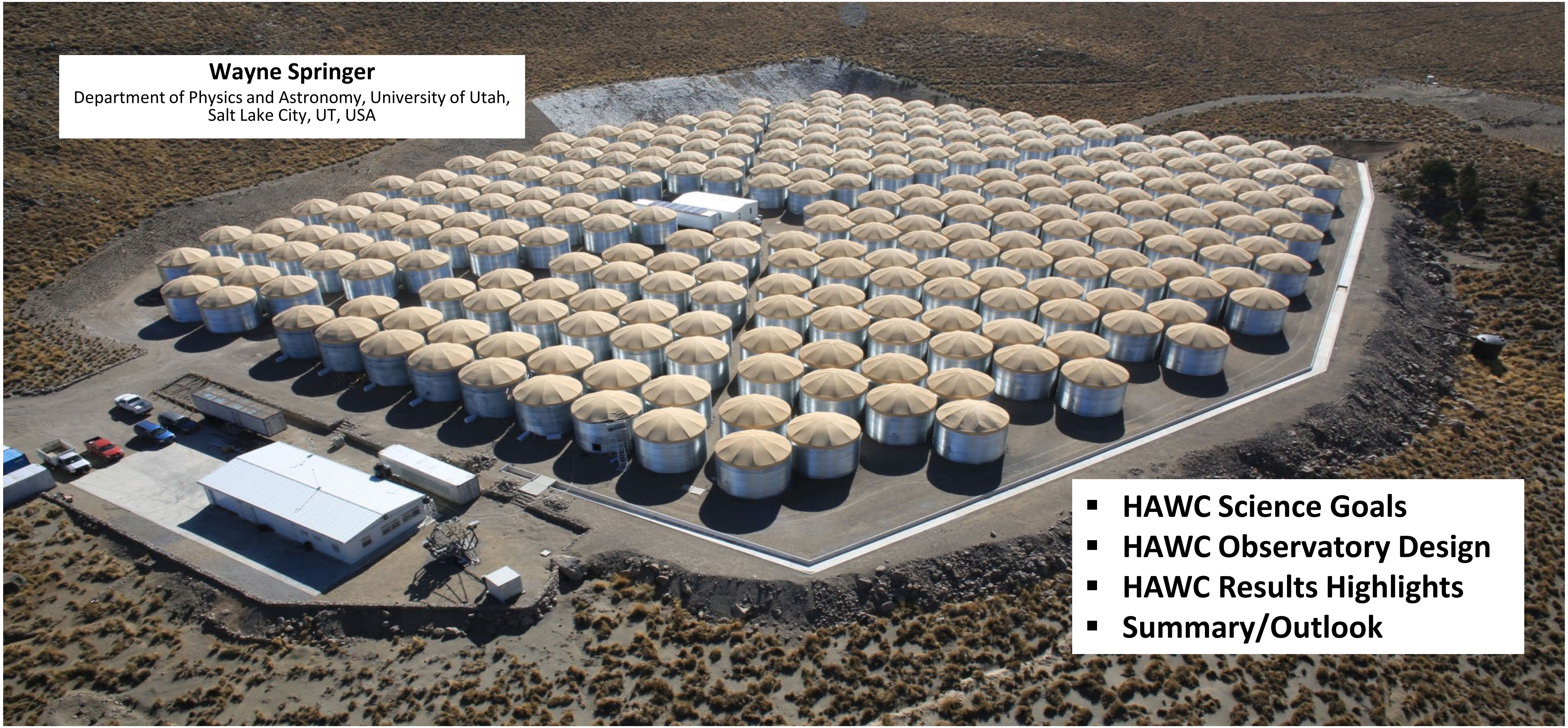
Results From The High-Altitude Water Cherenkov (HAWC) Observatory



Wayne Springer
Department of Physics and Astronomy, University of Utah, Salt Lake City, UT, USA

- HAWC Science Goals
- HAWC Observatory Design
- HAWC Results Highlights
- Summary/Outlook

The HAWC Collaboration

USA:
Pennsylvania State University
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
Univ. of California, Irvine
University of New Hampshire
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

Europe:
Max Planck Institute KernPhysik Heidelberg
Krakow Nuclear Institute, Poland
INFN Padova, Italy

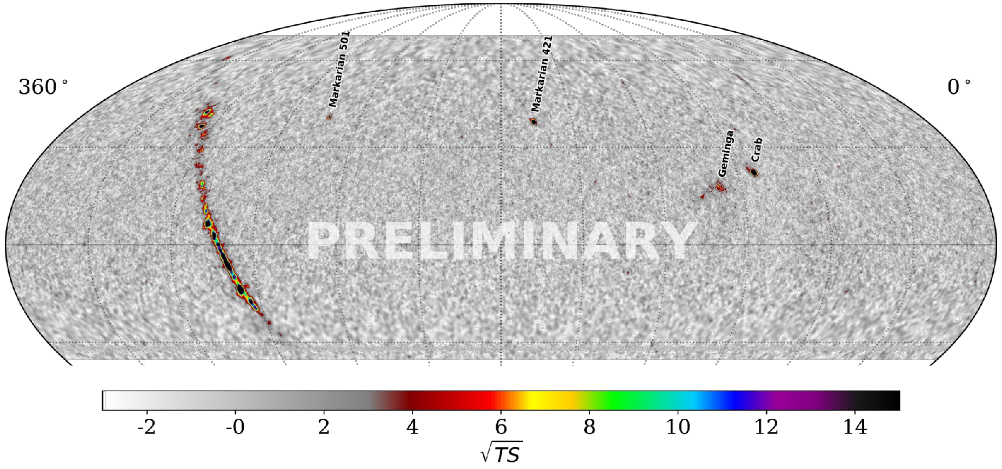
Mexico:
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

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

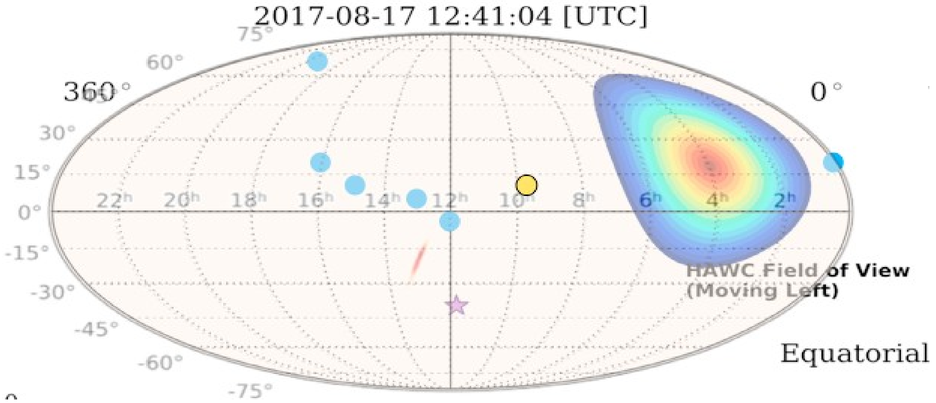
Central America:
University of Costa Rica

HAWC Observatory – Science Goals

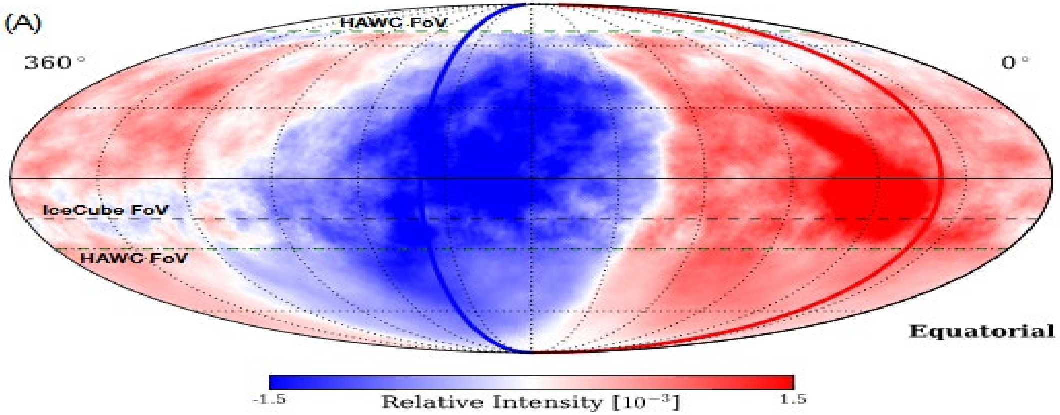
TeV Gamma Ray Sky



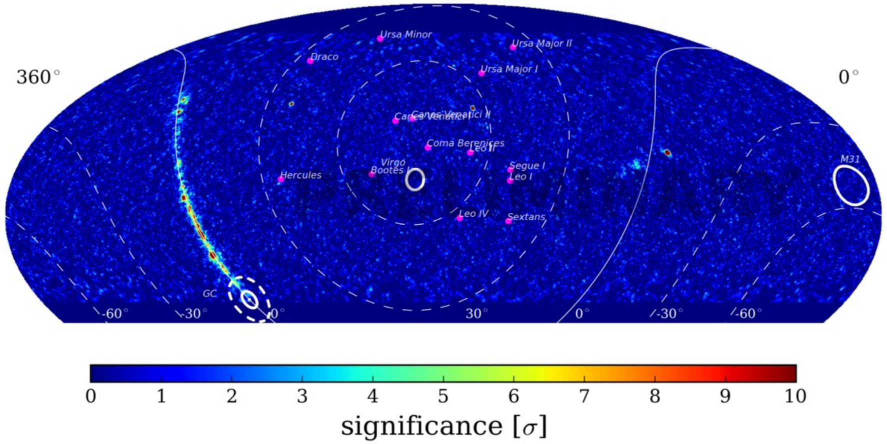
Multi-messenger Astrophysics



Cosmic Ray Studies



Searches and Exotica

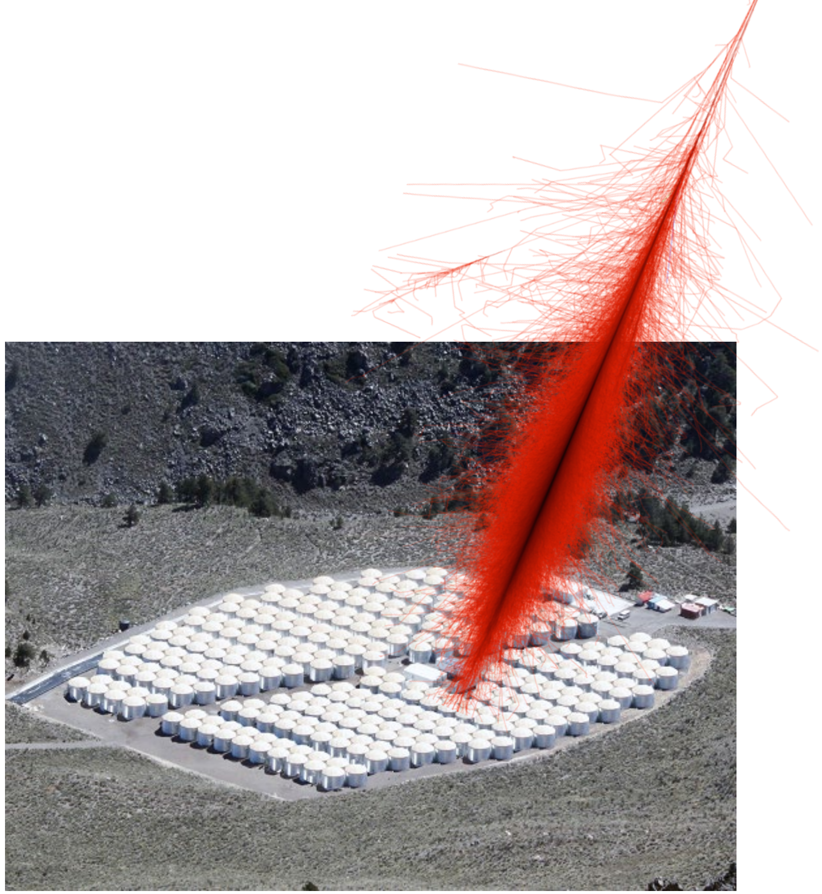


HAWC Observatory –Science Goals

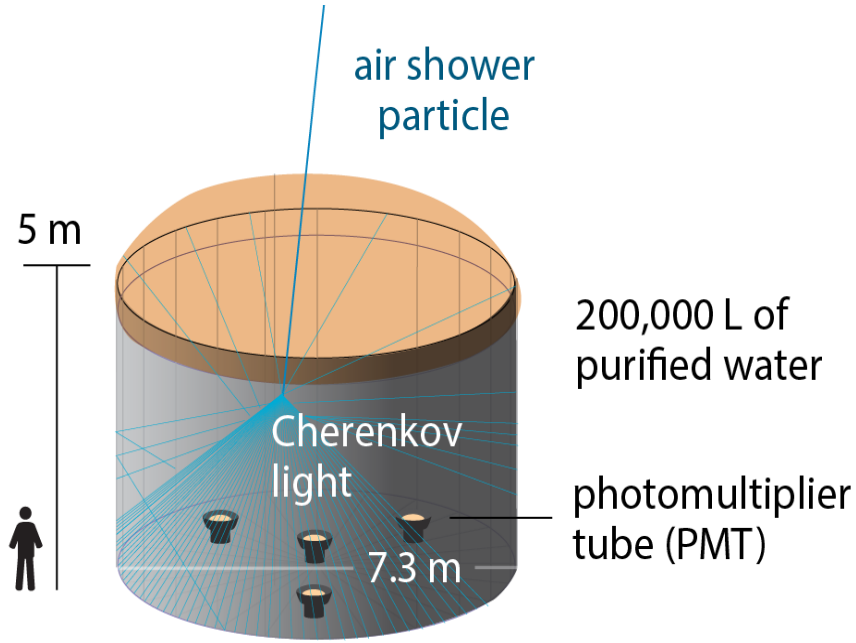
- **TeV Gamma Ray Sky**
  - Galactic Sources
    - Supernova Remnants
    - Pulsar Wind Nebula
    - Extended Sources
    - High Energy (>50TeV)
    - ...
  - Extra-galactic sources
    - Active Galactic Nuclei, Blazars
    - Gamma-Ray Burst searches
    - …
  - Monitoring of Transient/Variable Sources
- **Cosmic Ray Studies (1 TeV-1 PeV)**
  - Anisotropies of Arrival Directions
  - All-particle Energy Spectrum
  - Composition Studies
- **Multi-messenger Astrophysics**
  - TeV Gamma and Neutrino Coincidence
  - TeV Gamma and Gravitational Wave Coincidence
  - Multiwavelength (Fermi,Swift,…)
  - …
- **Searches and Exotica**
  - Search for Dark Matter
    - Dwarf galaxies
    - Searching for Dark Matter Decay within the Virgo Cluster
  - Search for Lorentz Invariance
  - Primordial Black Hole Burst Searches

HAWC Observatory - Design Principles

Atmosphere “converts” particle into an extensive air shower (EAS).

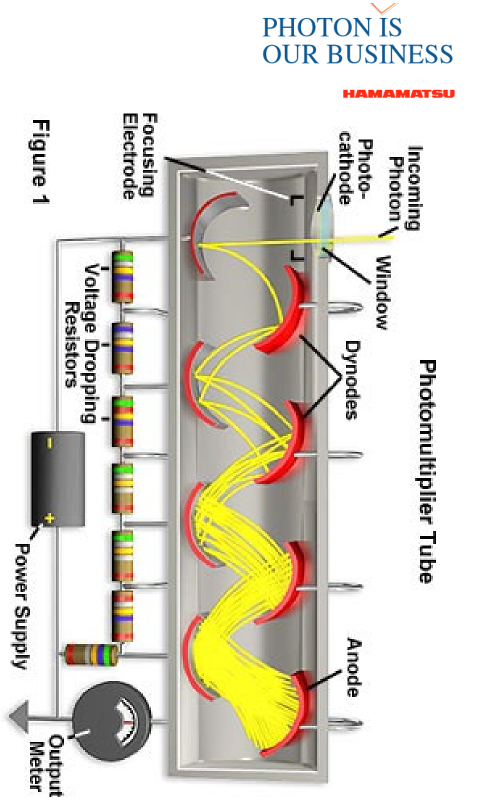


Water Cerenkov Detector Samples Extensive Air Shower particles by measuring their Cerenkov light emitted in water tank.

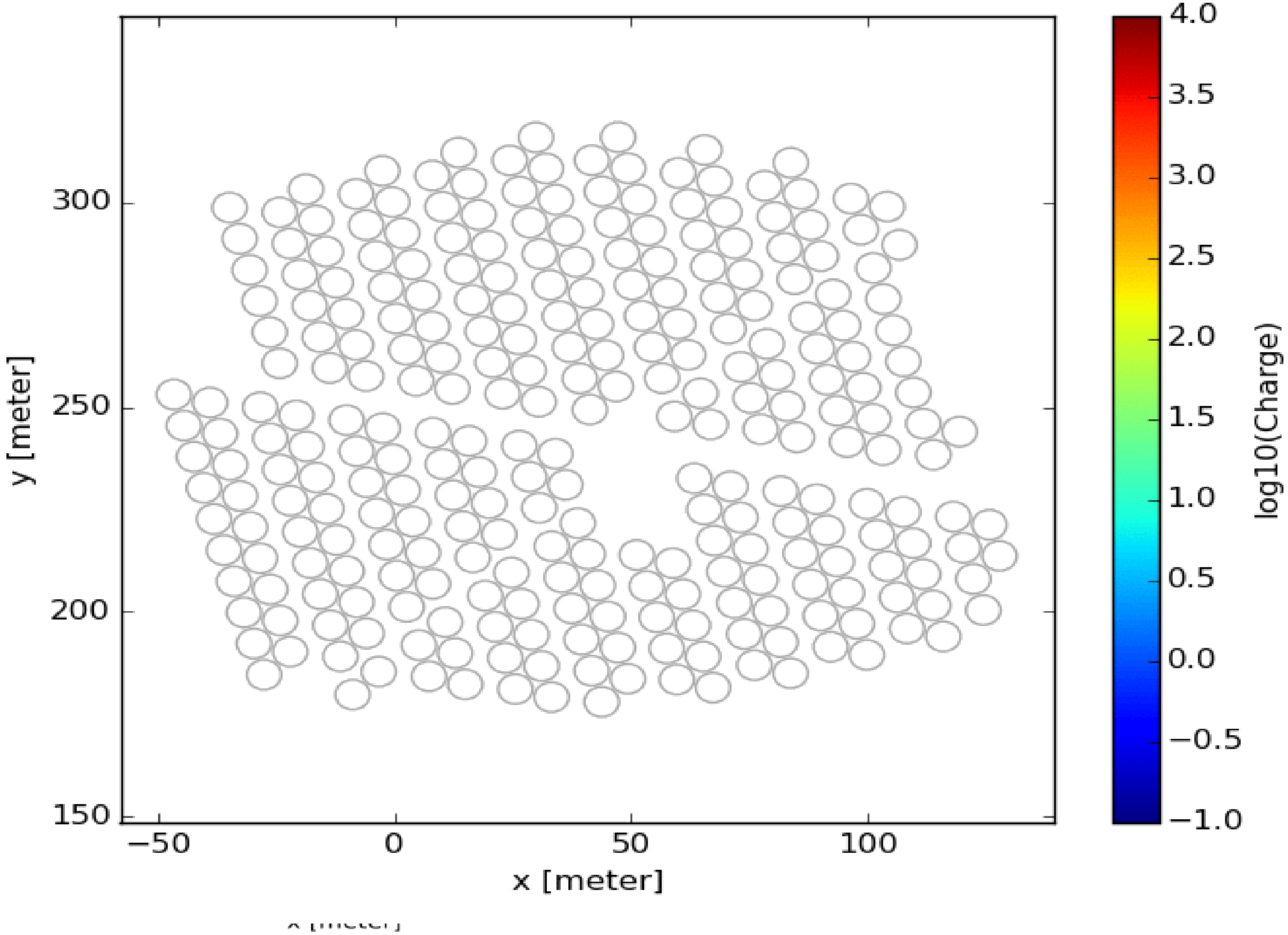


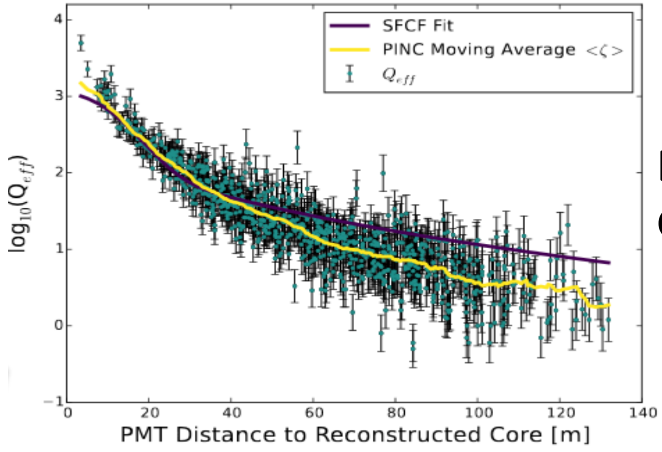
Based upon Milagro Experiment

PMT
Converts Cerenkov light into electrical signal.



