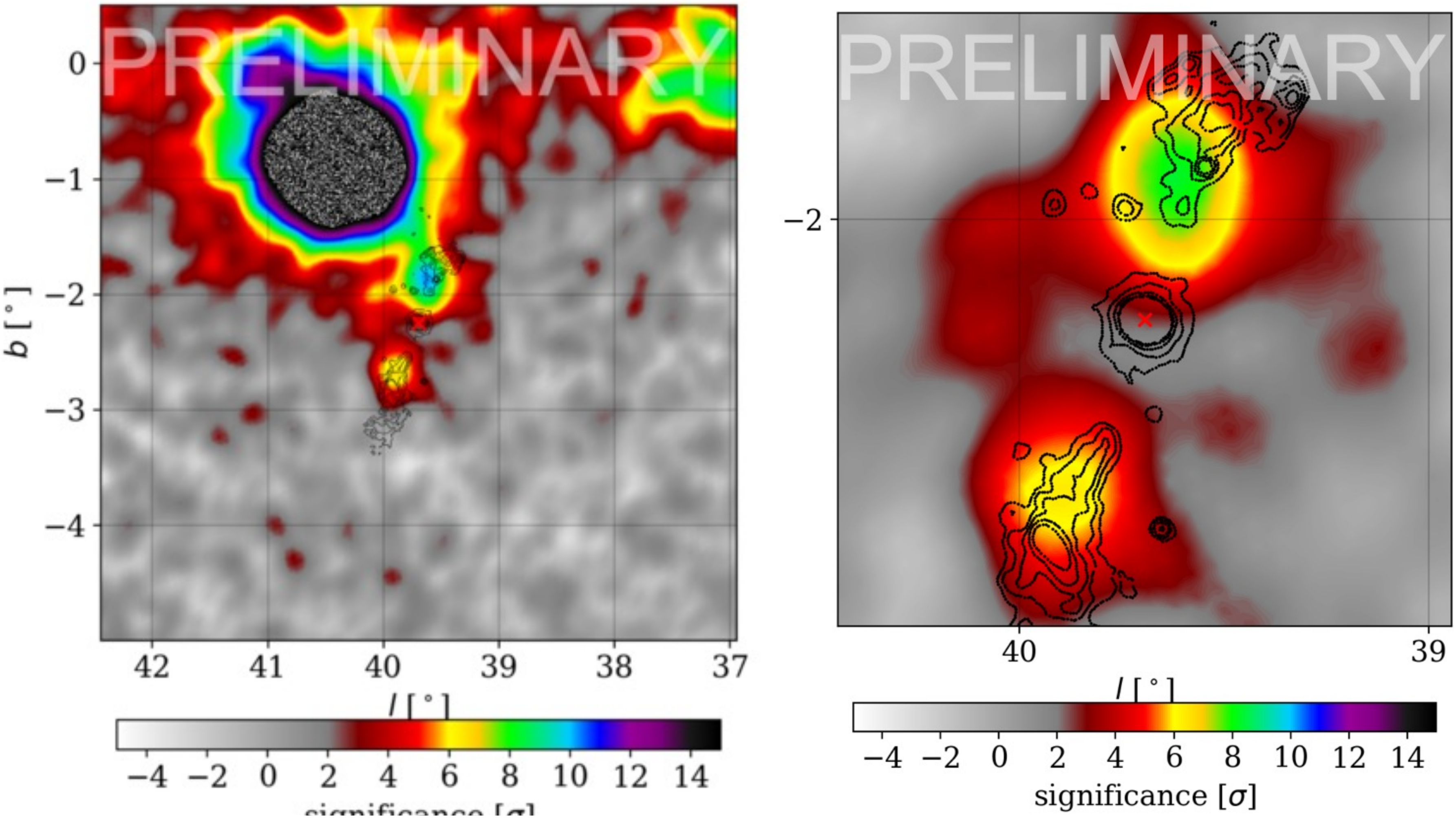
Origin of the emission

Nature, HAWC Coll 2018



- IC scattering off CMB photons, scattering off optical and infrared suppressed electron acceleration
- Electrons of at least 130 TeV required in a magnetic field of 16microGauss
- Hadronic emission assumes 10% conversion of jet energy into protons and 0.05 cm-3 density

Significance Map of SS 433 (Pass 5)



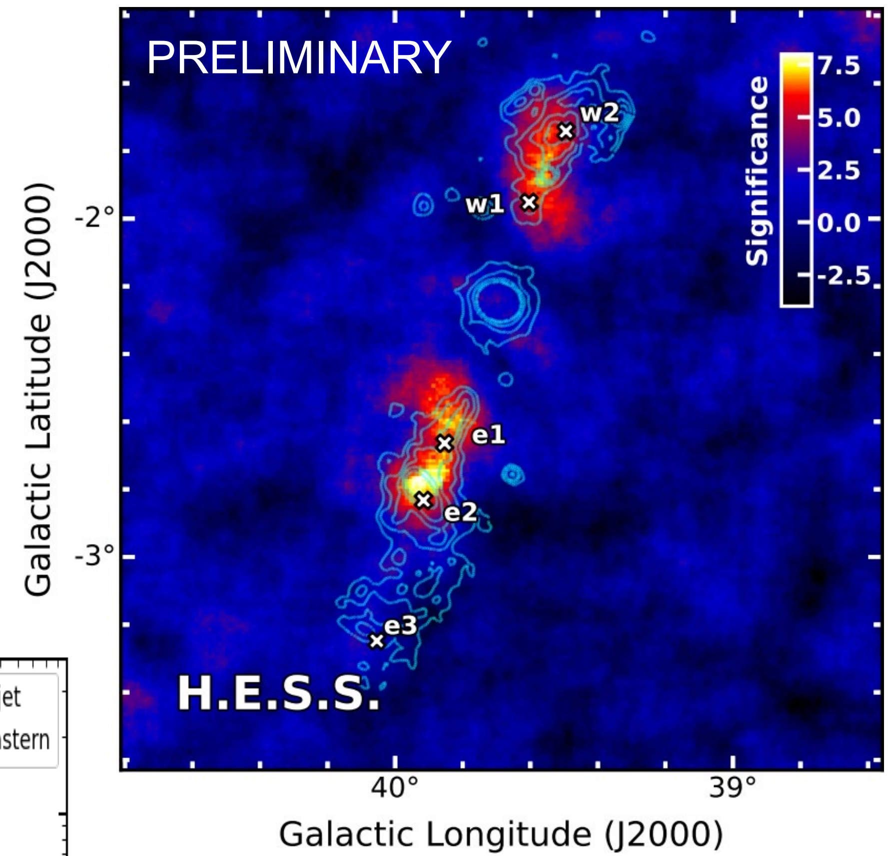
H.E.S.S. observations of SS433

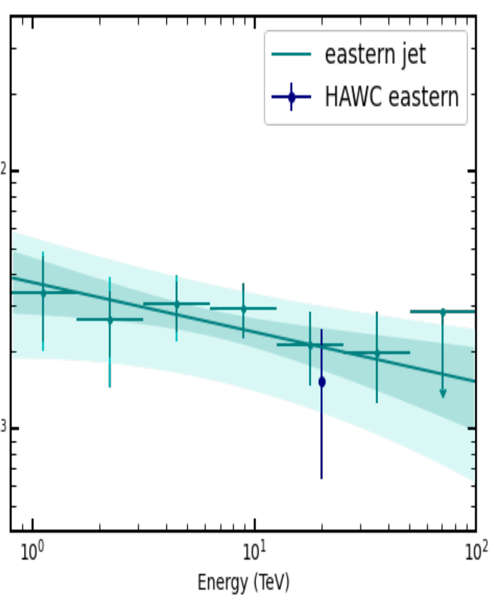
Two separate TeV excess consistent with each of the jets

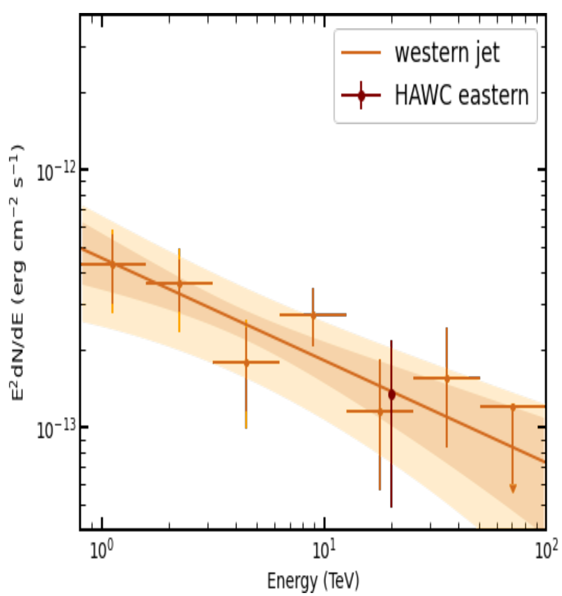
Western and eastern jet detected with 6.8σ and 7.8σ respectively

No detectable emission from the central binary

No detectable emission past the e2 region in eastern jet

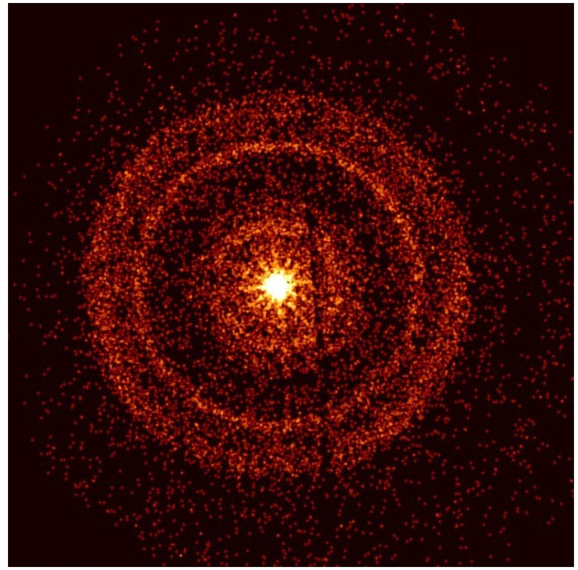




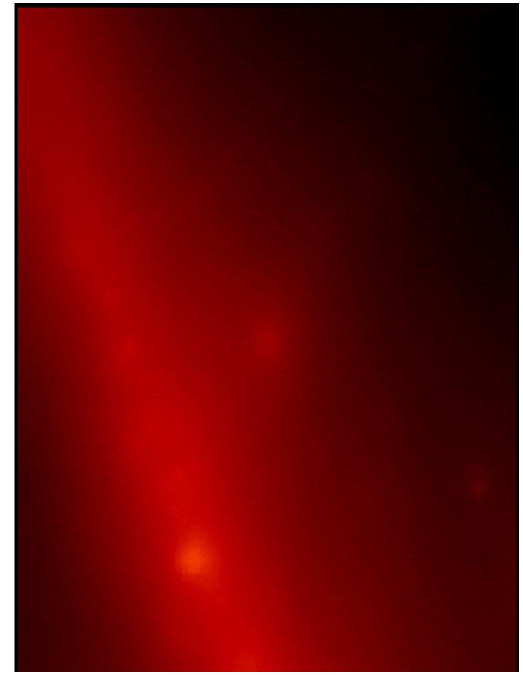


LHAASO detects the brightest ever GRB, GRB 221009A

Swift image taken just an hour after the first blast shows rings of X-ray light from the burst scattered by dust inside our Milky Way galaxy



Fermi LAT



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TITLE:   GCN CIRCULAR
NUMBER:  32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE:    22/10/11 09:21:54 GMT
FROM:    Judith Racusin at GSFC  <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen,  Min Zha, Cheng Liu, Zhiguo Yao and
Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642),
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy
band between 10^11 and 10^15 eV) and cosmic ray measurements.
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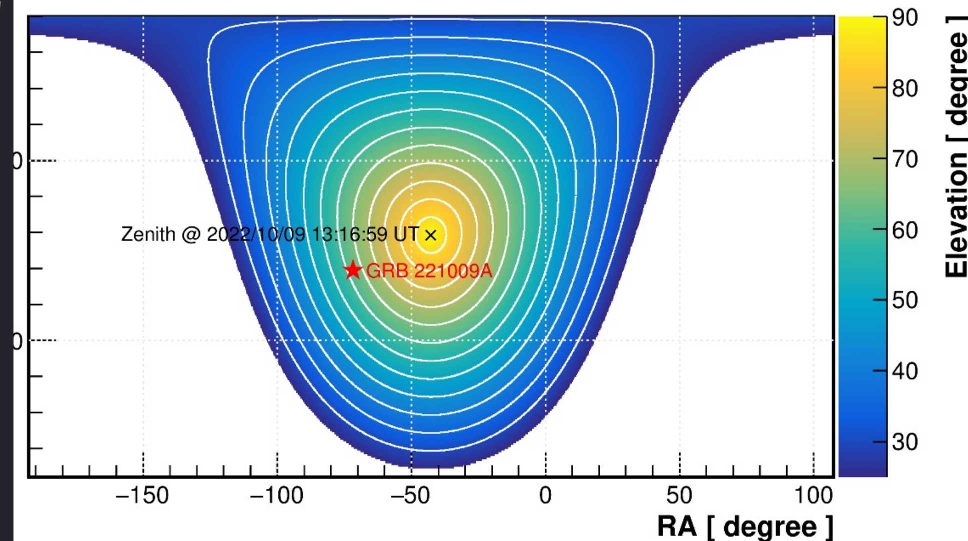
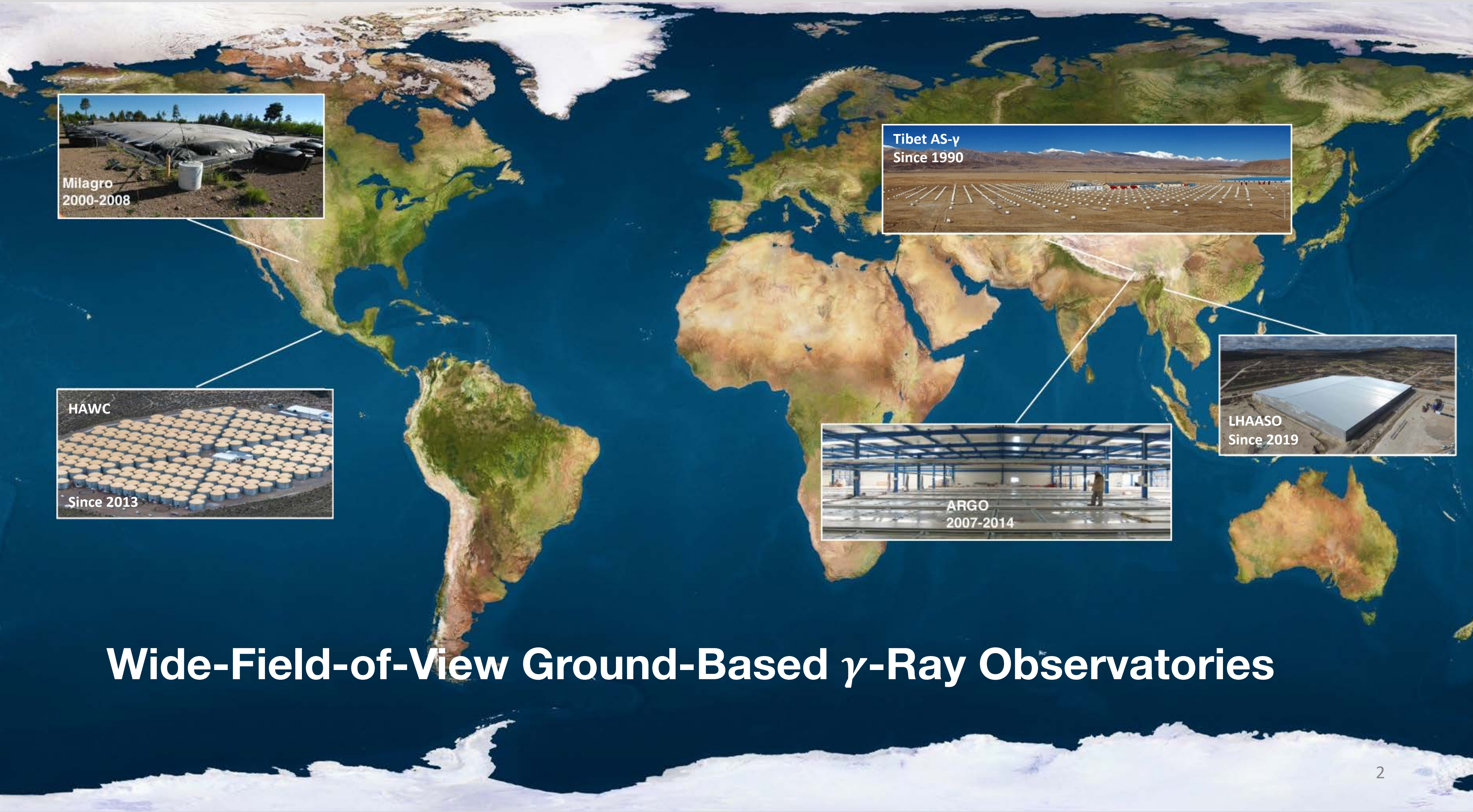


Covering different time zomnes



So important to follow transients such as GRBs. The bright GRB was unfortunately not in HAWC FoV but luckily in LHAASO FoV !

AGN Monitoring

Active Galaxies are powerful and highly variable emitters of high energy gamma rays

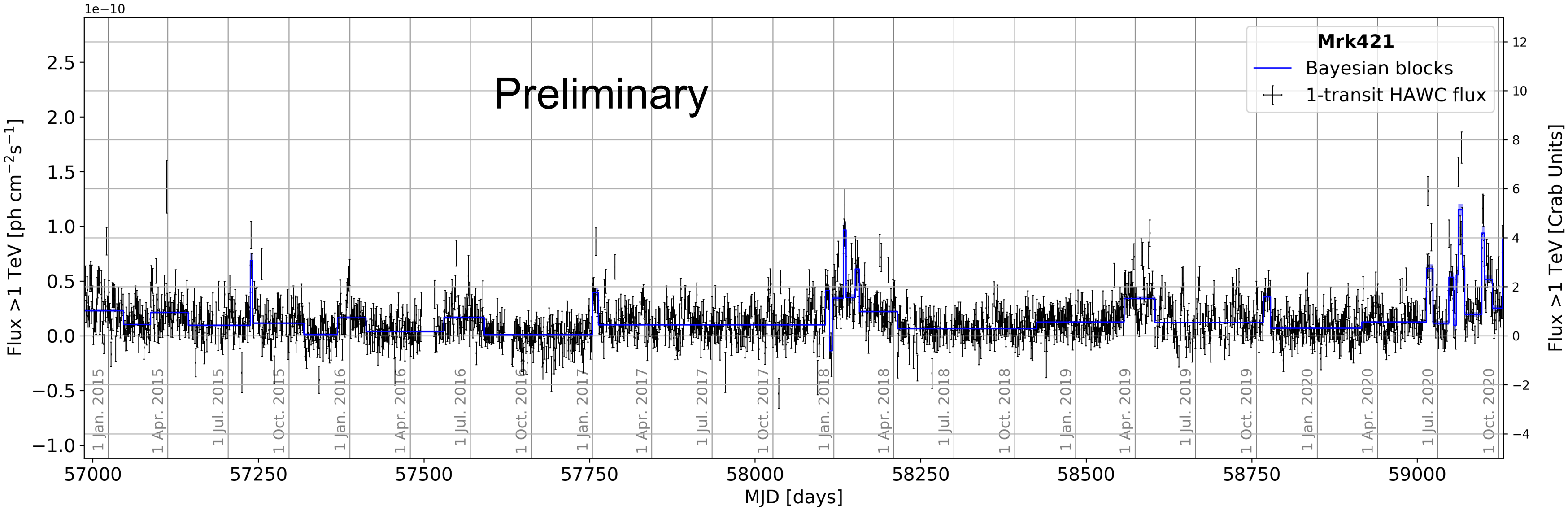
Very high energy photons are attenuated because of their interaction with the EBL

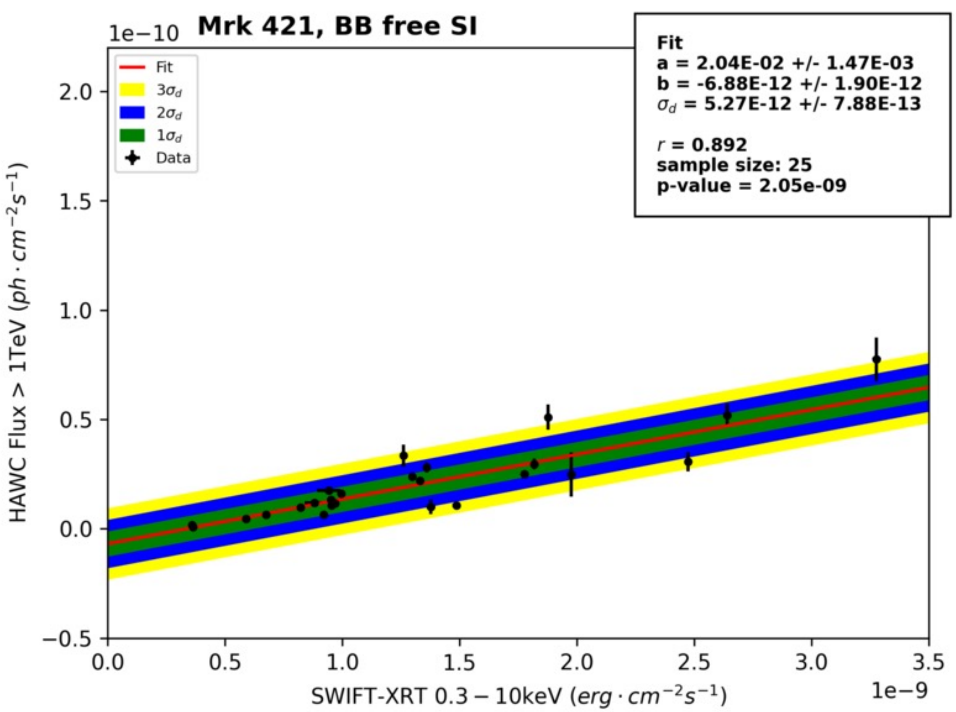
Mrk 421 and Mrk 501 both at about z=0.03 have been long monitored

Recent detections of 1ES 1215+303 and M87

Mrk 421 Sloan Dig Sky Survey

Daily Monitoring of Mrk 451





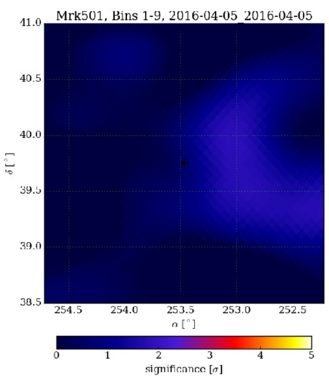
Comparison Swift - XRT vs HAWC flux

Transient Search - Mrk 501

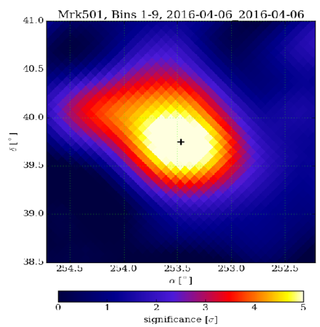
HAWC detection of increased TeV flux state for Markarian 501

ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

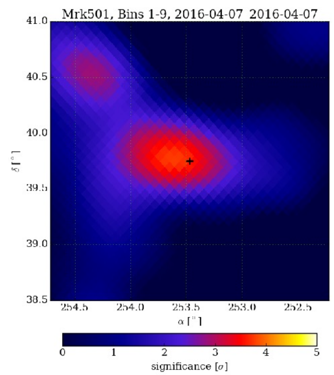
April 5, 2016



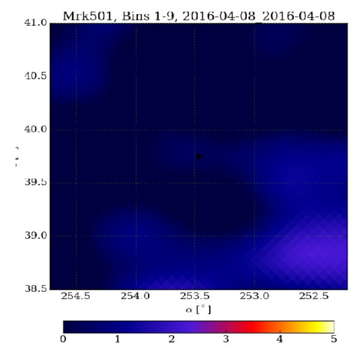
April 6, 2016



April 7, 2016



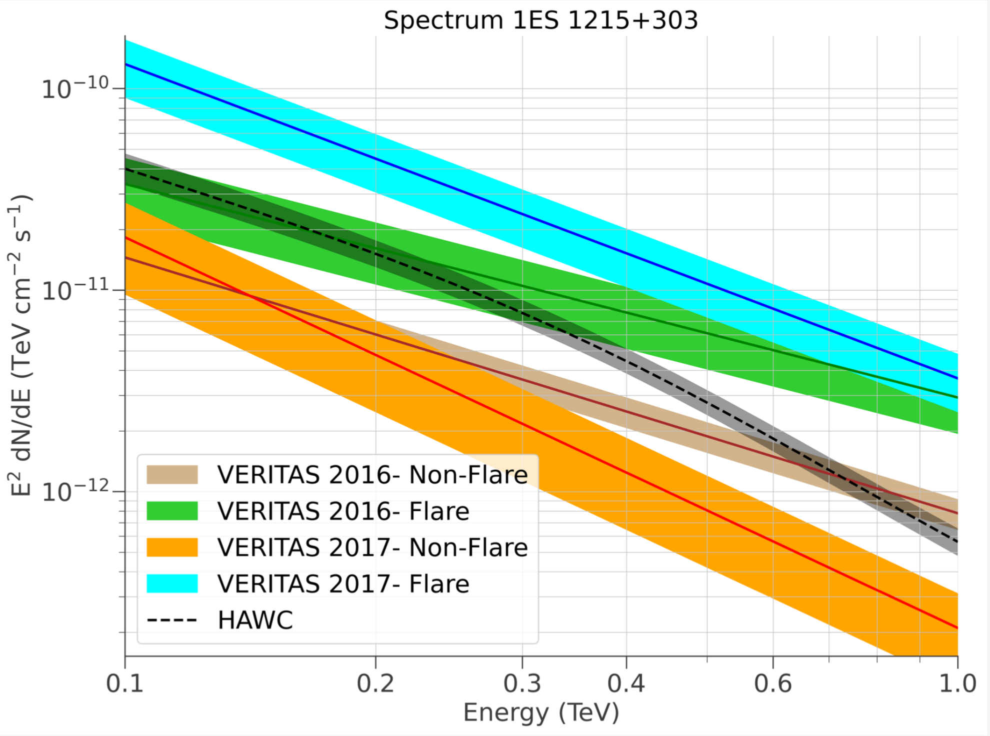
April 8, 2016



1ES 1215+303

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{obs} = K\left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\alpha} e^{-\tau(E,z)}$$

