HAWC Dark Matter Searches

Pat Harding

Los Alamos National Laboratory

17 January 2019

The High Altitude Water Cherenkov Collaboration

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

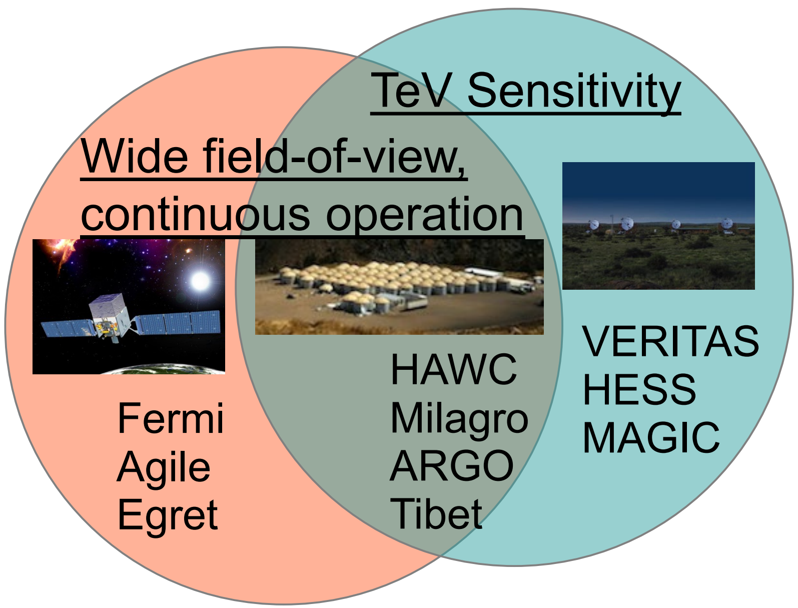
Mexico
Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE)
Universidad Nacional Autónoma de México (UNAM)
- Instituto de Física
- Instituto de Astronomía
- Instituto de Geofísica
- Instituto de Ciencias Nucleares

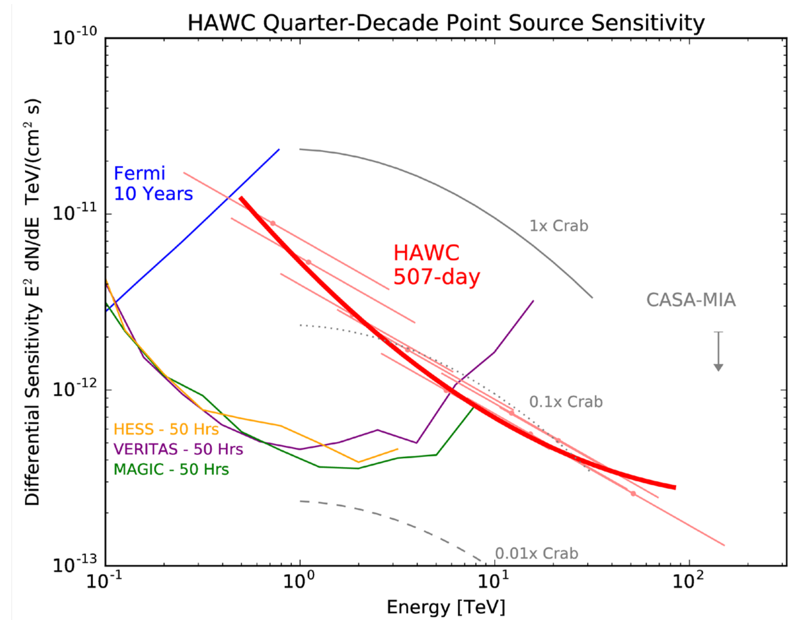
Universidad Politécnica de Pachuca
Benemérita Universidad Autónoma de Puebla
Universidad Autónoma de Chiapas
Universidad Autónoma del Estado de Hidalgo
Universidad de Guadalajara
Universidad Michoacana de San Nicolás de Hidalgo
Centro de Investigación y de Estudios Avanzados
Instituto Politécnico Nacional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

