The High Altitude Water Cherenkov (HAWC) telescope

Synergy with Fermi

Nicola Omodei, Stanford University for the HAWC Collaboration

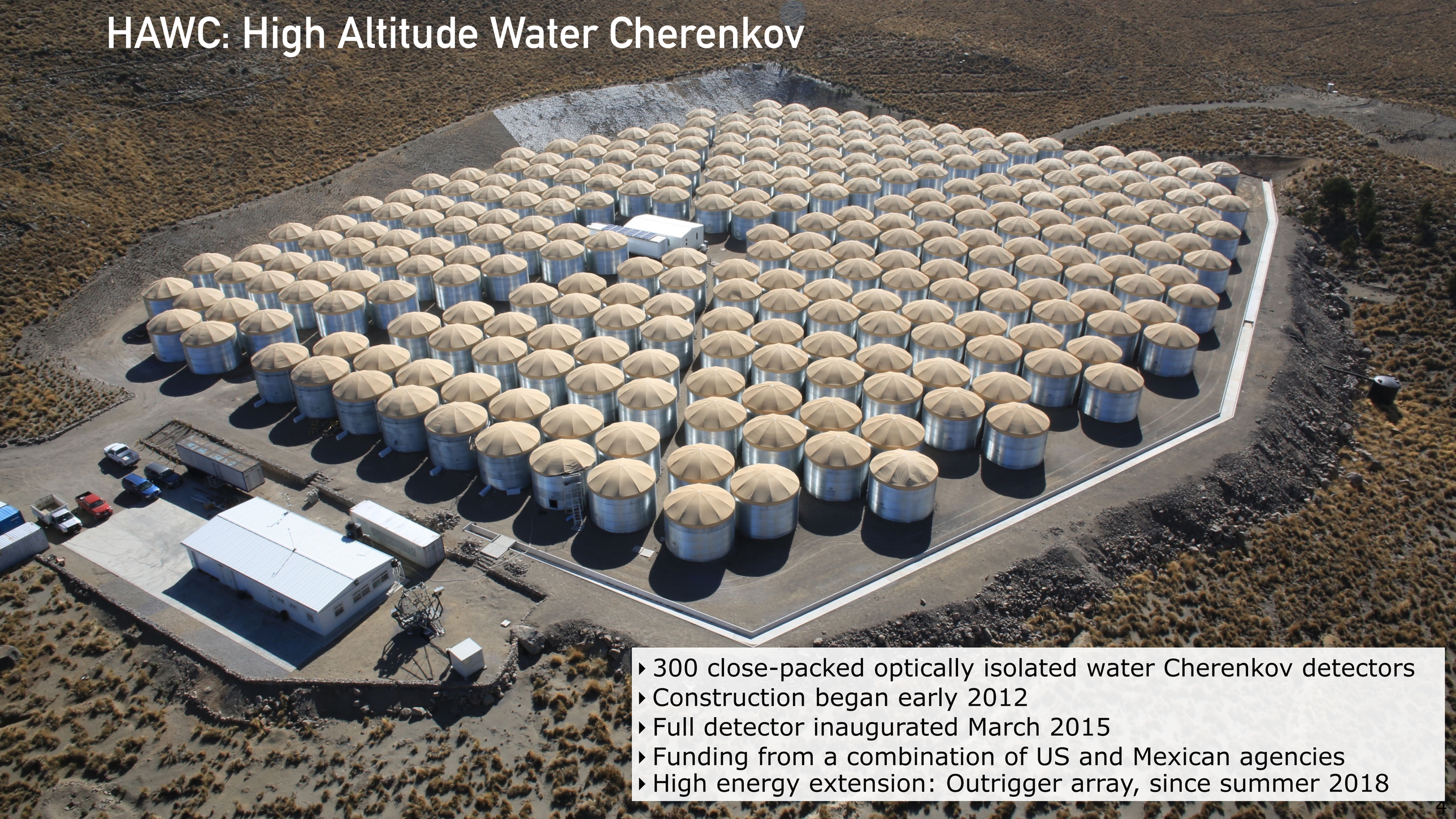
Second GraviGamma Workshop

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

HAWC Collaboration (Mexico, USA, Germany, Poland, Costa Rica and Italy)

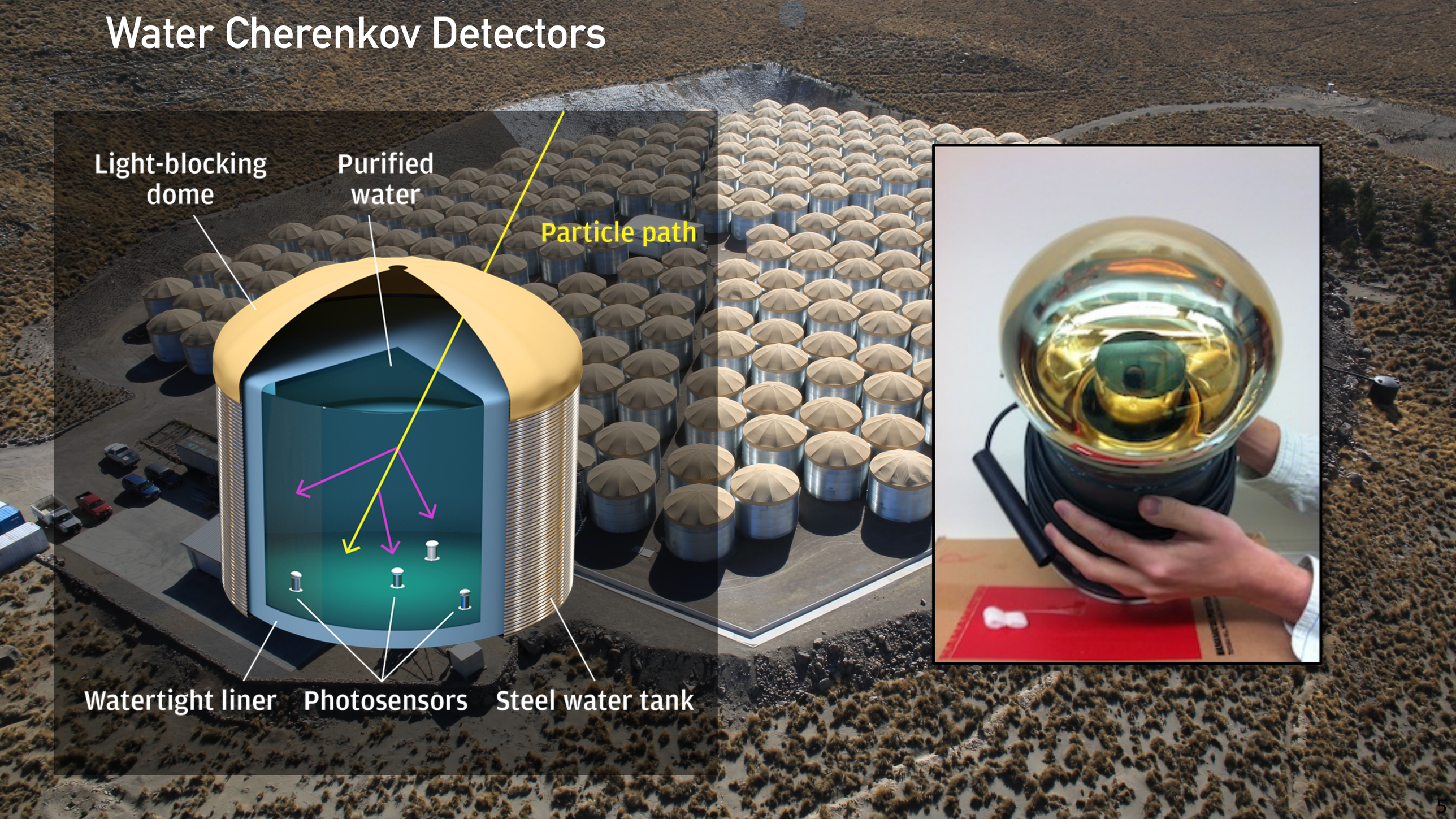

Pico de Orizaba
5636 m a.s.l.
Sierra Negra
Large Millimetric Telescope
4640 m a.s.l.
HAWC
4100 m a.s.l.

HAWC: High Altitude Water Cherenkov

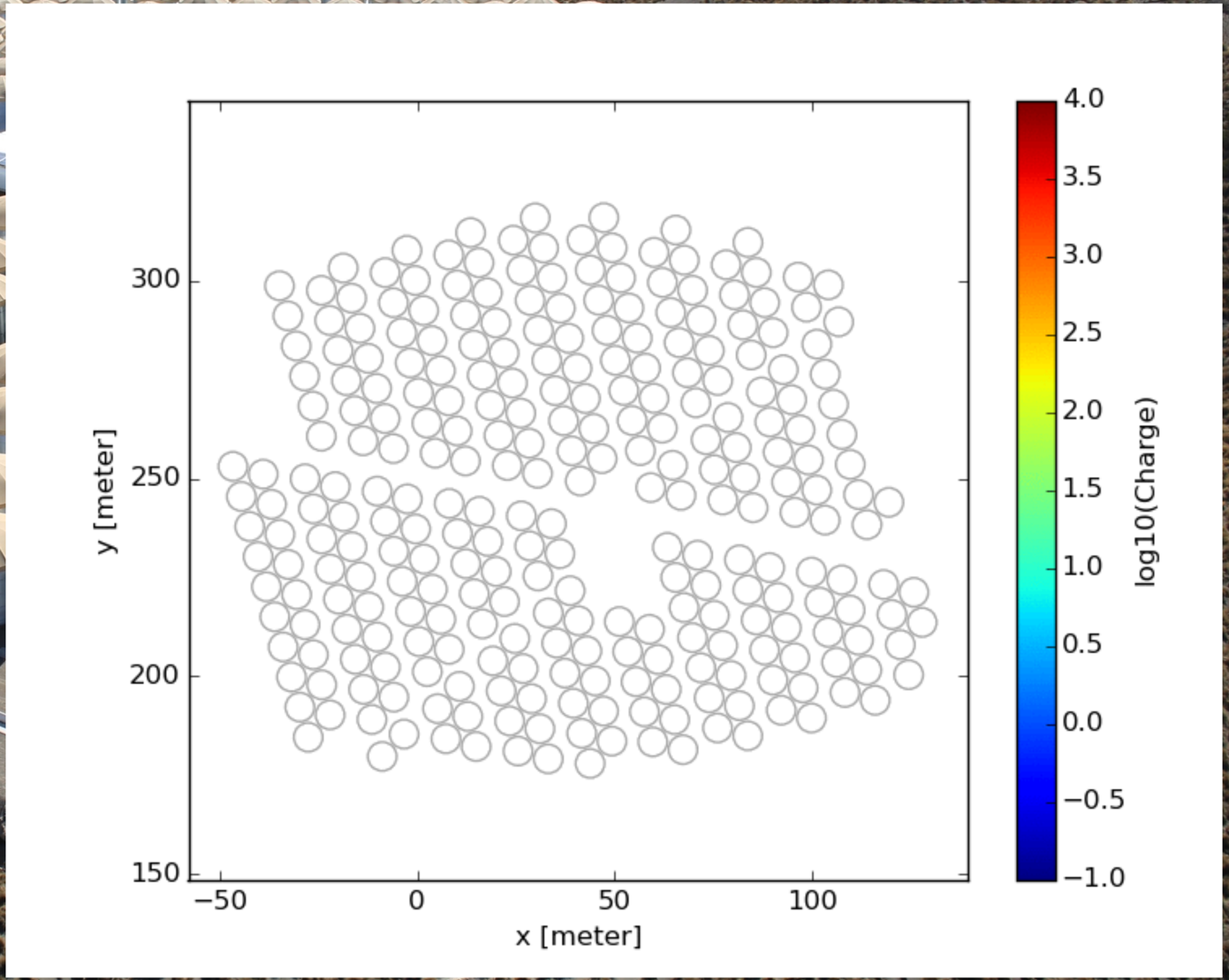


- 300 close-packed optically isolated water Cherenkov detectors
- Construction began early 2012
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, since summer 2018

