



Recent results from the HAWC experiment

Omar Tibolla
Universidad Politécnica de Pachuca
& Durham University



Collaboration



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
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**Universidad Nacional Autónoma
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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



Sierra Negra (4640 m): please note the Gran Telescopio Milimetrico (GTM)

Pico de Orizaba (5636 m)

HAWC

Latitude: +19 deg





High Altitude Water Cherenkov Observatory

HAWC Observatory

HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.



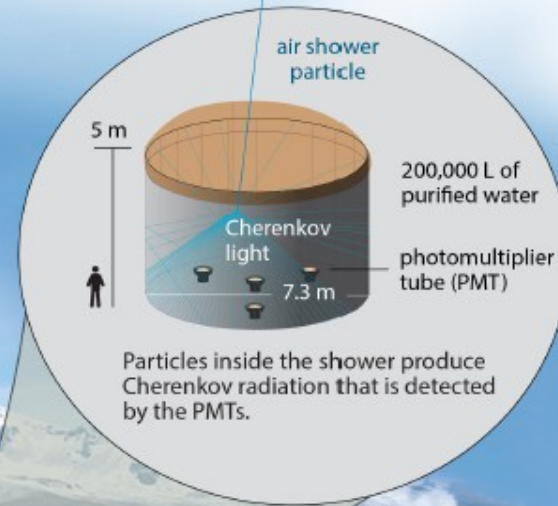
Pico de Orizaba
(5,626 m)

HAWC is located at 4,100 m above sea level, covering an area of 20,000 m².

HAWC

Water Cherenkov tank

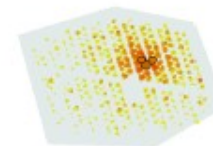
HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.



Gamma rays vs cosmic rays

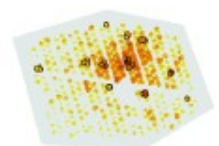
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower

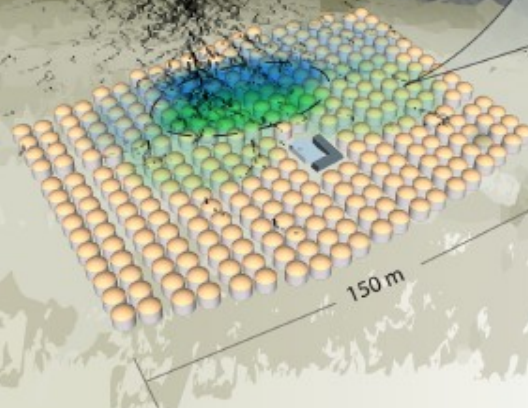


"hot" spots concentrate around the core

cosmic-ray shower



"hot" spots are more dispersed





HAWC summary

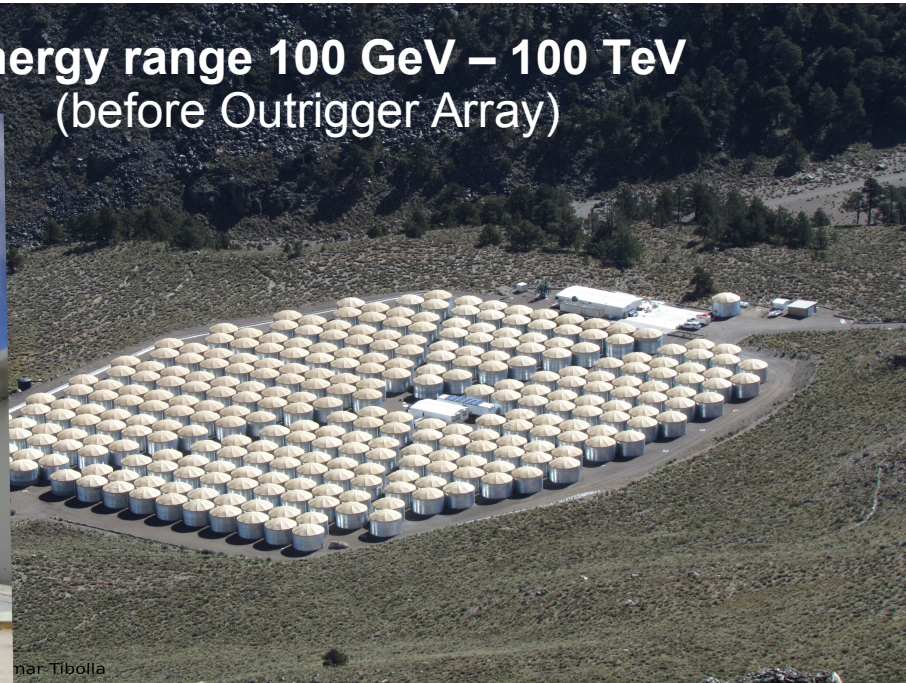
Instantaneous FOV = 1.8 Sr (15% of the sky)

HAWC scans 2/3 of the sky every sidereal day to a depth of 1 Crab at 5sigma

- transient events
- extended diffuse sources

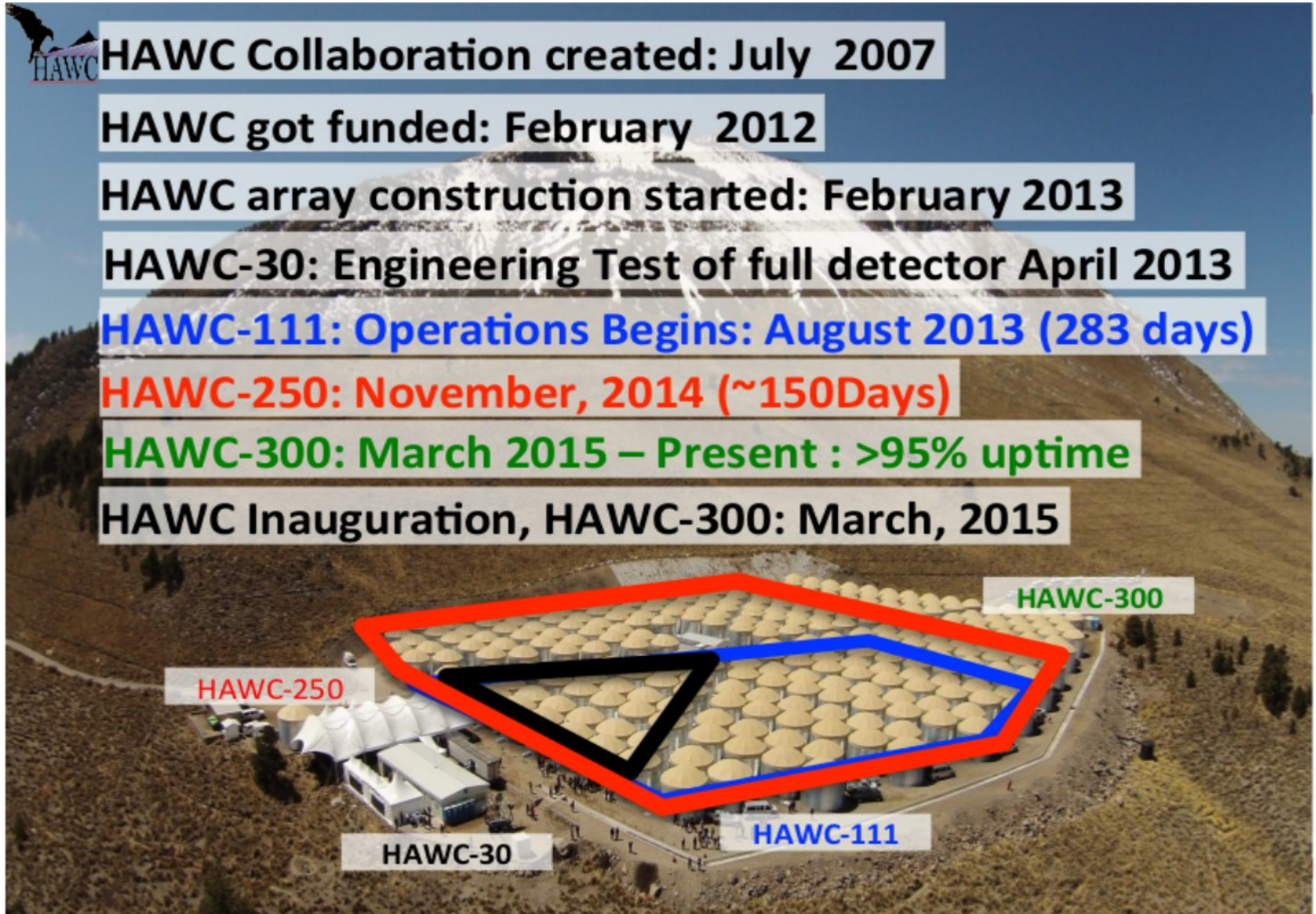
15 times more sensitive than Milagro (first generation water Cherenkov observatory)
HAWC registers 20000 cosmic rays per second and generates 2 Terabytes per day, every day (no limited duty cycle)