- $K = 1.08 \pm 0.54 \times 10^{-12}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\alpha = 3.56 \pm 0.19$
- $TS = 45.2\ (6.7\sigma)$

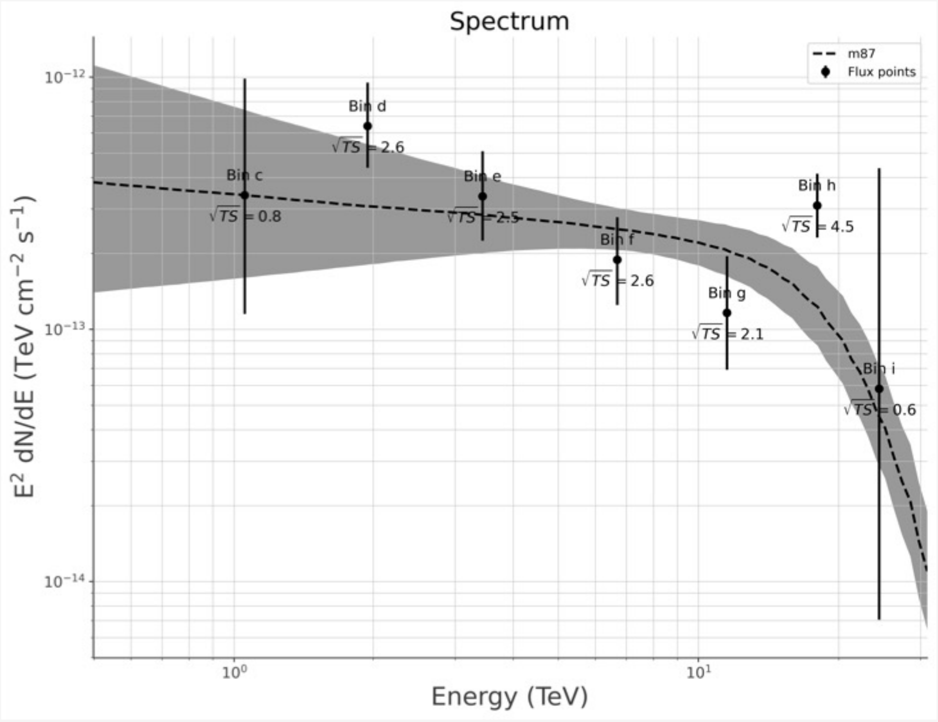


VERITAS results obtained from Valverde et al., 2020 https://iopscience.iop.org/article/10.3847/1538-4357/ab765d/pdf

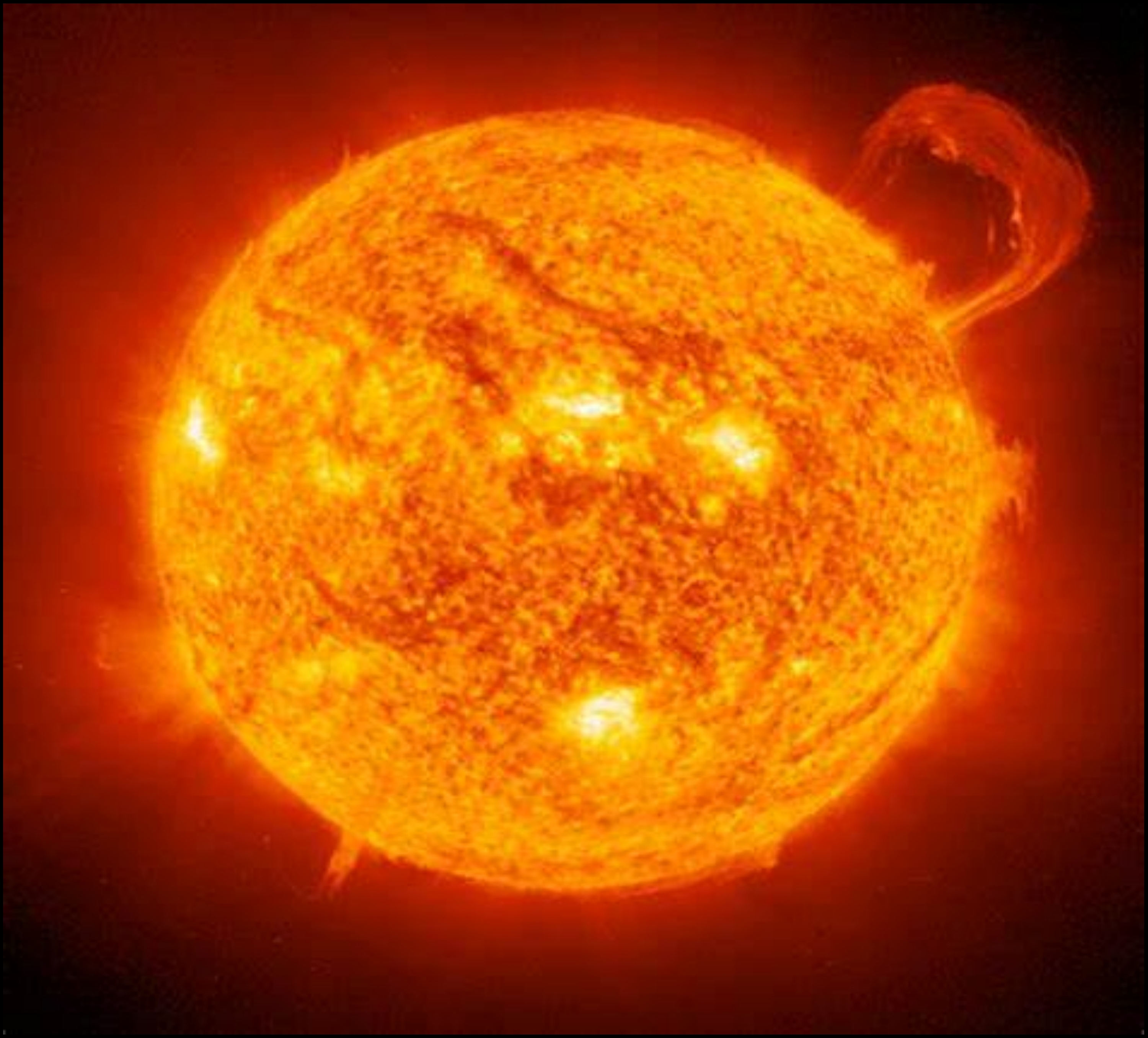
M 87 Spectrum

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{obs} = K\left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\alpha} e^{-\tau(E,z)}$$

- $K = 3.7 \pm 3.1 \times 10^{-13} \mathrm{TeV^{-1} cm^{-2} s^{-1}}$
- $\alpha = 2.1 \pm 0.5$
- $TS = 35.7\ (6\sigma)$



Looking for gamma rays from the Sun



Looking for Gamma-rays from the sun

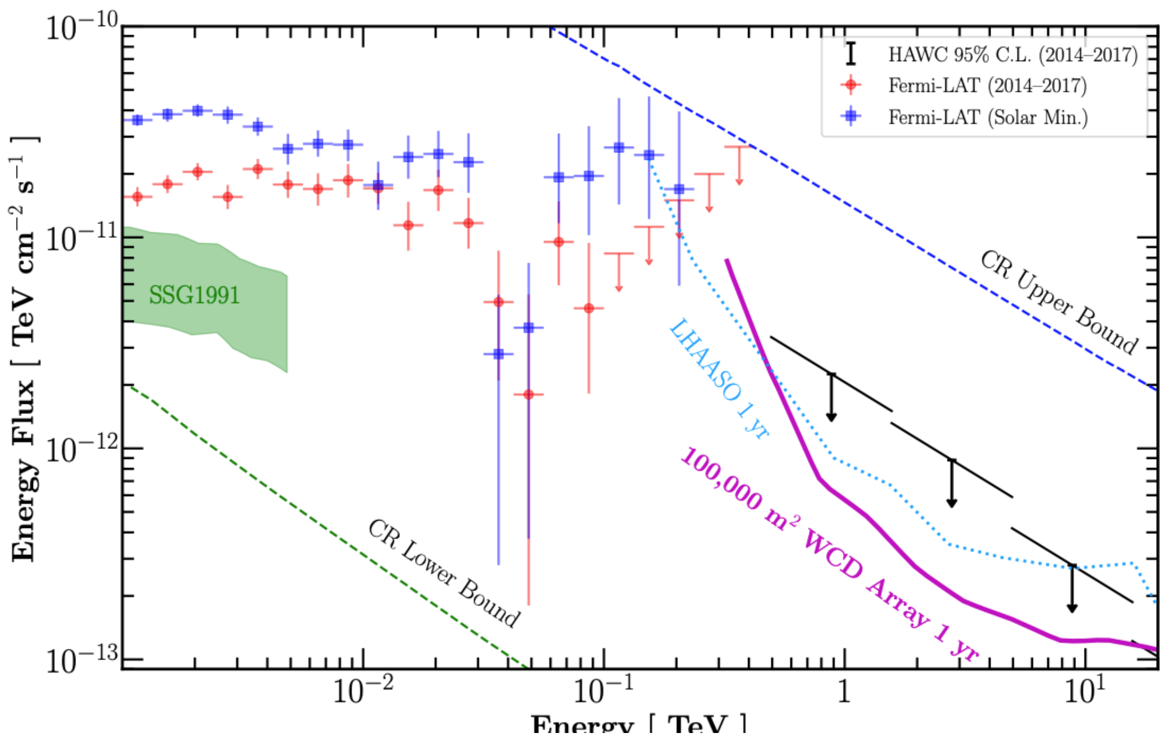
Fermi sees the sun up to ~100 GeV

Correlated to solar cycle. Higher flux at Solar Min

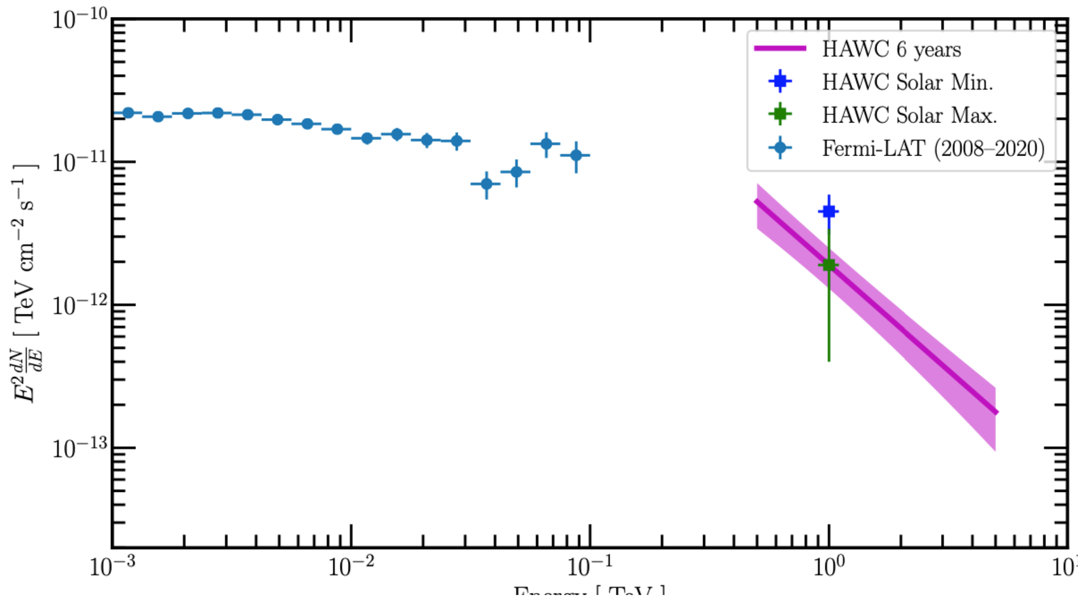
Emission mechanism thought to be from CR hadrons interacting with the atmosphere of the sun

Not necessarily in the limb

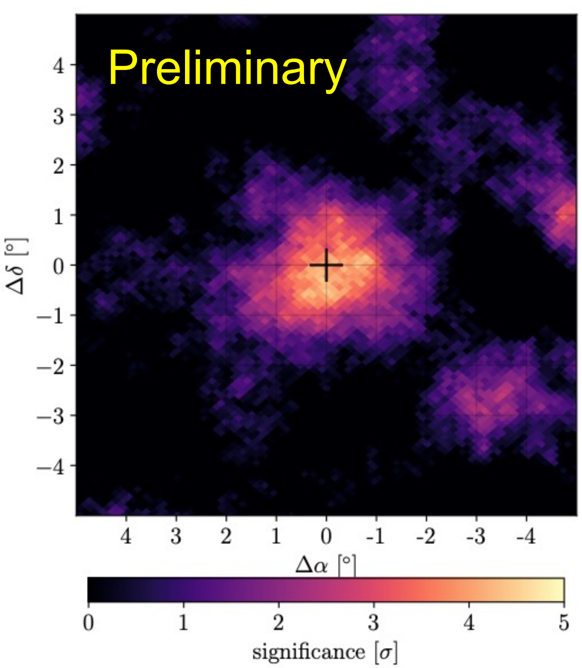
Un Nisa ICRC 2019

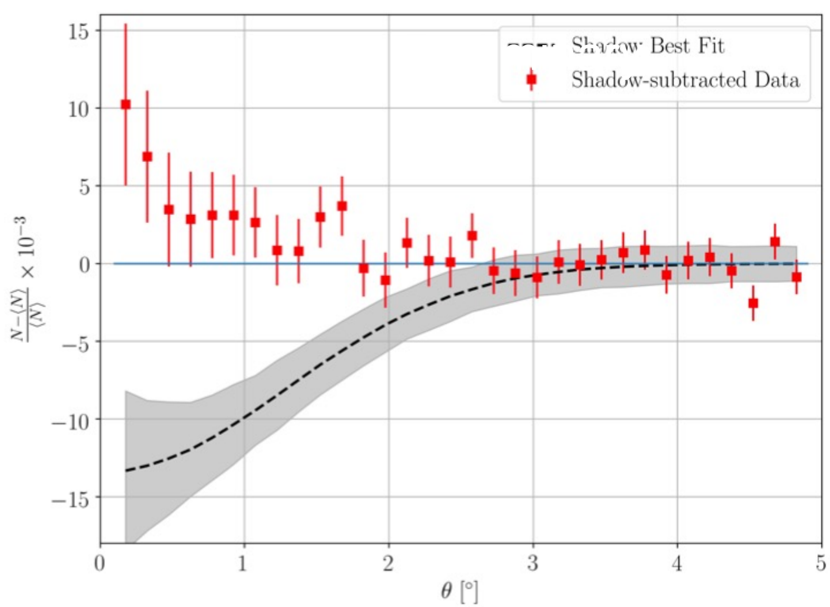


The Sun

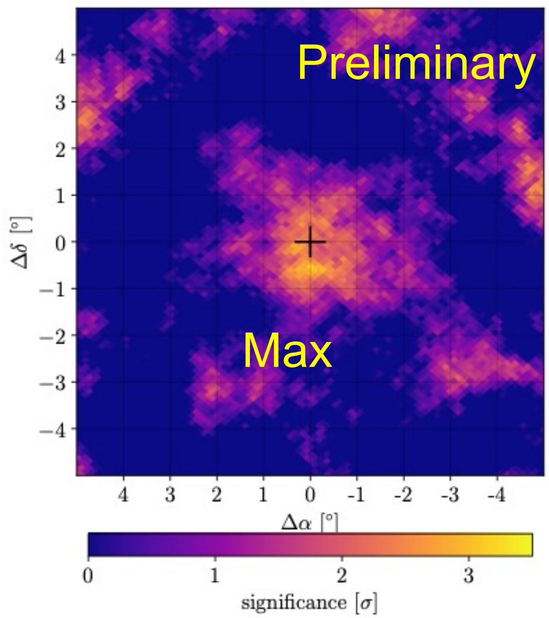


Subtract the CR shadow profile (1) from the raw gamma maps (2).
The subtraction is done in relative counts space.

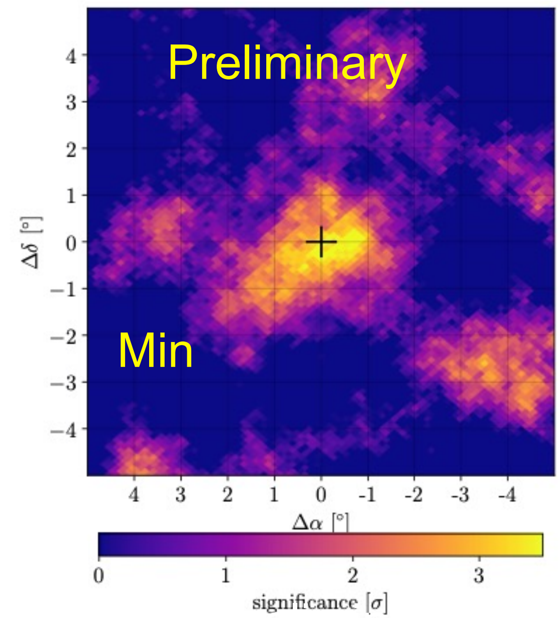


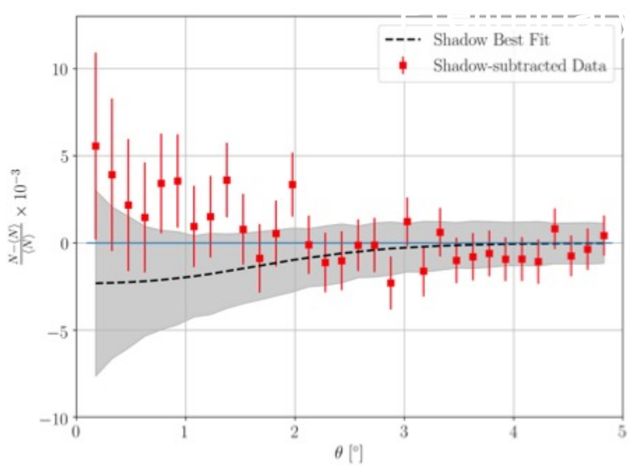


Solar Max and Solar Min

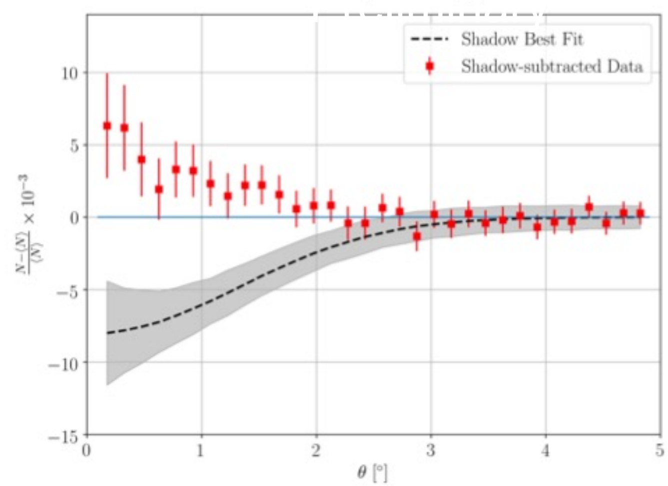


Overall
3.5σ vs 4.9 σ

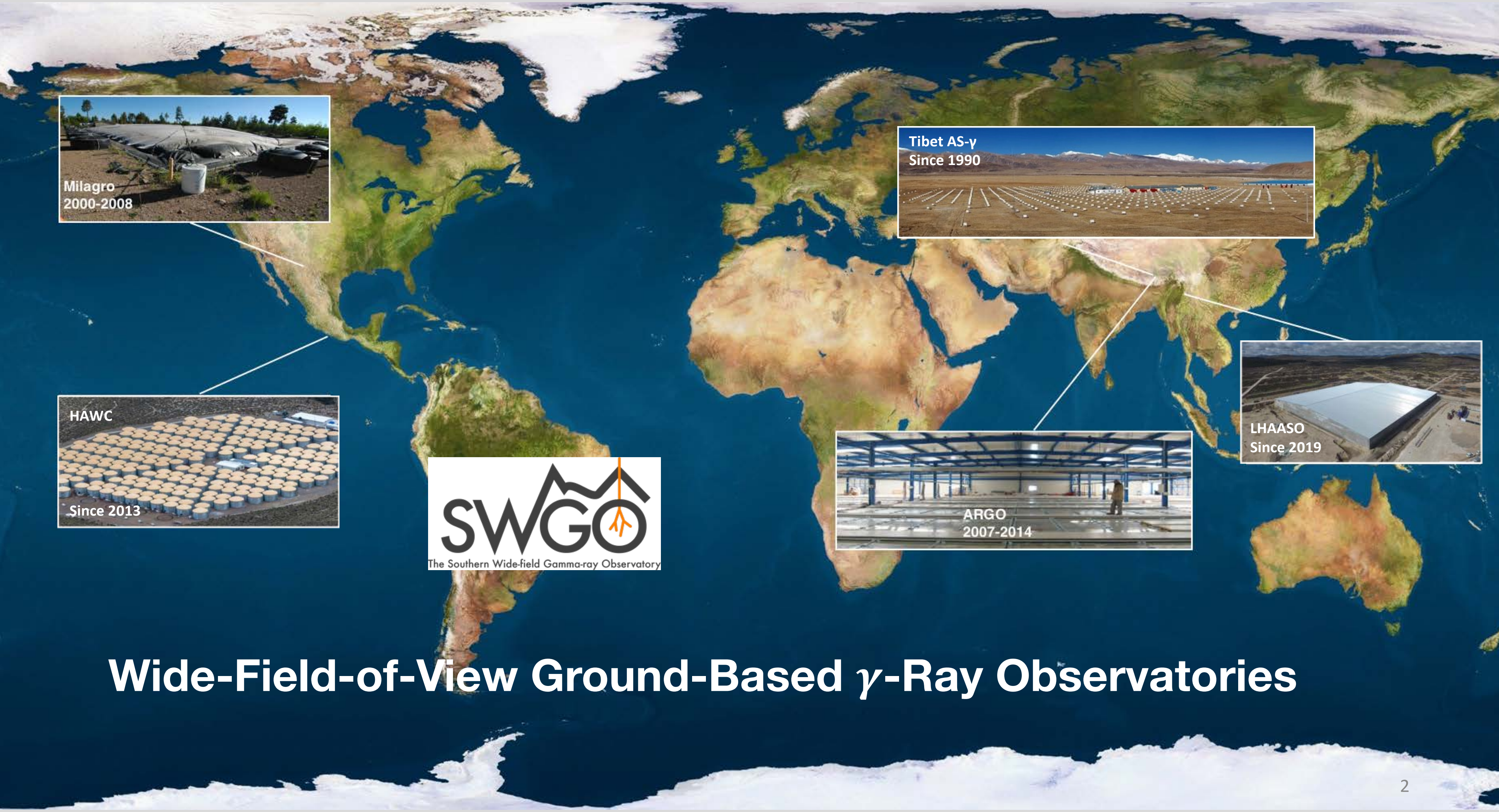




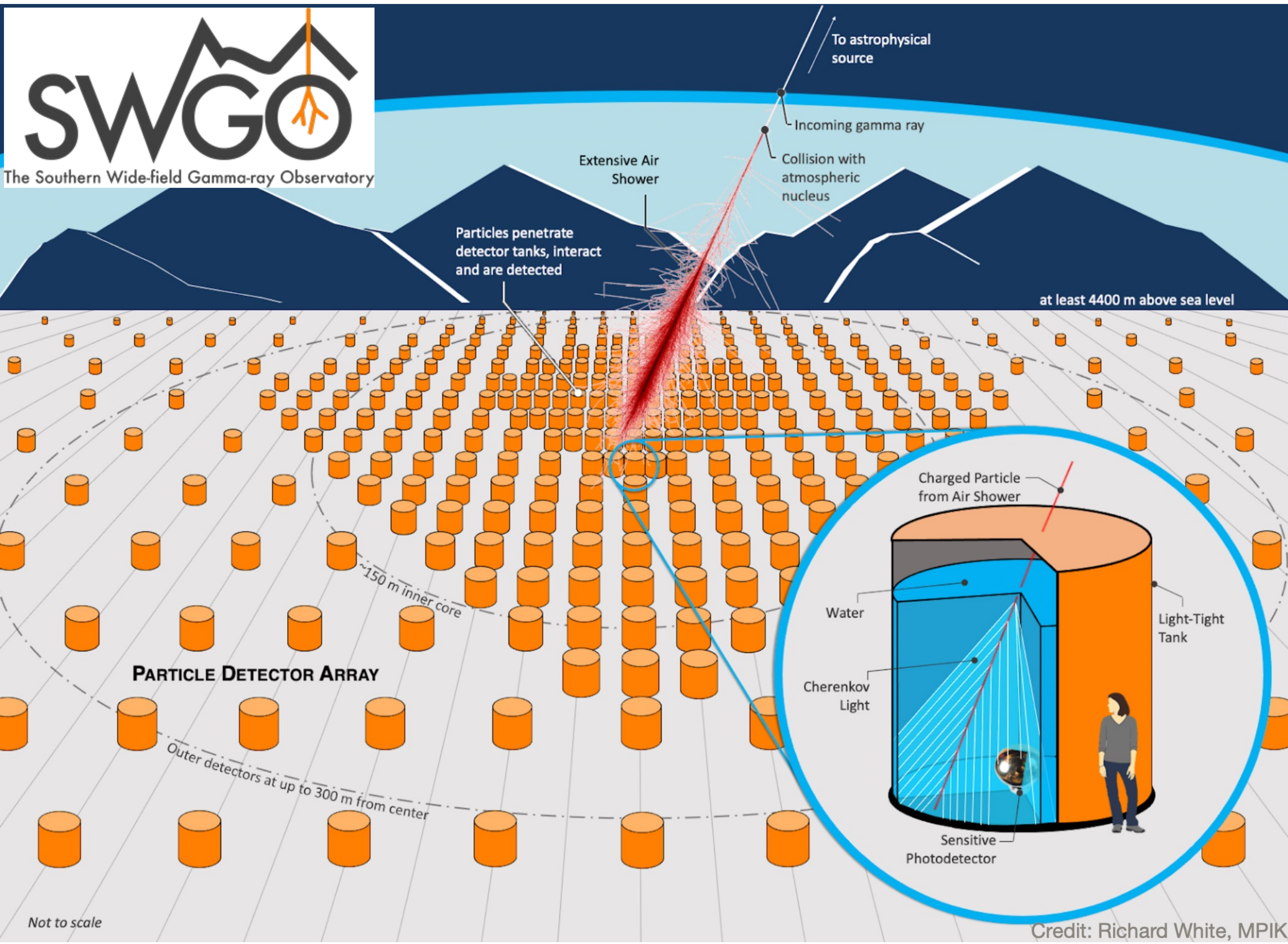
B3C0



Covering different time zones



Future : Covering the Southern Sky too !


