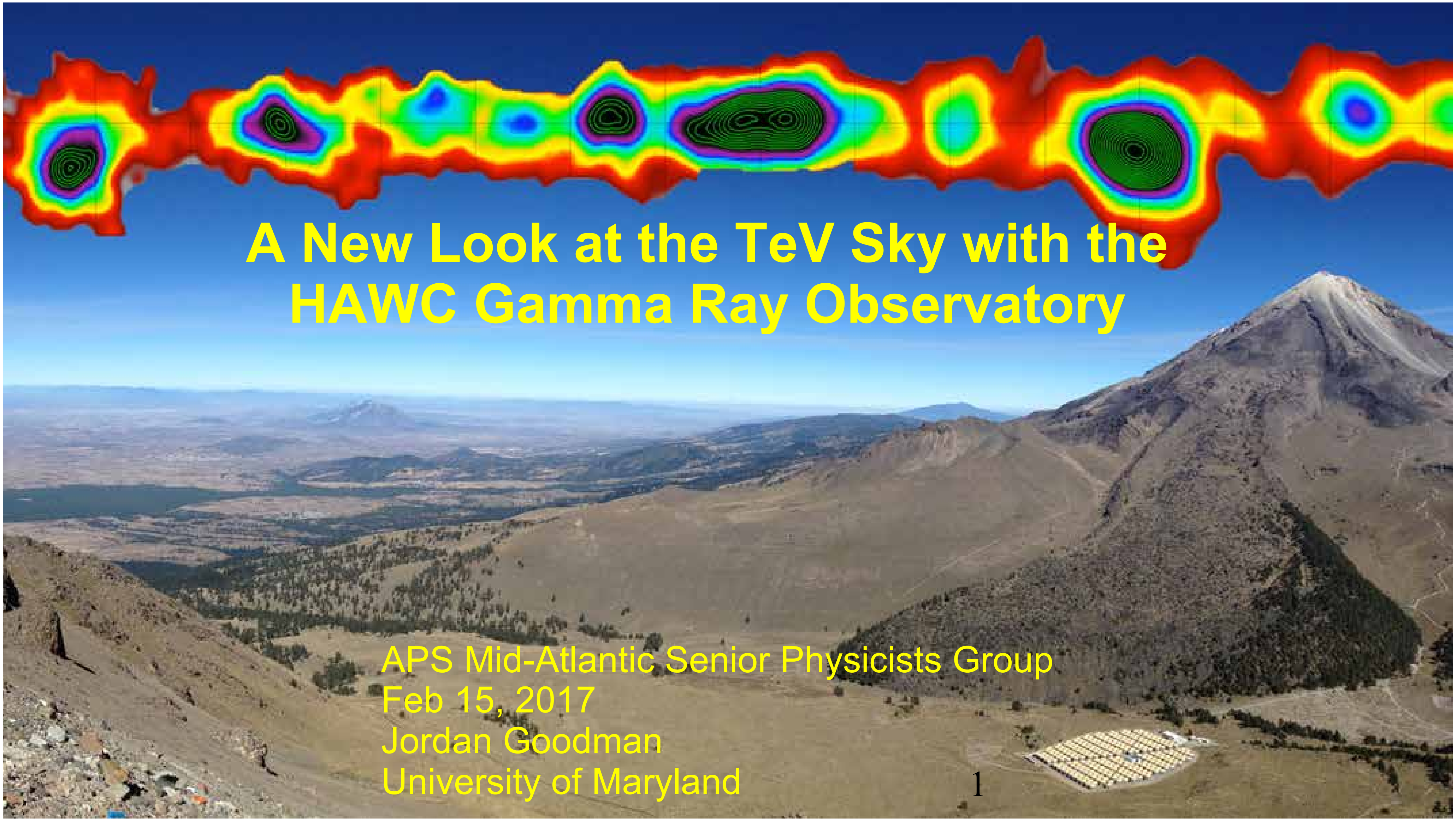
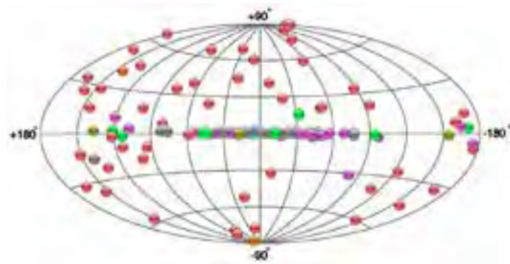


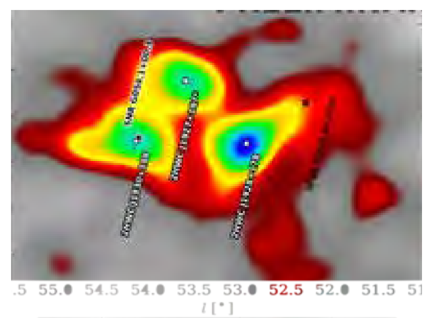
A New Look at the TeV Sky with the HAWC Gamma Ray Observatory

APS Mid-Atlantic Senior Physicists Group
Feb 15, 2017
Jordan Goodman
University of Maryland

Talk Overview

- TeV Radiation
  - Sources/ Techniques
  - IACTs/ Air Showers
- HAWC
  - Design
  - Construction
  - Performance
- The HAWC Catalog
- Other HAWC results
  - Transients - AGN, IceCube Event
  - Dark Matter Limits
  - Anisotropy





The HAWC Collaboration

USA

Mexico

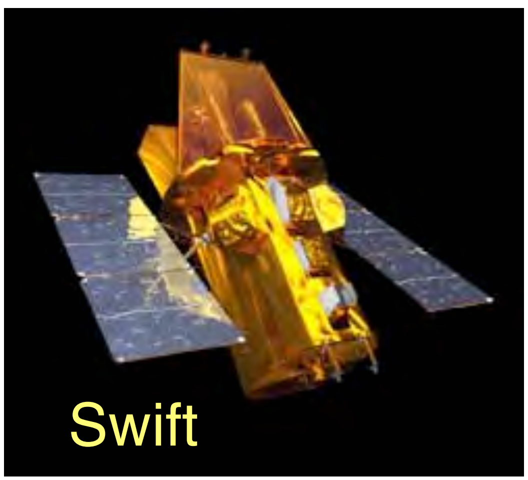
United States
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute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

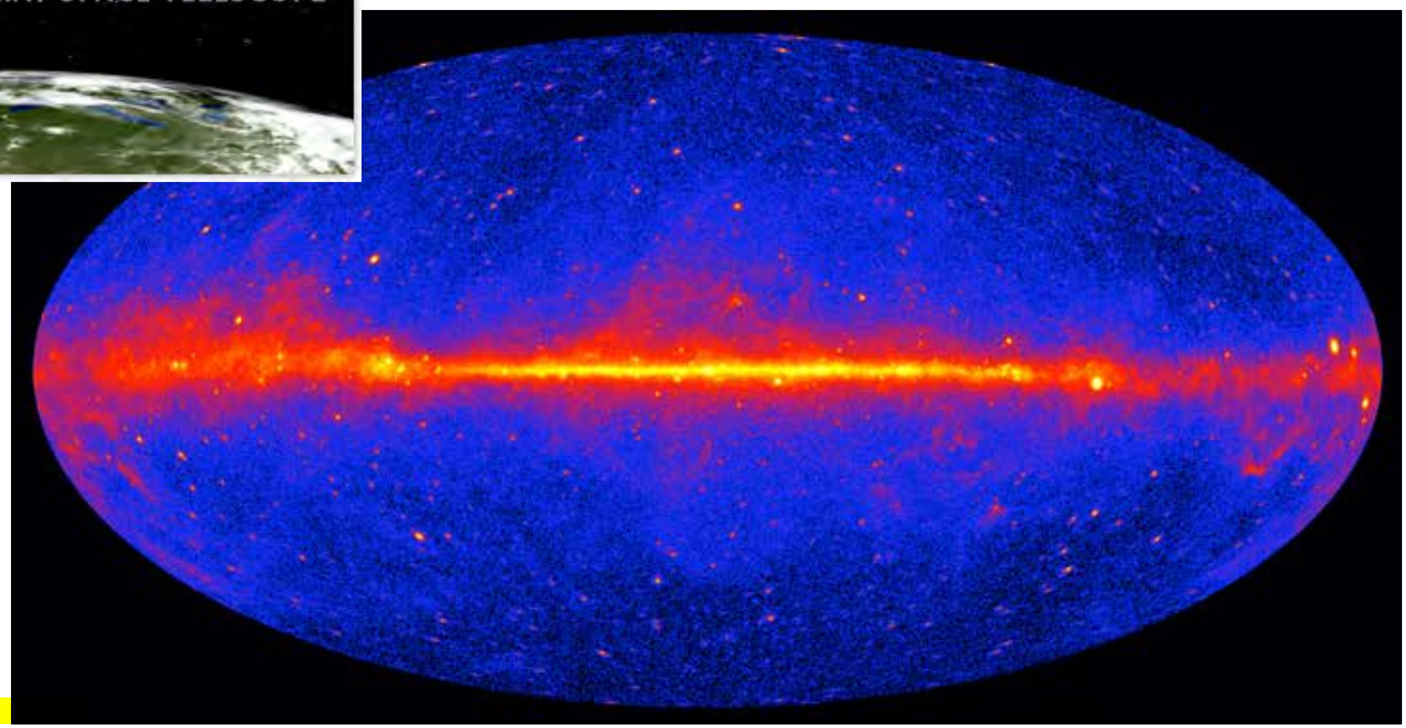
Mexico
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

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

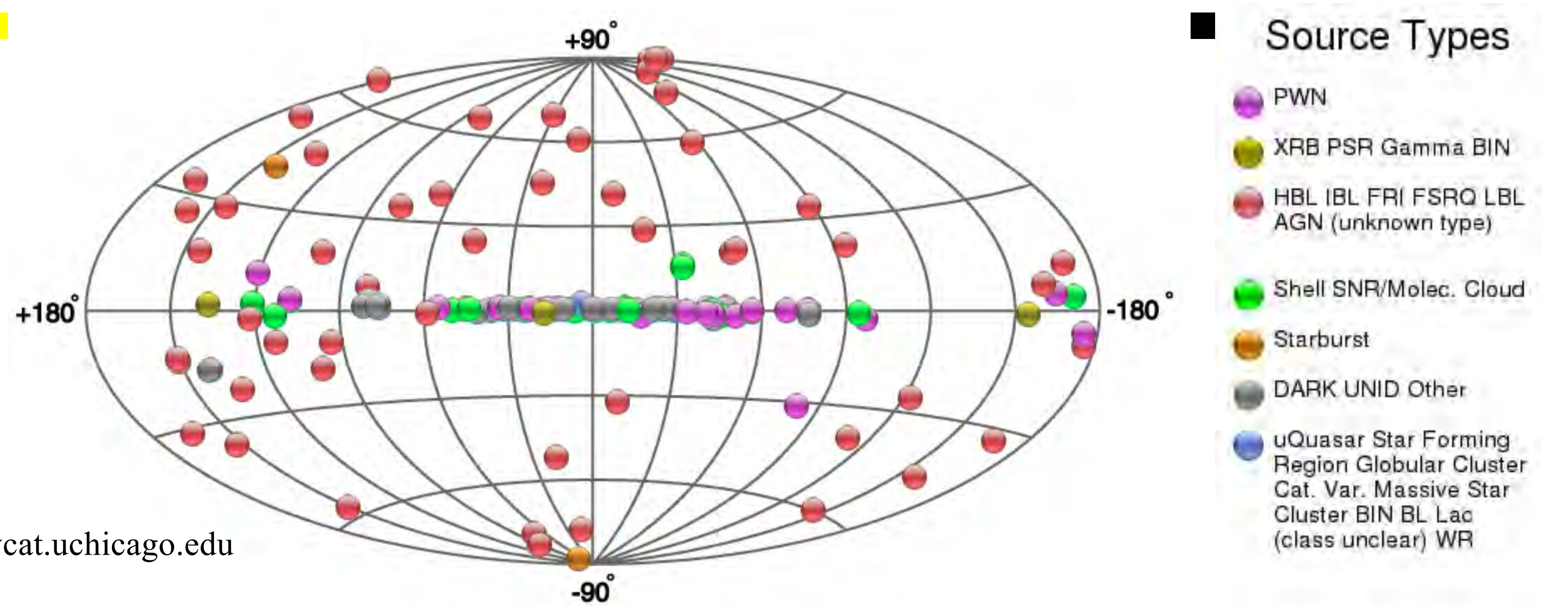
GeV Gamma-Rays from Space





TeV Gamma Ray Sources

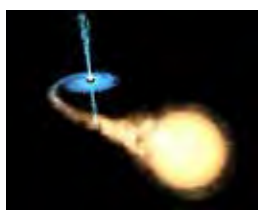
179 known TeV gamma-ray sources (as of October 2016)



tevcat.uchicago.edu

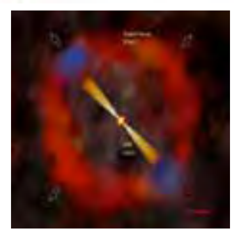
Galactic:

Supernova Remnants



Binary systems

Extragalactic:

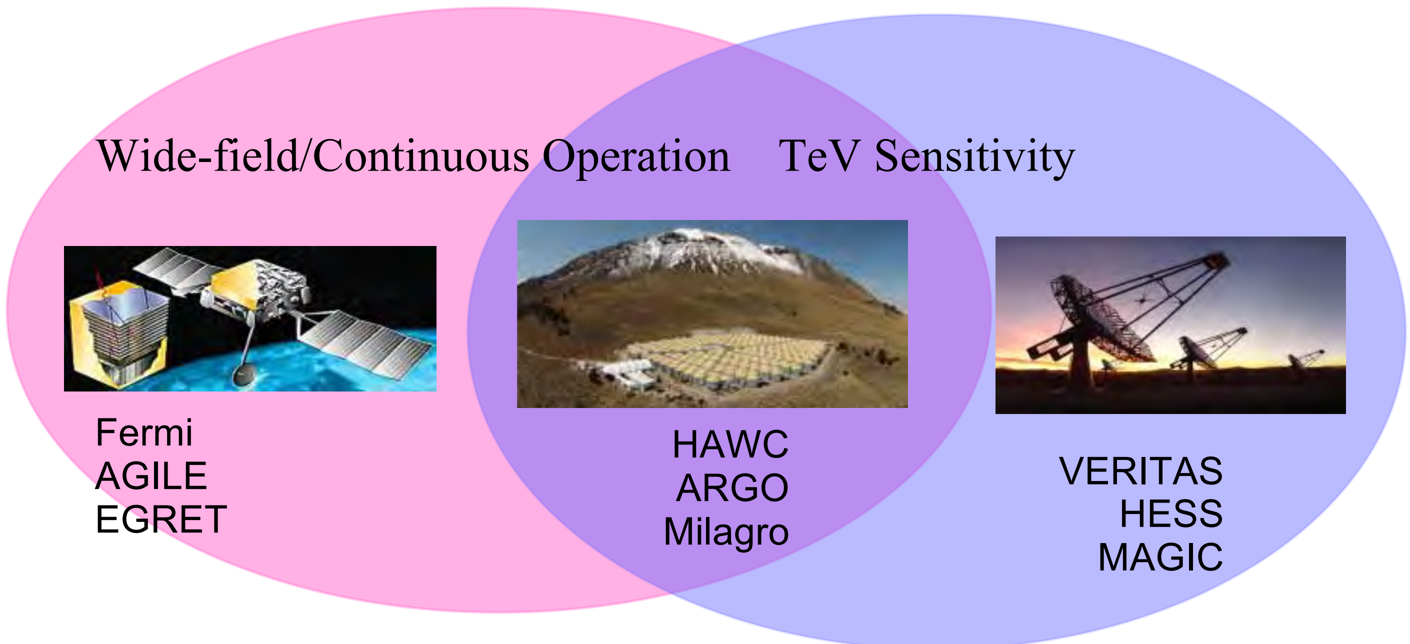


GRBs (GeV)

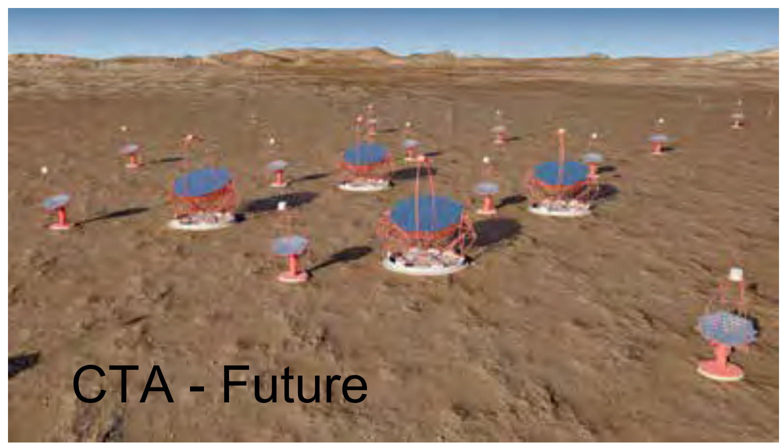
AGNs

Complementarity of Gamma-Ray Detectors

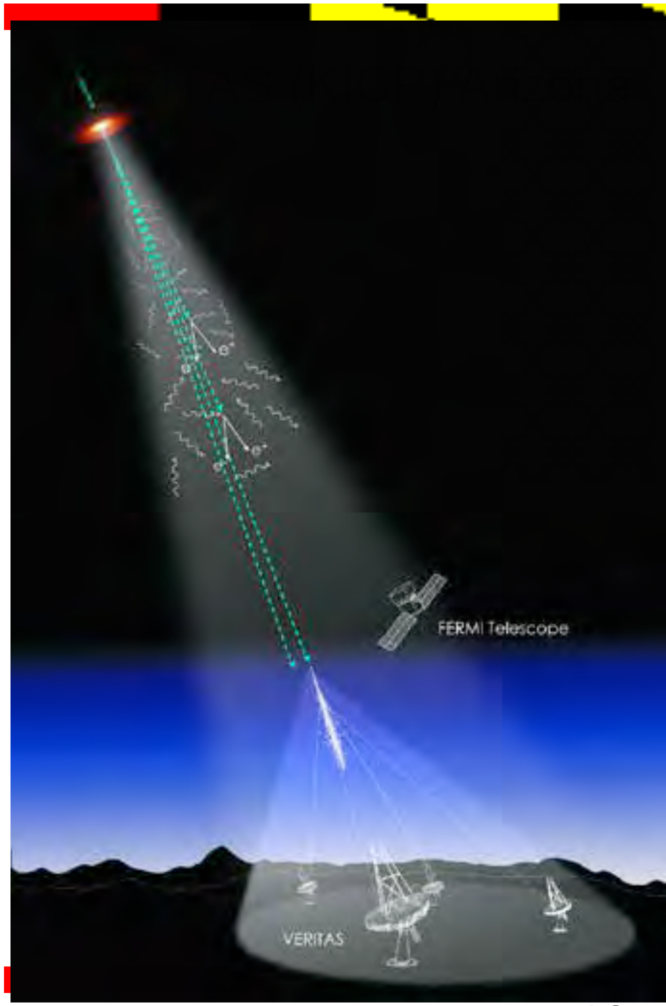
- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
  - IACTs (pointed) excellent energy and angle resolution
  - HAWC has 24-hour >1/2 sky coverage

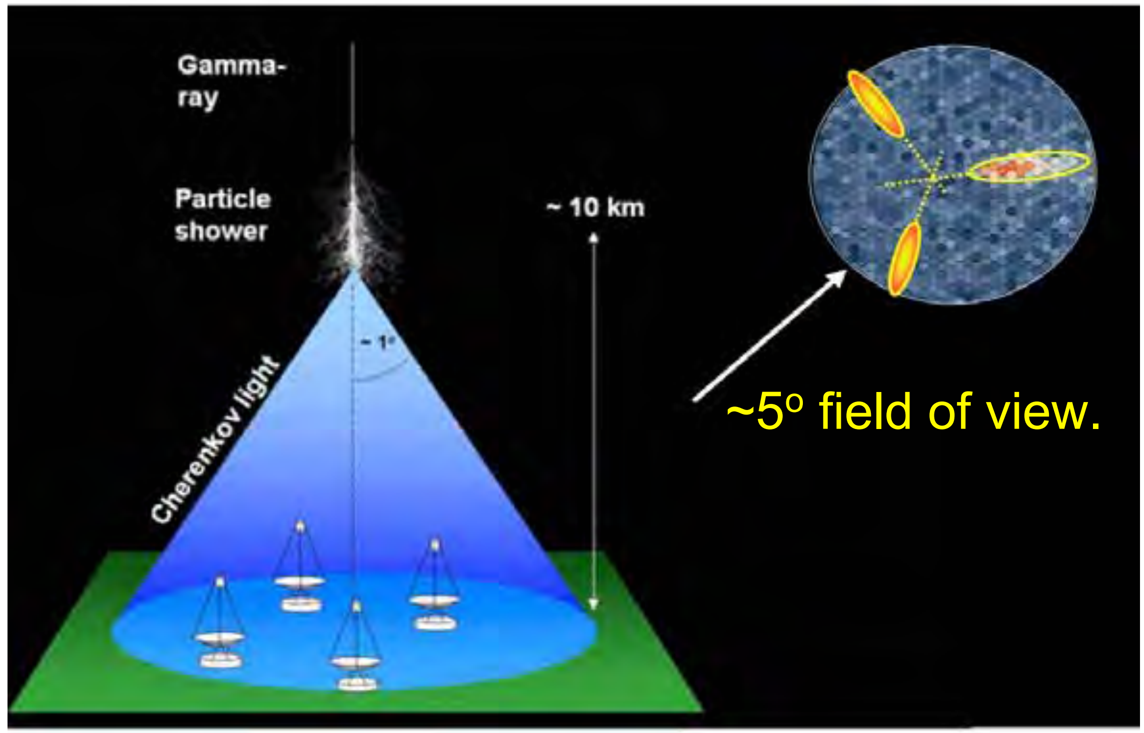


Imaging Atmospheric Cherenkov Telescopes



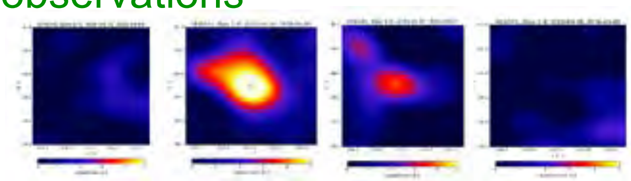
Imaging Atmospheric Cherenkov Telescopes



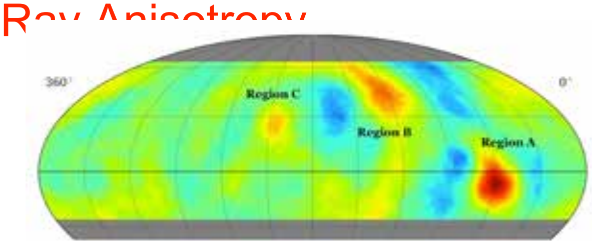


What can you do with a wide-field instrument?

- 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

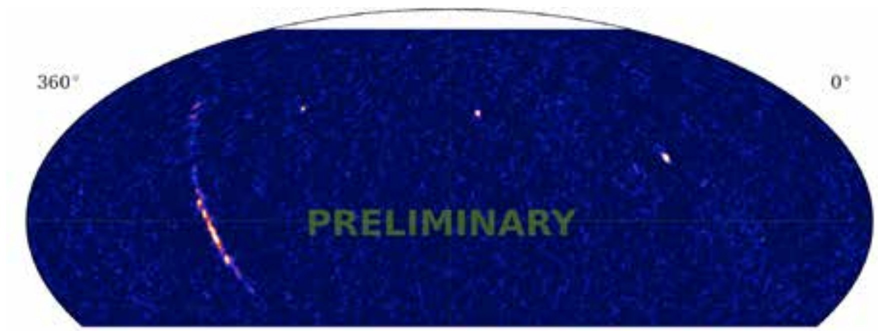


- Particle Physics
  - Dark Matter - can look for places with no visible signal
  - Primordial Black Holes
  - Violations of Lorentz Invariance
  - Look for sources of positron excess
- Cosmic Ray Anisotropy

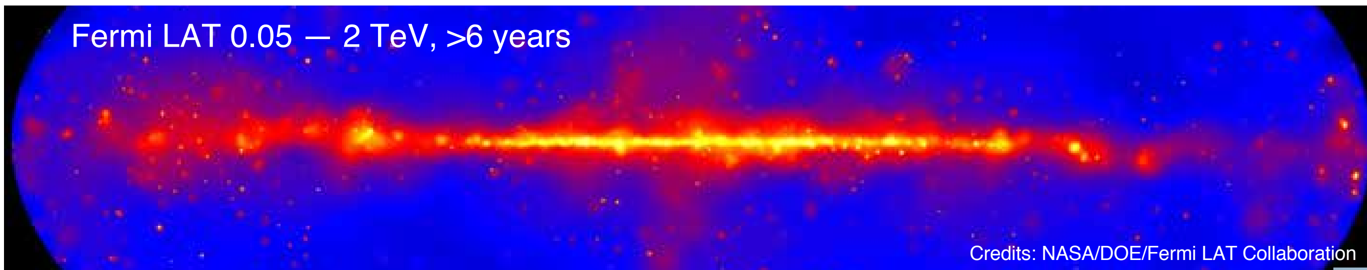


HAWC Science Goals

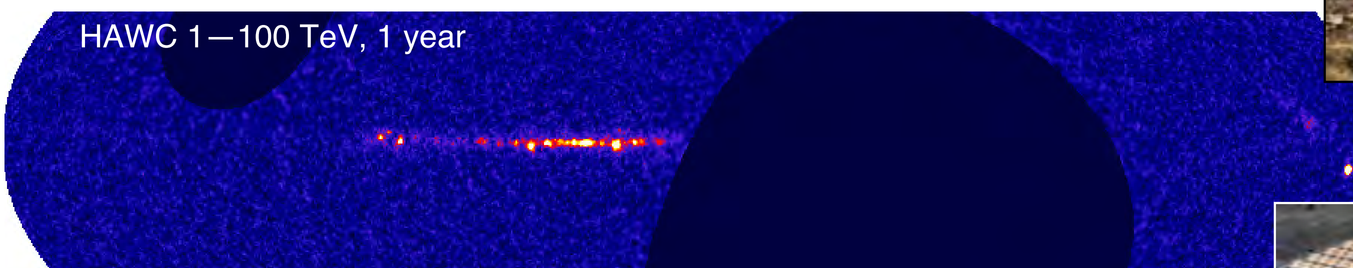
- Gamma Ray Astrophysics
  - Galactic Gamma-Ray Sources
    - Pulsars, PWNs, Binaries
    - Galactic Diffuse and Fermi Bubbles
  - Extragalactic Gamma-Ray Sources
    - Gamma-ray bursts
    - Active Galactic Nuclei
  - Inter Galactic Magnetic Fields (IGMF)
- Particle Physics
  - Dark Matter
  - Primordial Black Holes
  - Violations of Lorentz Invariance
  - Q-Balls
- Cosmic Ray Anisotropy
- Solar Physics

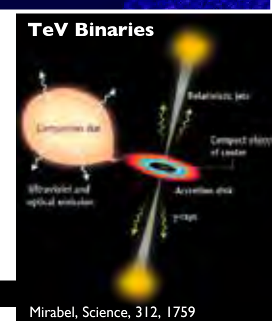


High Energy View of our Galaxy



HESS >1TeV, 10 years



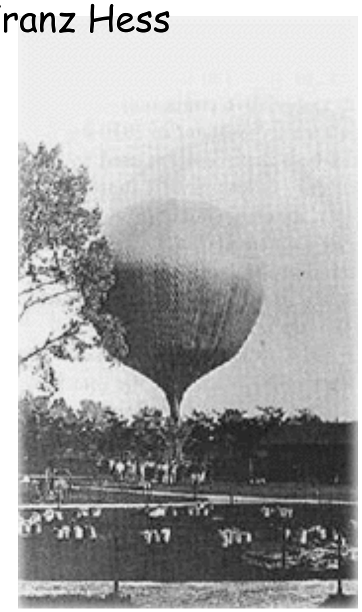


Cosmic Ray Discovery

- Physikalische Zeitschrift: “The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above.”

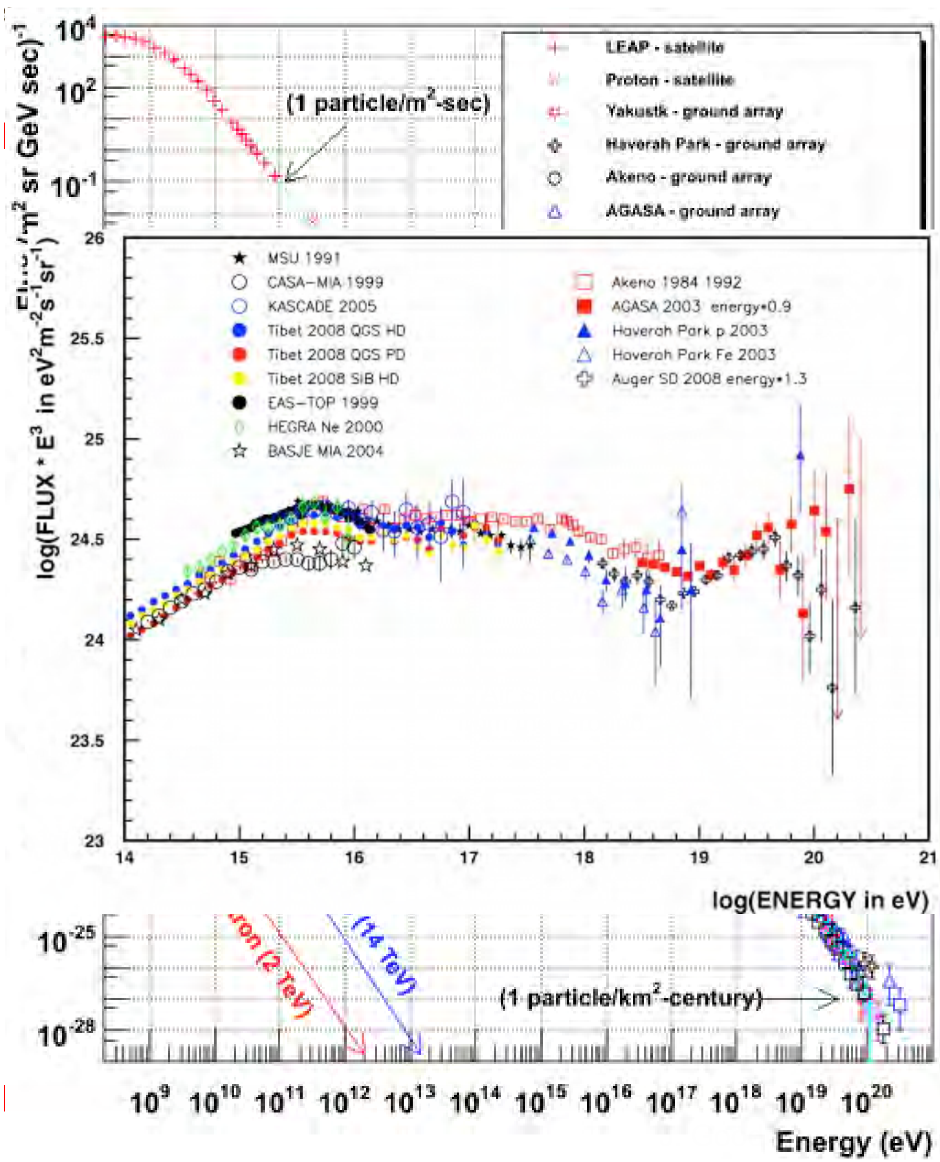
Elevation	Rate
Ground	12
1km	10
2 km	12
3.5 km	15
5 km	27

Victor Franz Hess



V. F. Hess. Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten. Physikalische Zeitschrift, 13:1084-1091, November 1912.


AERO
CLUB
WIEN

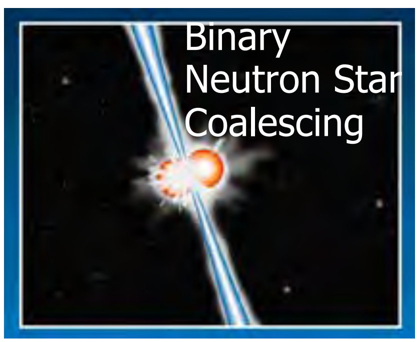


Cosmic Rays

- The flux charged cosmic rays follows nearly a single power law over:
  - 10 decades in energy
  - 30 decades in flux
- Single particles have been observed with energies above 10^{20}eV!
- There are several "kinks" in the spectrum where the exponent changes, steepening at the "knee" and flattening at the "ankle".
- The source of the high-energy cosmic rays remains elusive.

More than 100 Years Later

- We know a lot about Cosmic Rays
  - We have found sources of high energy photons (gamma rays)
  - We have a number of ideas of how particles can be accelerated to high energies
- But we still don't know the origin of the high energy Cosmic Rays!
  - Gamma-rays (and neutrinos) can point to the sources!

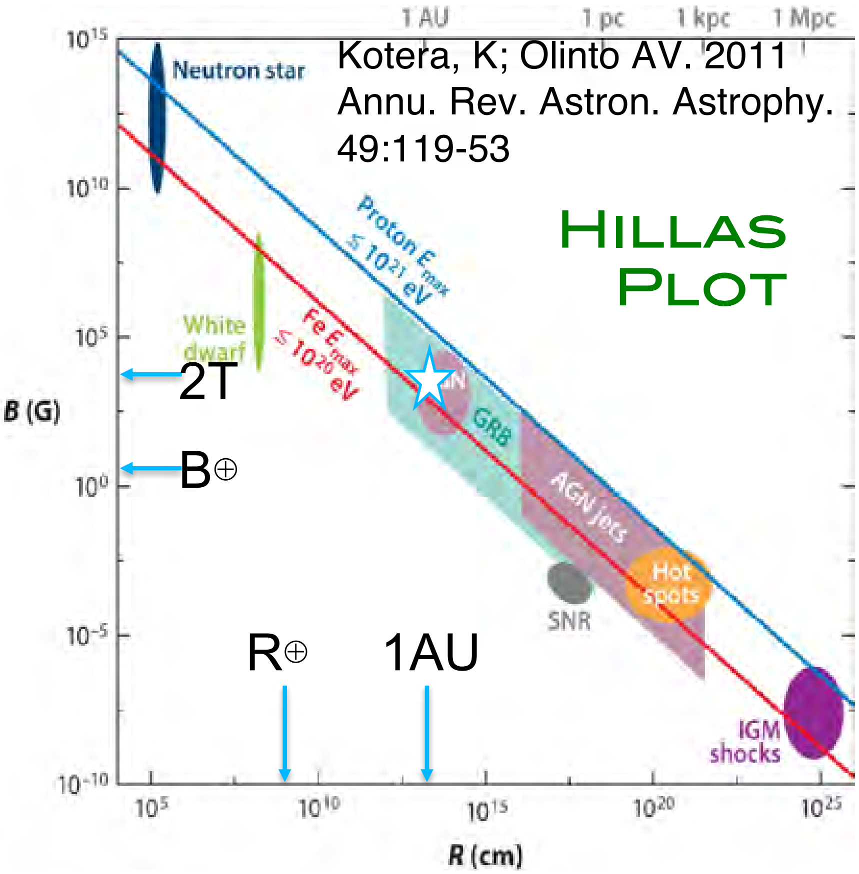


Why Not Cosmic Ray Astronomy?

- Charged Particles are bent in the magnetic fields of our galaxy and local cluster
- Energy of $>10^{19}$eV needed to point back to even galactic sources
- Very high energy photons interact with light when traveling long distances

We need another messenger!

