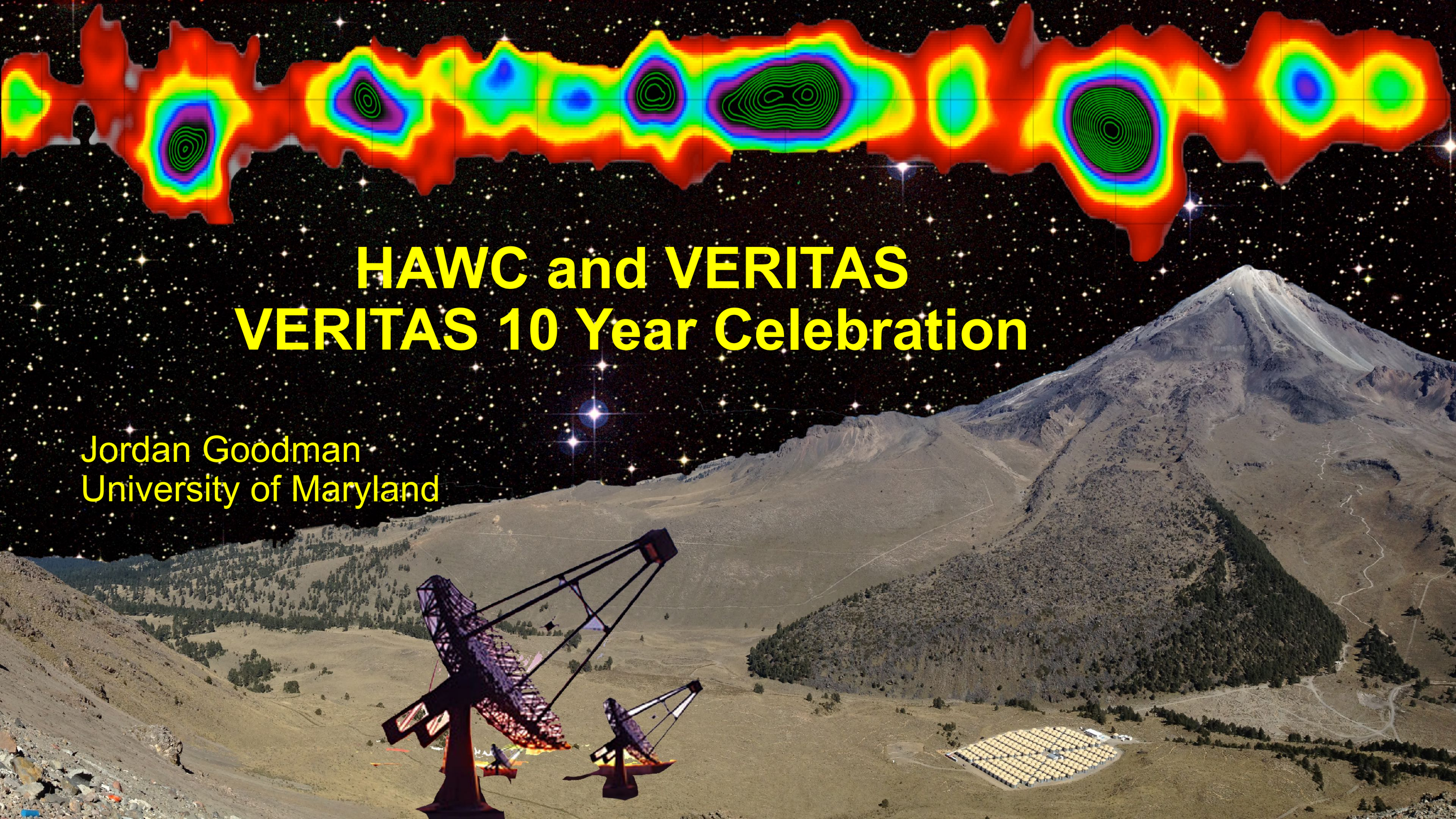
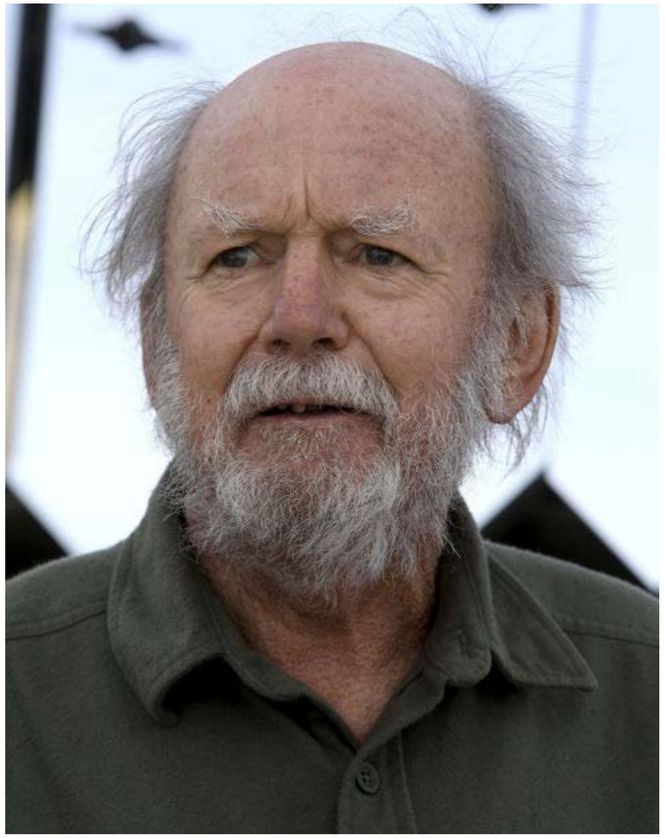
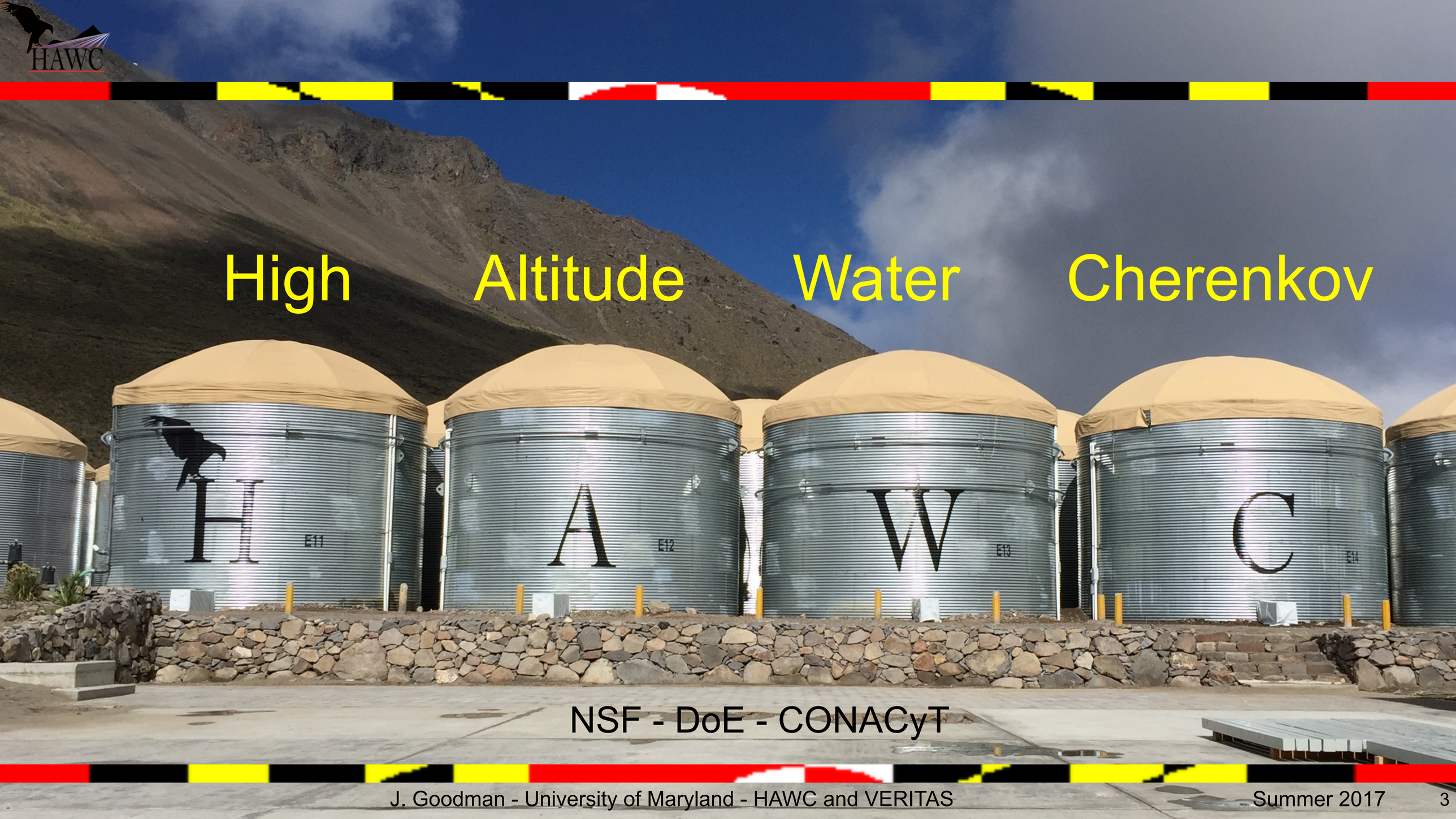


HAWC and VERITAS
VERITAS 10 Year Celebration

Jordan Goodman
University of Maryland

A Few Words About Trevor





NSF - DoE - CONACyT

The HAWC Collaboration

United States

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

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

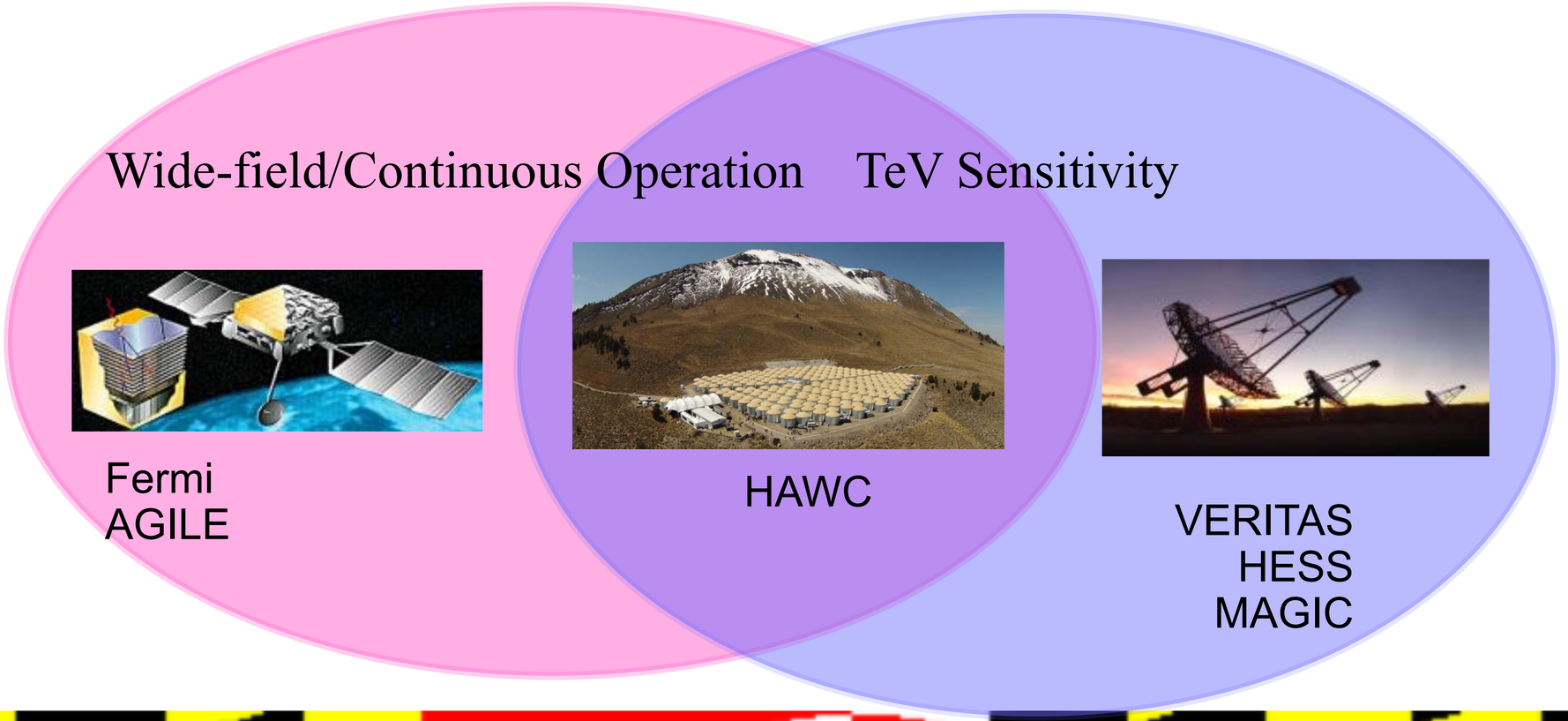
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional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

Europe

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

Complementarity of Gamma-Ray Detectors

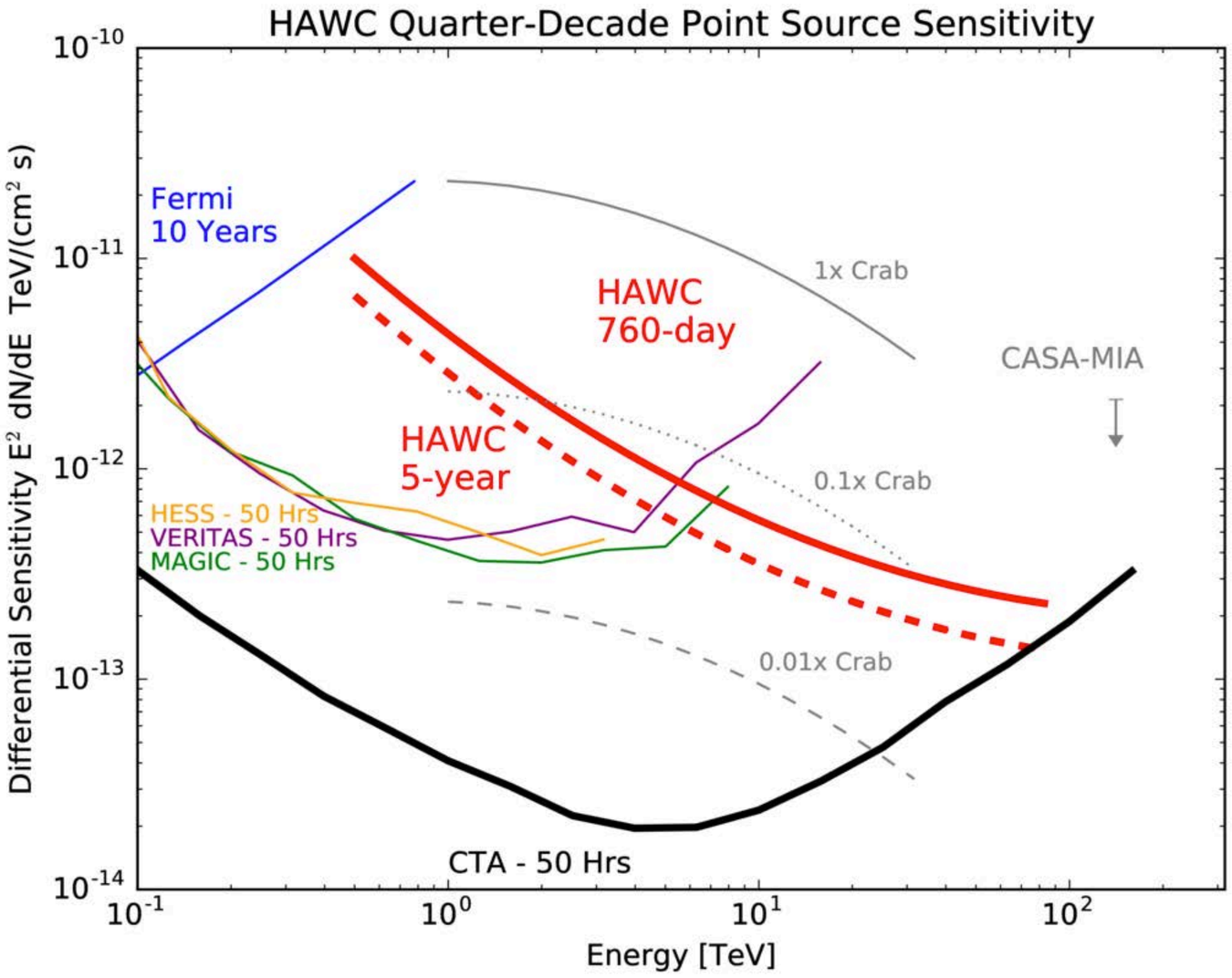
- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
  - IACTs (pointed) excellent energy and angle resolution
  - HAWC has 24-hour >1/2 sky coverage



Complementarity of Gamma-Ray Detectors

- VERITAS
  - Can detect a point source with 1% Crab Nebula strength within 25 hours
  - Has energy range from ~100 GeV to ~10 TeV
  - Has an angular resolution better than 0.1^{o} at 1 TeV
  - Sensitivity drops for sources with radius (r) > 0.1^{o} ~r/(0.1^{o})
- HAWC
  - Can detect a point source with ~5%-10% Crab Nebula strength over most of the northern sky with two years of data (~5-6$\sigma/\sqrt{d}$)
  - Has energy range from ~500 GeV to ~100 TeV, can extend spectra to high energies
  - Has angular resolution that varies from ~1^{o} at 1 TeV to better than 0.2 at 10 TeV
  - Sensitivity doesn't change appreciably for extended objects
  - Observes every visible source every day

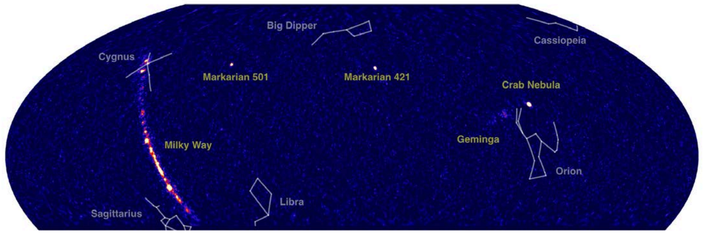
HAWC Differential Sensitivity

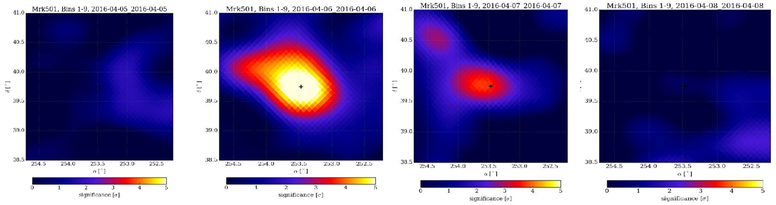


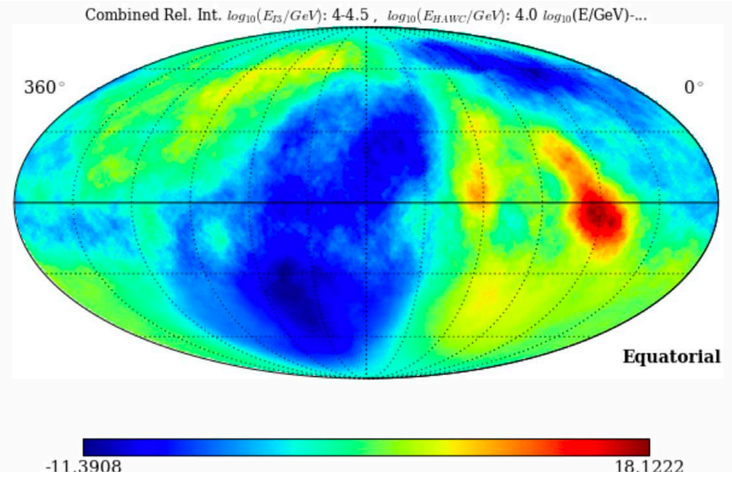
5 years of HAWC operations will give similar sensitivity at 10 TeV as 1 TeV for ACTs

What can you do with a wide-field instrument?

- Gamma Ray Astrophysics
  - Galactic Gamma-Ray Sources - Survey
    - Discovery of Pulsars, PWNs, Binaries - especially extended sources
    - Study of high energy behavior - source of galactic cosmic rays
    - Morphology of sources
    - Galactic Diffuse and Fermi Bubbles
  - Transients
    - Gamma Ray Bursts - high energy behavior
    - AGN - Continuous monitoring
    - IceCube, LIGO multimessenger observations
- Particle Physics
  - Dark Matter - can look for places with no visible signal
  - Primordial Black Holes
  - Violations of Lorentz Invariance
  - Look for sources of positron excess
- Cosmic Ray Anisotropy







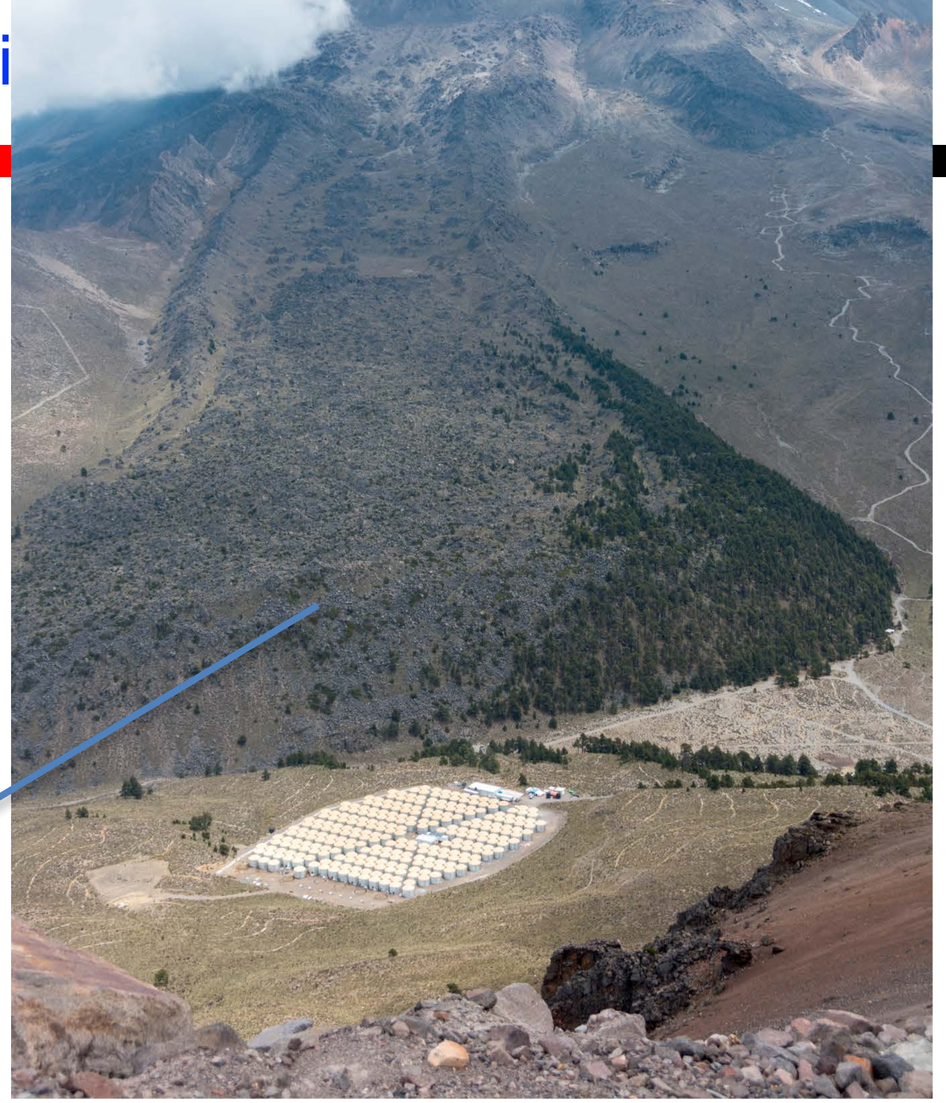
HAWC Design builds on Milagro

Milagro "1st Generation" Water Cherenkov detector
- 2650m (8600') elevation near Los Alamos, NM
- Covered pond of 4000 m^2
- Operated 2000-2008
- Crab at 5σ in 4-5 months

HAWC "2nd Generation" Water Cherenkov detector
- 4100m (13500') elevation near Puebla, Mexico
- 300 water tanks spread over 22,000 m^2
- Operation 2015-19(25)
- Crab at >5σ in a day

