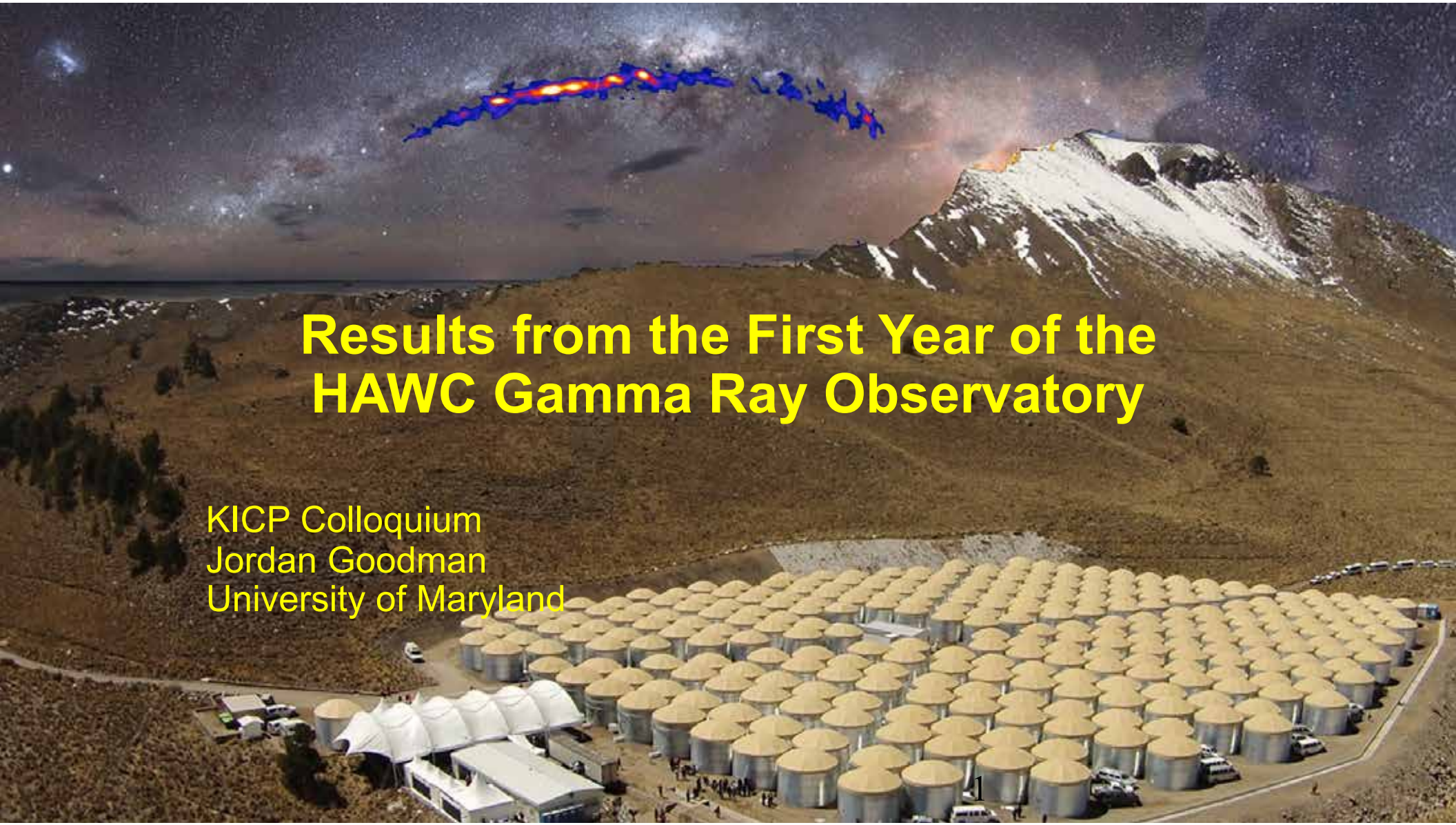
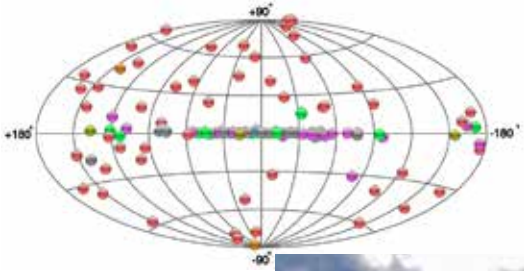


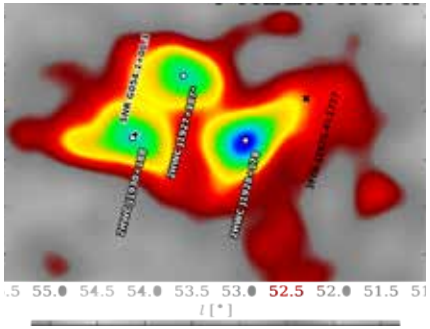
Results from the First Year of the HAWC Gamma Ray Observatory

KICP Colloquium
Jordan Goodman
University of Maryland

Talk Overview

- Intro
  - Gamma Ray Astronomy
  - Cosmic Rays
  - Ground based arrays and air showers
- HAWC
  - Design, Construction, Performance
- New Results
  - HAWC Survey and New Extended Sources
  - Transients - AGN, IceCube Event
  - Dark Matter Limits
  - Anisotropy





The HAWC Collaboration

USA

Mexico

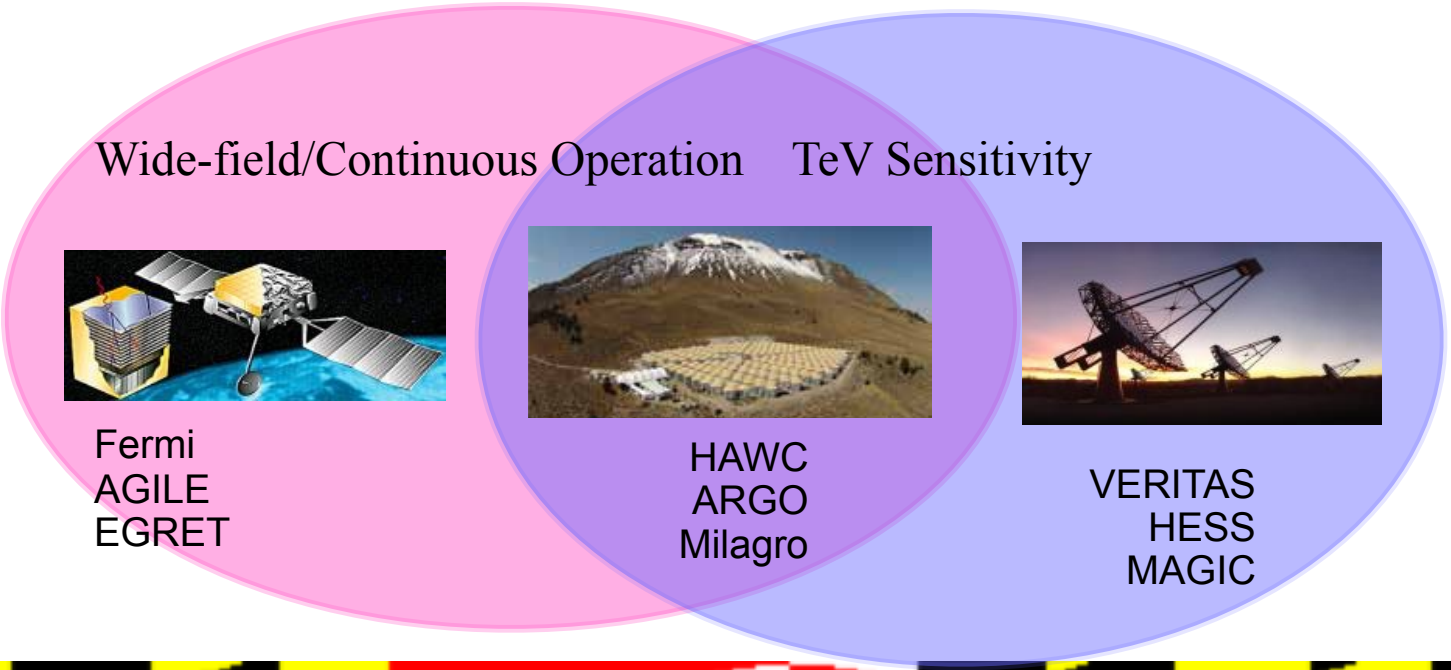
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology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

Michigan State University
University of Rochester
University of California Santa Cruz
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

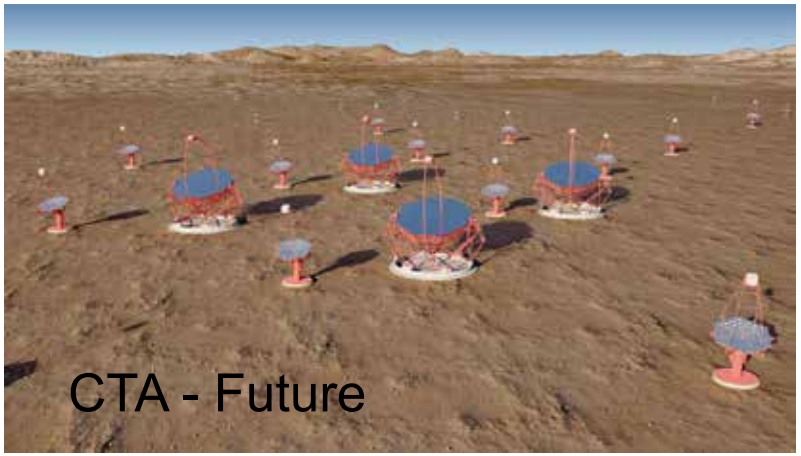
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional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

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

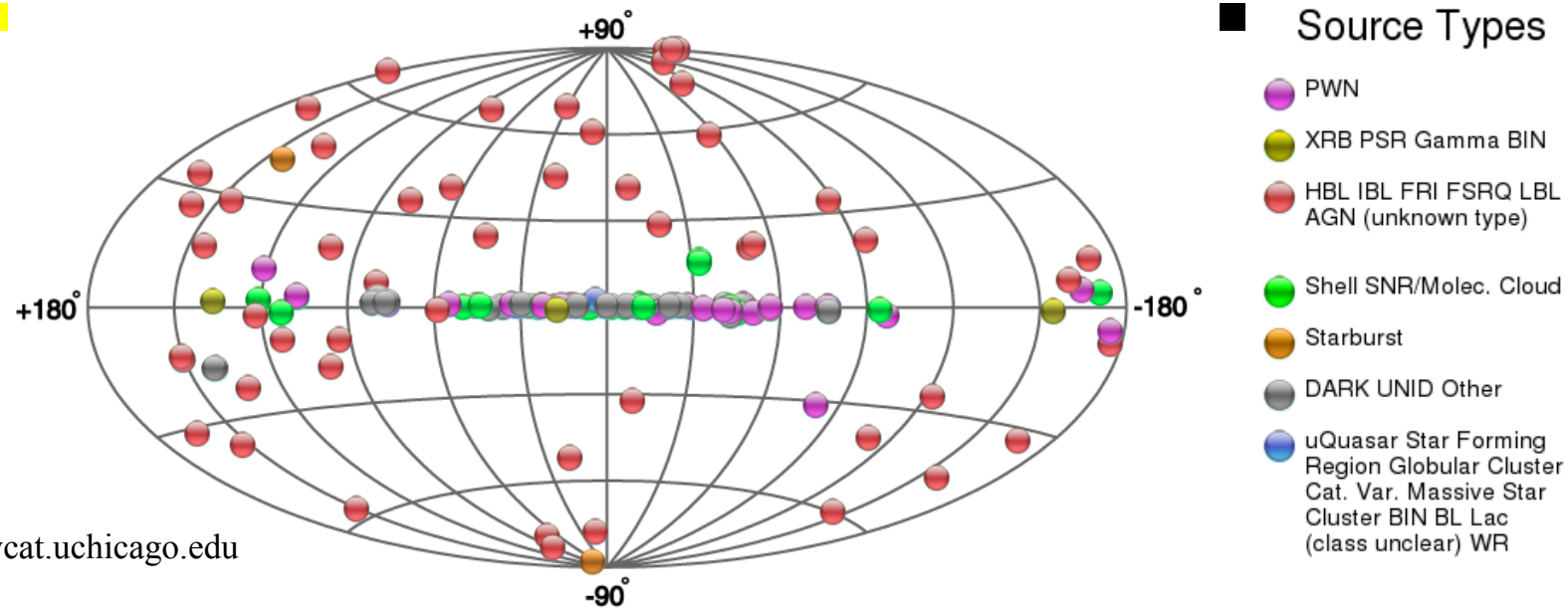


Imaging Atmospheric Cherenkov Telescopes



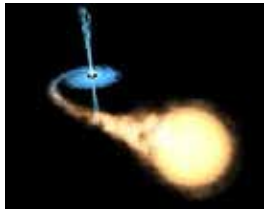
TeV Gamma Ray Sources

176 known TeV gamma-ray sources (as of May 2016)



tevcat.uchicago.edu

Galactic:



Extragalactic:

Supernova Remnants

Binary systems

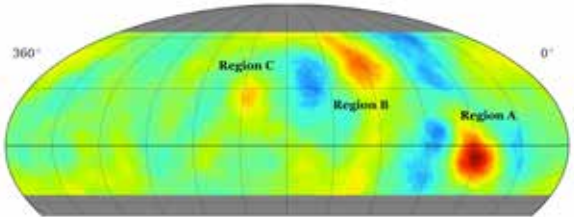
GRBs (GeV)

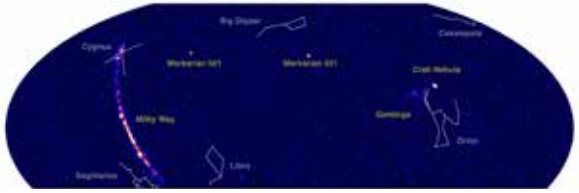
AGNs

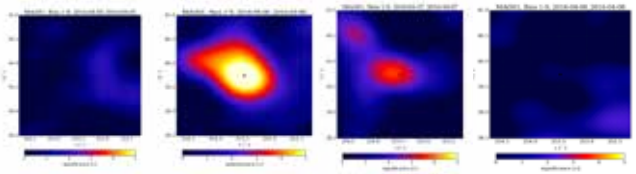
What can you do with a wide-field instrument?

- 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

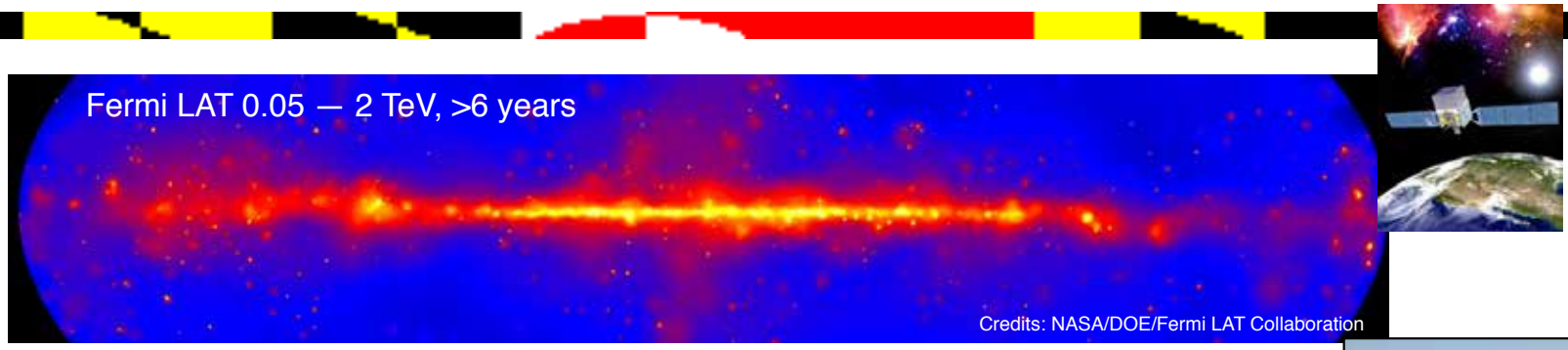
- Particle Physics
  - Dark Matter - can look for places with no visible signal
  - Primordial Black Holes
  - Violations of Lorentz Invariance
  - Look for sources of positron excess
- Cosmic Ray Anisotropy



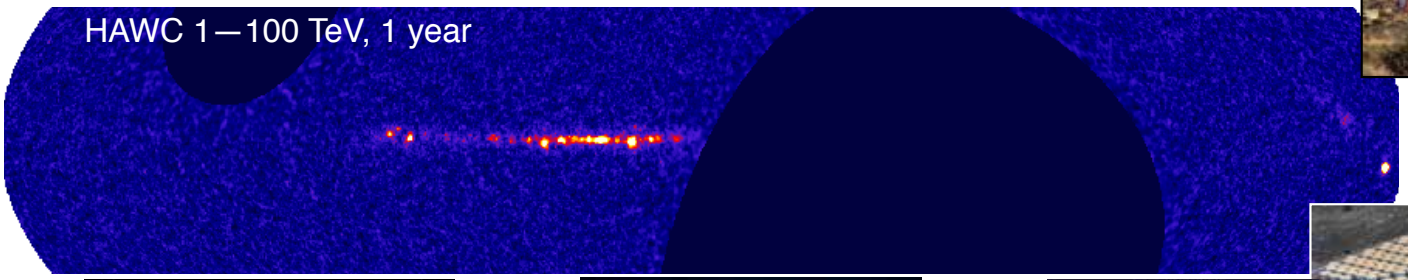


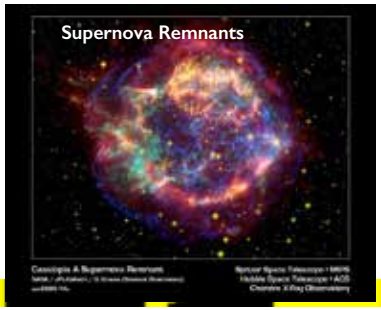


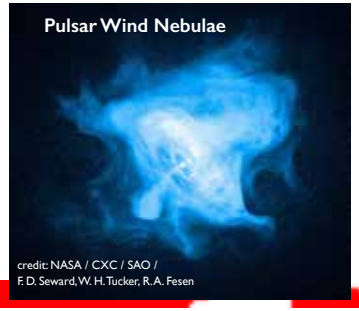
High Energy View of our Galaxy

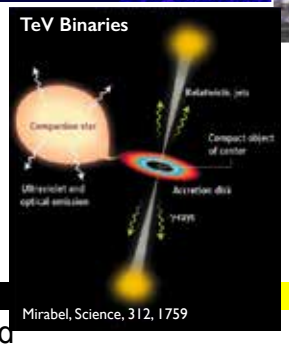


HESS >1TeV, 10 years









Cosmic Ray Discovery

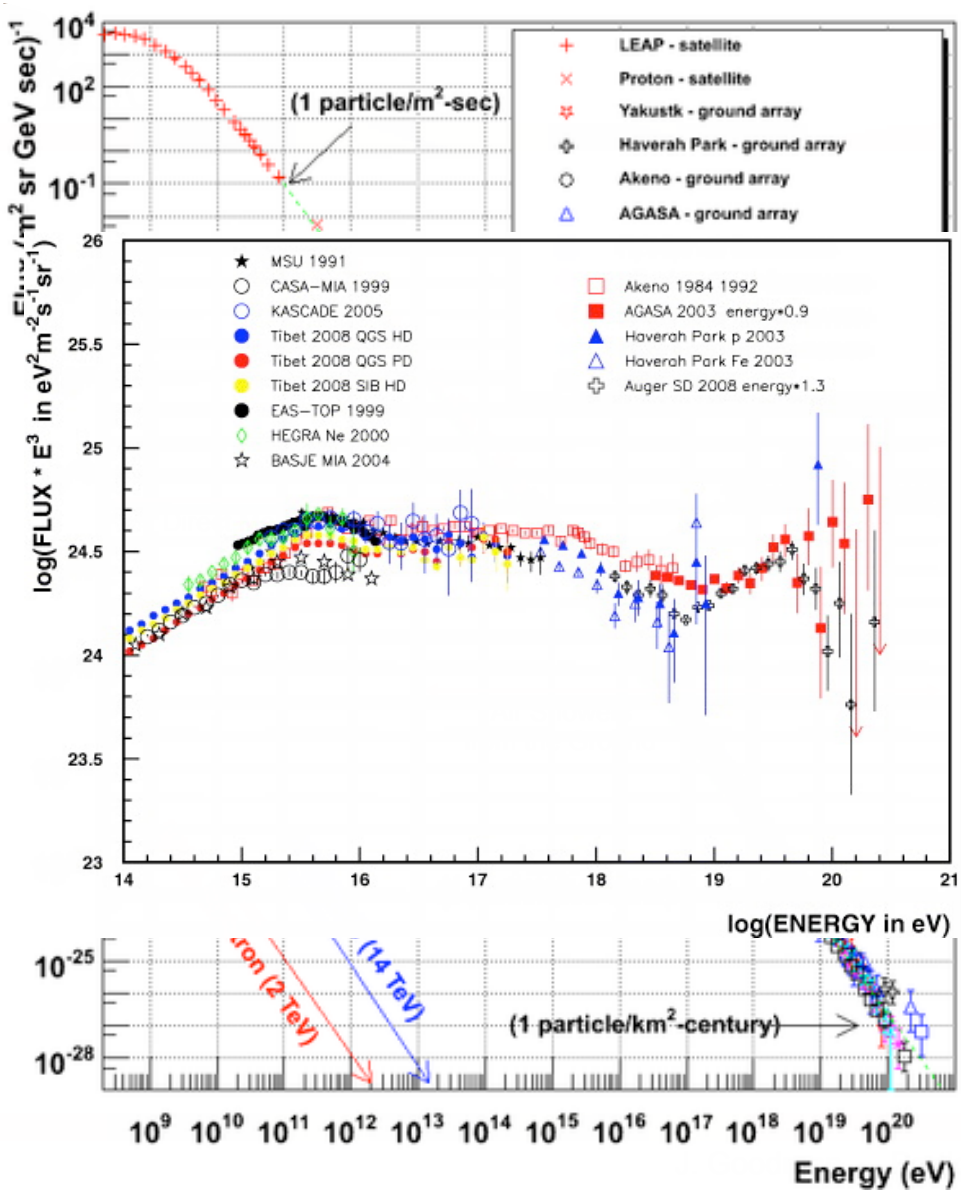
- Physikalische Zeitschrift: "The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above."

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

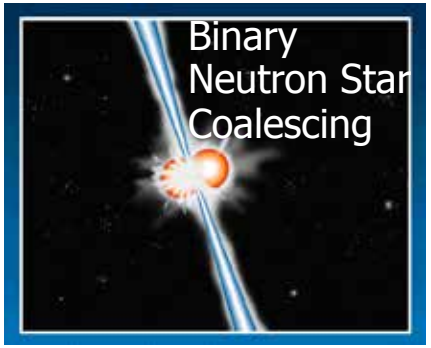


Cosmic Rays

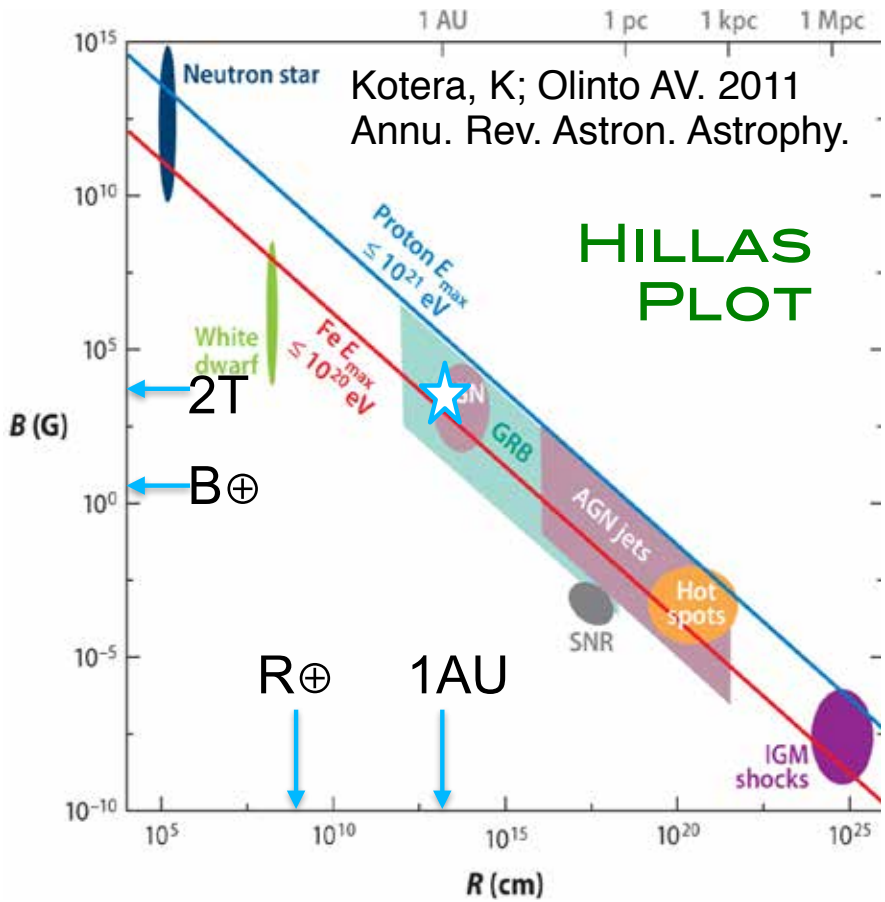
- The flux charged cosmic rays follows nearly a single power law over:
  - 10 decades in energy
  - 30 decades in flux
- Single particles have been observed with energies above 10^{20}eV!
- There are several “kinks” in the spectrum where the exponent changes, steepening at the “knee” and flattening at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



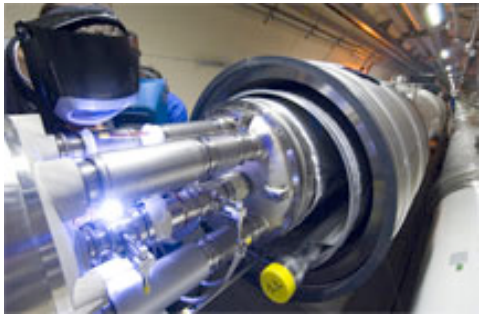
Candidate accelerators



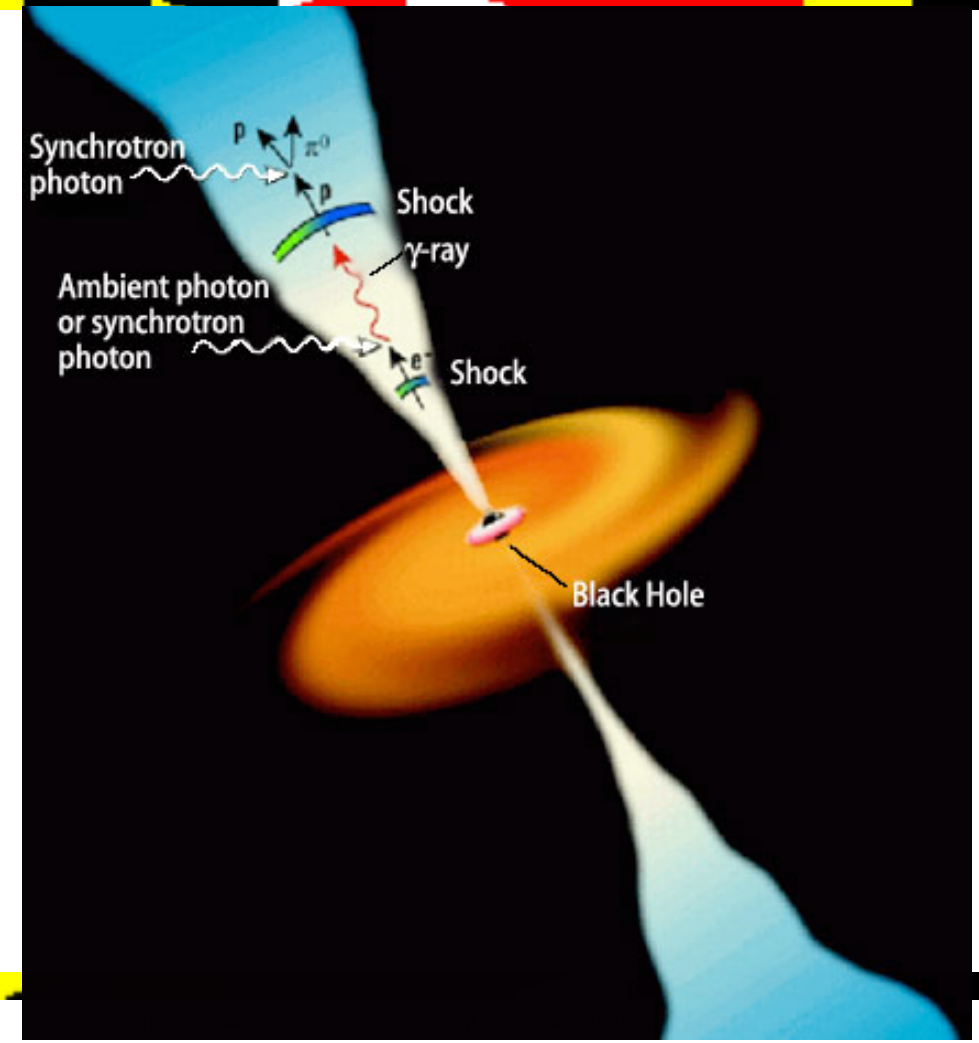
p=0.3 Br
p in Gev/c
B in Tesla
r in meters