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

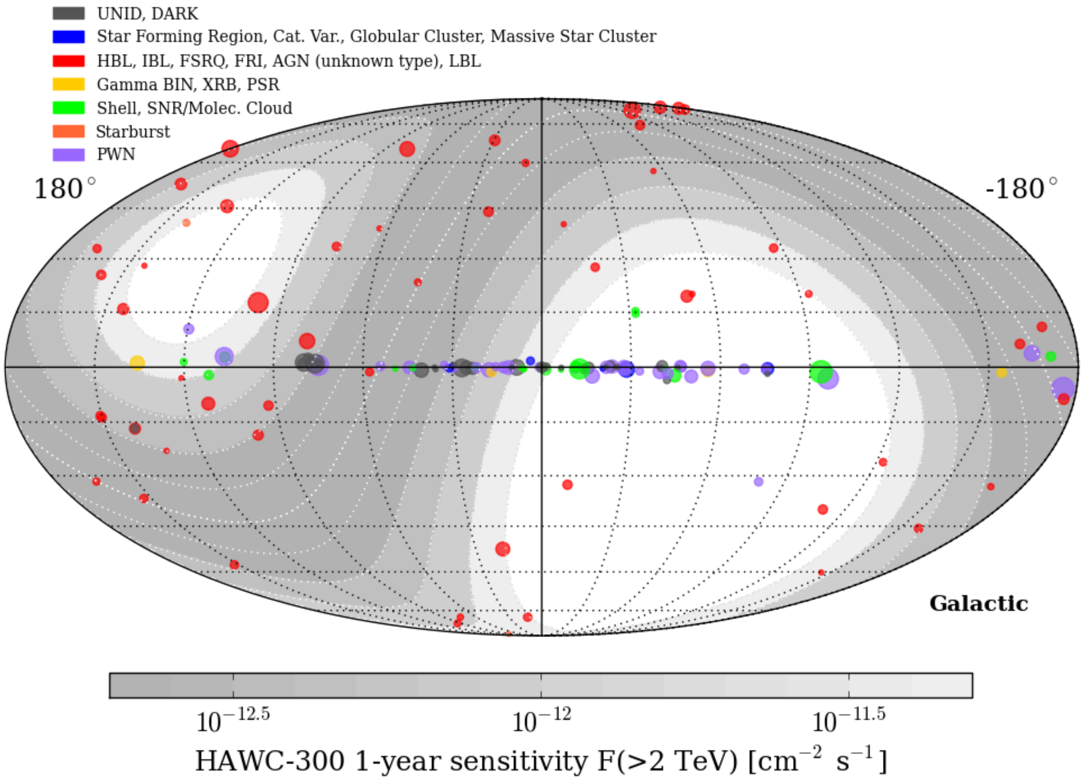
Complementarity of Gamma-Ray Detectors

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

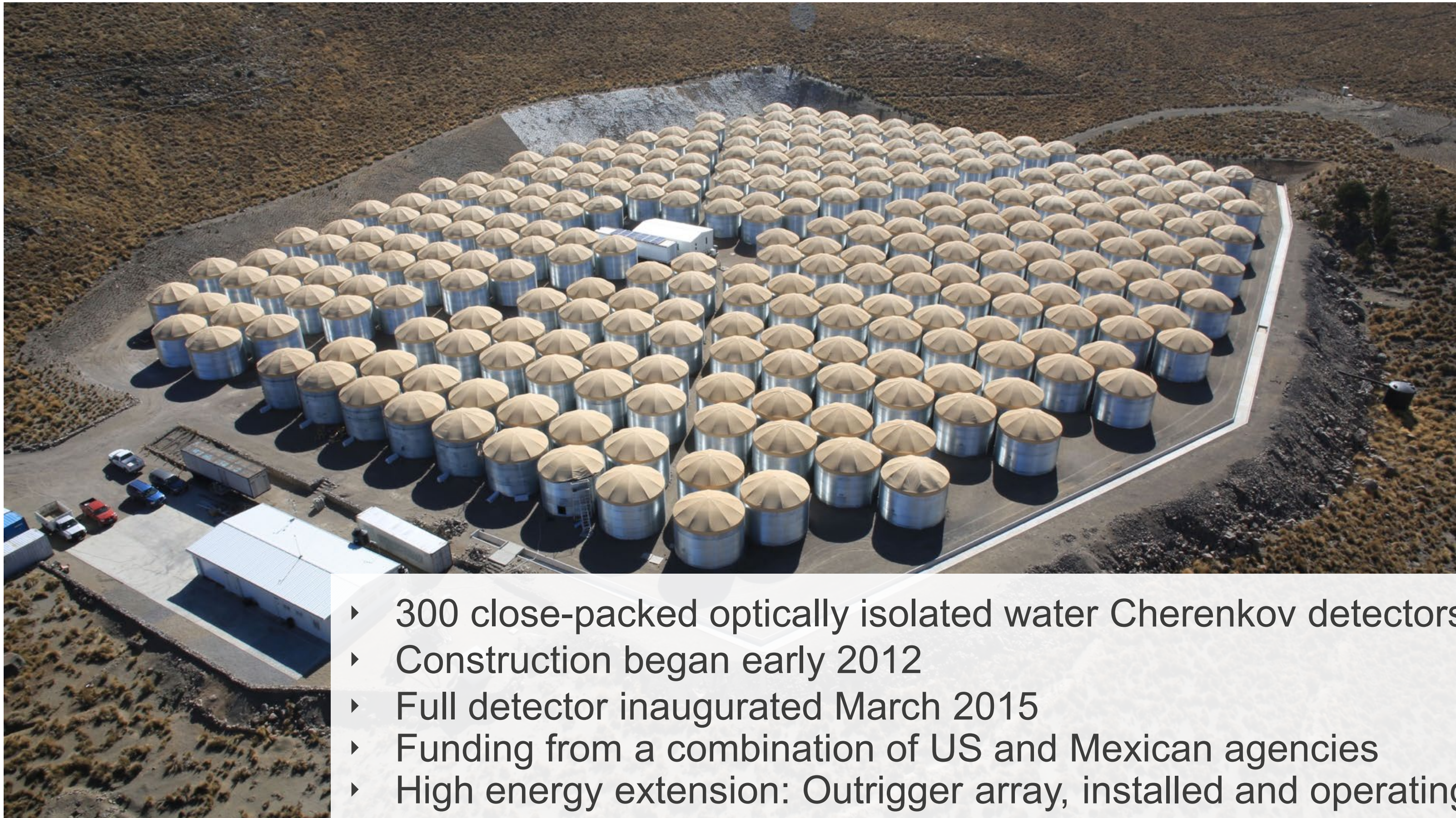




TeV Sky Observable By HAWC

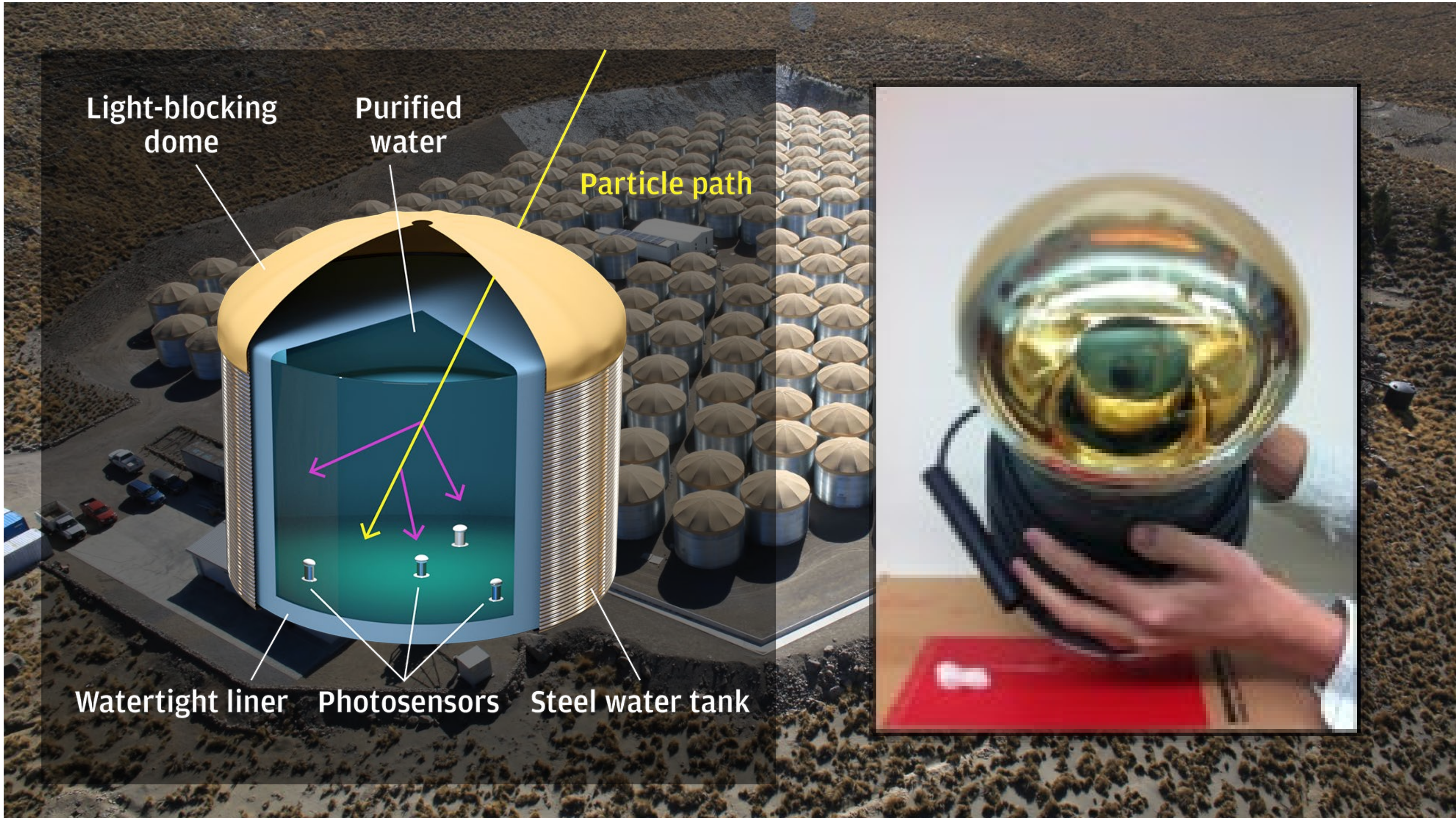


An Array of Water Cherenkov Detectors



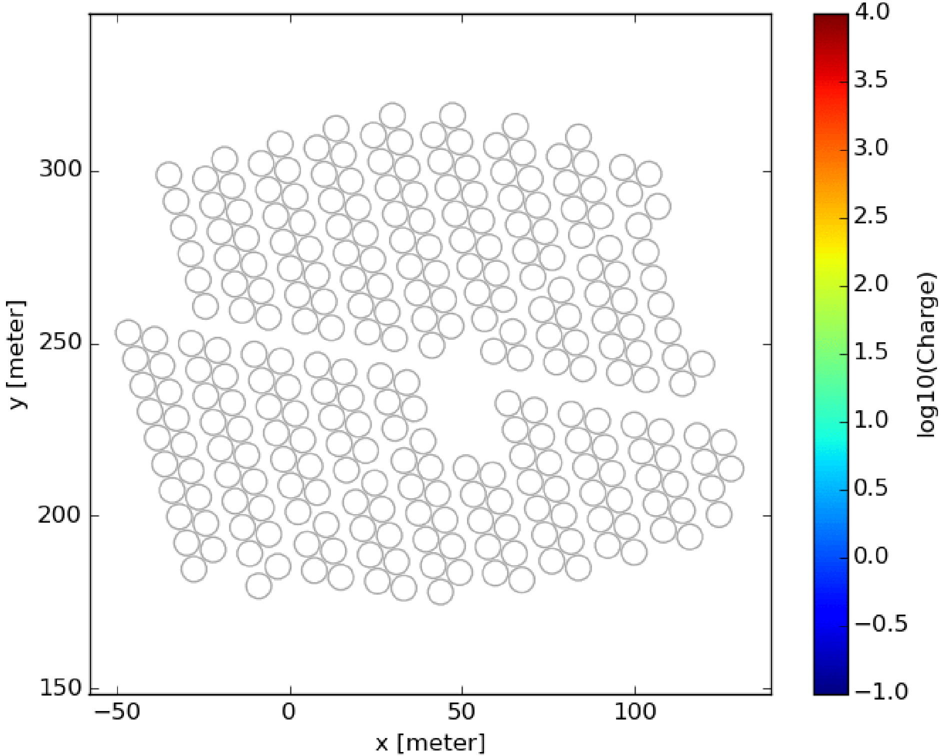
- 300 close-packed optically isolated water Cherenkov detectors
- Construction began early 2012
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, installed and operating