©Aurore Simonnet

The HAWC Si

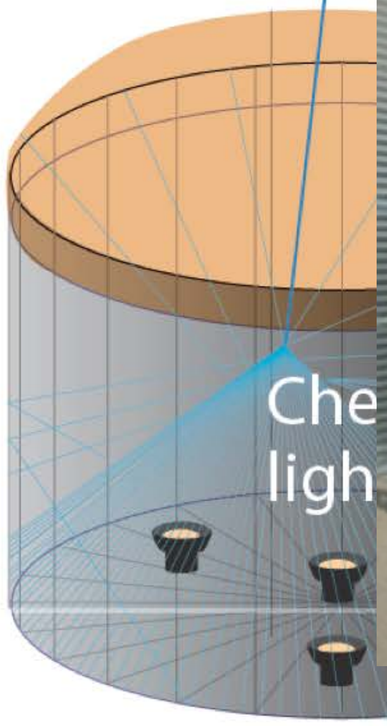


Latitude: 18°59.7’N

Longitude: 97°18.6’W

HAWC

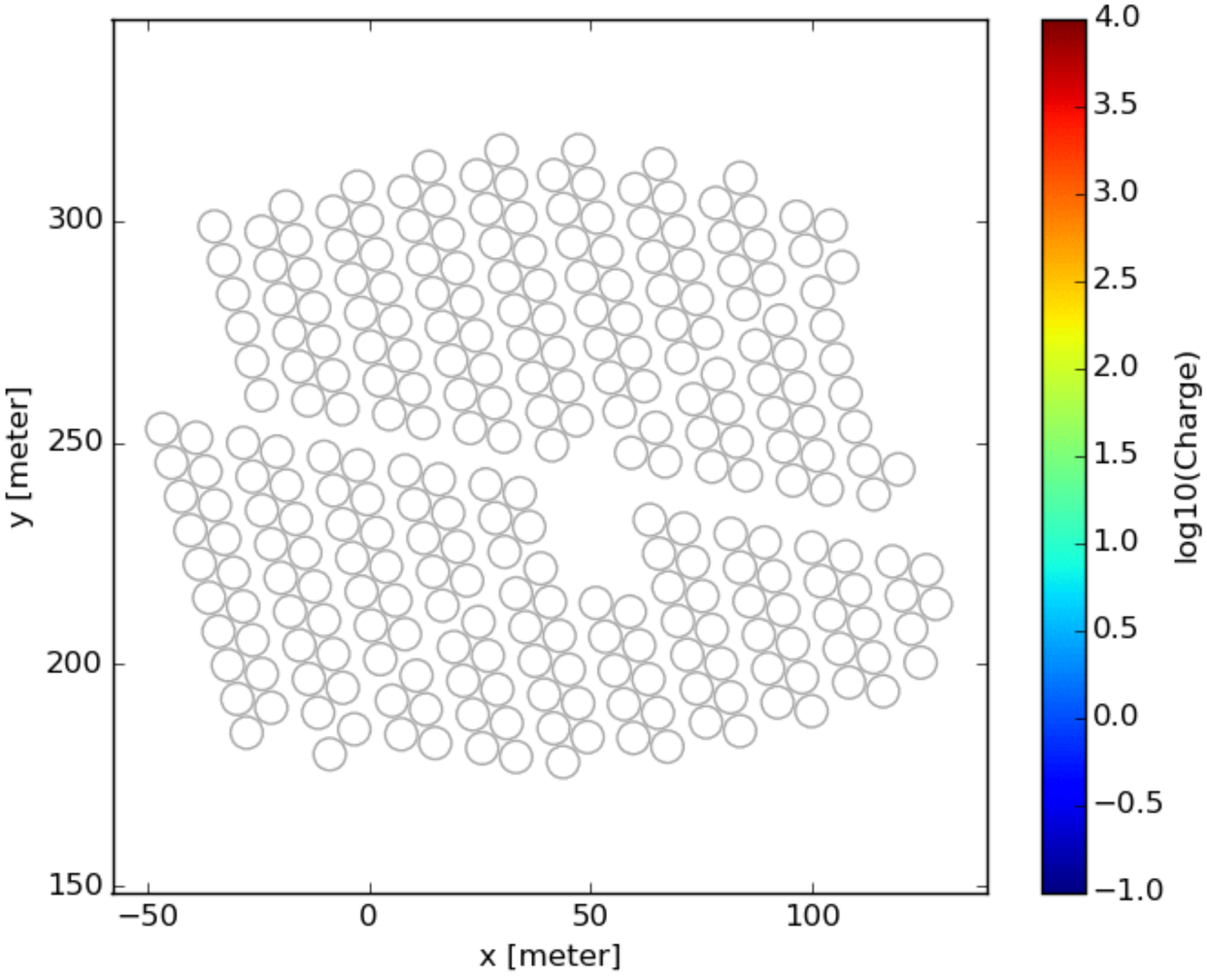
HAWC Tanks



air shower

Tank Construction

Angle Reconstruction Uses Timing



HAWC

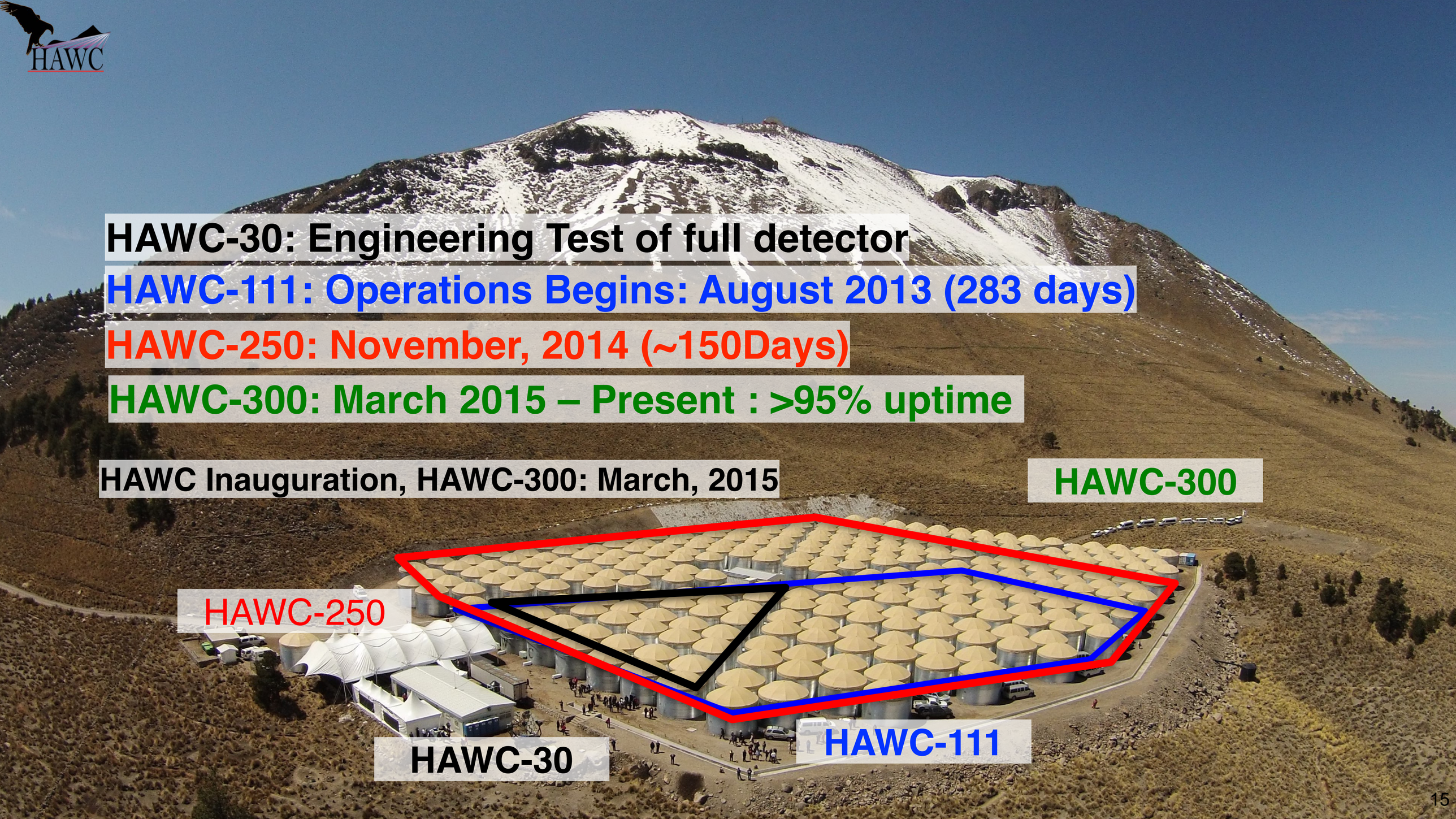
HAWC-30: Engineering Test of full detector

HAWC-111: Operations Begins: August 2013 (283 days)

HAWC-250: November, 2014 (~150Days)

HAWC-300: March 2015 – Present : >95% uptime

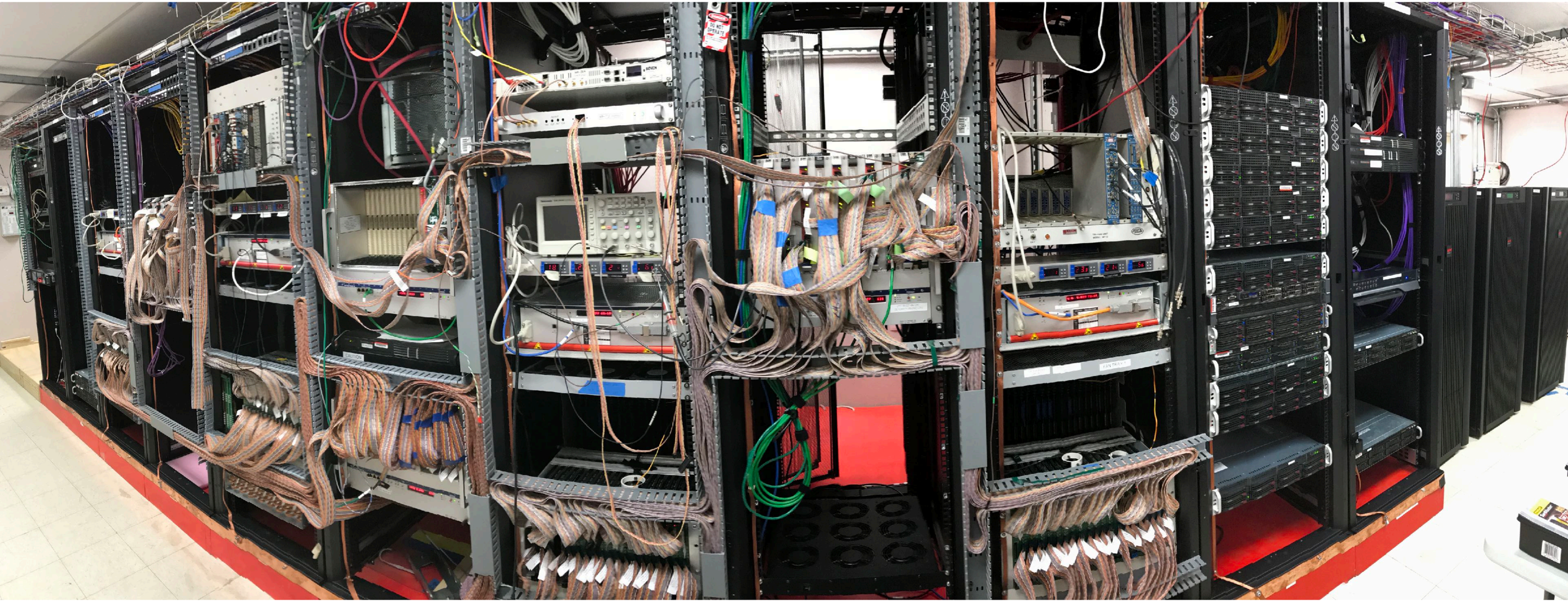
HAWC Inauguration, HAWC-300: March, 2015




300th WCD tank constructe
~3,900 tanker truck trips


H
E11
A
E12
W
C
Rotoplas
Rotoplas
Rotoplas
Rotoplas

HAWC Electronics



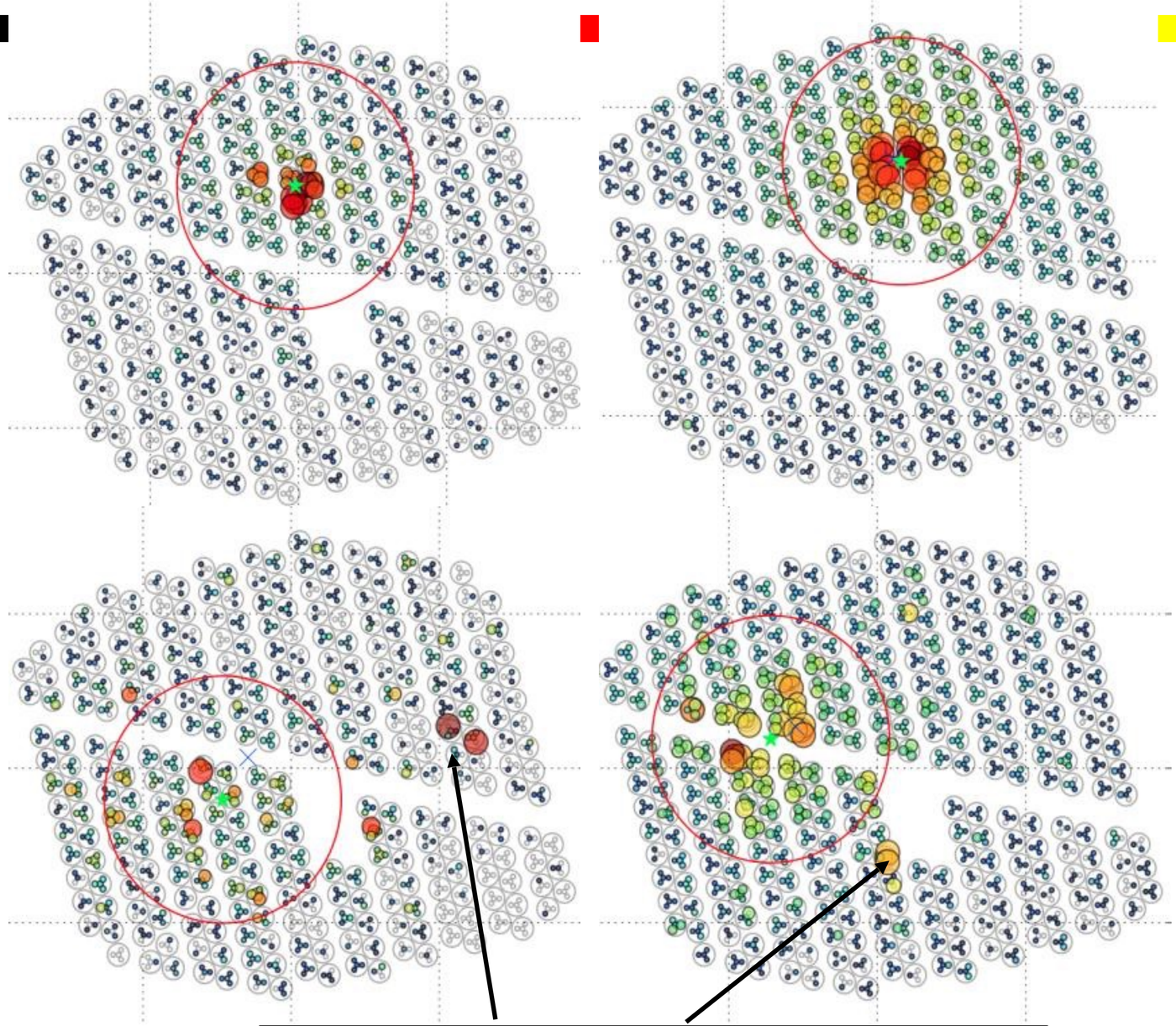
Reuses Milagro front-end boards - every hit recorded 500MB/s -> 22MB/s to disk

Gamma Hadron Separation (MC)

Gammas

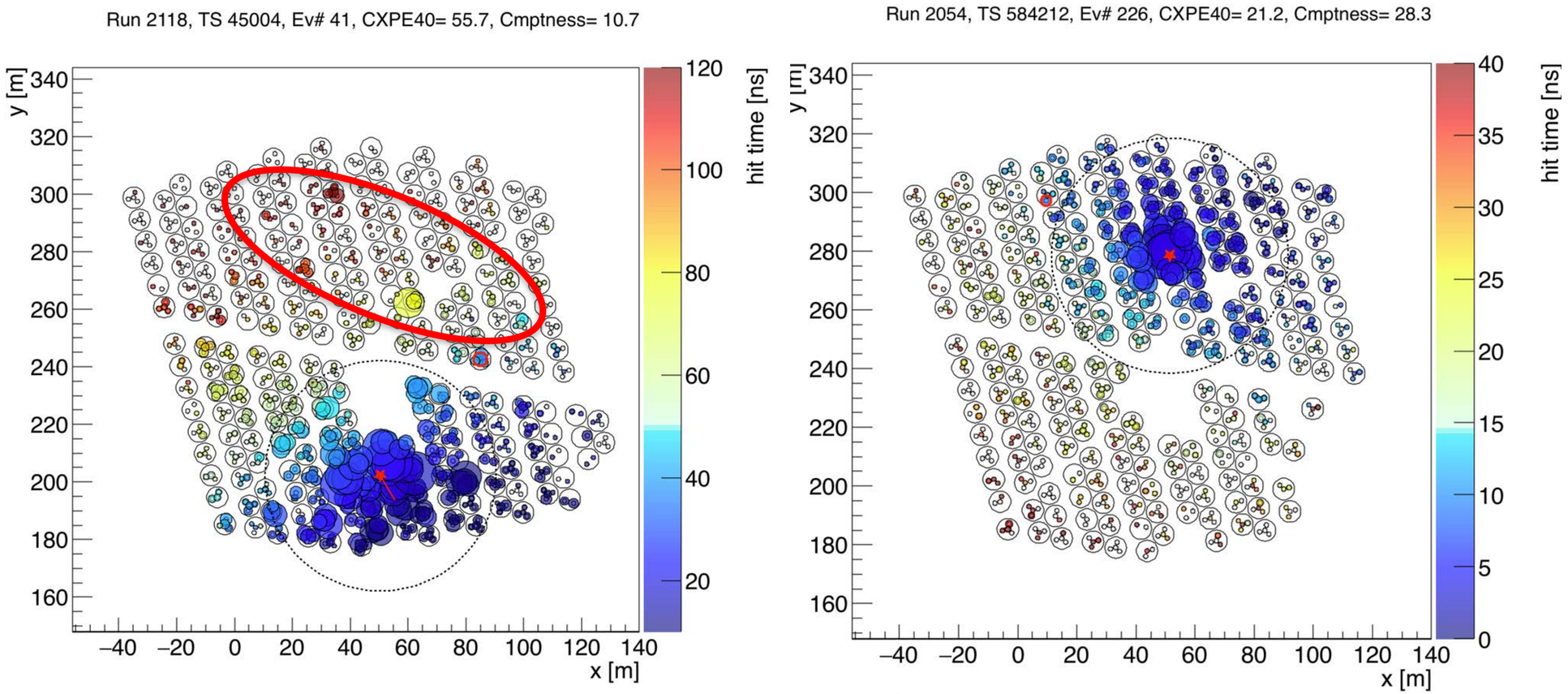
Monte Carlo Simulation

Protons



Energy deposited away from core

HAWC-250 Data



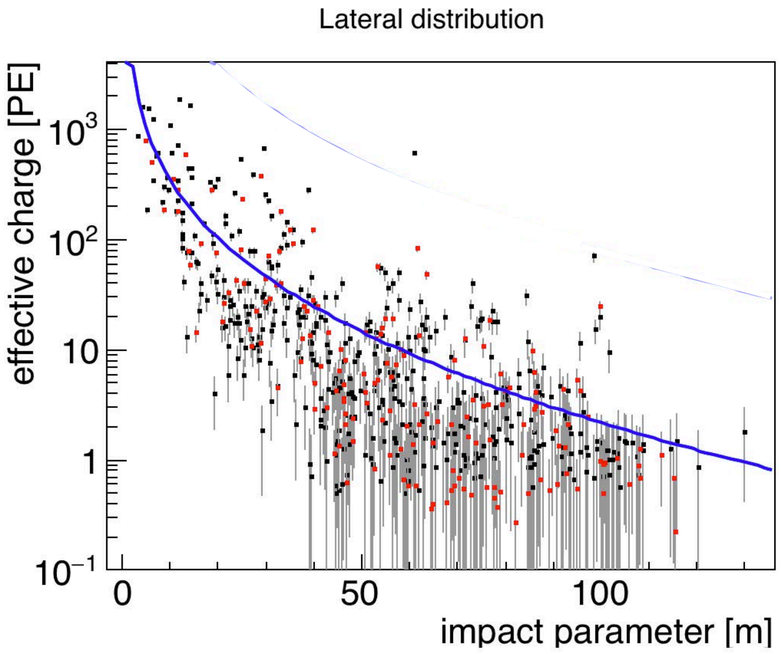
Hadron Shower (off source)

HAWC Data

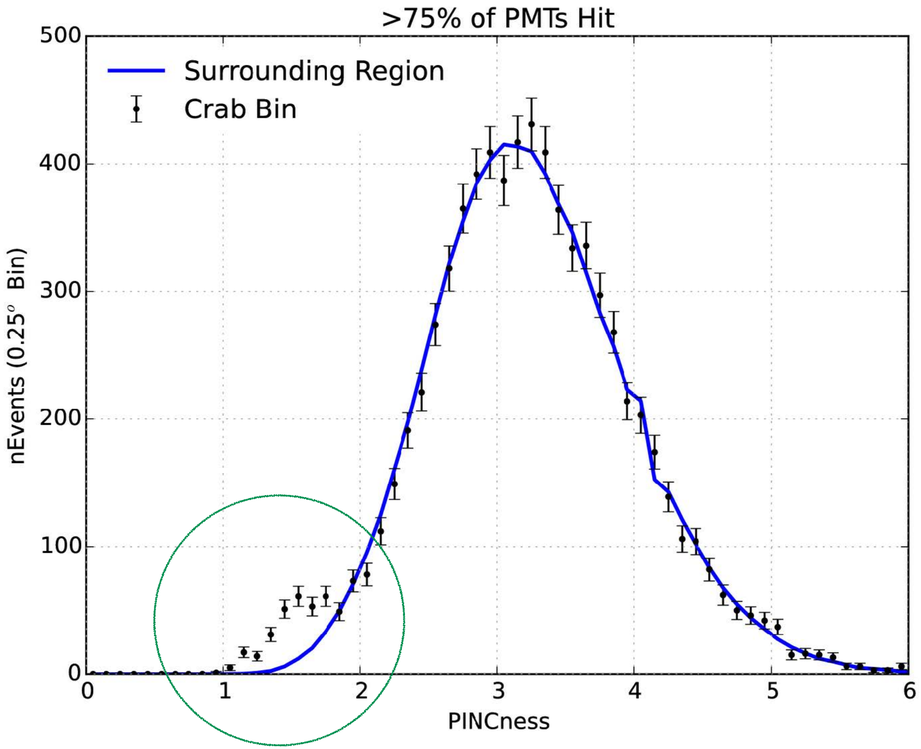
Likely Gamma Shower (Crab event)