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

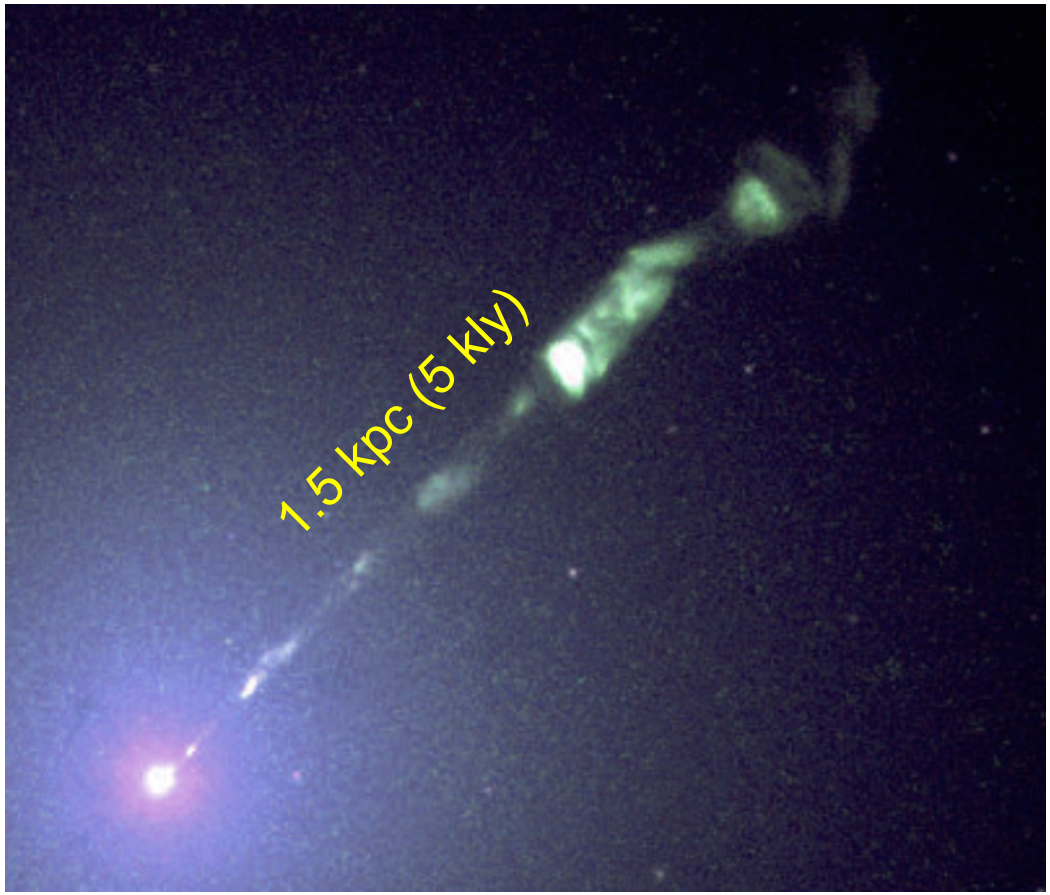
Large magnetic field



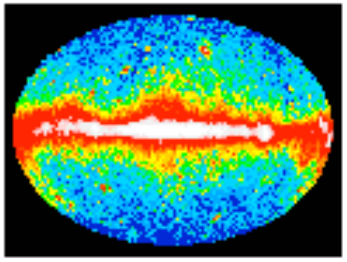
Active Galactic Nuclei (AGN)

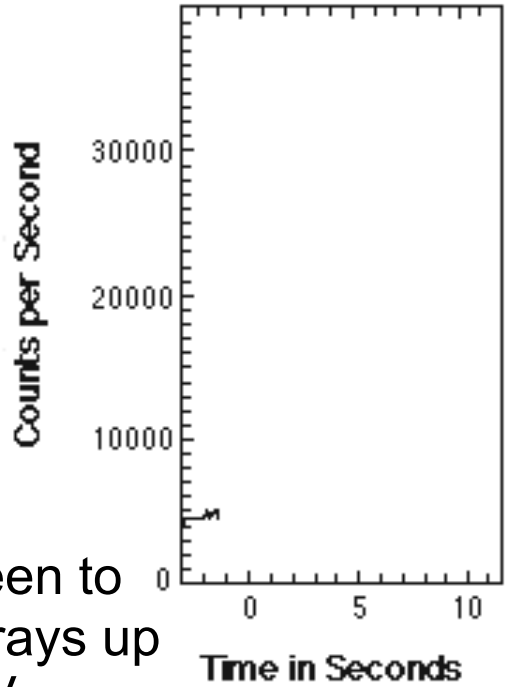


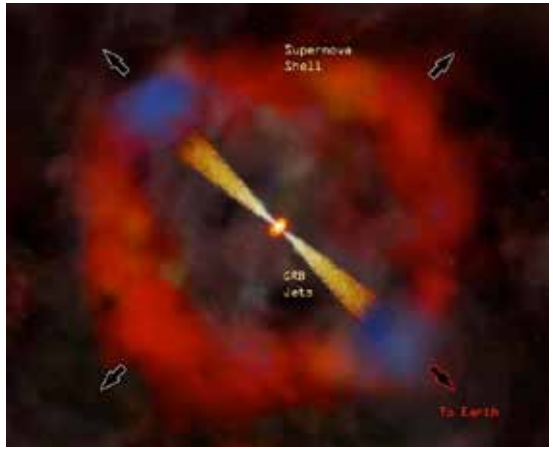
Hubble AGN M87

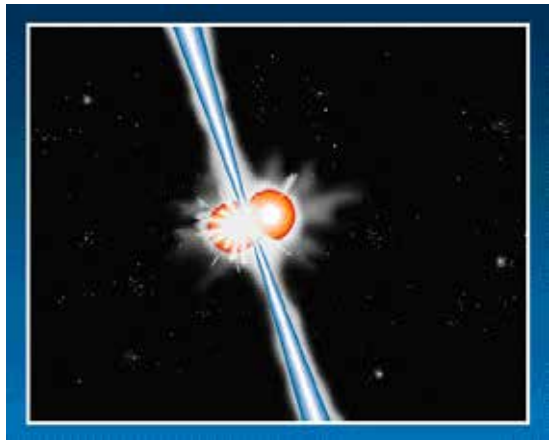


GRBs







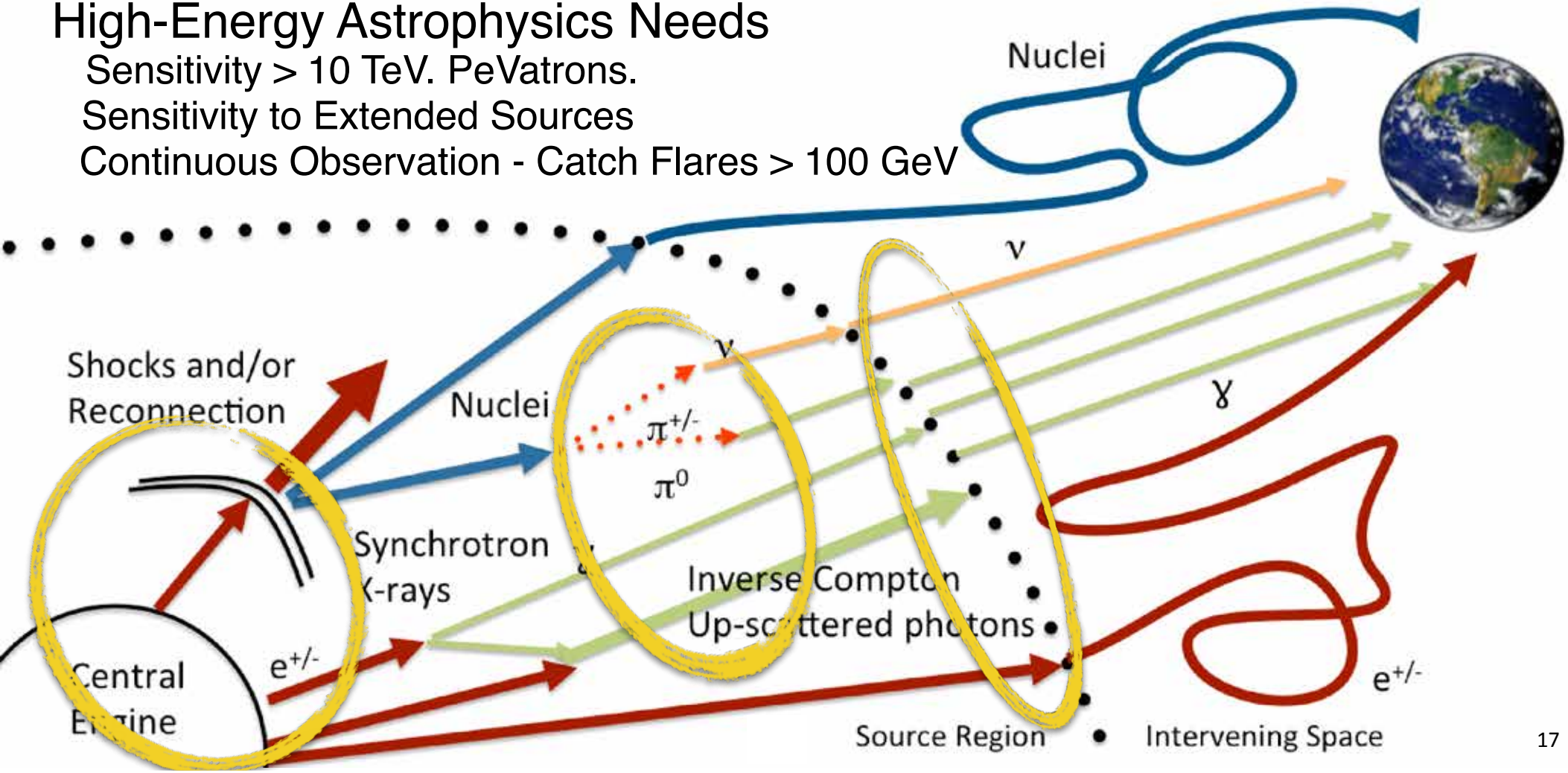


GRBs are now seen to produce gamma rays up to nearly 100 GeV

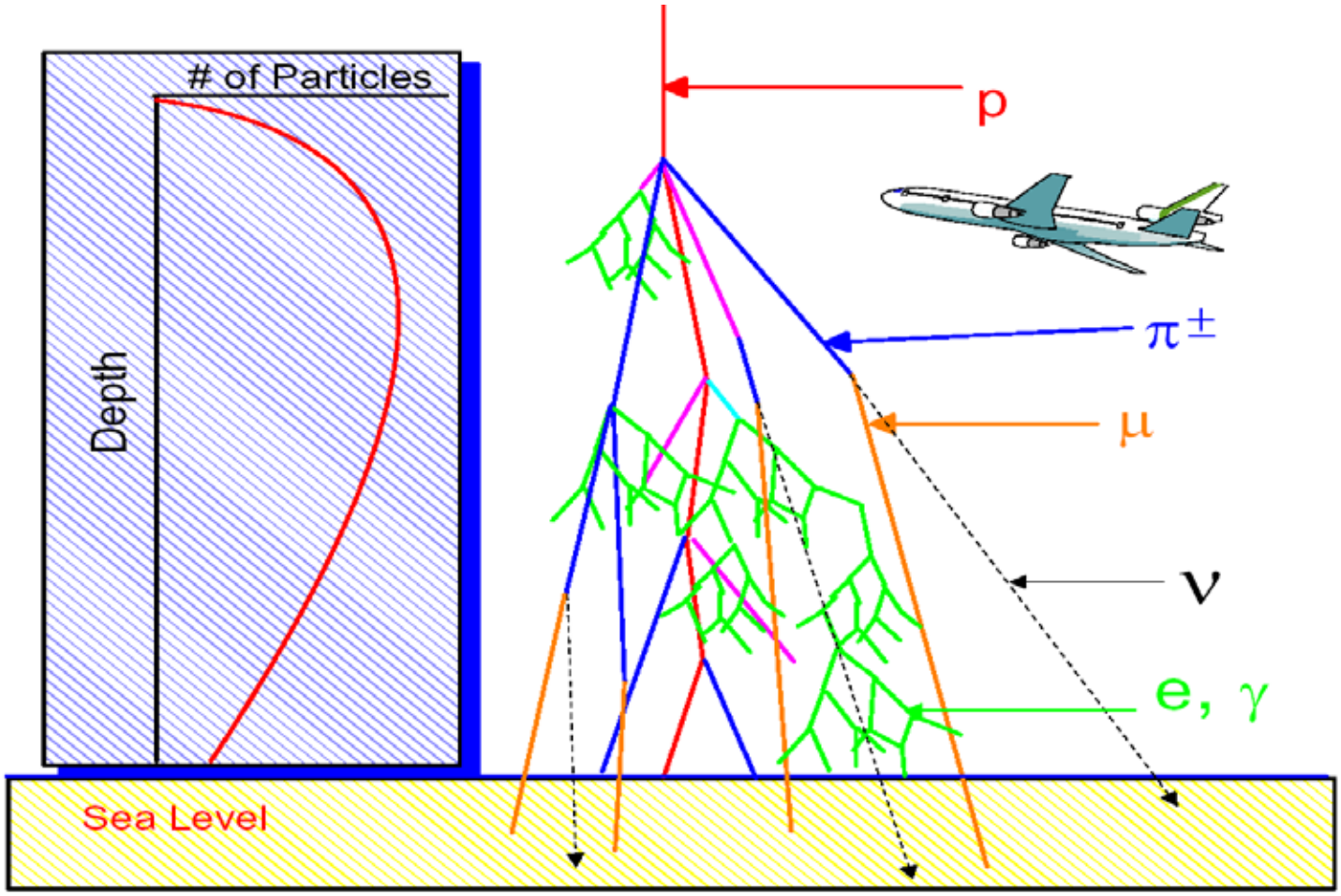
Acceleration / Emission Processes in Astrophysical Sources

High-Energy Astrophysics Needs

Sensitivity > 10 TeV. PeVatrons.
Sensitivity to Extended Sources
Continuous Observation - Catch Flares > 100 GeV



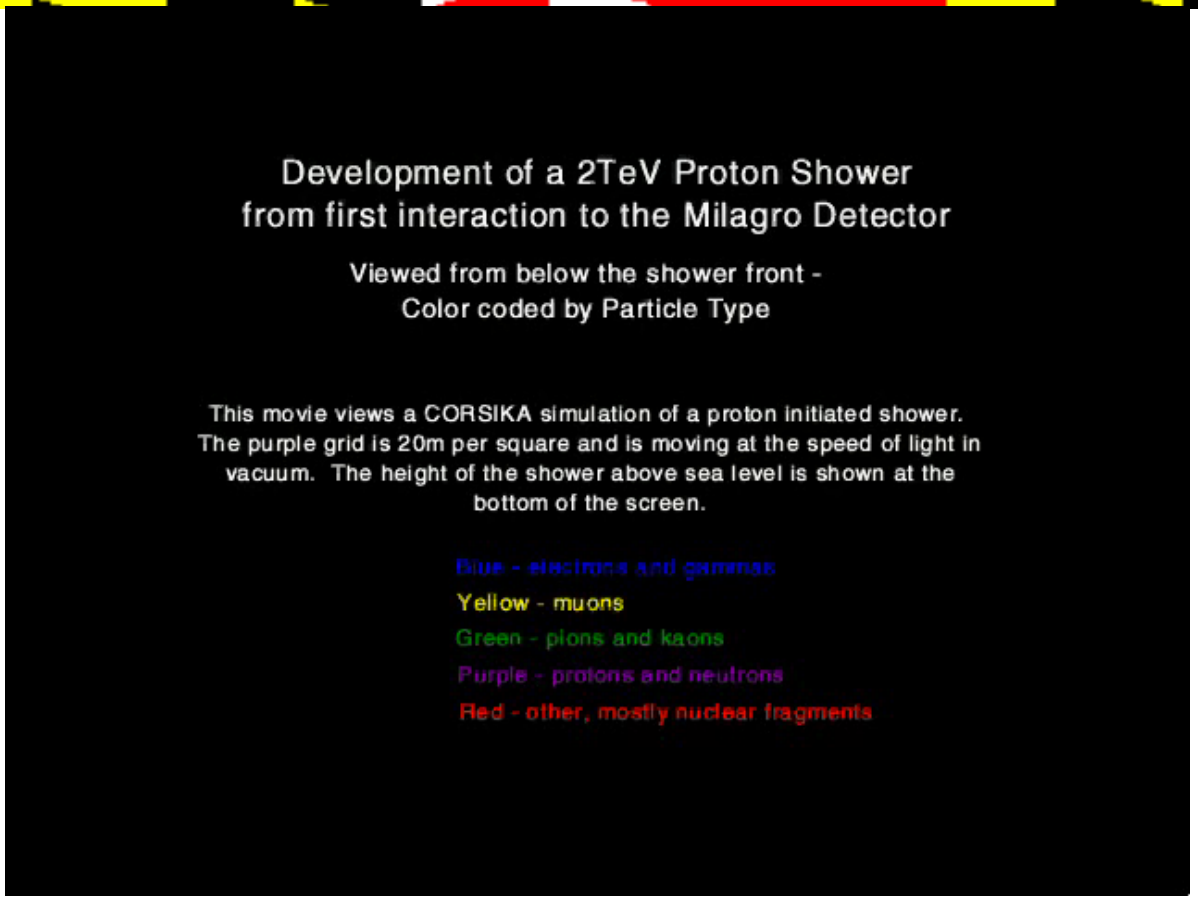
Extensive Air Shower Development



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

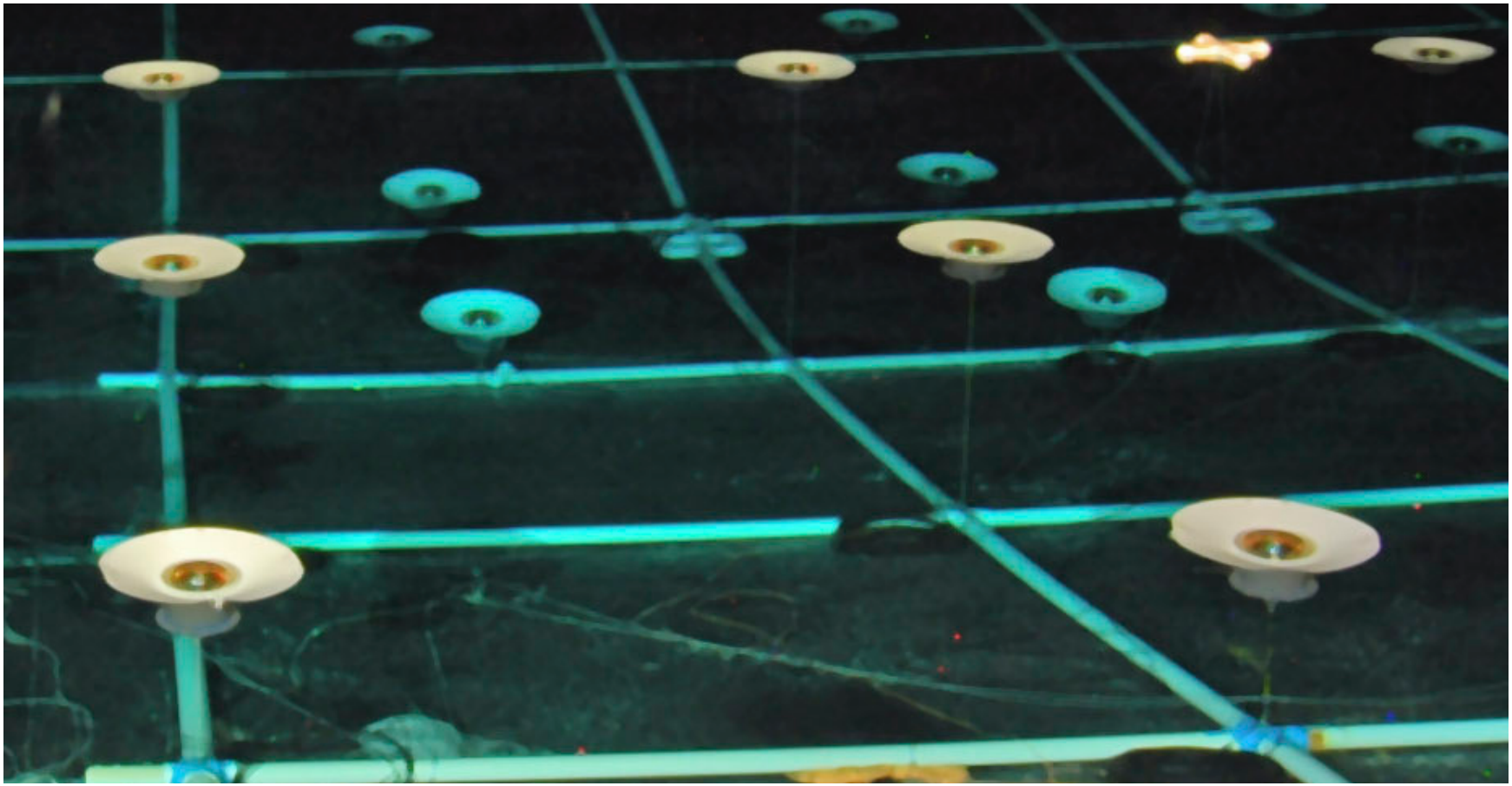
Milagro

- 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

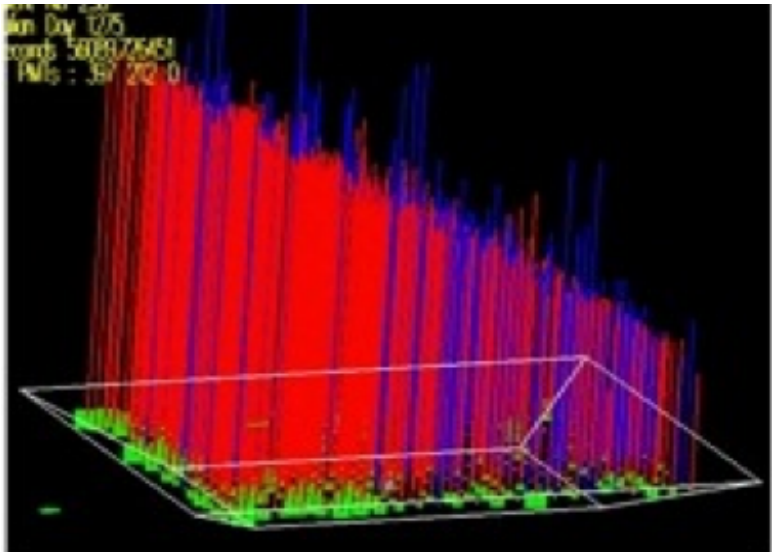
Milagro

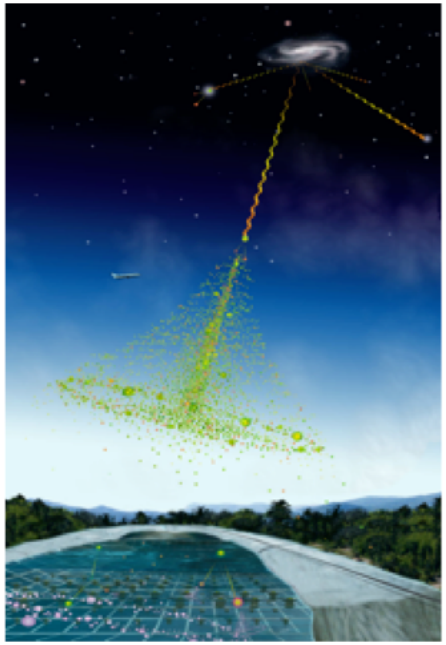
Milagro

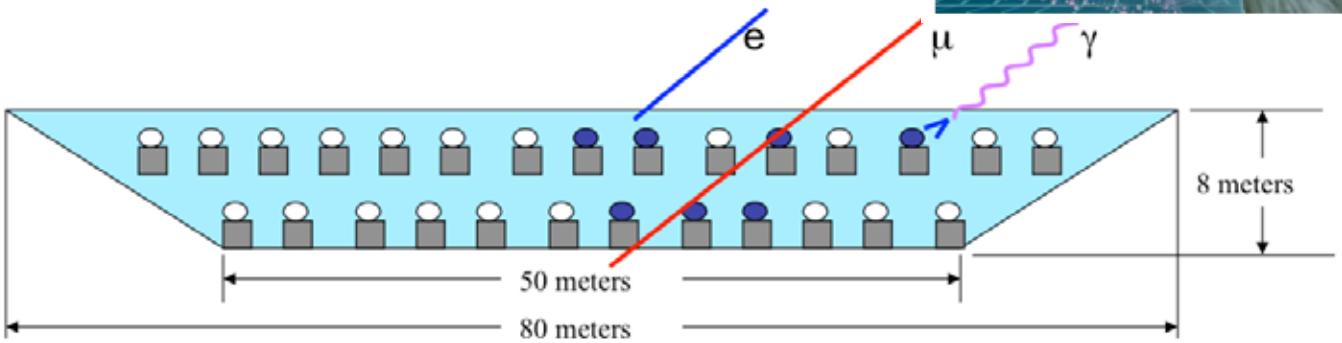
Milagro



Milagro

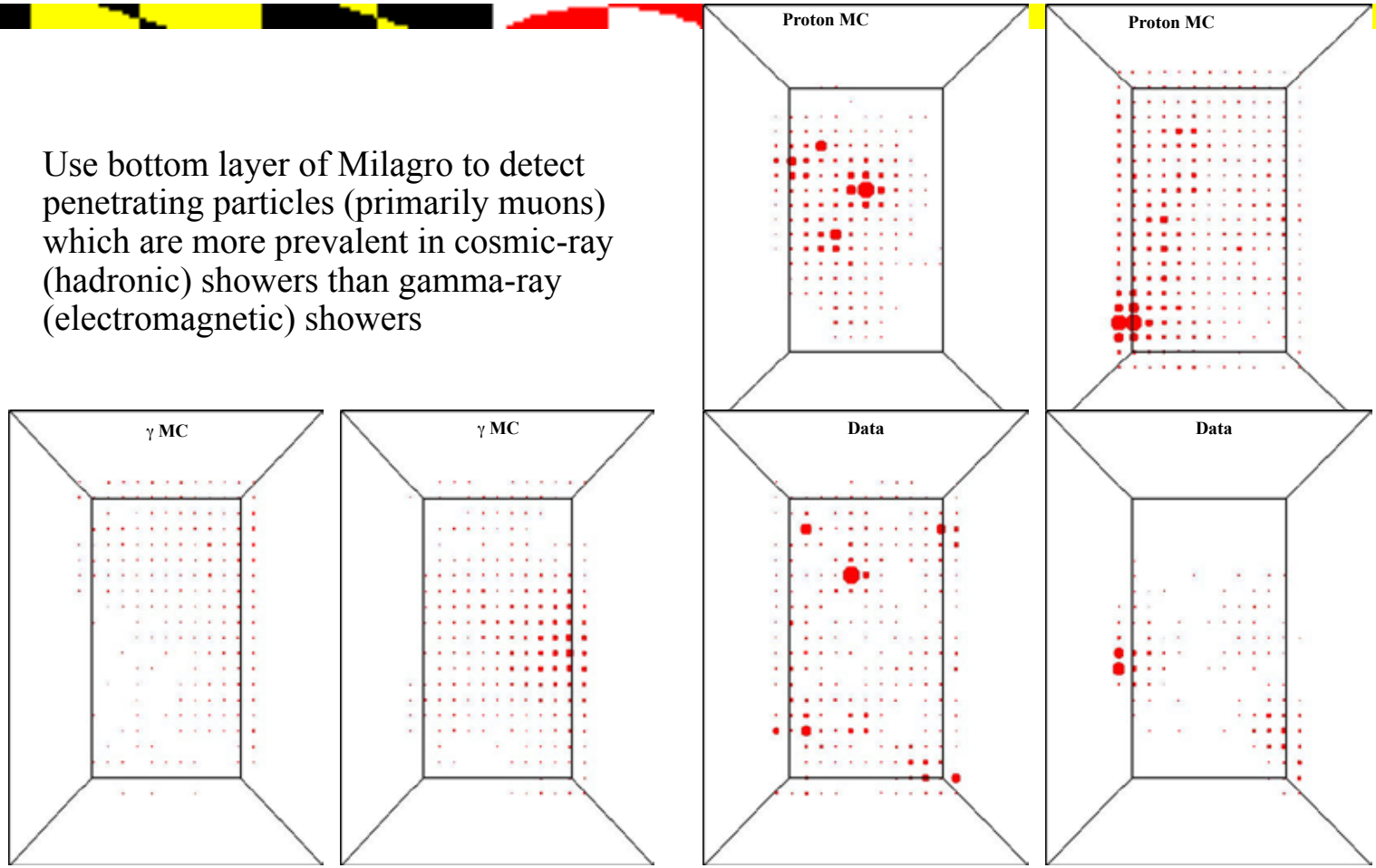




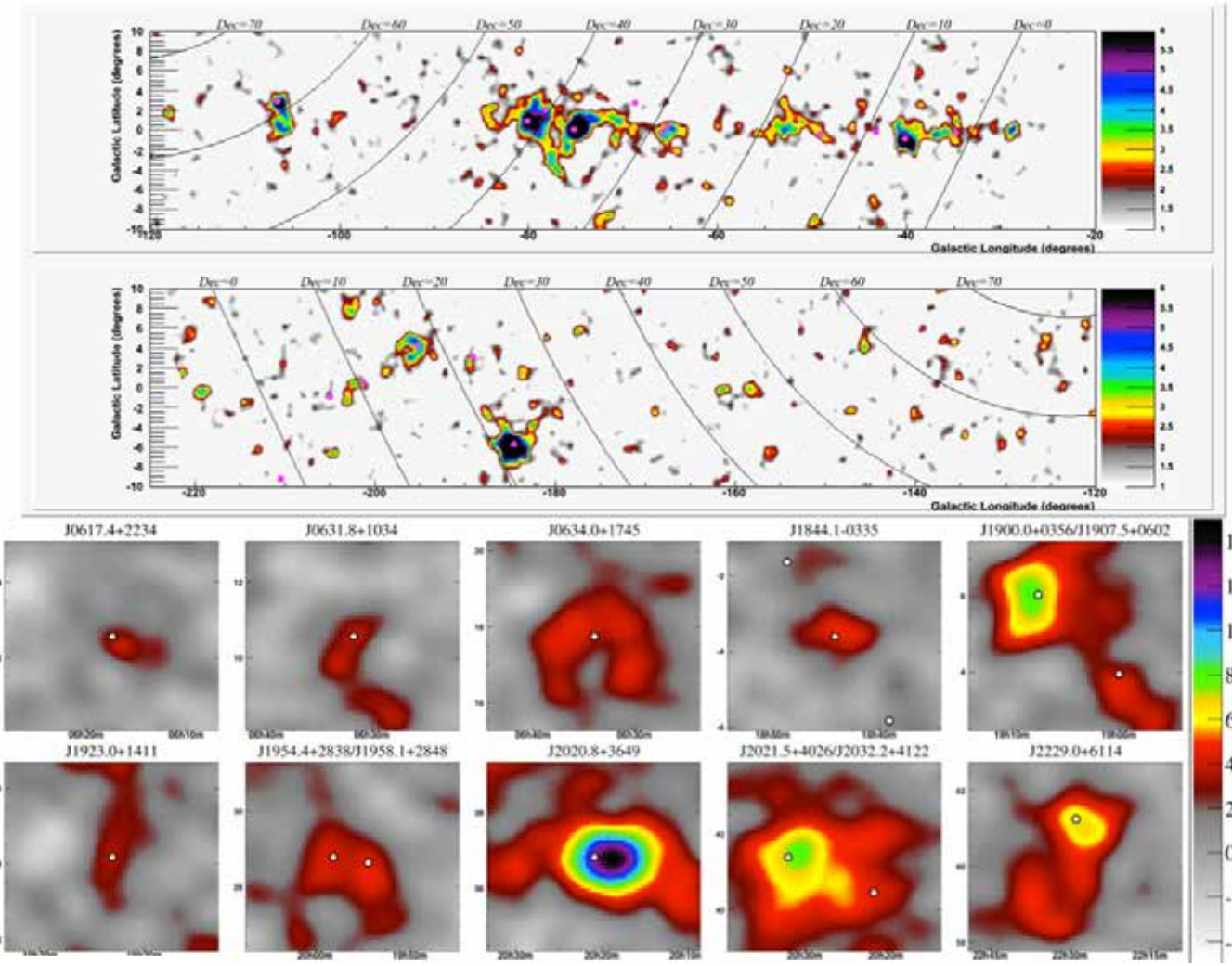


Background Rejection in Milagro

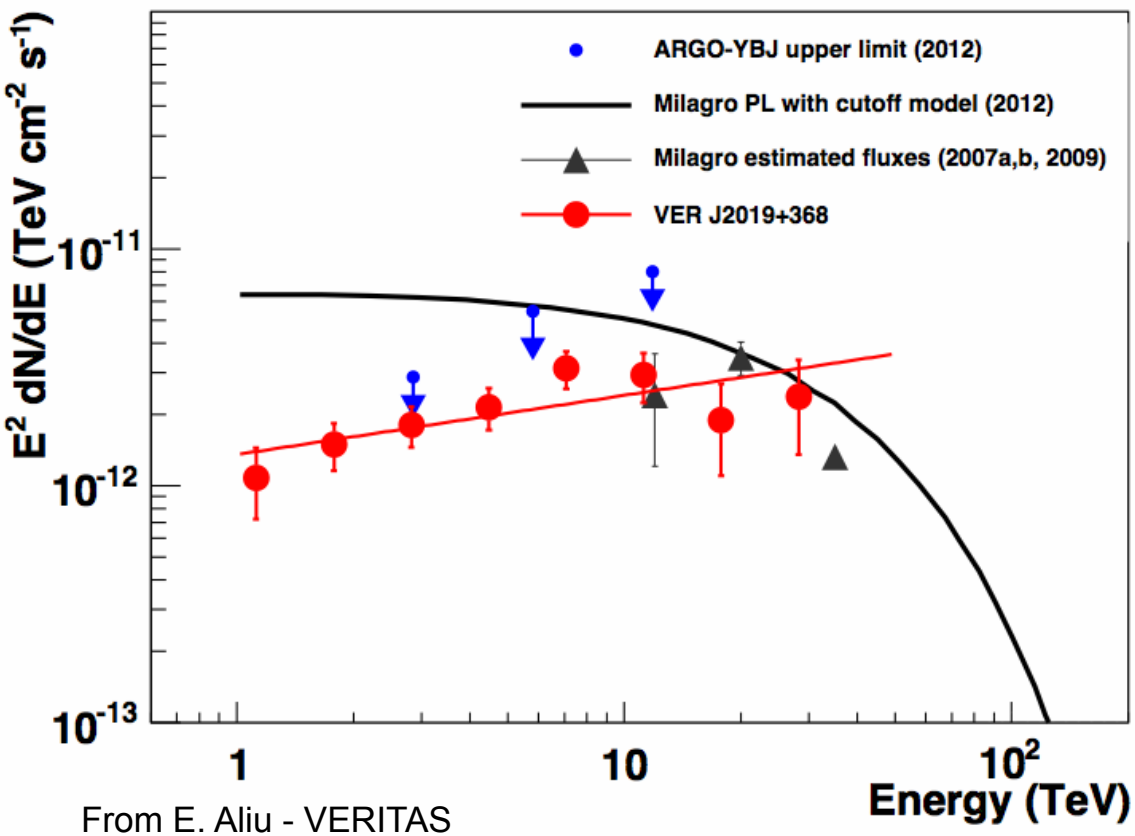
Use bottom layer of Milagro to detect penetrating particles (primarily muons) which are more prevalent in cosmic-ray (hadronic) showers than gamma-ray (electromagnetic) showers



