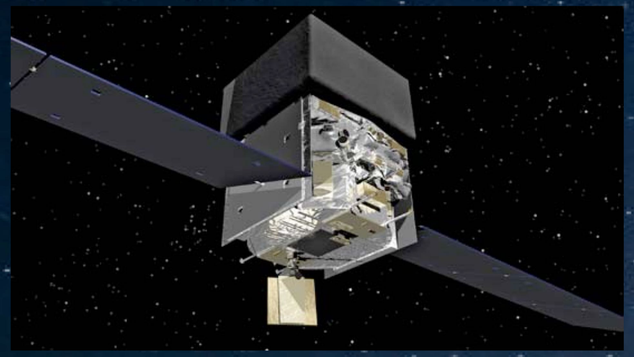
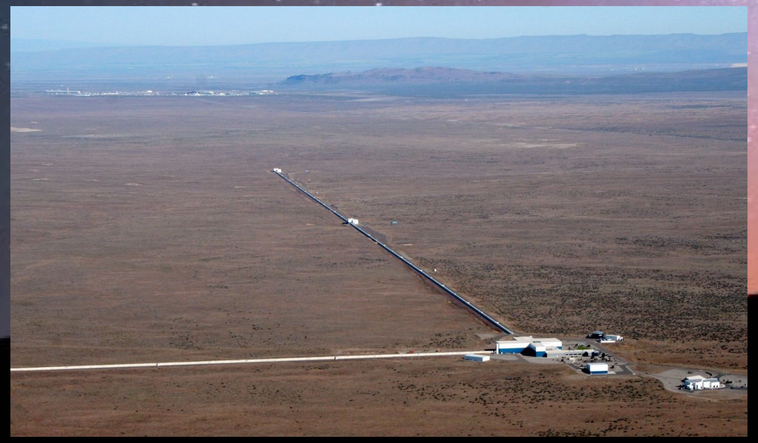
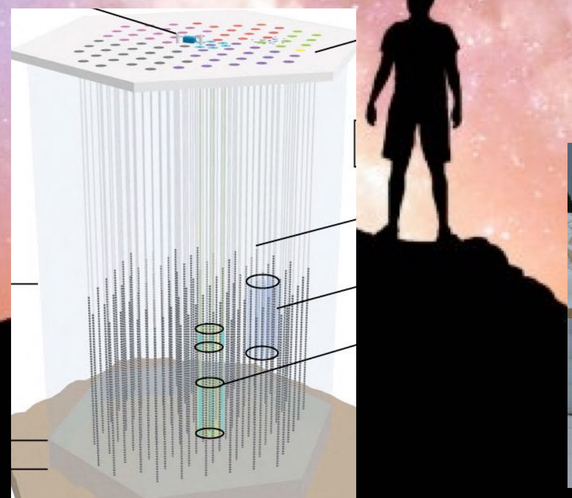
Multi-Messenger Astronomy with High Energy Gammas

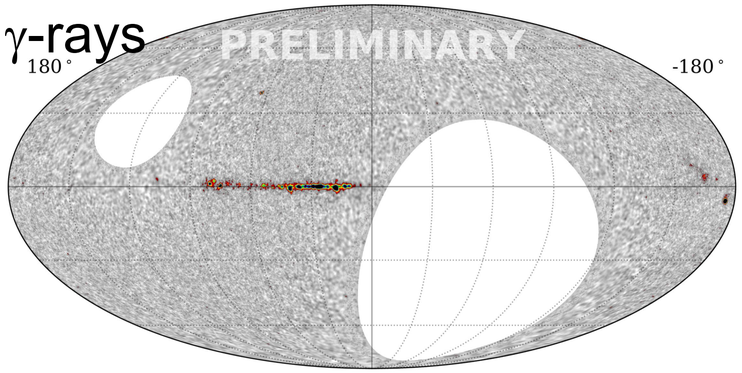


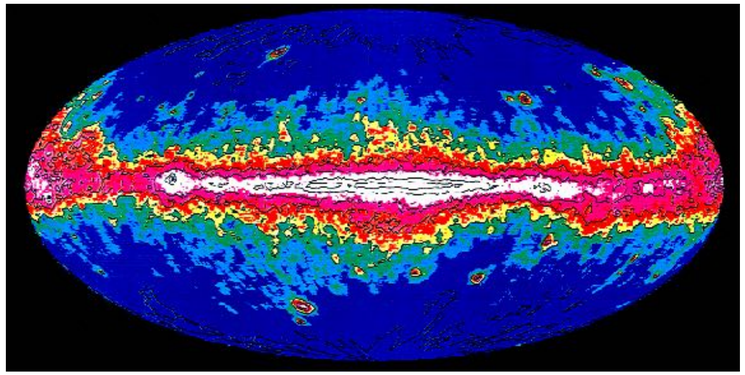
Jordan Goodman
University of Maryland

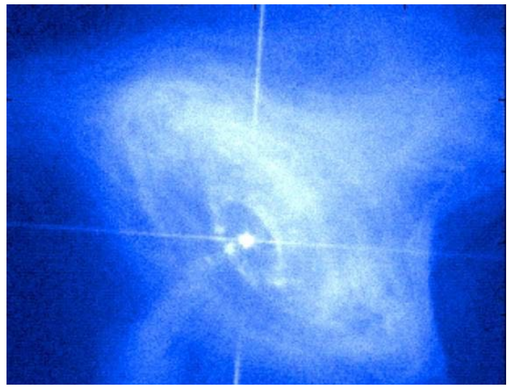




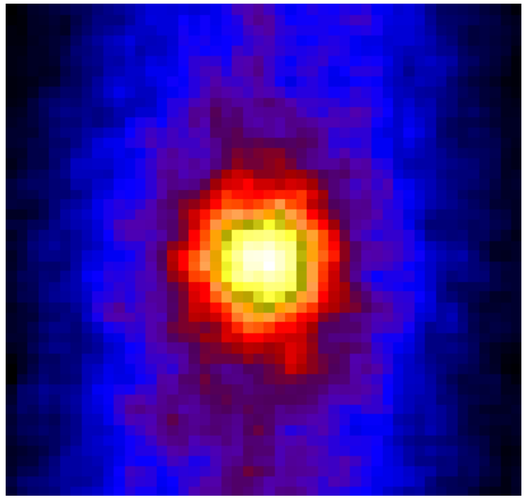
Multi-Messenger Astronomy



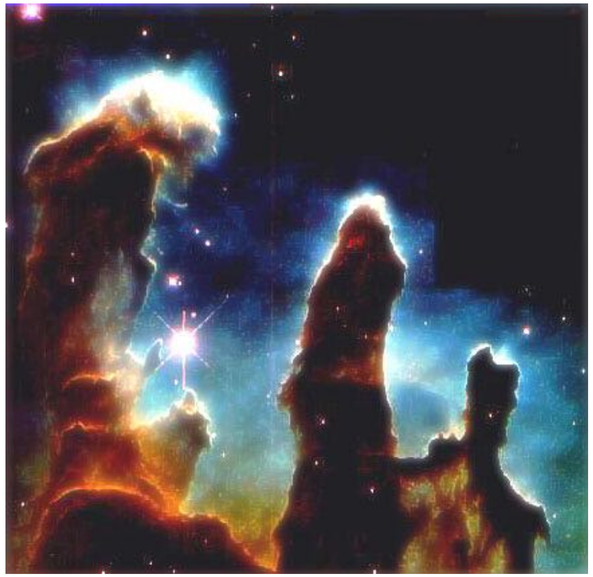




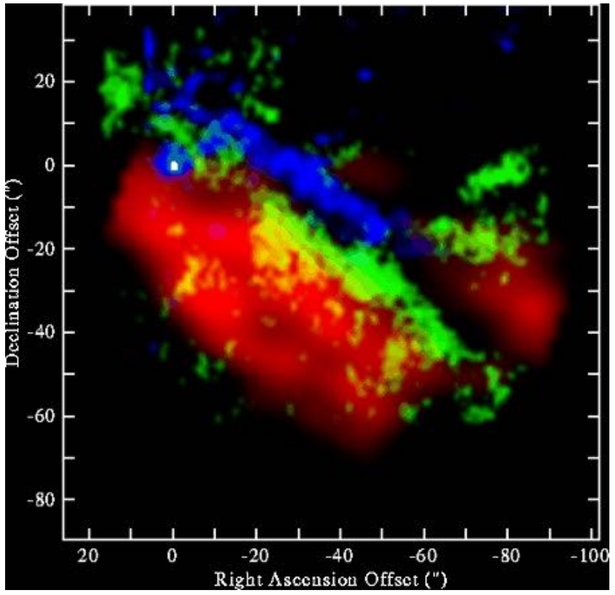
x-rays



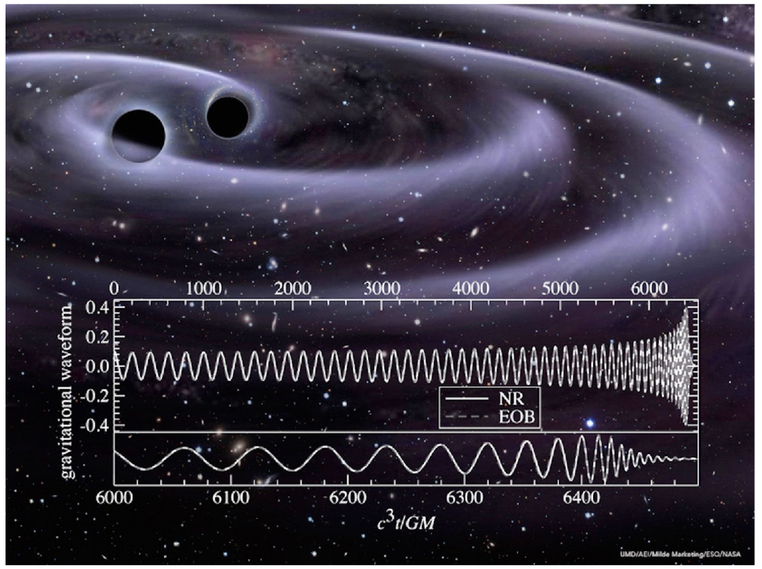
Neutrinos



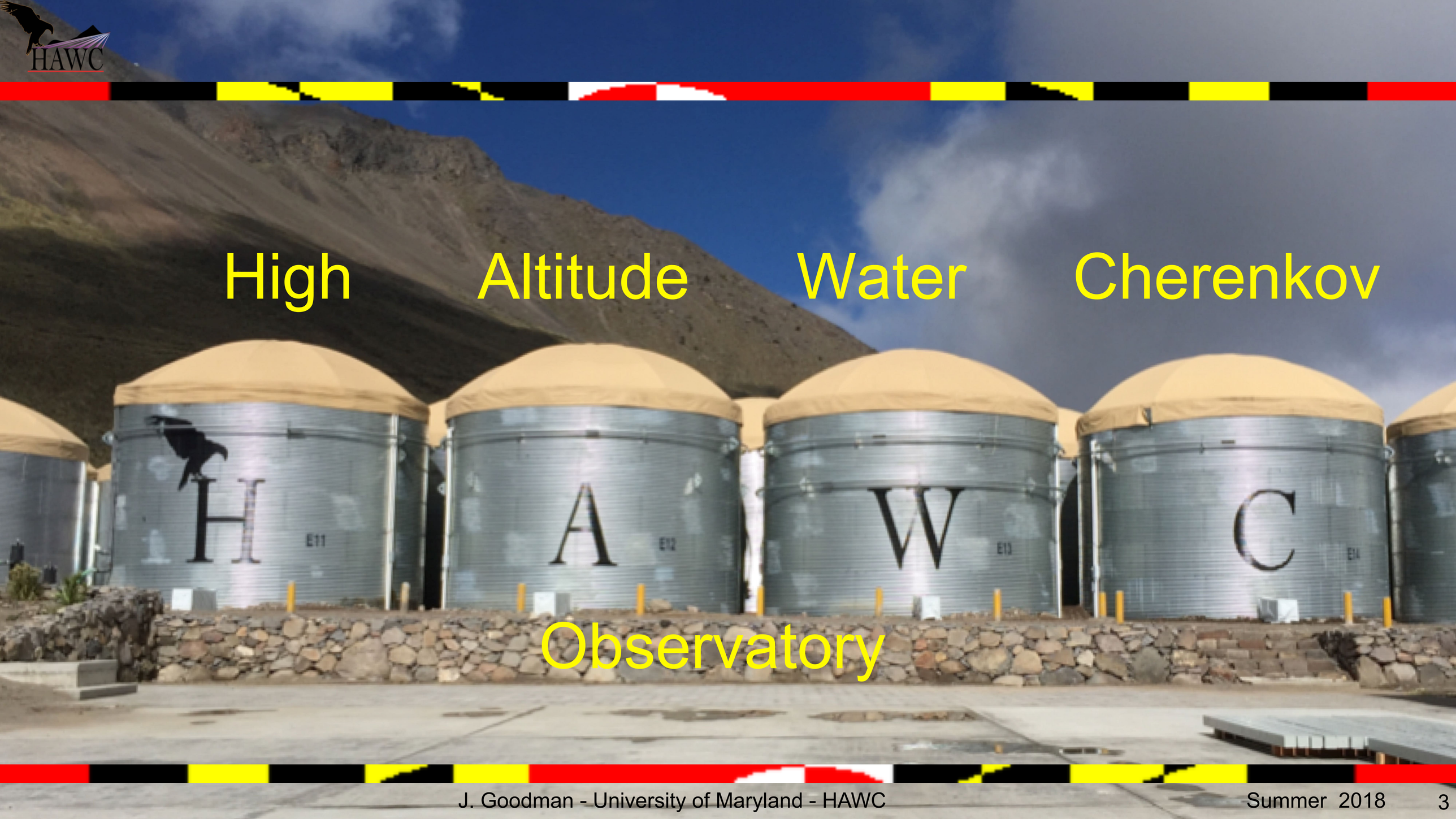
visible



radio



Gravitational Waves


High Altitude Water Cherenkov
H
A
W
C
Observatory

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

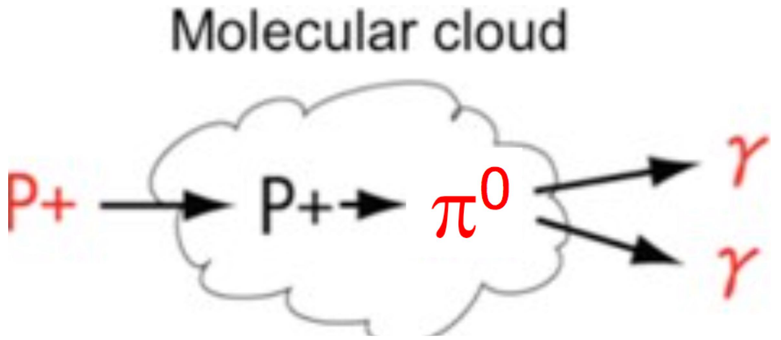
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional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

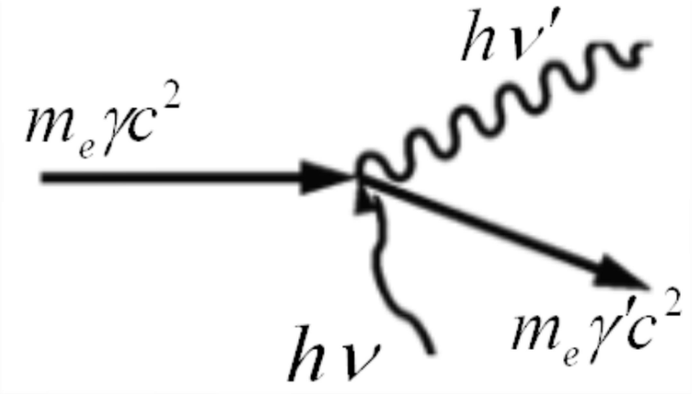
Europe

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

What Makes High Energy Gamma Rays

- Either hadronic or leptonic in origin
- Hadronic production comes from P-P collisions and then pion decay
- Leptonic production comes from inverse Compton Scattering
  - At energies above ~30 TeV the Compton drops (Klein-Nishina)
- So if spectra break they are likely leptonic if not they are more likely hadronic





HAWC Design builds on Milagro

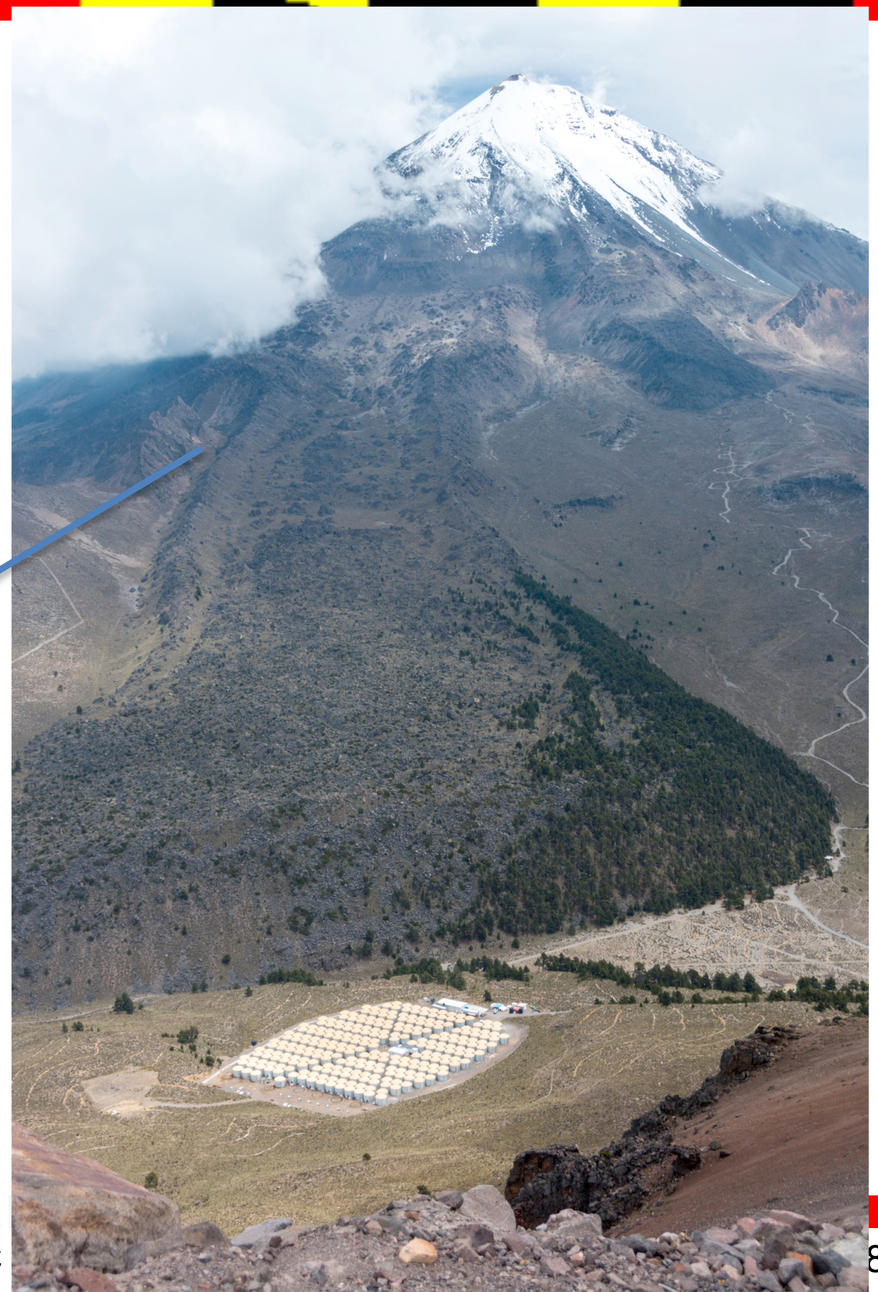
Milagro "1st Generation" Water Cherenkov detector
- 2650m (8600') elevation near Los Alamos, NM
- Covered pond of 4000 m^2
- Operated 2000-2008
- Crab at 5σ in 4-5 months

