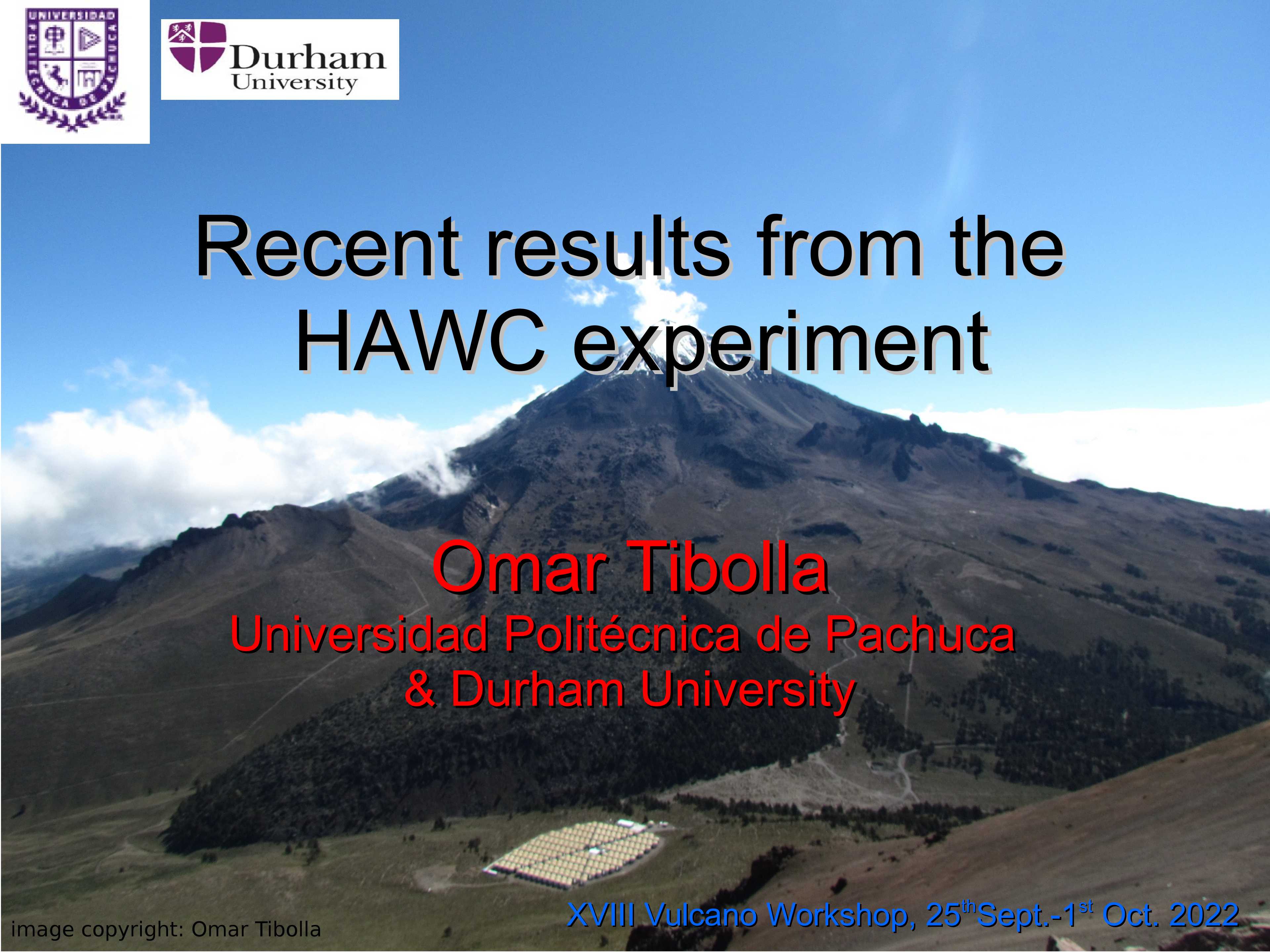


Recent results from the HAWC experiment

Omar Tibolla

Universidad Politécnica de Pachuca
& Durham University

XVIII Vulcano Workshop, 25^{th} Sept.-1^{st} Oct. 2022

Collaboration

USA

Mexico

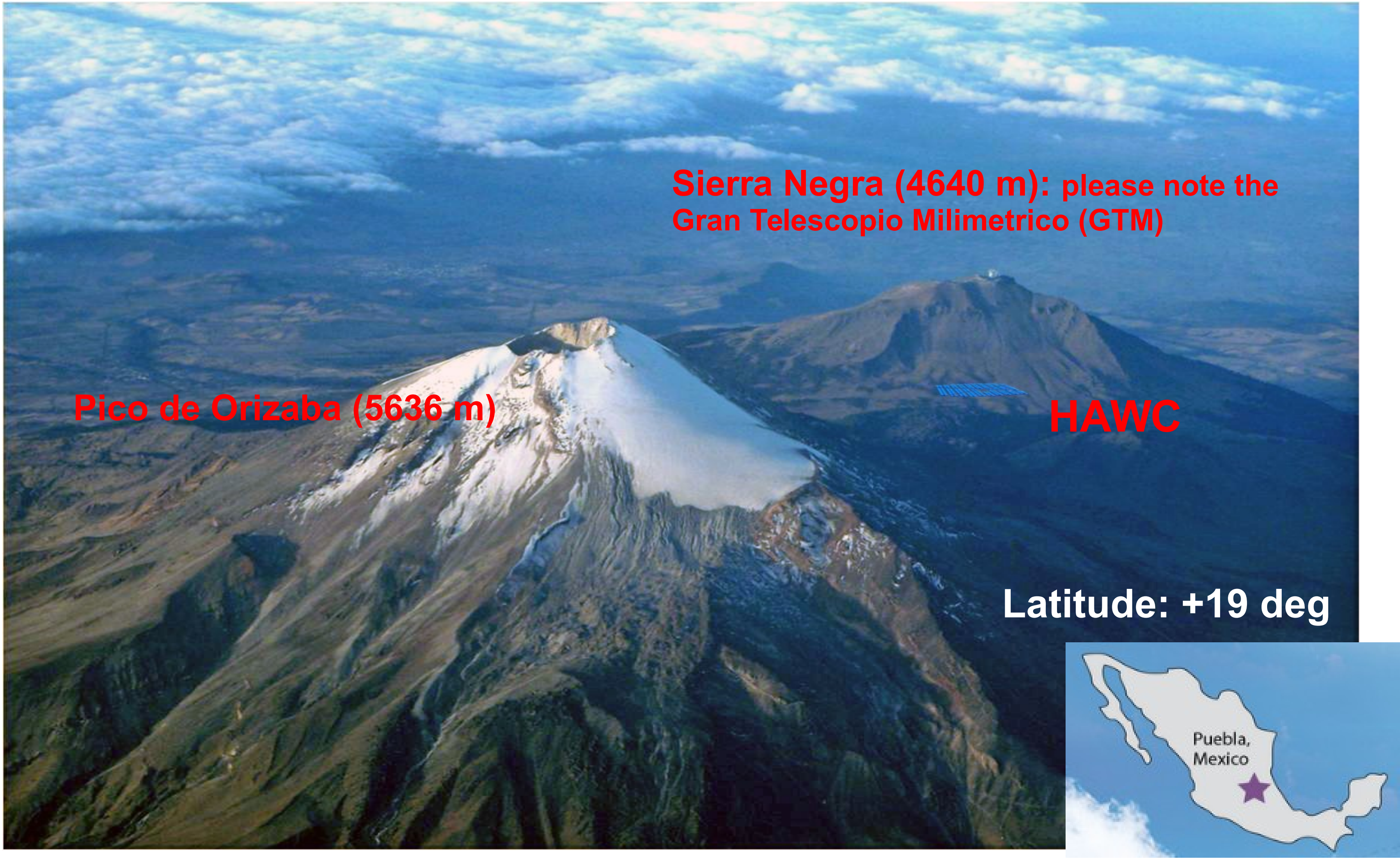
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Colorado State University

Michigan State University
University of Rochester
University of California Santa Cruz
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

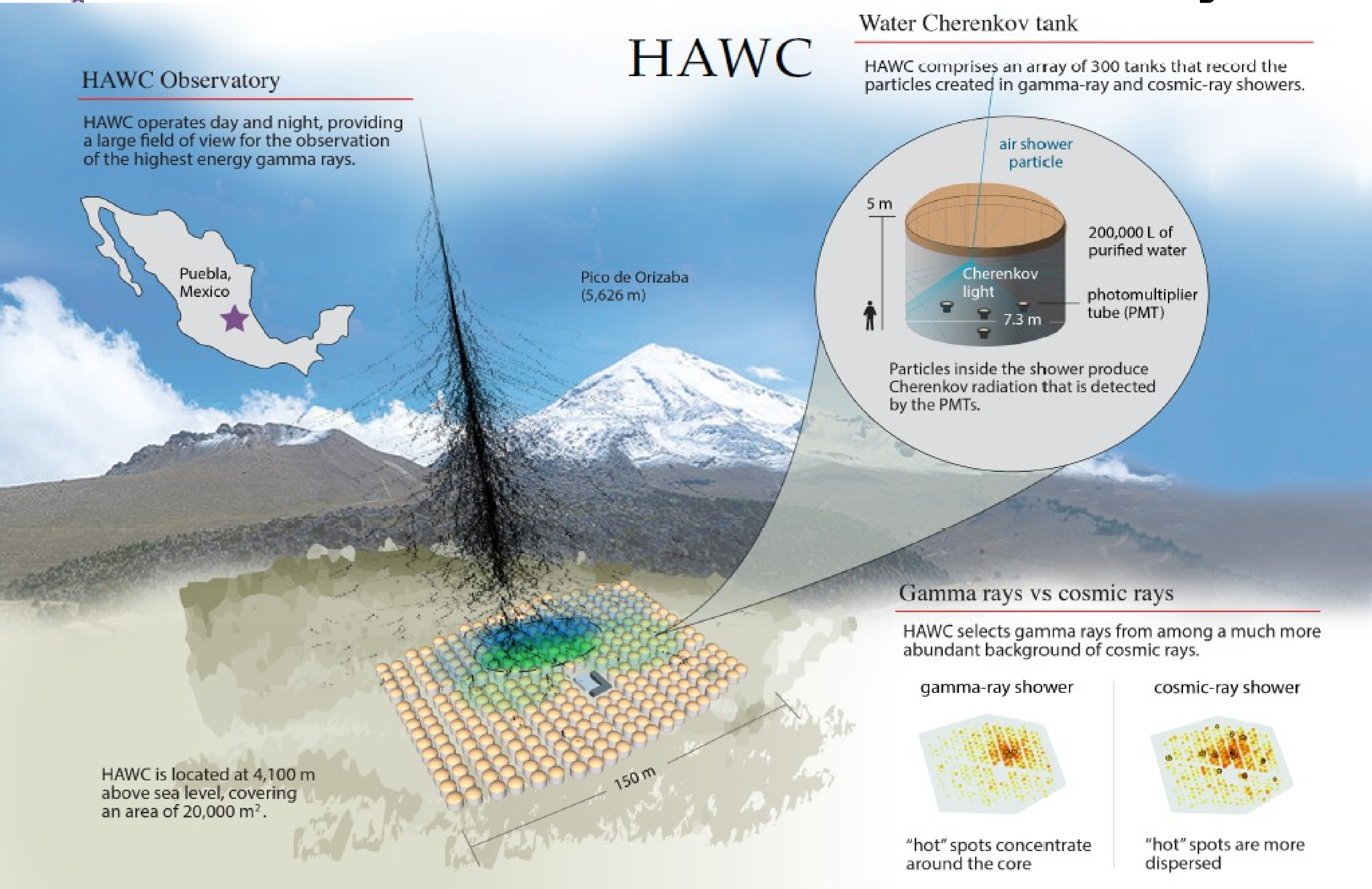
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional
Centro de Investigación en Computación – IPN
IFJ-PAN, Krakow
Max Plank Institut für Kernphysik Heidelberg
Stanford University

Originally Mexico & USA, now with participation of Europe, Asia and Latin America

HAWC location



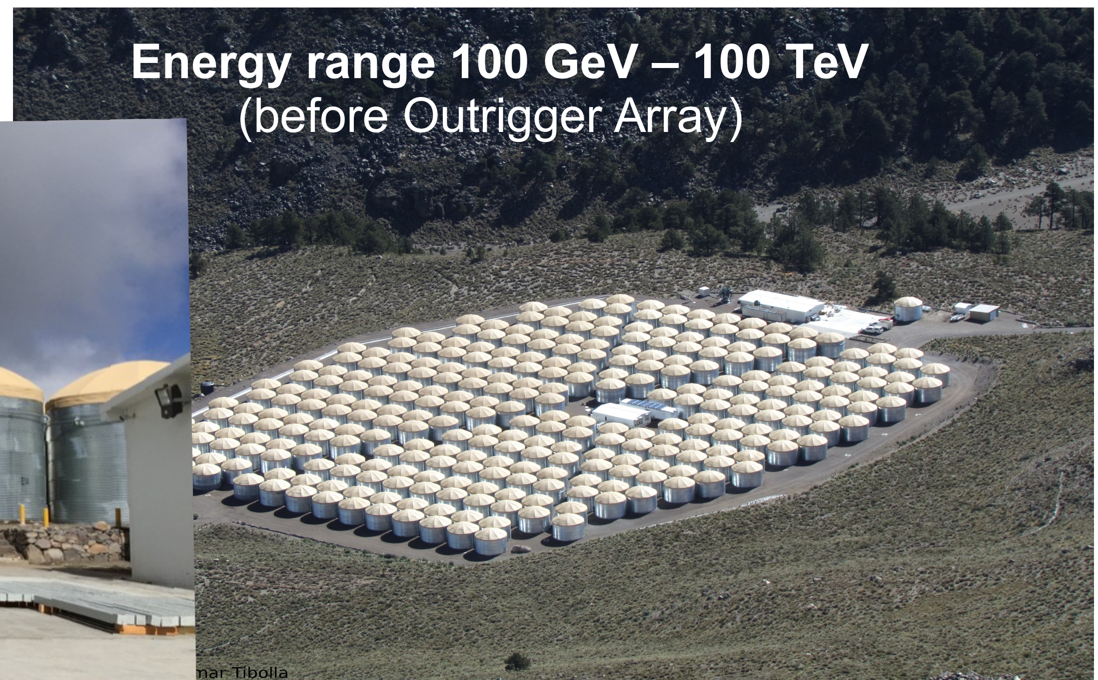
High Altitude Water Cherenkov Observatory



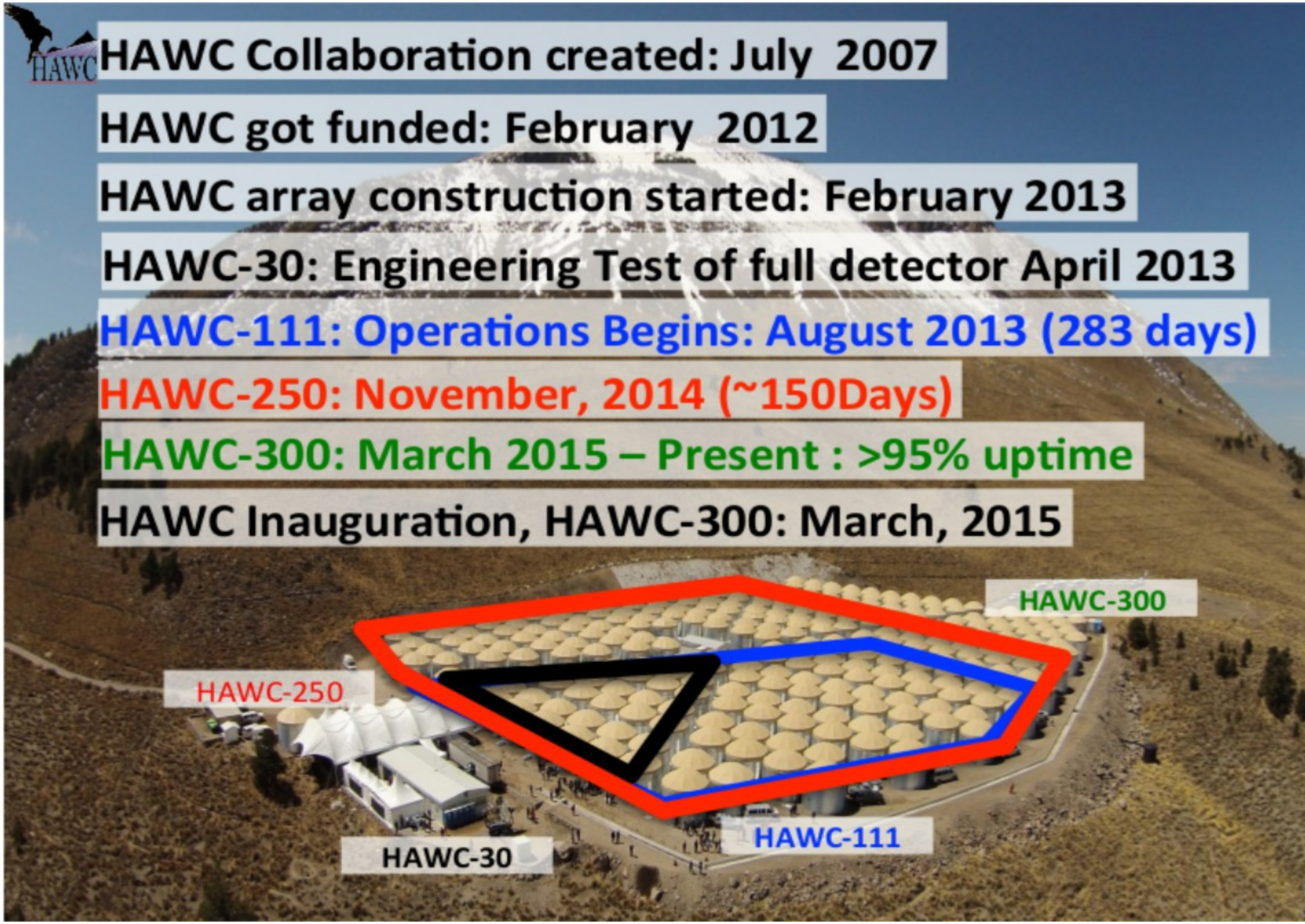
HAWC summary

Instantaneous FOV = 1.8 Sr (15% of the sky)
HAWC scans 2/3 of the sky every sidereal day to a depth of 1 Crab at 5sigma
- transient events
- extended diffuse sources

15 times more sensitive than Milagro (first generation water Cherenkov observatory)
HAWC registers 20000 cosmic rays per second and generates 2 Terabytes per day, every day (no limited duty cycle)



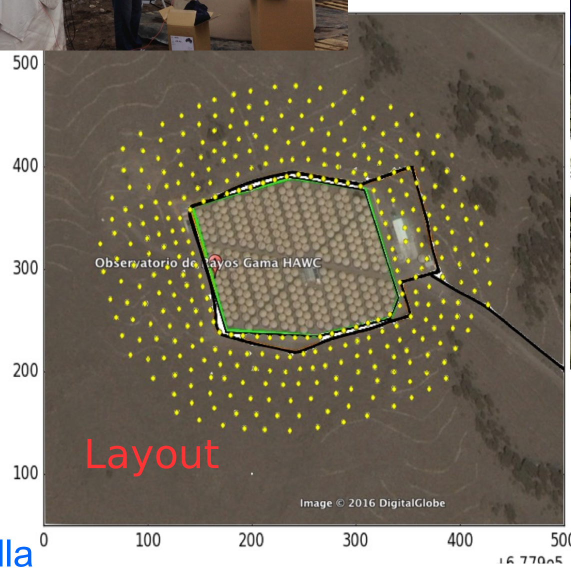
HAWC construction



Hardware upgrade: Outrigger Array

Since 2017-2018, we could increase the sensitivity to the highest energy events by determining the core position for showers that fall off the main array (i.e. a low cost extension to improve HAWC sensitivity > 10 TeV).