Candidate accelerators

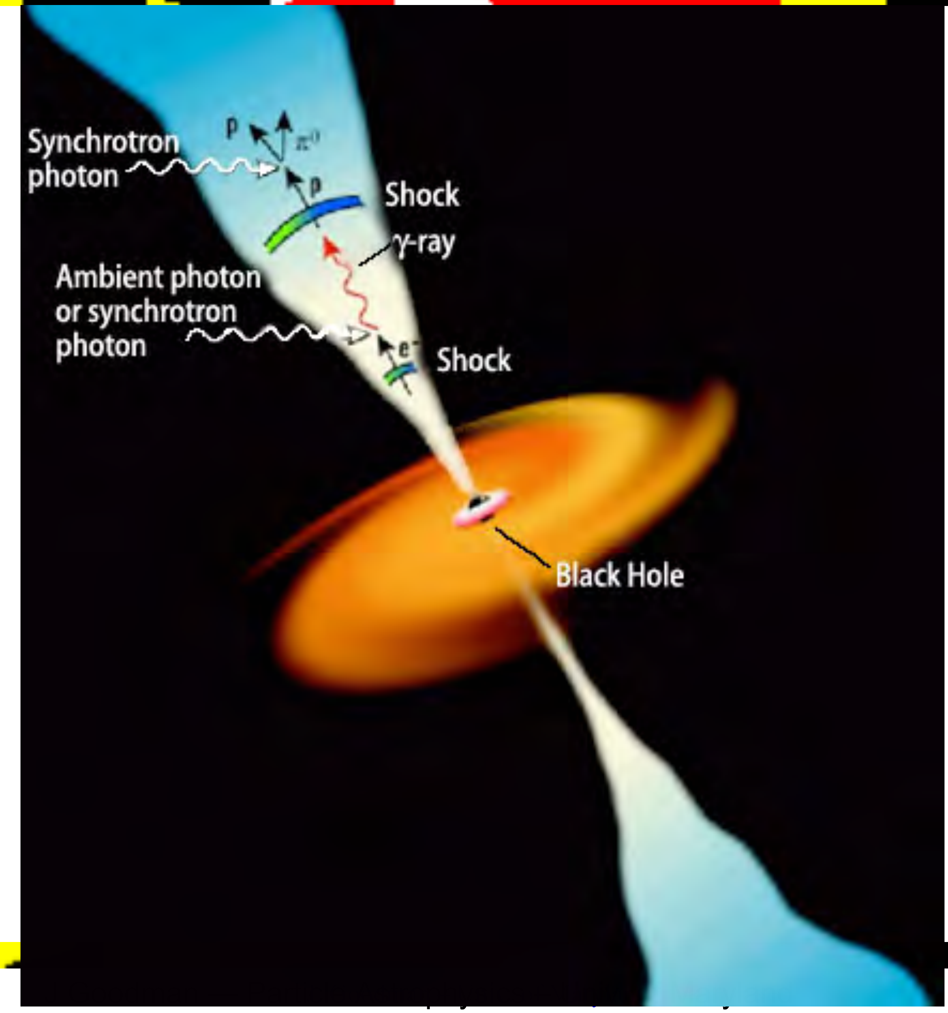


p=0.3 Br
p in Gev/c
B in Tesla
r in meters

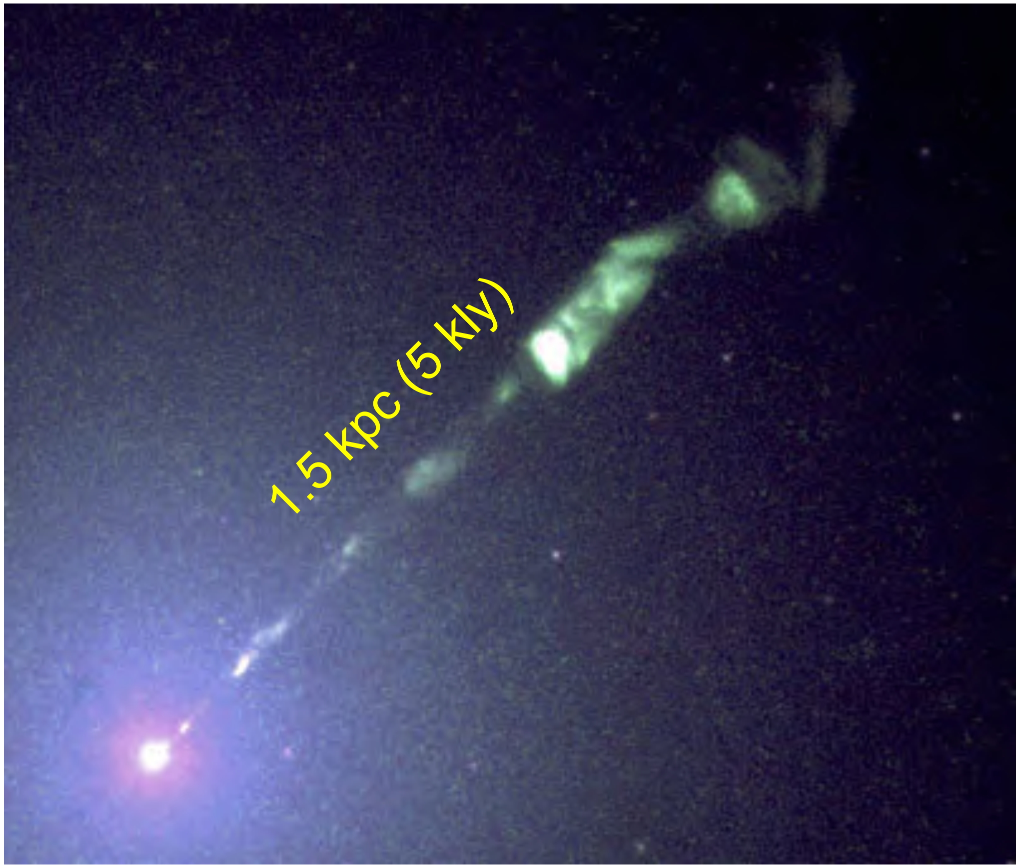
B=2T r=1.5x10^{11}m
p=10^{11} GeV/c
=10^{20} eV/c

Large magnetic field

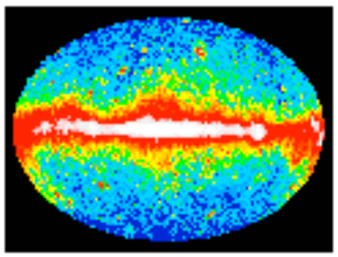
Active Galactic Nuclei (AGN)

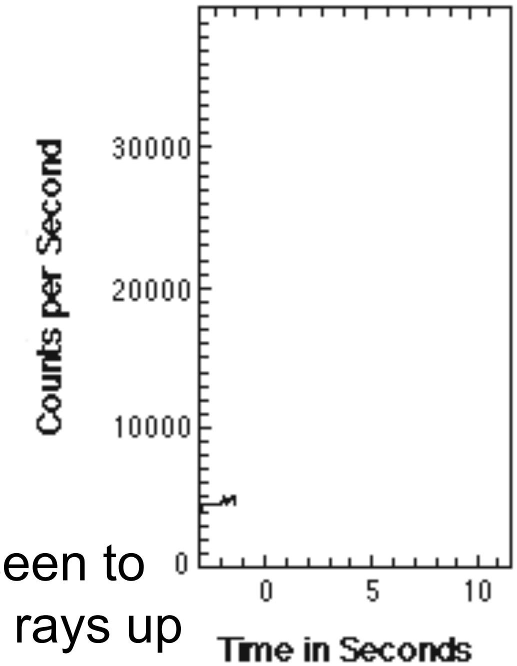


Hubble AGN M87

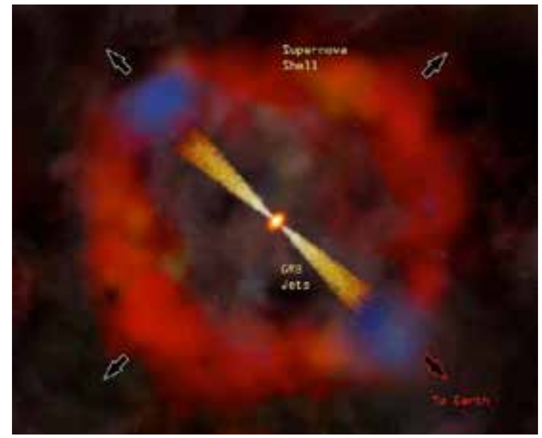


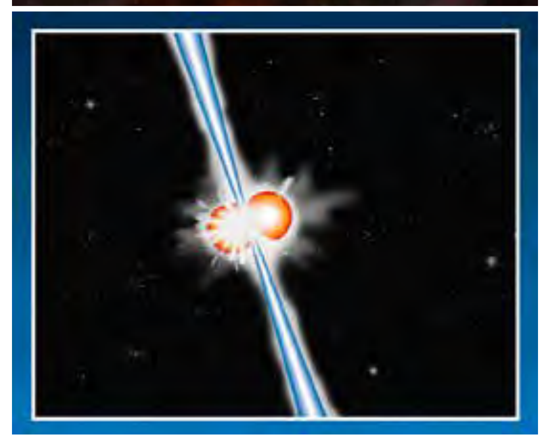
GRBs



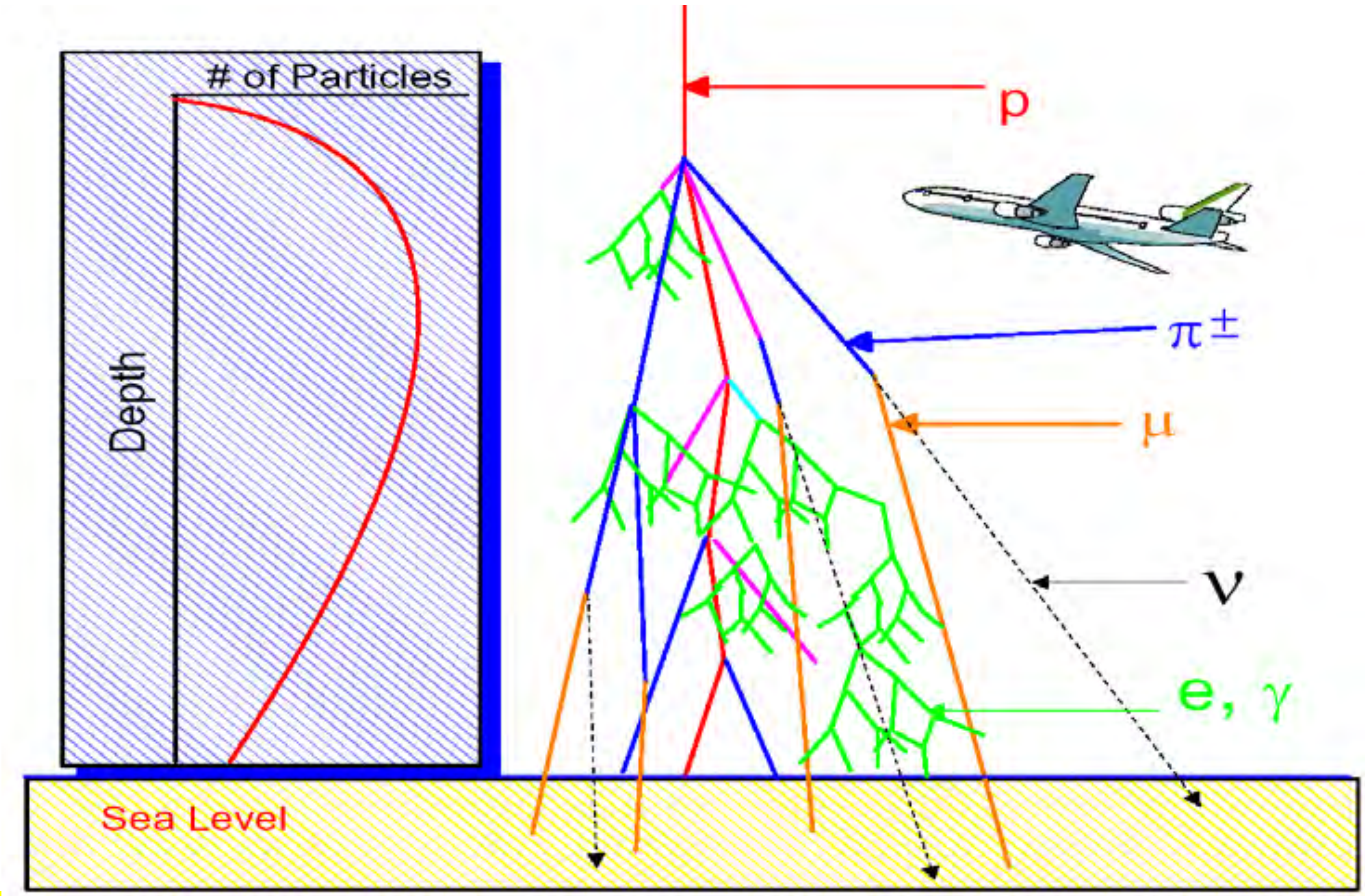


GRBs are now seen to produce gamma rays up to nearly 100 GeV

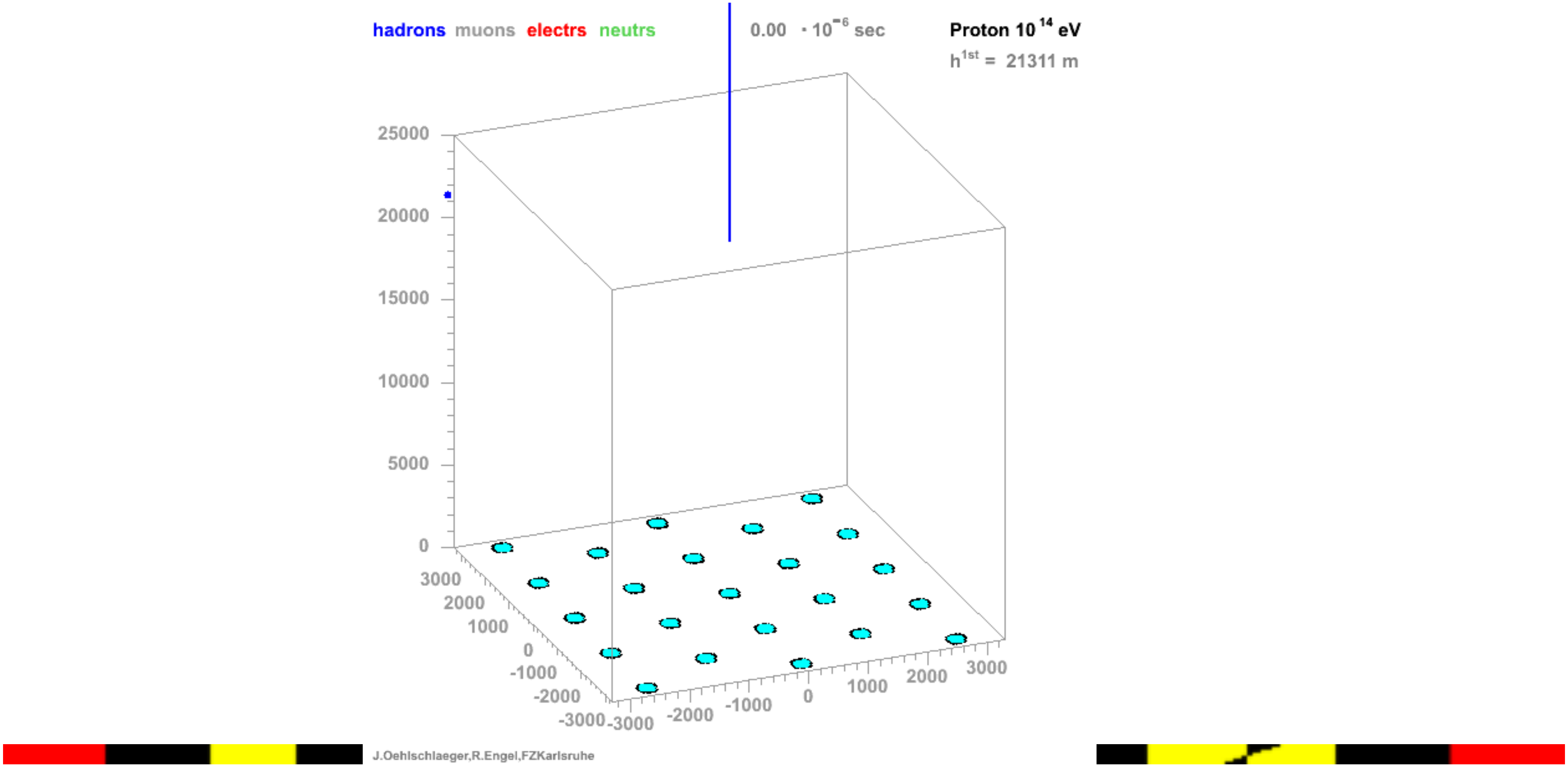




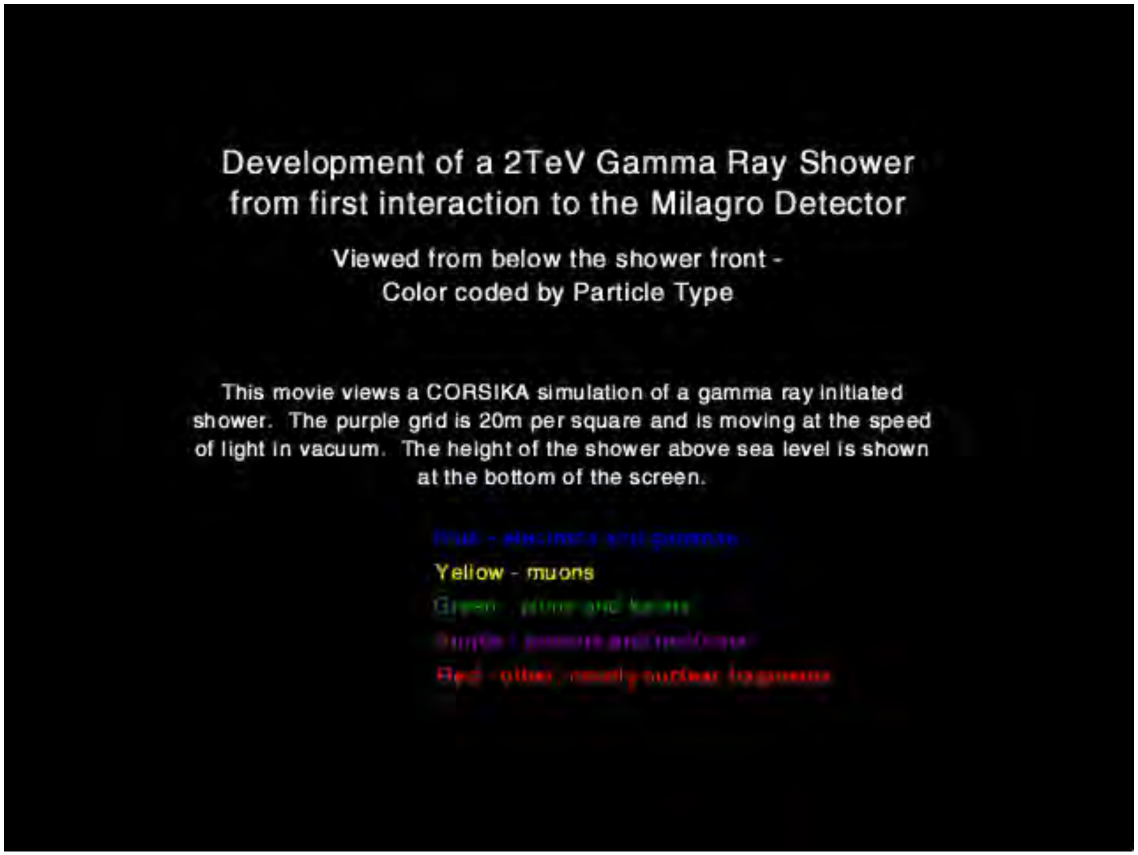
Extensive Air Shower Development



Proton - 100 TeV

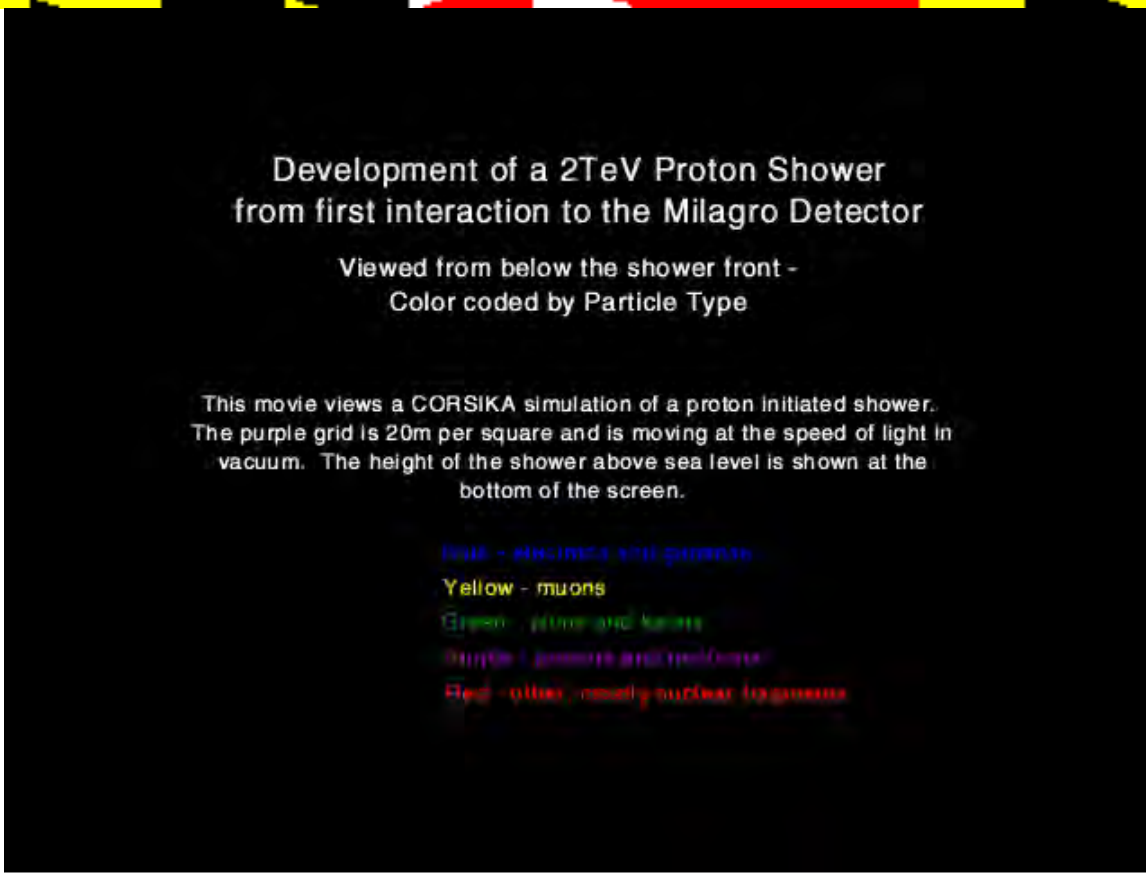


Gamma Shower 2 TeV (movies by Miguel Morales)



Blue – Electrons Muons – Yellow Pions – Green Nucleons – Purple

Proton Shower 2 TeV (movies by Miguel Morales)

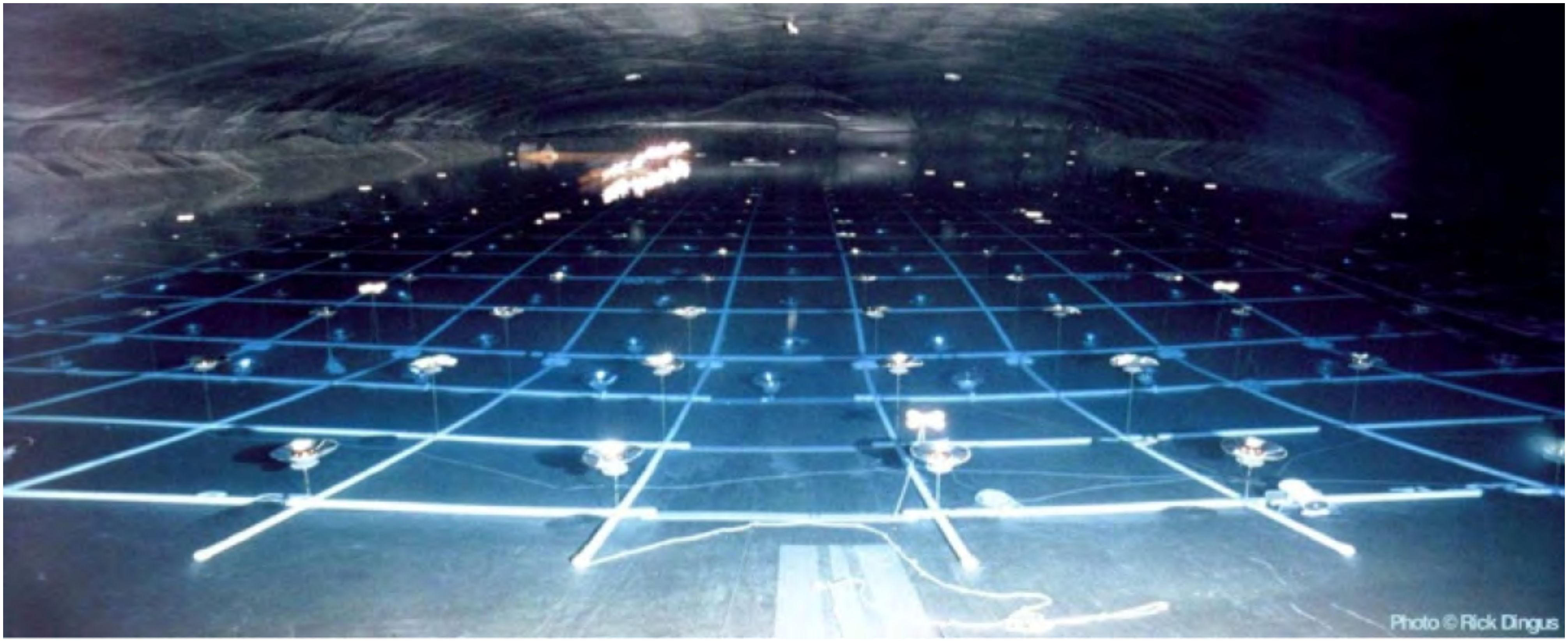


Blue – Electrons   Muons – Yellow   Pions – Green   Nucleons – Purple

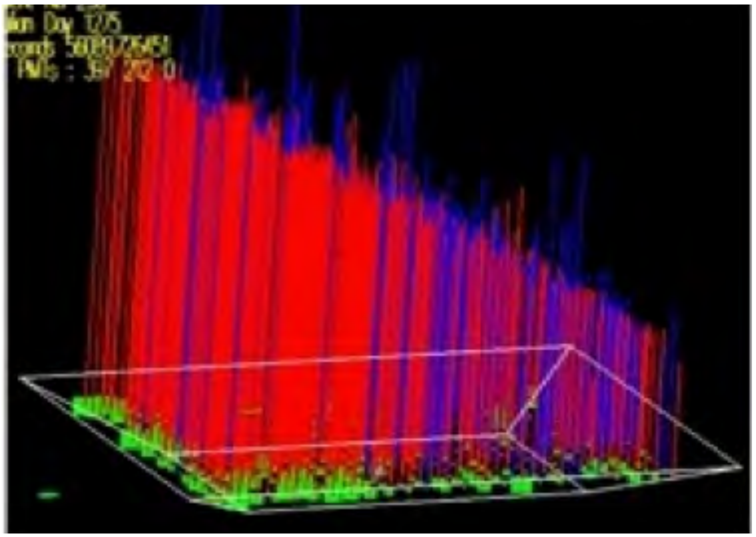
Milagro

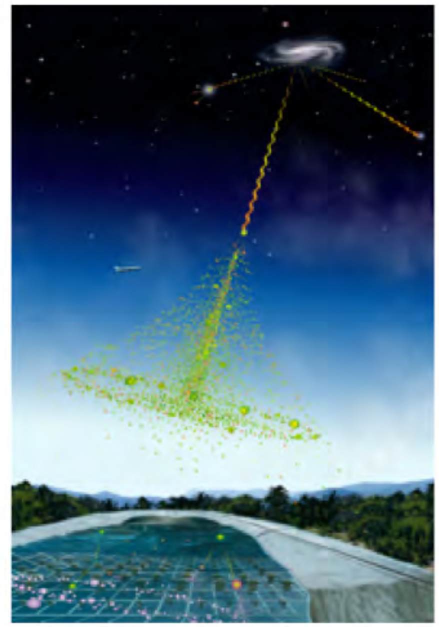
- In the mountains above Los Alamos at 2650m
- In an existing pond
  - 60m x 80m x 8m
  - 175 outriggers
  - 20,000 m^2
- Operated from 2000- 2008
- 1st wide-field TeV Observatory

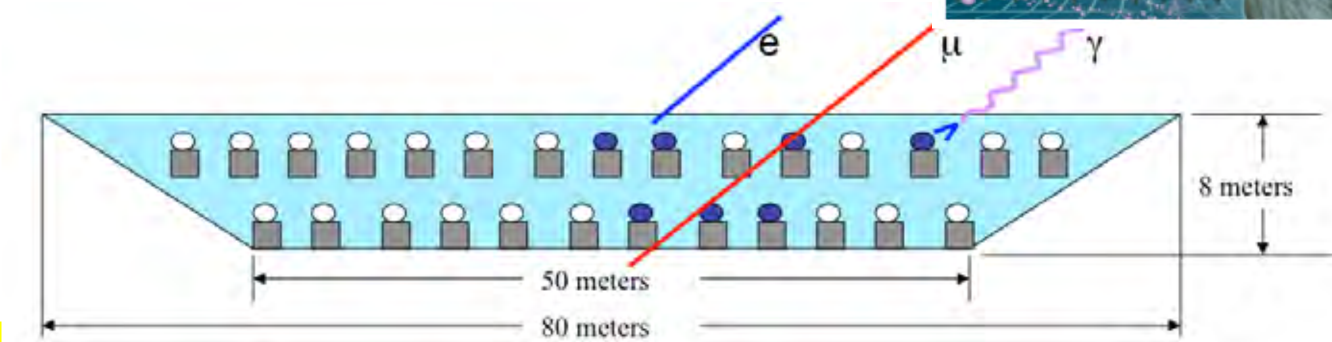
Milagro



Milagro

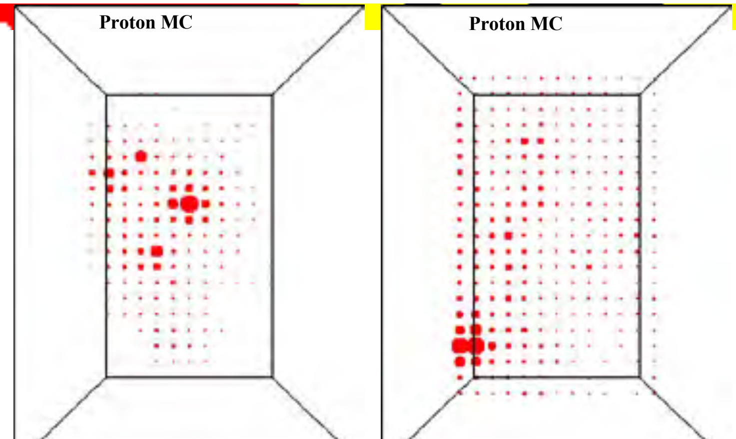


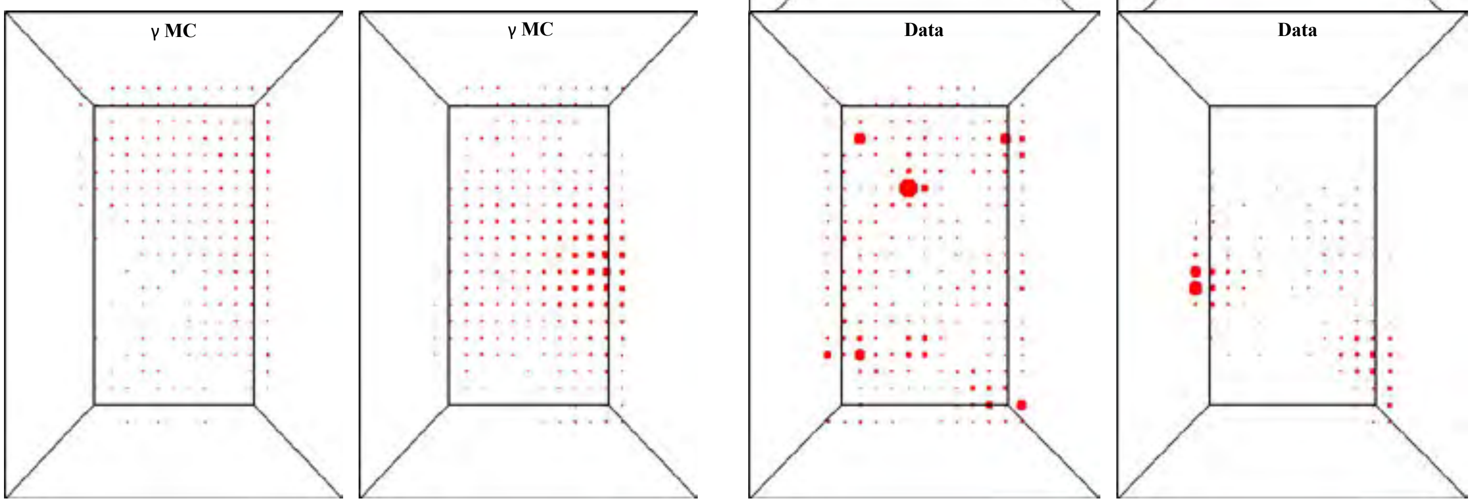




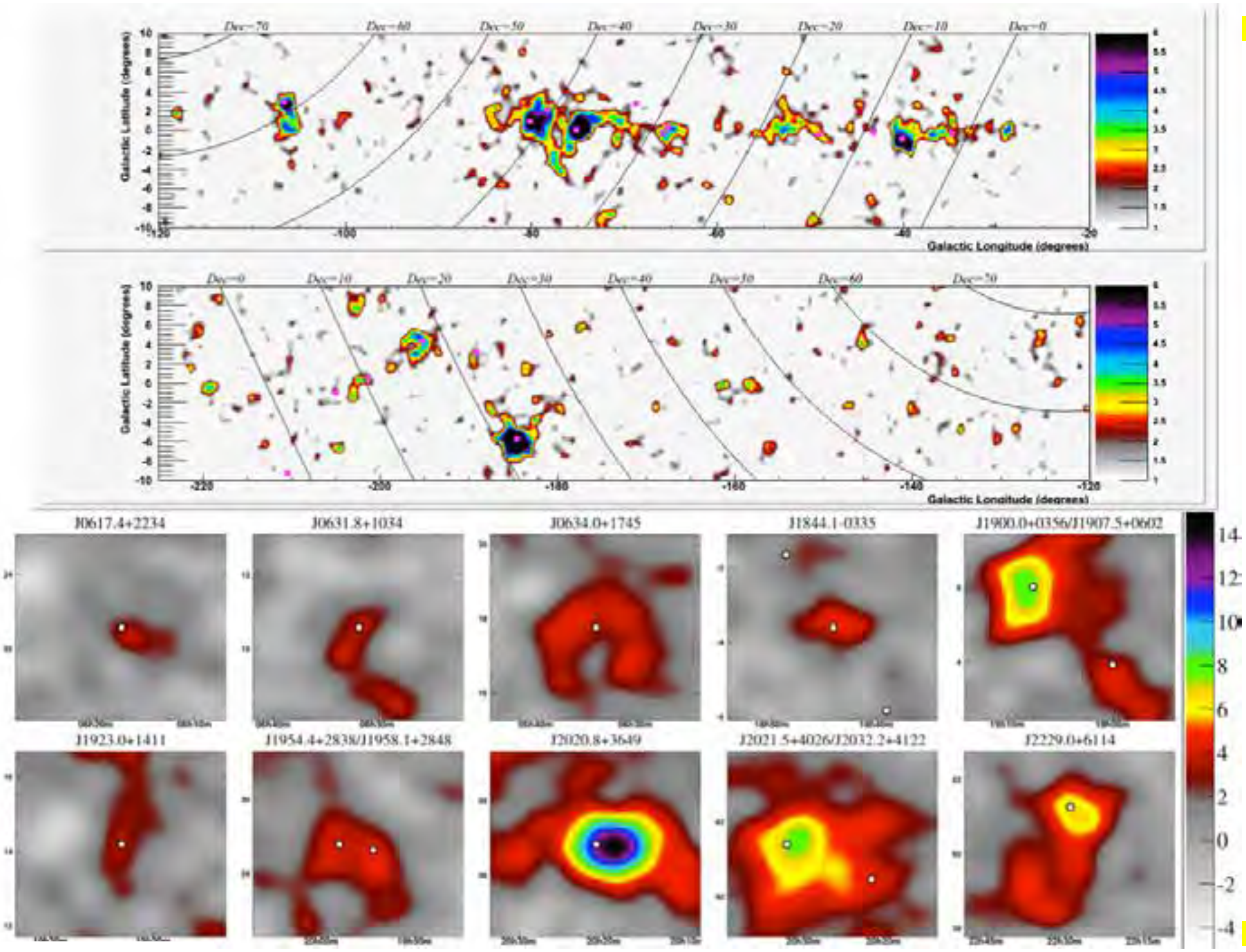
Background Rejection in Milagro

Use bottom layer of Milagro to detect penetrating particles (primarily muons) which are more prevalent in cosmic-ray (hadronic) showers than gamma-ray (electromagnetic) showers