Water Cherenkov Detectors

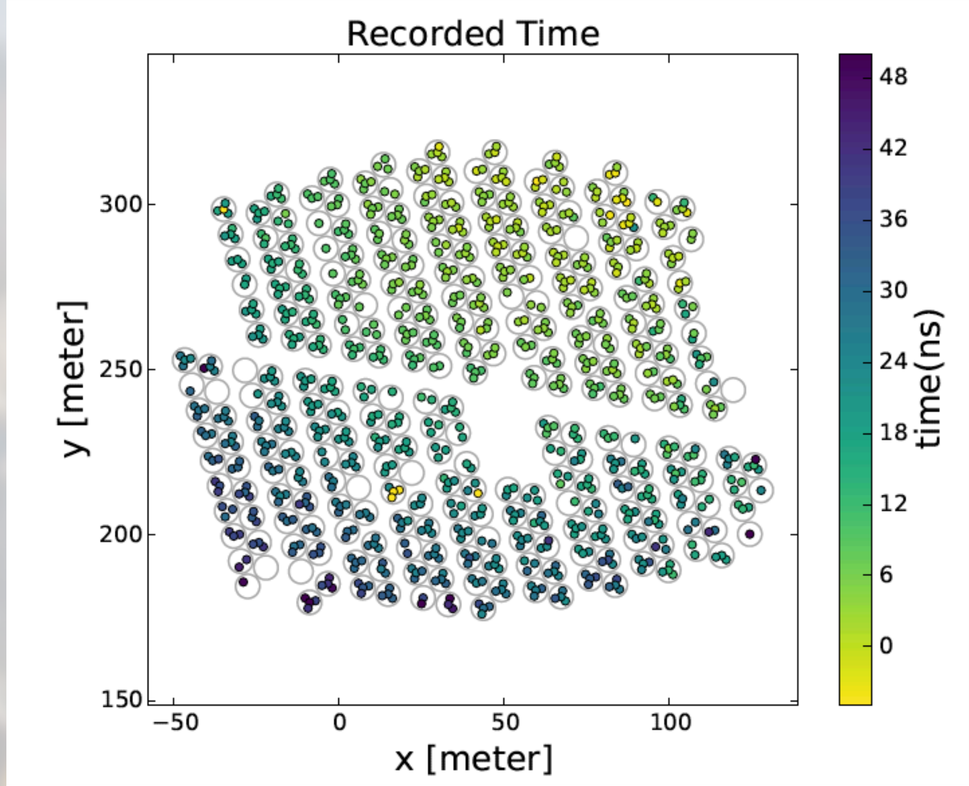


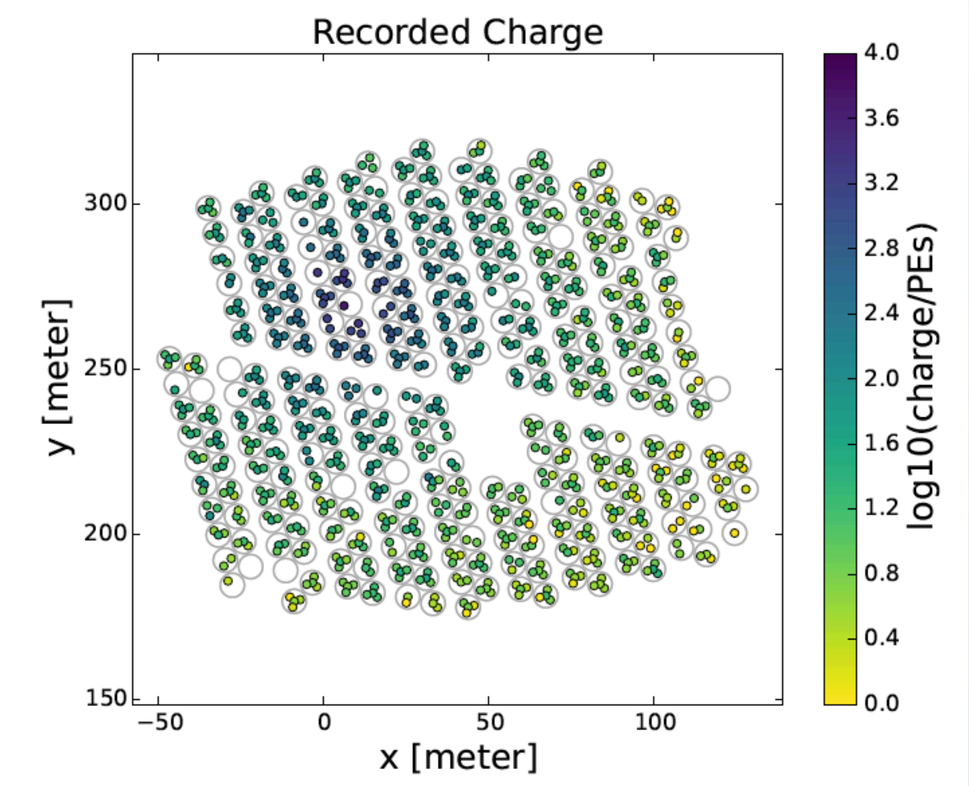
Water Cherenkov Detectors



Shower reconstruction

- Measure: time and light level in each PMT.
- Reconstruct: direction, location, energy, and background rejection.
- Reference: Crab paper, ApJ 843 (2017), 39.





Shower reconstruction

- Measure: time and light level in each PMT.
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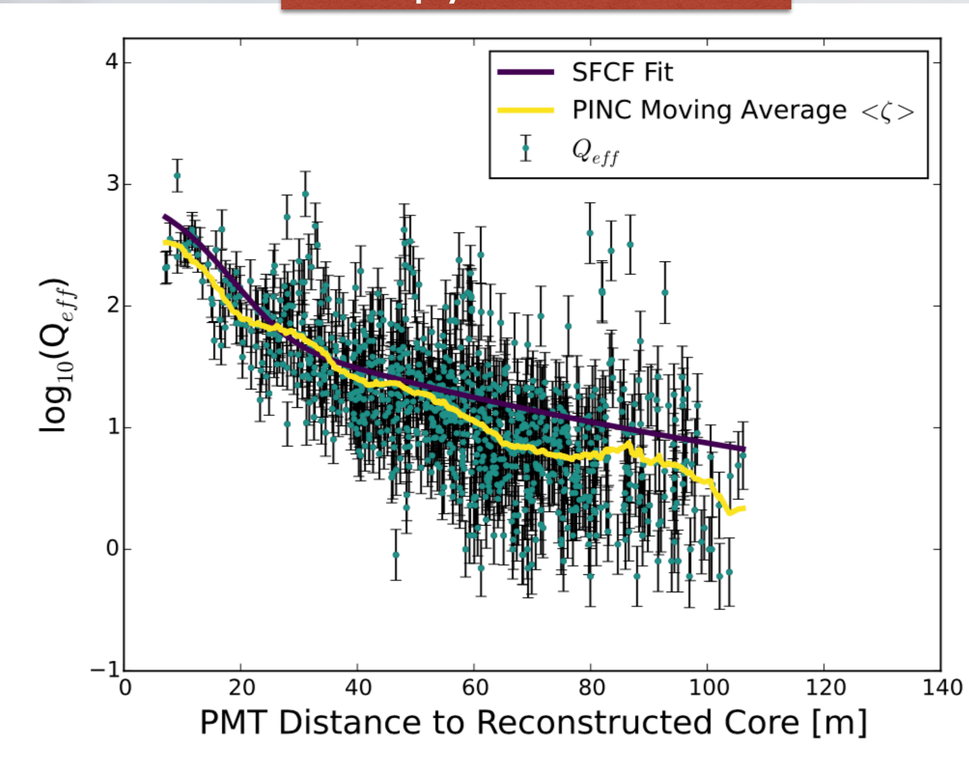
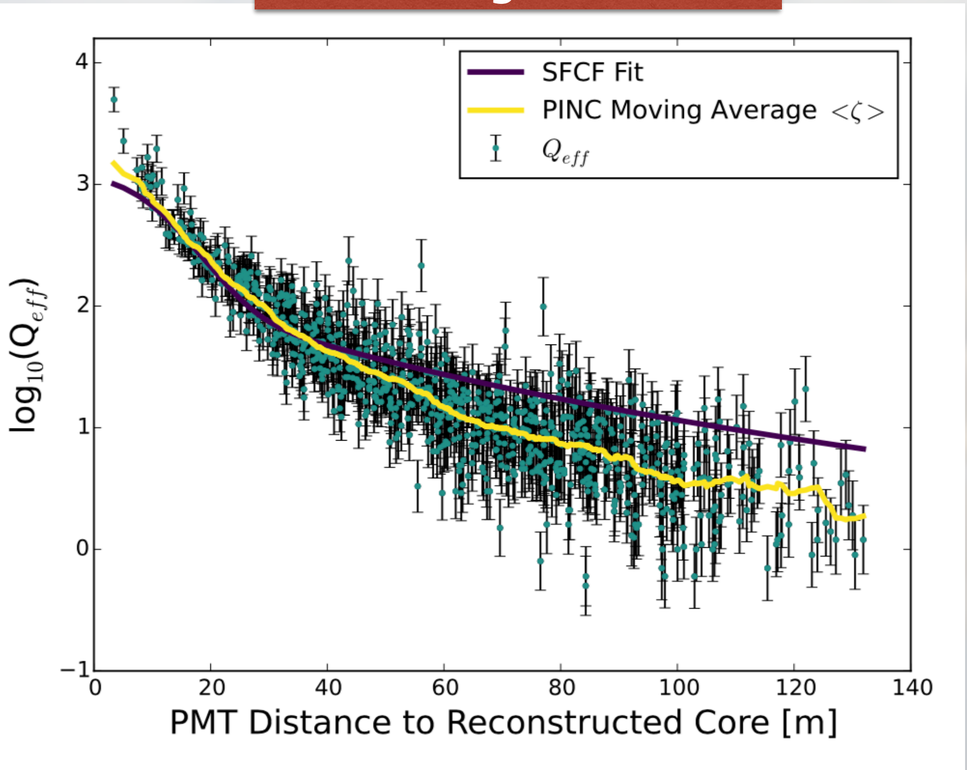
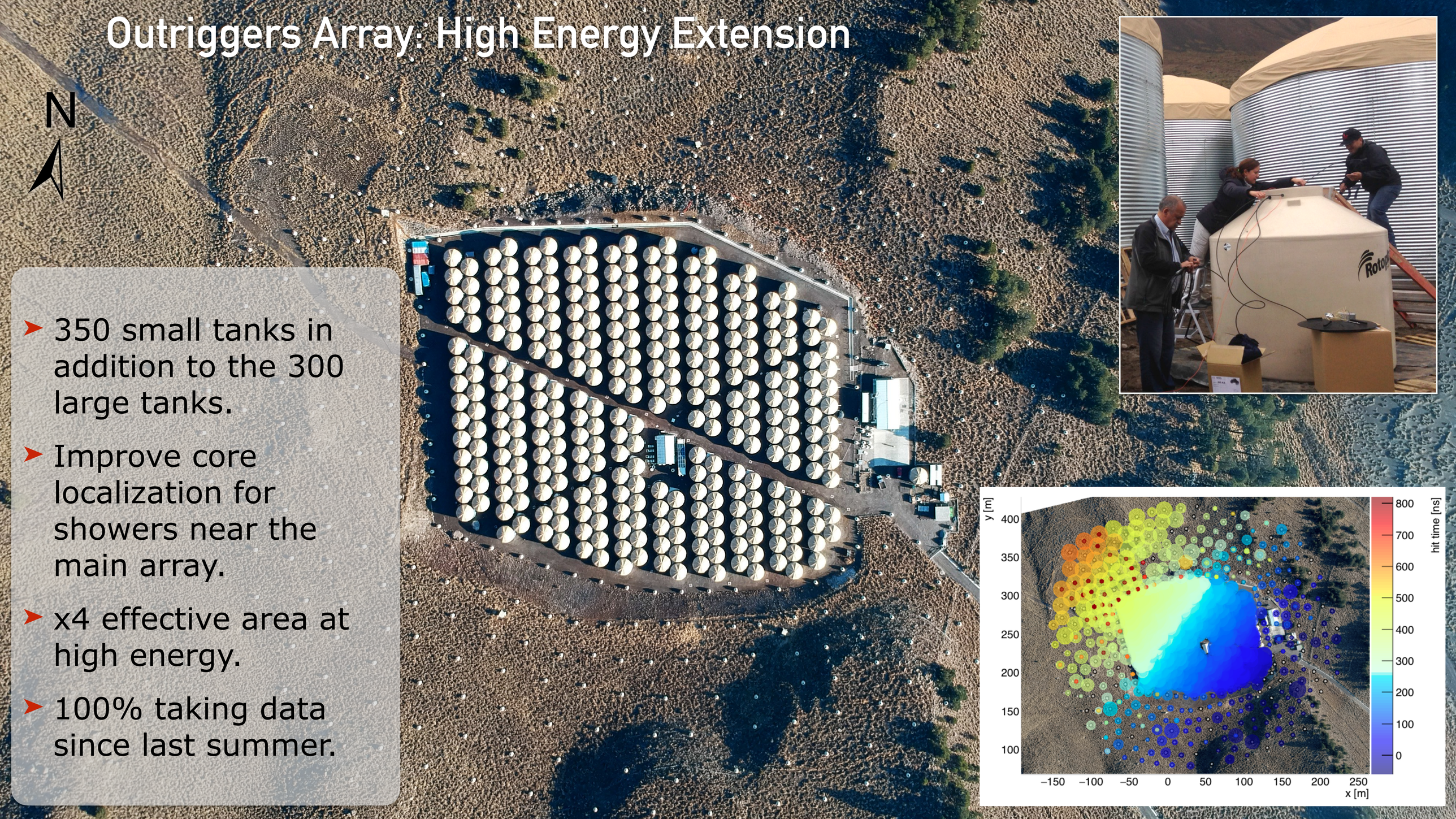
Clumpy: hadron-like



Smooth: gamma-like



Outriggers Array: High Energy Extension

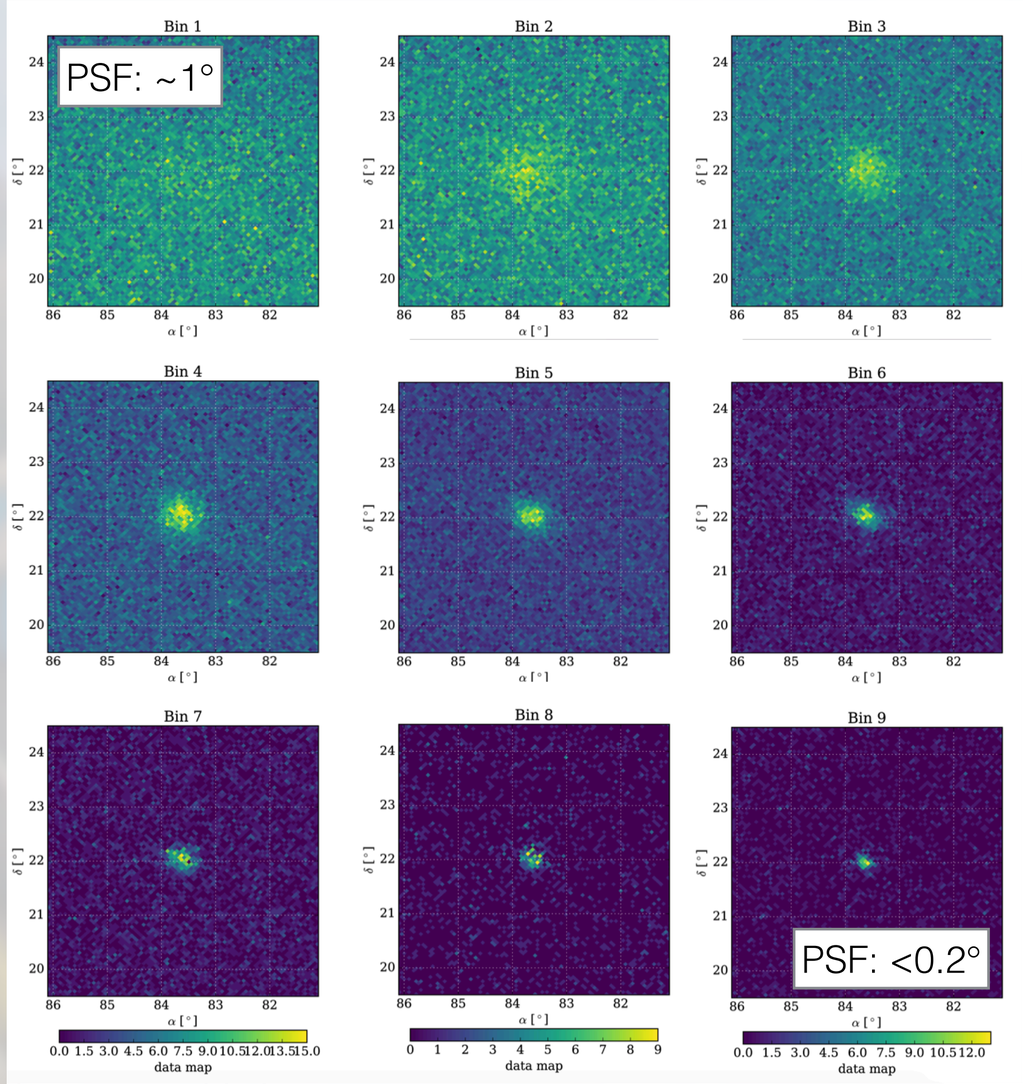


- 350 small tanks in addition to the 300 large tanks.
- Improve core localization for showers near the main array.
- x4 effective area at high energy.
- 100% taking data since last summer.