345 much smaller (2500 liters) outrigger WC detectors, which cover an area 4x HAWC and increase by 3-4x the sensitivity at 50 TeV

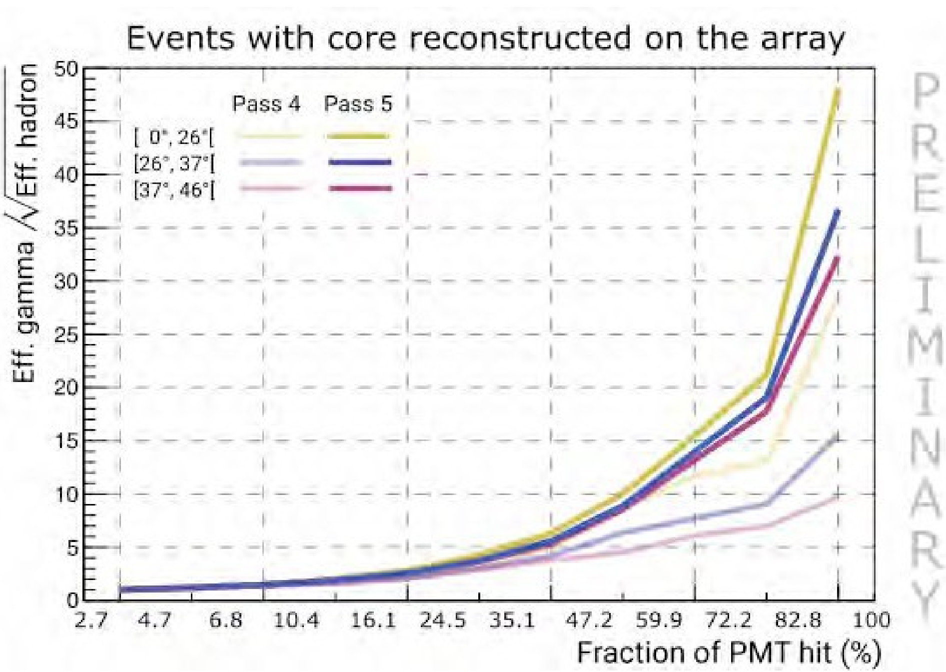


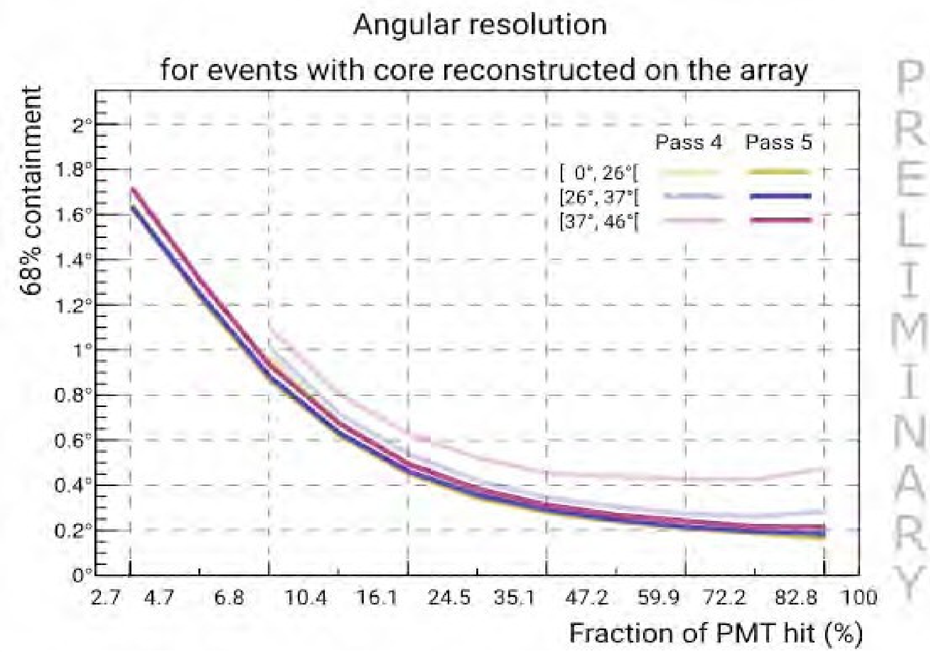
NEW "Pass 5" Improved Reconstruction

Large Events - Much improved gamma/hadron separation
(i.e. much better background rejection)

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

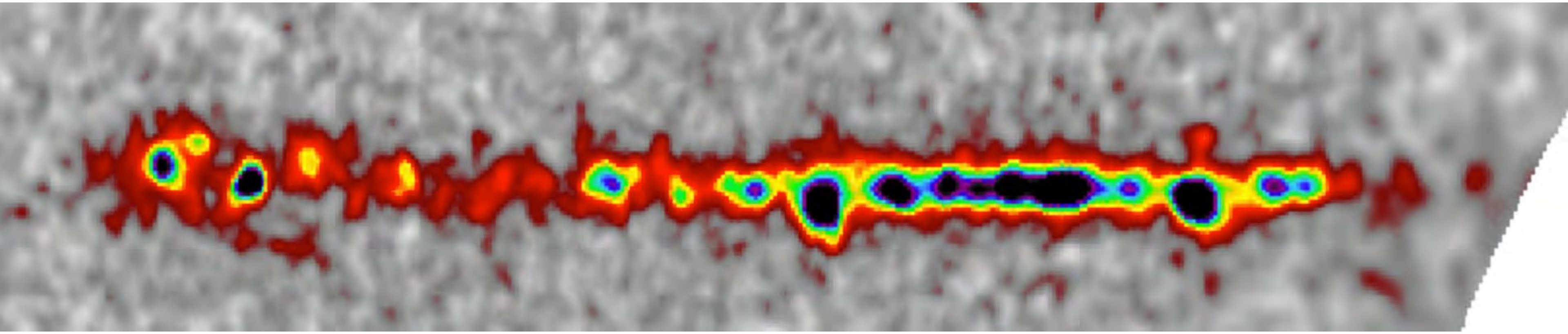
Wider FOV - Previous 45 deg - now 60 deg

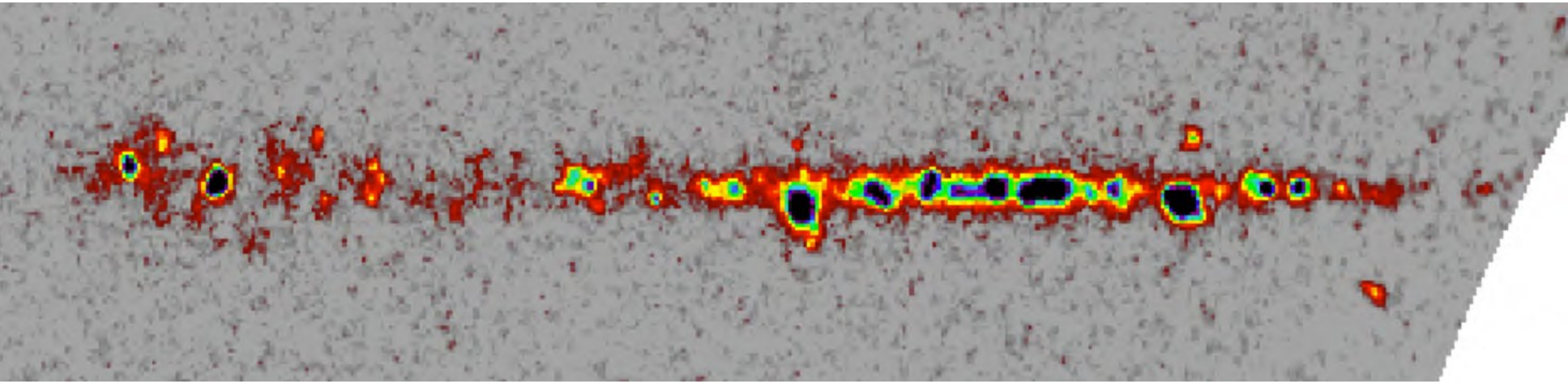




“Pass 4” VS “Pass 5”

Comparing “Pass 4” (1523 days)

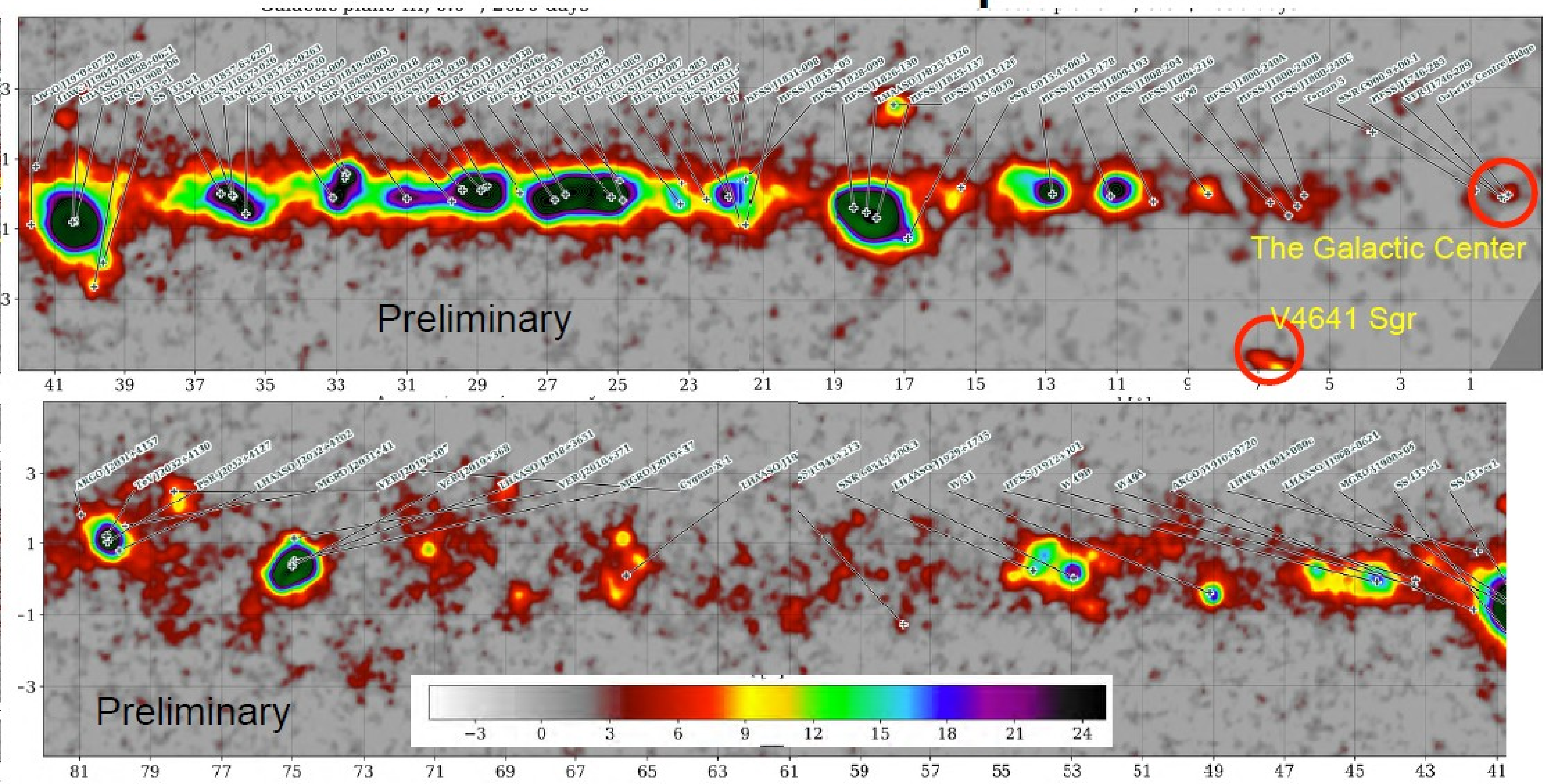




with “Pass 5” (2090 days)

“Pass 5” Galactic Plane

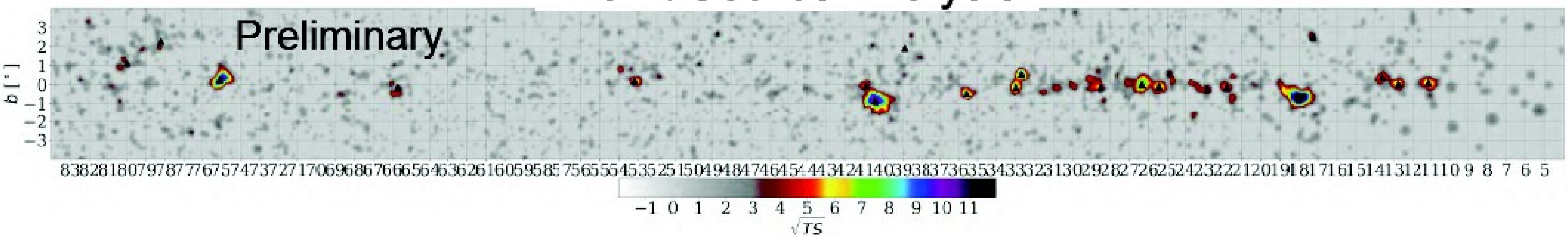
Pass 5 - 2090 map



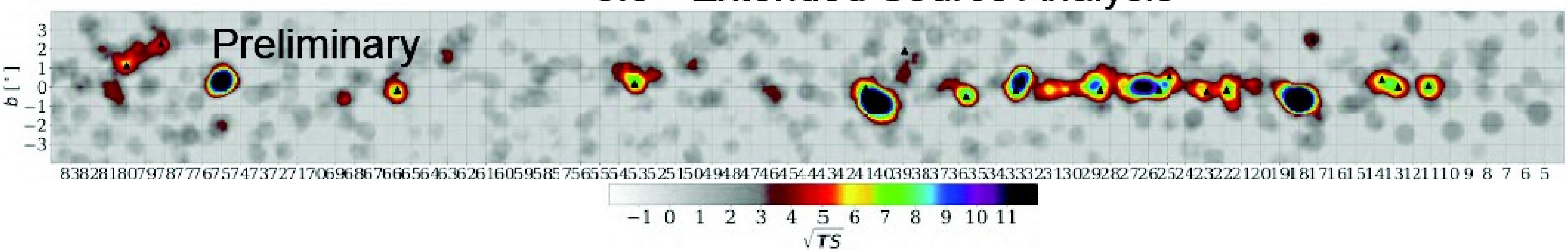
Pushing to the highest energies (>56 TeV)

Pass 5 is a tremendous tool to explore the highest energies bands:

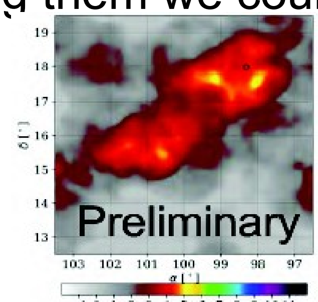
Point Source Analysis



0.5° Extended Source Analysis



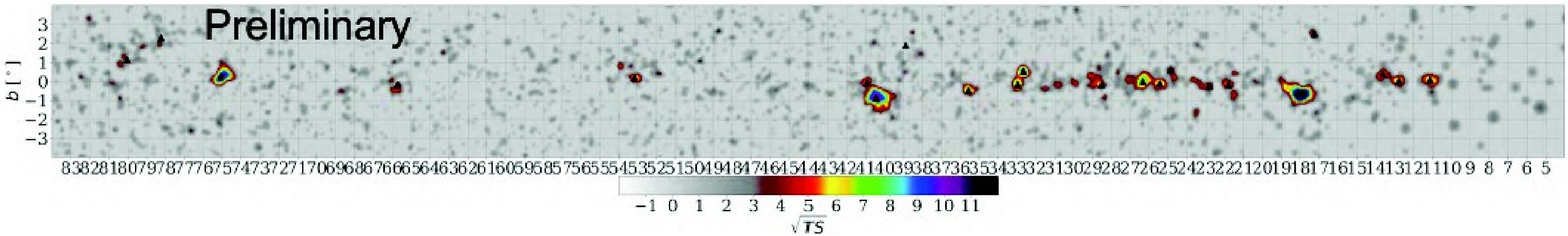
In Pass 5, 25 sources are identified above 56 TeV, compared to the 9 sources seen in Pass 4 *Abeysekara et al. 2020, PRL 124, 021102* . Most of these sources appear to be extended. Among them we count 8 PWNe, 1 SFR, 1 binary and 14 Unidentified Sources (even more than the ~50% unids in adjacent TeV band)



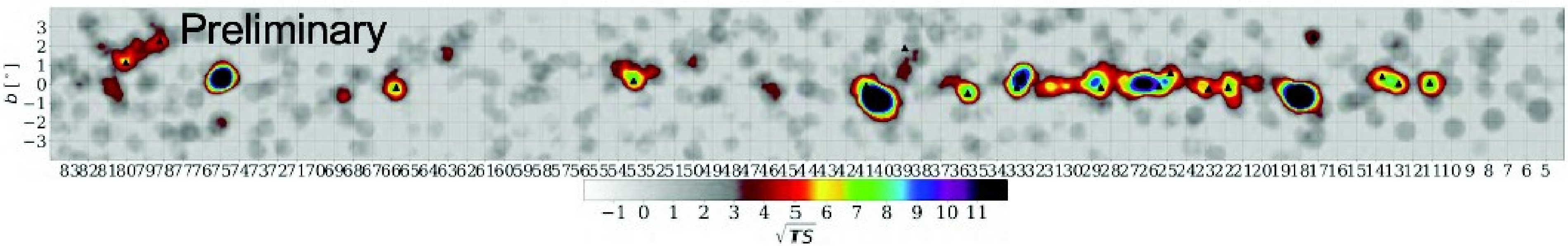
e.g. >56 TeV Geminga “TeV Halo”

Pushing to the highest energies (>100 TeV)

Point Source Analysis

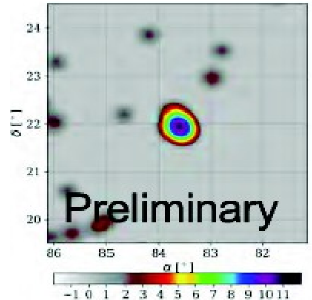


0.5° Extended Source Analysis



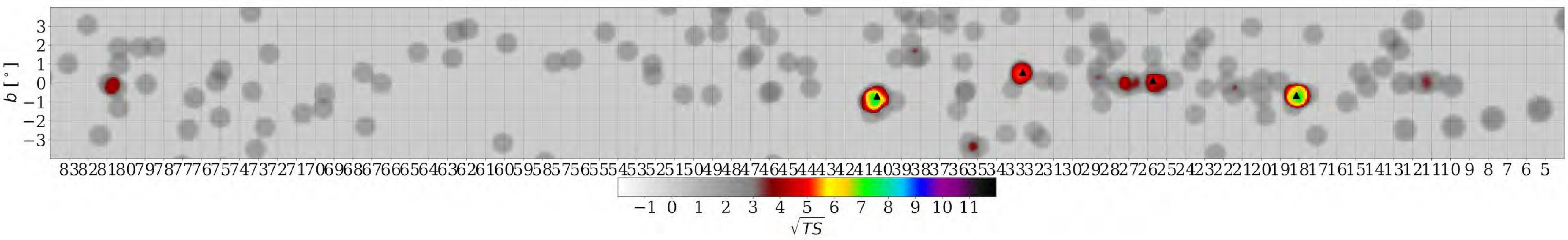
Within Pass 5, 18 sources are identified above 100 TeV, compared to 3 sources seen in Pass 4 *Abeysekara et al. 2020, PRL 124, 021102* . Most of these sources appear to be extended. All them seem either PWNe or Unidentified sources.