Energy range 100 GeV – 100 TeV
(before Outrigger Array)





HAWC construction

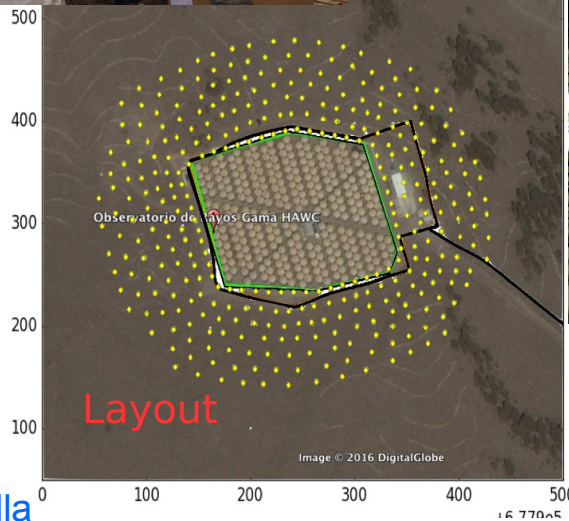




Hardware upgrade: Outrigger Array

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



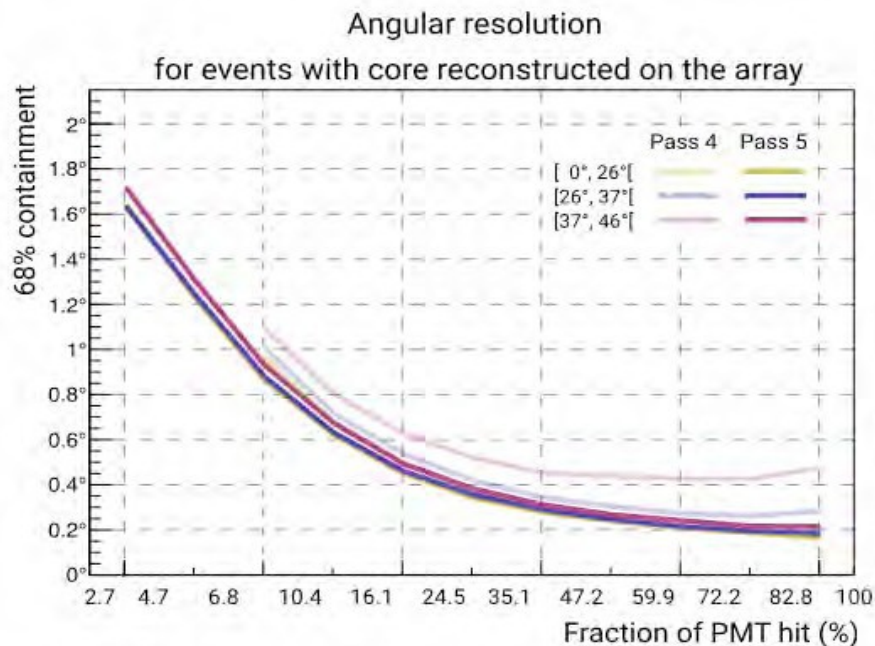
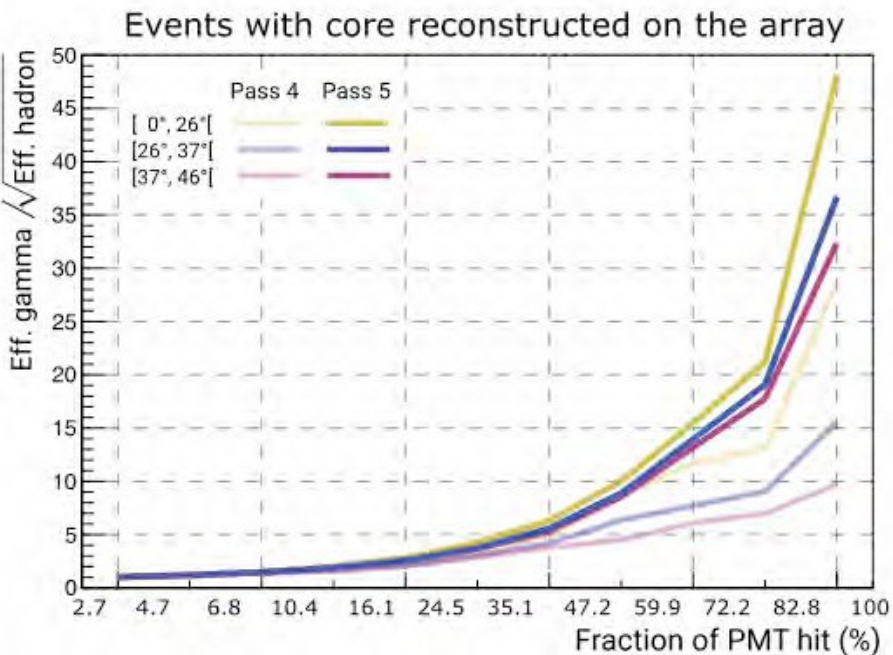


