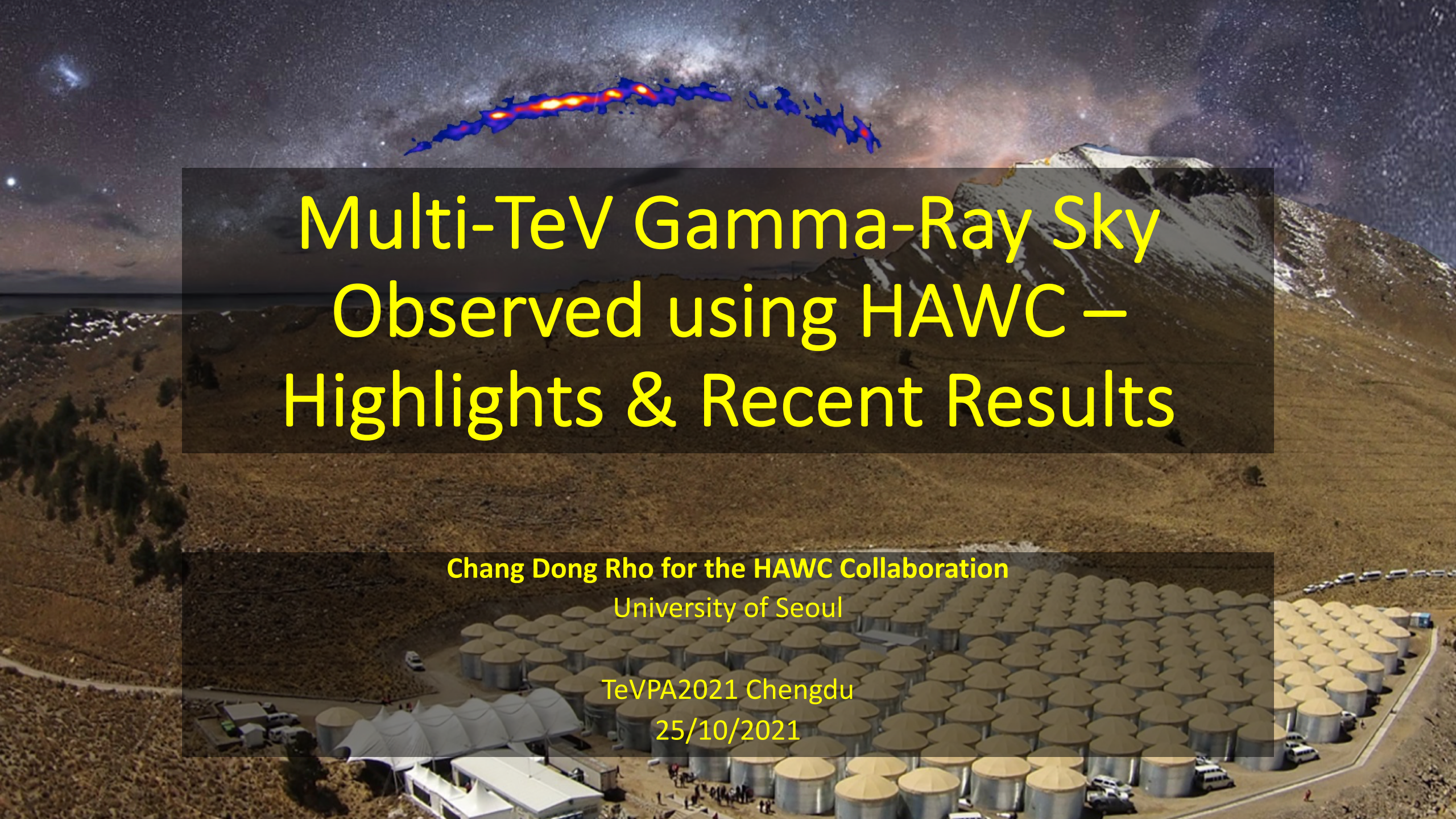


Multi-TeV Gamma-Ray Sky Observed using HAWC – Highlights & Recent Results

Chang Dong Rho for the HAWC Collaboration
University of Seoul

TeVPA2021 Chengdu
25/10/2021

The HAWC Collaboration

United States
University of Maryland
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
Michigan State University

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

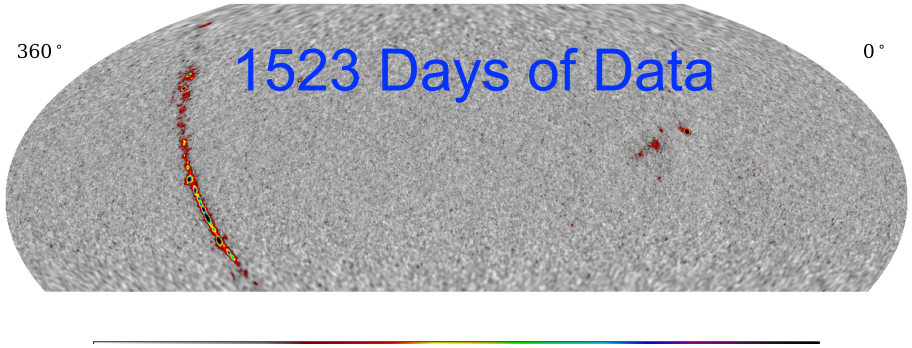
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapa
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional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

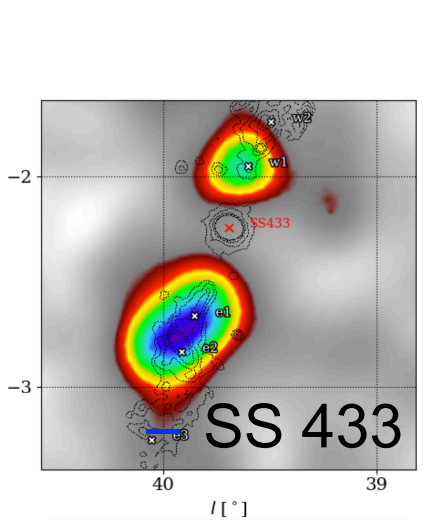
Europe
Max-Planck Institute for Nuclear Physics, Germany
IFJ-PAN, Krakow, Poland
National Institute for Nuclear Physics, Padova, Italy

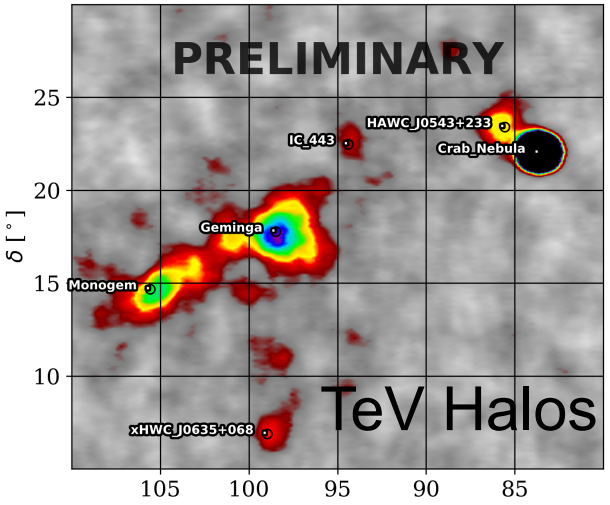
Asia
Shanghai Jiao Tong University, China
University of Seoul, South Korea

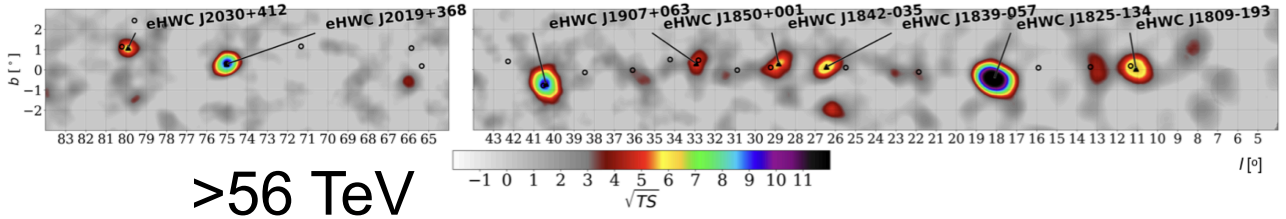
Overview

- New sky maps
  - 50 Sources - many previously unseen
  - New Source classes - TeV Halos, Microquasar
- Highest Energy Sky
- Other exciting science
  - Cygnus Cocoon
  - Stacking Analysis
  - Transient Sources
  - Dark Matter Limits
  - Lorentz Invariance Violation
- Multimessenger Observations
  - LIGO
  - IceCube









>56 TeV

High-**A**ltitude **W**ater **C**herenkov Gamma-Ray Observatory

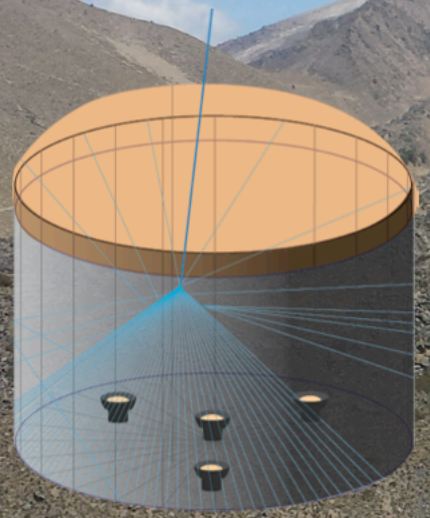
Pico de Orizaba
Puebla, Mexico (19°N)

Energy range:
~100 GeV - >100TeV

Field of view:
45° from zenith

Observing time:
>95% of the time

Angular resolution:
~0.1° - 1°



300 ×

5m tall, 7.3 m diameter
~200,000 L of water

4 PMTs facing upwards collect Cherenkov light produced by secondary particles

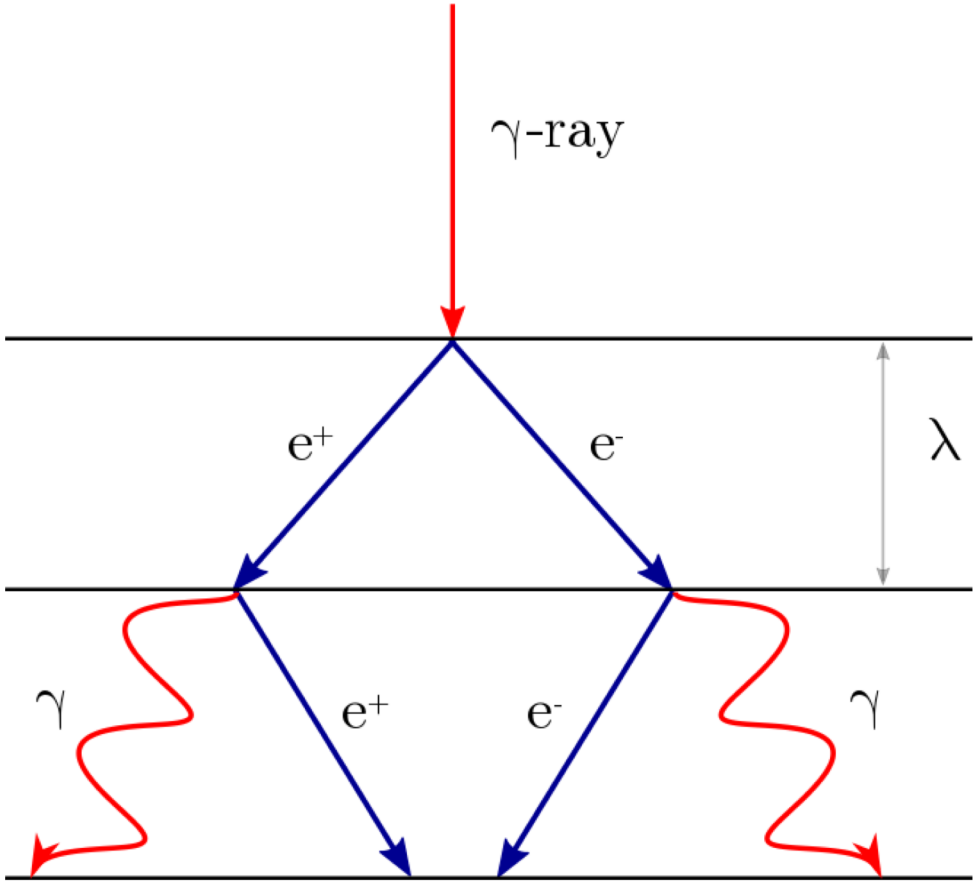
22,000 m²

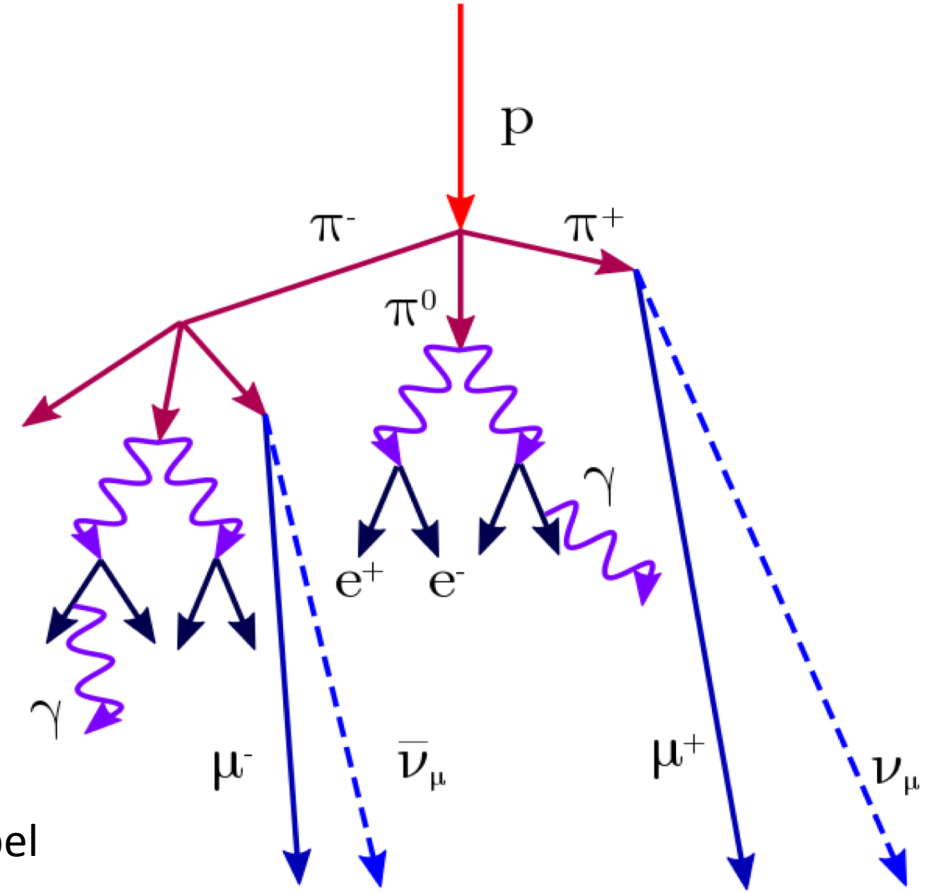
T-rex for scale

4,100 m.a.s.l.