Milagro TeV Sources



VERITAS Spectrum 2019+37

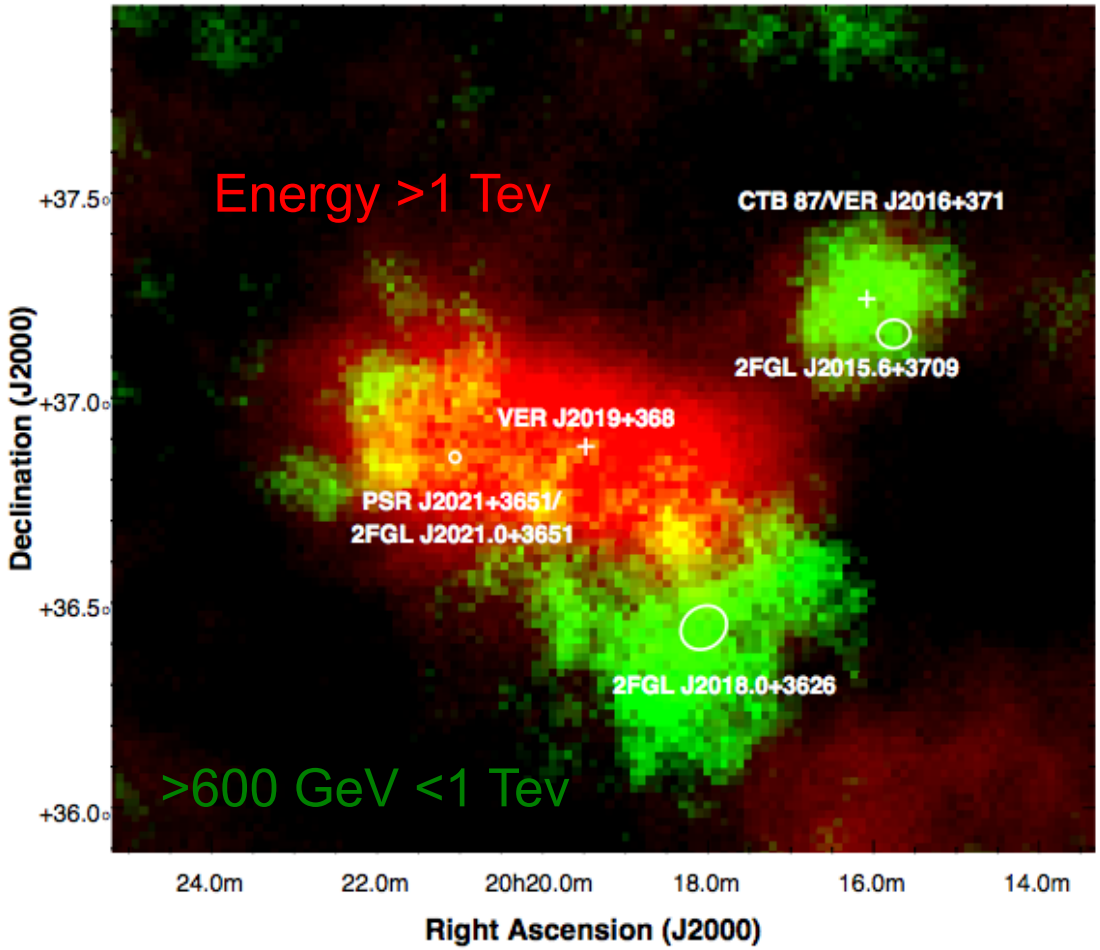


From E. Aliu - VERITAS

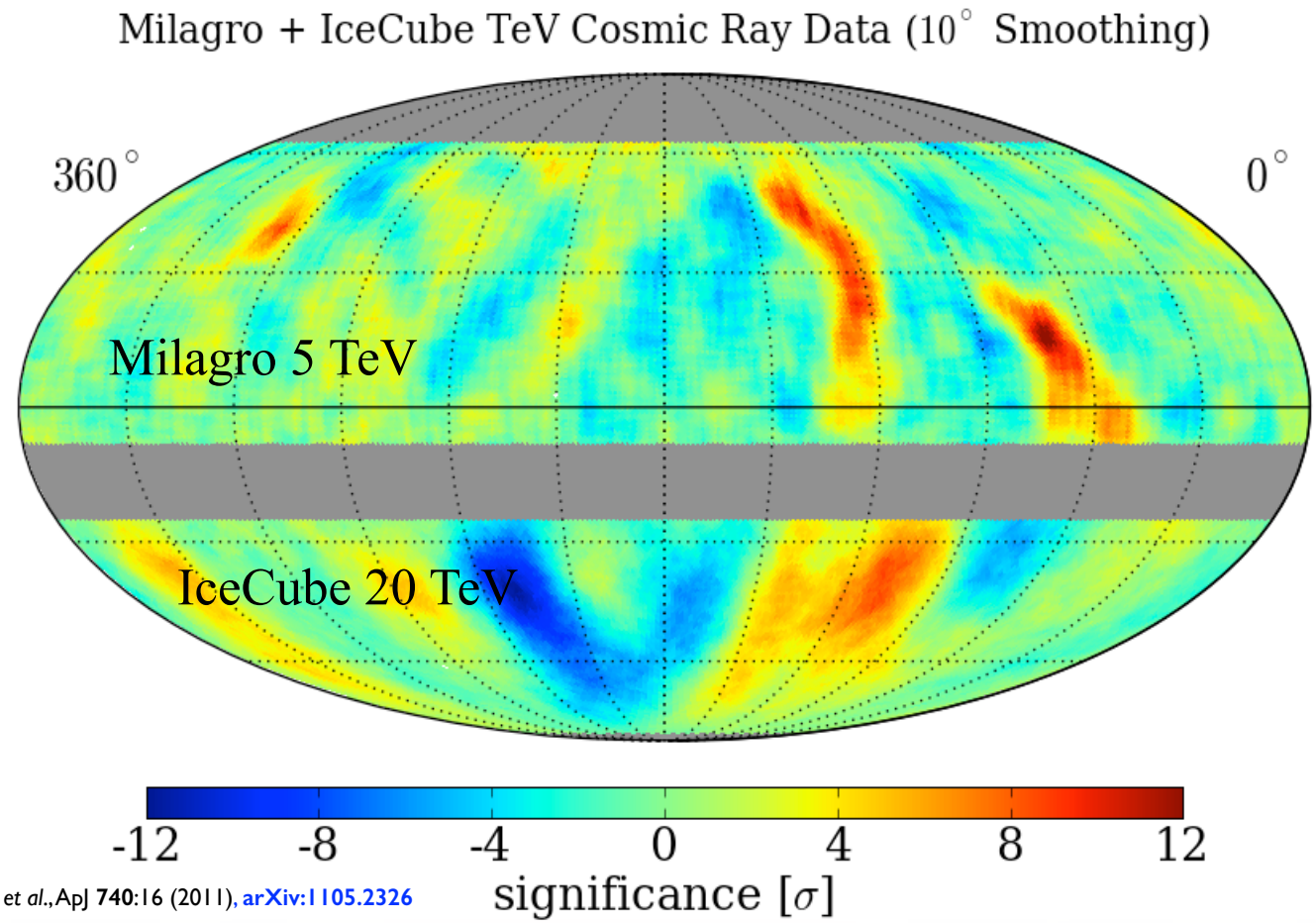
http://arxiv.org/pdf/1404.1841v1.pdf

- Measuring the spectrum from 30-100 TeV will tell if this a hadron accelerator
- High energy emission comes from a different spot than the lower energy

VERITAS Observation of 2019+37



Cosmic Ray Anisotropy

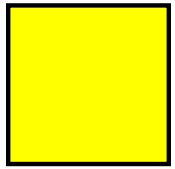


R. Abbasi *et al.*, ApJ **740**:16 (2011), arXiv:1105.2326


HAWC
High Altitude Water Cherenkov
H
A
W
C

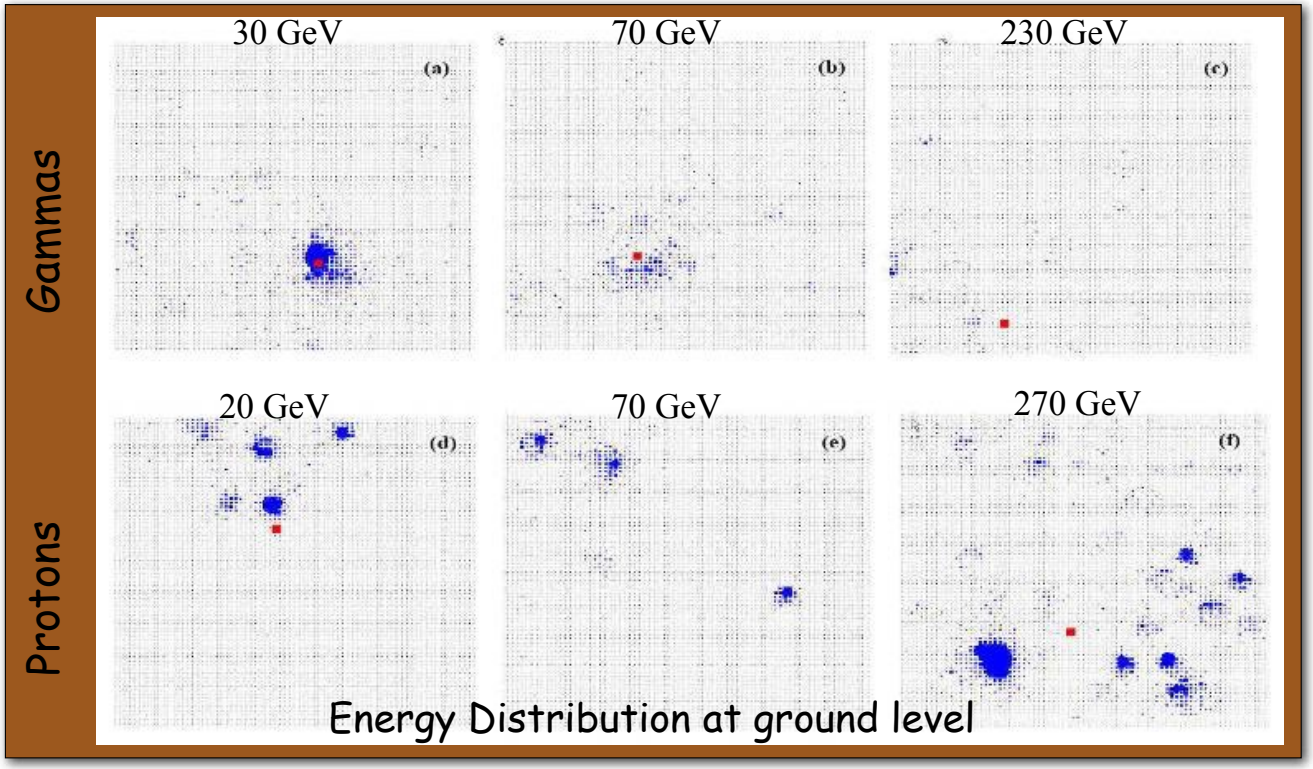
Gamma/Hadron Separation

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



Size of HAWC

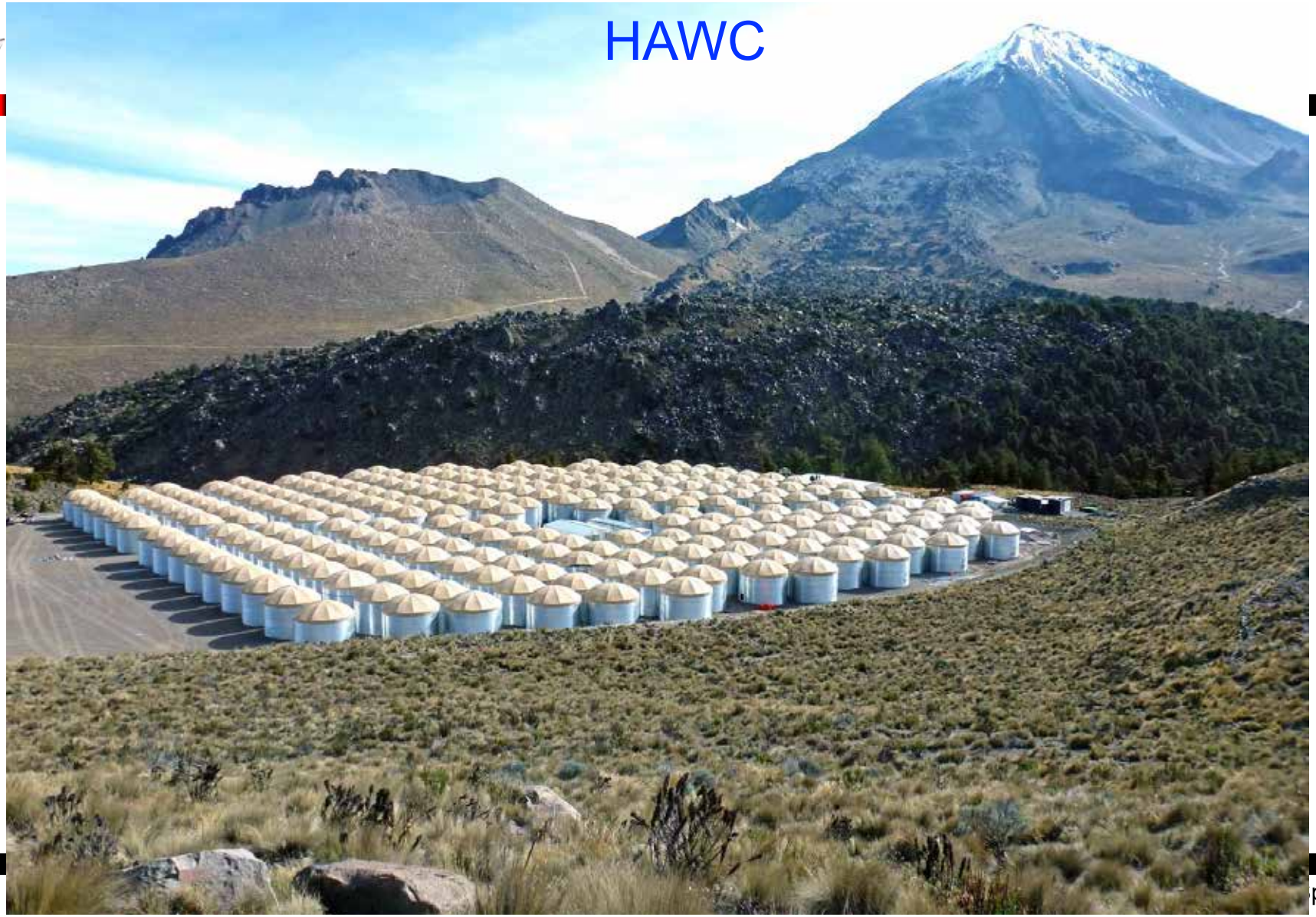
Size of Milagro deep layer



The HAWC Site

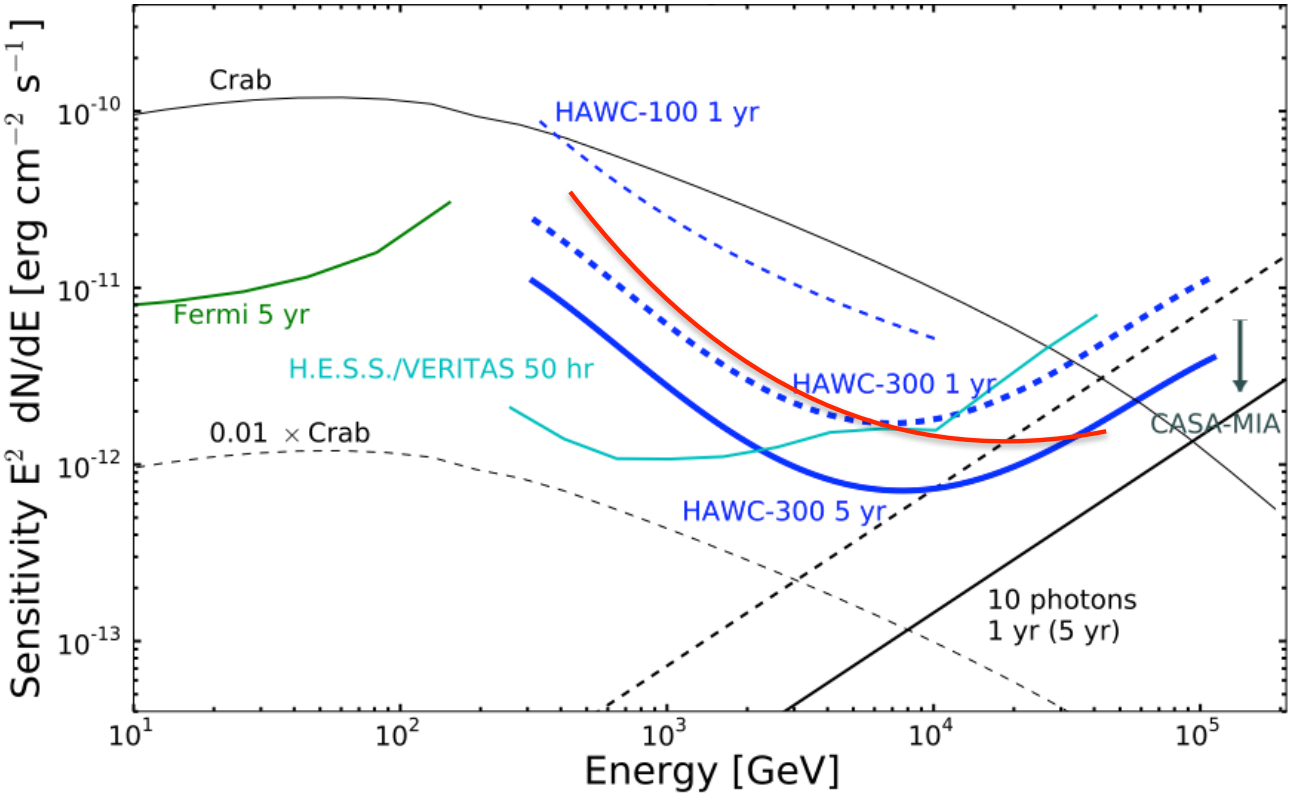
Latitude: 18º59.7'N
Longitude: 97º18.6'W

HAWC



HAWC Differential Sensitivity

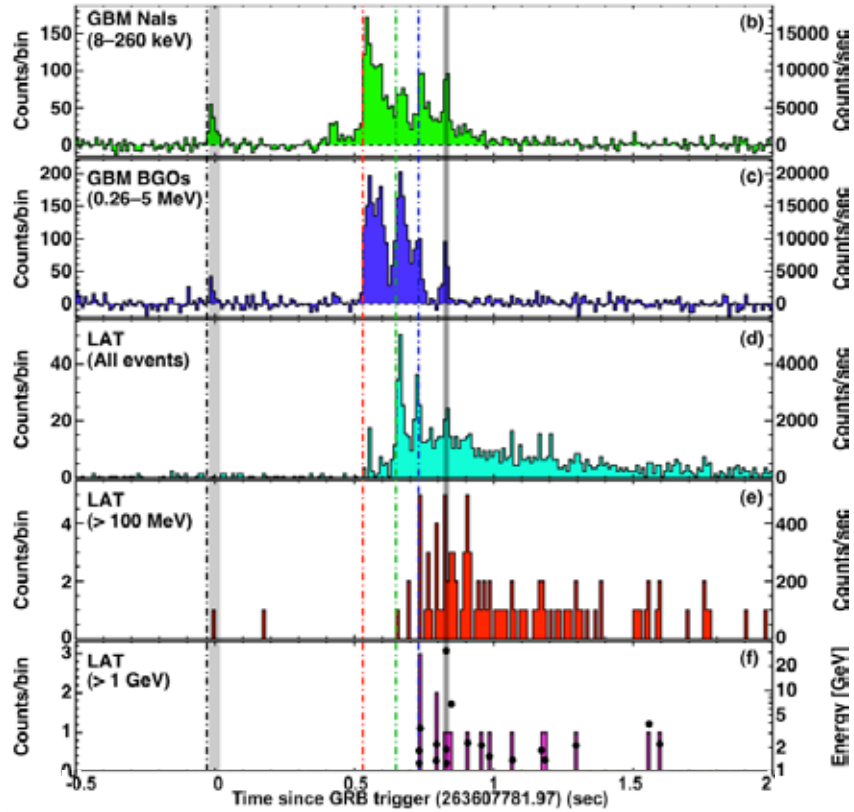
Differential Sensitivity per Quarter Decade of Energy



http://arxiv.org/abs/1306.5800 Astroparticle Physics 2013

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

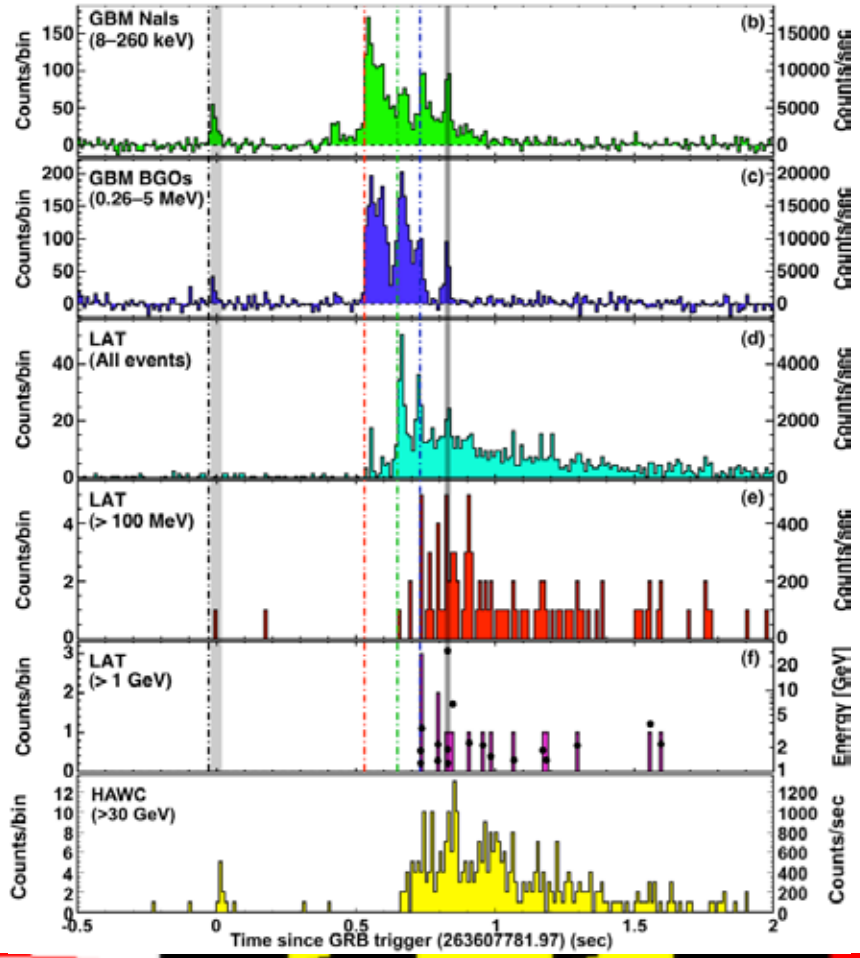
Fermi Observation of GRB 090510



Fermi Observation of GRB 090510 with

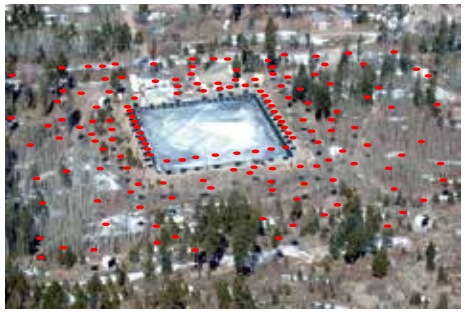
- Assume spectrum extends to 125 GeV and attenuation with EBL model of Gilmore
- HAWC: 200 events from GRB 090510 if near zenith
  ~few background events
- Major Improvements!
  - Low-threshold DAQ
  - 10-inch PMTs

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



Milagro/Fermi/HAWC Comparison

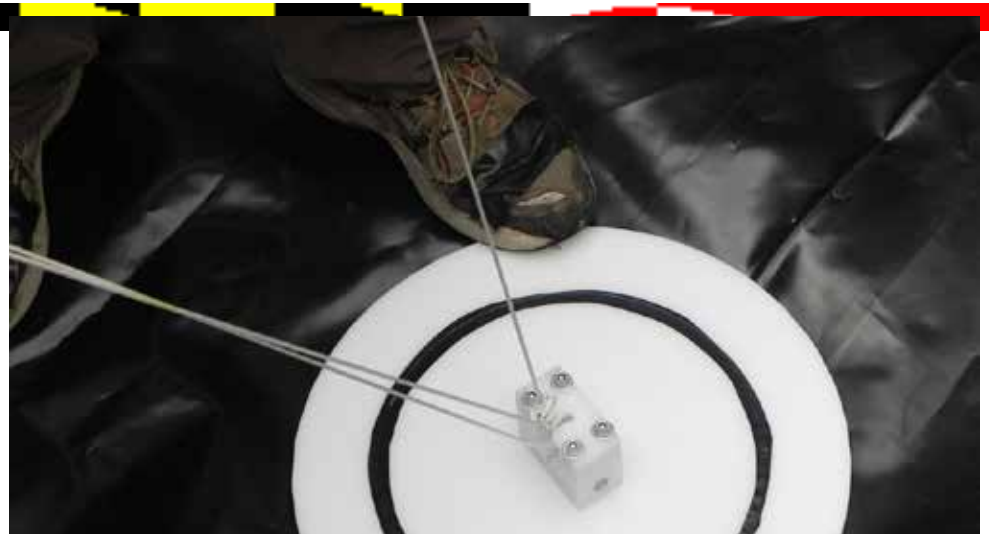
- HAWC is ~15x more sensitive (sig/√bg) than Milagro
  - HAWC sees the Crab at ~6σ in a day - Milagro took 6 months to see 6σ
- Taking into account the Fermi exposure and signal vs Milagro we find that for galactic sources Fermi is ~15x more sensitive than Milagro.
- HAWC at TeV has approximately the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