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

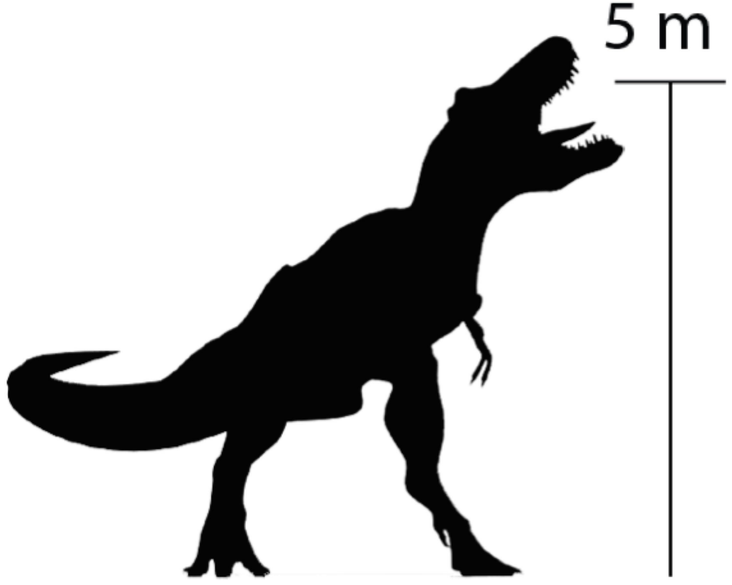
The HAWC Site

Latitude: 18°59.7'N
Longitude: 97°18.6'W



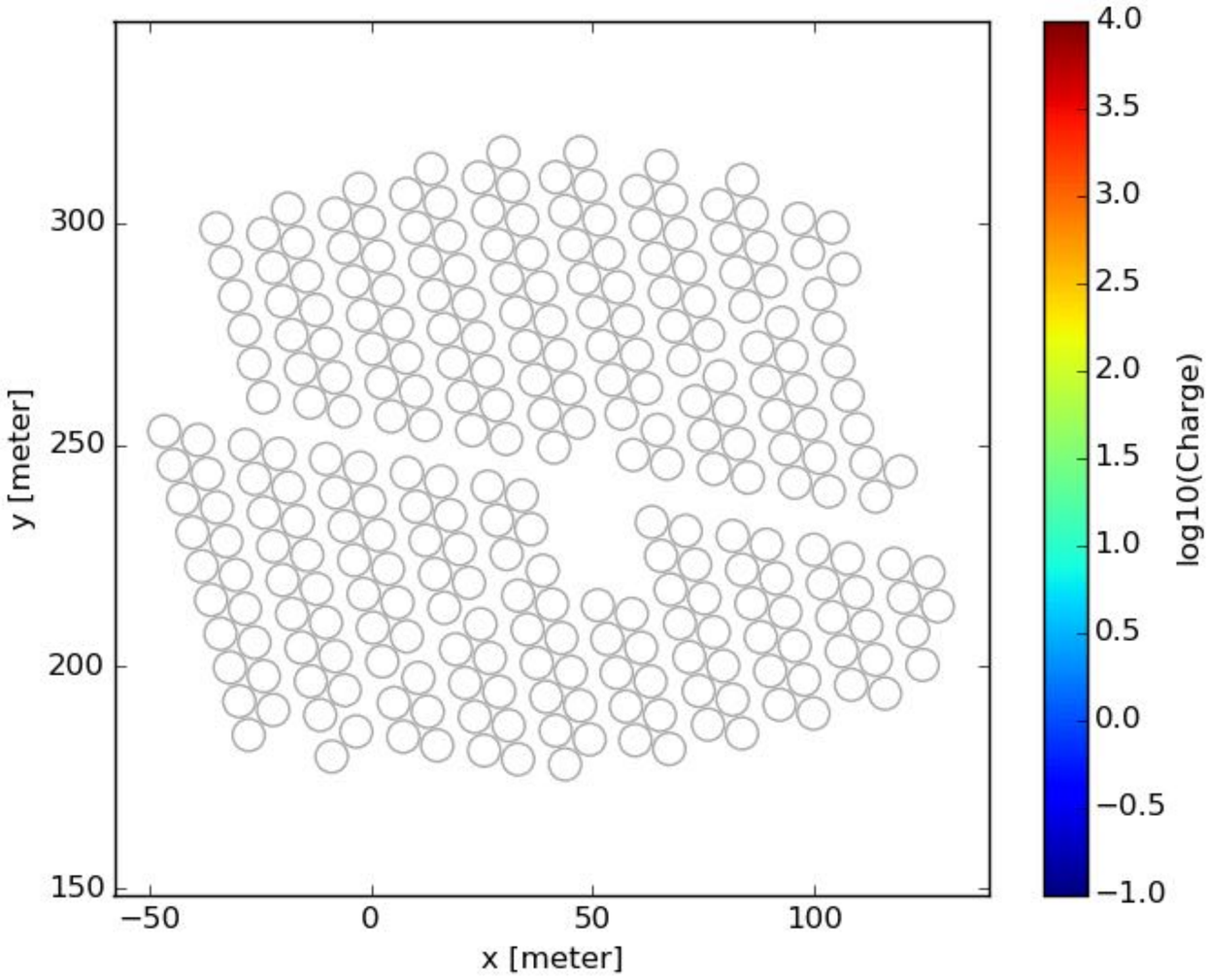
HAWC Tanks

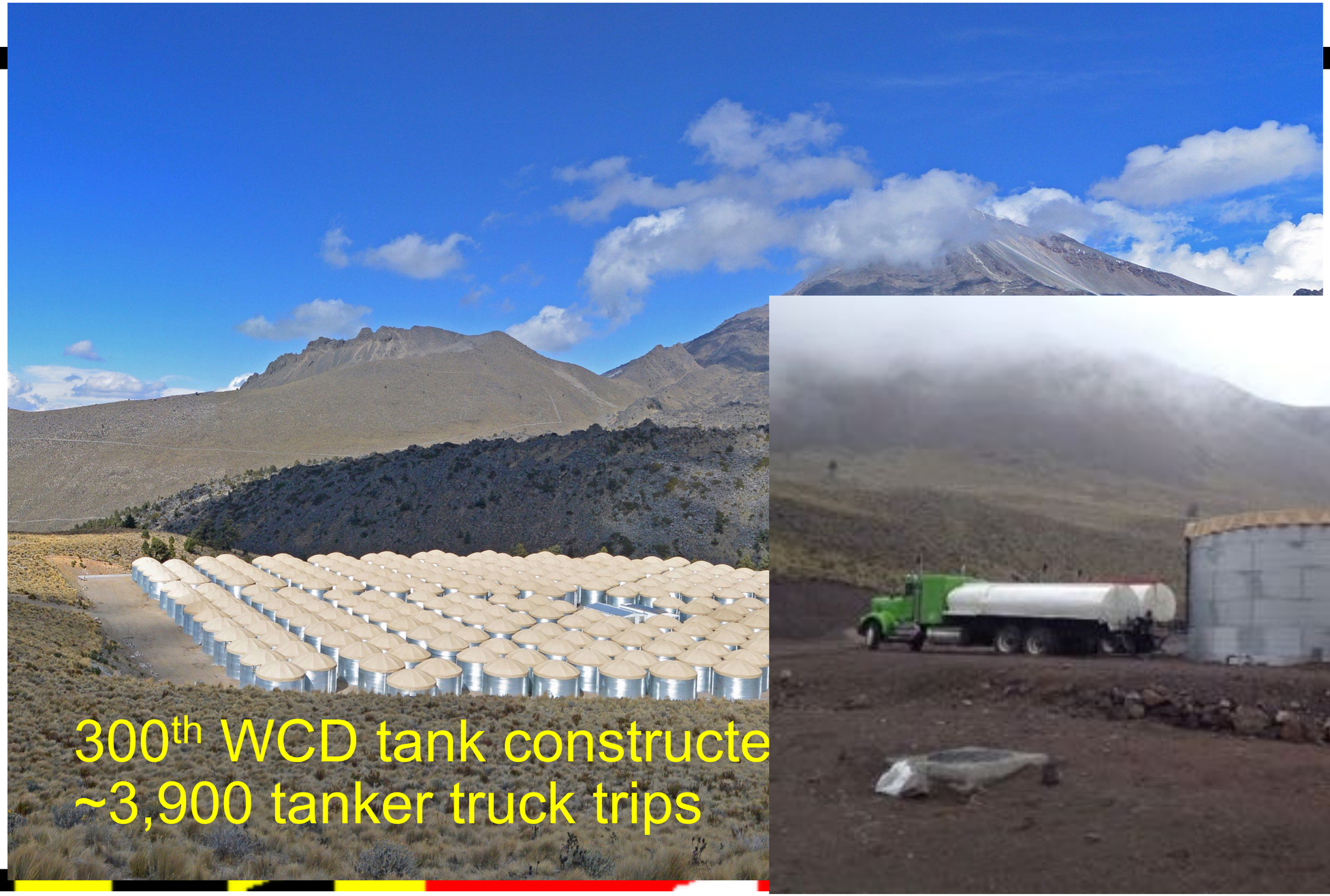
air shower



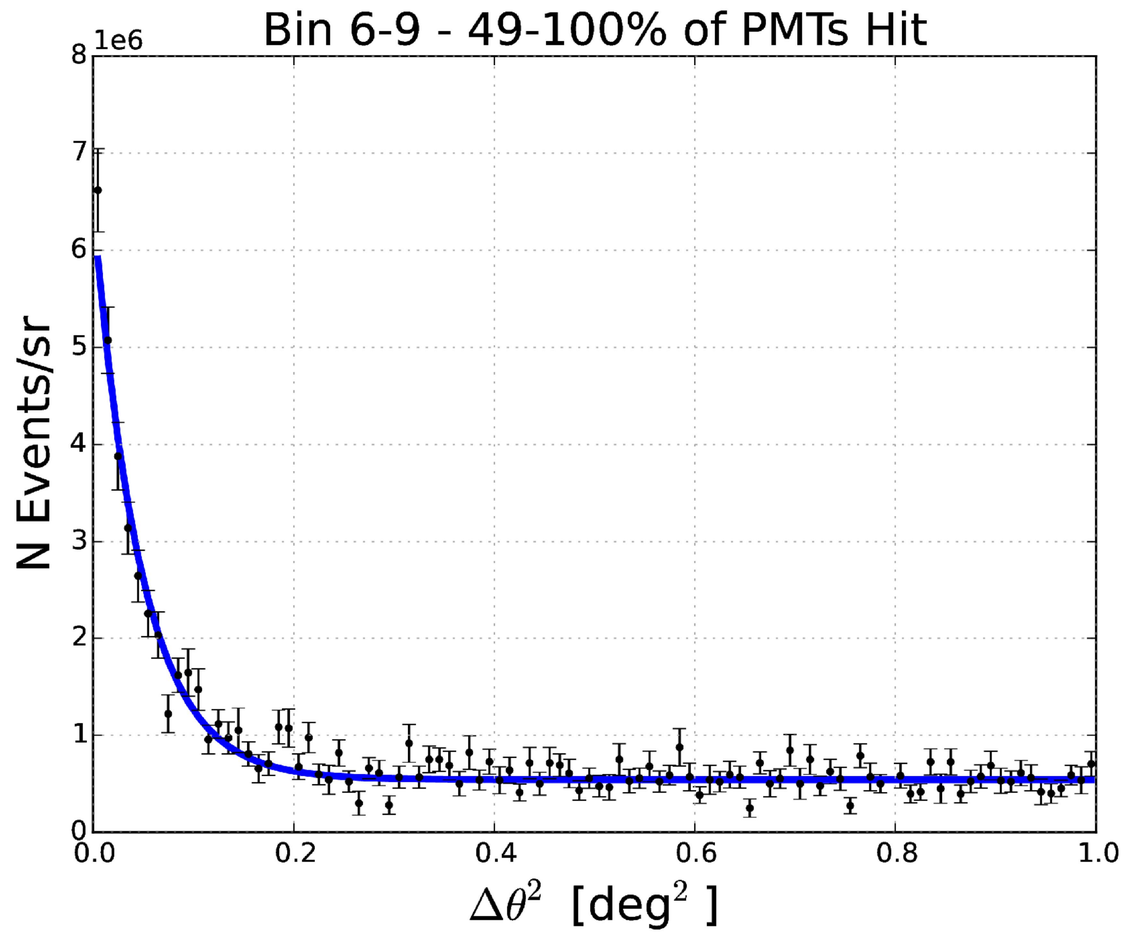
HAWC

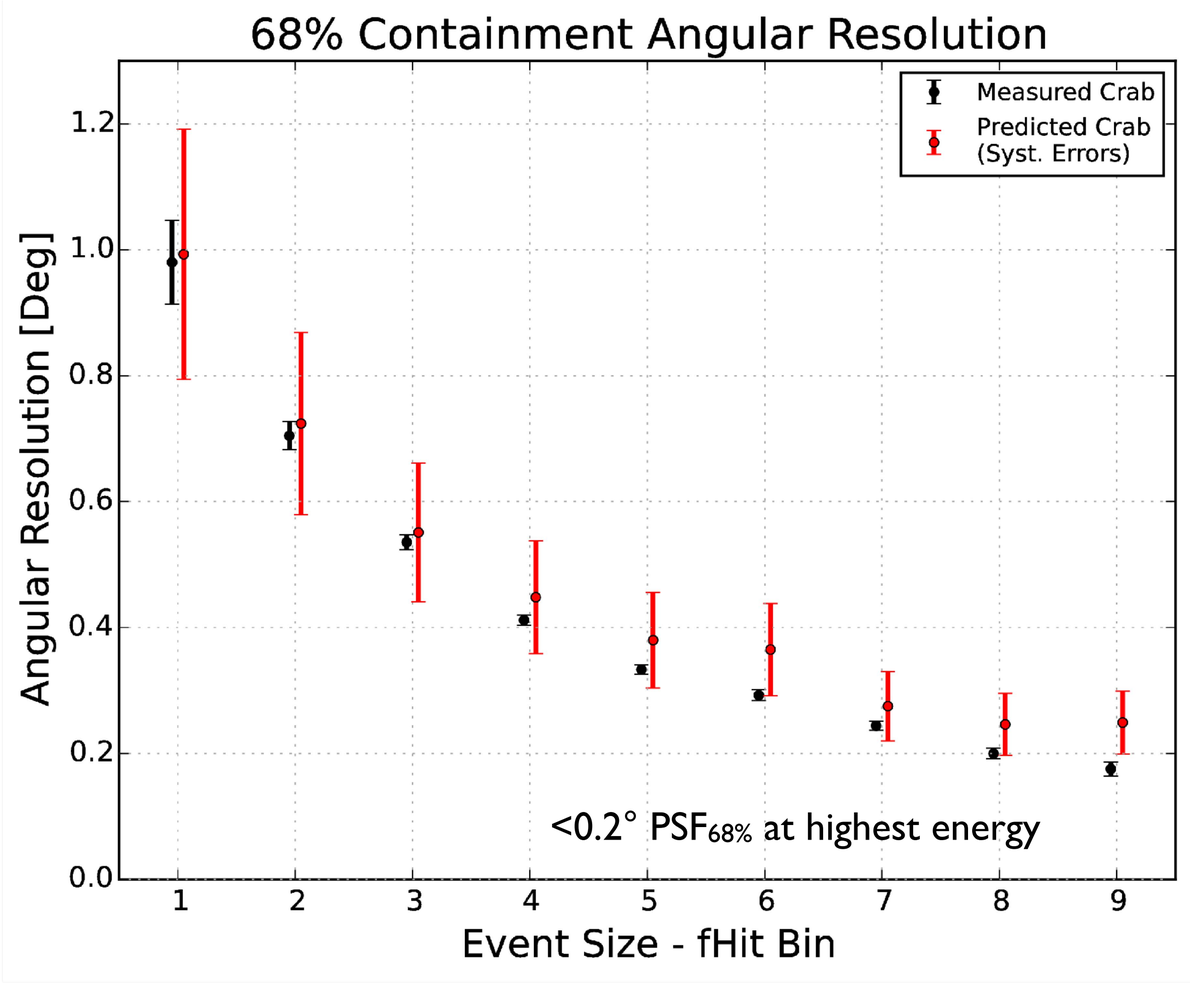
Angle Reconstruction Uses Timing



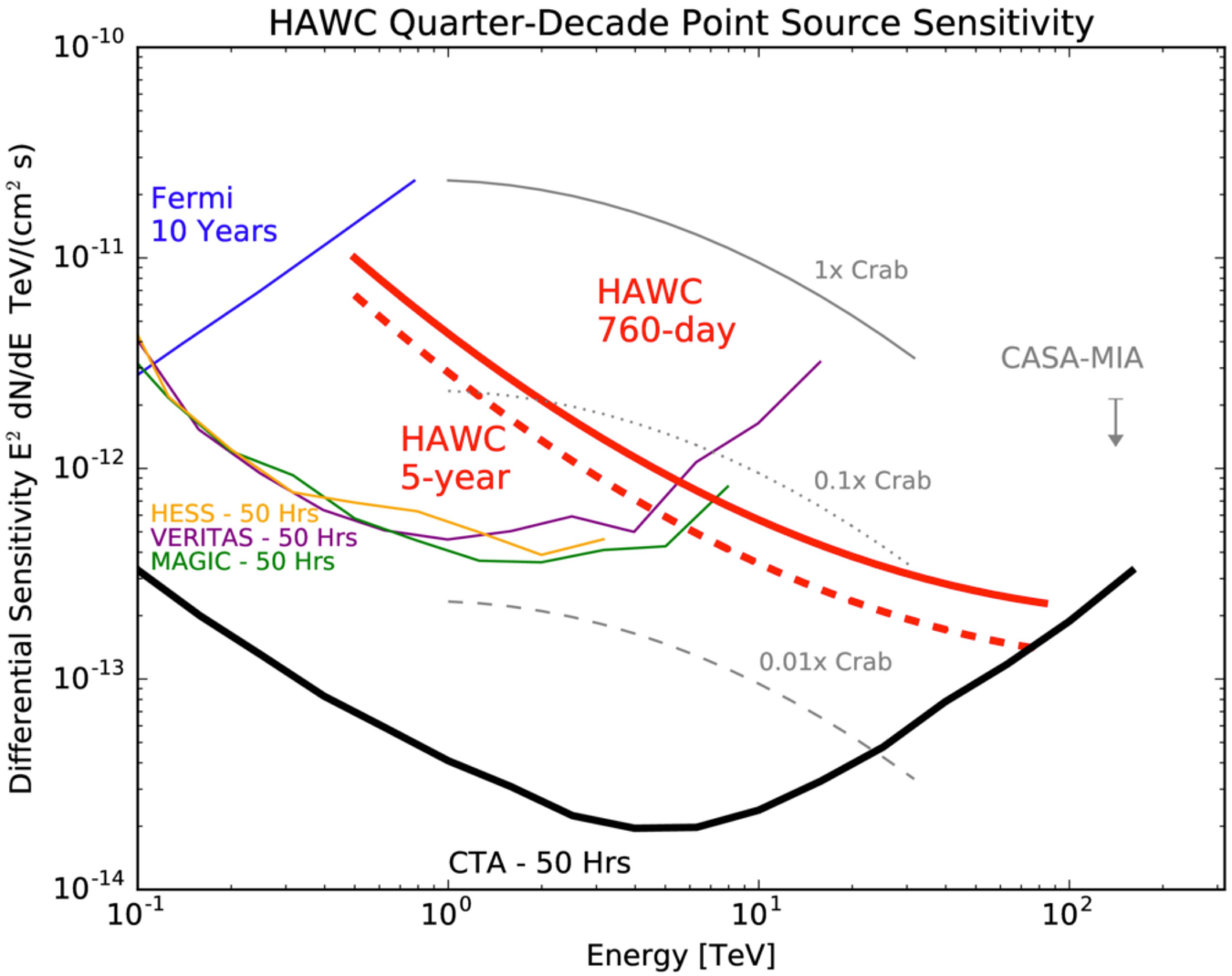

300th WCD tank constructe
~3,900 tanker truck trips

Angular Resolution





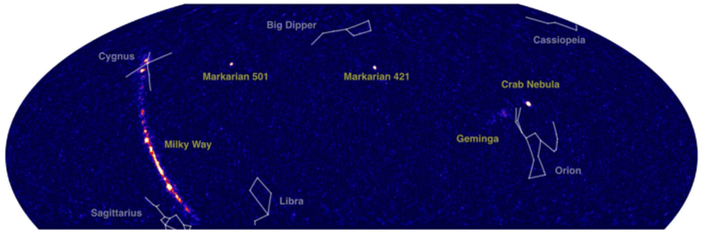
HAWC Differential Sensitivity

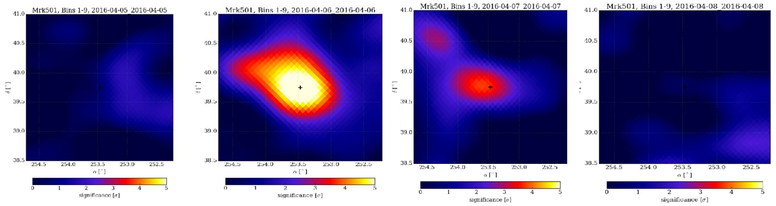


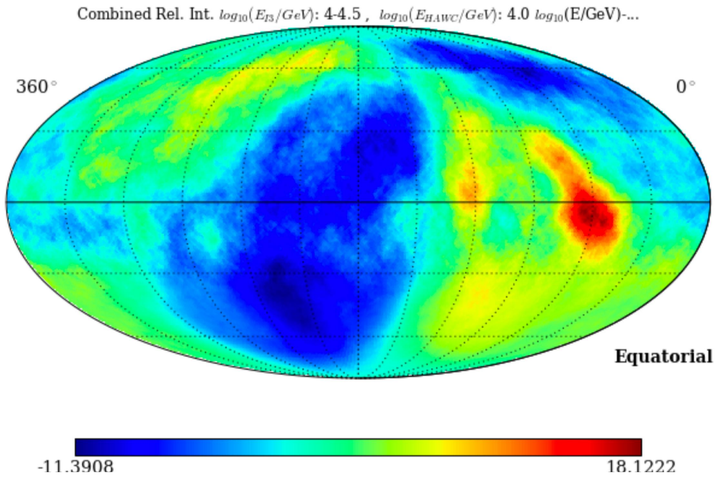
5 years of HAWC operations will give similar sensitivity at 10 TeV as 1 TeV for ACTs

What can you do with a wide-field instrument?