(the ratio of PWN and Unids seems increasing...)



e.g. >100 TeV point-like Crab Nebula

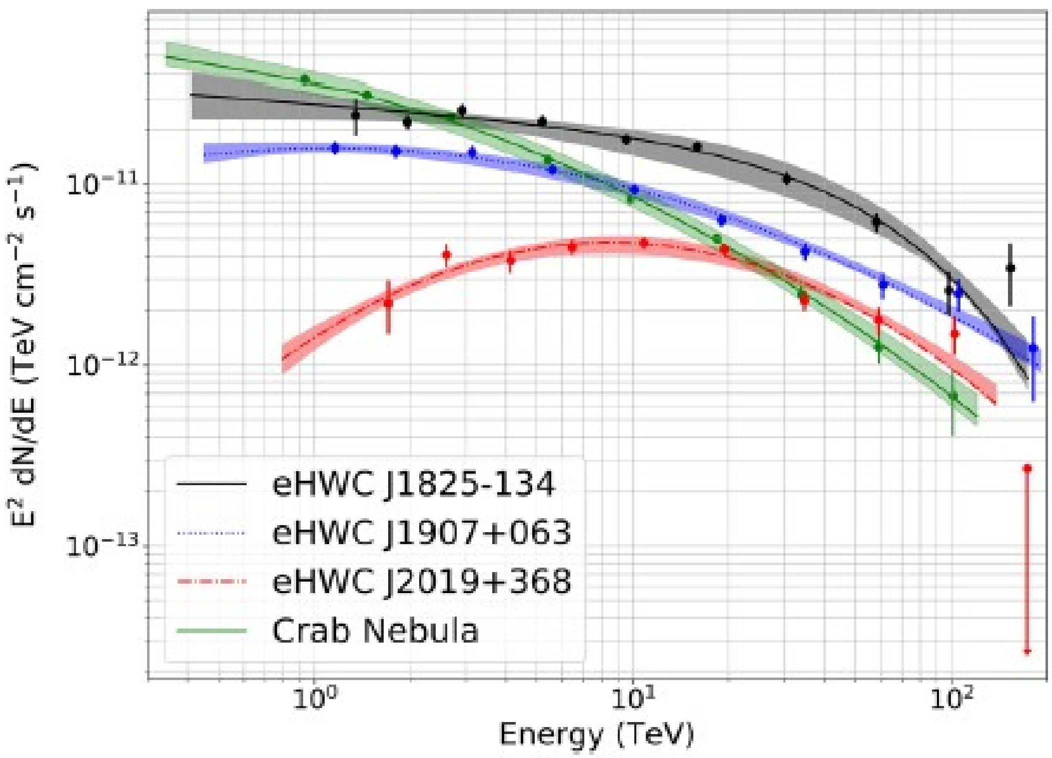
Pushing to the highest energies (>177 TeV)



Within Pass 5, 4 sources are identified above 177 TeV (none in Pass 4). Most of these sources appear to be extended. 3 of them are PWNe and 1 is Unidentified.

At first sight, there seems to be a predominance of leptonic acceleration at the highest energies (surprisingly?)..

A similar result was already present...



From *Abeysekara et al. 2020, PRL 124, 021102* the multi-TeV energy spectra of the 3 sources which were detected above 100 TeV + the Crab Nebula (as a reference): 2 PWNe and one Unidentified (candidate PWN) source...

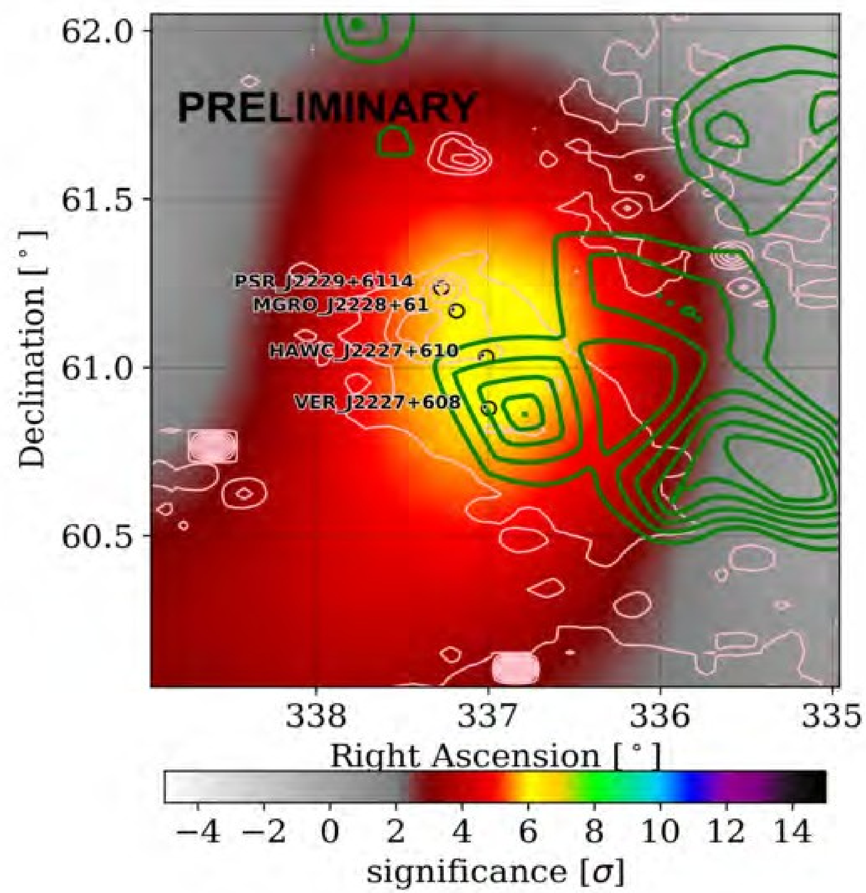
HAWC J2227+ 610 (Boomerang region)

SNR G106.3+2.7 is a comet-shaped radio source

PSR J2229+6114, seen in radio, X-rays, and gamma rays and it's pulsar wind nebula(PWN), Boomerang Nebula is contained in the remnant

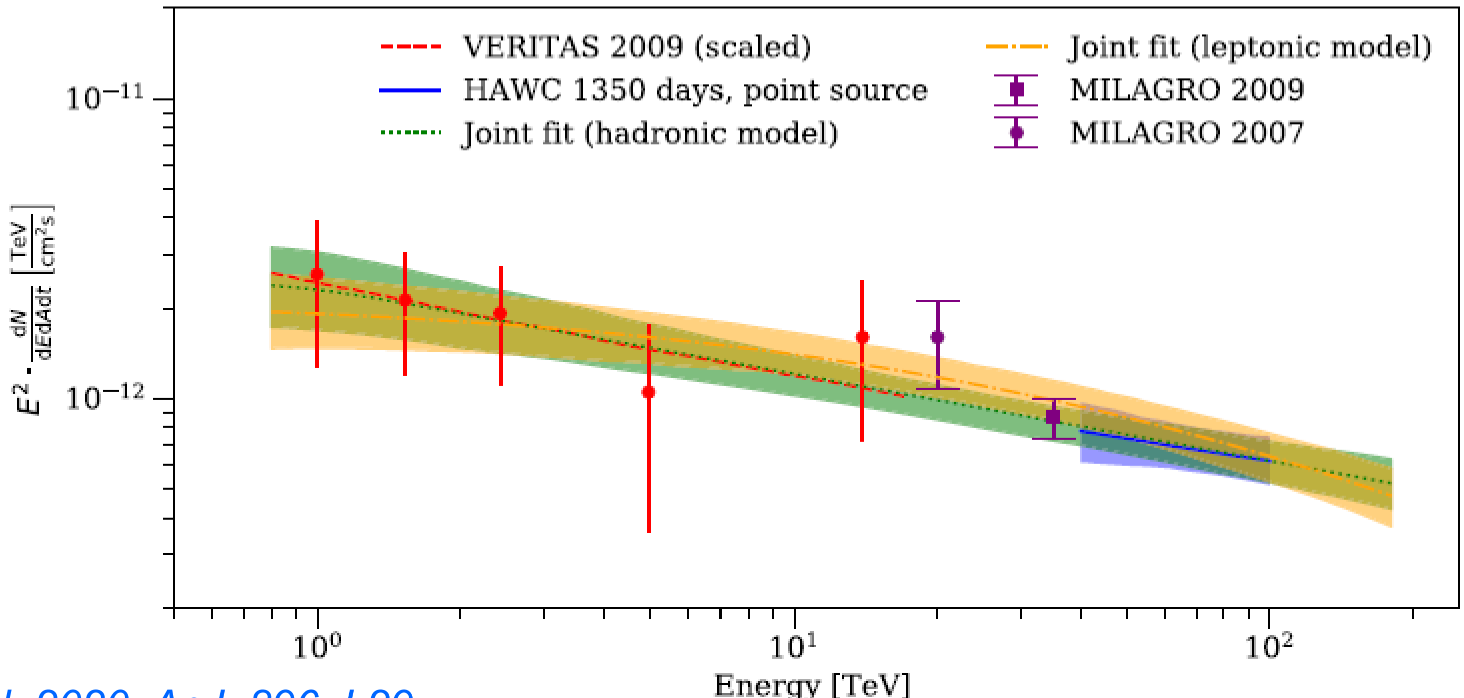
Both hadronic and leptonic scenarios are plausible.

Albert et al. 2020, ApJ, 896, L29



Boomerang: a new Galactic Pevatron?

The joint VERITAS-HAWC spectrum is well fit by a power law from 800 GeV to 180 TeV



Albert et al. 2020, ApJ, 896, L29

If hadronic, the cutoff energy in the underlying proton spectrum is constrained to be above 800 TeV

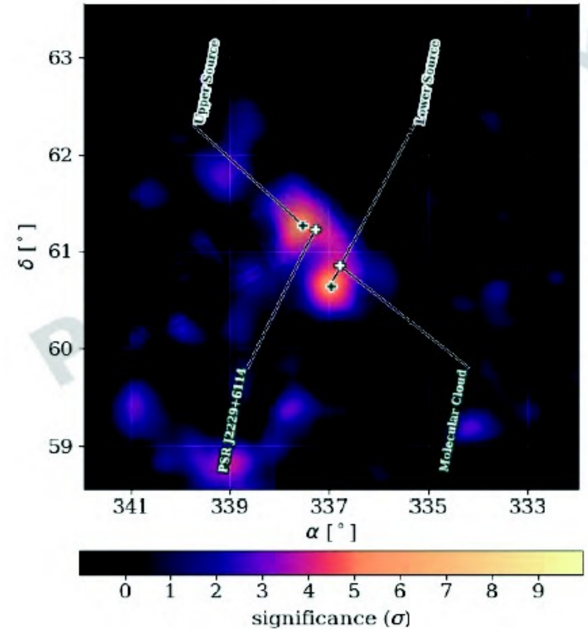
Boomerang in Pass 5

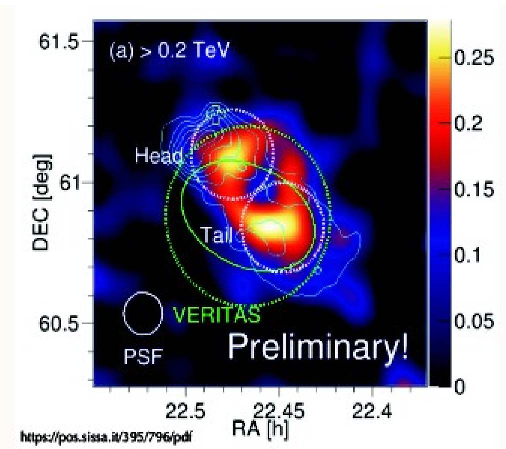
In Pass 5 Data, HAWC resolves the source into two distinct sources.

MAGIC sees two sources as well.

The Head Region (North West Source) contains the pulsar and its PWN => here only (i.e. IC scattering of relativistic leptons on background photons) leptonic scenarios seem plausible.

The Tail Region (South East Source) seems instead spatially coincident to the Molecular cloud shown before; hence hadronic scenarios are still a viable option!





LHAASO J2108+5157

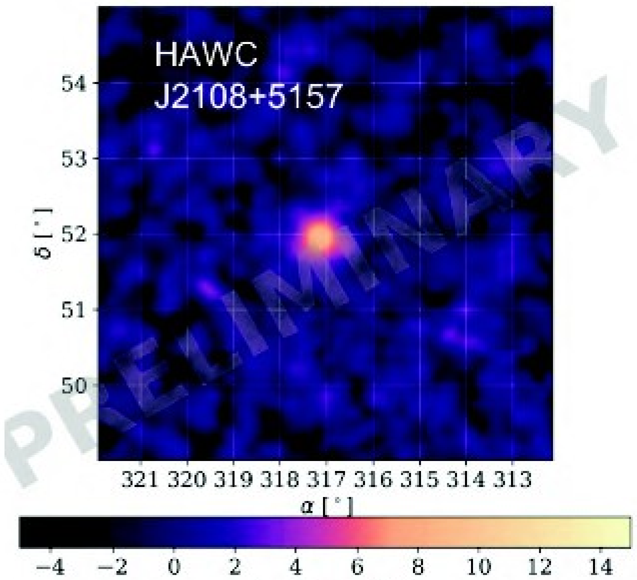
Discovered in LHAASO-KM2A survey

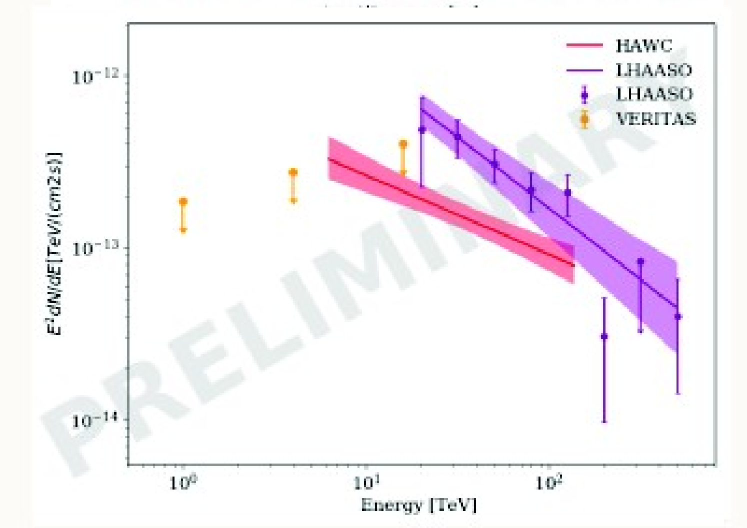
3 deg off-plane (north of Cygnus region)

Interesting target because it is spatially coincident with a molecular cloud, clearly suggesting an hadronic origin of the multi-TeV gamma-ray emission.

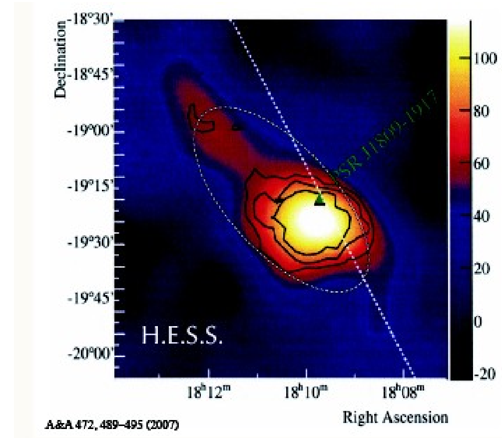
Joint analysis with VERITAS is undergoing.

Note: preliminary HAWC (only) spectrum indicates harder and lower flux than seen by LHAASO.