SWGO
The Southern Wide-field Gamma-ray Observatory
To astrophysical source
Incoming gamma ray
Collision with atmospheric nucleus
Extensive Air Shower
Particles penetrate detector tanks, interact and are detected
at least 4400 m above sea level
Charged Particle from Air Shower
Water
Light-Tight Tank
Cherenkov Light
Sensitive Photodetector
~150 m inner core
Particle Detector Array
Outer detectors at up to 300 m from center
Not to scale
Credit: Richard White, MPIK

Conclusions and Outlook

Since 2013 HAWC has shown that the Galaxy is full of VHE sources

- New source class : TeV halos
- Hundred TeV photons from gamma-ray binaries
- Hundred TeV photons from SFRs
- Monitoring of variable sources

Since 2019 LHAASO has opening up the PeV domain in astronomy.

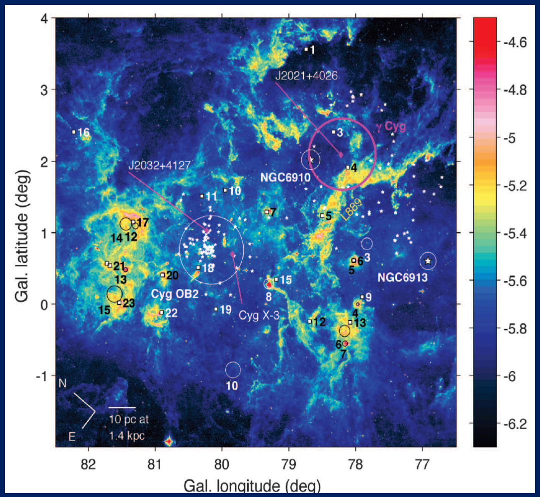
- Crab spectrum up to 1.1 PeV
- 1 photon a 1.4 PeV from the Cygnus cocoon
- First detection of TeV photons from a GRB with an EAS array

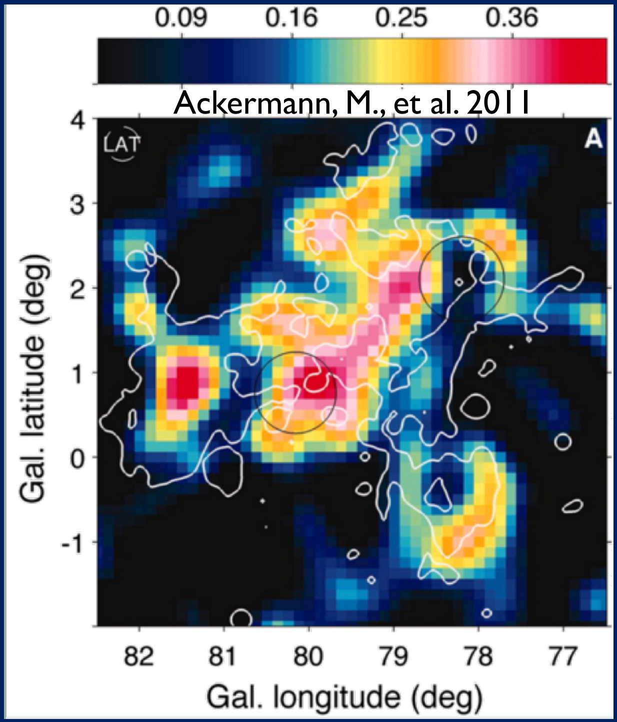
LHAASO has just started and has immense potentialities

Future Observatory in the Southern Hemisphere

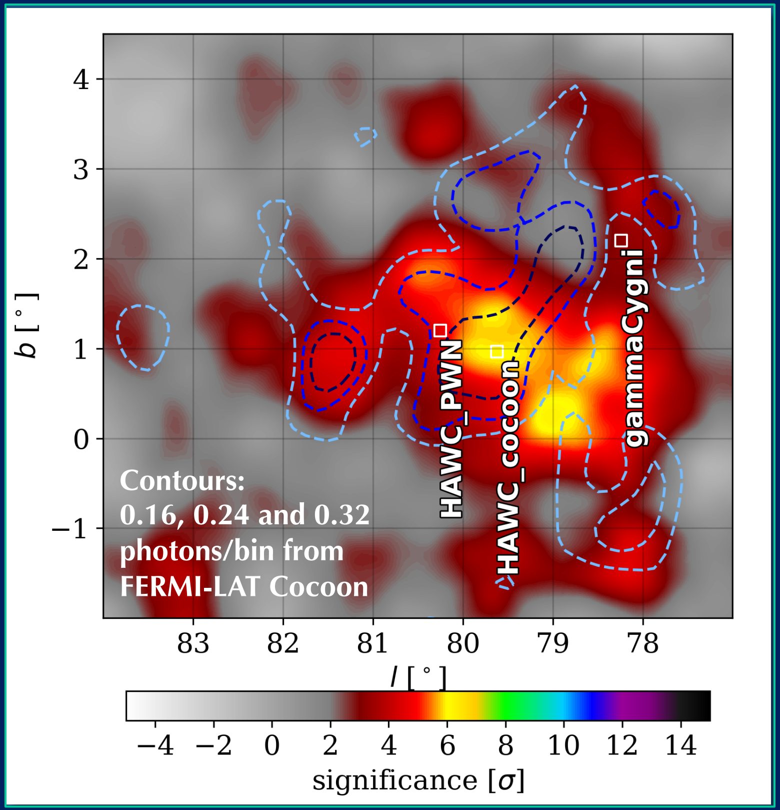
VHE AND UHE Photons from SFRs and the origin of Galactic CRs

Cyg OB2 in IR, GeV and TeV





HAWC significance map
of the Cygnus Cocoon



Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

HAWC Coll, NatAstr 2021

HAWC Discovery of hundred TeV photons from Cyg OB2

First superbubble seen from GeV to hundred TeV energies

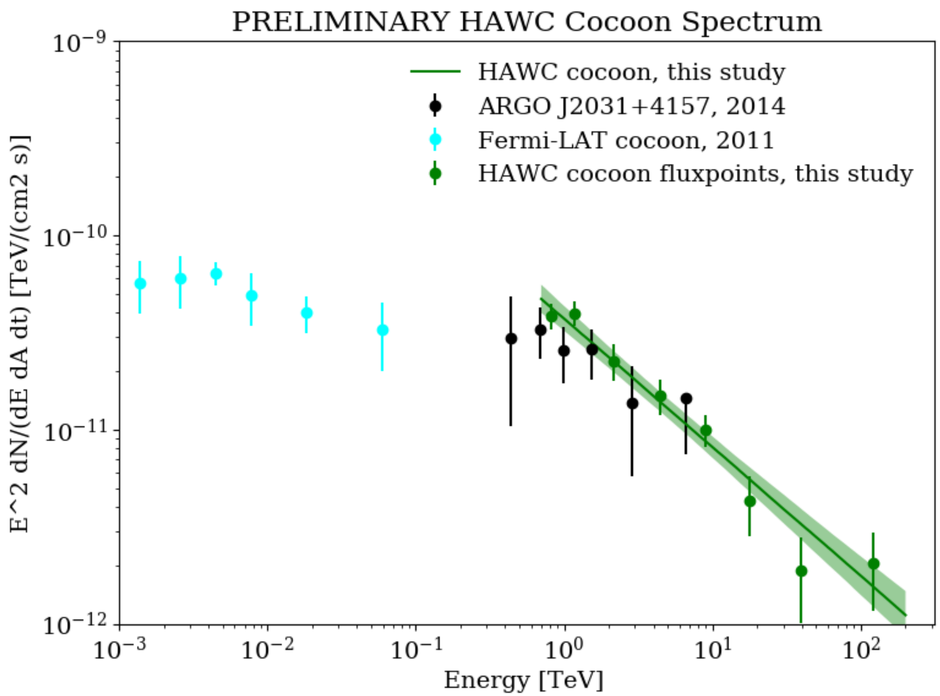
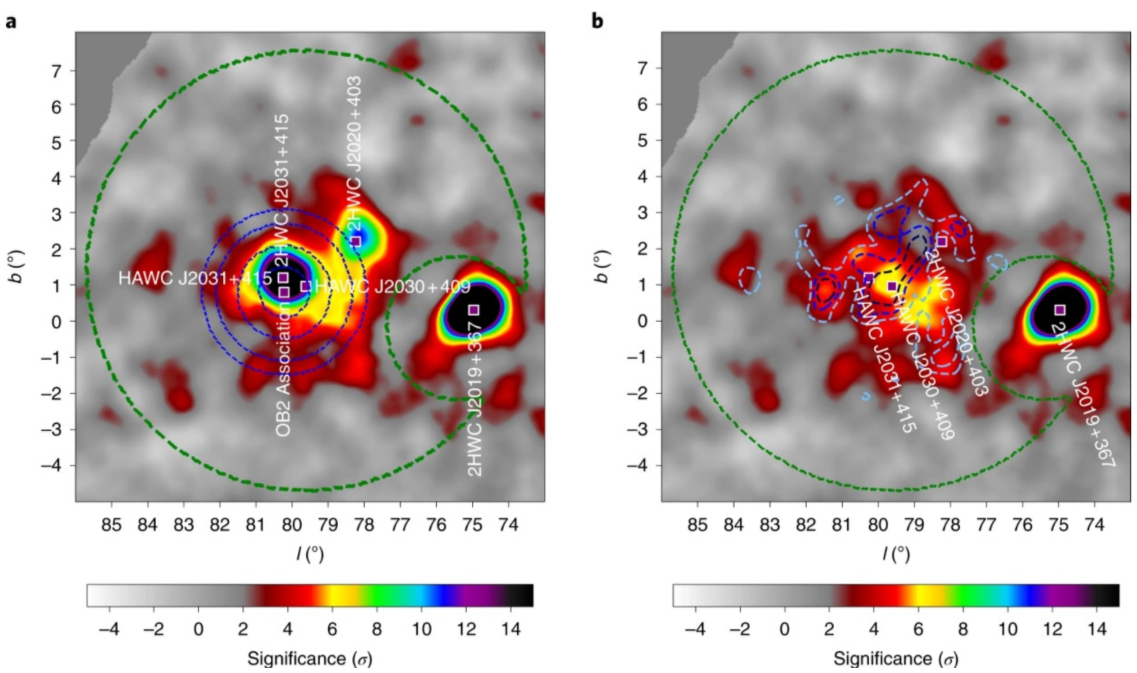
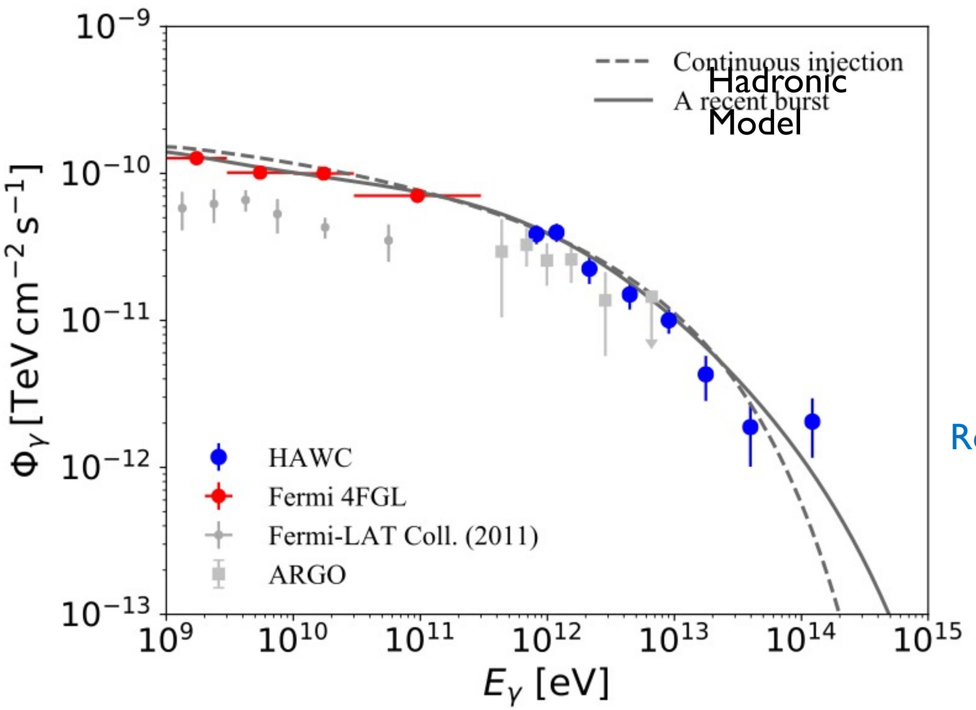


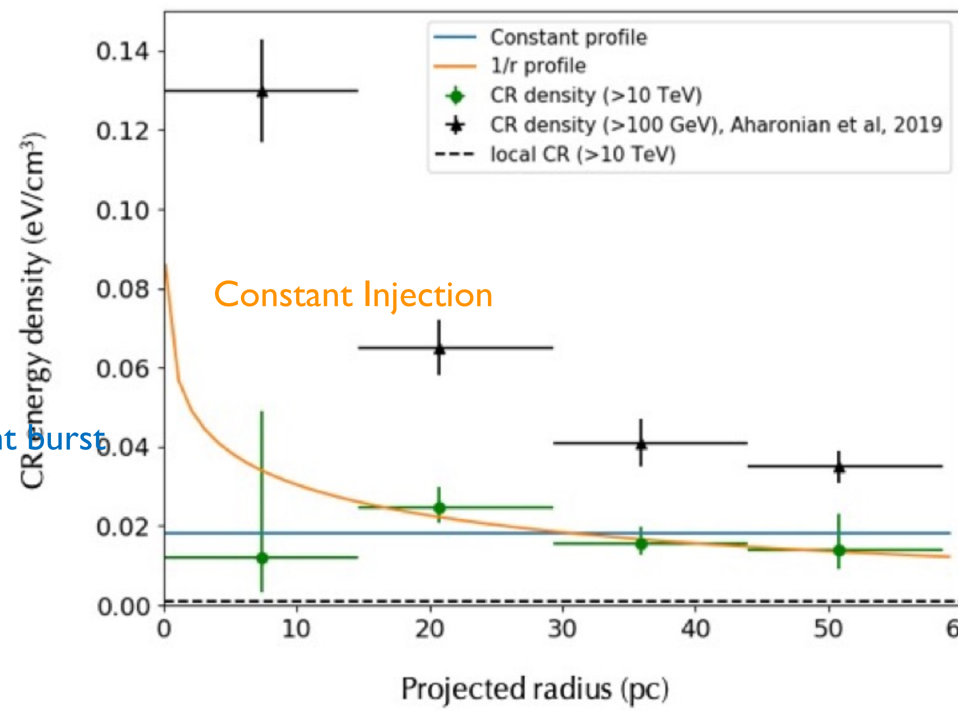
Fig. 1: Significance map of the Cocoon region before and after subtraction of t known sources at the region.

From: HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon



Cosmic Ray Acceleration in SFRs





Nat Astr, HAWC 2021

CRs up to PeV energies accelerated within a region the SFR

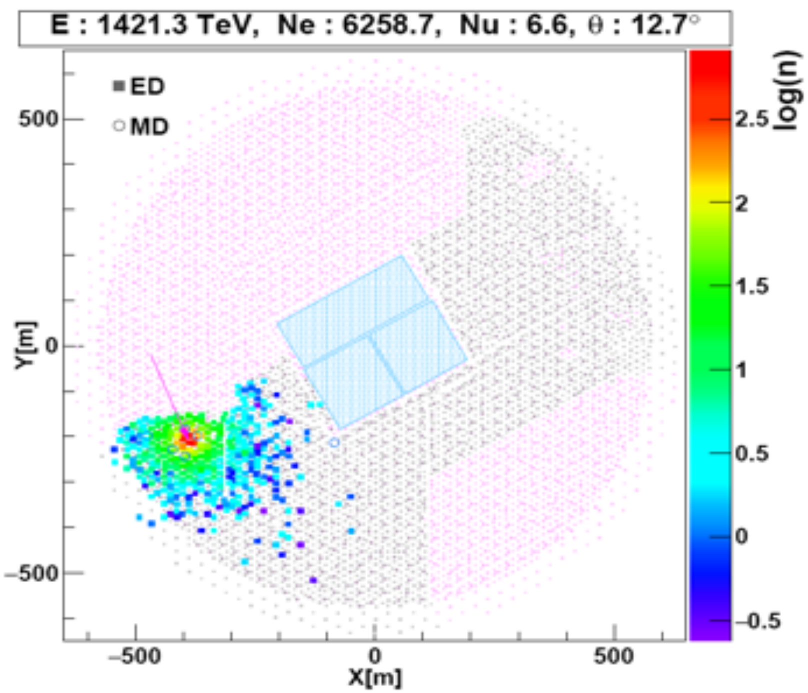
CR energy density > 10 TeV higher than local CR energy density

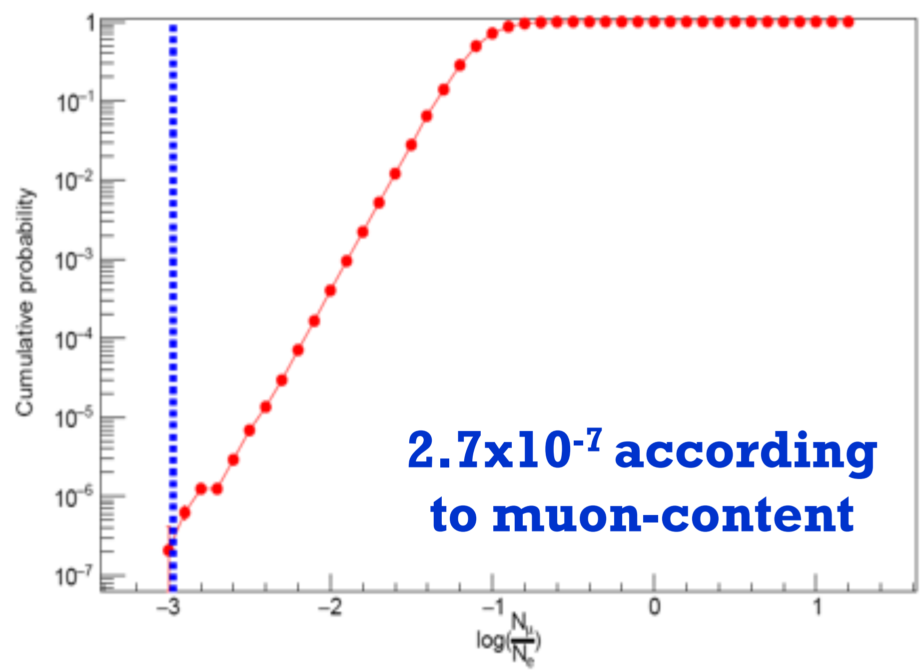
1/r profile - a continous injection. Constant profile - a recent burst event happened less than 0.1 Myr

10000 CygOB2 would be required for CRs Galactic population

Highest energy photon

- **1.42±0.13 PeV from the Cygnus region**
- **Chance probility due to cosmic ray background 0.028%.**





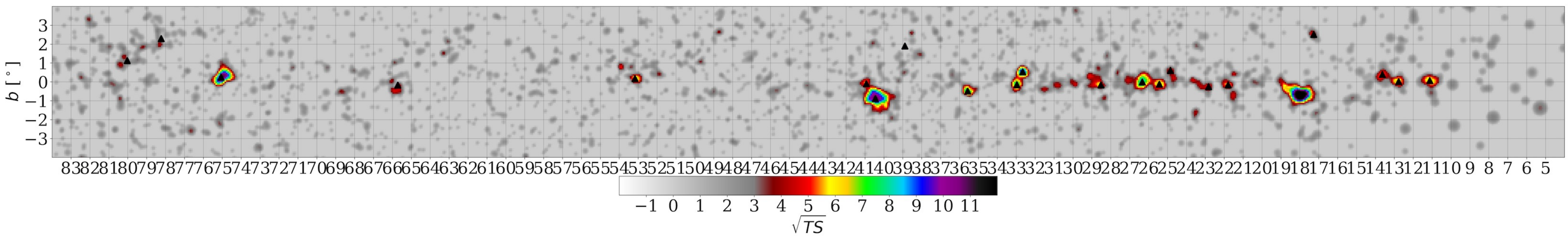
Nature 594:33-36 (2021)

Slide by Ruizhi Yang

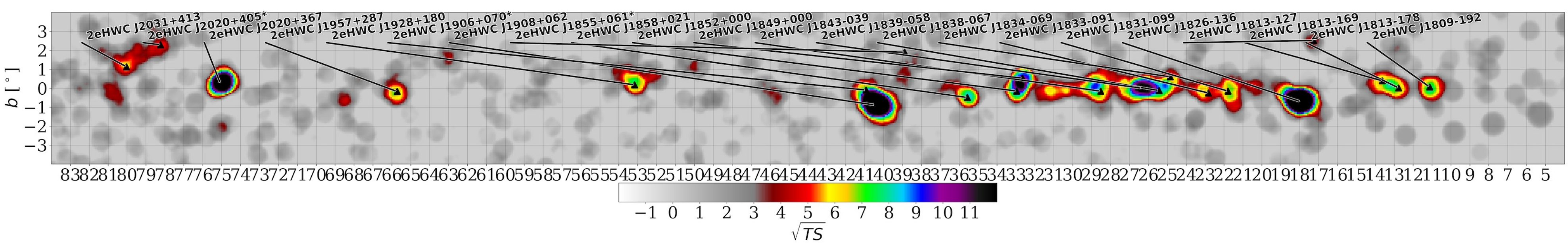
Gamma-Ray Sources > 100 TeV

Sources above 56 TeV

Point source map



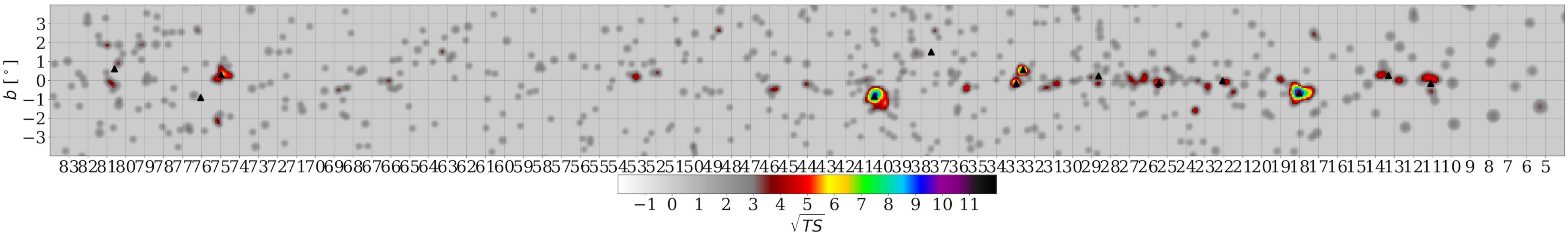
0.5 degree extended map



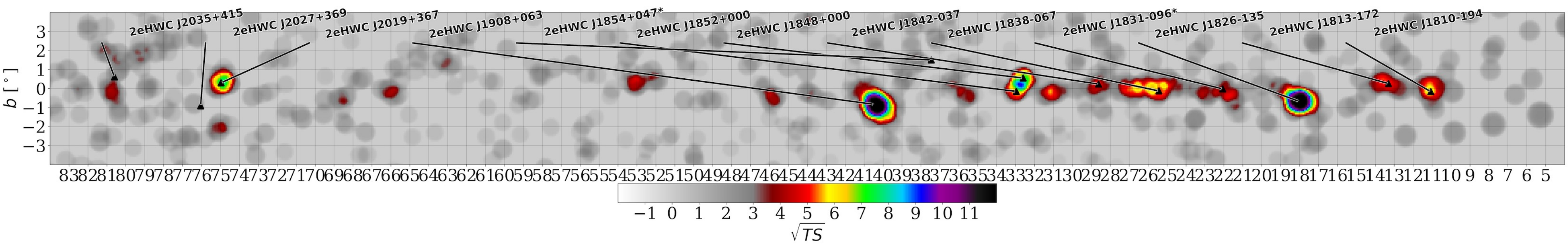
More than half unidentified and mostly extended