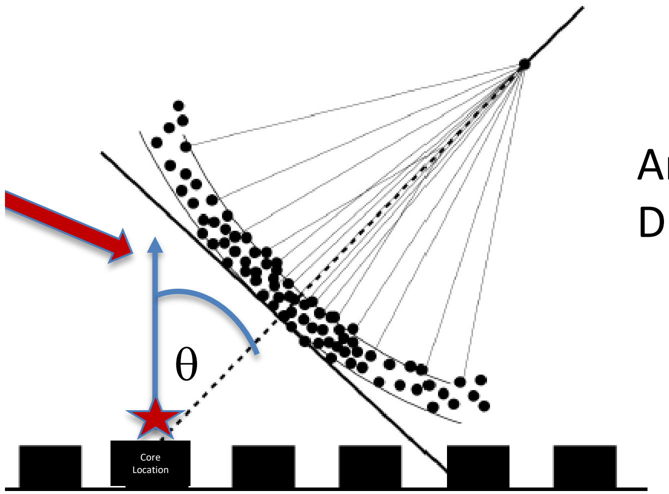
Shower Reconstruction : Core Location , Arrival Direction, Lateral Distribution.





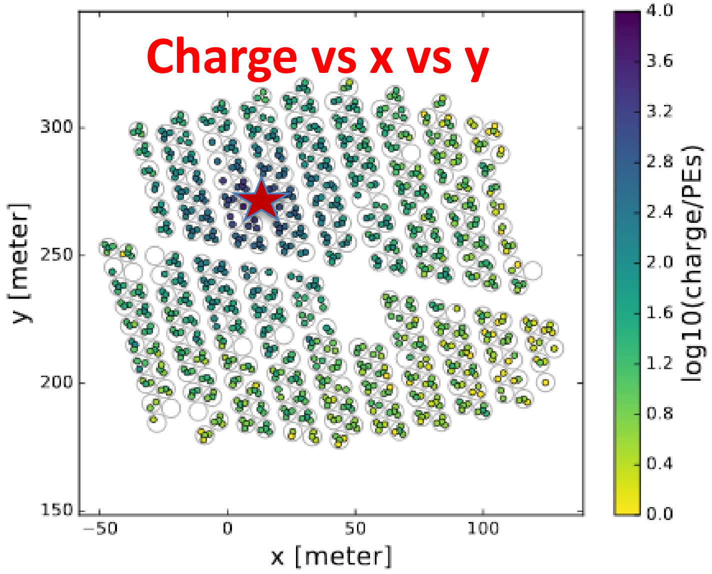
Energy
Gamma/Hadron

Lateral Distribution Function



Arrival
Direction

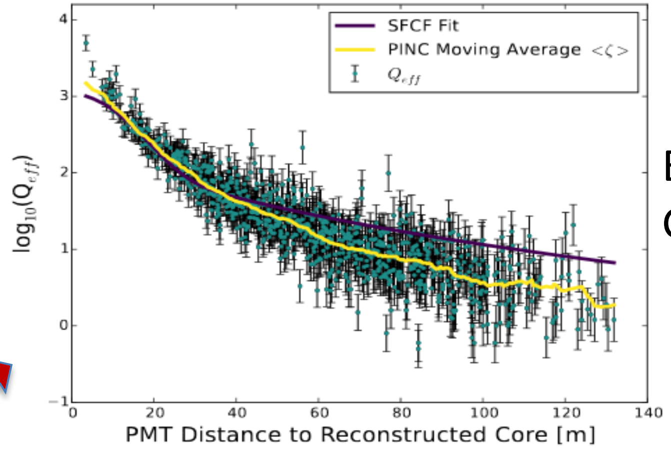
Shower Reconstruction : Core Location , Arrival Direction, Lateral Distribution.



$$x_{COM}, y_{COM} = \frac{\sum_{i=1}^{Nhit} x_i N_{pe,i}}{\sum_{i=1}^{Nhit} N_{pe,i}}, \frac{\sum_{i=1}^{Nhit} y_i N_{pe,i}}{\sum_{i=1}^{Nhit} N_{pe,i}}$$

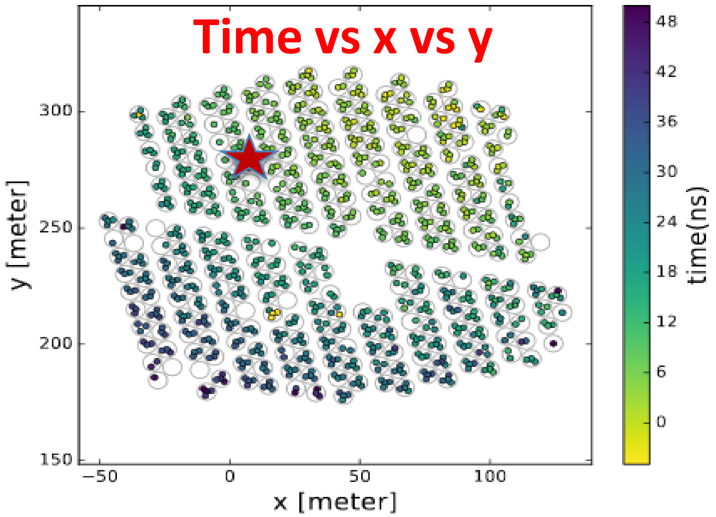
Location of Maximum Charge Density

Core Location



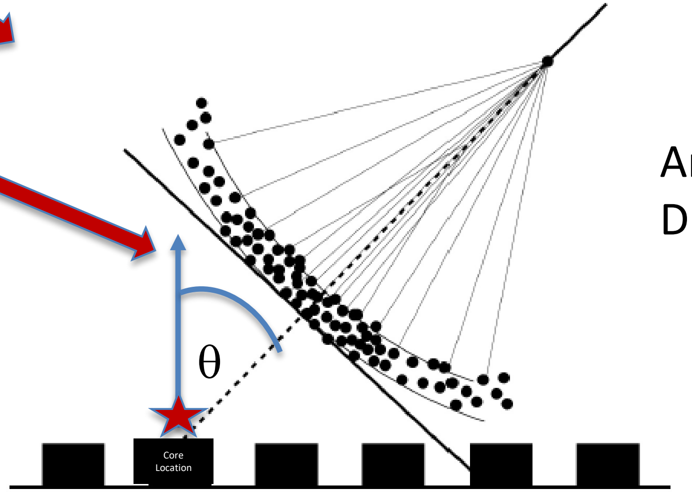
Energy
Gamma/Hadron

Lateral Distribution Function



Shower Plane

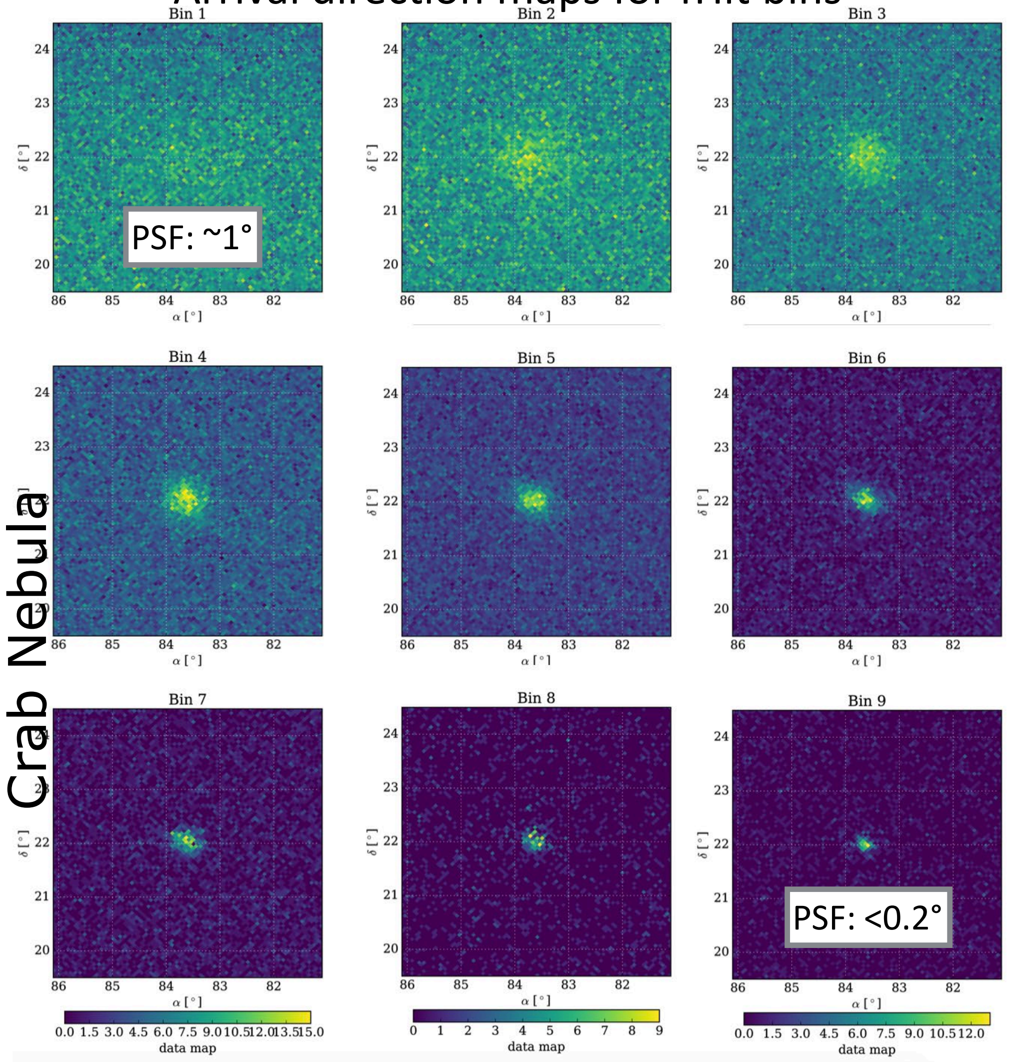
Zenith θ
Azimuth ϕ



Arrival Direction

Source search and Energy Spectrum Determination – Crab Nebula

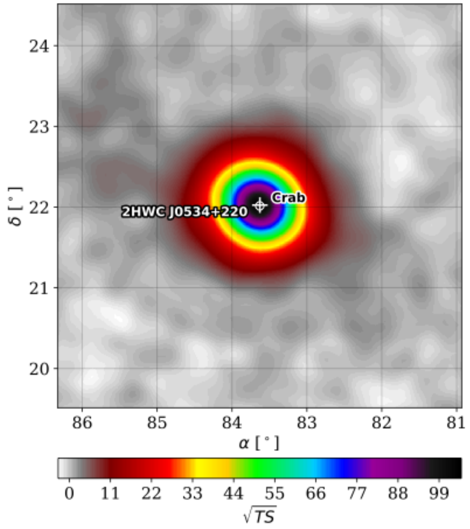
Arrival direction maps for fHit bins

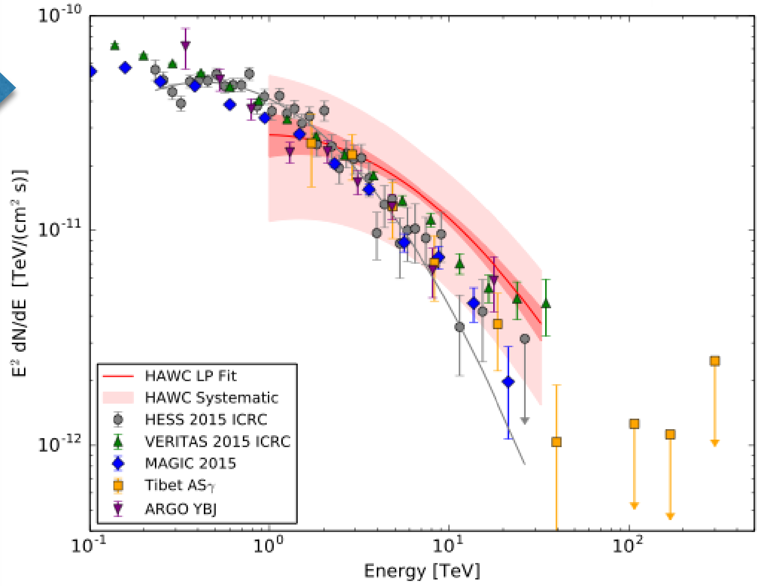


Detector response
&
Source model

Likelihood framework

Energy Spectrum

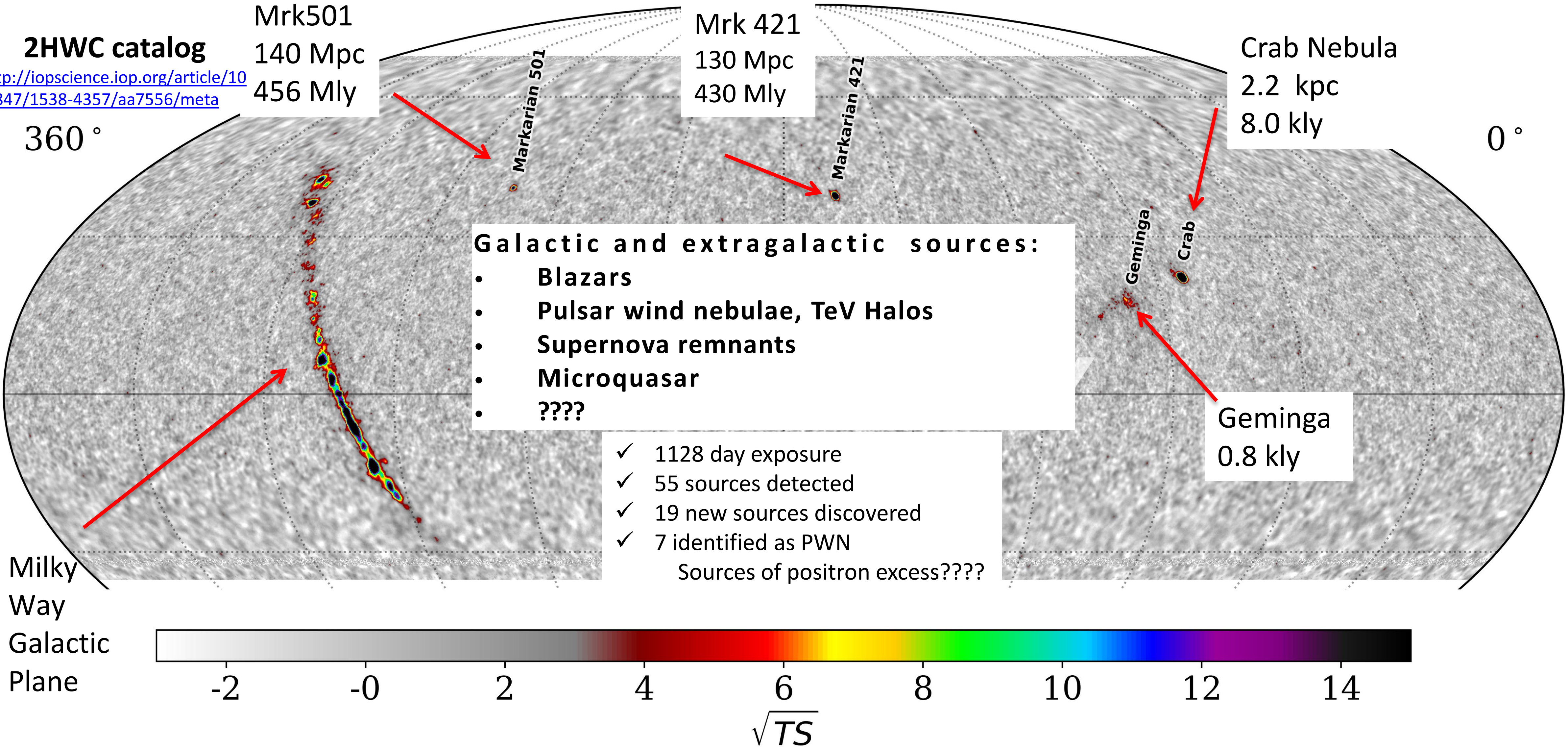




TeV Sky Results- HAWC point source TeV Sky Map xHWC Catalog

2HWC catalog

http://iopscience.iop.org/article/10.3847/1538-4357/aa7556/meta

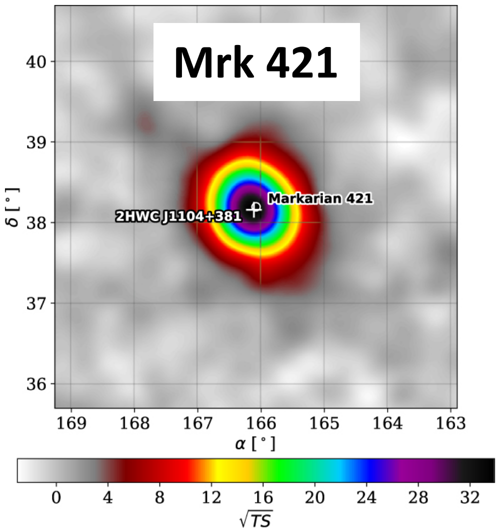


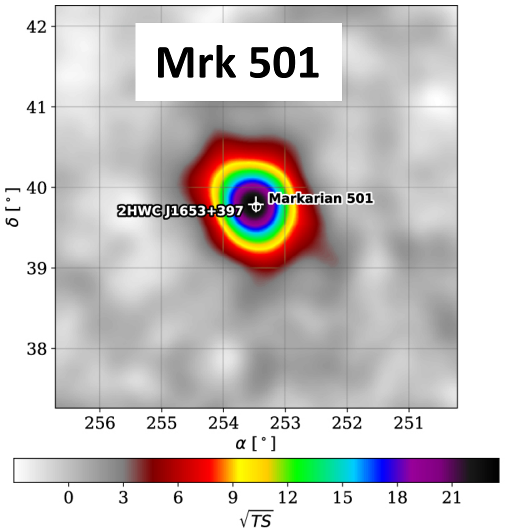
Galactic and extragalactic sources:

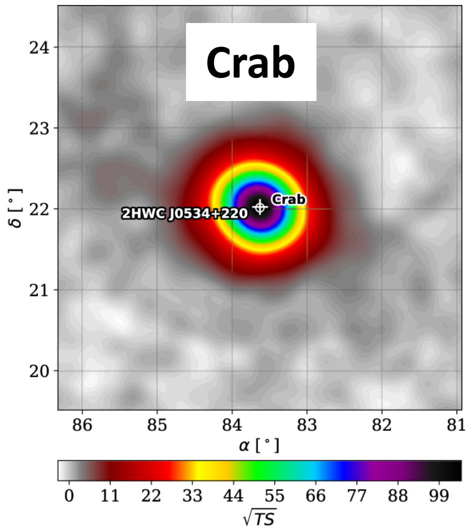
- **Blazars**
- **Pulsar wind nebulae, TeV Halos**
- **Supernova remnants**
- **Microquasar**
- **????**

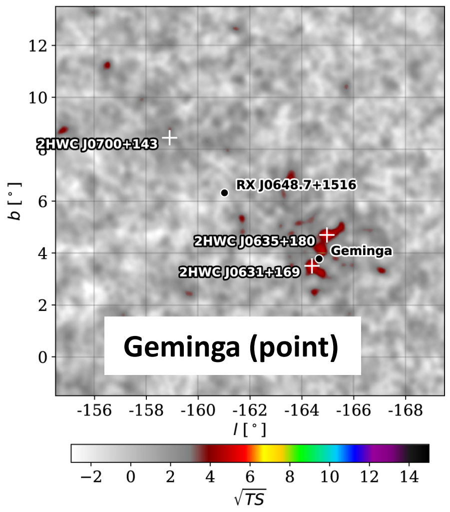
✓ 1128 day exposure
✓ 55 sources detected
✓ 19 new sources discovered
✓ 7 identified as PWN
Sources of positron excess????