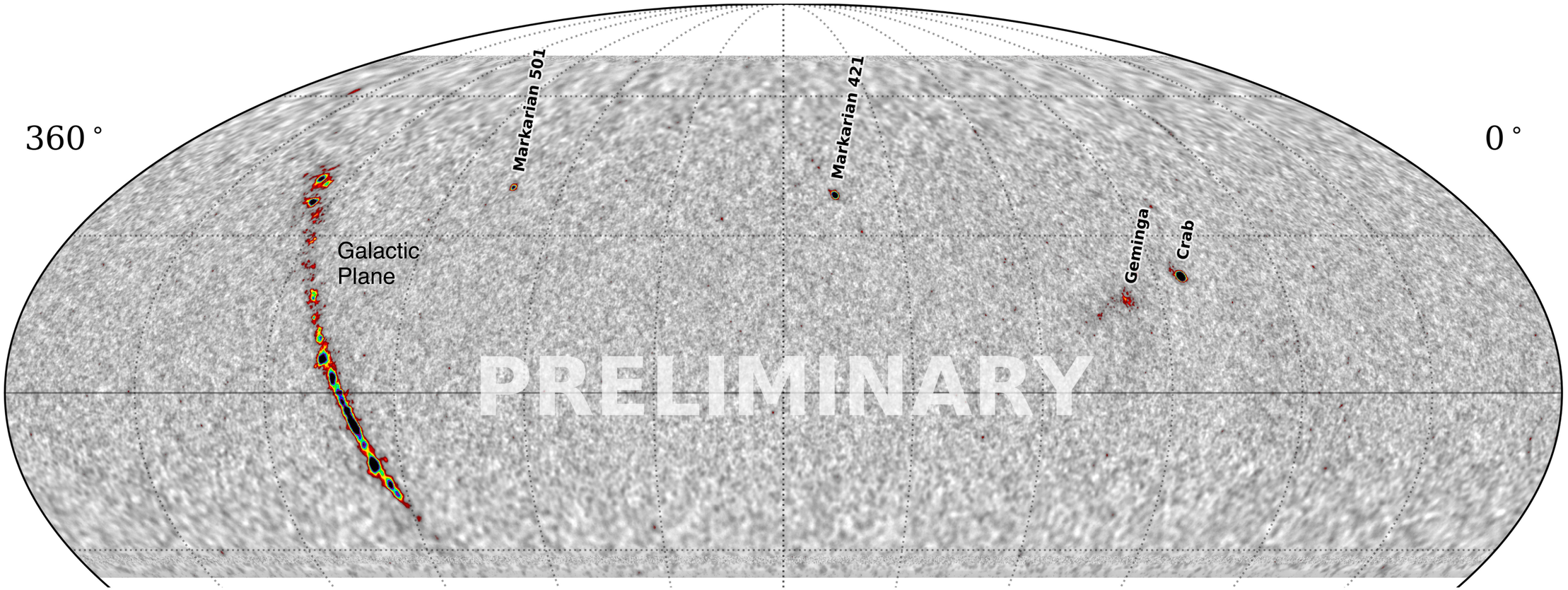
- Gamma Ray Astrophysics
  - Galactic Gamma-Ray Sources - Survey
    - Discovery of Pulsars, PWNs, Binaries - especially extended sources
    - Study of high energy behavior - source of galactic cosmic rays
    - Morphology of sources
    - Galactic Diffuse and Fermi Bubbles
  - Transients
    - Gamma 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

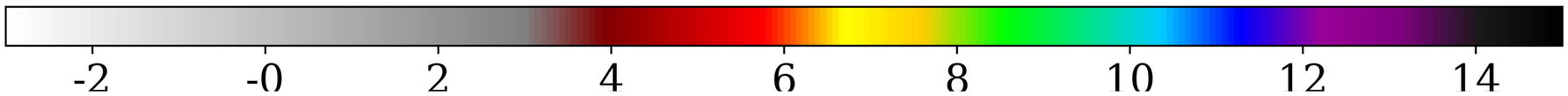


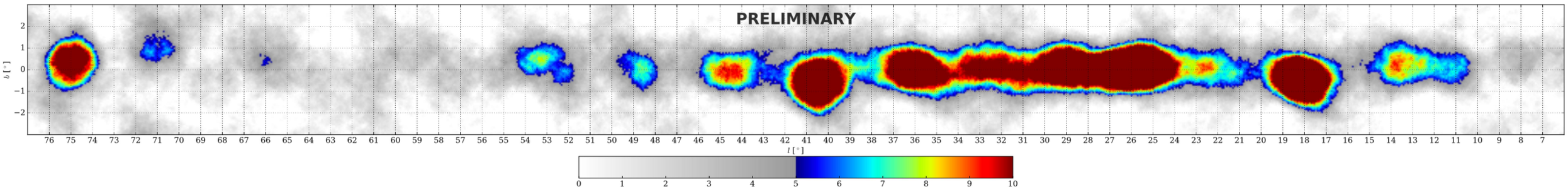


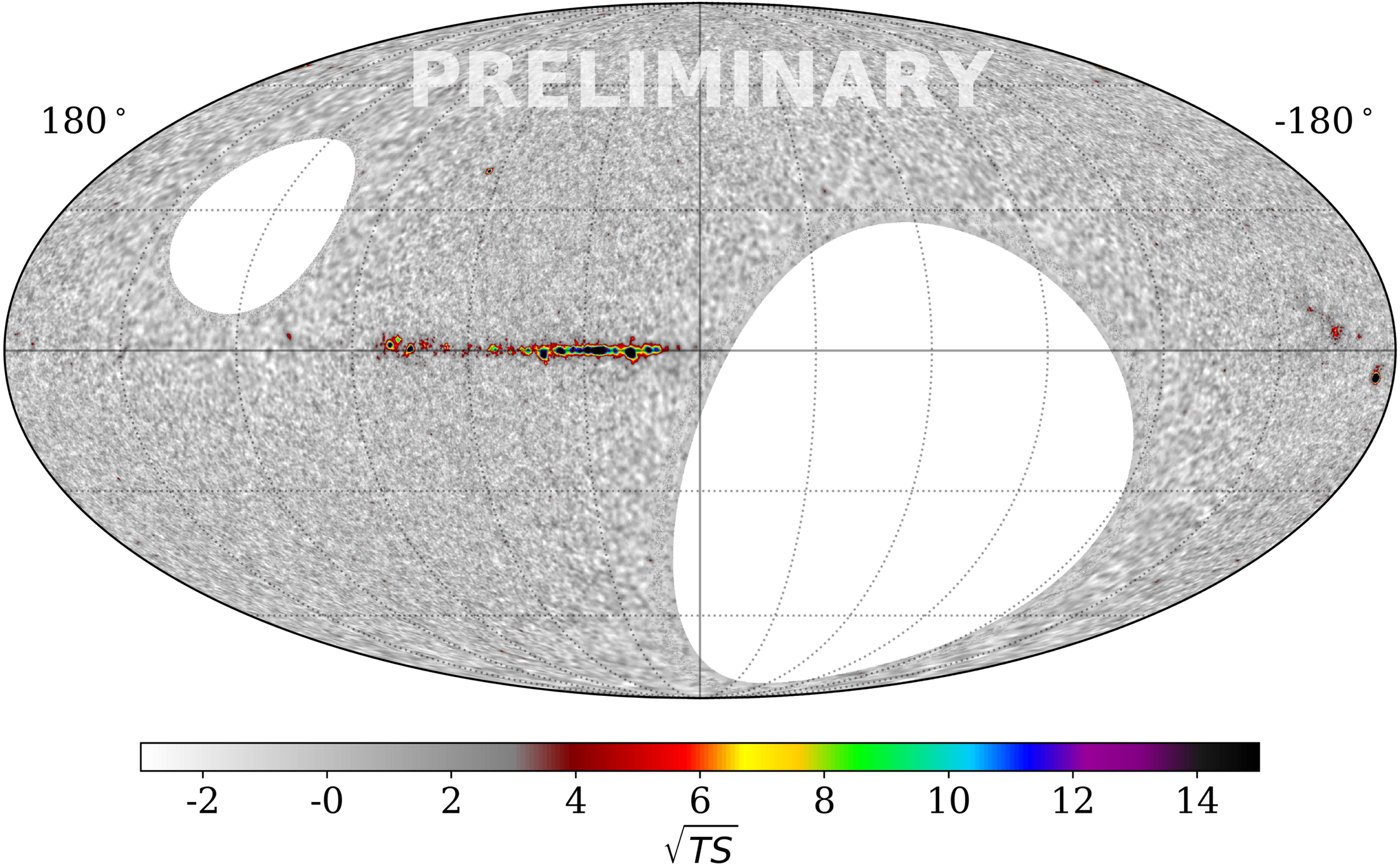


HAWC Sky Map 1017 Days of Data

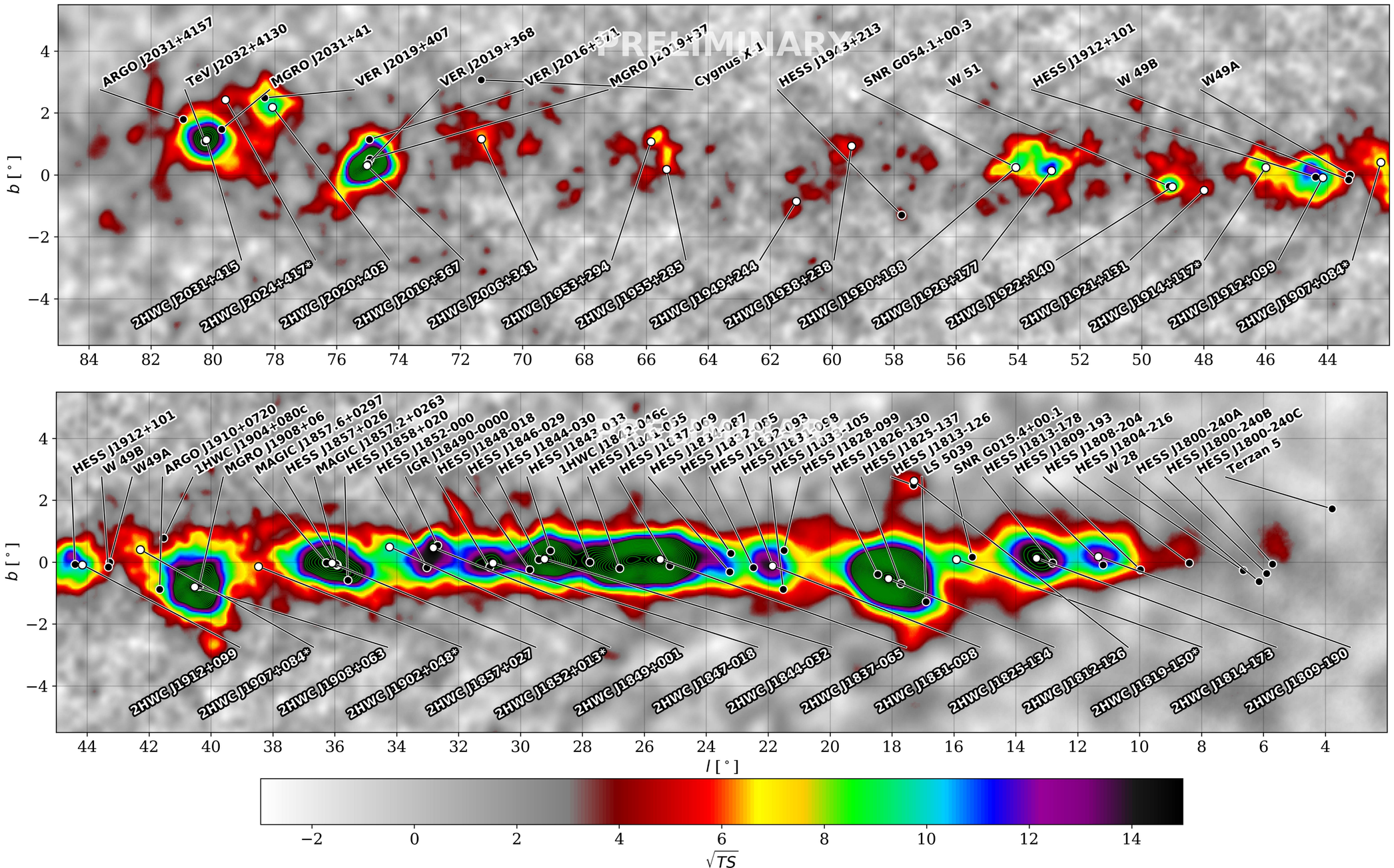


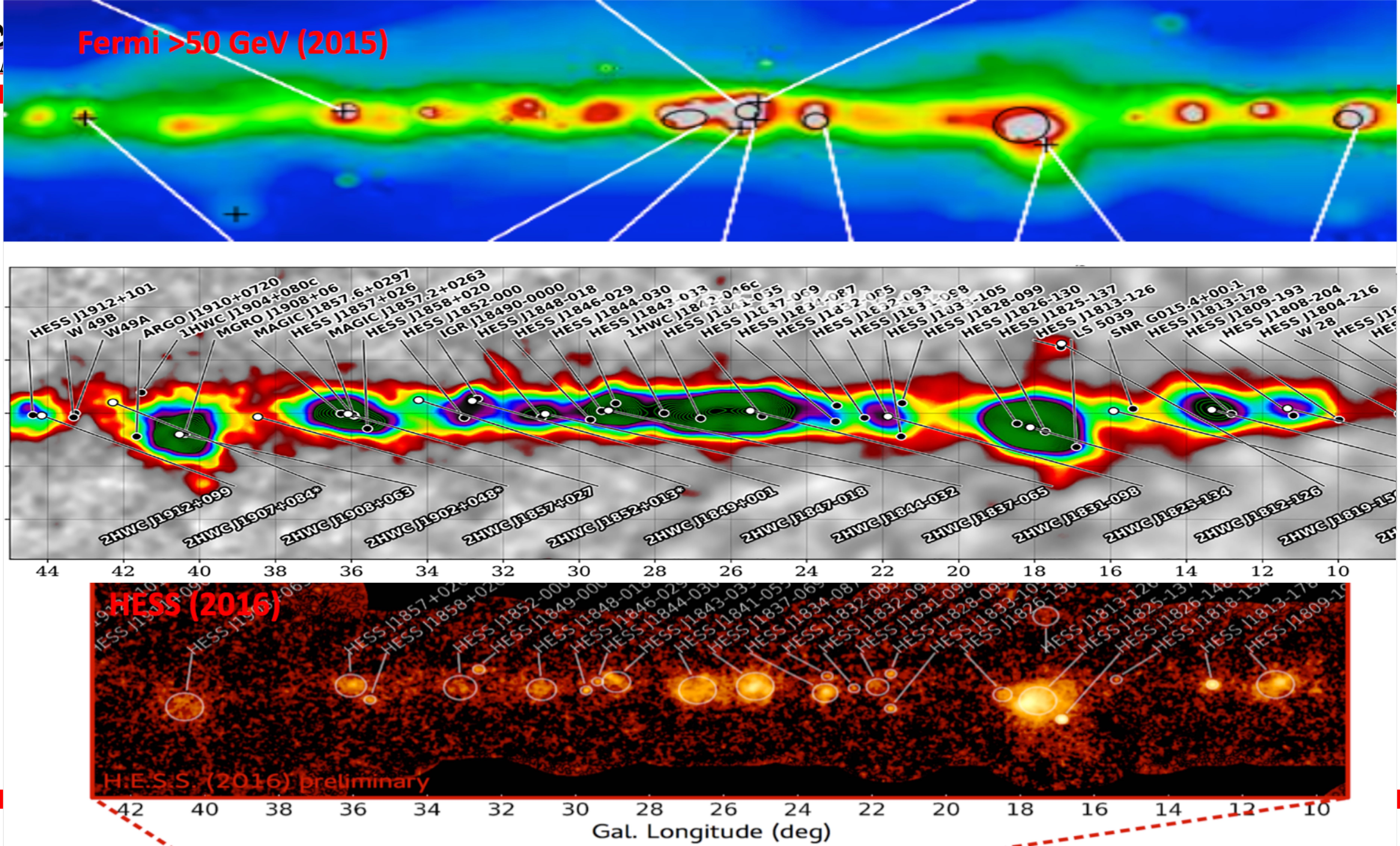





PRELIMINARY
180°
-180°
-2
-0
2
4
6
8
10
12
14
$\sqrt{TS}$

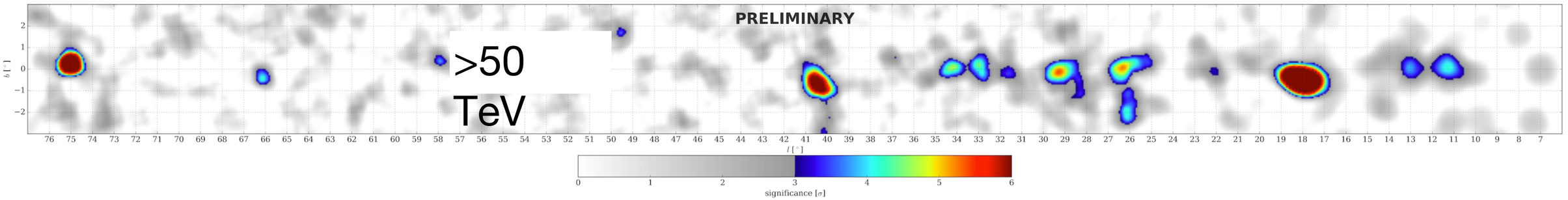
1017 Days of Data




Fermi >50 GeV (2015)
HESS J1912+101
W 49B
W49A
ARGO J1910+0720
1HWC J1904+080c
MGRO J1908+06
MAGIC J1857.6+0297
HESS J1857+026
MAGIC J1857.2+0263
HESS J1858+020
HESS J1852-000
IGR J18490-0000
HESS J1848-018
HESS J1846-029
HESS J1844-030
HESS J1828-099
HESS J1826-130
HESS J1825-137
HESS J1813-126
LS 5039
SNR G015.4+00.1
HESS J1813-178
HESS J1809-193
HESS J1808-204
HESS J1804-216
W 28
2HWC J1912+099
2HWC J1907+084*
2HWC J1908+063
2HWC J1902+048*
2HWC J1857+027
2HWC J1852+013*
2HWC J1849+001
2HWC J1847-018
2HWC J1844-032
2HWC J1837-065
2HWC J1831-098
2HWC J1825-134
2HWC J1812-126
44 42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10
HESS (2016)
H.E.S.S. (2016) preliminary
42 40 38 36 34 32 30 28 26 24 22 20 18 16 14 12 10
Gal. Longitude (deg)

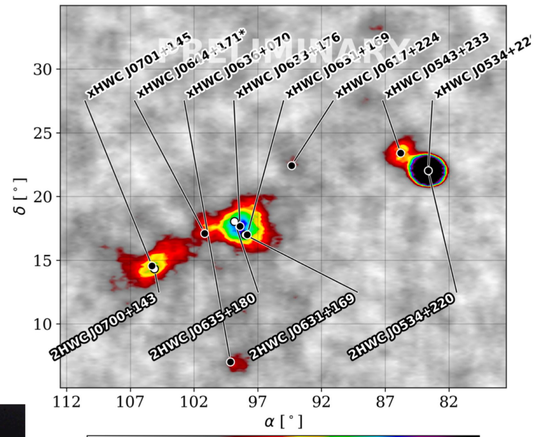
Highest Energy Sky

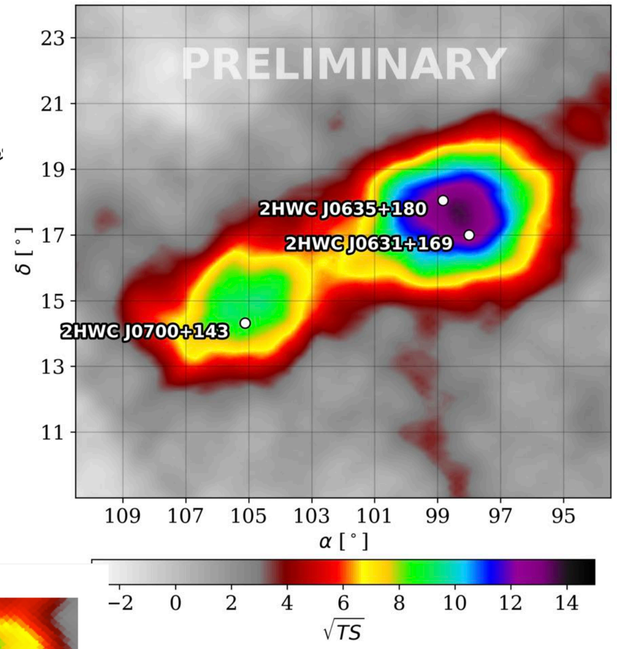
- By measuring spectra out beyond 30 TeV we can look for hadronic accelerators
- HAWC has produced the first map showing sources above 50 TeV
- Once we measure the spectra we can determine their origin

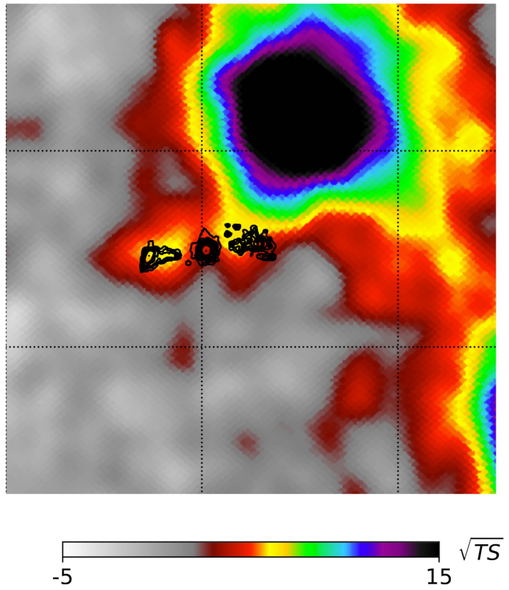


Other Exciting Galactic Results

- See Brenda Dingus' talk later this morning
  - Nearby middle-aged pulsars
    - Geminga and Monogem
    - J0543+233
  - Micro quasars
    - SS433





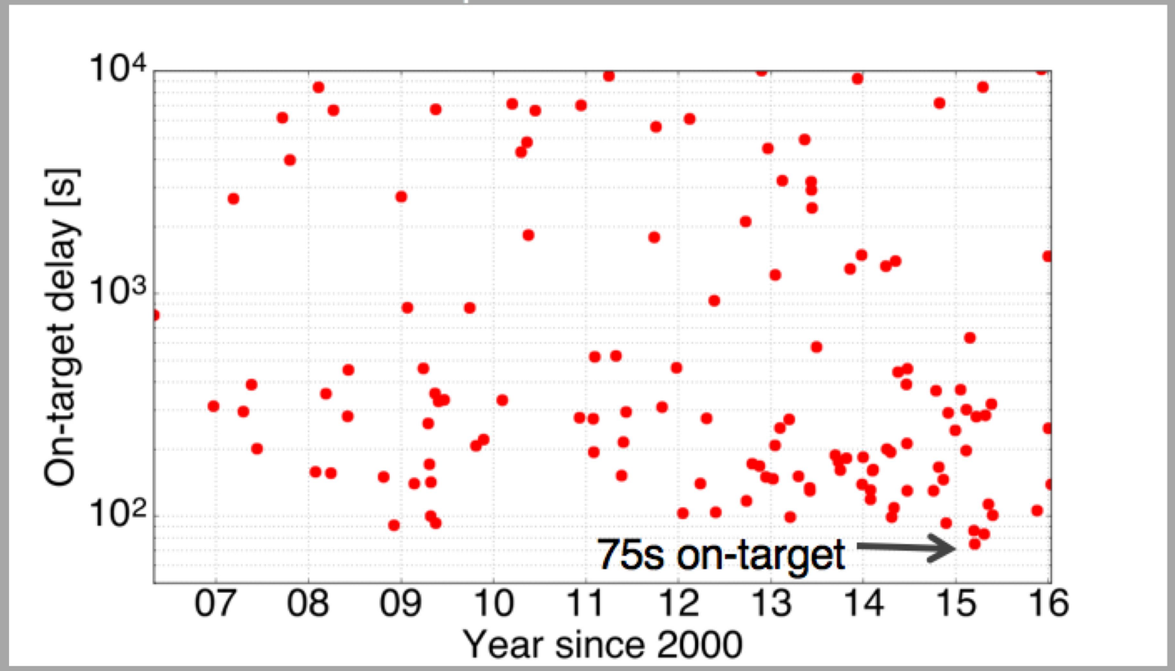


Mutli-Messenger Study of Transients

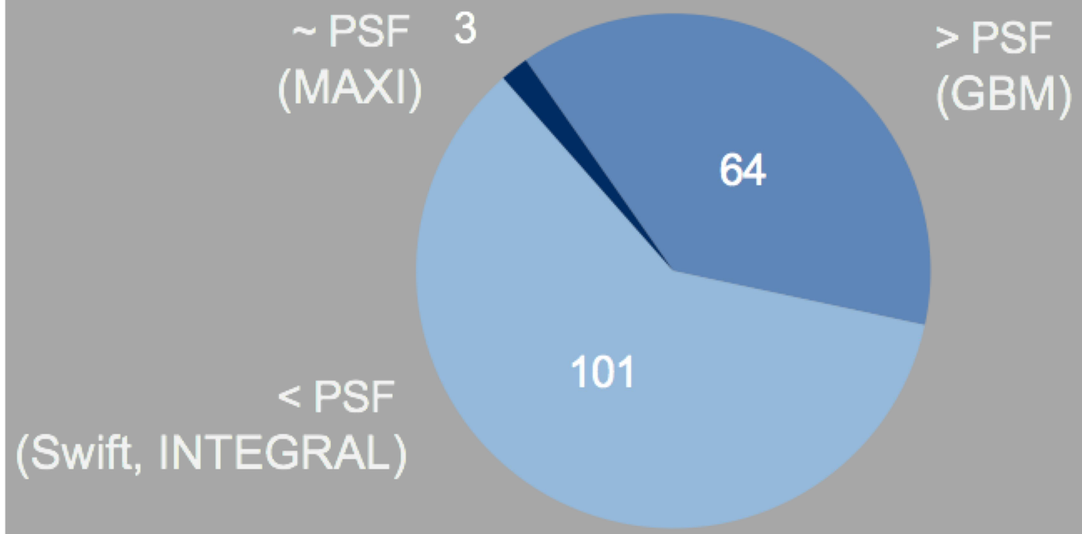
- Wide-field instruments play an important role the search for transients
  - Fermi
  - IceCube
  - LIGO
  - HAWC
- They require no alerts or slewing delays
- Right now HAWC is the only wide-field TeV instrument
- Future LHASSO
- IACTs have better sensitivity to high z objects, but scan the field of view to identify objects