Extensive Air Showers

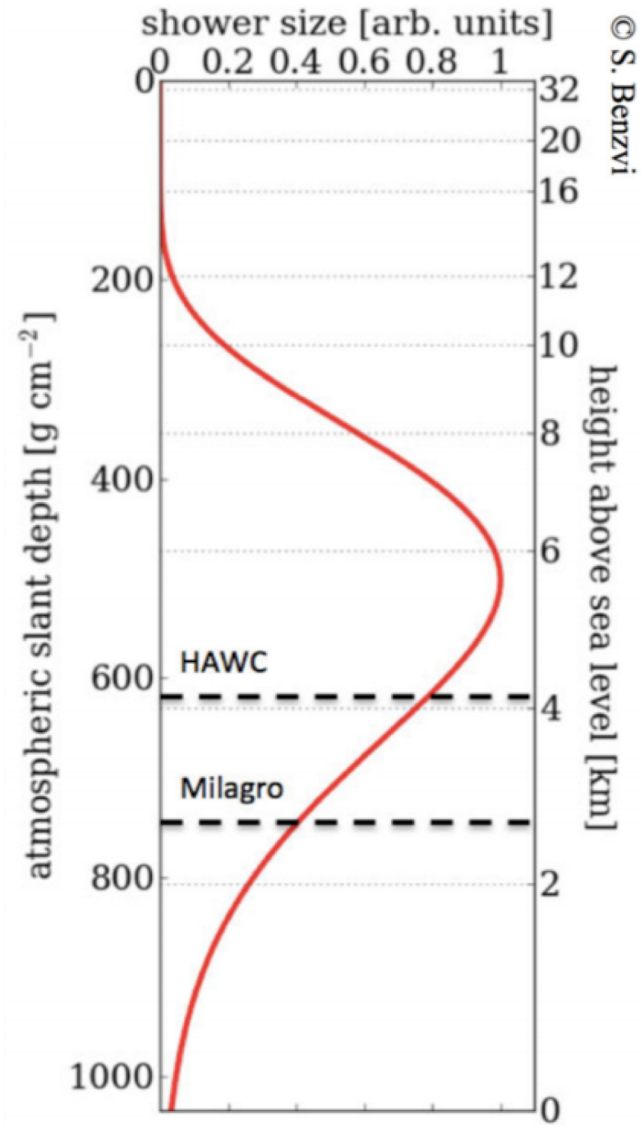
- The atmosphere of Earth is opaque to gamma rays -> It produces an extensive air shower.



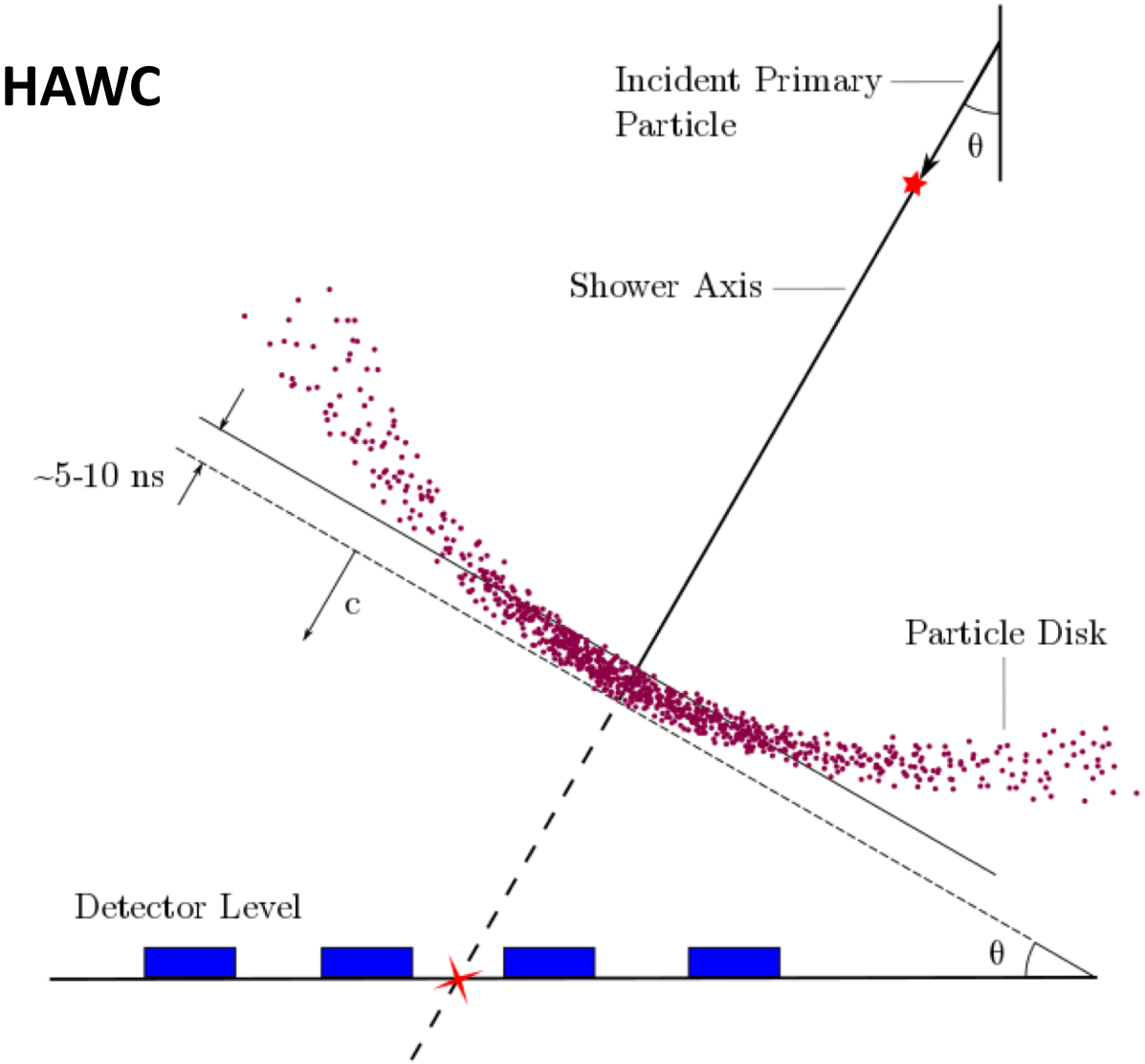


Z. Hampel

Detecting Extensive Air Showers



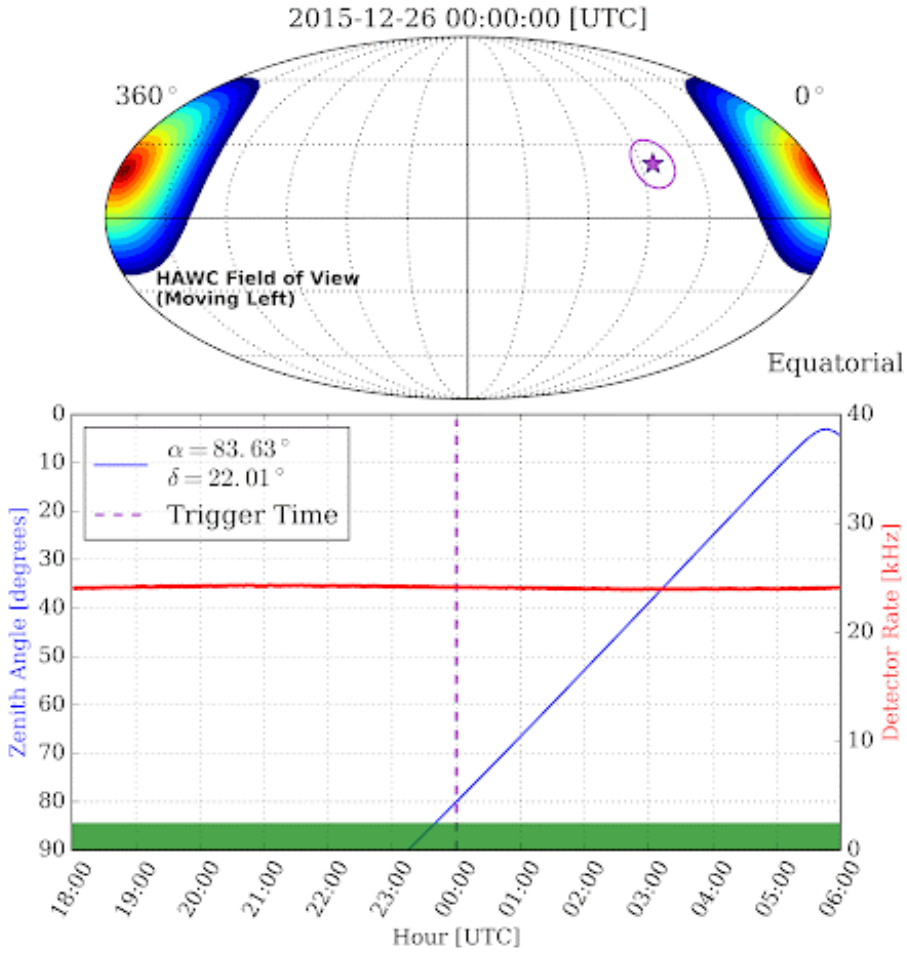
HAWC



Z. Hampel

How HAWC Sees the Gamma-Ray Sky

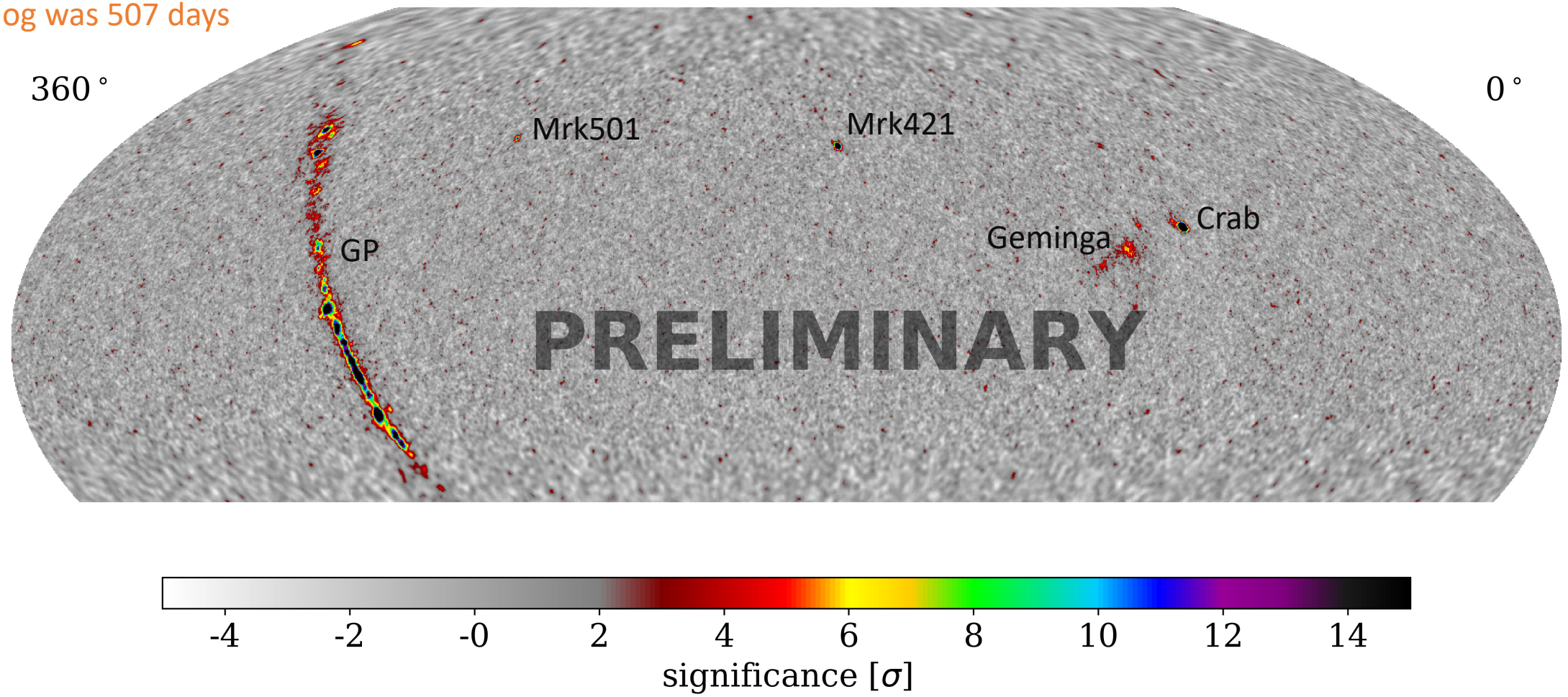
- Sky moves over HAWC, we say sources “transit” through our field of view
- Sources at HAWC’s zenith easiest to observe
- Data taking happens constantly day and night