Gamma - Hadron Separation

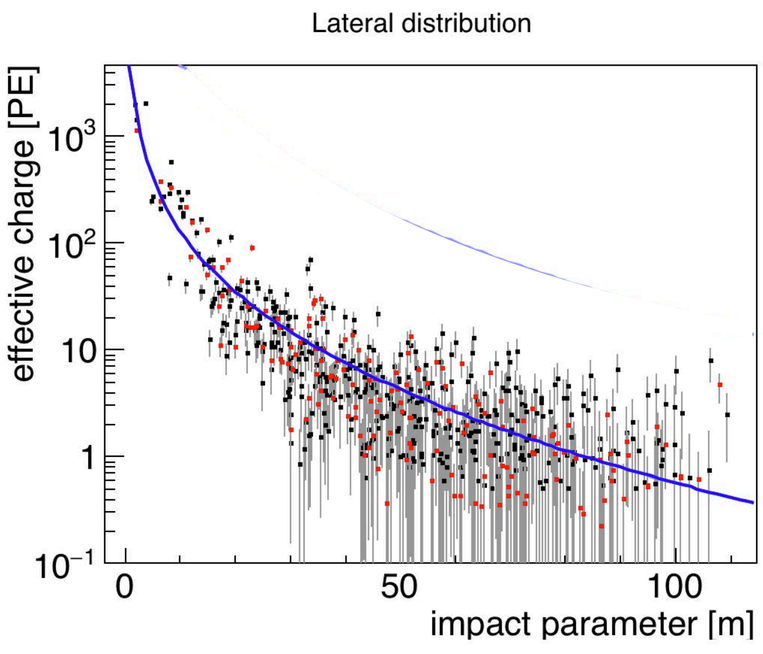
hadronic event



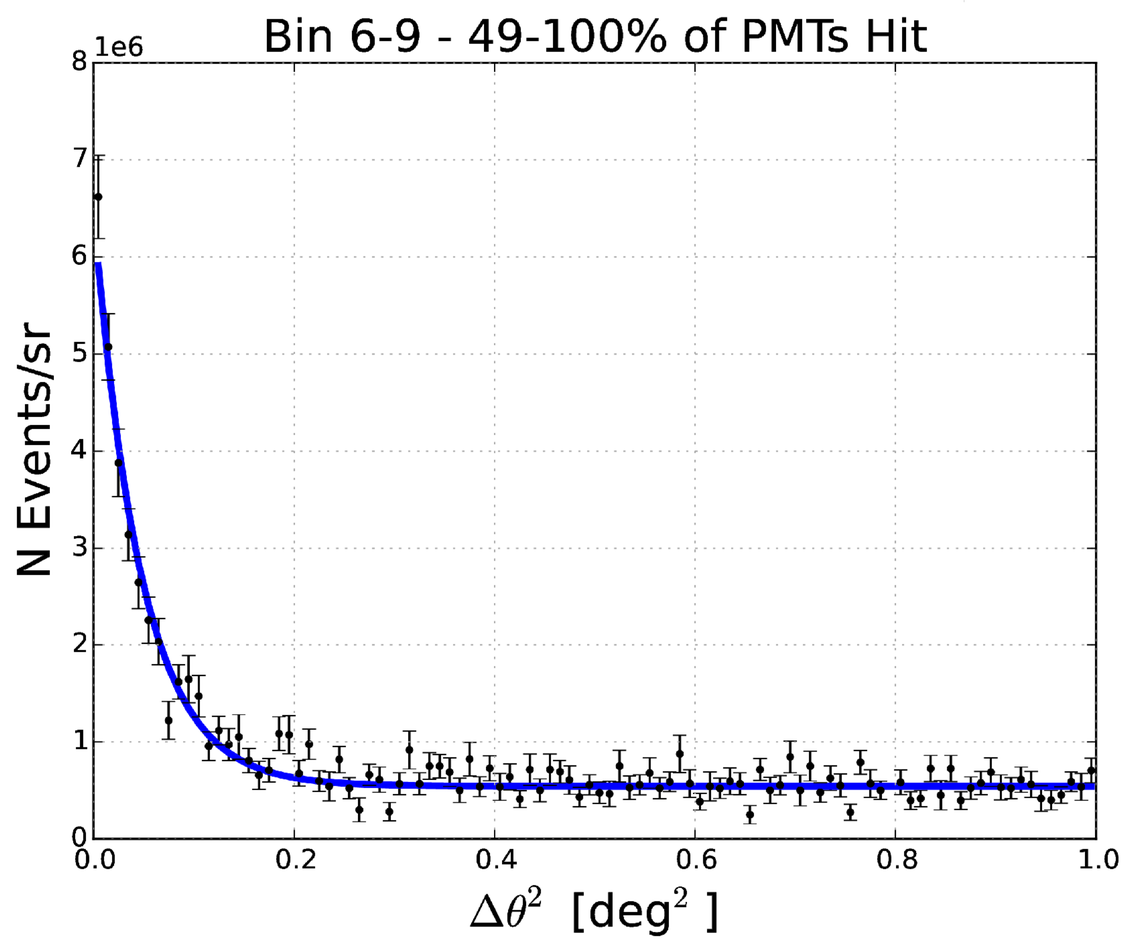
gamma/hadron parameter

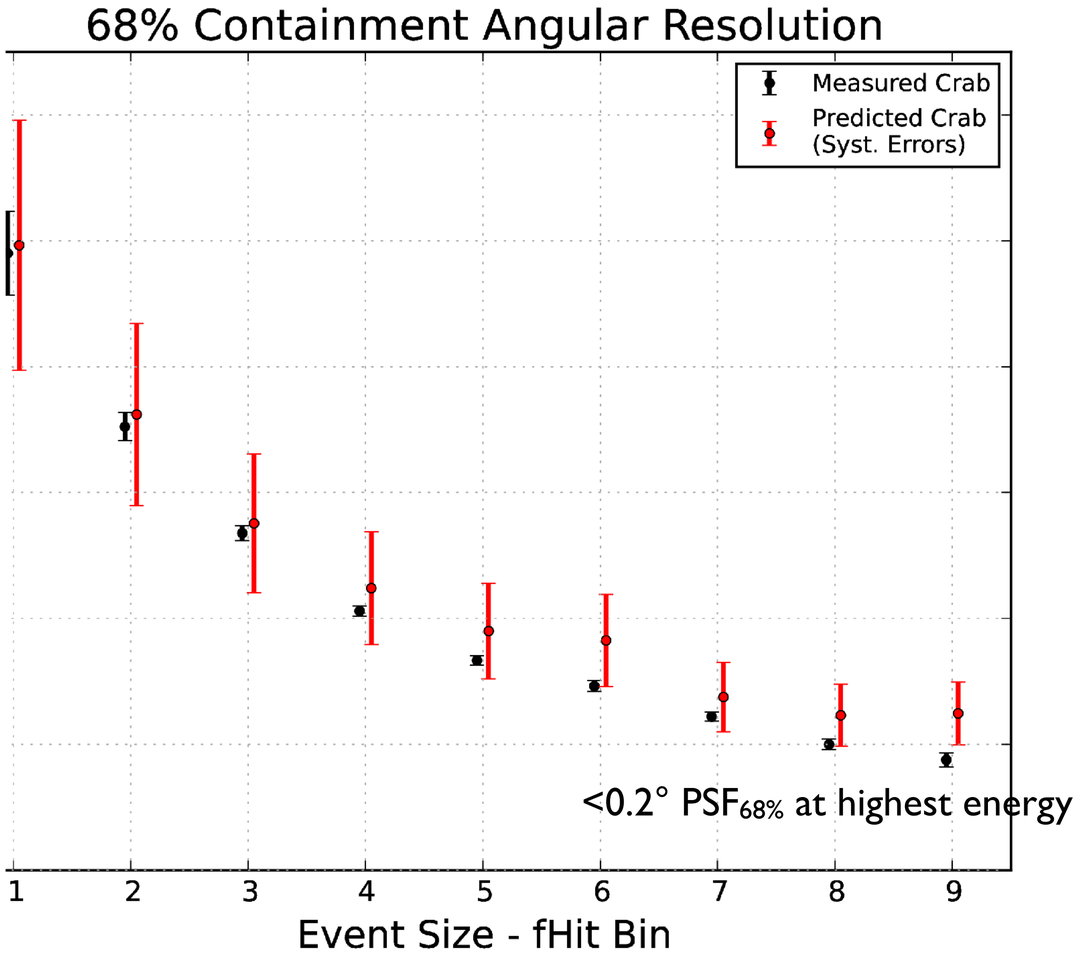


gamma ray-like event

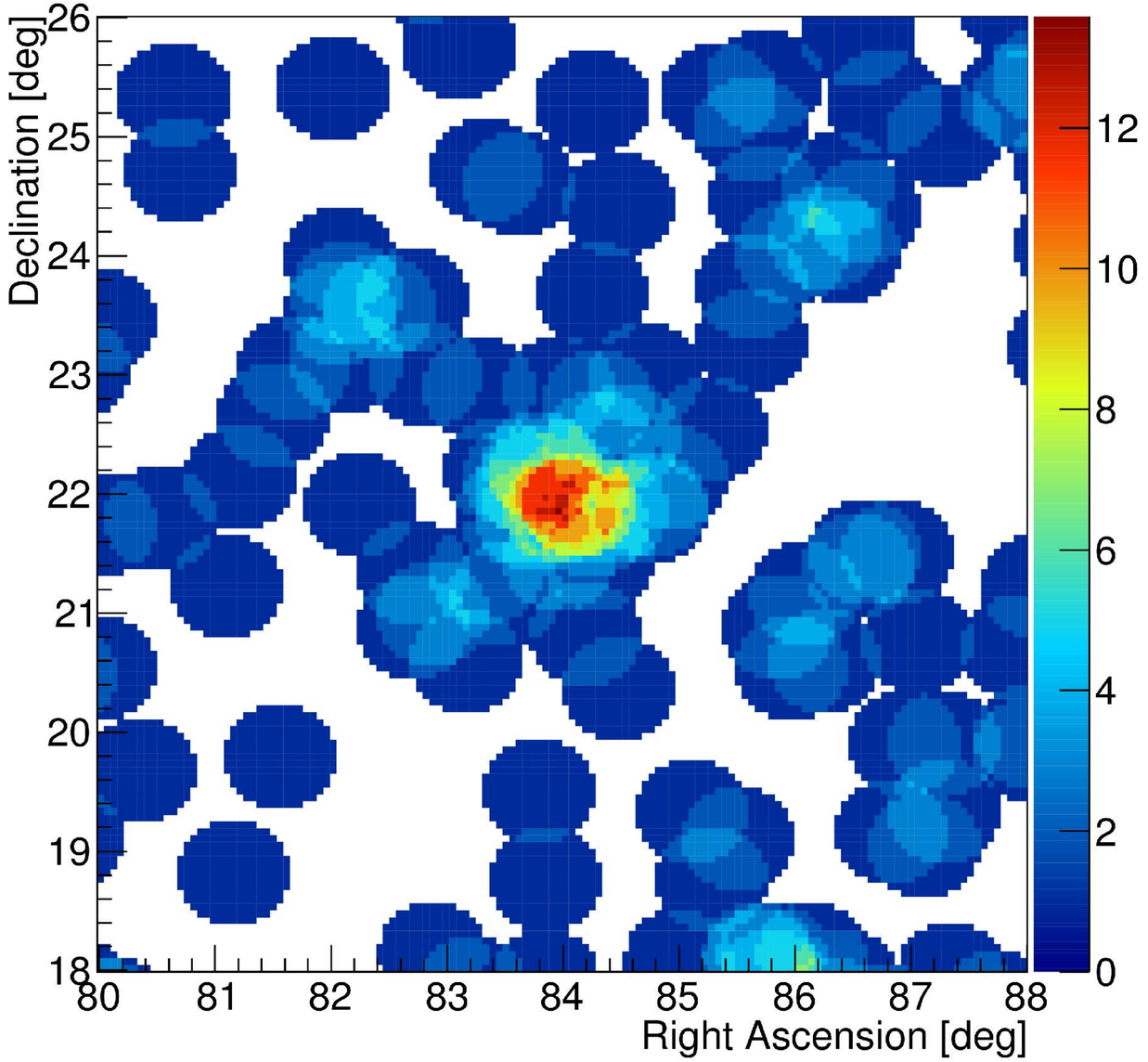


Angular Resolution





Photon rich sample from the Crab



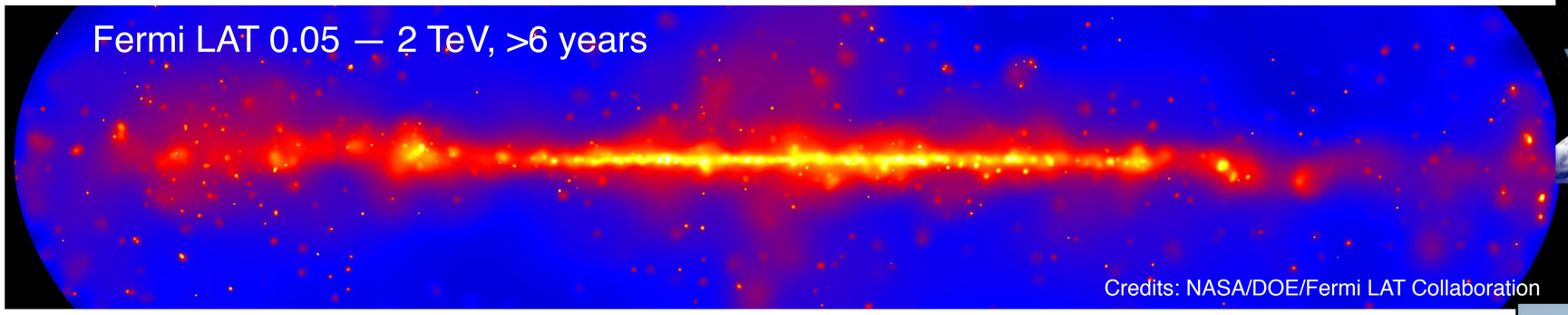
With Strong Photon Cut

1 in 10^4 Events Kept
25% Efficiency for Photons

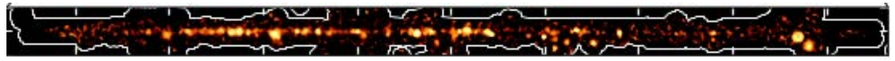
Potential Improved Algorithms

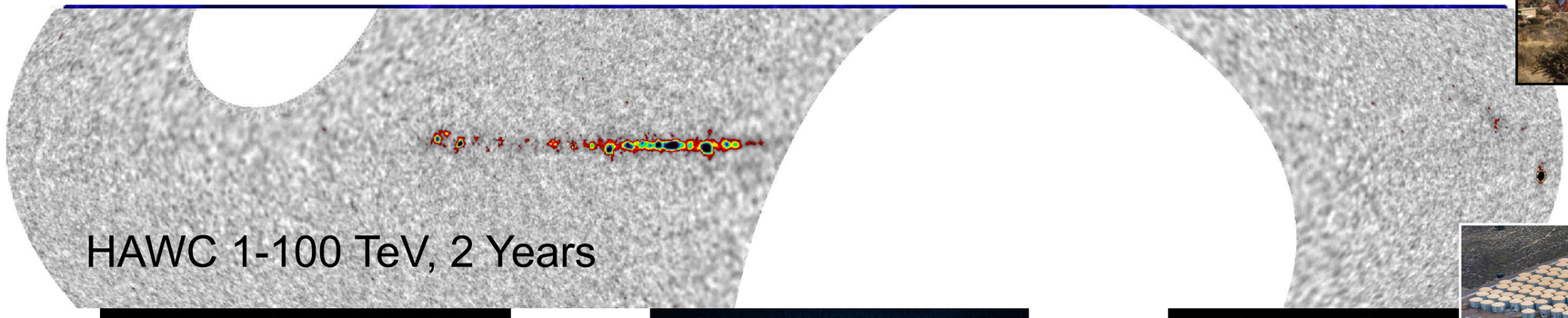
- Using sample of highest energy events, with our standard cuts, on the Crab we get:
  - Excess: 139.5 ev Background: 6.5 - signal/background >20 to 1
- Can reduce the background significantly using improved algorithms:
  - Excess: 116.0 Background: 1.0 - signal/background >100 to 1
- Can potentially reduce the background by 5x at highest energies