Sources above 100 TeV

Point source map



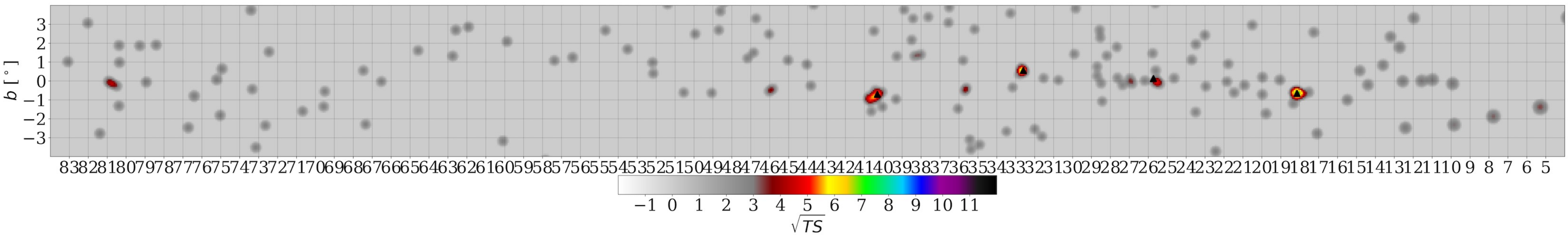
0.5 degree extended map



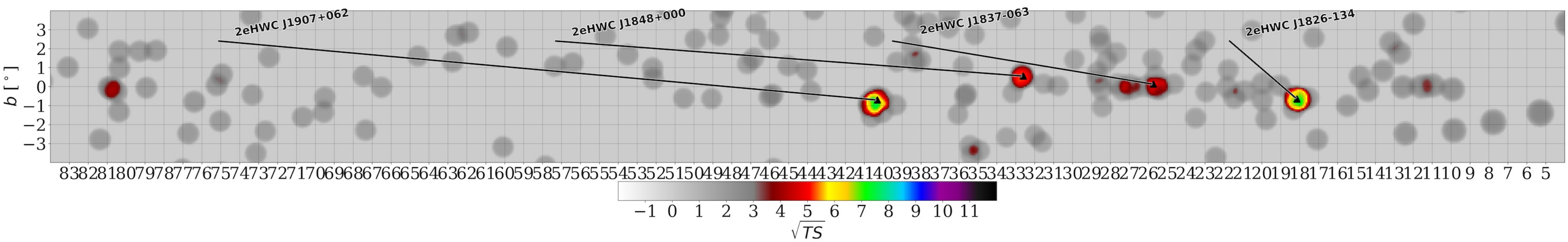
More than half unidentified and mostly extended

Sources above 177 TeV

Point source map



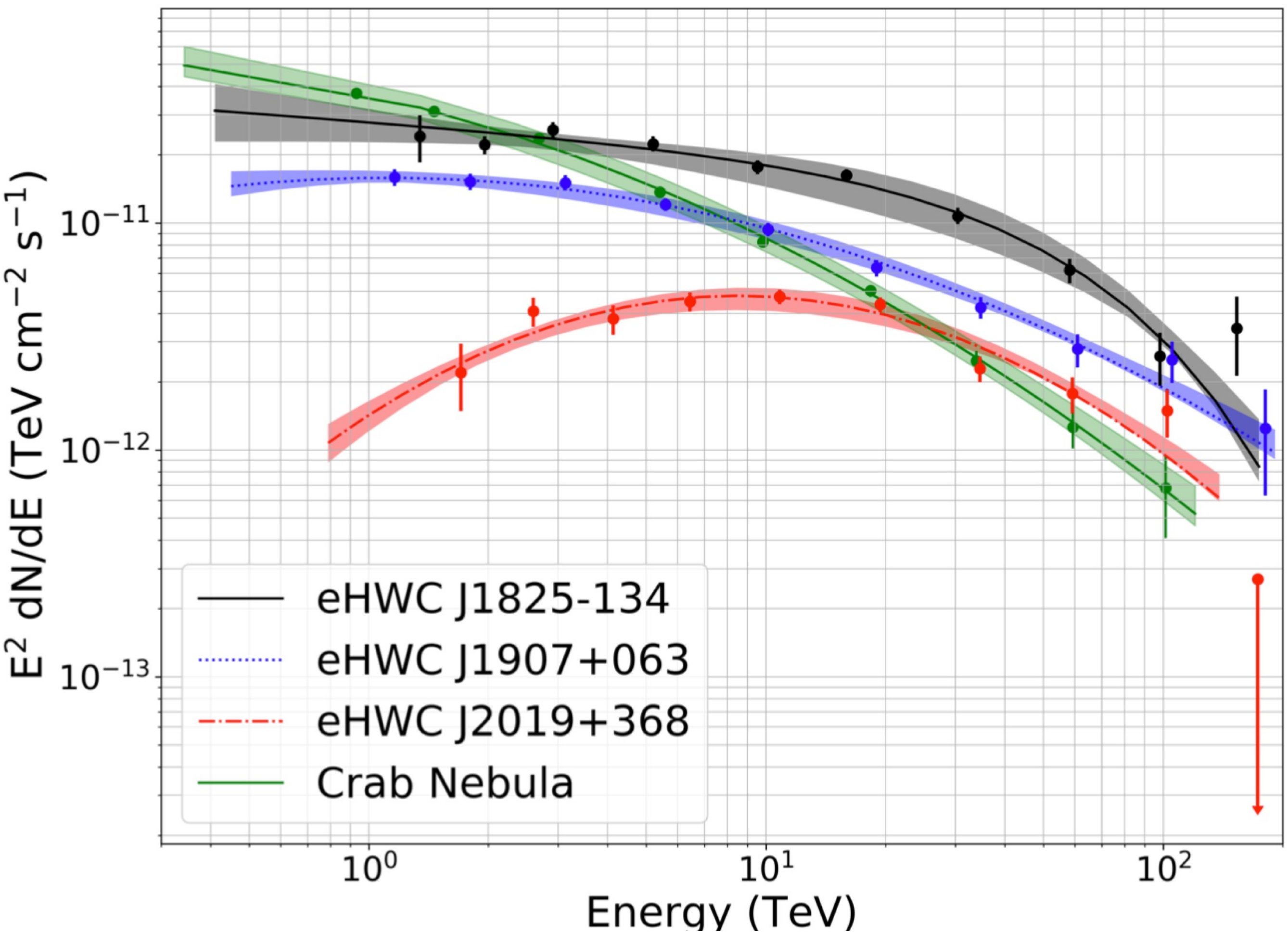
0.5 degree extended map



More than half unidentified and mostly extended

The Galaxy above 100 TeV: Spectra

HAWC Collaboration+20

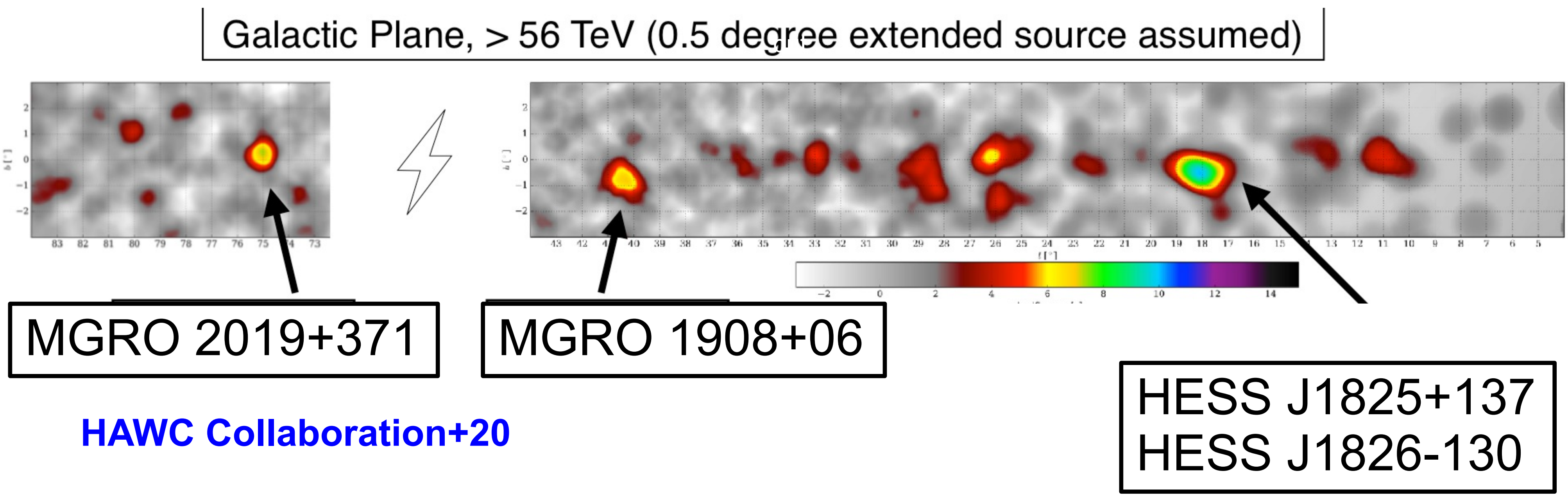


Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	α	E_{cut} (TeV)	PL diff
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4

Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	α	β	PL diff
eHWC J1907+063	37.8	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02	6.0
eHWC J2019+368	32.2	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05	8.2

The Galaxy above 56 TeV

Source name	RA (°)	Dec (°)	Extension > 56 TeV (°)	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{TS}$ > 56 TeV	nearest 2HWC source	Distance to 2HWC source(°)	$\sqrt{TS}$ > 100 TeV
eHWC J0534+220	83.61 ± 0.02	22.00 ± 0.03	PS	1.2 ± 0.2	12.0	J0534+220	0.02	4.44
eHWC J1809-193	272.46 ± 0.13	-19.34 ± 0.14	0.34 ± 0.13	$2.4^{+0.6}_{-0.5}$	6.97	J1809-190	0.30	4.82
eHWC J1825-134	276.40 ± 0.06	-13.37 ± 0.06	0.36 ± 0.05	4.6 ± 0.5	14.5	J1825-134	0.07	7.33
eHWC J1839-057	279.77 ± 0.12	-5.71 ± 0.10	0.34 ± 0.08	1.5 ± 0.3	7.03	J1837-065	0.96	3.06
eHWC J1842-035	280.72 ± 0.15	-3.51 ± 0.11	0.39 ± 0.09	1.5 ± 0.3	6.63	J1844-032	0.44	2.70
eHWC J1850+001	282.59 ± 0.21	0.14 ± 0.12	0.37 ± 0.16	$1.1^{+0.3}_{-0.2}$	5.31	J1849+001	0.20	3.04
eHWC J1907+063	286.91 ± 0.10	6.32 ± 0.09	0.52 ± 0.09	2.8 ± 0.4	10.4	J1908+063	0.16	7.30
eHWC J2019+368	304.95 ± 0.07	36.78 ± 0.04	0.20 ± 0.05	$1.6^{+0.3}_{-0.2}$	10.2	J2019+367	0.02	4.85
eHWC J2030+412	307.74 ± 0.09	41.23 ± 0.07	0.18 ± 0.06	0.9 ± 0.2	6.43	J2031+415	0.34	3.07



HAWC Collaboration+20

LHAASO KM2A Survey

Table 1 | UHE γ-ray sources

LHAASONat 2021

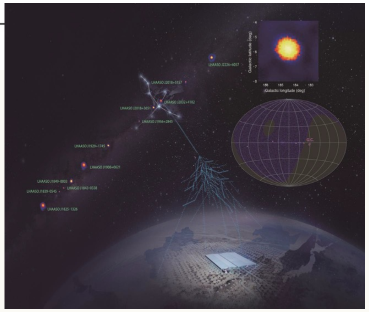
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	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)

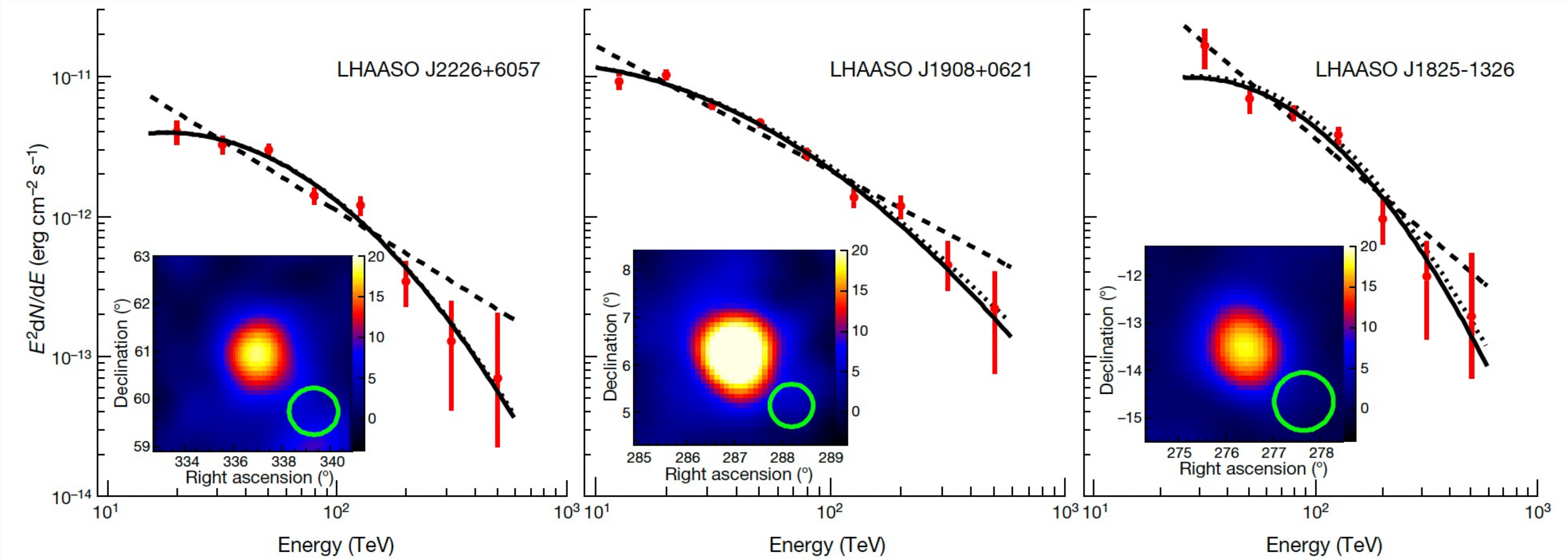
Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon 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.

12 high significance sources >7σ, 530 UHE Photons !

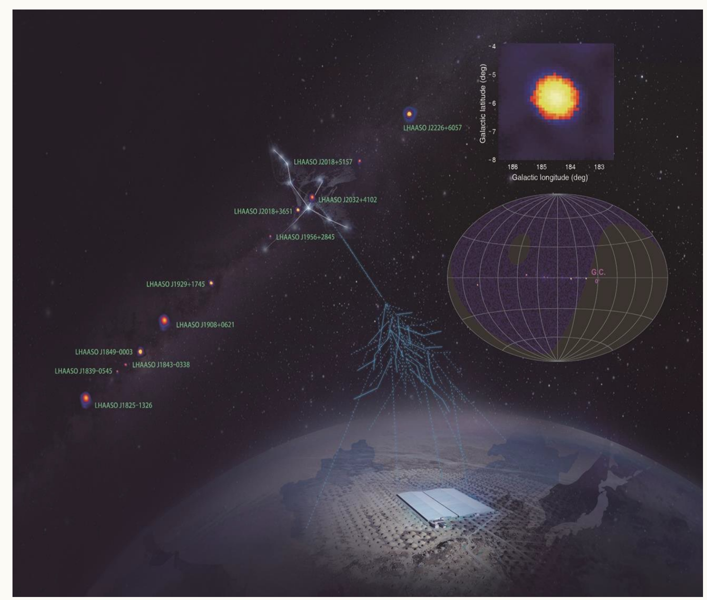
BG-free: Cosmic Ray background rejection rate<10^{-4}

Multiple Type of Sources



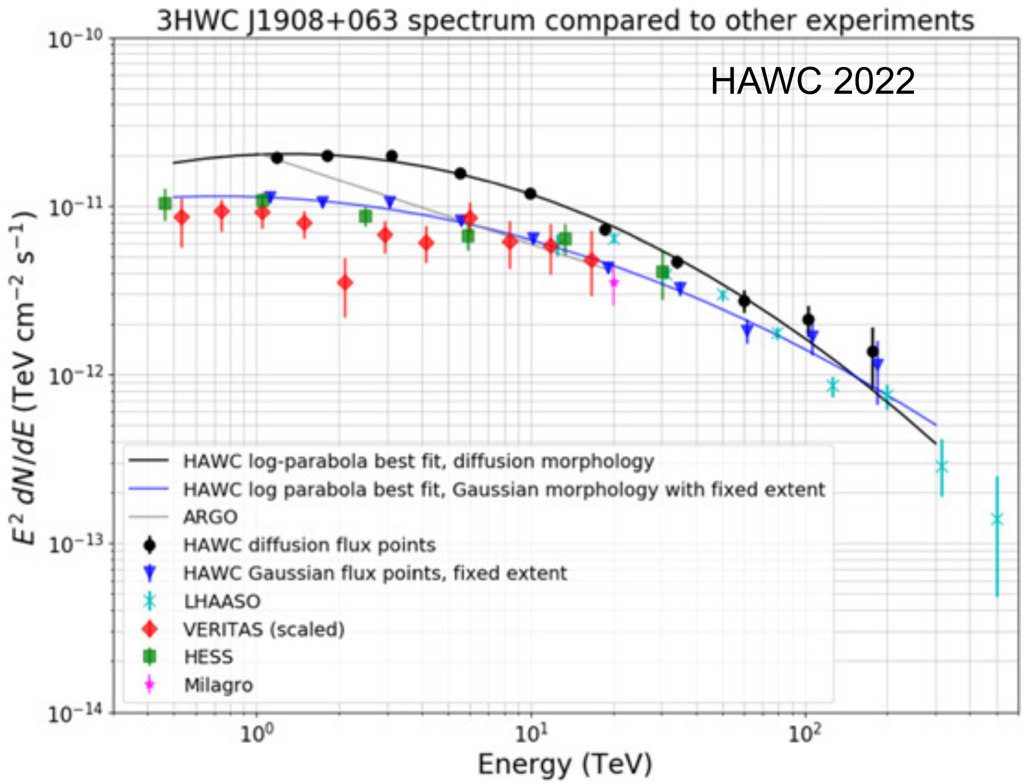


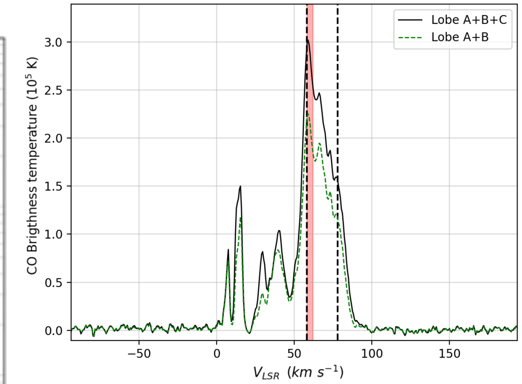
E_{max} (PeV) 0.57 +- 0.19 0.44 +- 0.55 0.42 +- 0.16