Source search and characterization

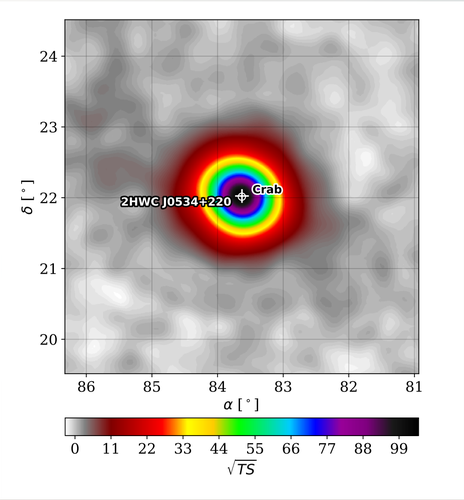
- Events sorted by "size" in *n* bins (with characteristic Point Spread Function, S/N ratio, energy), make *n* maps.
- Likelihood framework use *n* maps to test the presence of sources then characterize them.
- Reference: Crab paper, ApJ 843 (2017), 39.

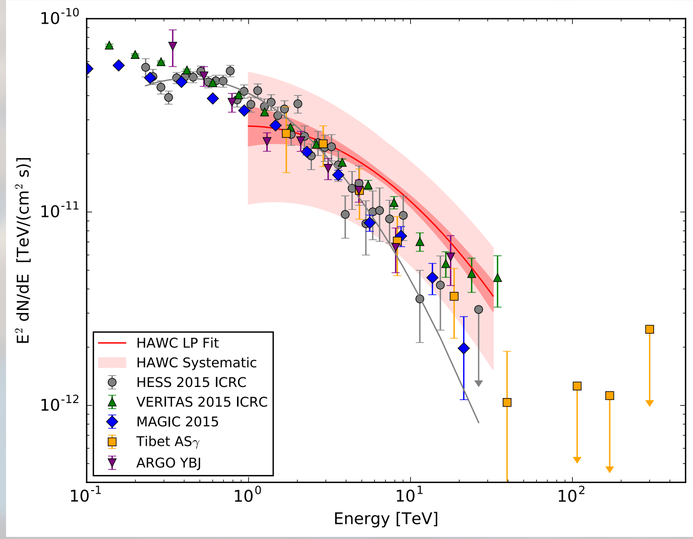
Crab Nebula



Detector response
Source model

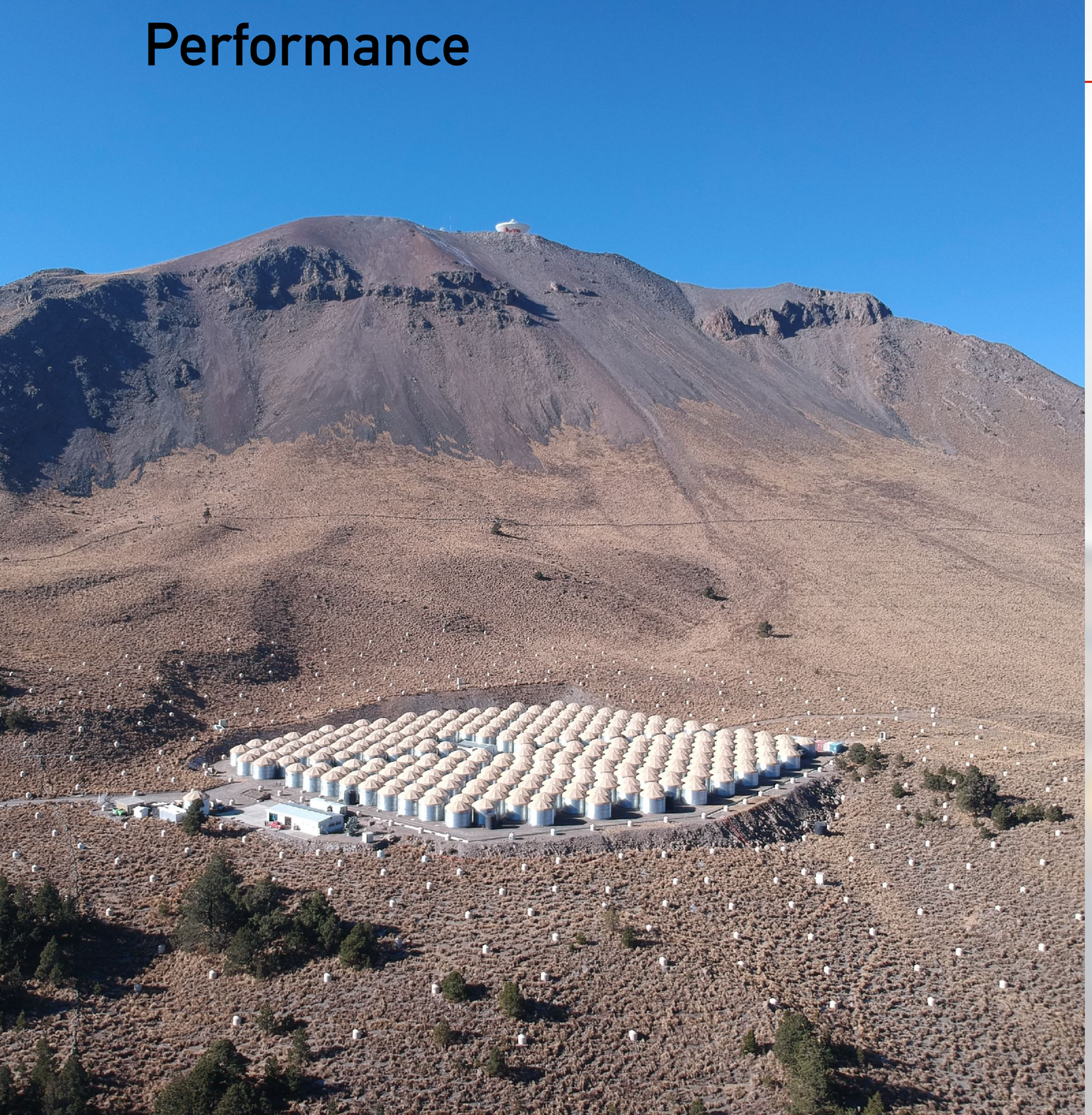
Likelihood framework



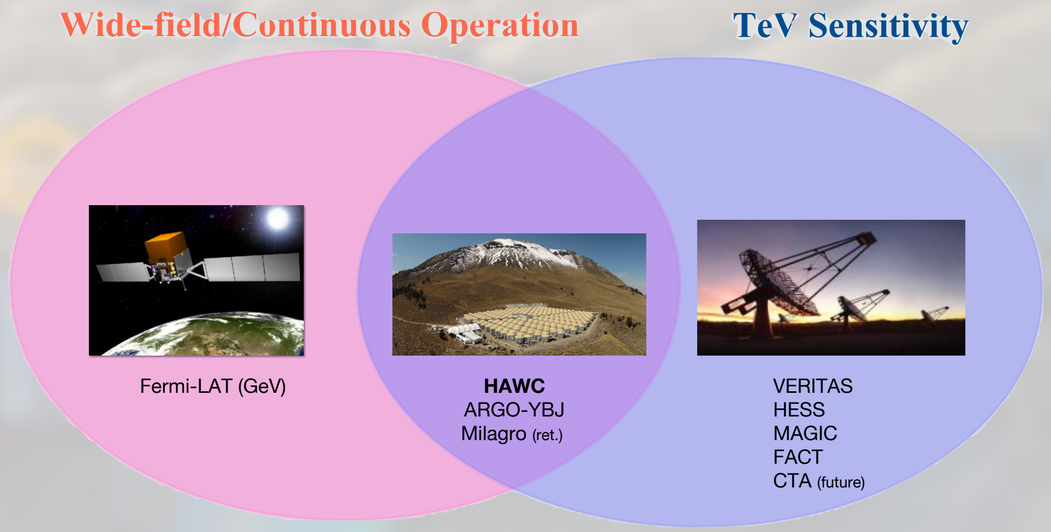


3ML
The Multi-Mission Maximum Likelihood framework

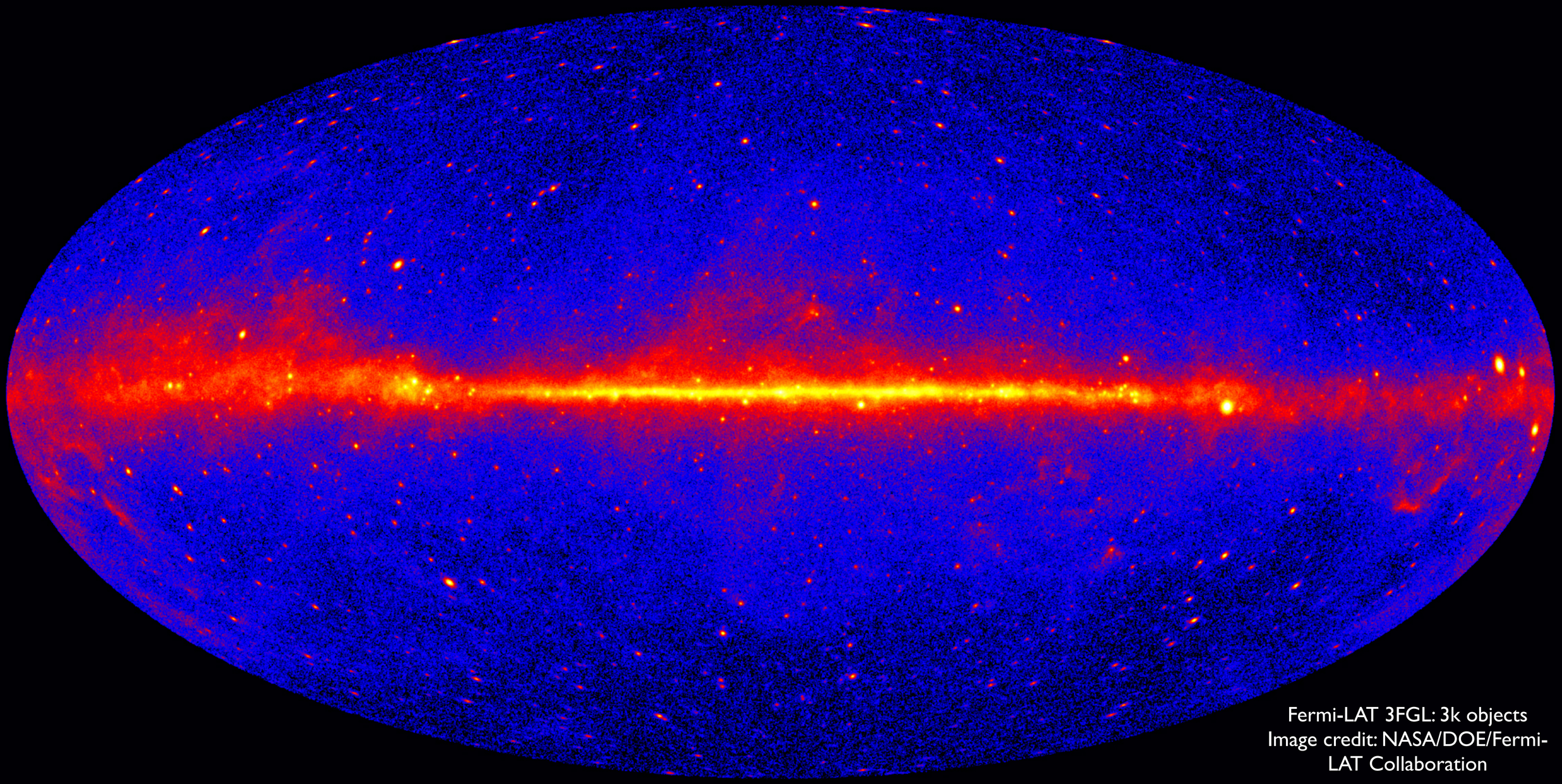
Performance



- Wide field (~2 sr), covers 2/3rd of the sky daily.
- Duty cycle > 90%.
- Sensitive to point sources and extended sources.
- Large exposure provides high energy reach.
- Sensitive from 100s of GeV to >100 TeV.