NEW "Pass 5" Improved Reconstruction

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

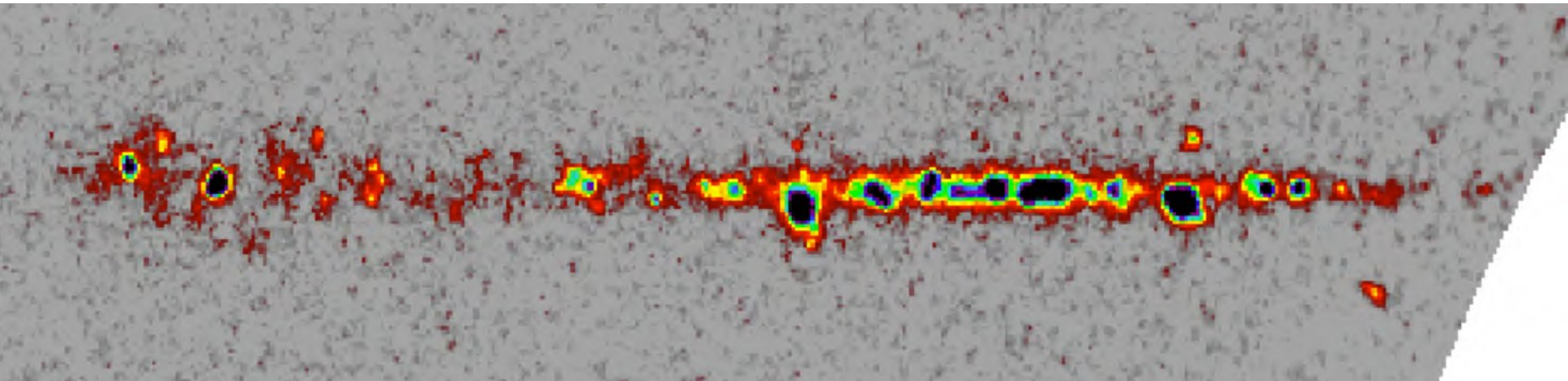
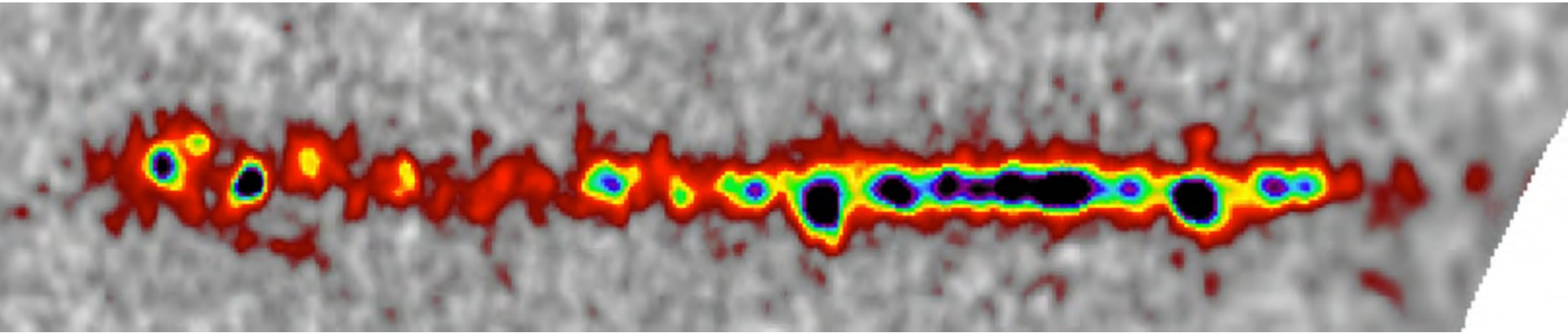


PRELIMINARY



“Pass 4” VS “Pass 5”

Comparing “Pass 4” (1523 days)



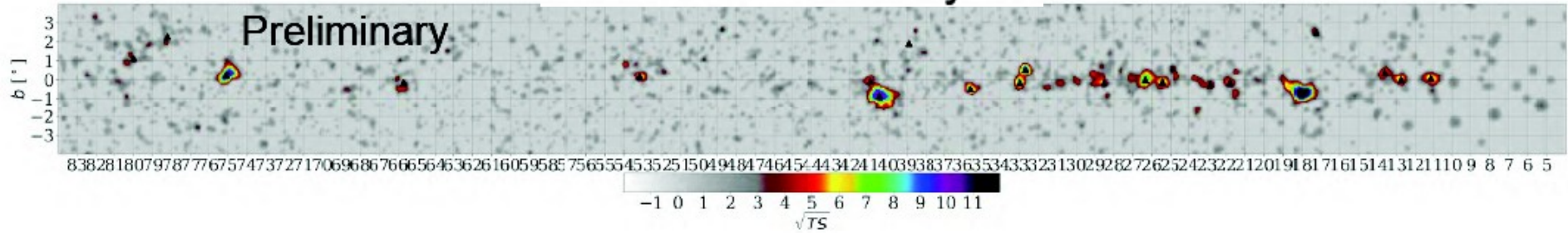
with “Pass 5” (2090 days)



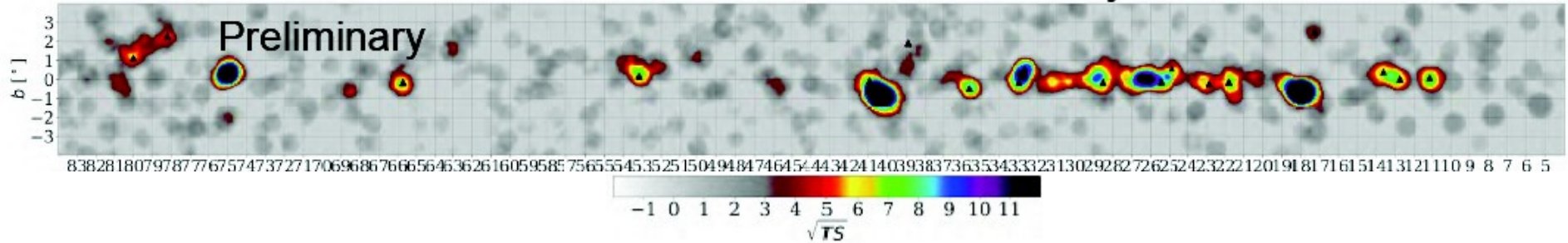
Pushing to the highest energies (>56 TeV)

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

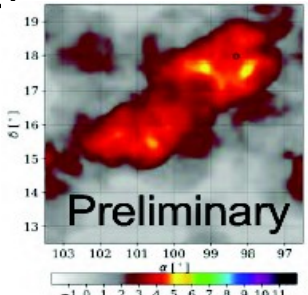
Point Source Analysis



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)

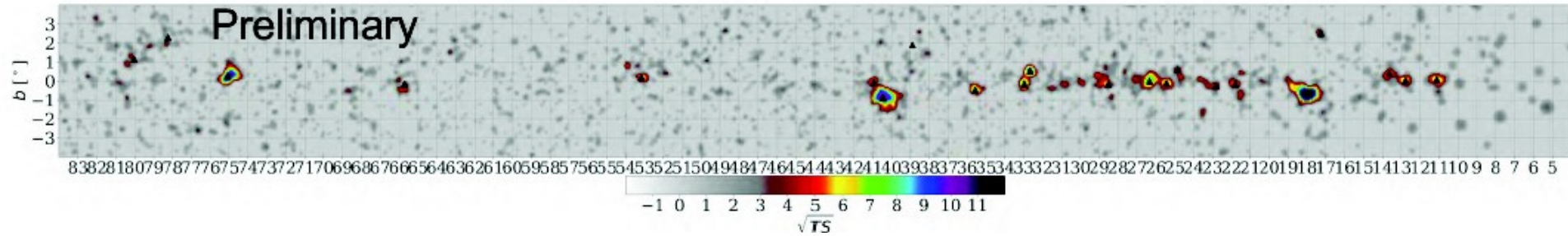


e.g. >56 TeV Geminga “TeV Halo”