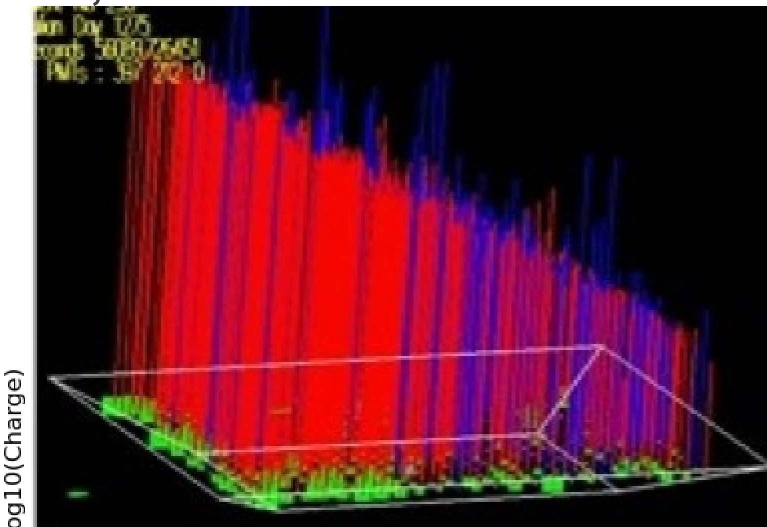
An Array of Water Cherenkov Detectors

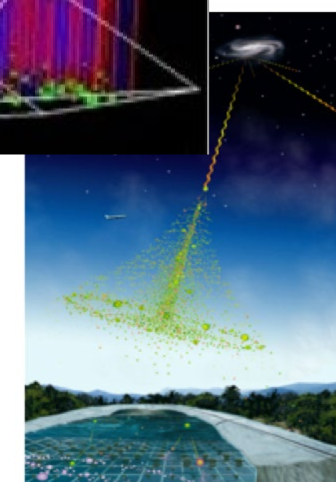


Direction

- **As the shower sweeps across the WCDs, we can reconstruct the direction it's sweeping from**

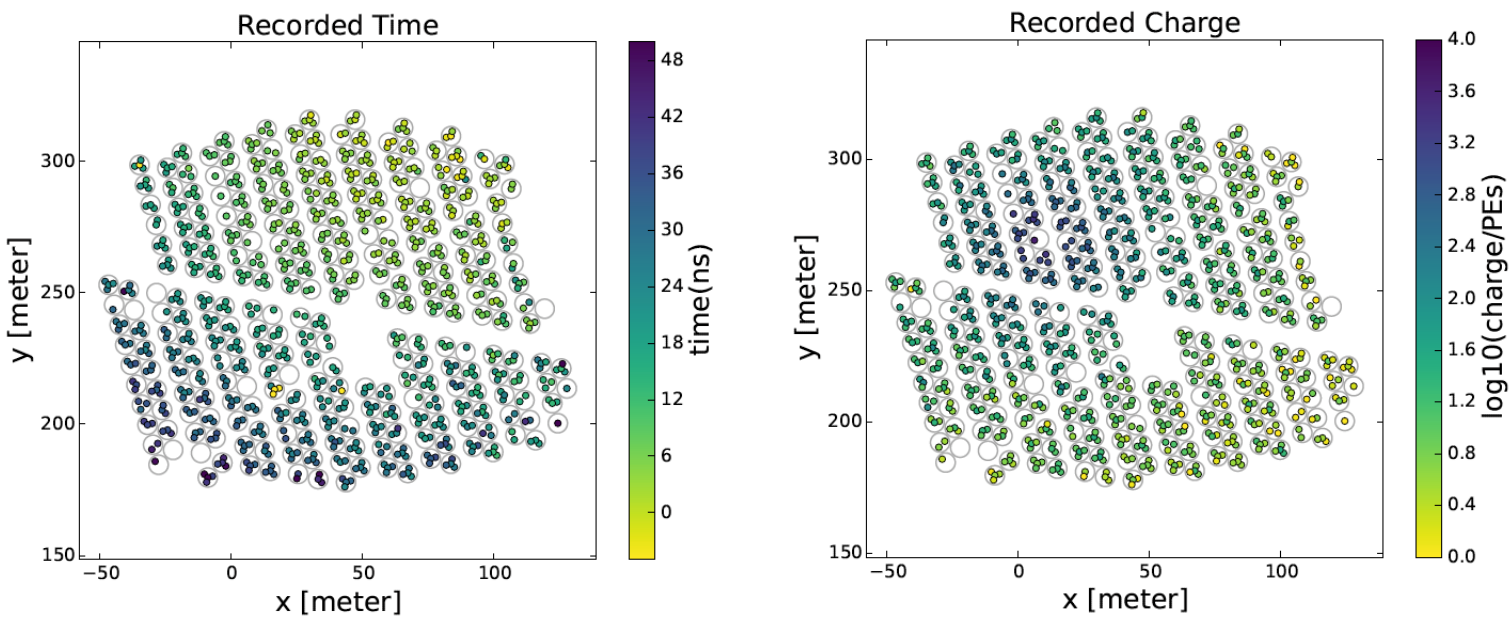






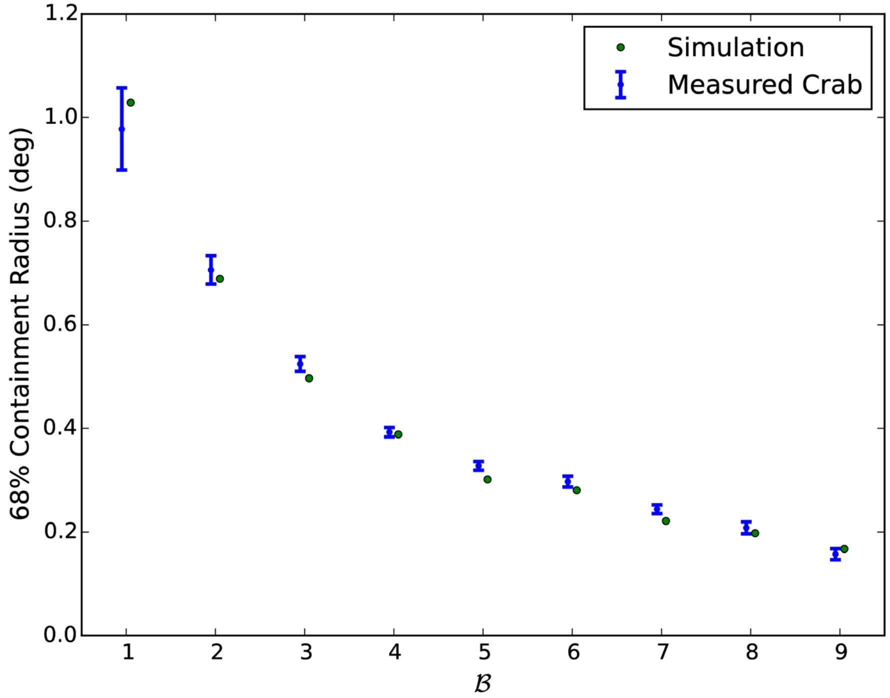
Energy

- The light level is each PMT and its Lateral Distribution Function (LDF) correlates with energy
- More PMTs hit, more light in PMTs → higher energy