VERITAS

Response time



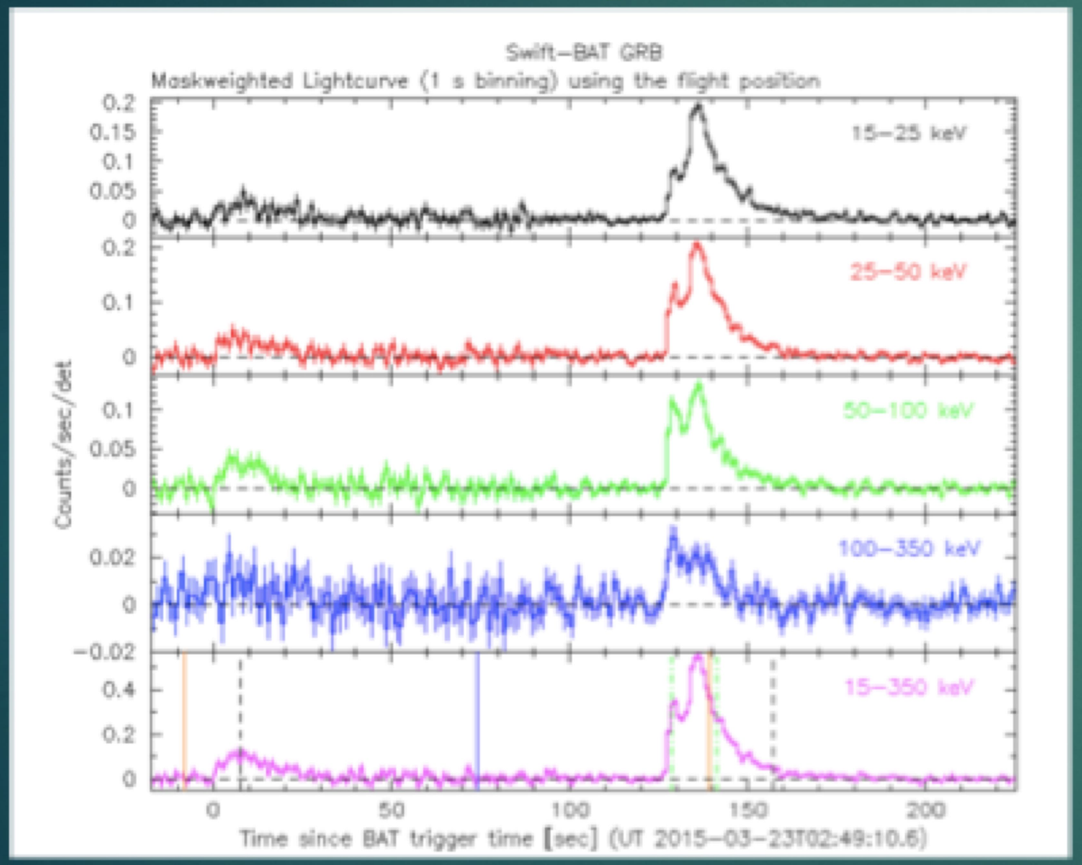
Localization uncertainty



Most Recently... GRB 150323A

"A strong limit on the very-high-energy emission from GRB 150323A"

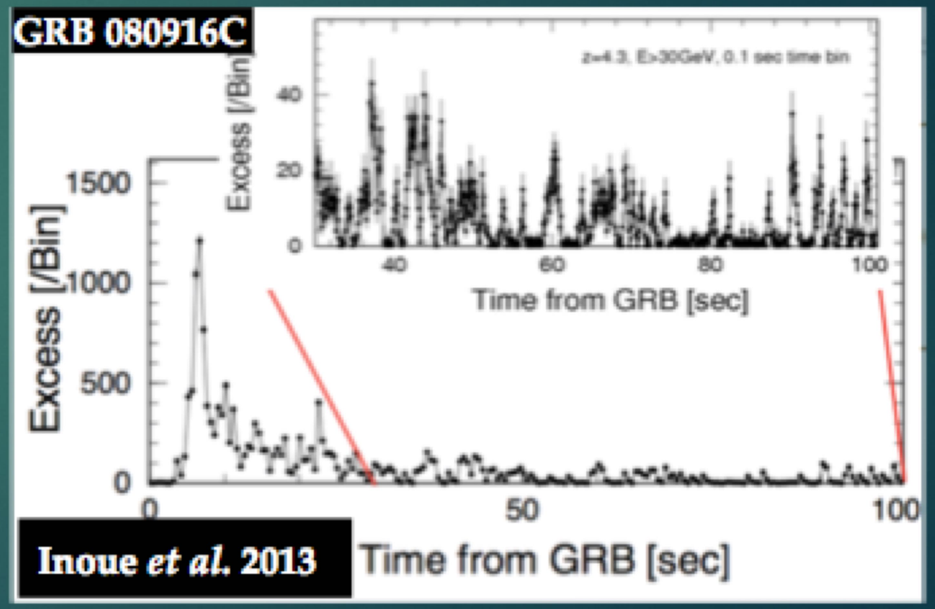
ApJ (2018, in press) arXiv/1803.01266



- Swift BAT burst at z ~ 0.6. VERITAS observation 2 min after the BAT emission peak.
- Upper limit at <1% prompt fluence.
- Lack of VHE emission favors explosion into the stellar wind of dense progenitor (Wolf-Rayet star), or a weak blast wave in a tenuous ISM.

CTA Transient/Multi-Messenger Follow-up

- **Rapid slewing!** Large Size Telescopes (LSTs) < 20 sec; Medium Size (MSTs) < 90 sec to any point on sky.
- **Real-time analysis (< 30 sec)** for transient detection and broadcasting of alerts.
- **Wide field of view: 4.5° (LST) / 8° (MST)** per telescope; rapidly cover large areas with tiling, divergent pointing.
- **Astrophysical neutrinos:** search for electromagnetic counterpart, to identify neutrino (and cosmic ray) origins.
- **Gravitational waves:** black hole or neutron star mergers; core collapse of massive stars.
- GRB light curves and spectra with high statistics (nearby).
- Triggers from optical/IR/radio transient factories: TDEs, FRBs, SNe, Galactic transients inc. novae, Crab Nebula flares...

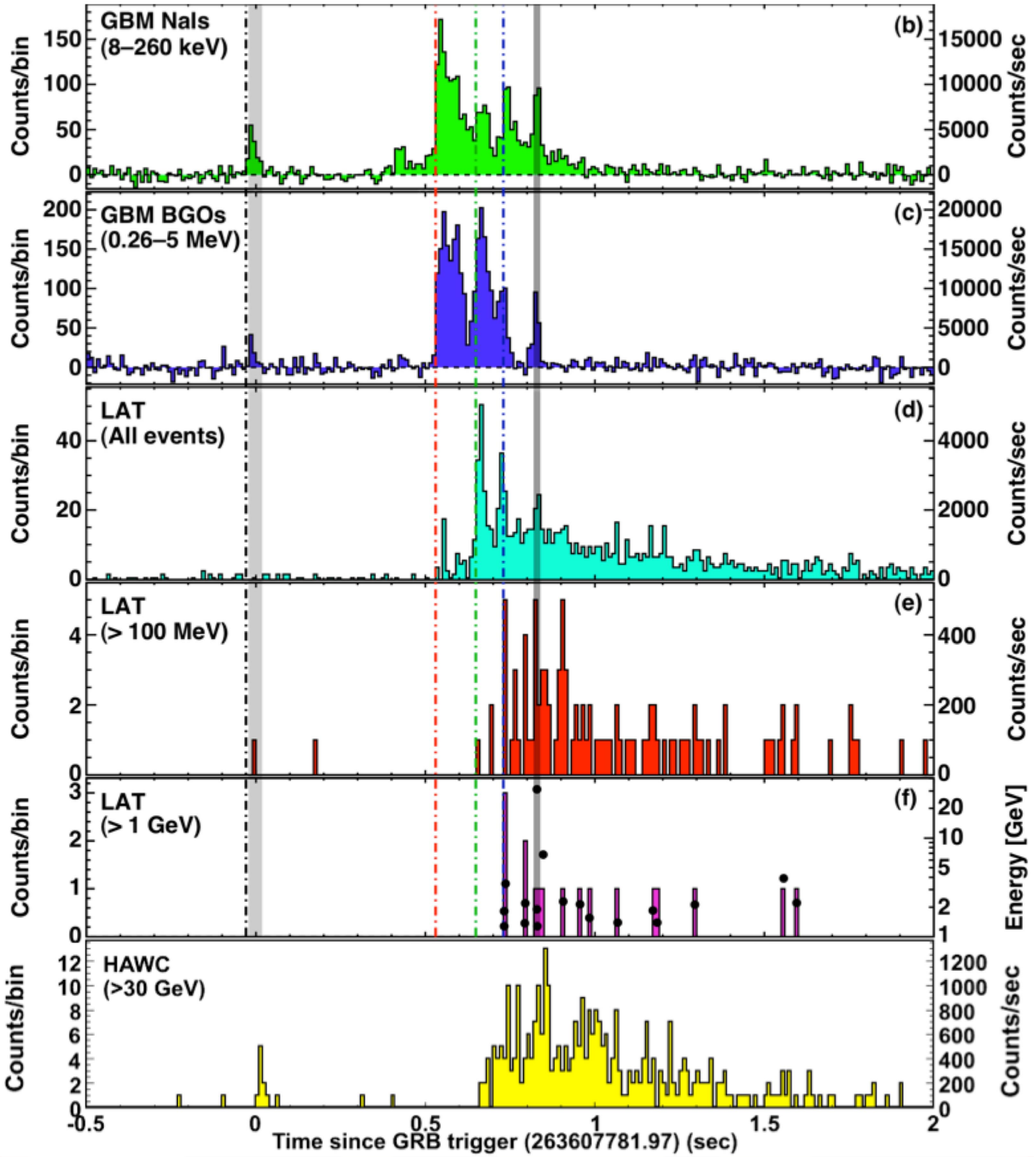


Fermi Observation of GRB 090510 with HAWC

- Assume spectrum extends to 125 GeV and attenuation with EBL model of Gilmore
- HAWC: 200 events from GRB 090510 if near zenith

  ~few background events
- Major Improvements!
  - Low-threshold DAQ
  - 10-inch PMTs

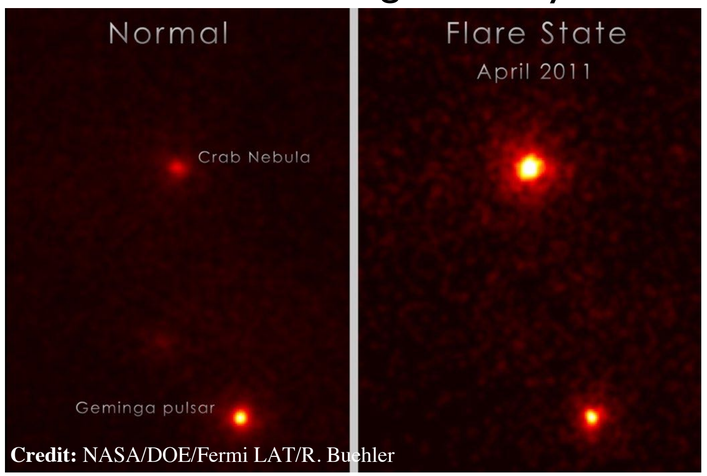
→ HAWC would observe 100s of events for spectrum to only 31 GeV

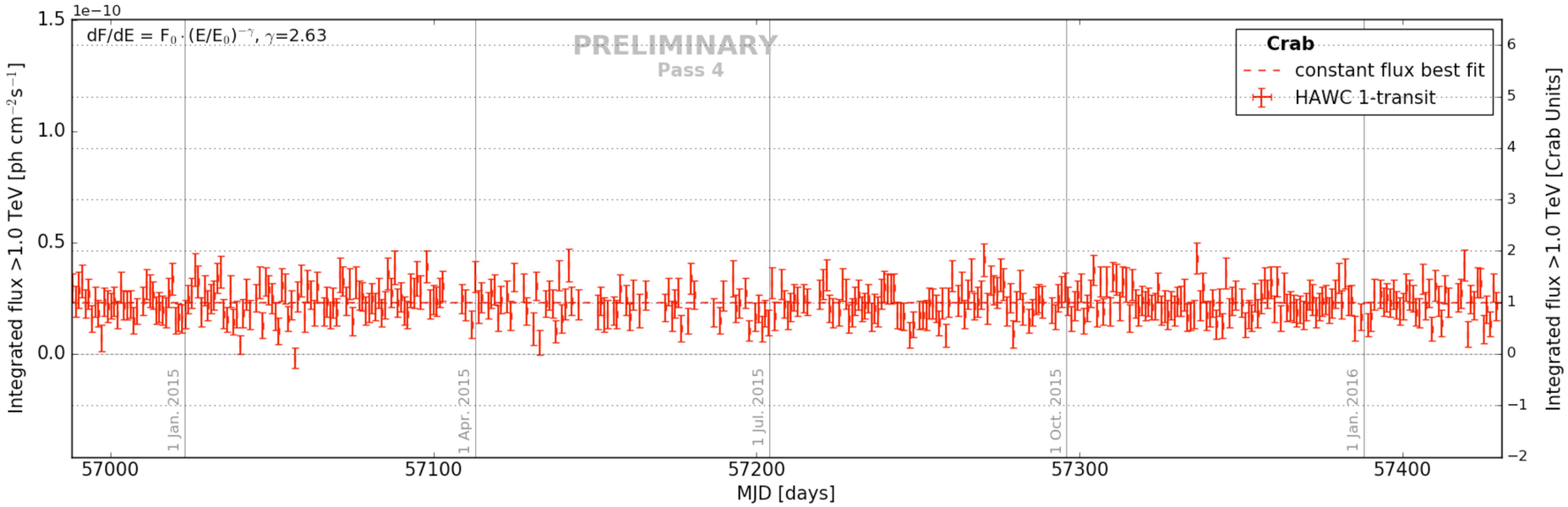


Transient Search - The Crab Nebula

- 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

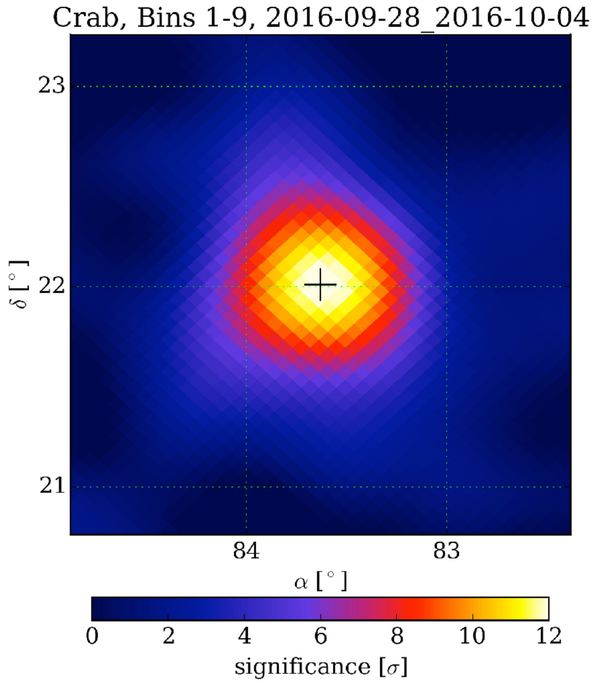


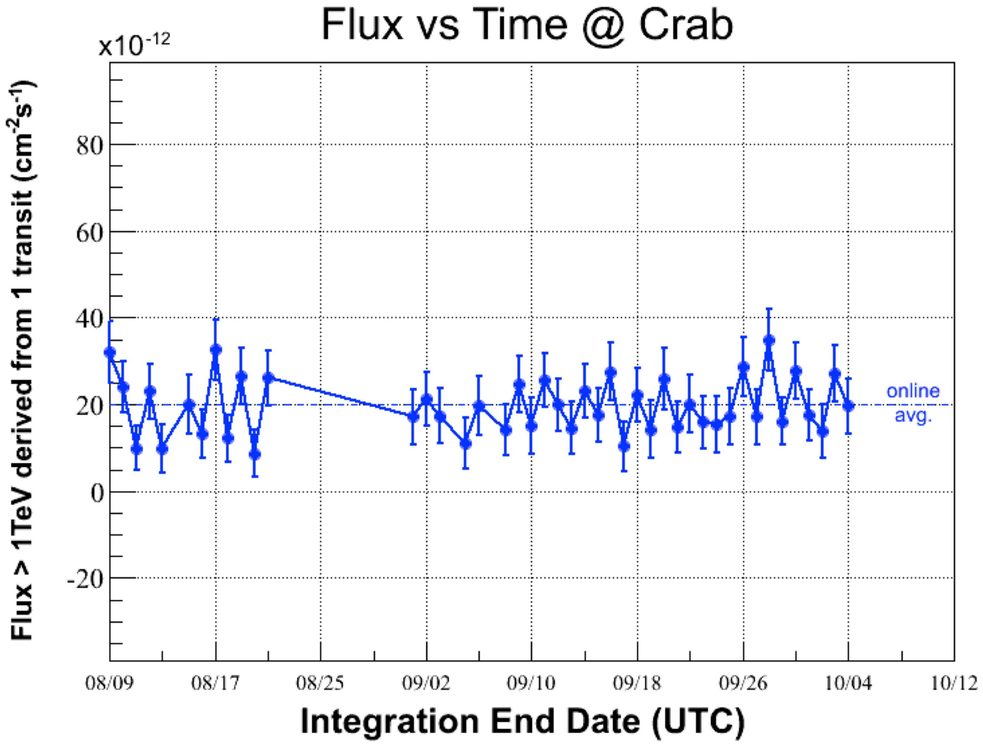


Transient Search - The Crab Nebula

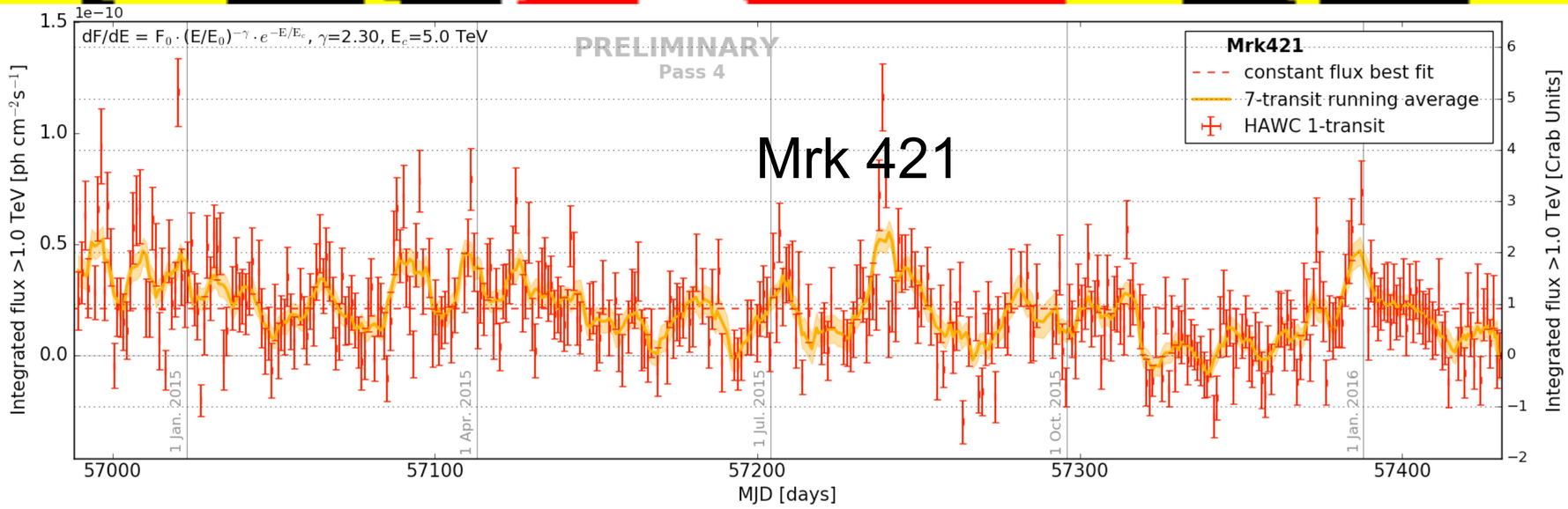
On October 3rd, 2016, AGILE (GeV) reported enhanced emission from the Crab Nebula (ATEL #9586). The Fermi-LAT *GeV) confirmed the detection in ATEL #9588, with flux up to 1.8 times larger than typical.