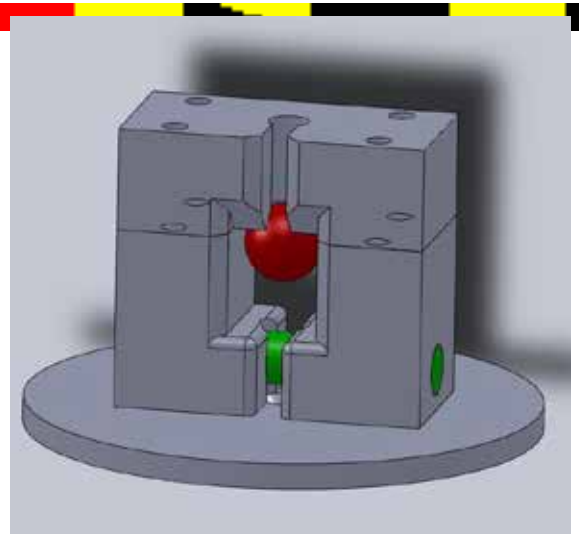


HAWC Tanks

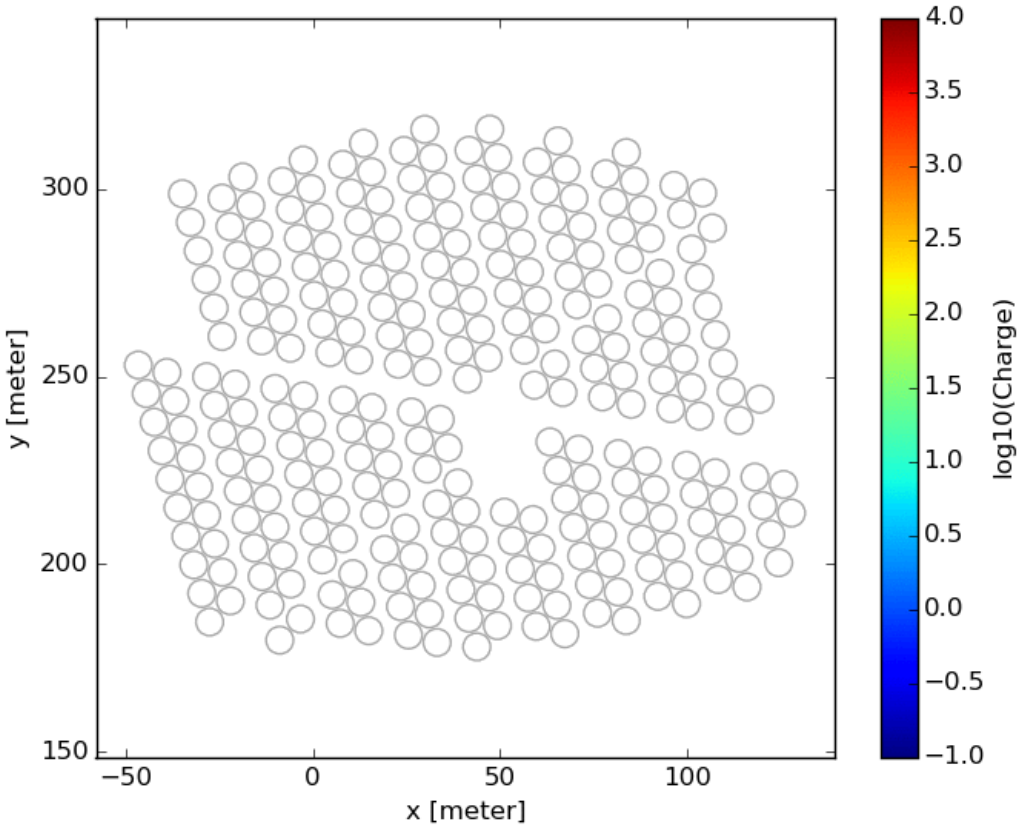
Tank Construction

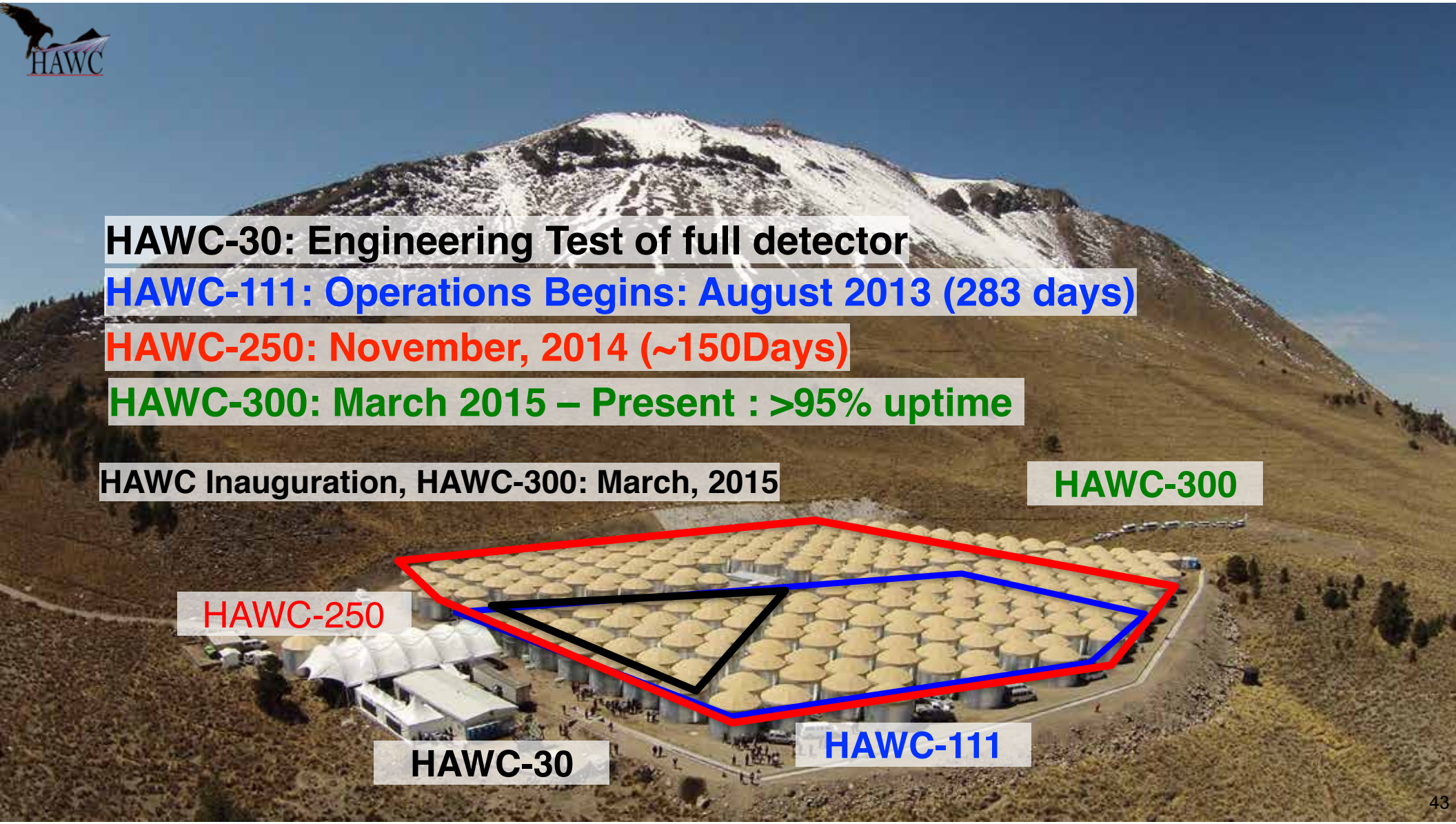
Safe PMT Deployment and Recovery

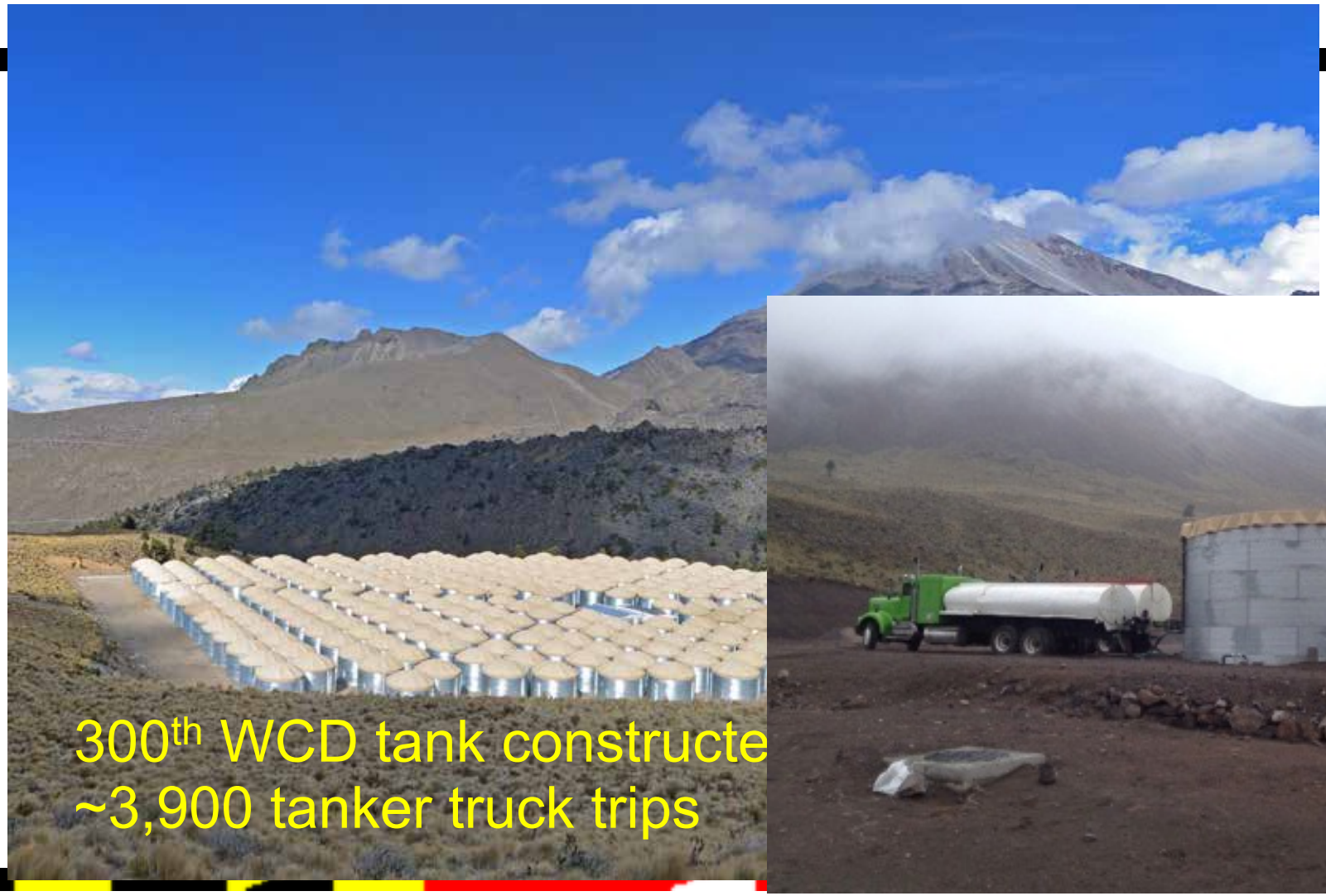




Angle Reconstruction




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
HAWC-300
HAWC-250
HAWC-111
HAWC-30


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


H
A
W
C

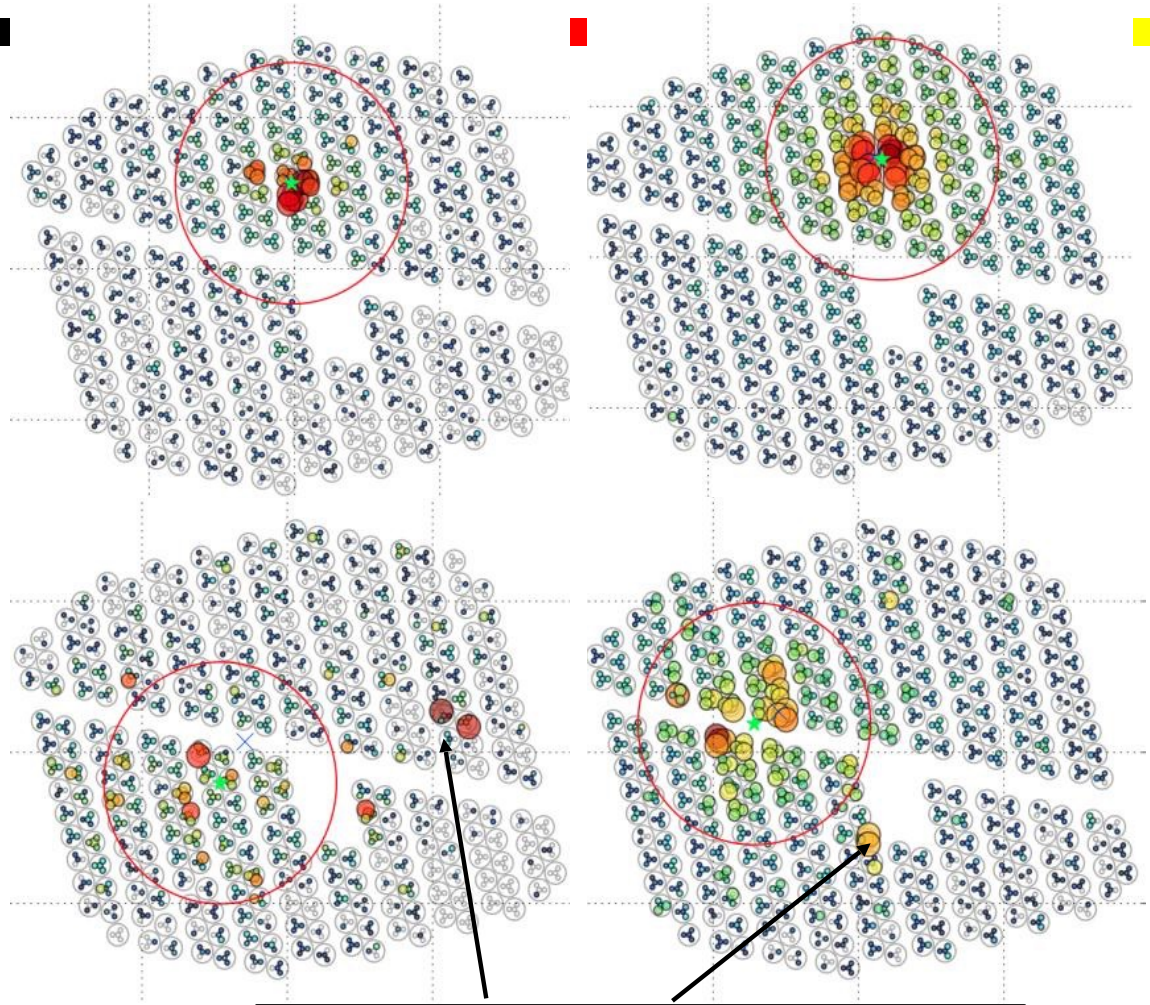
Construction Video

Gamma Hadron Separation (MC)

Gammas

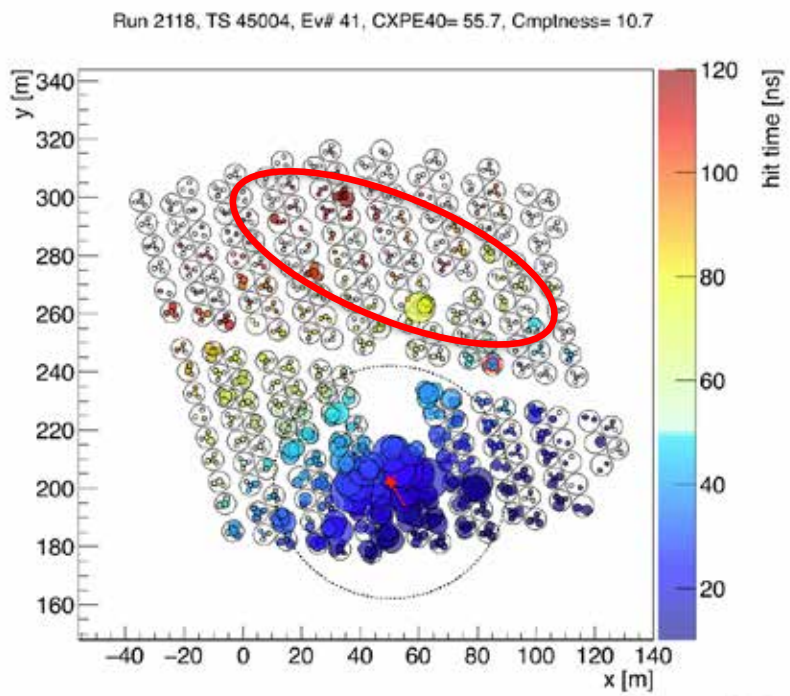
Monte Carlo Simulation

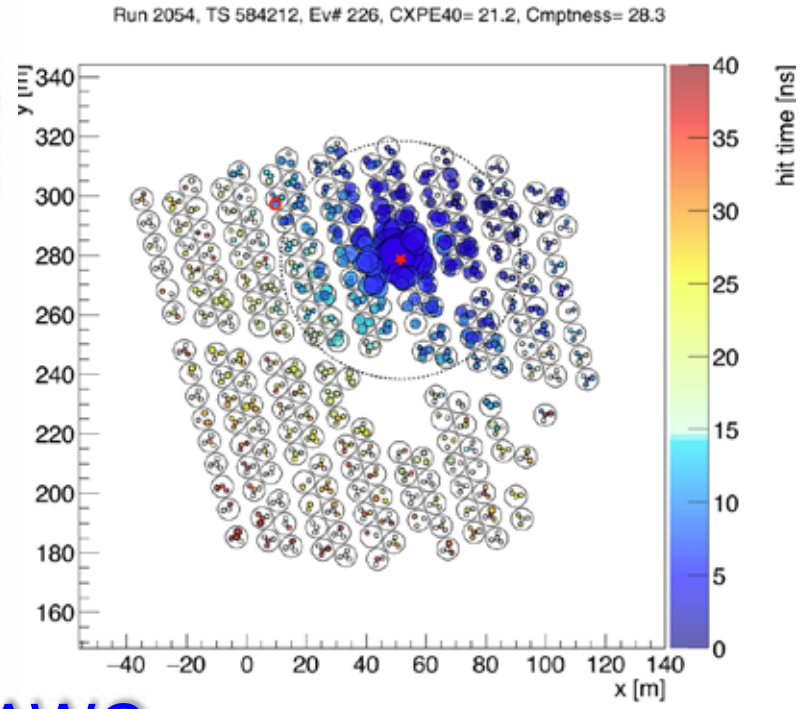
Protons



Energy deposited away from core

HAWC-250 Data





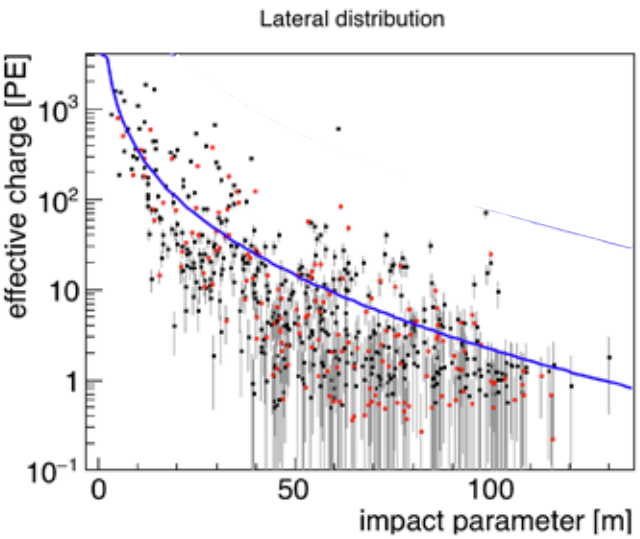
Hadron Shower (off source)

HAWC Data

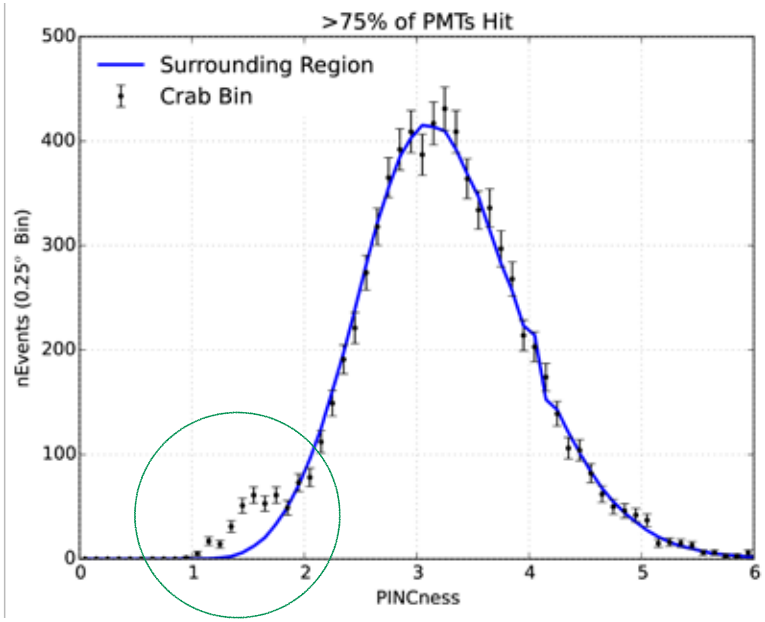
Likely Gamma Shower (Crab event)

Gamma - Hadron Separation

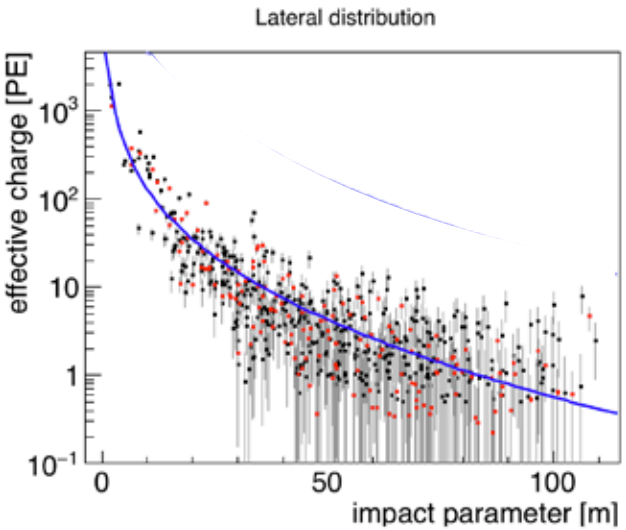
hadronic event

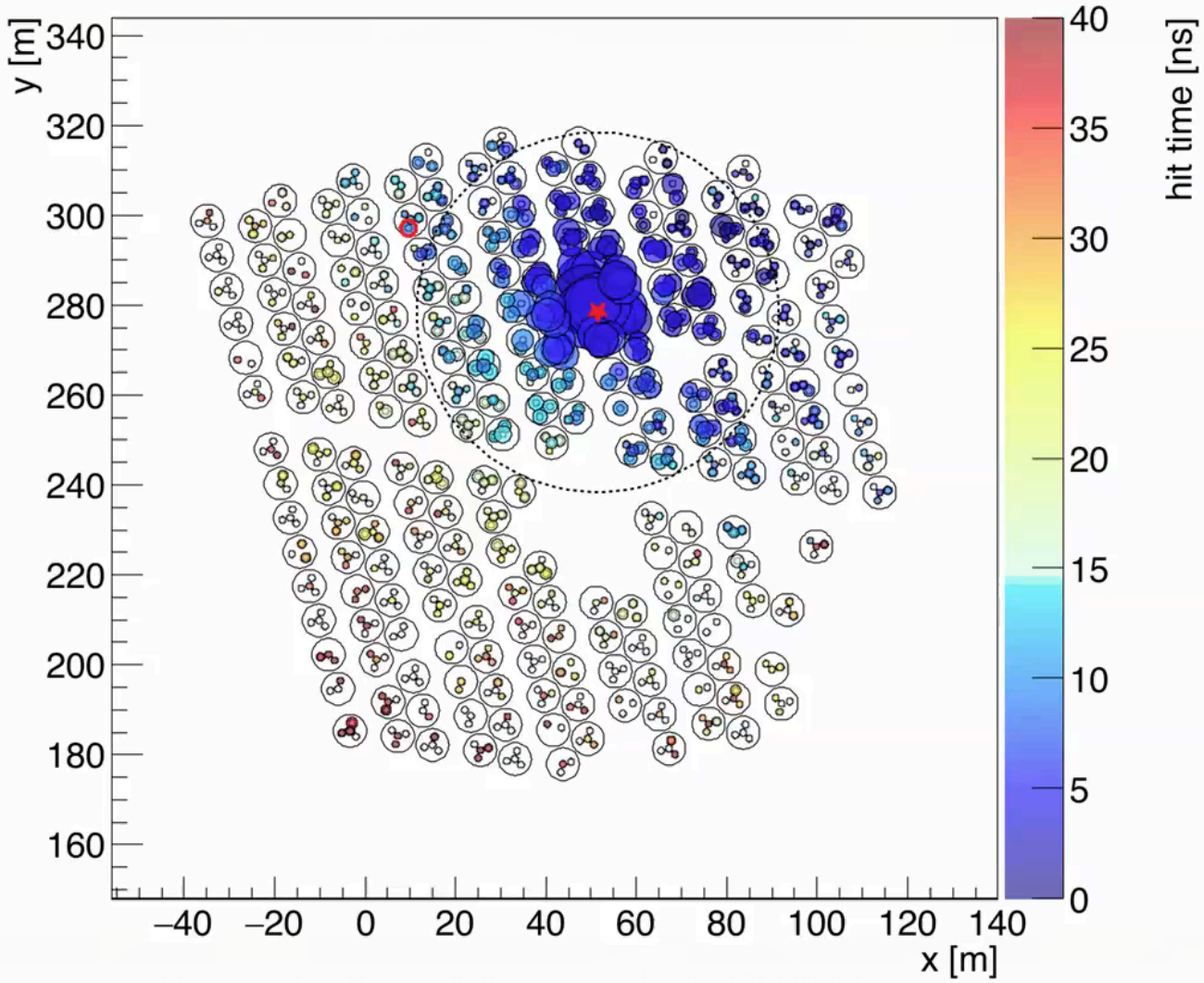


gamma/hadron parameter

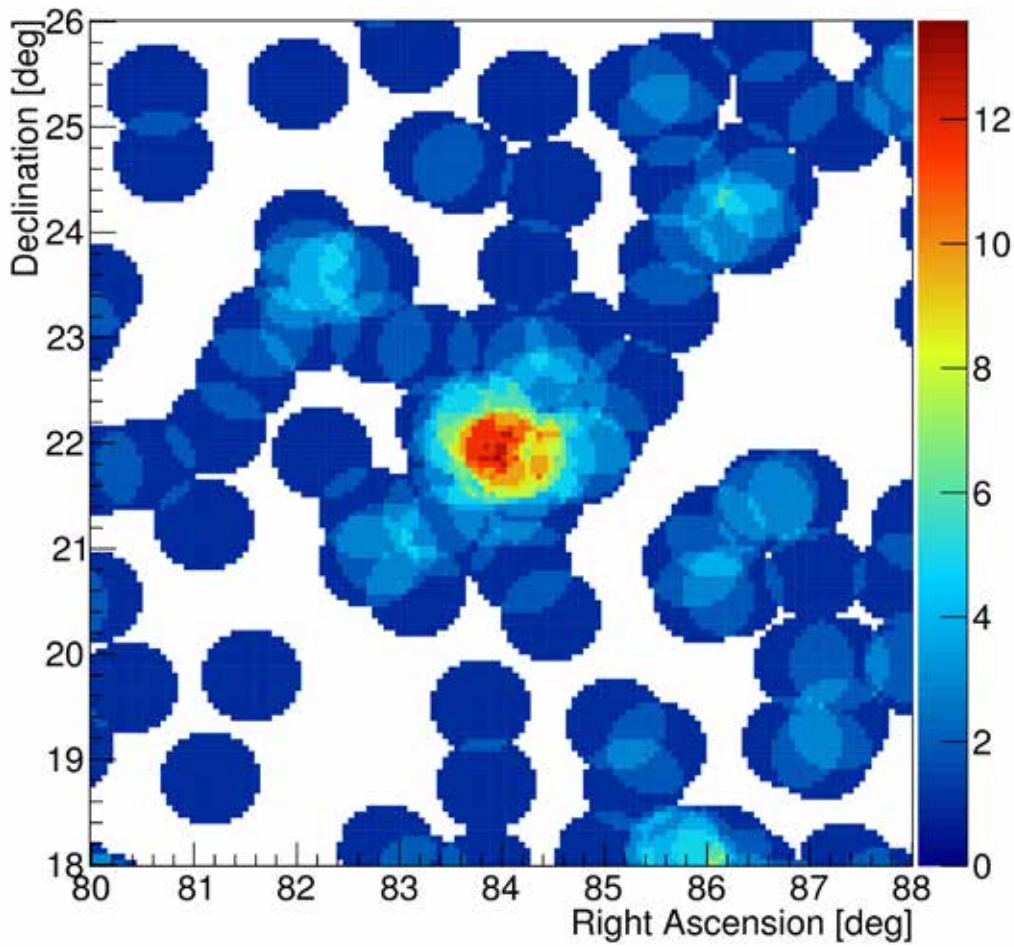


gamma ray-like event




Run 2054, TS 584212, Ev# 226, CXPE40= 21.2, Cmptness= 28.3
y [m]
340
320
300
280
260
240
220
200
180
160
–40
–20
0
20
40
60
80
100
120
140
x [m]
hit time [ns]
40
35
30
25
20
15
10
5
0