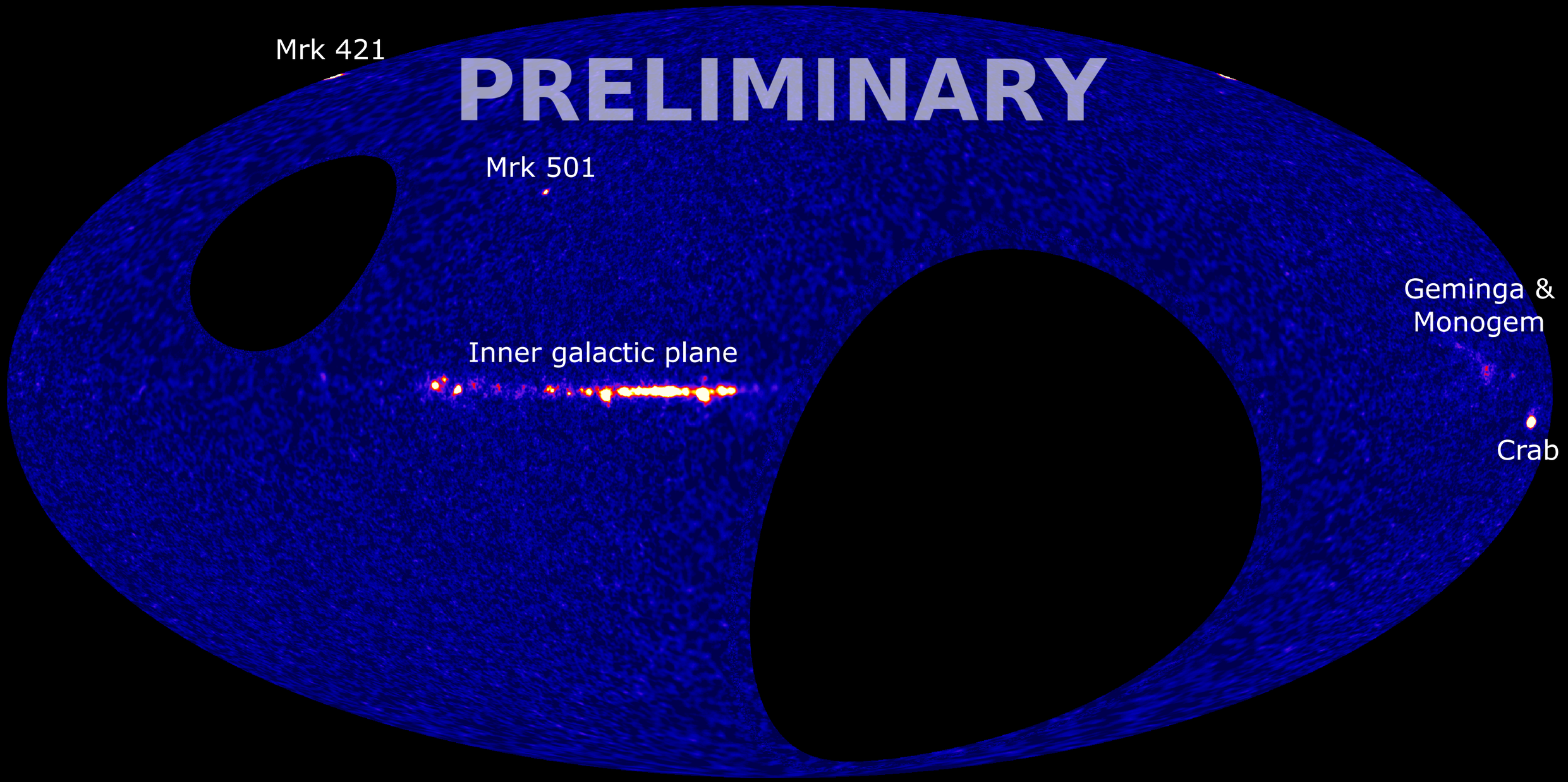


Sky — GeV gamma rays: thousands of sources



Fermi-LAT 3FGL: 3k objects
Image credit: NASA/DOE/Fermi-LAT Collaboration

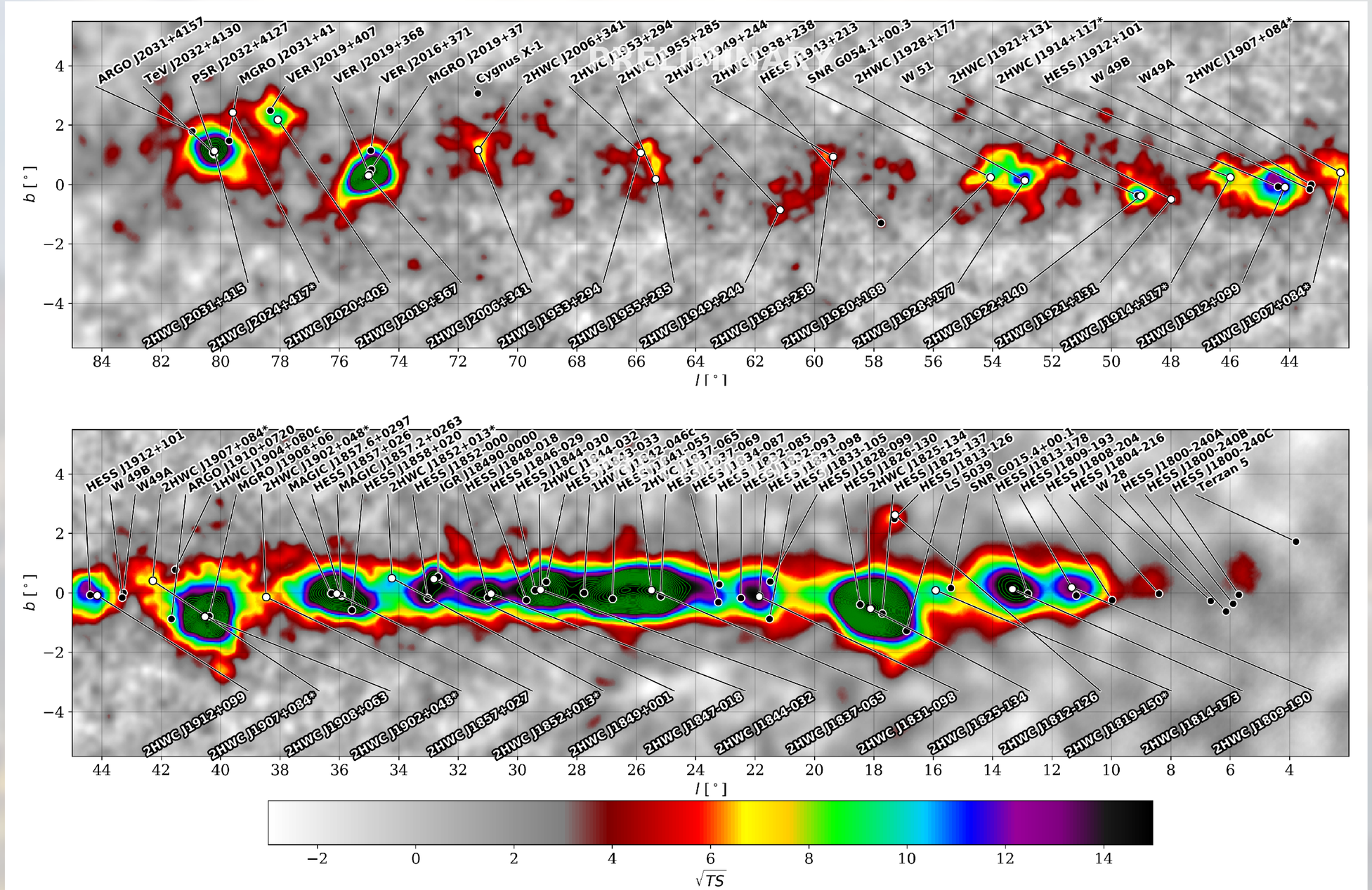
HAWC 3.5 year skymap — 1128d livetime: 2014-11 to 2018-04

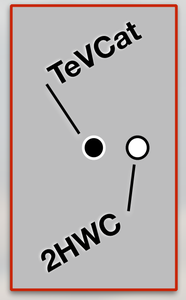


Galactic Science

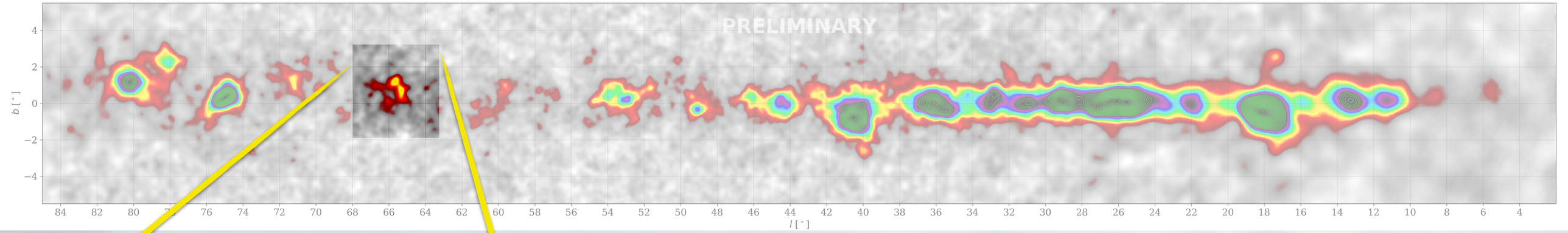
Inner Galactic plane — 1128d livetime (2014-11 to 2018-04)

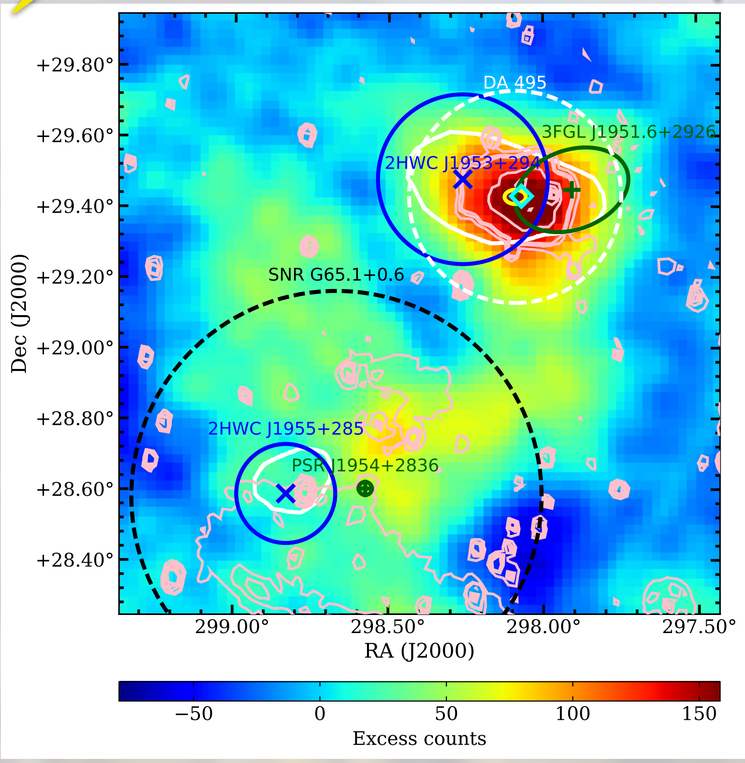
Update





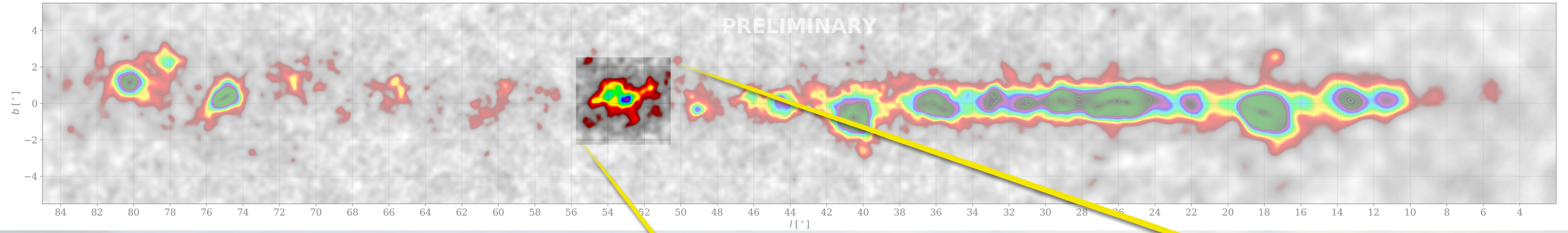
New Sources: 2HWC J1953+294



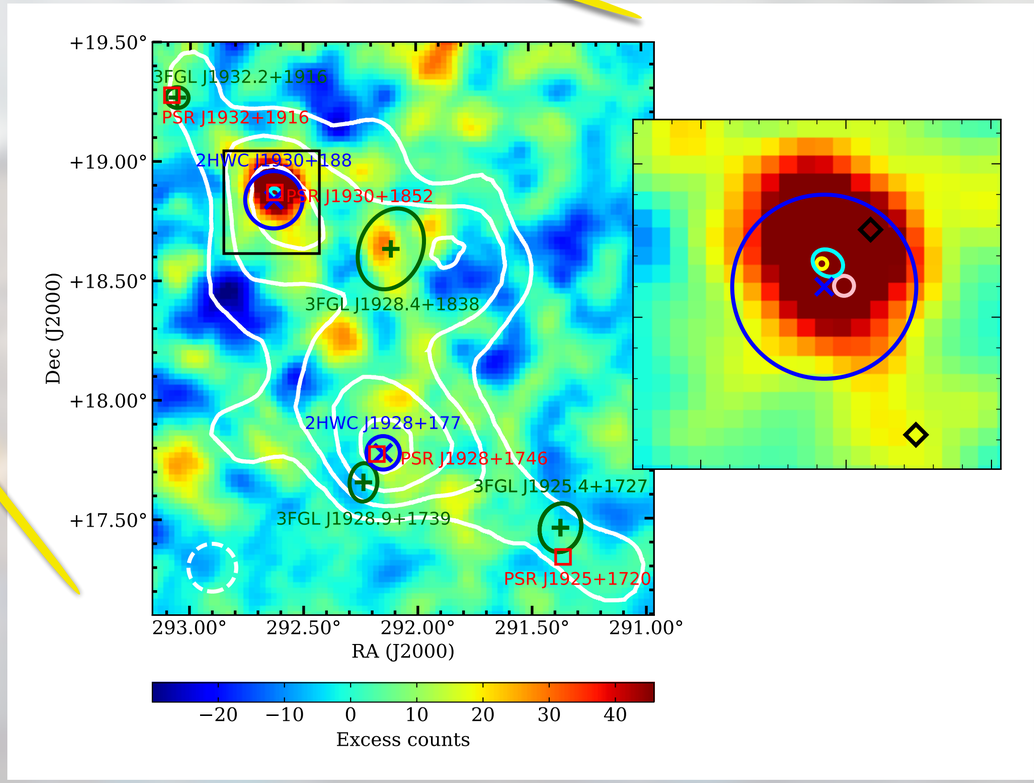


- **2HWC J1953+294**: No previously known TeV sources.
- Tentative association 3FGL J1951.6+2926 / PWN DA 495
- Shared privately with Imaging Atmospheric Cherenkov Telescopes
- New observations plus archival data by VERITAS: source confirmed.
  - *2018ApJ...866...24A*