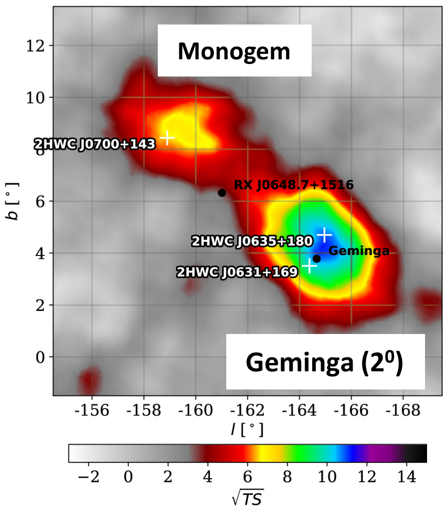
TeV Sky Results- Mrk 421, Mrk 501, Crab and Geminga









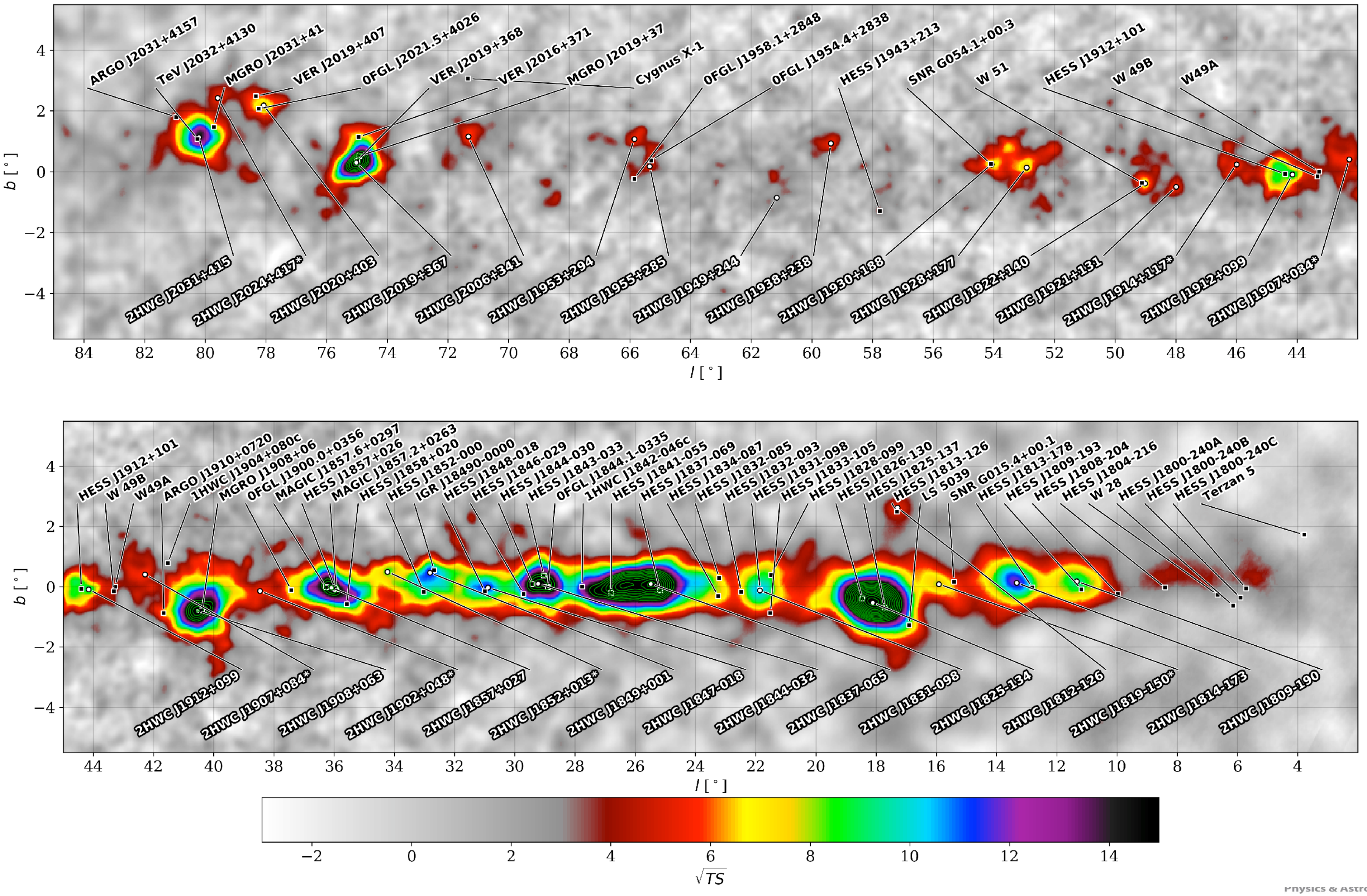


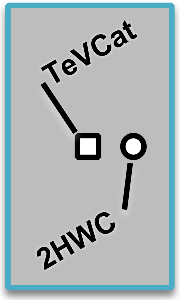
Beware of large PSF but Extended Sources Observed as well !!!!

Geminga and Friend

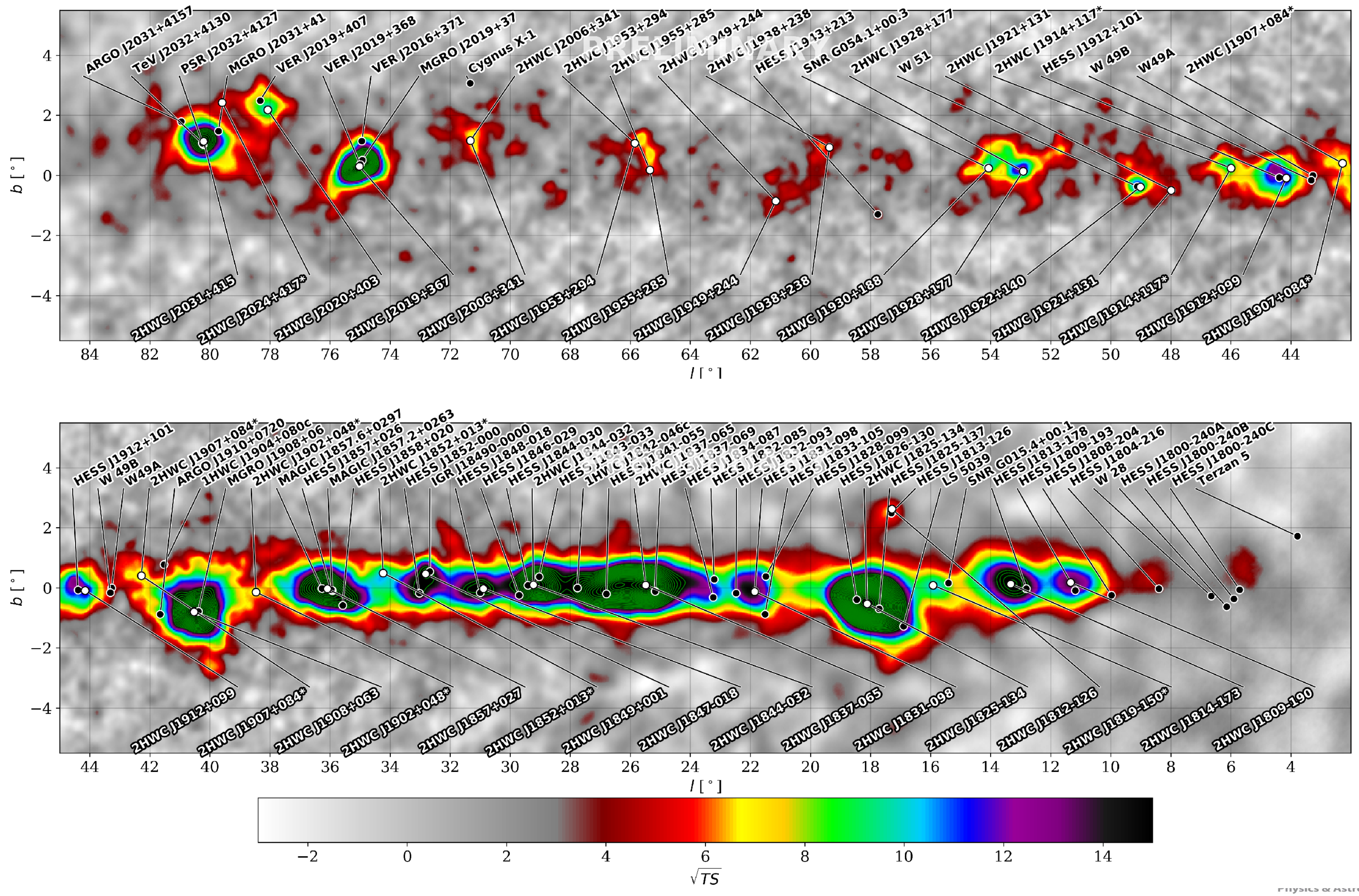
Inner Galactic plane — 507d livetime (2014-11 to 2016-06)

2HWC catalog
(ApJ 2017)

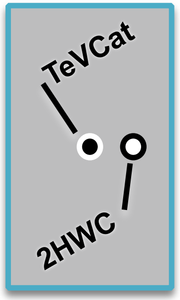




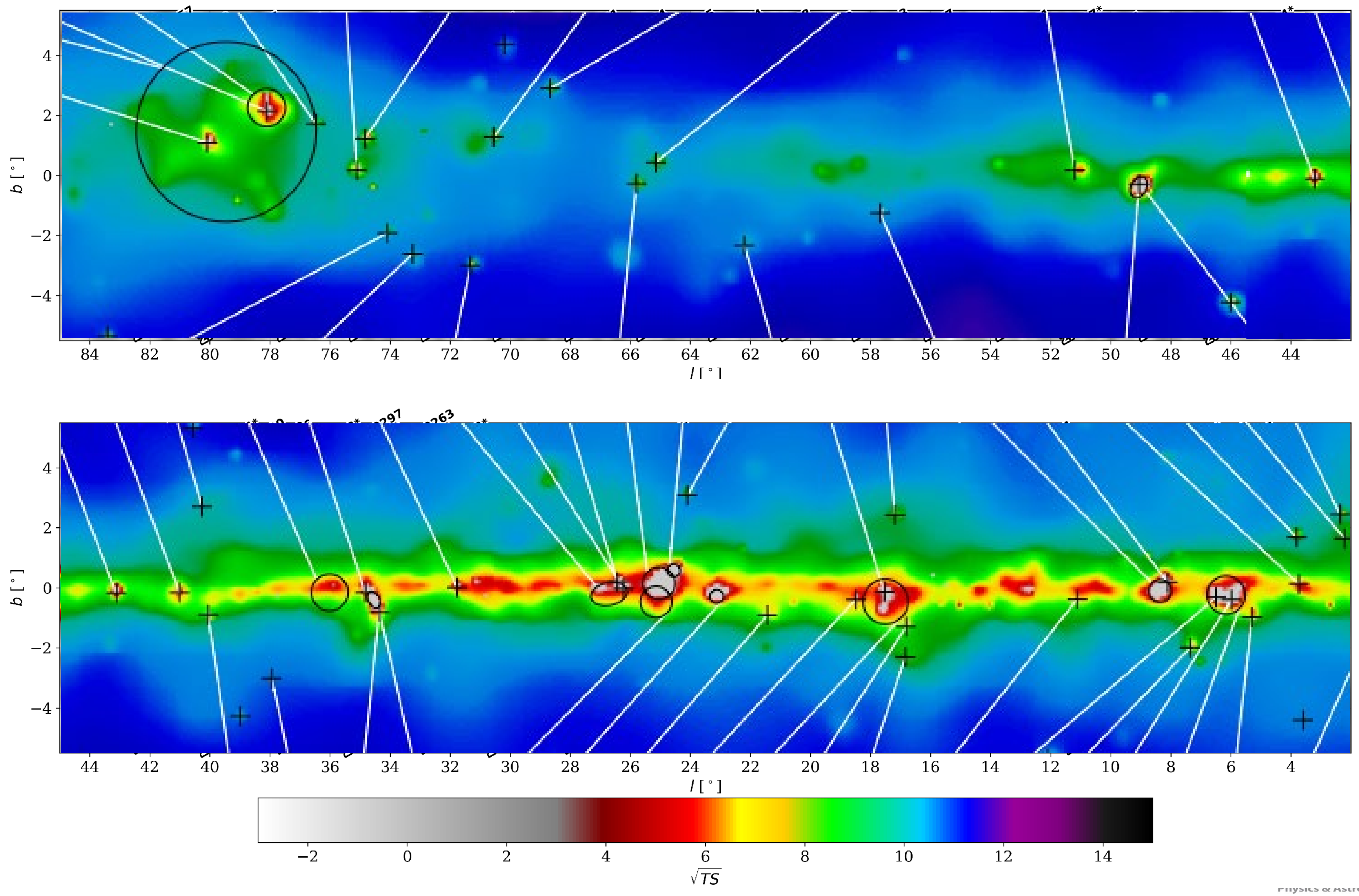
Inner Galactic plane — 1128d livetime (2014-11 to 2018-04)

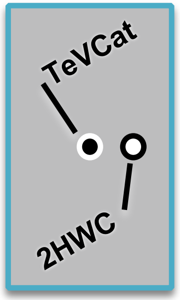


Update

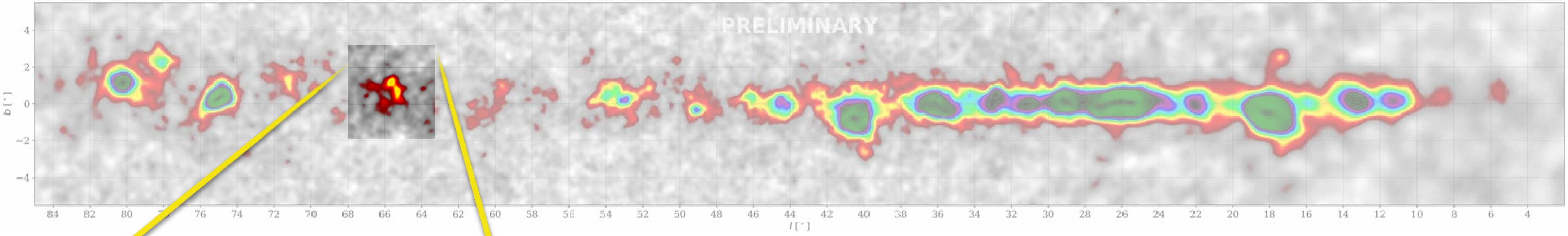


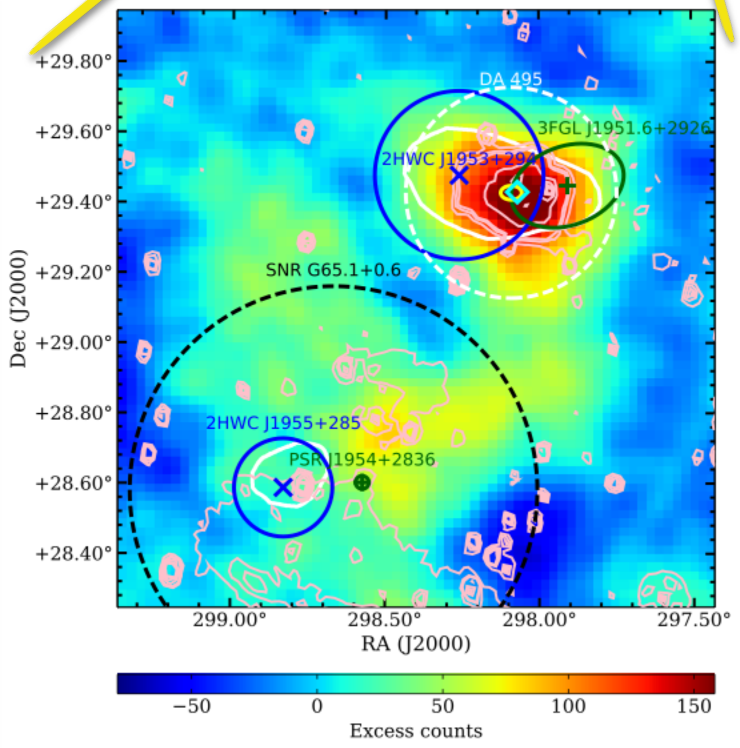
Inner Galactic plane — Fermi-LAT 3FHL (arXiv:1702.00664)