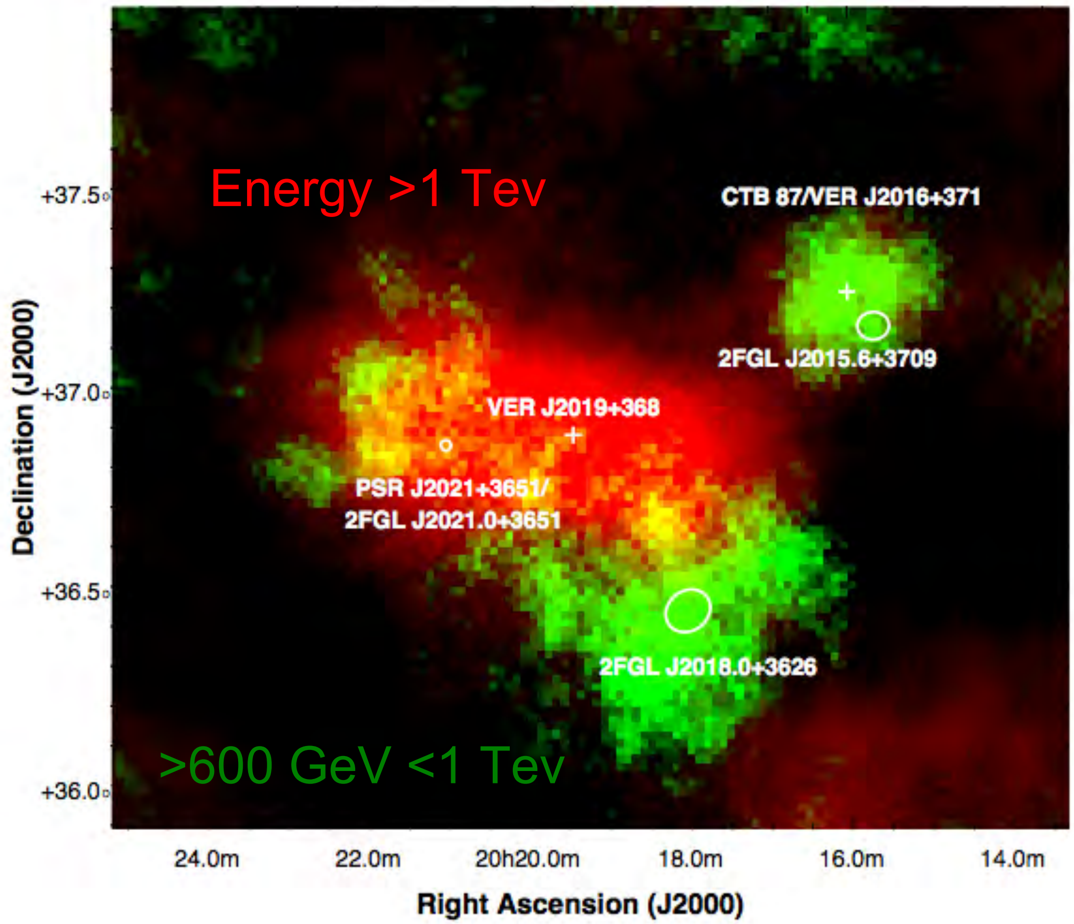




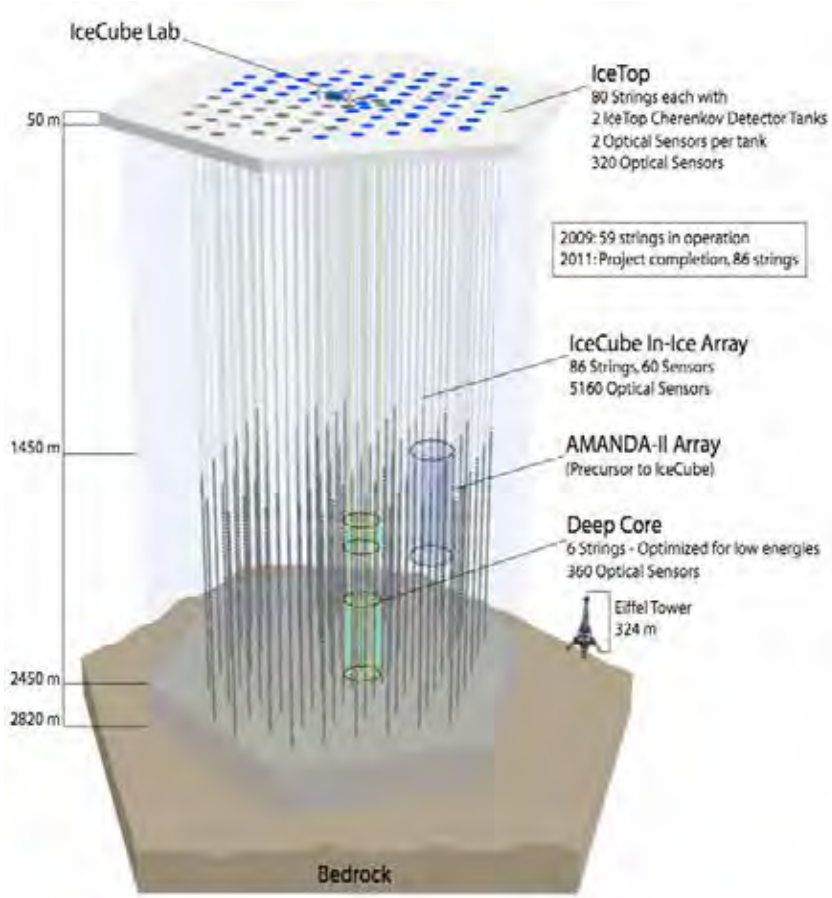
Milagro TeV Sources



VERITAS Observation of 2019+37

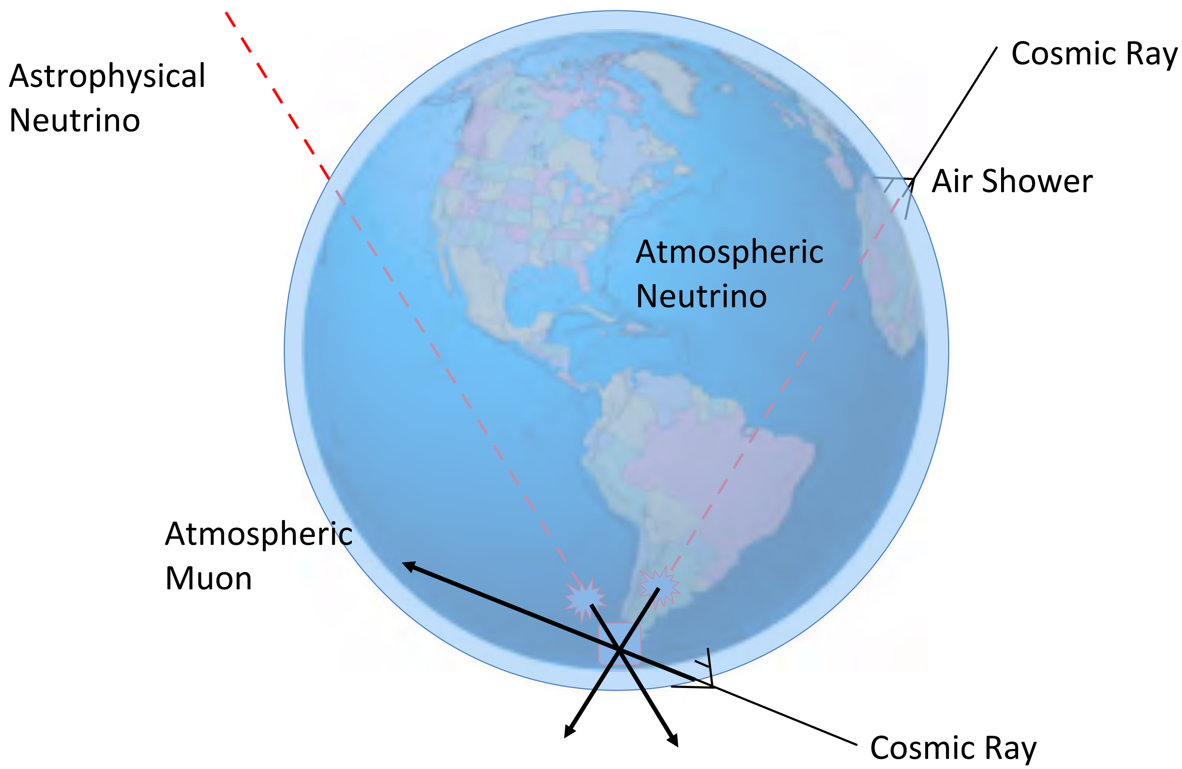


IceCube



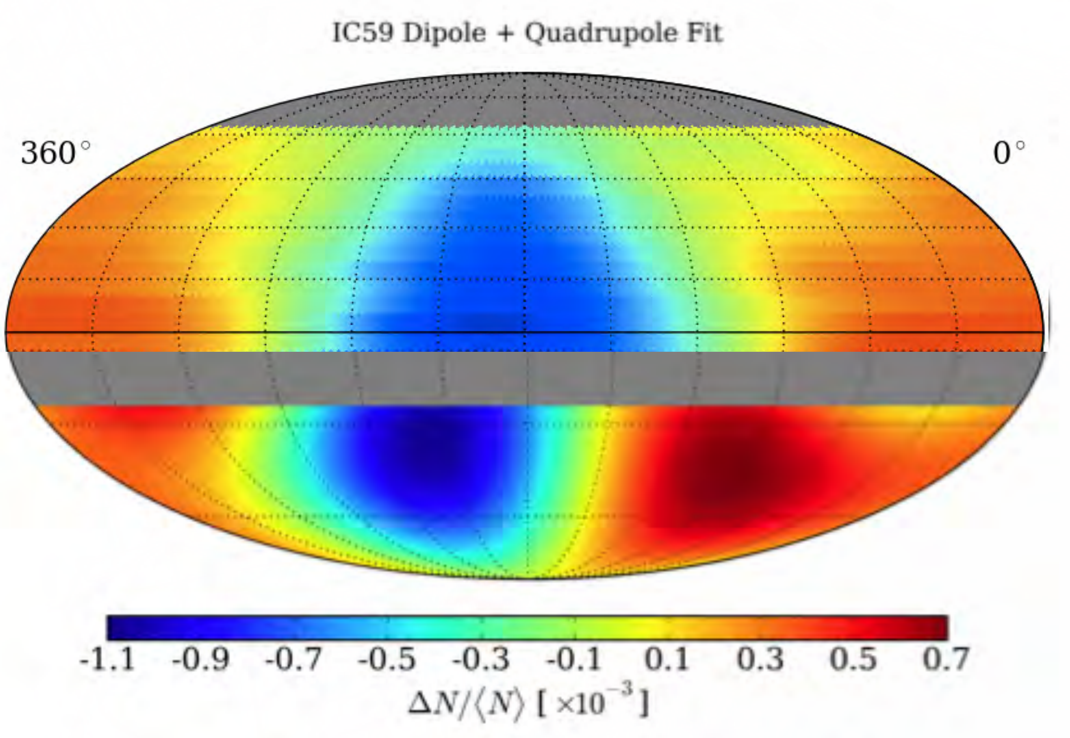
IceCube Lab
IceTop
80 Strings each with
2 IceTop Cherenkov Detector Tanks
2 Optical Sensors per tank
320 Optical Sensors
2009: 59 strings in operation
2011: Project completion, 86 strings
IceCube In-Ice Array
86 Strings, 60 Sensors
5160 Optical Sensors
AMANDA-II Array
(Precursor to IceCube)
Deep Core
6 Strings - Optimized for low energies
360 Optical Sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

IceCube

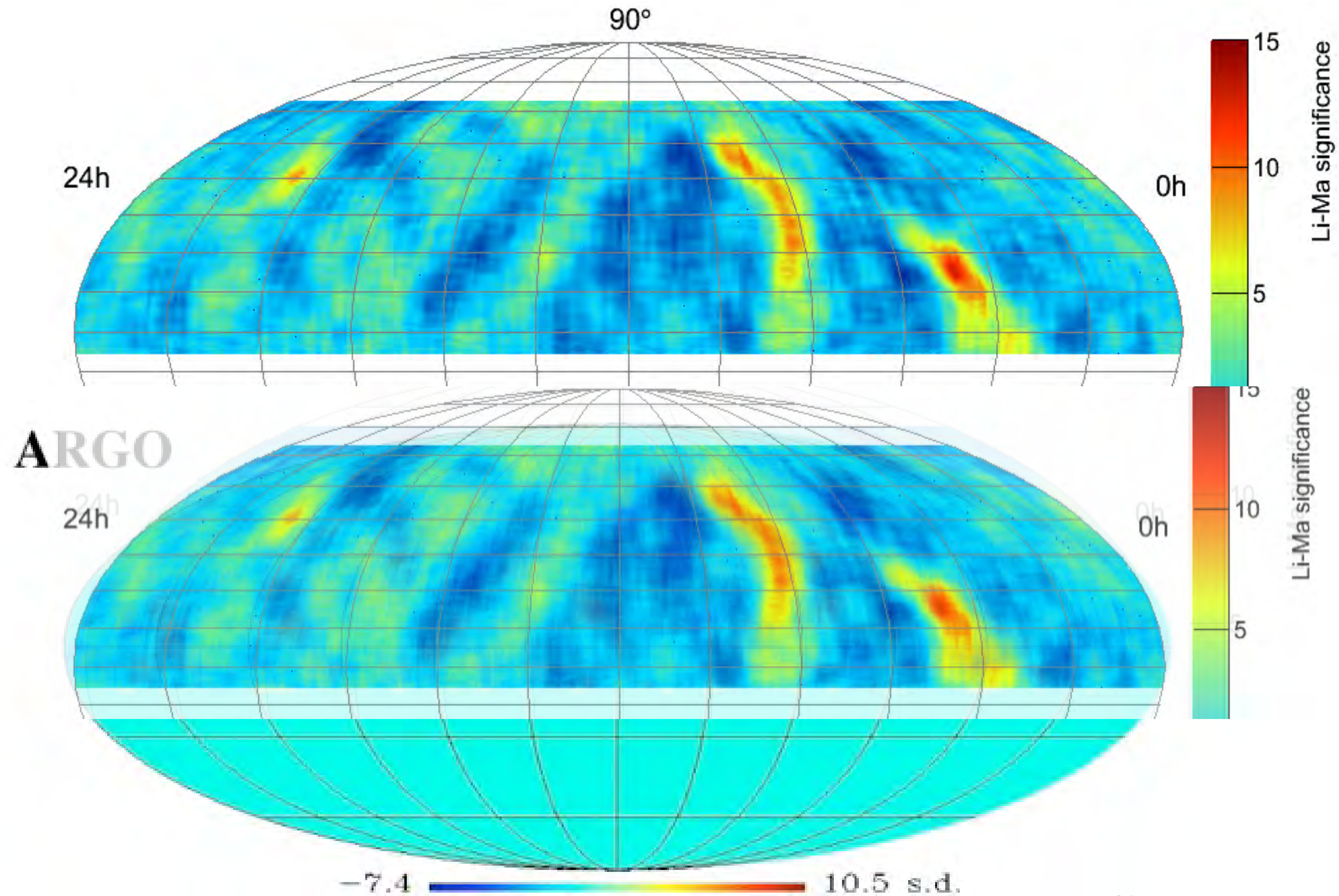


IcCube uses Atmospheric muons from the Southern Hemisphere

Milagro & IceCube

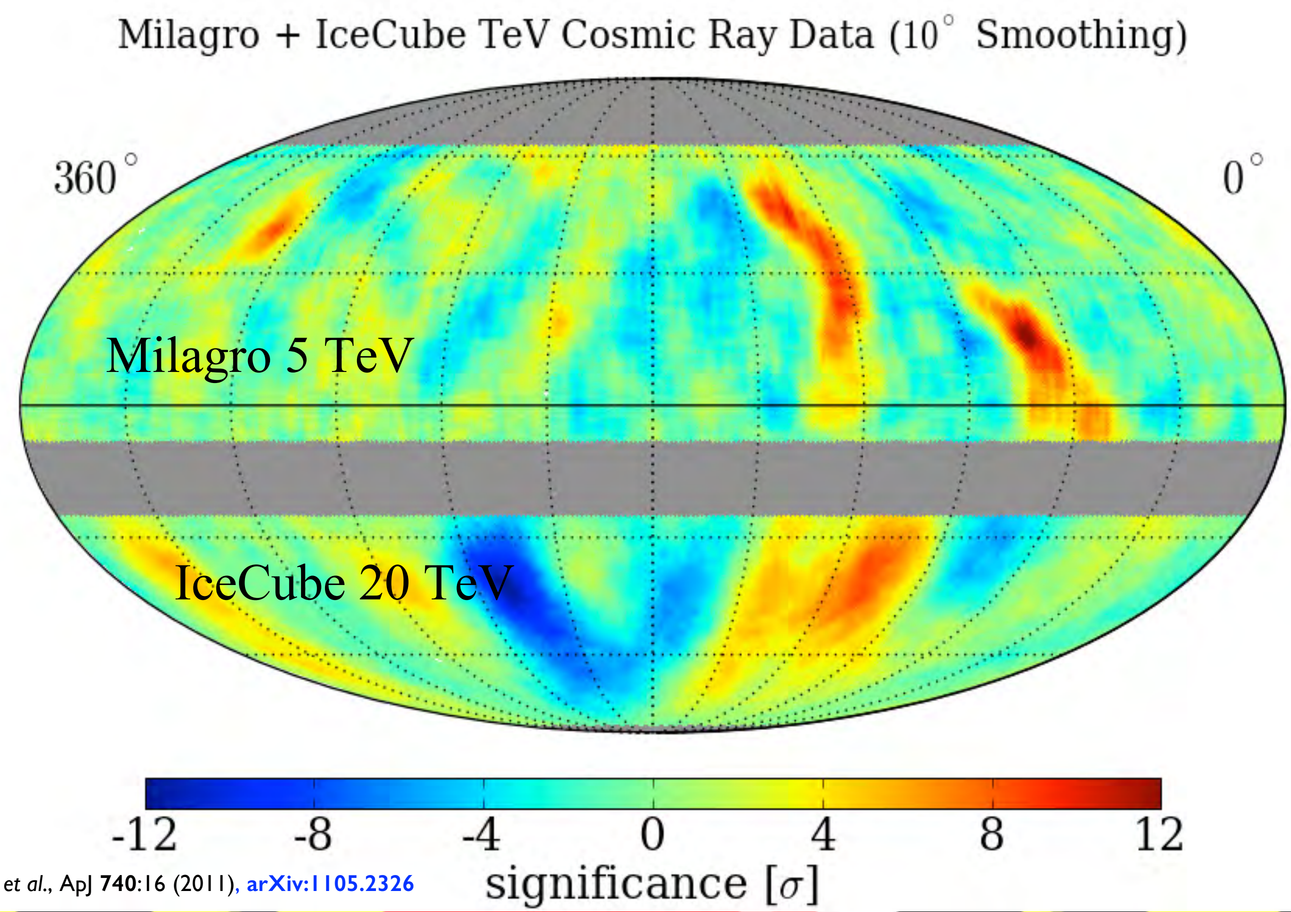


Small Scale Anisotropy



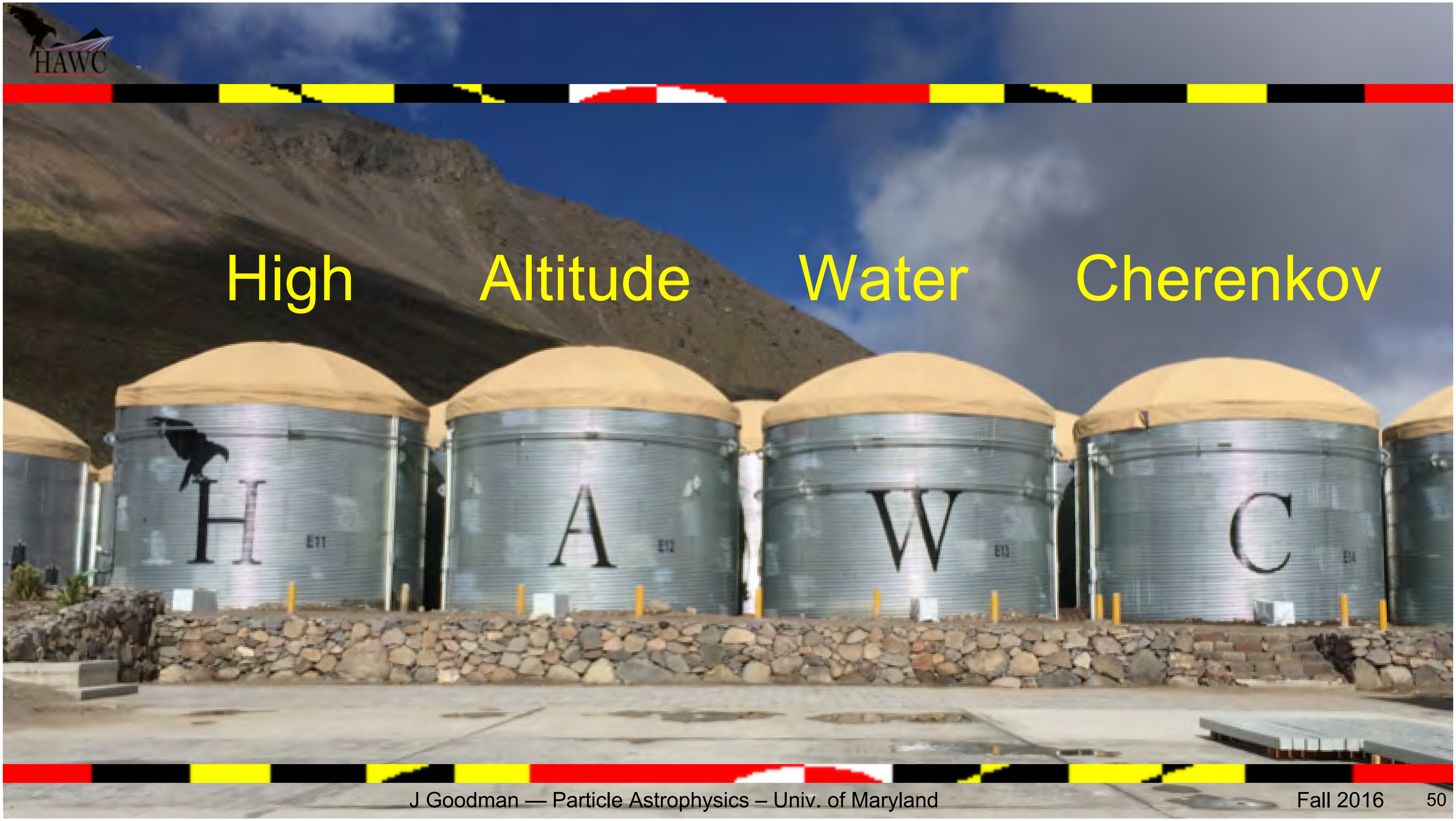
http://people.roma2.infn.it/~aldo/RICAP09_trasp_Web/Vernetto_ARGO_RICAP09ar.pdf

Cosmic Ray Anisotropy



R. Abbasi *et al.*, ApJ **740**:16 (2011), arXiv:1105.2326

High Altitude Water Cherenkov



HAWC Design builds on Milagro

Milagro "1st Generation" Water Cherenkov gamma-ray detector

- 2650m (8600') elevation near Los Alamos, NM
- Covered pond of 4000 m^2
- Operated 2000-2008
- Detected new Galactic sources, Galactic plane, cosmic ray anisotropy, and put upper limits on prompt emission from gamma-ray bursts

HAWC "2nd Generation" Water Cherenkov gamma-ray detector

- 4100m (13500') elevation near Puebla, Mexico
- 300 water tanks spread over 20,000 m^2
- Construction 2010-14, Operation 2015-2020(25)
- ~15x Milagro's sensitivity with ~10x lower energy threshold

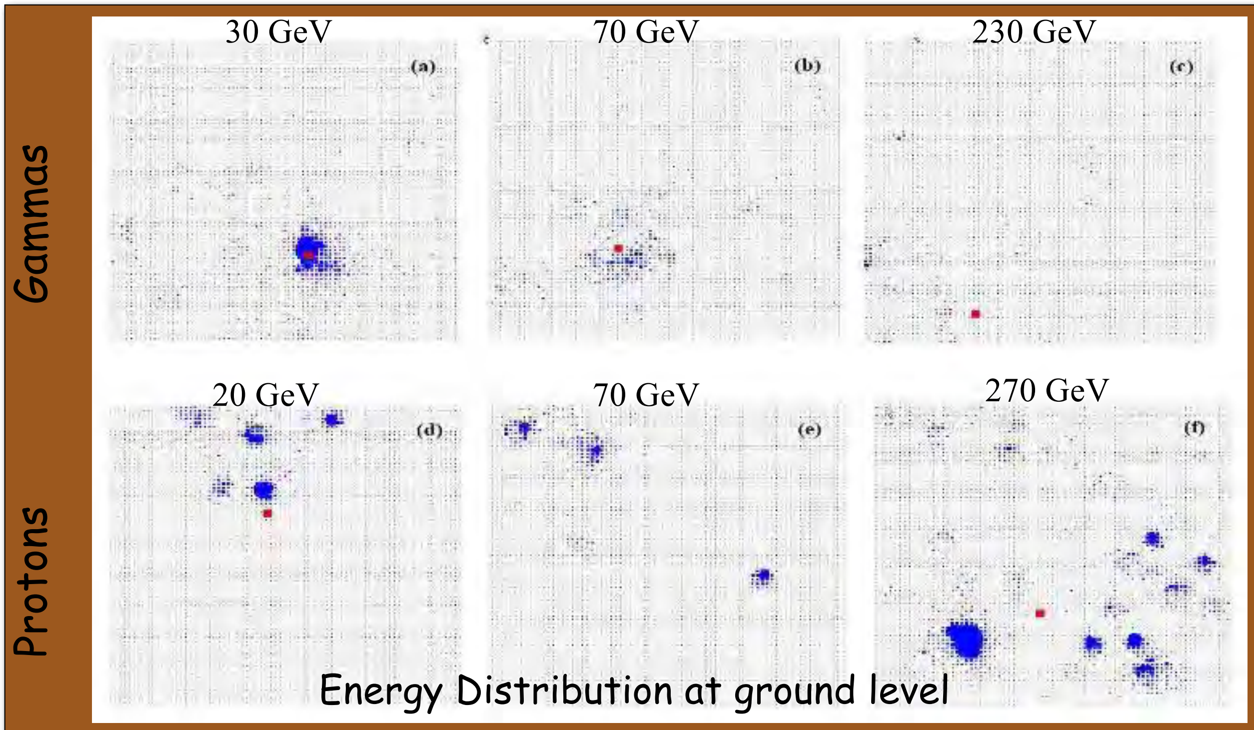
©Aurore Simonnet

Gamma/Hadron Separation

Rejection factor ~ $e^{-\langle \mu \rangle}$

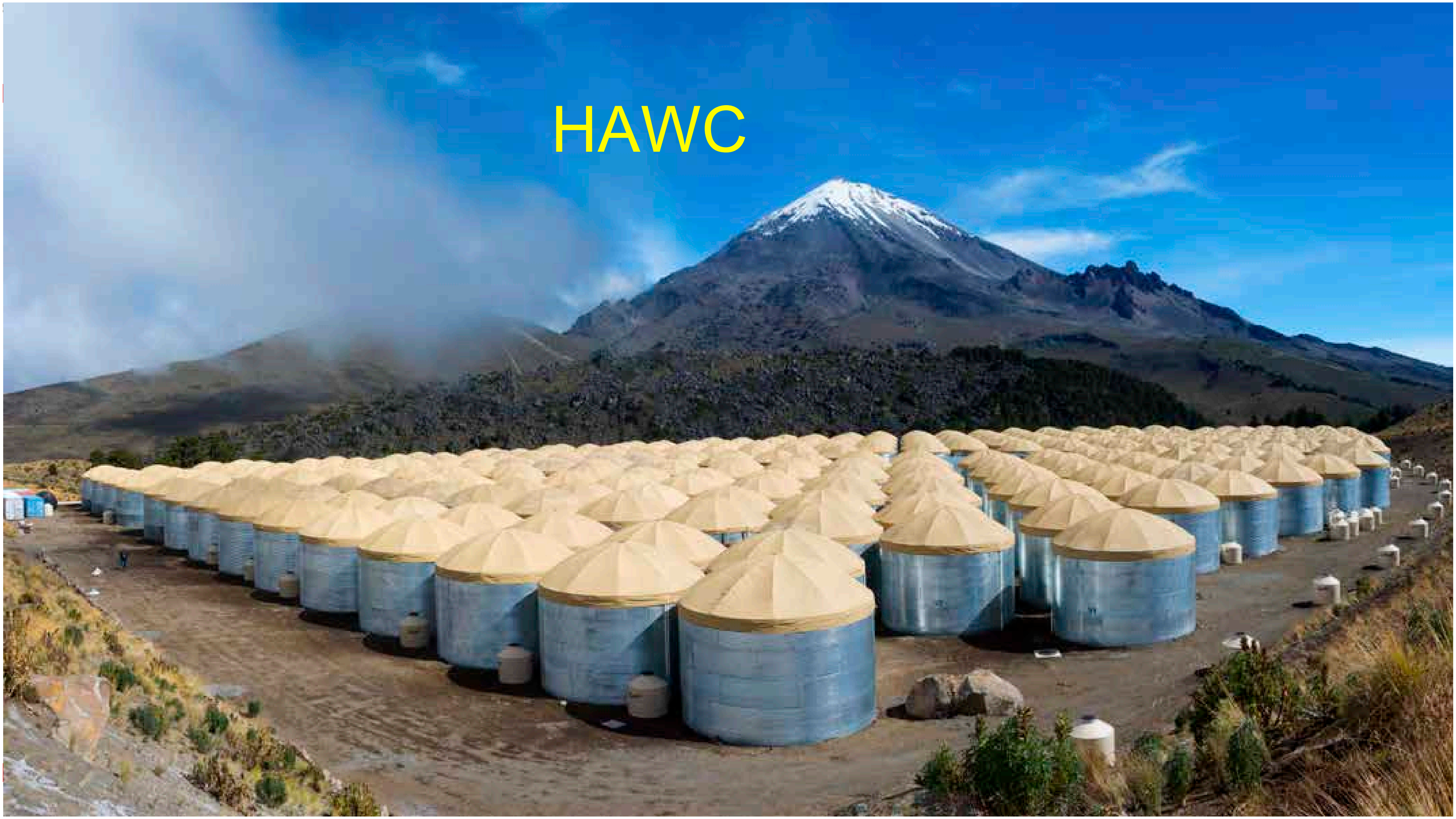
Size of HAWC

Size of Milagro deep layer

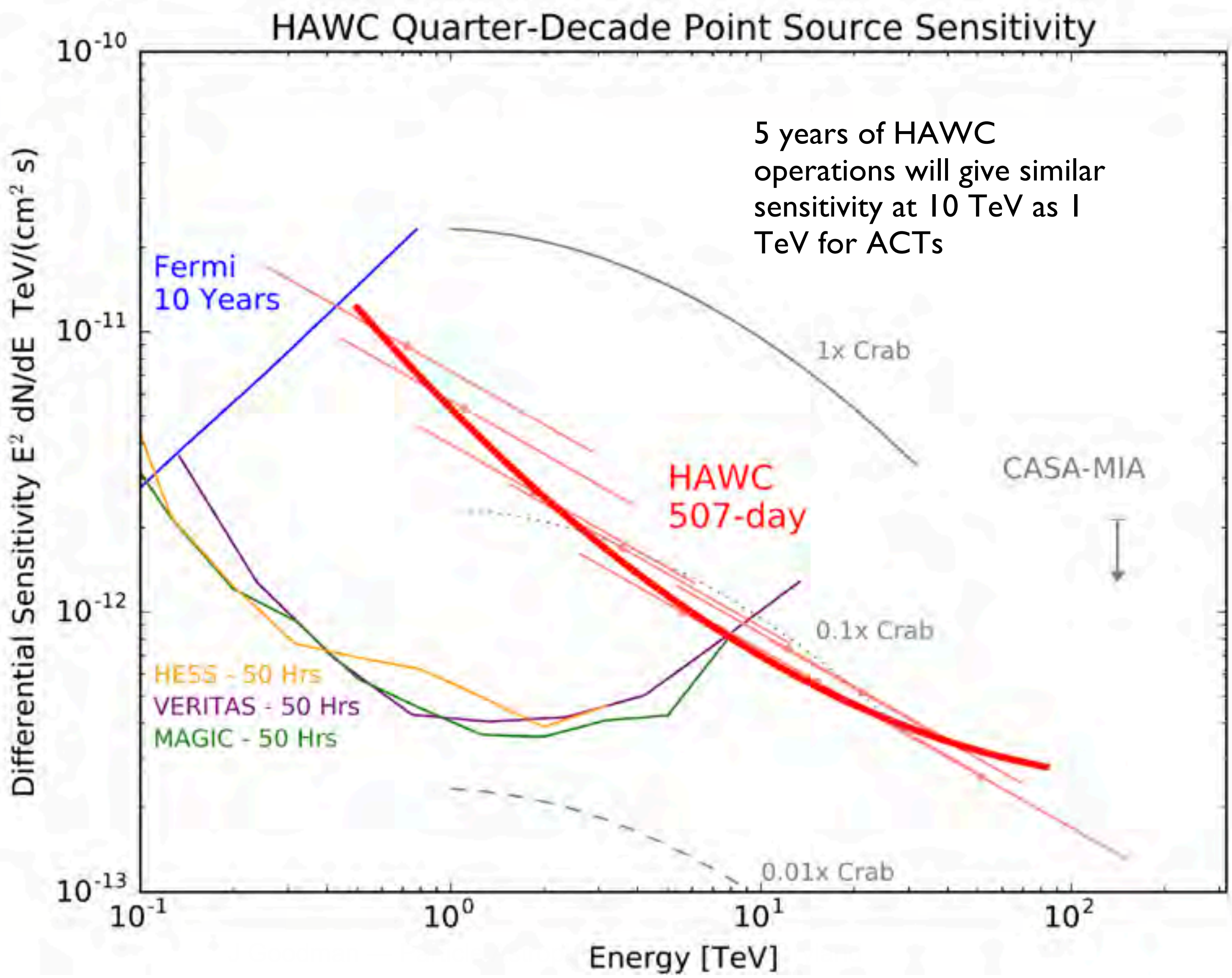


The HAWC Site

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

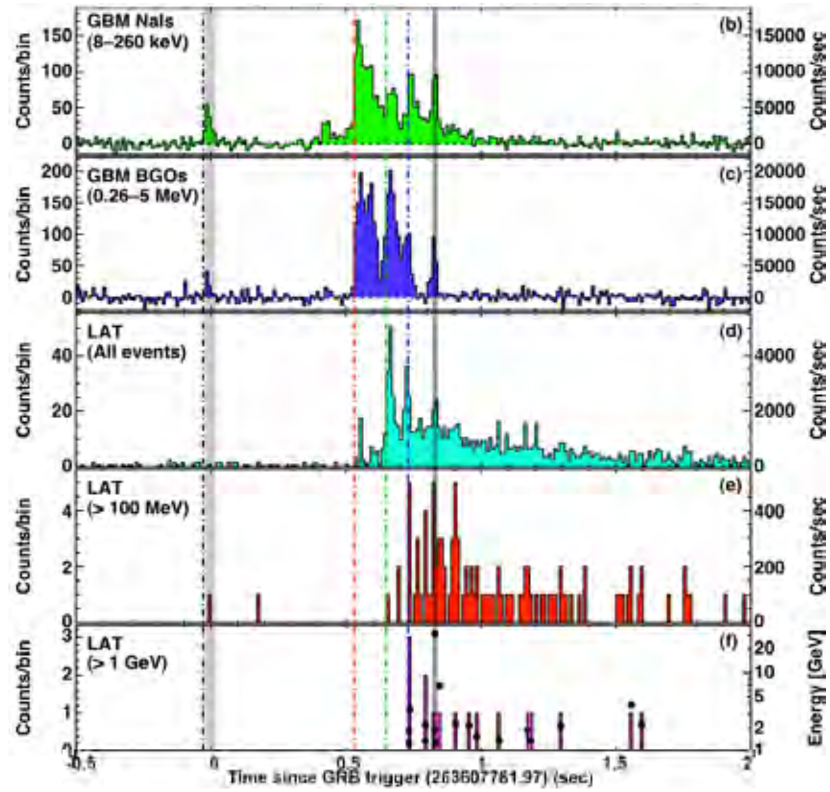

HAWC


HAWC



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

Fermi Observation of GRB 090510

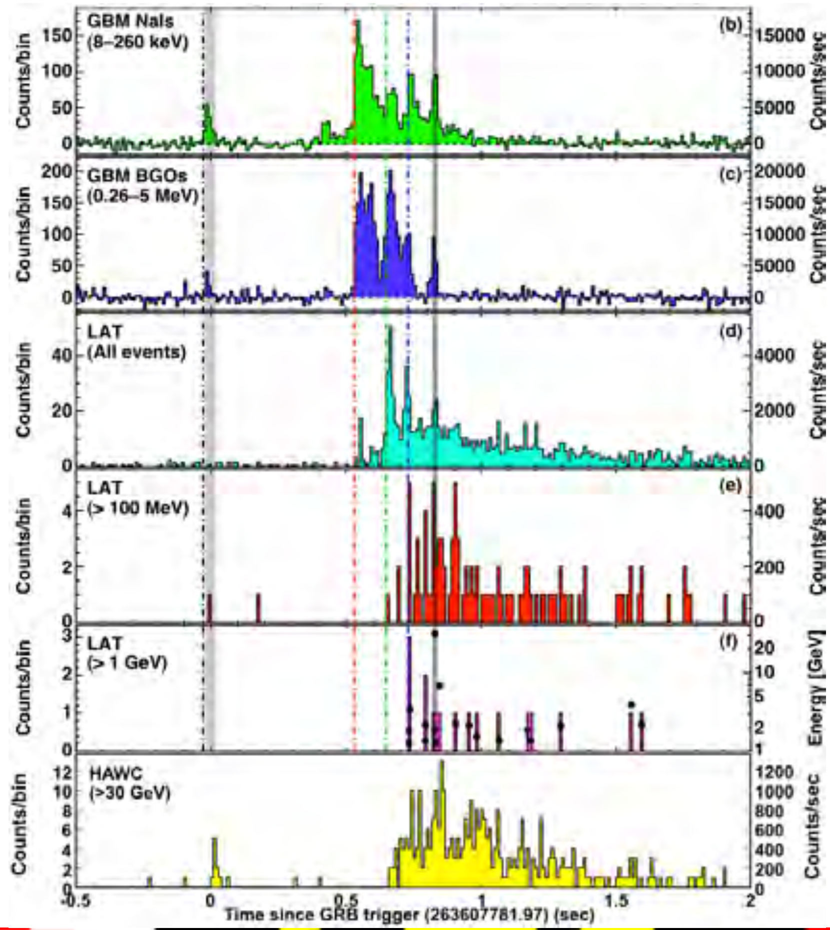


Fermi Observation of GRB 090510 with HAWC

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

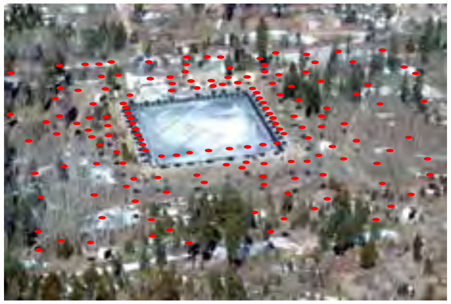
  ~few background events
- Major Improvements!
  - Low-threshold DAQ
  - 10-inch PMTs

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

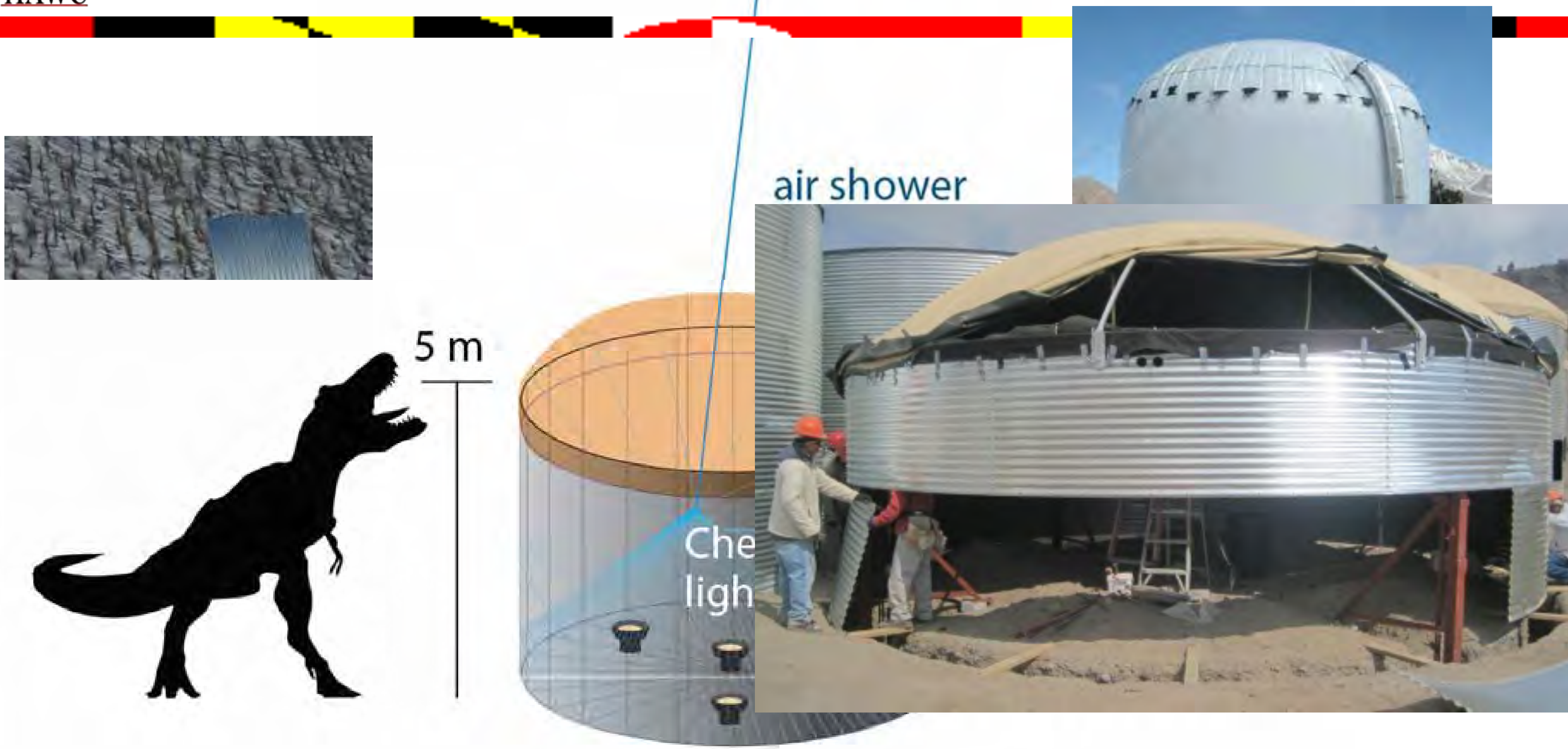


Milagro/Fermi/HAWC Comparison

- HAWC is ~15x more sensitive (sig/√bg) than Milagro
  - HAWC sees the Crab at ~6σ in a day - Milagro took 6 months to see 6σ
- Taking into account the Fermi exposure and signal vs Milagro we find that for galactic sources Fermi is ~15x more sensitive than Milagro.
- HAWC at TeV has approximately the same sensitivity as Fermi has at GeV for galactic sources.