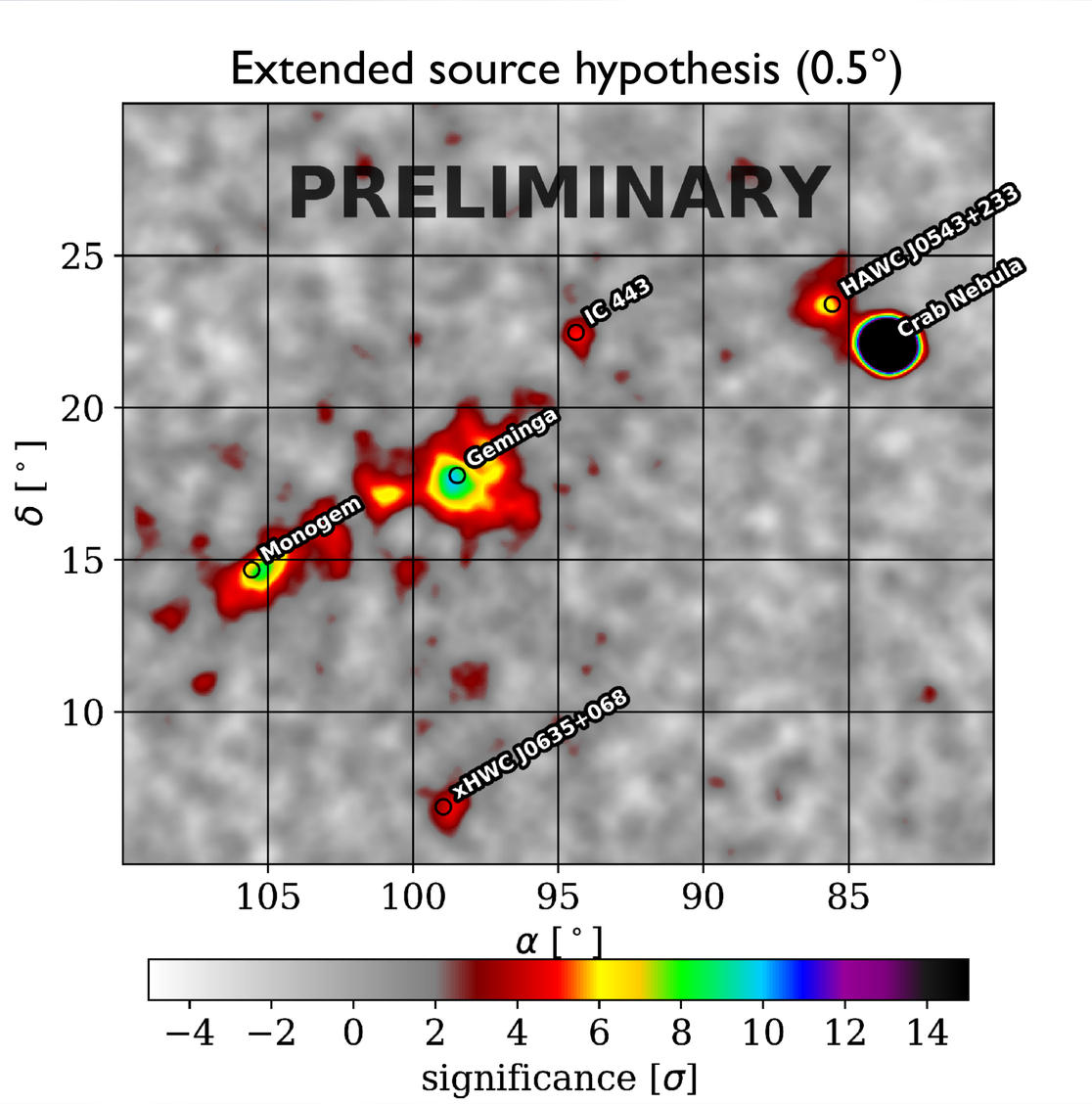
New Sources: 2HWC J1928+177



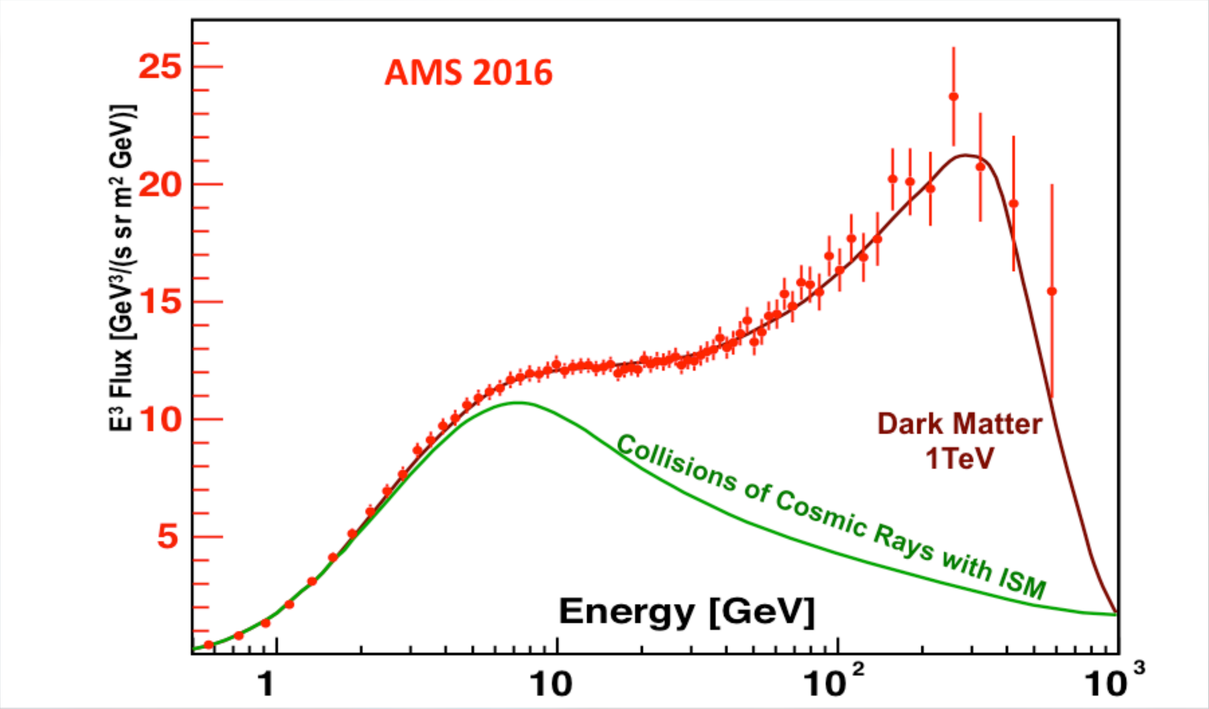
- **2HWC J1930+188** is a known TeV source associated to SNR G054.1+00.3, discovered by VERITAS source.
  - Source detected by Fermi LAT
  - Source consistent with SNRG54.1+0.3, a PWN at a distance of ~6.5kpc hosting a young, energetic pulsar, PSRJ1930+1852
- New source **2HWC J1928+177**, likely associated with energetic PSR J1928+1746. Not seen by VERITAS, set a flux limit.
  - Fermi spectrum not consistent with HAWC: Fermi might detect emission from the pulsar and HAWC the emission from the PWN
- *2018ApJ...866...24A*



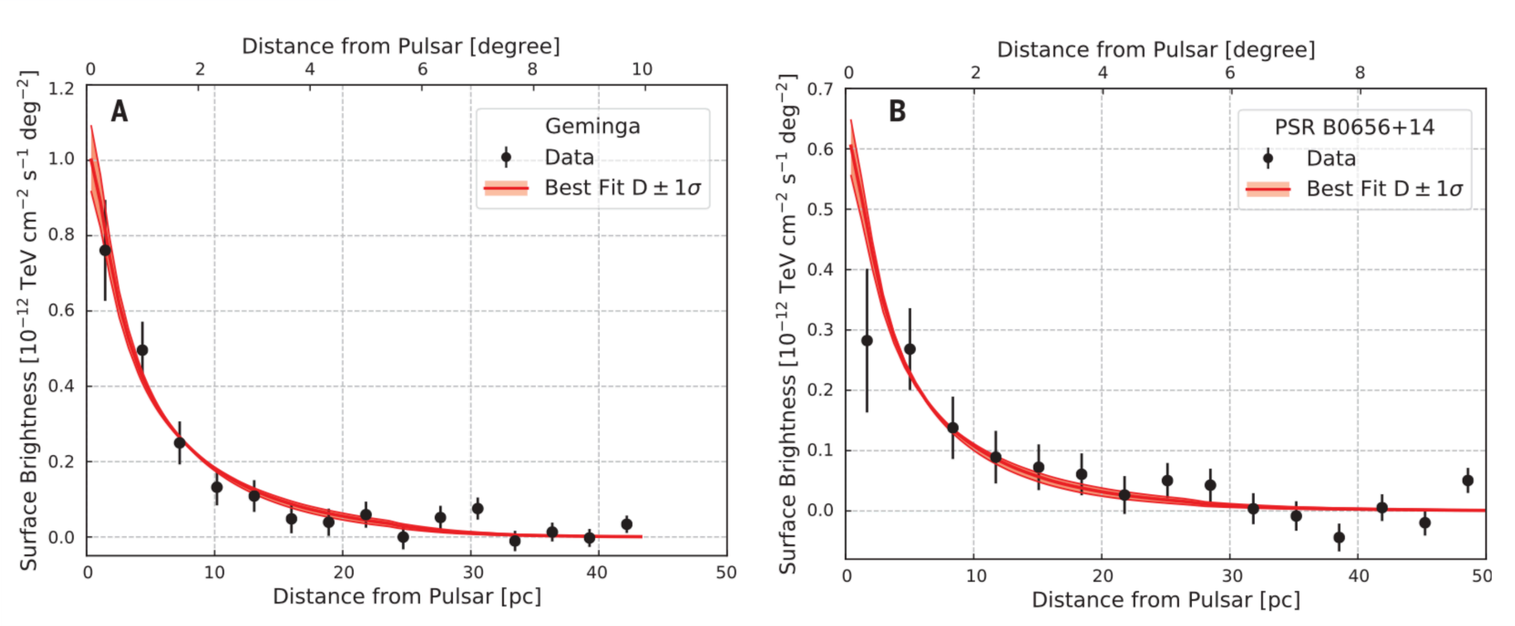
TeV halos

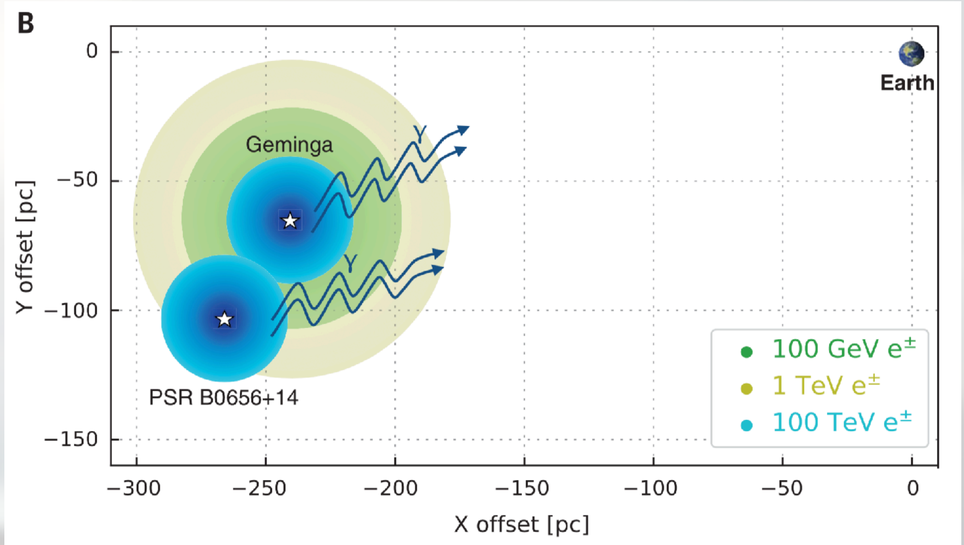


- Direct observation of electron diffusion around middle age pulsars
- Controversy about **positron excess** (Pamela, Fermi, AMS):
  - Dark Matter origin?
  - Local pulsar origin?



TeV halos: Geminga - Monogem (Science 2017)





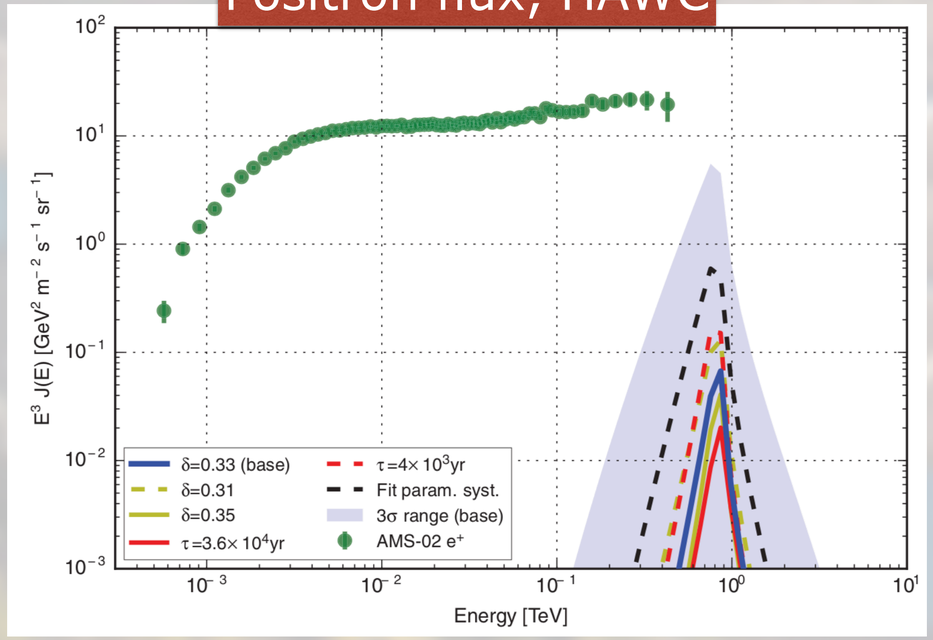
- **Very extended sources**, ~5° (10x the Moon).
- Orders of magnitude larger than x-ray PWN.
- **Yet ~10 times smaller than expected** from usual diffusion coefficient.
  - Direct measurement of the electron and positron diffusion around the source: $D_{100TeV} = 4.5 \pm 1.2 \times 10^{27}$ cm²/s
  - D_{100TeV} ~100 times smaller the ISM diffusion value derived from B/C ratio.

TeV halos: Geminga - Monogem, interpretations

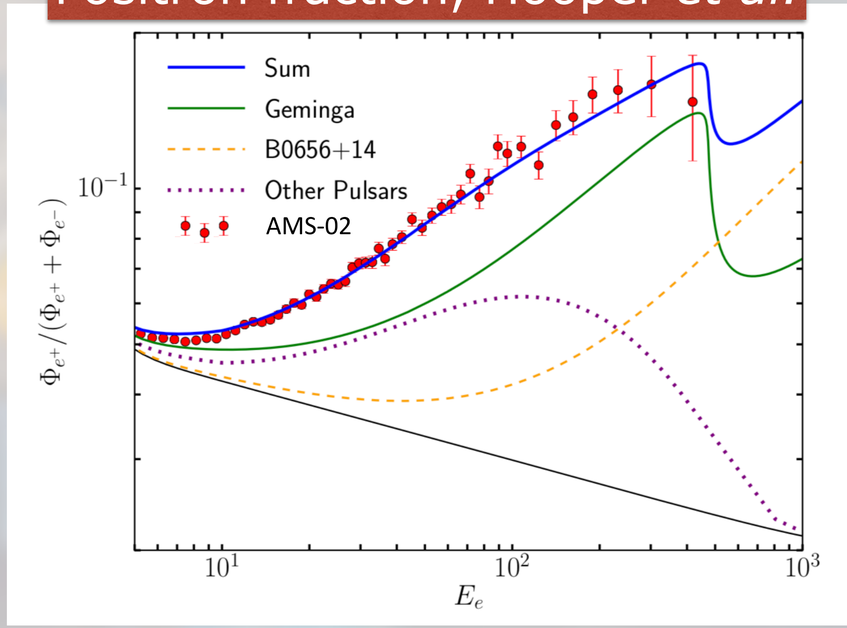
- HAWC Collaboration, Science (2017): Assuming uniform value diffusion constant, e^+/e^- cannot reach Earth, Geminga does not explain the positron excess.