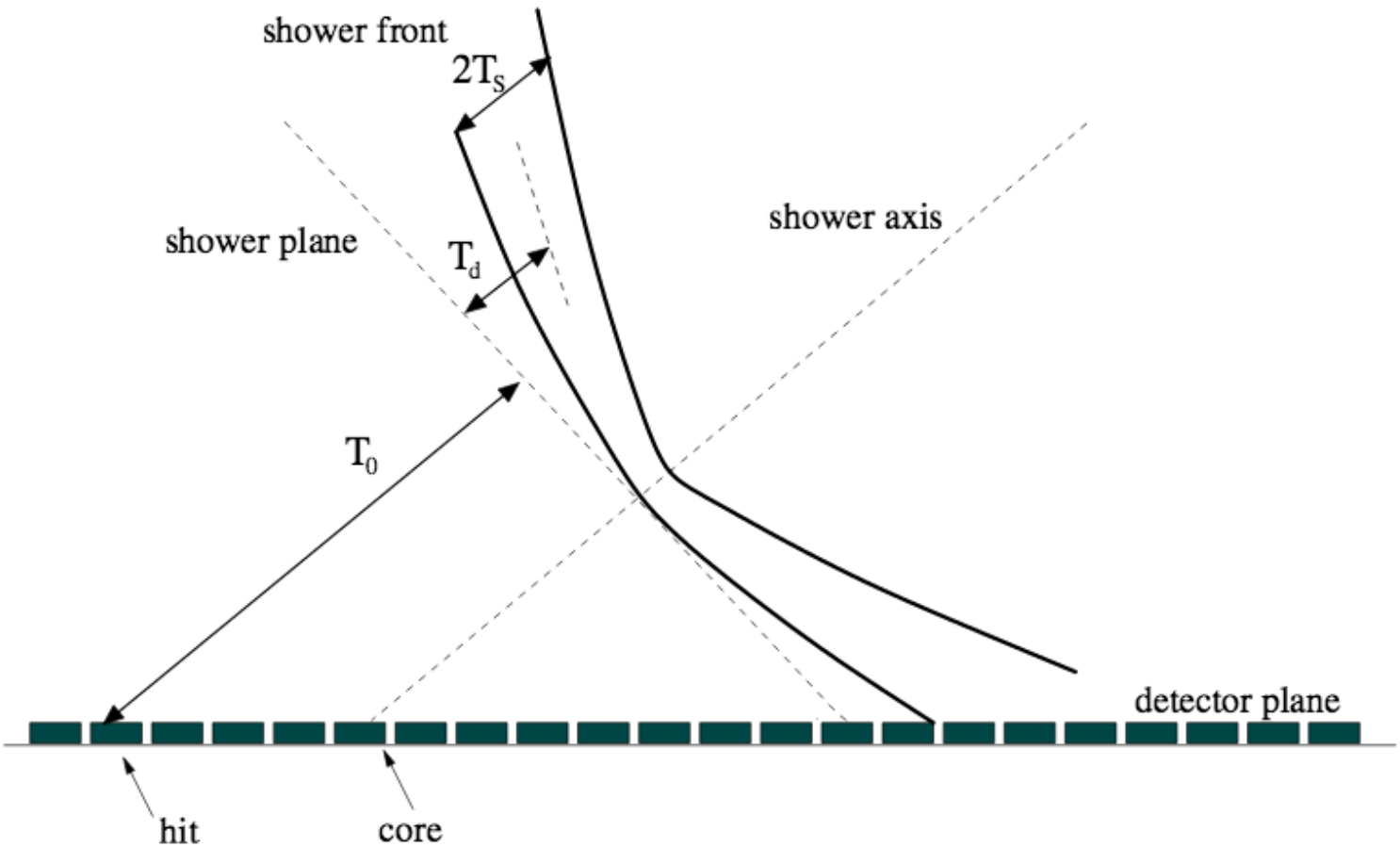
Photon rich sample from the Crab



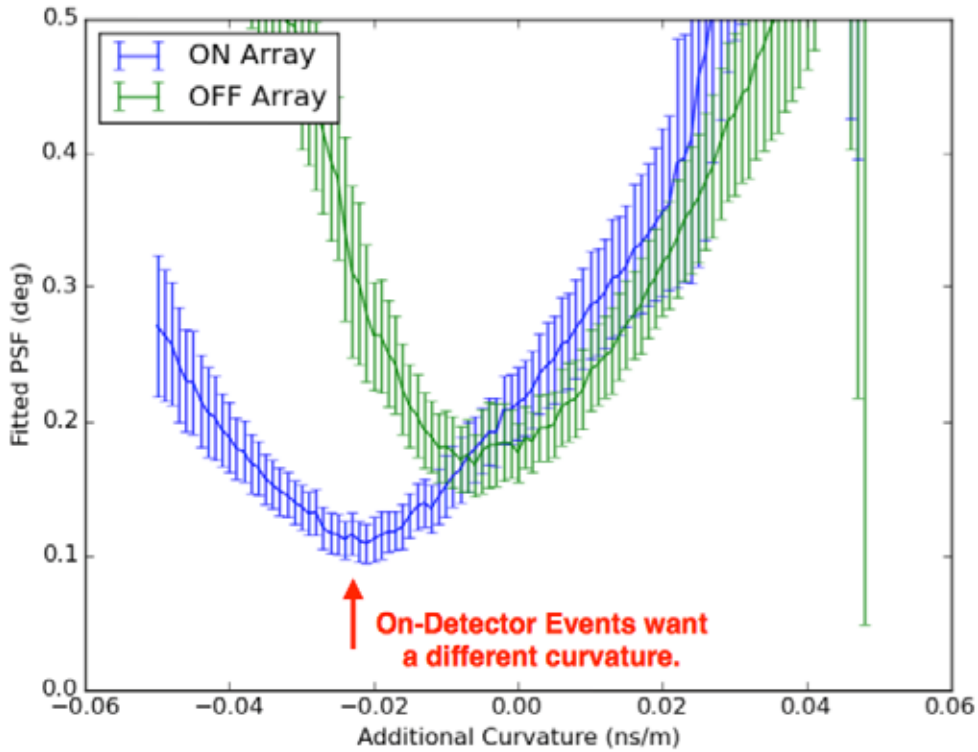
With Strong Photon Cut

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

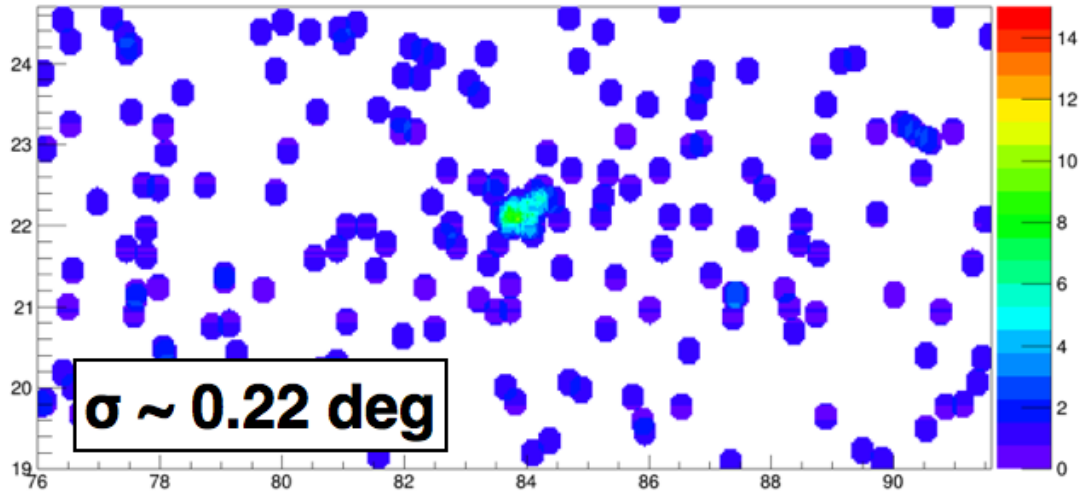
Shower Curvature



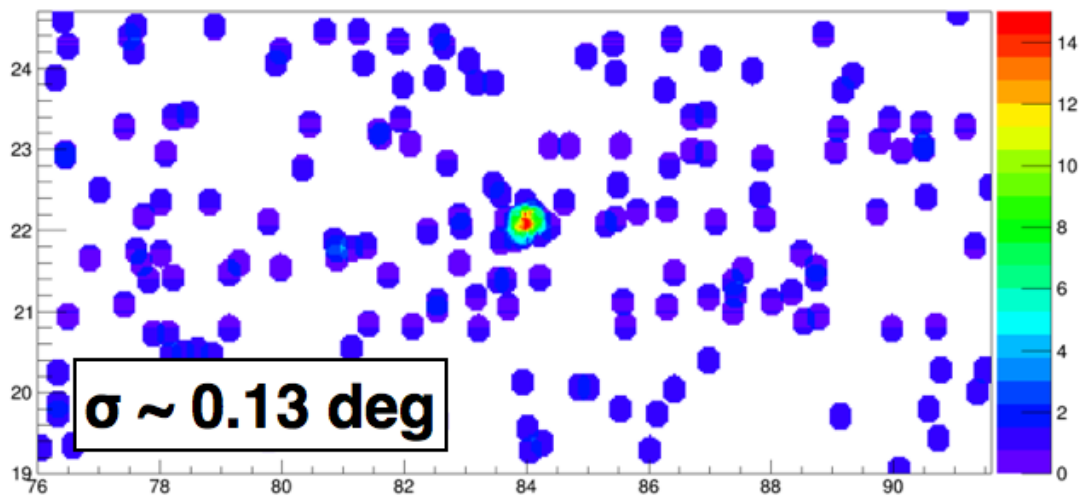
Curvature Correction



Gamma-Pure Sample: Before Curvature Correction Fix

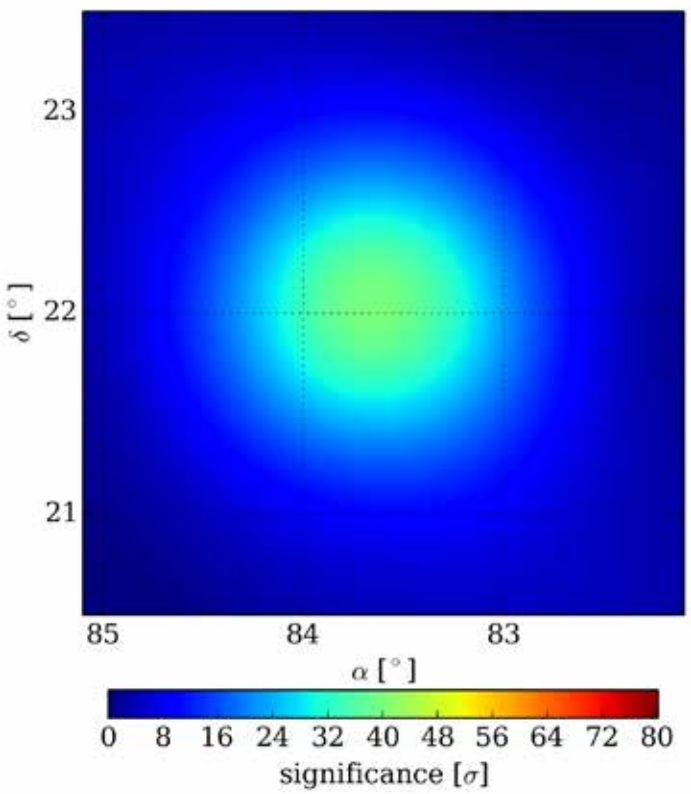


Gamma-Pure Sample: After Curvature Correction Fix

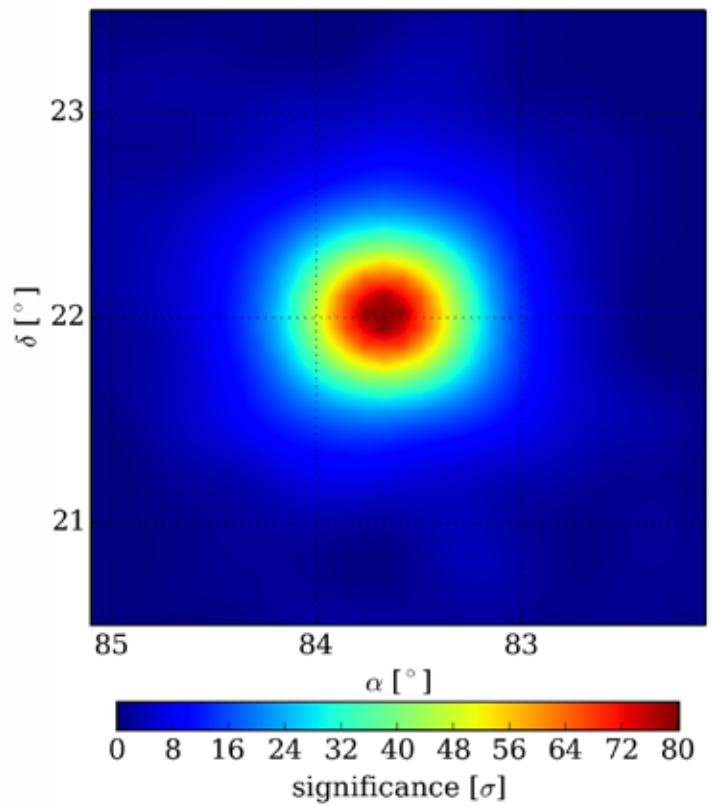


Significant Improvement

44σ (211d)

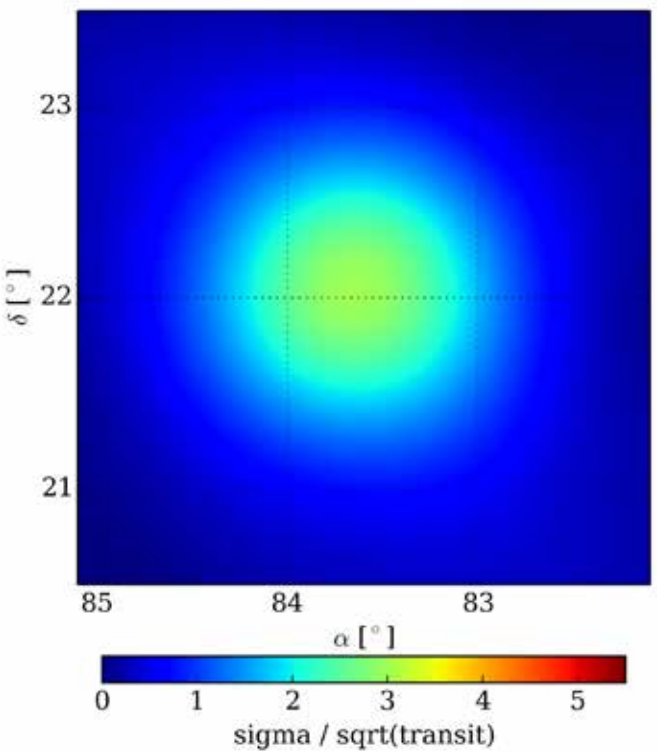


80σ (211d)

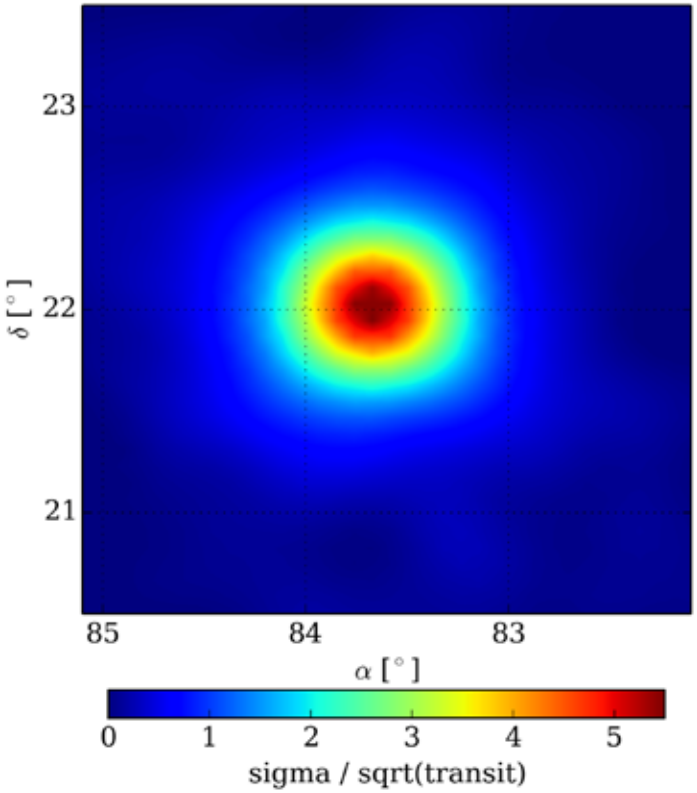


Significant Improvement

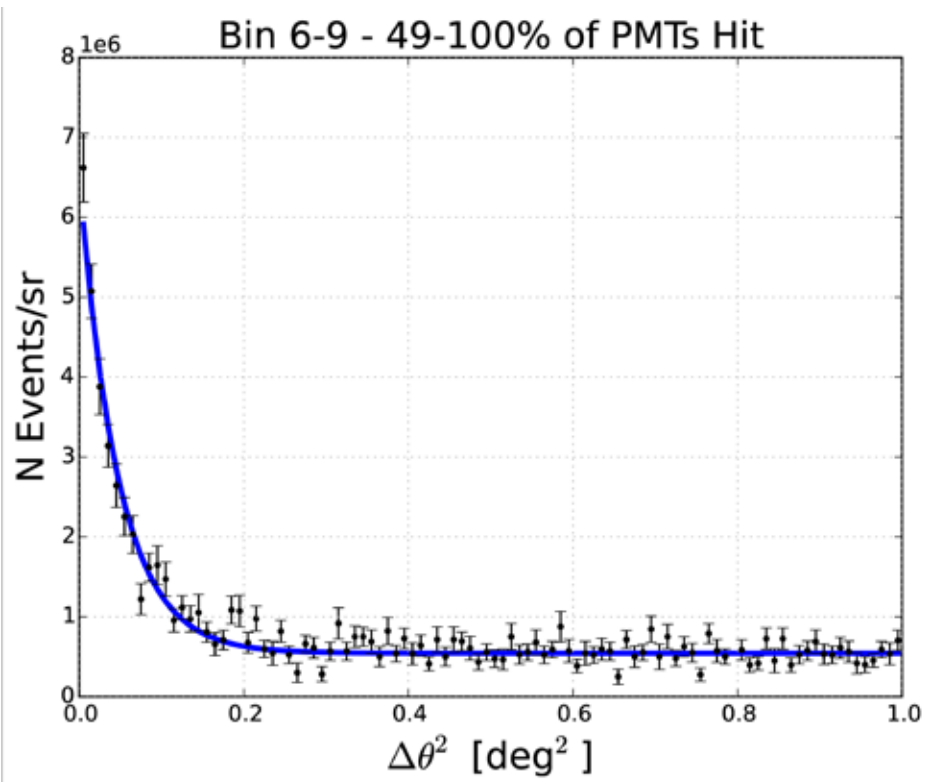
3σ/sqrt(day)

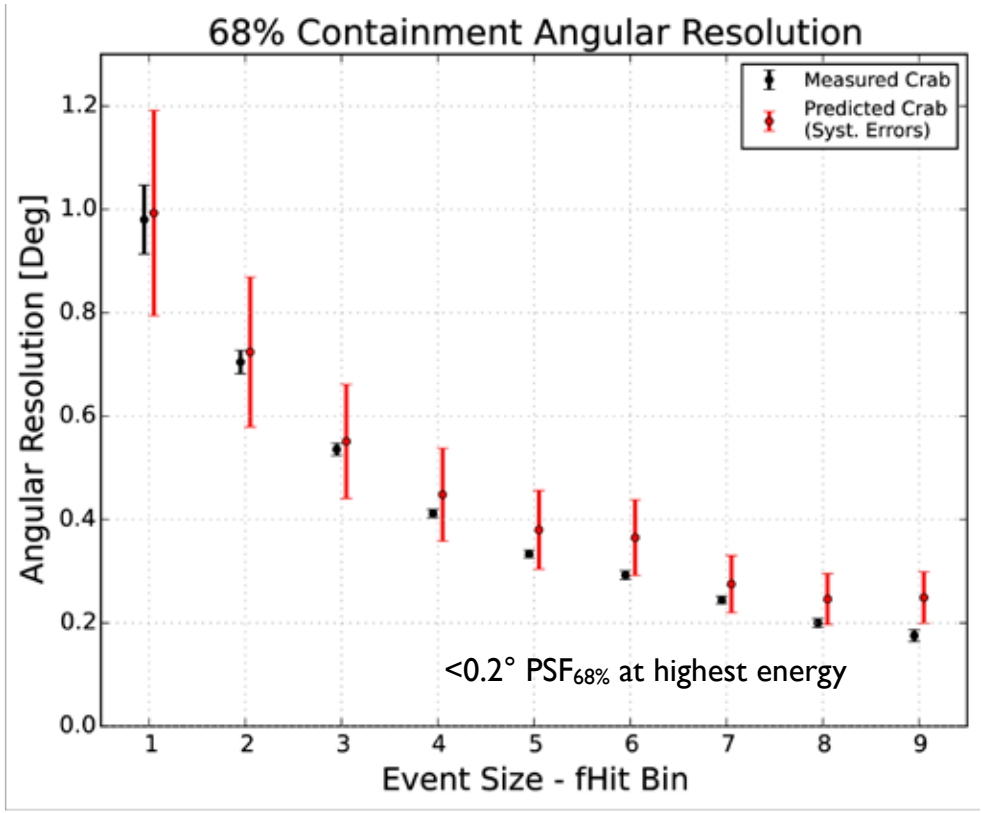


5.5σ sqrt(day)



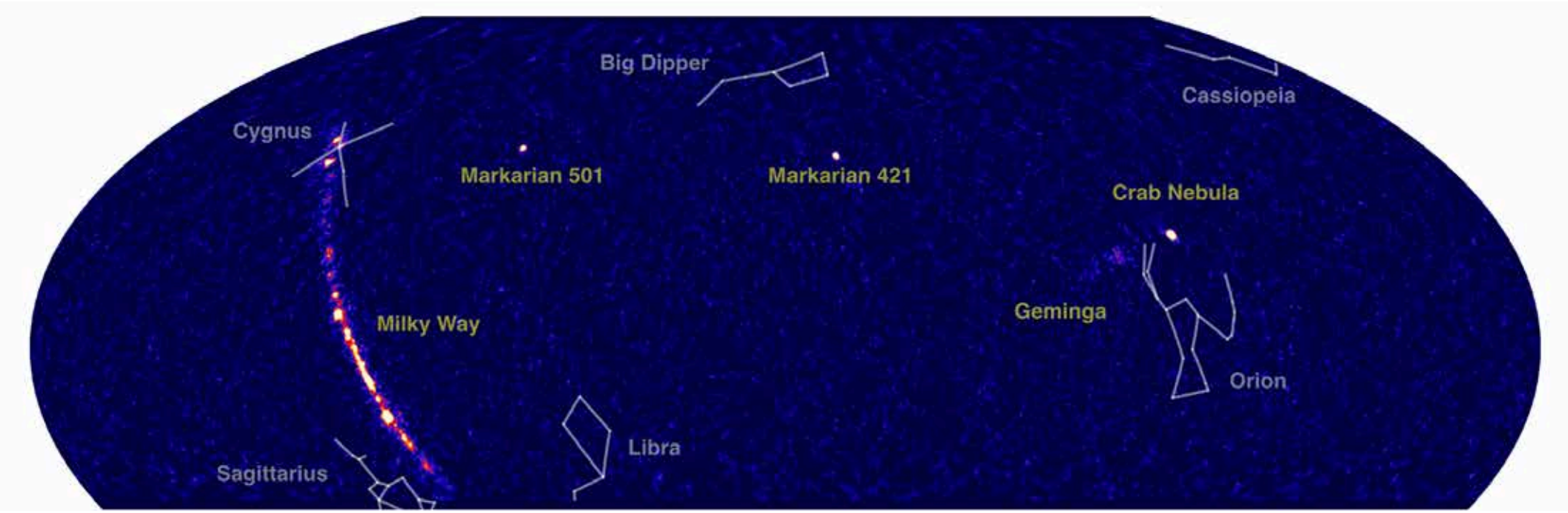
Angular Resolution





HAWC 341-Day TeV Sky Survey

- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.



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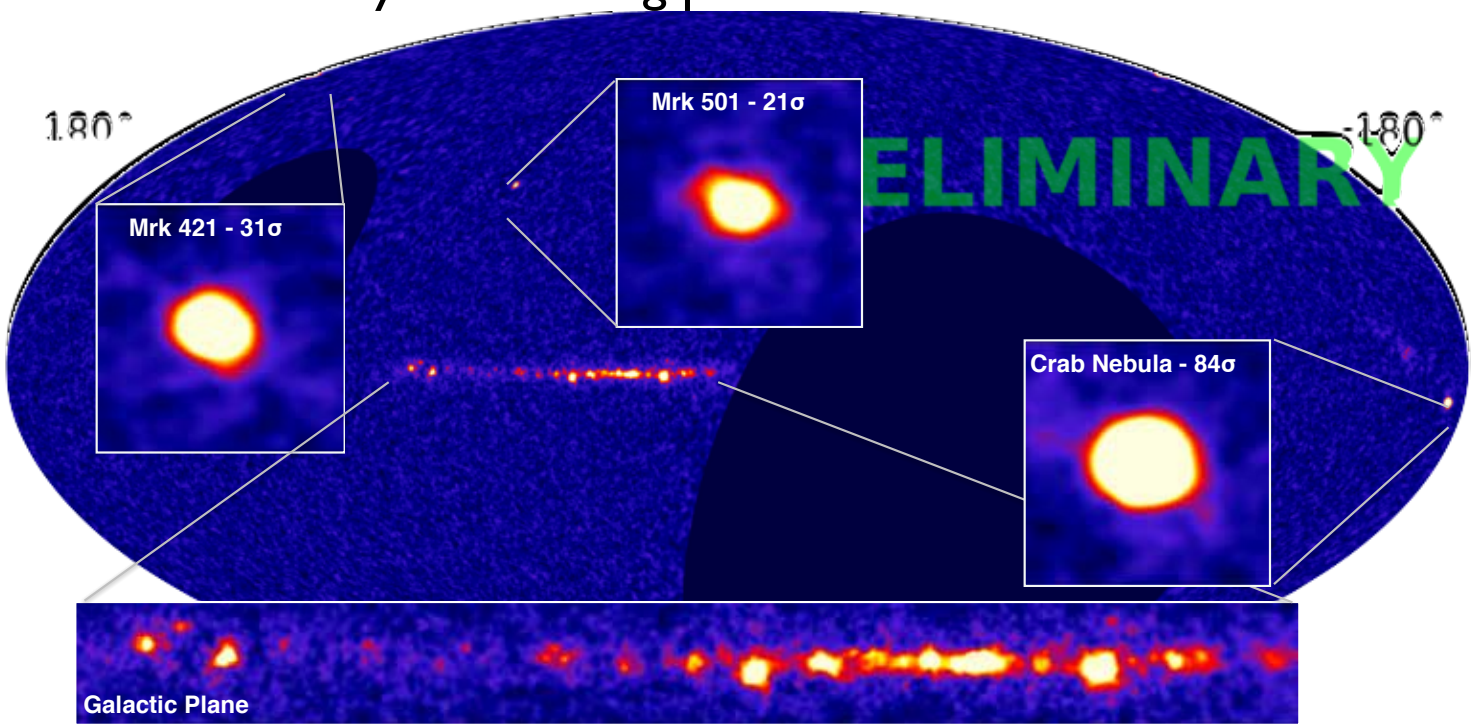
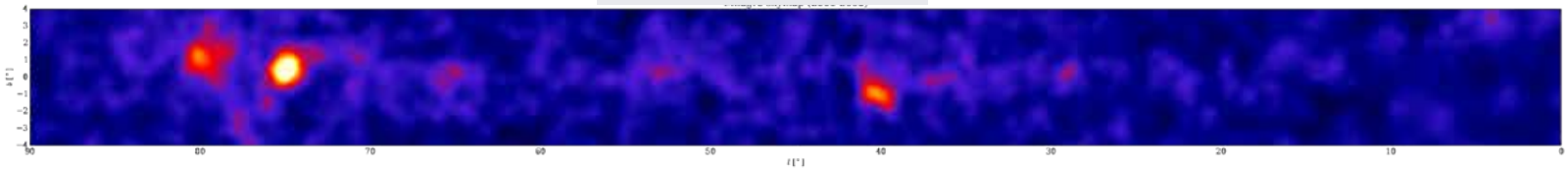
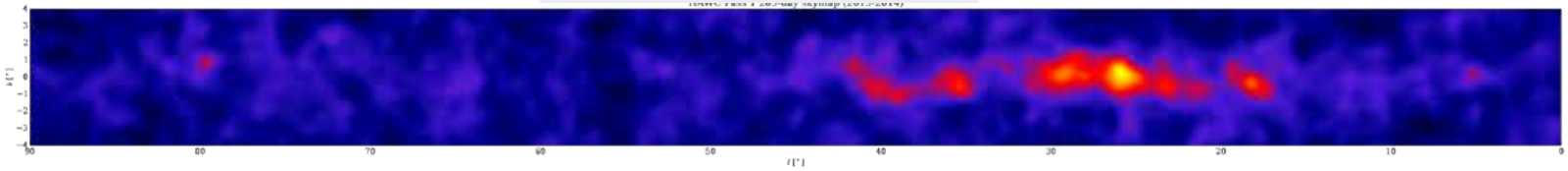


Galactic Plane

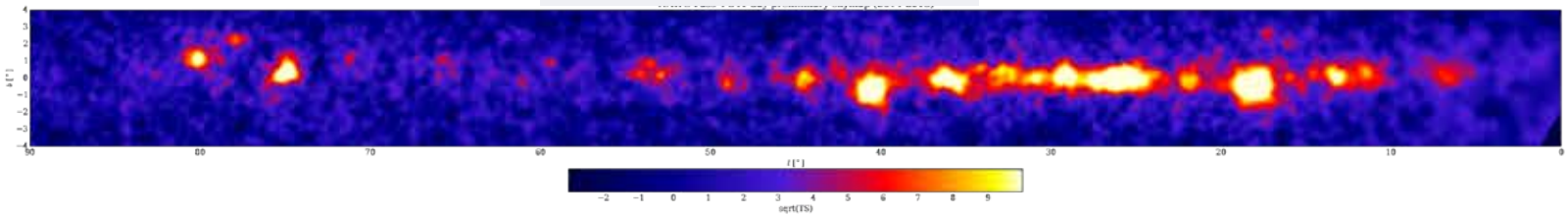
Milagro (2000-2008)



HAWC Pass 1 (2013-2014)



HAWC Pass 4 (2014-2015)



Milagro is located near Los Alamos, New Mexico different declination along Galactic plane. HAWC is ~15x more sensitivity with lower energy threshold, and more sensitive towards Galactic center.