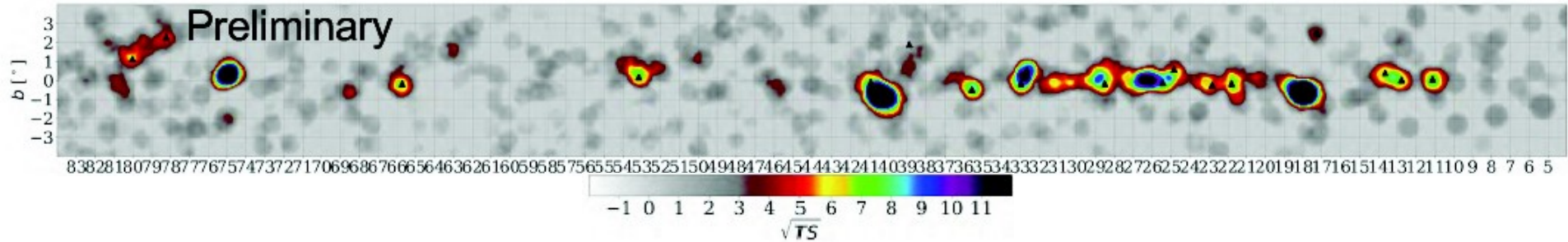


Pushing to the highest energies (>100 TeV)

Point Source Analysis



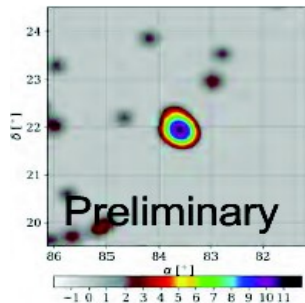
0.5° Extended Source Analysis



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.

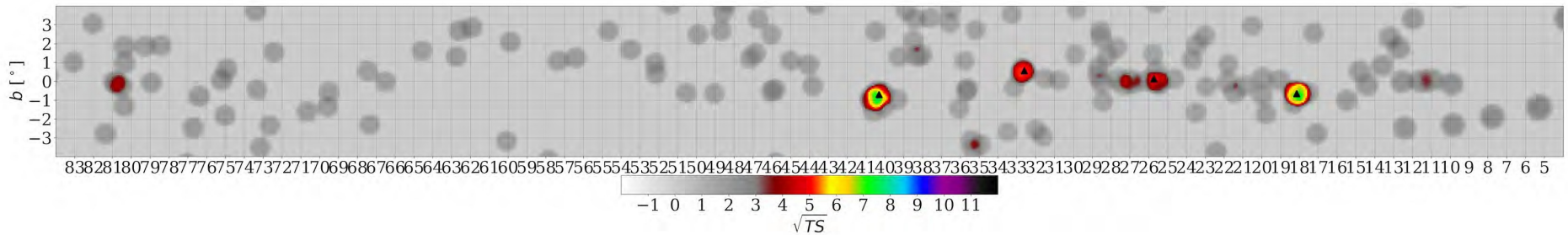
(the ratio of PWN and Unids seems increasing...)

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





Pushing to the highest energies (>177 TeV)

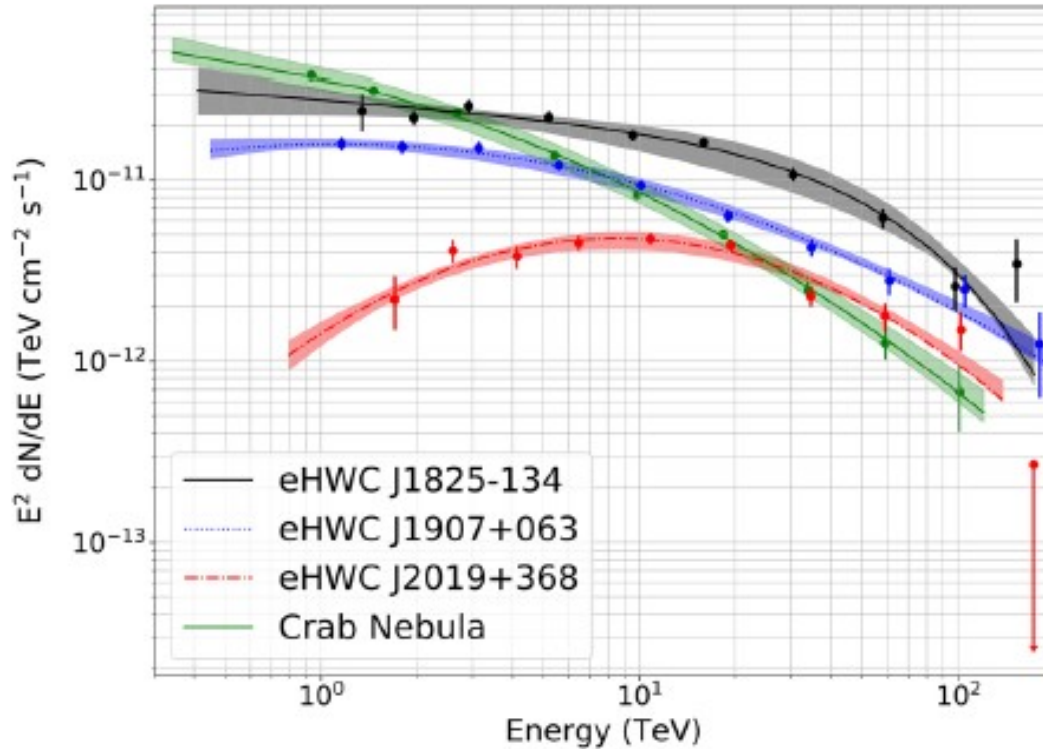


Within Pass 5, 4 sources are identified above 177 TeV (none in Pass 4). Most of these sources appear to be extended. 3 of them are PWNe and 1 is Unidentified.

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...

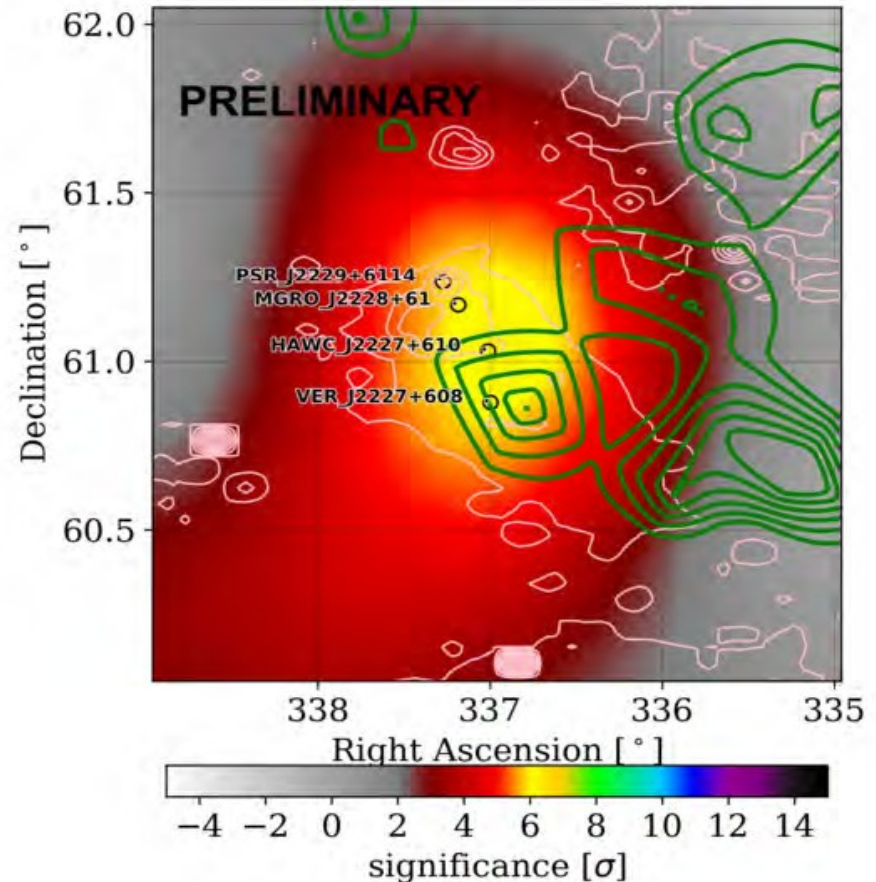


HAWC J2227+ 610 (Boomerang region)

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

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

Both hadronic and leptonic scenarios are plausible.