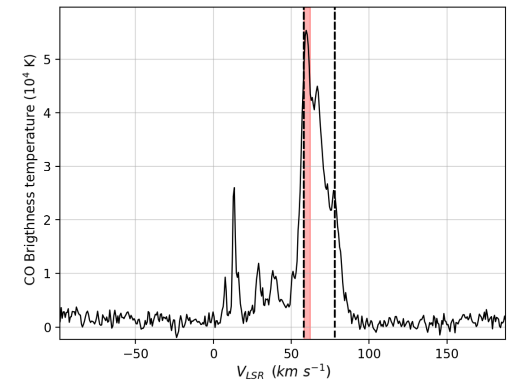


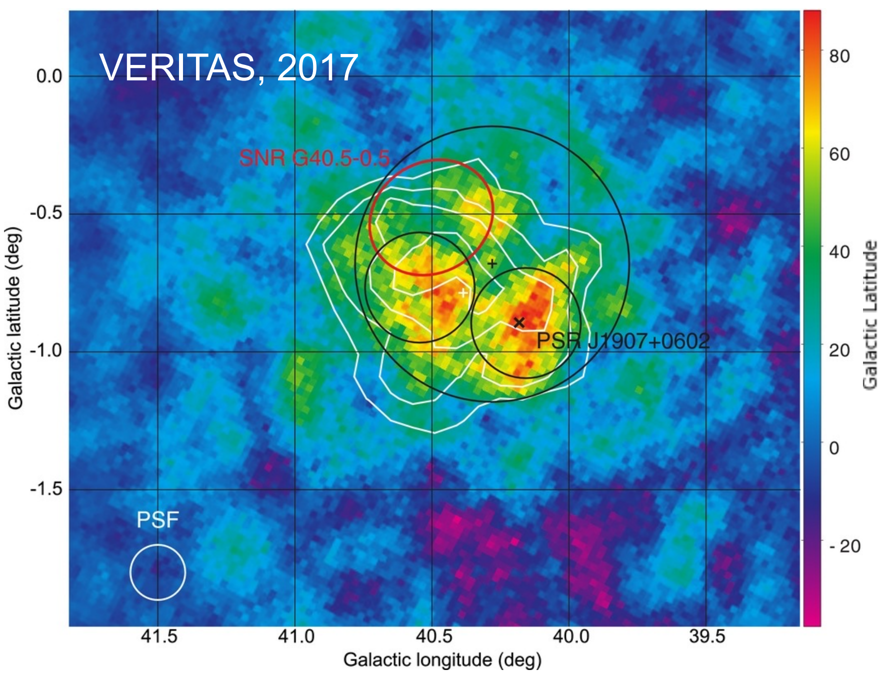
HAWC J1908 +063

l= 40° b= -0.79°

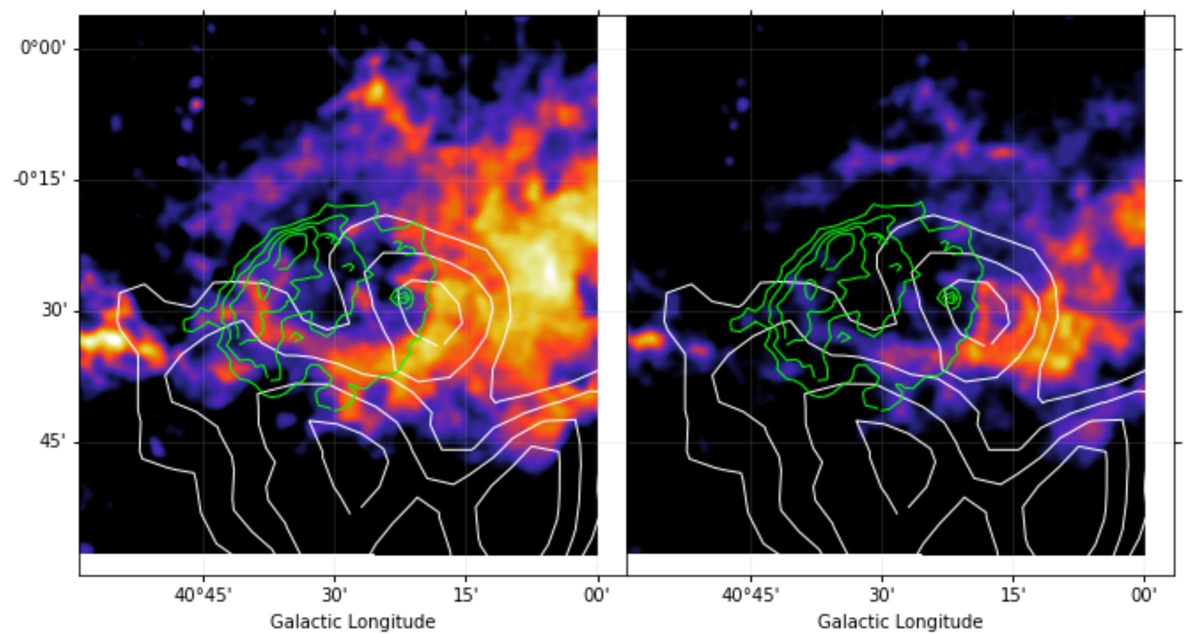




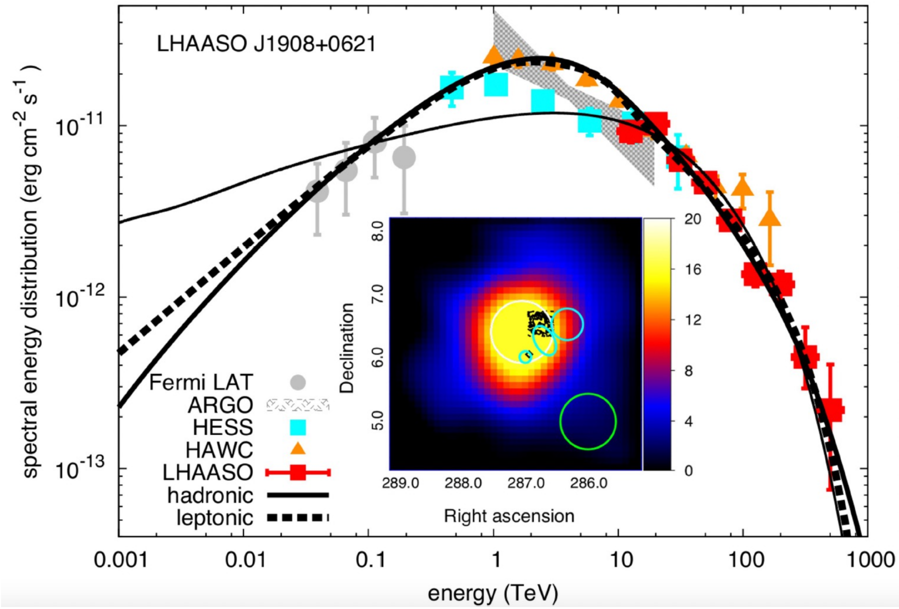


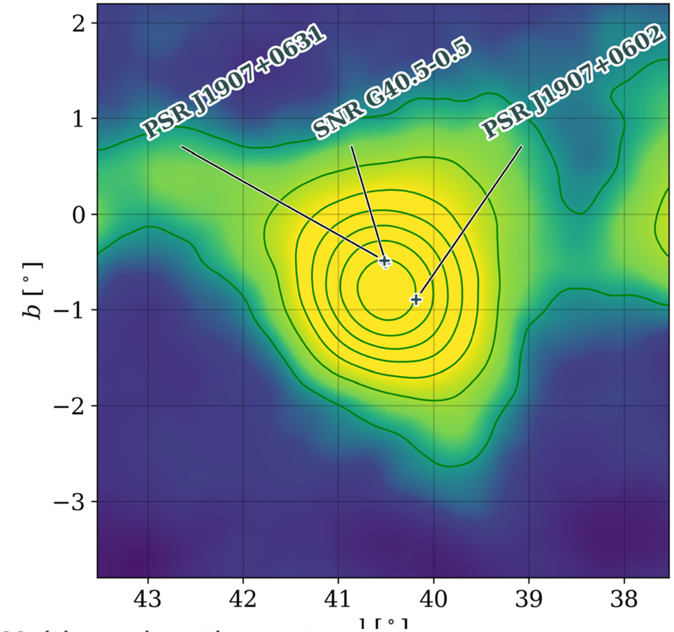


Crestan+ 2021

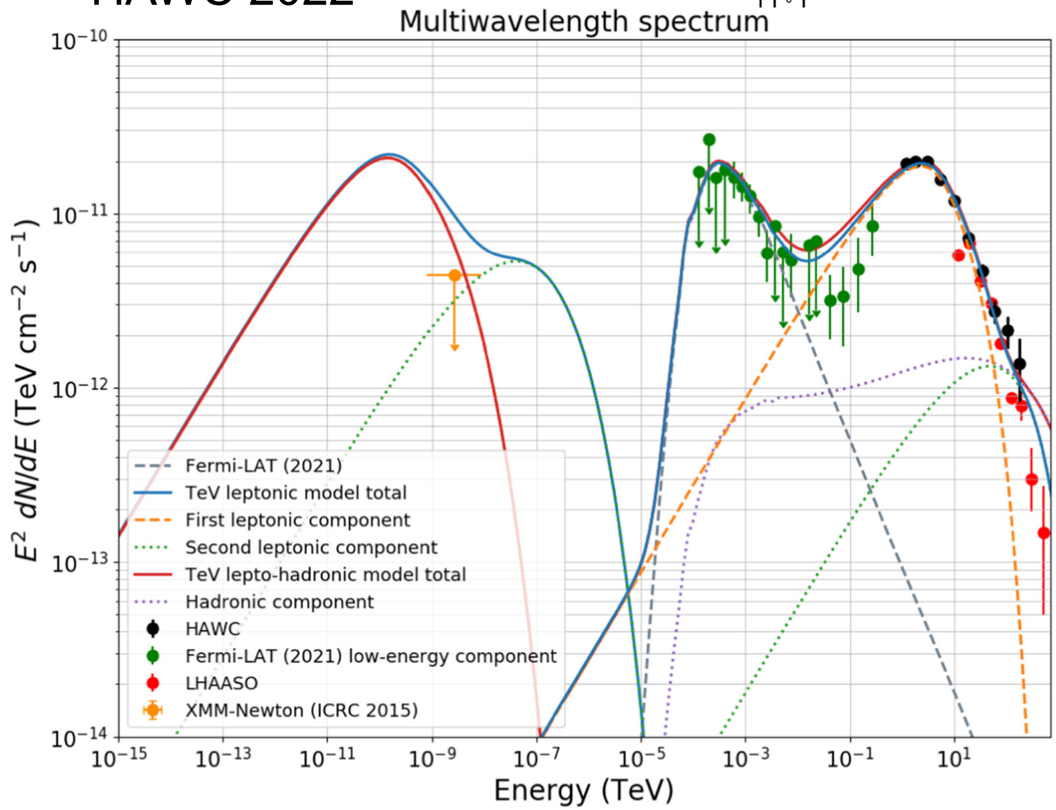


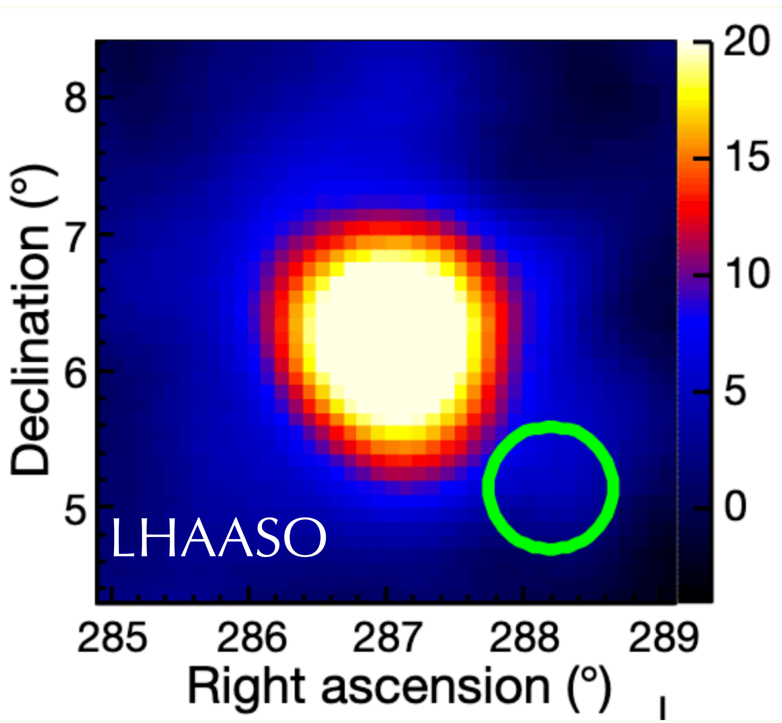
HAWC J1908 +063





HAWC 2022

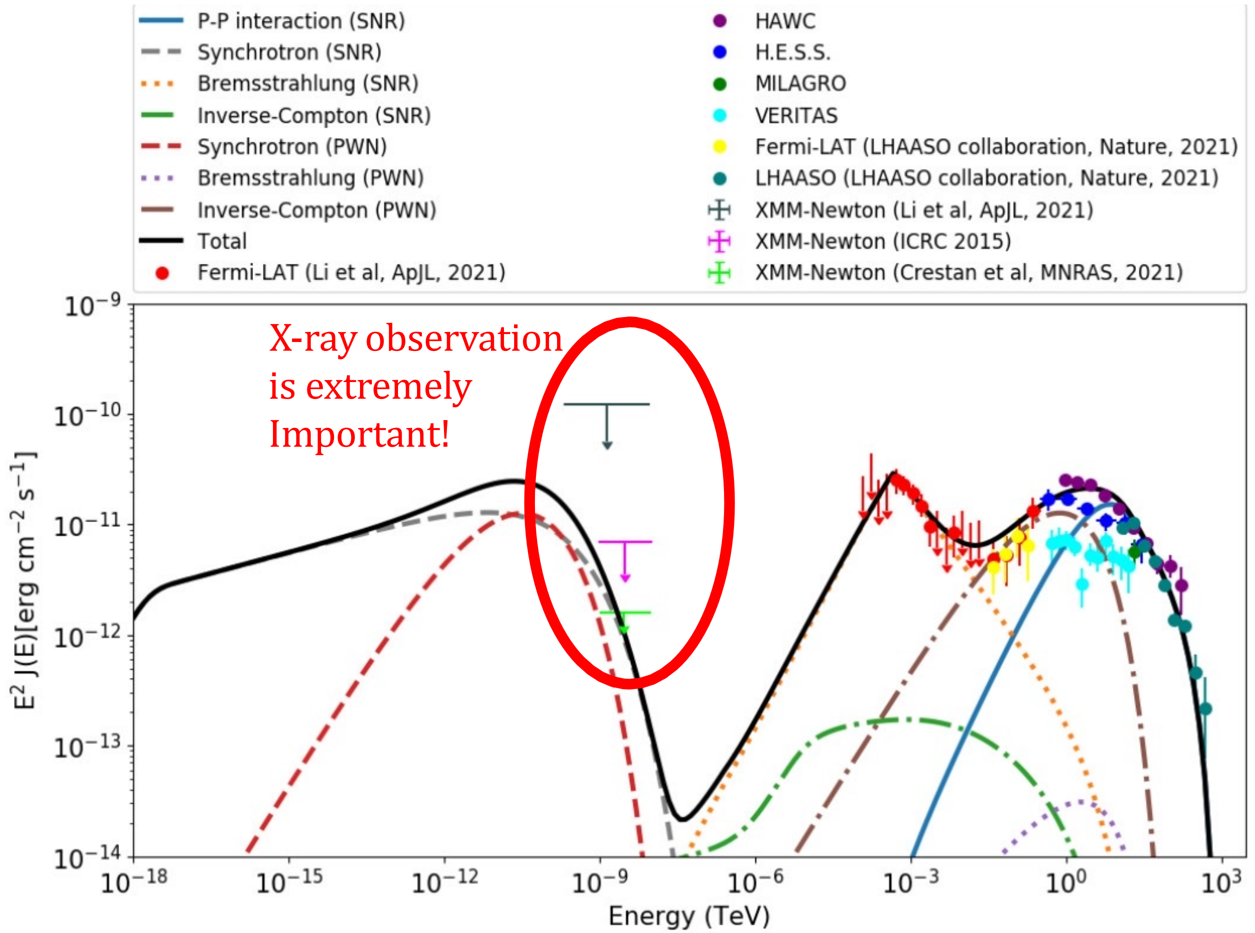




HAWC > 220 TeV, LHAASO 440 TeV

LHAASO J1908+0621

- Multi Wavelength analysis reveals more exciting features
- Hadronic process dominates the UHE emission ?
- SNRs may be still strong candidates for PeVatrons



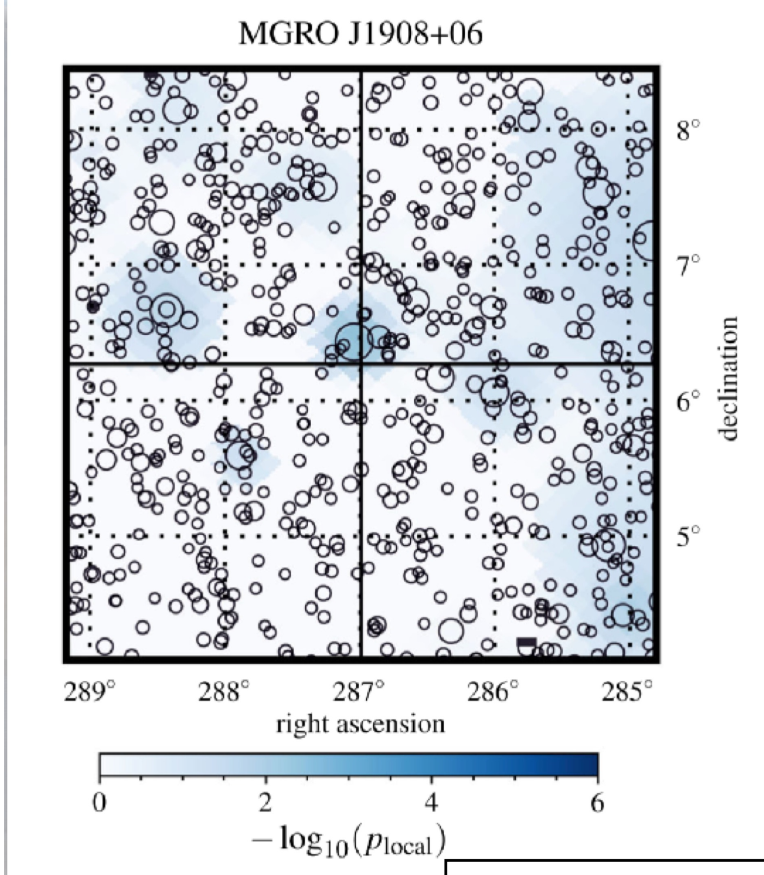
Agnibha De Sarkar, Nayantara Gupta, accepted by APJ, **arXiv:2205.01923**

HAWC J1908+06 as neutrino source?

Some HAWC PeV candidates are promising neutrino sources

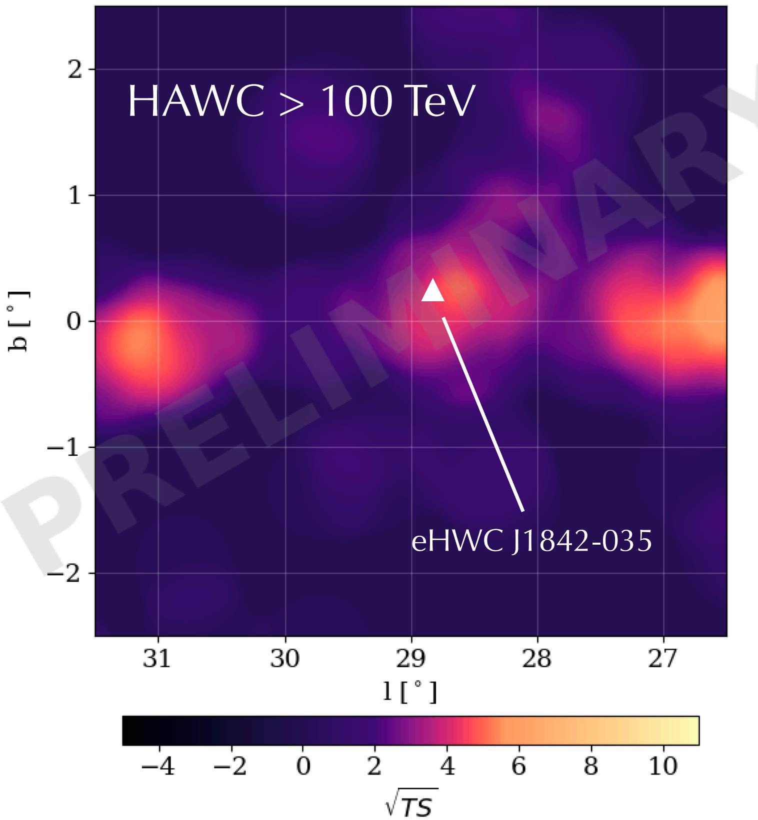
Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

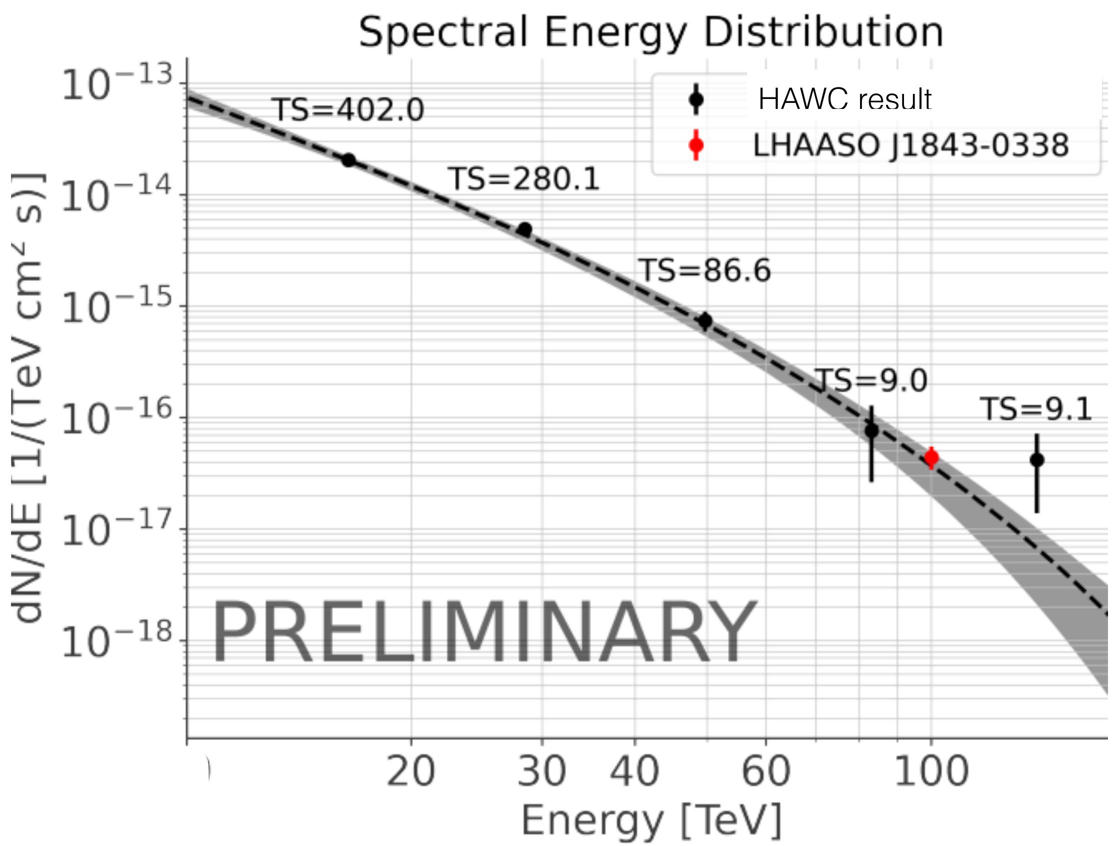
J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis



IceCube, European Physics Journal (2019)