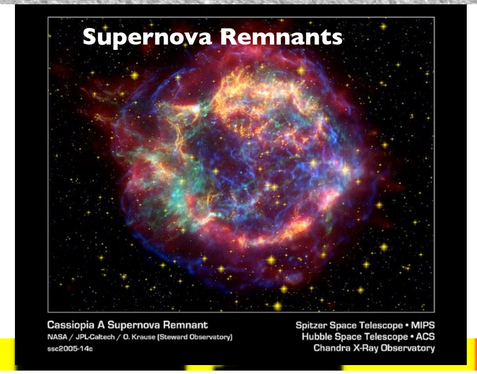
High Energy View of our Galaxy

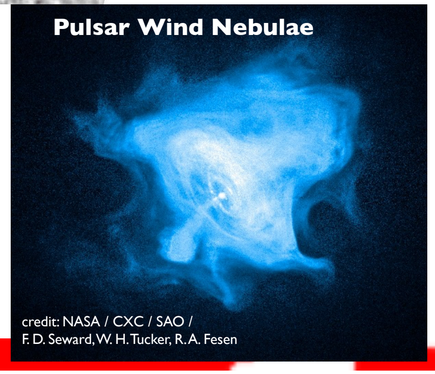


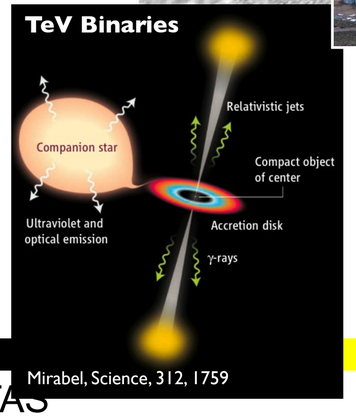
HESS >1TeV, 10 years



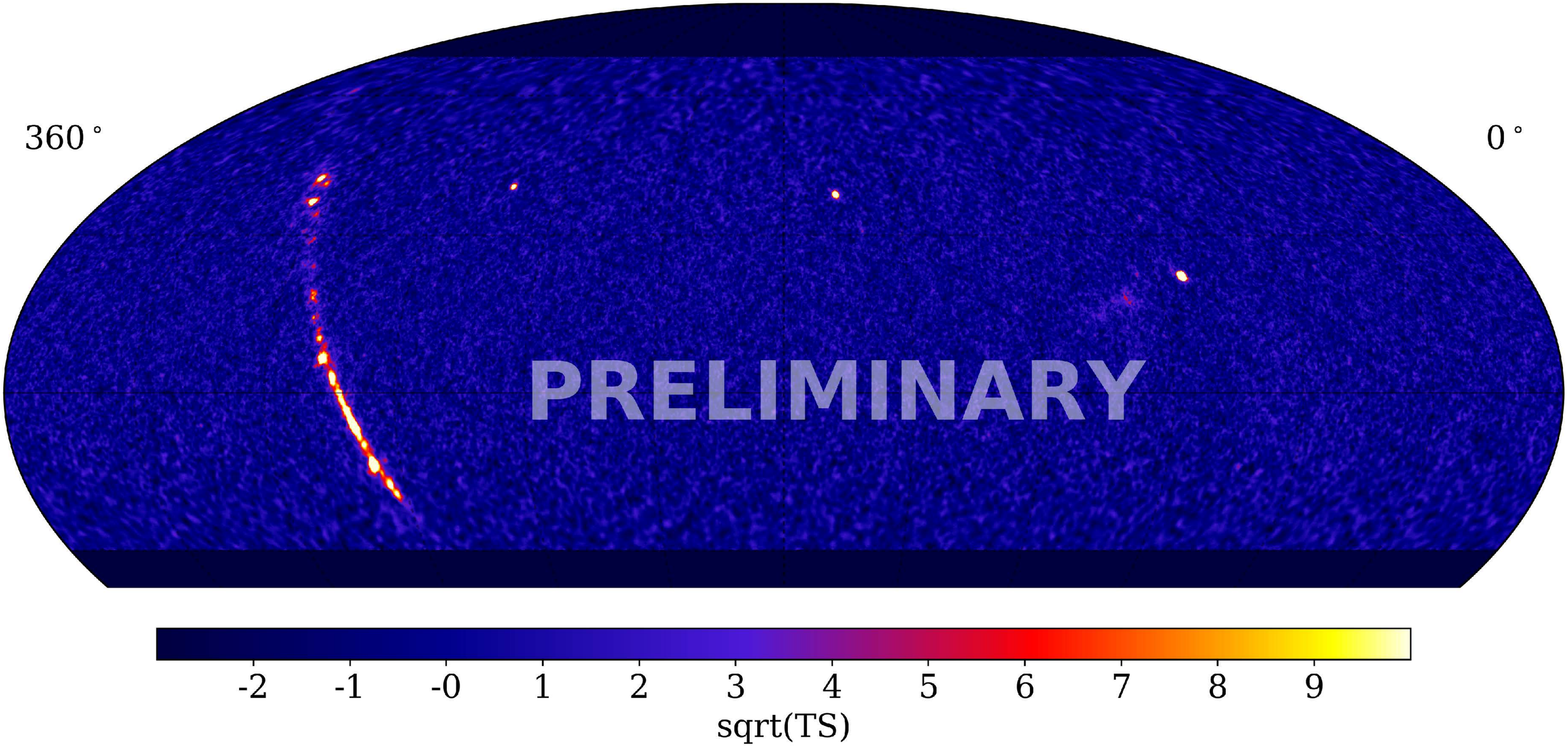




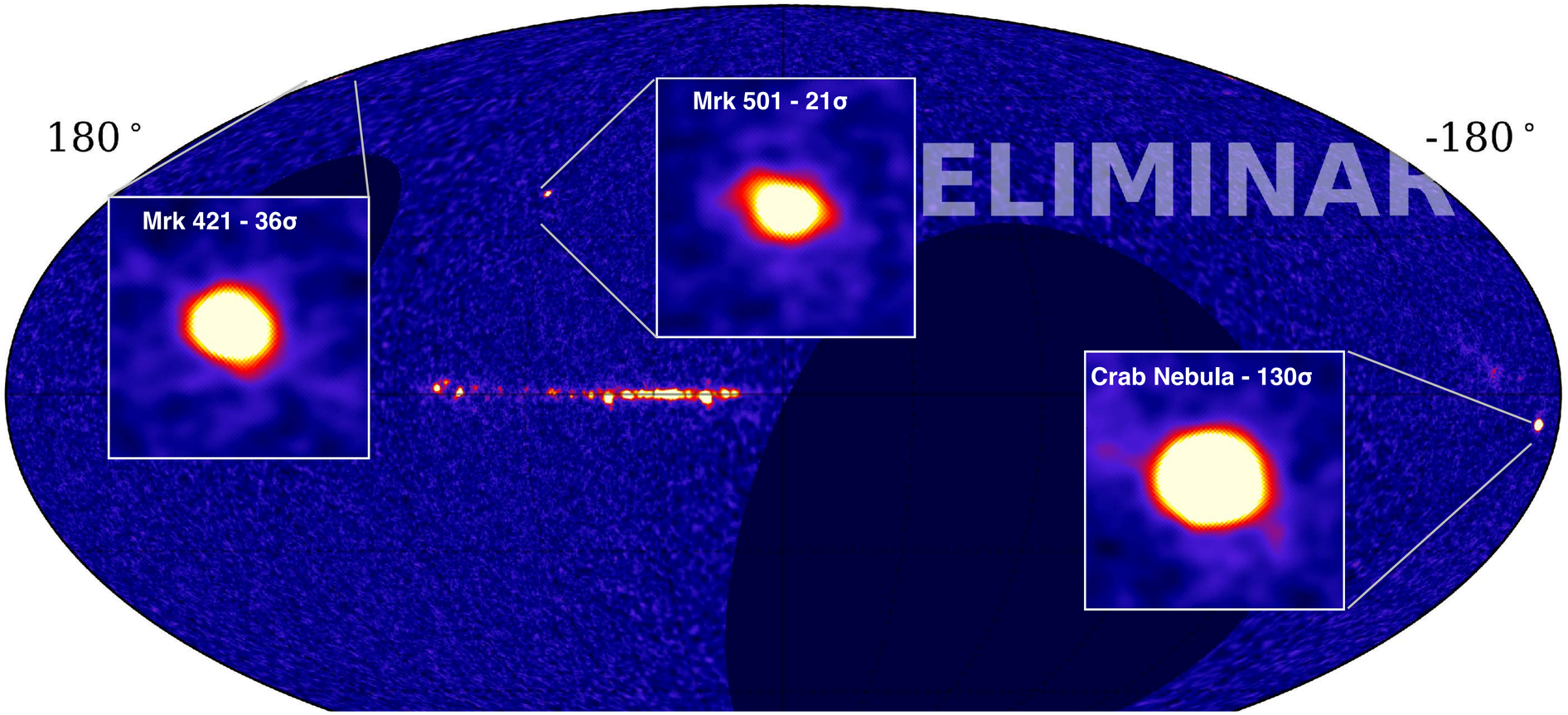


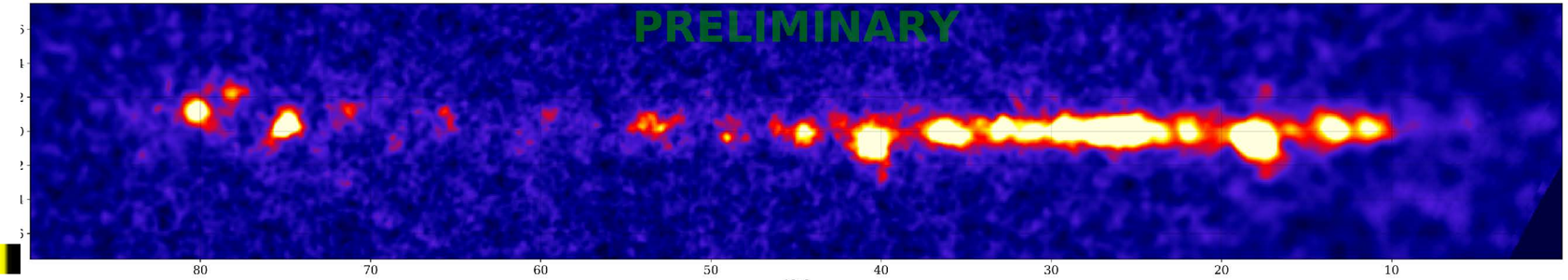


HAWC 25 Month TeV Sky Survey

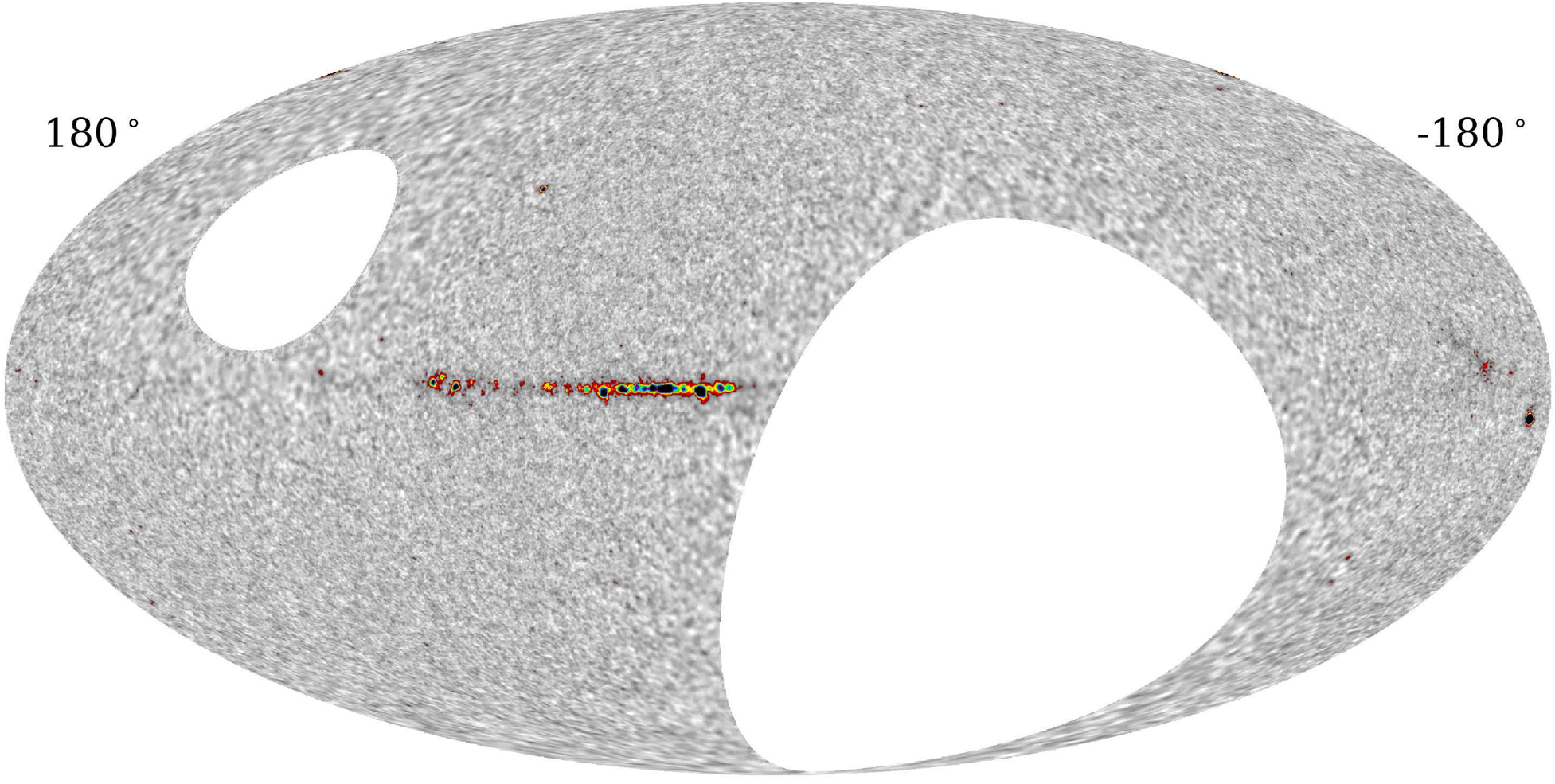


25 Month Data Set

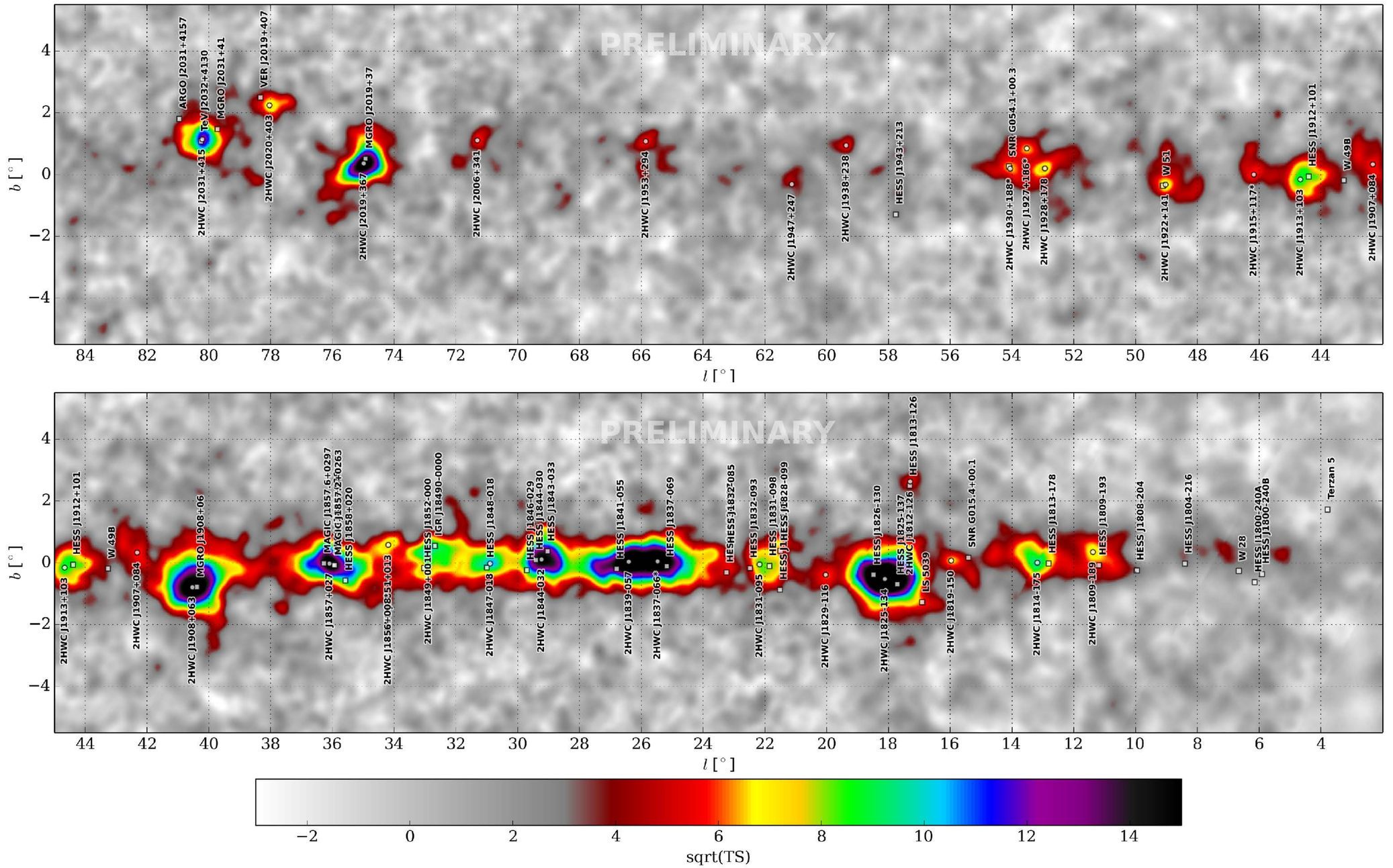




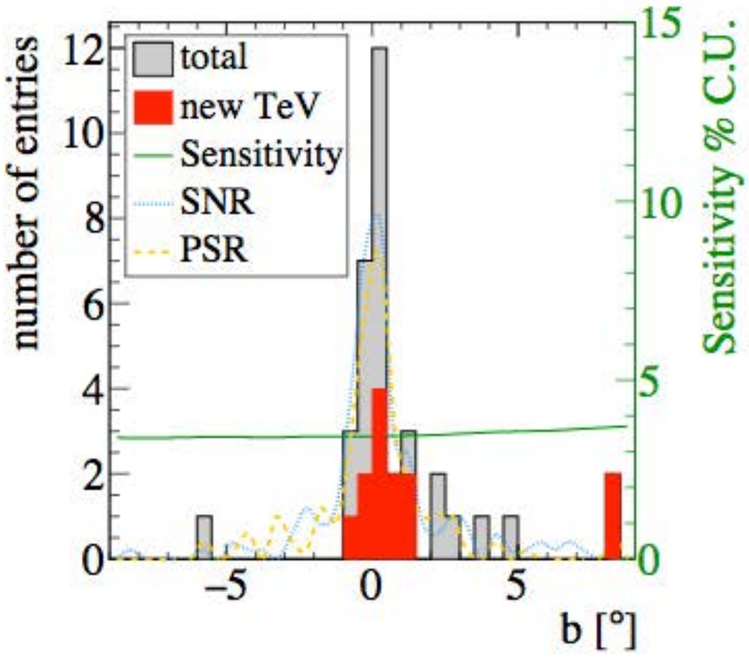
HAWC 760-Day TeV Sky Survey

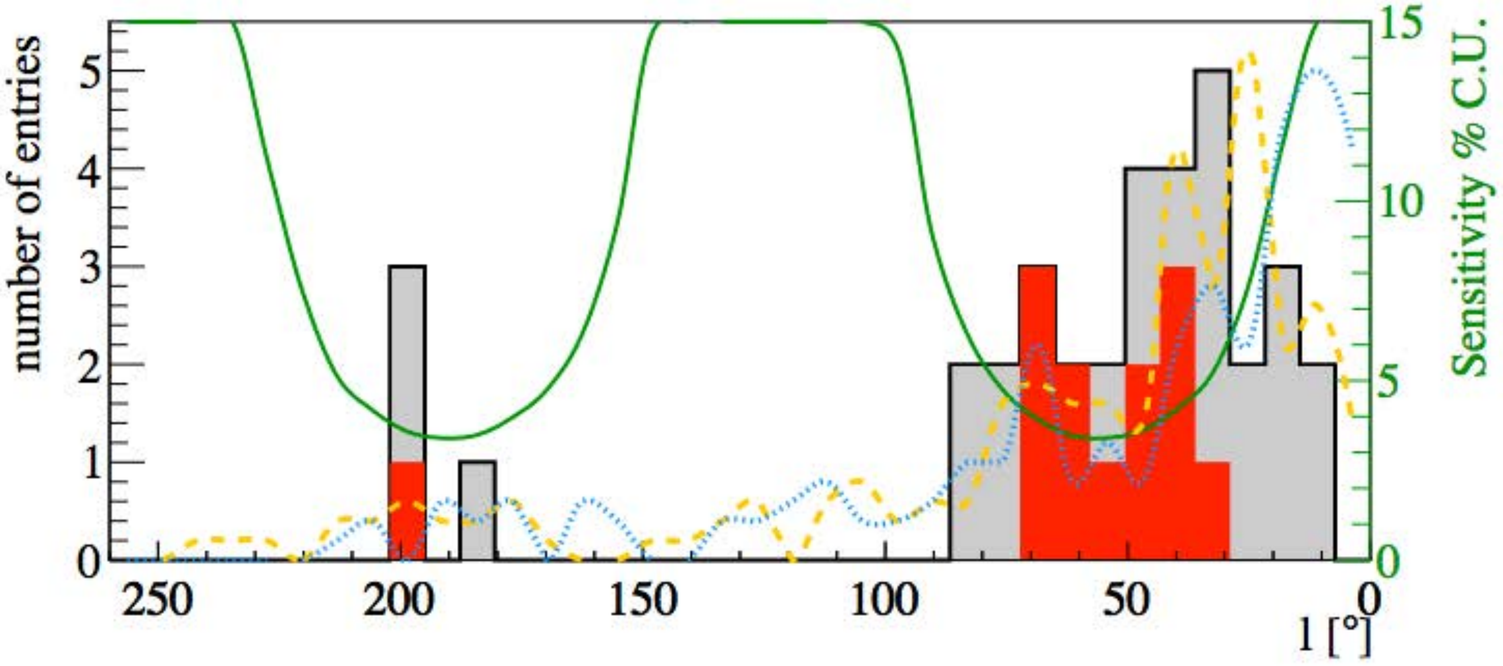


Inner Galactic plane 506 day data

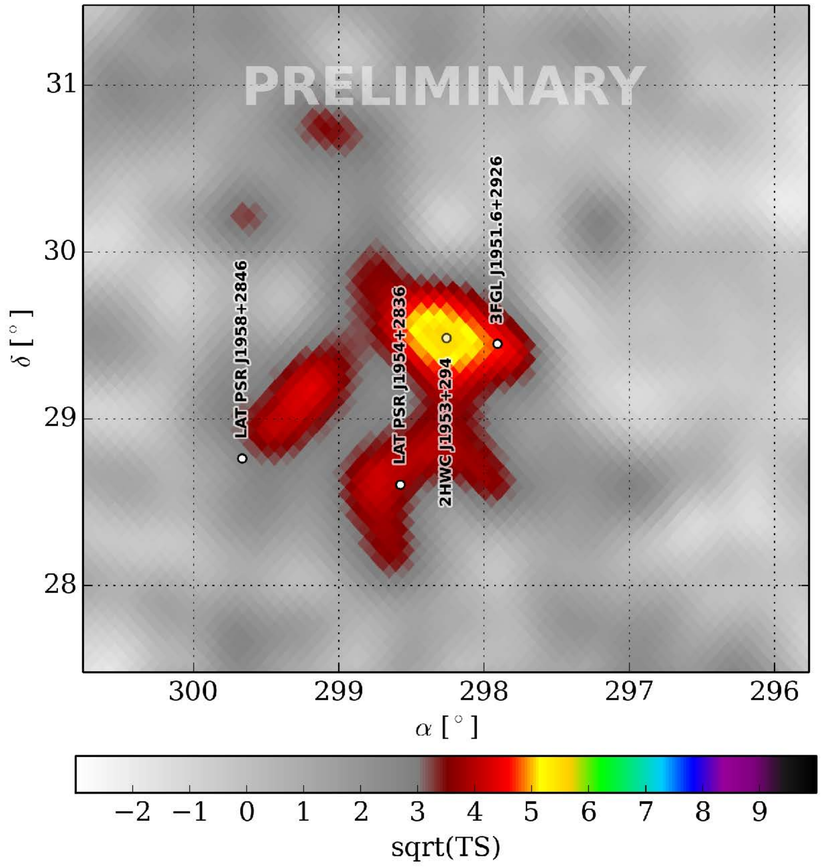


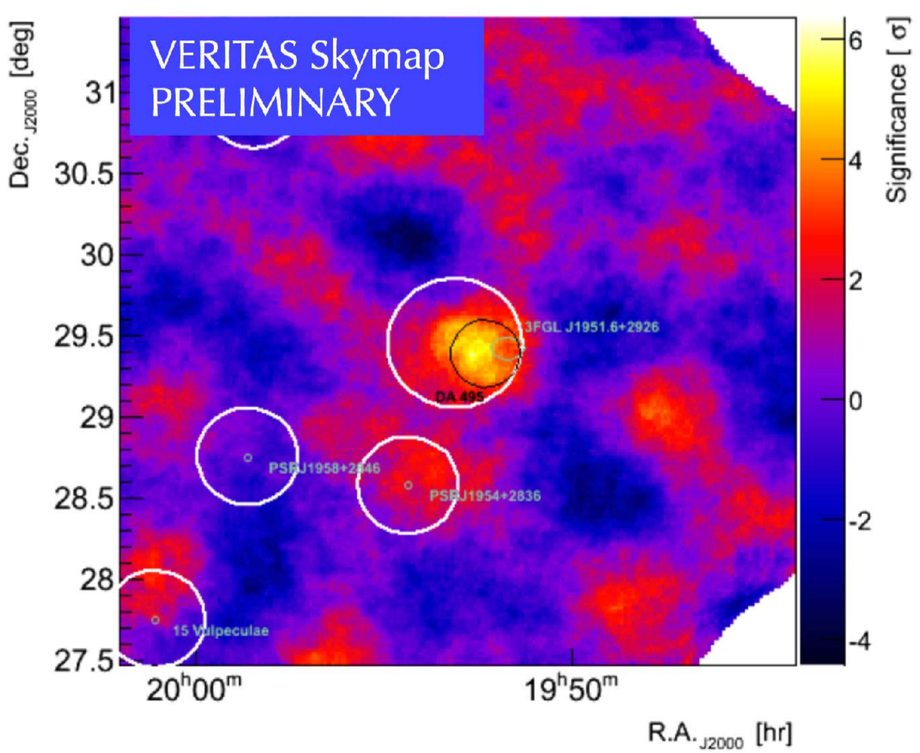
Published Catalog Results





2HWC J1953+294 - 12 months of data



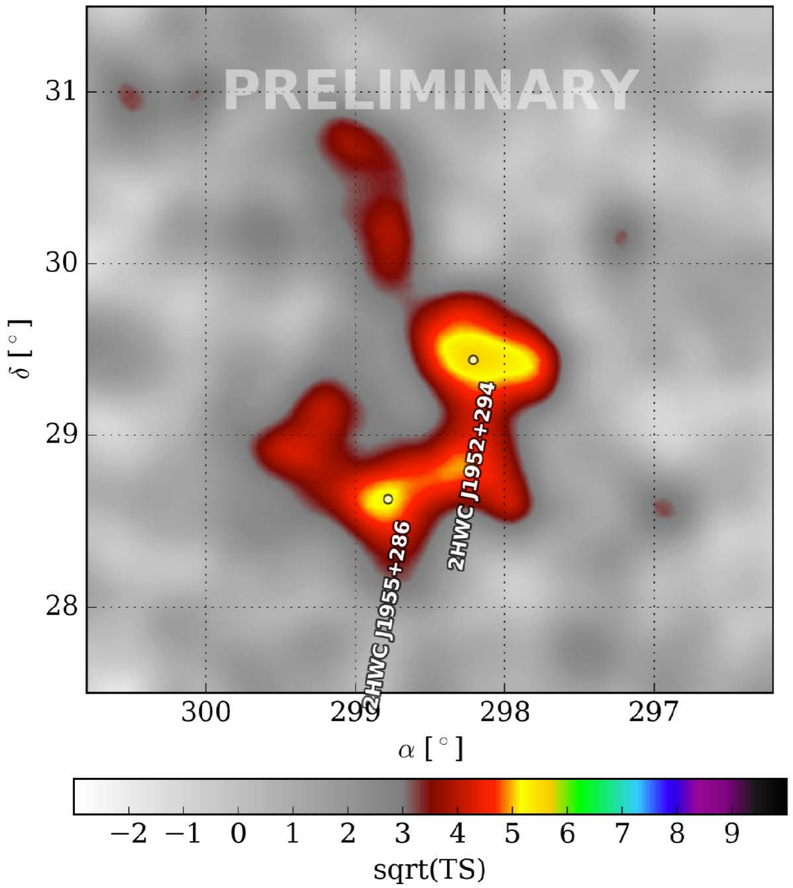


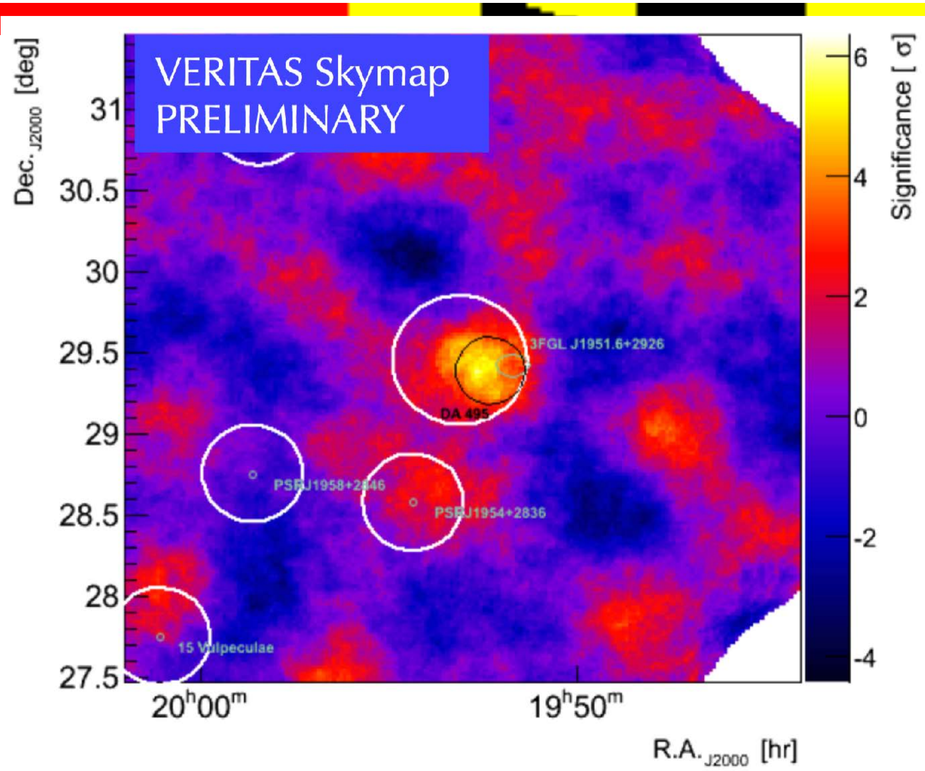
Name	$\sqrt{TS}$	Index	Flux for index at 7 TeV [$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$]
2HWC J1953+294	5.58	-2.76 ± 0.15	1.1e-14 ± 4.2e-15

Preliminary
Reported errors are stat. only

- **No previously known TeV source.**
- **New analysis by VERITAS, archival plus new data, source confirmed.**
- **Possible association 3FGL J1951.6+2926 / PWN DA 495?**

2HWC J1953+294 - 17 months of data



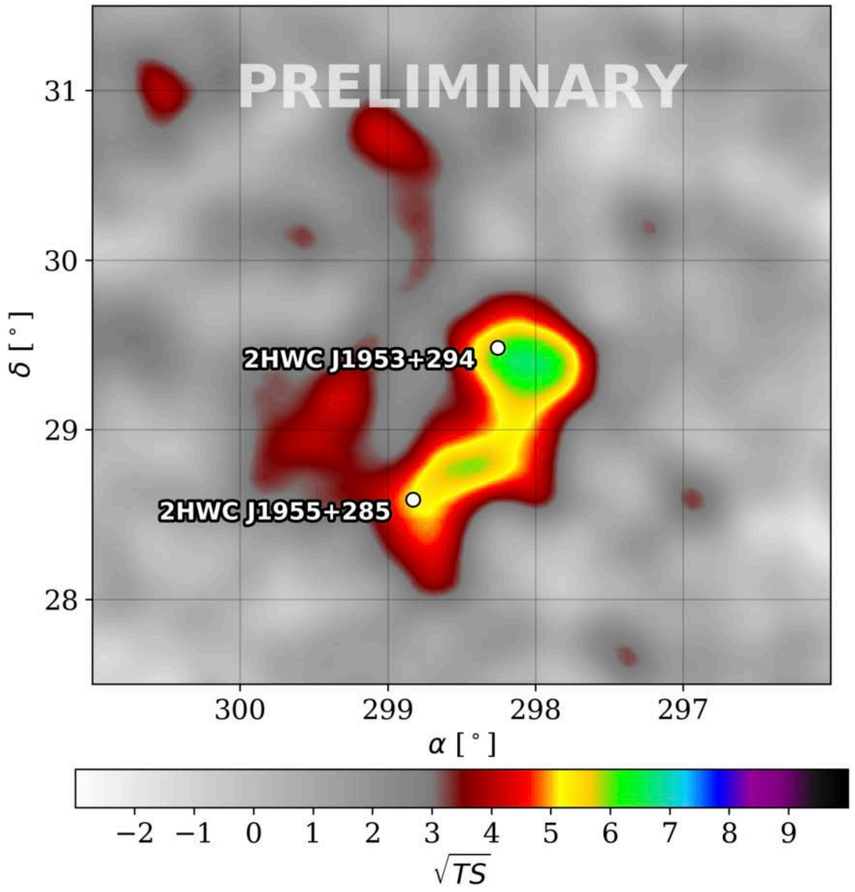


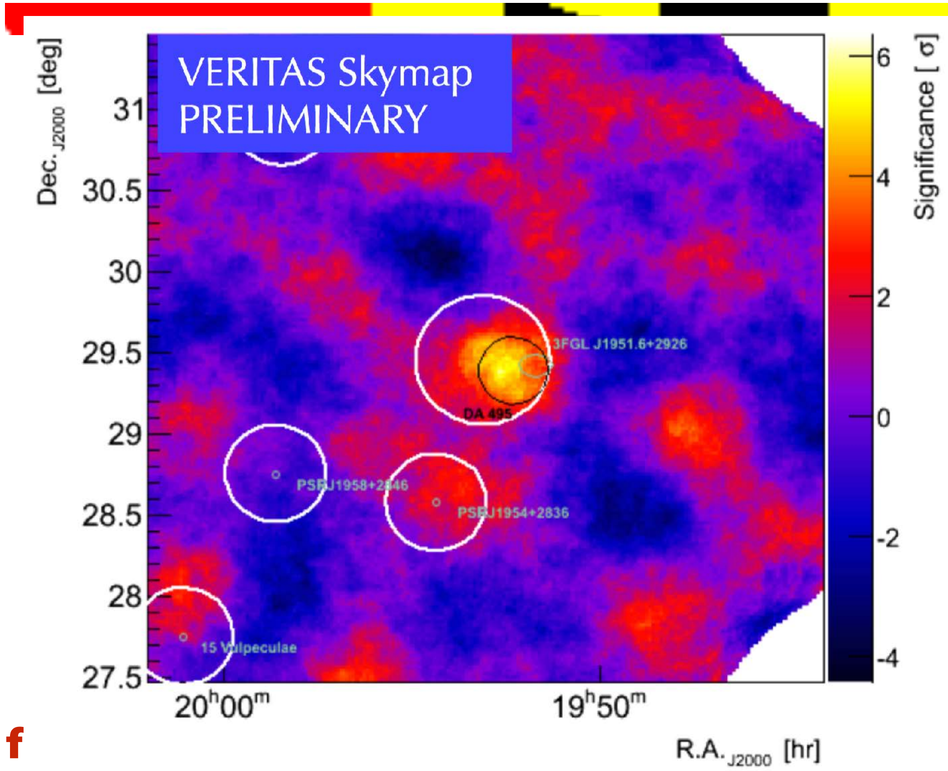
Name	$\sqrt{TS}$	Index	Flux for index at 7 TeV [$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$]
2HWC J1953+294	5.58	-2.76 ± 0.15	1.1e-14 ± 4.2e-15

Preliminary
Reported errors are stat. only

- **No previously known TeV source.**
- **New analysis by VERITAS, archival plus new data, source confirmed.**
- **Possible association 3FGL J1951.6+2926 / PWN DA 495?**