- 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 flux, HAWC



Positron fraction, Hooper *et al.*



Microquasar SS 433

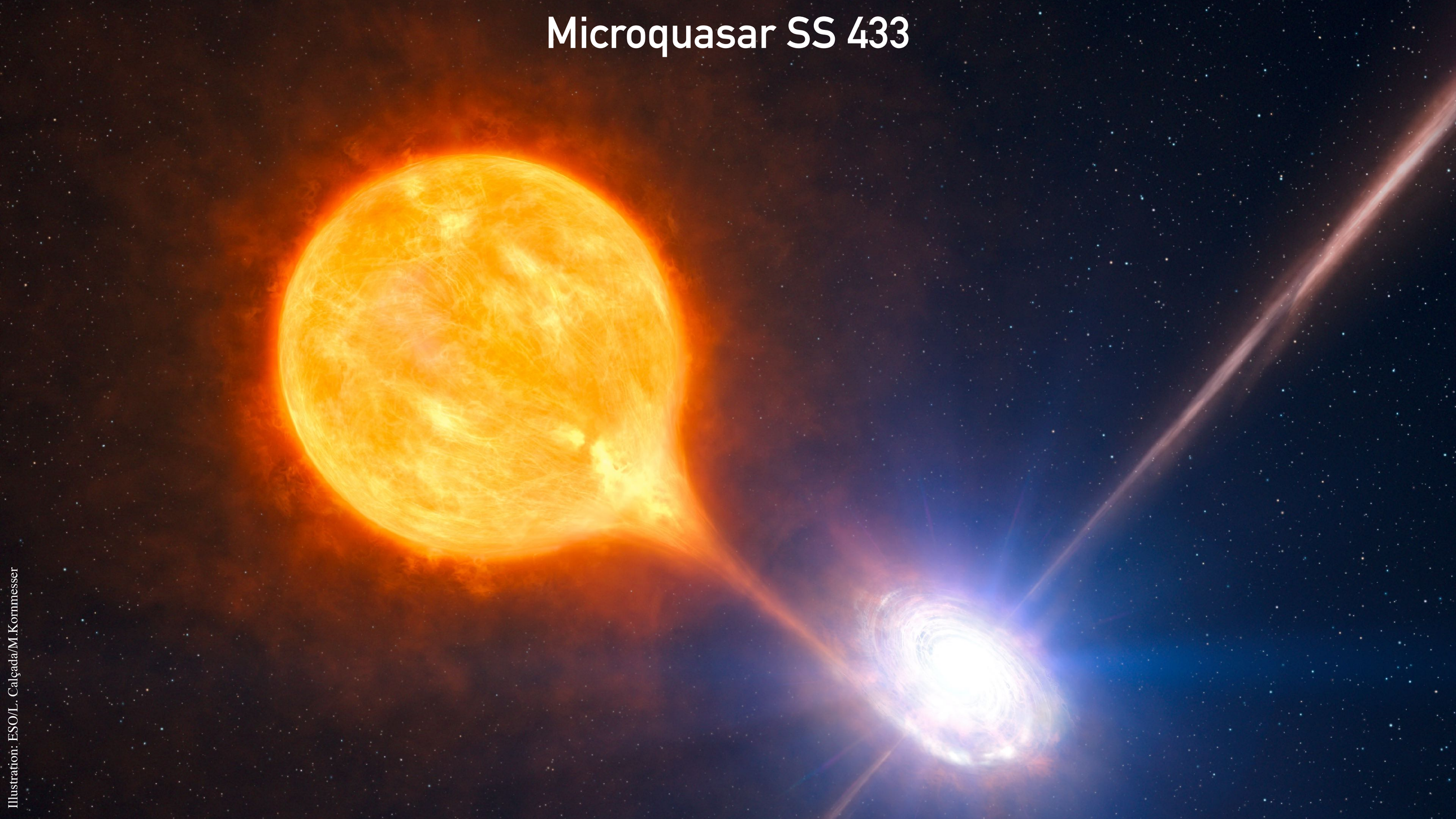
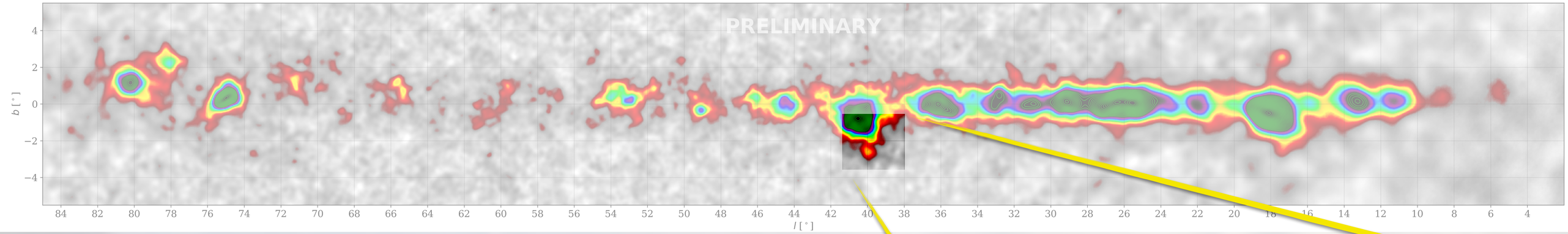
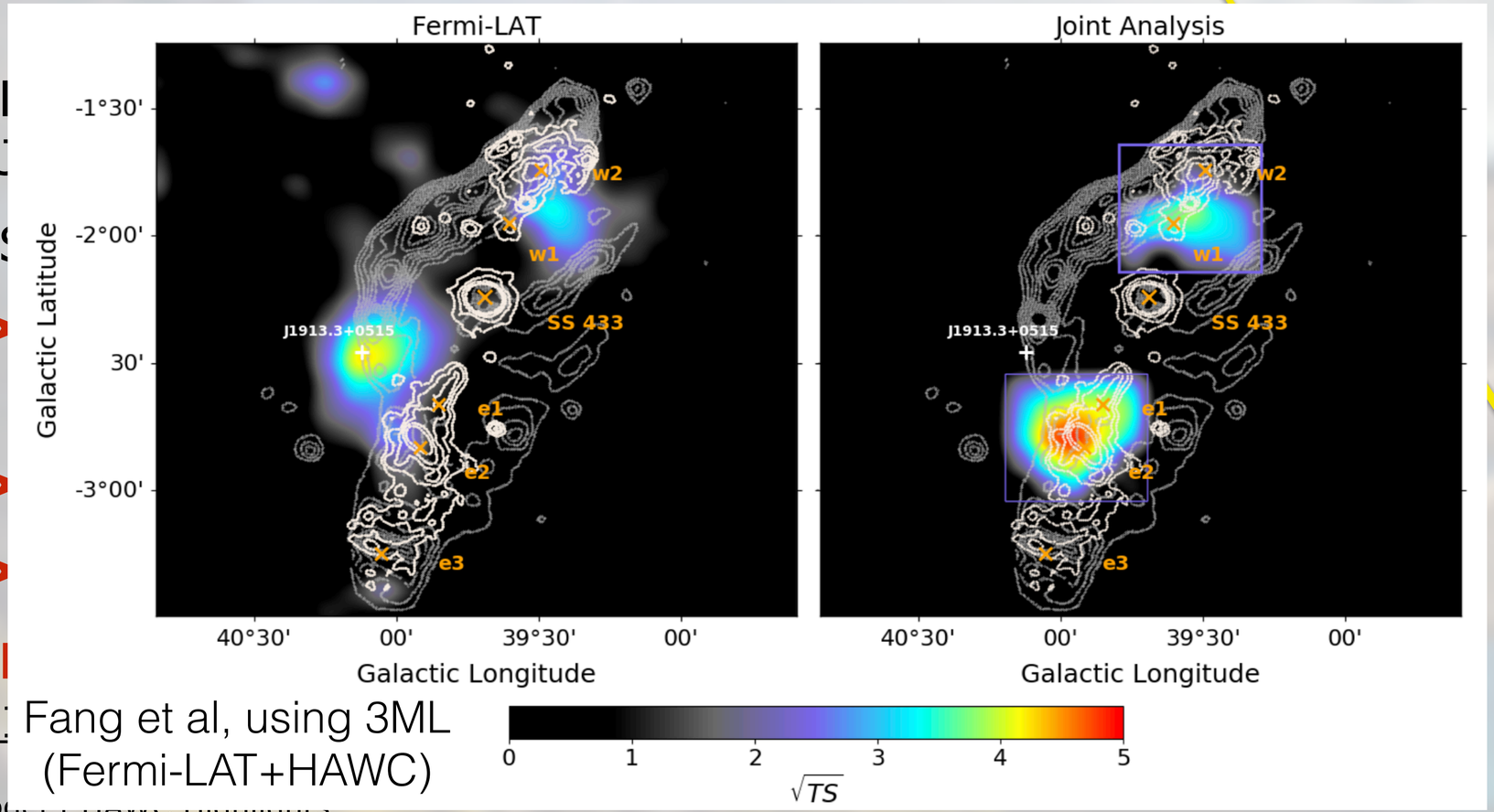
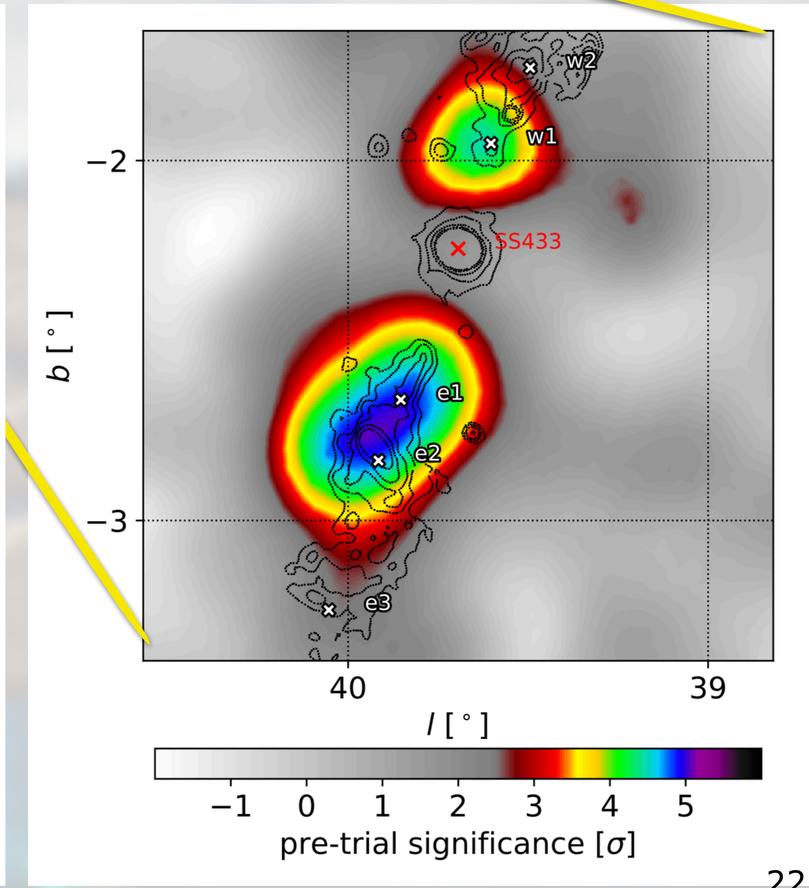