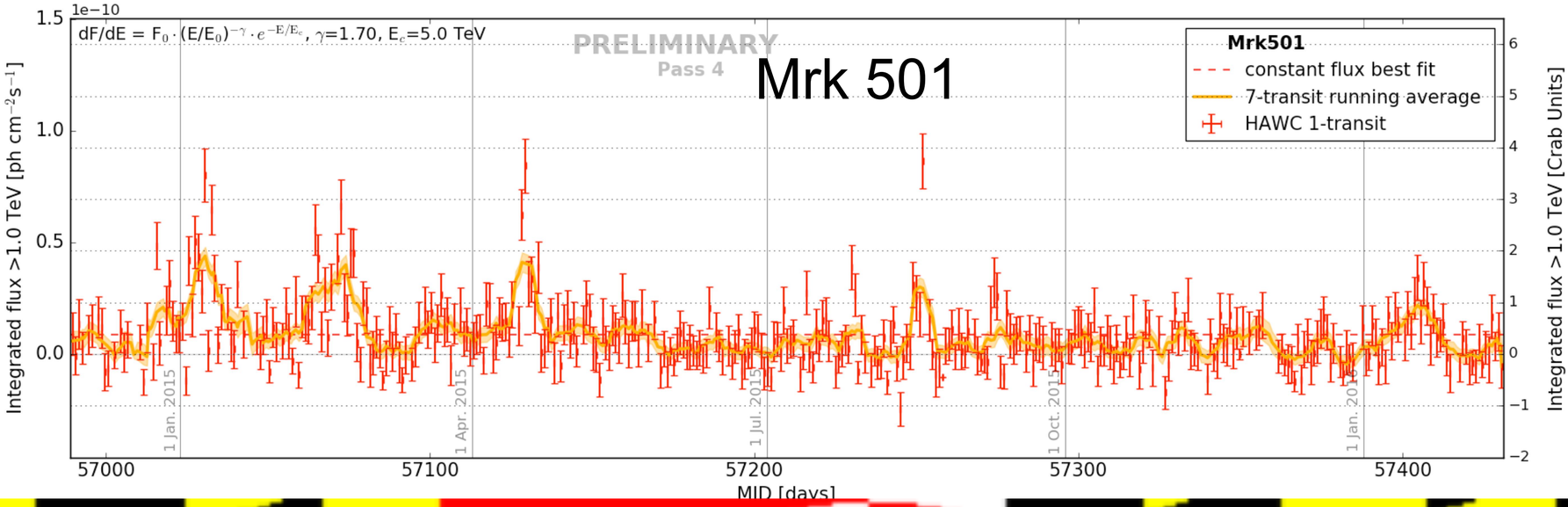
HAWC online monitoring shows the Crab to be fully consistent with its usual expectation over the same time period in the TeV.





Transient Search - Mrk 421 / Mrk 501



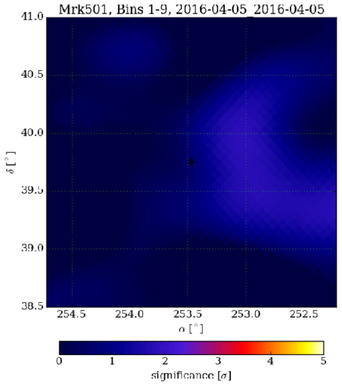


Transient Search - Mrk 501

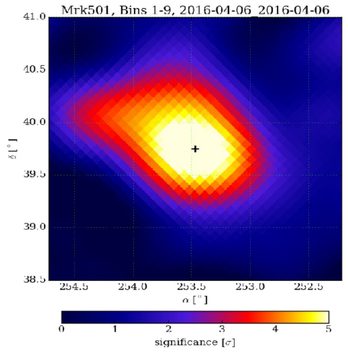
HAWC detection of increased TeV flux state for Markarian 501

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

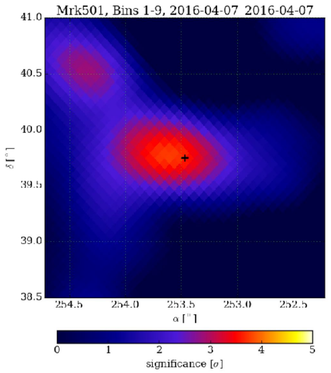
Astronomer's Telegram to immediately alert community of activity.



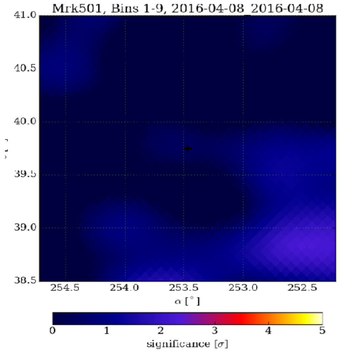
April 5, 2016



April 6, 2016



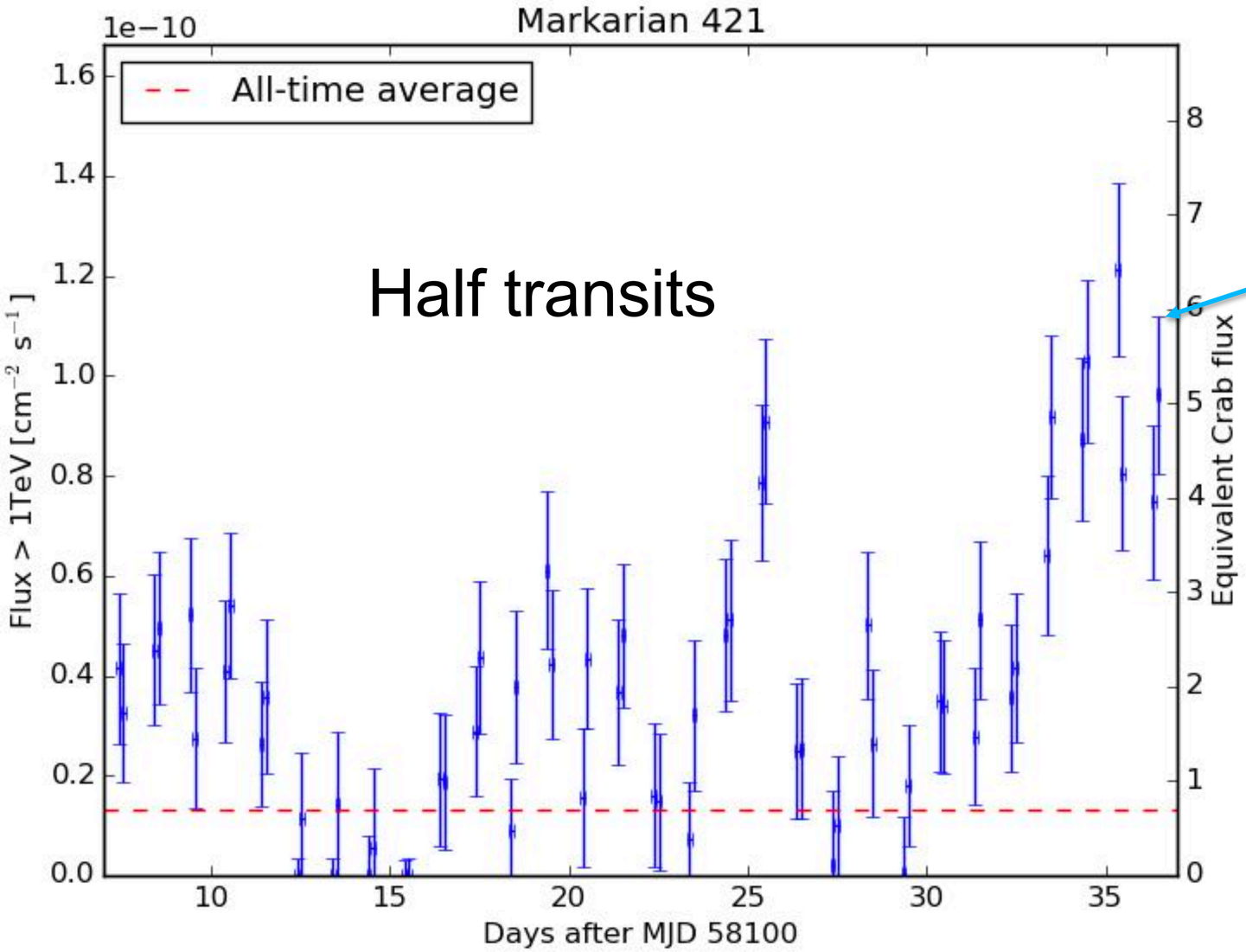
April 7, 2016



April 8, 2016

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

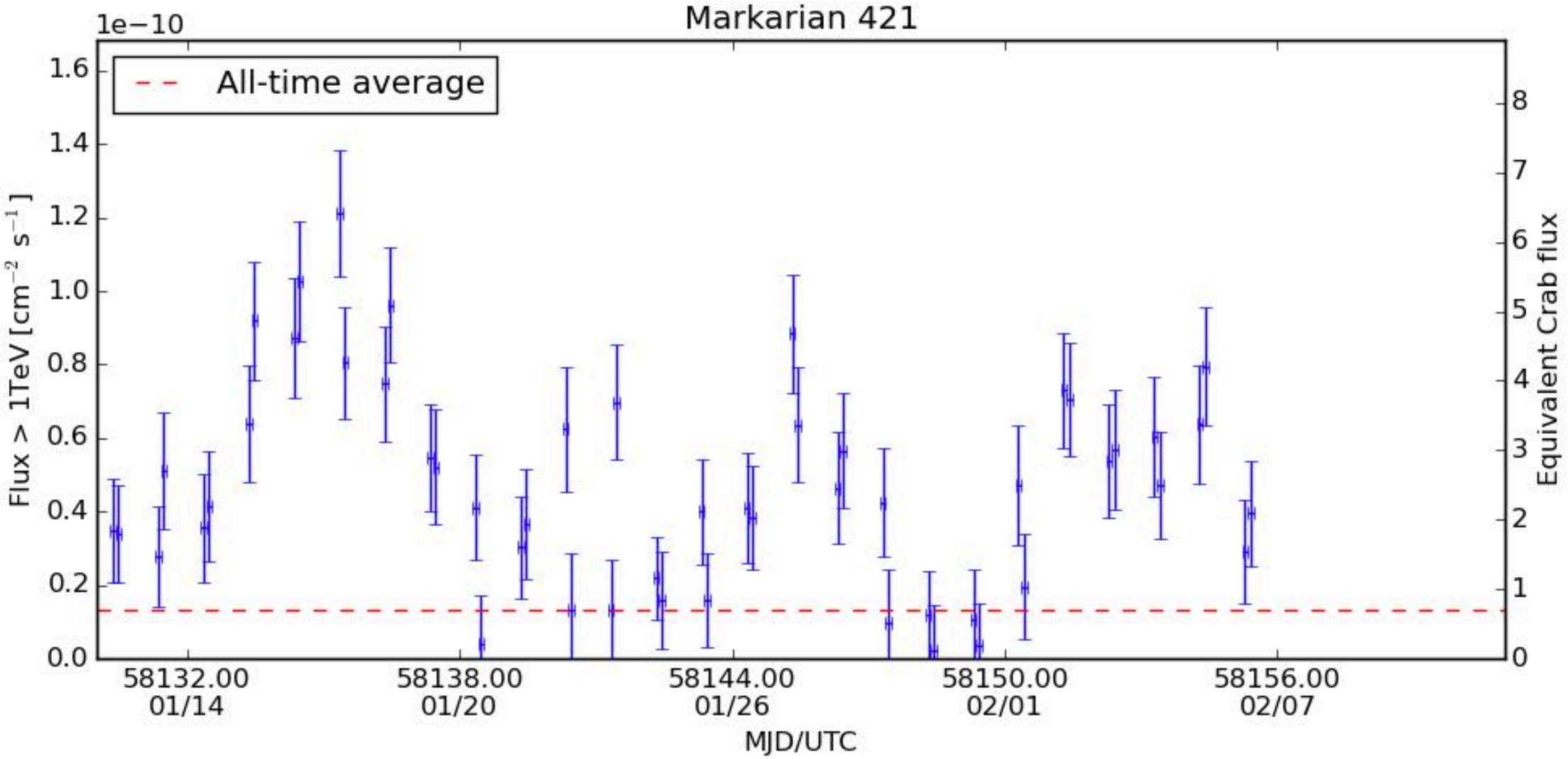
Mrk421 Starting 12-13-2017



Half transits

Atel sent

Mrk421 Starting Jan 2018

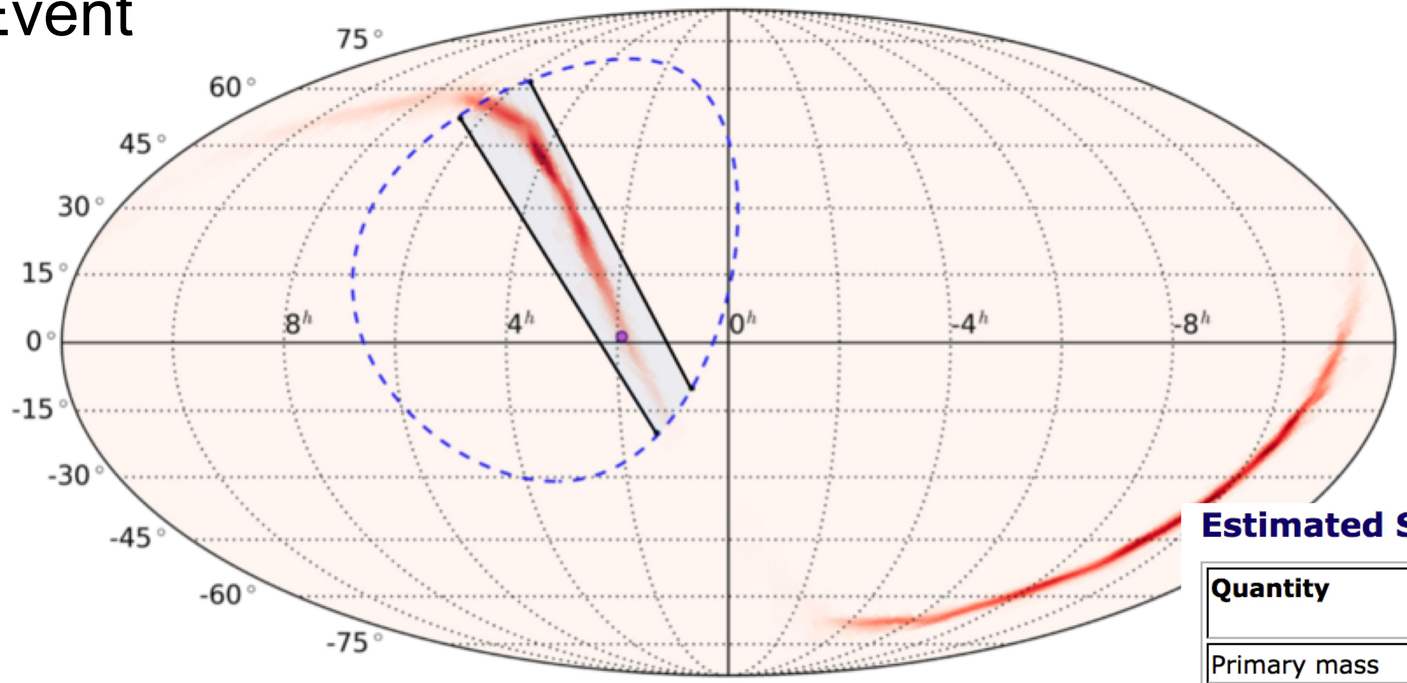


LIGO Events

- Responding to LIGO events
  - First event was below our horizon
  - Unlikely to se BH-BH mergers in gamma rays
- Before VIRGO developed algorithm to look in a region
  - Analysis searches for excess counts over the steady-state cosmic-ray background using 4 sliding time windows (0.1, 1, 10, and 100 seconds) shifted forward in time by 10% their width over the course of the entire day.

LIGO Follow-up

Boxing Day Event



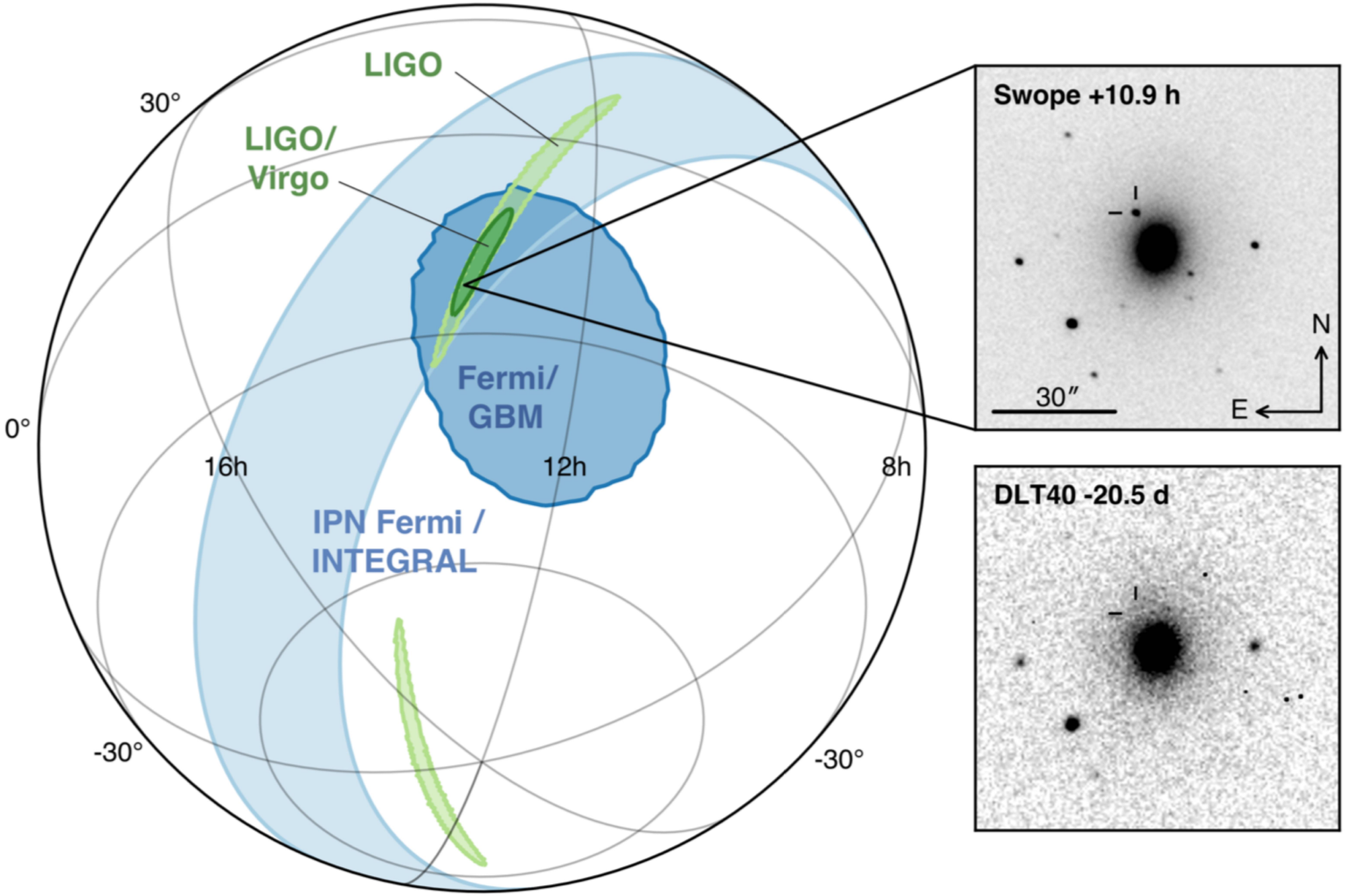
Candidate 1:
RA: 28.628 (+01h 54m 30.63s) J2000
Dec: +1.200 (+01d 11' 59.1") J2000
Error: +1.15 (square region, half side)
Duration: 10 seconds
Pre-trials p-value: 2.55e-07
Post-trials p-value: 0.08

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	

The LIGO event of August 17, 2017

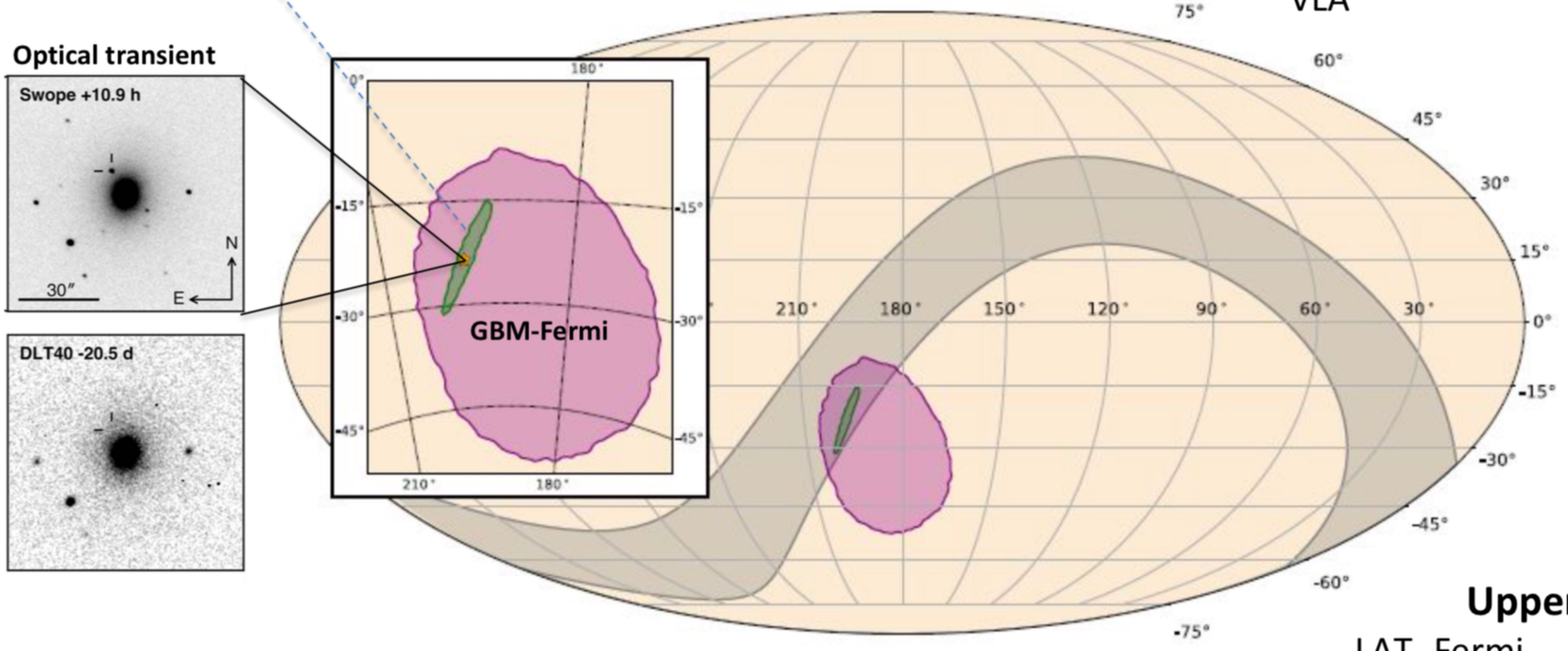
Merging Neutron Stars


LIGO
LIGO/
Virgo
Fermi/
GBM
IPN Fermi /
INTEGRAL
30°
0°
-30°
16h
12h
8h
-30°
Swope +10.9 h
30″
N
E
DLT40 -20.5 d