2HWC J1953+294 - 25 months of data





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analysis by V
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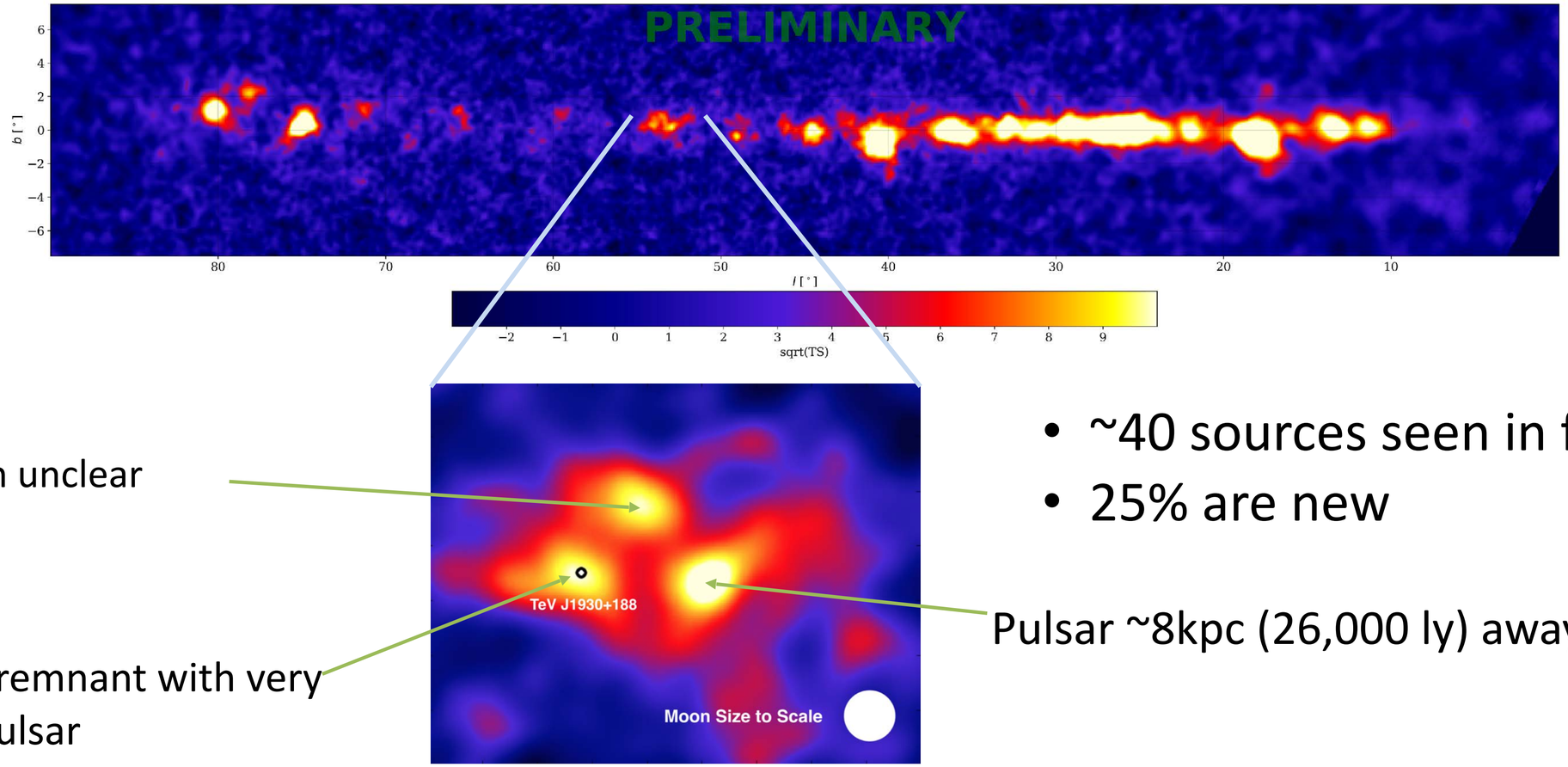
Name	$\sqrt{TS}$	Index	Flux for index at 7 TeV [$\mathrm{TeV^{-1}cm^{-2}s^{-1}}$]
2HWC J1953+294	5.58	-2.76 ± 0.15	1.1e-14 ± 4.2e-15

Preliminary
Reported errors are stat. only

HAWC view of the Galactic Plane



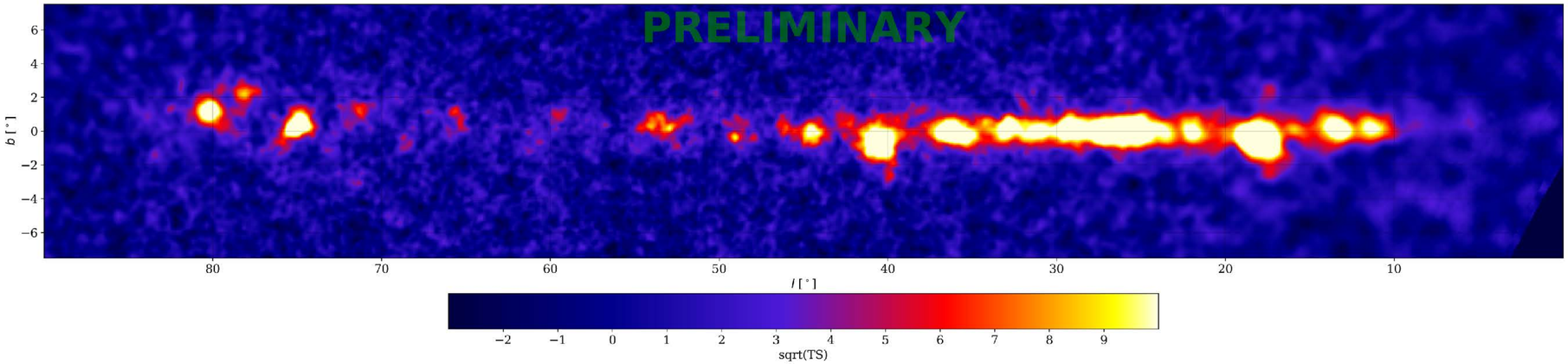
Association unclear

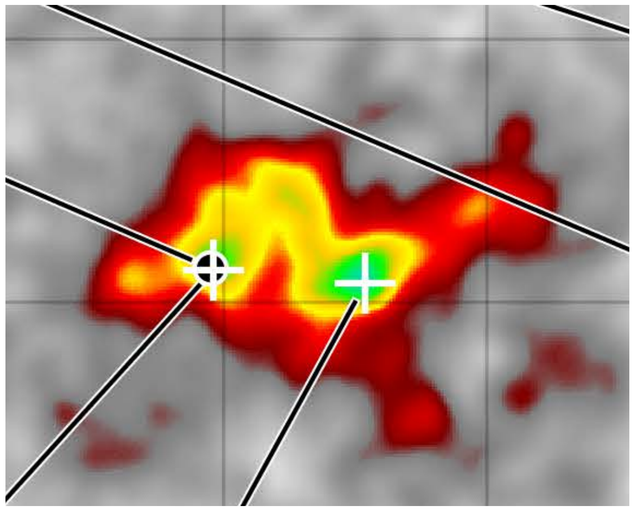
Supernova remnant with very energetic pulsar

- ~40 sources seen in first year
- 25% are new

Pulsar ~8kpc (26,000 ly) away

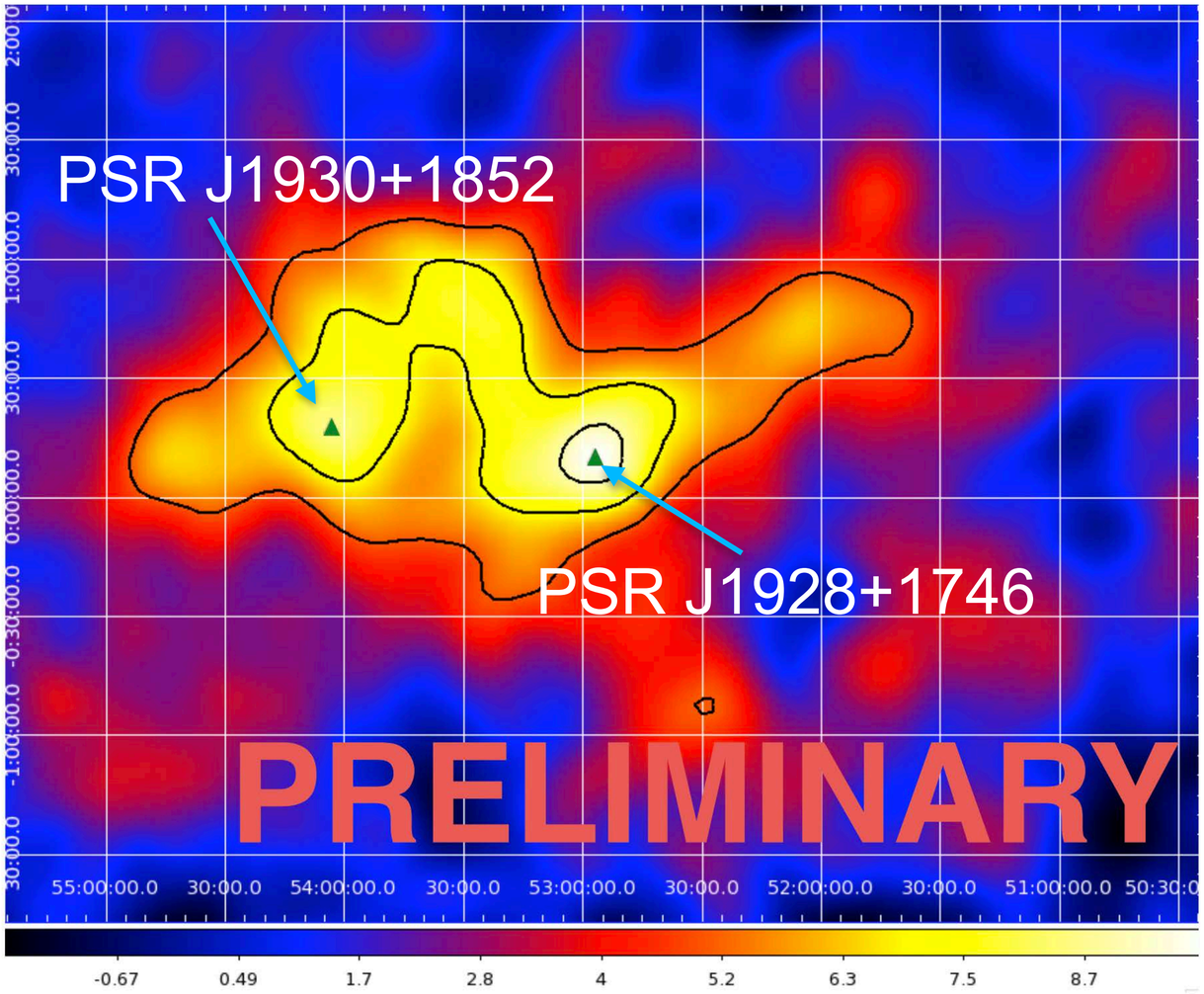
HAWC view of the Galactic Plane





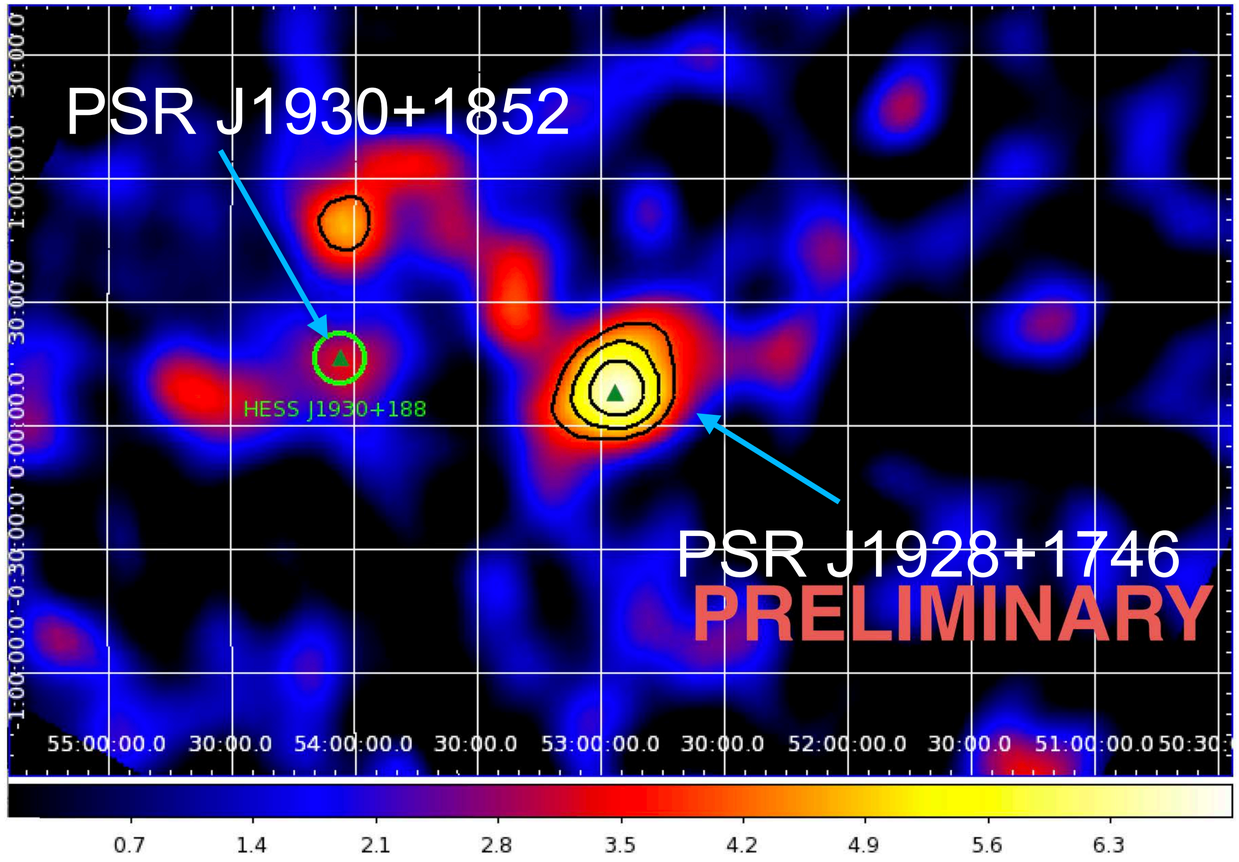
- ~40 sources seen in first year
- 25% are new
- 760 day view

2HWC J1928+177 - all fhit bins



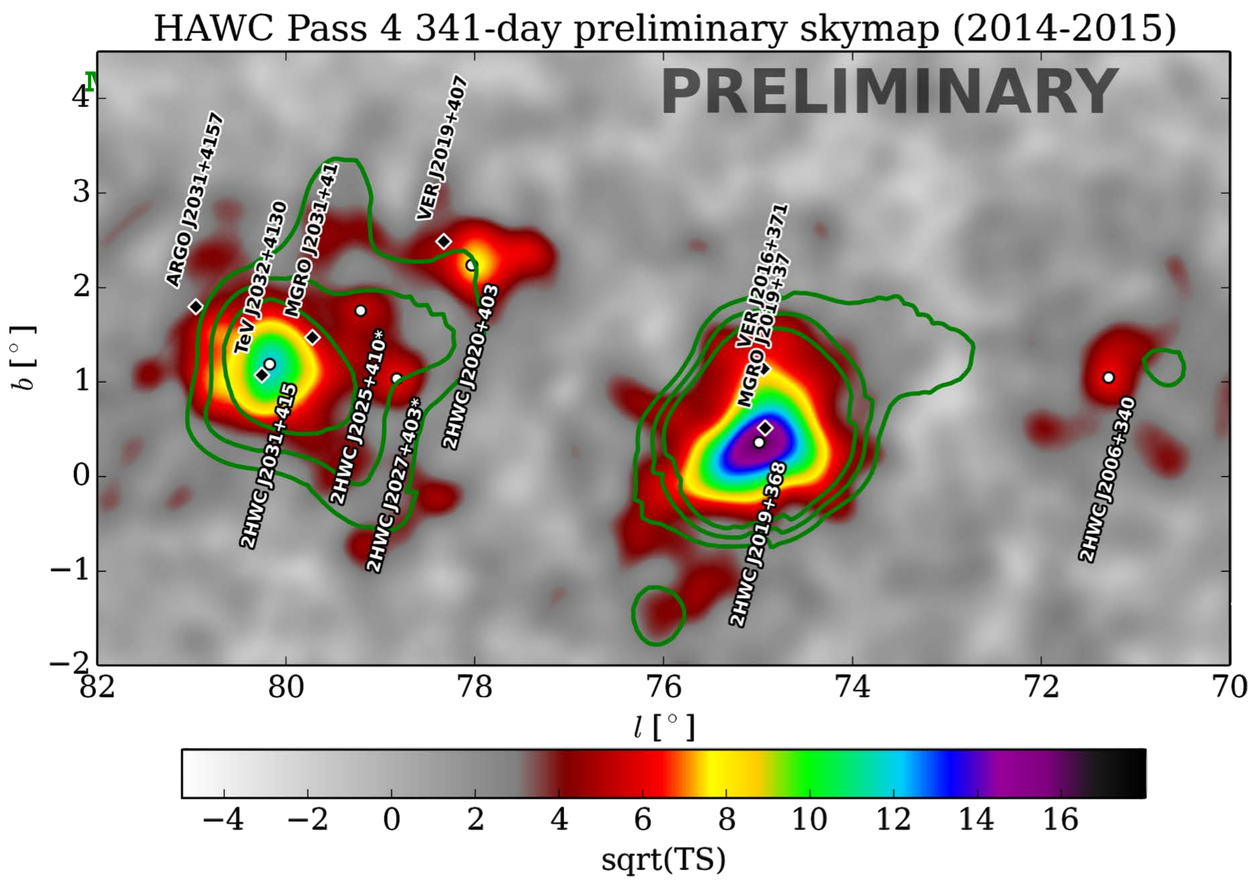
Black contours at sqrt(TS)=5, 7, 9.

2HWC J1928+177 - fhit bins 8, 9



Black contours at sqrt(TS)=4, 5, 6.

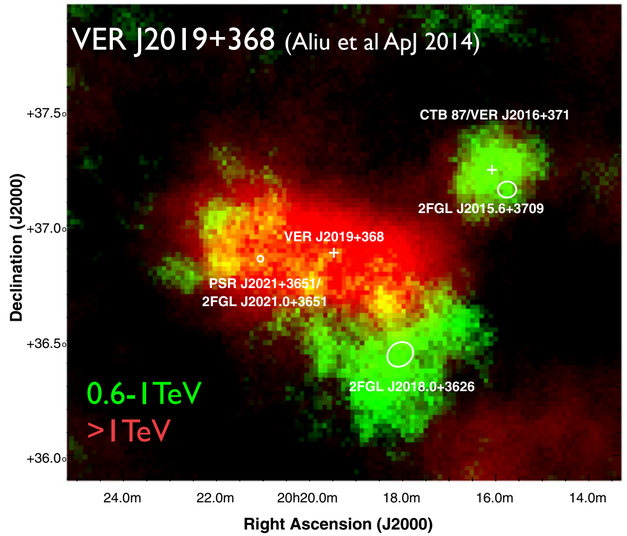
Cygnus Region



New TeV source

2HWCJ2006+340:

- >6σ pre-trials
- 0.6° from unidentified source 3FGL J2004.4+3338



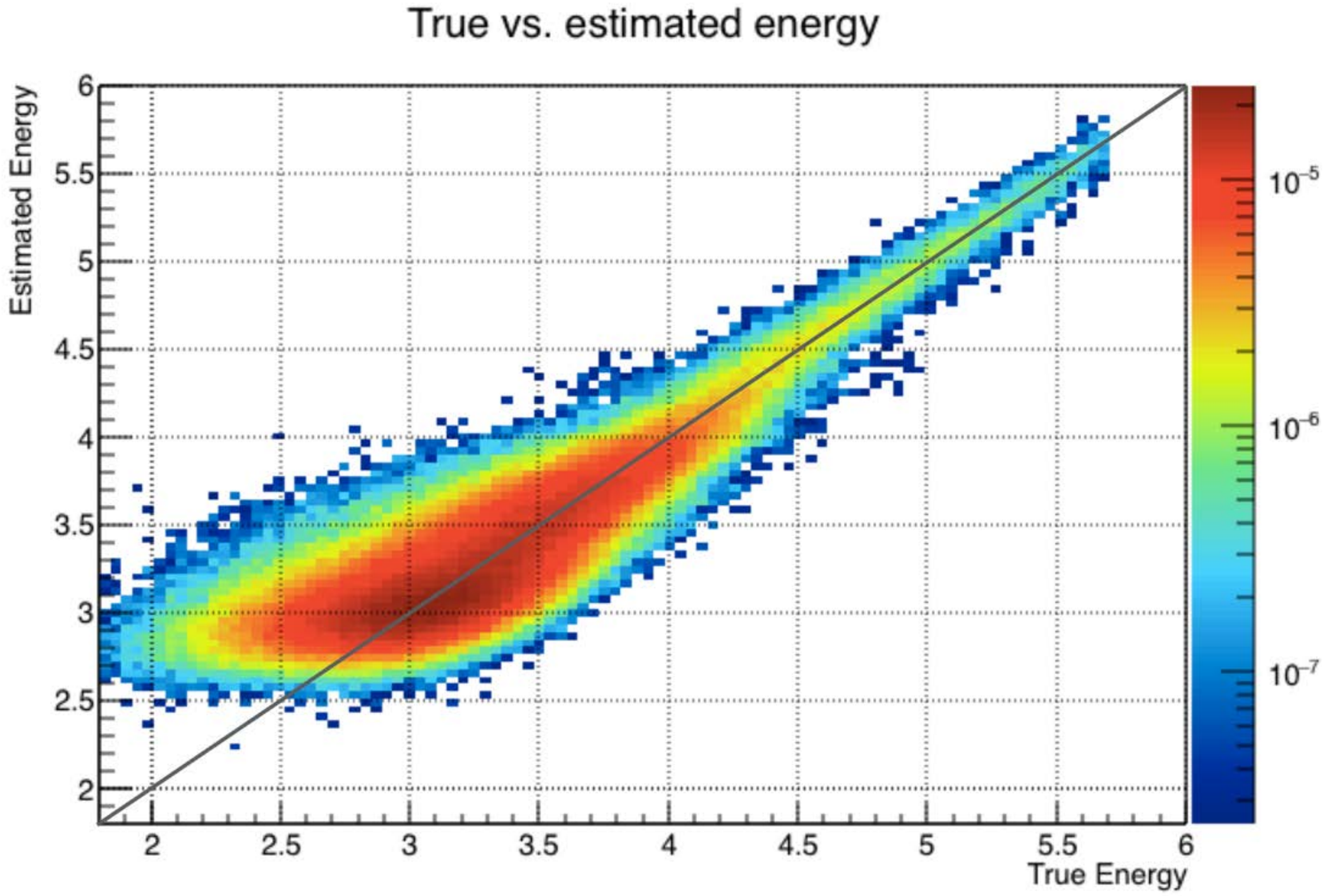
2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368

- extended emission including PSR J2021+3651 and HII region Sh 2-104

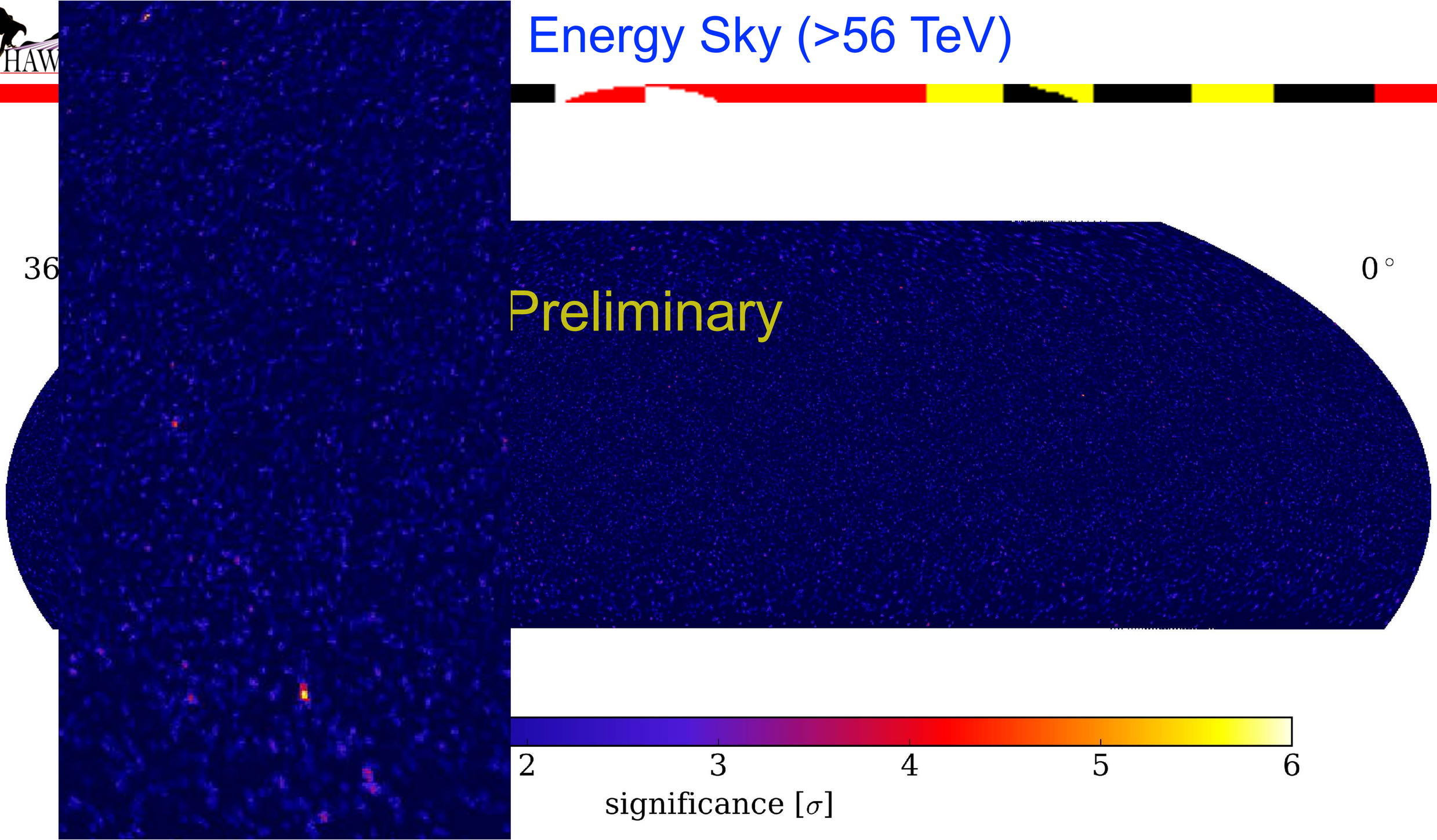
HAWC-VERITAS-Fermi Paper

- HAWC catalog sixteen sources that are not unambiguously associated with previously known TeV sources.
- We have studied twelve of these sources without known counterparts with VERITAS and Fermi-LAT.
- Working on a paper
- What can we learn from:
  - Observations:
    - Morphology, energy dependence, extended spectra
  - Non observations:
    - Extent, spectral hardness