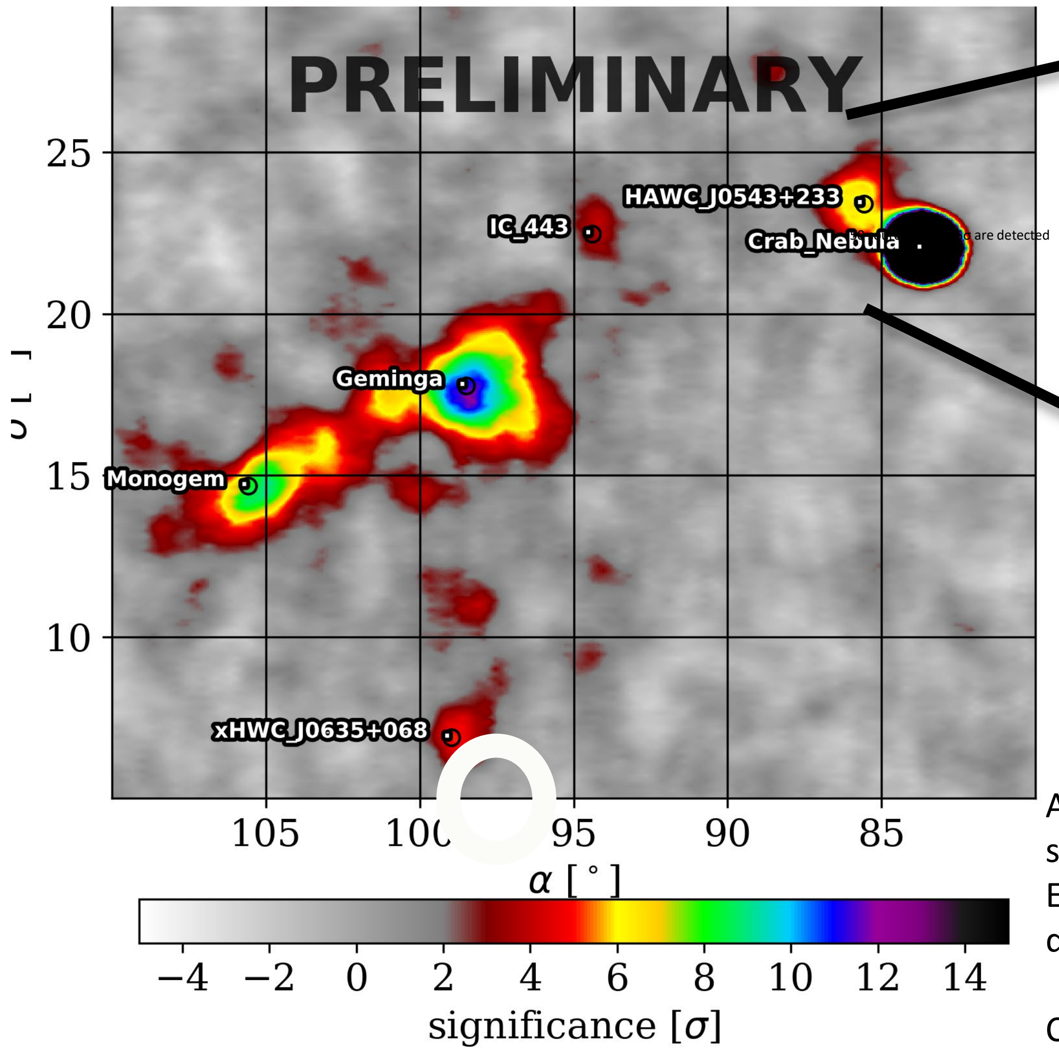
New Sources: 2HWC J1953+294

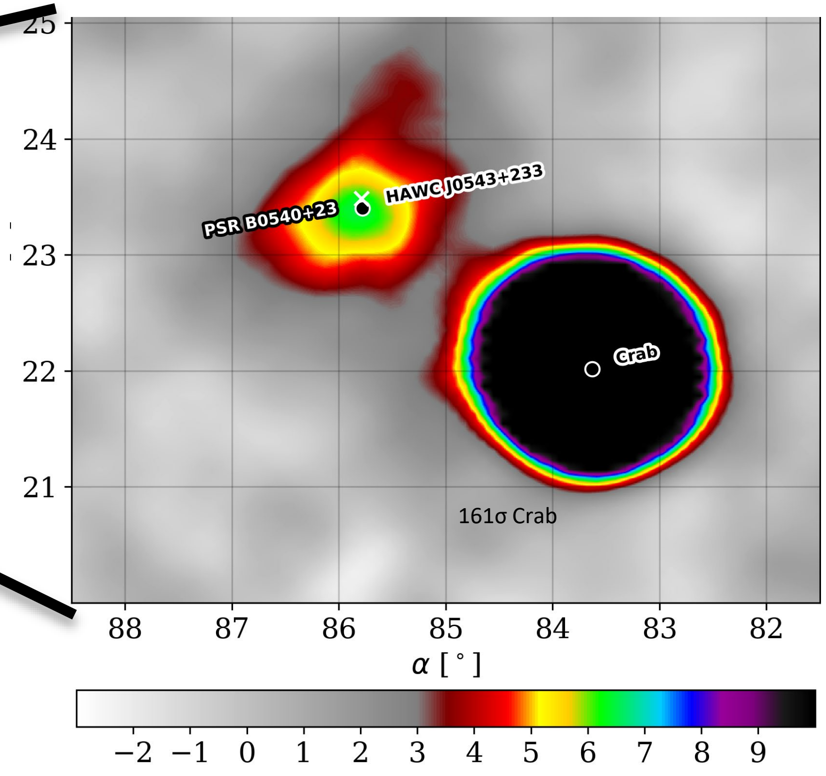




- **2HWC J1953+294**: No previously known TeV sources.
- Tentative association 3FGL J1951.6+2926 / PWN DA 495
- Shared privately with Imaging Atmospheric Cherenkov Telescopes
- New observations plus archival data by VERITAS: source confirmed.
- *Joint paper to appear ApJ (arXiv:1808.10423).*

New discoveries – some hiding in plain sight!





Another middle age PWN
similar to Geminga and B0656+14
Ė = 4.1 × 10^{34} erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

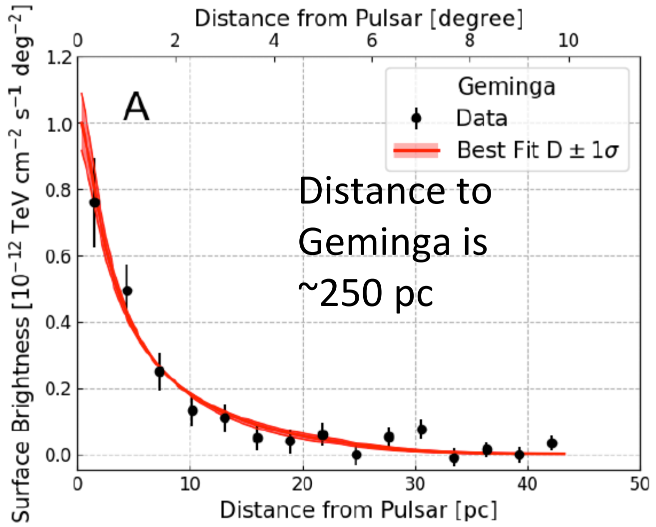
- More discoveries:
  - HAWC J0543+233 (ATel #10941),
  - HAWC J0635+070 (ATel #12013)
- Probe diffusion in various locations in the Galaxy and near various objects.
- + “invisible pulsars”?
- HAWC uniquely suited to study halos.

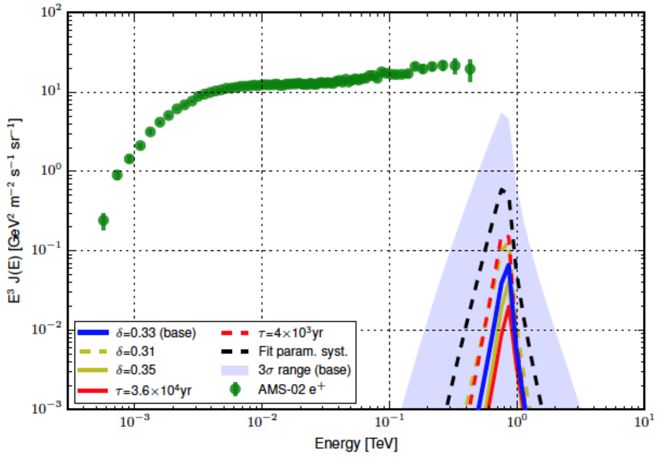
Science 17 November 2017

Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth

by the HAWC collaboration and LANL theorists Hui Li, Fan Gao, Haocheng Zhang

- HAWC observations prove that these sources are indeed accelerating electrons and positrons to ~100 TeV producing 25 TeV gamma-rays by inverse Compton scattering of CMB.
- HAWC observations measure the total energy released in electrons and positrons which is much of their measured spin down energy.
- HAWC observations of the angular extent of these TeV nebula measures the diffusion coefficient of their propagation in the interstellar medium.
- HAWC observations show that Geminga and Monogem do NOT contribute significantly to the AMS measured positron excess assuming a simple diffusion model.
- Other models argue otherwise….





- Linden suggest that there are more nearby PWN to be found based on spin down power and distance
- HAWC has already seen several of these

HAWC detection of TeV source HAWC J0635+070

ATel #12013; *Chad Brisbois (Michigan Technological University), Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andrew Smith (University of Maryland) on behalf of the HAWC collaboration*
on 6 Sep 2018; 14:47 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

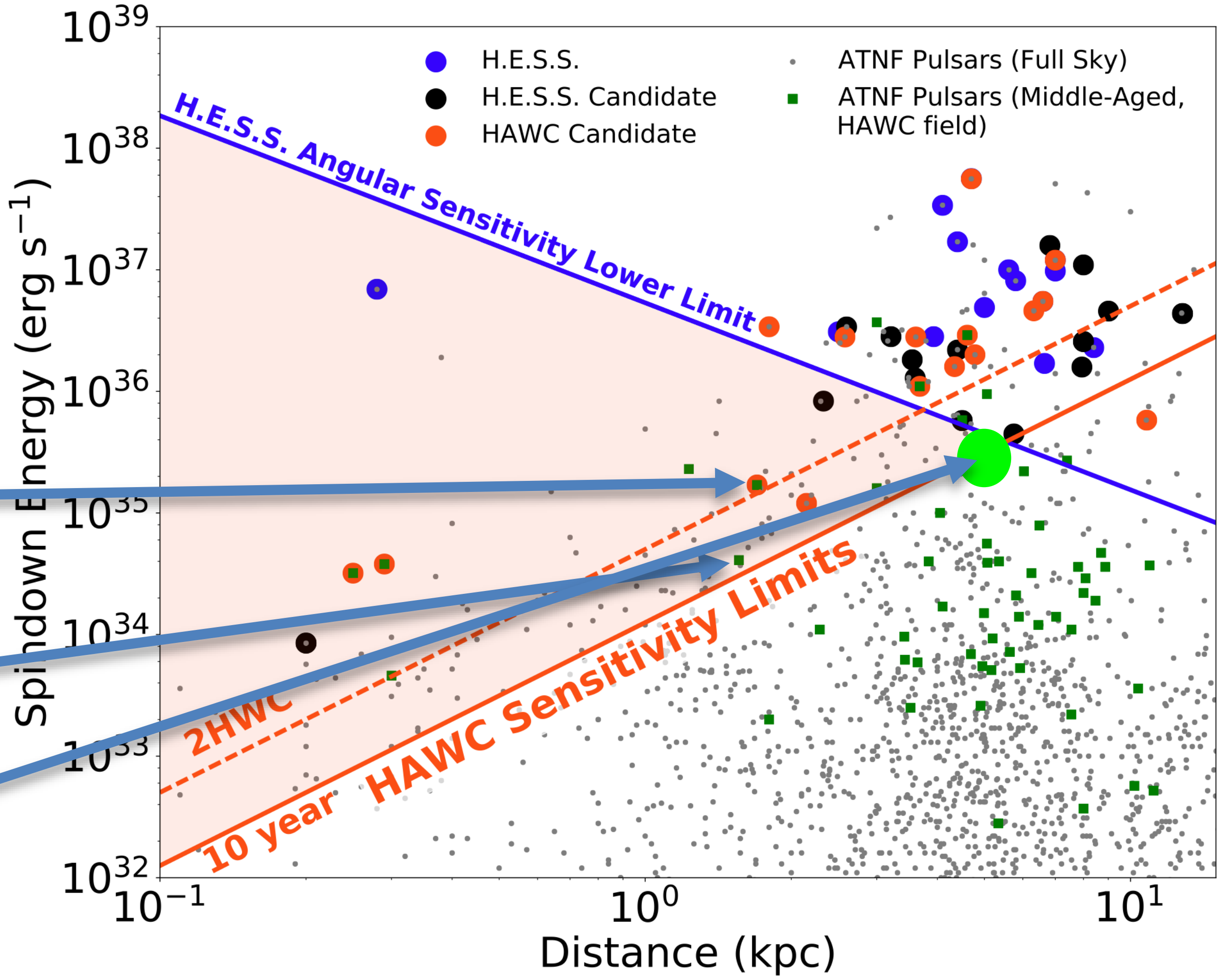
HAWC detection of TeV emission near PSR B0540+23

ATel #10941; *Colas Riviere (University of Maryland), Henrike Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration*
on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)

xHWC J2005+311

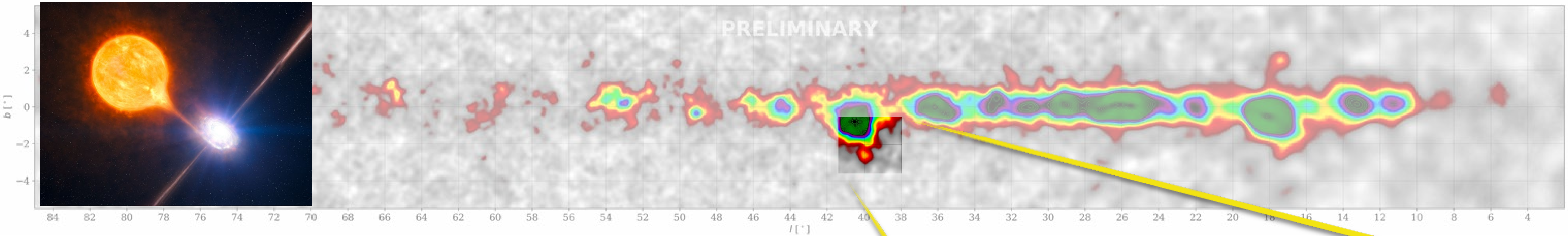
Shared with MOU partners

Newly discovered Fermi Pulsar



Linden et. al 2017 PhysRevD.96.103016

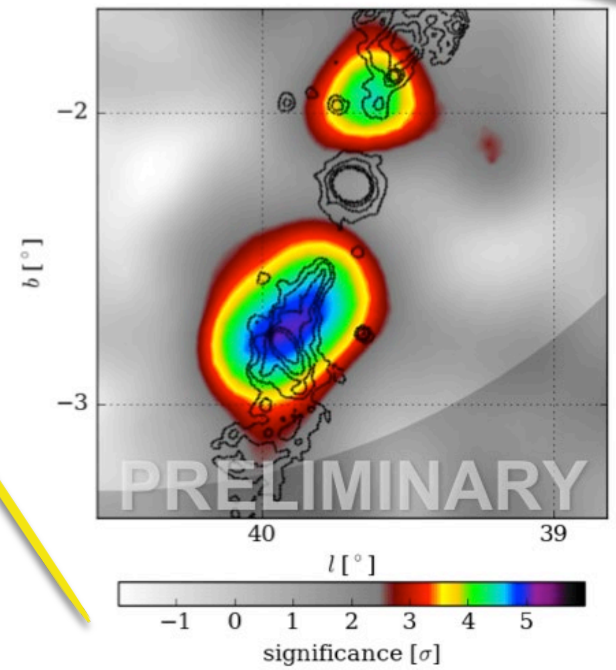
Microquasar SS-433 – Lobes Detection



First detection of lobes in TeV, 6σ after subtracting J1908+06

SS 433:

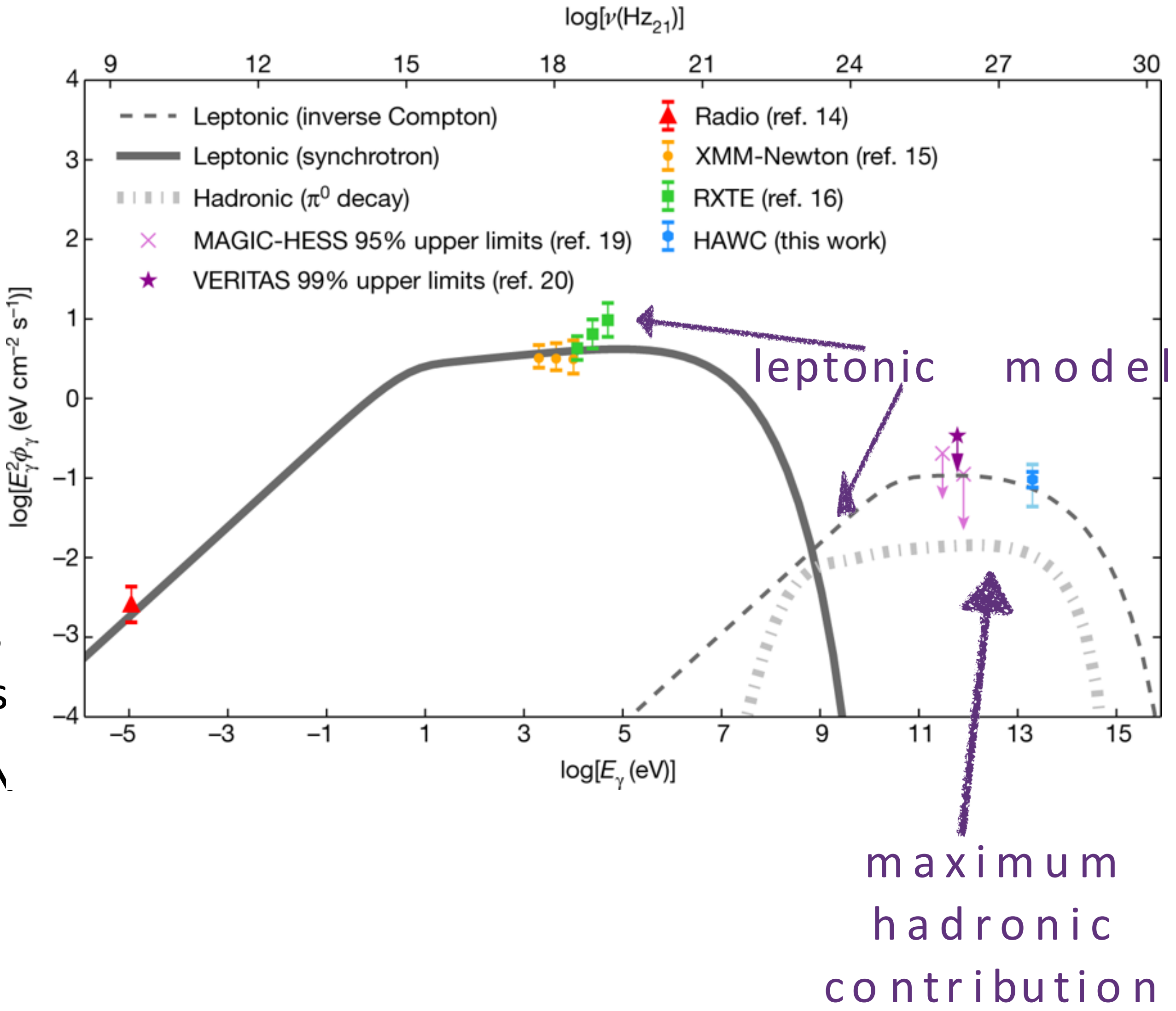
- Binary system: supermassive star (~30 M⊙), compact object (~10 M⊙)
- Powerful jets: ~10^{39} erg s^{-1}, speed ~c/4 — c/3
- Termination shocks in W50 nebula



HAWC data favors leptonic models over hadronic: energetics, emission localization

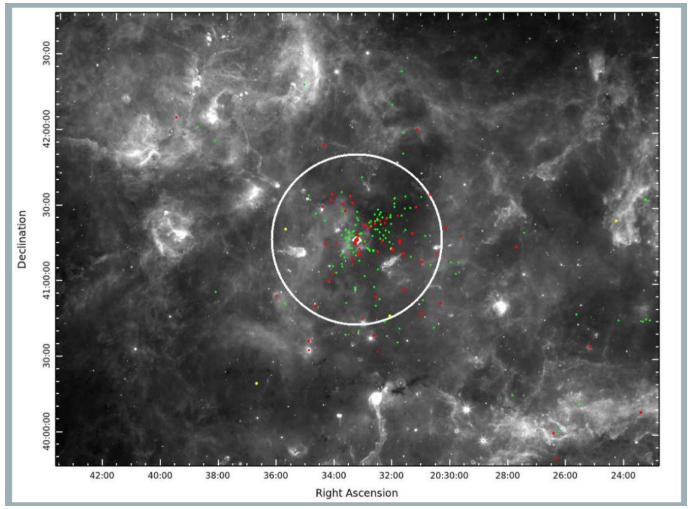
Microquasar SS-433 – Lobes Detection – PeVatron?