GRB170817A observations

Detections

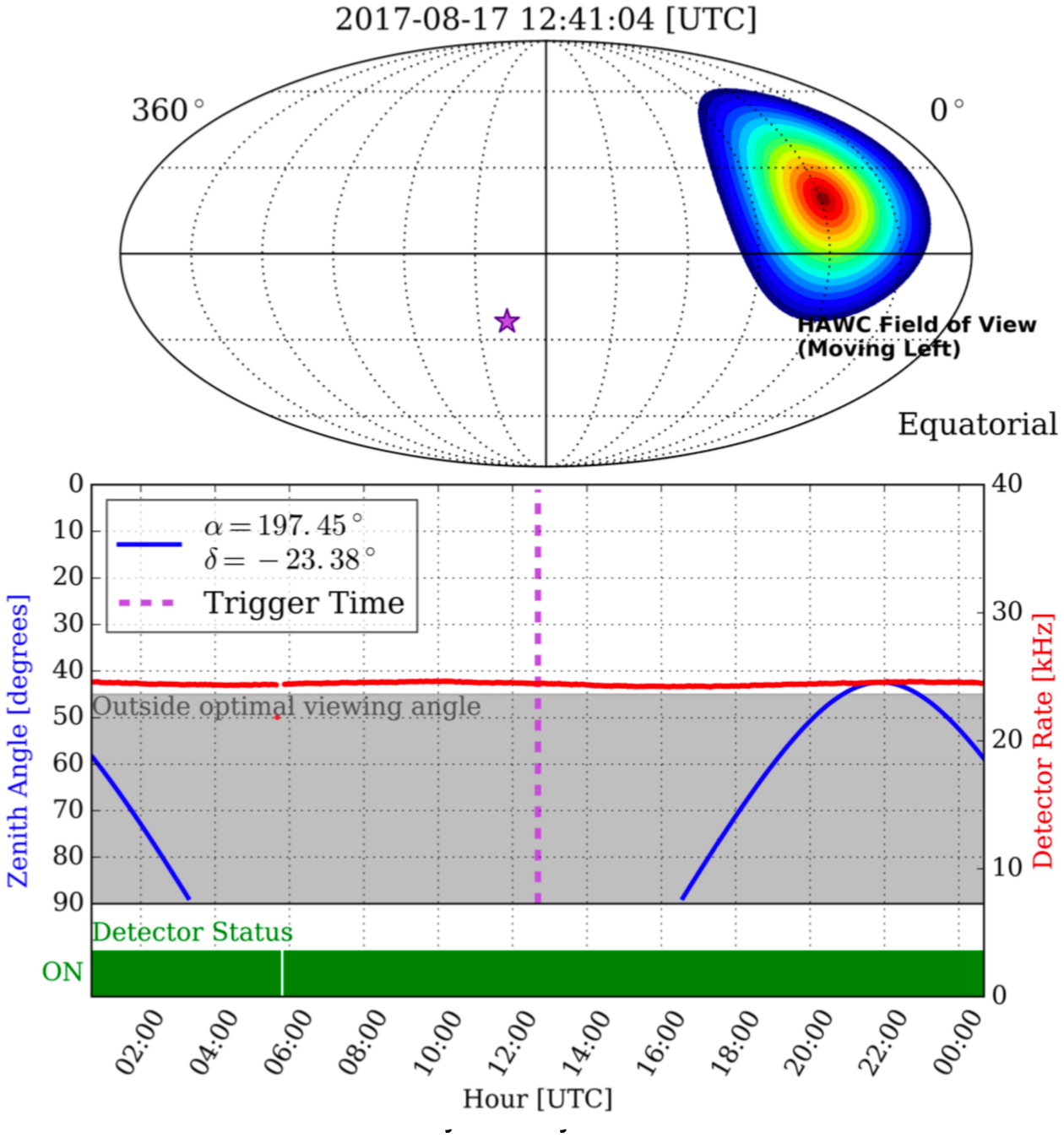
Ligo/Virgo
Fermi-GBM
Chandra
Many Optical/IR telesc.
VLA



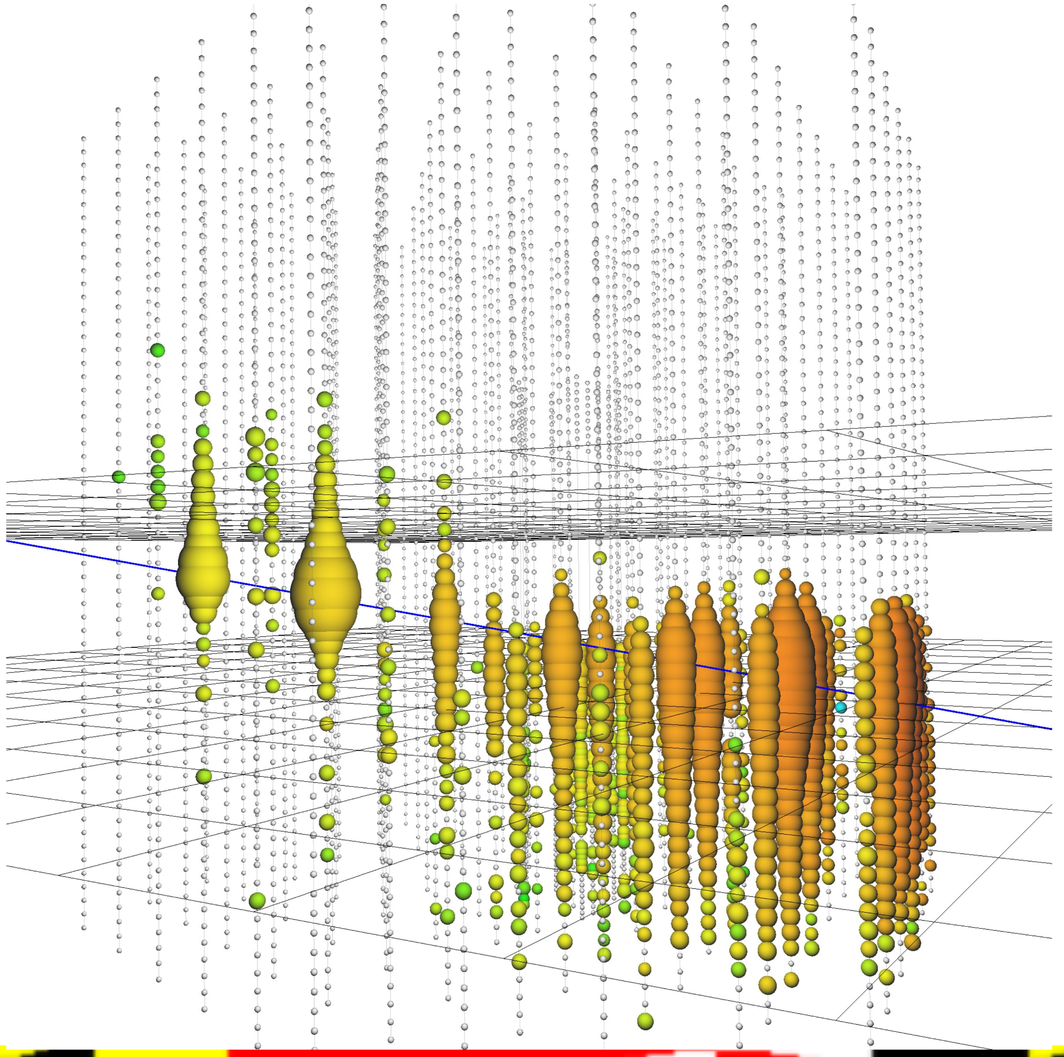
Upper Limits

LAT- Fermi
HAWC
+ 30 experiments

Abbott et al 2017a
Abbott et al 2017b


2017-08-17 12:41:04 [UTC]
360°
0°
HAWC Field of View
(Moving Left)
Equatorial
$\alpha = 197.45°$
$\delta = -23.38°$
Trigger Time
Outside optimal viewing angle
Zenith Angle [degrees]
Detector Rate [kHz]
Detector Status
ON
Hour [UTC]
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
00:00

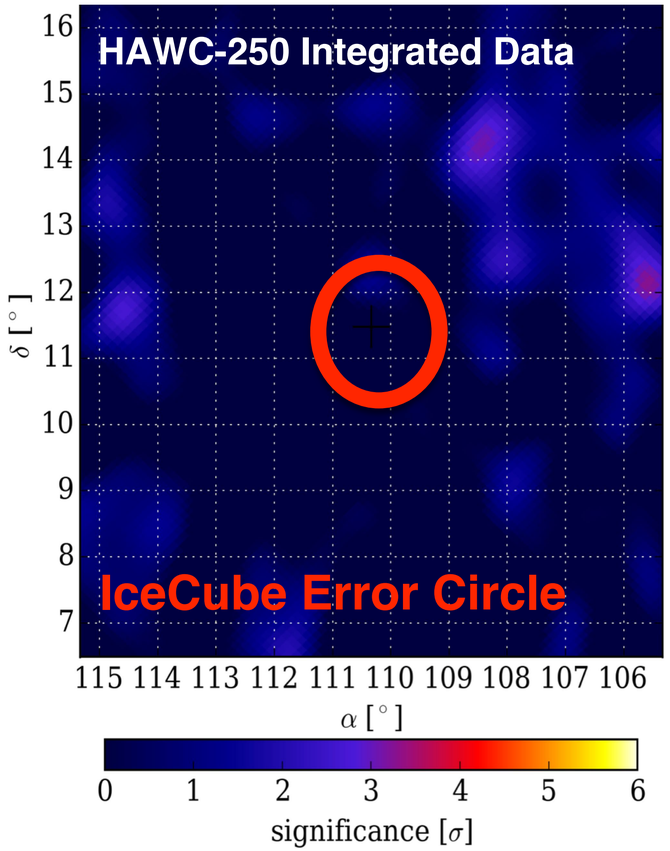
IceCube Follow-up



2.6 ± 0.3 PeV

IceCube >2.6 PeV Muon Neutrino

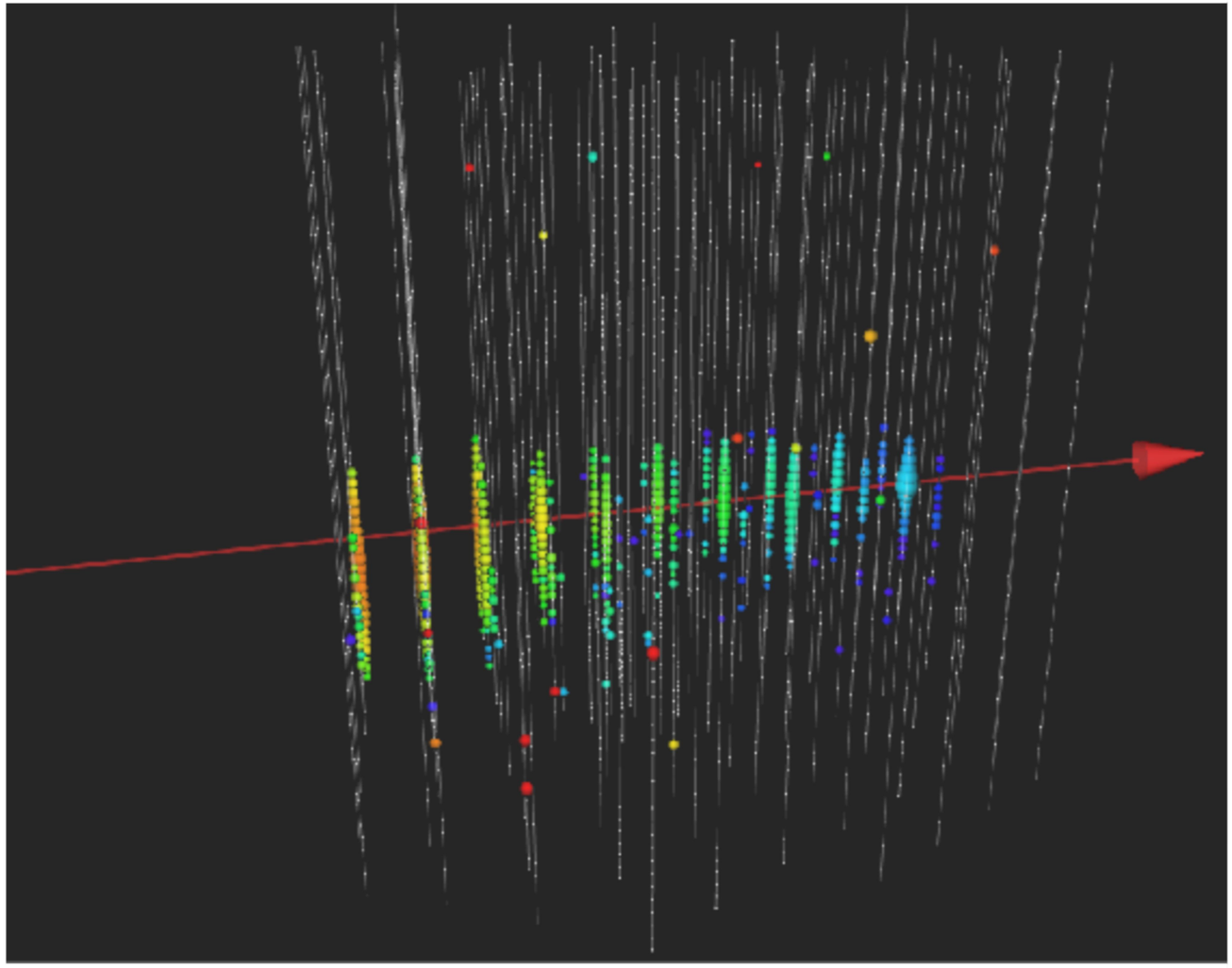
- HAWC-111 live. Several hours out of HAWC's FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015 dataset)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
- All searches consistent with cosmic-ray background.



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

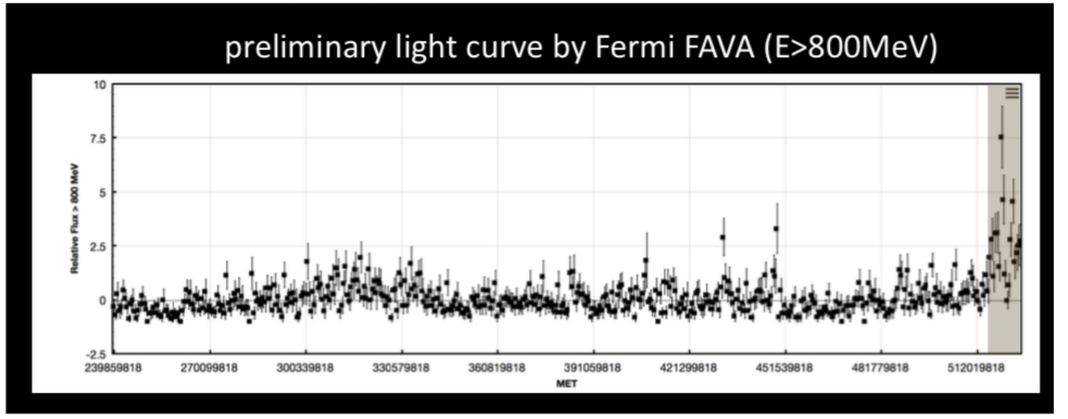
IceCube-170922A

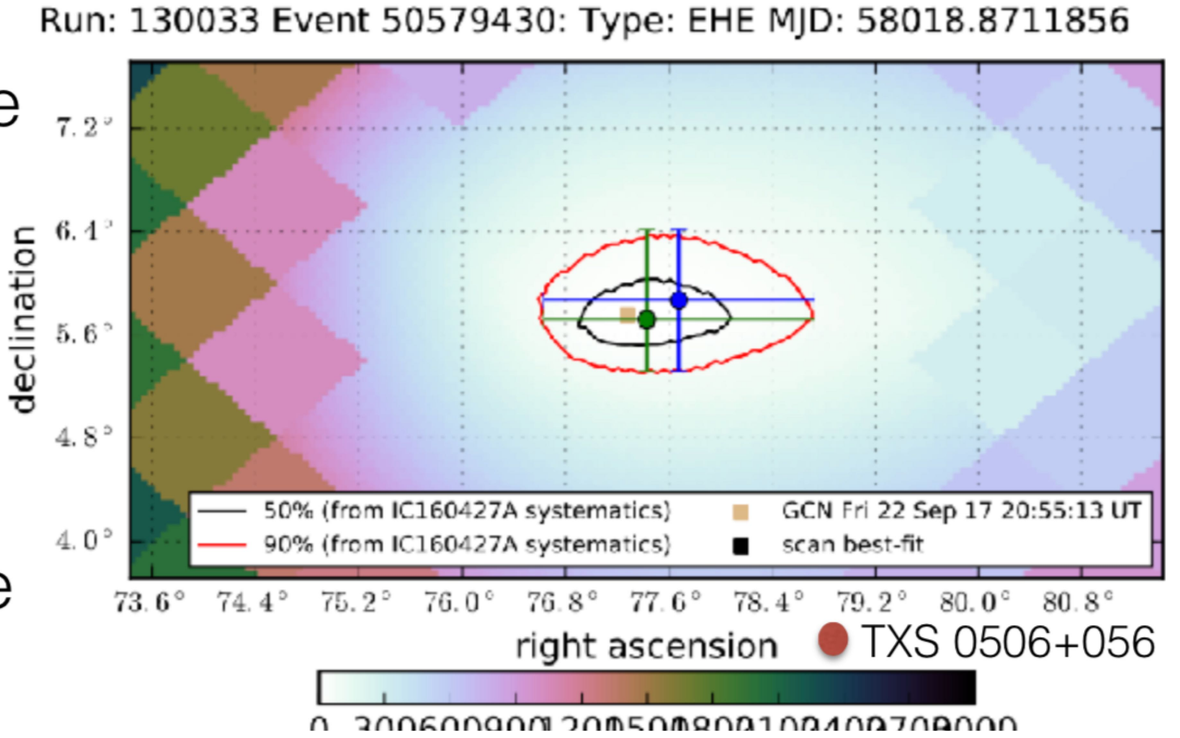
- Very recent EHE track alert
  - 17/09/22 at 20:54:30.43 UTC
  - RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF cont.) J2000
  - Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF cont.) J2000
- Wide community followup with some interesting results being seen



IceCube-170922A

- Fermi 3FGL catalog item within ~0.1 degree
  - TXS 0506+056
  - x 6 increase over base flux level over ~2 wk
- X-ray Swift XRT
  - Brightening x-ray source, perhaps some evolution?



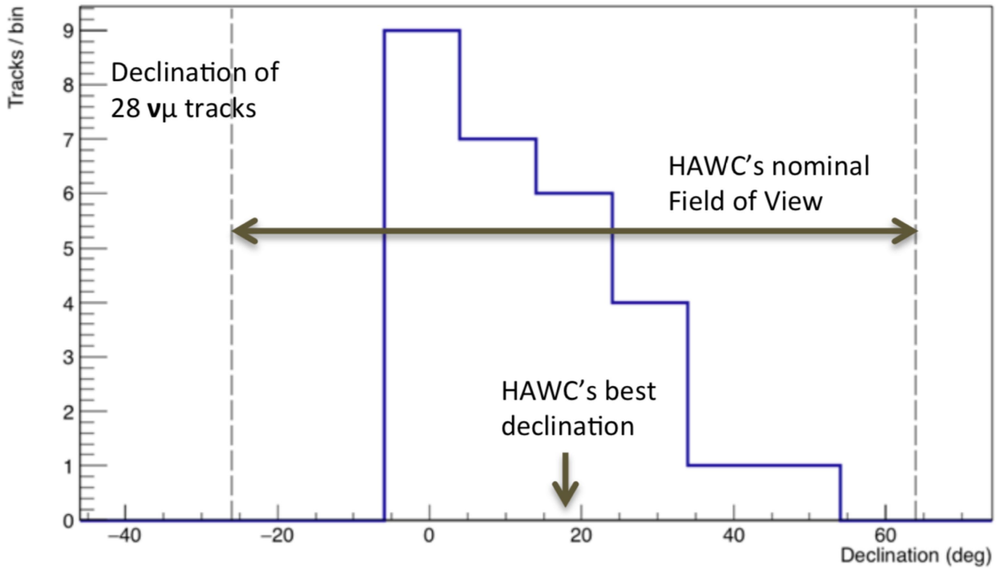


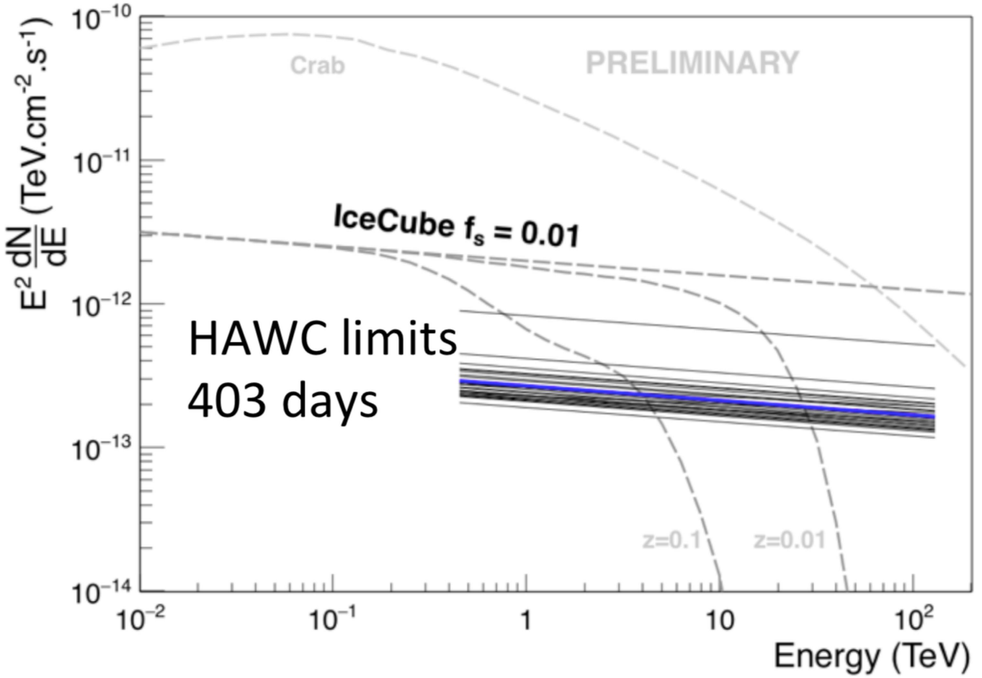
IceCube 170922A

- Other reported observations
  - AGILE - increased gamma-ray signal ~days before neutrino
  - Optical observation of brightening optical source (ASAS-SN, others)
  - MAGIC recently reported 5σ detection above 100 GeV
    - HAWC no observations, HESS no online detection
  - ANTARES saw no up-going neutrino tracks

TeV Counterparts to IceCube Neutrinos

- We have looked for γ sources in the direction from where the 28 highest energy ν_μ arrived.