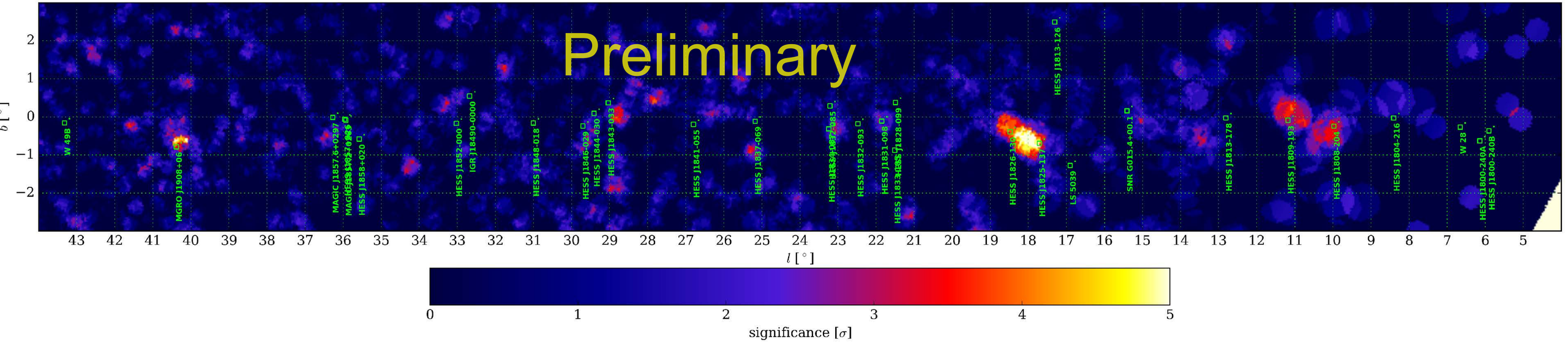
Energy Estimation



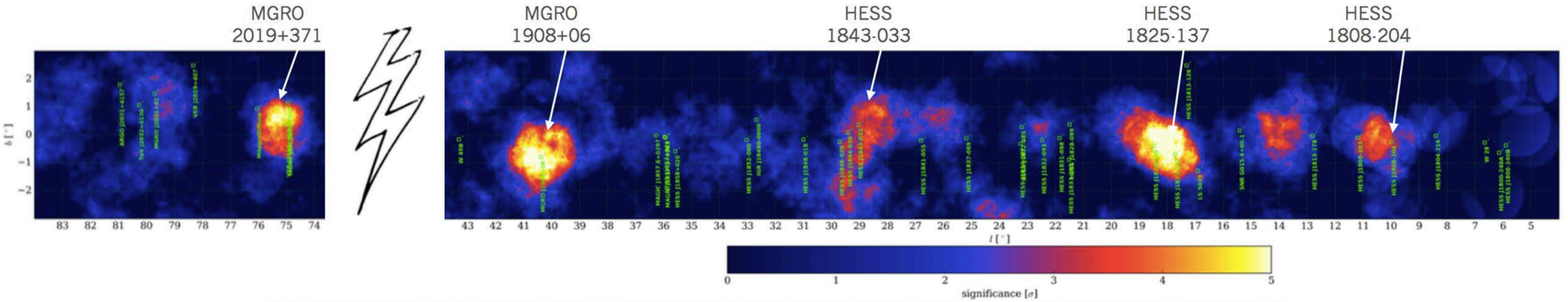
Energy Sky (>56 TeV)

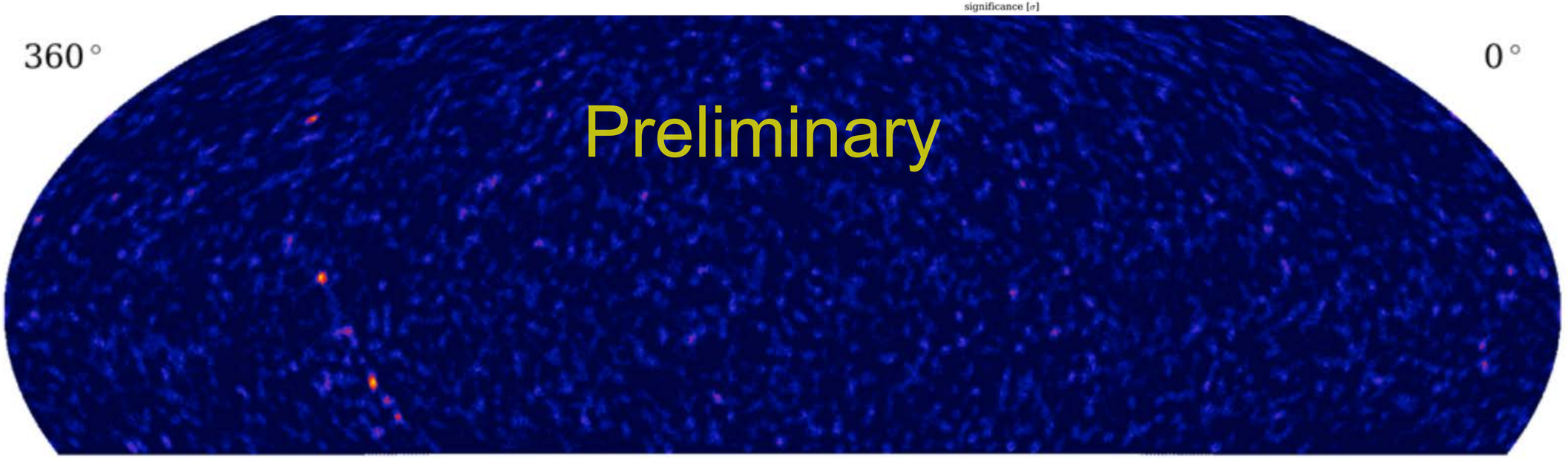


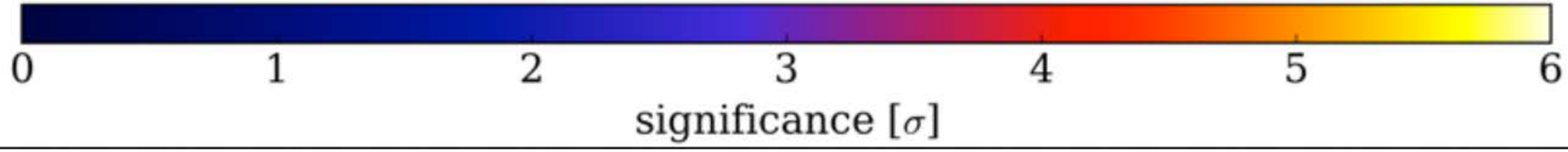
High Energy Sky (>56 TeV)



High Energy Sky (>56 TeV) with 1°

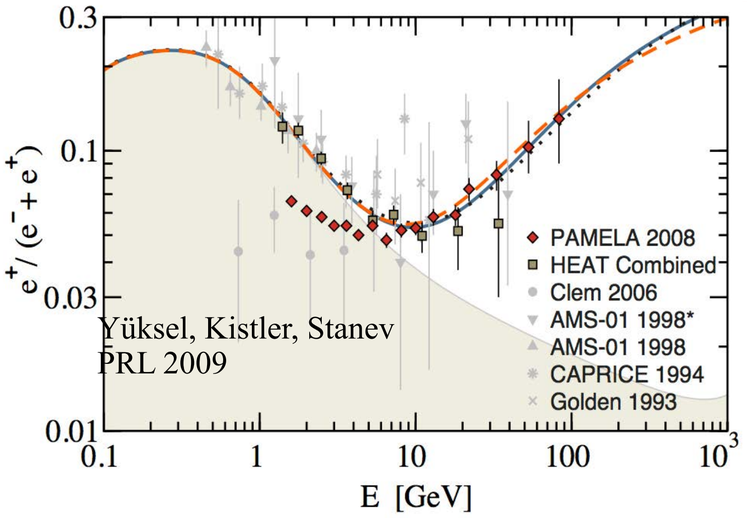


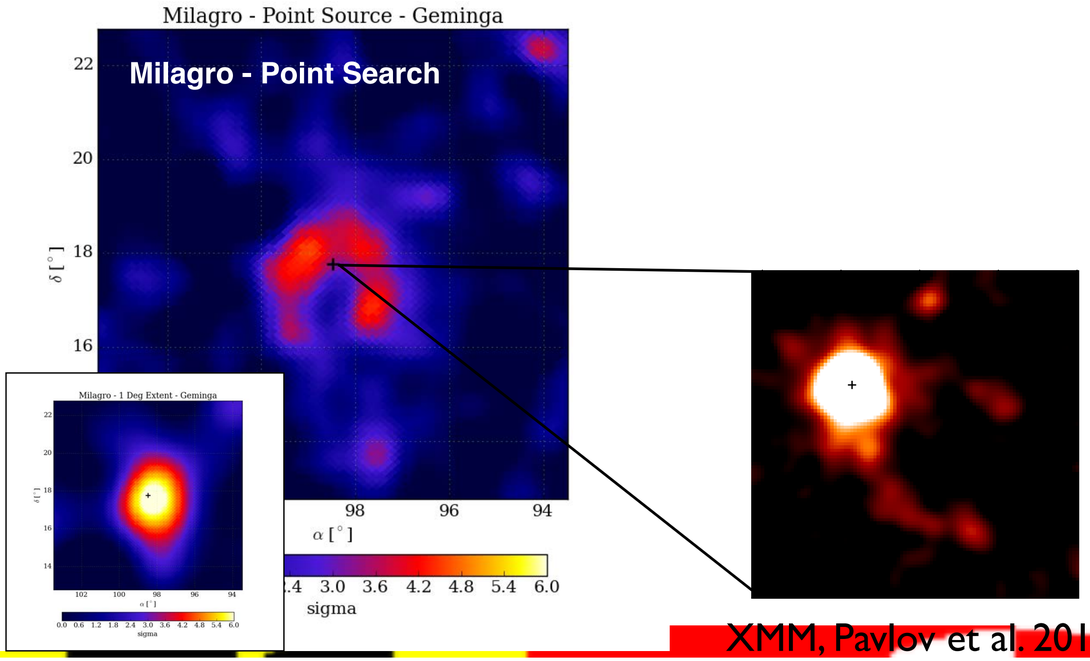




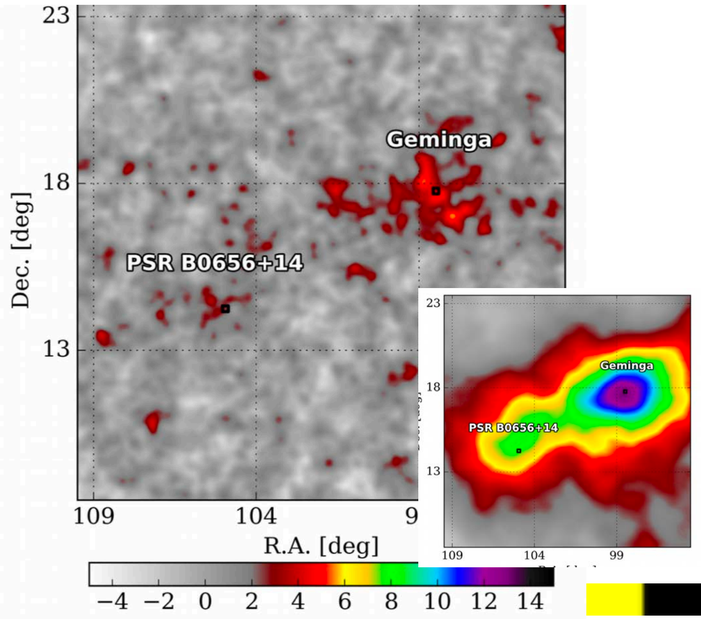
Pulsar Wind Nebulae - Geminga and PSR B0656+14

- Geminga is closest (250 psec) known middle aged (300ky) pulsar
- PSR B0656+14 (Mongogem) 300ps, 100ky
- Possible nearby cosmic ray acceleration site
  — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV



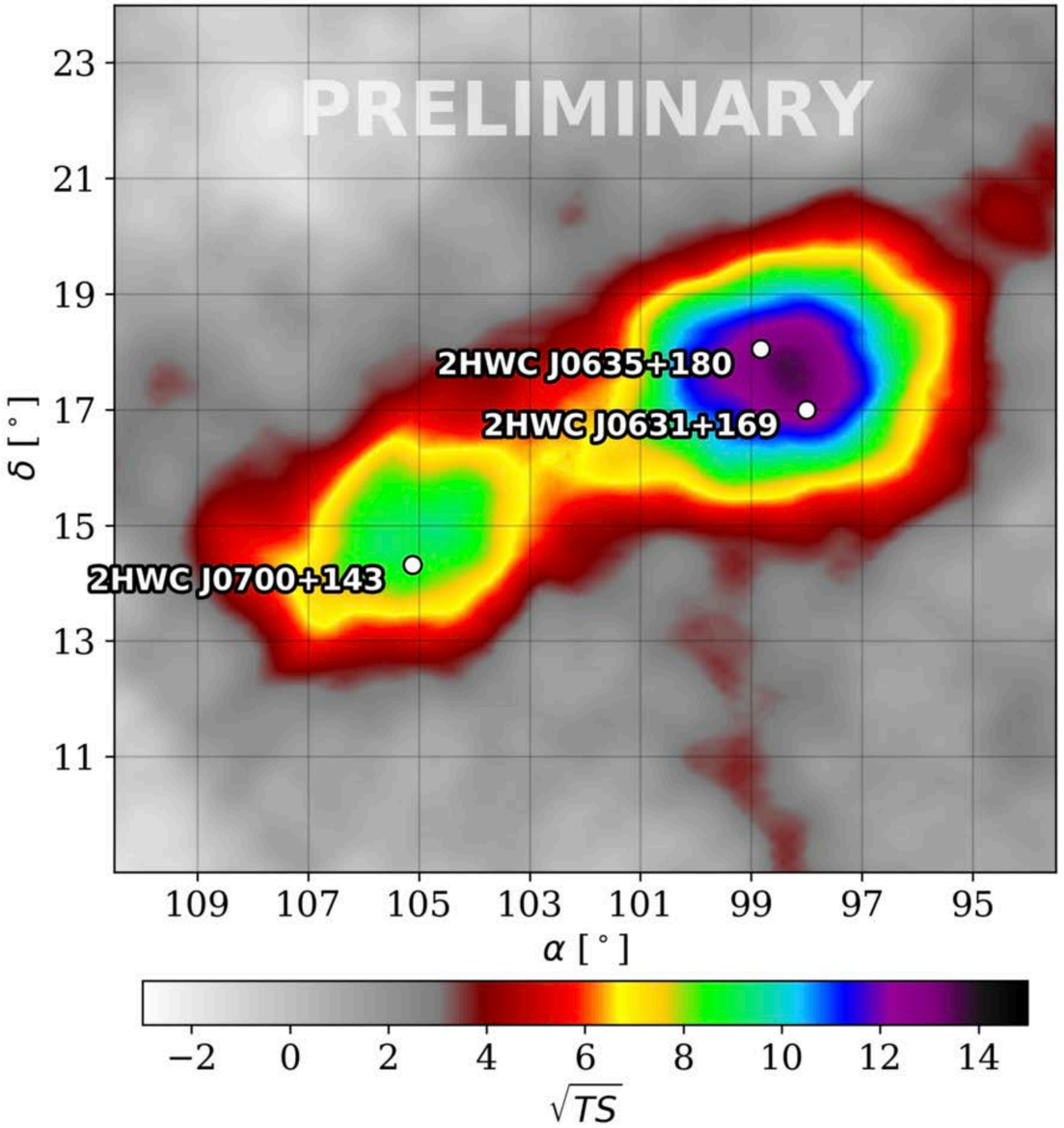


XMM, Pavlov et al. 2010



Geminga and PSR B0656+14 760 day data

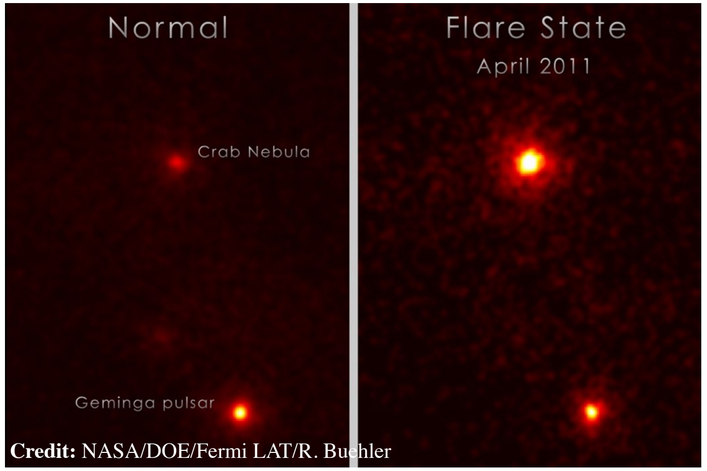
- PSR B0656+14 - similar age and distance as Geminga
- Gamma's above 20 TeV
  - These come from 100 TeV electrons
  - This is much bigger than the x-ray PWN
  - Fitting the radial distribution will allow us to measure the diffusion coefficient at high energies
- This can tell us if these are a source of local positrons seen by AMS and others

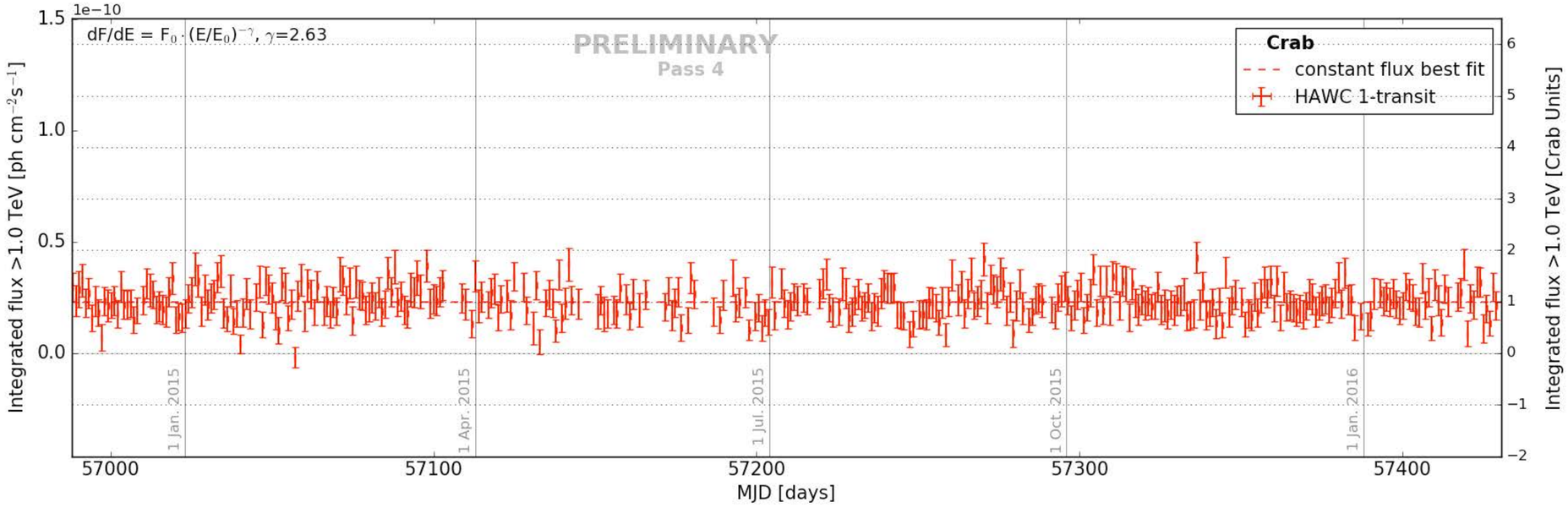


Transient Search - The Crab Nebula

- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.
- HAWC Pass 4 data from Nov 26 2014 to June 2016.
- >105σ in 315 transits.
- Lightcurve binned in sidereal day.
- Consistent with constant flux.

MeV-GeV gamma ray

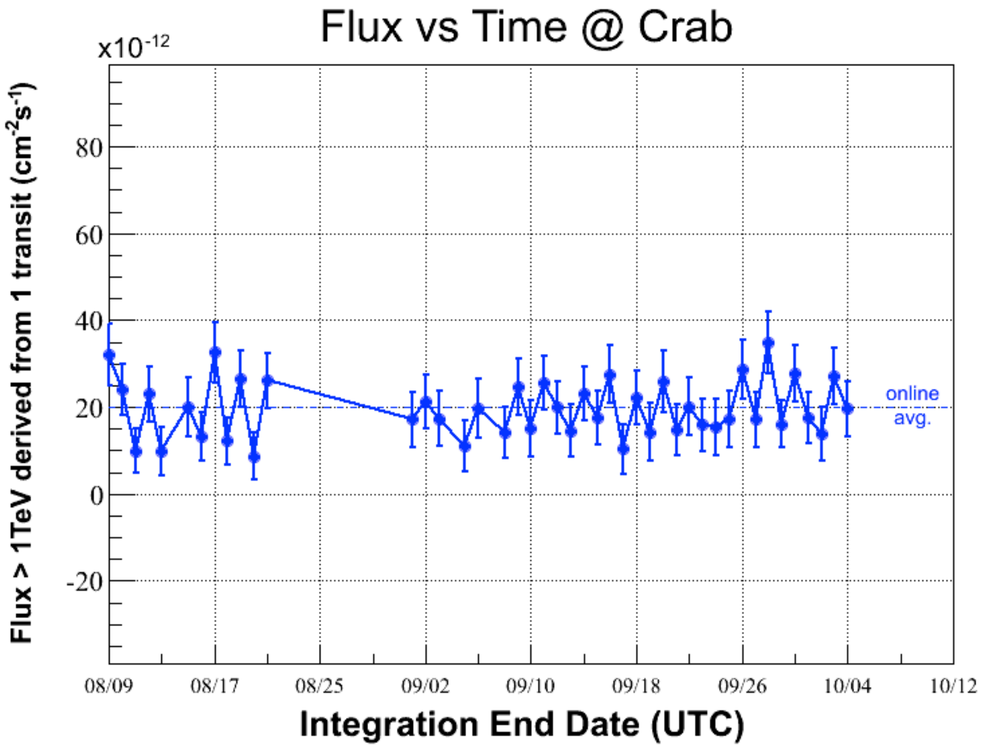


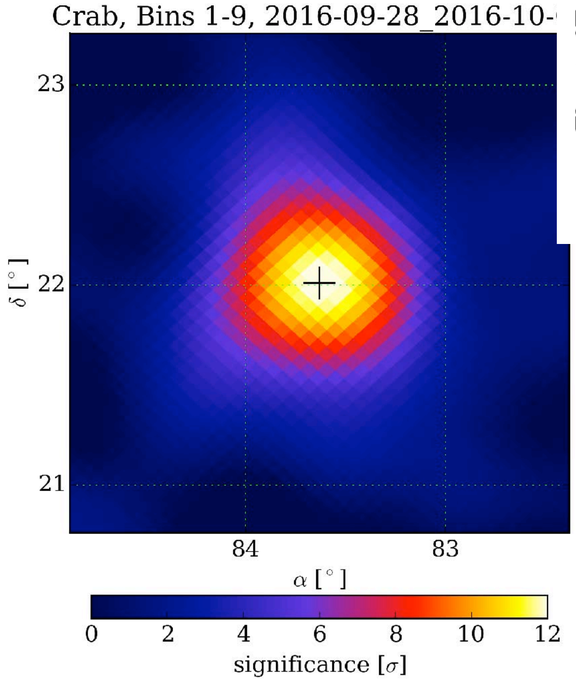


Transient Search - The Crab Nebula

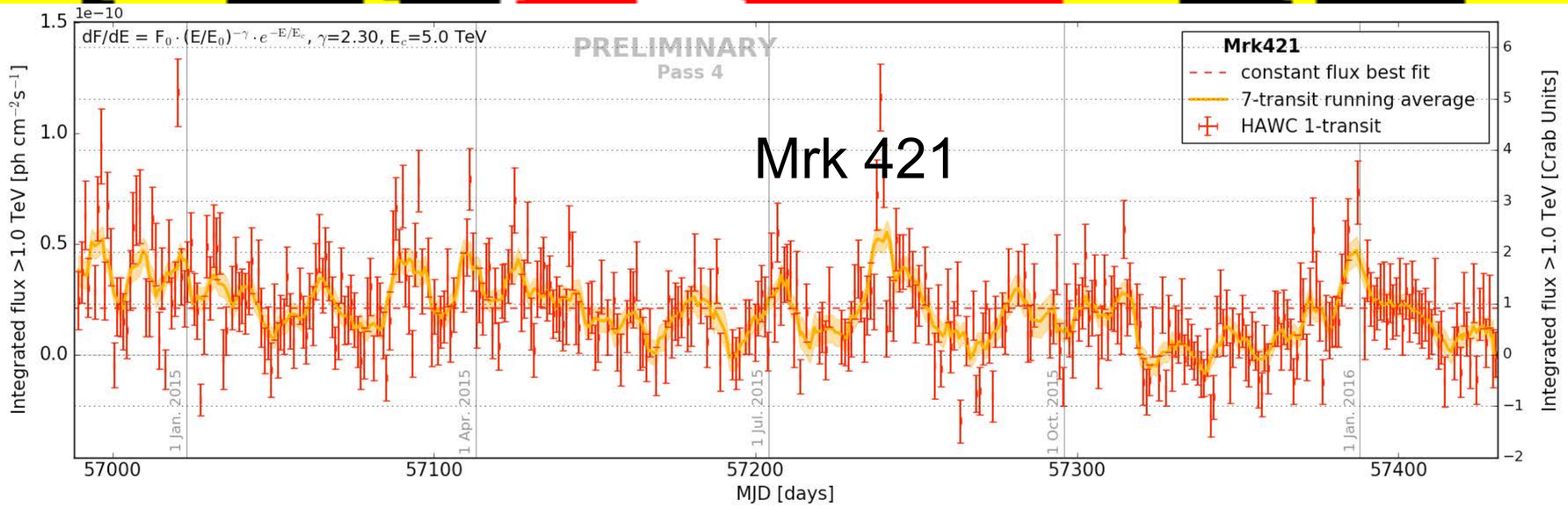
On October 3rd, 2016, AGILE (GeV) reported enhanced emission from the Crab Nebula (ATEL #9586). The Fermi-LAT *GeV) confirmed the detection in ATEL #9588, with flux up to 1.8 times larger than typical.