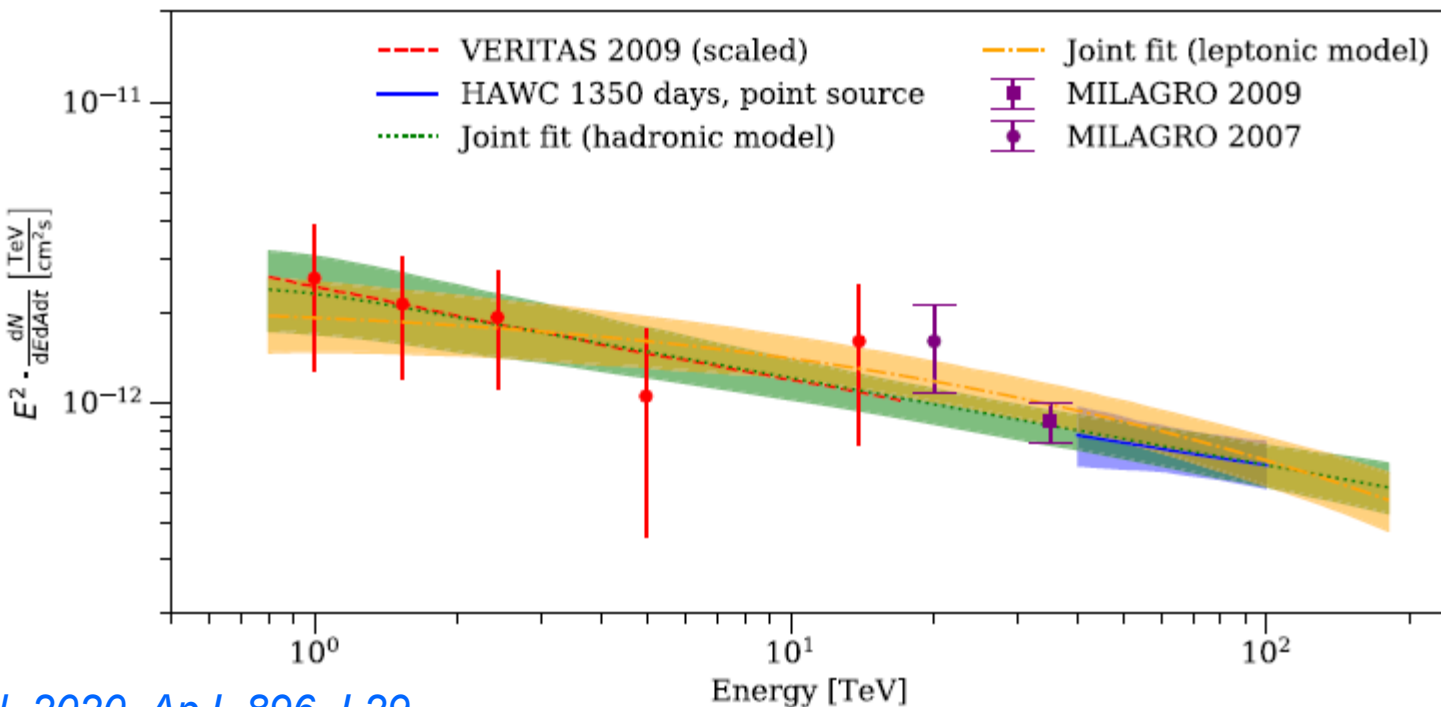


Albert et al. 2020, ApJ, 896, L29



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



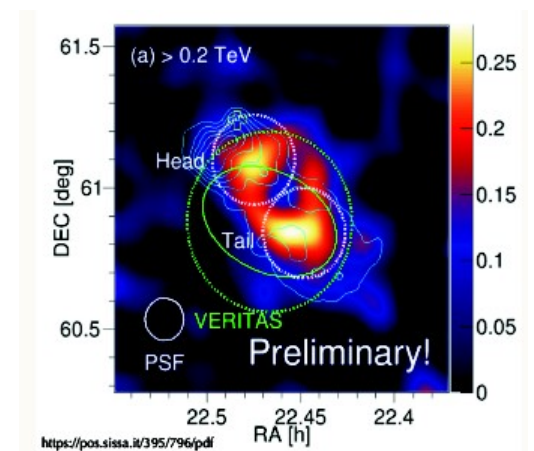
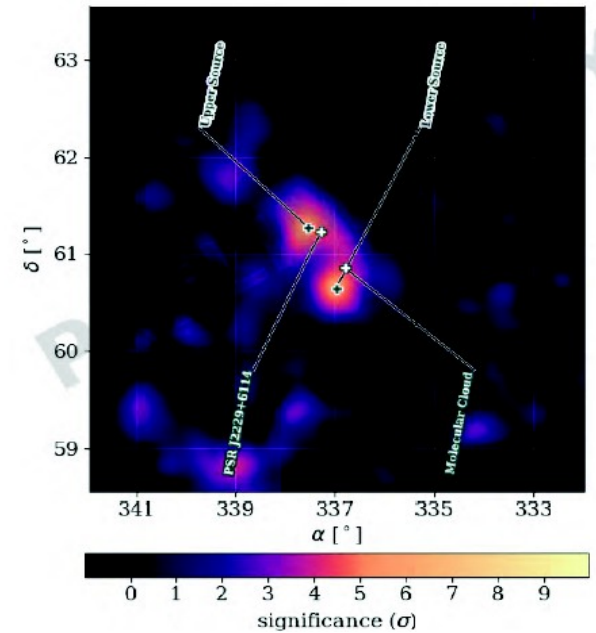
Boomerang in Pass 5

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

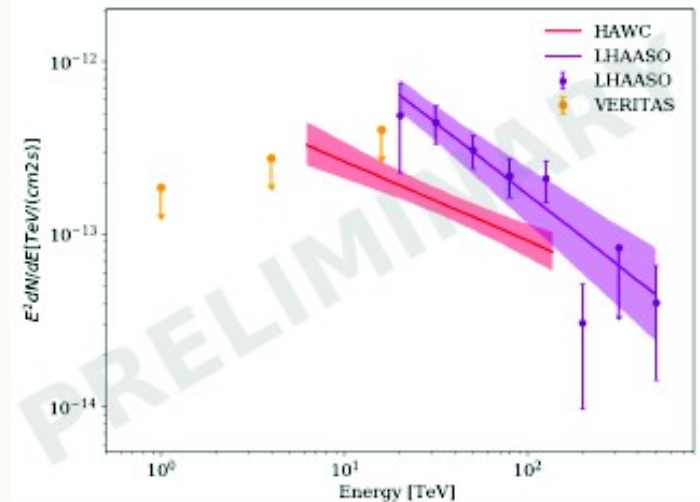
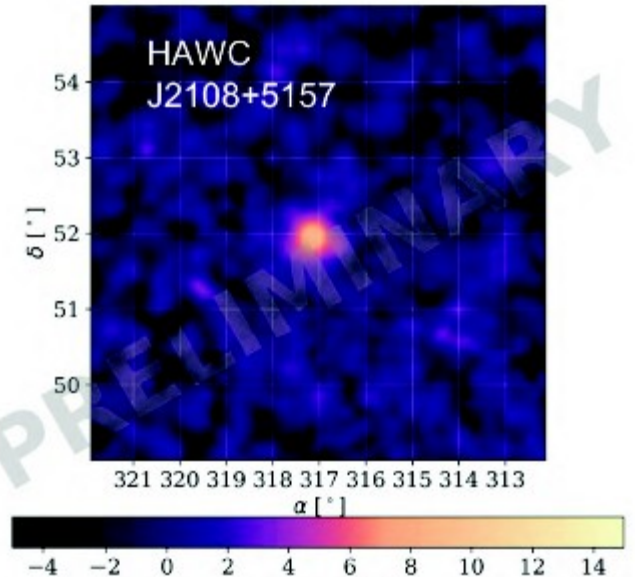
Discovered in LHAASO-KM2A survey