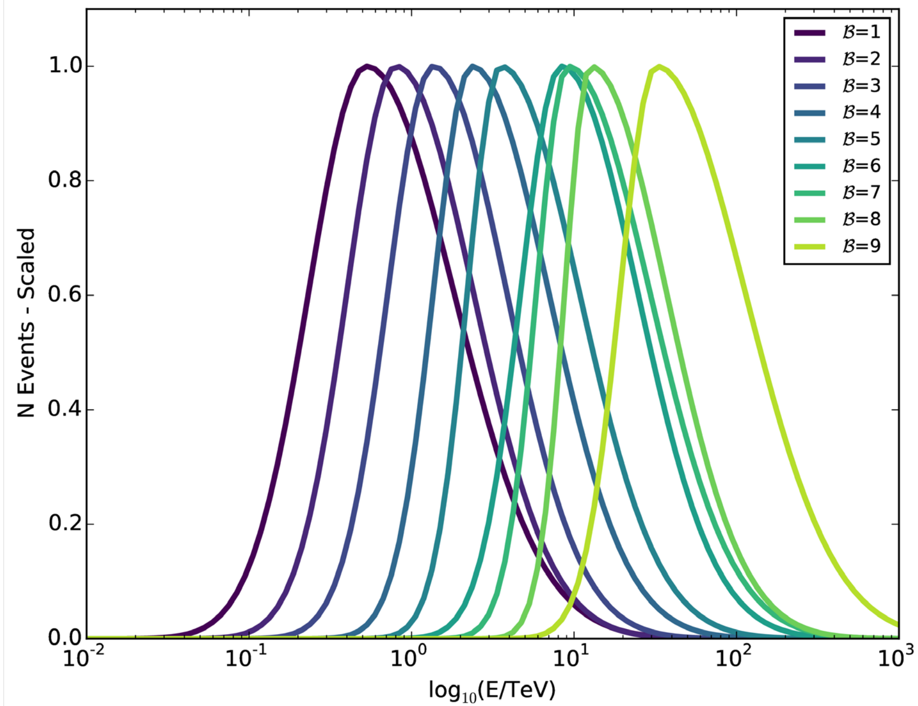


HAWC Resolution

Angular Resolution Tuned on Crab Nebula

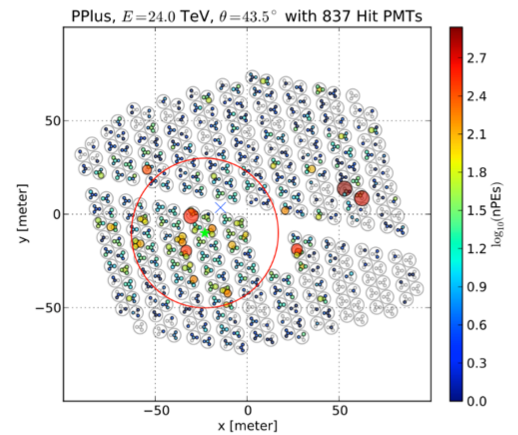


Energy Resolution from Monte Carlo Simulations

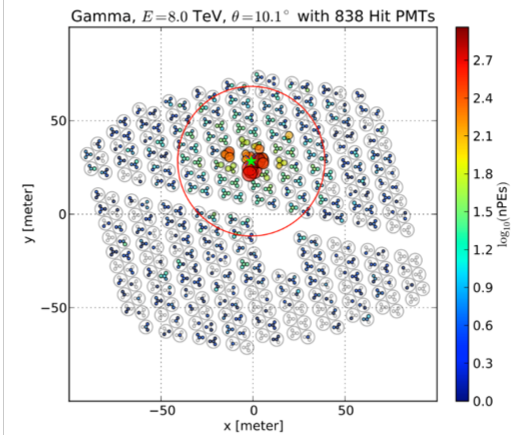


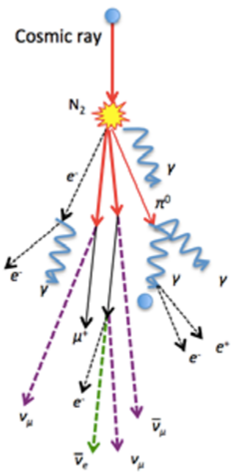
Particle Type

Proton

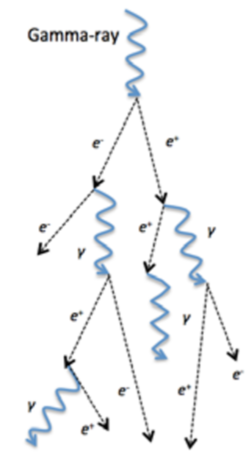


Gamma





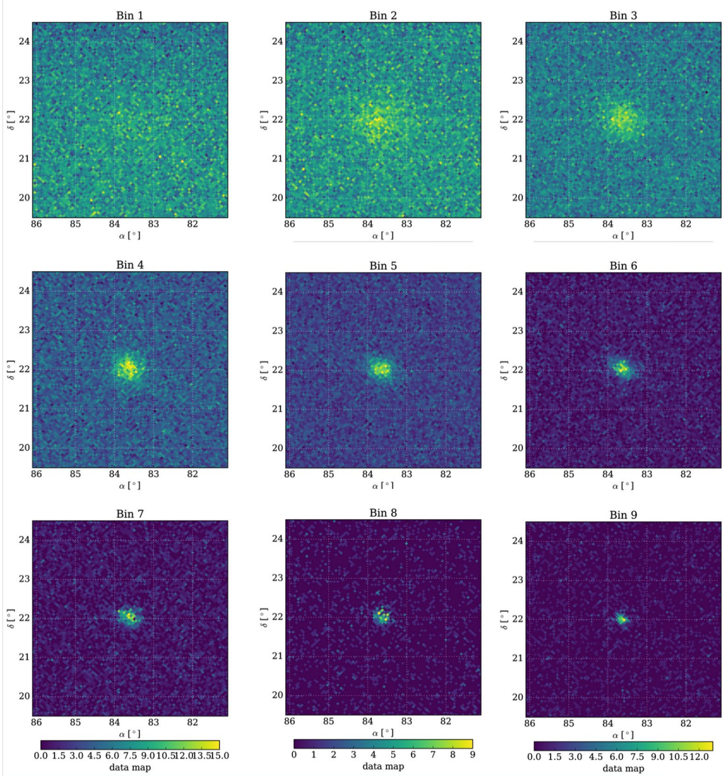
- Hadron-induced showers produce subshowers with a lot of transverse momentum and muons, so their distributions tend to clump in several regions on the array
- Gamma-ray showers produce a smoother, more peaked distribution on the array
- Looking for the sub-showers on the array and the larger spread of the hadronic showers, we can distinguish gammas from hadrons



Source Characterization – Forward Folding

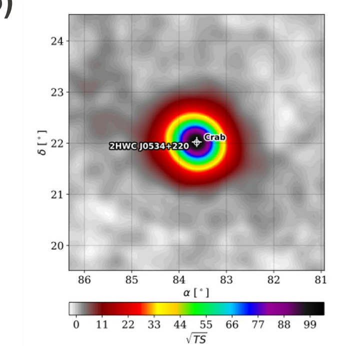
- Events sorted by "size" in n bins (with characteristic Point Spread Function, S/N ratio, energy), make n maps
- Likelihood framework uses n maps to test the presence of sources and characterize them
- Reference: Crab paper, ApJ 843 (2017), 39 (here: 507 days of data)
- Use HAWC LiFF likelihood code or open 3ML likelihood code (threeml.readthedocs.io)

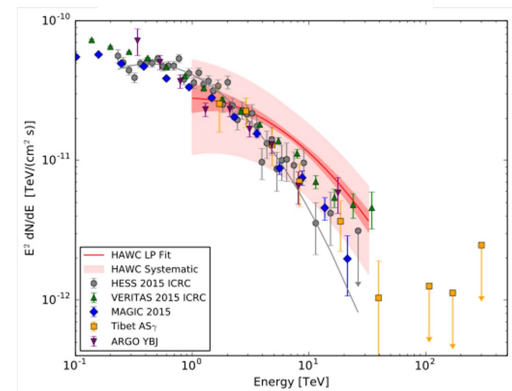
Crab Nebula



Detector response
Source model

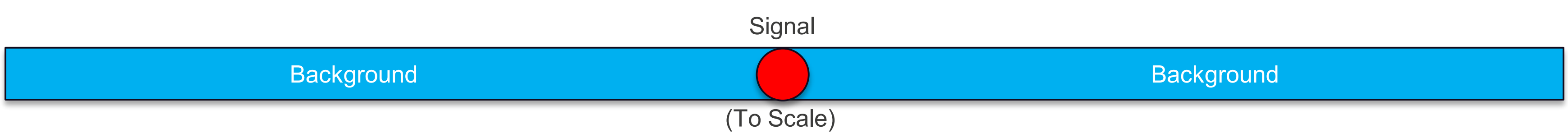
Likelihood framework





Background Estimation – Direct Integration

- **HAWC sensitivity is primarily dependent on the source declination, with smaller exposure corrections in RA**
- **Instead of On-Off in a small field-of-view, HAWC uses “Direct Integration” to calculate its backgrounds (post-cuts) (Atkins+ ApJ 595, 2003)**
- **This gets the background around a source by looking a the same HAWC-local coordinates over 2 hours of RA from the source at the same declination and averaging the counts in that region**
  - Large Background region enables search for highly extended source, like DM