- HAWC observation of SS433 is the first direct evidence of particle acceleration to ~PeV in jets
  - Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
  - Hadronic acceleration disfavored due to extreme energetics required
  - Acceleration does not happen at the black hole because the cooling time of the electrons is too short to make the observed gamma-rays
- Fermi observes similar phenomena in AGN AGN (Cen A & Fornax)
- Published in Nature Oct 4, 2018



Galactic CRs accelerated in relativistic shocks up to the knee.

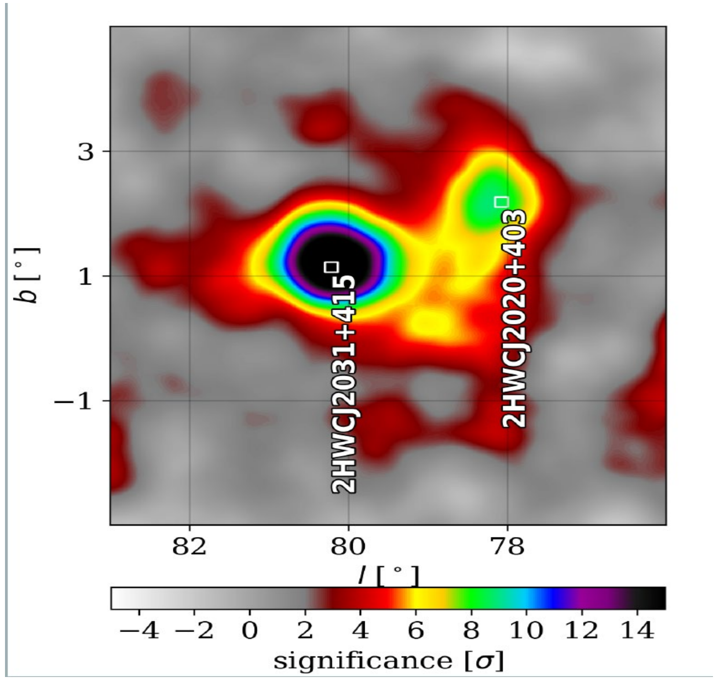
- SNRs?
- Binaries?
- Star-forming regions?



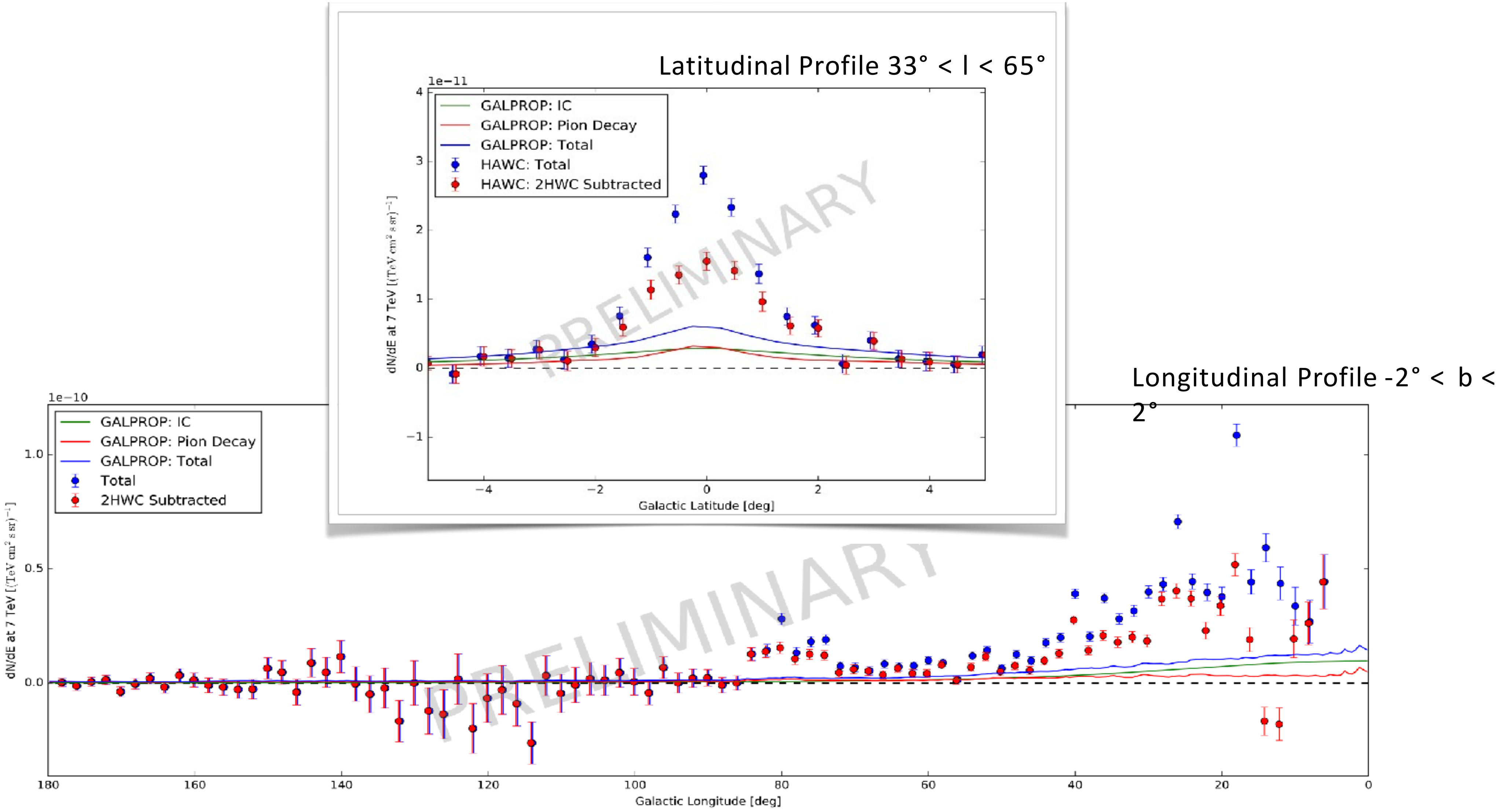
White circle: Cygnus OB2 association in 12 µm image of the Cygnus X cloud. Red, green and yellow dots represent O, B and Wolf Rayet stars respectively

(Wright, N. J. et al, https://arxiv.org/abs/1502.05718)

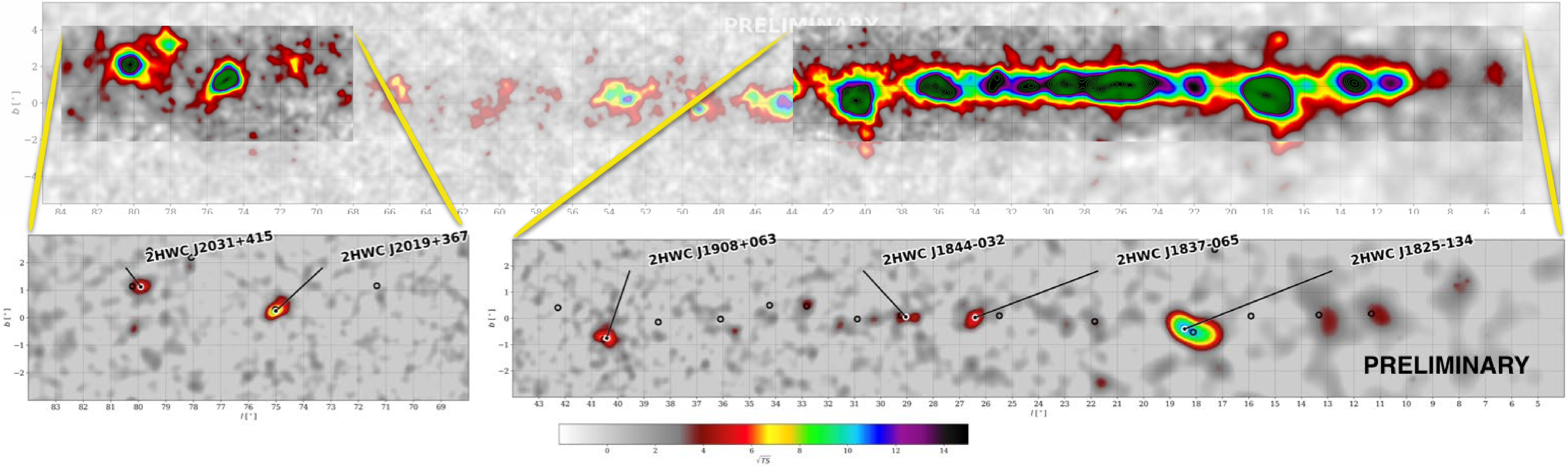
HAWC significance map of Cocoon - Cygnus Star Forming Region



Galactic Diffuse Emission (+unresolved sources)

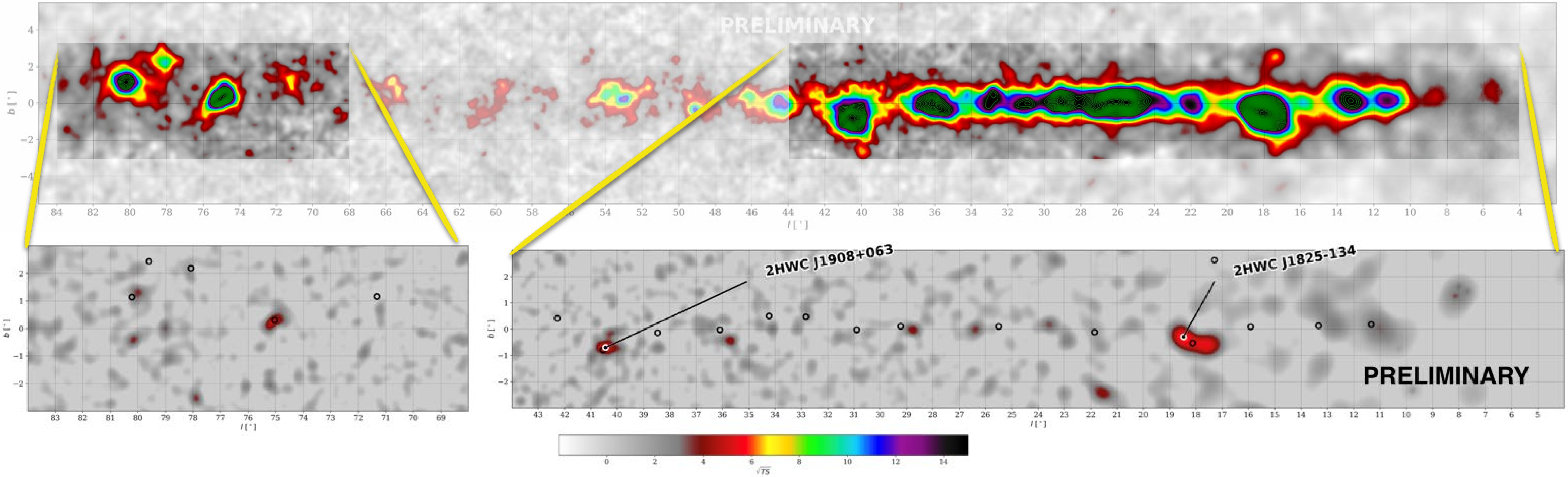


Pushing to the Highest Energies: (E_{reco} > 56 TeV)



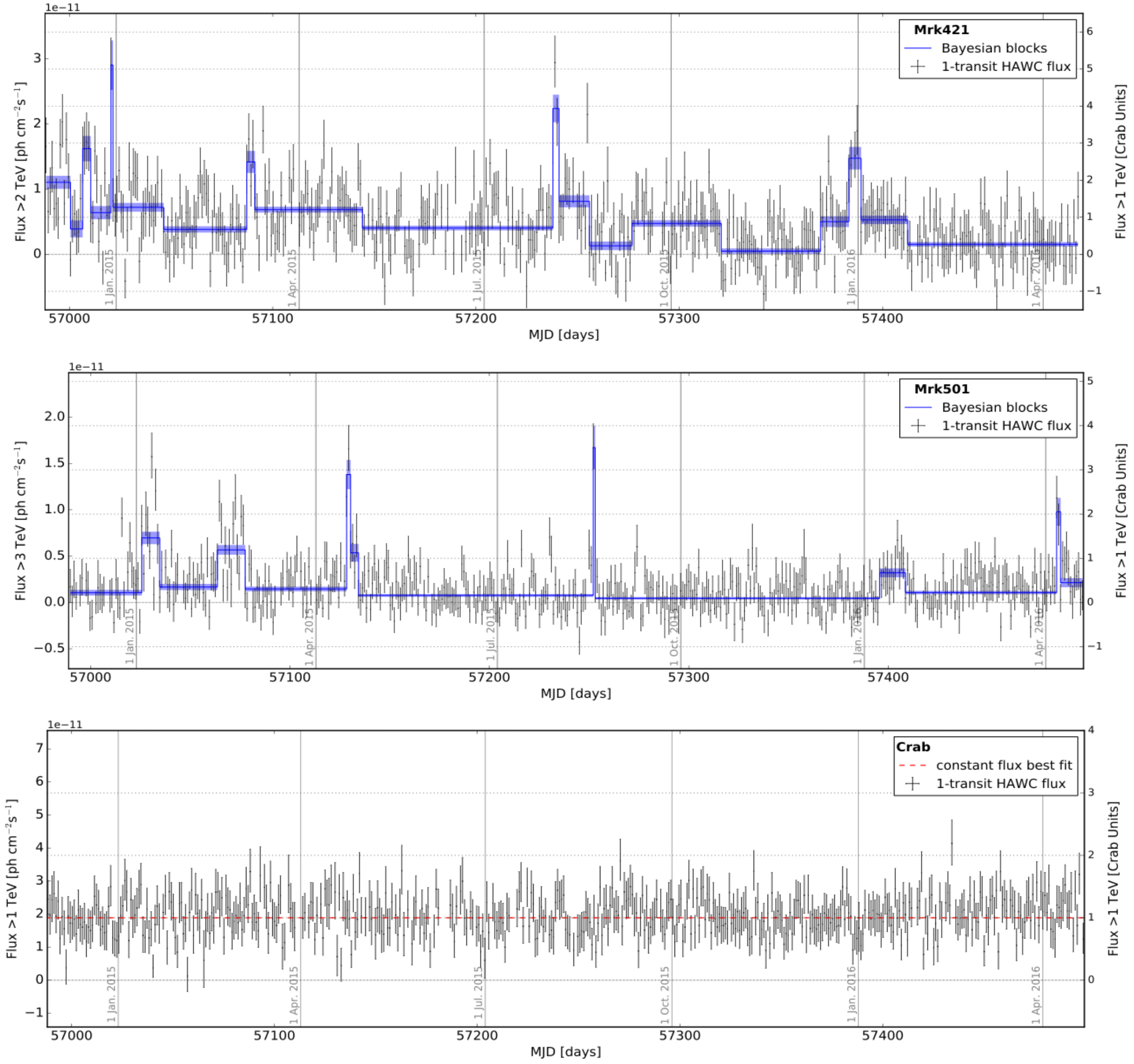
- Preliminary! Caveats: Reconstructed energy (bin migration), systematics studies ongoing.
  - Acceleration mechanisms: hadronic?
  - Correlation with neutrinos?
  - Prospects for testing Lorentz Invariance Violation.

Pushing to the highest energies (E_{reco} > 100 TeV)

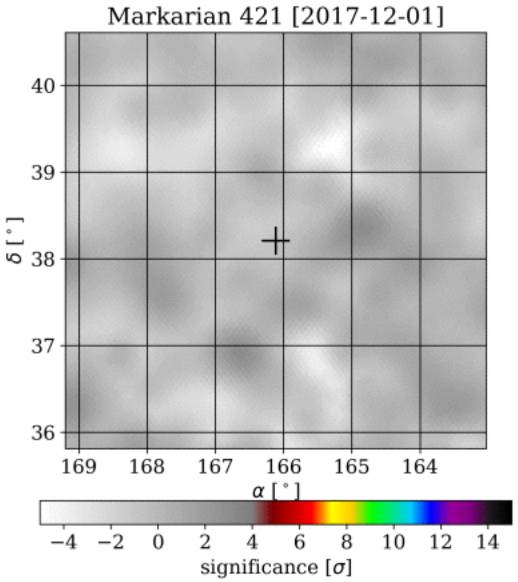


- Nine sources > 56 TeV, three sources > 100 TeV.
- PeVatron candidates?
- Lower limits on Lorentz Invariance Violation in the 10^{30} eV range (linear term)

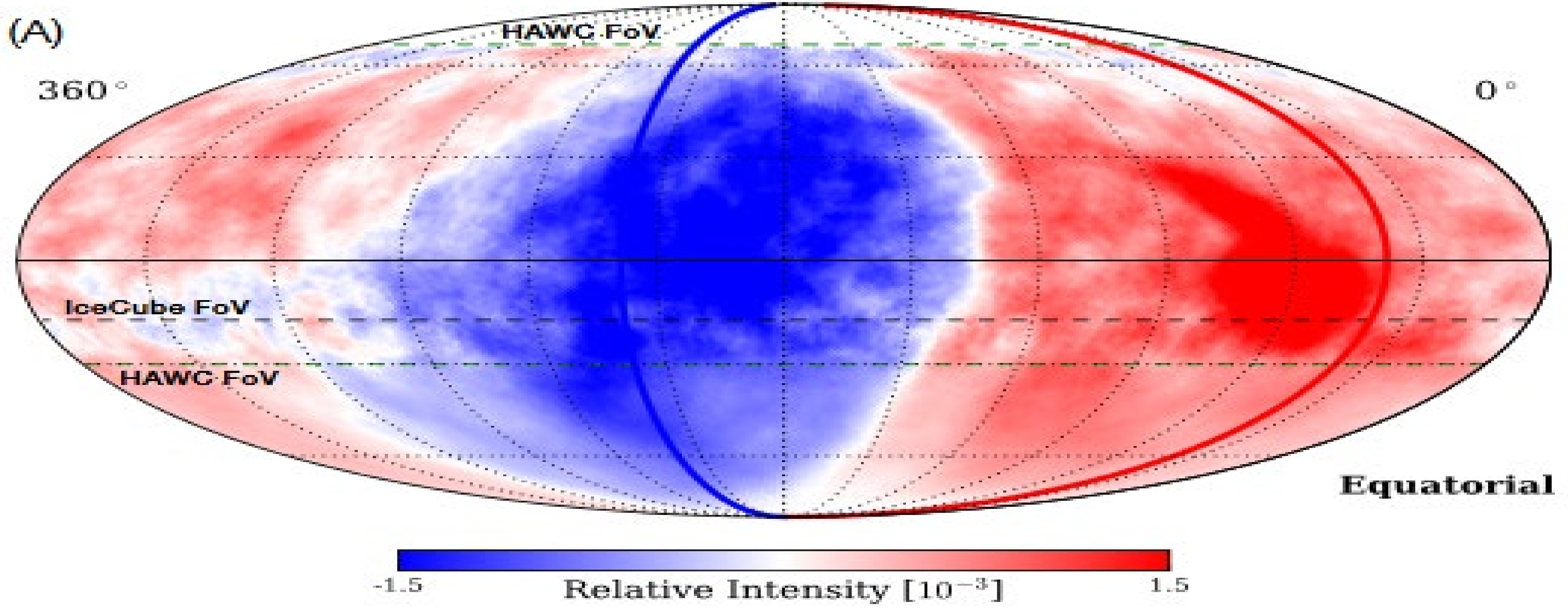
Monitoring of flaring sources MKN 421, MKN 501 and Crab



- Monitoring AGN flares:
  - ATel #8922, #9137, #9936, #9946, #11077, #11194.
  - Many notifications under MoU.
- Monitoring few hundreds sources on multiple time scales (seconds to days).