eHWC J1842-035



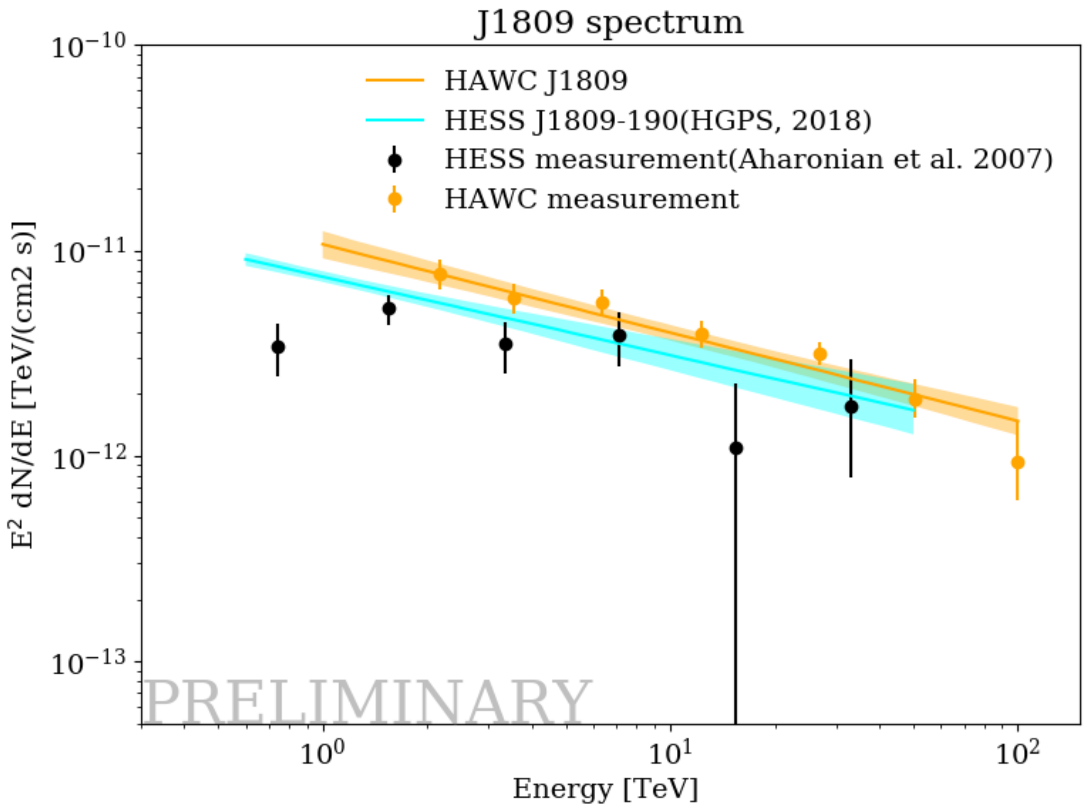


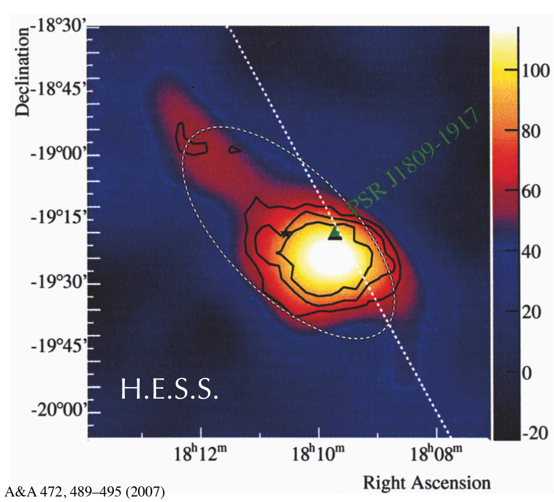
Complex morphology , 0.3-0.4 deg

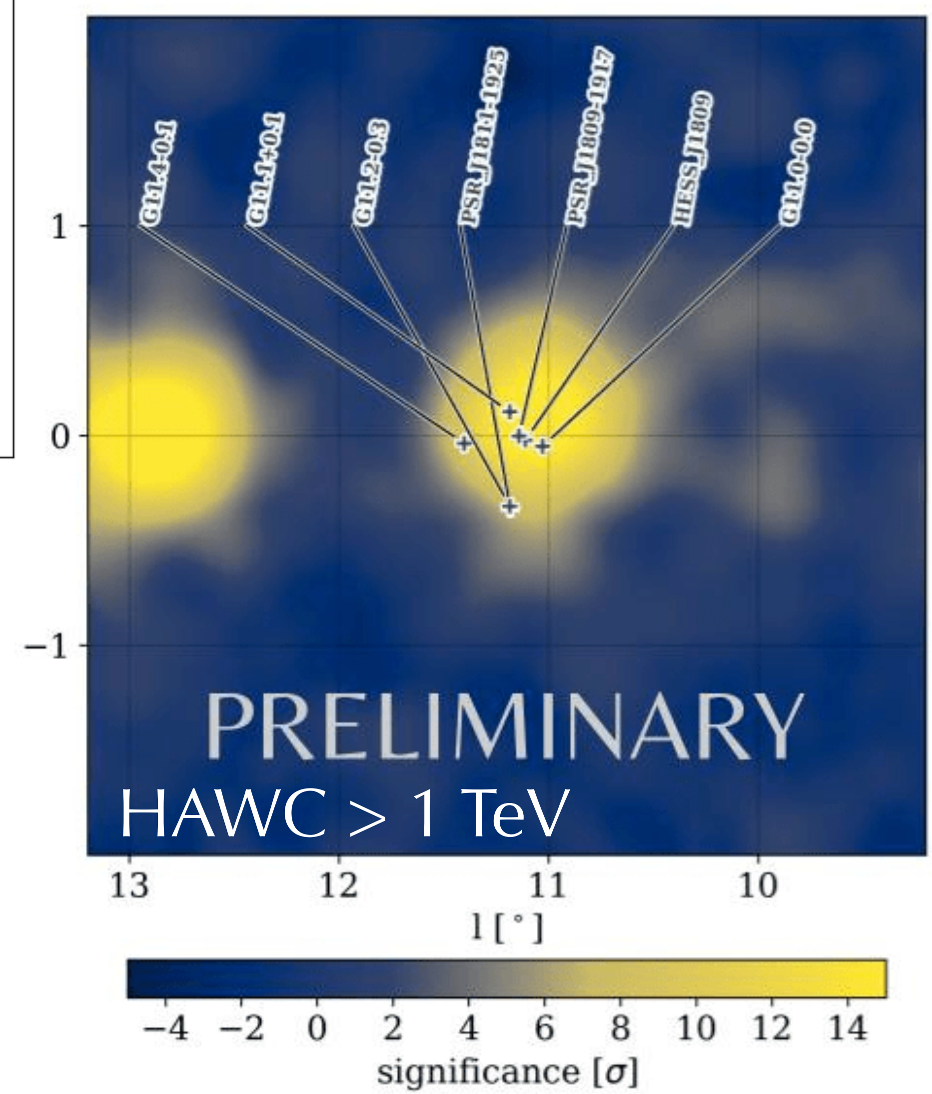
Maximum energy in HAWC > 100 TeV

Study ongoing

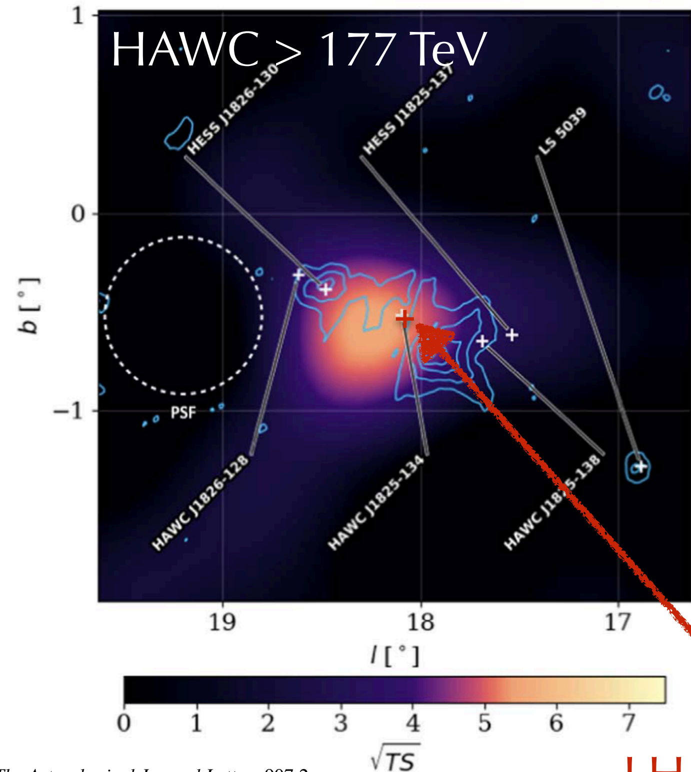
HESS J1809 -1917





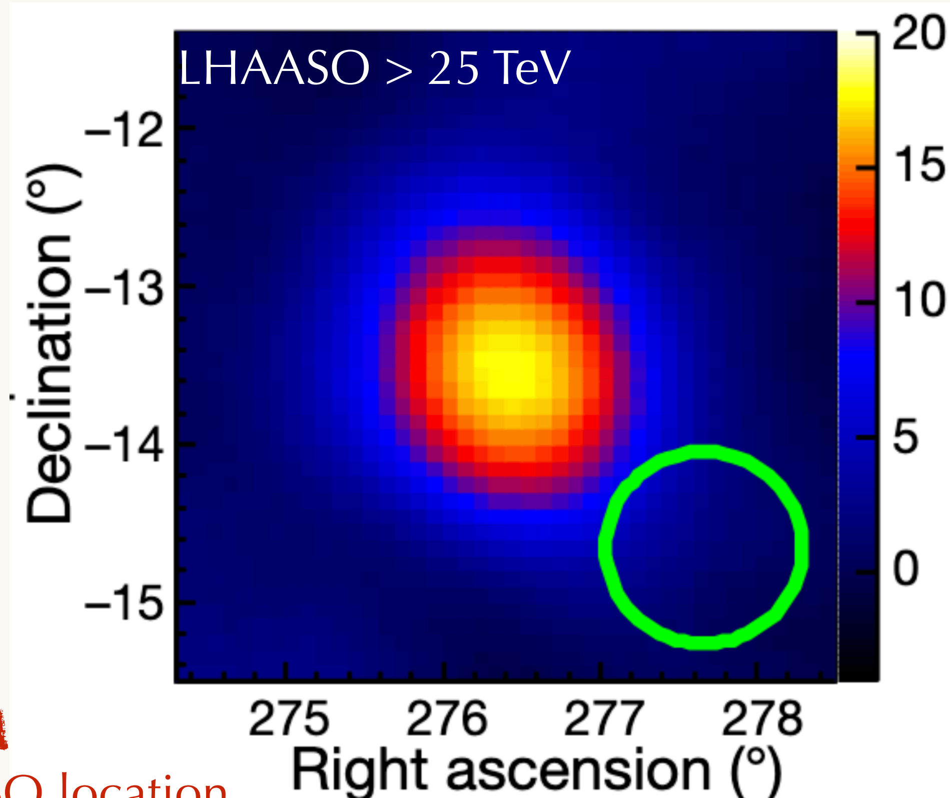


eHWC J1825-134

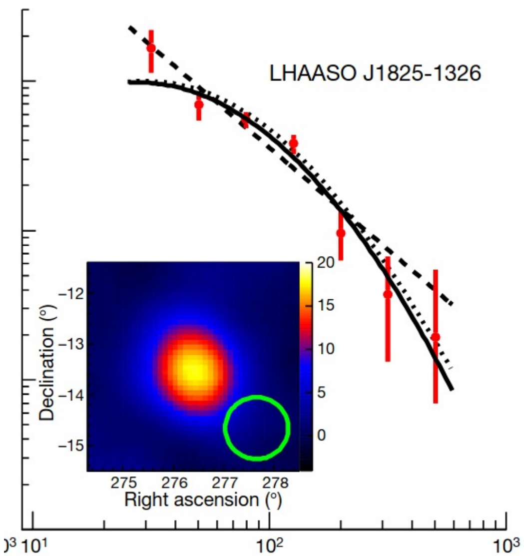


The Astrophysical Journal Letters 907.2

LHAASO location



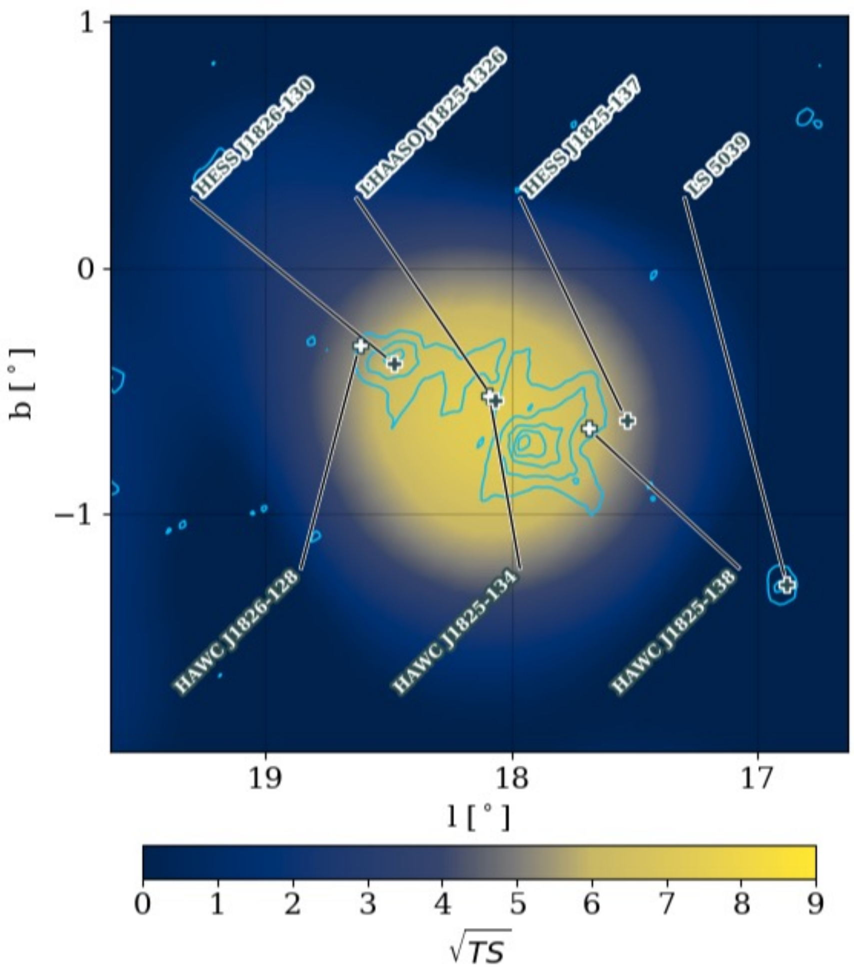
Nature 594.7861 (2021): 33-36



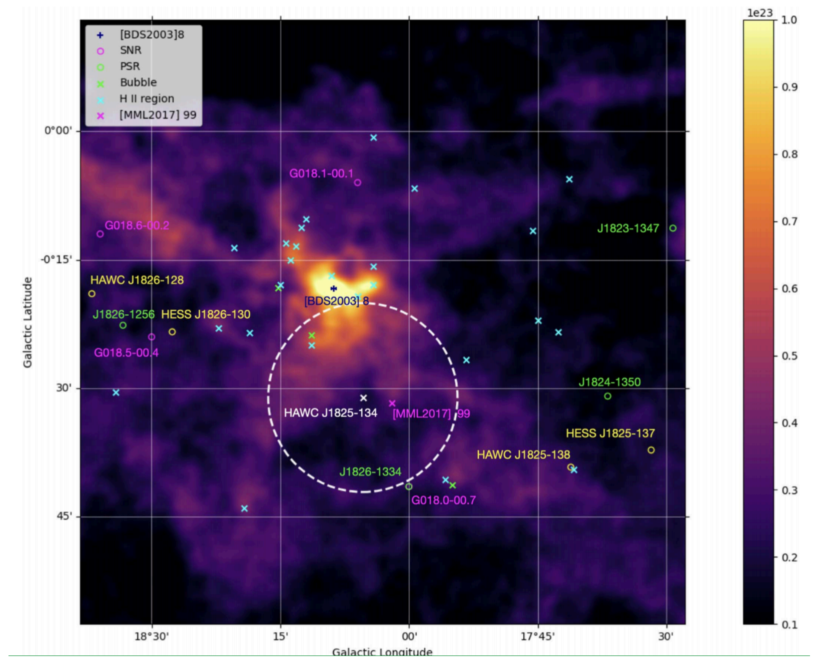
	HAWC	LHAASO
Location	**R.A. 276.44° Dec. -13.42°**	**R.A. 275.45° Dec. -13.45°**
Morphology	2 extended sources + 1point source	0.3 ° extension template
Maximum measured energy	>200 TeV	420 TeV
Origin of TeV emission	Proton accelerated by SFR Electron accelerated by PSR J1826-1334	

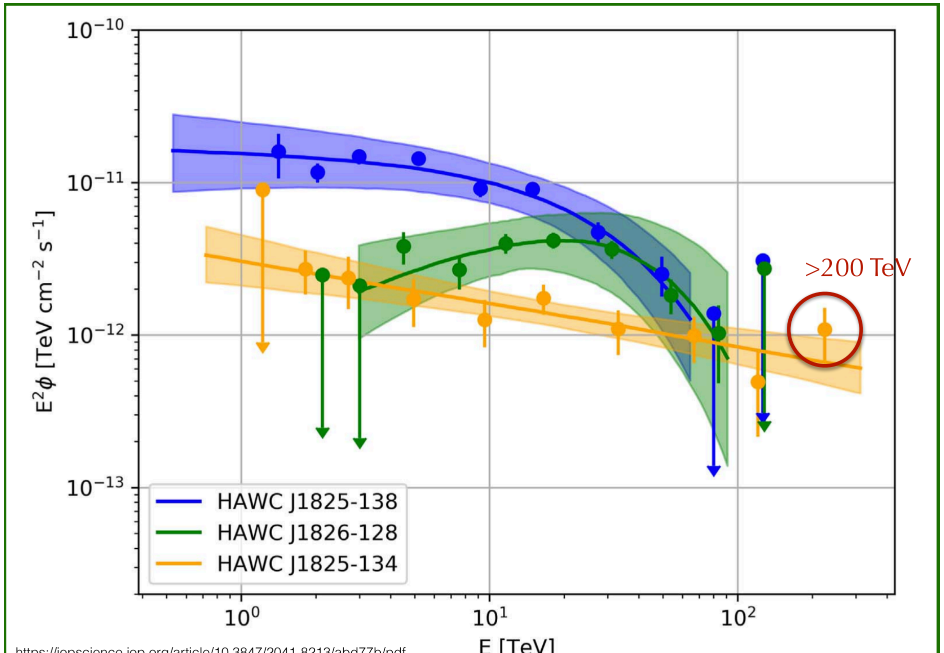
Multiple Sources

HAWC Coll ApJL 2021

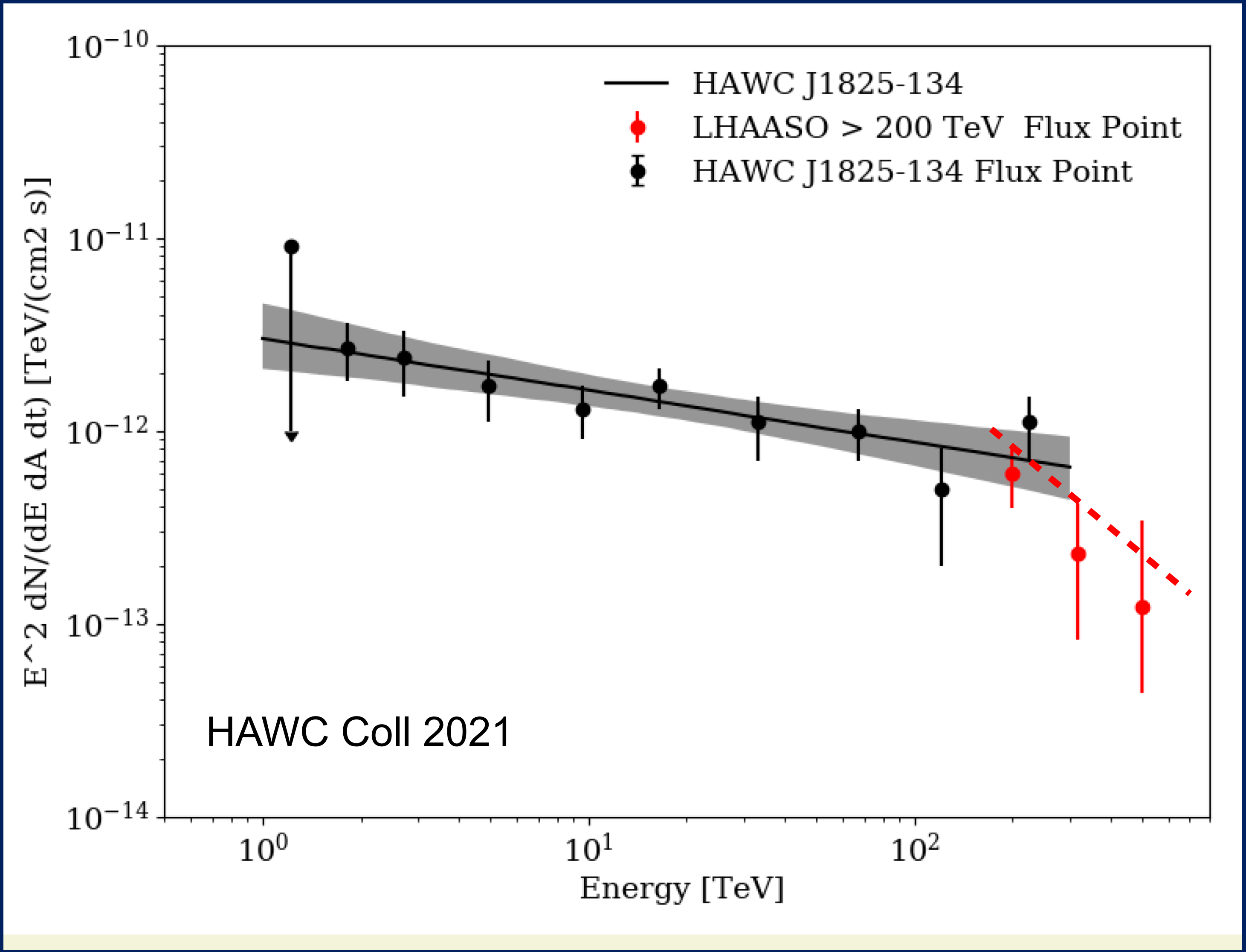


Above 177 TeV





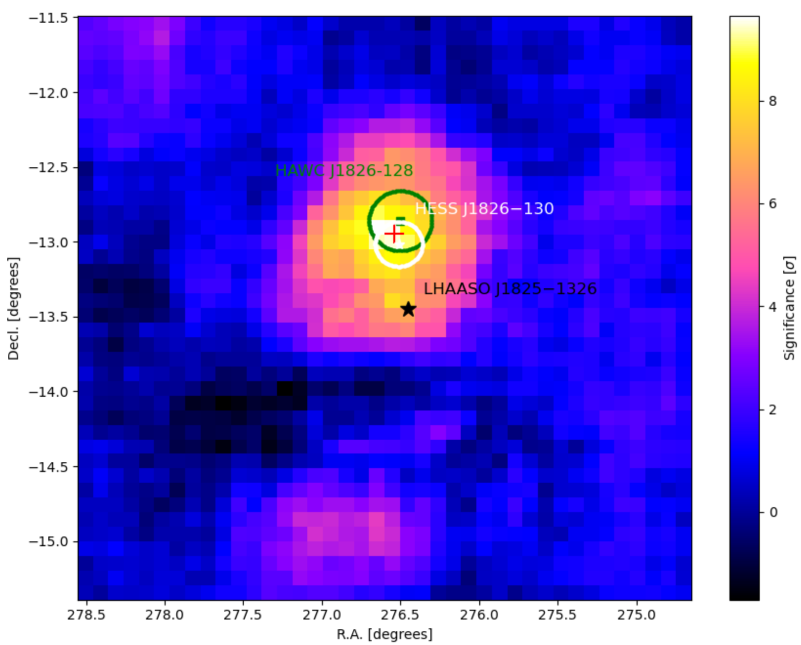
HAWC J1825-134 and LHAASO J1825-136 above 200 TeV



LHAASO J1826-1256 & J1825-1345(>25 TeV)

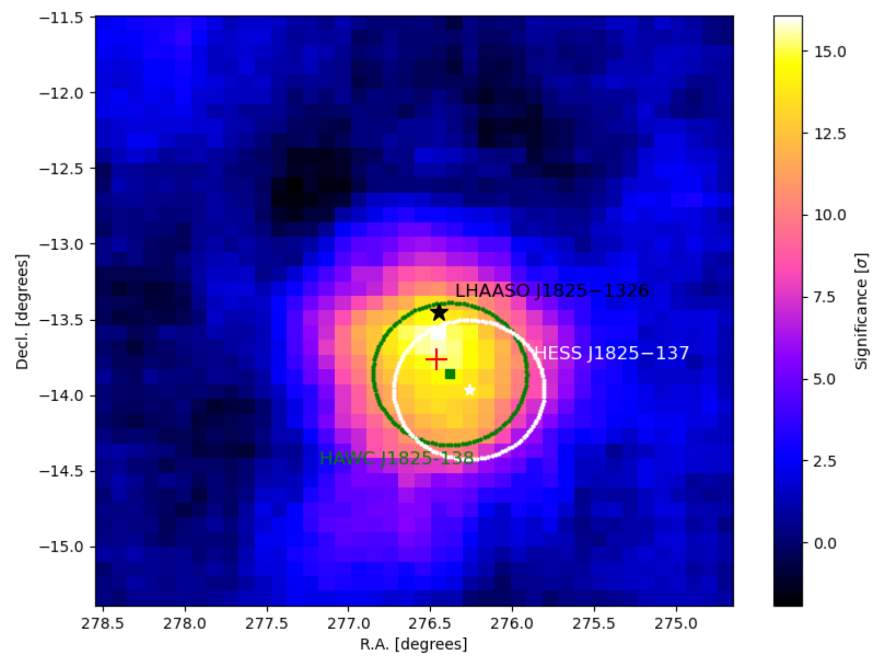
HAWC

LHAASO J1826-1256



TS=214.08

LHAASO J1825-1345



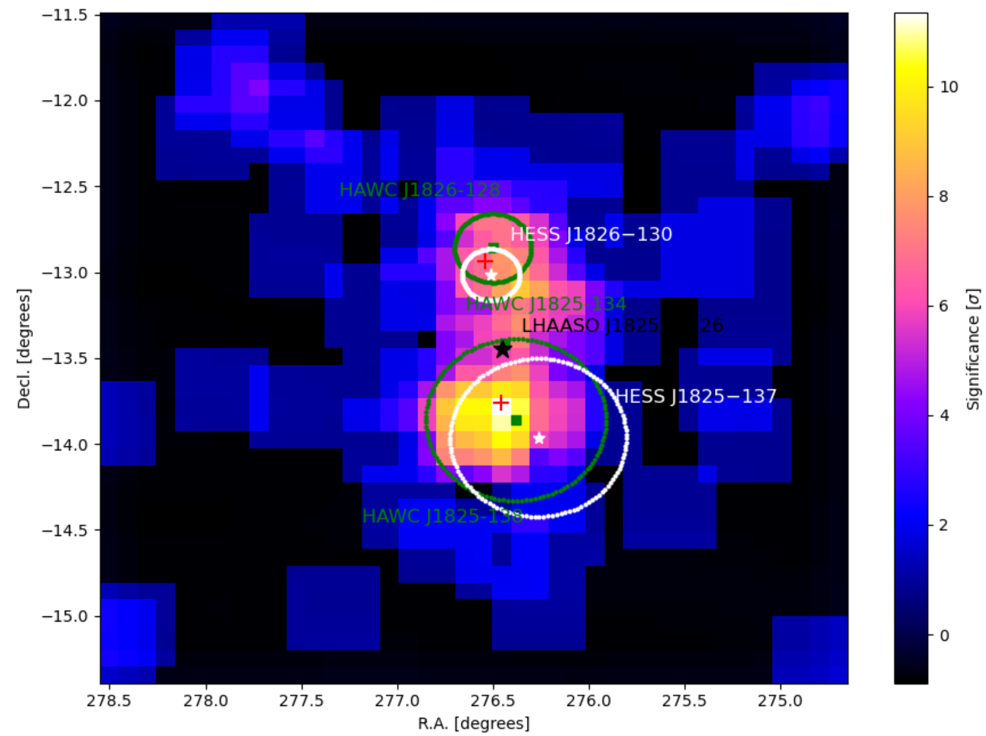
TS=393.73

LHAASO J1826-1256 & J1825-1345 (>100 TeV)

LHAASO J1825-1326

LHAASO J1826-1256
TS=100.95

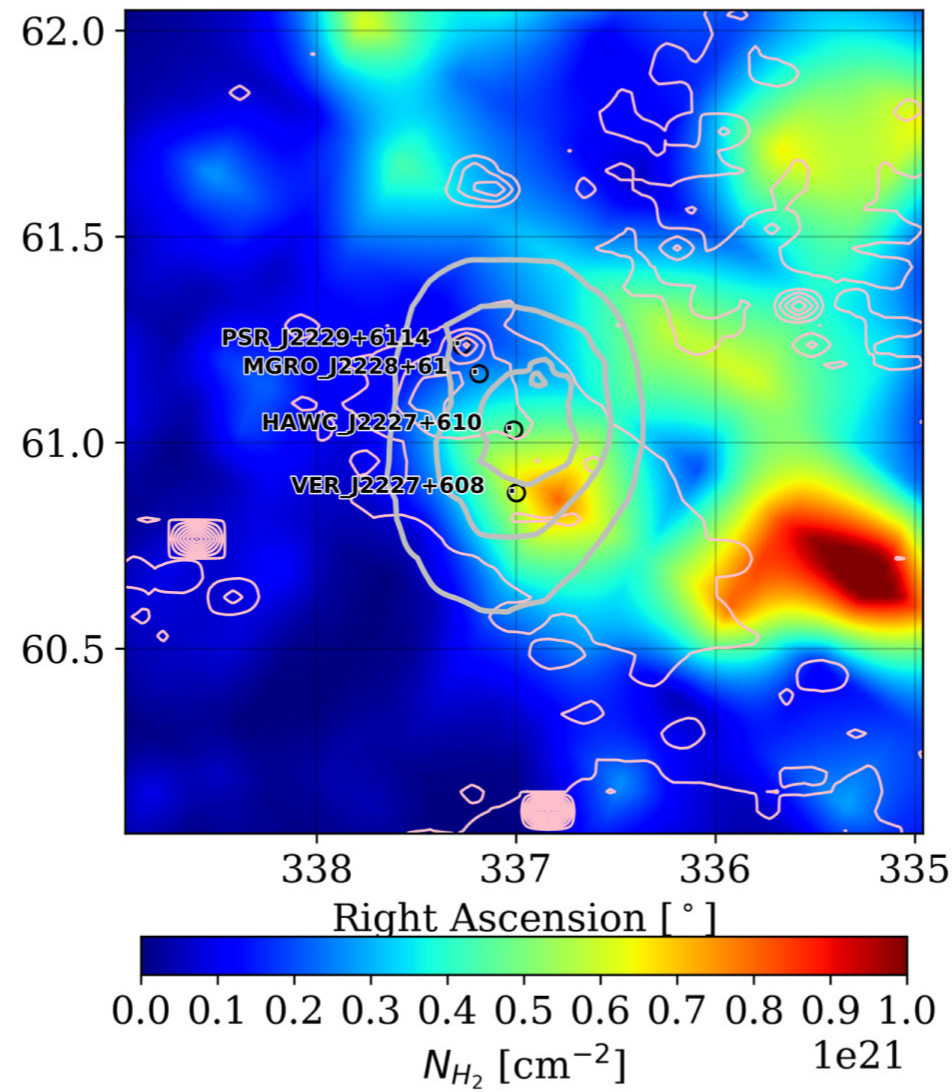
LHAASO J1825-1345
TS=164.88



SNR G106.3+2.7: Galactic PeVatron ?