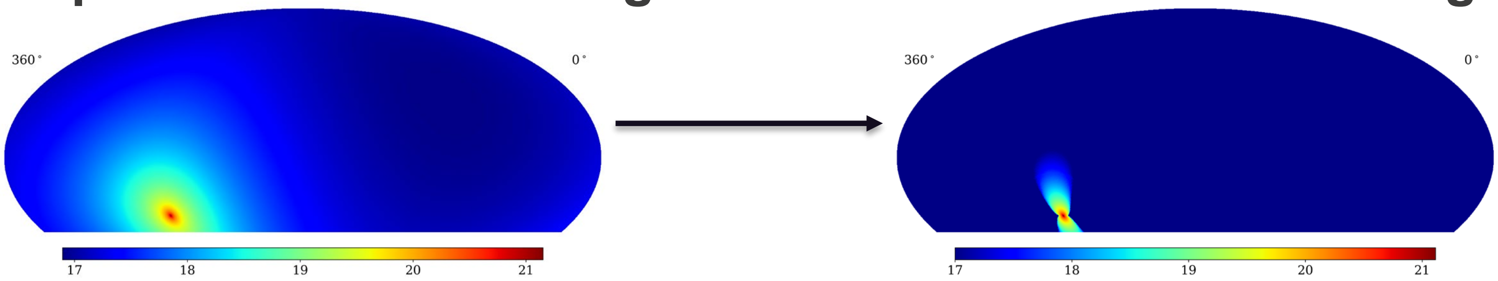


Background Caveat – Signal in the Background

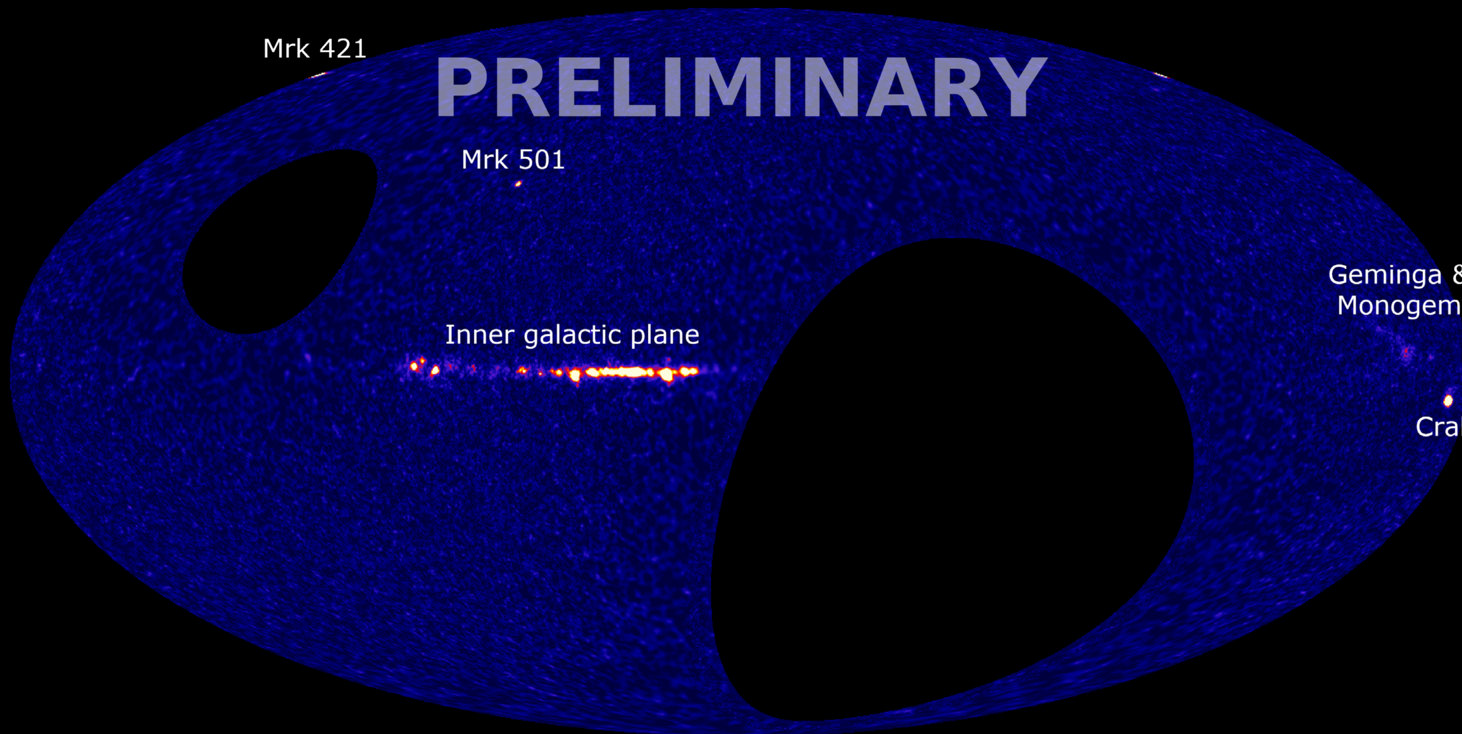
- *All* background estimations from data have a subtraction issue if there is signal in the region of background estimation
- For small background regions near extended objects, this is particularly an issue. A lesser issue for large-angle direct integration

1. Masking. Restrict your background region to be far from your contaminating signal. Works if signal is not too extended
2. Use a larger background region that extends beyond any mask
3. Account for signal loss in your background

Example: 2-hour Direct Integration on Galactic Center DM signal



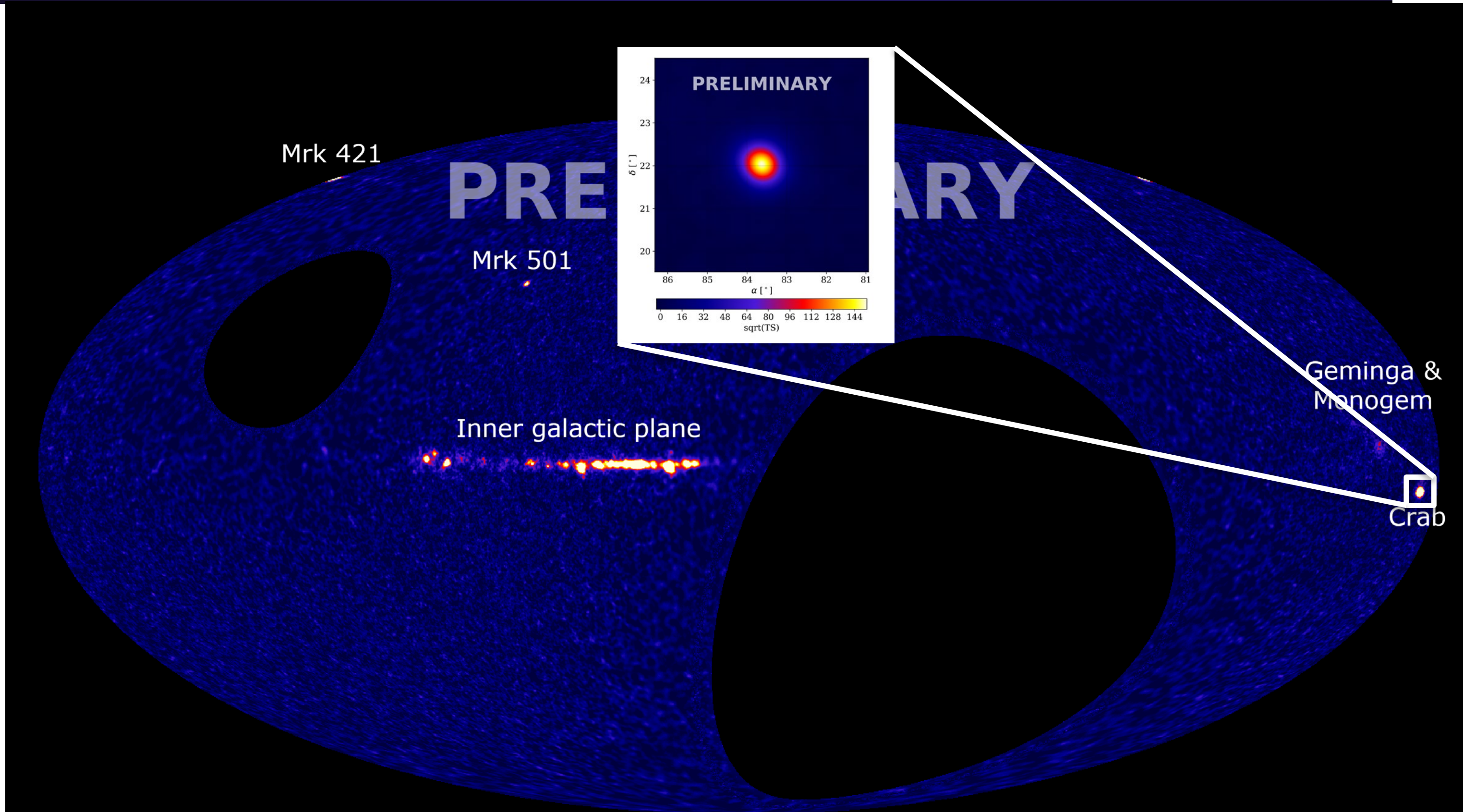
HAWC 3-year Skymap – 1017 days from 11/14 – 12/17



2HWC catalog (ApJ 2017) was 507 days, with 39 sources of which 10 were new.