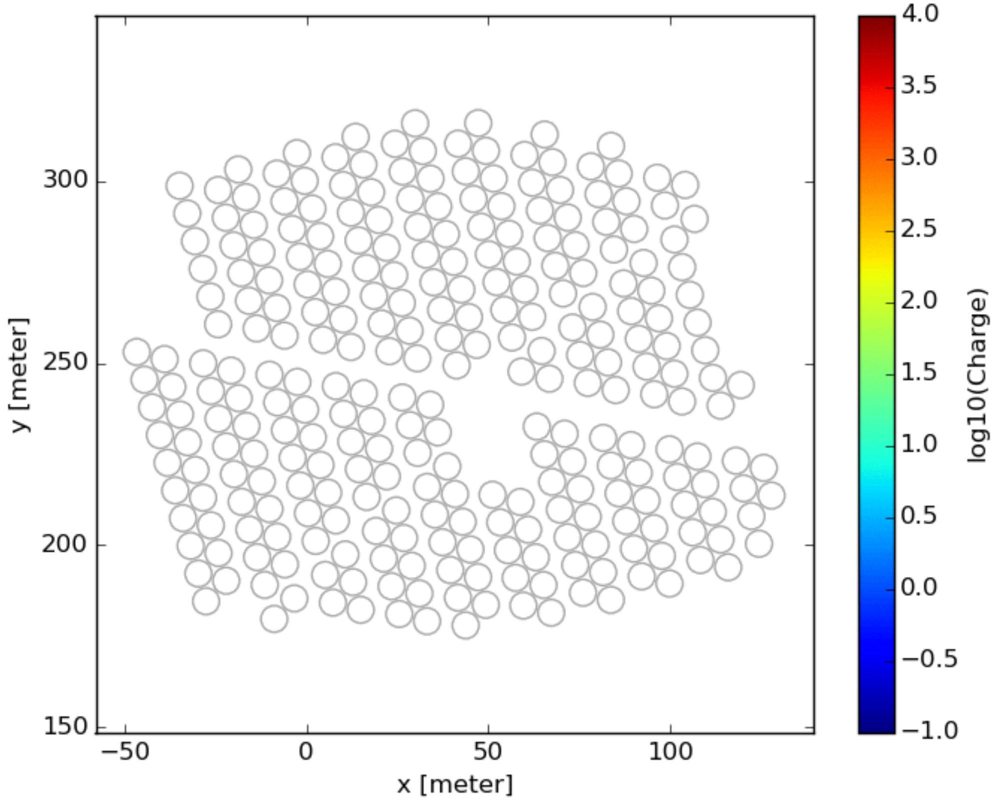


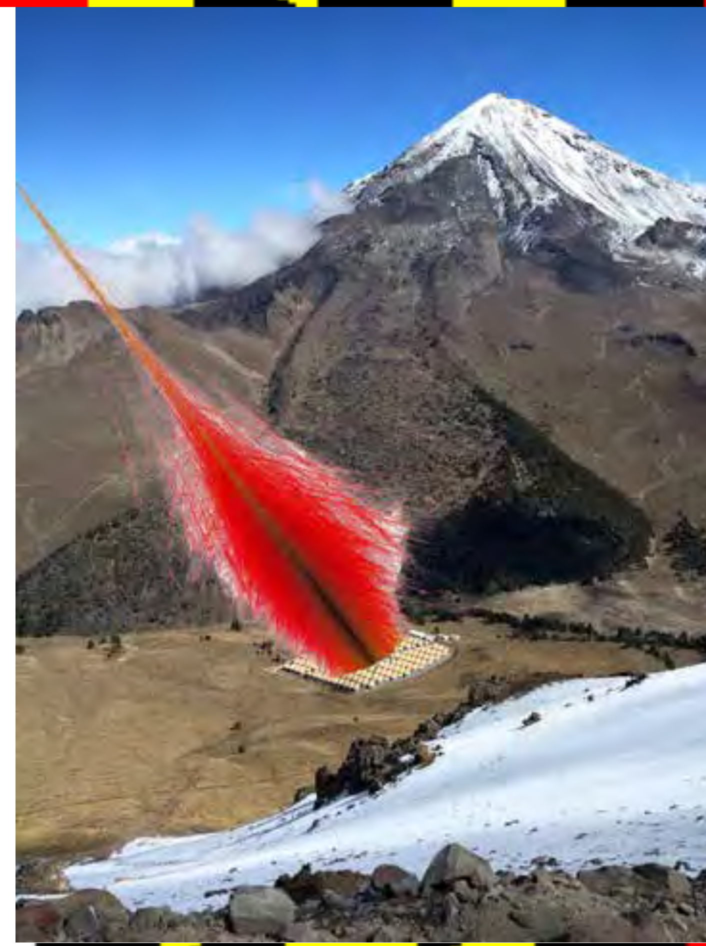
HAWC Tanks



Tank Construction

Angle Reconstruction



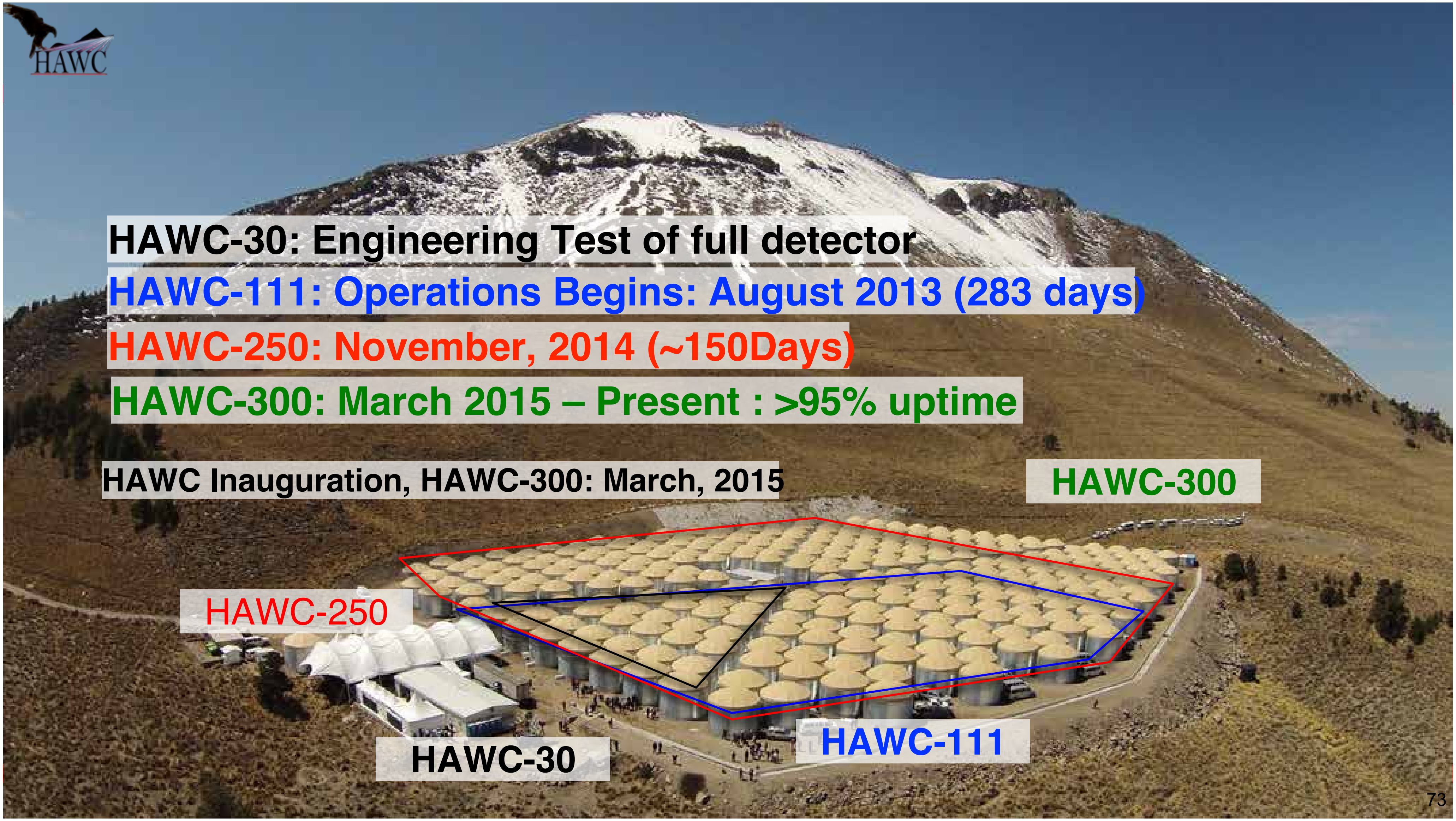


HAWC-30: Engineering Test of full detector

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

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

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

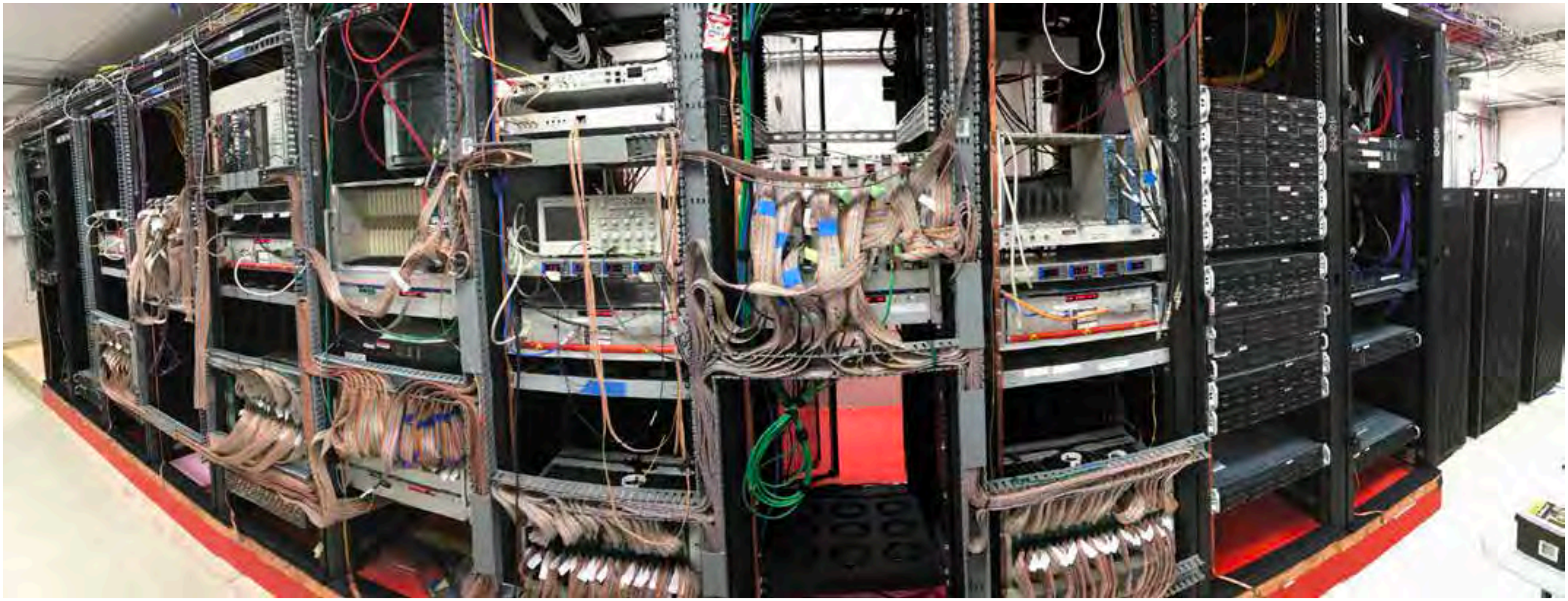



300th WCD tank constructe
~3,900 tanker truck trips


H
A
W
C

Construction Video

HAWC Electronics



HAWC Data

- We read in every PMT hit all the time
  - Raw data rate - 500MB/s -10 VME Backplanes
- Trigger in Software
  - Trigger rate requiring ~30 hits in 300ns is ~25kHz
- Process in near real time
- Rate to disk ~24MB/s -> ~2TB/day (everyday)
- Data is moved by portable disk arrays to UNAM
  - About once a week it's driven to Mexico City
  - Moved over Internet II to UMD
- Raw Data plus processed data is stored in Mexico and Maryland
  - About a petabyte a year
  - Currently we have about 4 PB of storage at UMD

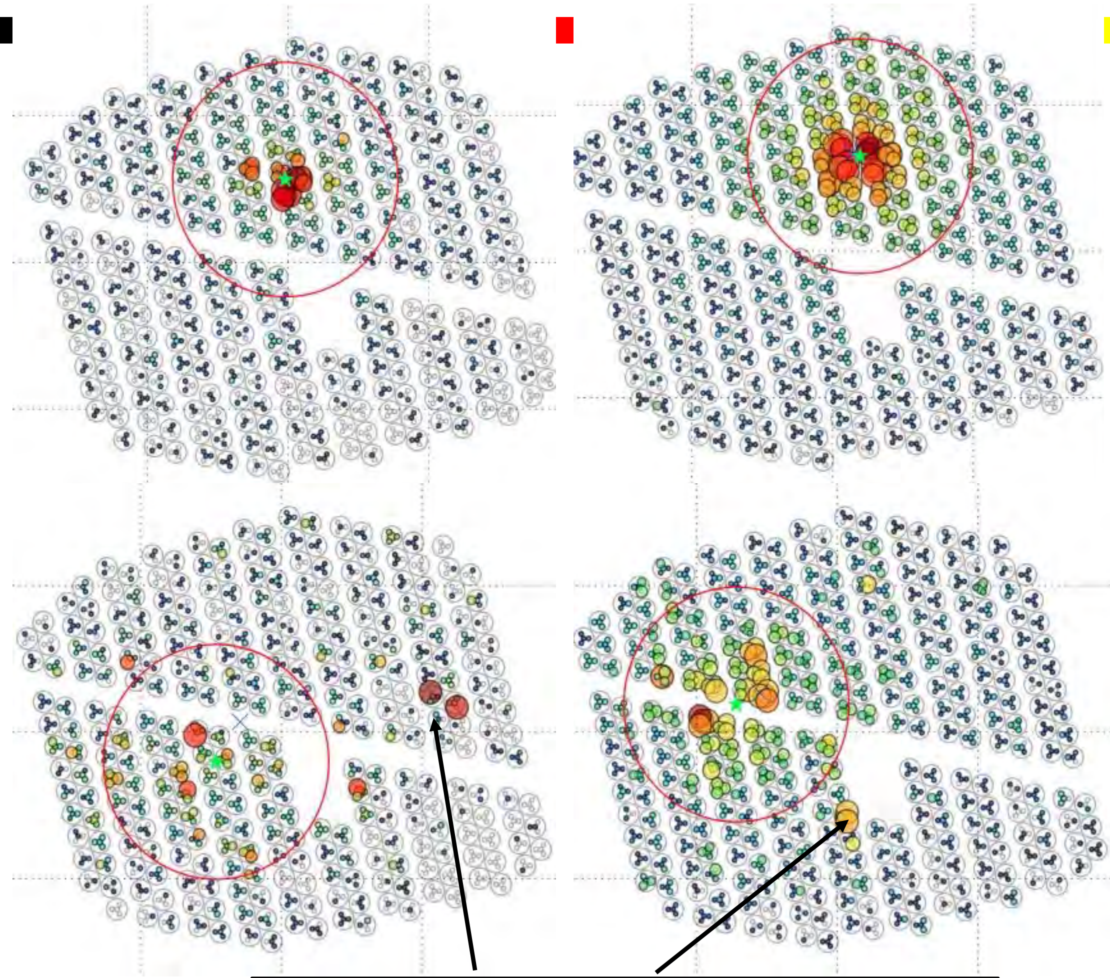
The Data Bus

Gamma Hadron Separation (MC)

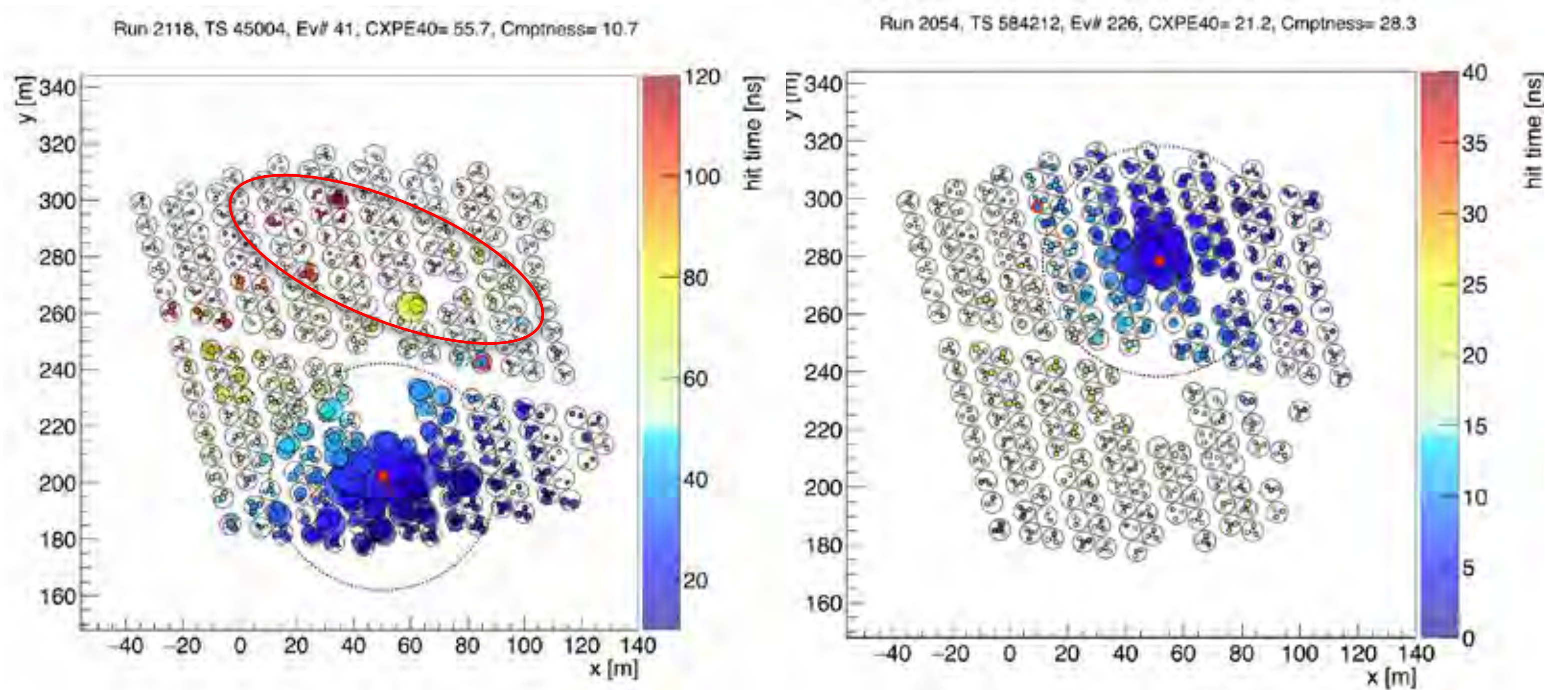
Gammas

Protons

Monte Carlo Simulation



HAWC-250 Data



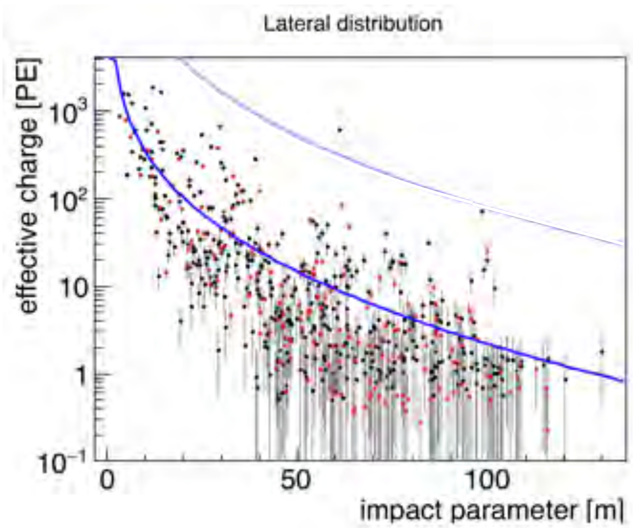
Hadron Shower (off source)

HAWC Data

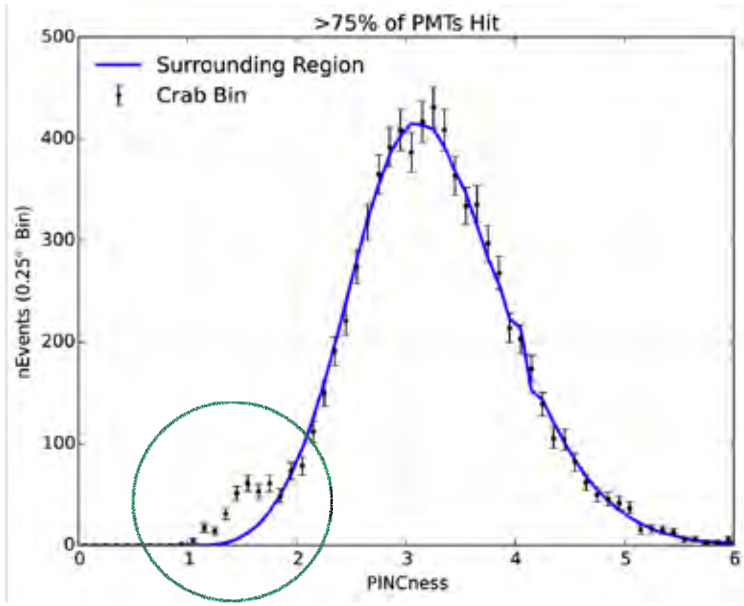
Likely Gamma Shower (Crab event)

Gamma - Hadron Separation

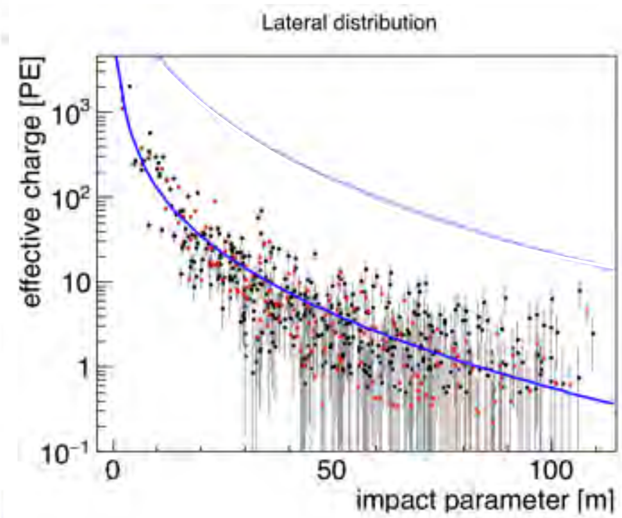
hadronic event



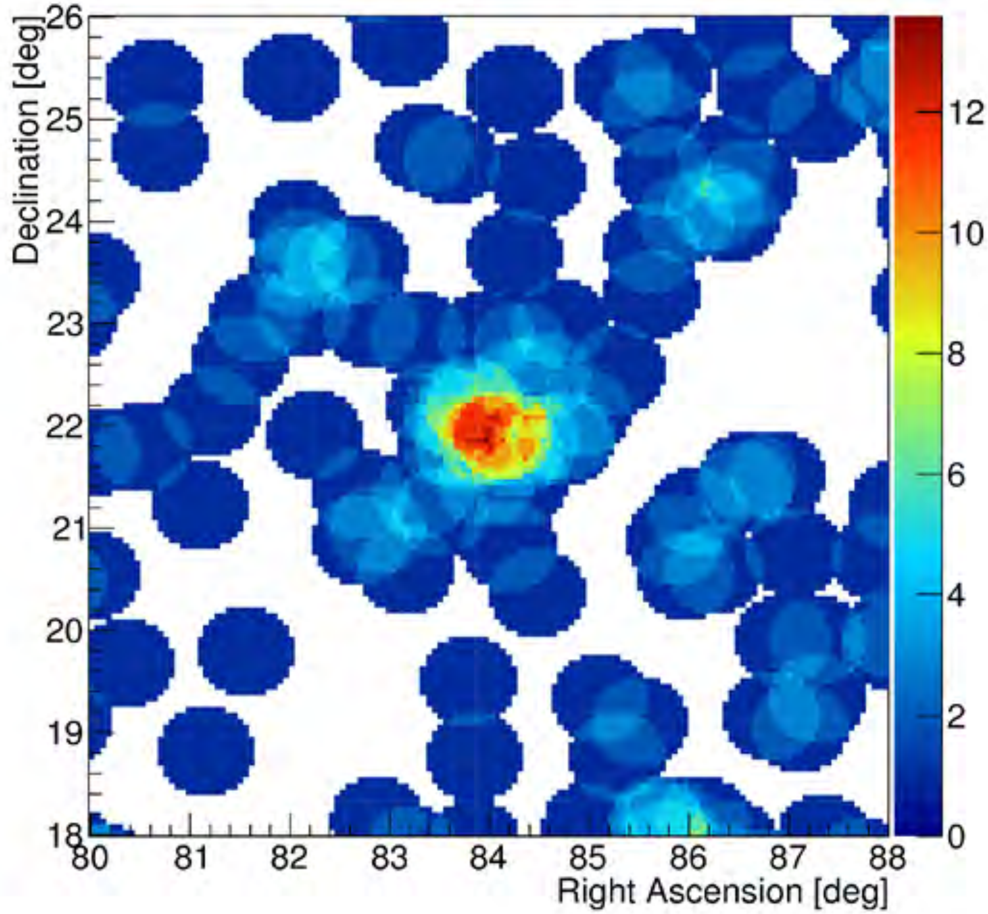
gamma/hadron parameter



gamma ray-like event



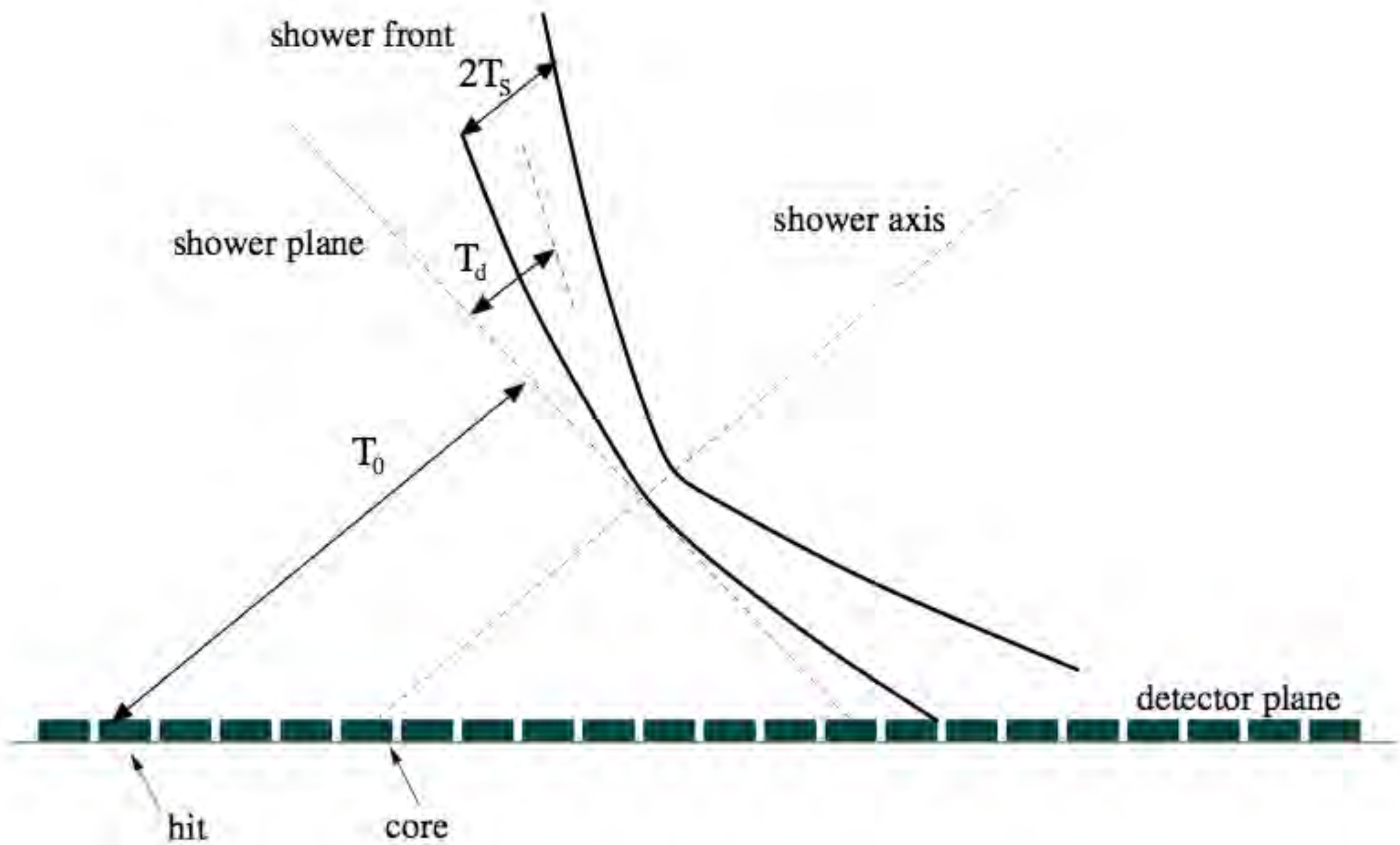
Photon rich sample from the Crab



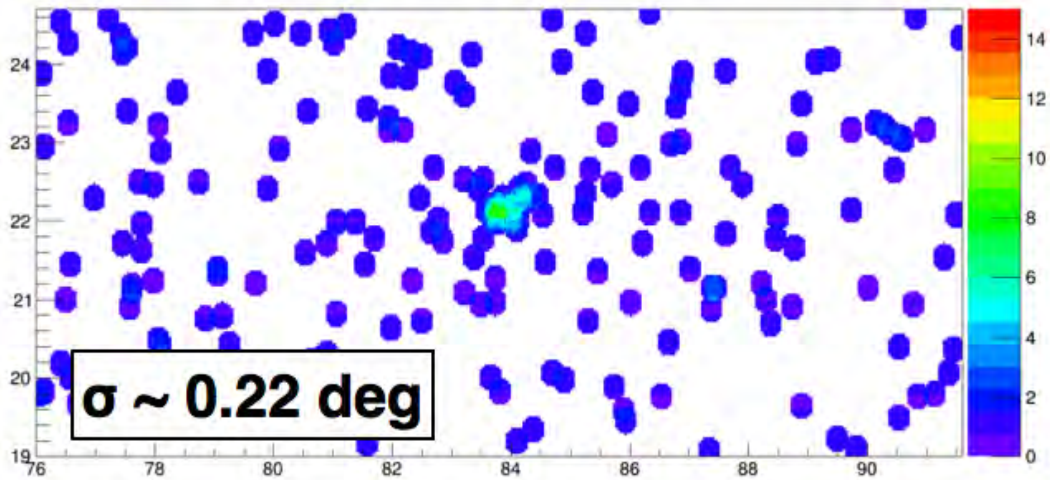
With Strong Photon Cut

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

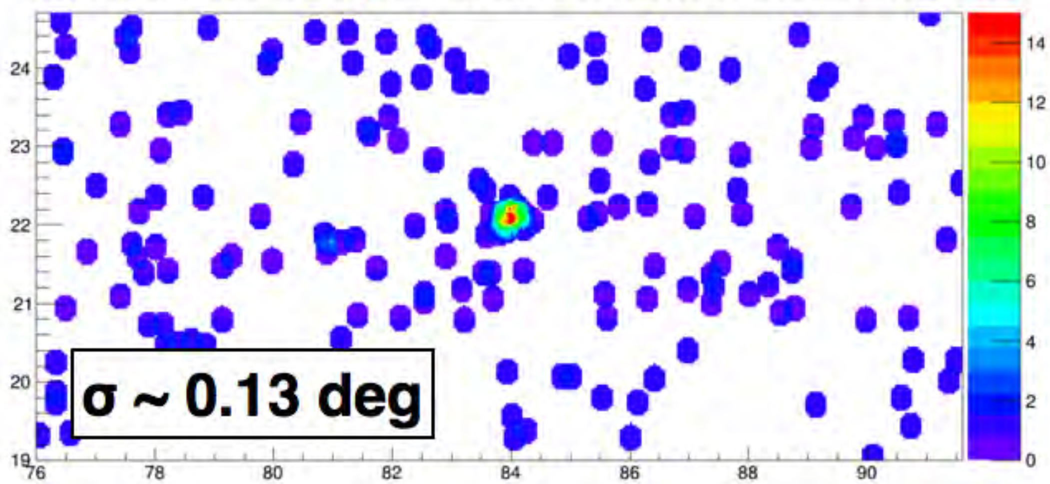
Shower Curvature



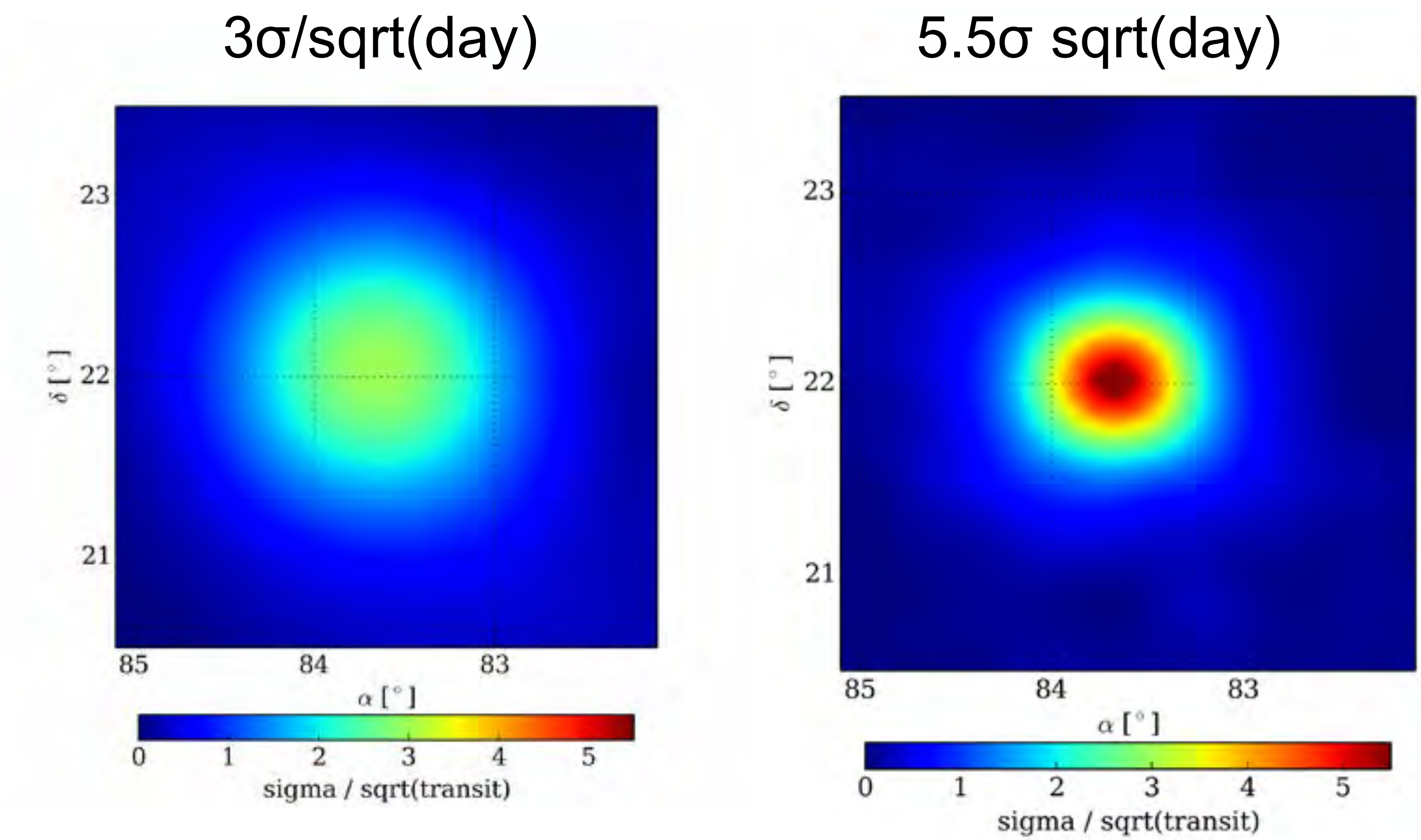
Gamma-Pure Sample: Before Curvature Correction Fix