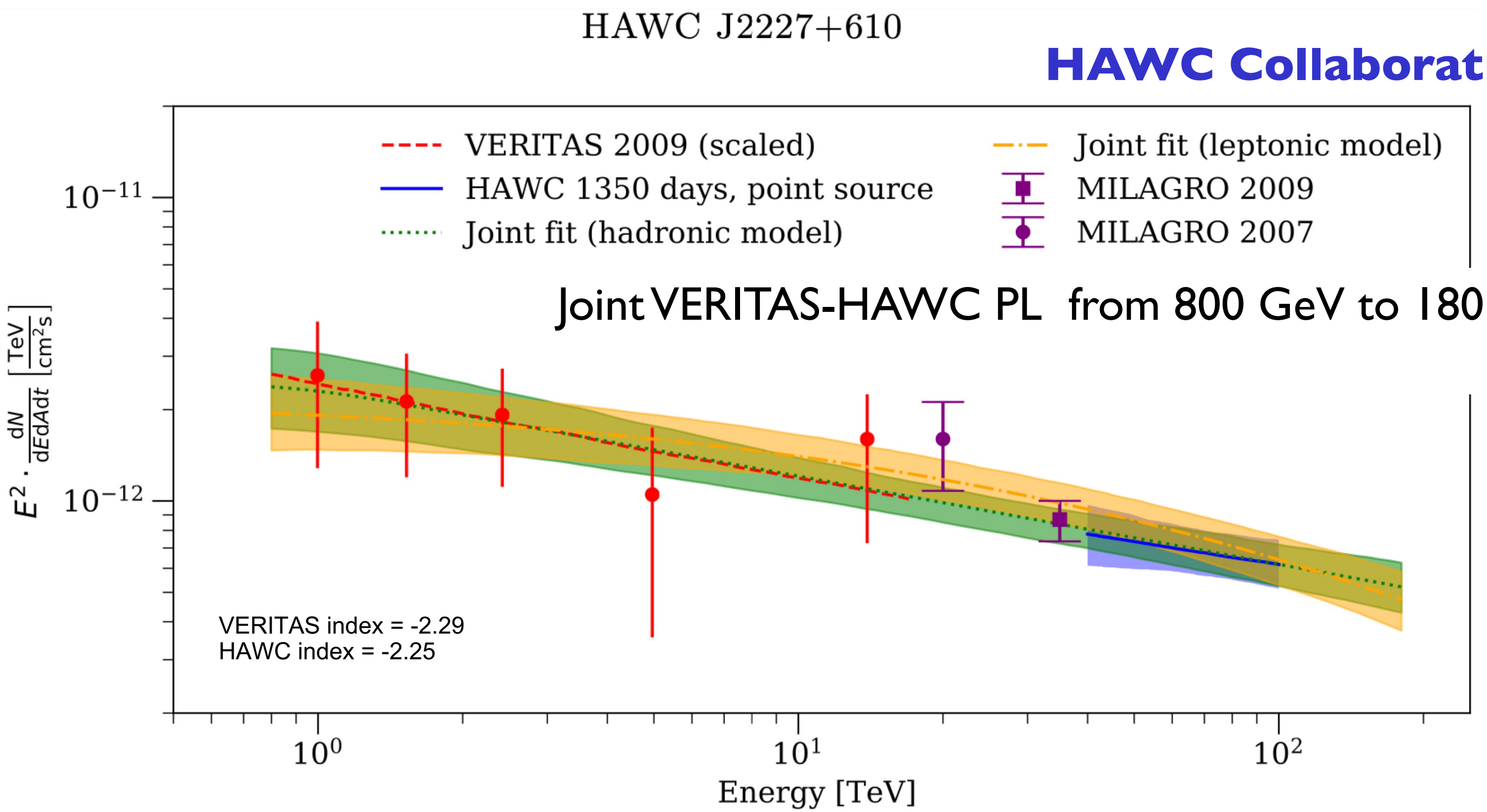
HAWC Collaboration, ApJL 2020

- SNR G106.3+2.7 is a 10kyr comet-shaped radio source at 0.8 kpc
- PSR J2229+6114, seen in radio, X-rays, and gamma rays
- Boomerang Nebula is contained in the remnant
- VERITAS source (energy range 900 GeV – 16 TeV)
- HAWC emission pointlike, morphology compatible with VERITAS source and coincident with a region of high gas density



G106.3+2.7 : a Galactic PeVatron?

HAWC Collaboration, ApJL 2020



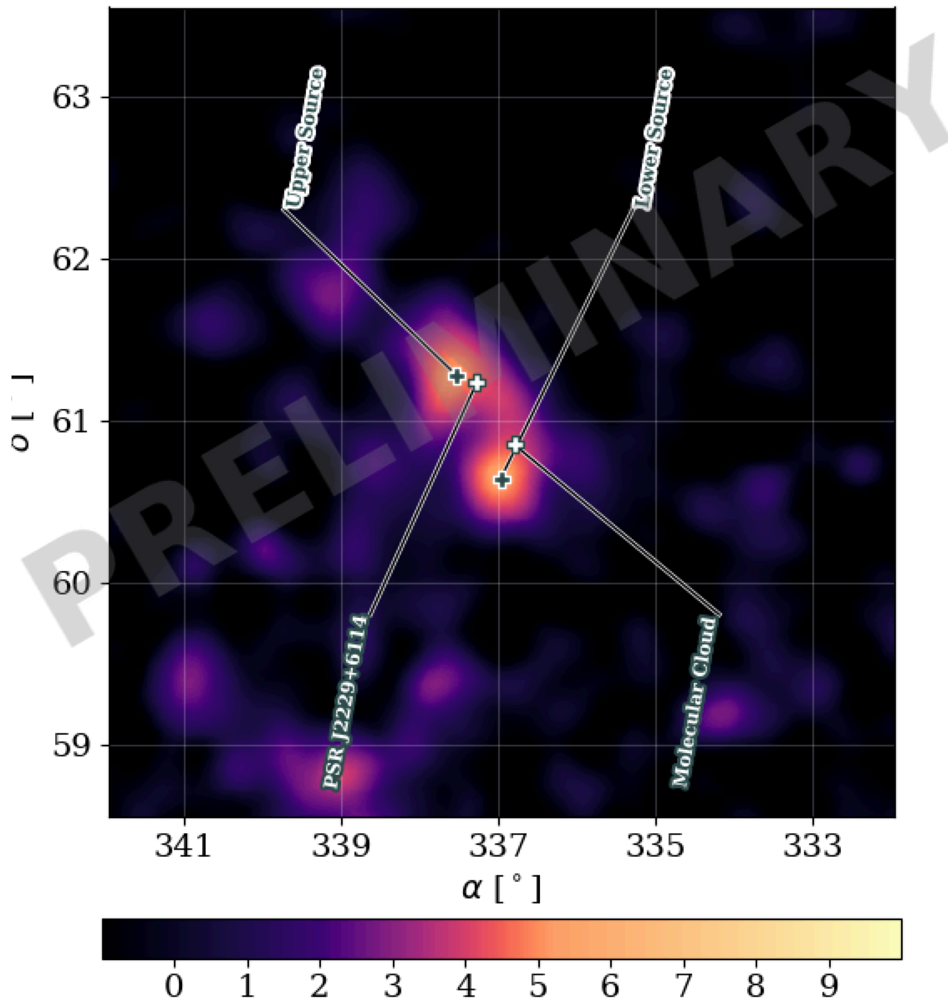
Joint VERITAS-HAWC PL from 800 GeV to 180 TeV

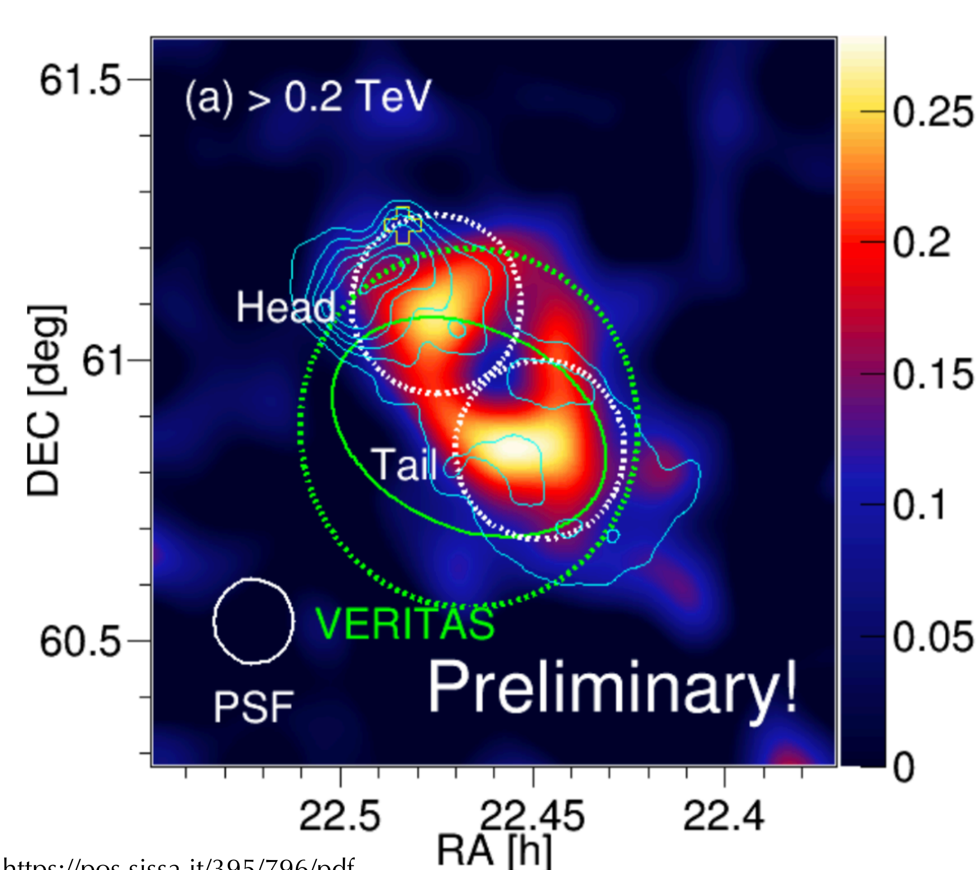
Gamma PL : 2.29, Lower limit on gamma Ecut = 120 TeV

Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

Wp = 10^{48} $(n/50)^{-1}$ erg

HAWC J2227+ 610 (Boomerang region)



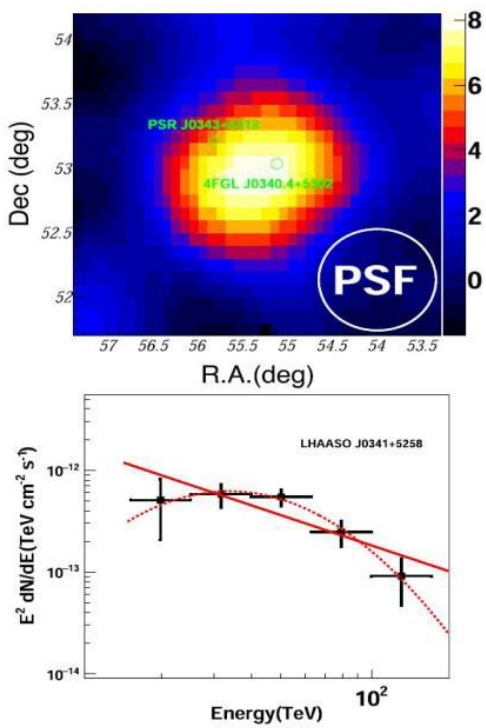


https://pos.sissa.it/395/796/pdf

New Source Discovery

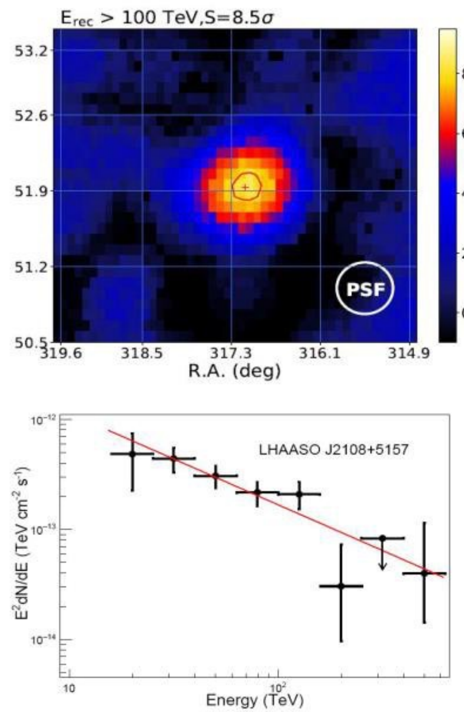
- WCDA has accumulated data for 16 months
- KM2A for 12 months
- LHAASO catalog Ver-1 will be published soon with many new VHE/UHE sources discovered

LHAASO J0341+5258



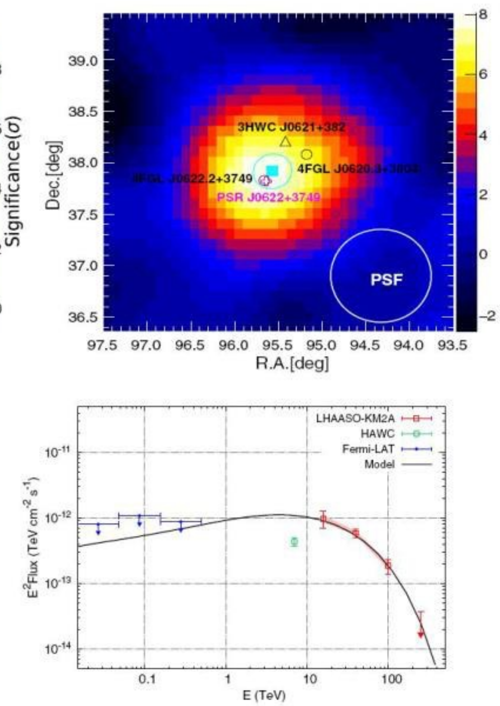
ApJL 917:L4 (2021)

LHAASO J2108+5157



ApJL 919:L22 (2021)

Halo of PSR J0622 + 3749



PRL 126:241103 (2021)

http://english.ihep.cas.cn/lhaaso/index.html

TeV-PeV pulsar Wind Nebulae and halos

Geminga - PWN

Geminga is one of the brightest GeV sources in the northern sky

It's a middle-aged 340kyr, pulsar T=0.237s

It's close to earth - 250^{+250}_{-62} pc

X-Ray PWN seen to be very small

First seen in TeV by Milagro at 40 TeV in 2009

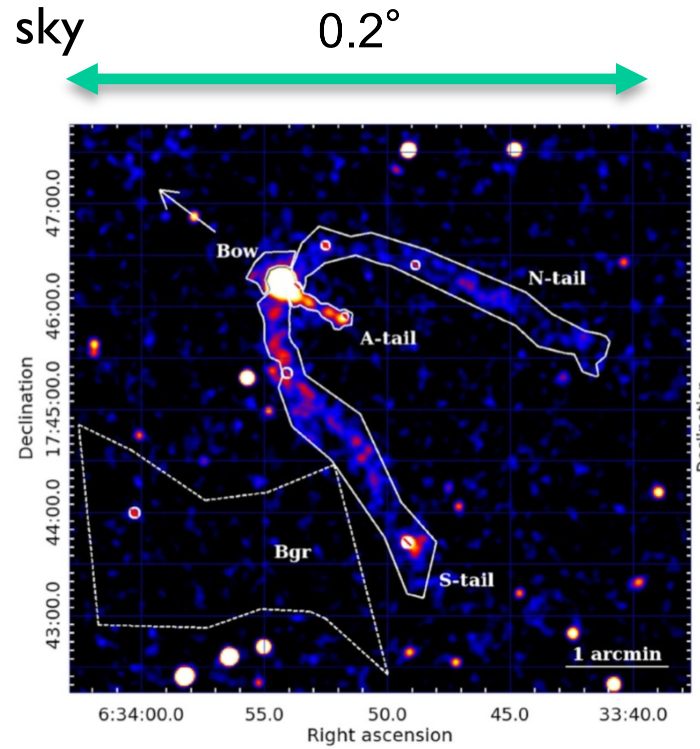
HAWC also sees energies above 25TeV

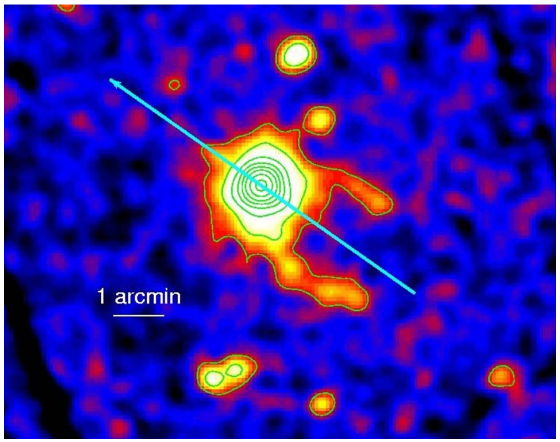
Very extended in the TeV - ~5 degrees across

Geminga and Monogem, similar in age and distance,

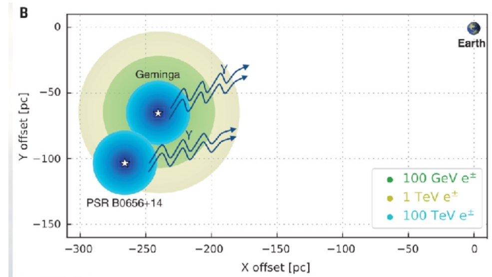
were suggested as contributors of the positron fraction

(Aharonian+1995).

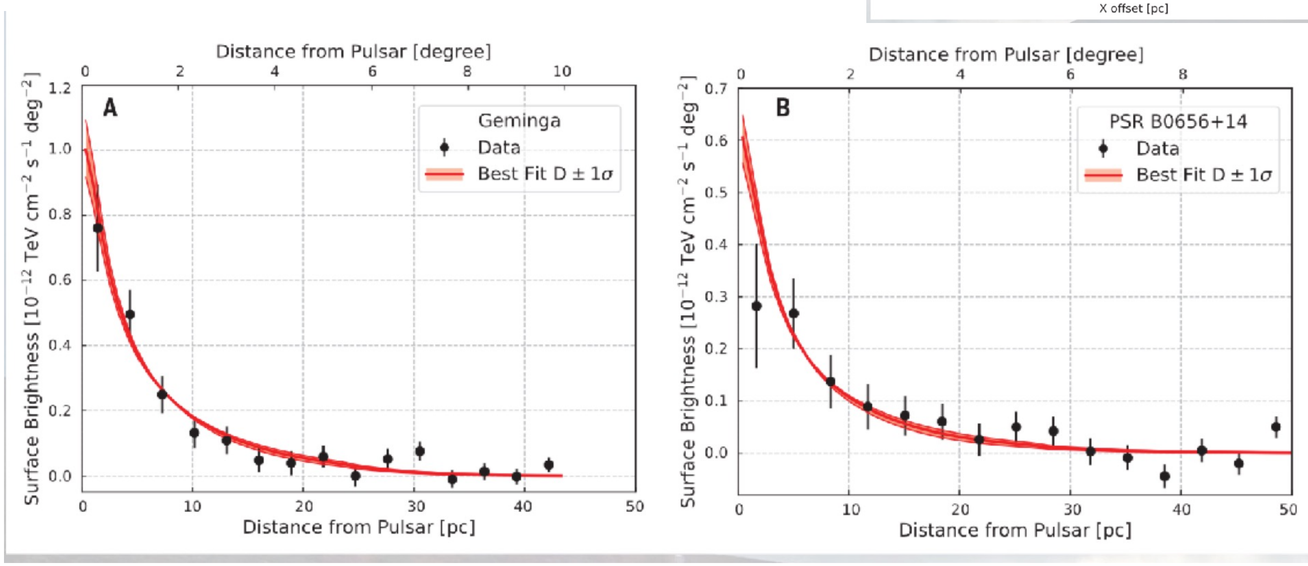


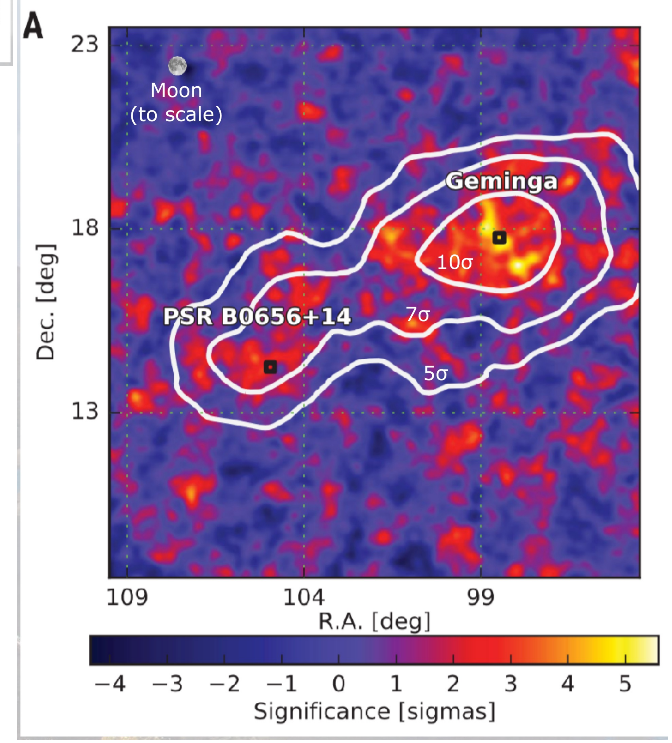


Extended TeV emission around the pulsars Geminga and Monogem



HAWC, Science 2017

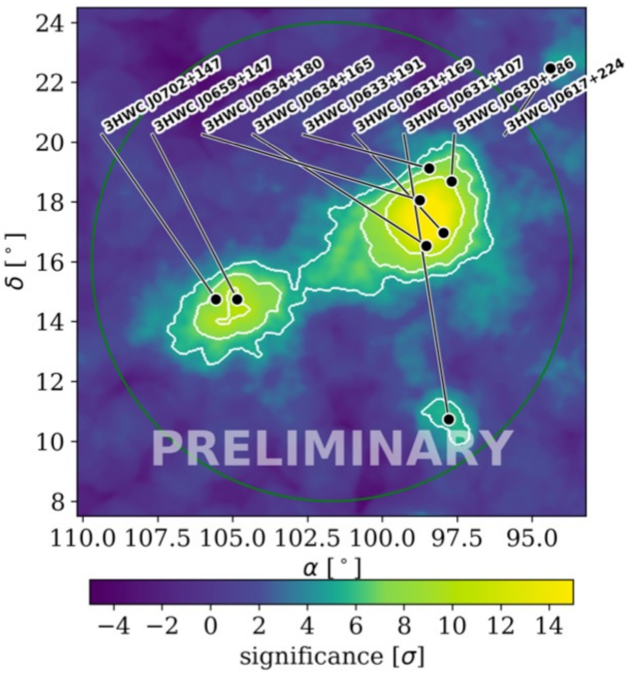


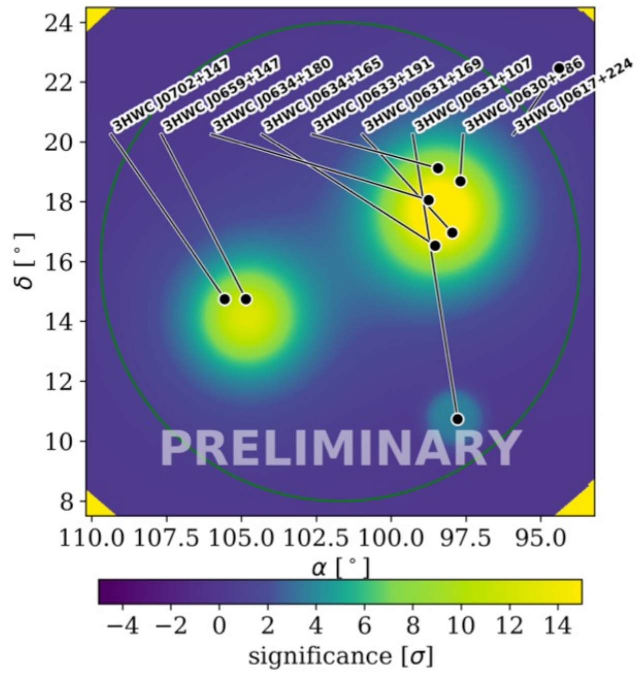


Geminga and Monogem : about 5 deg ext

- Assuming emission from electrons diffusing in the ISM, then extension is a direct measurement of particle diffusion θ(20TeV) α √ [D(100TeV)]
- D(100 TeV) = (4.5 ± 1.2) 10^{27} cm^2/s, roughly 100 times smaller than diffusion from B/C ratio