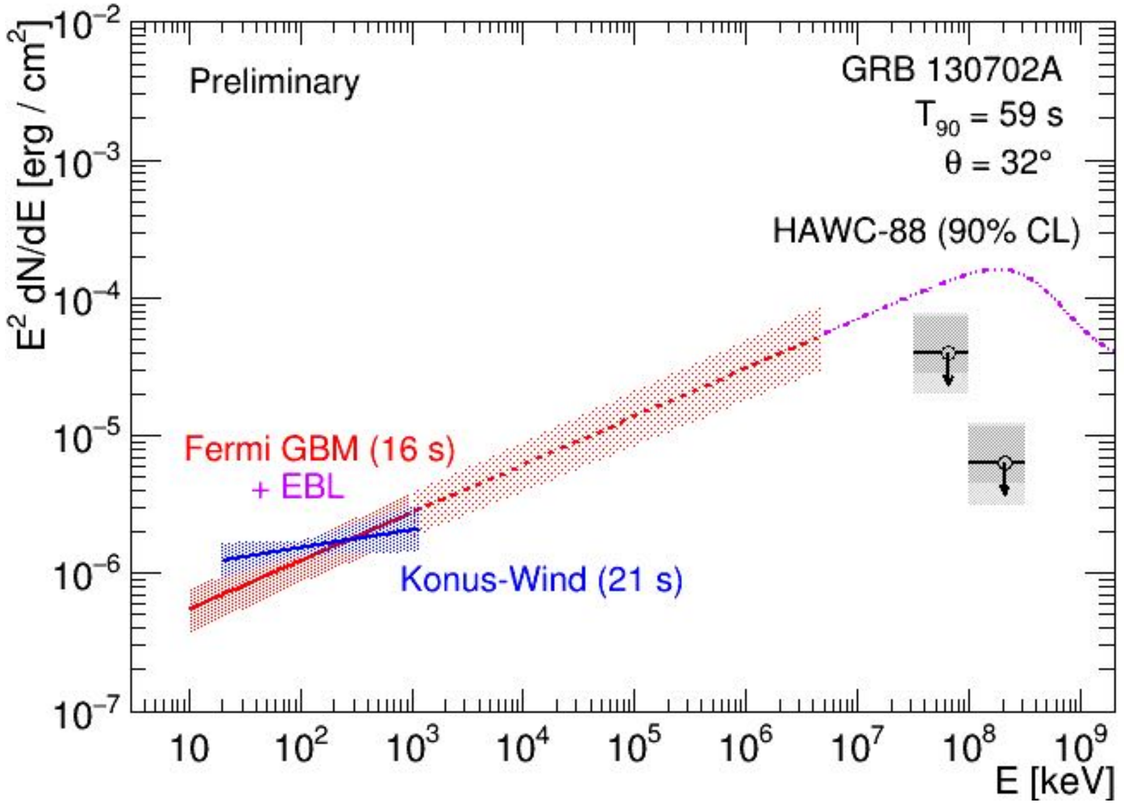


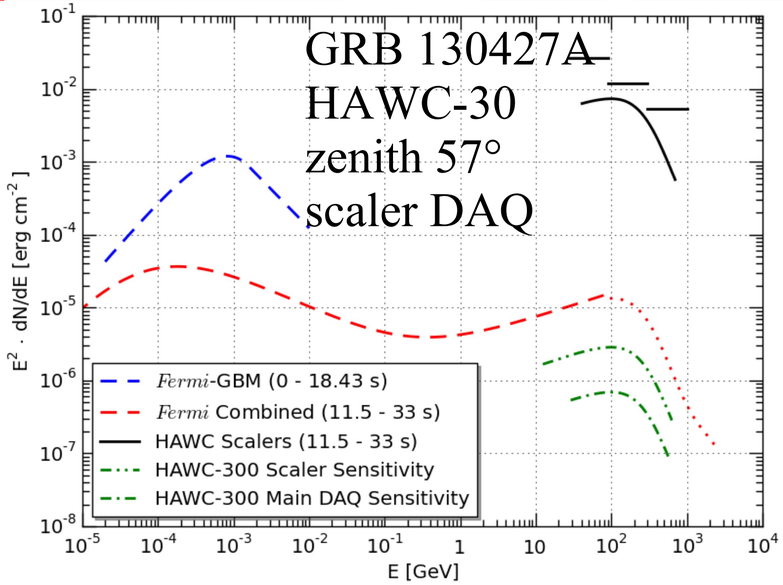


- No sources detected
  - sources opaque to γ ?
  - sources too far away ?
  - too many sources?

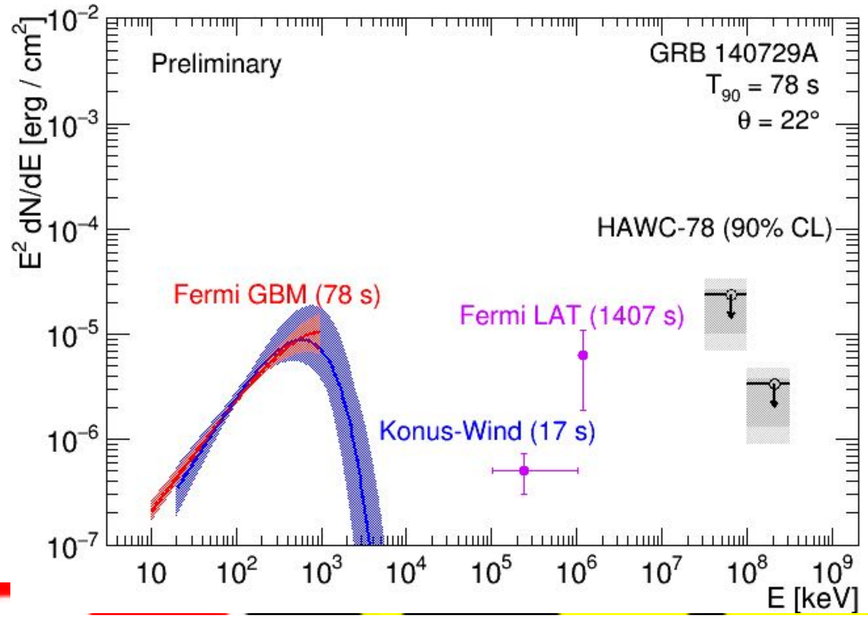
Also searching in real time
in case they are transient

Transients: Gamma Ray Bursts





[Astrophys. J. 800 (2015), 78]

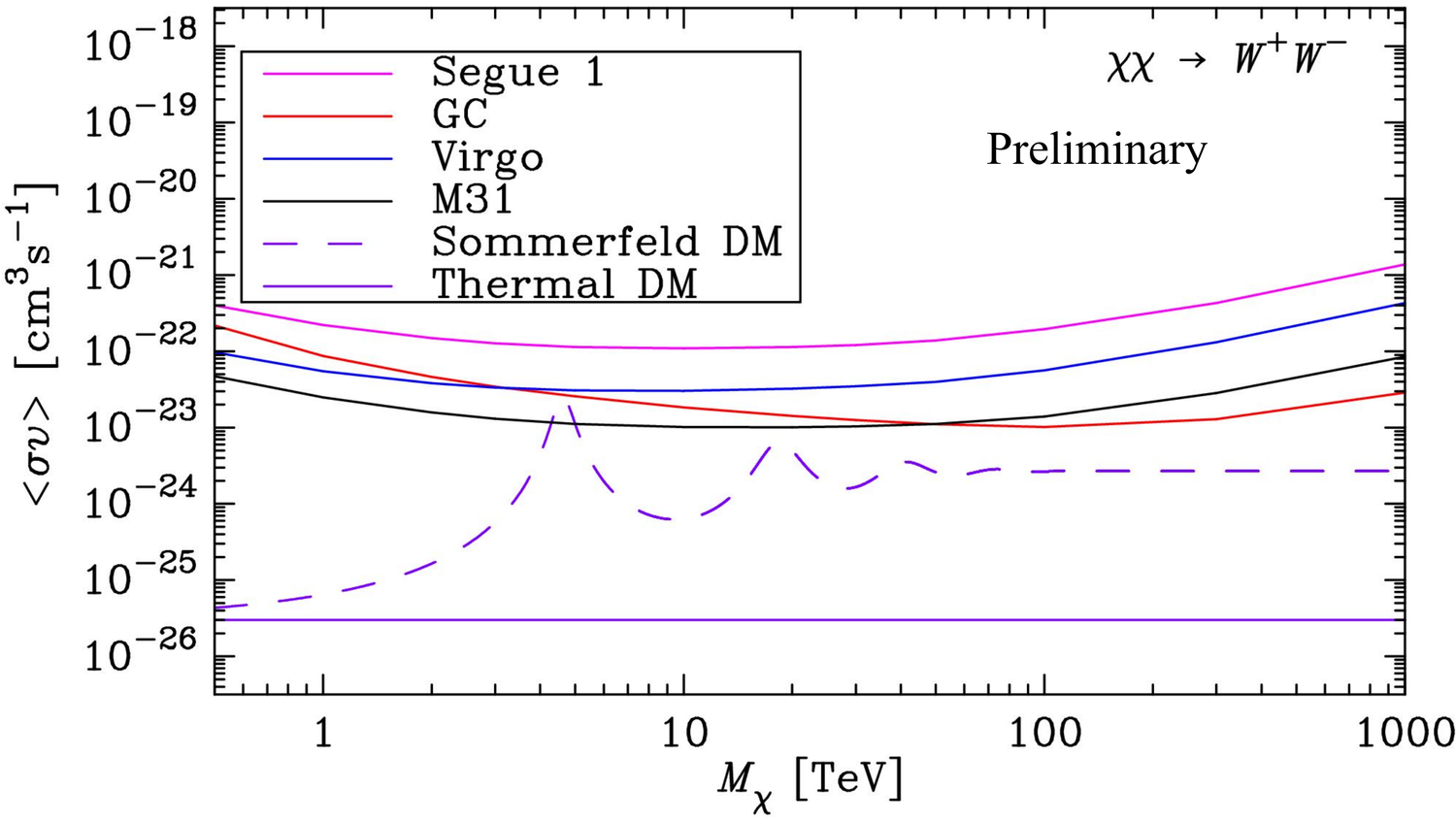


[K. Sparks Woodle]

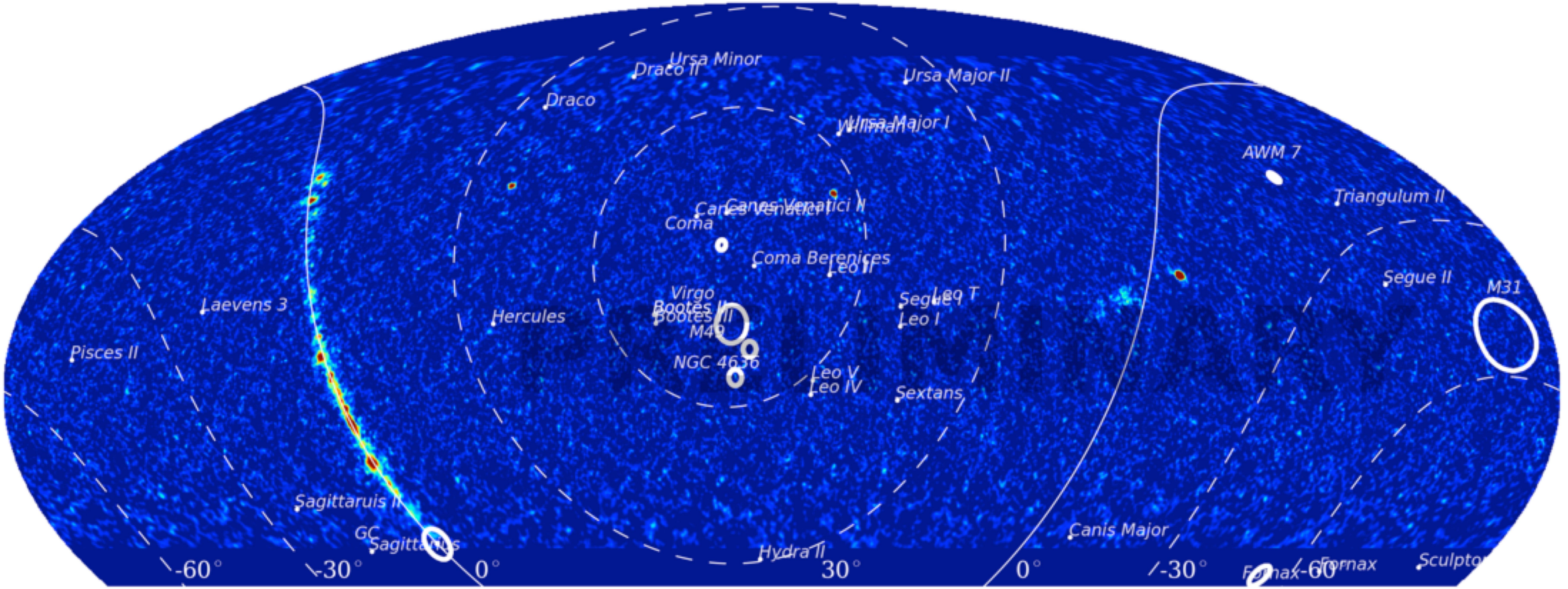
TITLE: GCN CIRCULAR NUMBER: 19423
SUBJECT: GRB 160509A: non-observation of VHE emission with HAWC
DATE: 16/05/11 17:27:37 GMT

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***

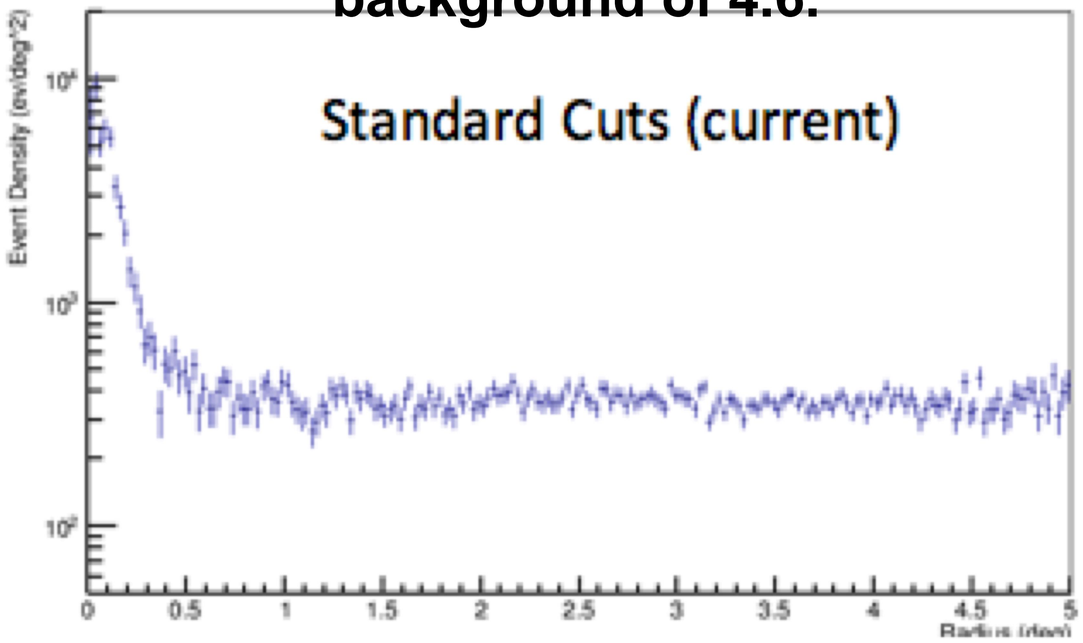


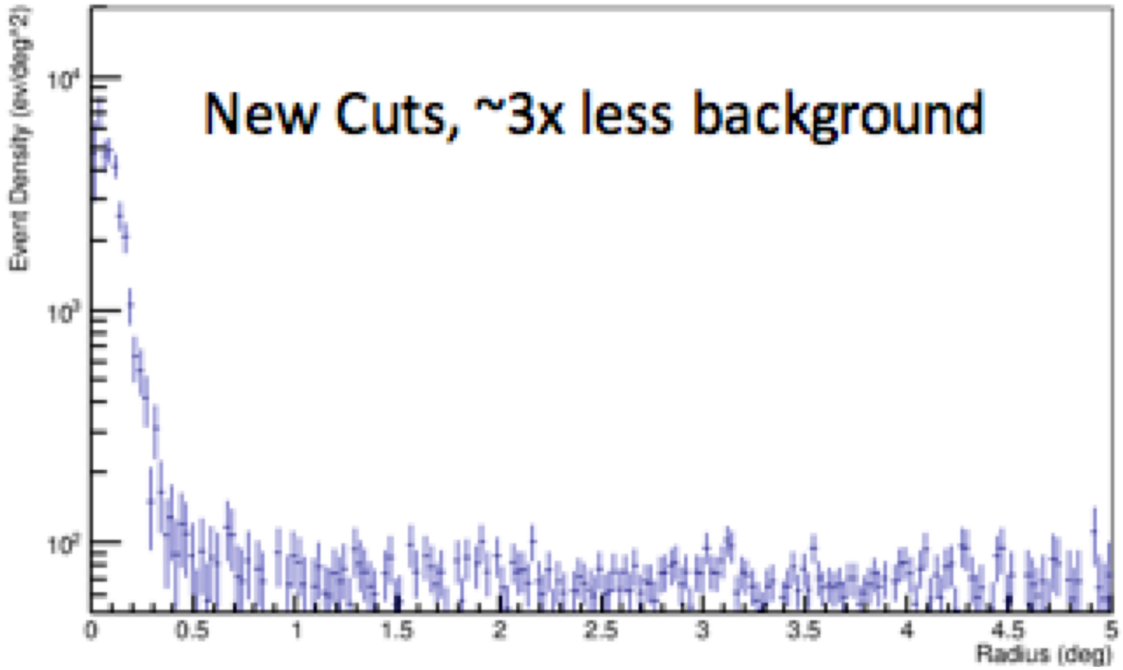
Lots of Potential Targets



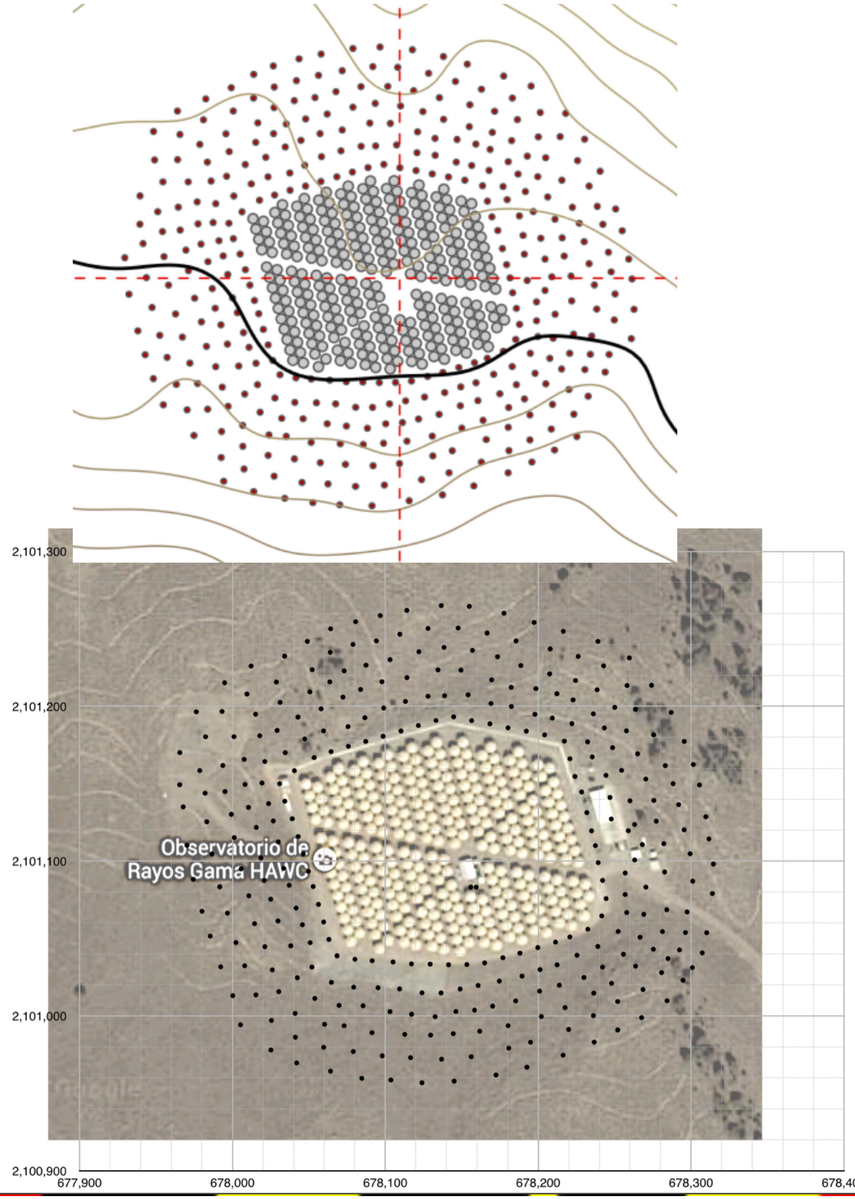
Improvements to HAWC

Using standard cuts on high energy events from the Crab, we observe an excess of 183.6 events with a background of 12.4. Using our improved algorithms we get an excess of 193.4 with a background of 4.6.