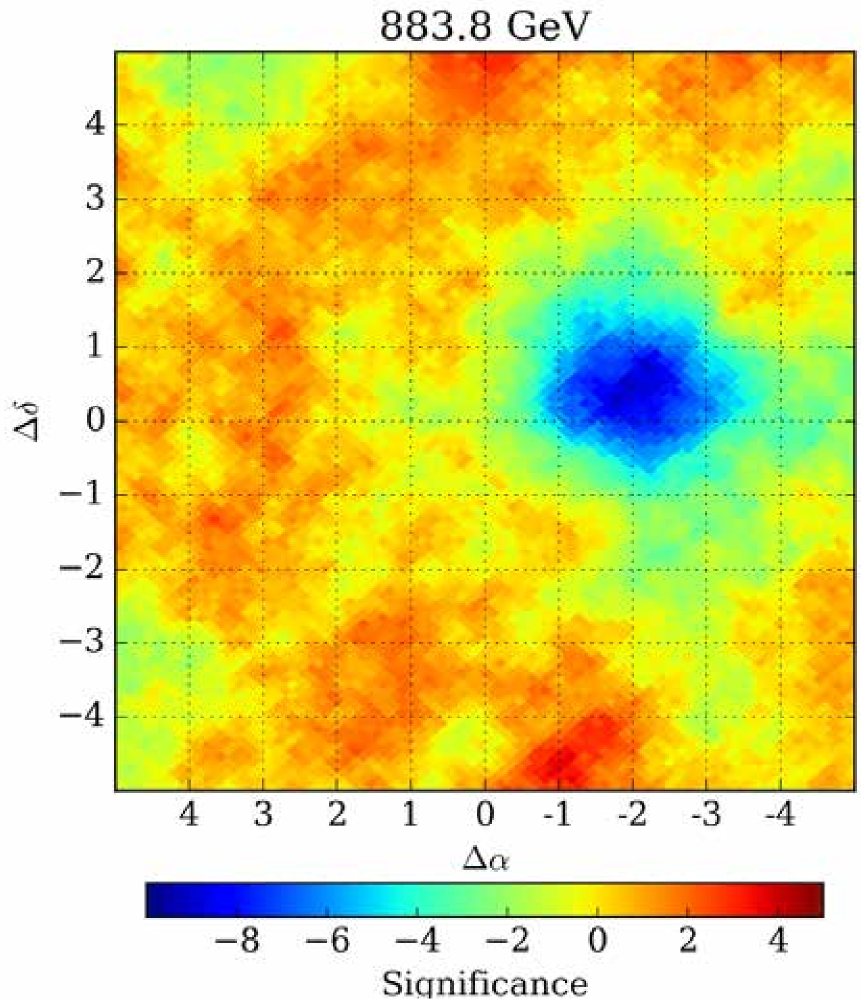
Gamma-Pure Sample: After Curvature Correction Fix



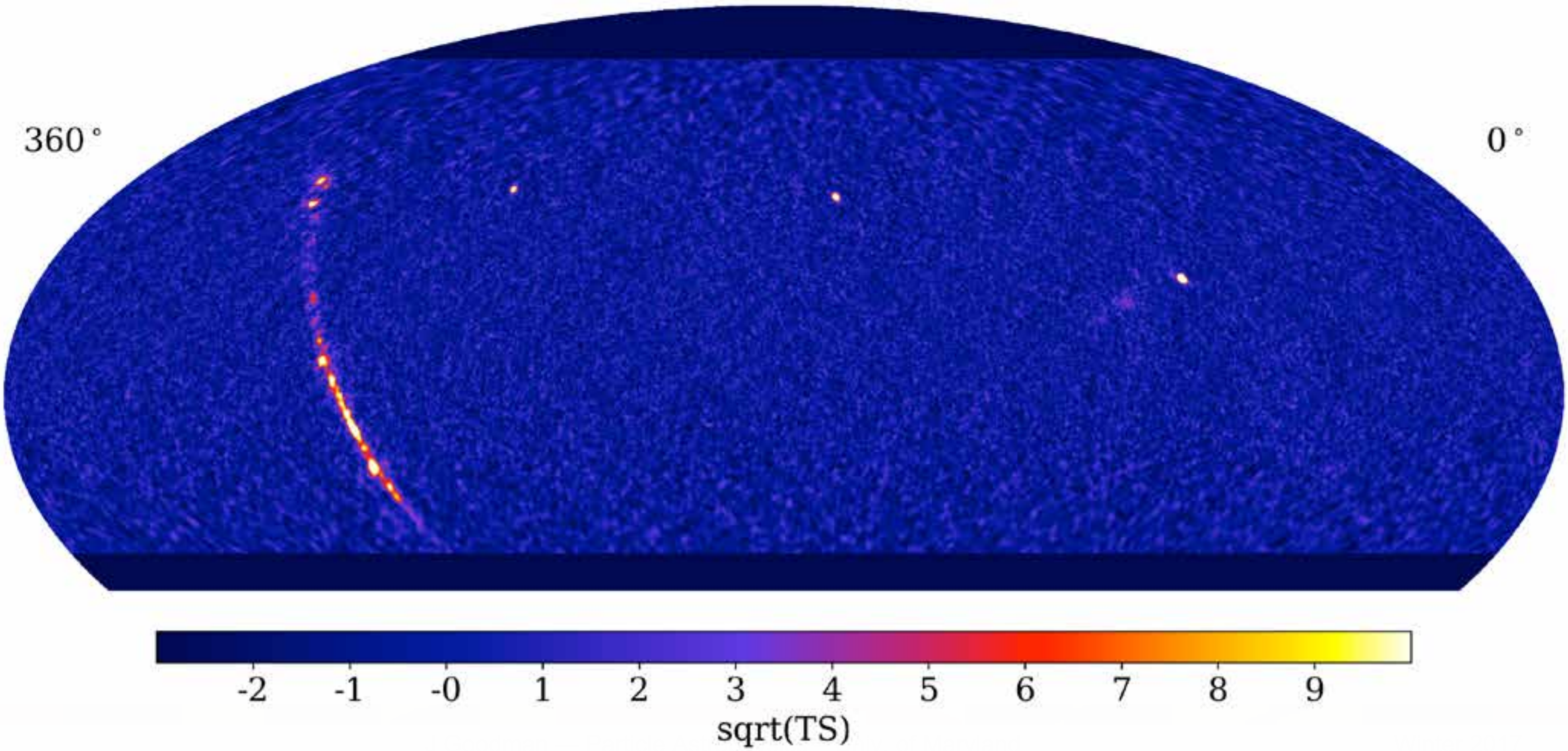
Significant Improvement



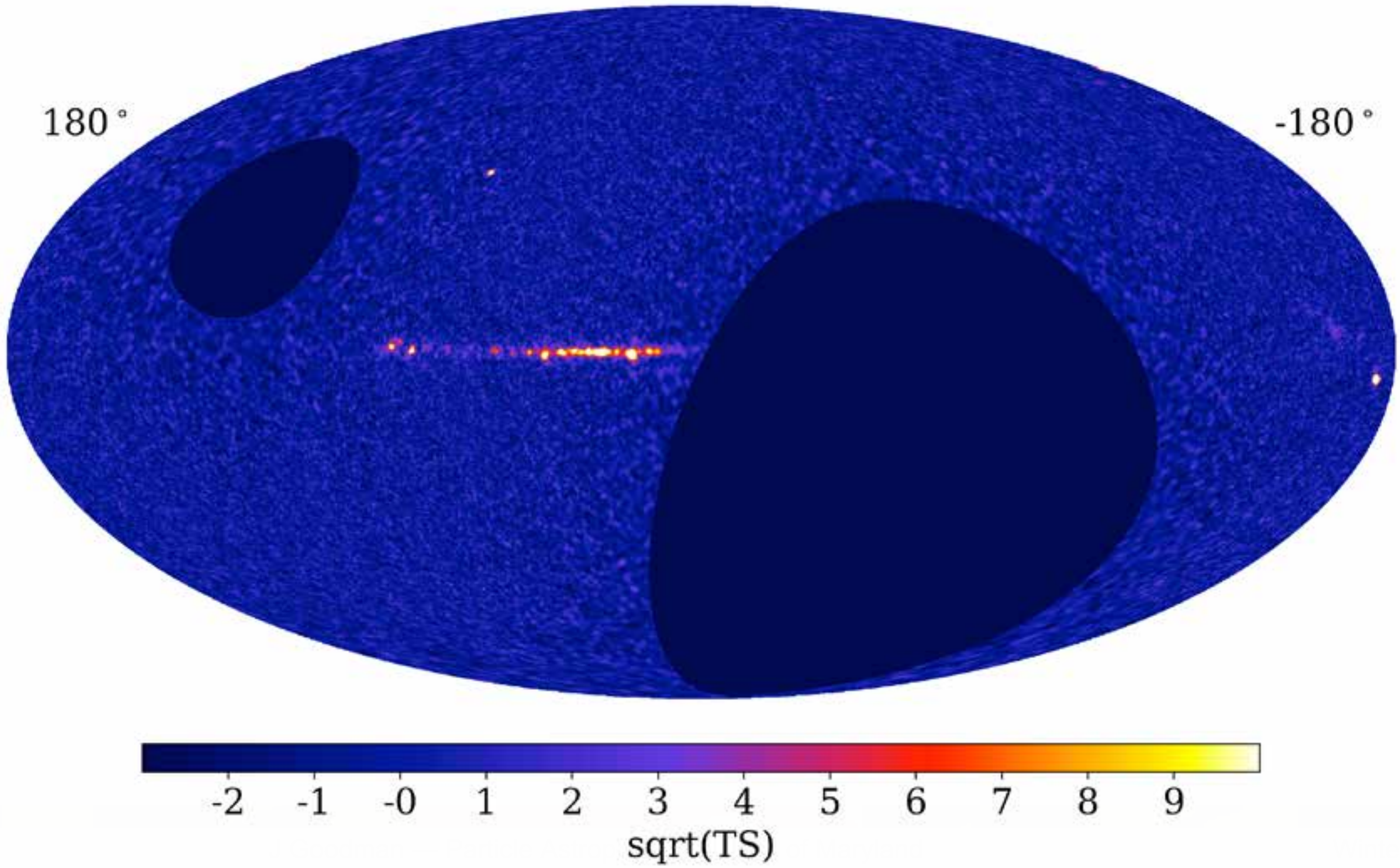
Moon Shadow



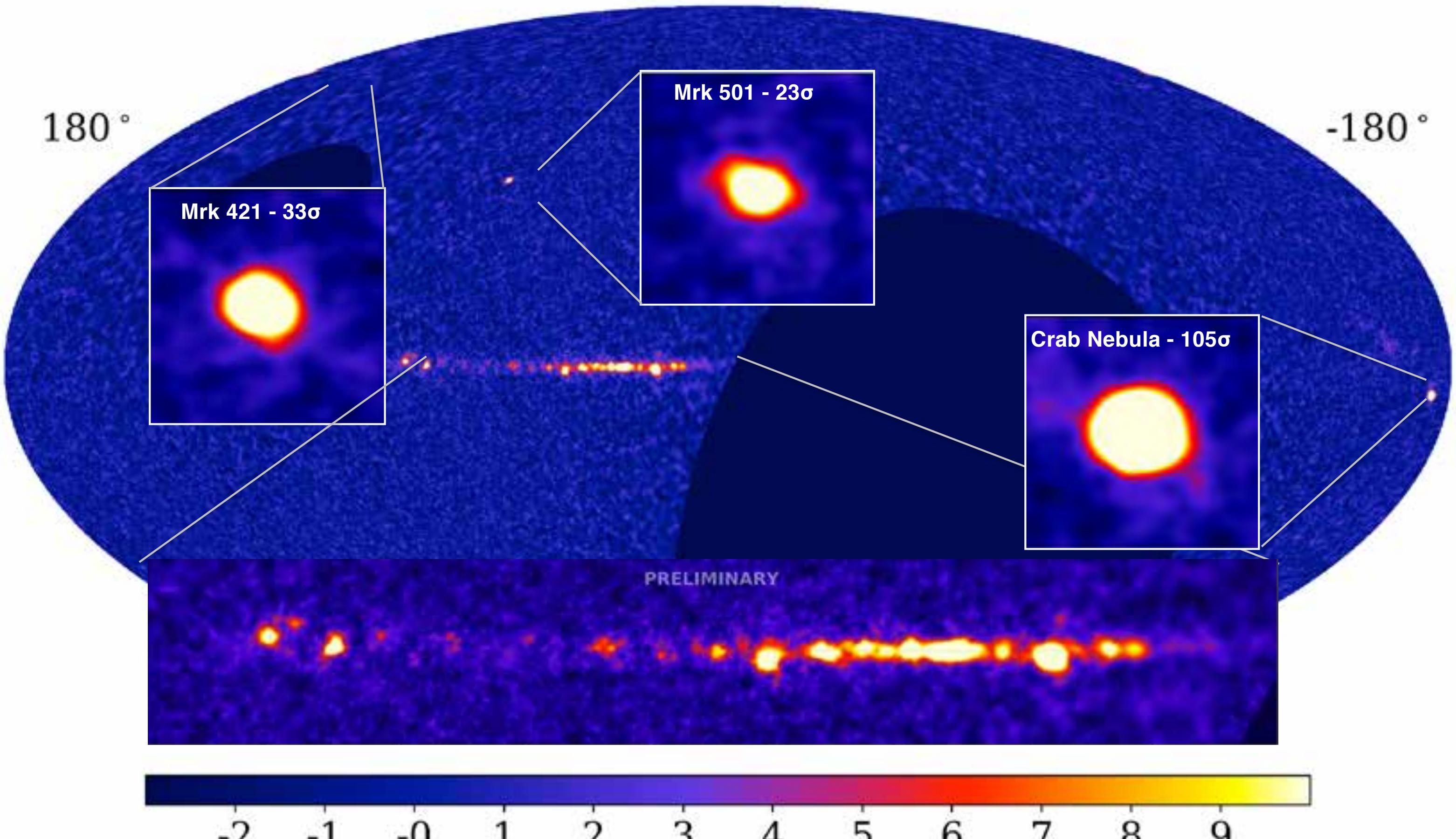
17 Months of Data



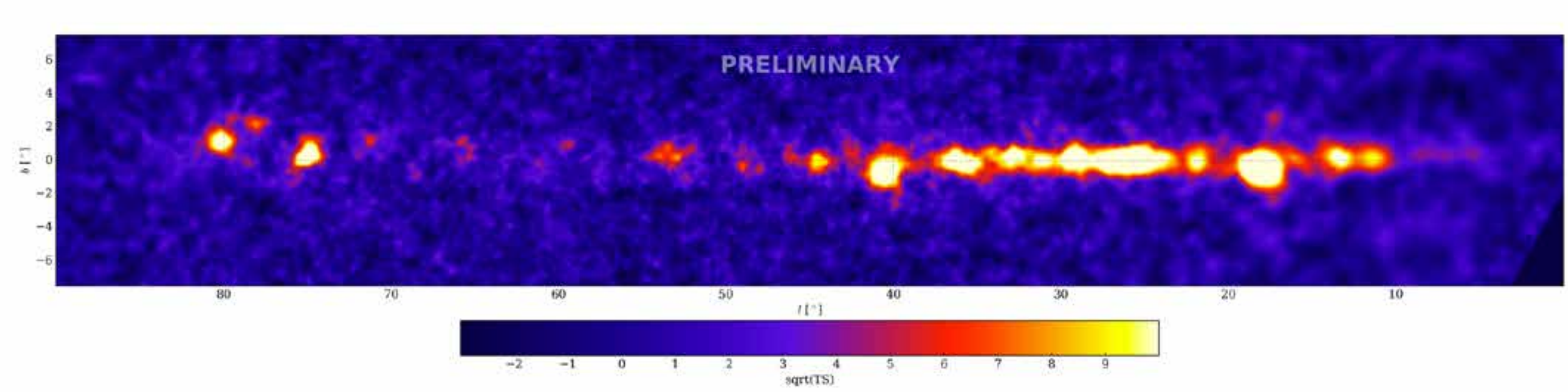
17 Months of Data



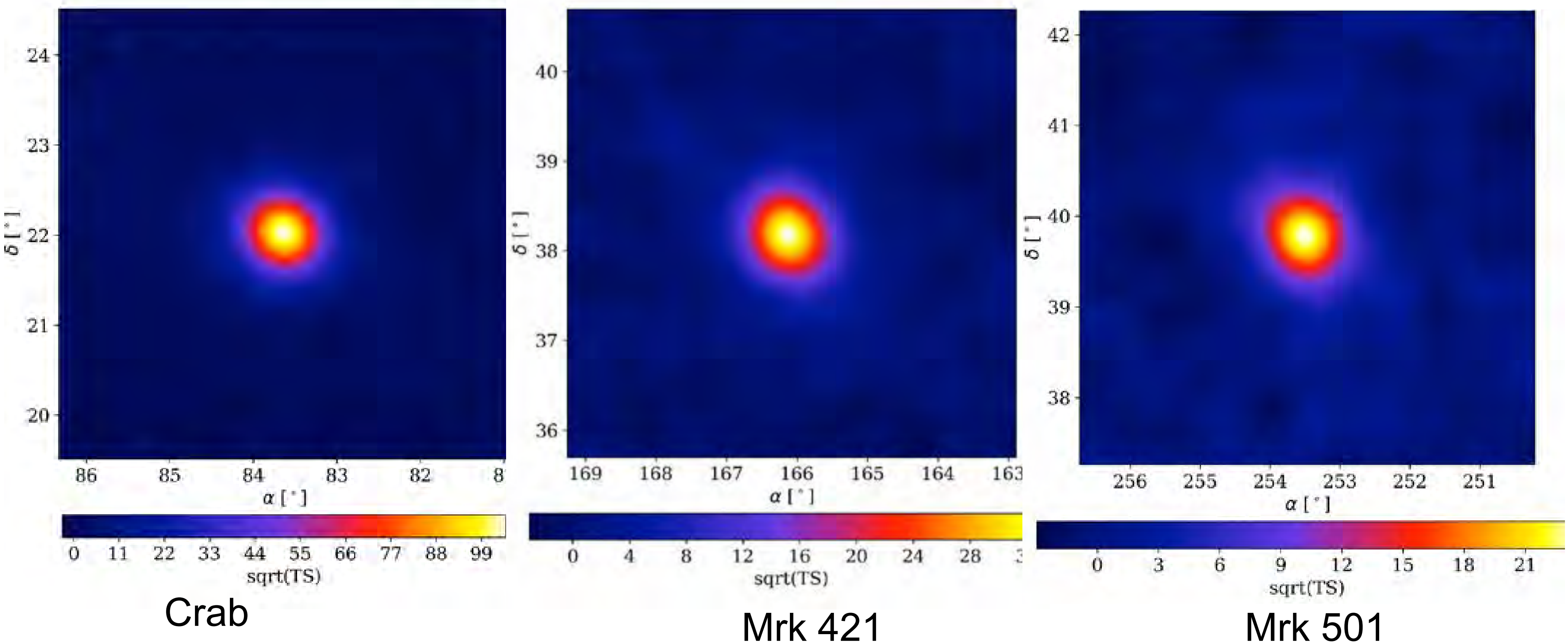
17 Months of Data



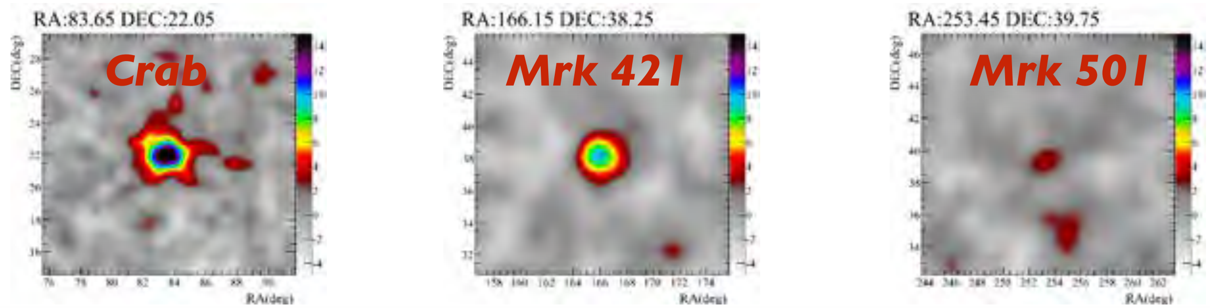
17 Months of Data

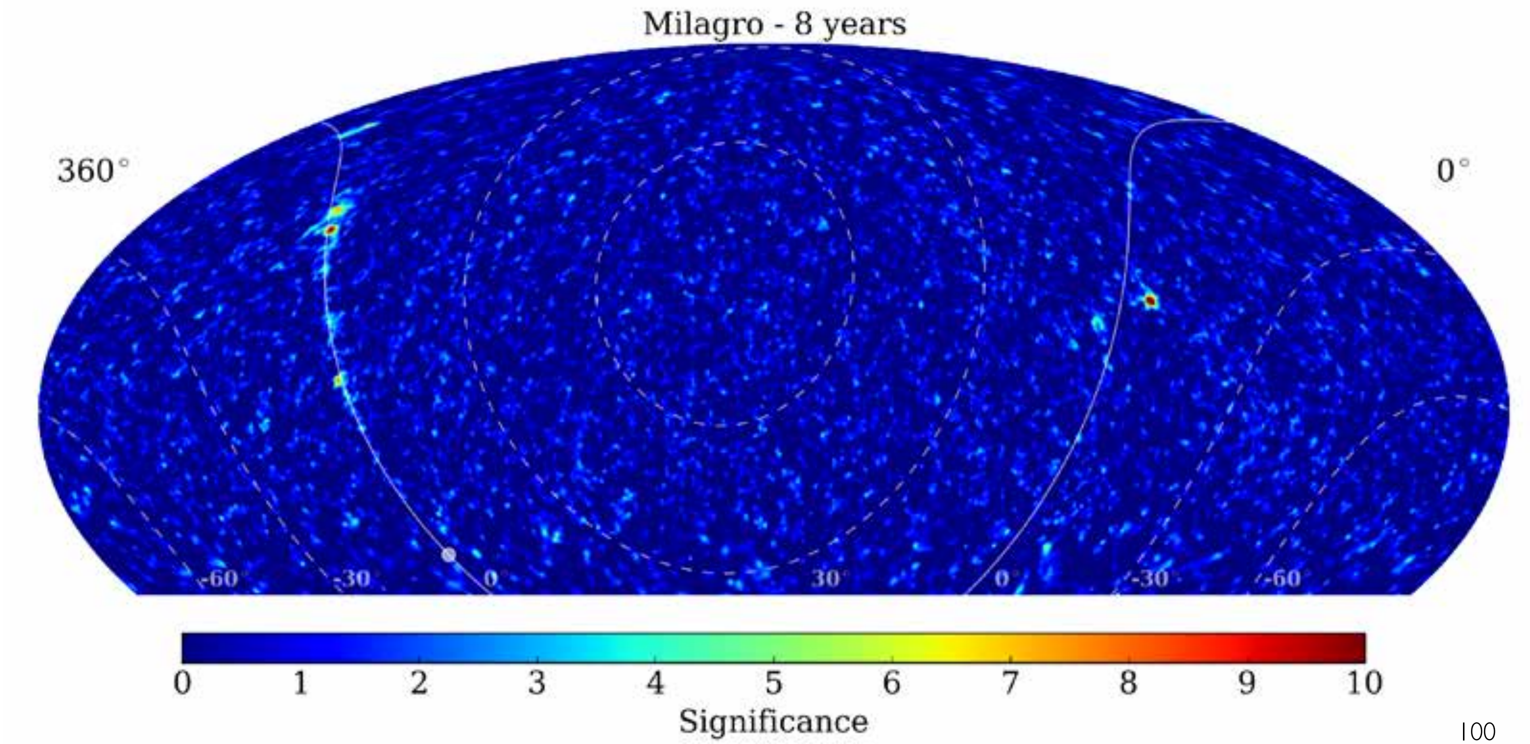


17 Months of Data

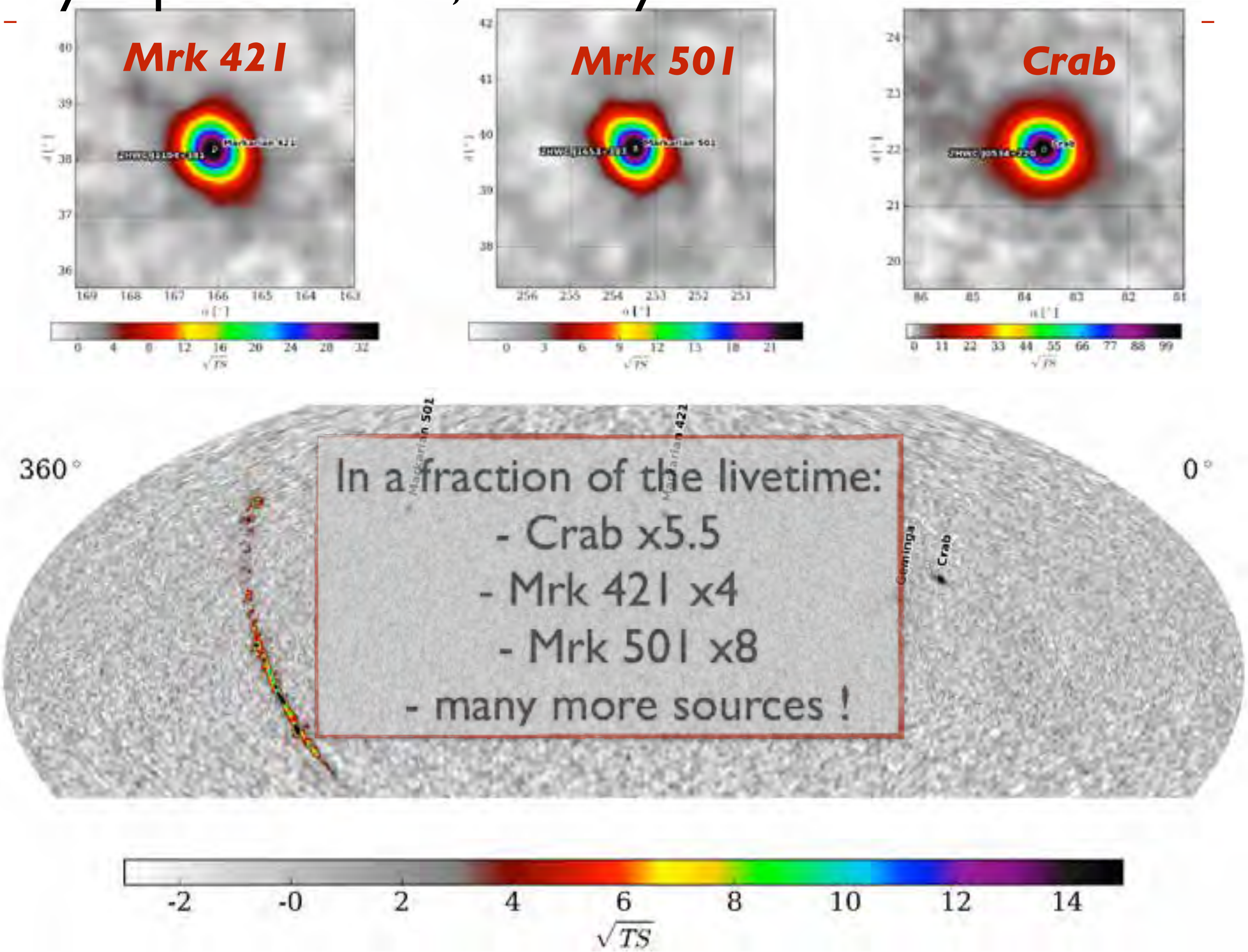


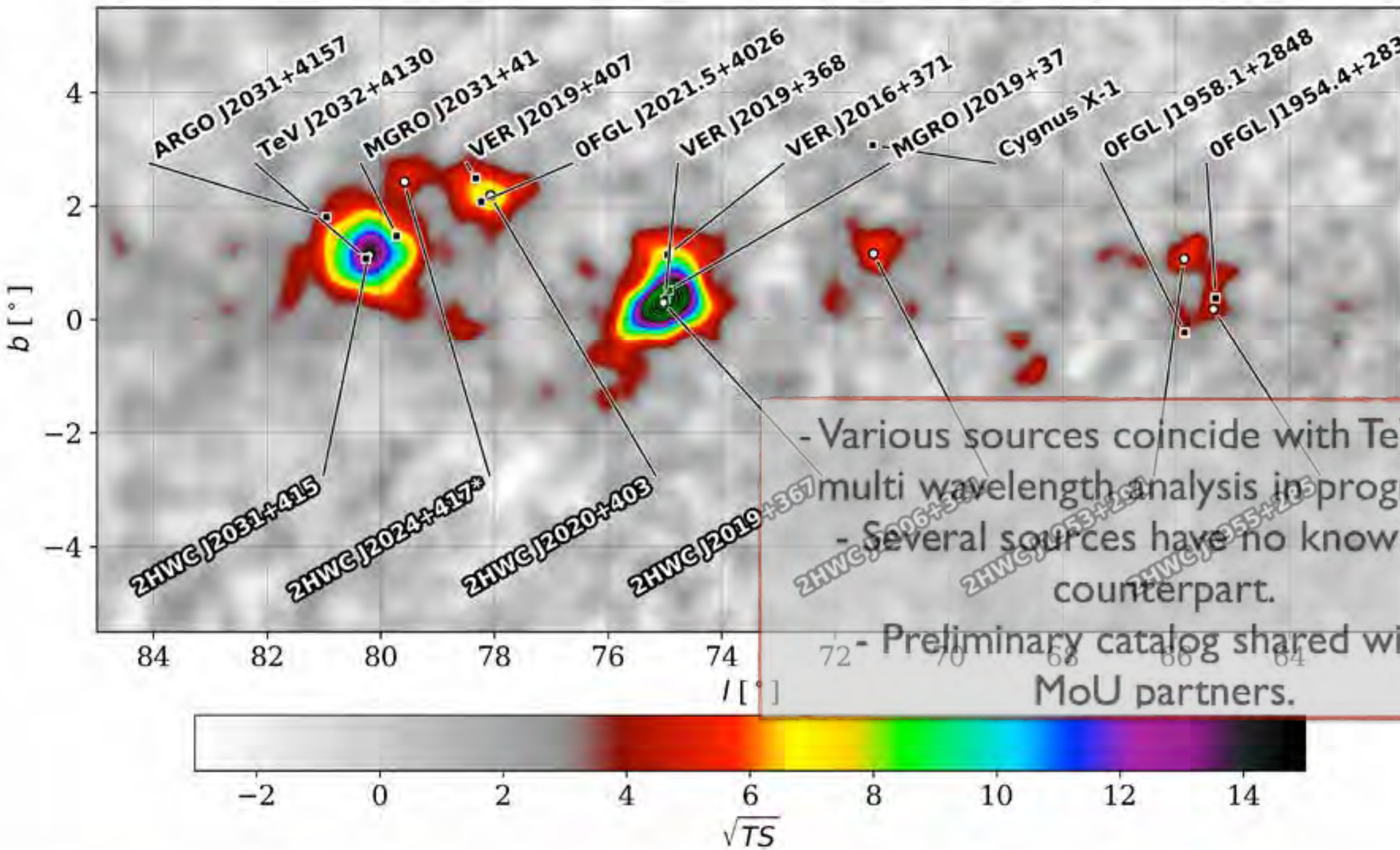
Skymap — Milagro, 8 years



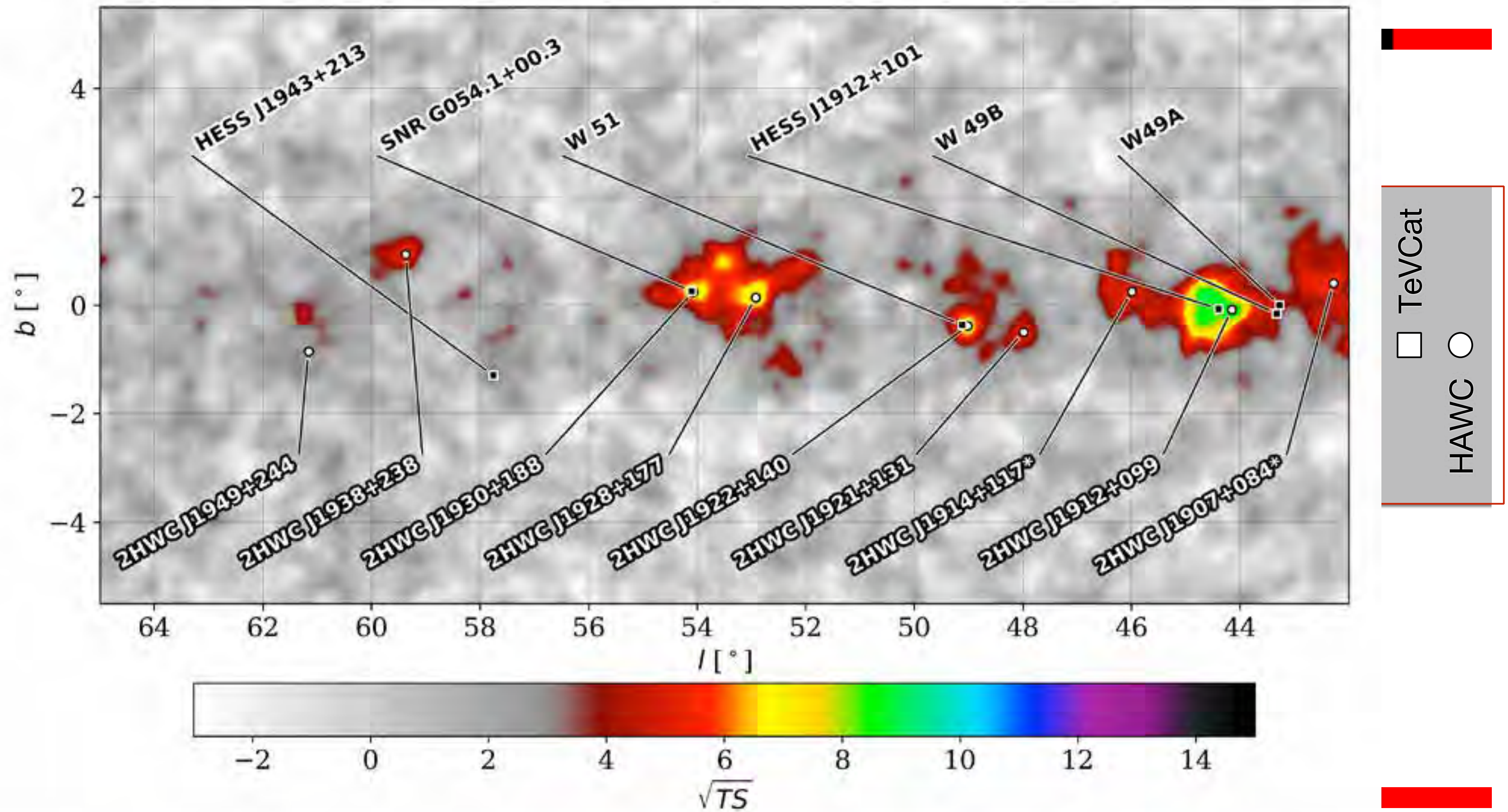


Skymap — HAWC, 507 days

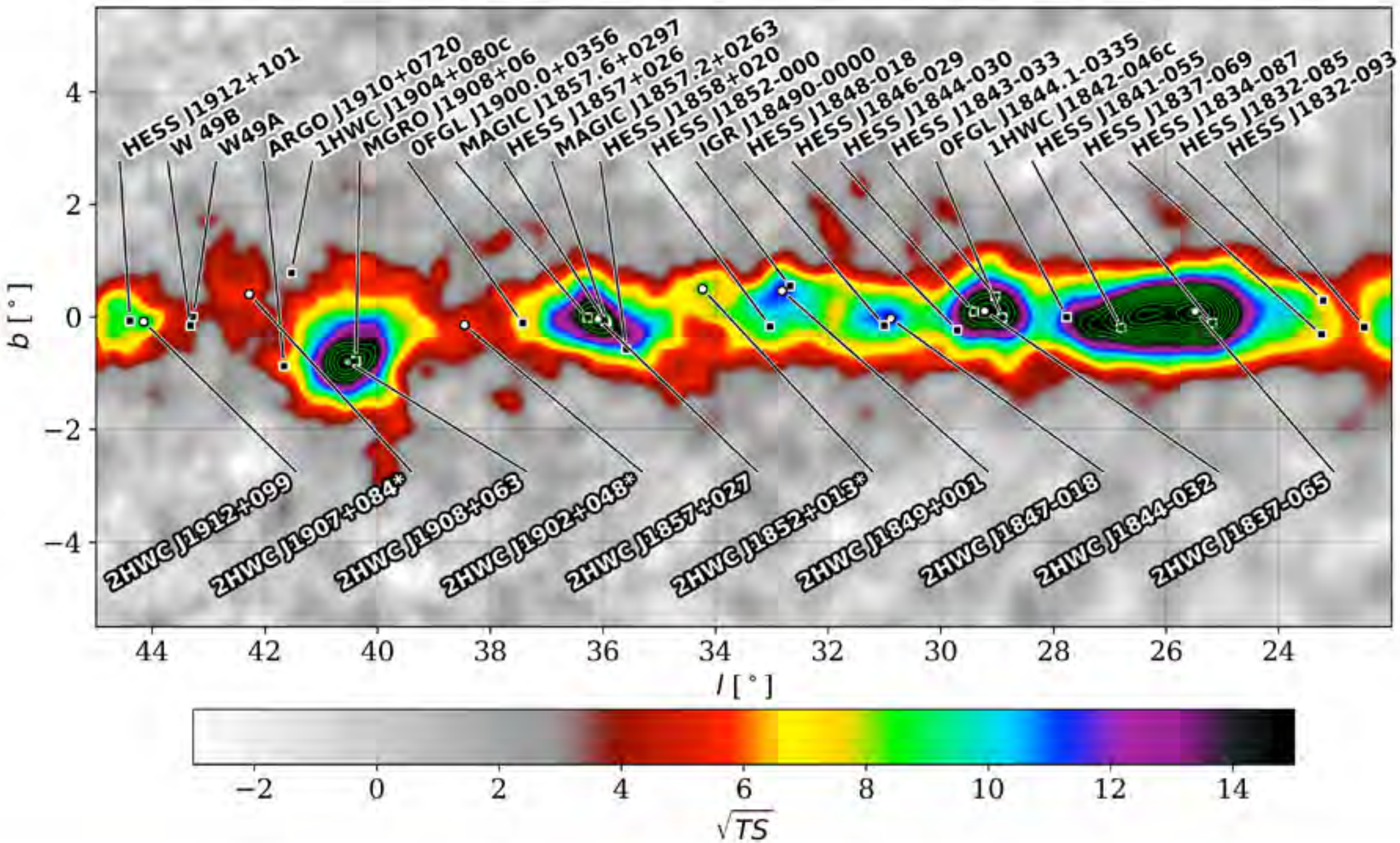


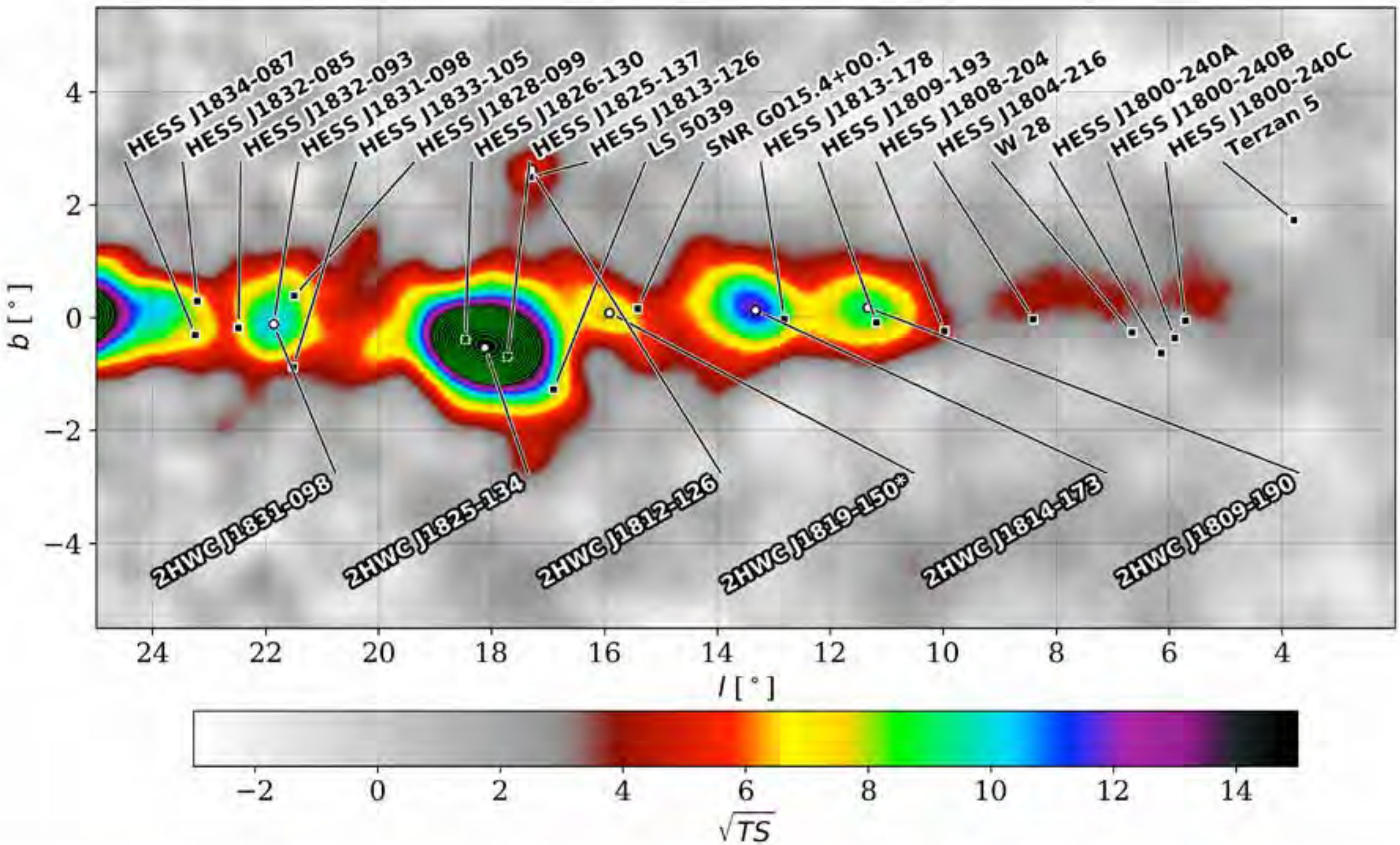


- Various sources coincide with TeVCat, multi wavelength analysis in progress.
- Several sources have no known TeV counterpart.
- Preliminary catalog shared with 8 MoU partners.