Illustration: ESO/L. Calçada/M.Kornmesser

Microquasar SS 433: lobes detection



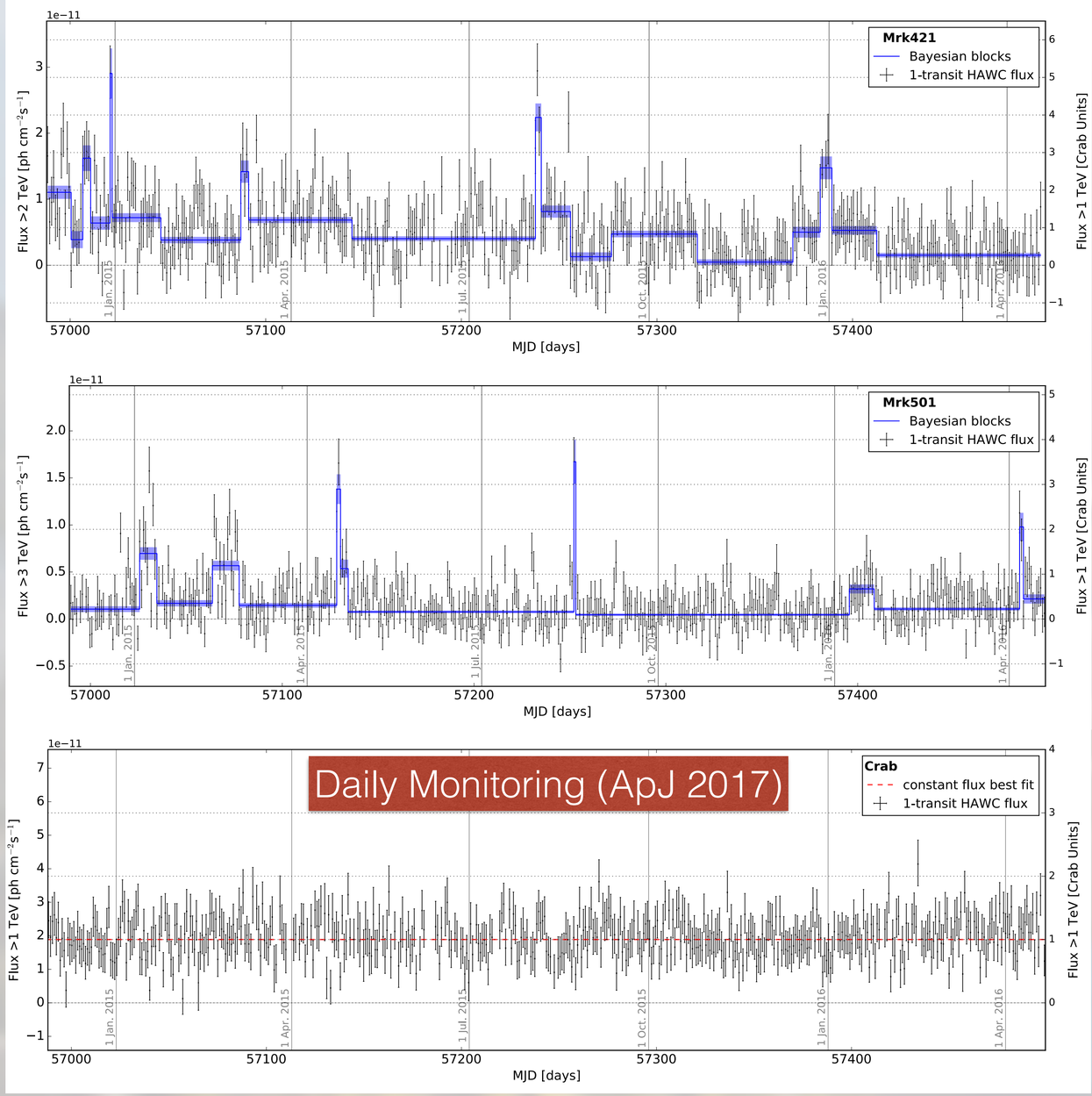




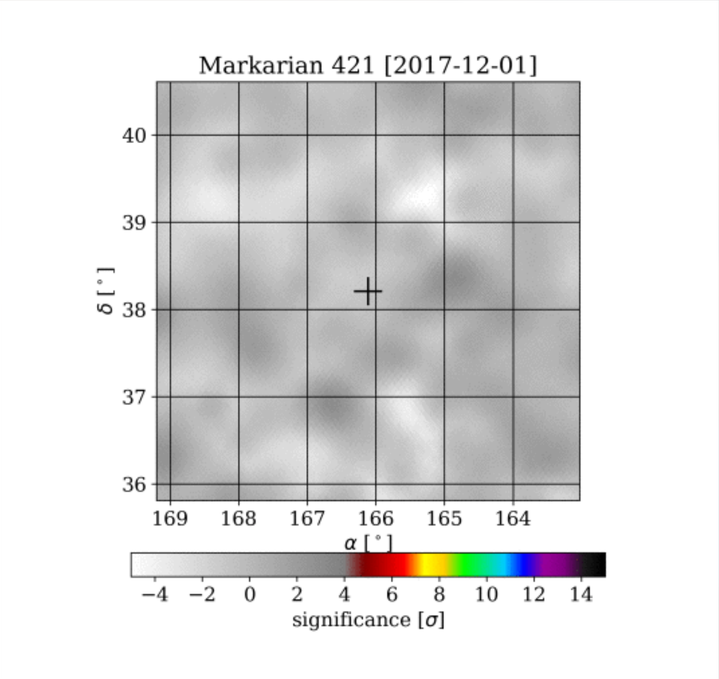
Fang et al, using 3ML (Fermi-LAT+HAWC)

Extragalactic Science

Monitoring of flaring sources



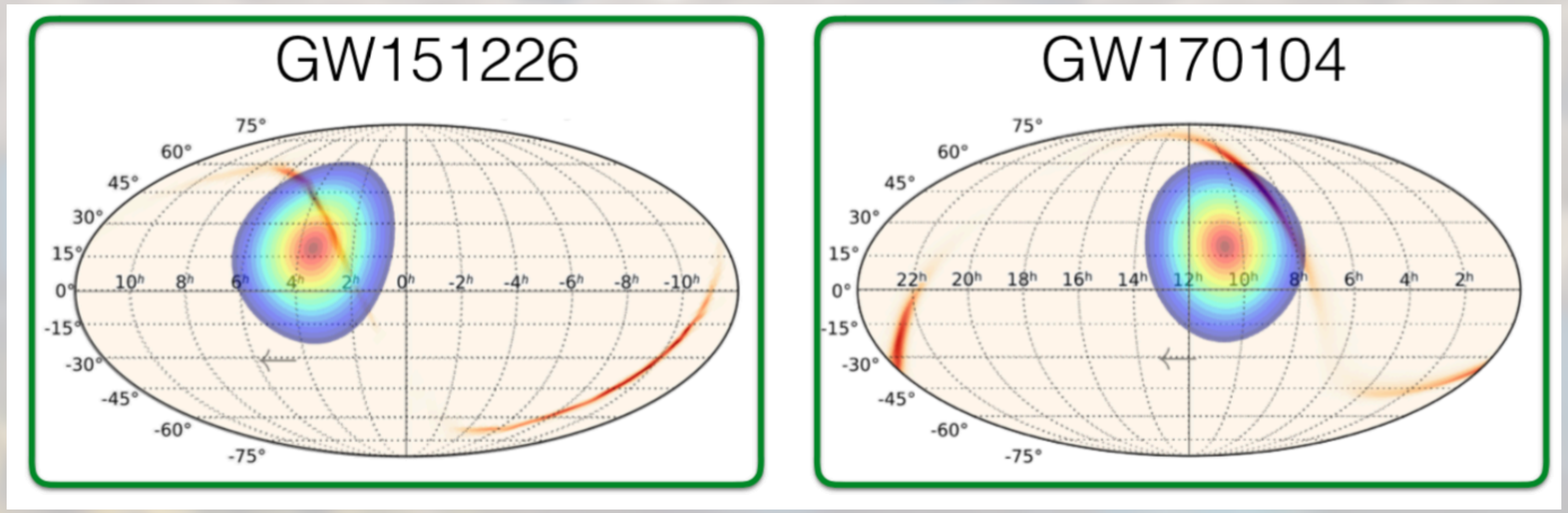
- Monitoring AGN flares:
  - ATel #8922, #9137, #9936, #9946, #11077, #11194.
  - Many notifications under MoU.
- Monitoring few hundreds sources on multiple time scales (seconds to days).



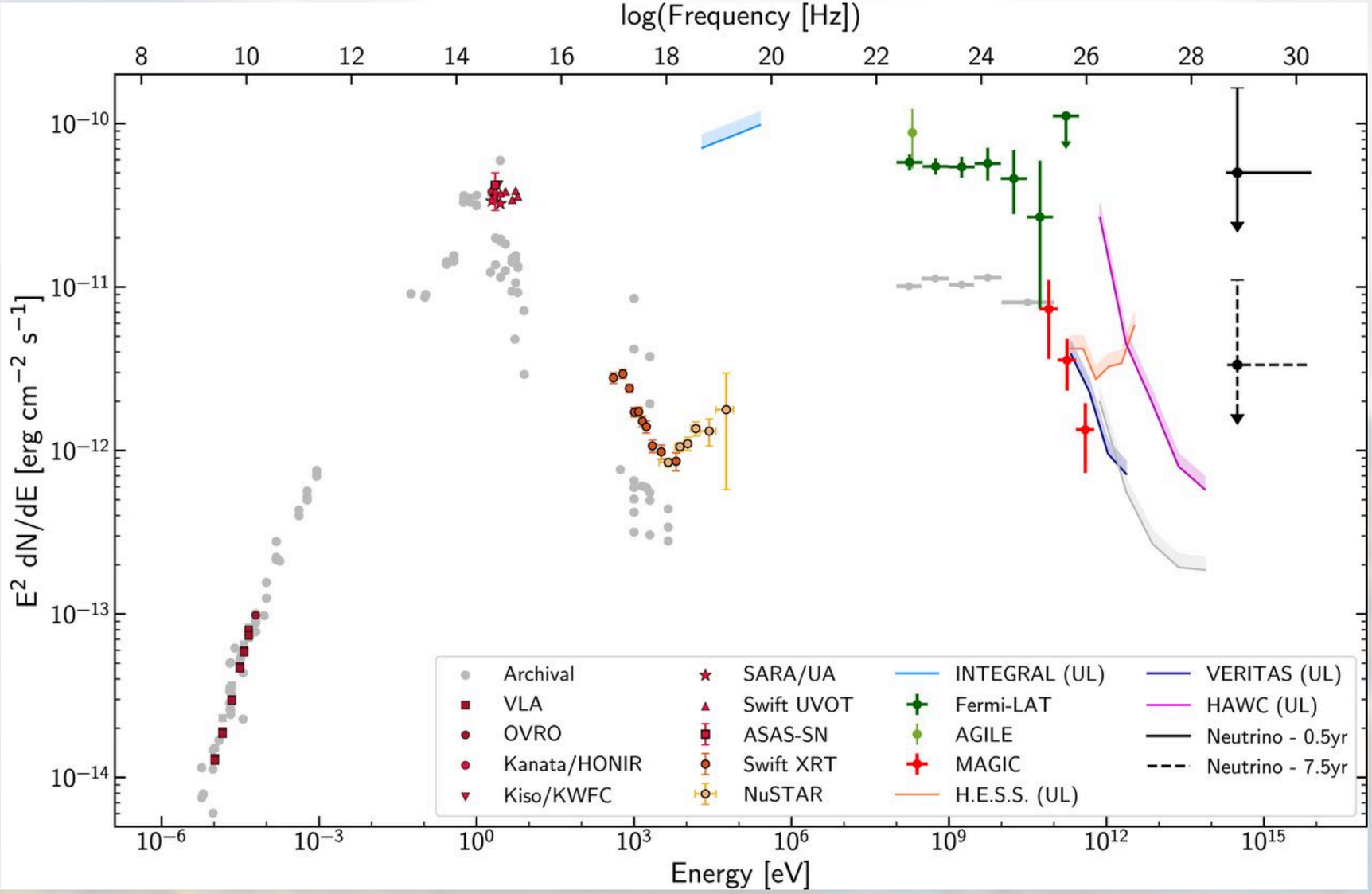
Transients and multi-messenger

- HAWC can 1) send alerts 2) followup transients even after the fact
- No detection yet, but searches in coincidence with
  - GRBs (ApJ 2017)
  - Gravitational Wave events (ApJ 2017, w. LIGO, Virgo, etc.)
  - IceCube PeV neutrinos (A&A 2017 w. IceCube, *Fermi*-LAT)
  - IceCube TXS 0506+056 flare (Science 2018 w. IceCube, *Fermi*-LAT, MAGIC and many more)
  - Joint IceCube / HAWC analysis to search for galactic neutrinos
- Self triggered transient (ApJ 2017)

HAWC FoV at the time of the GW events



IceCube TXS 0506+056 flare

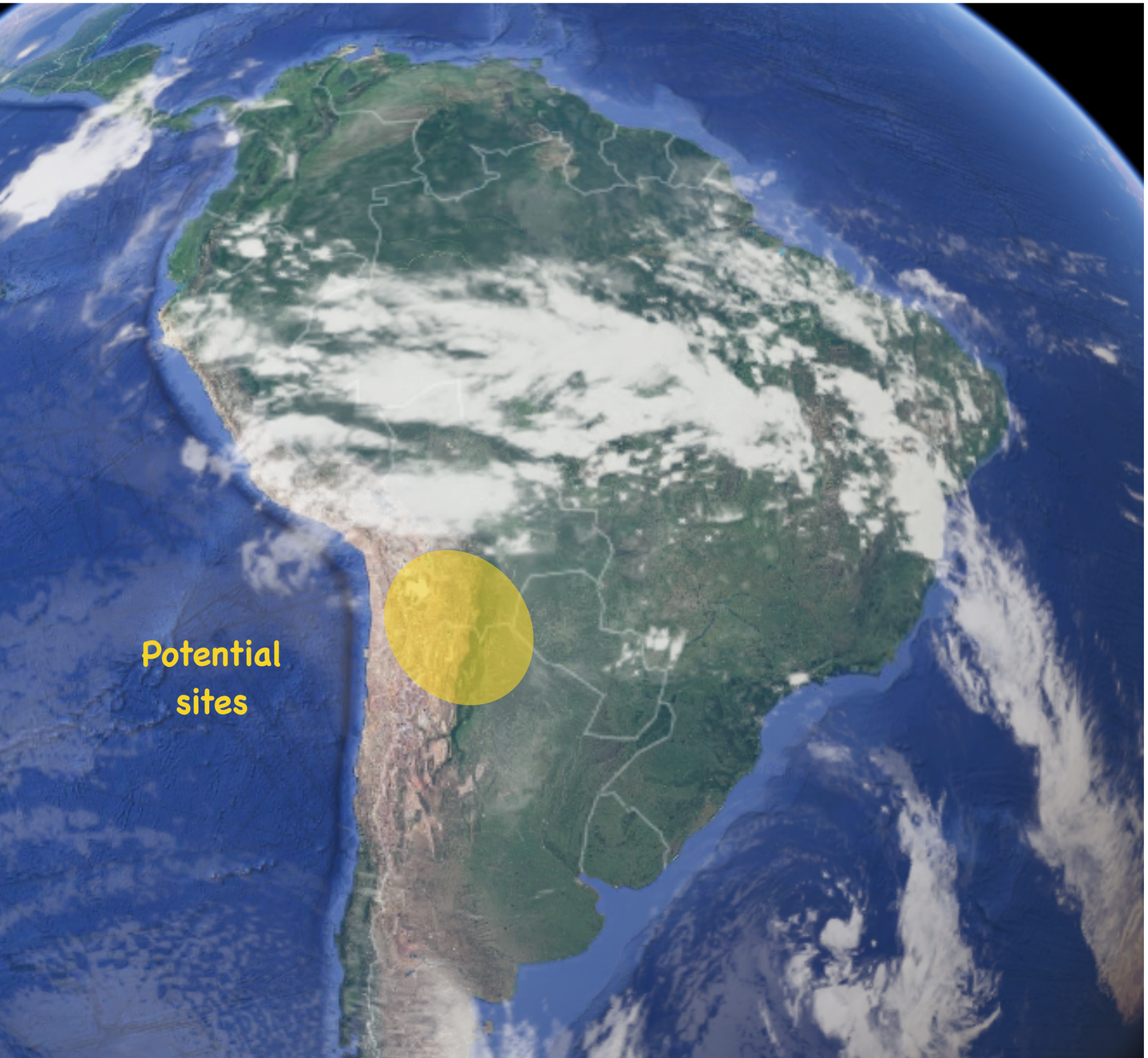


https://arxiv.org/pdf/1807.08816.pdf

Science 13 Jul 2018

Next generation — SGSO

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY



- Proposed wide field of view instrument to be located in the southern hemisphere
- Several candidate sites considered, including in Argentina, Chile, Bolivia, and Peru
- Latitude of ~24° S optimizes sensitivity to Galactic sources, especially Galactic Center
- Improvements to sensitivity
  - Higher altitude: extend sensitivity to lower energies (aim for 200—300 GeV)
  - Larger detector
  - Better gamma/hadron separation
  - Better electronics