Point Sources

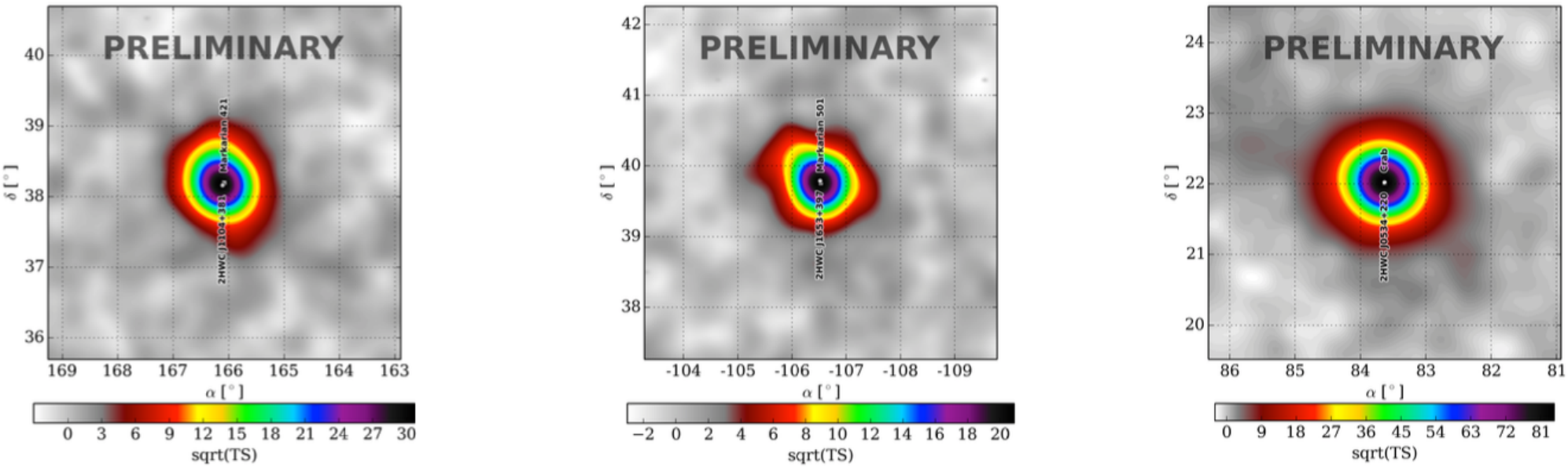
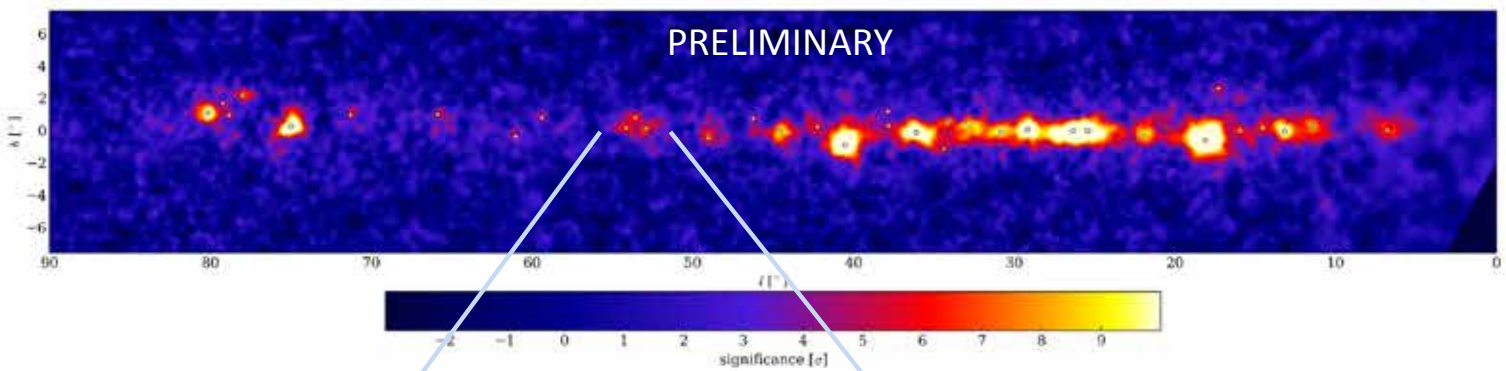
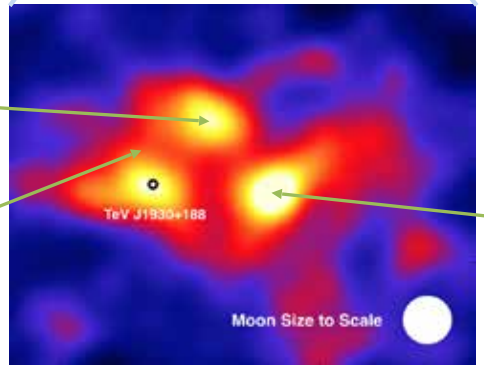


Figure 3: Markarian 421, Markarian 501, Crab.

HAWC view of the Galactic Plane





Association unclear

Supernova remnant with very energetic pulsar

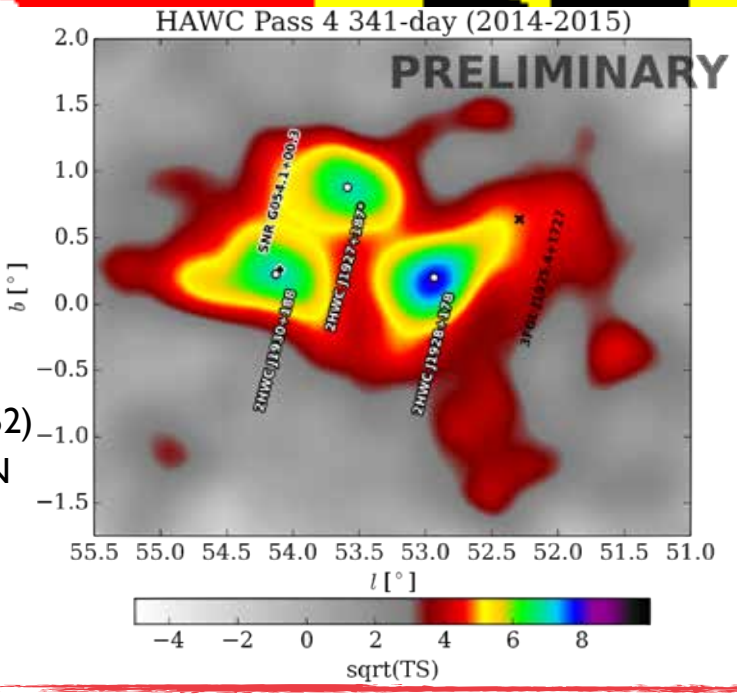
Pulsar ~8kpc (26,000 ly) away

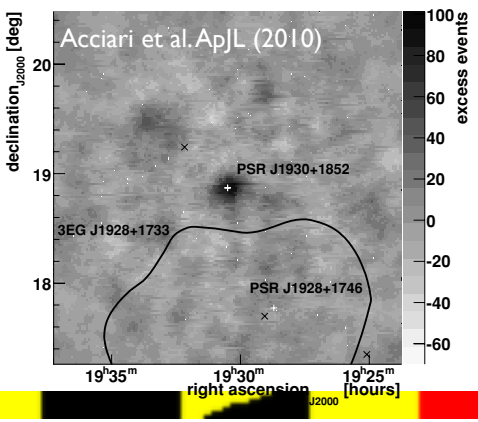
- ~40 sources seen in first year
- 25% are new

New TeV Sources!

New TeV emission region
2HWC J1927+187*
- ~7σ pre-trials
- current blind search algorithm identify this region associated with 2HWC J1930+188, ongoing analysis on spatial morphology

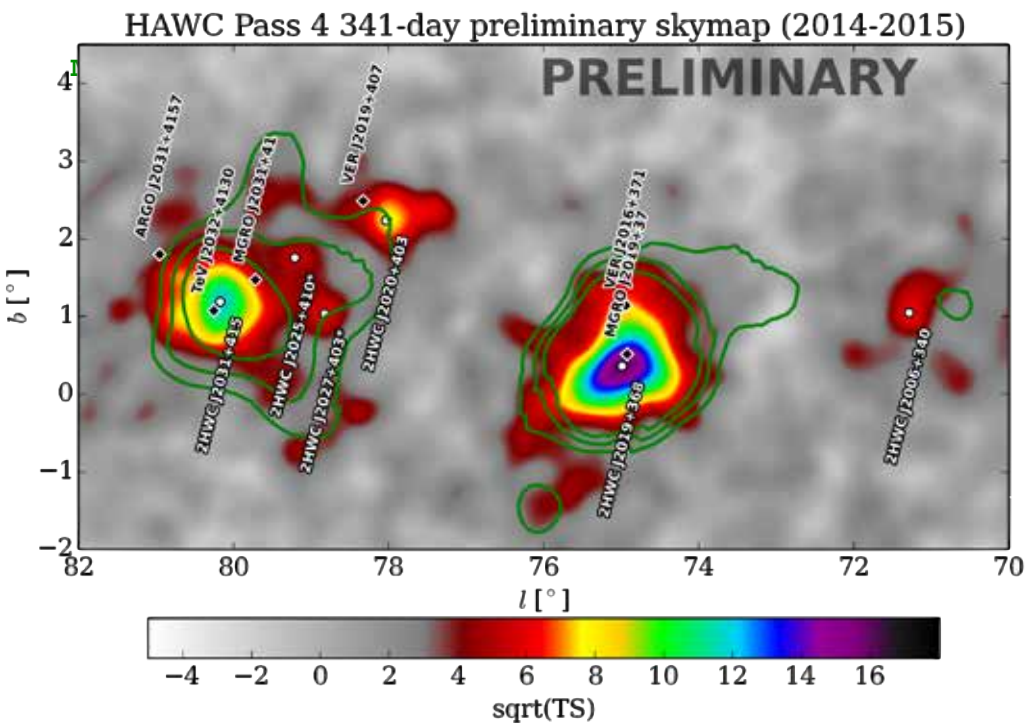
2HWC J1930+188
- coincident w/ VER J1930+188 (SNR G54.1+00.3 -PSR J1930+1852)
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud



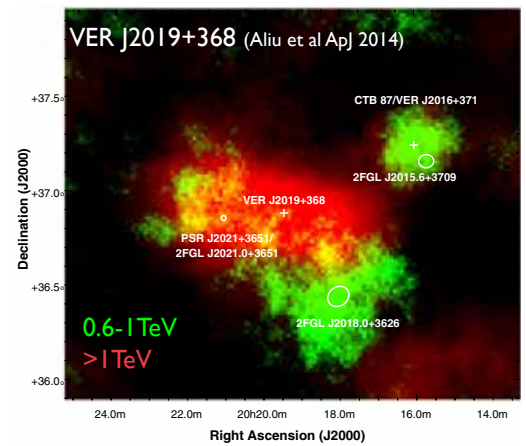


New TeV source
2HWC J1928+178
- ~8σ pre-trials
- coincident with PSR J1928+1746
- tail towards unidentified source 3FGL J1925.4+1727
- VERITAS point source upper limit ~1.4% of Crab

Cygnus Region

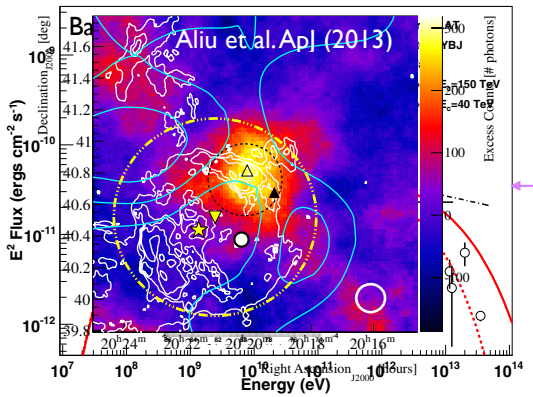


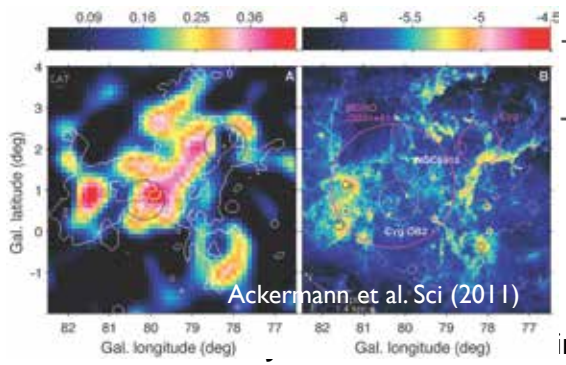
New TeV source
2HWCJ2006+340:
- >6σ pre-trials
- 0.6° from unidentified source 3FGL J2004.4+3338

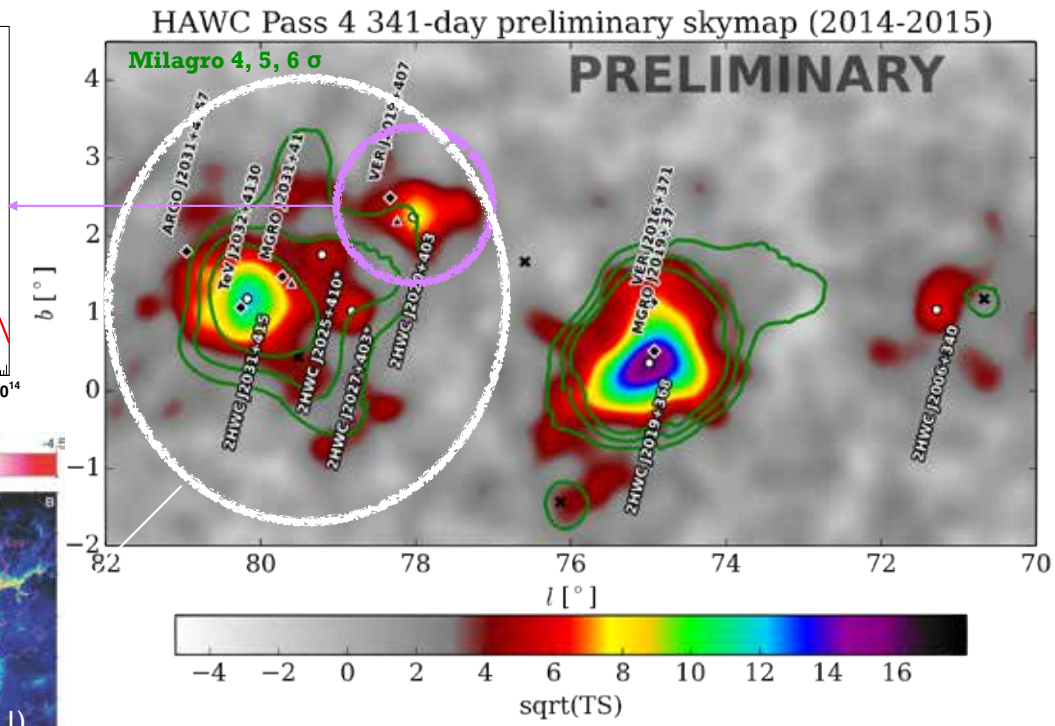


2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368
- extended emission including PSR J2021+3651 and HII region Sh 2-104

Cygnus Region



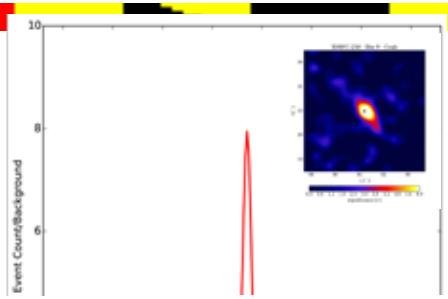




into two distinct TeV sources:

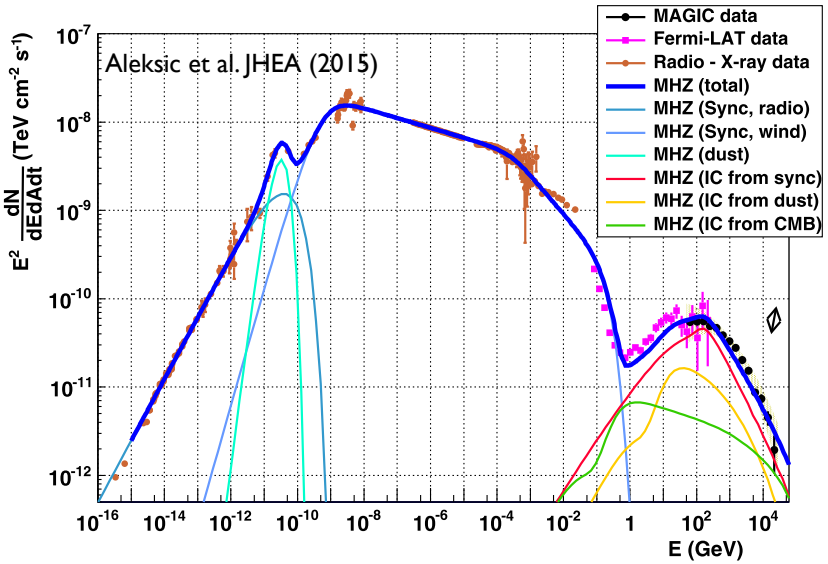
- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410* and 2HWC J2027+403* at Fermi cocoon

Pulsar Wind Nebulae - Crab



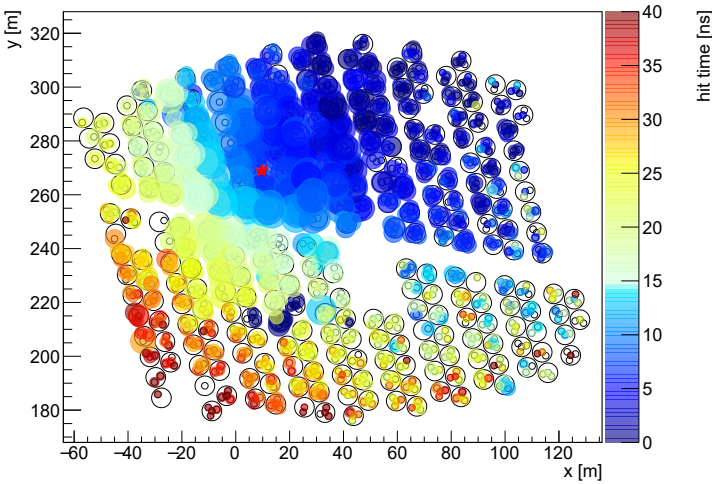
Crab Nebula at highest energies

- photons up to 80TeV reported by IACTs
- insight into magnetic field environment and efficiency of particle acceleration



S. Marinelli

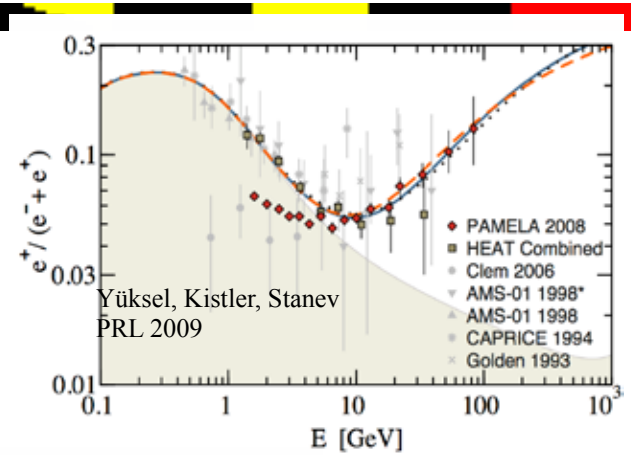
- Direction consistent with Crab Nebula.
- Signal to noise in this bin is 7.

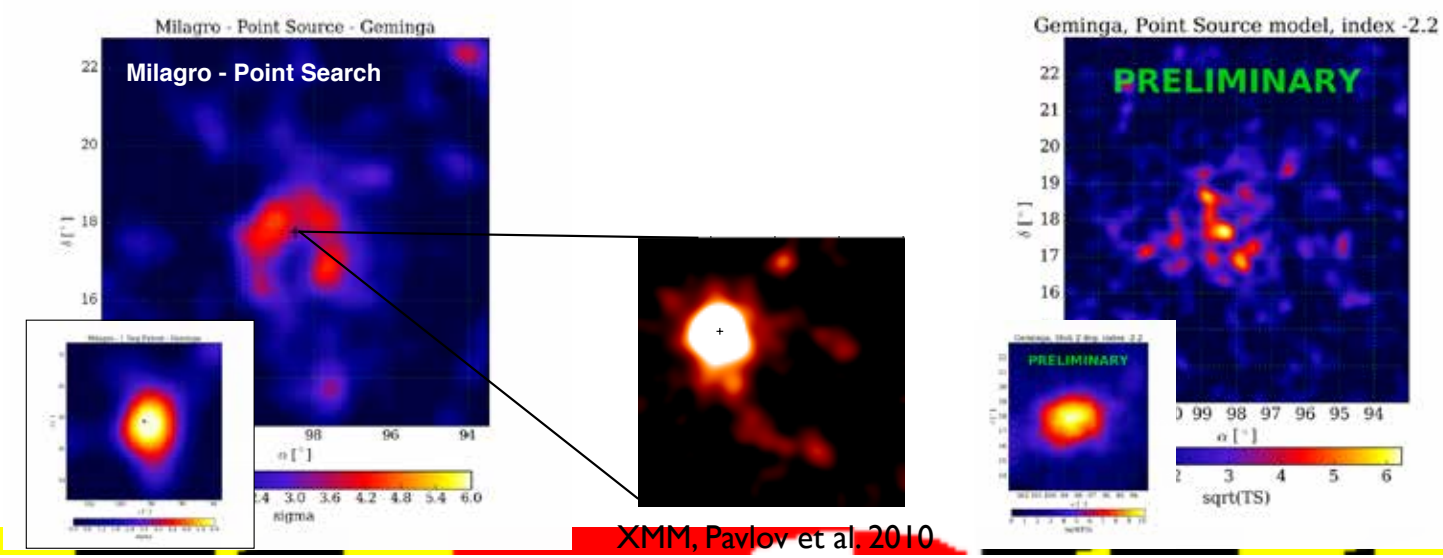


Estimator	Estimate (TeV)
NN	60
Likelihood	56
Ground parameter	58

Pulsar Wind Nebulae - Geminga

- Closest known middle aged 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

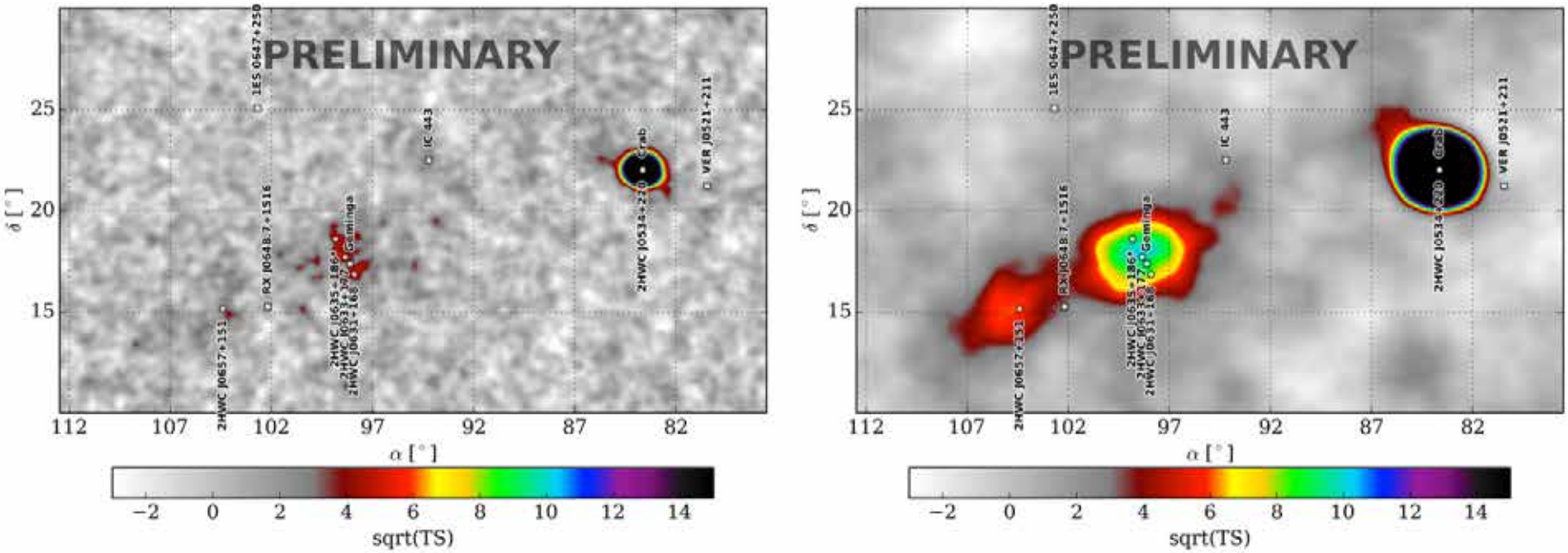
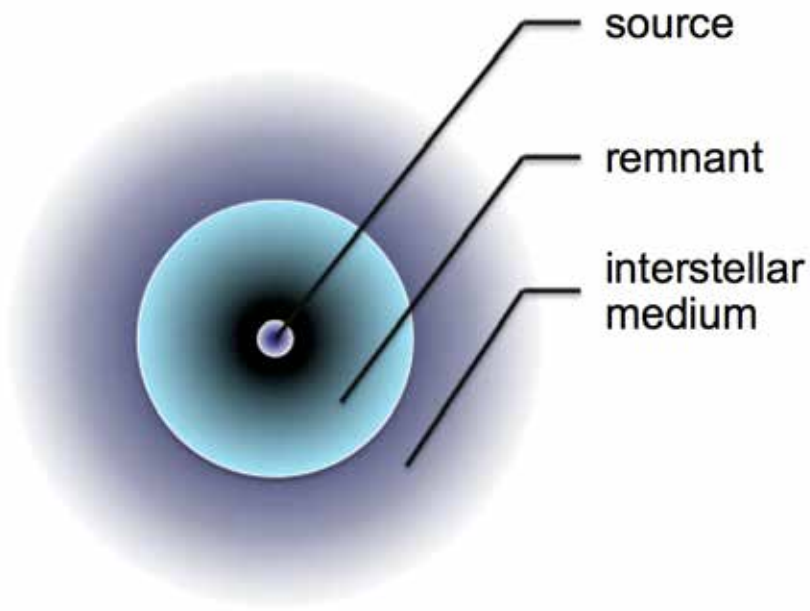


Figure 4: Region around Geminga. Left: TS map for a point source hypothesis with a spectral index of -2.7. Right: TS map for an extended source hypothesis represented by a disk of radius 2.0 degrees with a spectral index of -2.0.