1523-day HAWC Sky Map – 3HWC Catalog

Astrophys. J., 905(1):76, 2020

Note that 2HWC Catalog was 507 days



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Astrophys. J., 905(1):76, 2020

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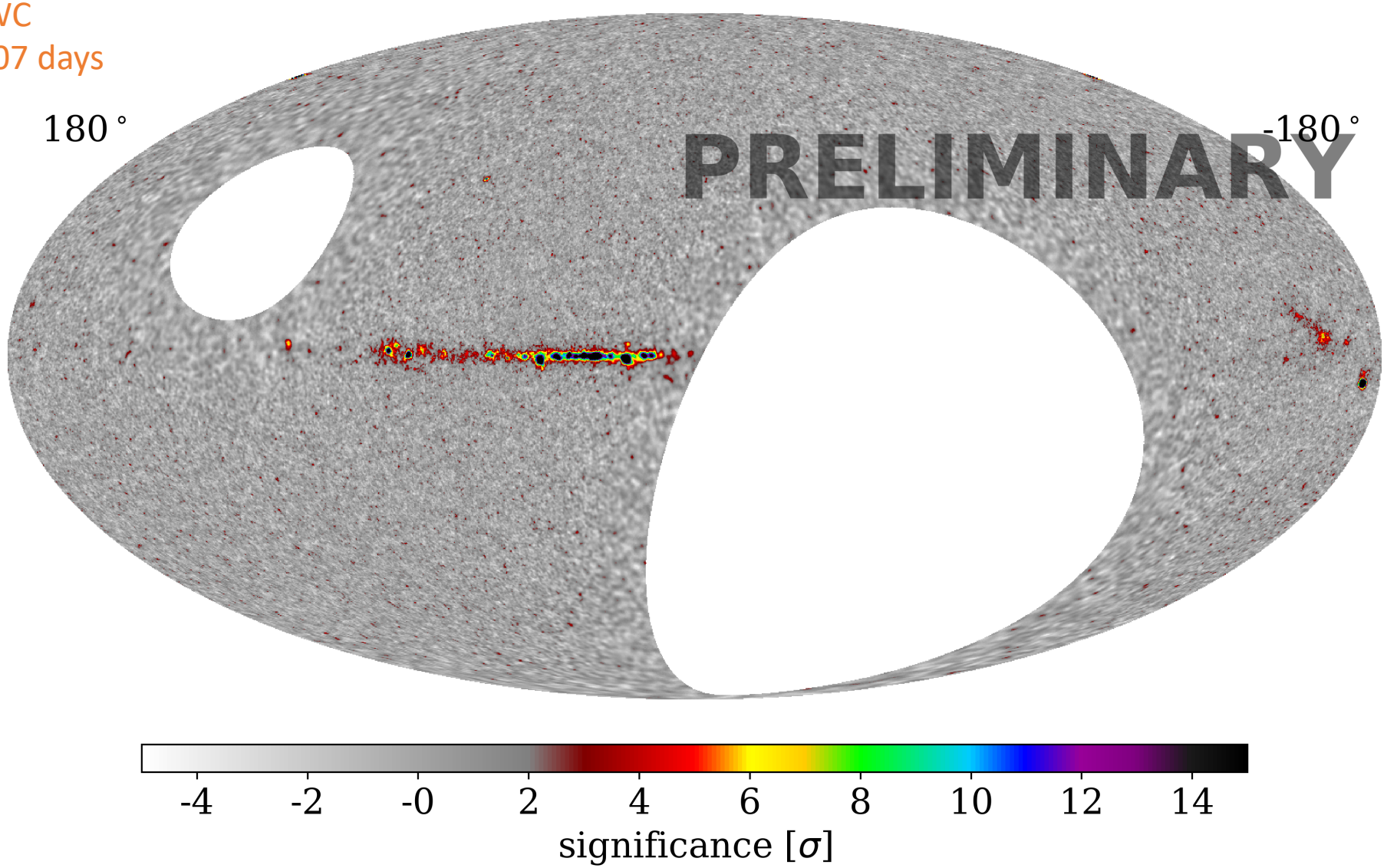
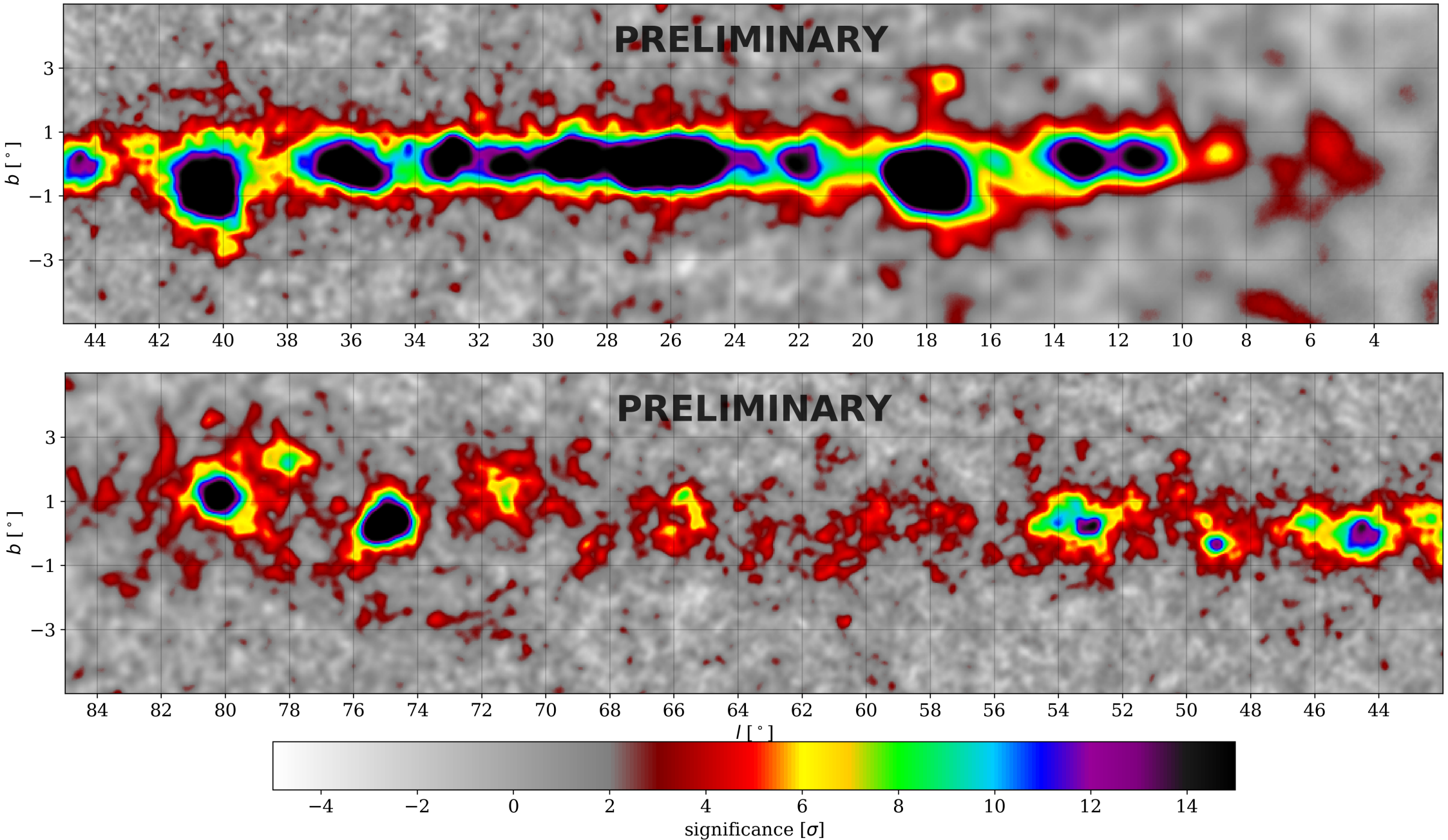
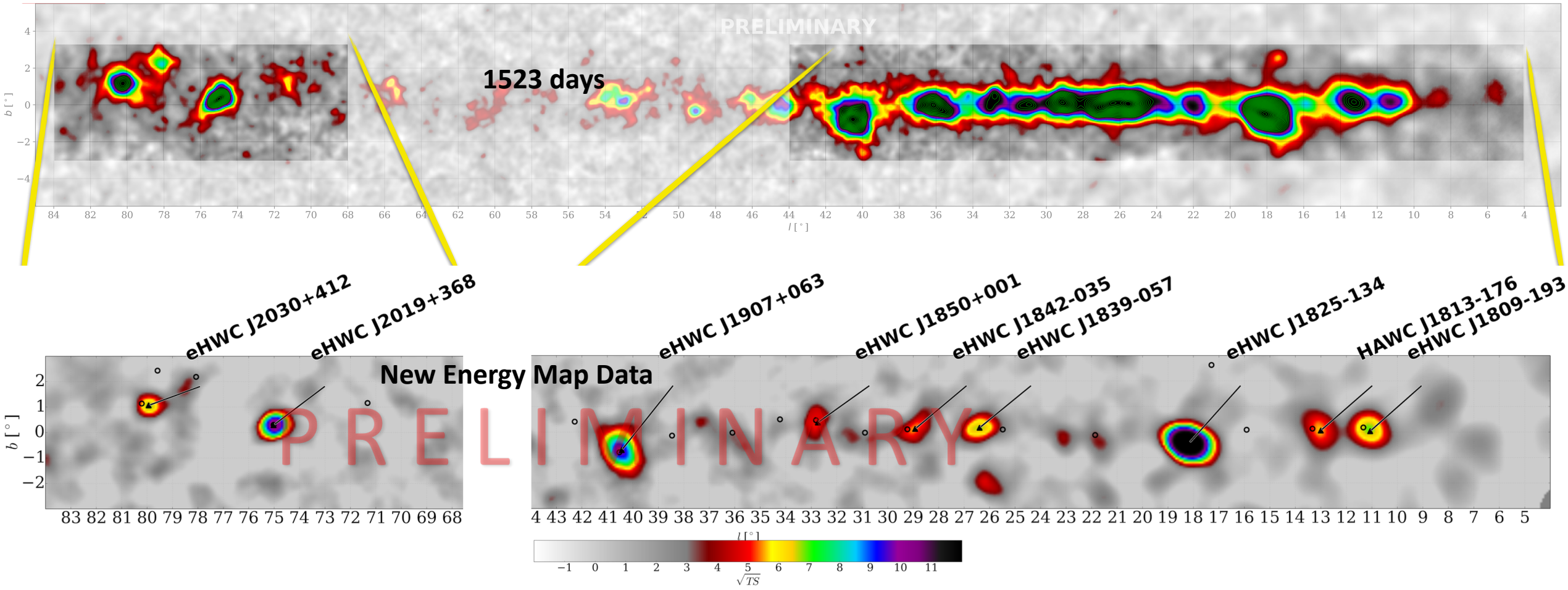


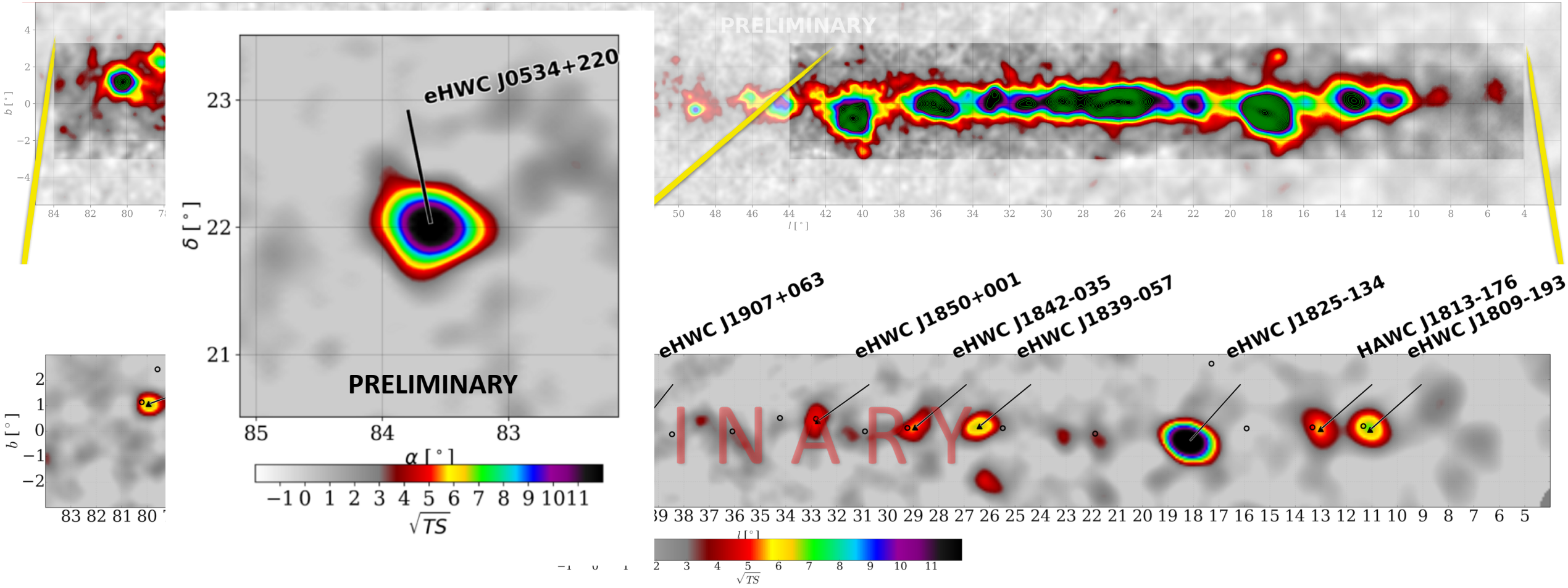
1523 Days of Data



Pushing to the Highest Energies (>56 TeV)