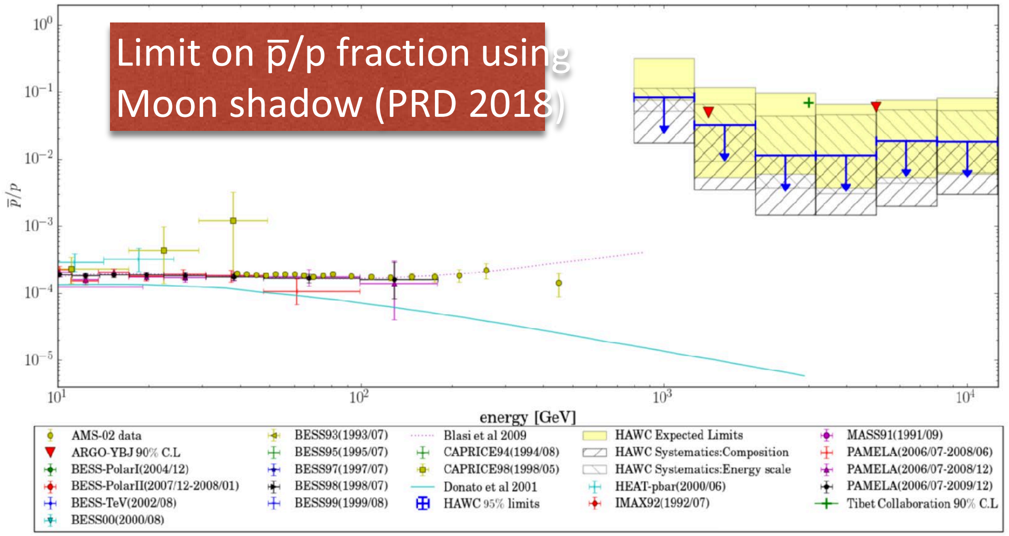
HAWC/IceCube Joint Fit to the Cosmic Ray Anisotropy



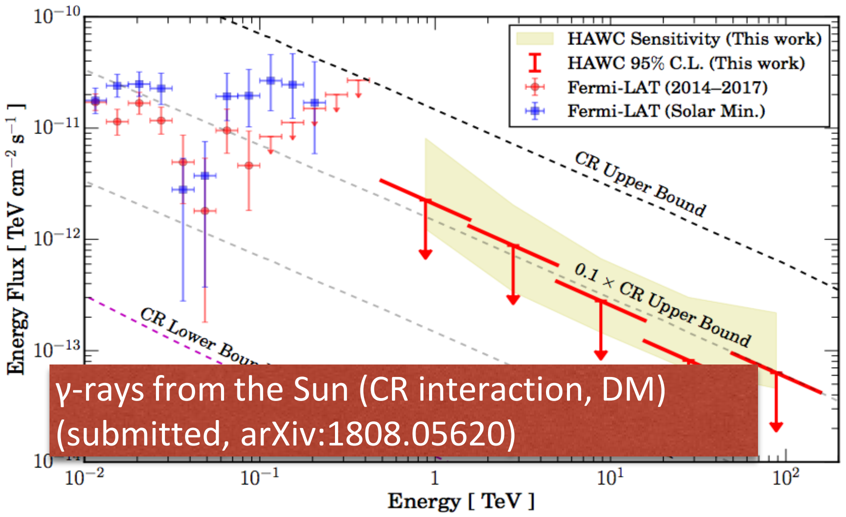
https://arxiv.org/pdf/1812.05682.pdf

Combined HAWC/Icecube Cosmic Ray Large Scale Anisotropy Measurement

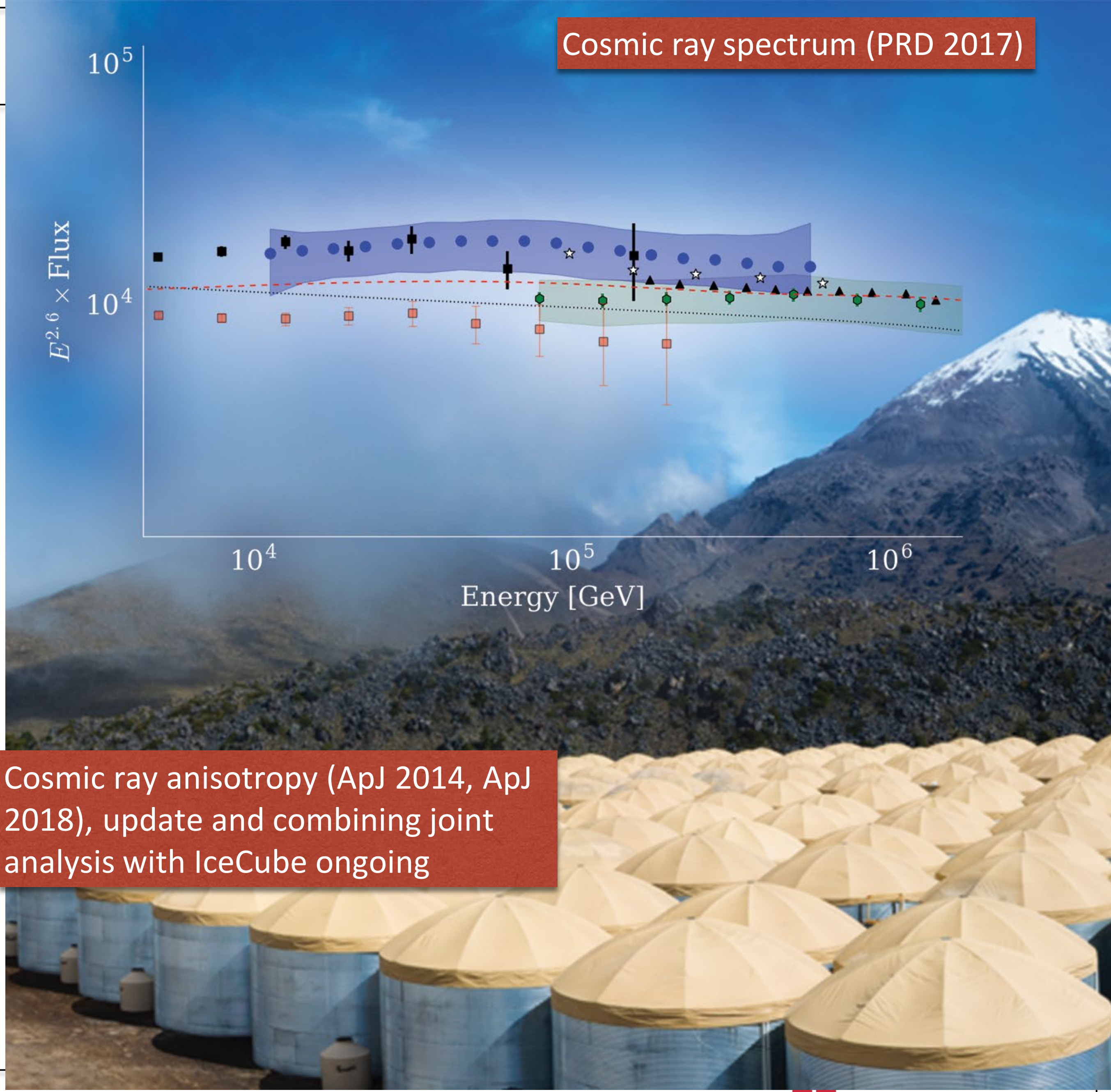
Results - Cosmic rays



Limit on p̄/p fraction using Moon shadow (PRD 2018)



γ-rays from the Sun (CR interaction, DM) (submitted, arXiv:1808.05620)



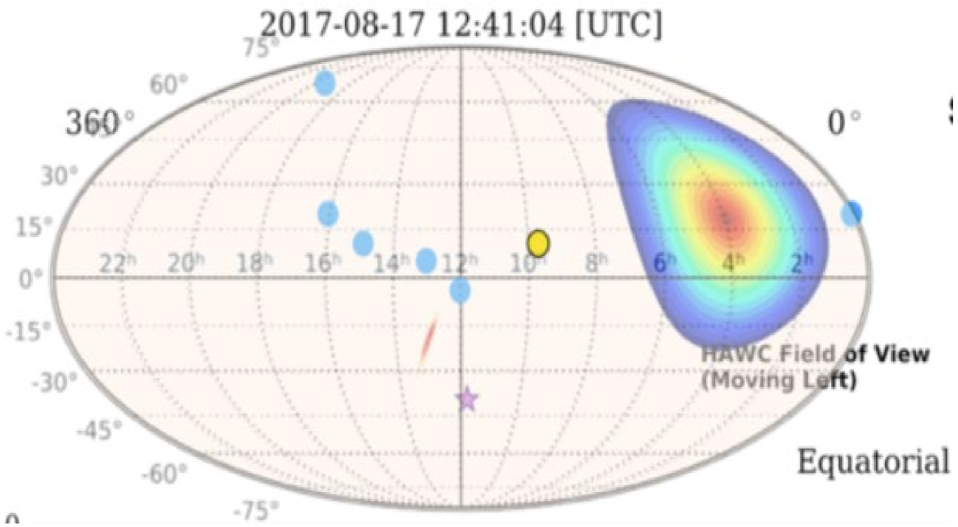
Cosmic ray spectrum (PRD 2017)

Cosmic ray anisotropy (ApJ 2014, ApJ 2018), update and combining joint analysis with IceCube ongoing

HAWC Multimessenger studies

Multi-messenger Observations of a Binary Neutron Star Merger

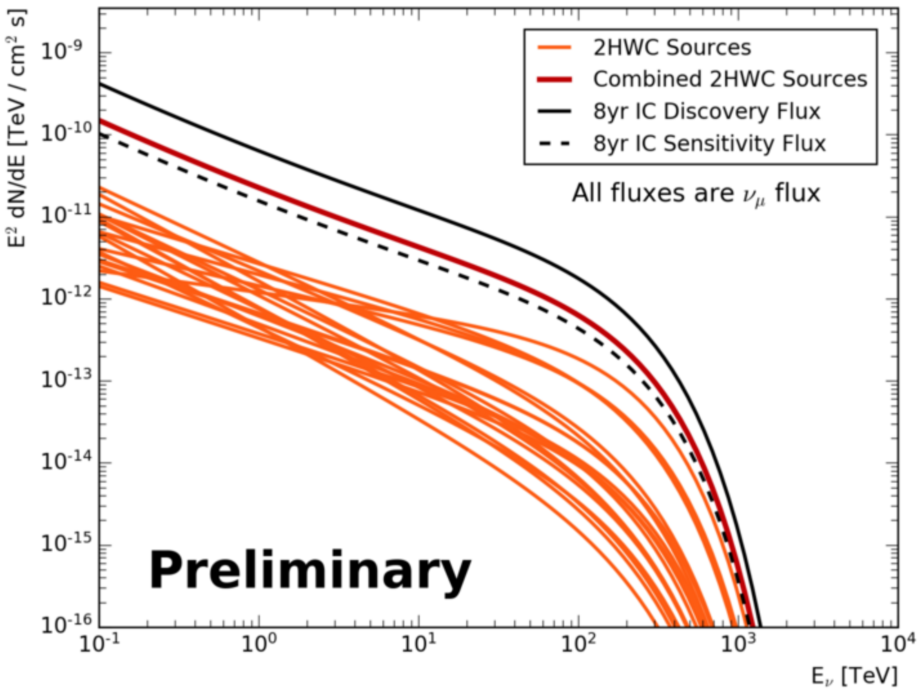
LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact



HAWC field of view at time of LIGO Virgo binary neutron star merger event GW170817. The star indicates the merger location indicated by the Fermi GBM data.

- A significant fraction of the astronomical community is an author on the LIGO Binary Neutron Star Merger paper…
- HAWC has a plethora of MOUs with many observatories to facilitate multi-wavelength (messenger) studies of astrophysical phenomenon.

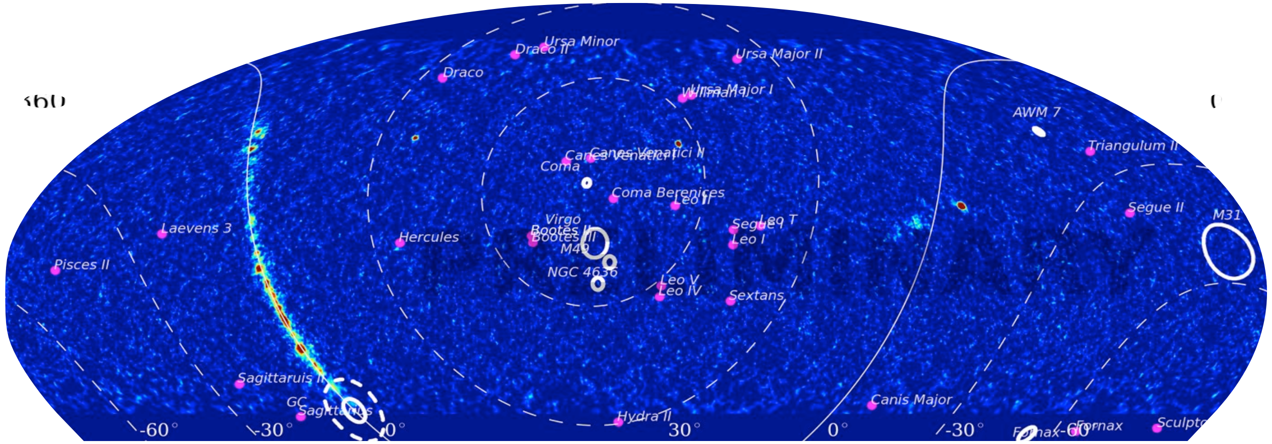
Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

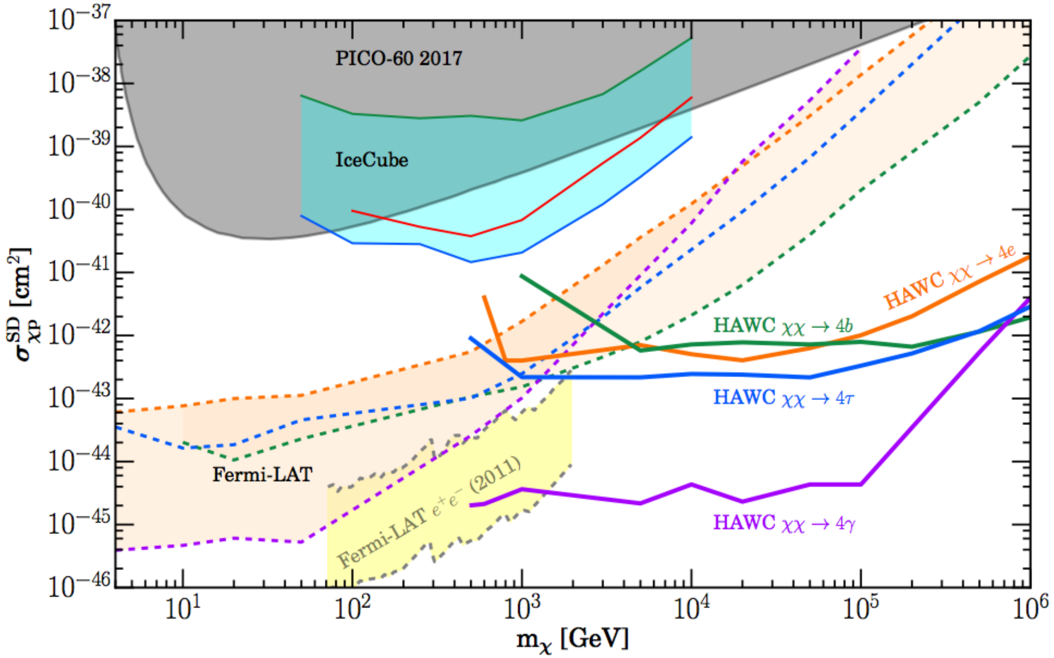


Stacked sensitivity (dashed black) and discovery (black) flux for diffuse northern track νμ sample IC86 2012-15. Also shown is the neutrino expectation based on the HAWC photon flux of sources in our list. **All fluxes in this plot are neutrino fluxes!**

- Large sky coverage → variety of targets to look for annihilation or decay signal:
  - Dwarf Spheroidal Galaxies (ApJ 2017)
  - Galactic Halo (JCAP 2018)
  - Andromeda Galaxy (JCAP 2018)
  - All sky search
  - Sun (submitted, arXiv:1808.05624)
  - Virgo cluster
  - Etc.