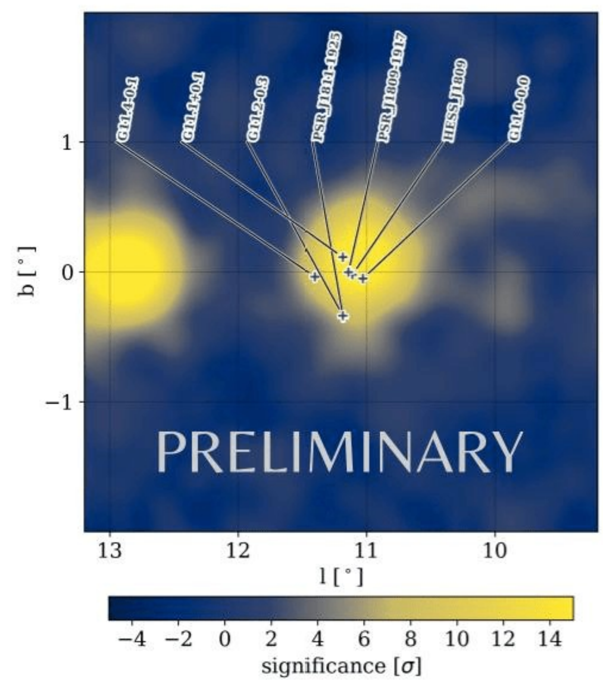


HESS J1809-1917 another PeVatron candidate

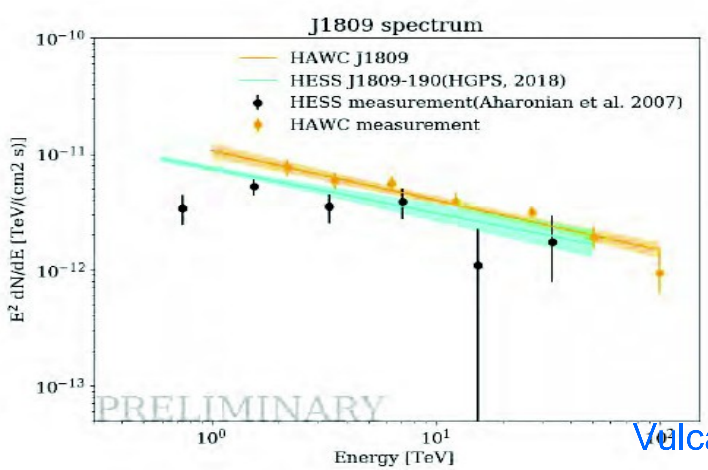


Not detected by LHAASO's 12 UHE sources (it seems at the edge of their FOV)
Several plausible counterparts:
- PSR J1809-1917 is a quite powerful (spin-down luminosity ~1.8 x10^36 erg s−1) 51 kyr pulsar, close to the H.E.S.S. emission peak => PWN?

- Several SNRs are in the region as well, in particular G11.0-0.0 is spatially coincident with the peak of the TeV (H.E.S.S.) emission => Possibly Hadronic PeVatron.



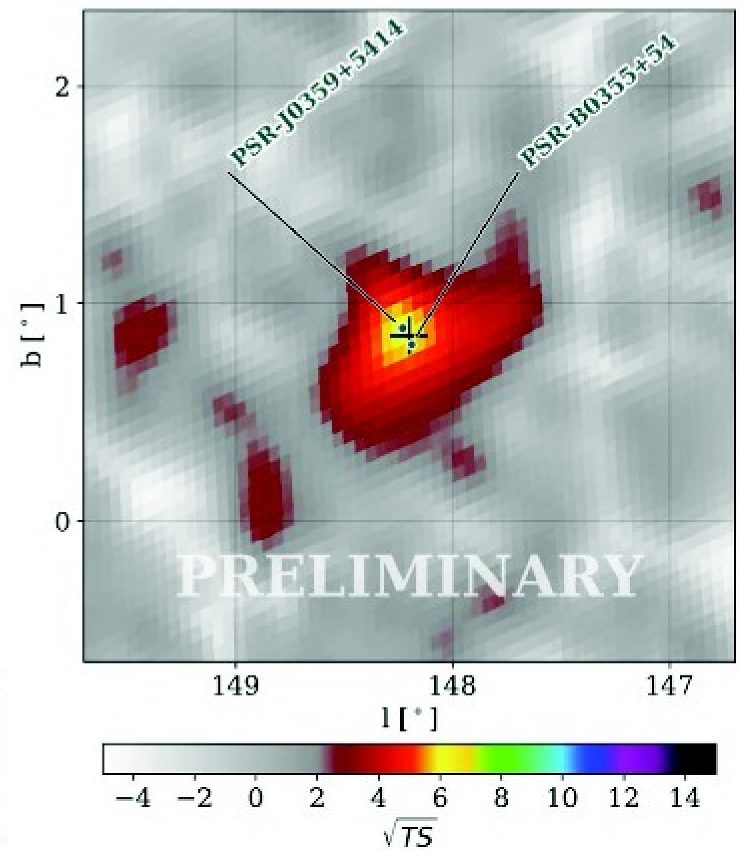
Preliminary analysis shows good agreement with H.E.S.S. spectrum, SED extended to 100 TeV without cutoff.

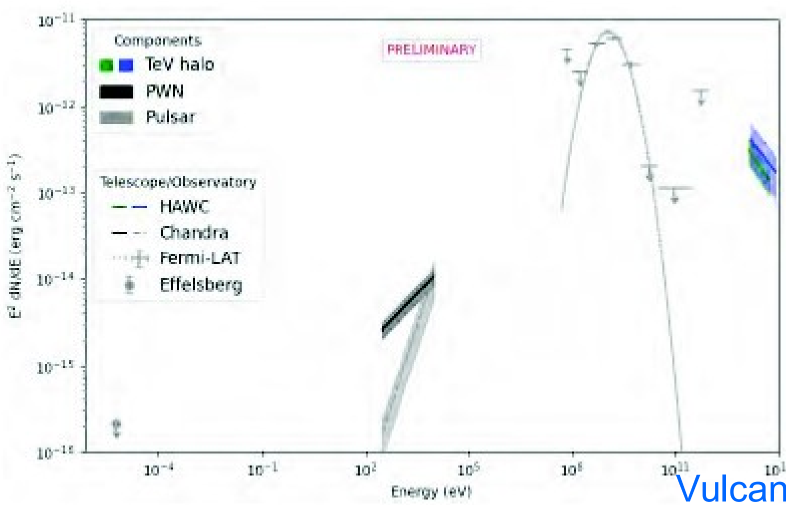


TeV halo/PWN candidate surrounding PSR J0359+5414

Newly discovered multi-TeV gamma-ray source surrounding PSR J0359+5414, a radio-quiet high spin-down power (E_dot = 1.3 × 10^36 erg/s) pulsar.

PSR J0359+5414 is isolated, 3.45 kpc far away and slightly off-set from the Galactic plane; it has been detected at GeV energies with Fermi-LAT. At VHE has not been detected before by any IACT or EAS experiment.



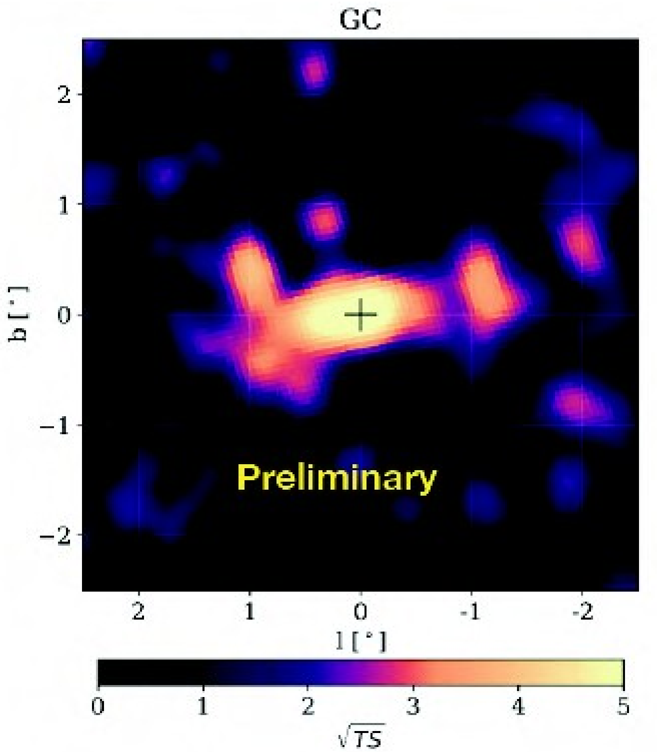


Galactic Center (Pass 5)

GC transits with a minimum zenith angle of 47 deg

(Pass 4 had a cut at 45 deg)

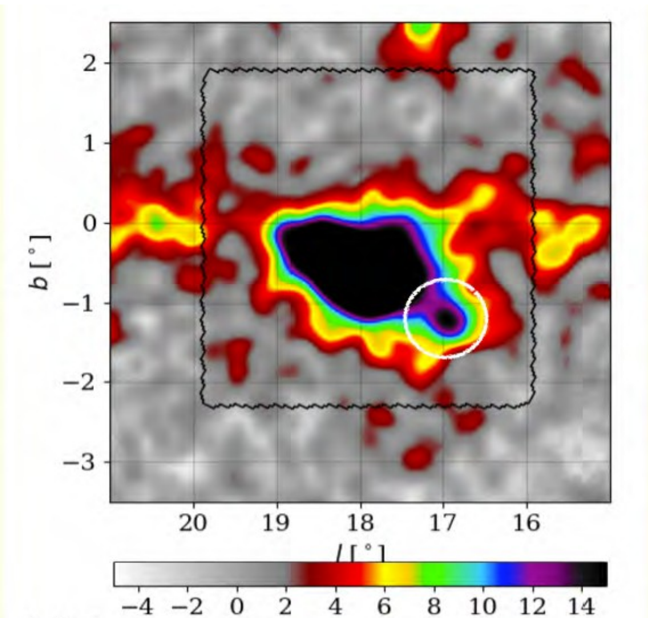
Work in progress, the energy spectrum is still being checked but it seems to have comparable error bars to H.E.S.S. spectrum beyond 20 TeV.

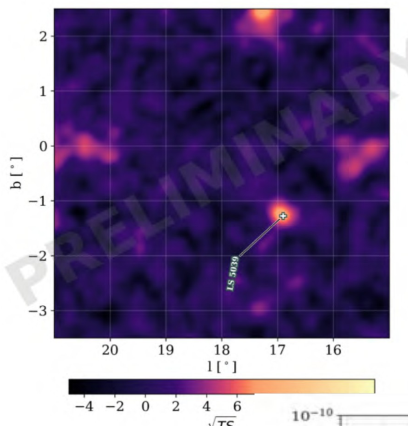


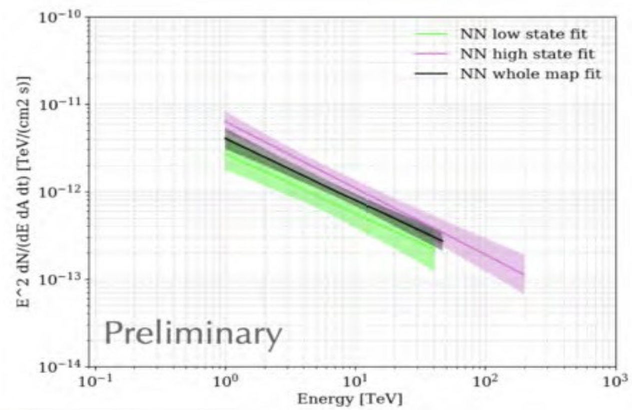
LS 5039

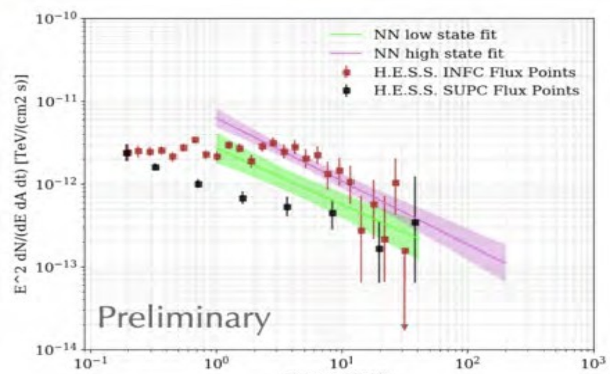
Thanks to the improved angular resolution we could disentangle LS 5039 from J1825-138 and study the energy spectra in both high and low states.

LS 5039 consists of a massive O-type main-sequence star, and a compact object (either a black hole or a pulsar).Radio Quiet.
The two objects orbit each other every 3.9 days in an eccentric orbit.









SS433

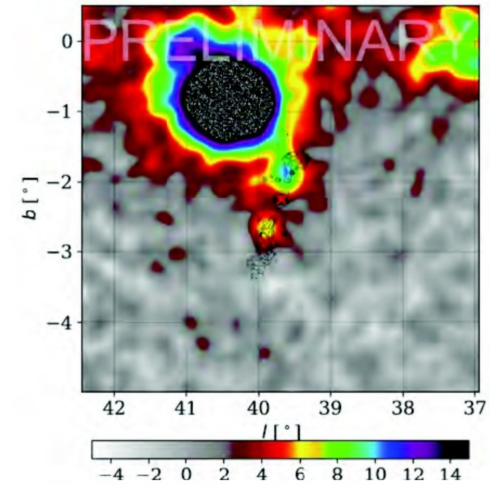
SS433 is a microquasar near the very bright extended source J1908+06

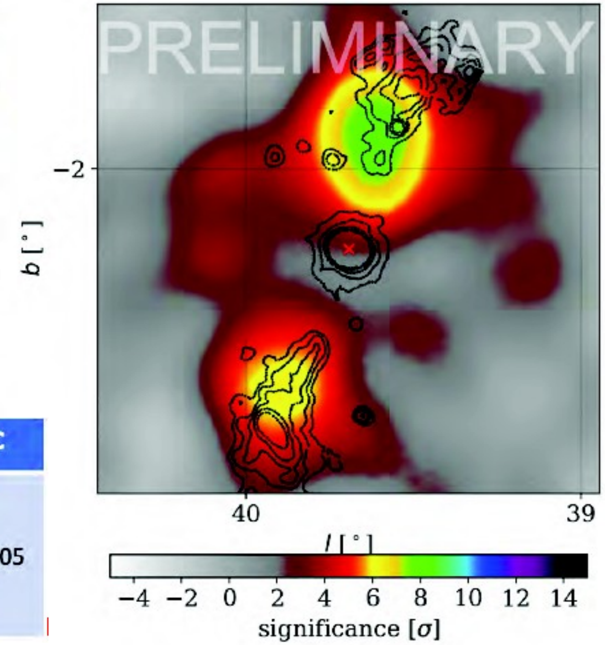
The black hole is located at the red x; its jets form (east and west) lobes detected at X-rays and TeV gamma-rays

The HAWC discovery was published in *Abeysekara et al. 2018, Nature, 562, 82*

Significance of each lobe is now 7-9 sigma.

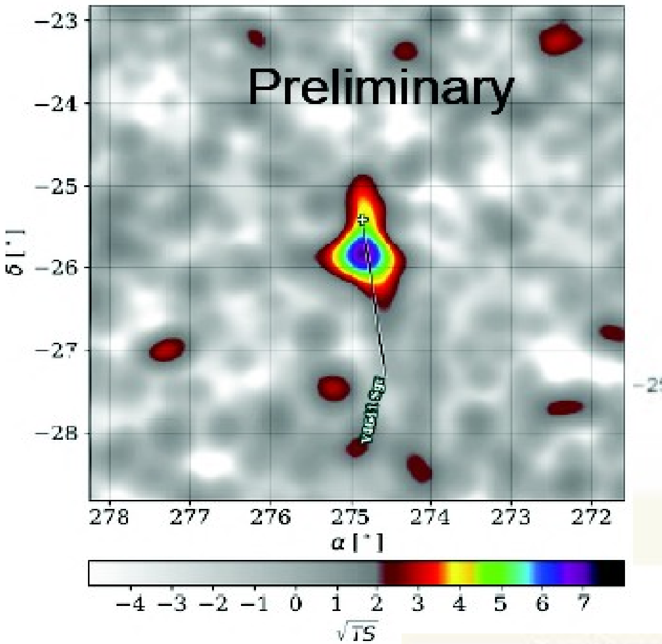
Upcoming results on spectra of each lobe will be out soon





Name	E_{piv} [TeV]	Flux [TeV^{-1} cm^{-2} s^{-1}]	Idx	Size	TS	BIC
J1908	7	$1.08 + 0.04 - 0.04 \times 10^{-13}$	$-2.35 + 0.02 - 0.02$	$0.42 + 0.01 - 0.01°$	1982.2	
east	10	$2.2 + 0.4 - 0.3 \times 10^{-15}$	$-2.47 + 0.12 - 0.12$		58.6	499305
west	10	$3.0 + 0.4 - 0.4 \times 10^{-15}$	$-2.41 + 0.09 - 0.09$		85.1	

Another binary system: V4641 Sgr

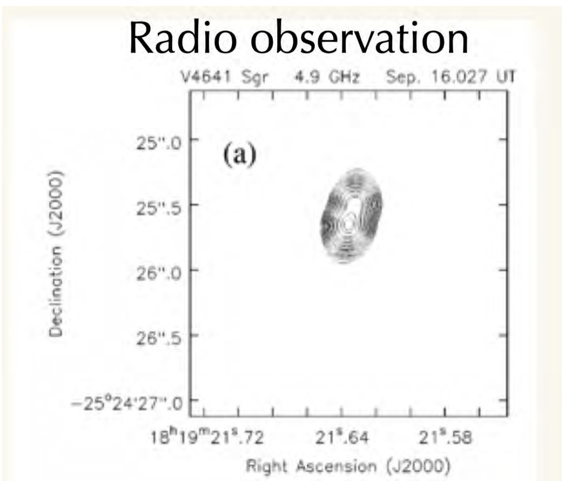


Newly discovered TeV microquasar

One of the fastest superluminal jets in the Milky Way galaxy:
This implies that the jet point toward us
The radio jet is very small

It seems slightly extended (<0.25 deg)

9.7σ in Pass 5



High zenith angle (45 deg) for HAWC

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

AGN

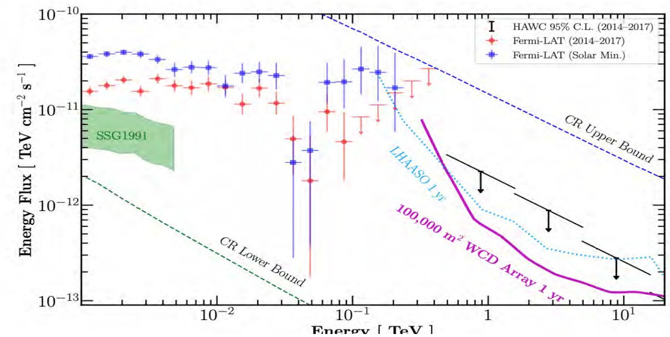
After monitoring Mrk 421 and Mrk 501 for many years, now (i.e. thanks to Pass 5) M87, 1ES1215+303, VER J0521+211 are significantly detected.