Pushing to the Highest Energies (>56 TeV)



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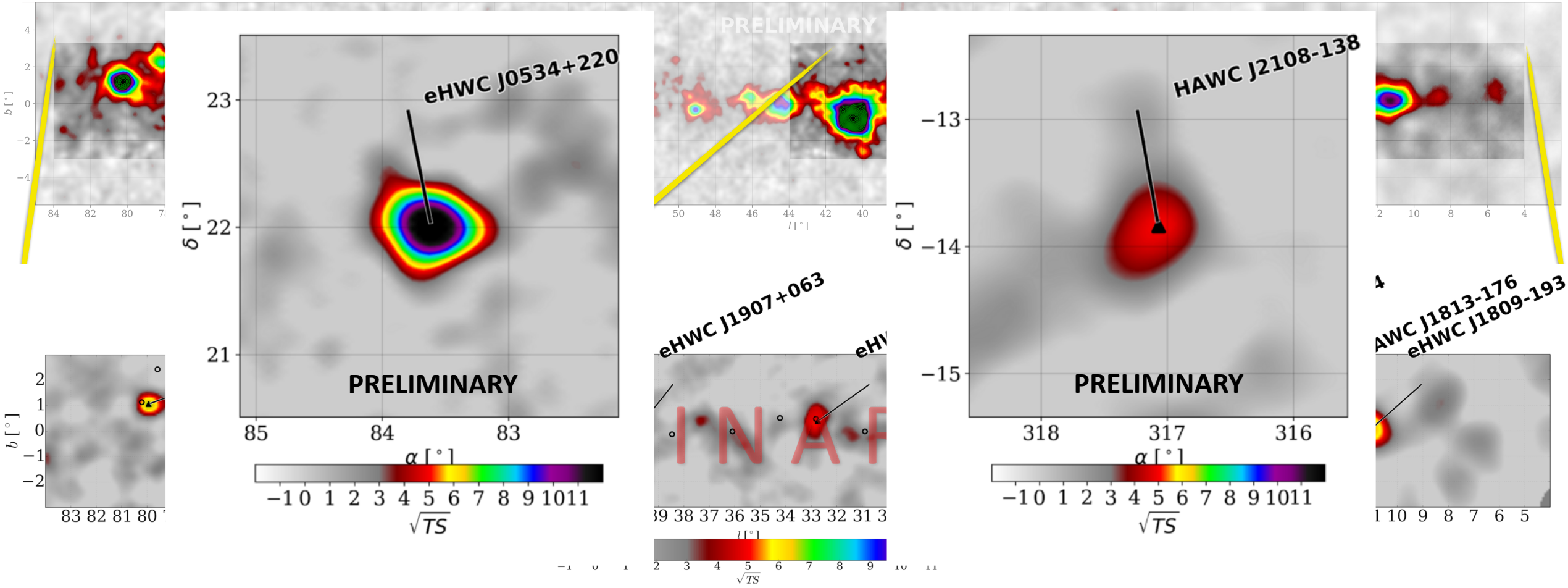
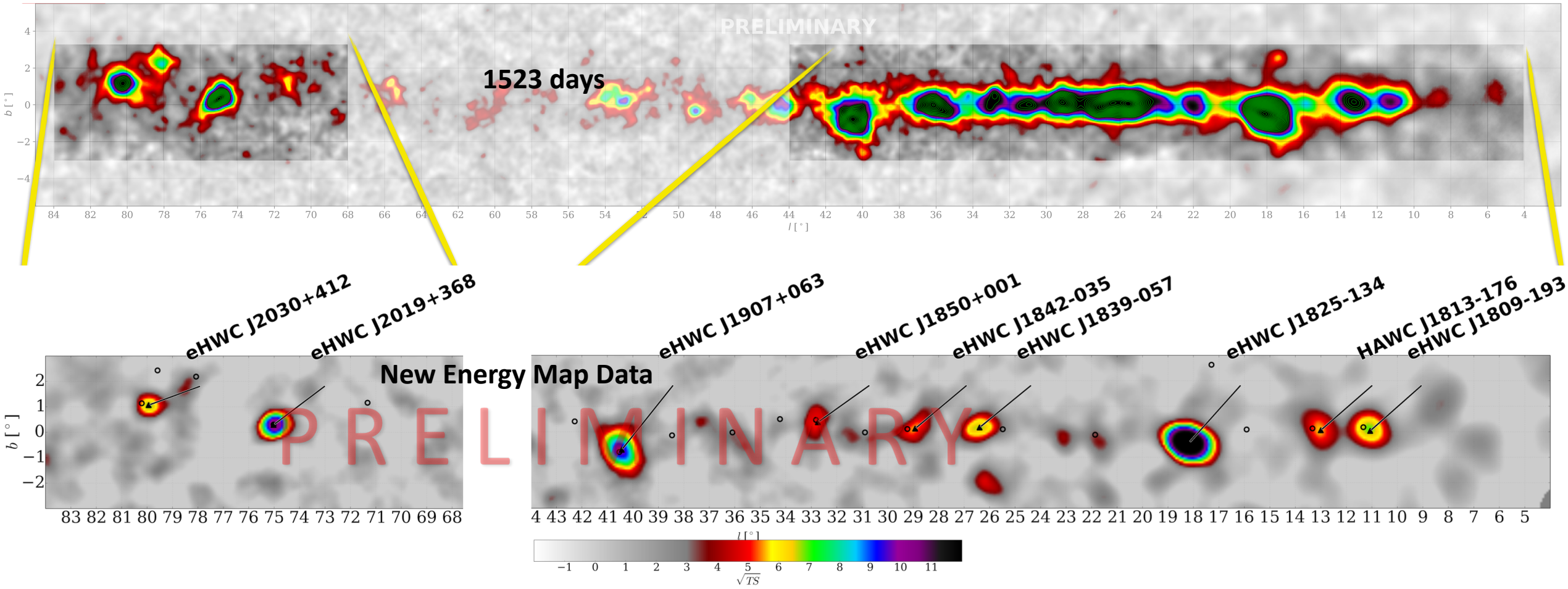


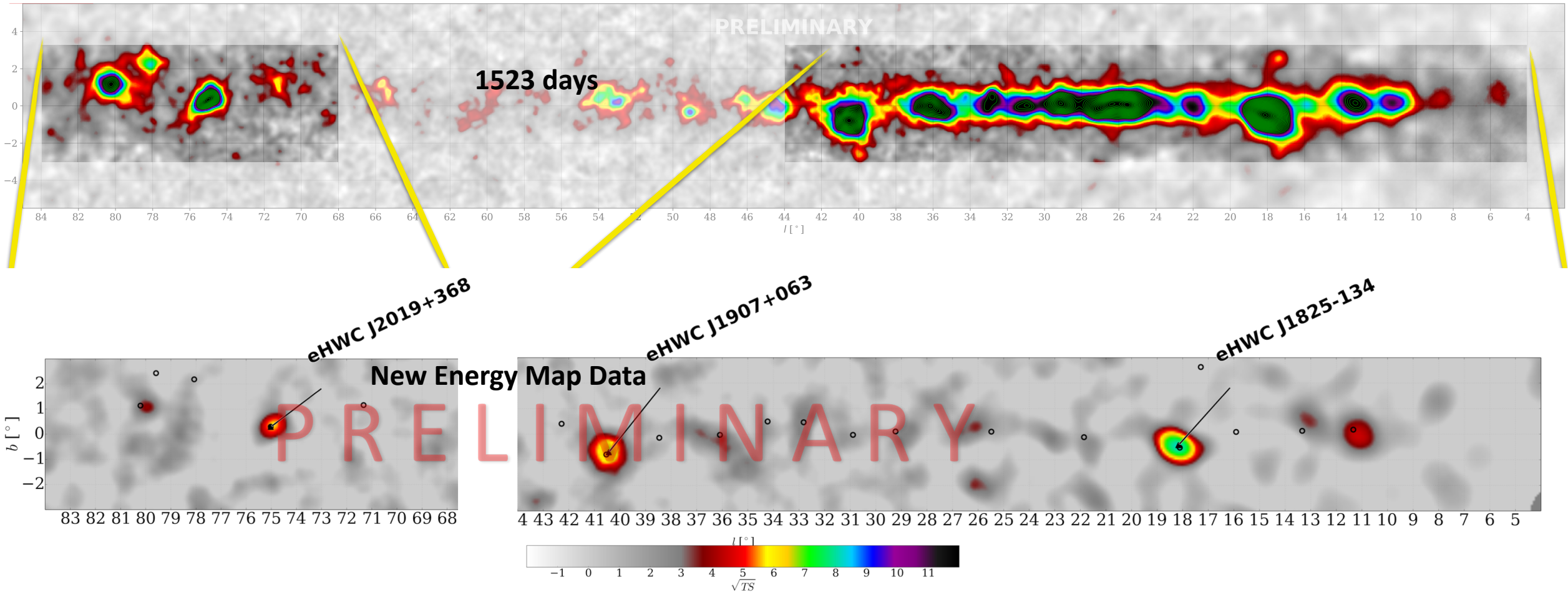
Pushing to the Highest Energies (>56 TeV)



- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?

Not yet published. For older dataset:
Phys. Rev. Lett. **124**, 021102, Jan 2020

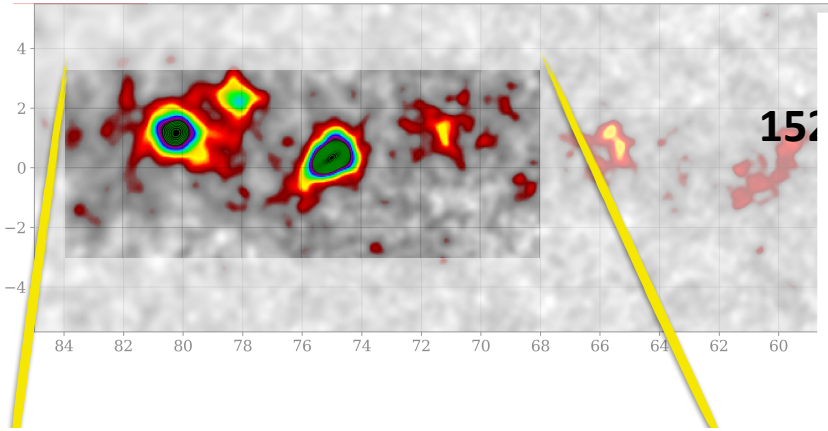
Pushing to the Highest Energies (>100 TeV)

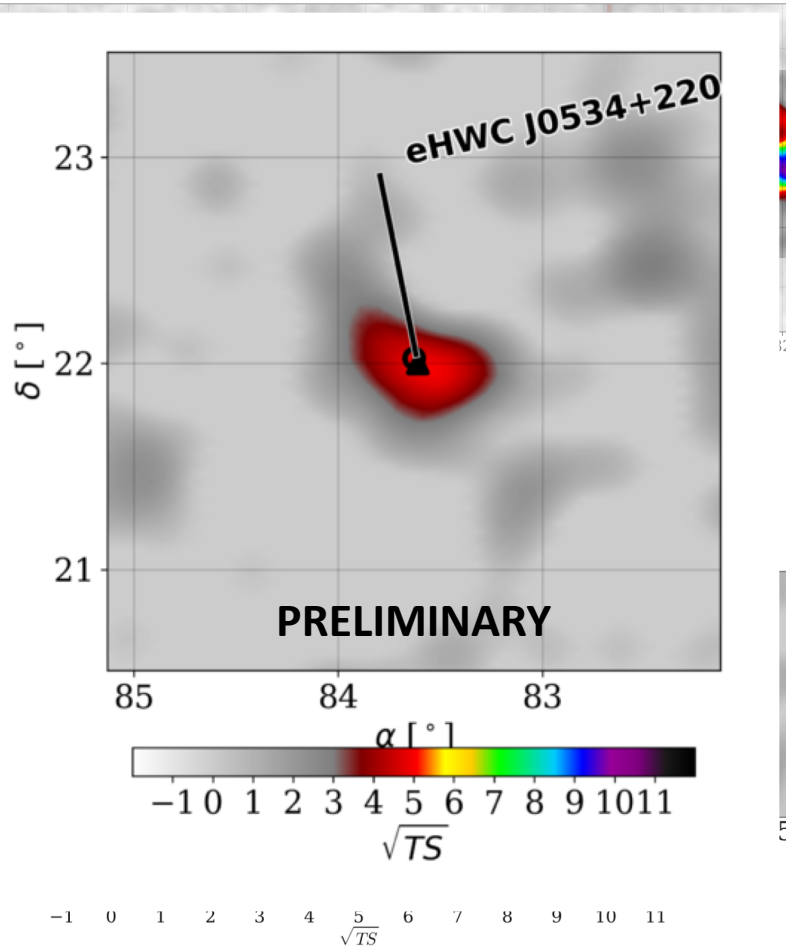


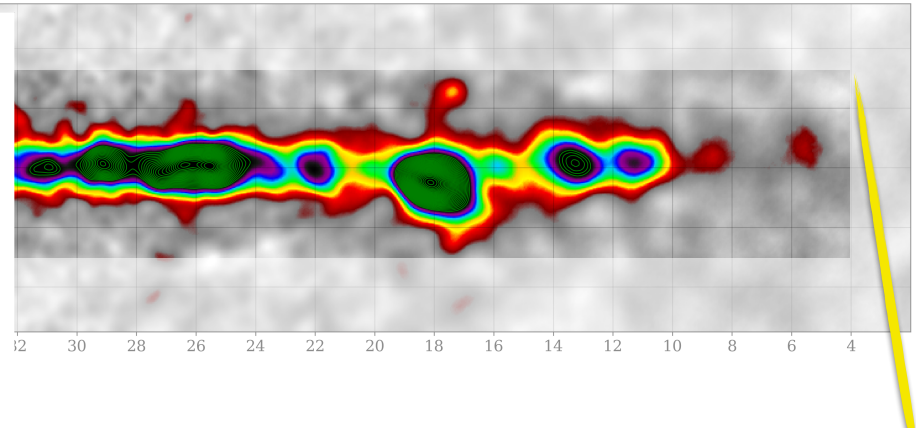
- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?