14

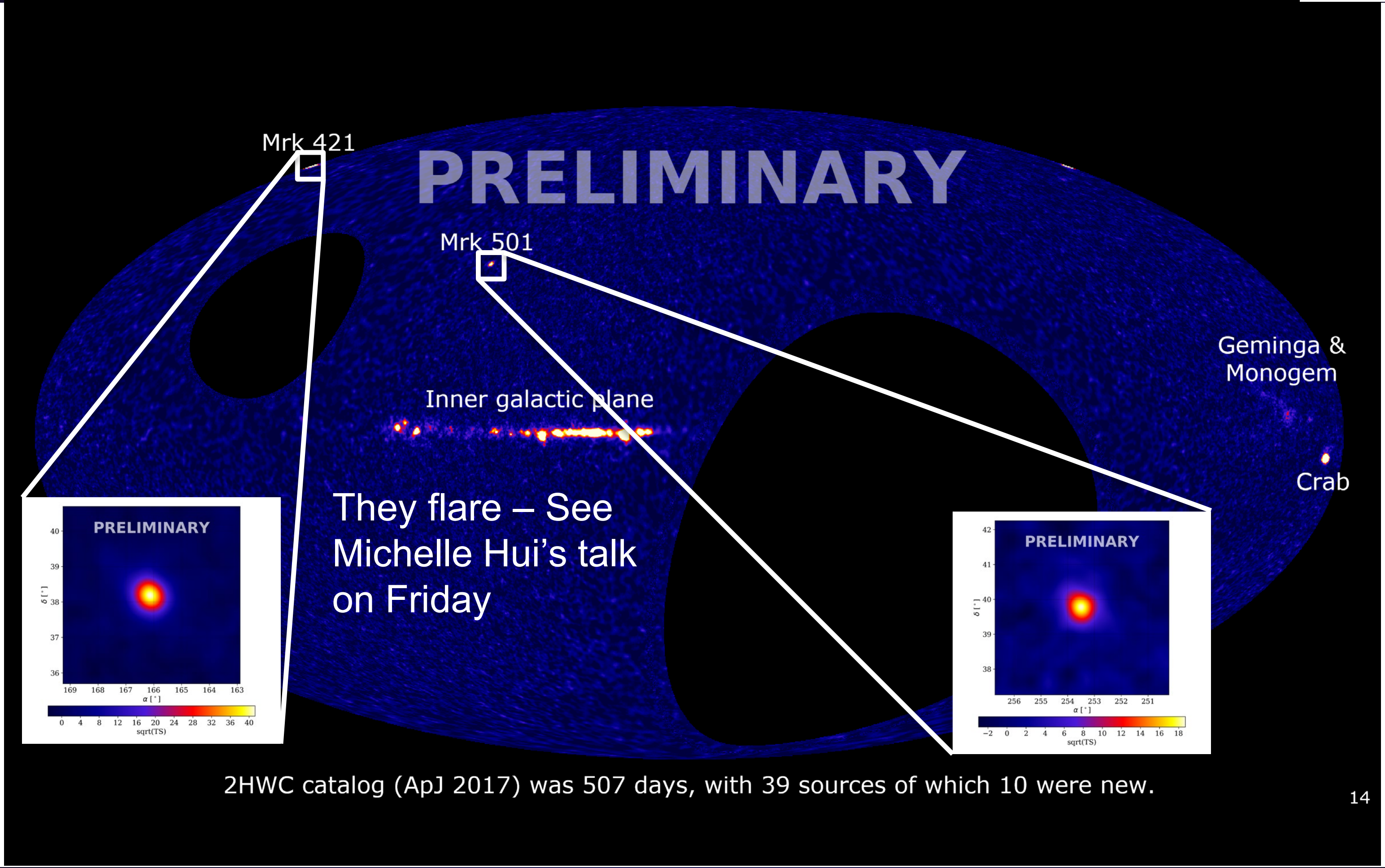
HAWC 3-year Skymap – 1017 days from 11/14 – 12/17



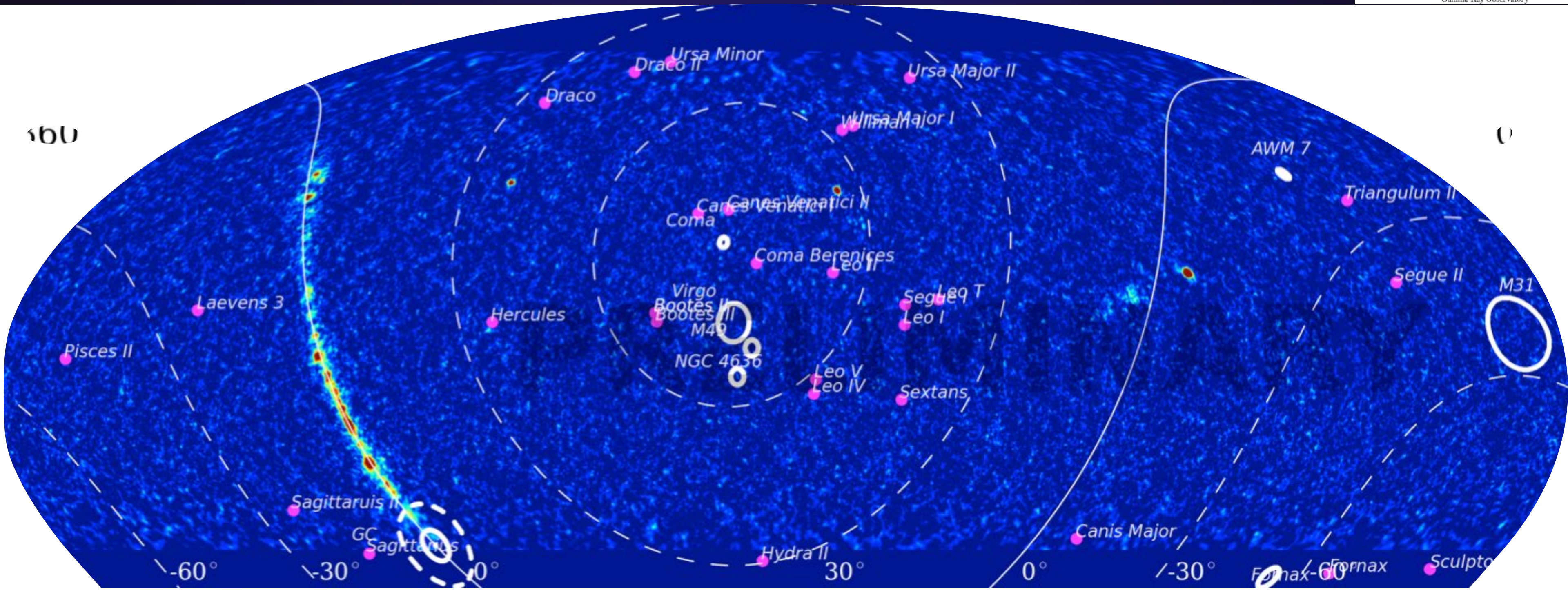
2HWC catalog (ApJ 2017) was 507 days, with 39 sources of which 10 were new.