Source	Redshift	"Pass 4" TS	"Pass 5" TS
M87	0.004	13.2	29.6
1ES1215+303	0.130	12.8	43.8
VER J0521+211	0.108	10.3	18.2

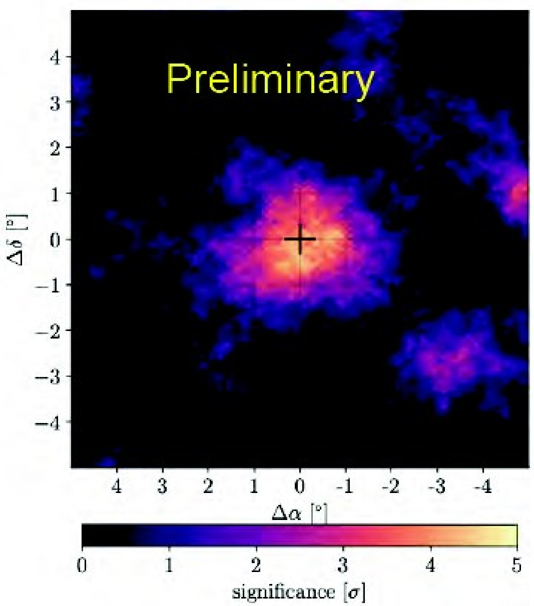
If interested, the preliminary energy spectra of the three sources are in the spare slides, as well as the daily monitoring of Mrk421

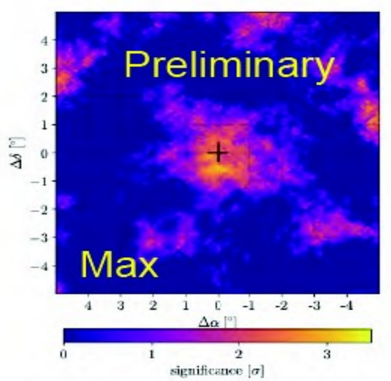
Gamma-rays from the Sun

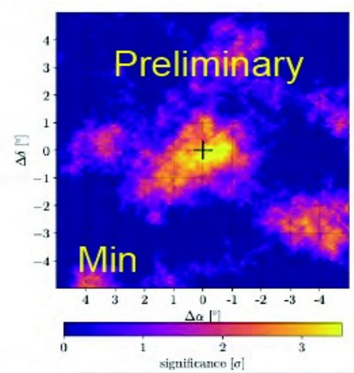
Fermi-LAT sees the Sun up to ~100 GeV.
Its emission is correlated to solar cycle (i.e. higher flux at Solar Minimum).
The emission mechanism is thought to be from CR hadrons interacting with the Sun's atmosphere.

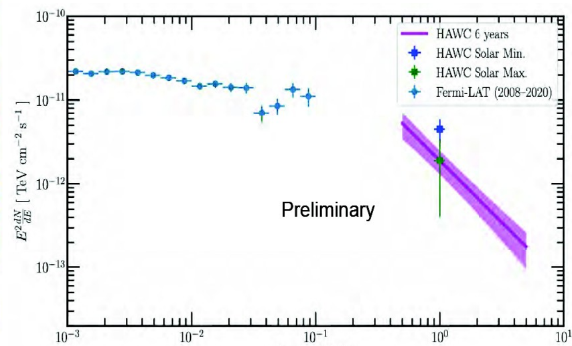


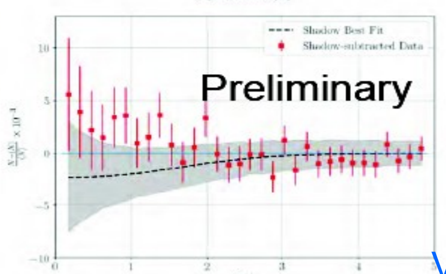
At multi-TeV energies the Sun is mainly a “negative source”, but knowing its shadow amplitude and shape, we can subtract it from the map, (1) detecting the Sun in gamma-rays, and (2) we can compare Solar Maximum and Solar Minimum.

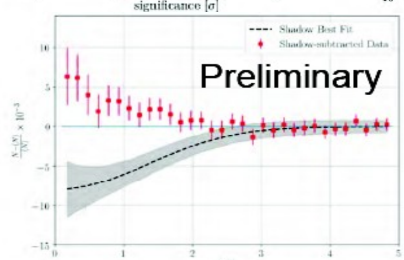












Conclusions (+ CR, DM UL, fundamental physics...)

Just reminding that in addition to the topics summarized here (searching for *hadronic Pevatrons*, *VHE Pulsar Wind Nebulae*, *Galactic Center*, *Binary Systems* and *Microquasars, Active Galactic Nuclei* and *Solar Physics*) there are several other HAWC activities that I could not mention here, such as:

Cosmic Rays studies: we just published the H + He energy spectrum *Albert et al. 2021 Phys. Rev. D 105, 063021* and we are now studying the "all particle" energy spectrum (some preliminary spectra are in the spare slides)

Dark Matter upper limits for several targets, such as dwarf galaxies *Albert et al. 2020 Phys. Rev. D 101, id.103001*, Andromeda galaxy *Abeysekara et al. 2018 JCAP, Issue 06, article id. 043*, and the Galactic Halo *Abeysekara et al. 2018 JCAP, Issue 02, article id. 049* .

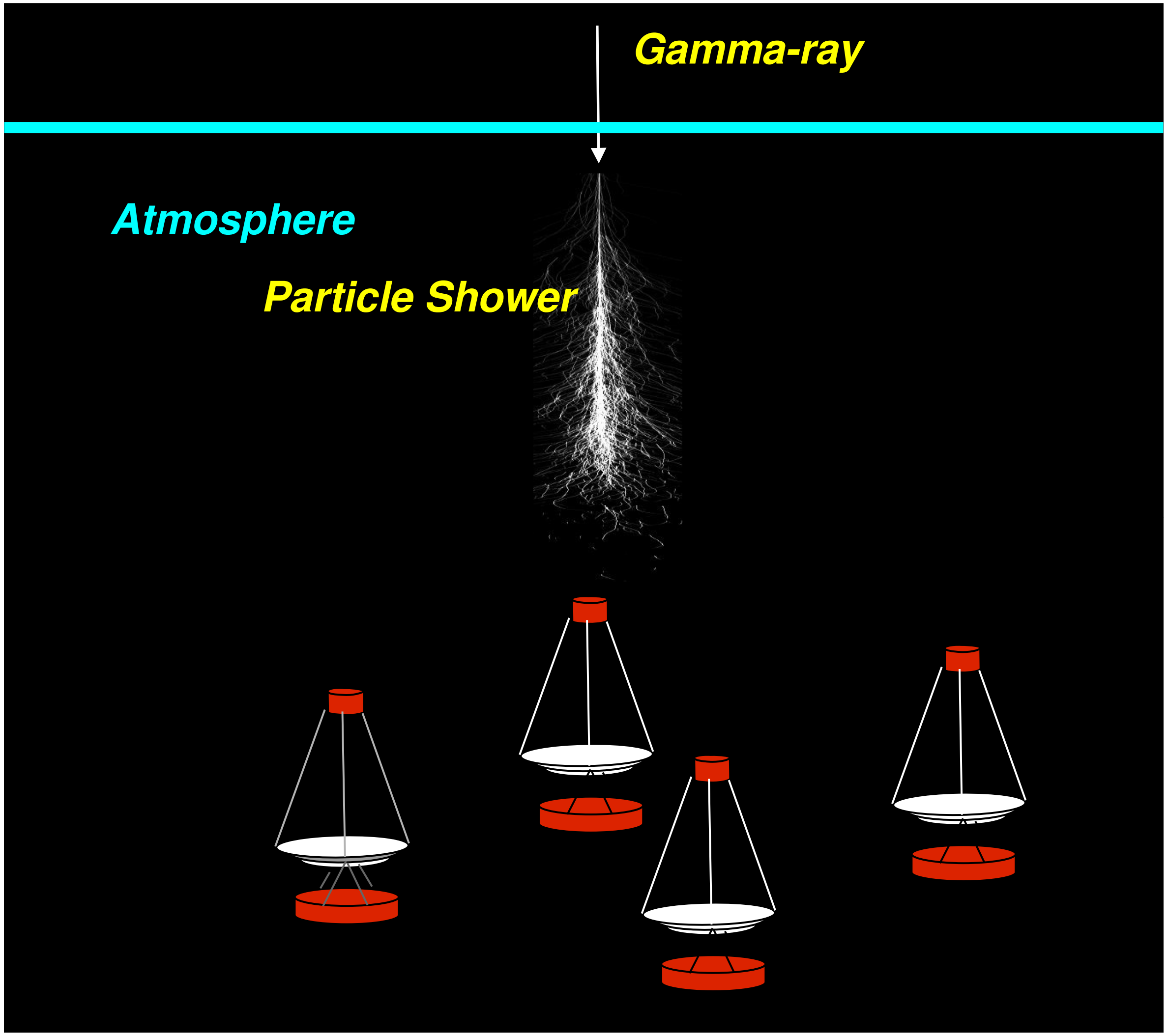
Fundamental Physics, such as constraining on Lorentz invariance violations *Albert et al. 2020 PRL 124, 131101*.

(Obviously) Multimessenger activities, such as searching for gamma-ray counterparts of GW (e.g. *Abbott et al. 2017; ApJ, 848, id. L12*) and neutrino (e.g. *Aartsen et al. 2017; A&A, 607, id. 115*) events.

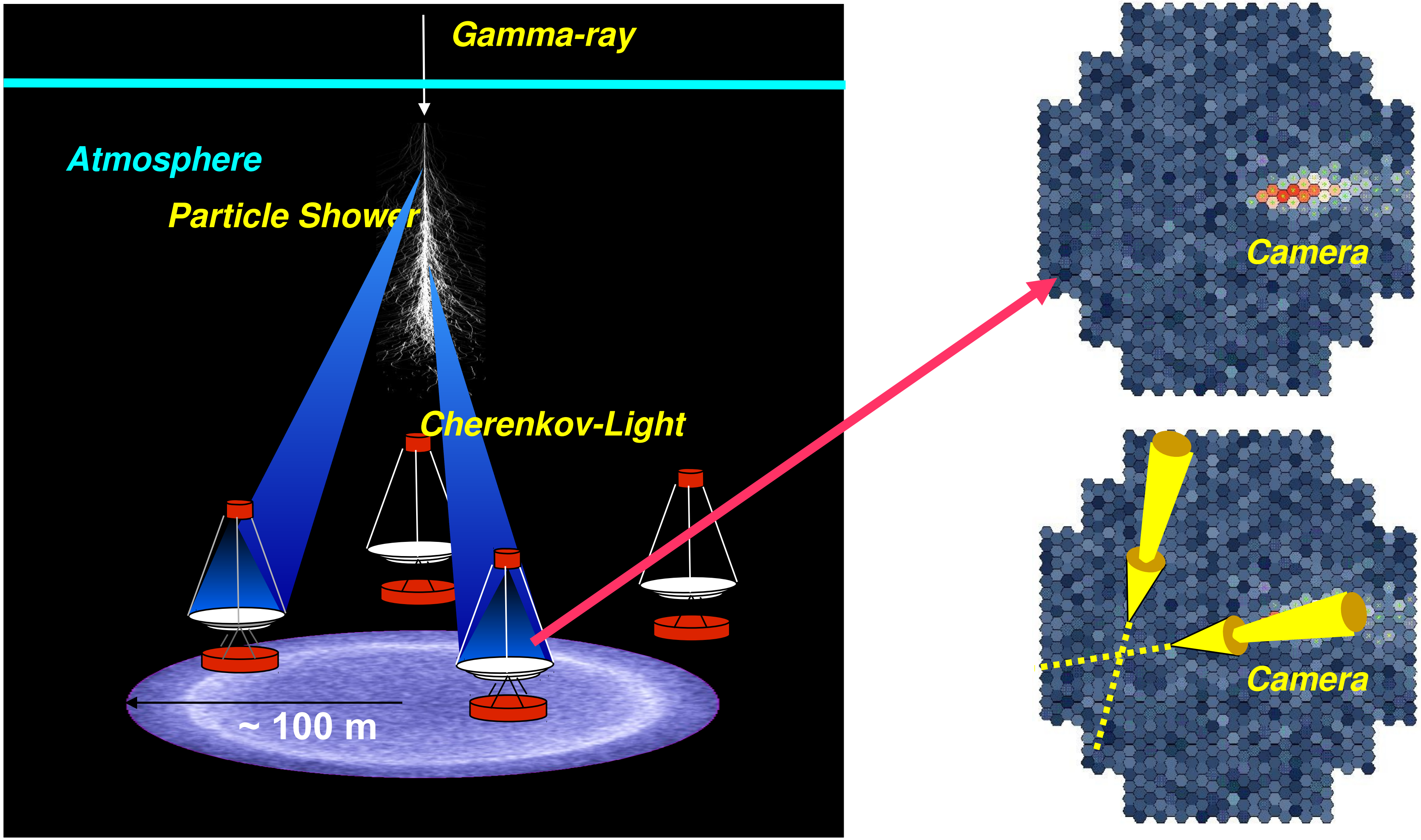
Thanks for your attention!

Spare slides

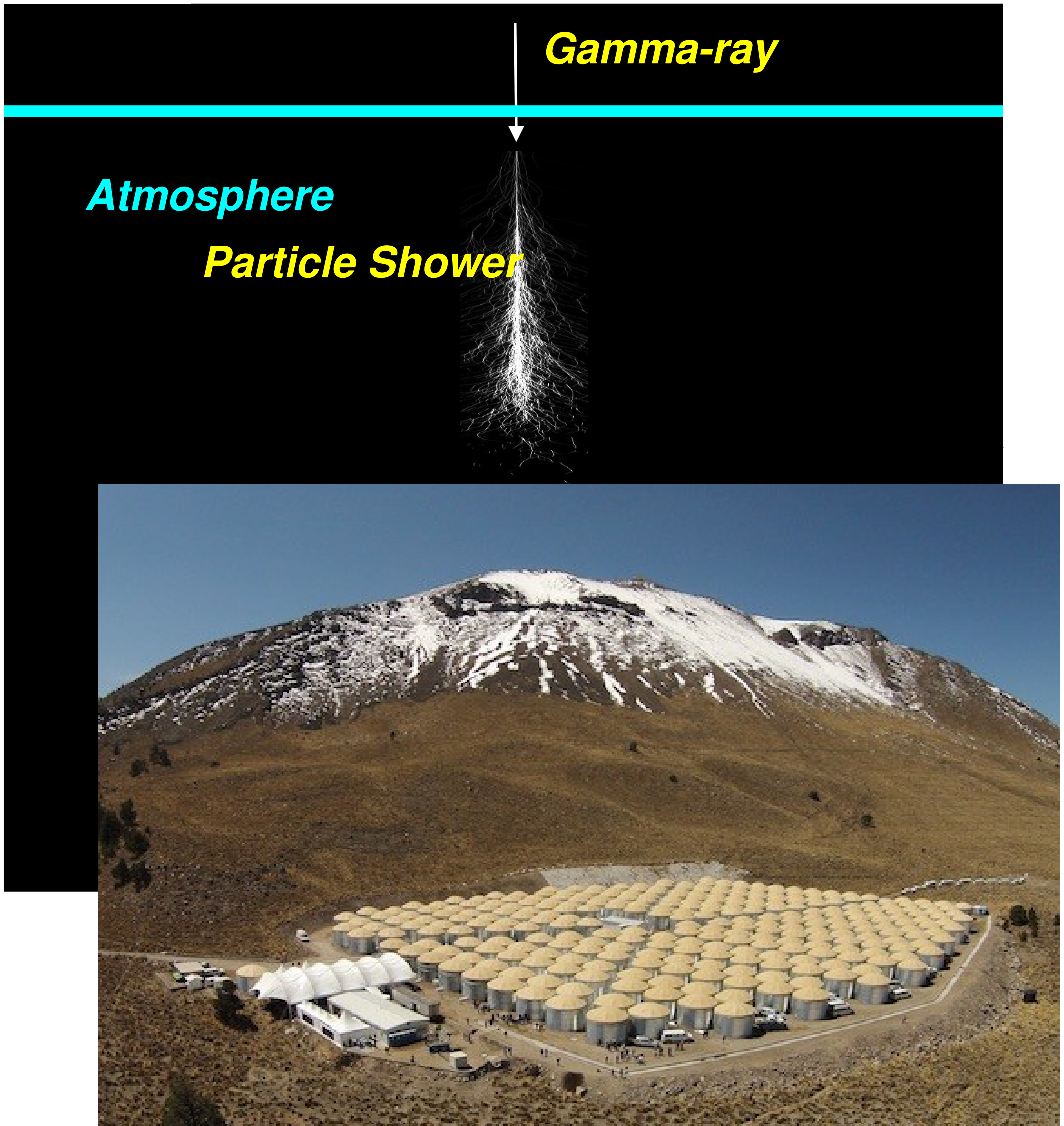
Detection principle (IACT)



Detection principle: IACT stereo approach



Water Cherenkov - HAWC



...or a different kind of detector, such as EAS (Extensive Air Shower) detectors, (e.g. Milagro, ARGO-YBJ, etc.)