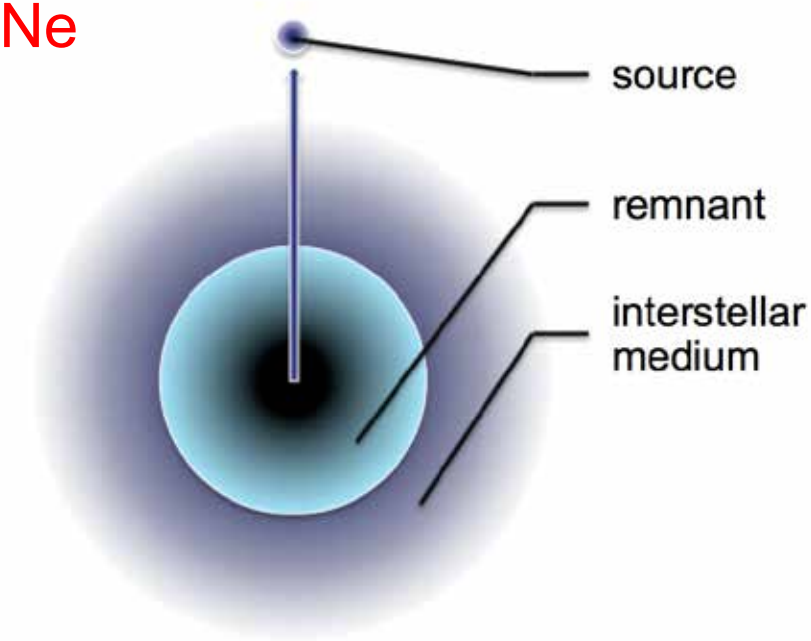
Propagation of Positrons out of their Sources

- Knowing details of the pulsar not the same as knowing input to the interstellar medium (ISM)
- Does the nebula…
  - …pass all positrons to ISM?
  - …modify the spectrum?
  - …absorb all positrons?
- Need to model propagation through nebula to determine input to ISM



Geminga

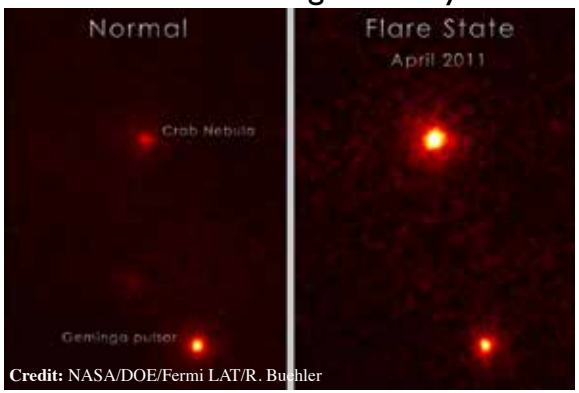
- Old pulsars with high velocity may escape their remnant
- If remnants absorb positrons, perhaps pulsars like Geminga are the only PWNe supplying positrons to ISM

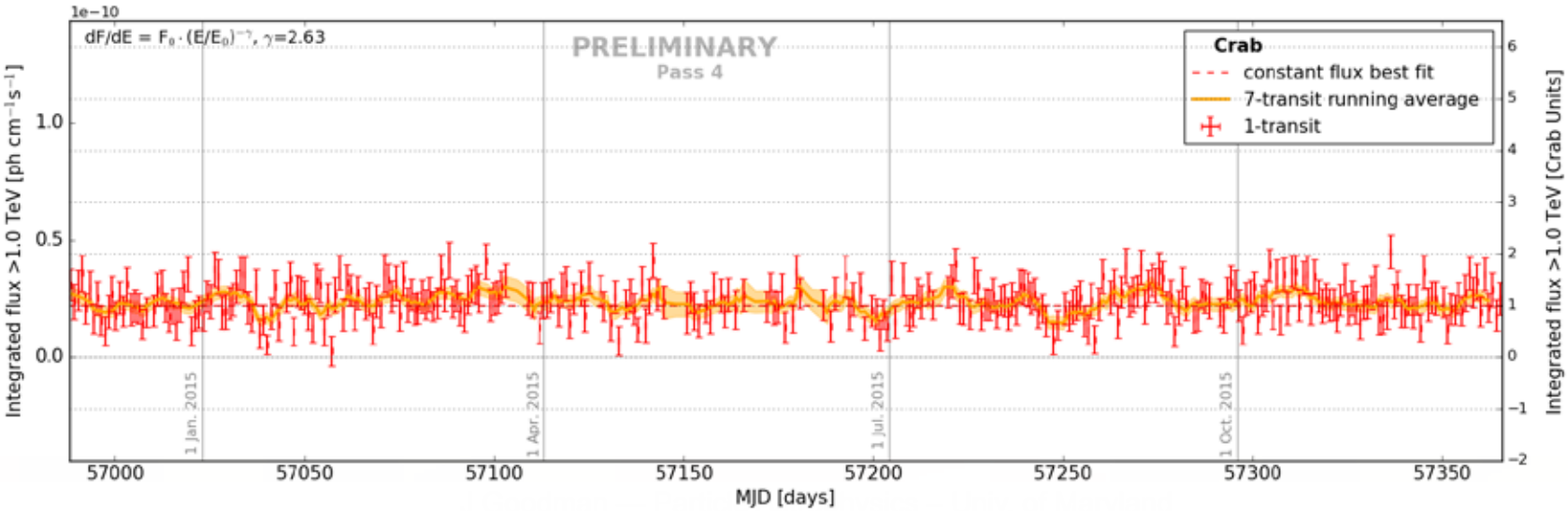


Transient Search - The Crab Nebula

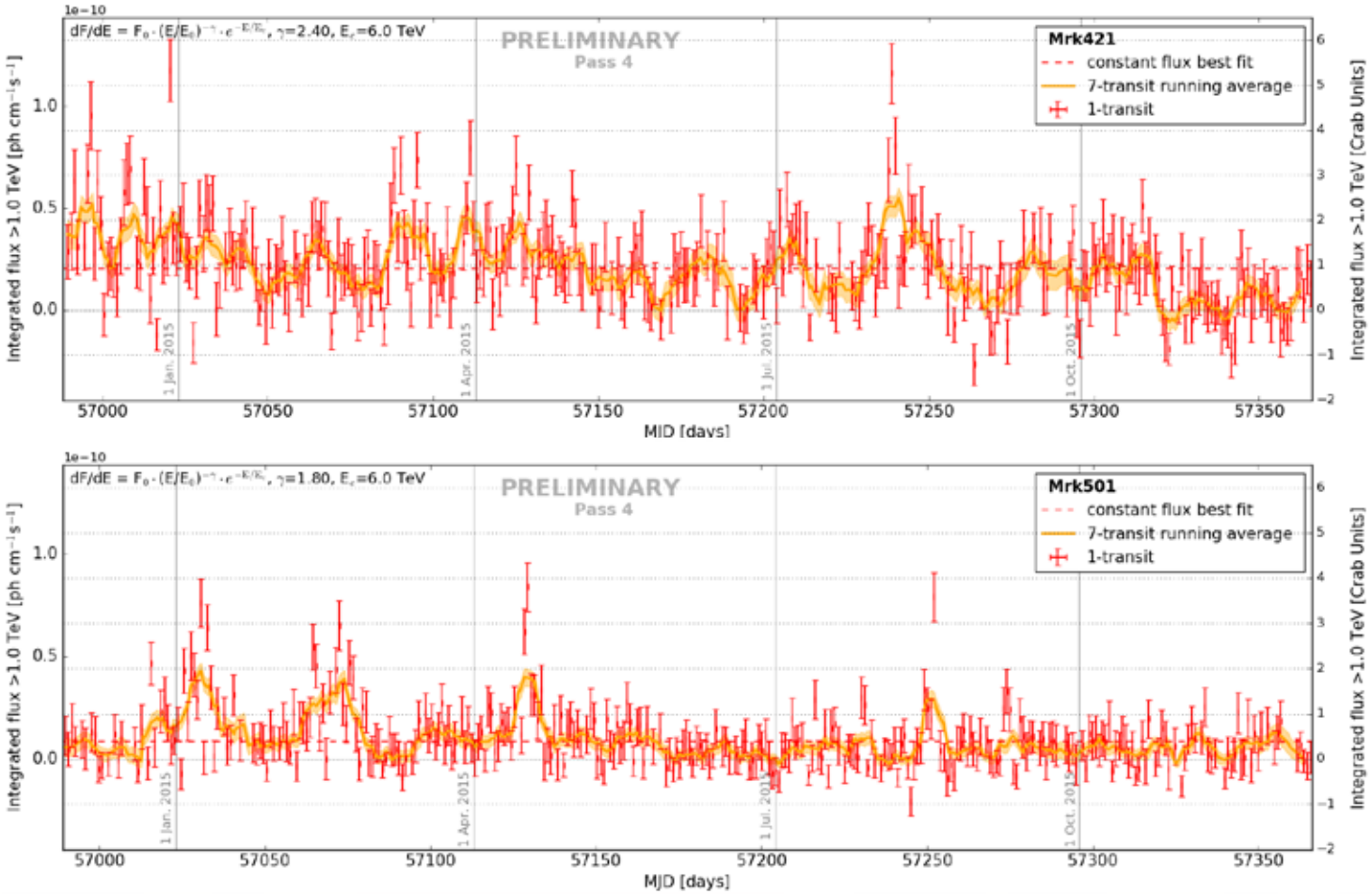
- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.
- HAWC Pass 4 data from Nov 26 2014 to Dec 9 2015.
- >80σ in 315 transits.
- Lightcurve binned in sidereal day.
- Consistent with constant flux.

MeV-GeV gamma ray





Transient Search - Mrk 421 / Mrk 501

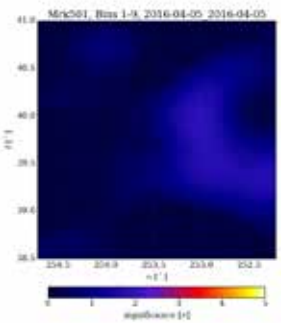


Transient Search - Mrk 501

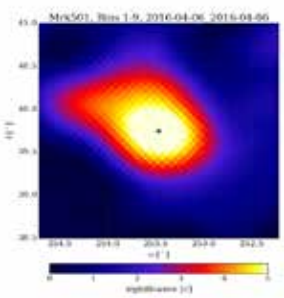
HAWC detection of increased TeV flux state for Markarian 501

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

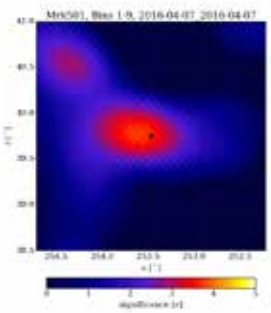
Astronomer's Telegram to immediately alert community of activity.



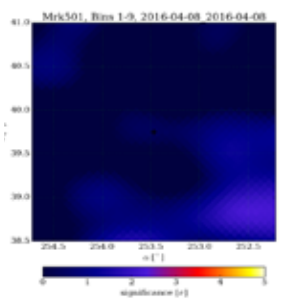
April 5, 2016



April 6, 2016



April 7, 2016



April 8, 2016

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

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:

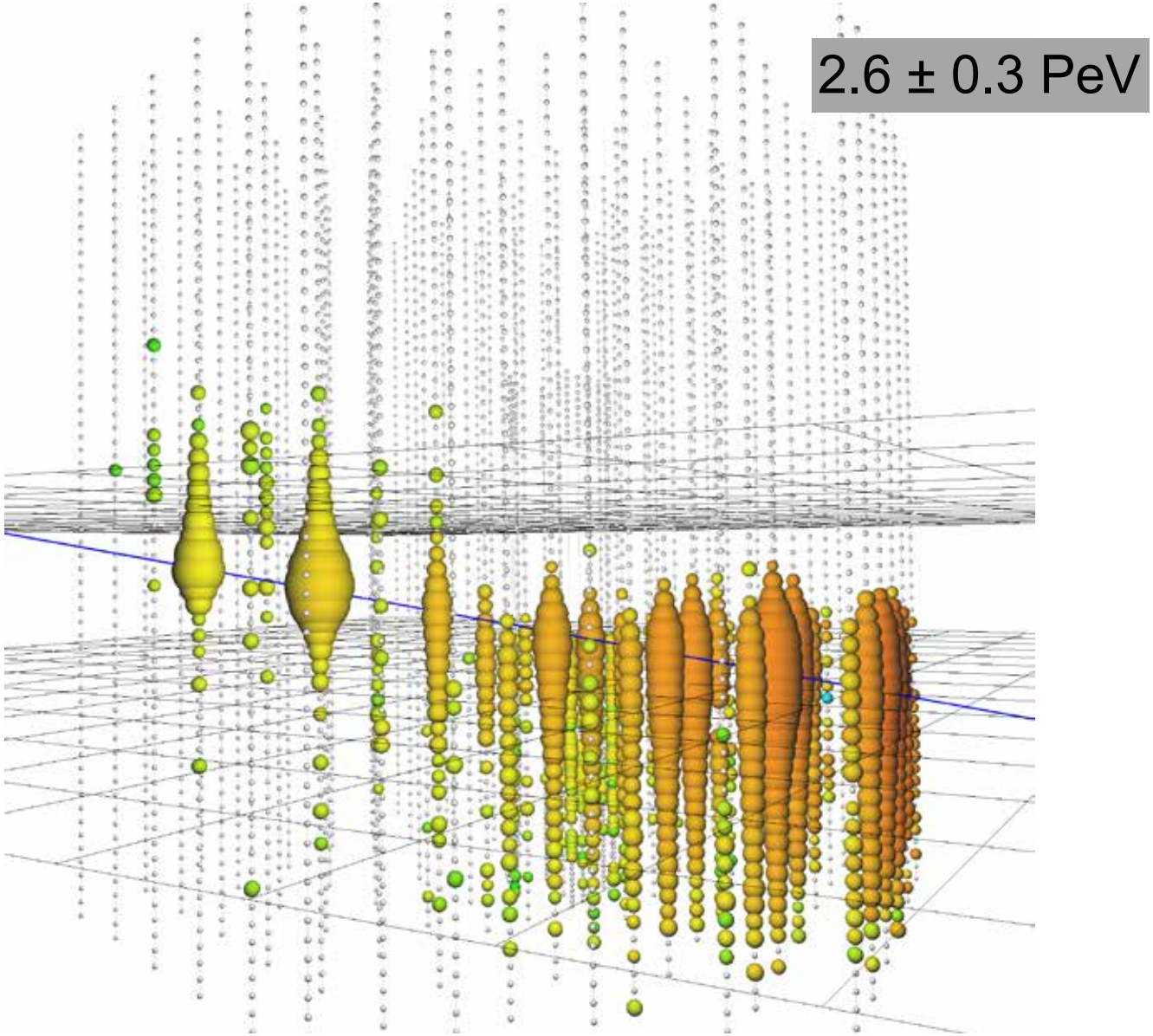
- New source candidates lists.
  - follow-up observations by IACTs such as VERITAS and MAGIC from Pass 1 release.
- Flares from known gamma-ray sources.

HAWC ATel #8922
on Mrk 501 flare

Externally triggered:

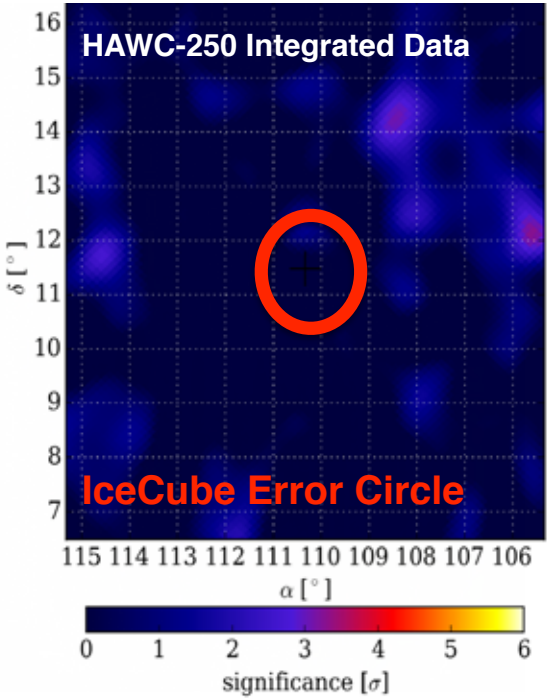
- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitation wave event follow-up

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


2.6 ± 0.3 PeV

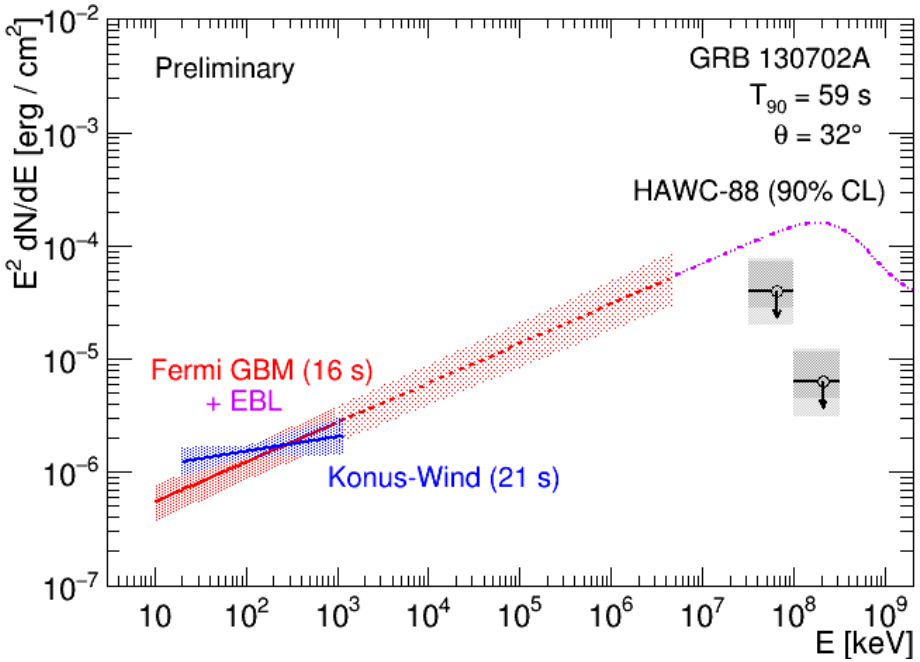
IceCube >2.6 PeV Muon Neutrino

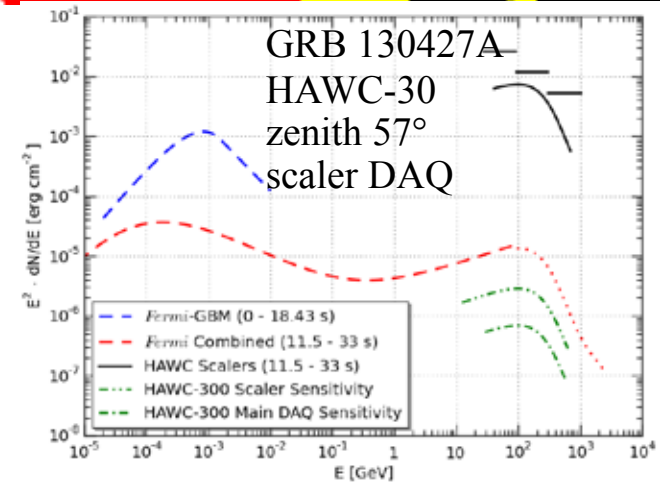
- HAWC-111 live. Several hours out of HAWC's FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015 dataset)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
- All searches consistent with cosmic-ray background.



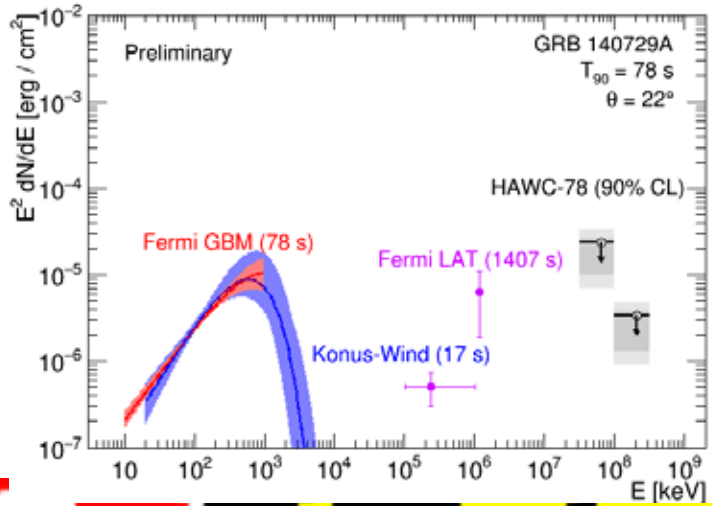
IceCube ATel: #7856
HAWC Follow-up ATel: #7868

Transients: Gamma Ray Bursts





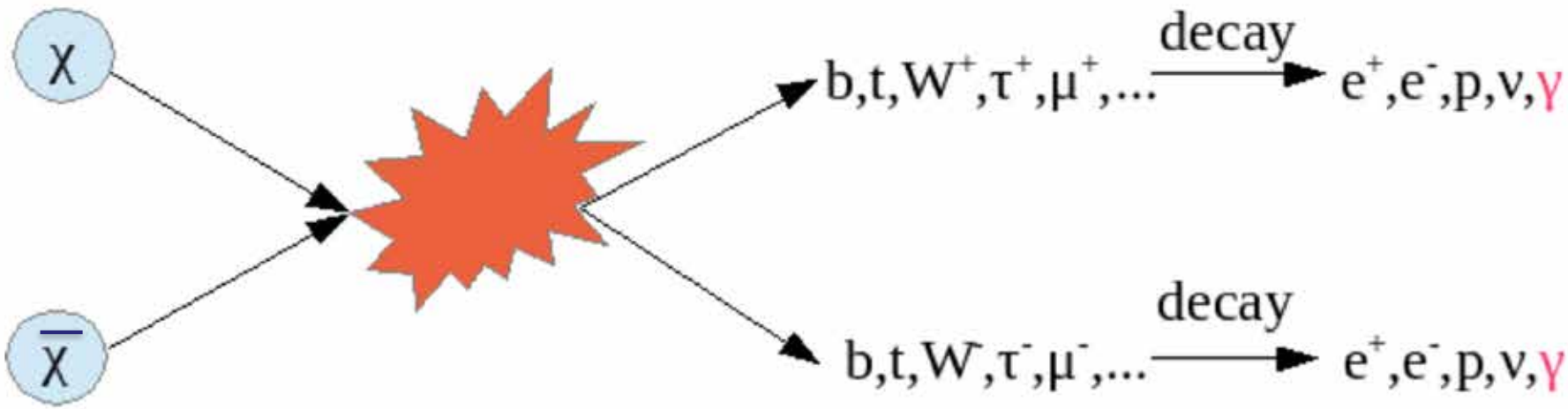
[Astrophys. J. 800 (2015), 78]



[K. Sparks Woodle]

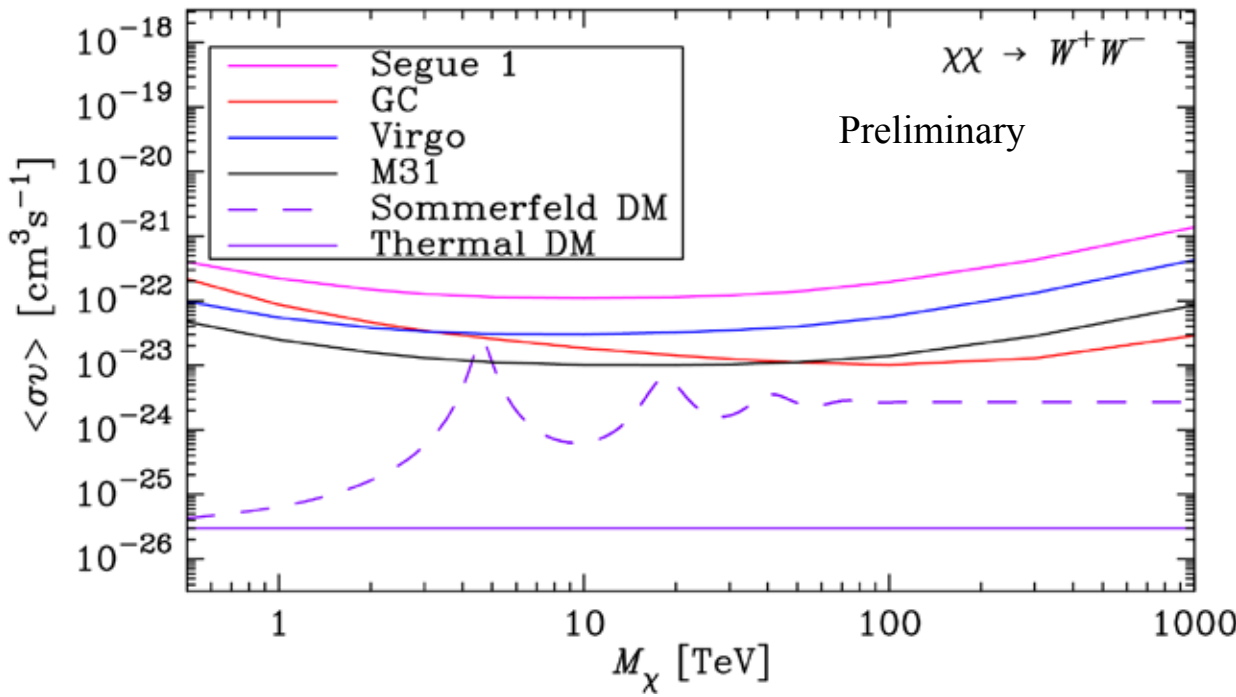
TITLE: GCN CIRCULAR NUMBER: 19423
SUBJECT: GRB 160509A: non-observation of VHE emission with HAWC
DATE: 16/05/11 17:27:37 GMT

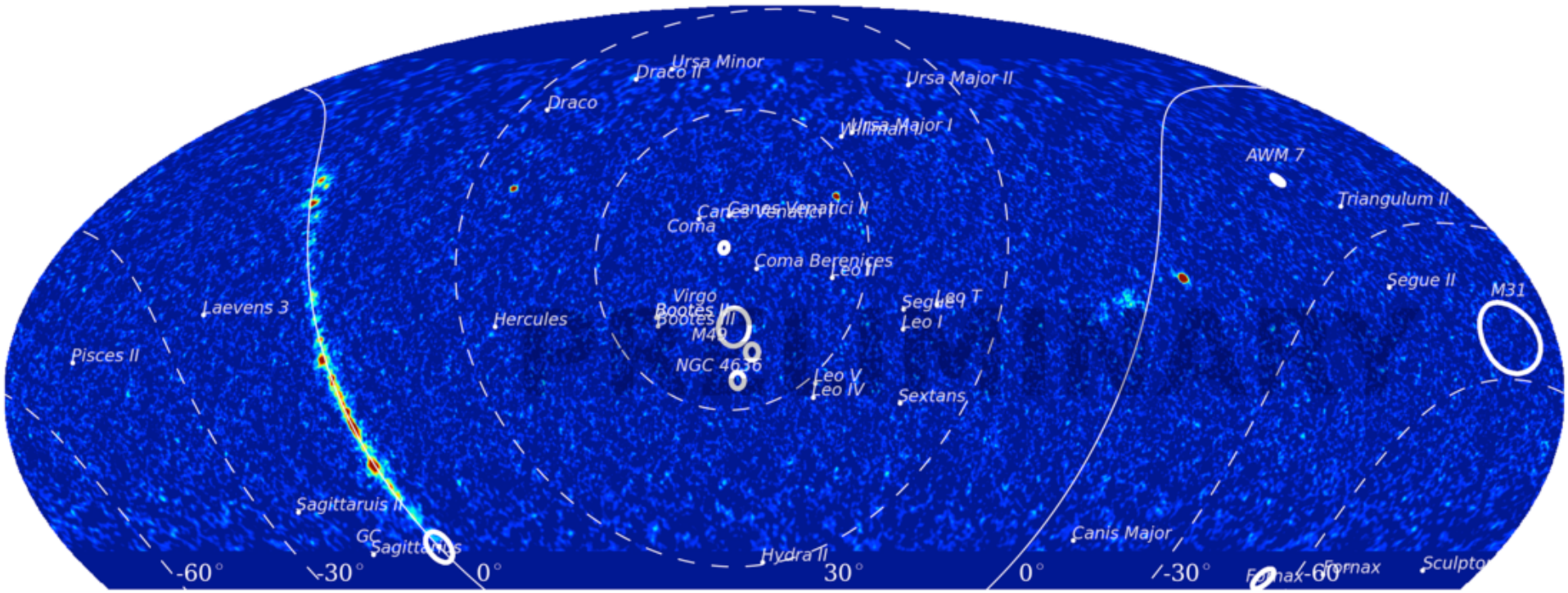
Dark Matter



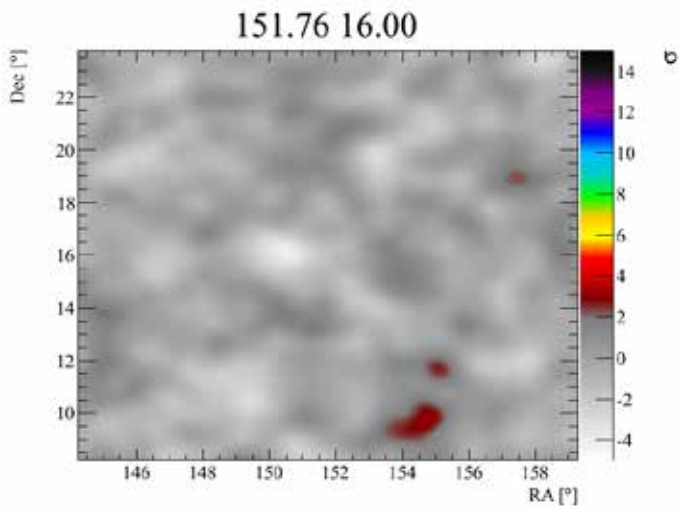
HAWC: Dark Matter

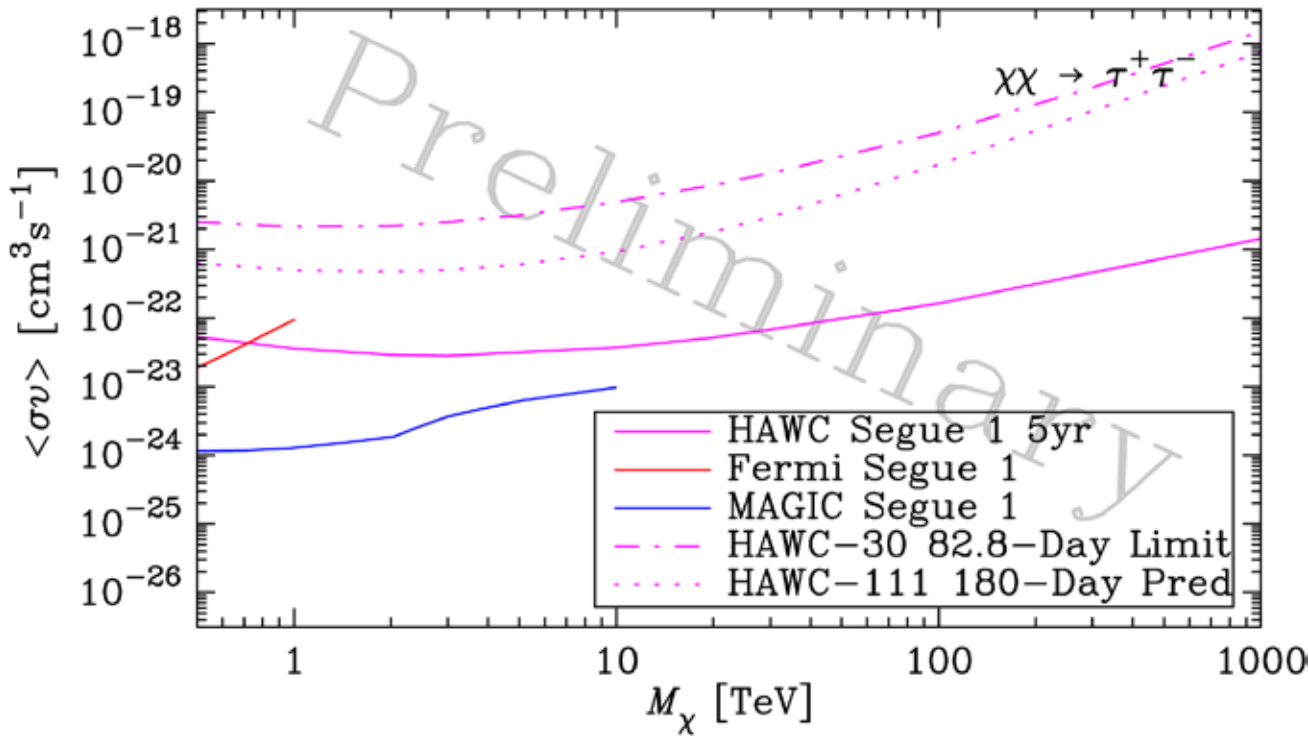
- HAWC has sensitivity to indirect detection of TeV WIMPs in:
  - Satellite galaxies, the Galactic Center, and galaxy clusters
- Cosmological simulations predict more satellite galaxies than observed
  - Higher M/L galaxies have been found by Sloan Deep Survey
  - HAWC will observe all M/L galaxies in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