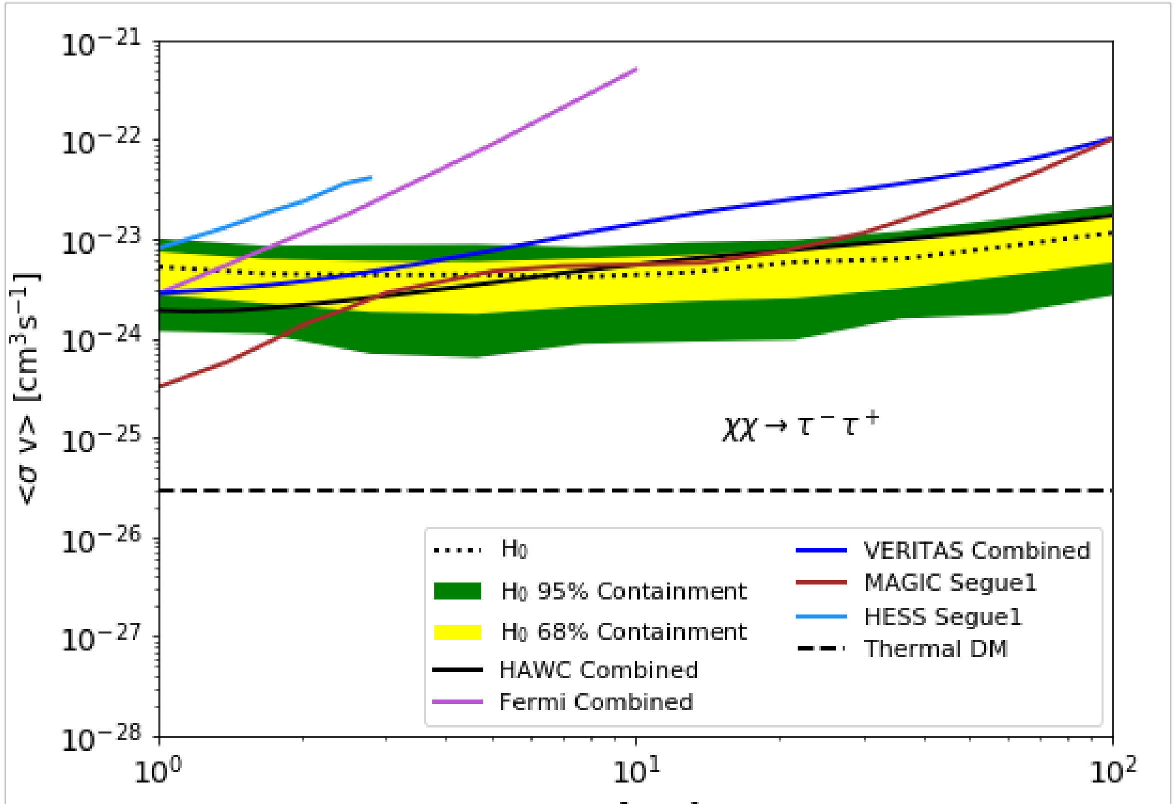
M31, 3° across





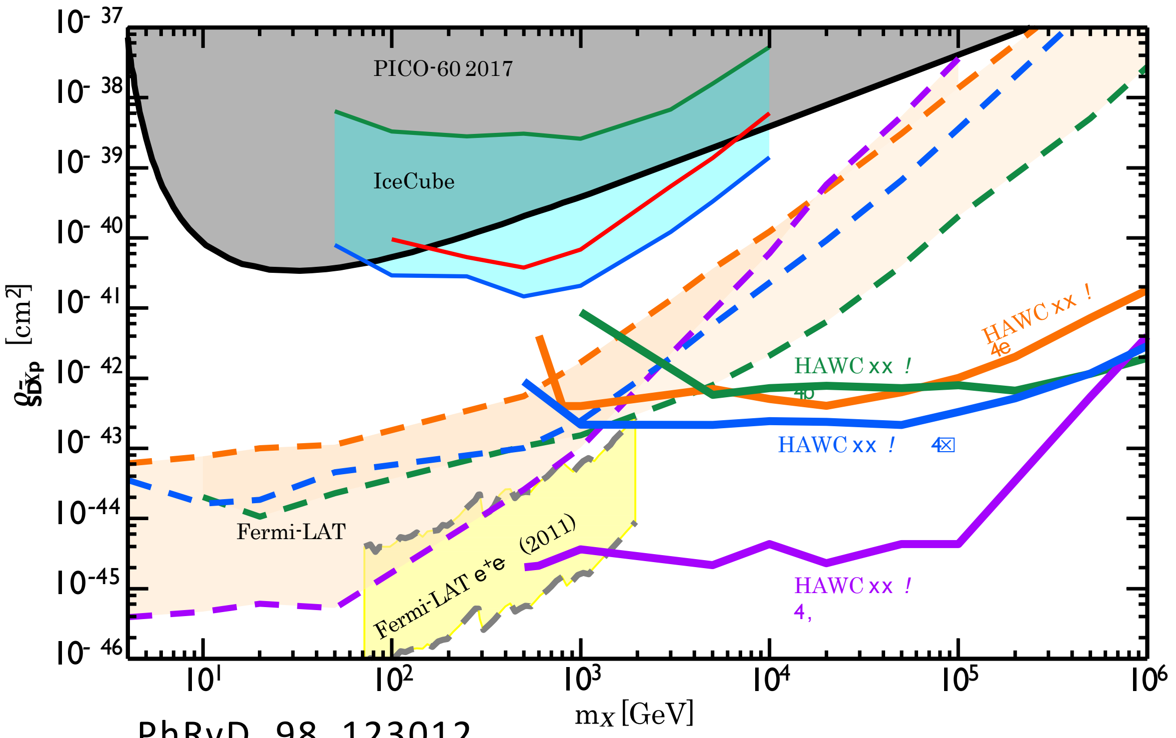
Dark Matter Searches

No gamma-rays from dwarf spheroidal galaxies (most sensitive limits > 30 TeV)



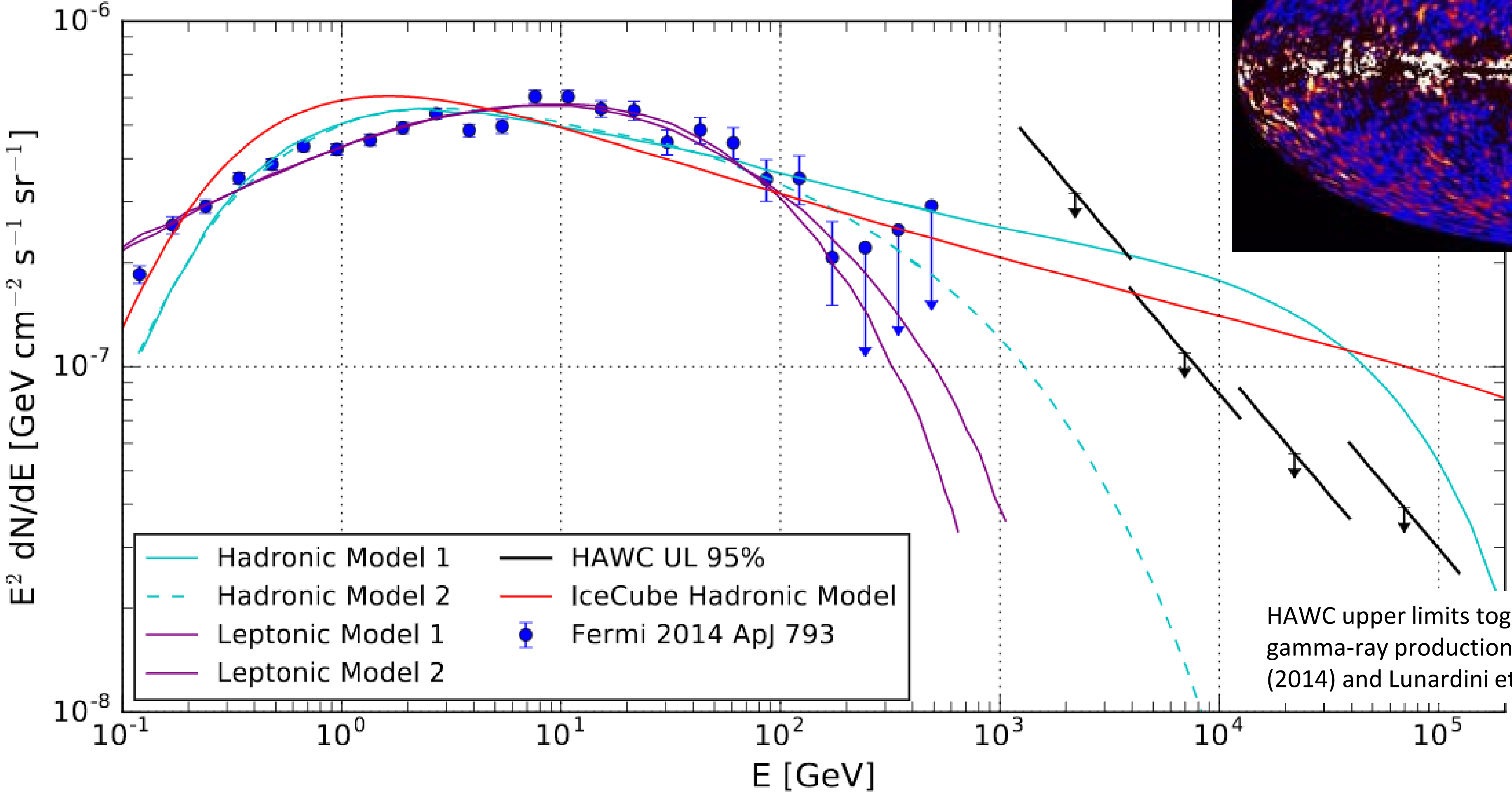
Astrophysical Journal, 154, 13

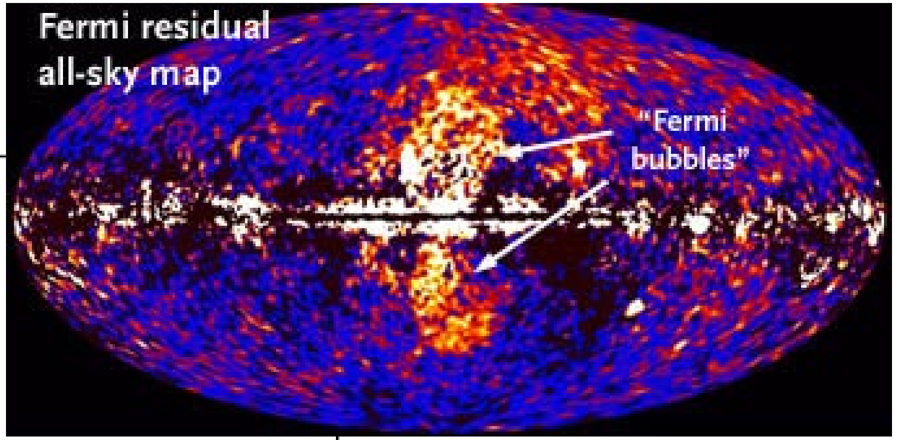
No gamma-rays from the Sun



PhRvD, 98, 123012

HAWC 90%CL upper limits on Fermi Bubbles

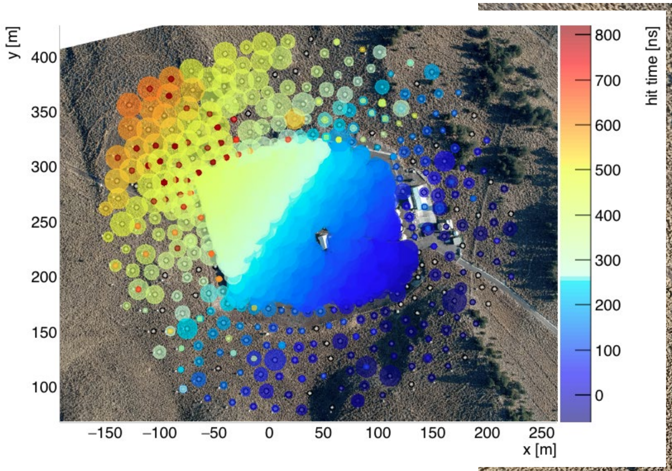




HAWC upper limits together with the Fermi data and gamma-ray production models from Ackermann et al. (2014) and Lunardini et al. (2015

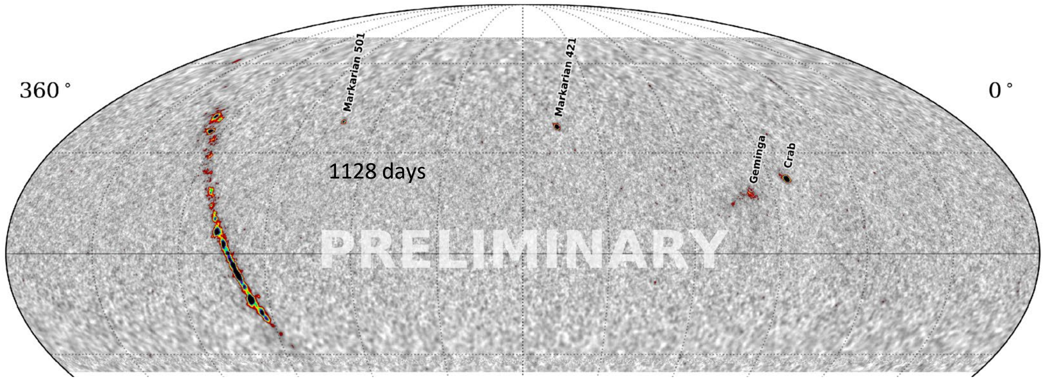
Outriggers Array: High Energy Extension

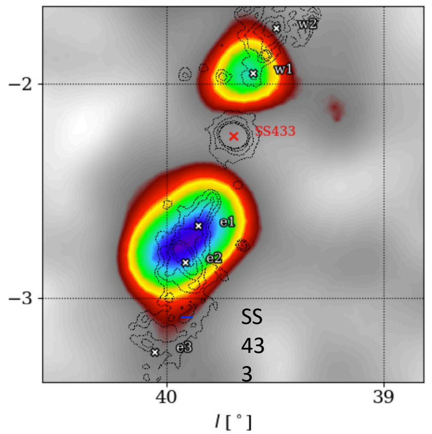
- 345 small tanks in addition to the 300 large tanks.
- Improve core localization for showers near the main array.
- x4 effective area at high energy.
- 100% taking data since last summer.

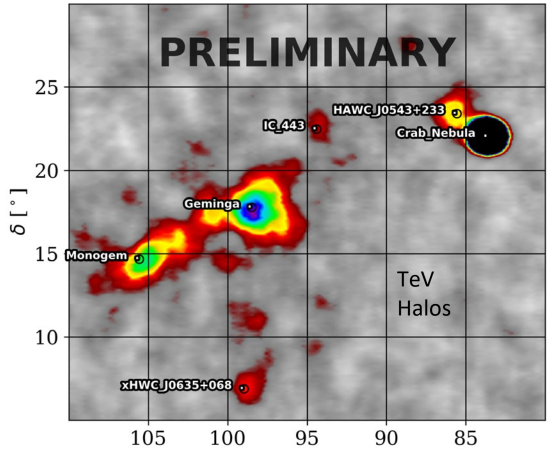


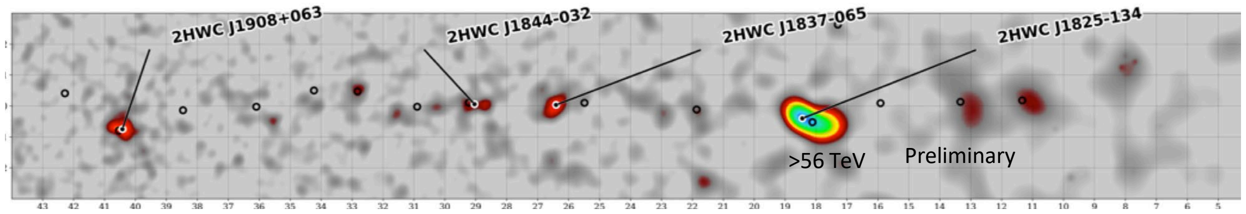
HAWC – Summary/Outlook

- **Recent Results**
  - New sky maps
    - 50 Sources - many previously unseen
    - New Source classes - TeV Halos, Micro-Quasar
  - High impact papers
    - Geminga -Science Nov. 2017
    - SS 433 - Nature - October 2018
  - Highest Energy Sky
  - Other exciting science
    - Dark Matter Limits
    - Fermi Bubbles
  - Cosmic Ray Anisotropy
- **Publications** (https://www.hawc-observatory.org/publications/)
- **Public Data** (https://data.hawc-observatory.org/)
- **Outlook**
  - Outrigger Array Expansion ➔ Higher Energies
  - Improved Reconstruction Techniques ➔ Lower Energies
  - Ongoing analyses in production (EBL,LIV,…)
  - Support Multi-messenger observations in conjunction with growing community of VHE observatories…
- **LHAASO ,CTA and others (SGSO?)** have many things to explore!!!!





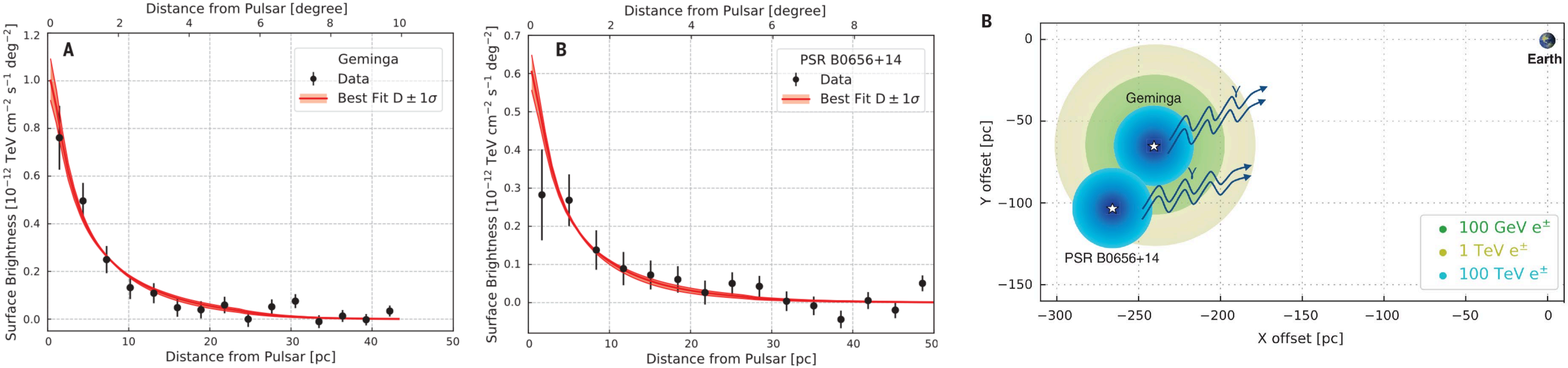




HAWC Construction

Backup slides

TeV halos: Geminga - Monogem (Science 2017)

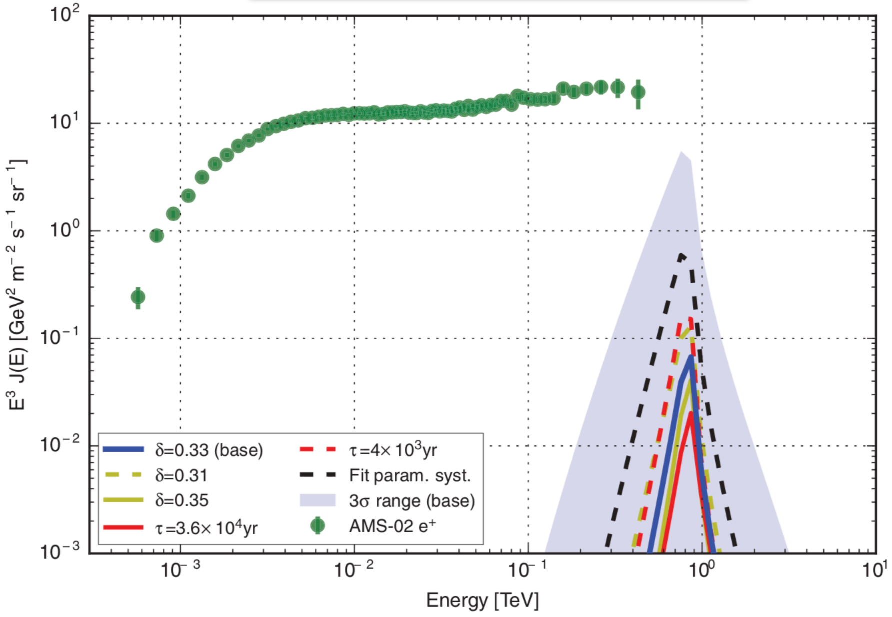


- **Very extended sources**, ~5° (10x the Moon).
- Orders of magnitude larger than x-ray PWN.
- **Yet ~10 times smaller than expected** from usual diffusion coefficient.
  - Direct measurement of the electron and positron diffusion around the source: $D_{100TeV} = 4.5 \pm 1.2 \times 10^{27}$ cm^2/s
  - D_{100TeV} ~100 times smaller the ISM diffusion value derived from B/C ratio.