14

HAWC 3-year Skymap – 1017 days from 11/14 – 12/17

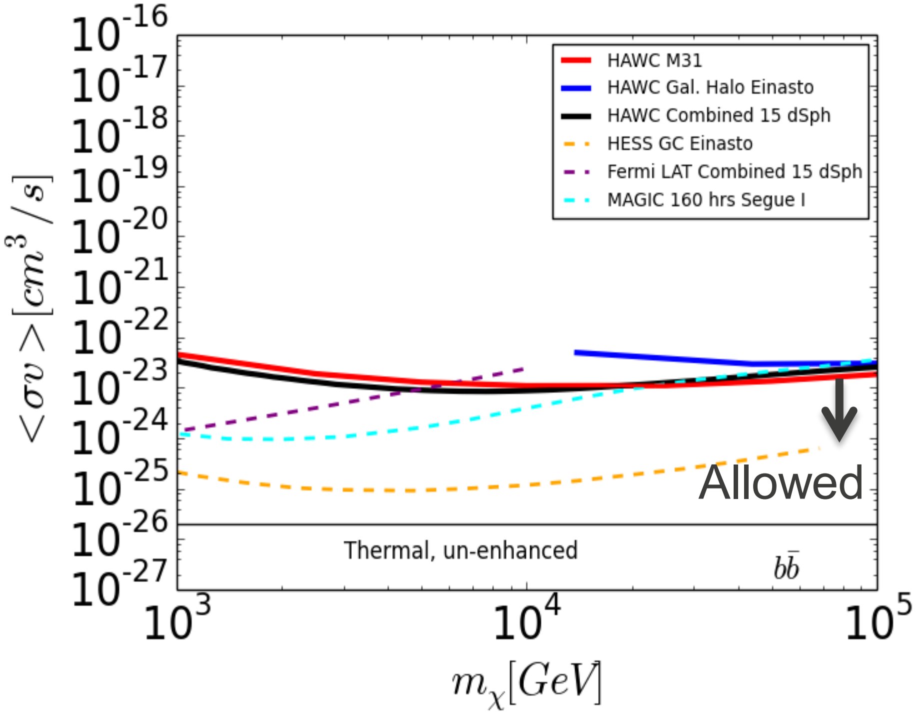


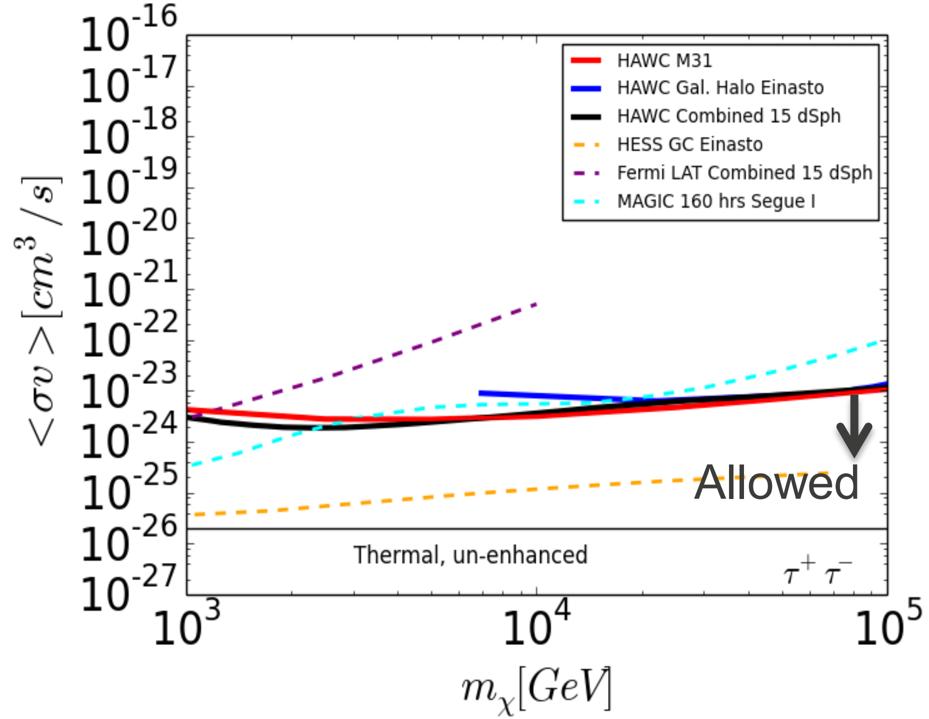
Dark Matter with HAWC



- **Lots of source classes to look at**
  - Milky Way Galactic Center, dwarf galaxies, galaxy clusters, M31 (Andromeda) galaxy
  - Large statistical sample

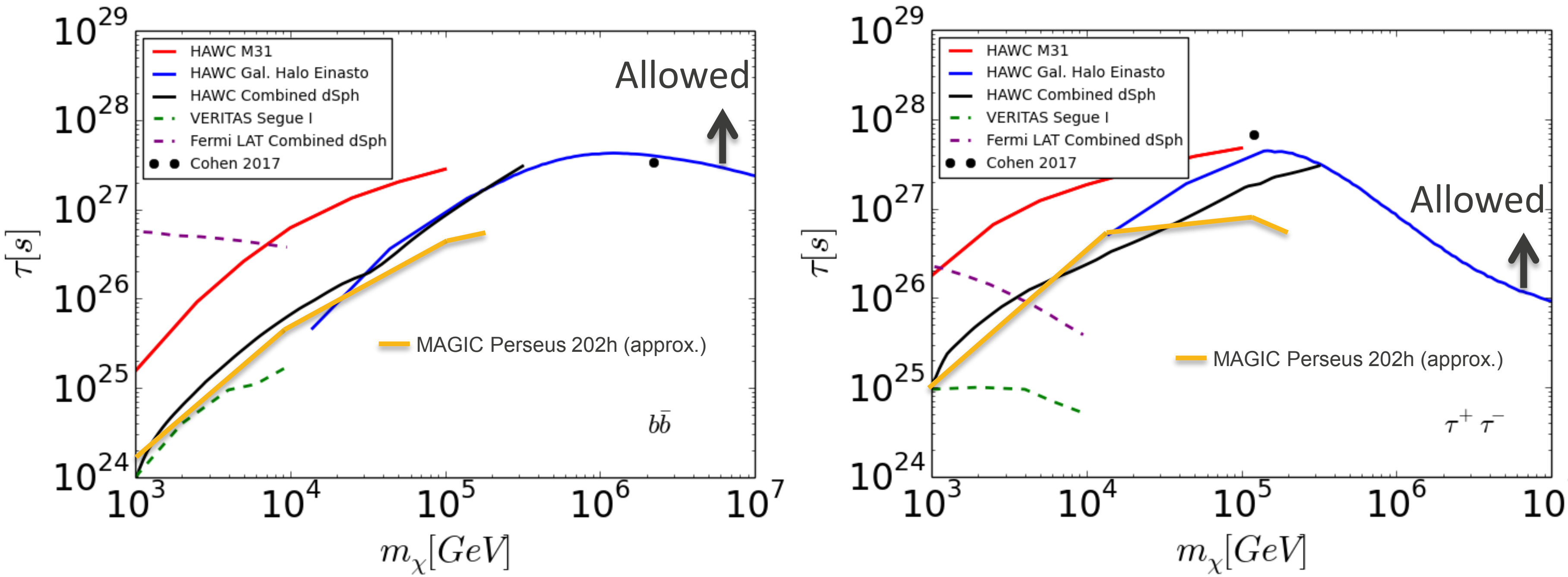
Dark Matter Annihilation Limits with HAWC





- **Multiple sources make HAWC limits robust**
  - Detection requires observations in multiple targets

Dark Matter Decay Limits with HAWC



- **DM decay signal is angularly extended so requires large field of view of HAWC**
- **DM decay is not as sensitive to DM distribution uncertainties as annihilation is**
- **HAWC can exclude IceCube DM interpretations (Cohen, 2017) for hadronic DM**

Lorentz Invariance Violation

- **HAWC can constrain violations of Lorentz invariance 2 ways:**

Observing high-energy, short-duration transients

(Nellen 2015)

$$E_\gamma^2 \approx p^2c^2\left[1+\xi_n\left(\frac{pc}{E_{scale}}\right)^n\right]$$

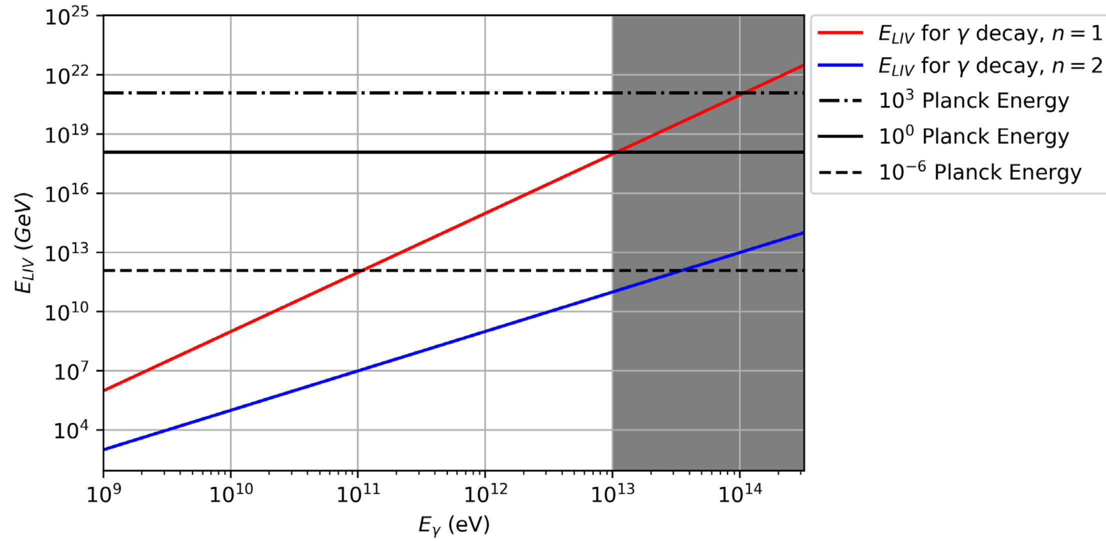
$$E_{LIV}^{(n)} > E_\gamma\left[\frac{E_\gamma^2 - 4m_e^2}{4m_e^2}\right]^{\frac{1}{n}}$$

$$\Delta t = \frac{n+1}{2H_0}\frac{\Delta E^n}{\left(E_{QG}^{(n)}\right)^n}\int_0^z \frac{(1+z')^n\,dz'}{\sqrt{\Omega_\Lambda + \Omega_m(1+z')^3}} = \frac{(n+1)\,d}{2c}\frac{\Delta E^n}{\left(E_{QG}^{(n)}\right)^n}$$

Source [Ref.]	Experiment	Limit on $E_{QG}^{(1)}$	$E_{QG}^{(2)}$
Crab [46, 47]	VERITAS	$1.7 \cdot 10^{17}$ GeV	$7 \cdot 10^{9}$ GeV
GRB090510A [51]	Fermi-LAT	$9.1 \cdot 10^{19}$ GeV	$1.3 \cdot 10^{11}$ GeV
PKS 2155-304 [48]	H.E.S.S.	$2.1 \cdot 10^{18}$ GeV	$6.4 \cdot 10^{10}$ GeV
PG 1553+113 [49]	H.E.S.S., Fermi-LAT	$4.3 \cdot 10^{17}$ GeV	$2.1 \cdot 10^{10}$ GeV