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

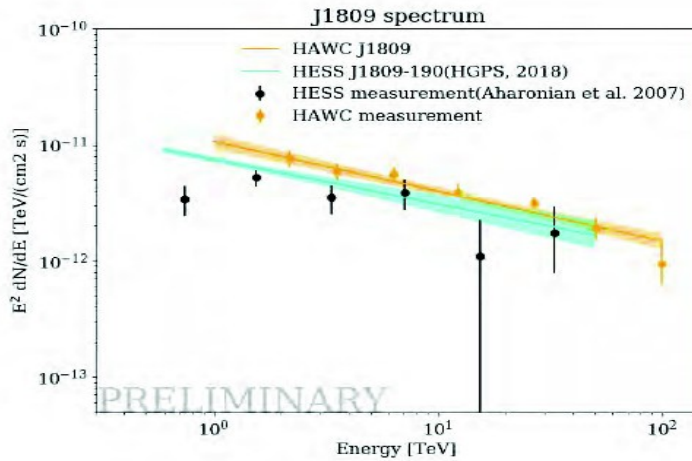
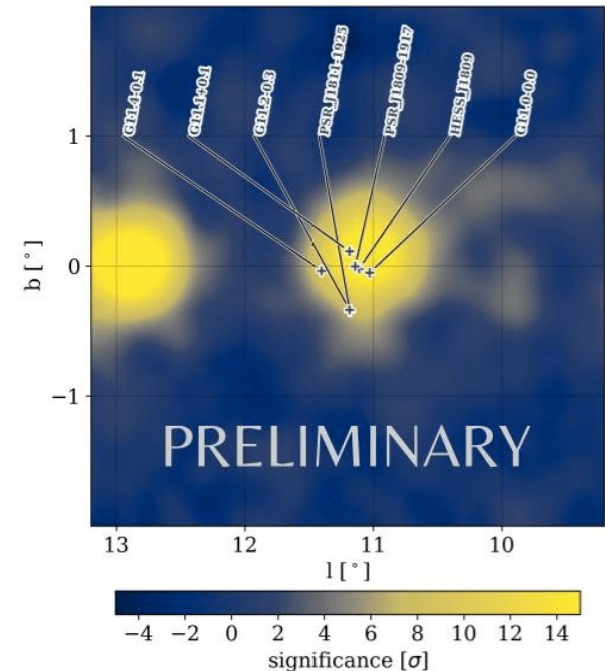
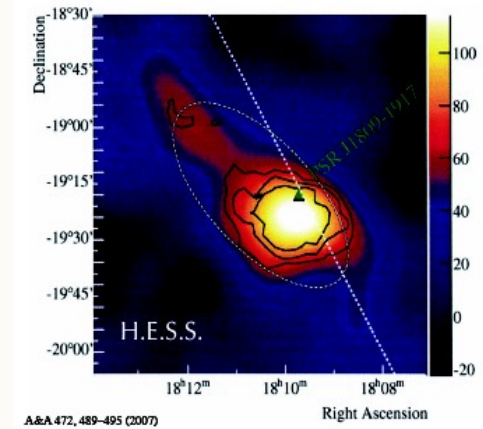
Not detected by LHAASO's 12 UHE sources (it seems at the edge of their FOV)

Several plausible counterparts:

- PSR J1809-1917 is a quite powerful (spin-down luminosity $\sim 1.8 \times 10^{36}$ 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.

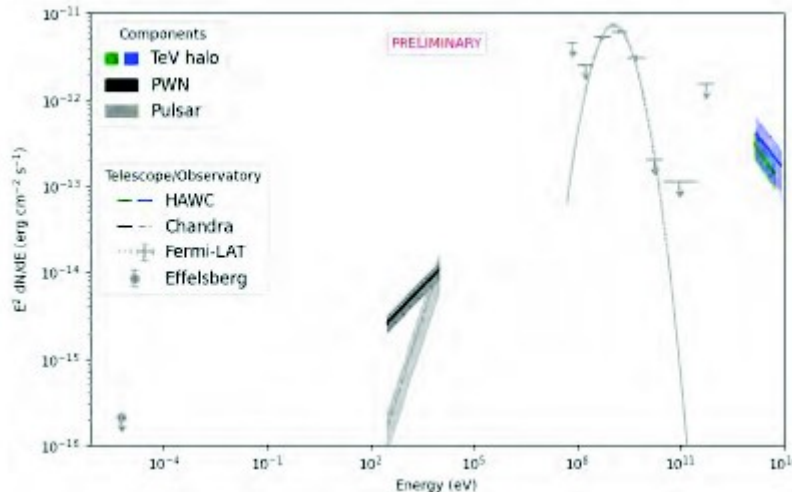
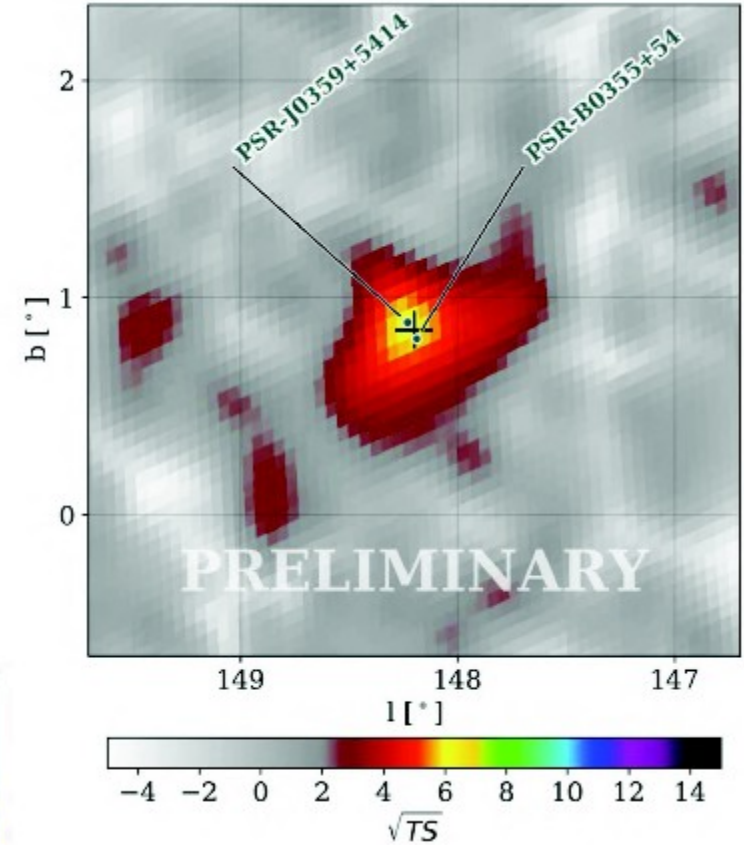




TeV halo/PWN candidate surrounding PSR J0359+5414

Newly discovered multi-TeV gamma-ray source surrounding PSR J0359+5414, a radio-quiet high spin-down power ($\dot{E} = 1.3 \times 10^{36}$ 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.