TeV halos: Geminga - Monogem, interpretations

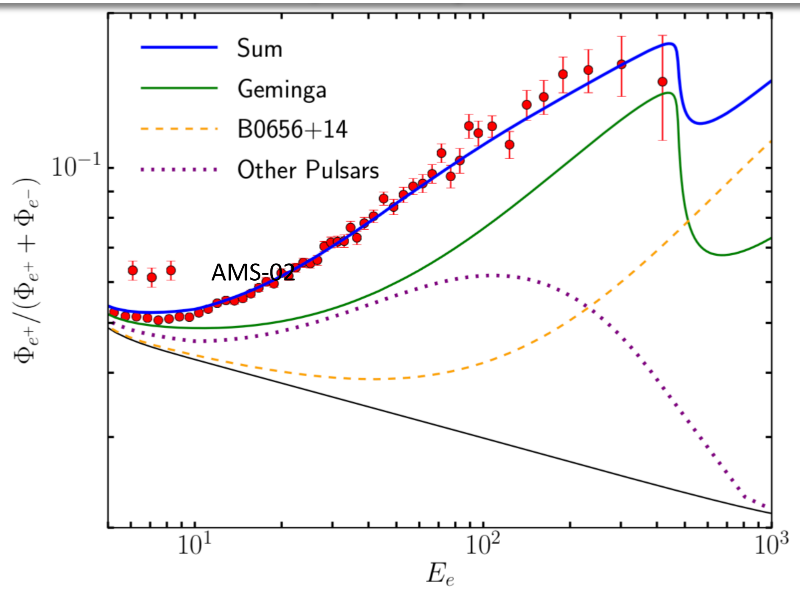
- HAWC Collaboration, Science (2017): Assuming uniform value diffusion constant, e^+/e^- cannot reach Earth, Geminga does not explain the positron excess.

Positron flux, HAWC

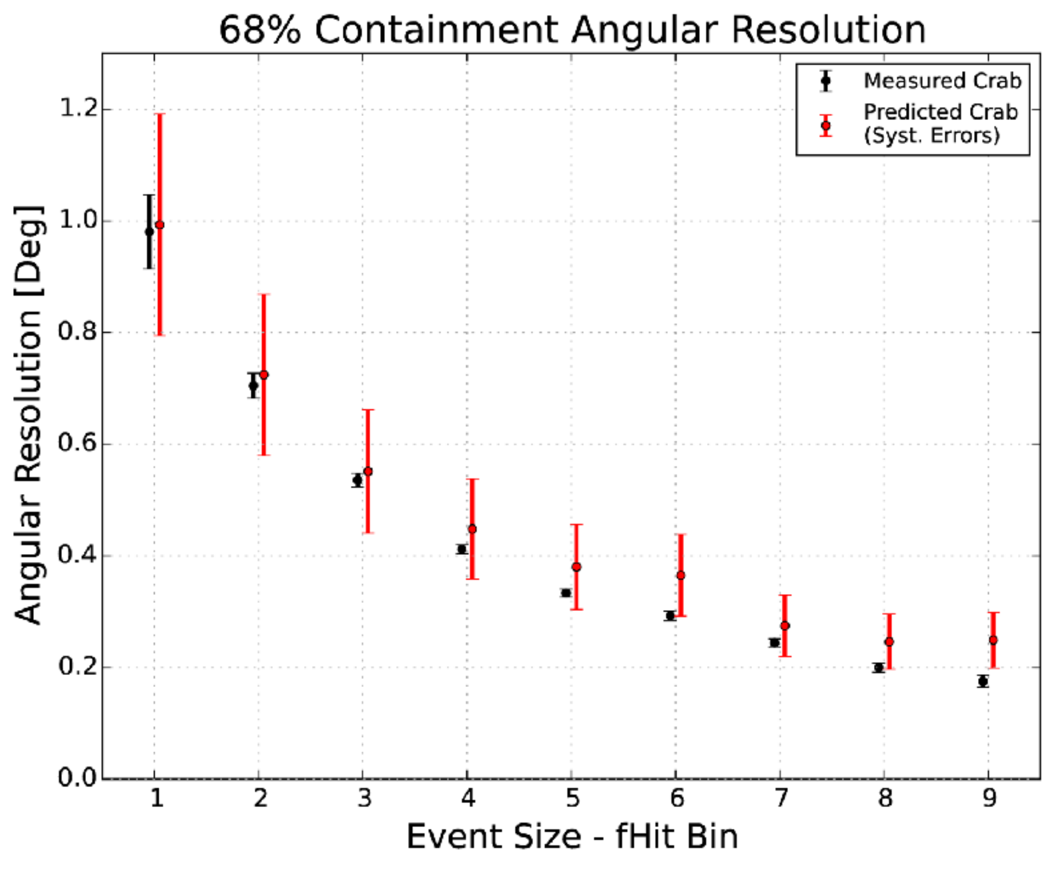


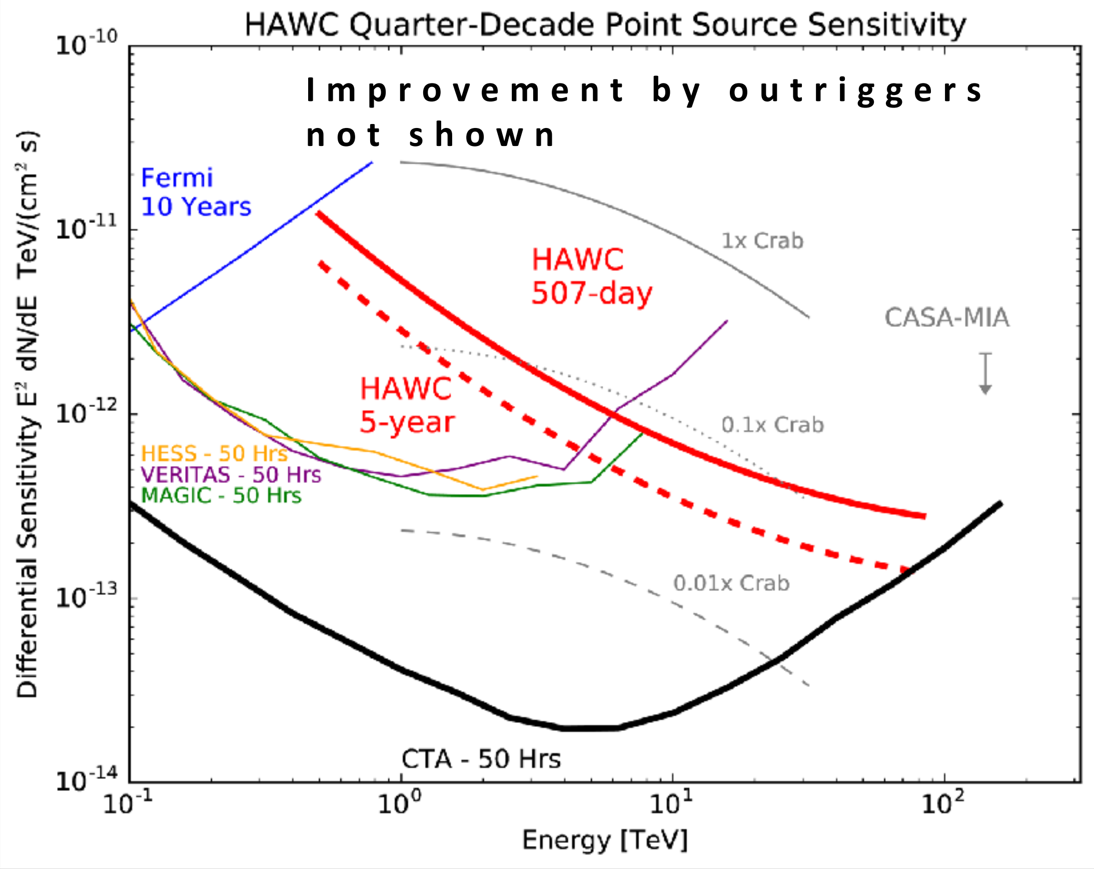
- Assuming variable diffusion constant, can possibly explain positron excess:
  - D. Hooper *et al.*, PRD 96, 103013 (2017)
  - K. Fang *et al.*, arXiv:1803.02640
  - S. Profumo *et al.*, arXiv:1803.09731

Positron fraction, Hooper *et al.*



H A W C Performance Characteristics





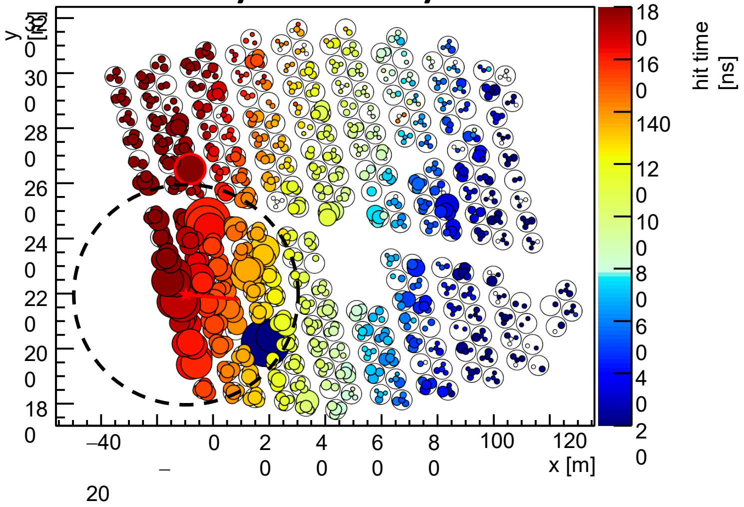
Abeysekara et al, The Astrophysical Journal, 843, 39

Shower Reconstruction - Photon / Hadron Separation

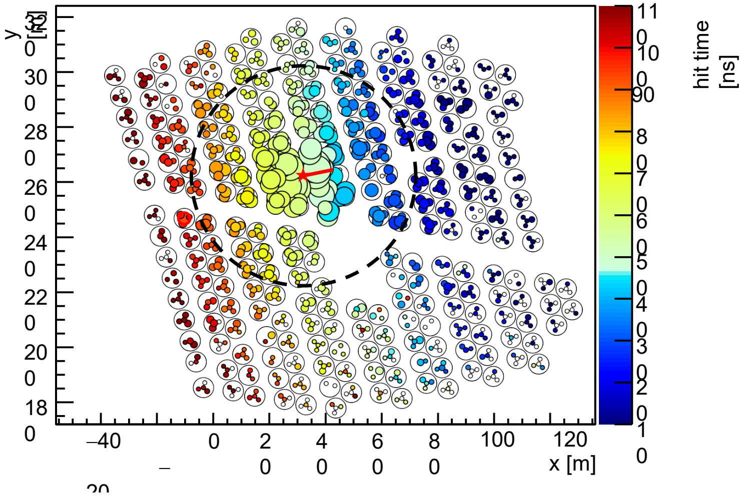
"Clumpiness"➔Hadron

"Smoothness"➔Photon

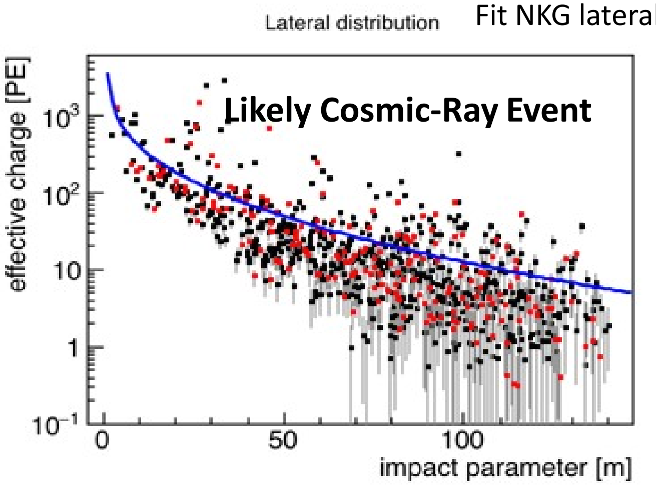
Likely Cosmic-Ray Event

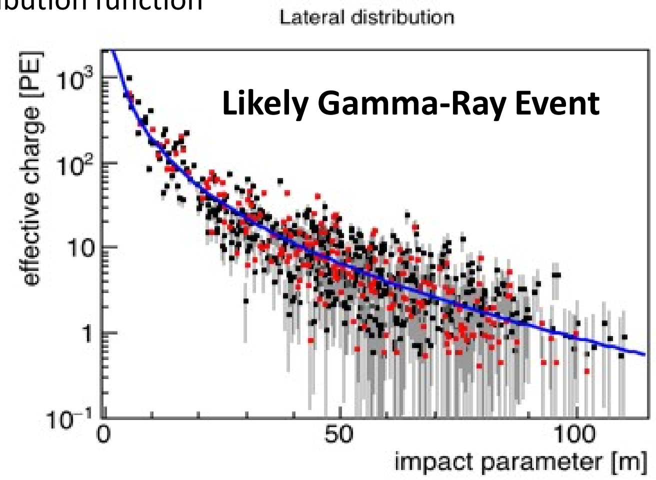


Likely Gamma-Ray Event



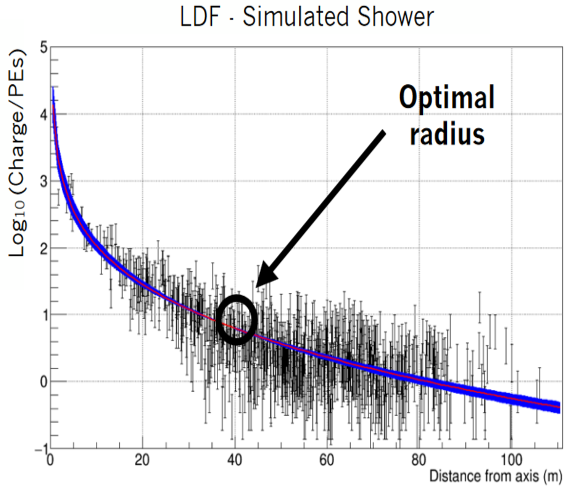
Fit NKG lateral –distribution function





Shower Reconstruction - Energy

Bin	N_{chan} Bin	E_{log} (GeV)	$\sigma_{E_{log}}$
1	39–59	2.5	0.46
2	60–69	2.6	0.47
3	70–90	2.7	0.44
4	91–147	2.9	0.40
5	148–231	3.0	0.35
6	232–349	3.2	0.32
7	350–495	3.5	0.28
8	496–655	3.7	0.24
9	656–789	3.8	0.21
10	790–1200	4.0	0.18
11	790–1200	4.2	0.18
12	790–1200	4.6	0.07
13	790–1200	5.1	0.13
14	790–1200	5.5	0.10



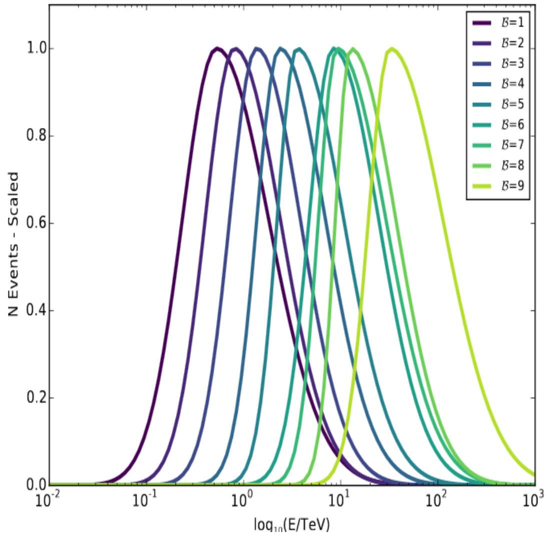
Energy Estimators

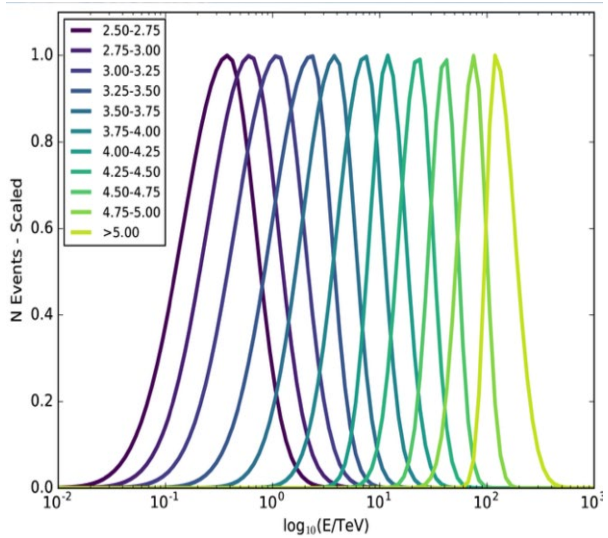
- Shower "size" bin $\mathcal{B}$ ($f_{hit}=N_{hit}/N_{tot}$)
- Ground Parameter
- Neural Net

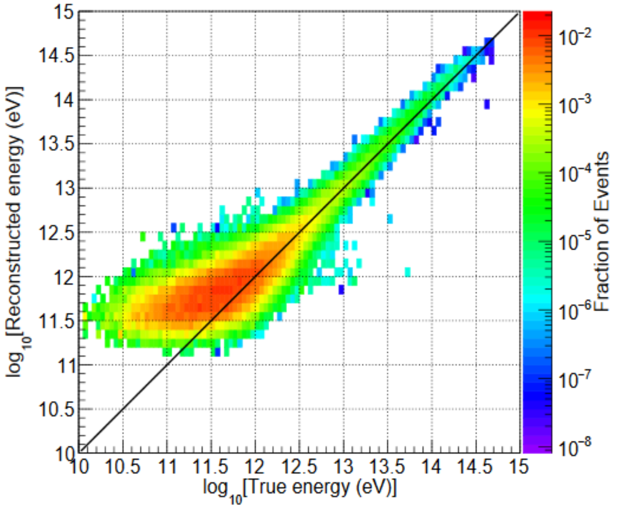
Shower "size"

Ground Parameter

Neural Net







Pushing to the Highest Energies: New Energy Reconstruction

- So far, use the number of PMT seeing light as energy proxy. 10 and 50 TeV events are not differentiated.
- **New energy estimators** (neural network, ground parameter) using signal amplitude, zenith angle, etc.
- Break degeneracy, increase energy dynamic range.
- **Best performance above 10 TeV**, far from threshold effects.