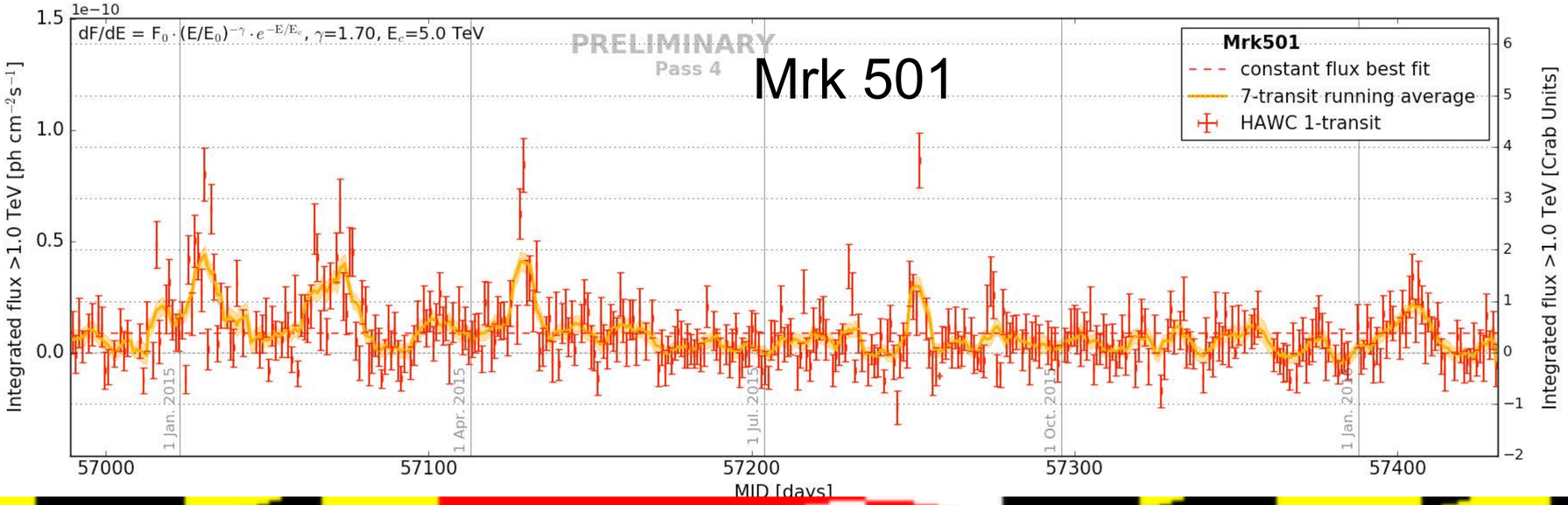
HAWC online monitoring shows the Crab to be fully consistent with its usual expectation over the same time period in the TeV.





Transient Search - Mrk 421 / Mrk 501



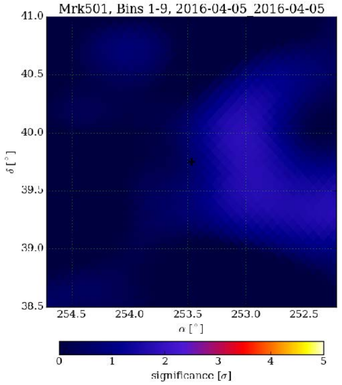


Transient Search - Mrk 501

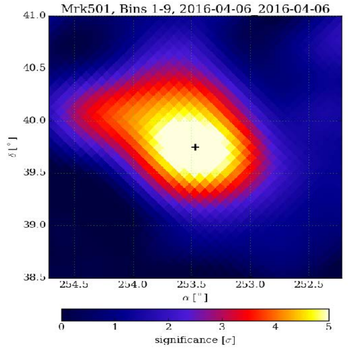
HAWC detection of increased TeV flux state for Markarian 501

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

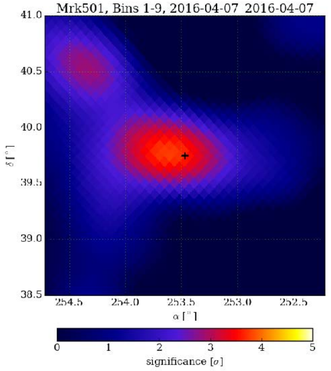
Astronomer's Telegram to immediately alert community of activity.



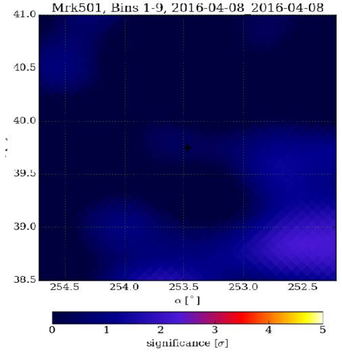
April 5, 2016



April 6, 2016



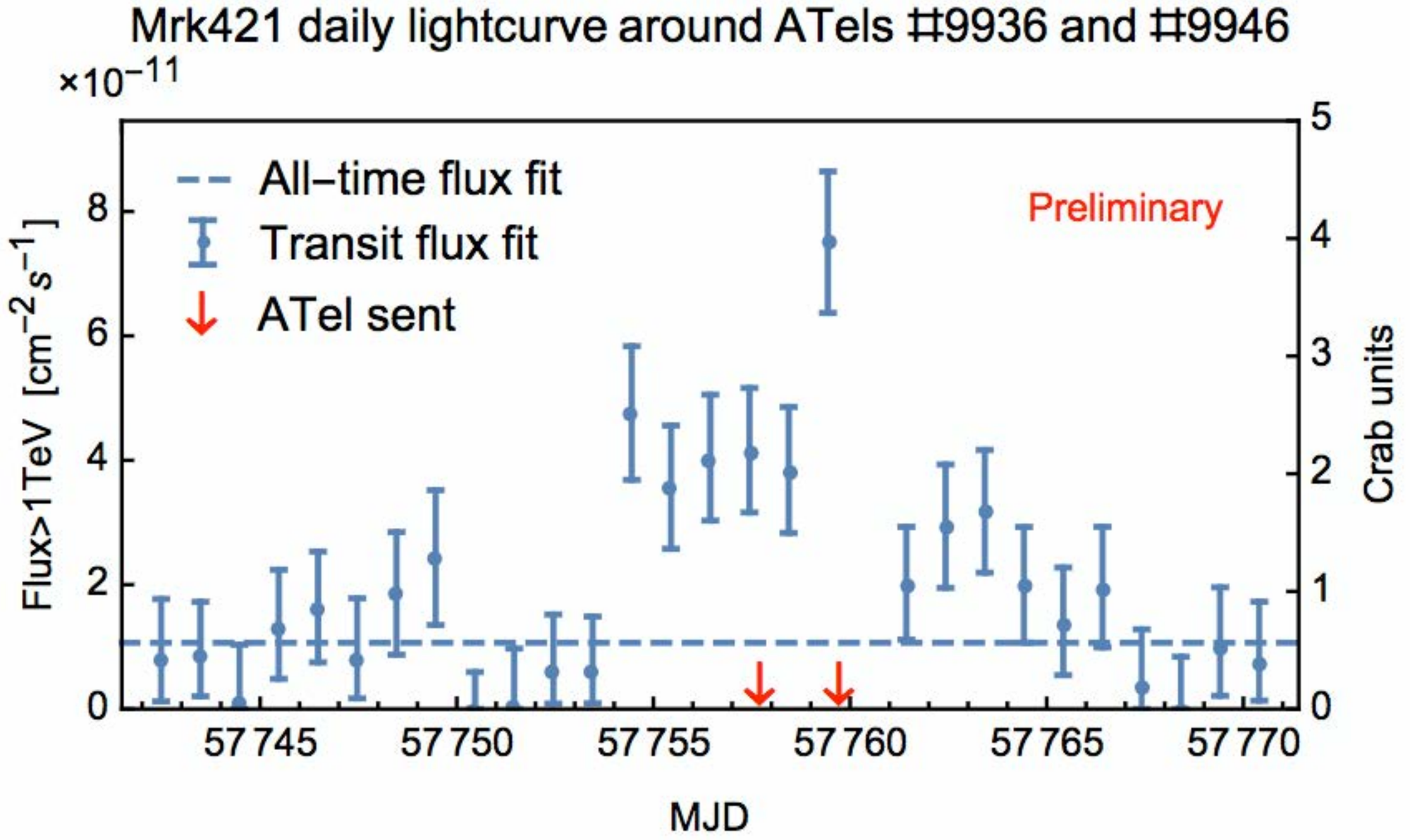
April 7, 2016



April 8, 2016

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

Mrk421 January 1-6, 2017



Multi-wavelength / Multi-messenger

- We have follow-up agreements with:
  - Swift
  - Fermi-LAT
  - IACTs
    - FACT
    - HESS
    - MAGIC
    - VERITAS
  - AMON
  - IceCube
  - ANTARES
  - LIGO/VIRGO

HAWC-triggered:

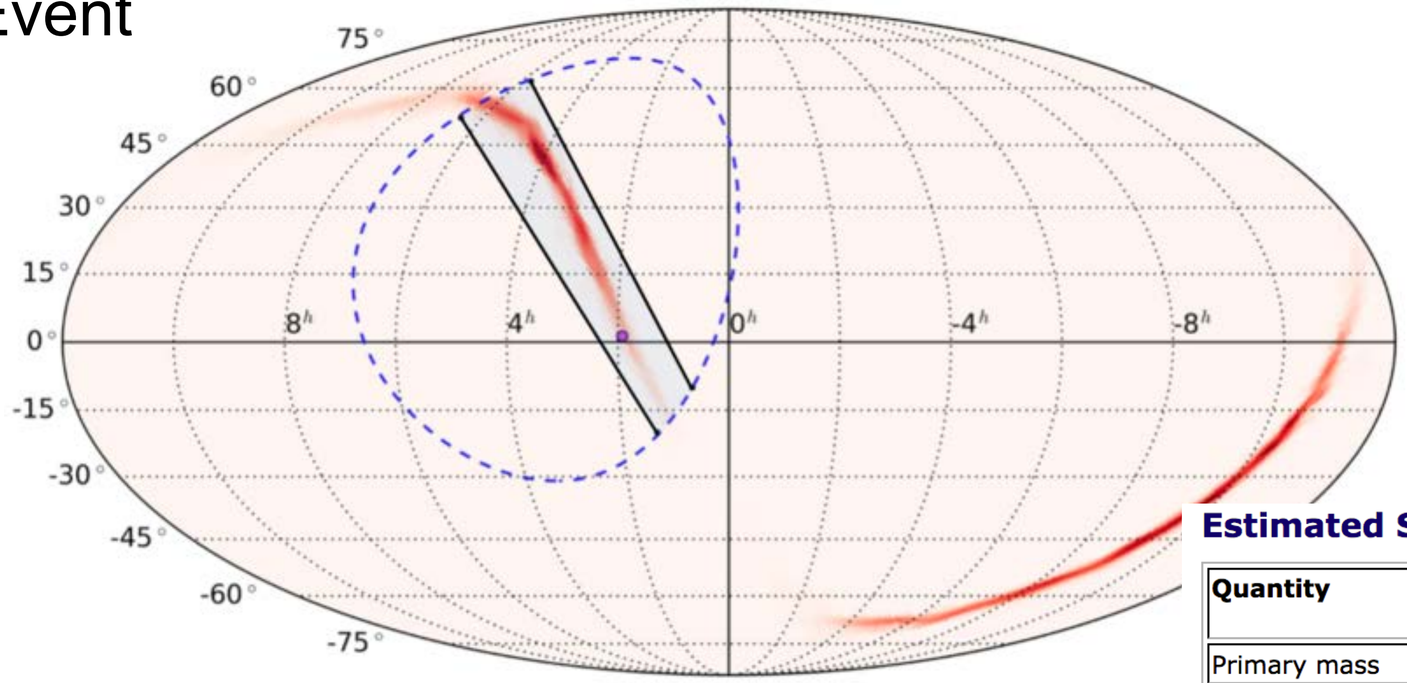
- New source candidates lists.
  - follow-up observations by IACTs such as VERITAS and MAGIC from Pass 1 release.
- Flares from known gamma-ray sources.

Externally triggered:

- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitation wave event follow-up

LIGO Follow-up

Boxing Day Event

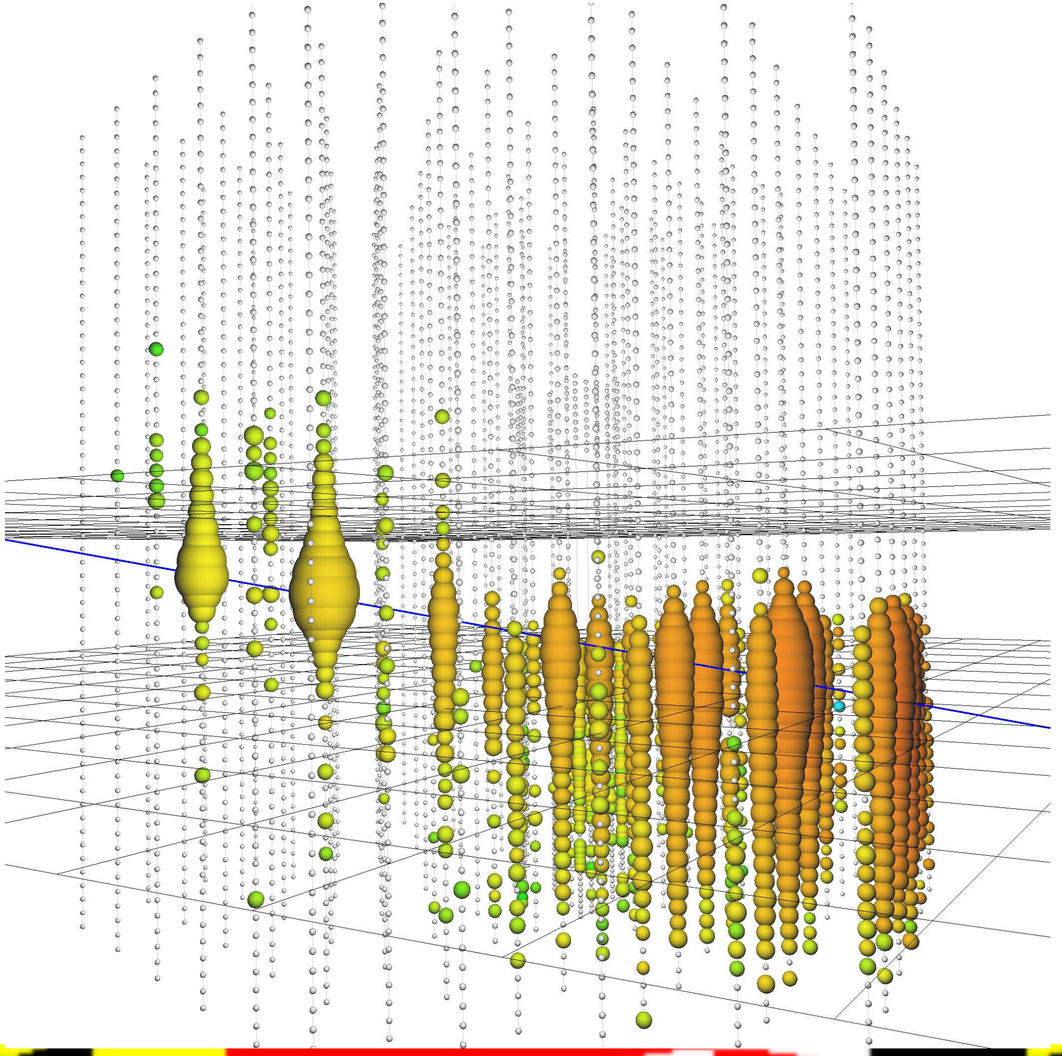


Candidate 1:
RA: 28.628 (+01h 54m 30.63s) J2000
Dec: +1.200 (+01d 11' 59.1") J2000
Error: +1.15 (square region, half side)
Duration: 10 seconds
Pre-trials p-value: 2.55e-07
Post-trials p-value: 0.08

Estimated Source Parameters

Quantity	Value	Upper/Lower error estimate	Unit
Primary mass	**14.2**	+8.3 -3.7	M sun
Secondary mass	**7.5**	+2.3 -2.3	M sun
Chirp mass	**8.9**	+0.3 -0.3	M sun
Total mass	**21.8**	+5.9 -1.7	M sun
Final mass	**20.8**	+6.1 -1.7	M sun
Final spin	**0.74**	+0.06 -0.06	
Radiated gravitational-wave energy	**1.0**	+0.1 -0.2	M sun c^2
Peak luminosity	**3.3**	+0.8 -1.6	10^{56} erg/s
Luminosity distance	**440**	+180 -190	Mpc
Source redshift *z*	**0.09**	+0.03 -0.04	

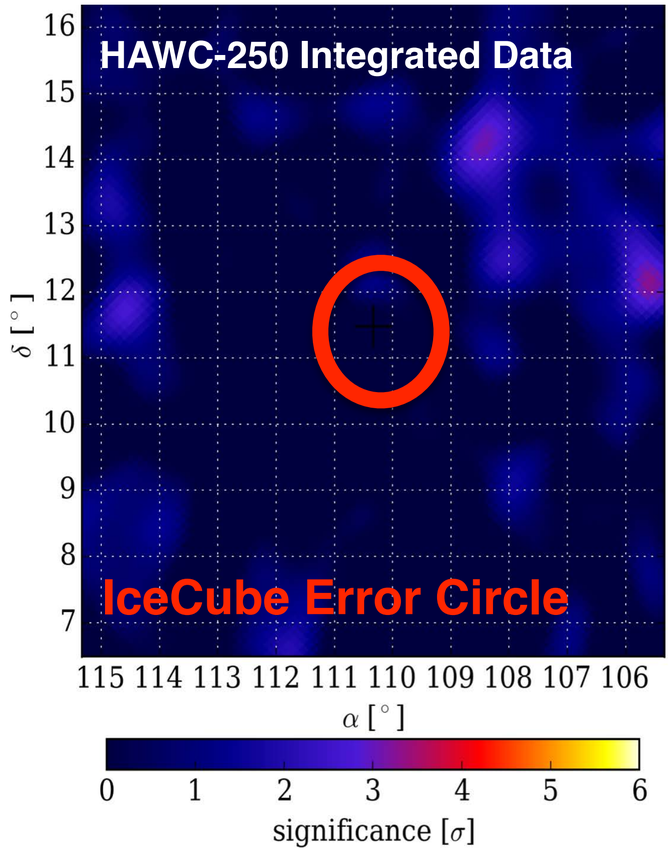
IceCub Follow-up



2.6 ± 0.3 PeV

IceCube >2.6 PeV Muon Neutrino

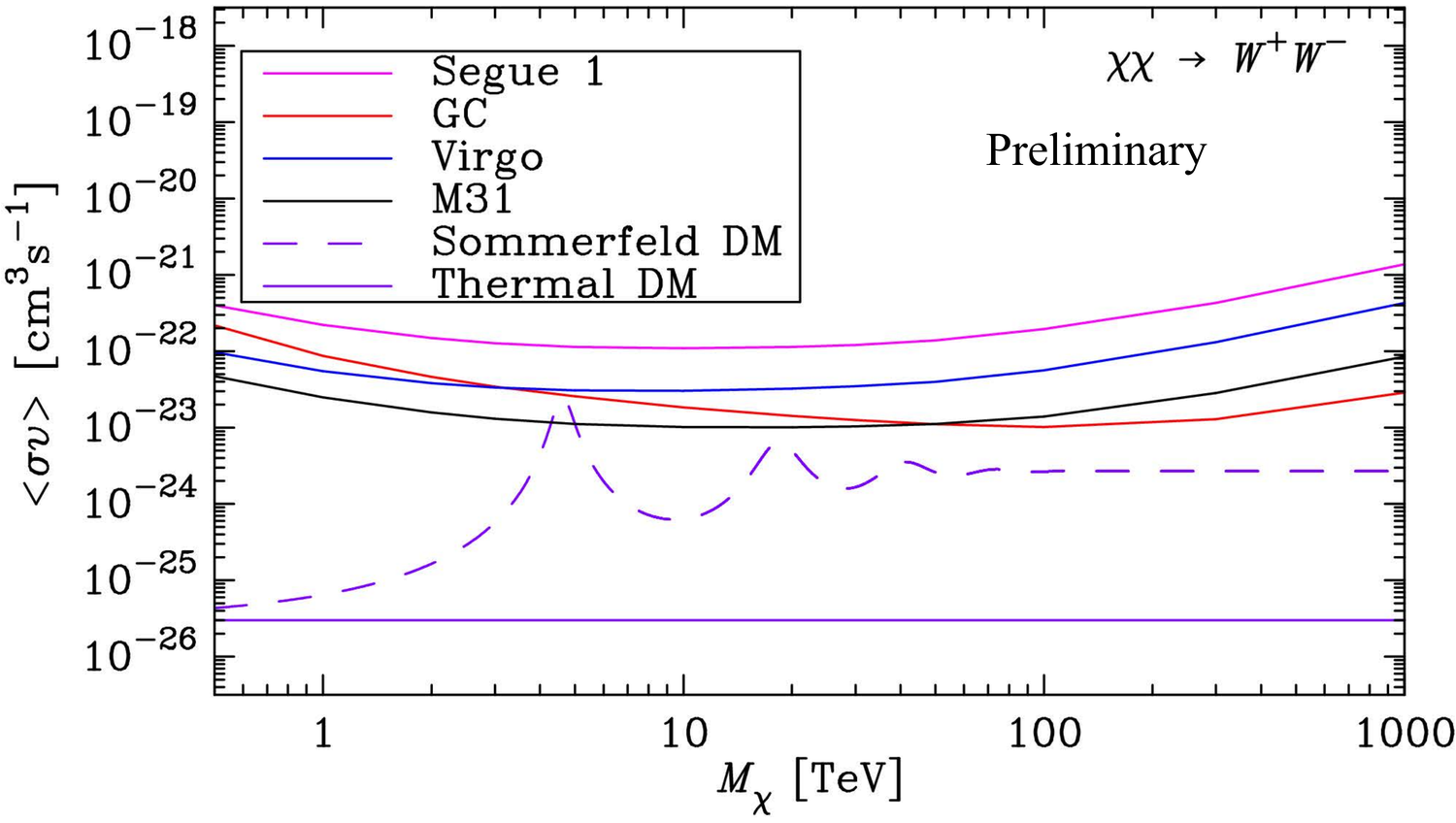
- HAWC-111 live. Several hours out of HAWC's FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015 dataset)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
- All searches consistent with cosmic-ray background.