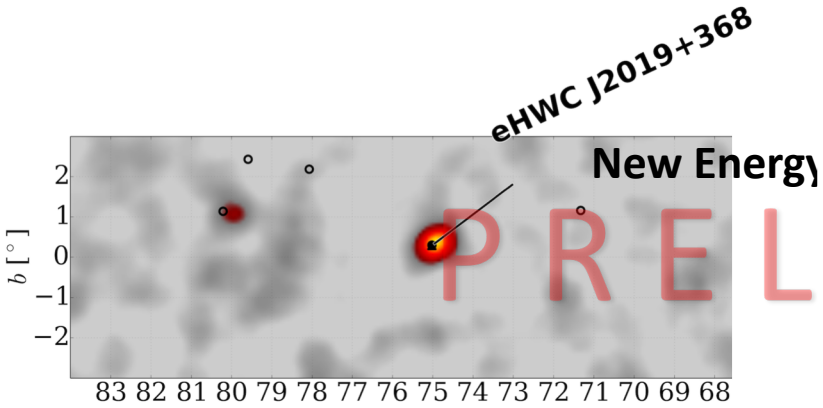
Not yet published. For older dataset:
Phys. Rev. Lett. **124**, 021102, Jan 2020

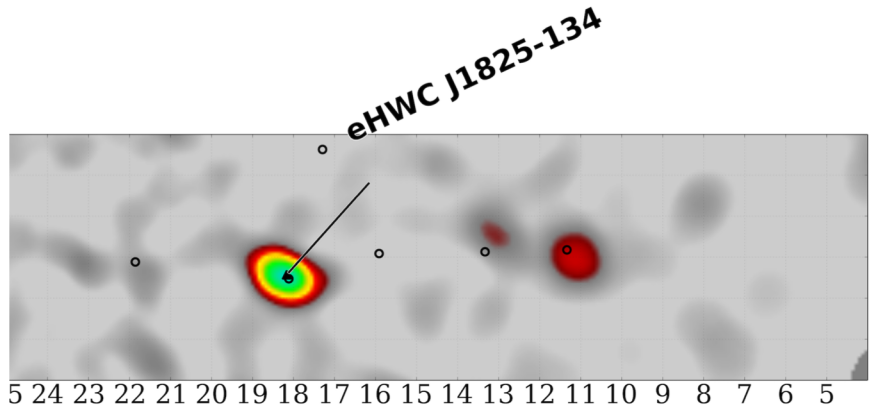
Pushing to the Highest Energies (>100 TeV)







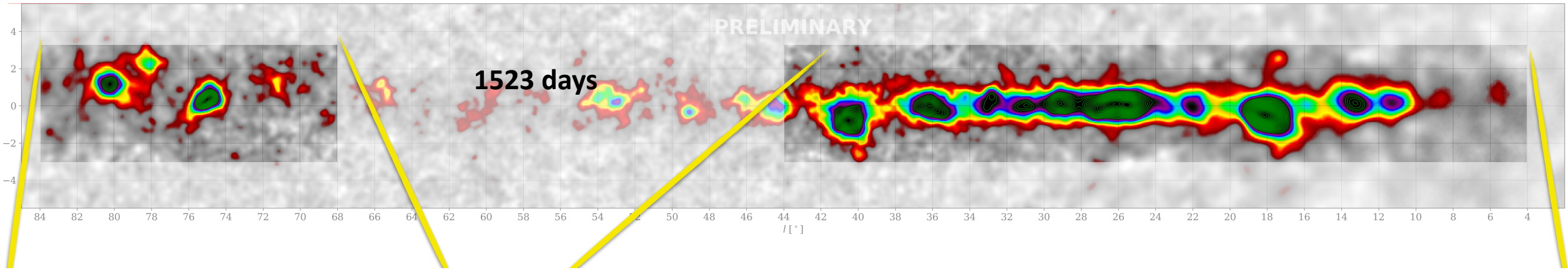


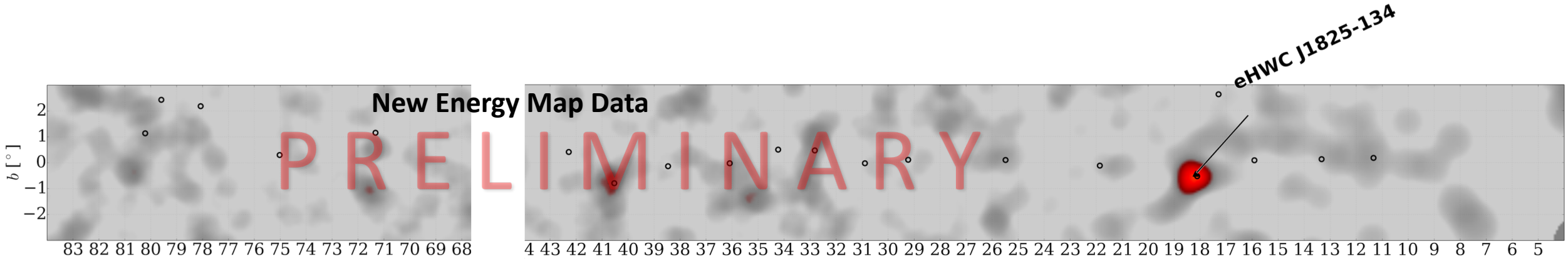


- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?

Not yet published. For older dataset:
Phys. Rev. Lett. **124**, 021102, Jan 2020

Pushing to the Highest Energies (>177 TeV)

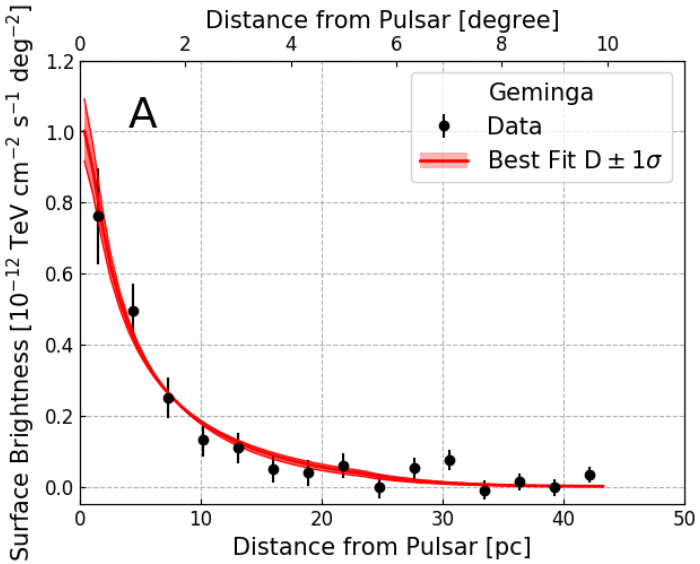


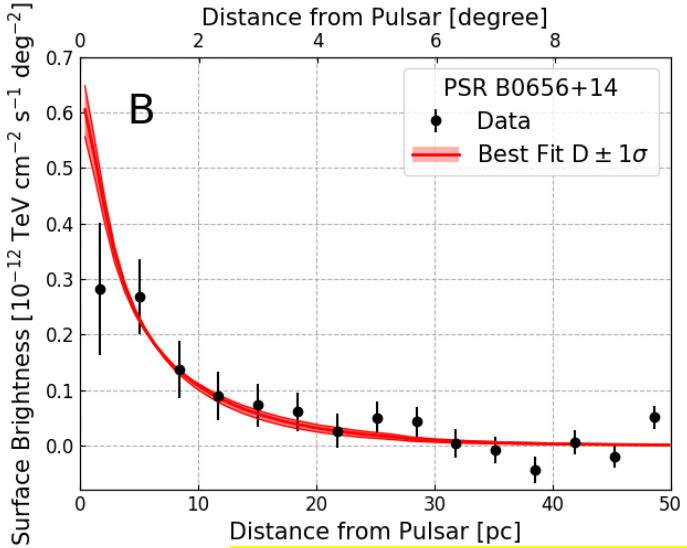


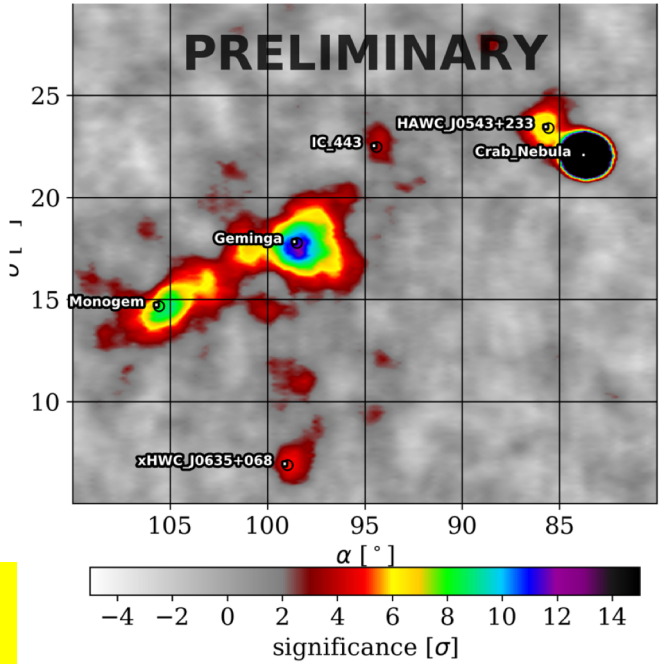
- Acceleration mechanisms: hadronic or leptonic?
- Correlation with neutrinos?

Not yet published. For older dataset:
Phys. Rev. Lett. **124**, 021102, Jan 2020

Discovery of TeV Halos – Geminga & Monogem

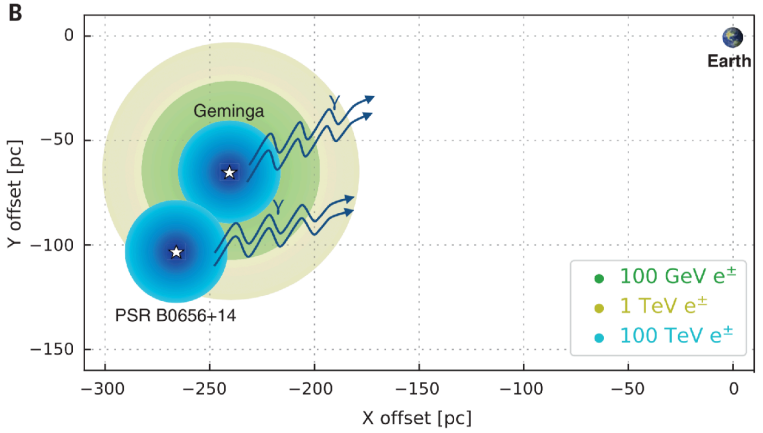






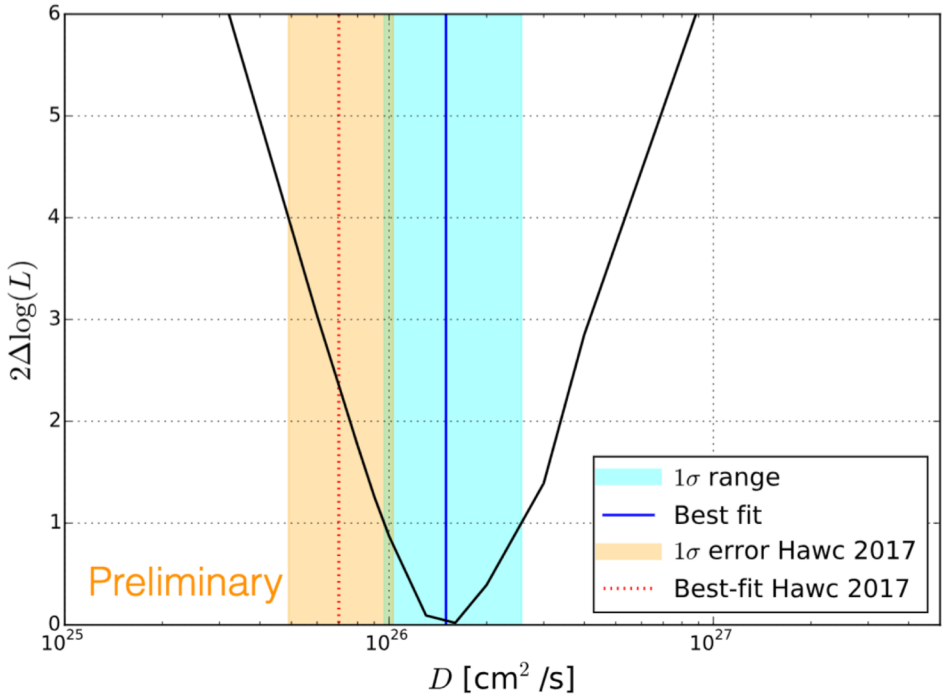
Science Vol. 358, Issue 6365, pp. 911-914, 2017