Geminga and Monogem in Pass 5





Source Name	$K(dE/dt \to e^- e^+)$	$\log_{10} D_0$ [cm^2/s]	α_e	TS
Geminga	$(6.3 \pm 0.9) \times 10^{-2}$	$(2.602 \pm 0.008) \times 10$	1.11 ± 0.09	834.73
Monogem	$(4.3 \pm 0.6) \times 10^{-2}$	$(2.616 \pm 0.007) \times 10$	1.10 ± 0.11	363.13

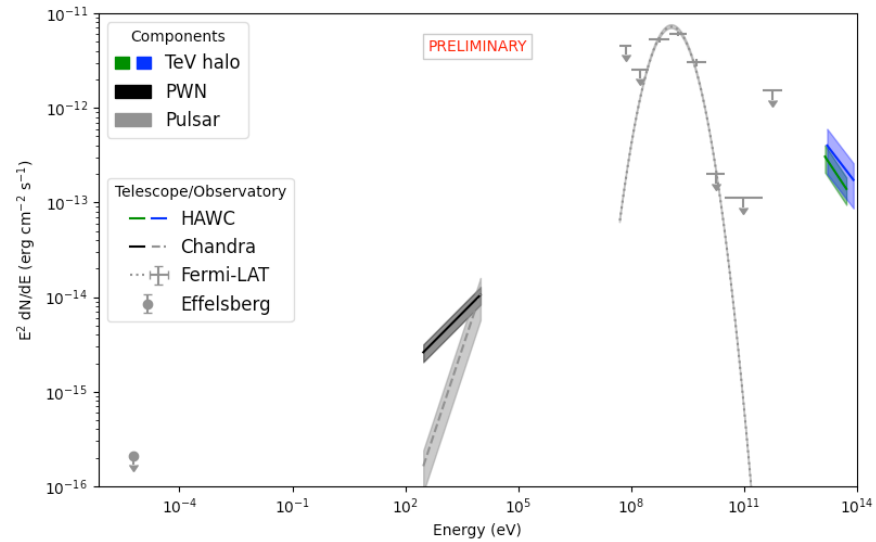
PWN Halos - PSR J0359+5414

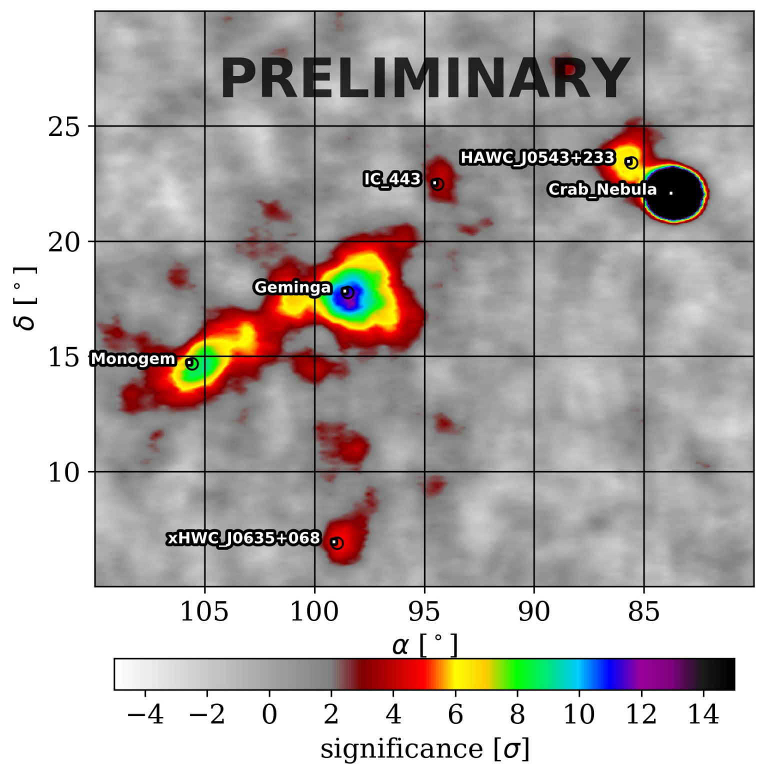
PSR J0359+5414 - Newly discovered TeV Halo

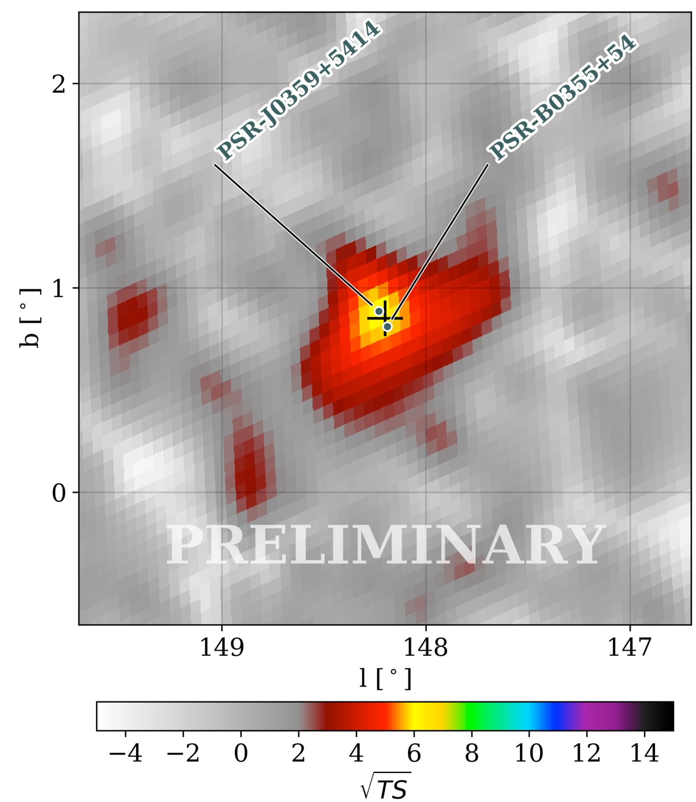
Outer galaxy, isolated

Age = 75kyr

High Spin-down power: 10^{36} ergs/s



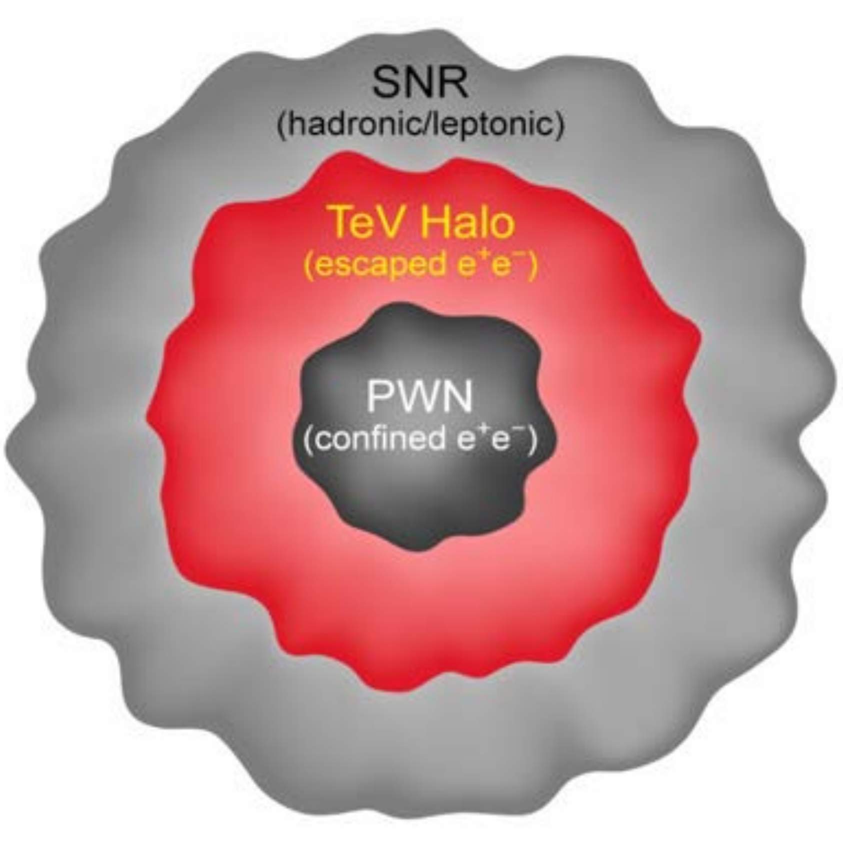


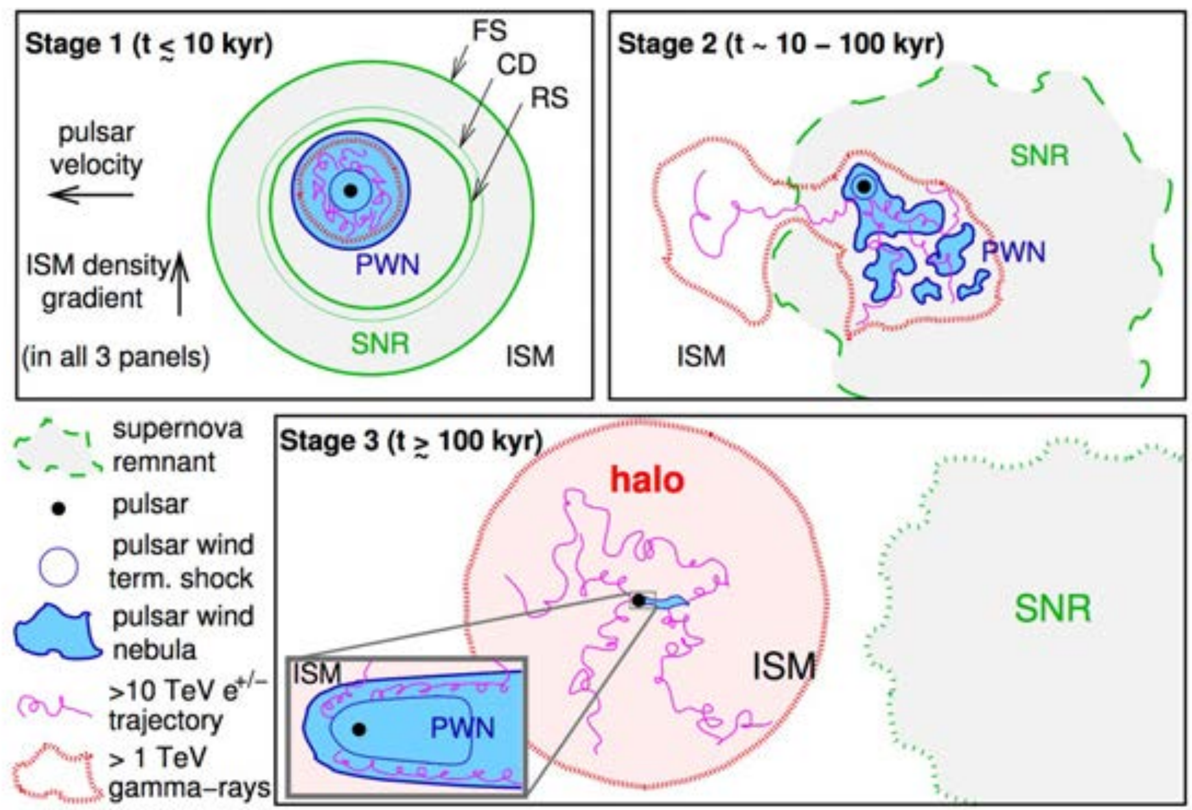


TeV Halos

PRD, 100, 043016 (2019)

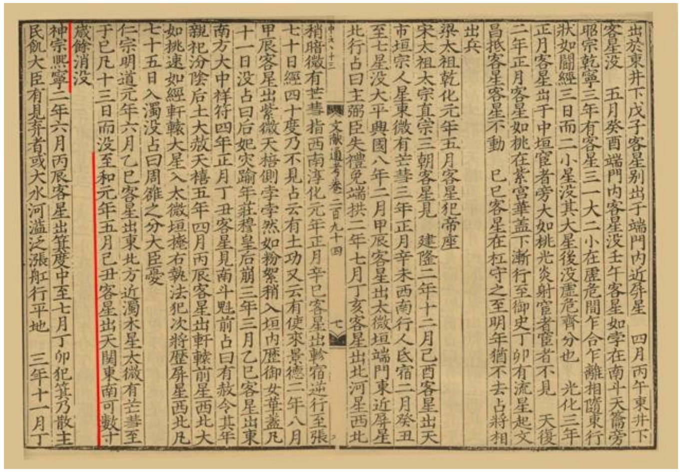
A&A 636, A113 (2020)





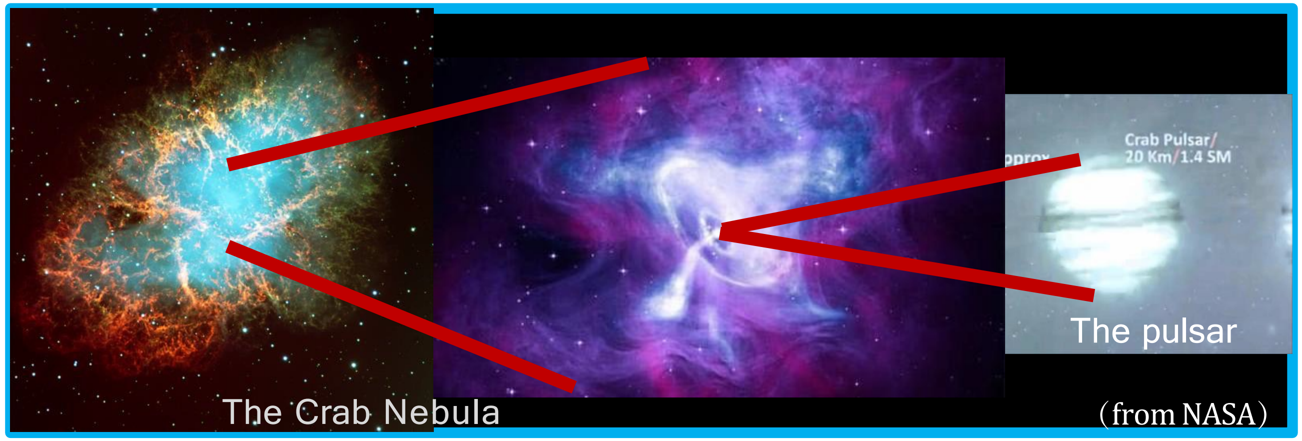
The Geminga halo discovery and the discovery of several extended TeV PWNe by H.E.S.S. lead to the hypothesis that extended ***"Halos"*** are a common feature of pulsars

The Crab up to PeV with LHAASO


出於東井下戊子客星別出于端門內近屛星　四月丙午東井下
客星沒　五月癸酉端門內客星沒壬午客星如孛在南斗天籥旁
昭宗乾寧三年有客星三一大二小在虛危間乍合乍離相隨東行
狀如鬬經三日而二小星沒其大星後沒虛危齊分也　光化三年
正月客星出于中垣宦者旁大如桃光炎射宦者宦者不見　天復
二年正月客星如桃在紫宮華蓋下漸行至御史丁卯有流星起文
昌抵客星客星不動　己巳客星在杠守之至明年猶不去占將相
出兵
梁太祖乾化元年五月客星犯帝座
宋太祖太宗真宗三朝客星見　建隆二年十二月己酉客星出天
市垣宗人星東微有芒彗三年正月辛未西南行入氐宿二月癸丑
至七星沒大平興國八年二月甲辰客星出太微垣端門東近屛星
北行占曰主弼臣失禮免端拱二年七月丁亥客星出北河星西北

文獻通考卷二百九十四　七

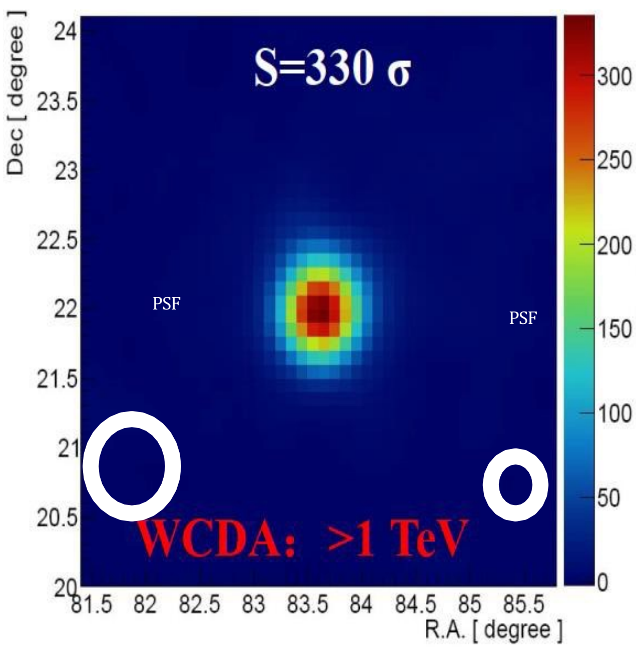
稍暗微有芒彗指西南淳化元年正月辛巳客星出軫宿逆行至張
七十日經四十度乃不見占云有土功又云有使來景德二年八月
甲辰客星出紫微天棓側孛孛然如粉絮稍入垣內歷御女華蓋凡
十一日沒占曰后妃災踰年莊穆皇后崩三年三月乙巳客星出東
南方大中祥符四年正月丁丑客星見南斗魁前占曰有赦令其年
親祀汾陰后土大赦天禧五年四月丙辰客星出軒轅前星西北大
如桃速如經軒轅大星入太微垣掩右執法犯次將歷屛星西北凡
七十五日入濁沒占曰周雒之分大臣憂
仁宗明道元年六月乙巳客星出東北方近濁木星太微有芒彗至
于己凡十三日而沒至和元年五月己丑客星出天關東南可數寸
歲餘消沒
神宗熙寧二年六月丙辰客星出箕度中至七月丁卯犯箕乃散主
民飢大臣有見弃者或大水河溢泛漲舡行平地　三年十一月丁

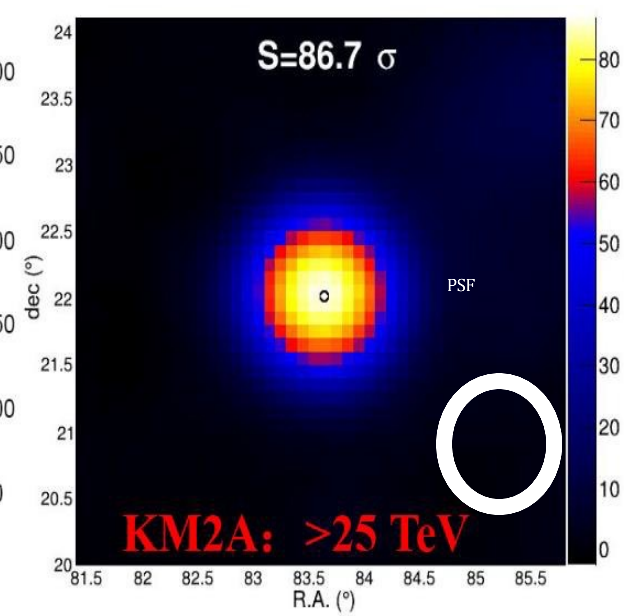


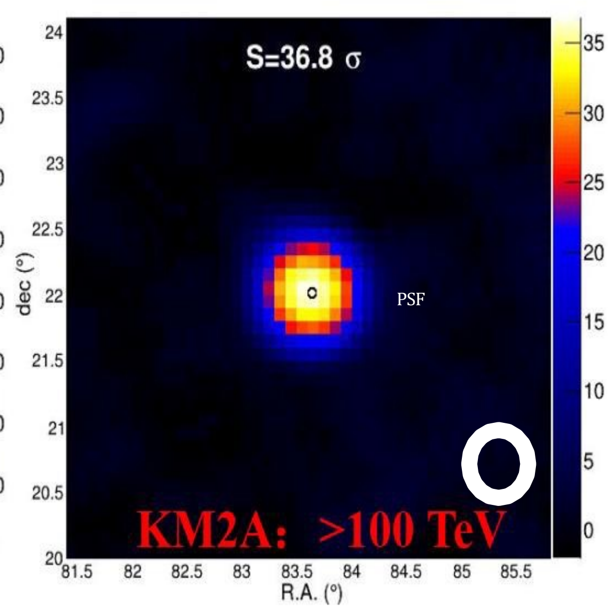
The coverage of 3.5 orders of magnitudes of energy

PSF: 0.22°　　25-100 TeV 0.30°　　0.1-1.2 PeV 0.15°

Pointing accuracy:

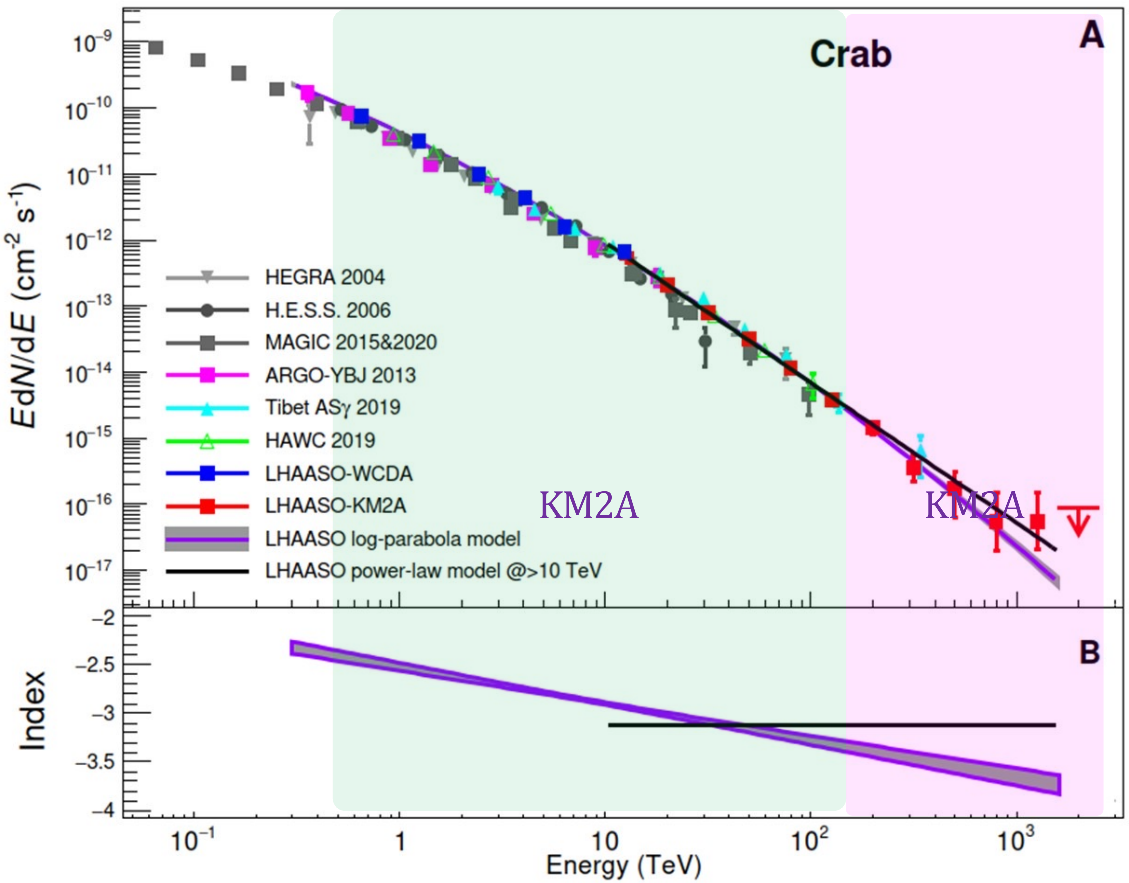






Crab Spectrum up to PeV photons

- LHAASO:
  - Self cross-checking between WCDA & KM2A
- LHAASO-KM2A:
  - Unique UHE SED
  - A PeVatron without ambiguity
  - Clear origin: a well-known PWN
- An extreme e-accelerator:
  - 2.3 PeV electrons
  - in ~0.025 pc compact region
  - accelerating efficiency of 15% (1000 × better than SNR shock waves)



Crab Spectrum up to PeV photons

- Perfect interpretation of one-zone electronic origin up to 50TeV
- Reasonable extension up to 1 PeV, with a deviation of 4 σ
- Can not rule out proton origin of photons ~1.1 PeV, yet

LHAASO Science 2021