300 Water Cherenkov Detectors, (covering an area of four football fields)

HAWC: High Altitude Water Cherenkov Observatory

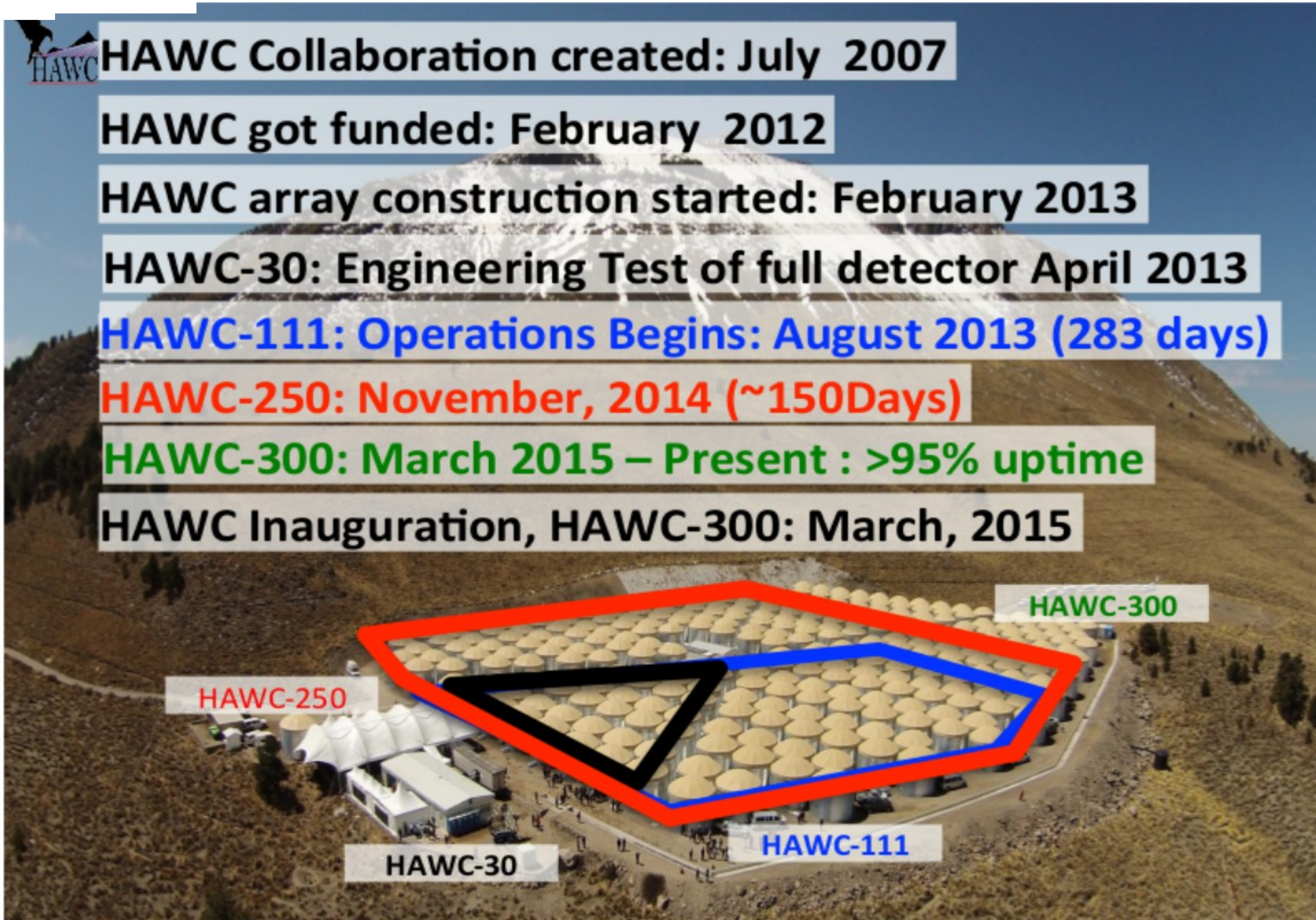
2 main advantages (if compared with IACTs):

- full-sky instrument

- no limited duty cycle

HAWC construction

HAWC construction (more details)

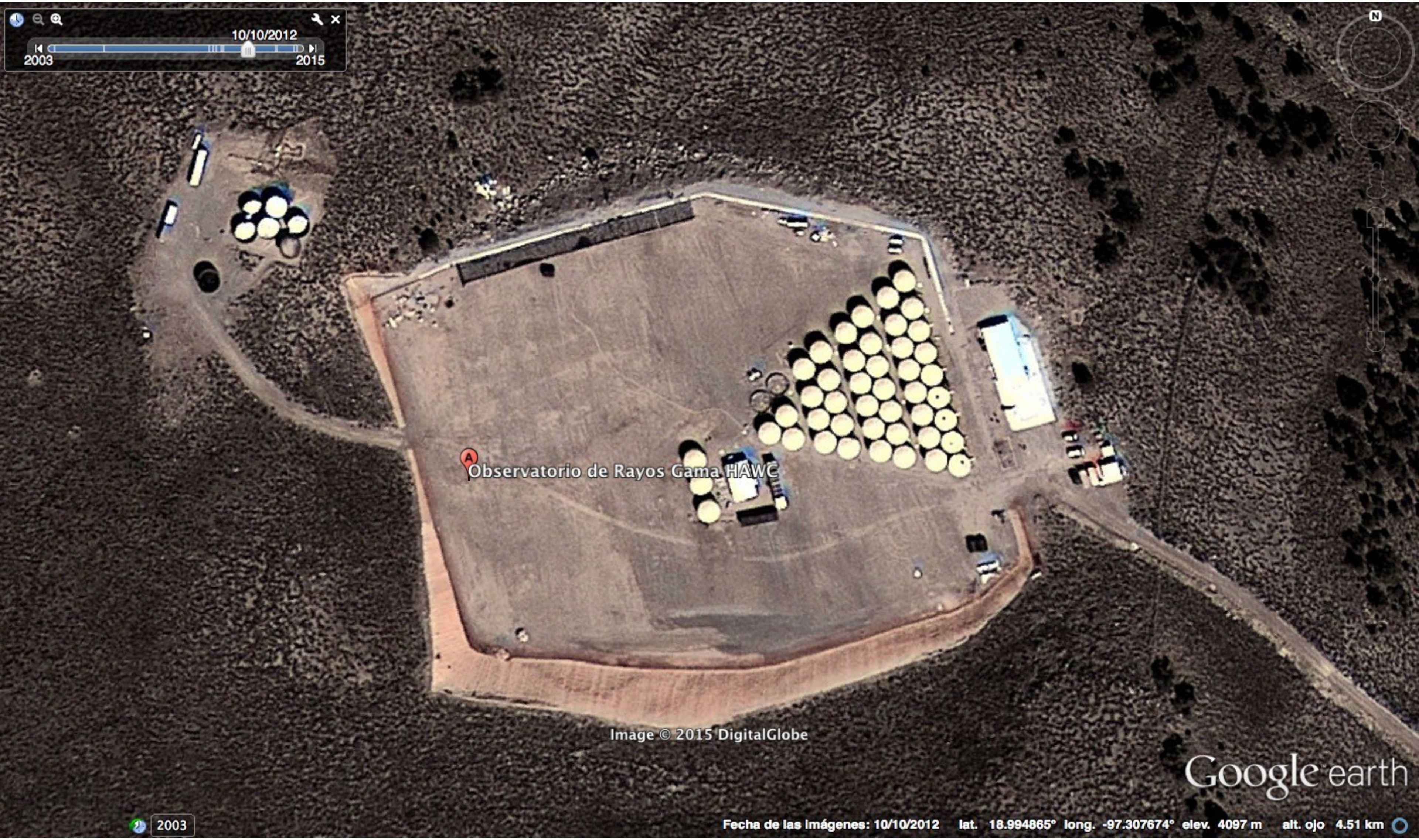


HAWC “timeline”

HAWC “timeline” (2)

HAWC “timeline” (3)

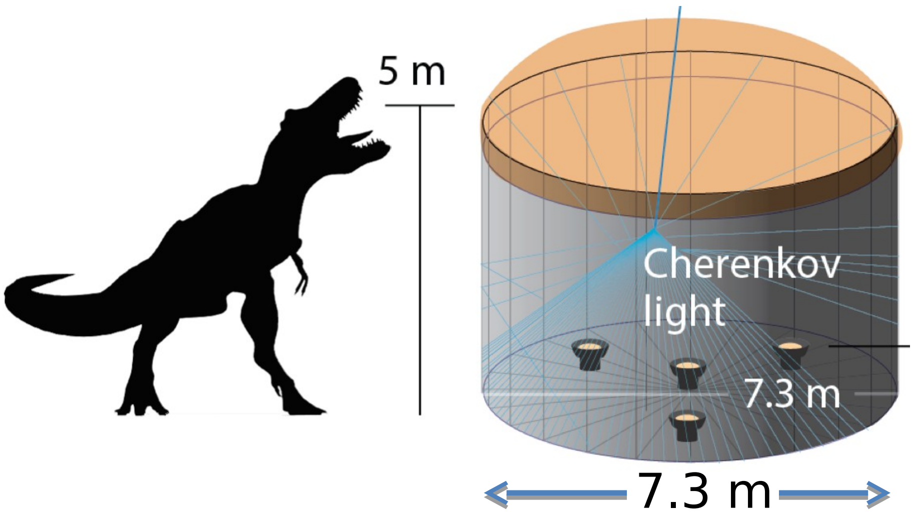
HAWC “timeline” (4)



HAWC “timeline” (5)

HAWC "timeline" (6)

300 Water Cherenkov Detectors



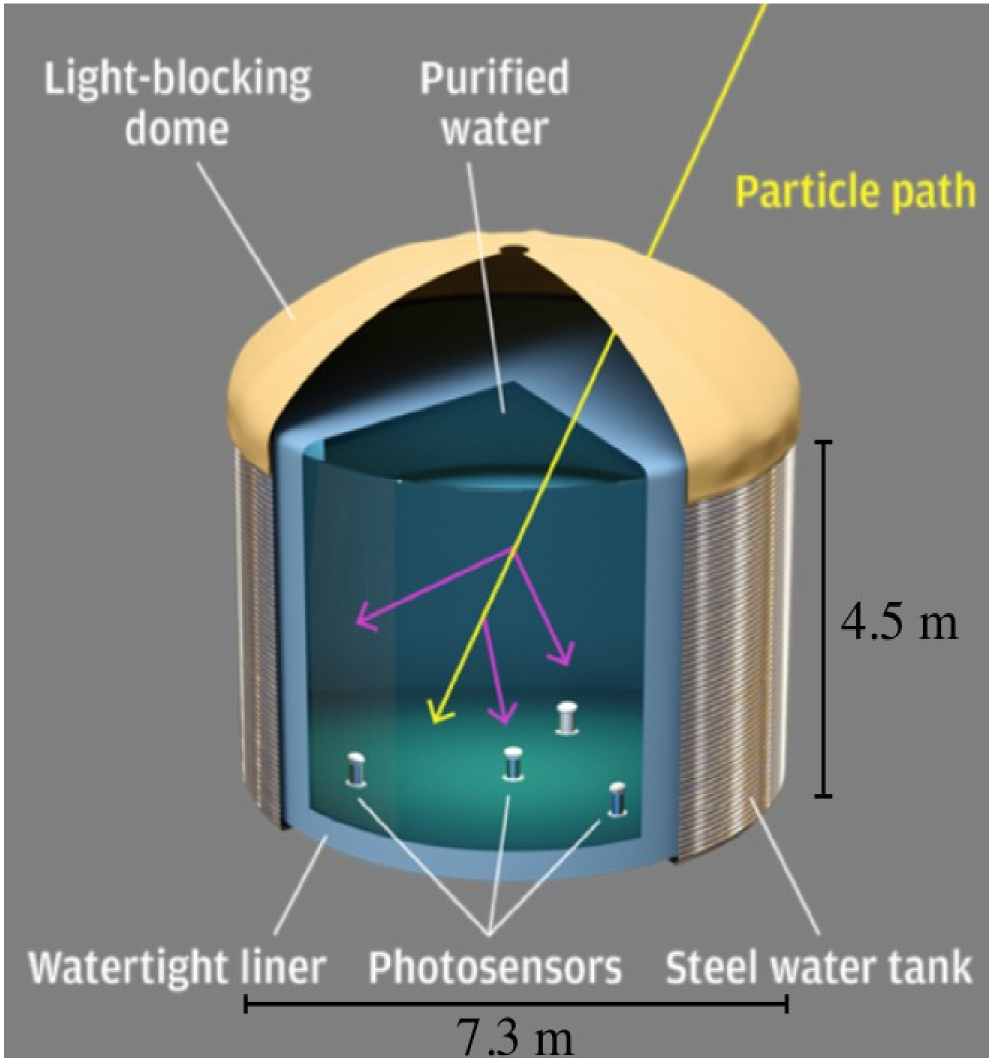
Each water cherenkov detector (WCD) contains 180000 liters of purified water (treated for transparency)

Each WCD has 4 PMTs: fast response and high QE to Cherenkov light

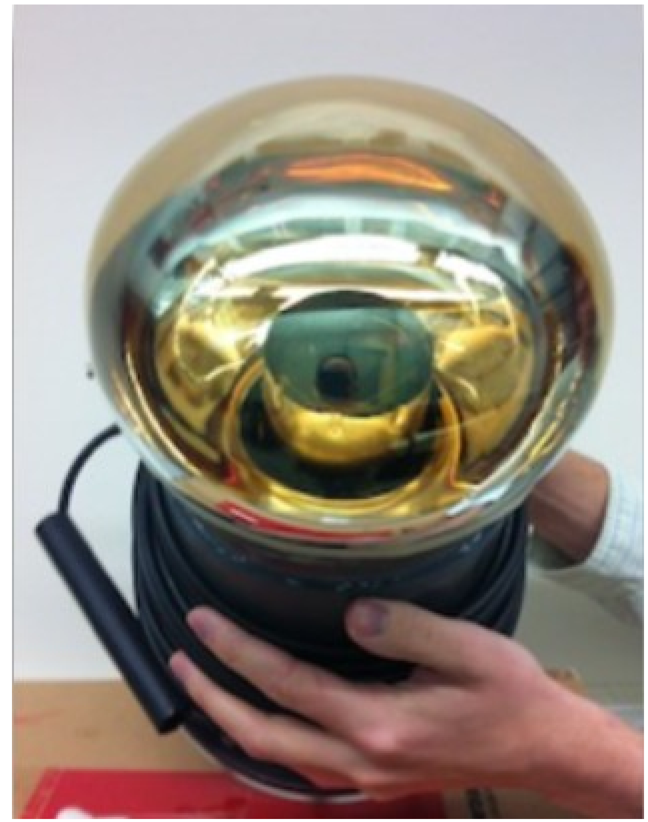
Optical fibre system for calibration

Each WCD is connected to the central counting house (180km of cabling)

Detection



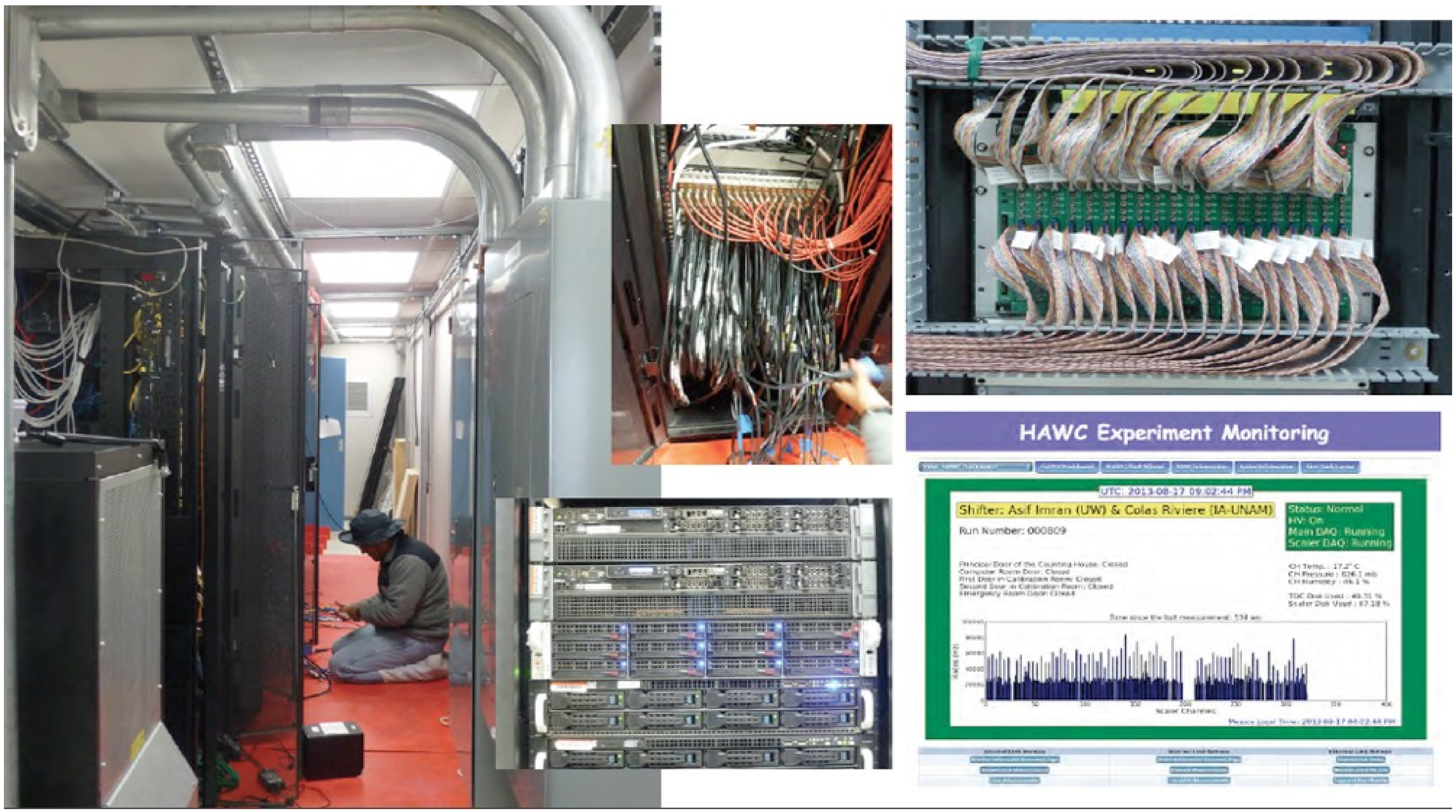
Light-blocking dome
Purified water
Particle path
4.5 m
Watertight liner
Photosensors
Steel water tank
7.3 m



Counting house & Datacenter

Each WCD is connected to the central counting house → 180 km of cables (!!)

HAWC registers 20000 cosmic rays per second and generates 2 Terabytes per day – every day
HAWC data centers at ICN-UNAM and UMD



Data analysis

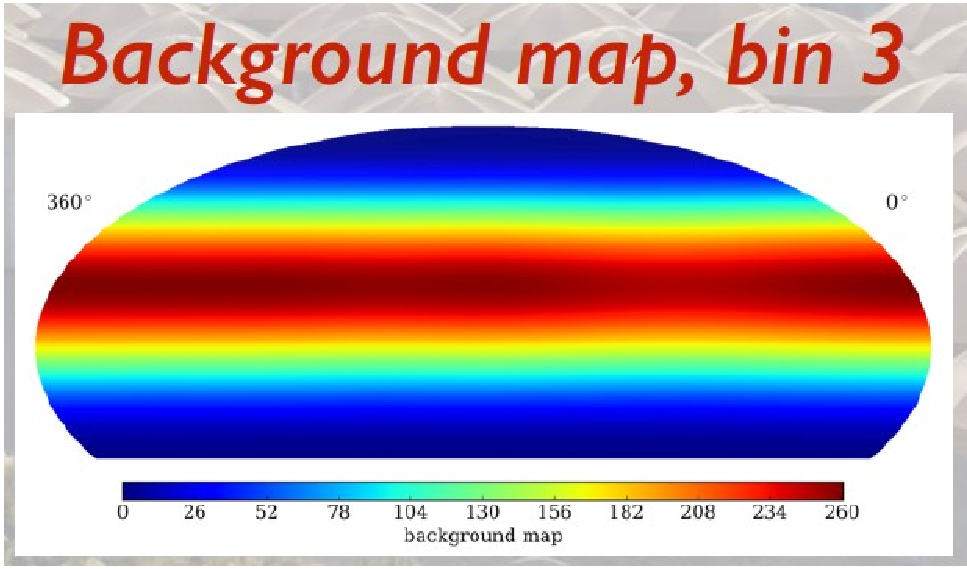
- we measure hits: time and charge in each channel.