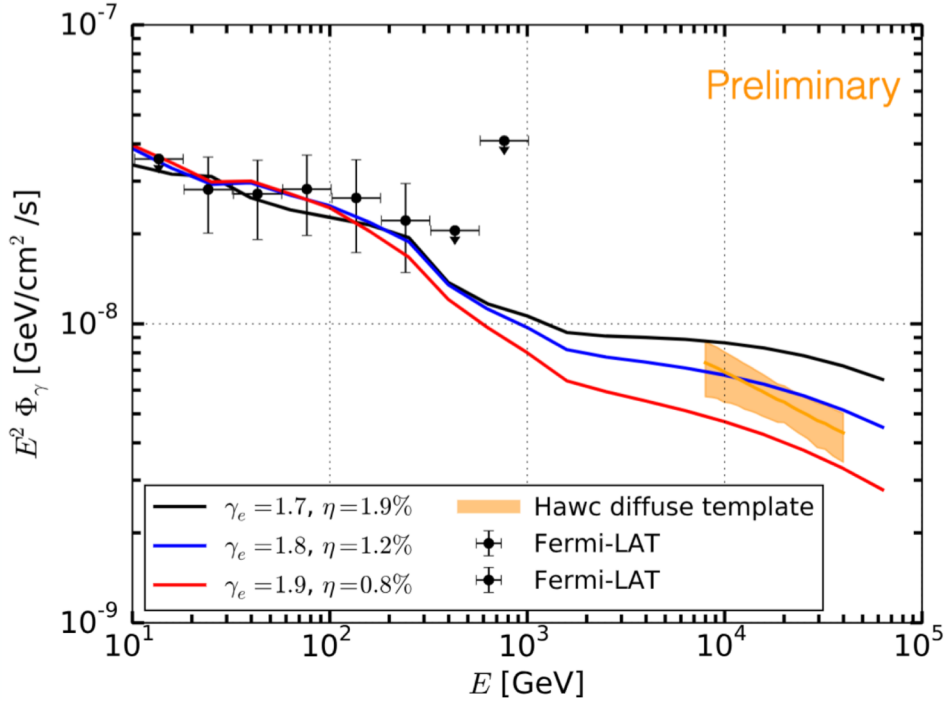
- 100 TeV e^- inverse Compton scattering off CMB
- Measured size 10x smaller than expected from expected standard value of $D_{100\ TeV}$
- Assuming a simple model - they can't be the source of the positron excess



Discovery of TeV Halos – Geminga & Monogem

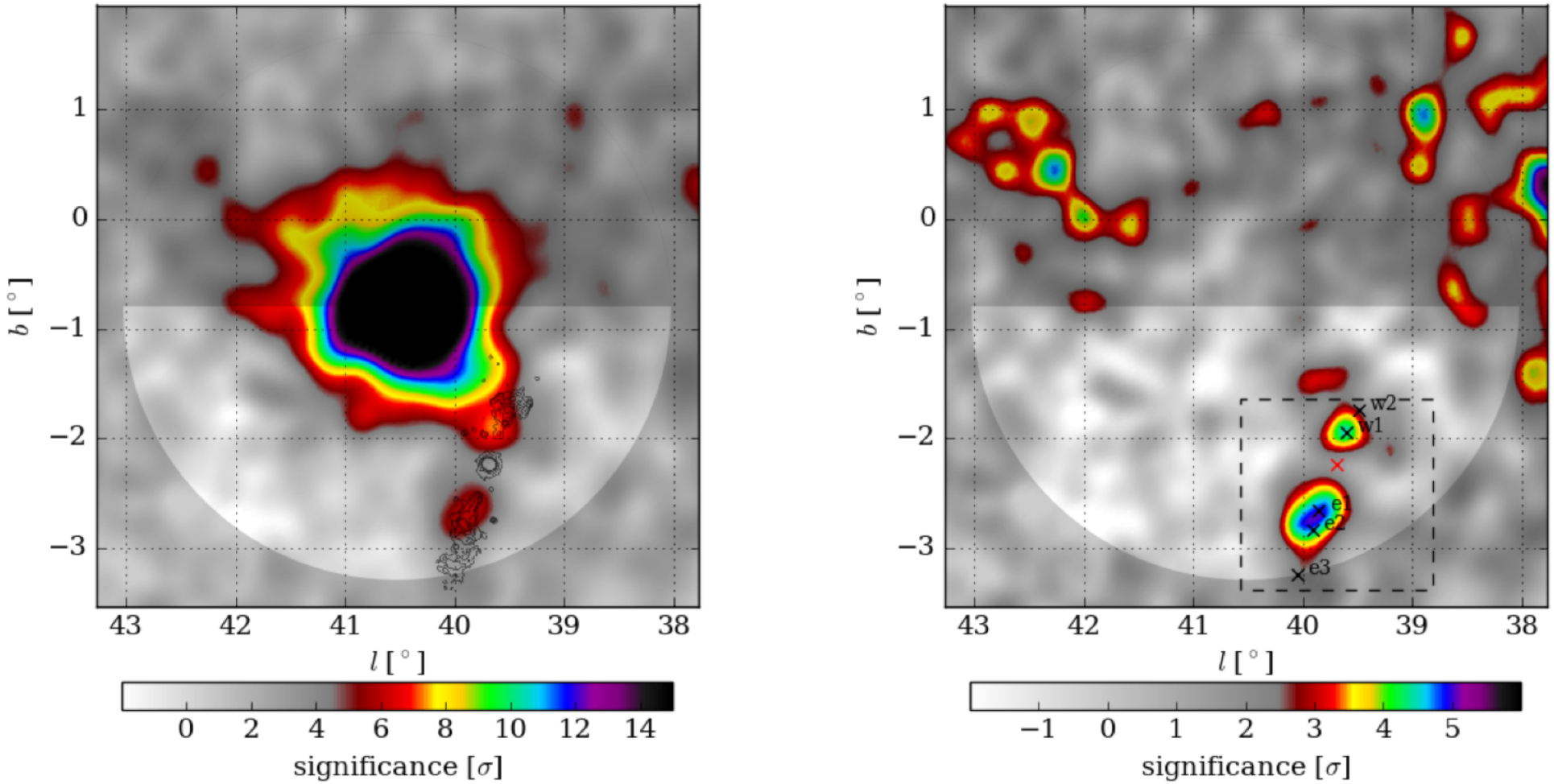
- Geminga halo also confirmed by Fermi LAT
- Diffusion Coefficient is consistent with HAWC observation (left)
- Joint Fermi-HAWC spectrum constrains acceleration efficiency (right)





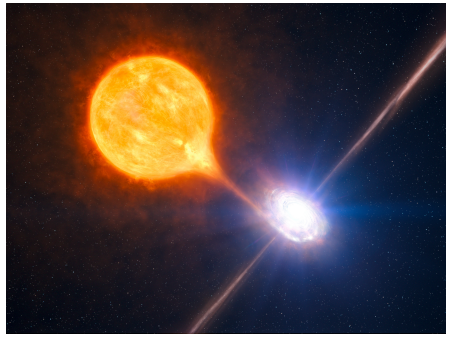
Discovery of TeV Microquasar – SS 433

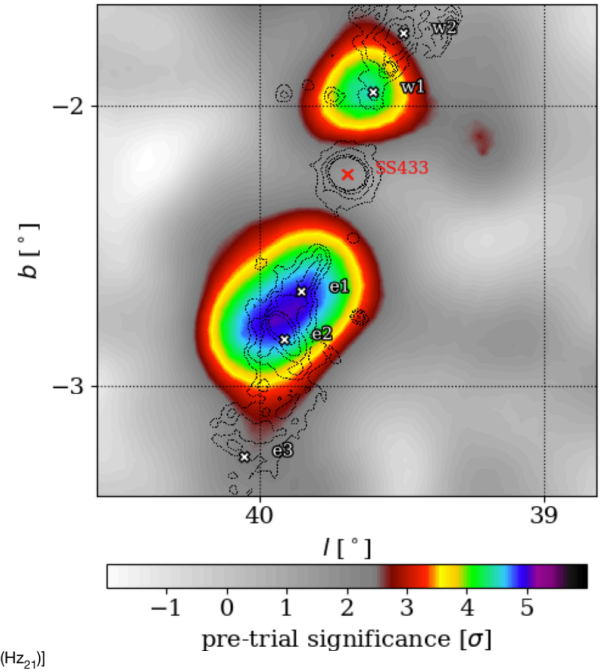
The central source is MGRO J1908+06 and below it are the lobes of SS 433

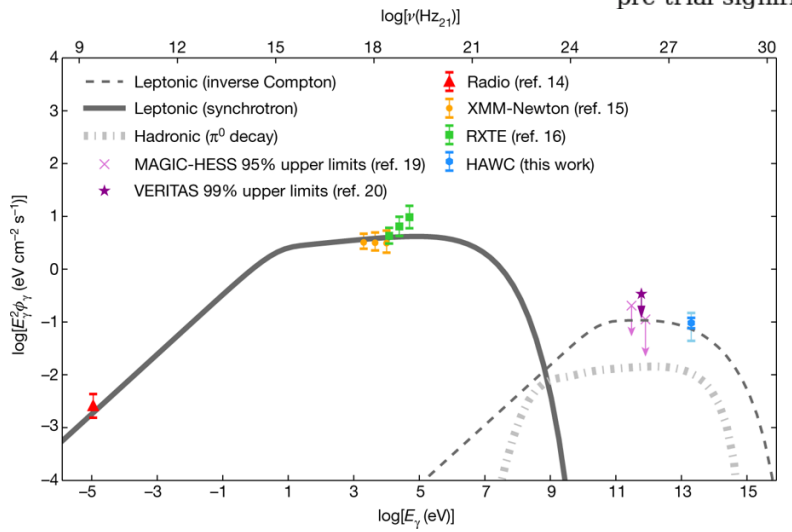


Discovery of TeV Microquasar – SS 433

- 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
  - Hadronic acceleration disfavored due to extreme energetics required
  - Acceleration does not happen at the black hole because the cooling time of the electrons is too short to make the observed gamma-rays





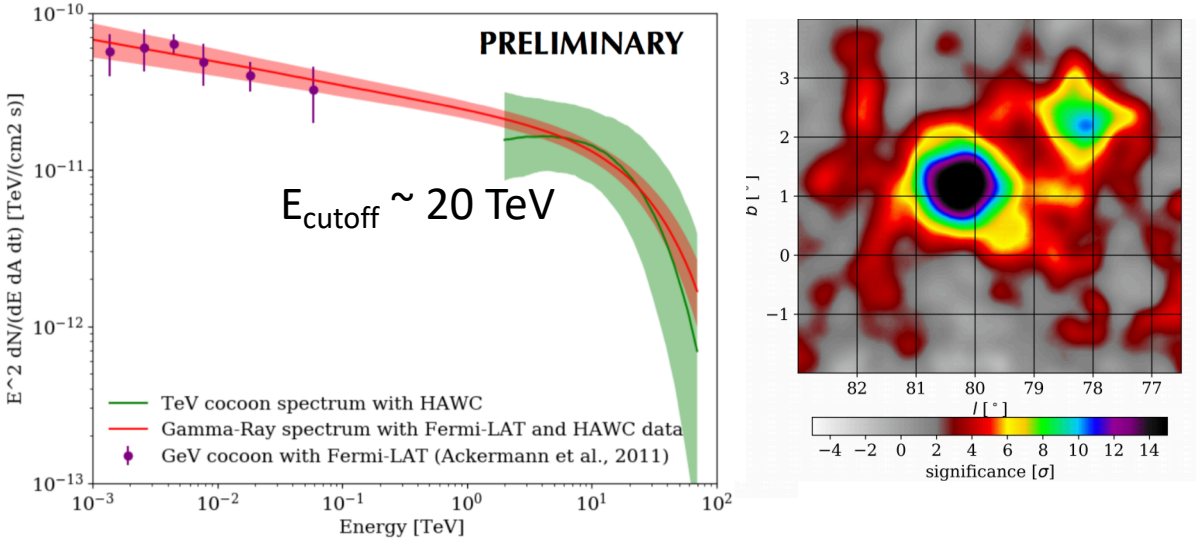


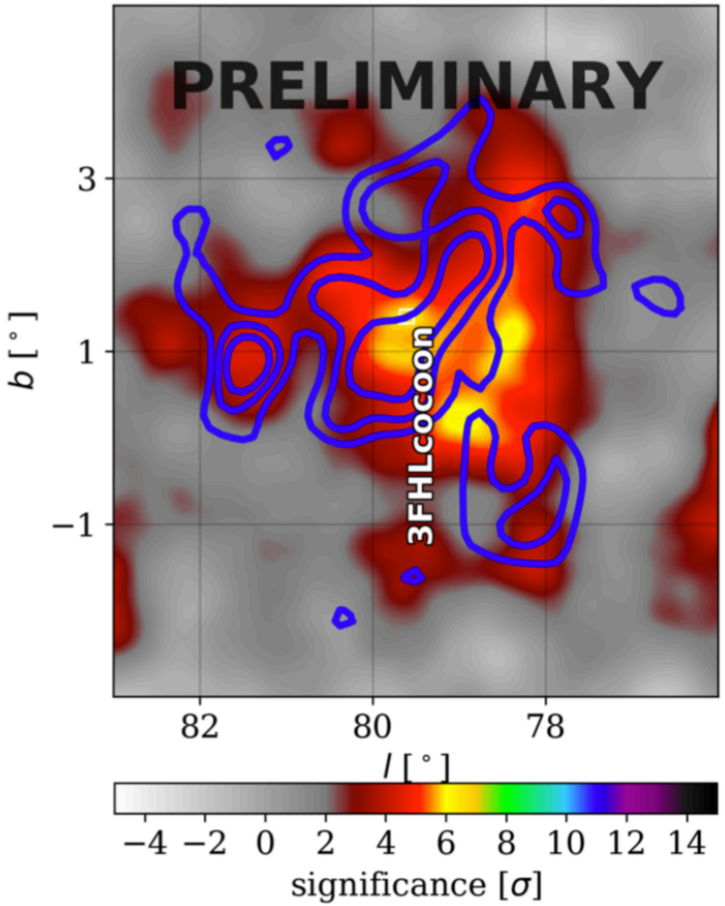
Nature **562,** 82–85 (2018).
https://doi.org/10.1038/s41586-018-0565-5