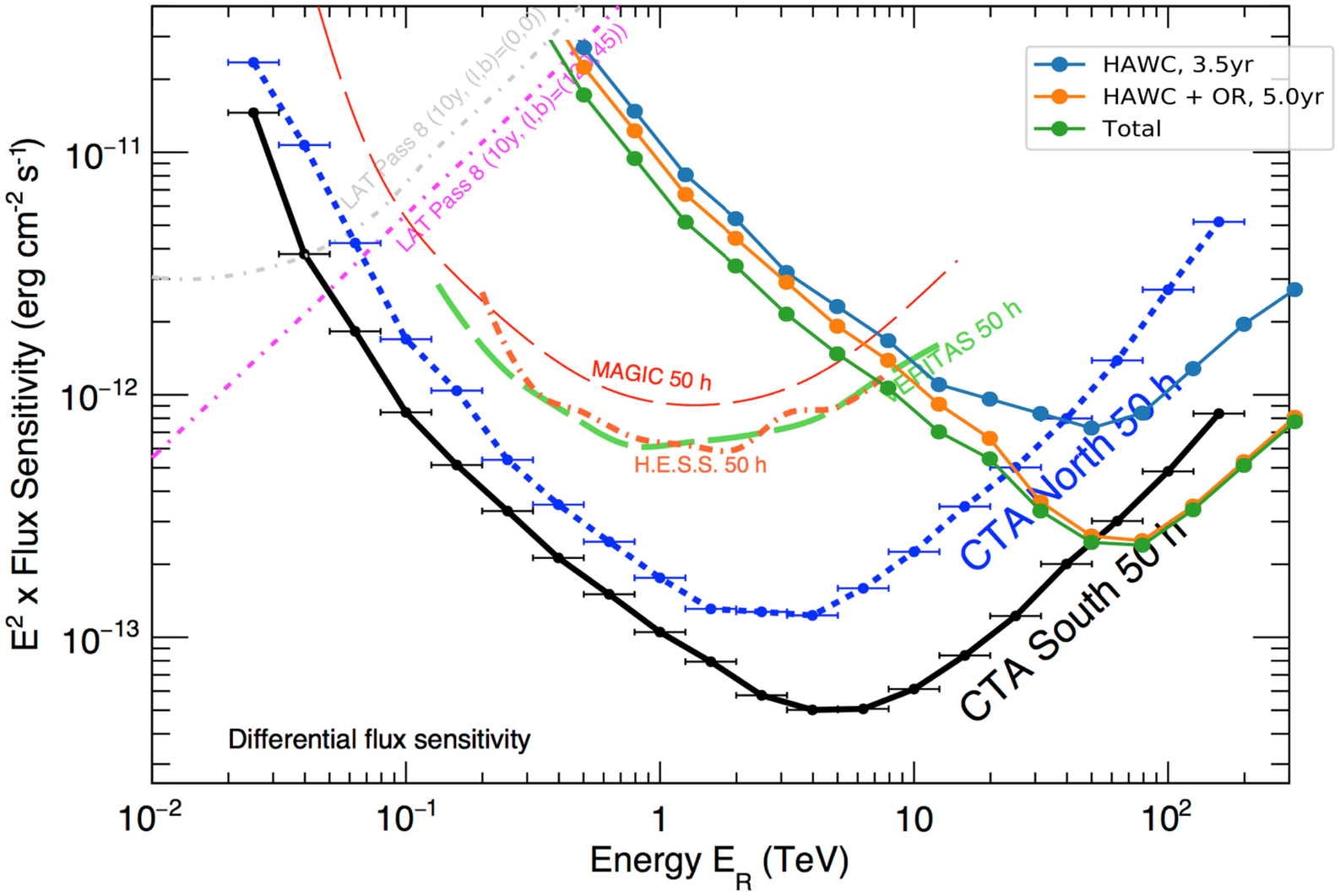


Outriggers

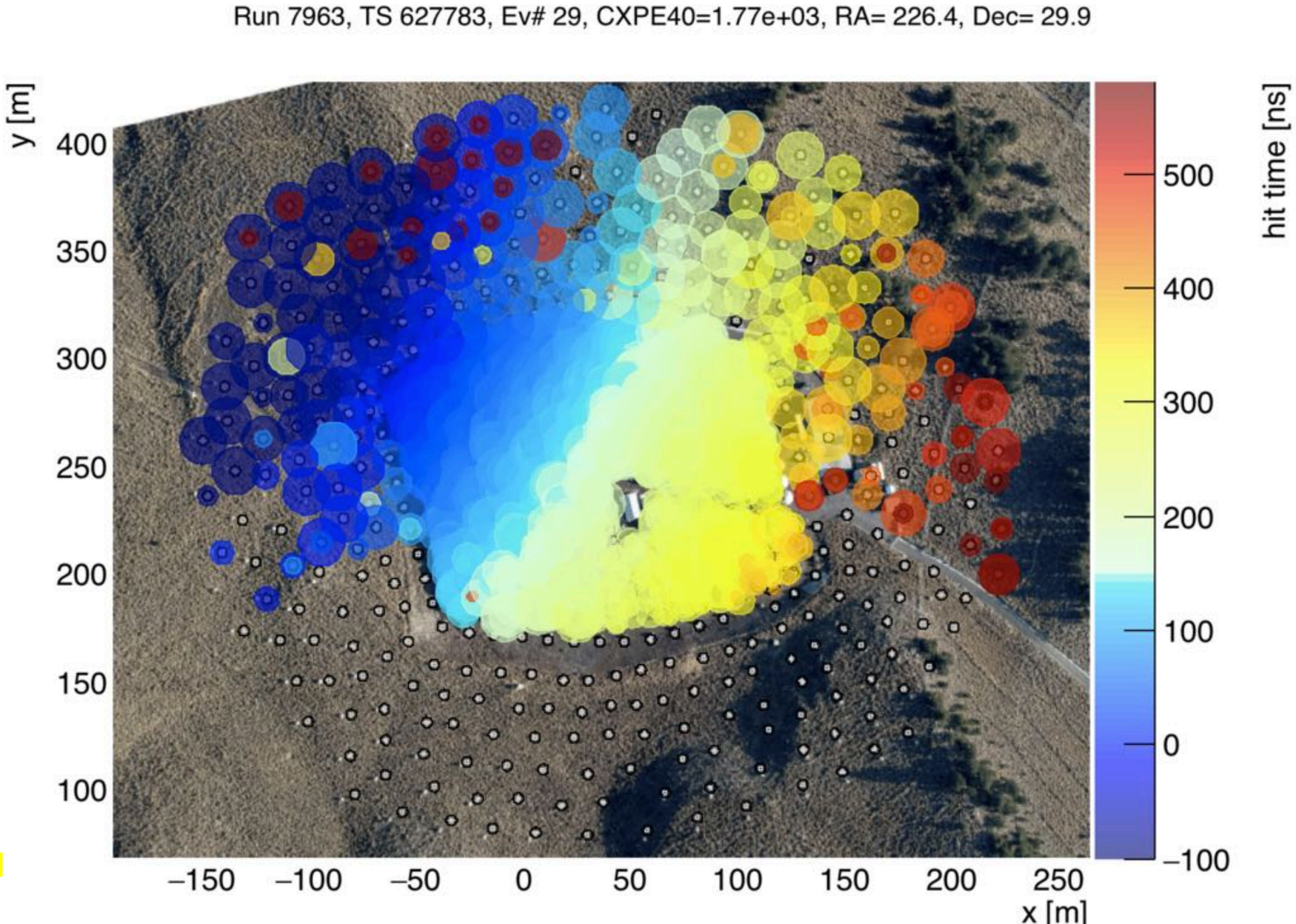


- HAWC Sparse Outrigger Array being deployed now:
  Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
  - Increase effective area above 10 TeV by ~4x
- Funded by LANL/MPIK (Heidelberg)/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.

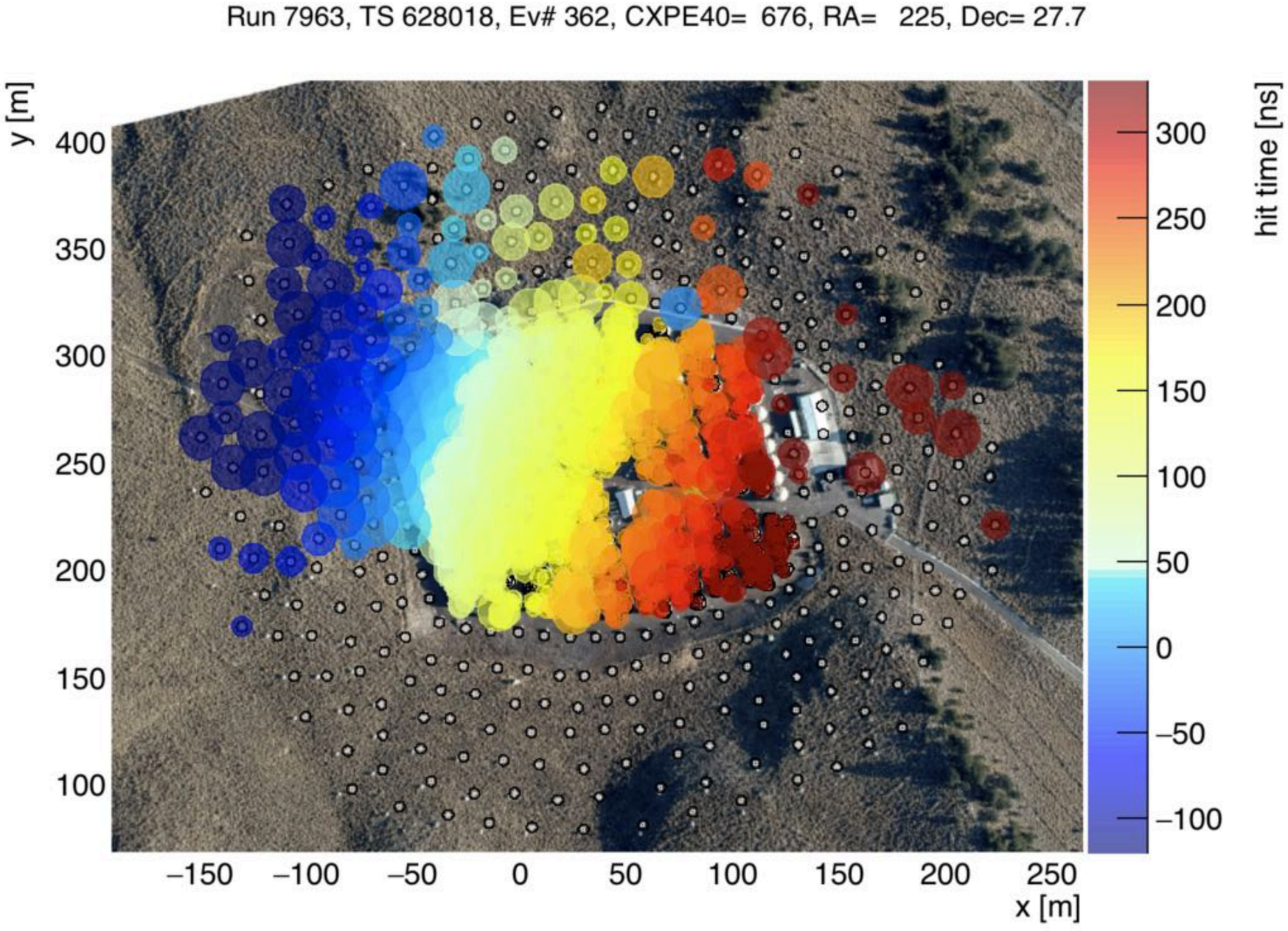
HAWC with Outriggers

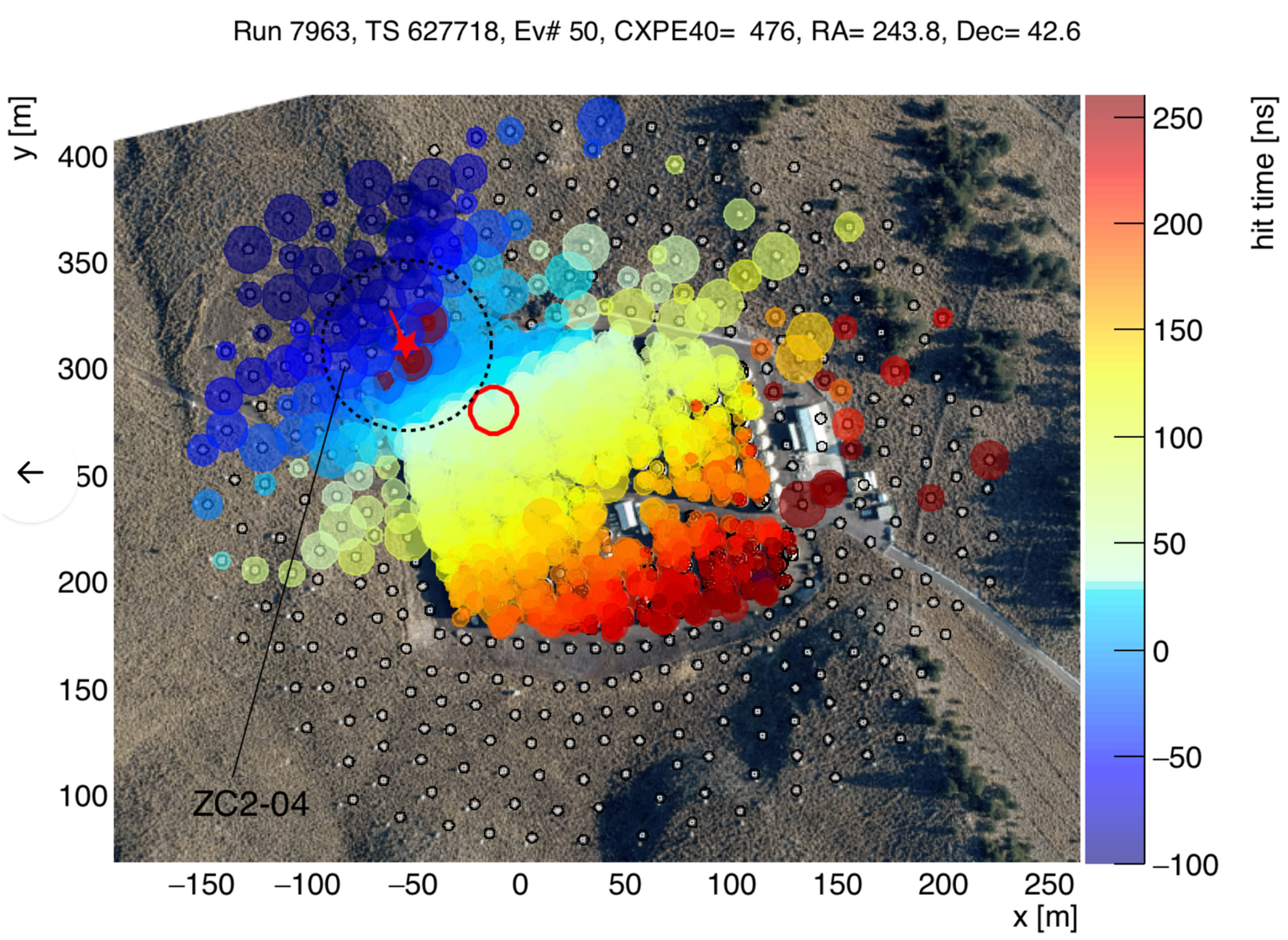


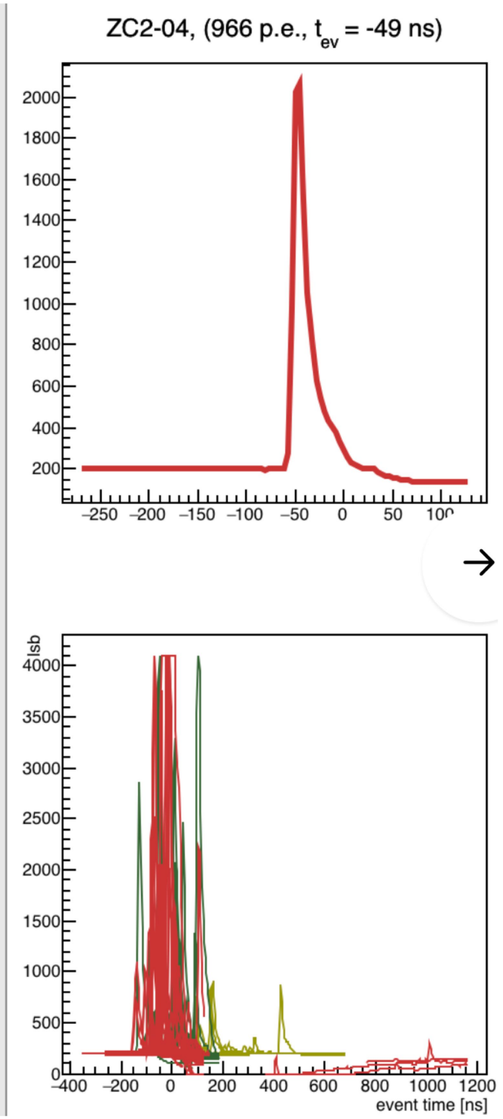
Very first (preliminary) look at Outrigger data

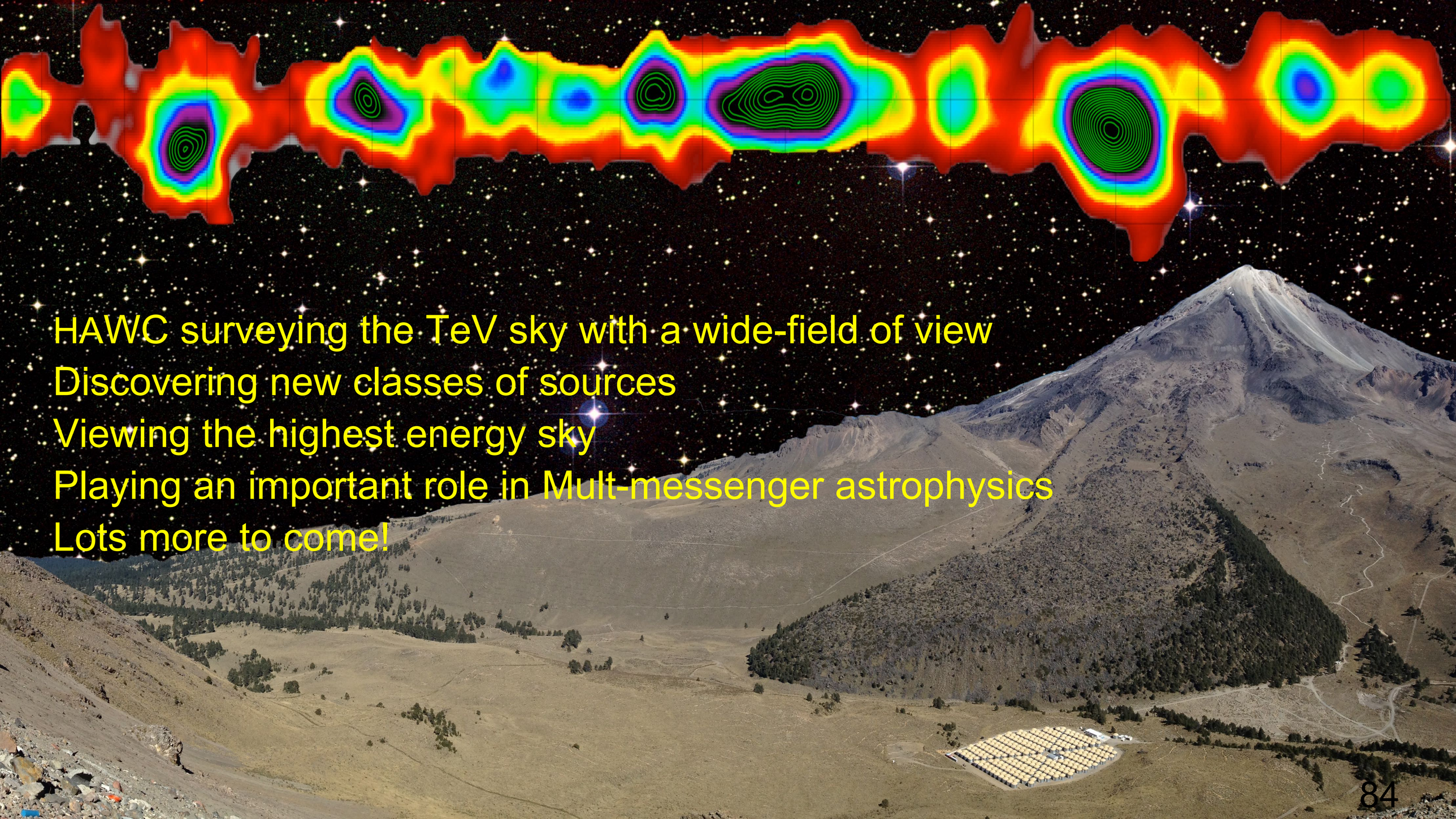


Very first (preliminary) look at Outrigger data




Run 7963, TS 627718, Ev# 50, CXPE40= 476, RA= 243.8, Dec= 42.6
y [m]
400
350
300
250
200
150
100
ZC2-04
−150 −100 −50 0 50 100 150 200 250
x [m]
hit time [ns]
250
200
150
100
50
0
−50
−100


ZC2-04, (966 p.e., t_{ev} = -49 ns)
2000
1800
1600
1400
1200
1000
800
600
400
200
−250 −200 −150 −100 −50 0 50
adc
4000
3500
3000
2500
2000
1500
1000
500
0
−400 −200 0 200 400 600 800 1000 1200
event time [ns]



HAWC surveying the TeV sky with a wide-field of view
Discovering new classes of sources
Viewing the highest energy sky
Playing an important role in Mult-messenger astrophysics
Lots more to come!