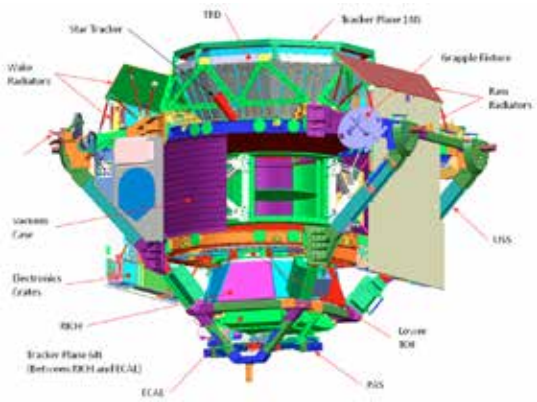

Ursa Minor
Draco II
Draco
Ursa Major II
Ursa Major I
Willman 1
AWM 7
Triangulum II
Canes Venatici II
Canes Venatici I
Coma
Coma Berenices
Leo II
Segue II
M31
Laevens 3
Virgo
Bootes II
Bootes III
Segue I
Leo T
Leo I
Hercules
M49
Pisces II
NGC 4636
Leo V
Leo IV
Sextans
Sagittaruis II
GC
Sagittarius
Hydra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

Dark Matter - Segue-1





AMS Results



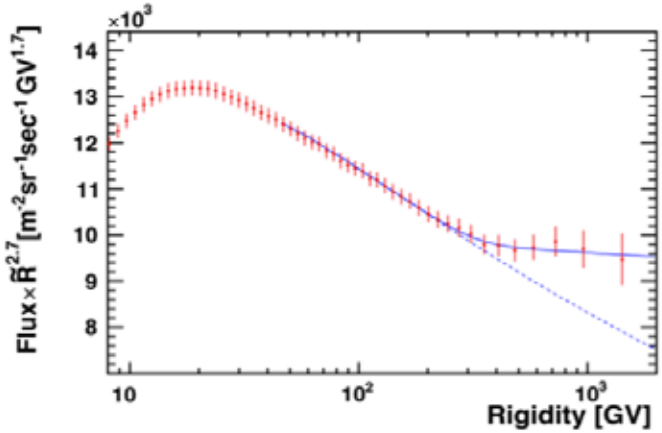
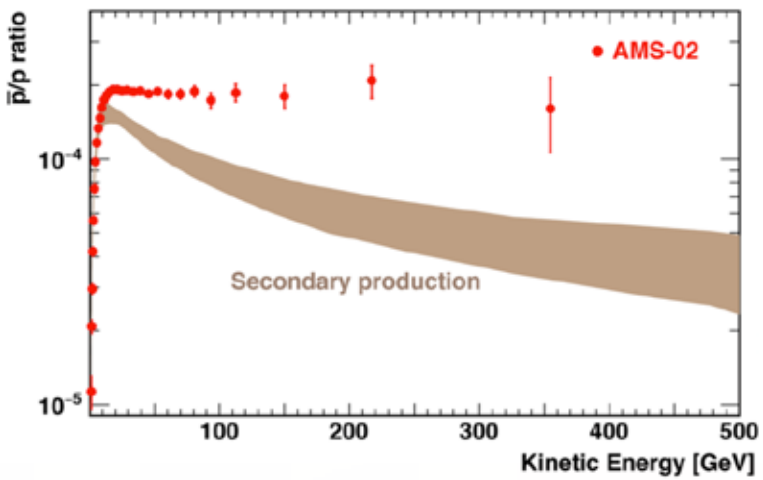
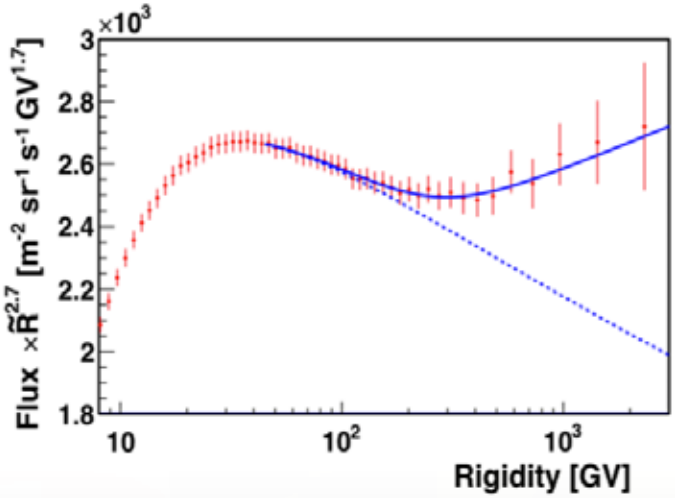


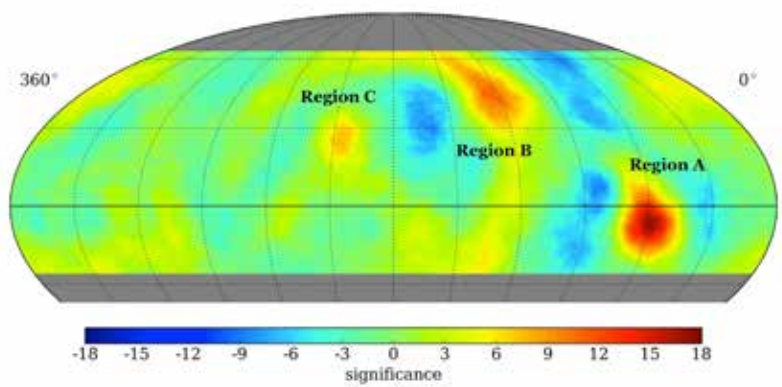
Figure 2. Measured proton flux as a function of rigidity.

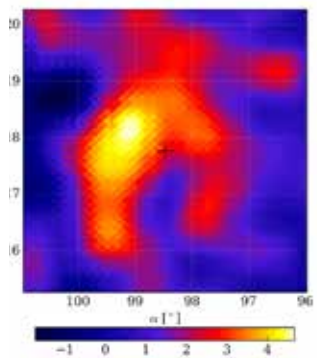


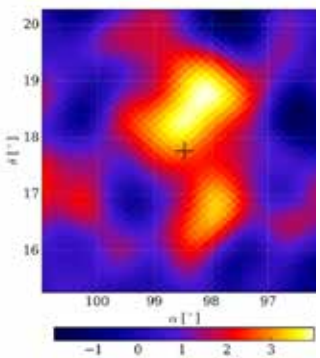


From AMS

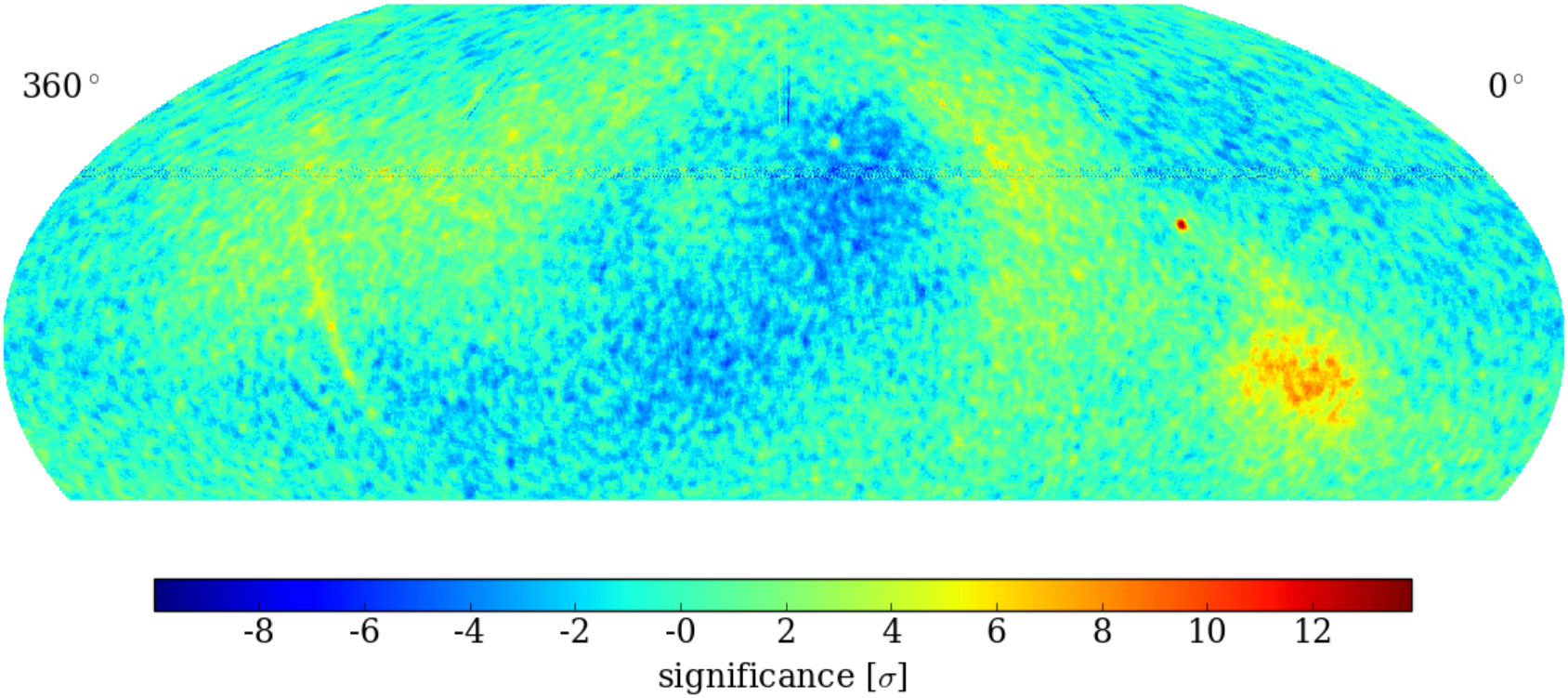
- *The AMS results on the positron fraction, the electron spectrum, the positron spectrum, and the combined electron plus positron spectrum are consistent with dark matter collisions and cannot be explained by existing models of the collision of ordinary cosmic rays.*
- *There are many new models showing that the results may be explained by new astrophysical sources (such as pulsars) or new acceleration and propagation mechanisms (such as supernova remnants).*







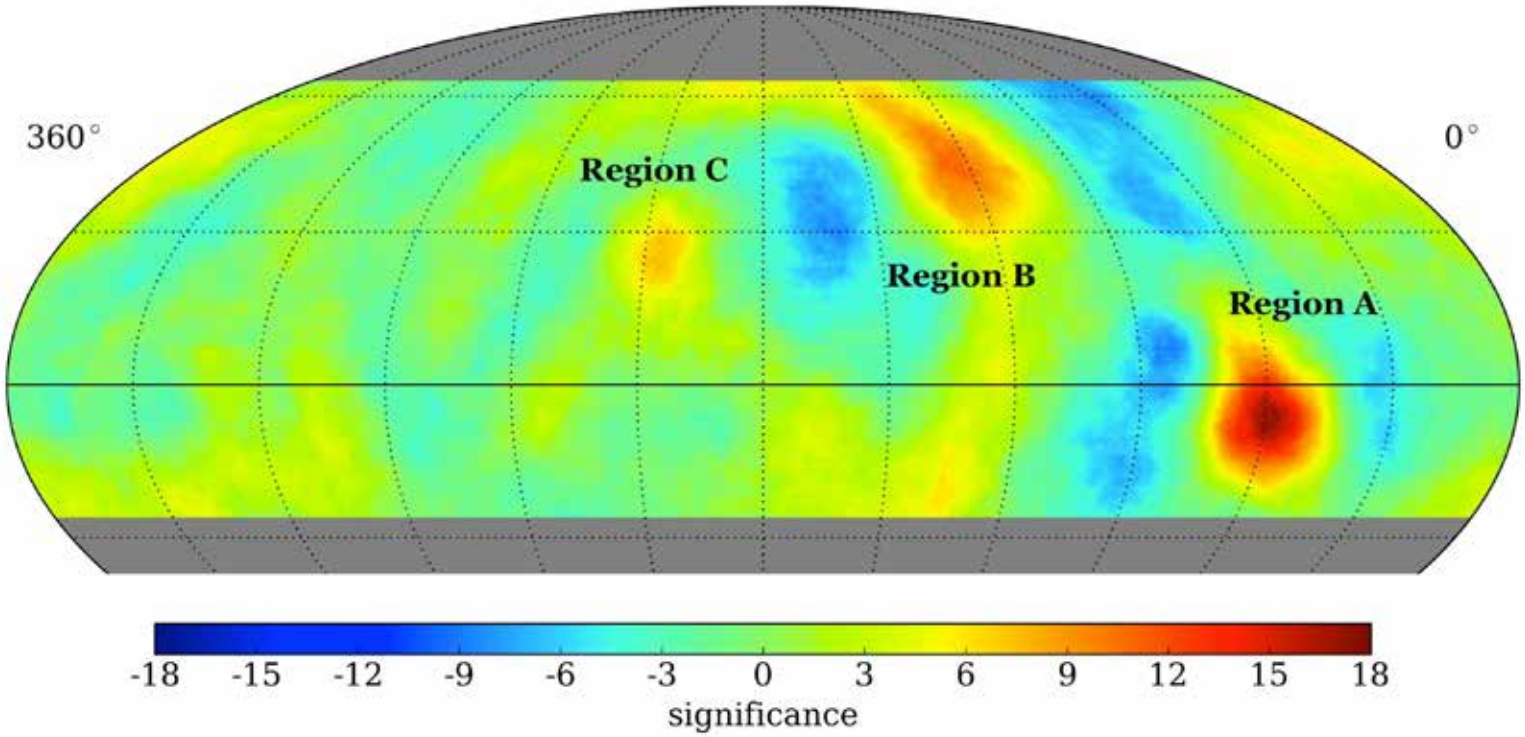
HAWC Data - no gamma ray cut



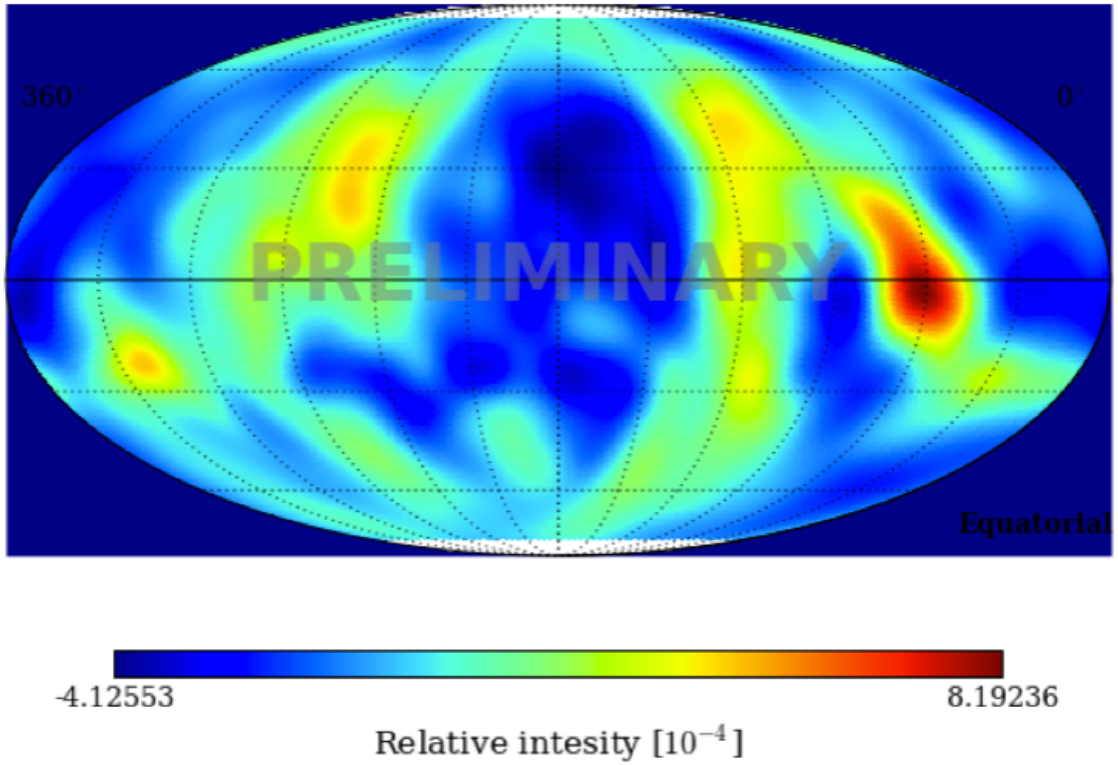
Anisotropy

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)



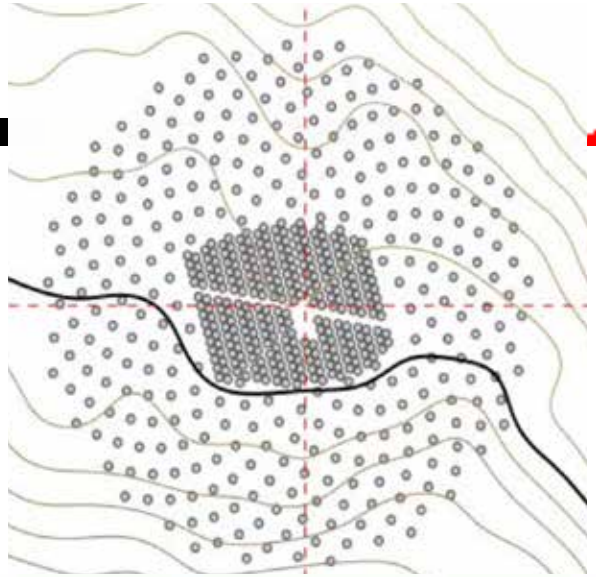
IceCube/HAWC
Small-scale Anisotropy***



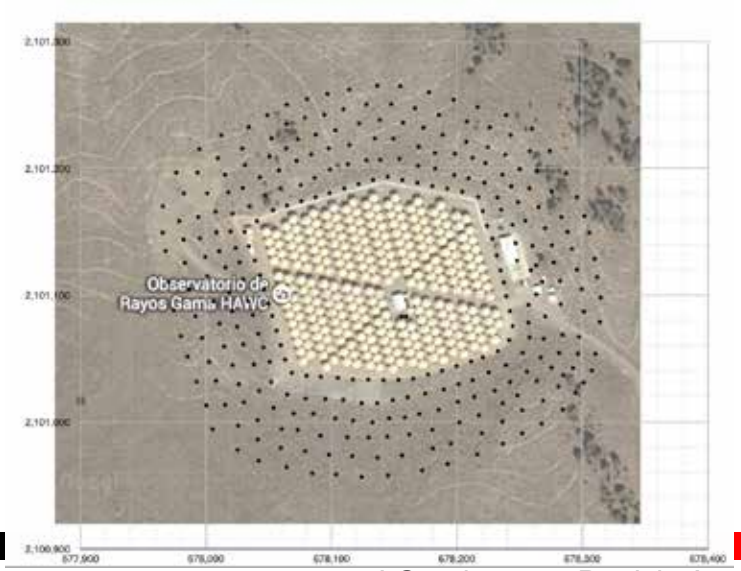
HAWC250: bins 3-5
IC86: bins 0-2

HAWC250: Direct Int Δt = 4hr
IC86: Δt =24, ell≤3 subtracted

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.

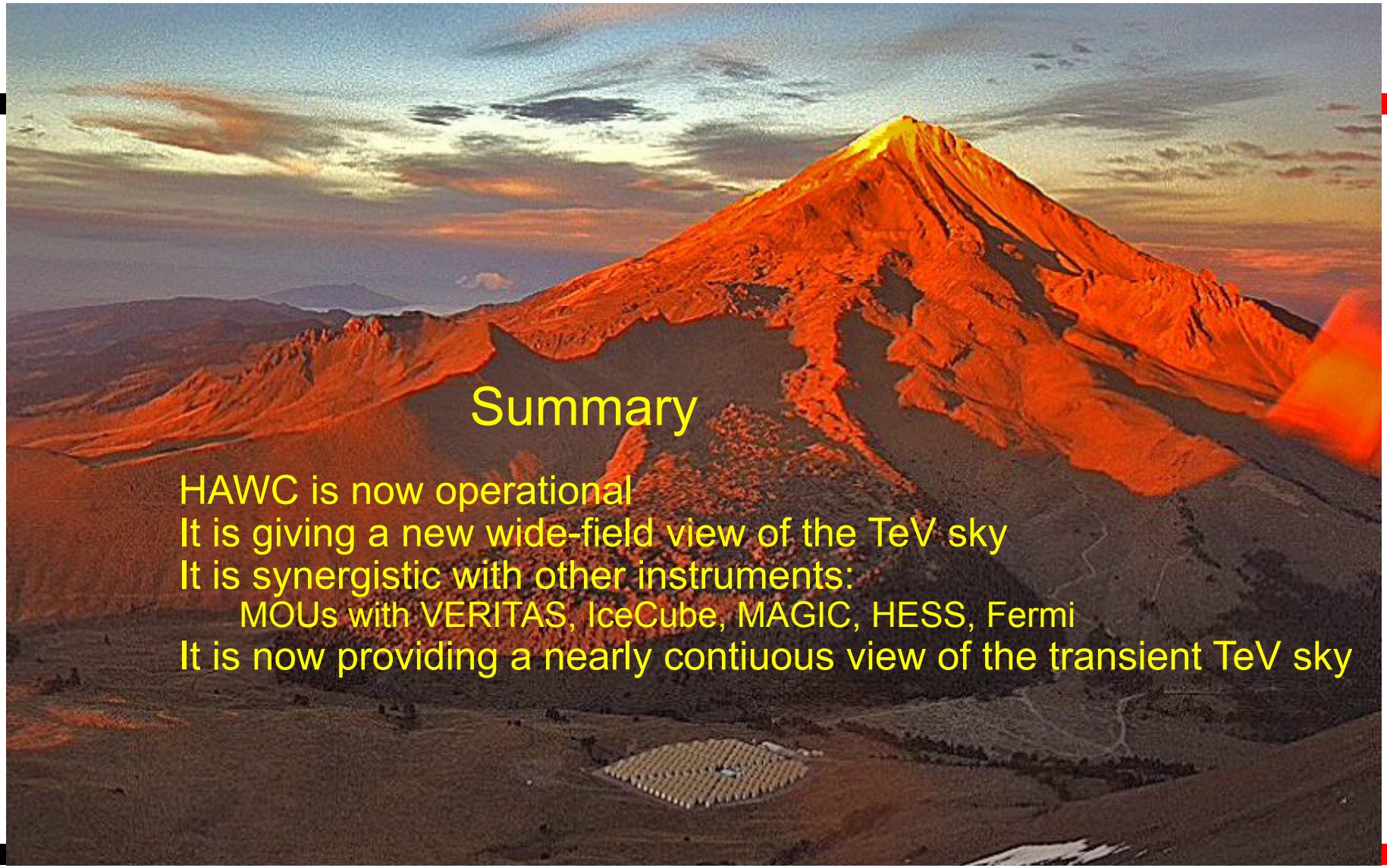


Storm on the 13-14 January


Rotoplas

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.

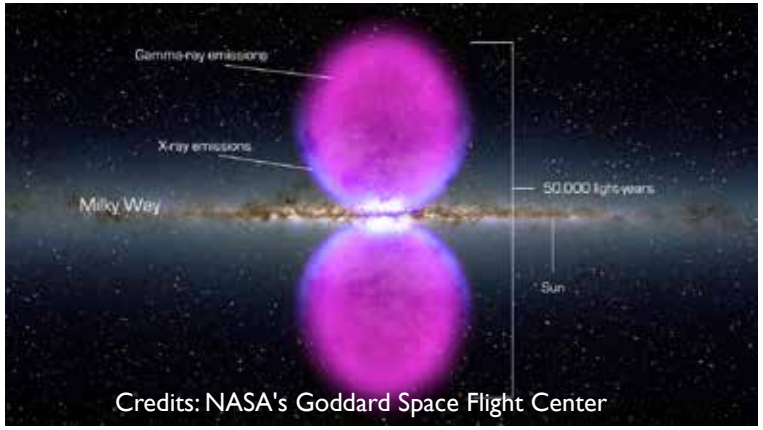


Summary

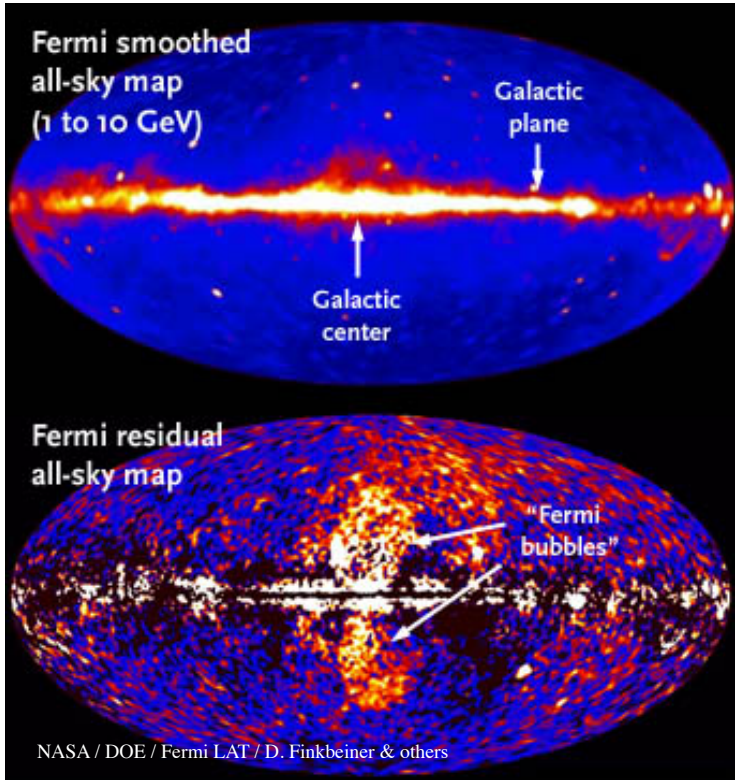
HAWC is now operational
It is giving a new wide-field view of the TeV sky
It is synergistic with other instruments:
    MOUs with VERITAS, IceCube, MAGIC, HESS, Fermi
It is now providing a nearly contiuous view of the transient TeV sky

Large-scale structures e.g. Fermi Bubbles

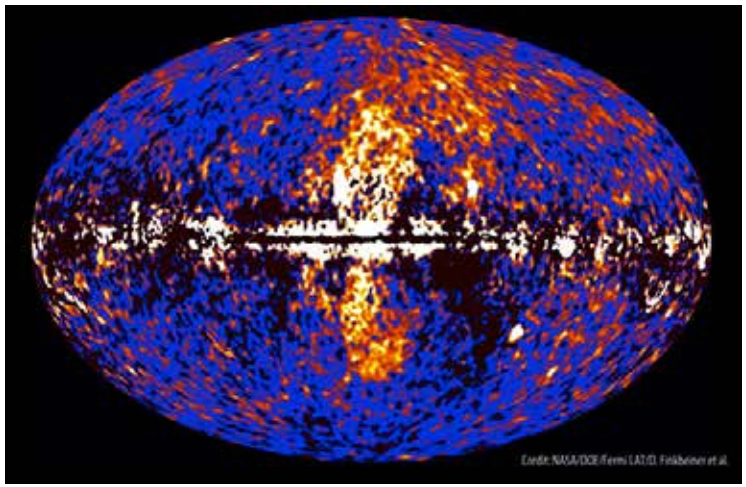
- Large scale, non-uniform structures extending above and below the Galactic center.
  - Edges line up with X-ray features.
  - Correlate with microwave excess (WMAP haze)
  - Both hadronic and leptonic model fit Fermi LAT data. Leptonic model can explain both gamma ray and microwave excess.
- First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

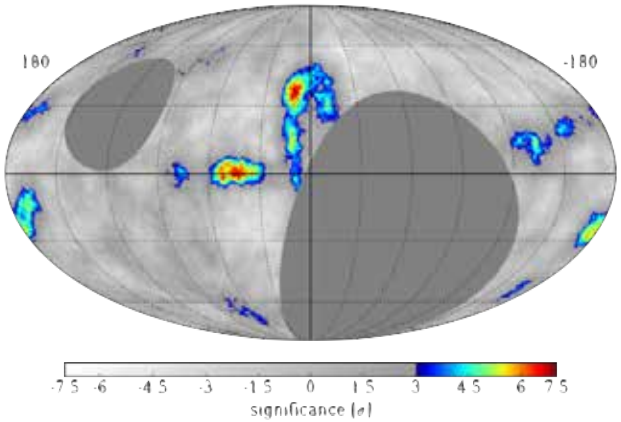


Credits: NASA's Goddard Space Flight Center

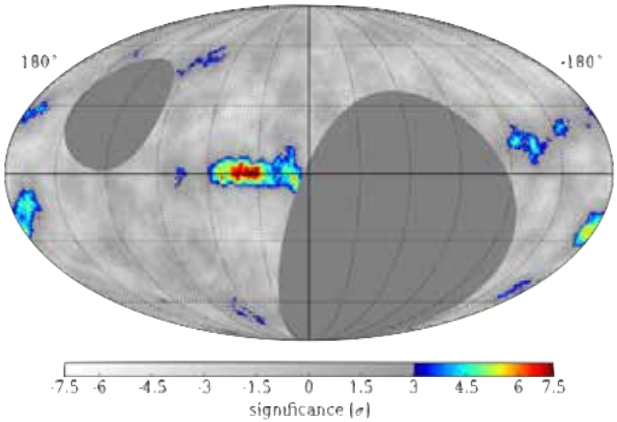


Diffuse Emission





No Cut-off



150 GeV Cut-off

Fermi Bubbles

Large-scale structures e.g. Fermi Bubbles

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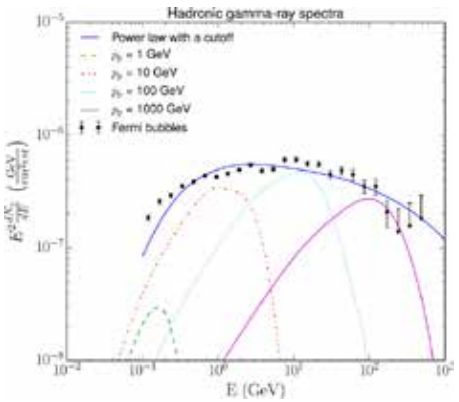

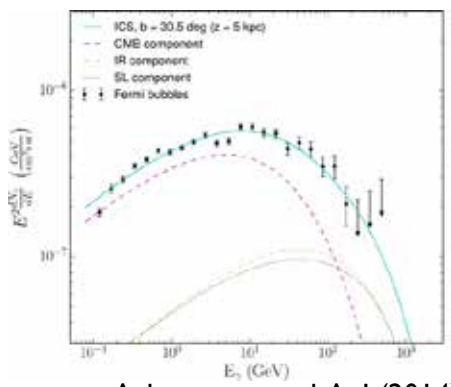

Ackermann et al. ApJ (2014)

H. Ayala (E13: DM, Indirect, Gamma-rays, Apr 16)