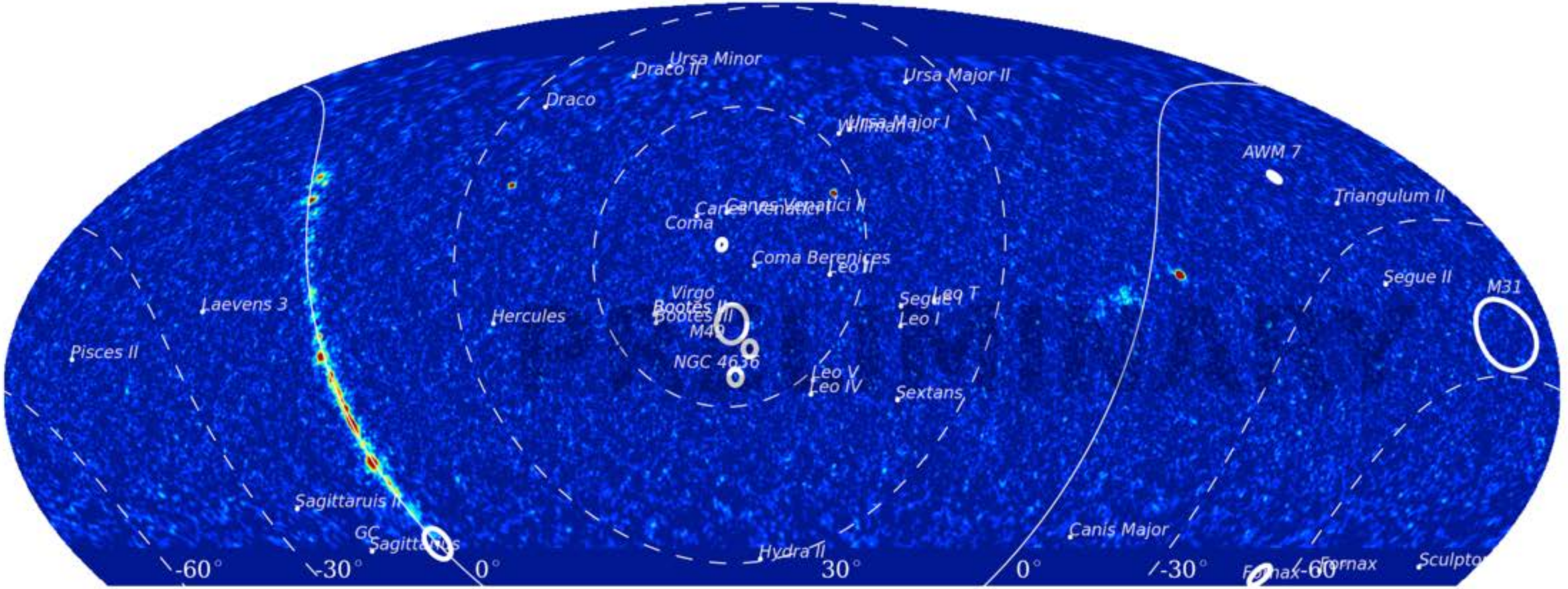
IceCube ATel: #7856
HAWC Follow-up ATel: #7868

HAWC: Dark Matter

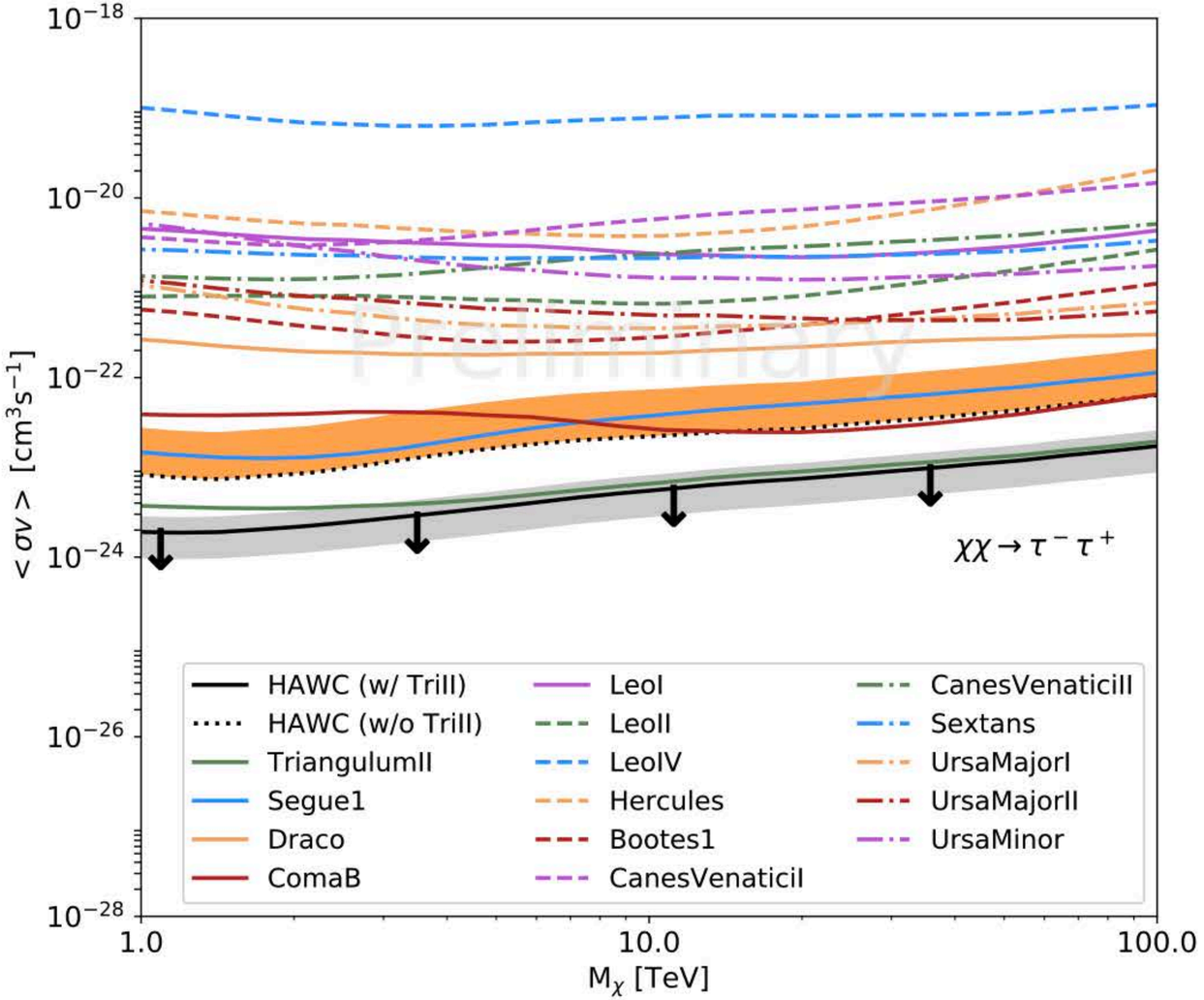
- HAWC has sensitivity to indirect detection of TeV WIMPs in:
  - Satellite galaxies, the Galactic Center, and galaxy clusters
- Cosmological simulations predict more satellite galaxies than observed
  - Higher M/L galaxies have been found by Sloan Deep Survey
  - HAWC will observe all M/L galaxies in half the sky, ***even if L=0***

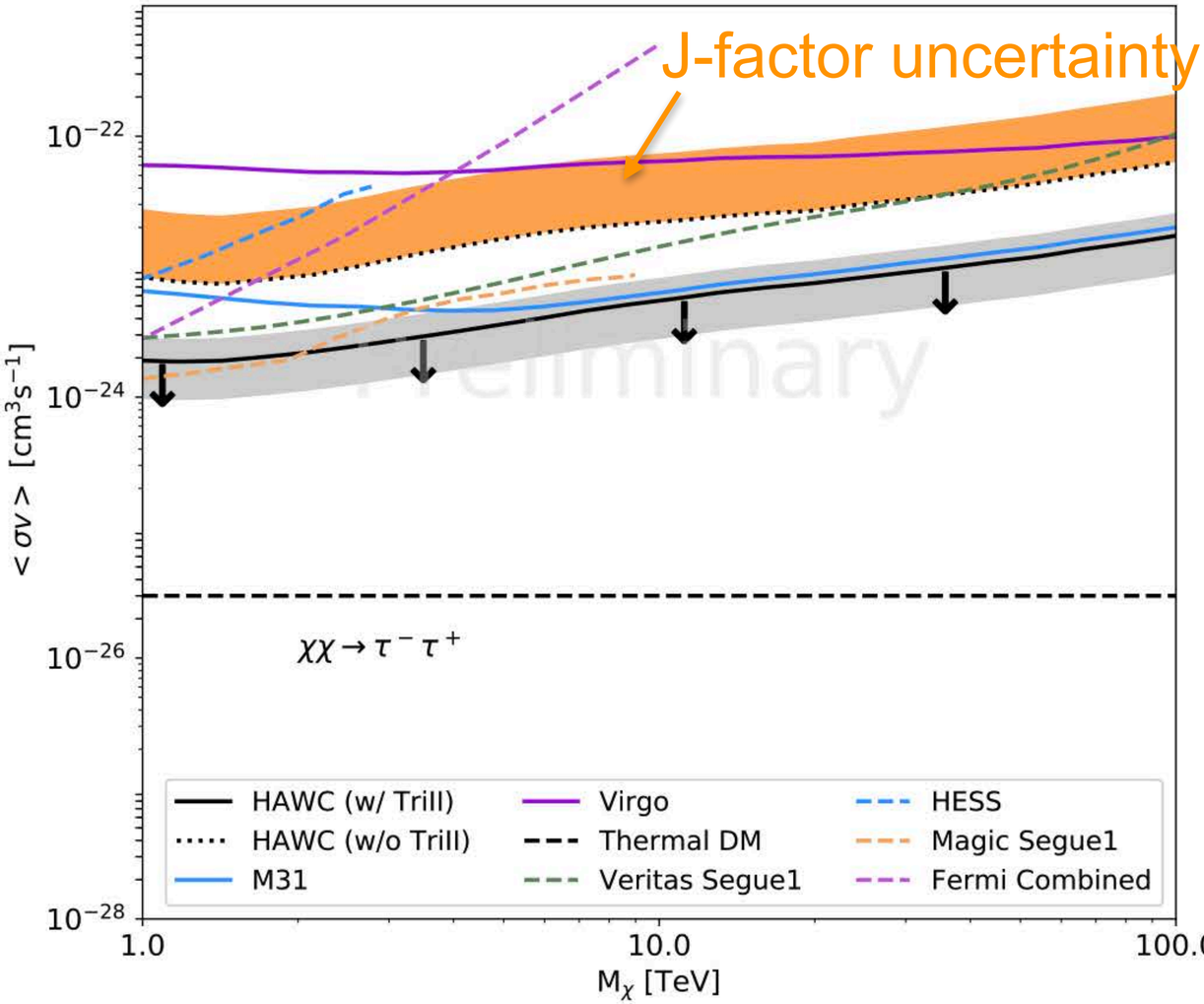


Lots of Potential Targets



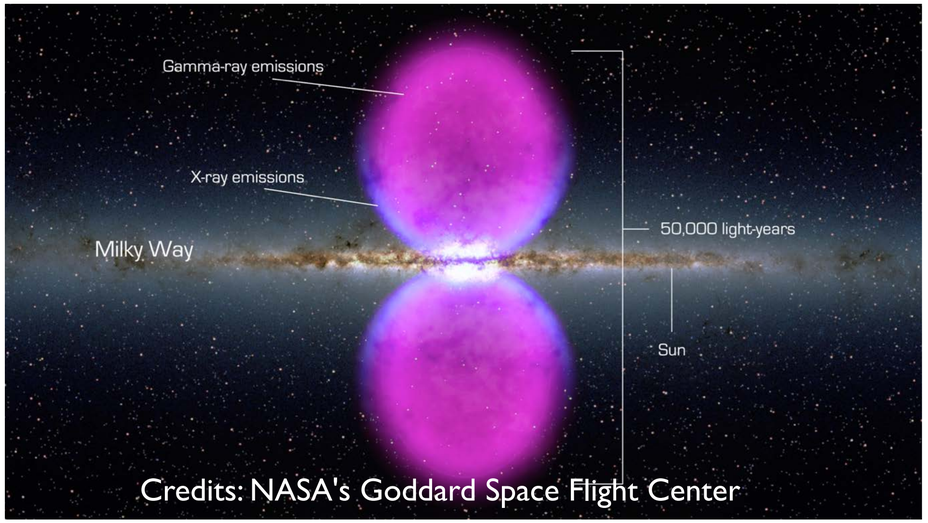
HAWC Does Well at High Masses

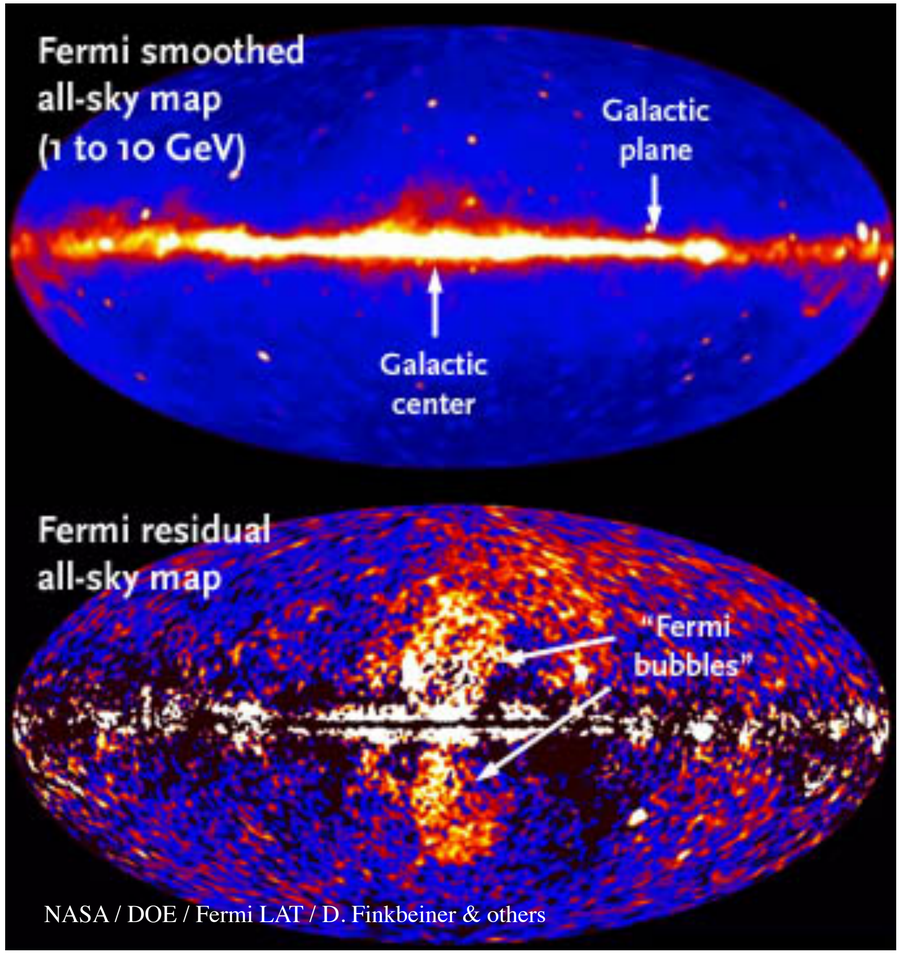




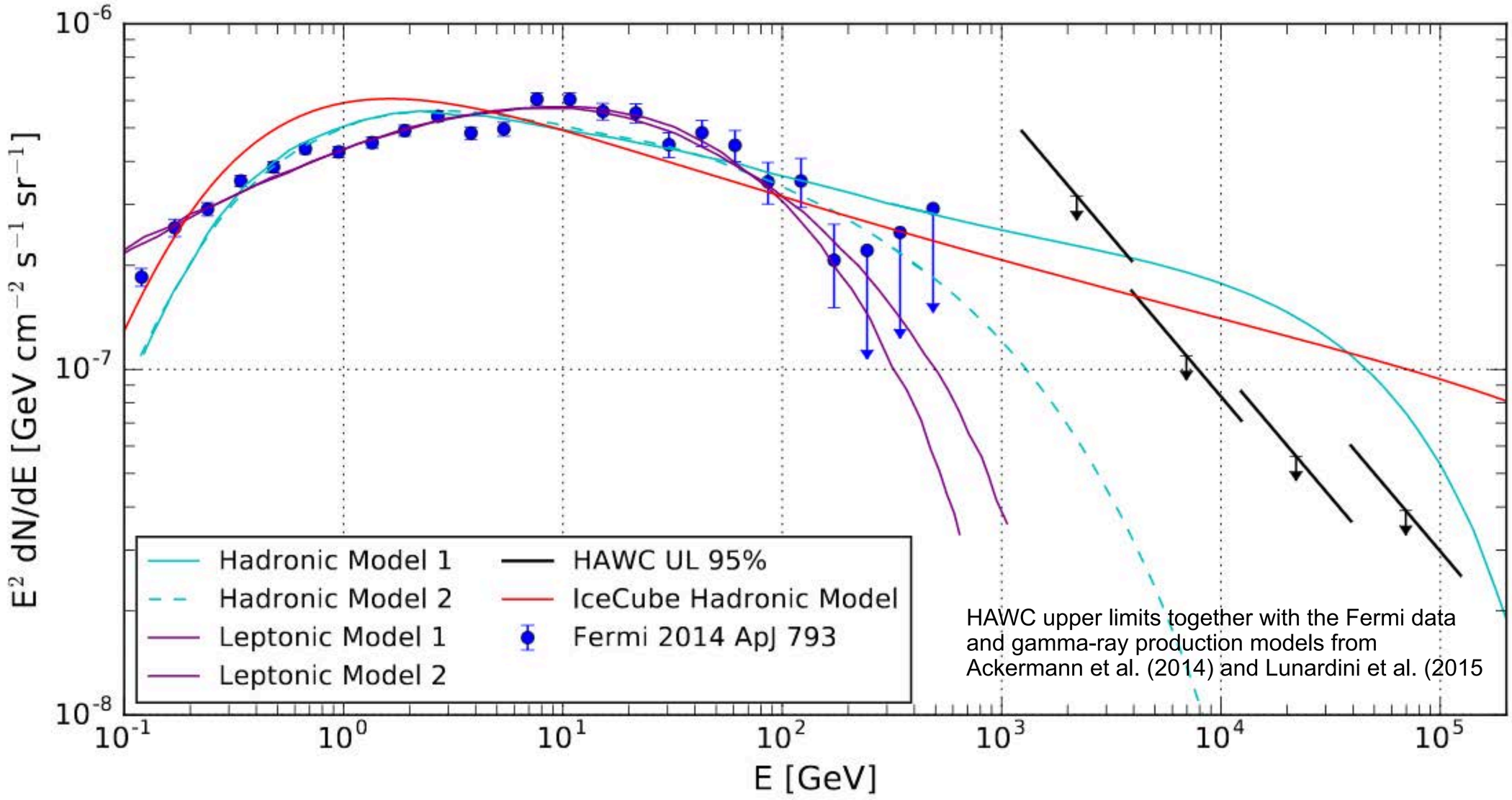
Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
- First limits in TeV, **hard spectrum is highly unlikely.**



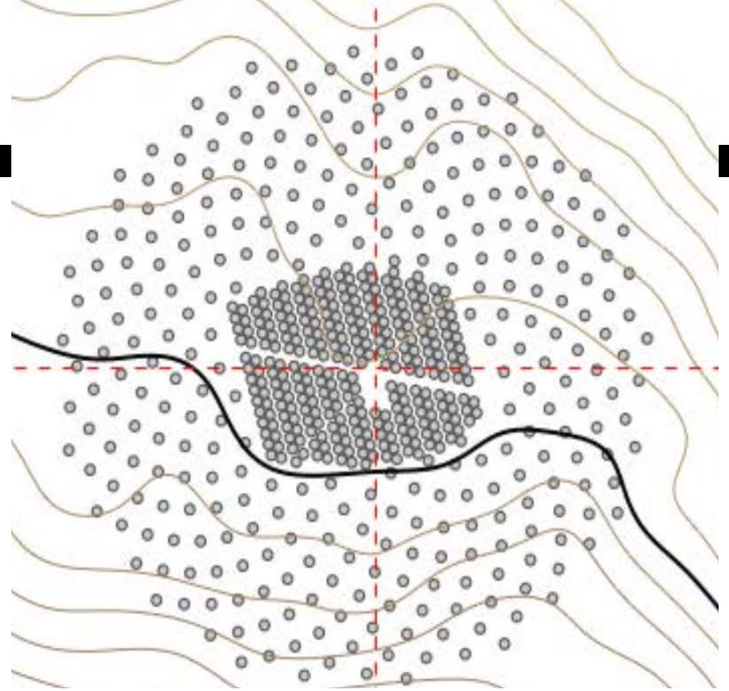


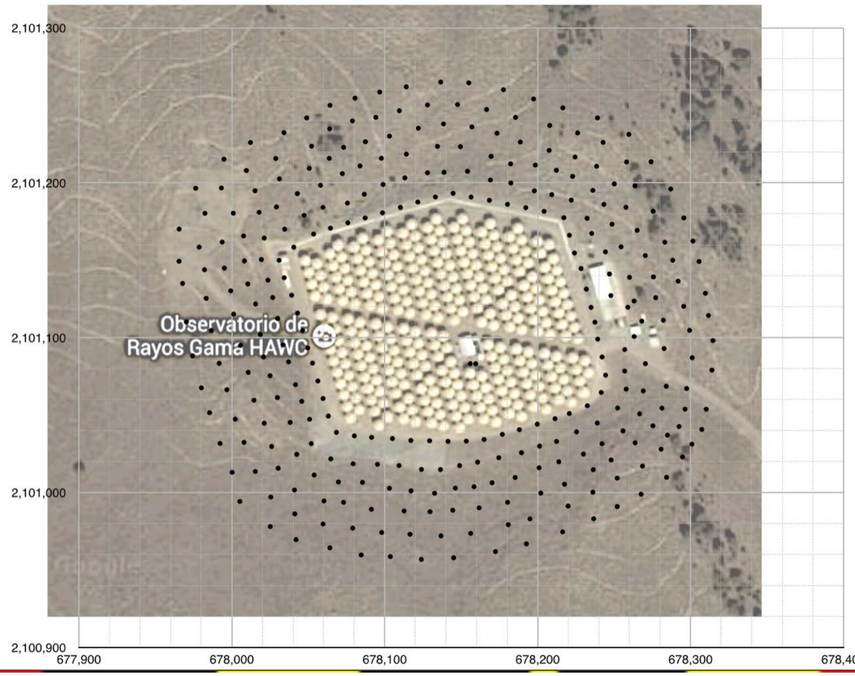
HAWC 90%CL upper limits



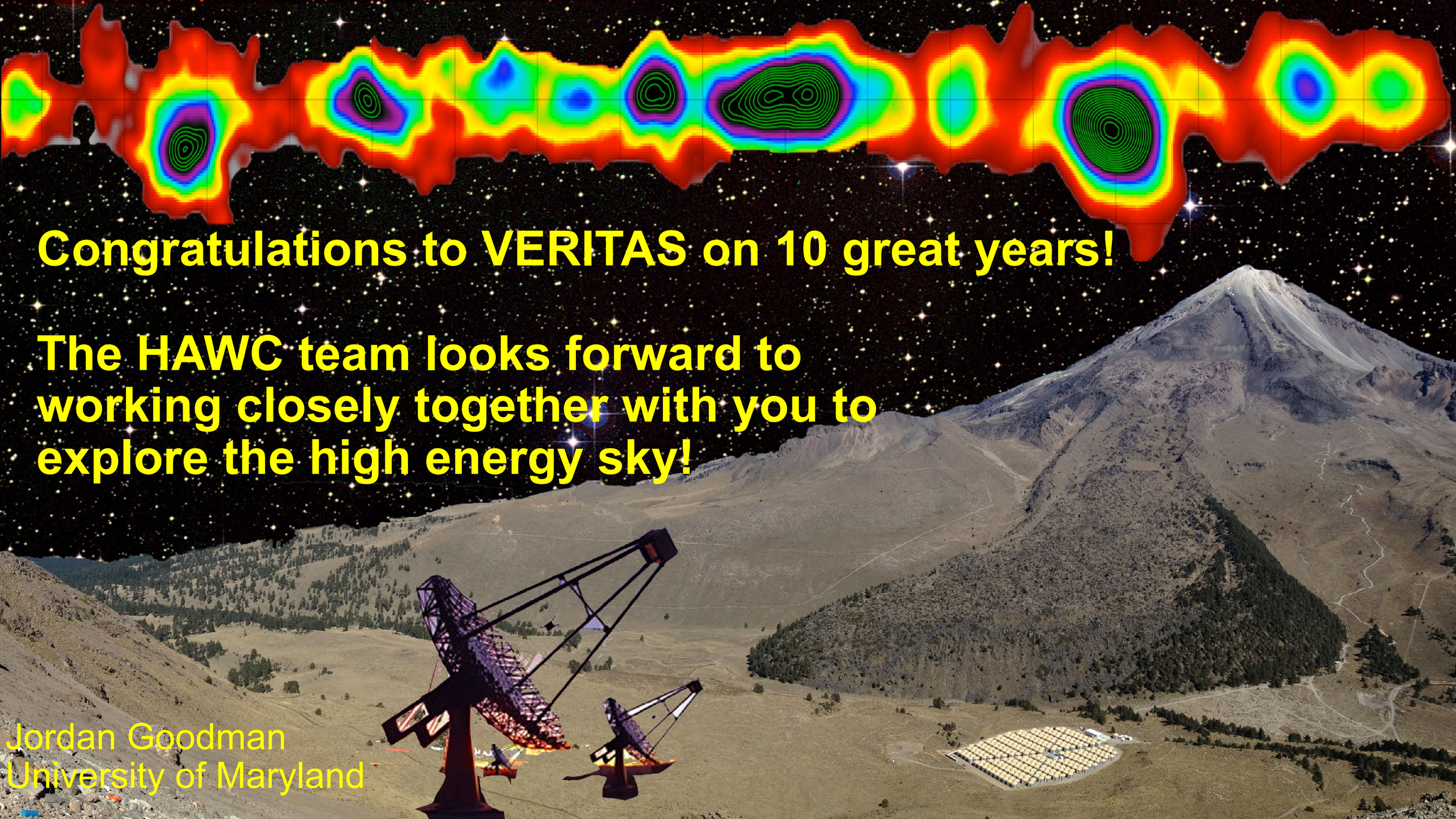
HAWC upper limits together with the Fermi data and gamma-ray production models from Ackermann et al. (2014) and Lunardini et al. (2015

Outriggers





- HAWC Sparse Outrigger Array being deployed now: Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
  - Increase effective area above 10 TeV by 3-4x
- Funded by LANL/MPIK (Heidelberg)/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.



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University of Maryland