- estimations of: core position, shower direction, size, gamma/hadron separation, energy

- we use 9 analysis bins, each with particular: event size, cuts, gamma/hadron efficiency, PSF, energy interval

- background maps (via direct integration)

- create maximum likelihood maps

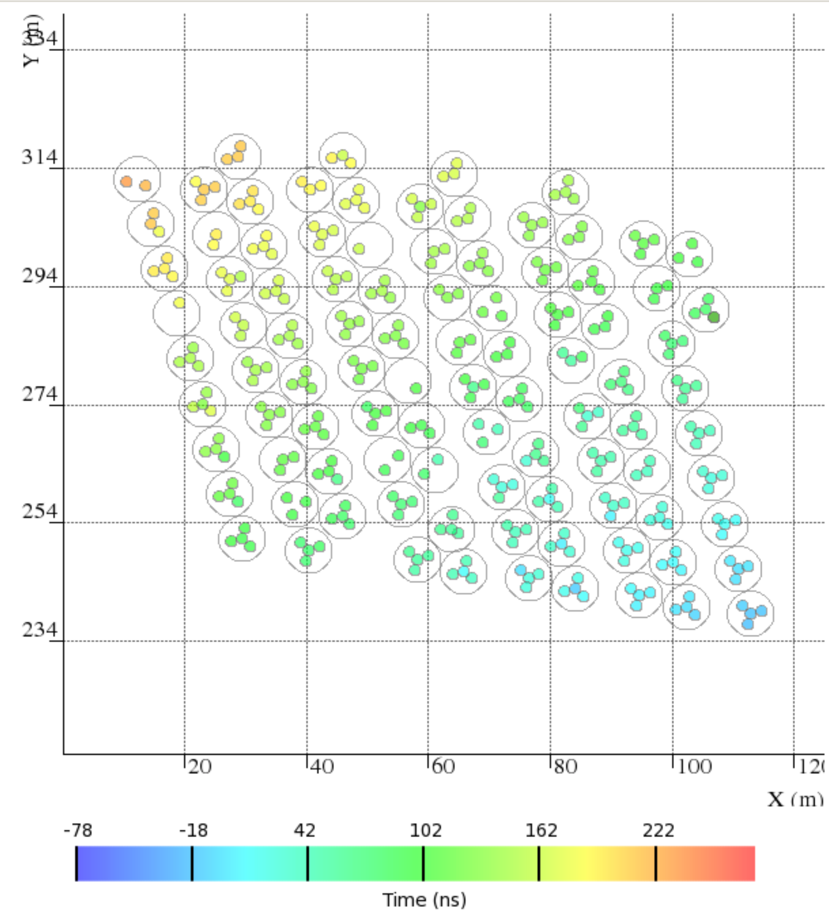


Timing information

- relative timing of PMT signals allows to determine the arrival direction of primary particles

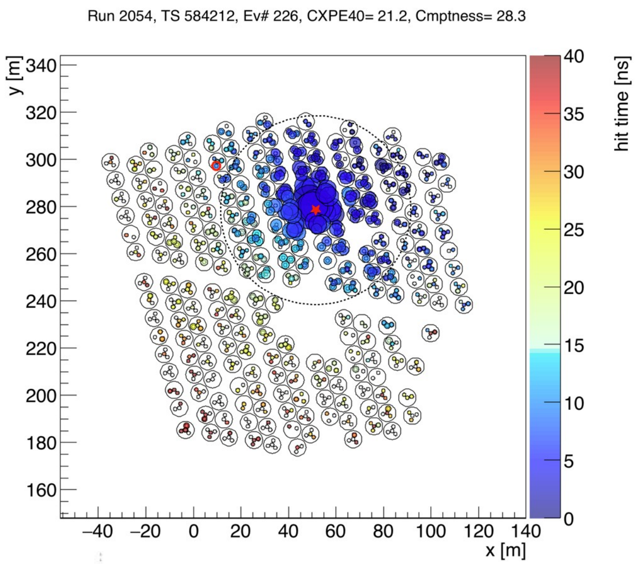
- tank spacing ~25 to 50 light-ns.

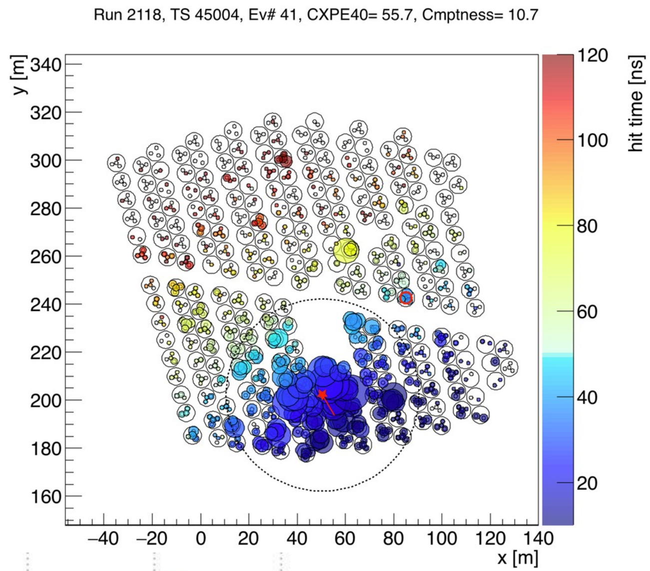
- arrival times are fitted to a curved plane with sub-ns timing residuals.



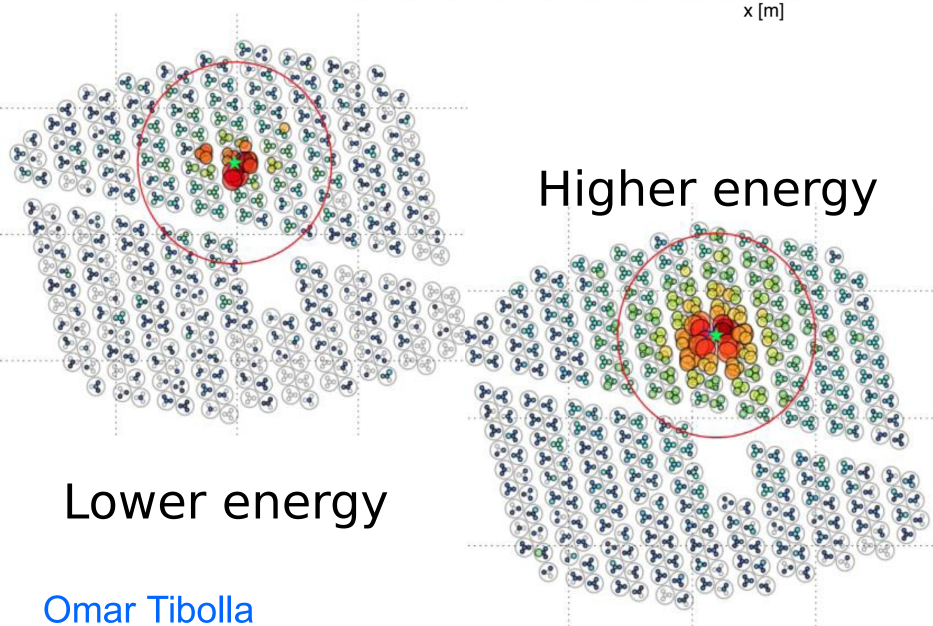
Gamma-hadron identification

gamma



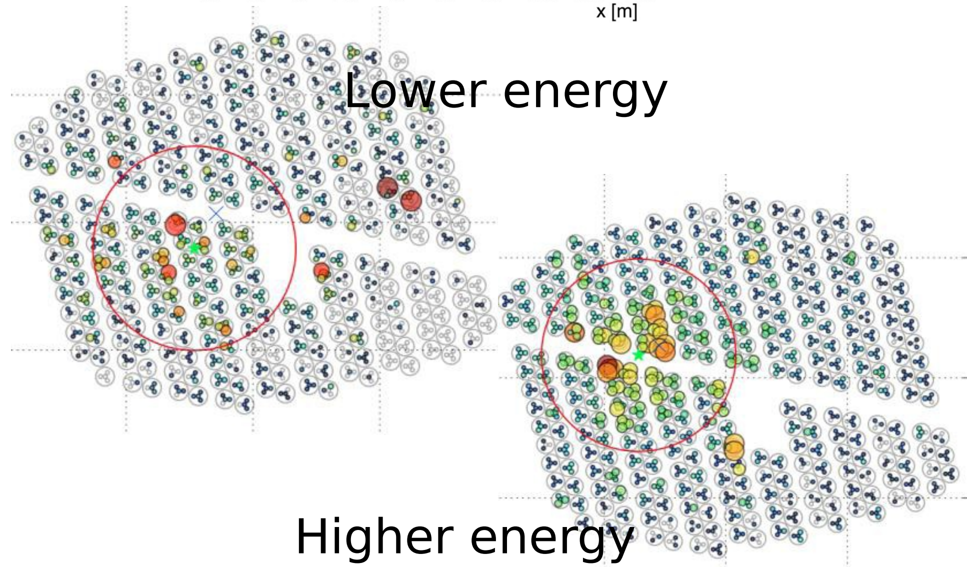


hadron



Lower energy

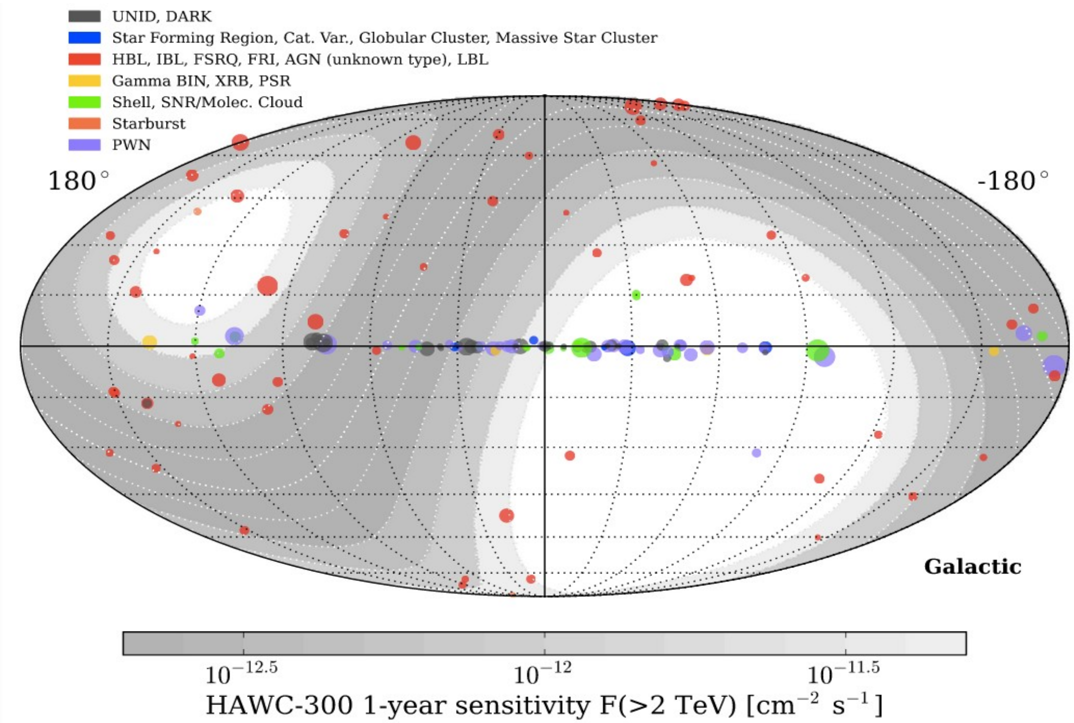
Higher energy



Lower energy

Higher energy

HAWC sensitivity & FoV



FoV ~1.8 sr

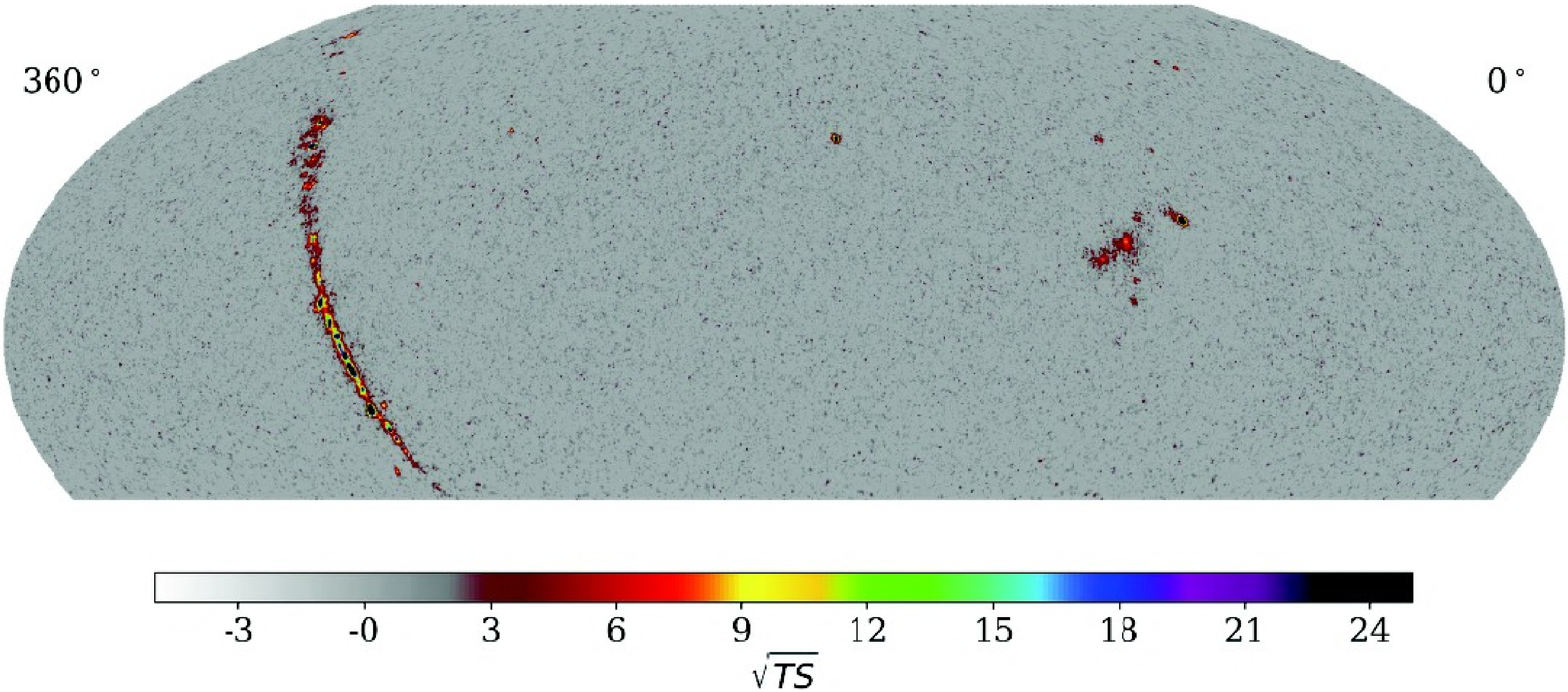
HAWC scans 2/3 of the celestial sphere every sidereal day to a depth of 1 Crab at 5 standard deviations.

i.e. ~60 mCrab/year

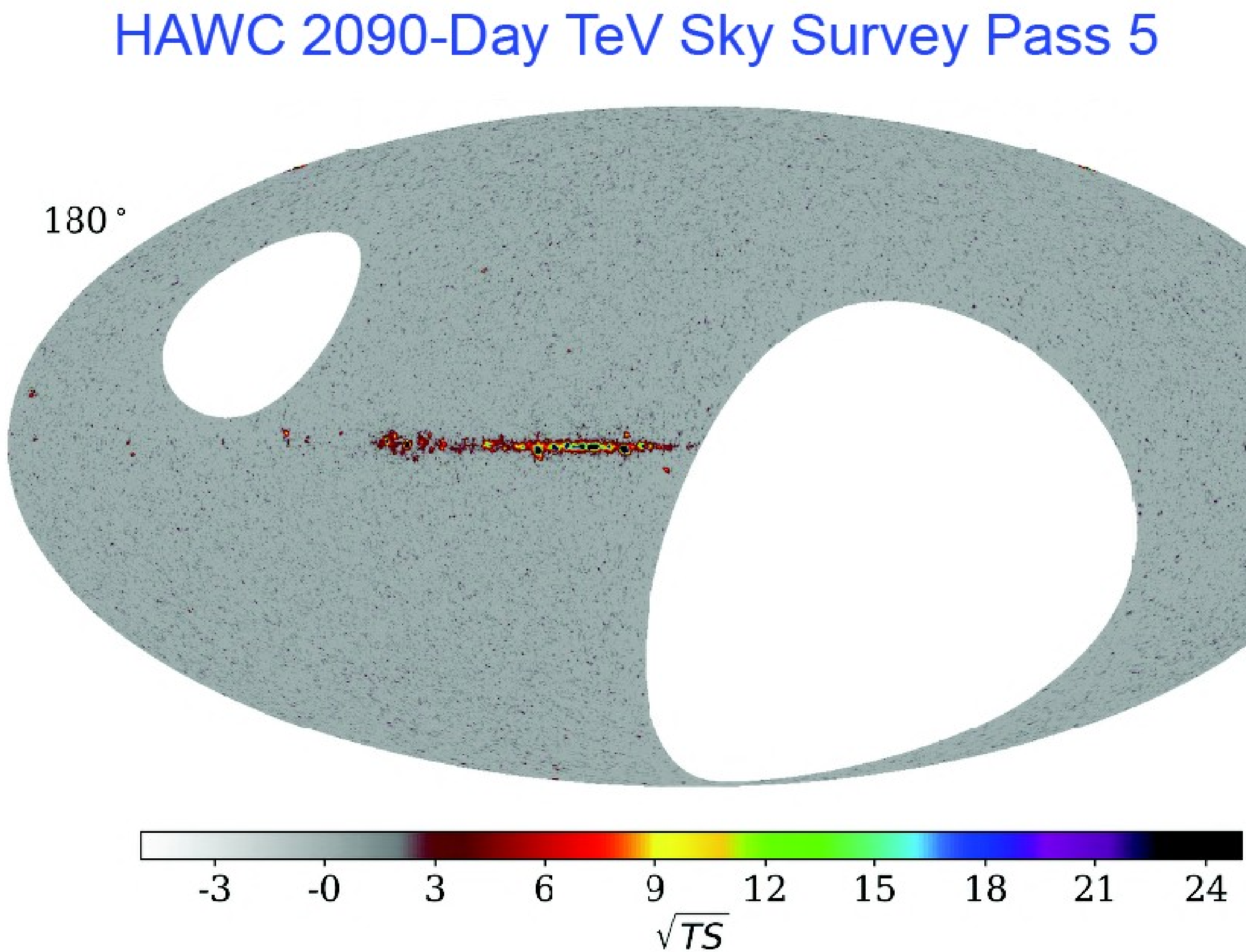
Allowing us to study transients and extended/diffuse sources