Cygnus Cocoon Region

Nature Astronomy, 5(5):465–471, 2021

- Can these SFR accelerate particles to high energies?
- **Candidate: OB2 association in Cygnus Region**
  - *Fermi detection at GeV* (Ackermann et al., ***Science*** 334, 2011, '*The Cocoon*')
  - *HAWC detection of a likely TeV counterpart*
  - **Only SFR seen from GeV to TeV!**
- Energy budget and diffusion profile consistent with proton acceleration in collective star winds





Fermi-LAT Contours

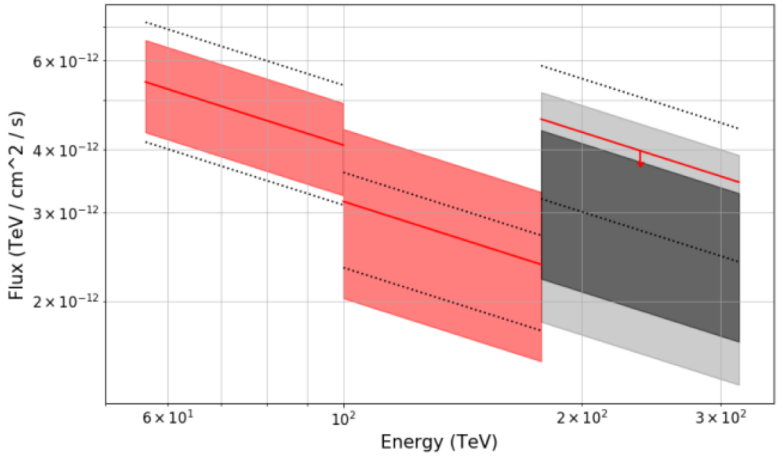
HAWC Map after subtraction of PWN & γ-Cygni

Stacking Analyses

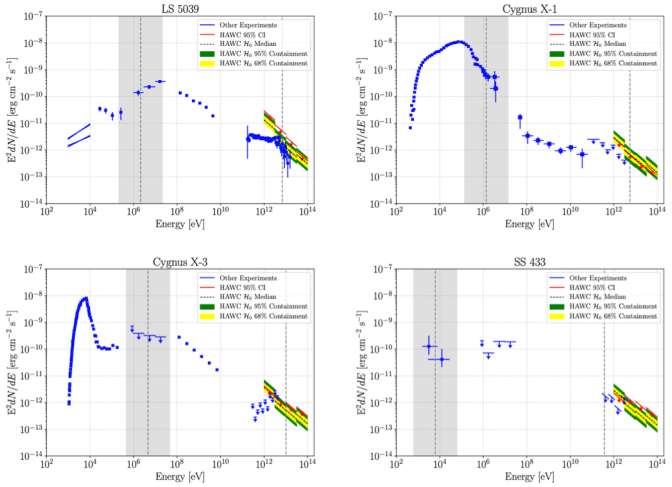
- Stacking of likelihoods method used to study multiple sources simultaneously as a single “source species”

- Three stacking analyses in 2021:
  1. High $\dot{E}$ pulsars at >56 TeV
  2. High-mass microquasars
  3. Giant molecular clouds as sea of CR

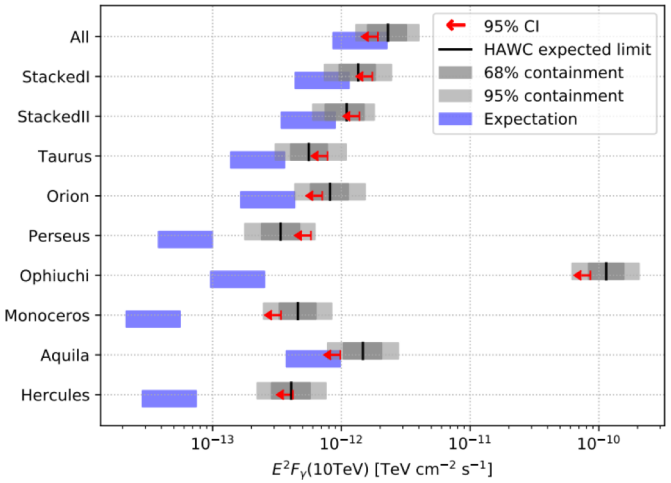
Astrophys. J. Lett., 911(2):L27, 2021



Astrophys. J. Lett., 912(1):L4, 2021



Astrophys. J., 914(2):106, 2021

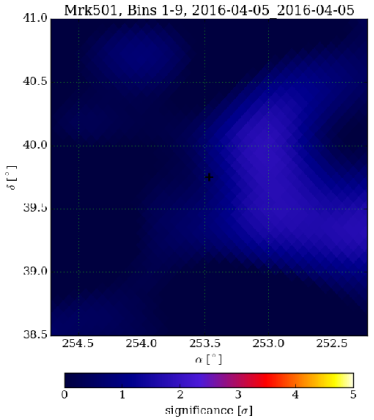


Transient Sources – Mrk 501 and Mrk 421

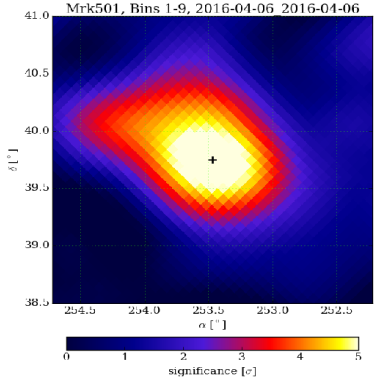
HAWC detection of increased TeV flux state for Markarian 501

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

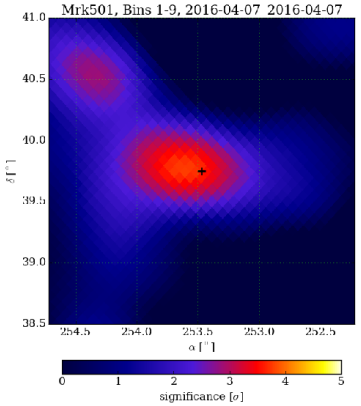
Astronomer's Telegram to immediately alert community of activity.



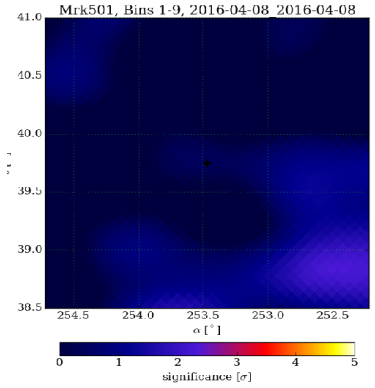
April 5, 2016



April 6, 2016



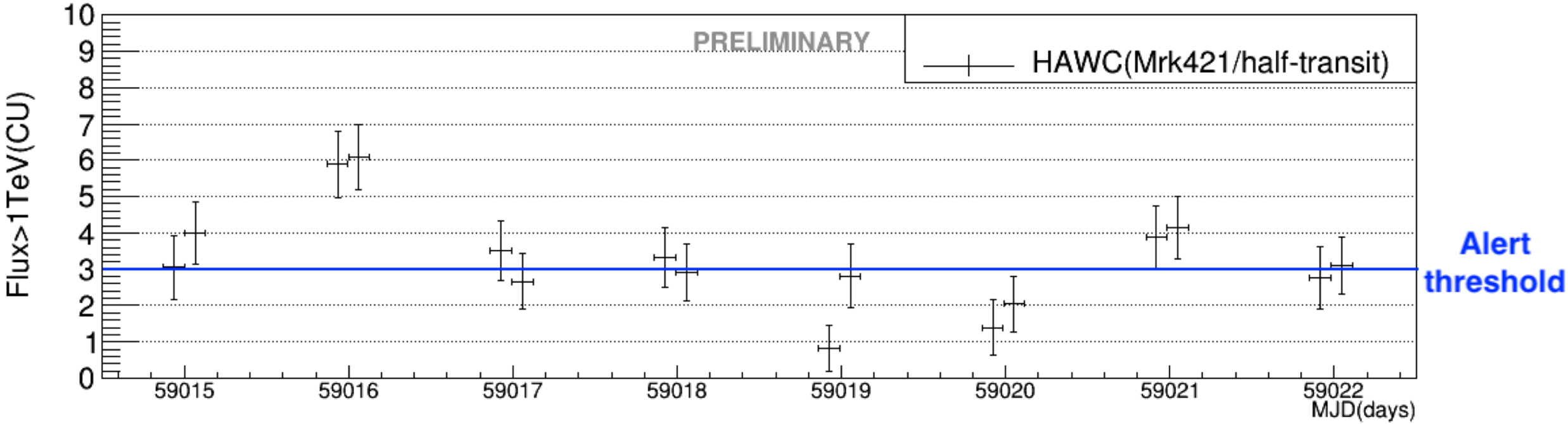
April 7, 2016



April 8, 2016

Monitoring all gamma-ray sources visible to HAWC every day.

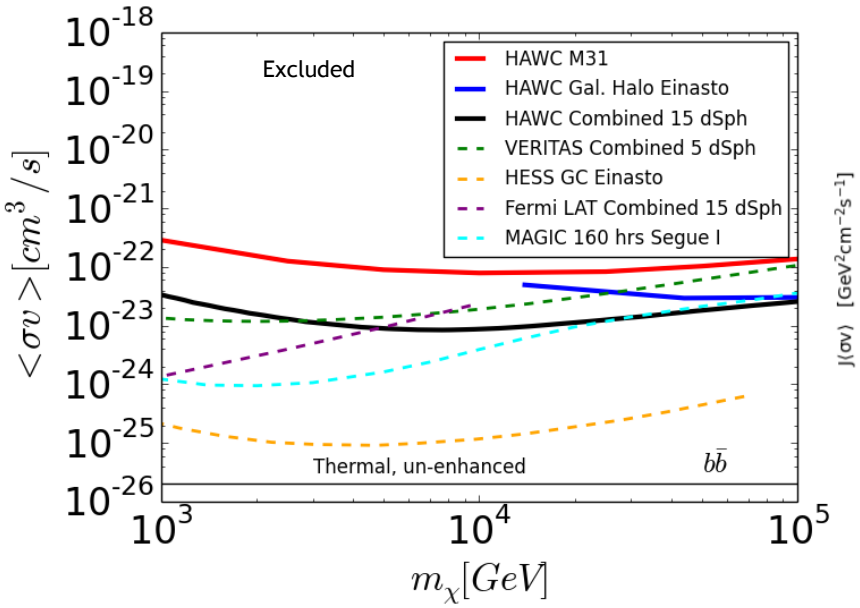
Transient Sources – Mrk 501 and Mrk 421

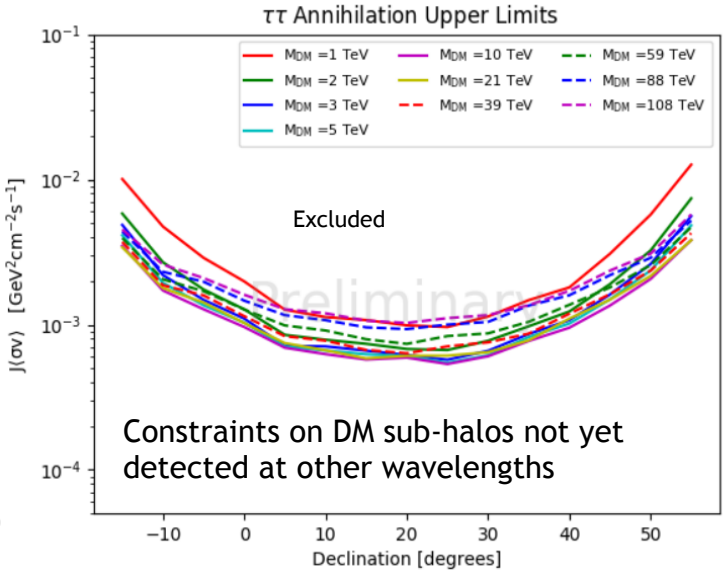


Dark Matter Study

- Many dark matter targets in HAWC F.o.V.:
  - ❖ Dwarf spheroidal galaxies, M31, Galactic center halo, galaxy clusters

- HAWC can place limits if DM annihilation or decay -> gamma rays
  - ❖ For masses higher than models with direct detection or LHC





JCAP, 1802(02):049, 2018

Astrophys. J., 853(2):154, 2018

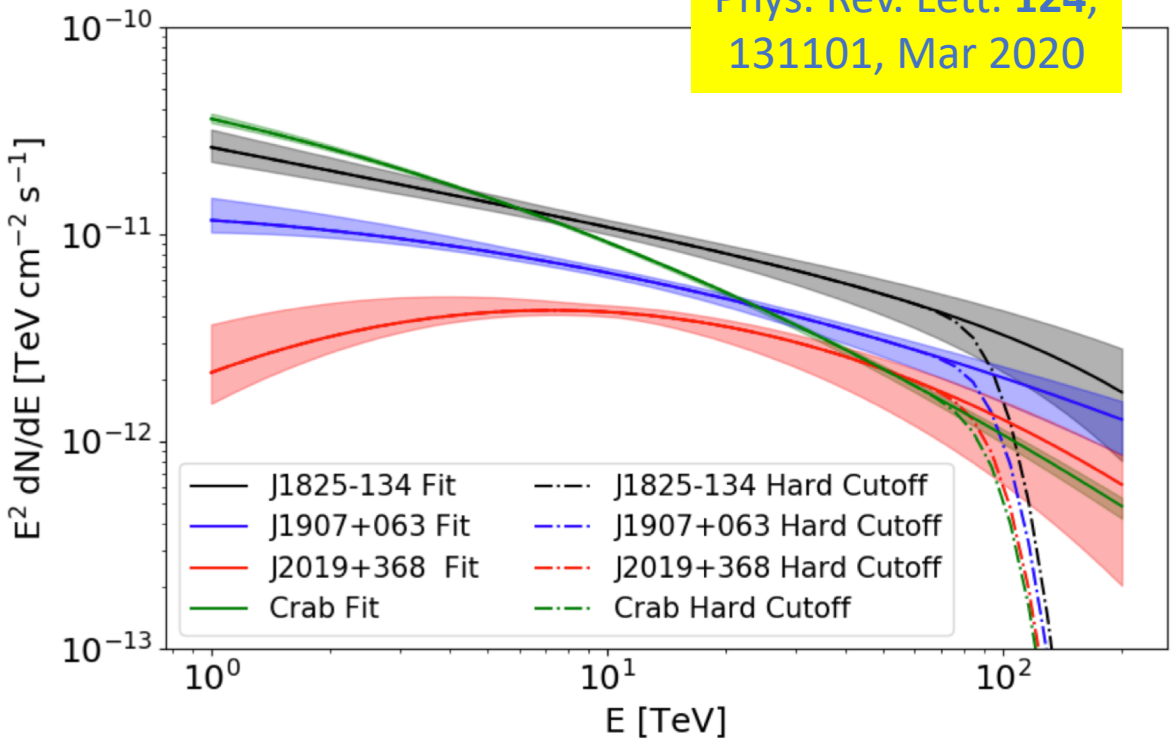
Lorentz Invariance Violation

- Photon decays forbidden in C.R.