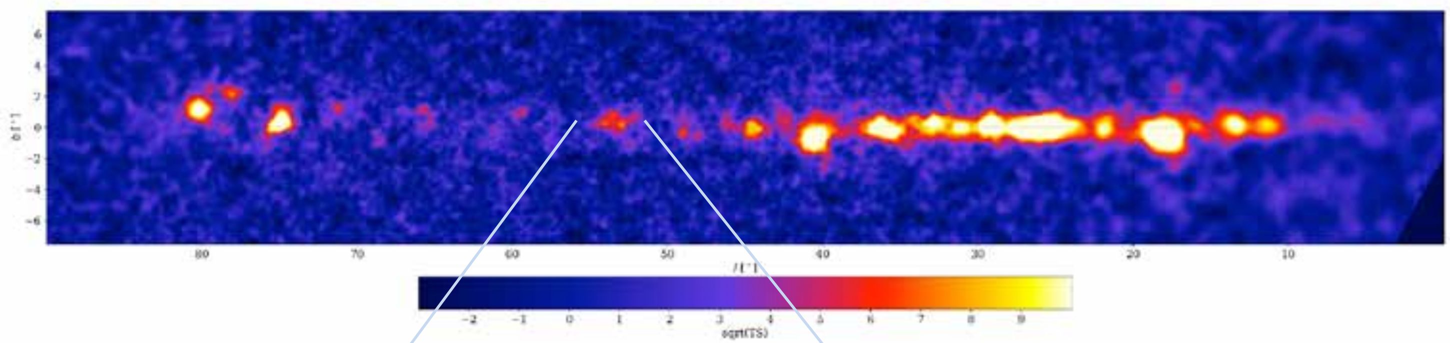


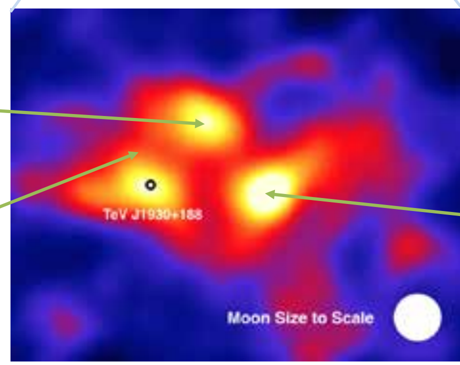
HAWC
HESS J1943+213
SNR G054.1+00.3
W 51
HESS J1912+101
W 49B
W49A
2HWC J1949+244
2HWC J1938+238
2HWC J1930+188
2HWC J1928+177
2HWC J1922+140
2HWC J1921+131
2HWC J1914+117*
2HWC J1912+099
2HWC J1907+084*
b [°]
4
2
0
−2
−4
64
62
60
58
56
54
52
50
48
46
44
l [°]
−2
0
2
4
6
8
10
12
14
√TS
TeVCat
HAWC


HESS J1912+101
W 49B
W49A
ARGO J1910+0720
1HWC J1904+080c
MGRO J1908+06
0FGL J1900.0+0356
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 J1843-033
0FGL J1844.1-0335
1HWC J1842-046c
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1832-085
HESS J1832-093
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
b [°]
l [°]
√TS


HESS J1834-087
HESS J1832-085
HESS J1832-093
HESS J1831-098
HESS J1833-105
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
HESS J1800-240A
HESS J1800-240B
HESS J1800-240C
Terzan 5
2HWC J1831-098
2HWC J1825-134
2HWC J1812-126
2HWC J1819-150*
2HWC J1814-173
2HWC J1809-190
b [°]
l [°]
√TS

HAWC view of the Galactic Plane





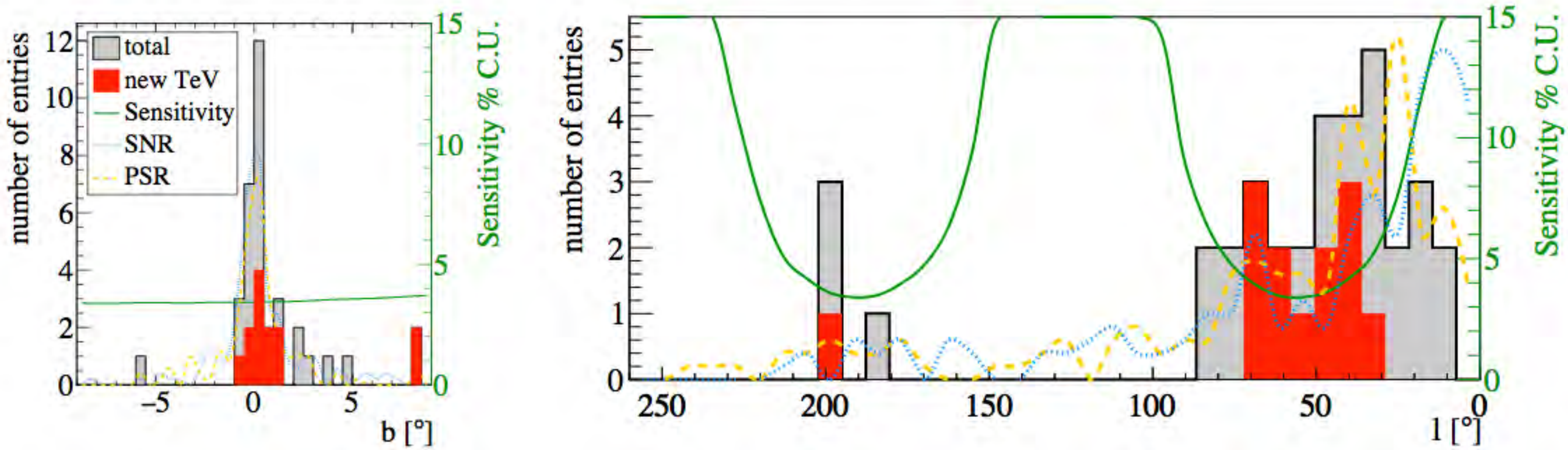
Association unclear

Supernova remnant with very energetic pulsar

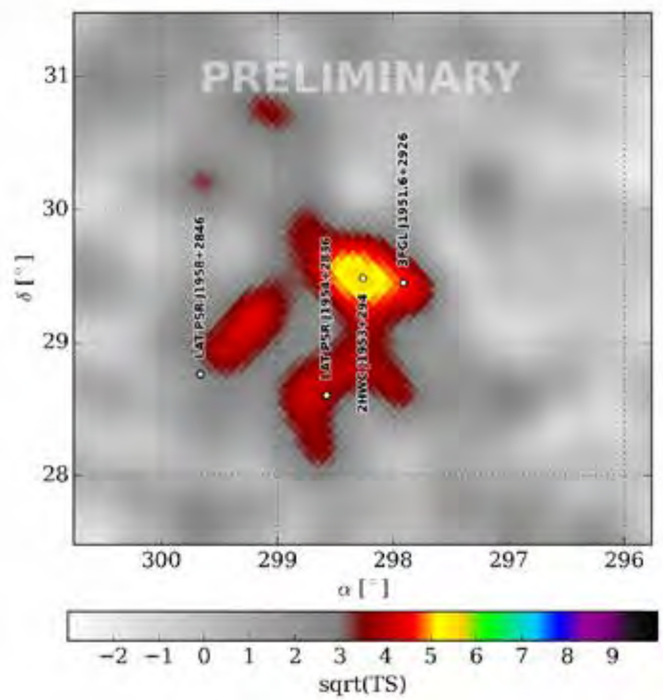
Pulsar ~8kpc (26,000 ly) away

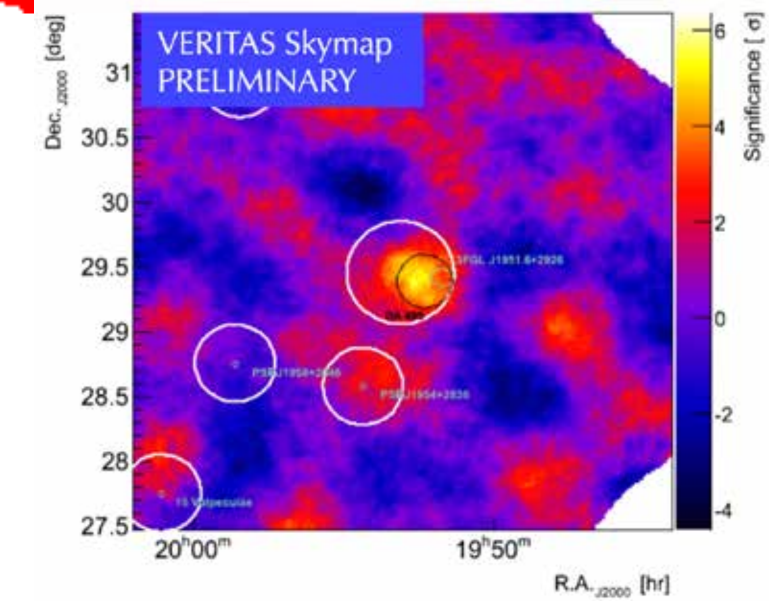
- ~40 sources seen in first year
- 25% are new

Survey Results



2HWC J1953+294 - 12 months of data



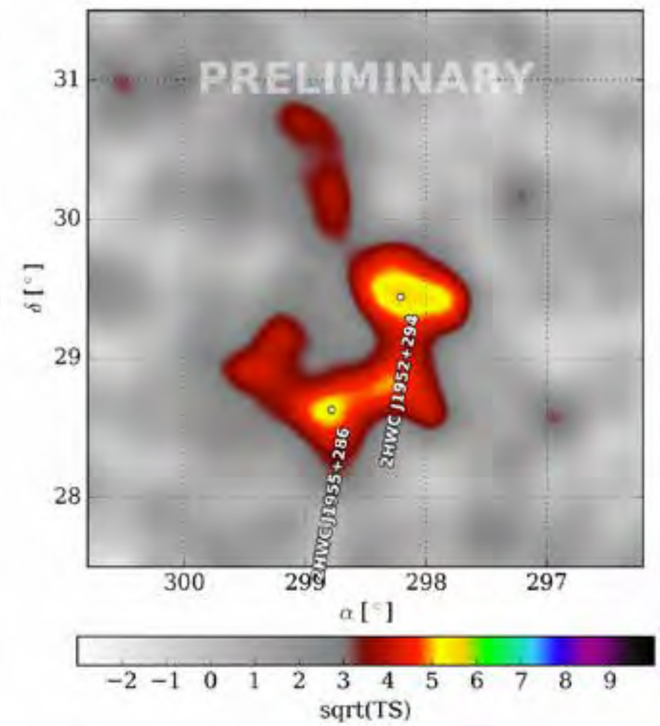


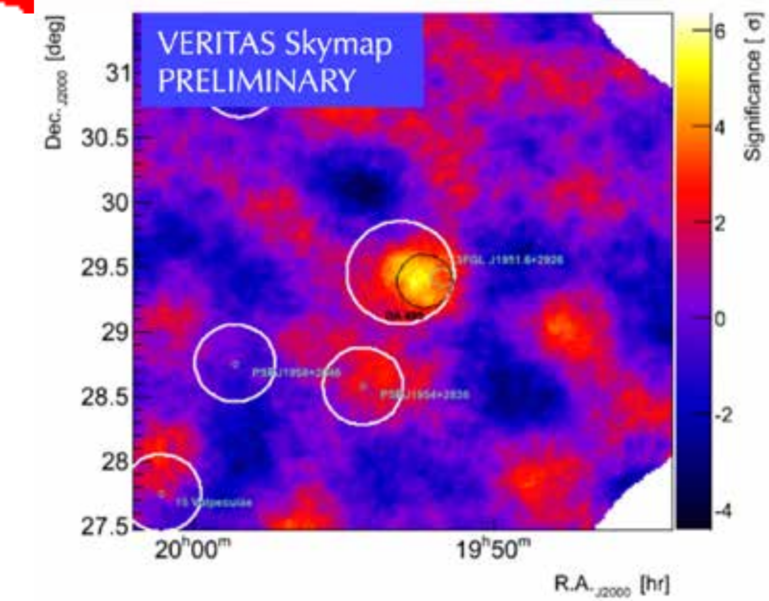
Preliminary Reported errors are stat. only

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

- **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





Preliminary
Reported errors are stat. only

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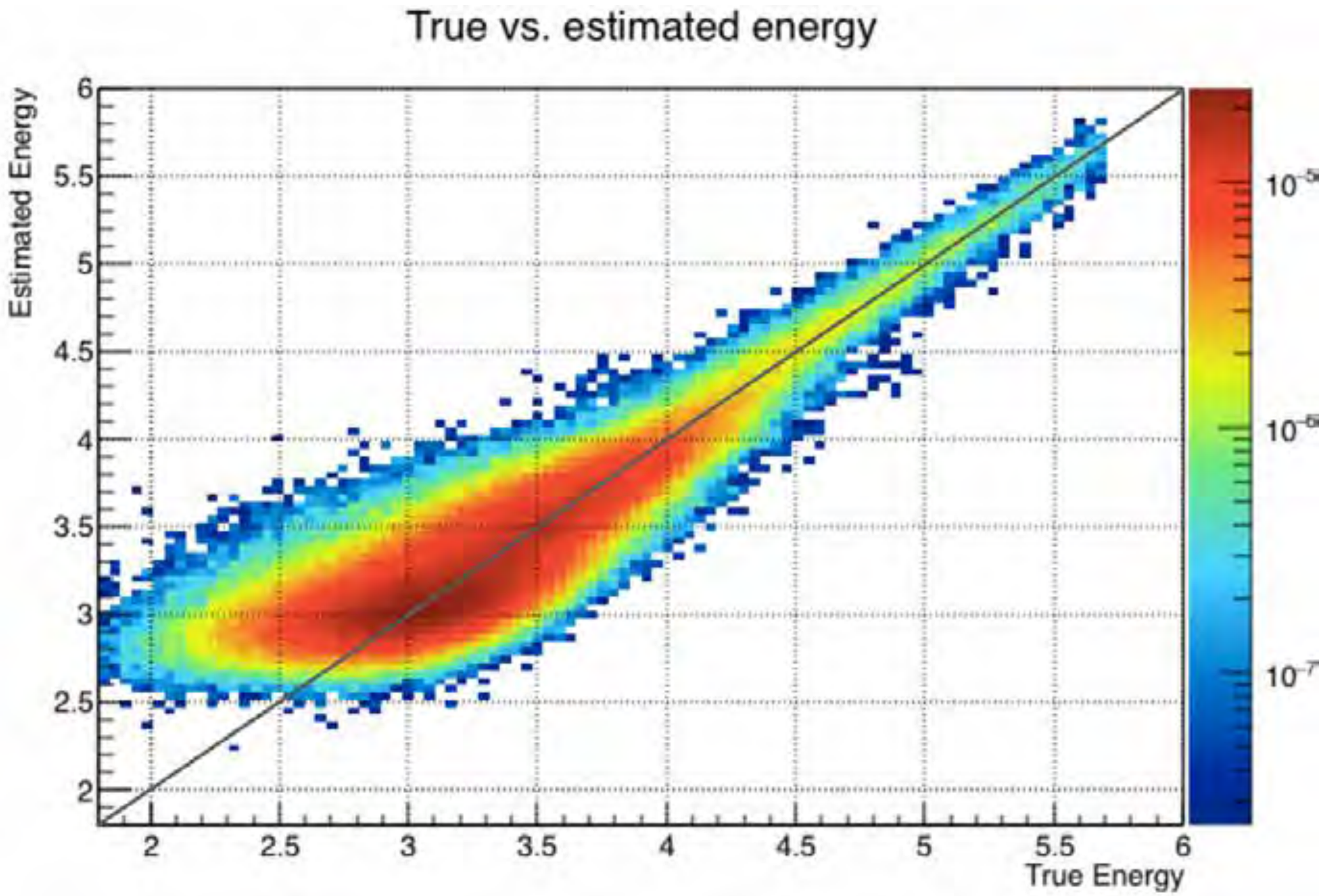
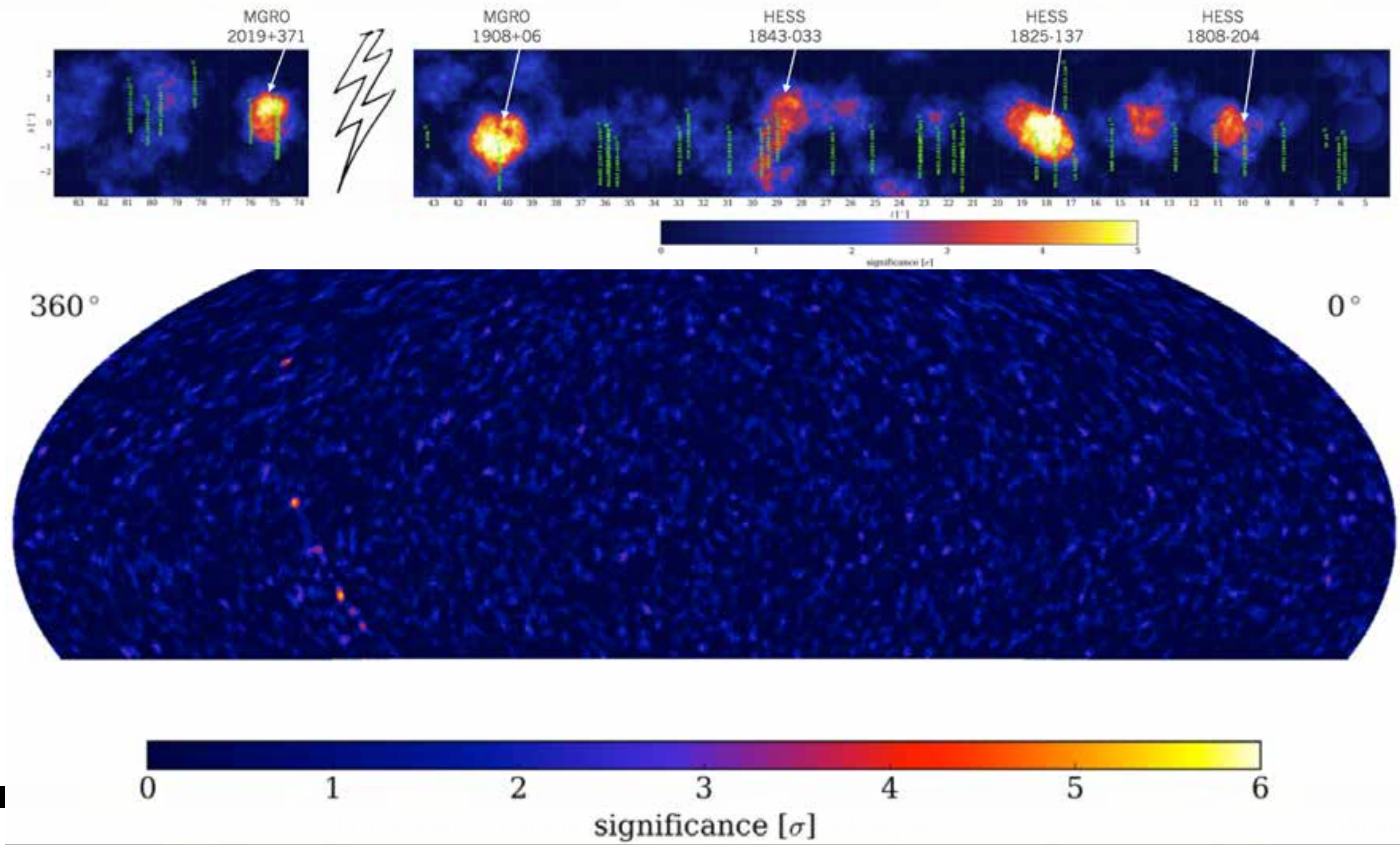
2HWC J1953+294	5.58	-2.76 ± 0.15	1.1e-14 ± 4.2e-15

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

Energy Estimation

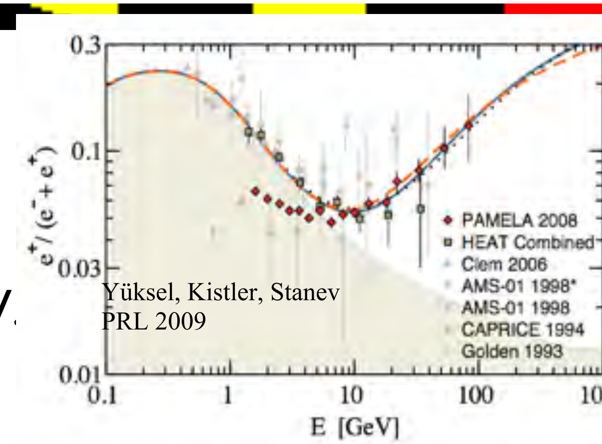


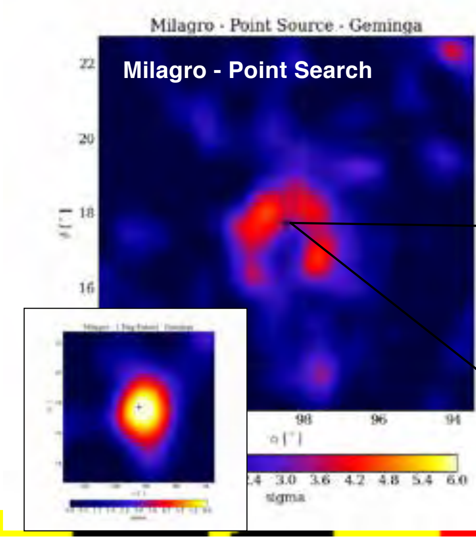
High Energy Sky (>56 TeV) with 1º

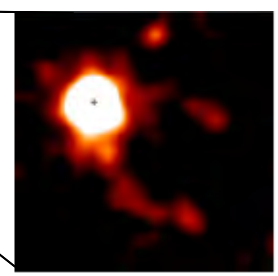


Pulsar Wind Nebulae - Geminga

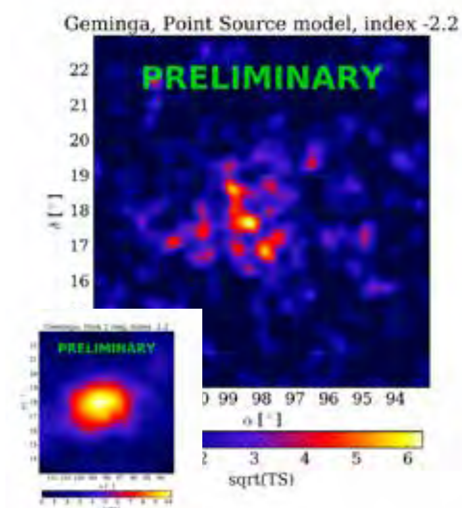
- Closest (250 parsecs) known middle aged (300ky) pulsar
- Possible nearby cosmic ray acceleration site
  — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV.
- Ongoing morphological and spectral studies







XMM, Pavlov et al. 2010



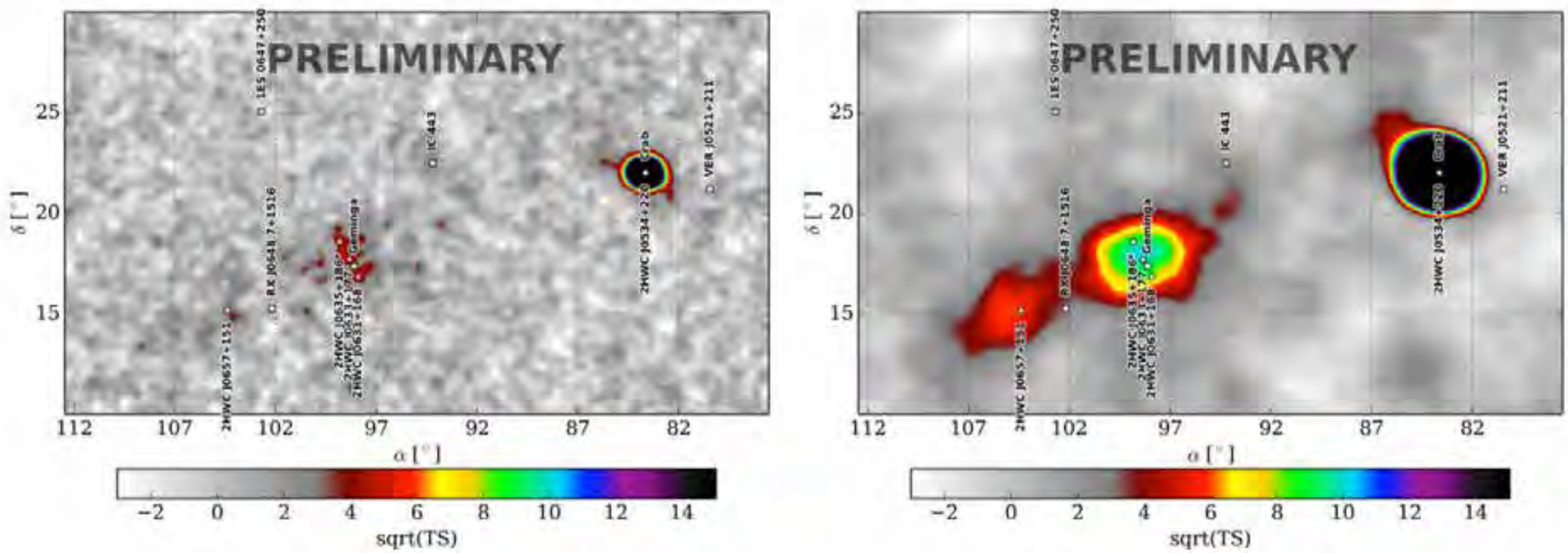
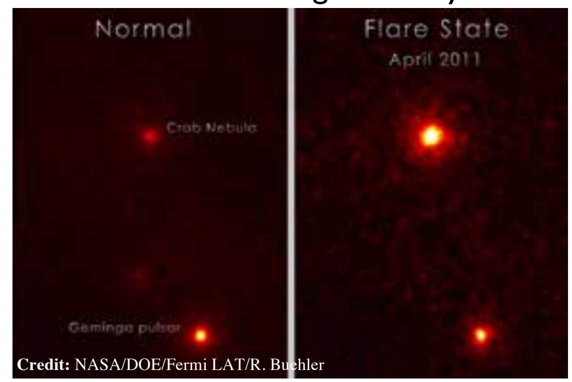


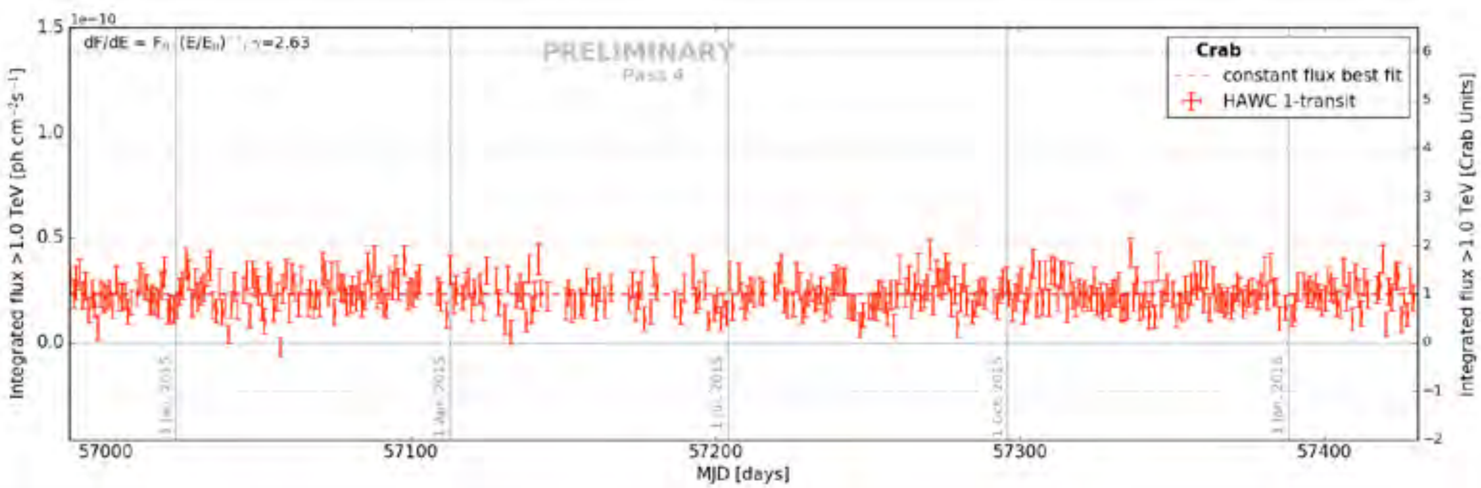
Figure 4: Region around Geminga. Left: TS map for a point source hypothesis with a spectral index of -2.7. Right: TS map for an extended source hypothesis represented by a disk of radius 2.0 degrees with a spectral index of -2.0.

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.

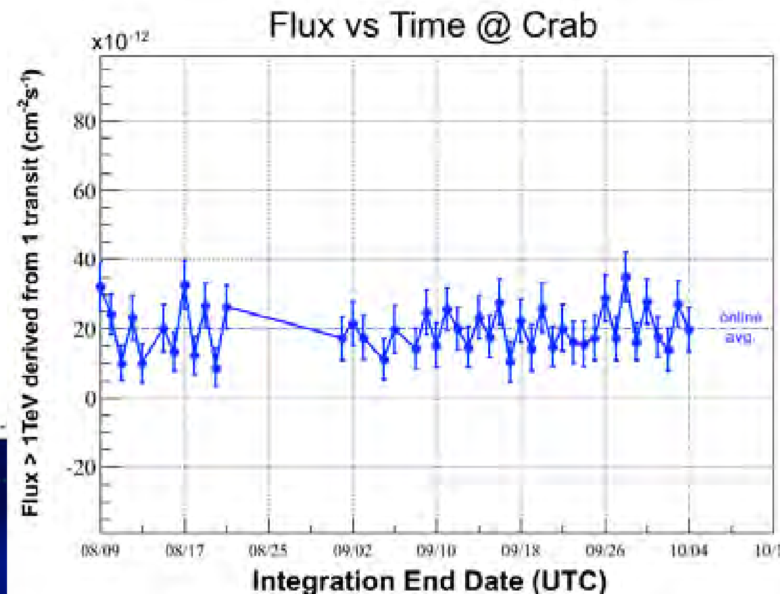
MeV-GeV gamma ray



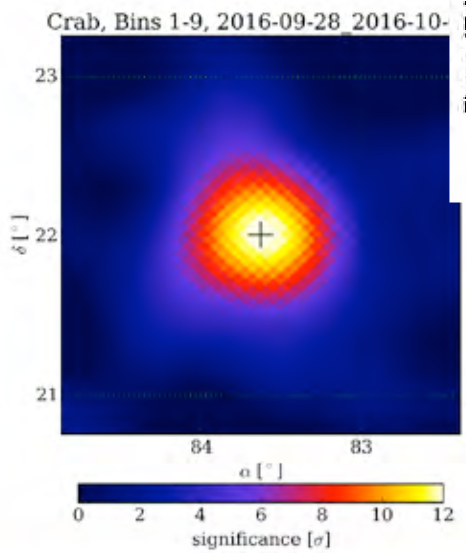


Transient Search - The Crab Nebula

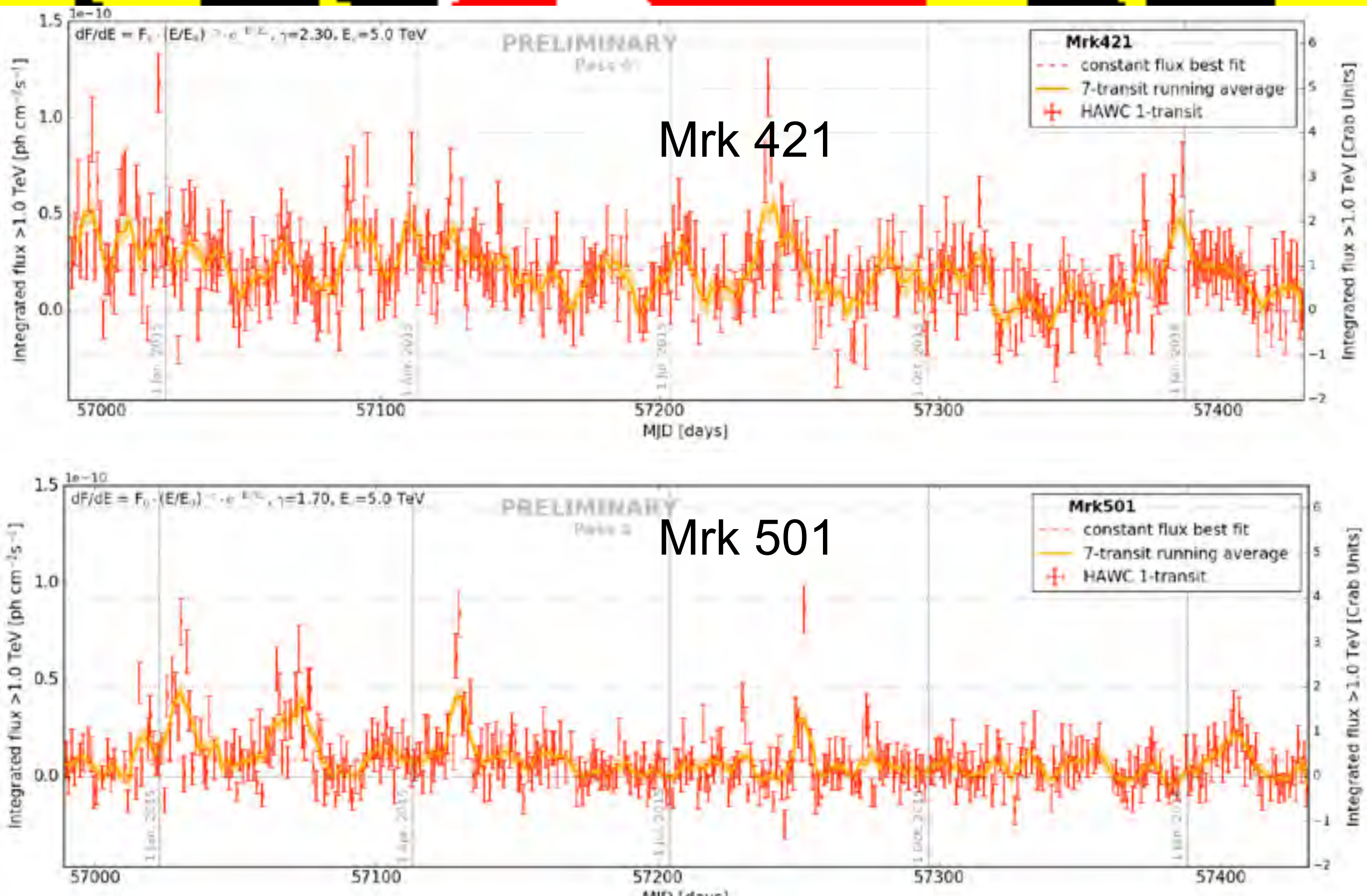
On October 3rd, 2016, AGILE (GeV) reported enhanced emission from the Crab Nebula (ATEL #9586). The Fermi-LAT *GeV) confirmed the detection in ATEL #9588, with flux up to 1.8 times larger than typical.