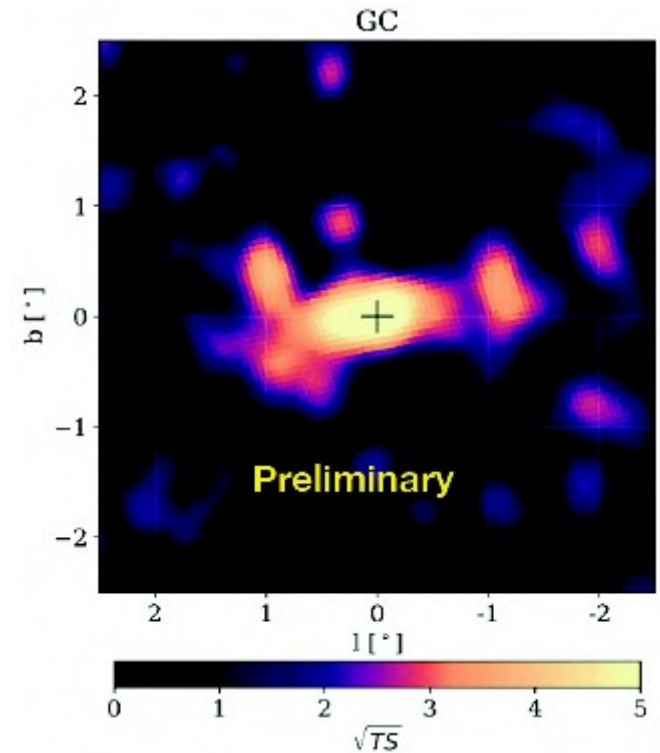


Galactic Center (Pass 5)

GC transits with a minimum zenith angle of 47 deg

(Pass 4 had a cut at 45 deg)

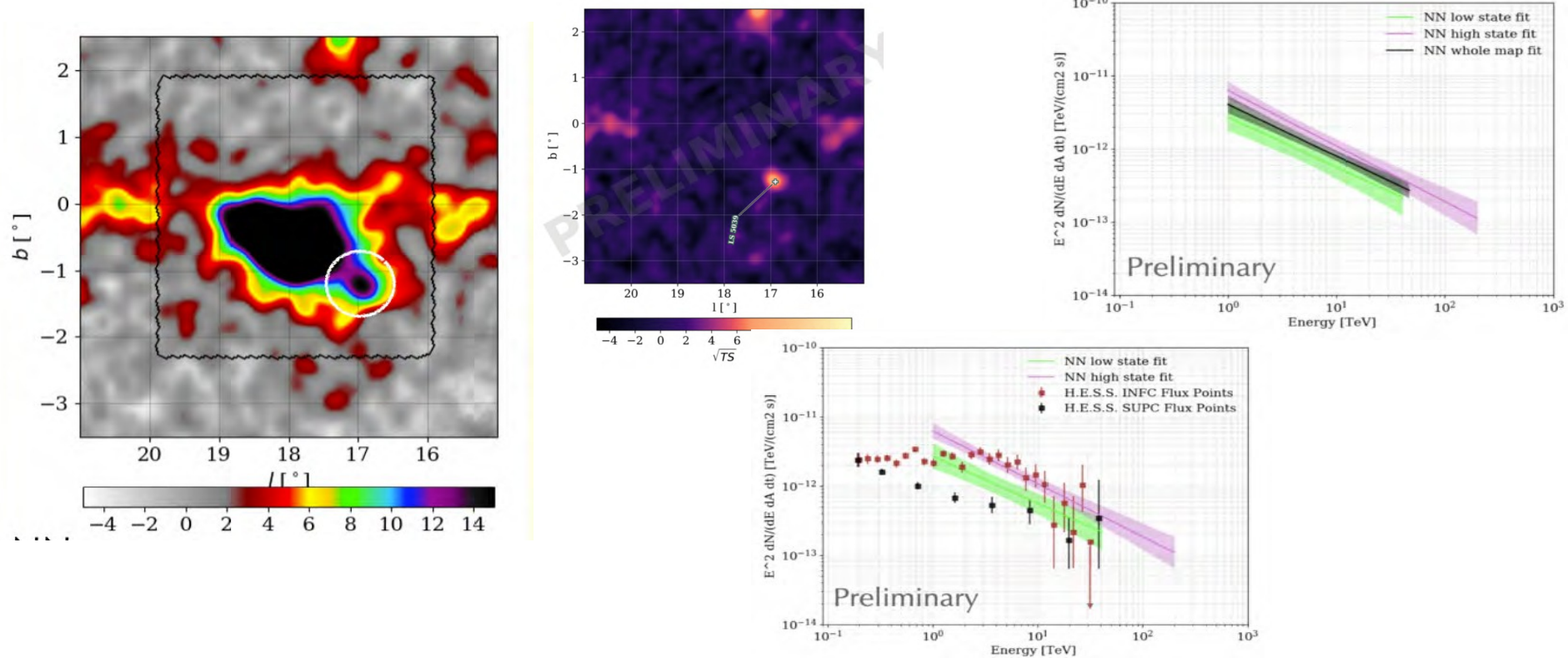
Work in progress, the energy spectrum is still being checked but it seems to have comparable error bars to H.E.S.S. spectrum beyond 20 TeV.



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.



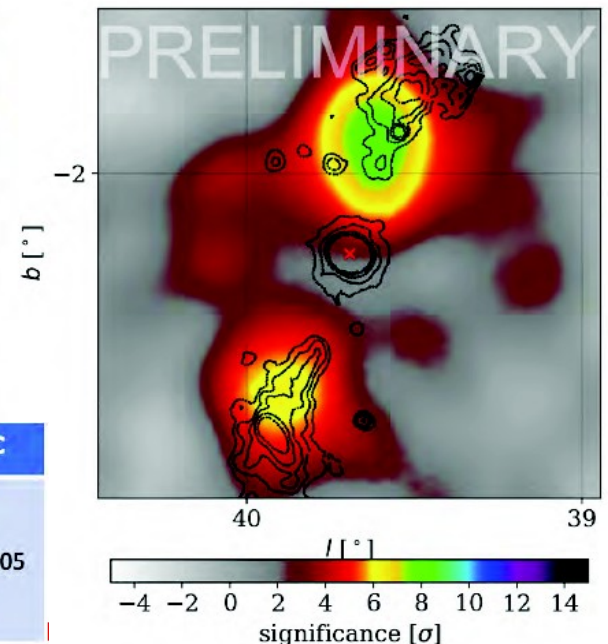
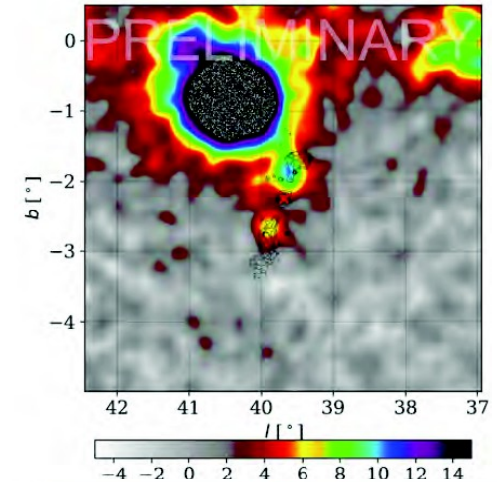
SS433 is a microquasar near the very bright extended source J1908+06