Pass 5 – Equatorial coordinates

HAWC Sky Map 2090 Days of Data - Pass 5



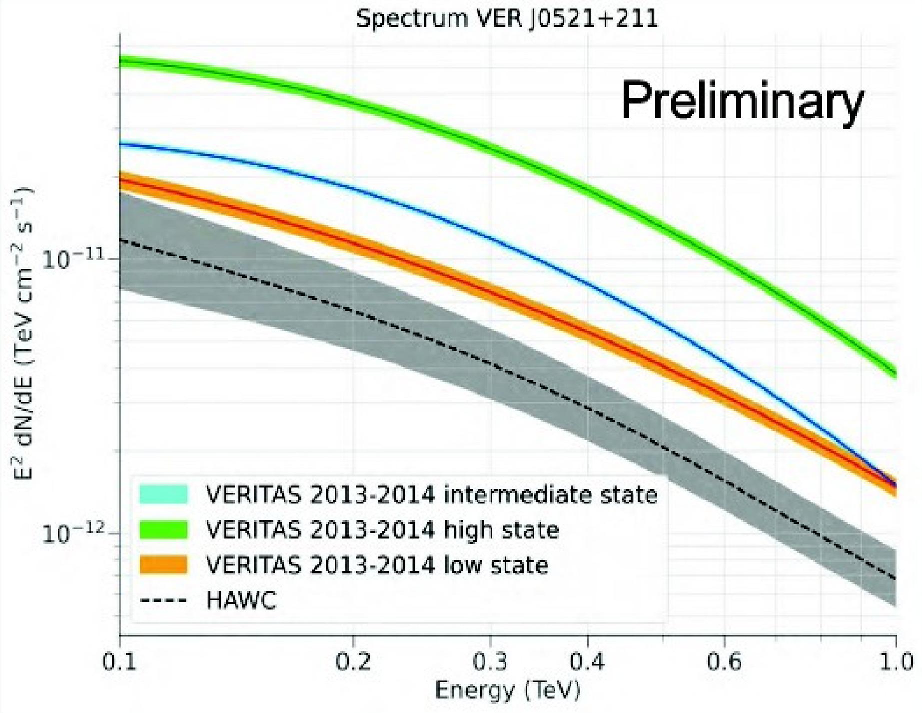
Pass 5 – Celestial coordinates



Spectrum of VER J0521+211

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

- $K = 2.15 \pm 0.61 \times 10^{-12}\ \mathrm{TeV^{-1}cm^{-2}s^{-1}}$
- $\alpha = 2.75 \pm 0.32$
- $TS = 15.9\ (4.0\sigma)$

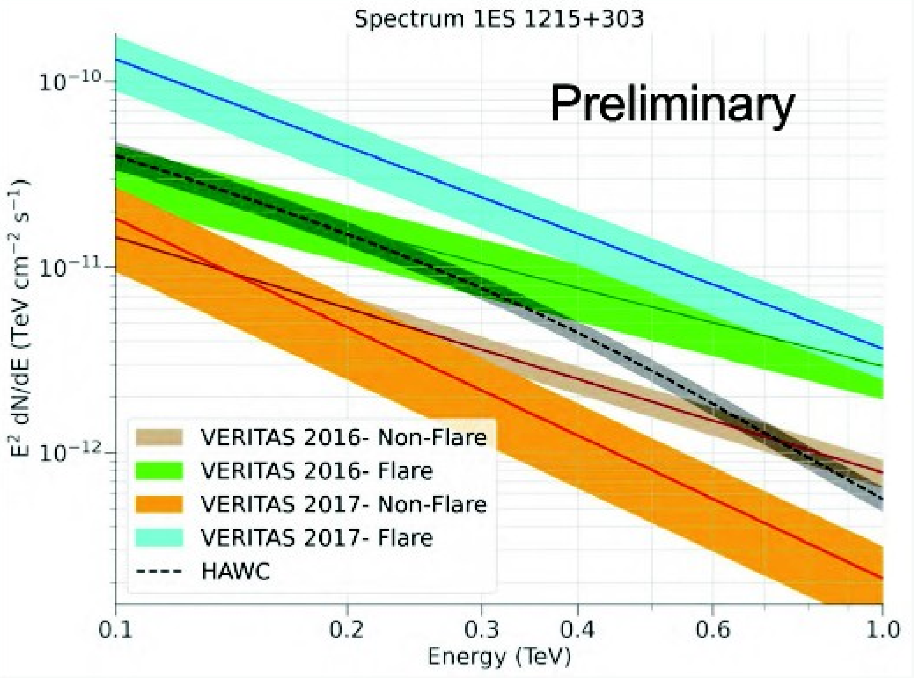


VERITAS results obtained from The VERITAS Coll. et al. 2022 https://arxiv.org/pdf/2205.02808.pdf

Spectrum of 1ES 1215+303

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

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

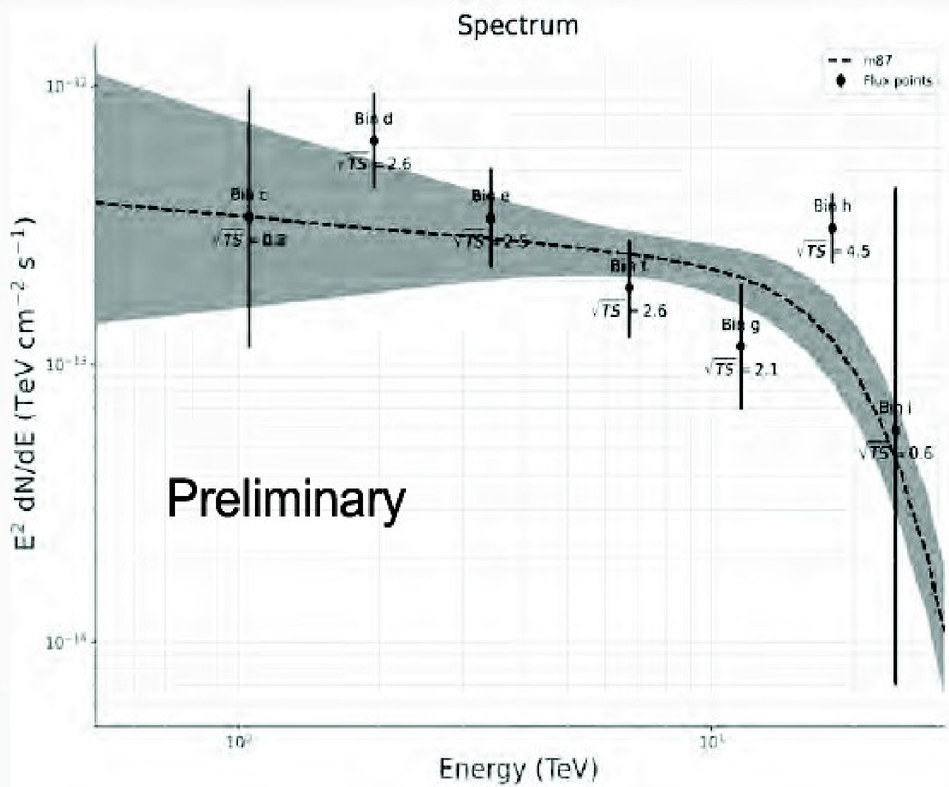


VERITAS results obtained from Valverde et al., 2020 https://iopscience.iop.org/article/10.3847/1538-4357/ab765d/pdf

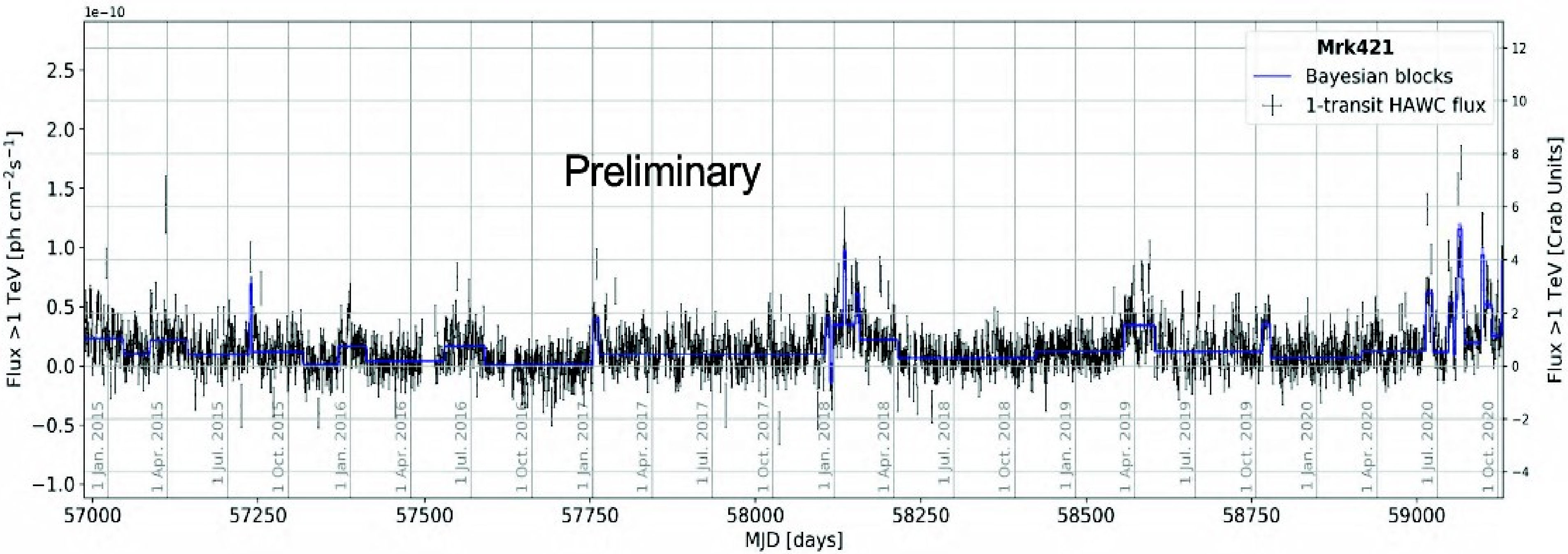
Spectrum of M87

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

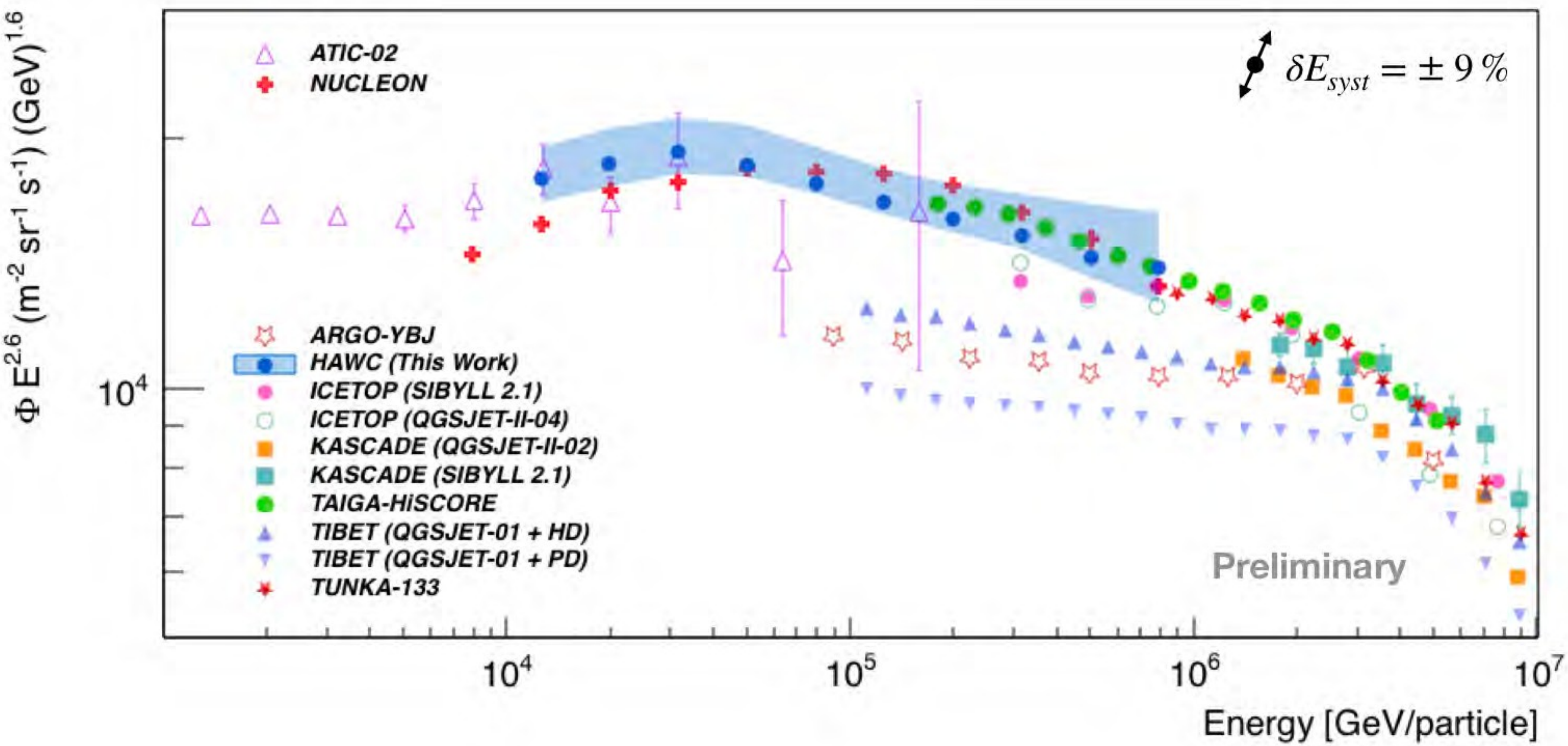
- $K = 3.7 \pm 3.1 \times 10^{-13}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\alpha = 2.1 \pm 0.5$
- $TS = 35.7\ (6\sigma)$



Daily monitoring of Mrk421

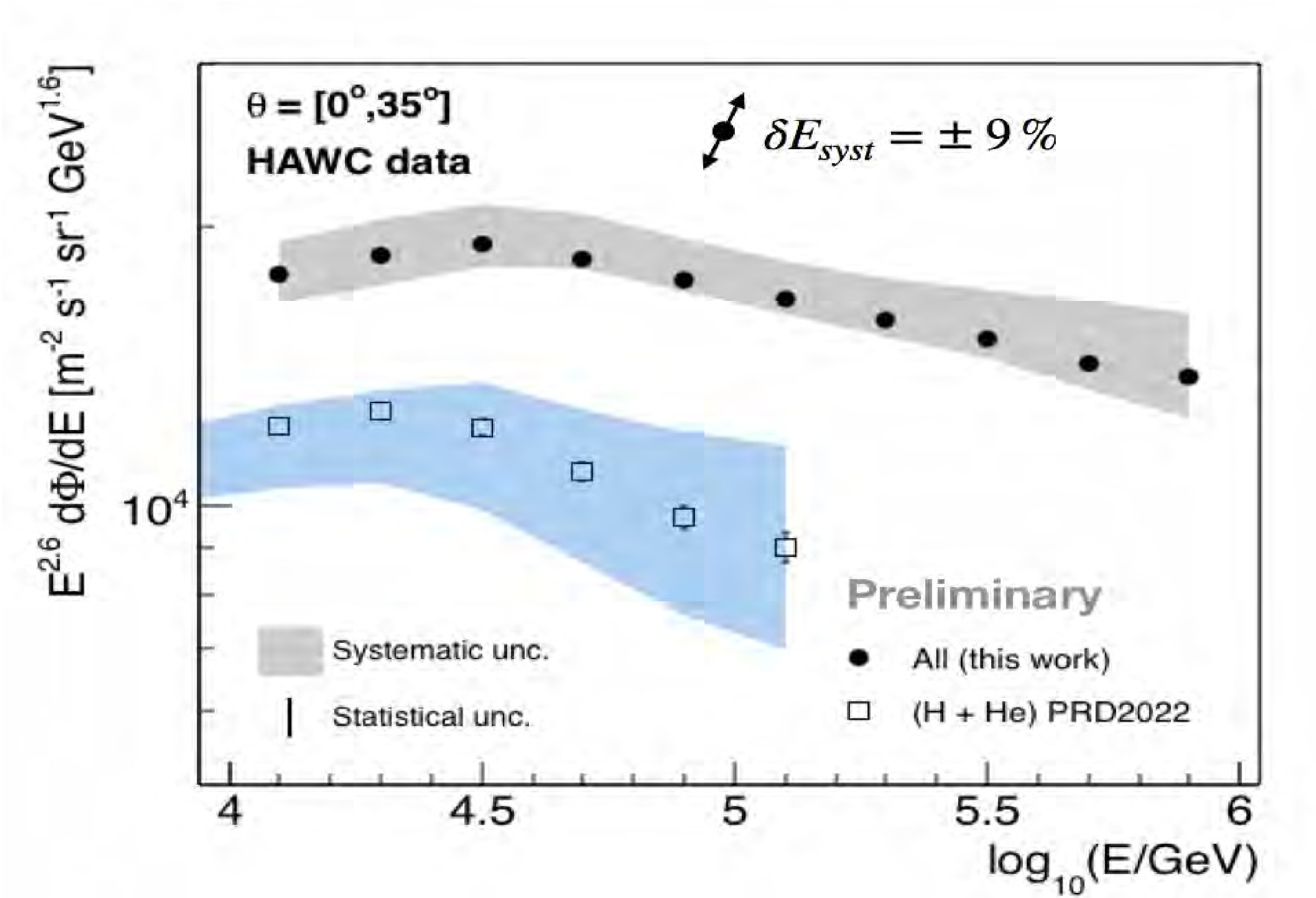


CRs



ATIC-02
NUCLEON
$\delta E_{syst} = \pm 9\,\%$
ARGO-YBJ
HAWC (This Work)
ICETOP (SIBYLL 2.1)
ICETOP (QGSJET-II-04)
KASCADE (QGSJET-II-02)
KASCADE (SIBYLL 2.1)
TAIGA-HiSCORE
TIBET (QGSJET-01 + HD)
TIBET (QGSJET-01 + PD)
TUNKA-133
Preliminary
$\Phi\ E^{2.6}\ (m^{-2}\ sr^{-1}\ s^{-1})\ (GeV)^{1.6}$
10^4
10^4
10^5
10^6
10^7
Energy [GeV/particle]

CRs



θ = [0°,35°]
HAWC data
$\delta E_{syst} = \pm 9\,\%$
$E^{2.6}\ d\Phi/dE\ [m^{-2}\ s^{-1}\ sr^{-1}\ GeV^{1.6}]$
10^4
Preliminary
Systematic unc.
Statistical unc.
All (this work)
(H + He) PRD2022
4
4.5
5
5.5
6
$\log_{10}(E/GeV)$