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

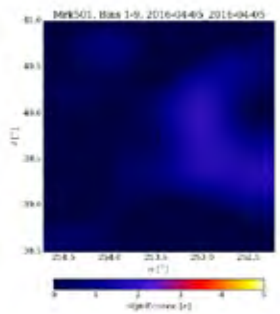


Transient Search - Mrk 501

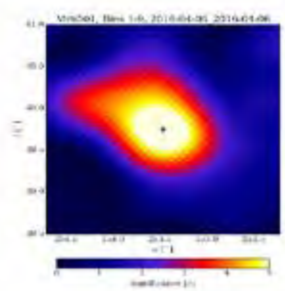
HAWC detection of increased TeV flux state for Markarian 501

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

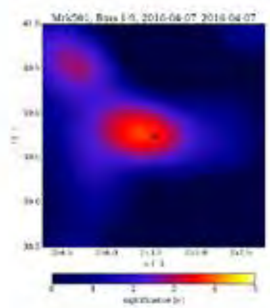
Astronomer's Telegram to immediately alert community of activity.



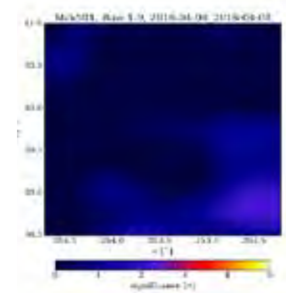
April 5, 2016



April 6, 2016



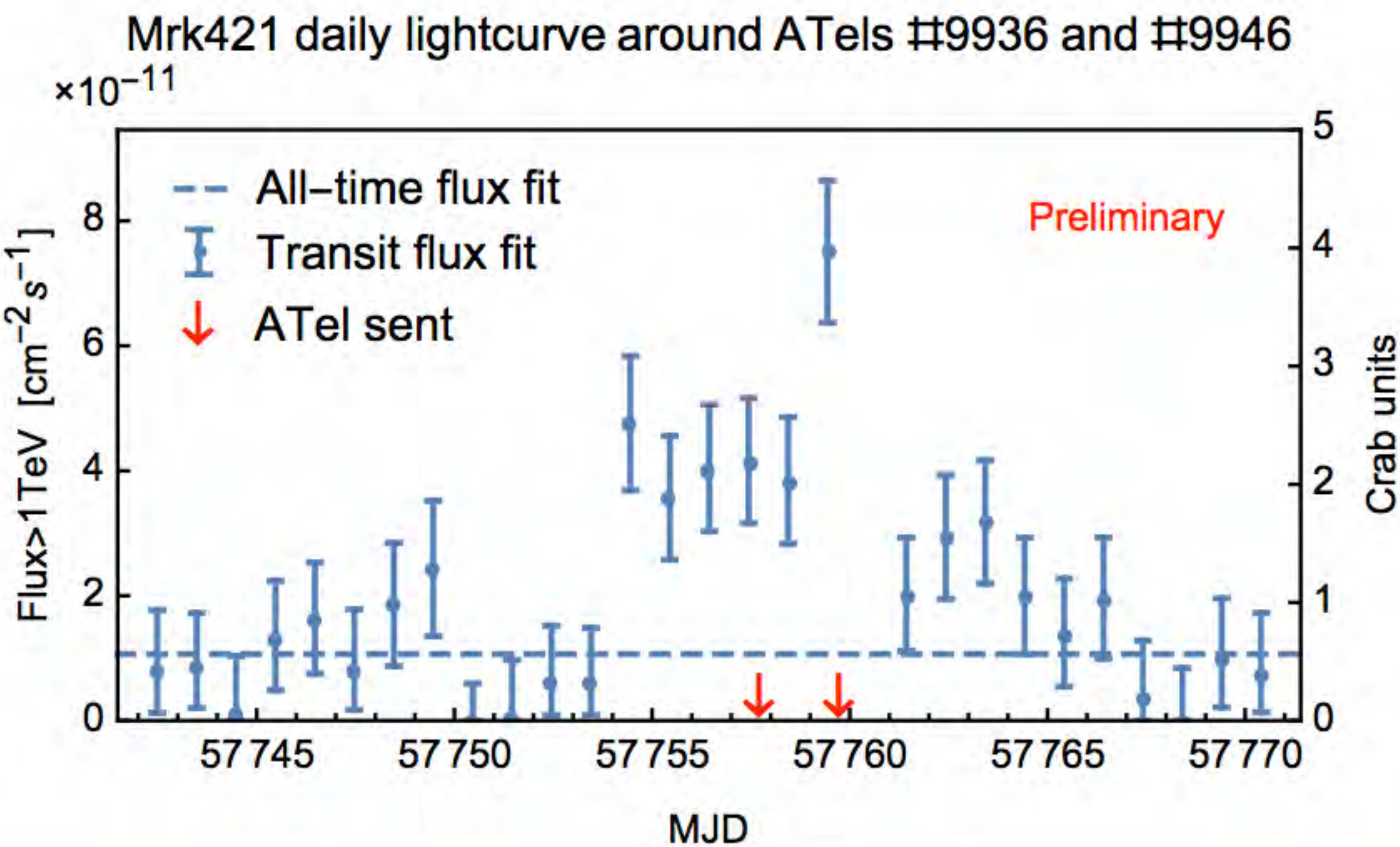
April 7, 2016



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 I release.
- Flares from known gamma-ray sources.

HAWC ATel #8922 on Mrk 501 flare

Externally triggered:

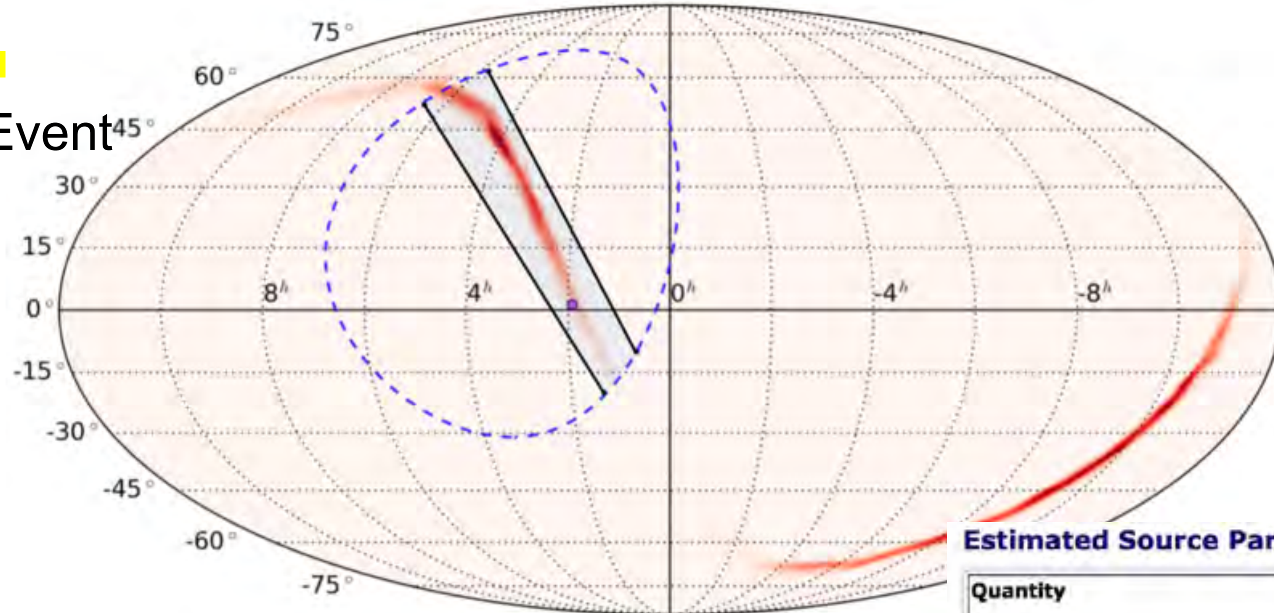
- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitation wave event follow-up

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

LIGO Events

- Responding to LIGO events
  - Sent Private GCN on first event
  - It was below our horizon
- 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.

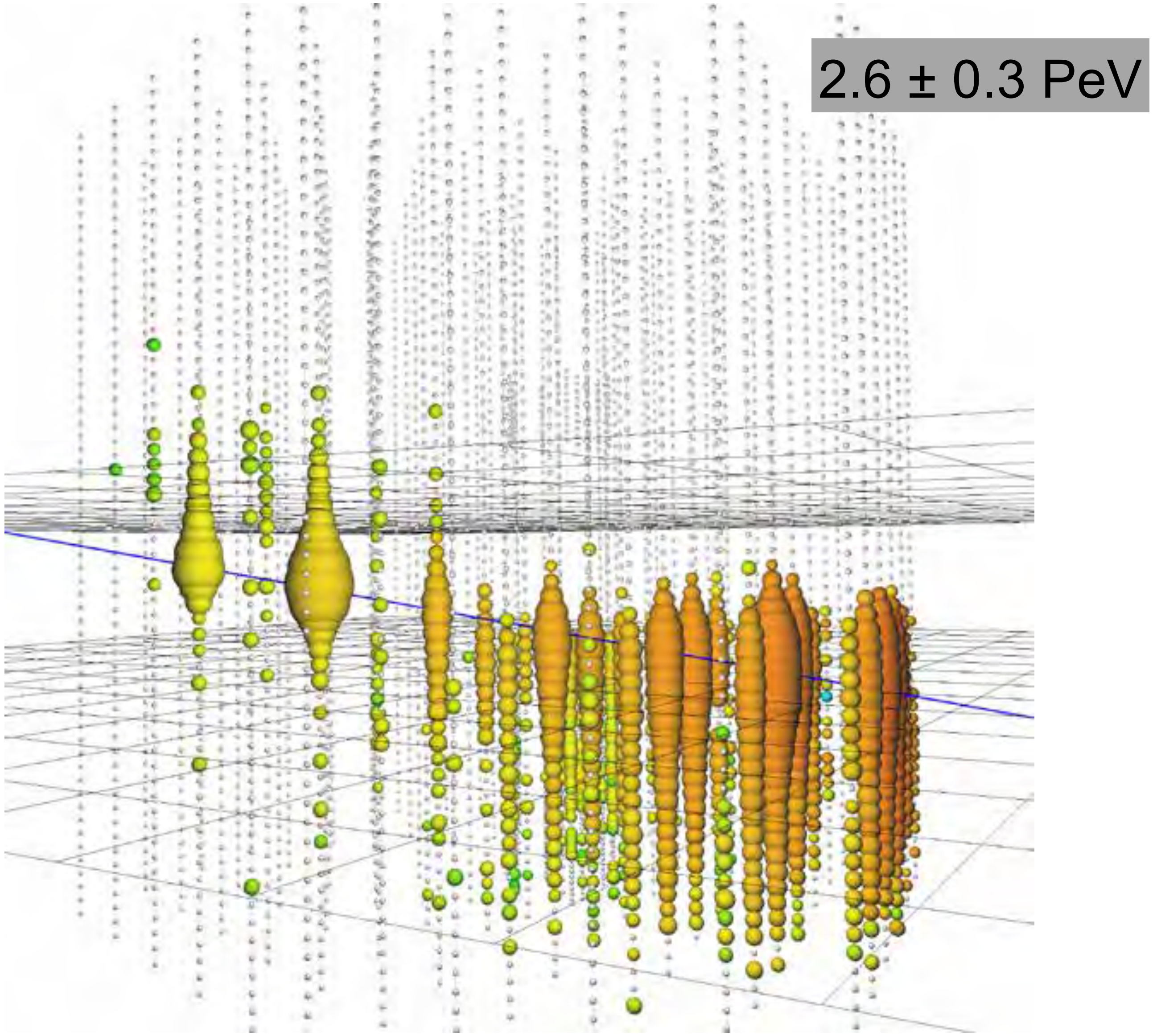
Boxing Day Event



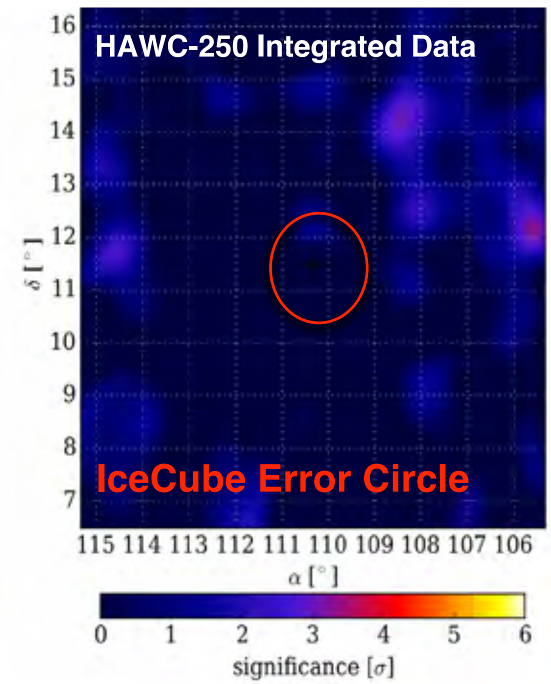
Candidate 1:
RA: 28.628 (+01h 54m 30.63s) J2000
Dec: +1.200 (+01d 11' 59.1") J2000
Error: +1.15 (square region, half side)
Duration: 10 seconds
Pre-trials p-value: 2.55e-07
Post-trials p-value: 0.08

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	

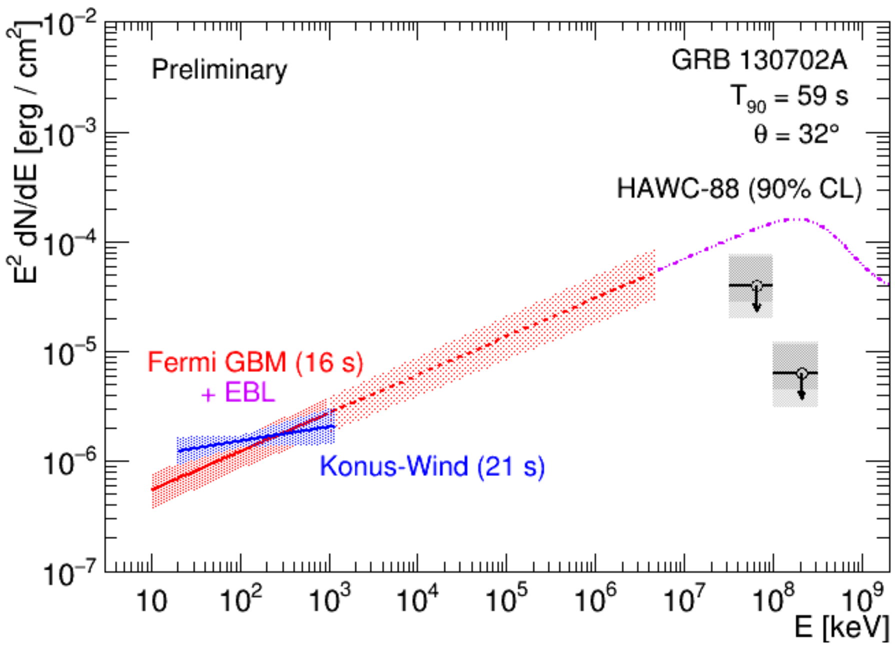

2.6 ± 0.3 PeV

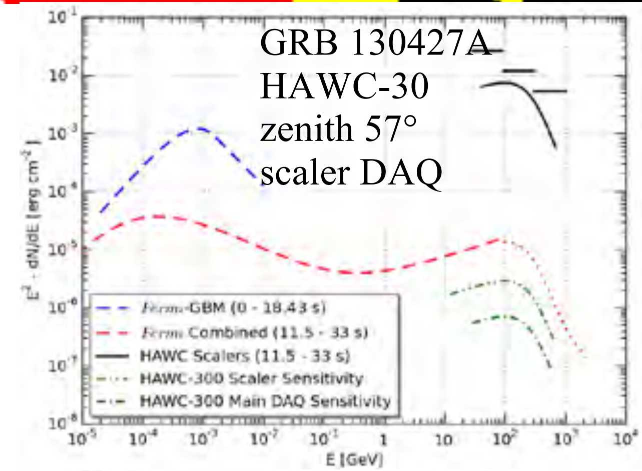
- HAWC-111 live. Several hours out of HAWC's FOV.
- Searches:
  – Integrated dataset (Steady, Aug 2013-May 2015 dataset)
  – Next Day / Prior Day
  – ±2 and ±5 days around the event.
- All searches consistent with cosmic-ray background.



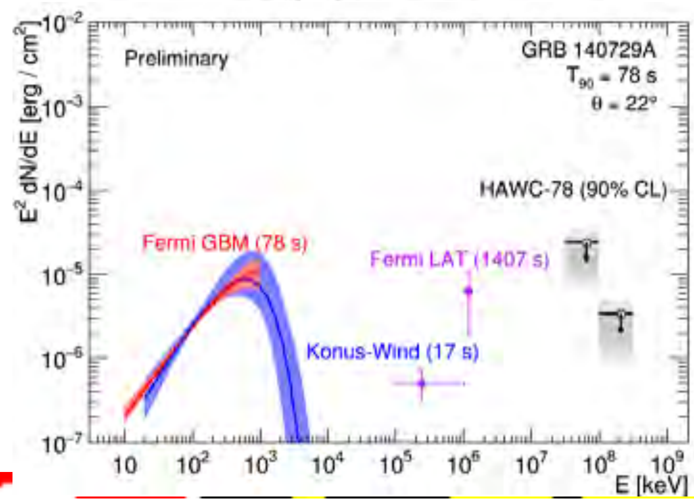
IceCube ATel: #7856
HAWC Follow-up ATel: #7868

Transients: Gamma Ray Bursts





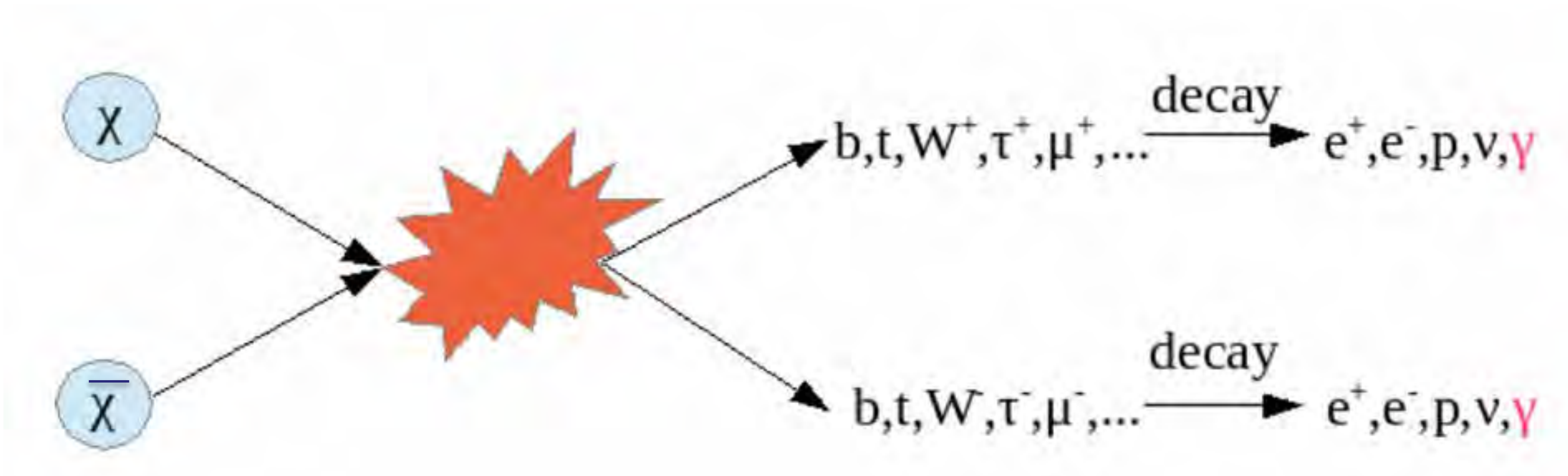
[Astrophys. J. 800 (2015), 78]



[K. Sparks Woodle]

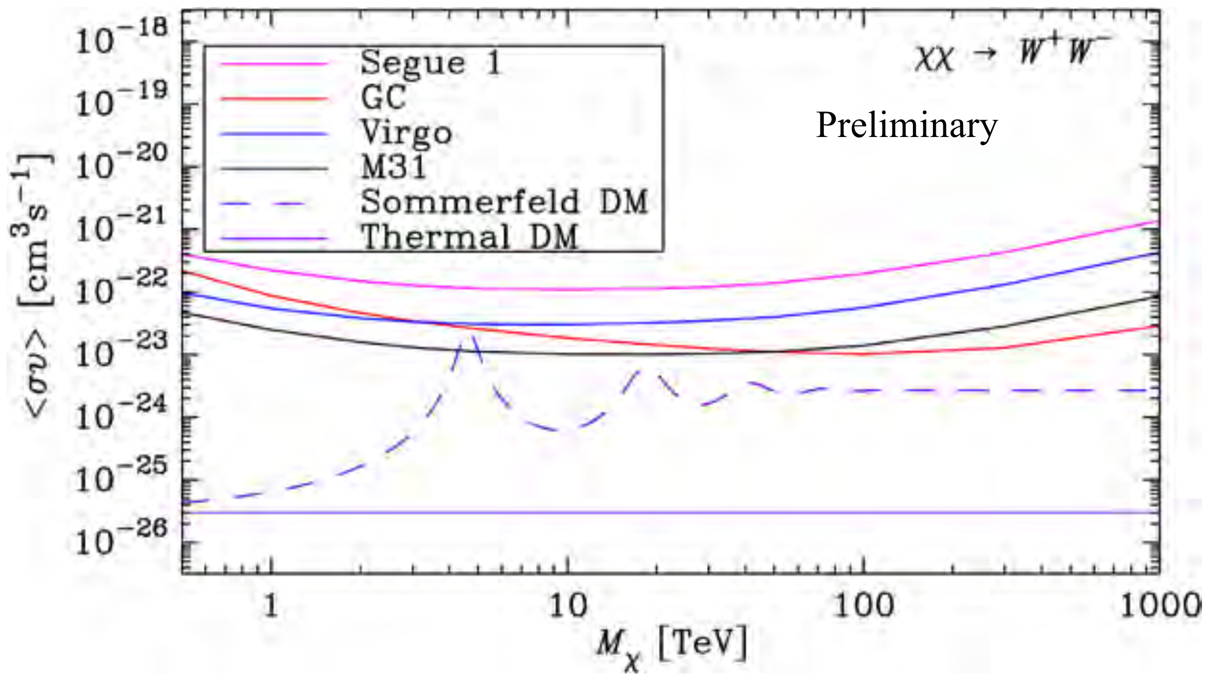
TITLE: GCN CIRCULAR NUMBER: 19423
SUBJECT: GRB 160509A: non-observation of VHE emission with HAWC
DATE: 16/05/11 17:27:37 GMT

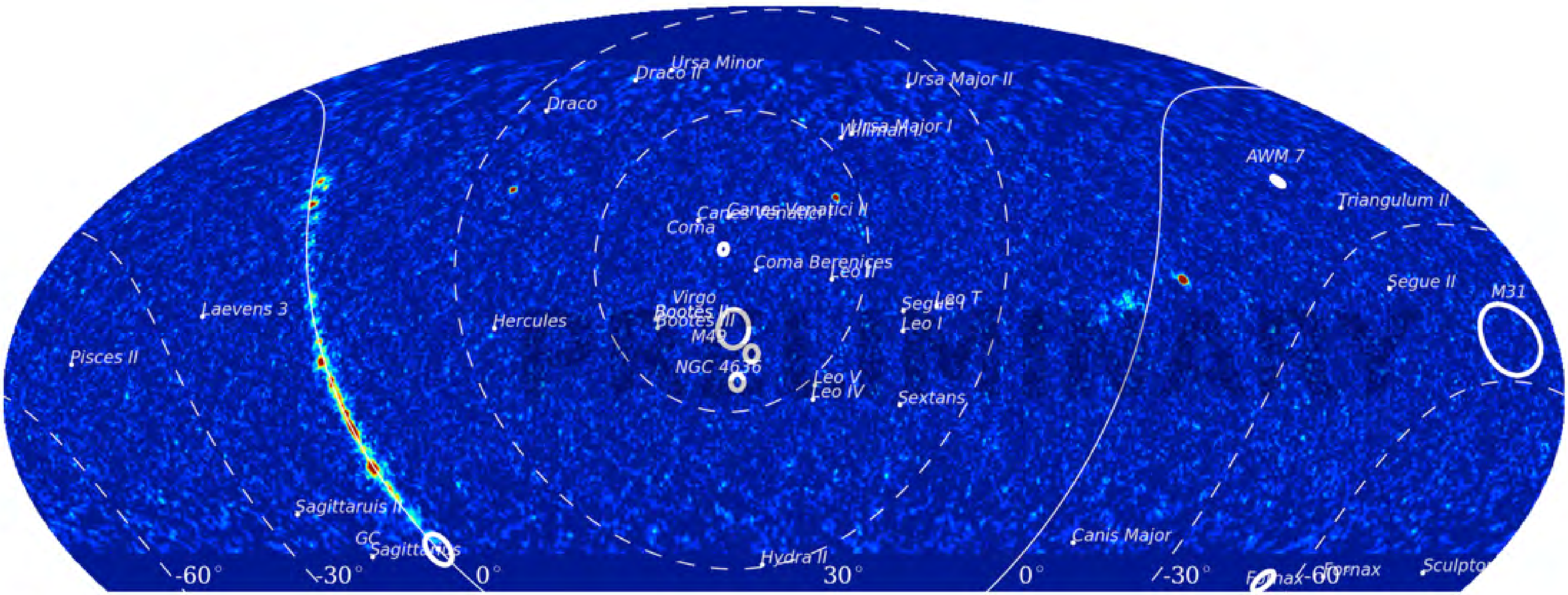
Dark Matter



HAWC: Dark Matter

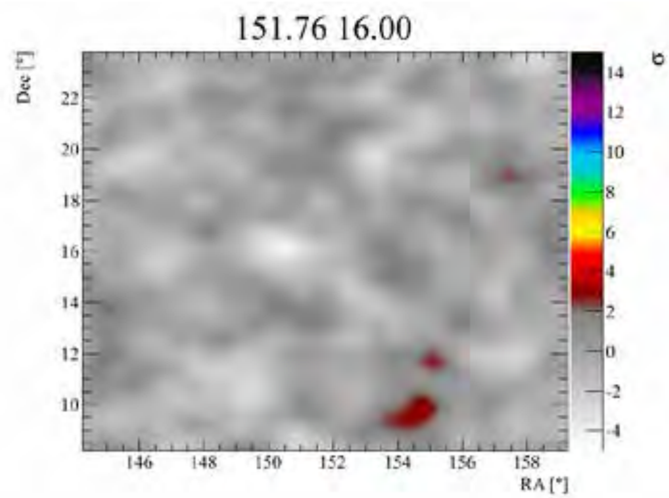
- HAWC has sensitivity to indirect detection of TeV WIMPs in:
  - Satellite galaxies, the Galactic Center, and galaxy clusters
- Cosmological simulations predict more satellite galaxies than observed
  - Higher M/L galaxies have been found by Sloan Deep Survey
  - HAWC will observe all M/L galaxies in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

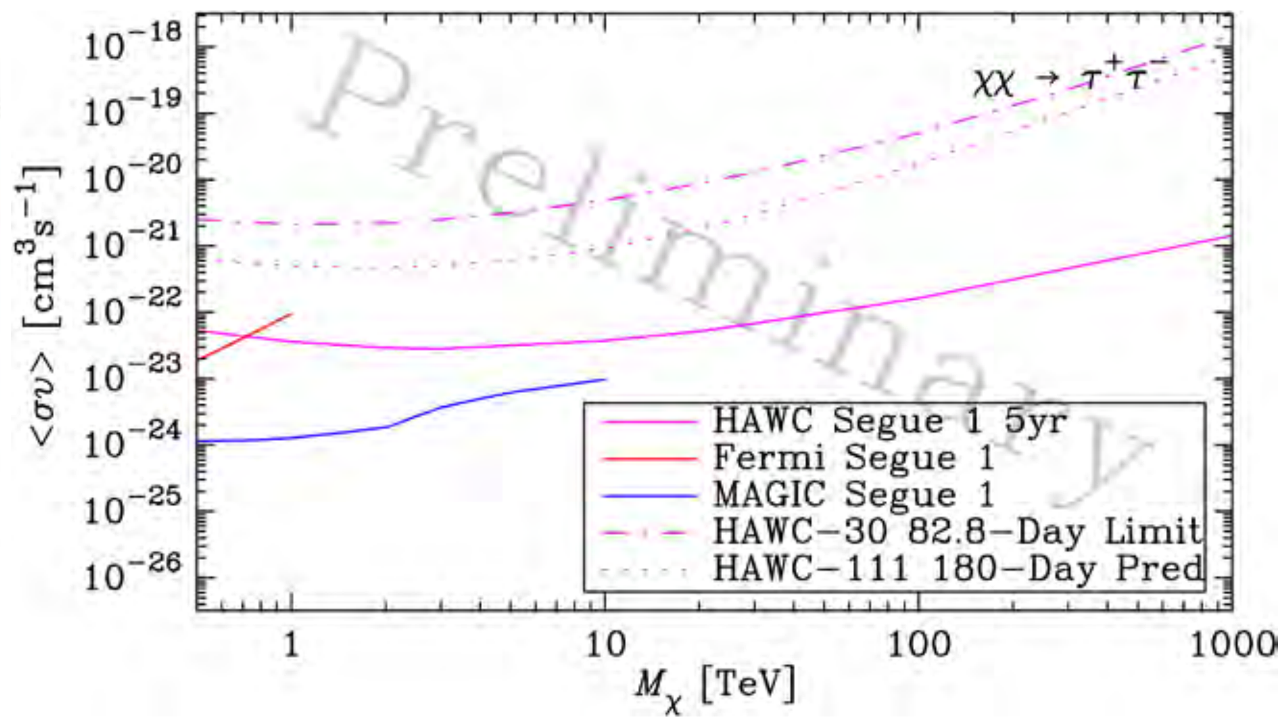




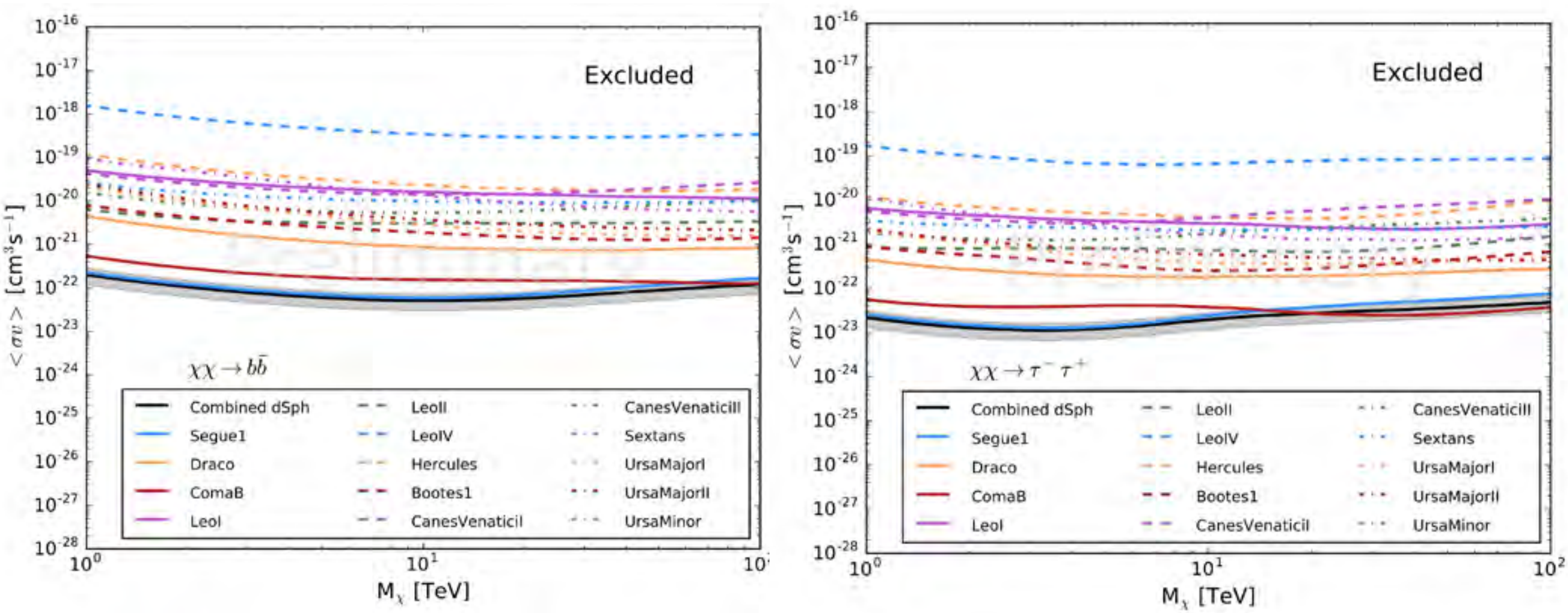
Ursa Minor
Draco II
Ursa Major II
Draco
Ursa Major I
AWM 7
Triangulum II
Canes Venatici II
Coma
Coma Berenices
Leo II
Segue II
M31
Virgo
Bootes II
Bootes III
M49
Hercules
Laevens 3
Segue 1
Leo T
Leo I
Pisces II
NGC 4636
Leo V
Leo IV
Sextans
Sagittaruis II
GC
Hydra II
Canis Major
Fornax
-60°
-30°
0°
30°
0°
-30°
-60°