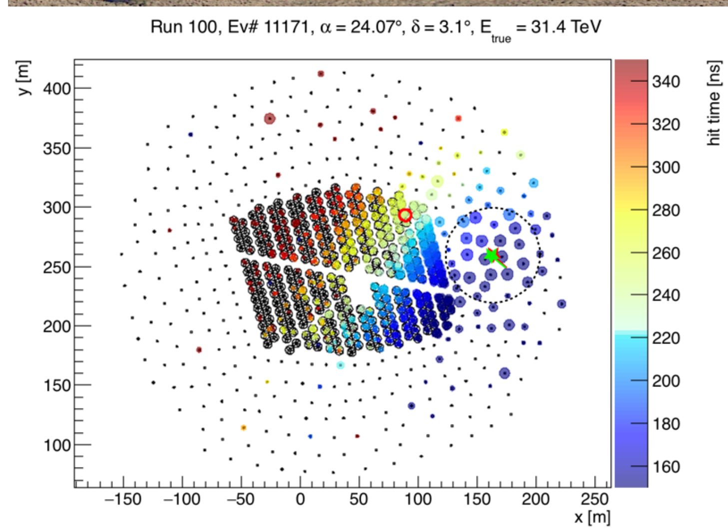
Observing extremely high-energy photons

(Martinez-Huerta & Perez-Lorenzana 2017)

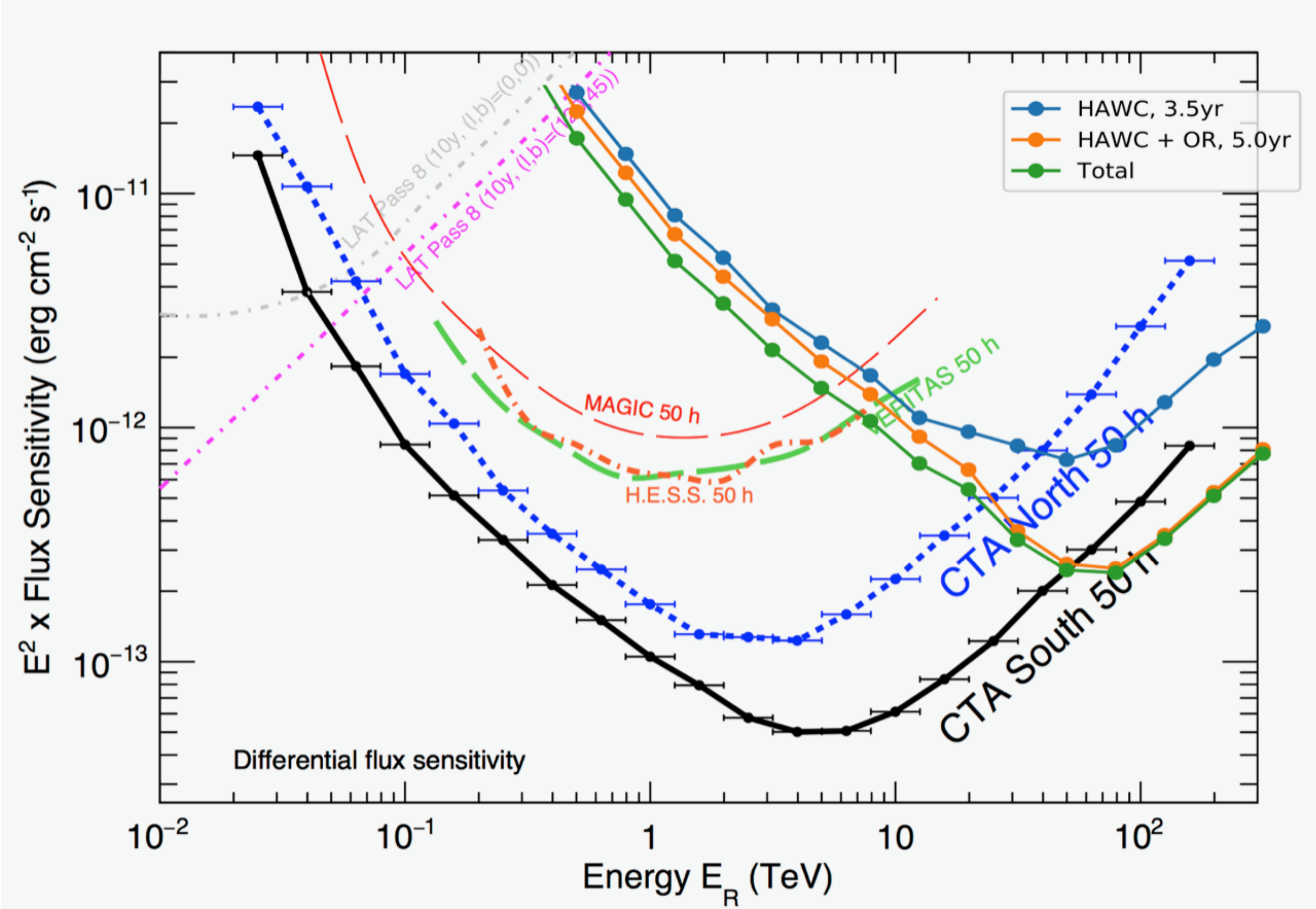


HAWC Upgrade: Outriggers

- Expands total effective area >10TeV with the addition of 350 outrigger tanks spread over 100,000 m2
- Funded by LANL LDRD, Max Planck Institute in Heidelberg, and CONACyT in Mexico
- All tanks are deployed, 100% are cabled, and 80% are taking data
- 100% operational by June 2018
- With the outriggers, HAWC will see the highest energy photon ever detected



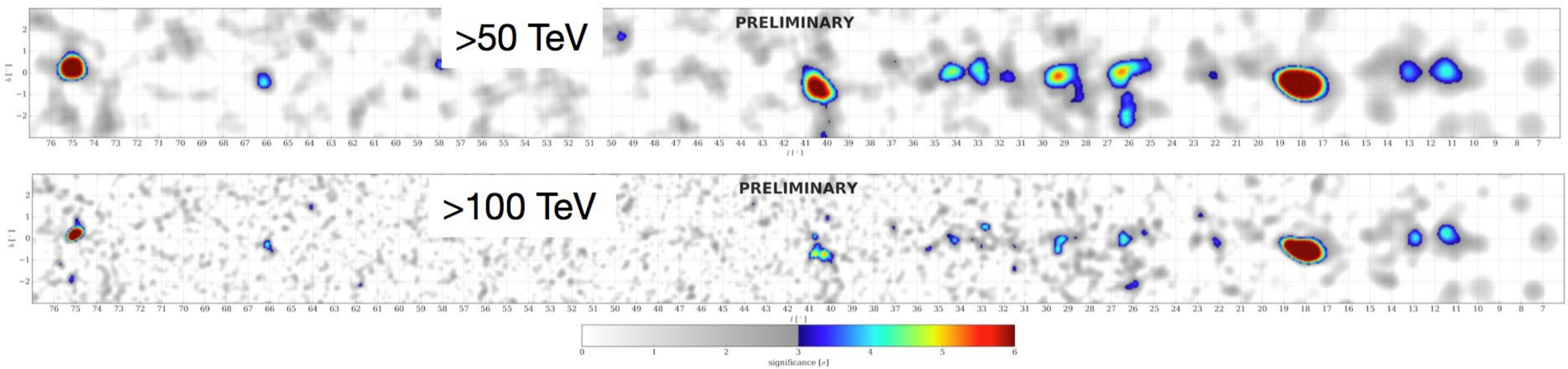
HAWC Sensitivity with Outriggers



This sensitivity does not include improvements in HAWC reconstruction and analysis algorithms which are about to be implemented retroactively

Pushing HAWC to the Highest Energies

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory



- **HAWC already detects sources > 50 TeV, so outriggers will detect even more**
- **Detection of >100 TeV gamma-rays stresses models of particle acceleration**
- **Essential to discovering the source of cosmic rays up to the knee ($3x10^{15}$ eV protons produce 100-200 TeV gamma-rays)**
- **Algorithm development will improve HAWC energy response**
  - First papers on improvements due out later this year

Where do I get some HAWC data to play with?

- **Public data: data.hawc-observatory.org**
- **Some dataset already available, planning to add more:**
  - Significance and flux maps corresponding to the 2HWC paper (507d livetime).
  - Geminga & Monogem dataset.
  - Daily light curves (2014-11-26 to 2016-04-20):
    - Crab
    - Mrk 421
    - Mrk 501
- **Please use for your own analysis, and contact us if you want to collaborate or for more information!**
  - Joint Fermi/HAWC/HESS/MAGIC/VERITAS dwarf analysis in progress