- If LIV were to exist:
  - $E_\gamma^2 - p_\gamma^2 = \pm|\alpha_n| p_\gamma^{n+2}$
  - Photons would decay; producing a cut-off in the highest energy photons

- HAWC data used to set LIV limits since HAWC finds evidence of >100 TeV photons with no hard cut-off

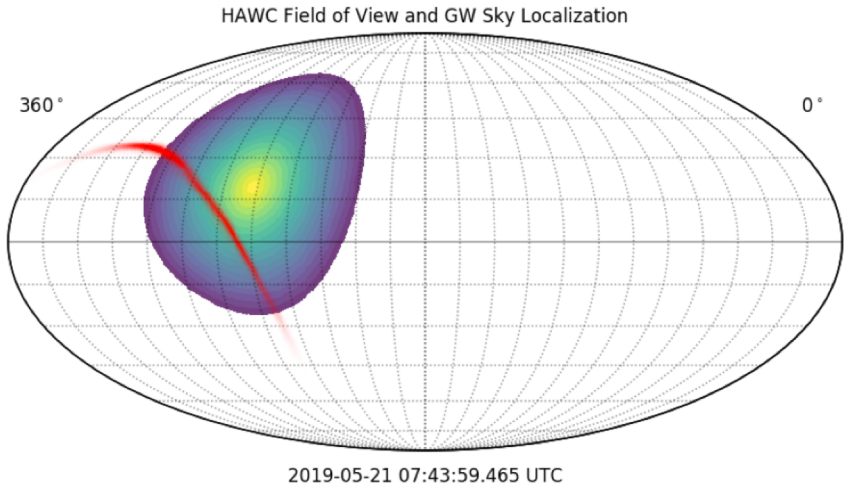
Phys. Rev. Lett. **124**, 131101, Mar 2020



Multi-Messenger Astronomy – GW

- Gravitational Waves – LIGO
  - Automatic search of GRB when GCN alert (LIGO)
  - $\Delta t = 0.3, 1, 3, 10, 30, 100$ sec

B. P. Abbott et al. Astrophys. J., 848(2):L12, 2017

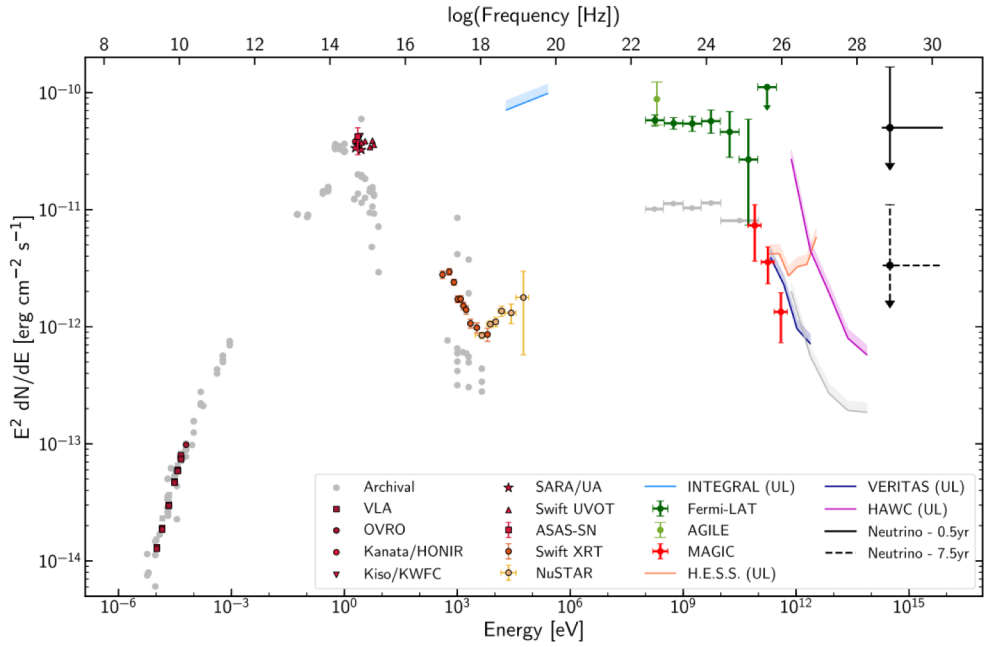


- Pre-approved to send detection and non-detection alerts as GCN circulars
- If detection ($> 3\sigma$), we send the circular as soon as possible, providing the hotspot coordinates
- If non-detection, wait for all timescales to finish, then we provide our sensitivity range

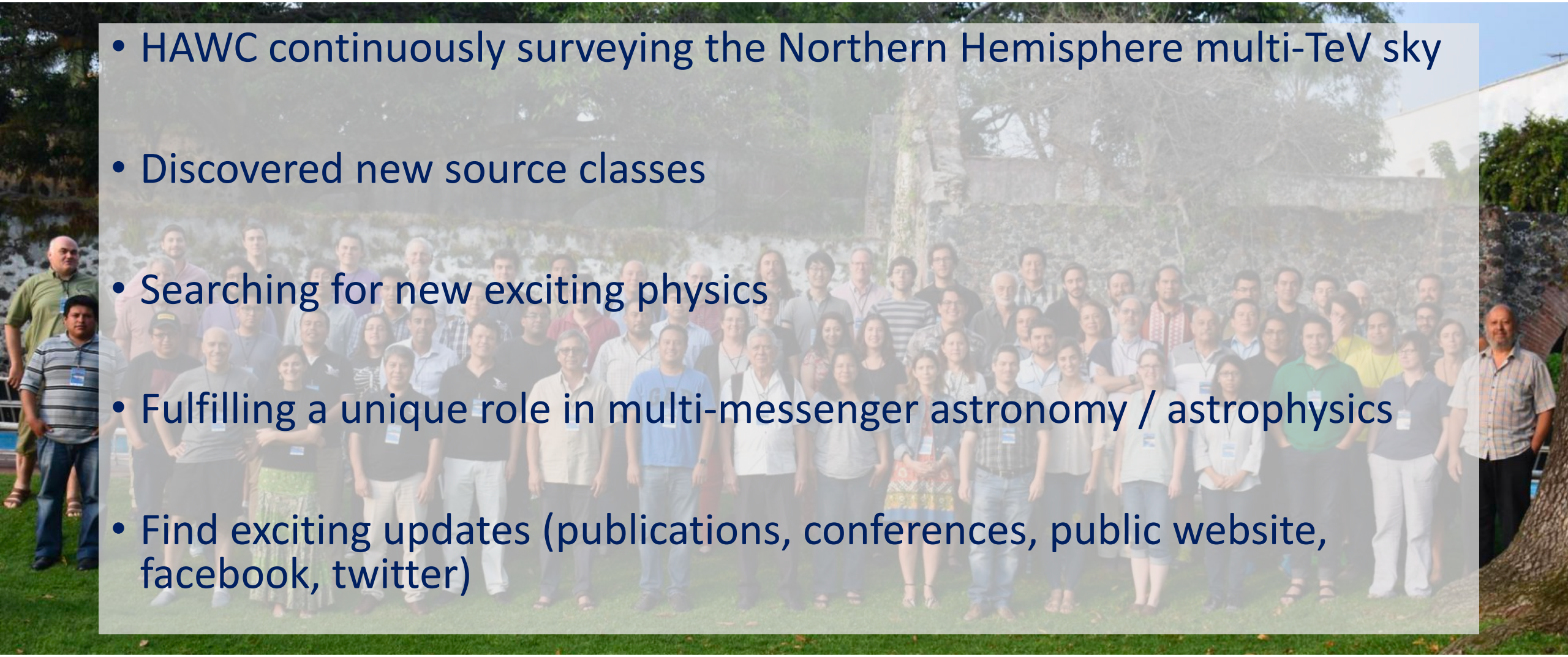
Multi-Messenger Astronomy – Neutrinos

- Simultaneous detection of γ-rays and neutrinos always interesting!
- Neutrinos – IceCube (170922A)
  - Associated with a known gamma-ray blazar TXS 0506+056
- No detection from HAWC, but produced interesting limits

Science Jul 2018: Vol. 361, Issue 6398, eaat1378



Summary

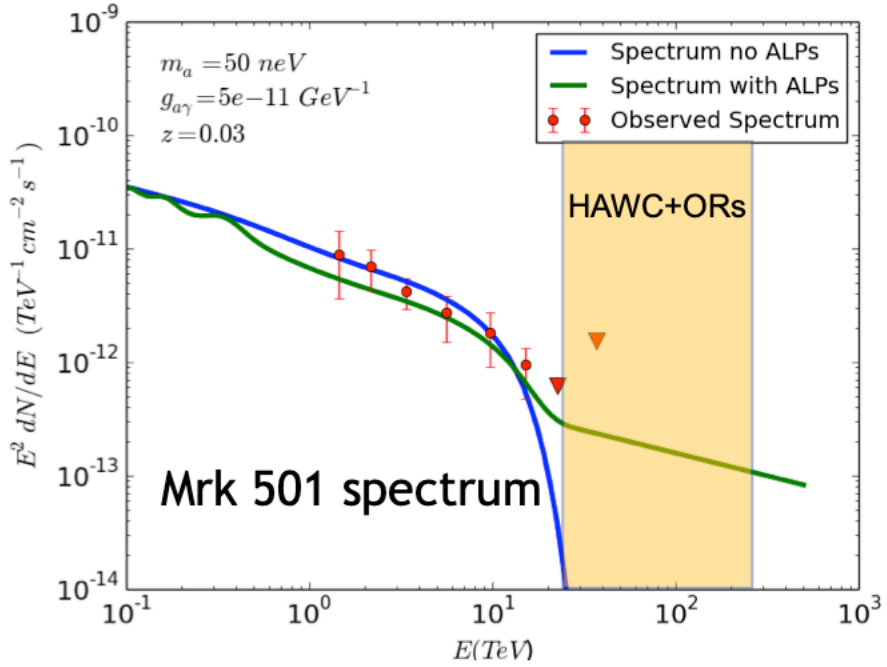


- HAWC continuously surveying the Northern Hemisphere multi-TeV sky
- Discovered new source classes
- Searching for new exciting physics
- Fulfilling a unique role in multi-messenger astronomy / astrophysics
- Find exciting updates (publications, conferences, public website, facebook, twitter)

Back Up

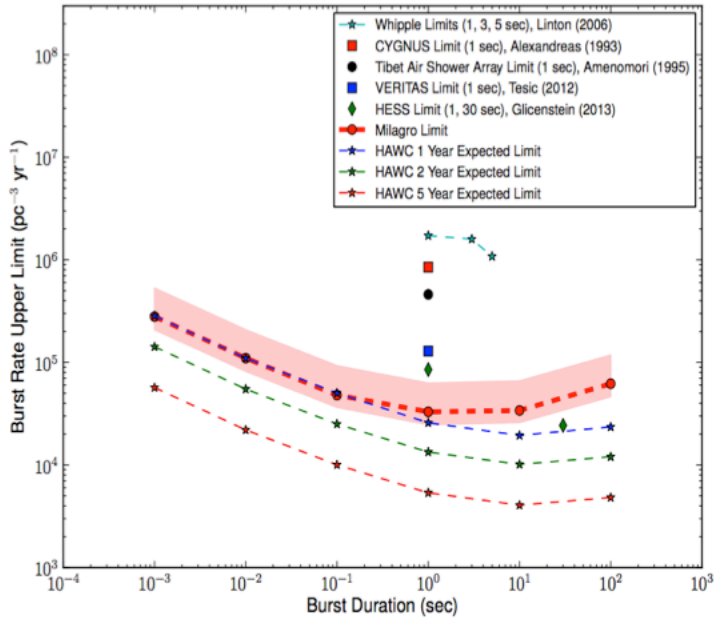
Other Beyond the Standard Model Physics

- Axion-like-particle searches (ALP)
  - Gamma-rays in magnetic fields can convert to ALPs
  - ALPs modify observed spectra of AGN
  - More high-energy emission than expected



HAWC collaboration, in preparation, 2018

- Primordial black holes (PBH)
  - Evaporating PBHs emit bursts of gamma rays
  - Could be seen by HAWC as transient emissions
  - Light curve probes SM



Abdo et al, Astroparticle Physics, 2015