Dark Matter - Segue-1

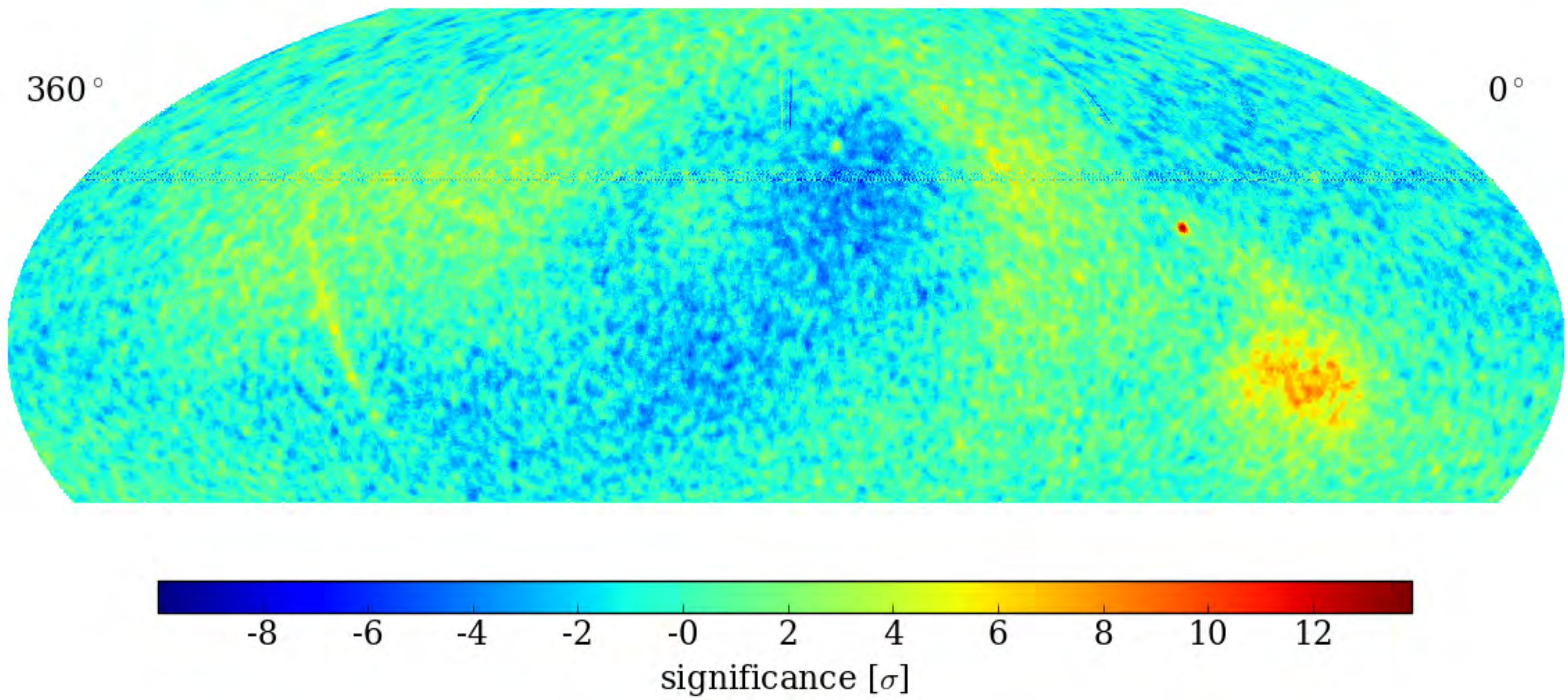




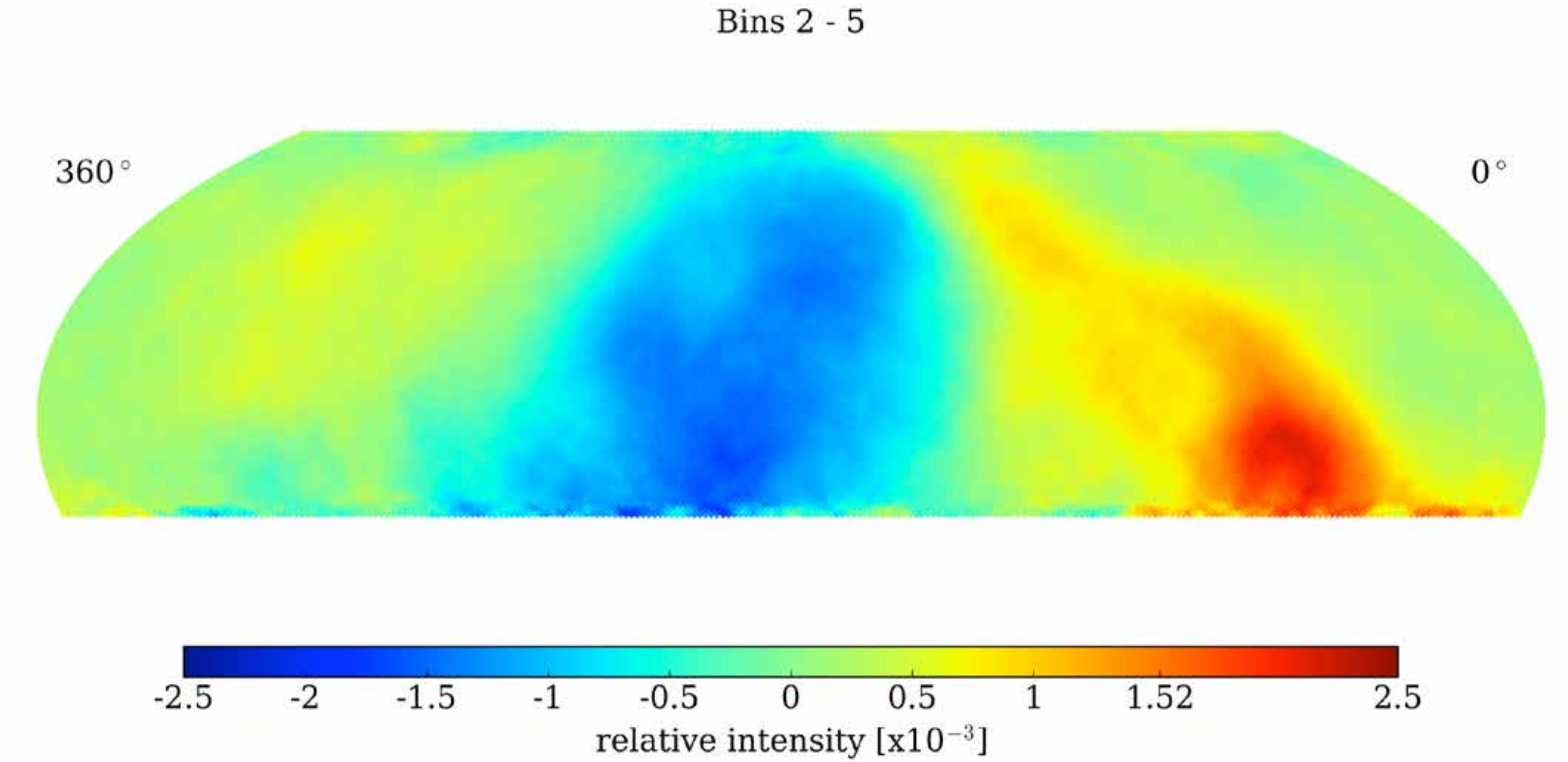
Dark Matter Limits



HAWC Data - no gamma ray cut



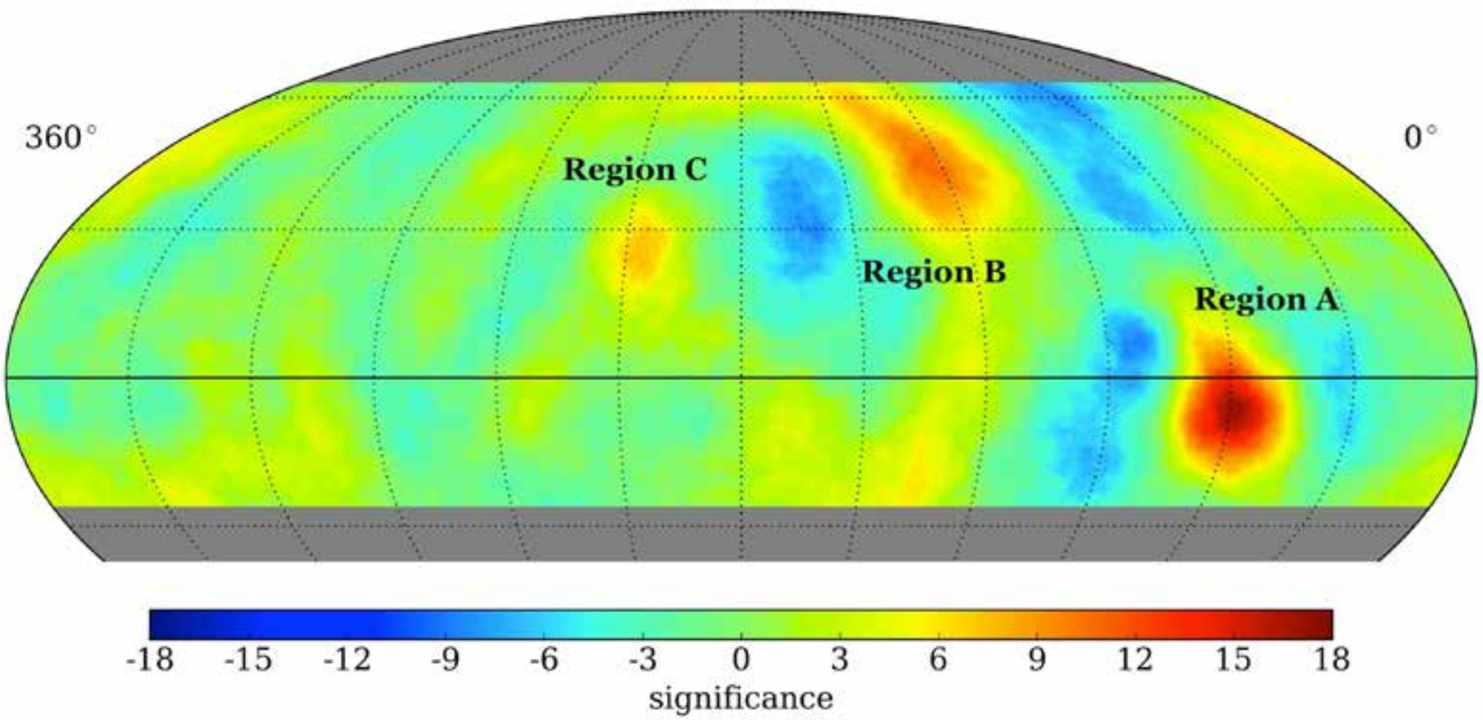
Large Scale Anisotropy

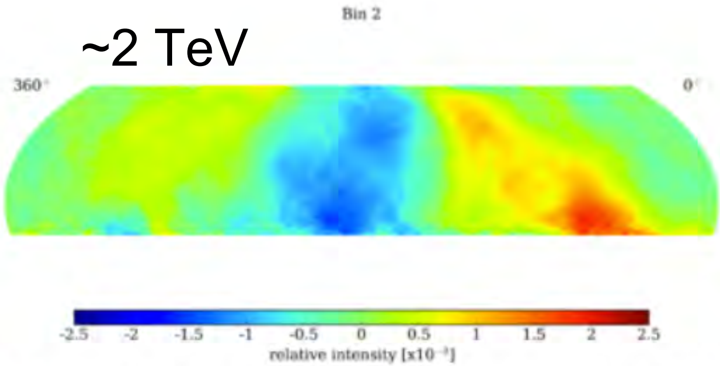


Anisotropy

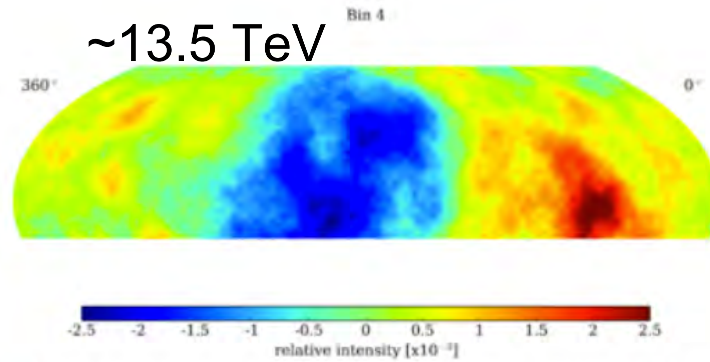
Fit dipole+quadrupole+octupole to map for 24-hr background estimation
Subtracted fit relative intensity from 24-hr map

Regions A, B and C are the only statistically significant excesses (>5σ post-trials)

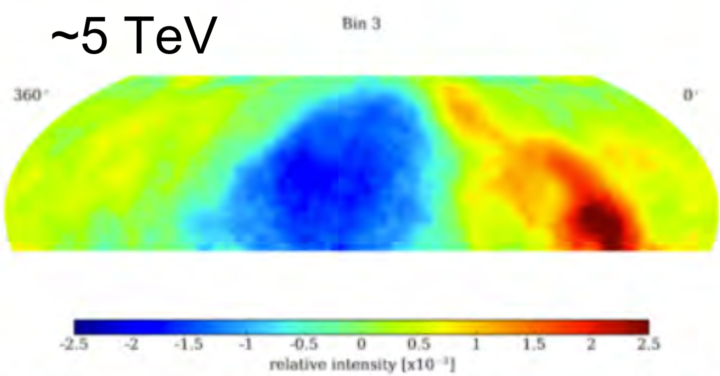




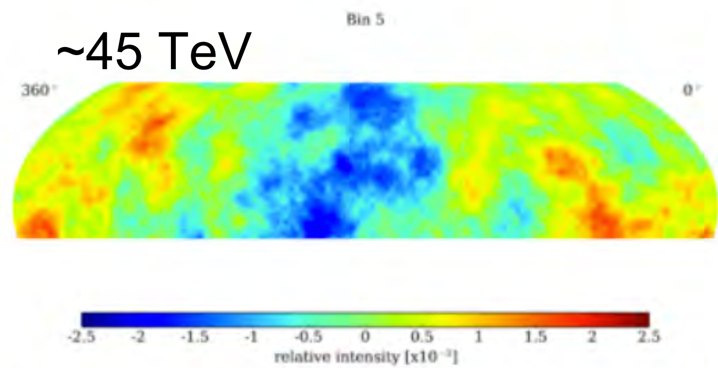
- Large-scale anisotropy for energy bin 2. Median energy is 1.86 (+ 3.03, -1.54) TeV



- Large-scale anisotropy for energy bin 4. Median energy is 13.5 (+ 16.0, -9.03) TeV

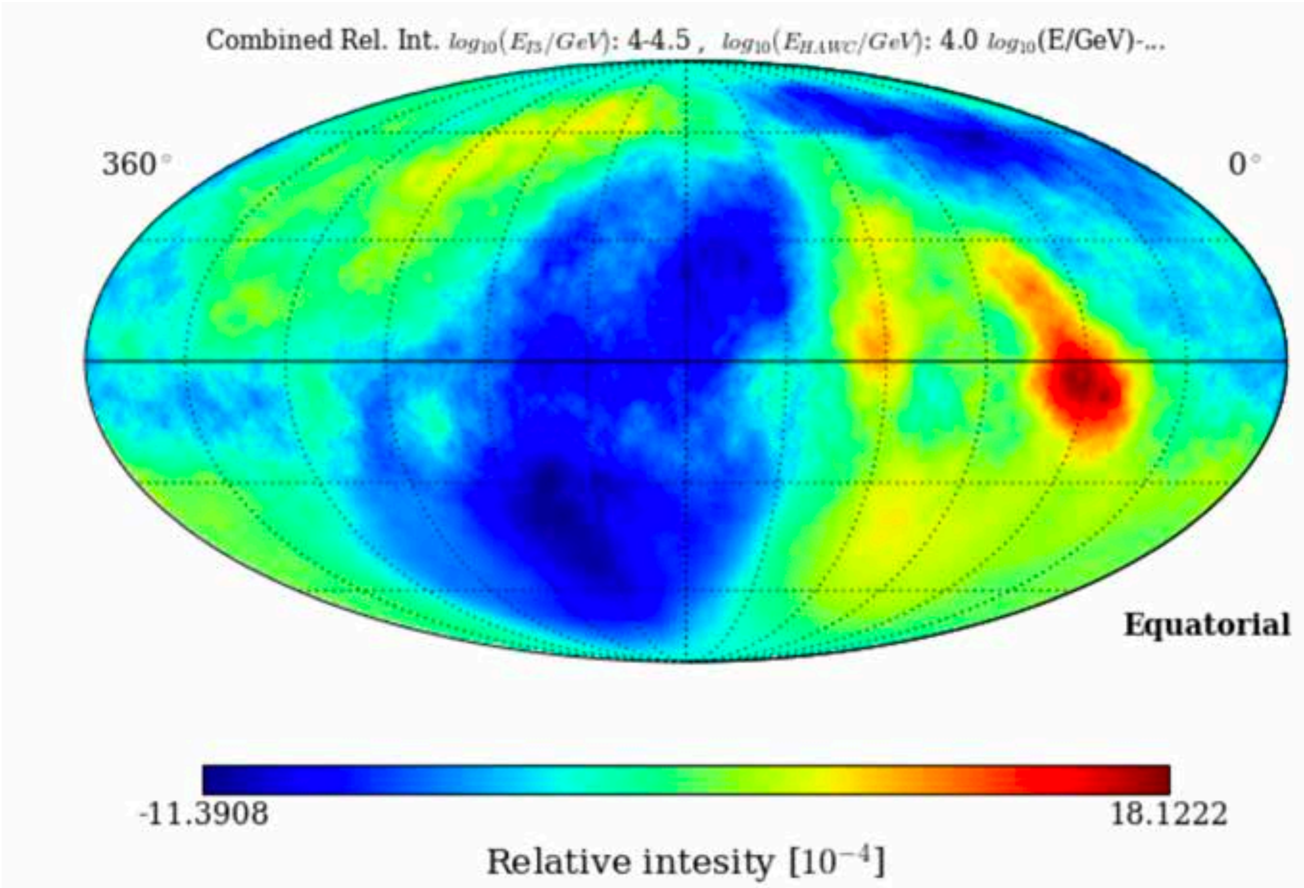


- Large-scale anisotropy for energy bin 3. Median energy is 4.90 (+ 6.85, -3.35) TeV



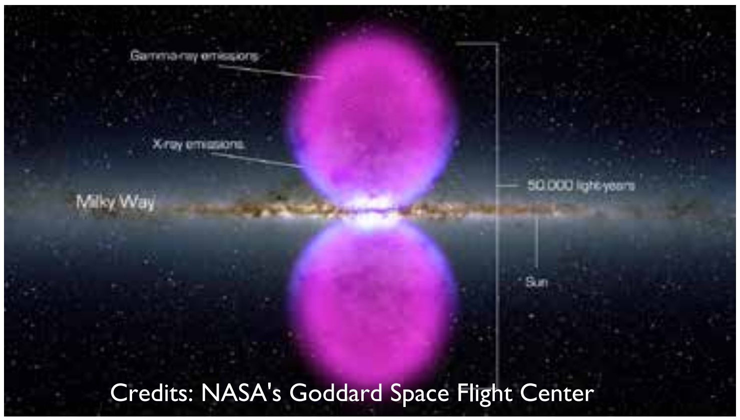
- Large-scale anisotropy for energy bin 5. Median energy is 44.7 (+ 67.6, -27.7) TeV

HAWC IceCube Joint Fit

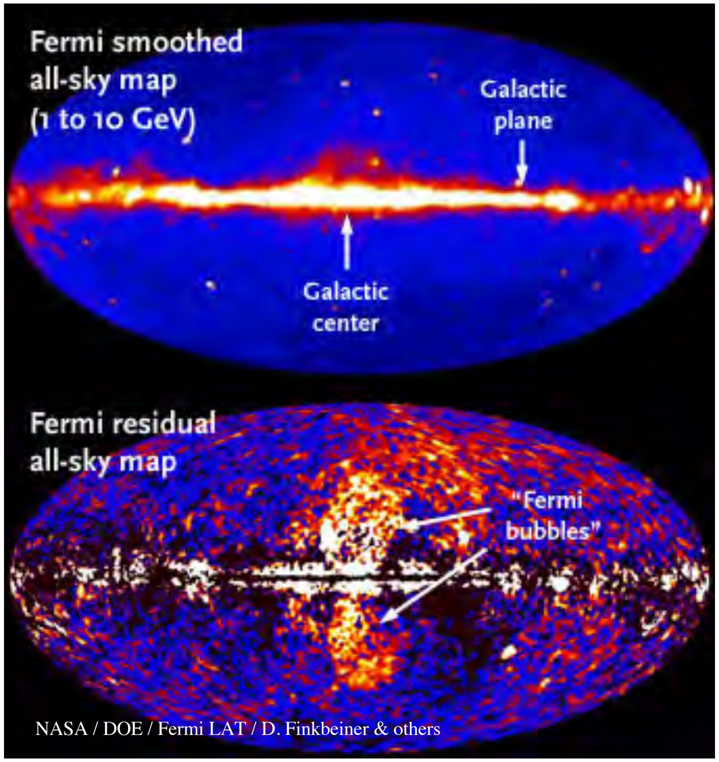


Large-scale structures e.g. Fermi Bubbles

- 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.**

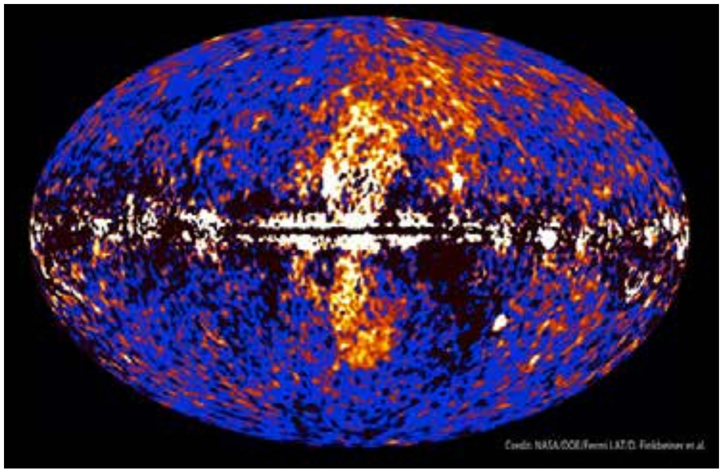


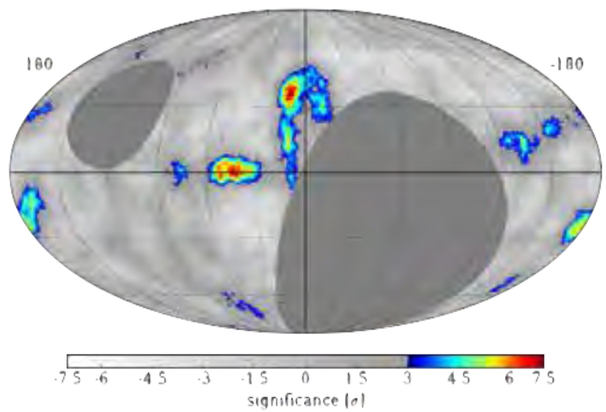
Credits: NASA's Goddard Space Flight Center



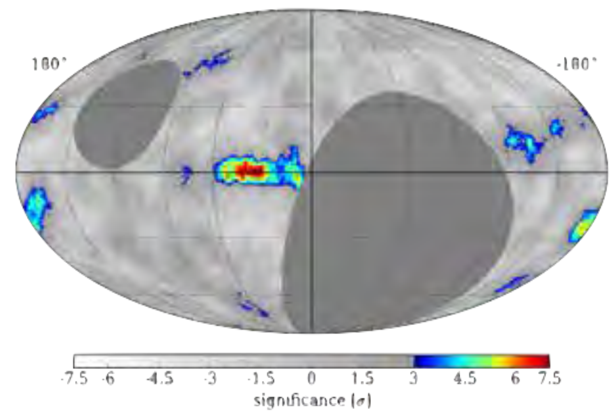
NASA / DOE / Fermi LAT / D. Finkbeiner & others

Diffuse Emission





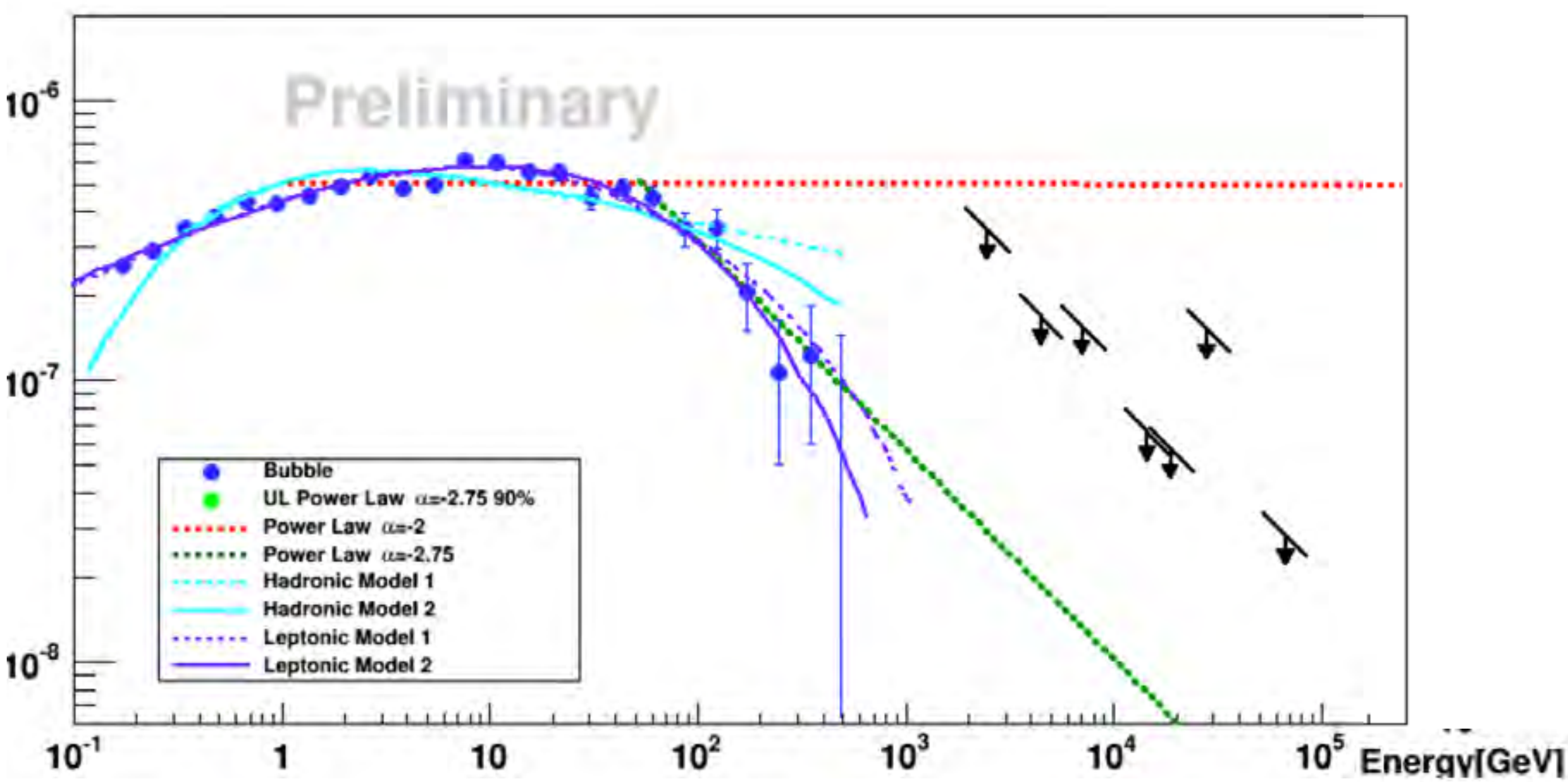
No Cut-off



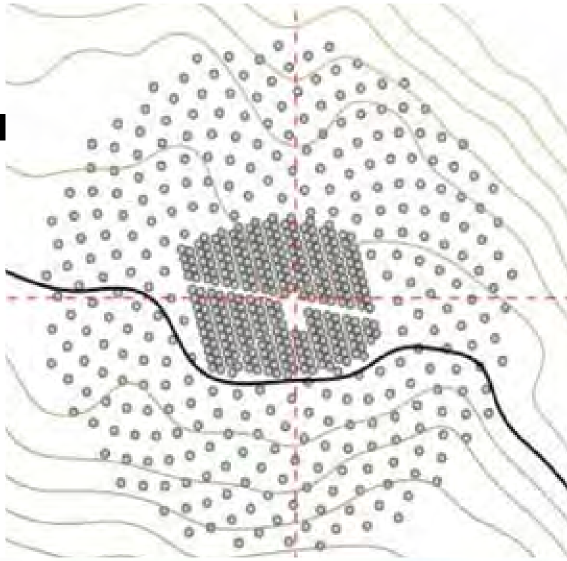
150 GeV Cut-off

Fermi Bubbles

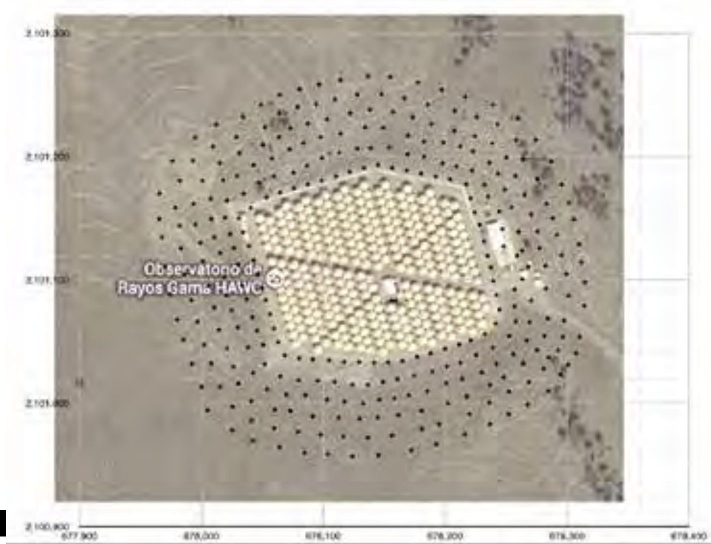
HAWC 90%CL upper limits



Outriggers



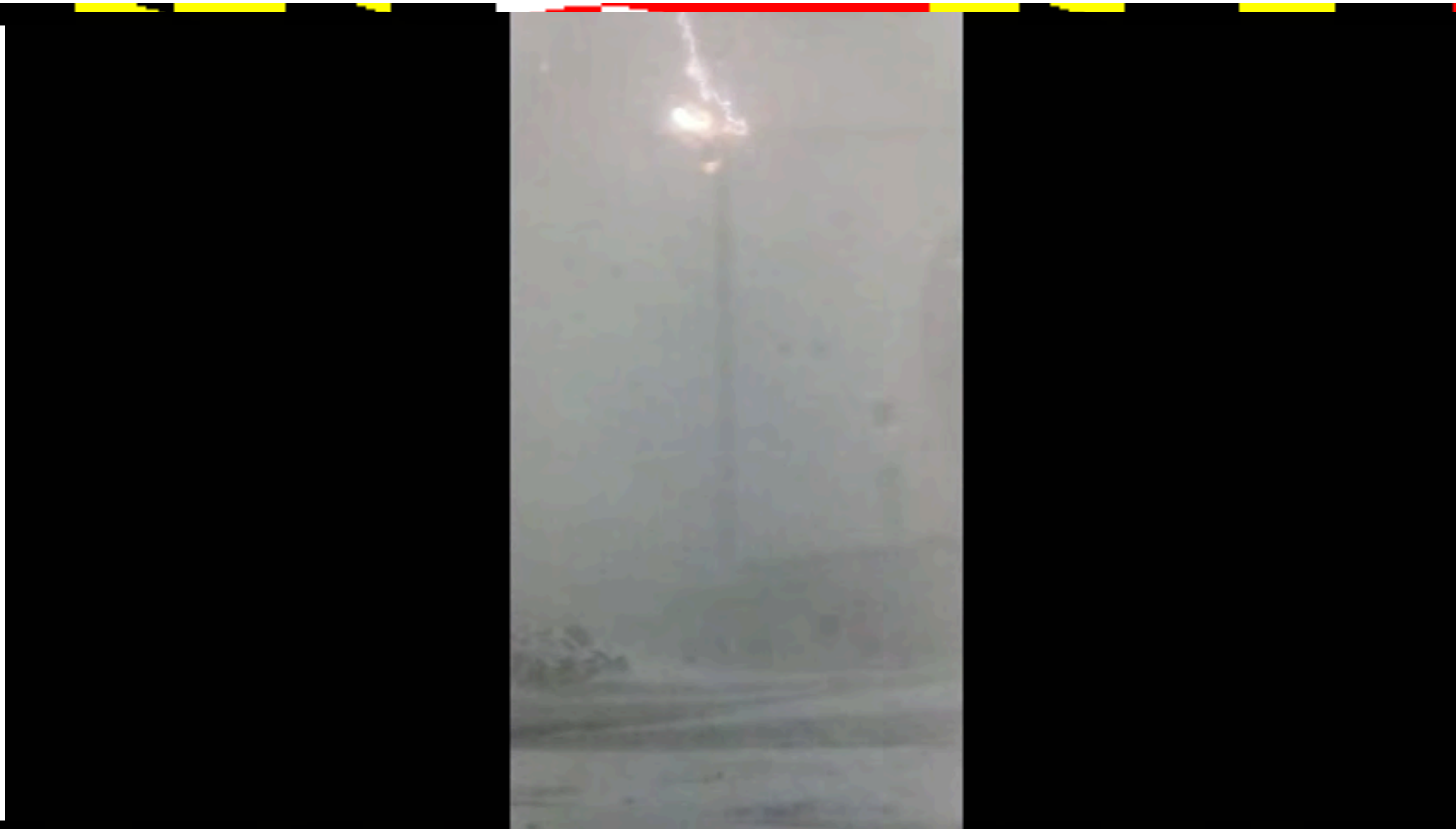
- HAWC Sparse Outrigger Array: Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
- Increase effective area above 10 TeV by 3-4x
- Funded by LANL/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.



Storm on the 13-14 January 2016


Rotoplas

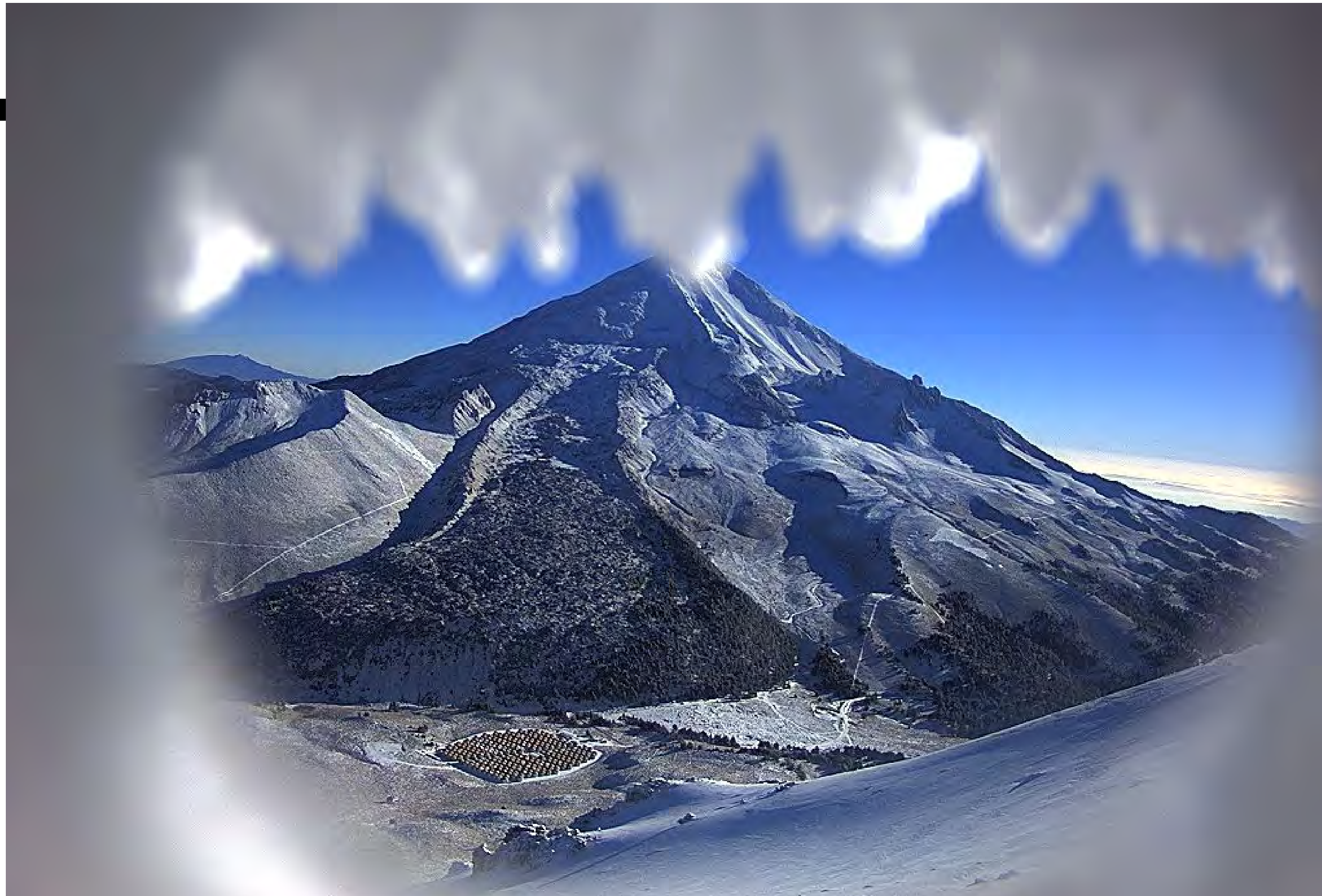
Storm on the 19th of August

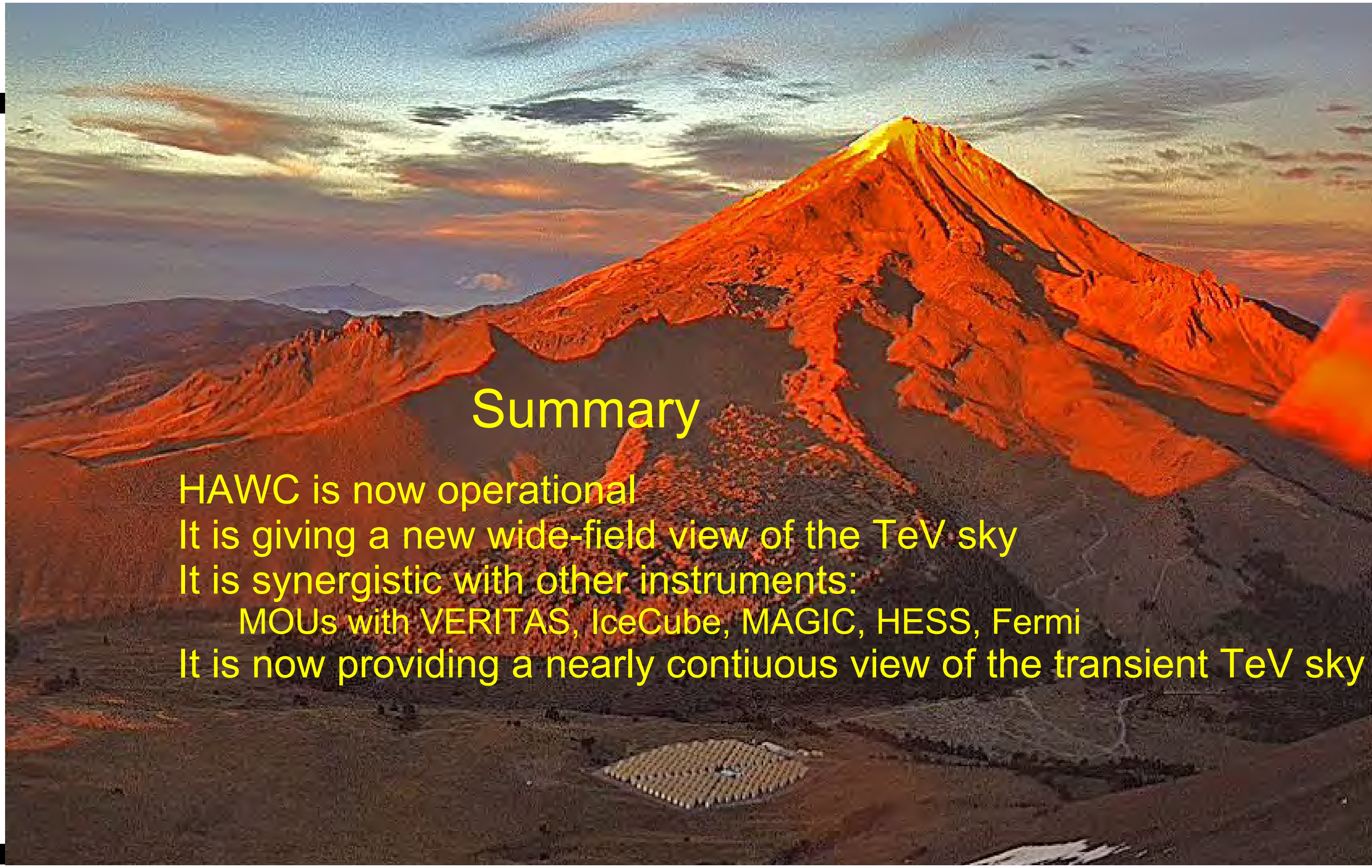


Popocatépetl

Outlook

- The HAWC observatory began full-scale operation in March 2015.
- It is now providing a nearly contiuous view of the transient TeV sky
- Catalog of first year full operation is in prep (2HWC), with new TeV sources!
- Diverse science results, stay tuned!
- Upgrade to expand the array to enhance effective area >10 TeV by 3-4x is currently under installation.





Summary

HAWC is now operational
It is giving a new wide-field view of the TeV sky
It is synergistic with other instruments:
- MOUs with VERITAS, IceCube, MAGIC, HESS, Fermi

It is now providing a nearly contiuous view of the transient TeV sky