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](#)

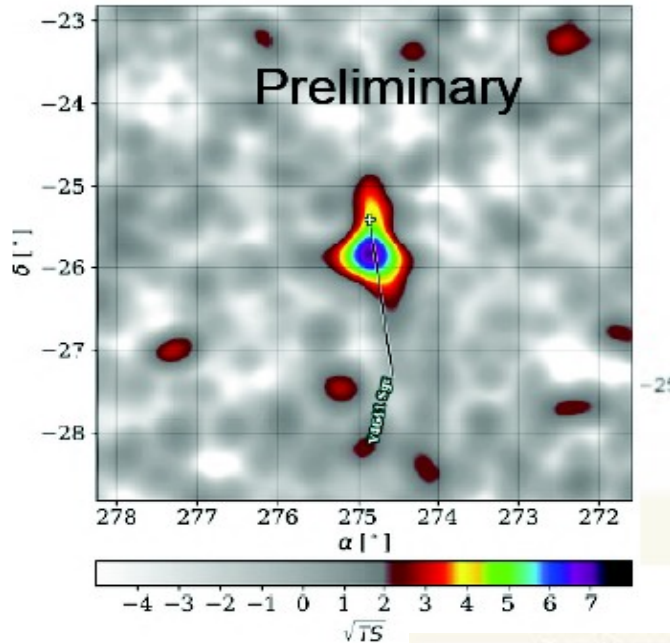
Significance of each lobe is now 7-9 sigma.

Upcoming results on spectra of each lobe will be out soon



Name	E_{piv} [TeV]	Flux [$\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$]	Idx	Size	TS	BIC
J1908	7	$1.08 + 0.04 - 0.04 \times 10^{-13}$	$-2.35 + 0.02 - 0.02$	$0.42 + 0.01 - 0.01^\circ$	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



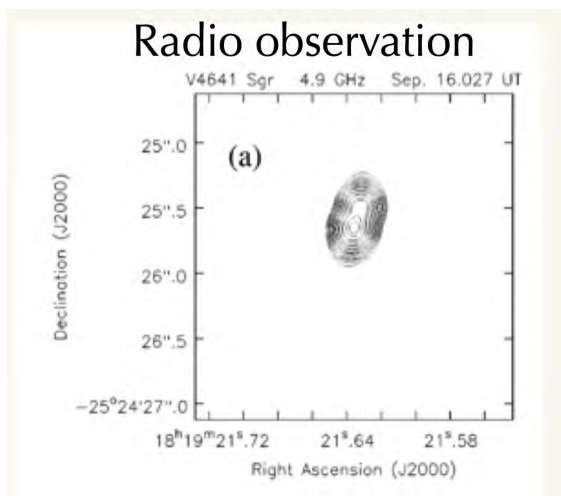
Newly discovered TeV microquasar

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



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.

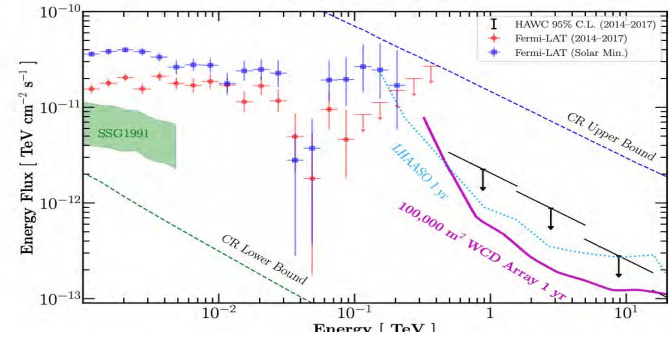
Source	Redshift	“Pass 4” TS	“Pass 5” TS
M87	0.004	13.2	29.6
1ES1215+303	0.130	12.8	43.8
VER J0521+211	0.108	10.3	18.2

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

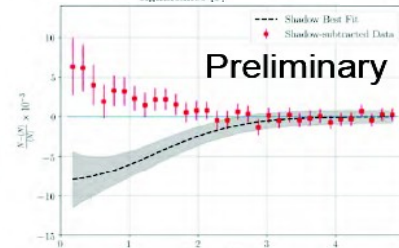
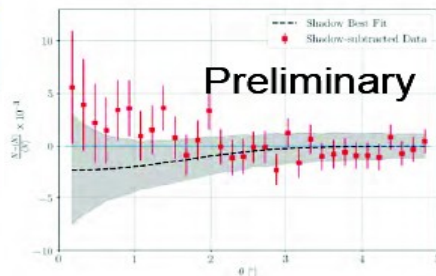
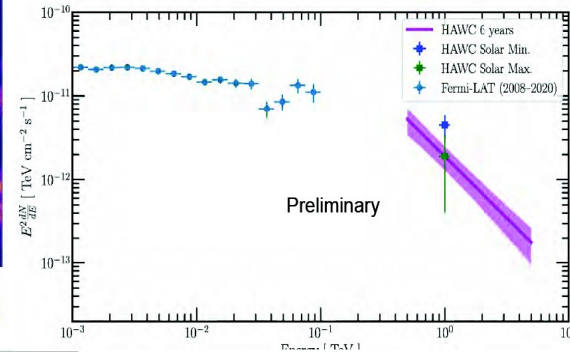
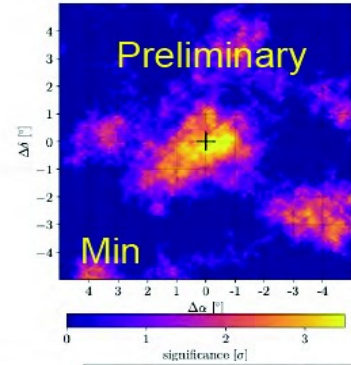
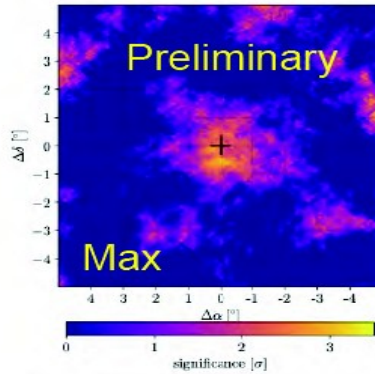
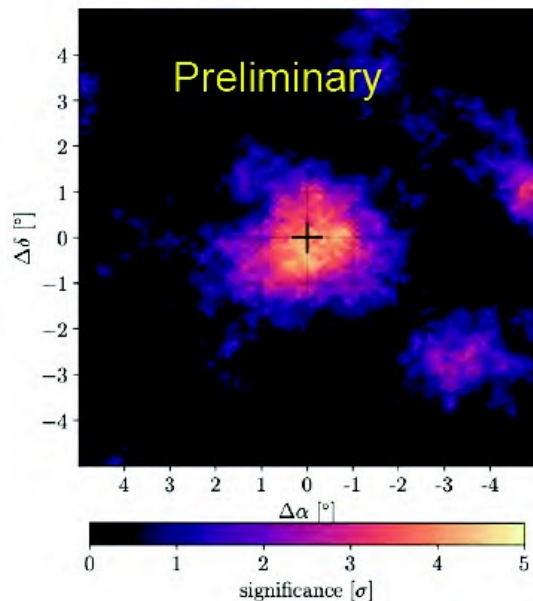


Gamma-rays from the Sun

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](#).



Durham
University

**Thanks for
your attention!**