More info and join at:
https://www.sgso-alliance.org

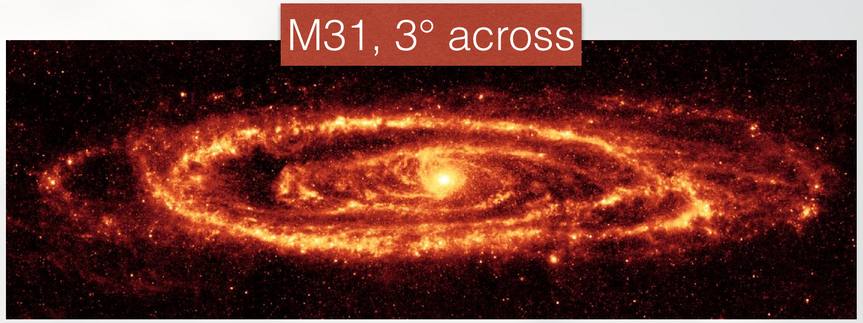
Summary

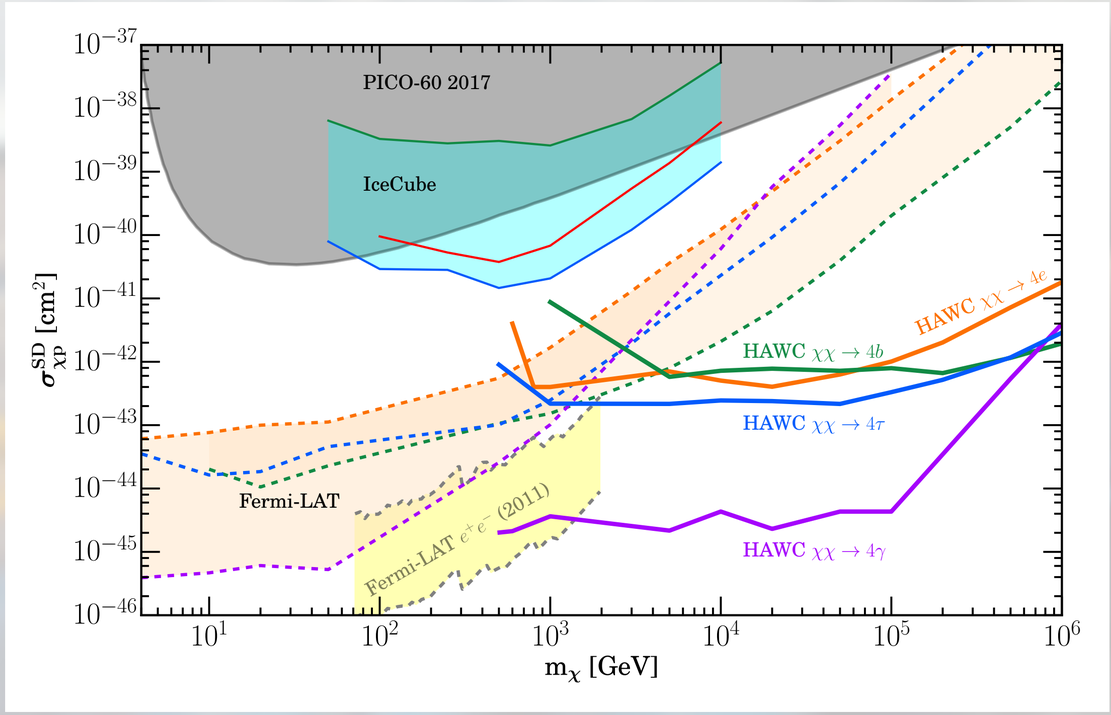
- Analyses are running, new sources are discovered and characterized, science results.
- HAWC uniquely suited for extended sources and high energy.
- New class of nearby TeV halos (Geminga, Monogem, …), inefficient diffusion.
- First observation of jets in TeV: SS 443, likely leptonic.
- Exciting multi-messenger / multi-instrument activities.
- Public data available at data.hawc-observatory.org
- **Strong Overlap with Fermi LAT - Several projects ongoing**
  - **ThreeML for joint analysis between Fermi-VERITAS-HAWC (X-rays,…)**

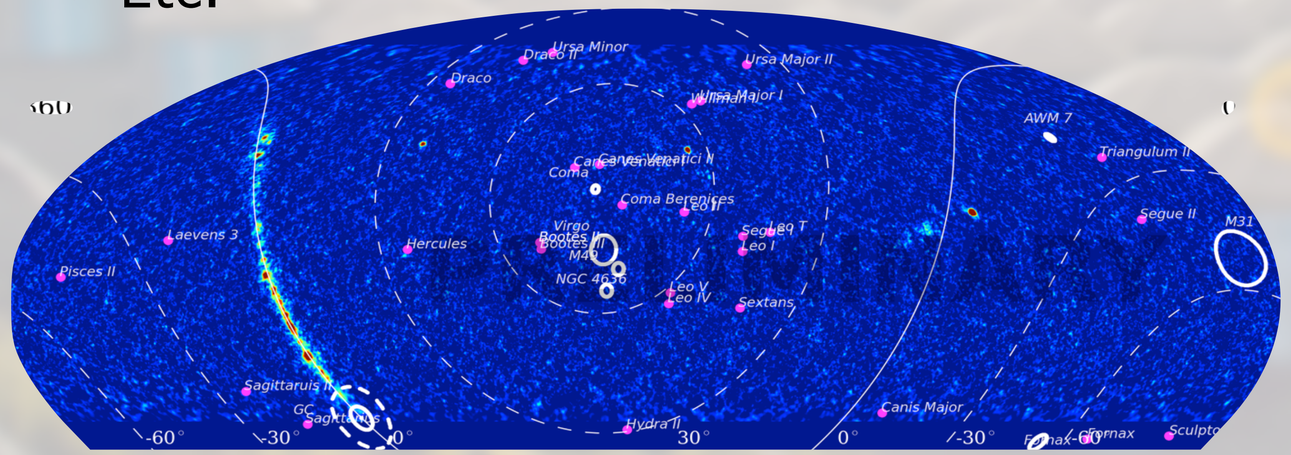
Backup Slides

Dark matter searches

- 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.

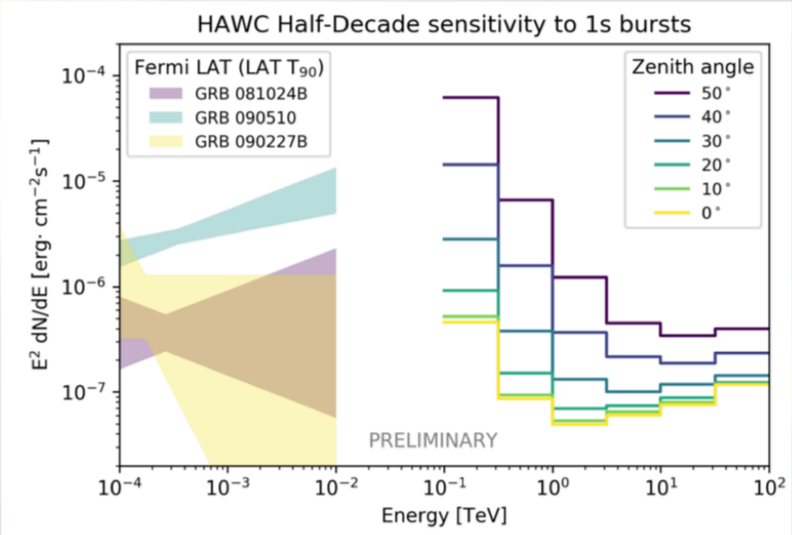


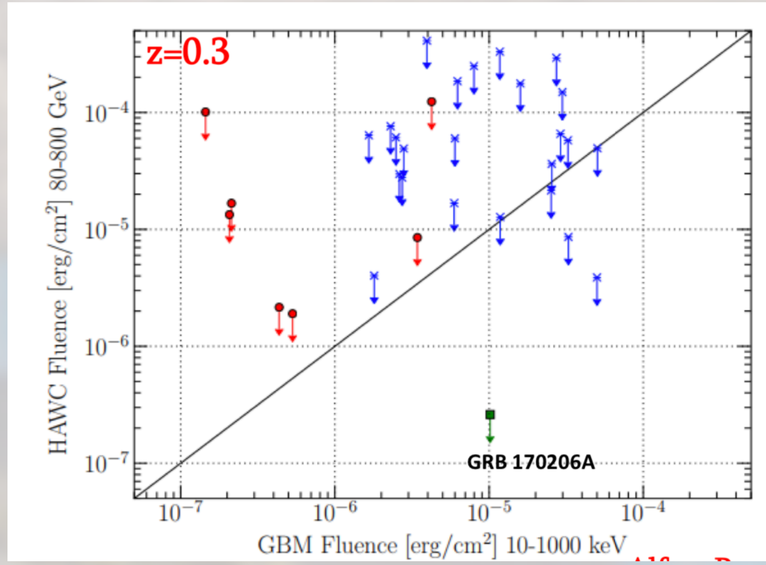


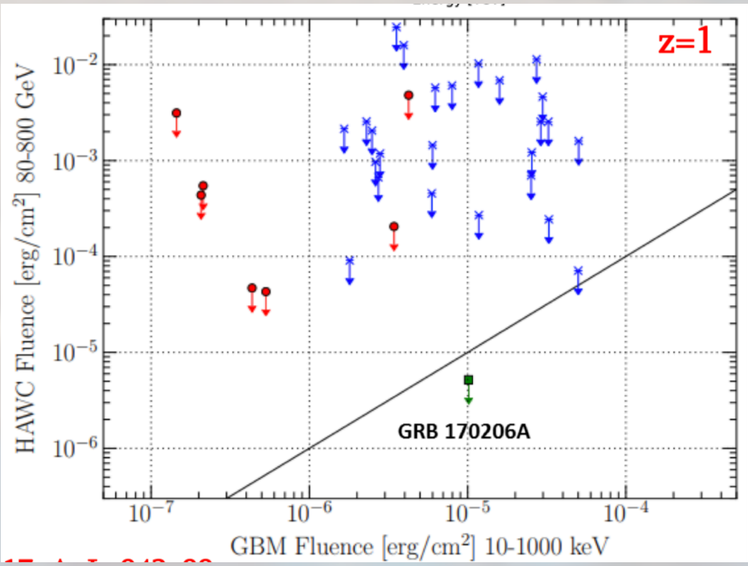


Gamma-Ray Bursts

- Sensitivity studies show that brightest GRB can be detected by HAWC
- GRB 170206A with 11° zenith angle is the only GRB where the fluence implied by the HAWC upper limits in the HAWC energy range is below the Fermi-GBM fluence in the GBM energy range.
- The current limits on the GRB detection rate in HAWC still do not allow strong conclusions about the distribution of the high-energy photon index or cut-offs and more years of operation are needed for definite conclusions.



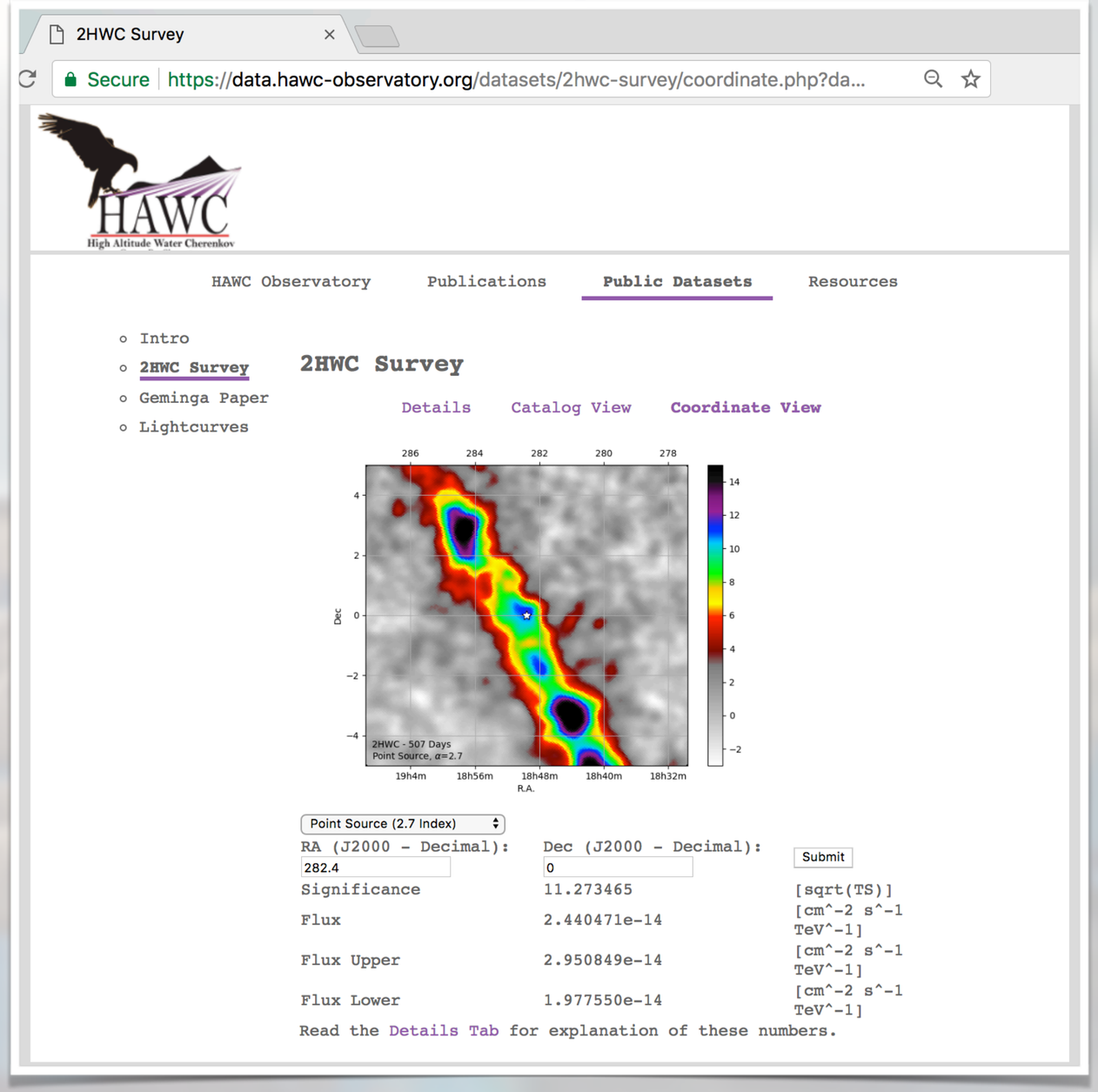




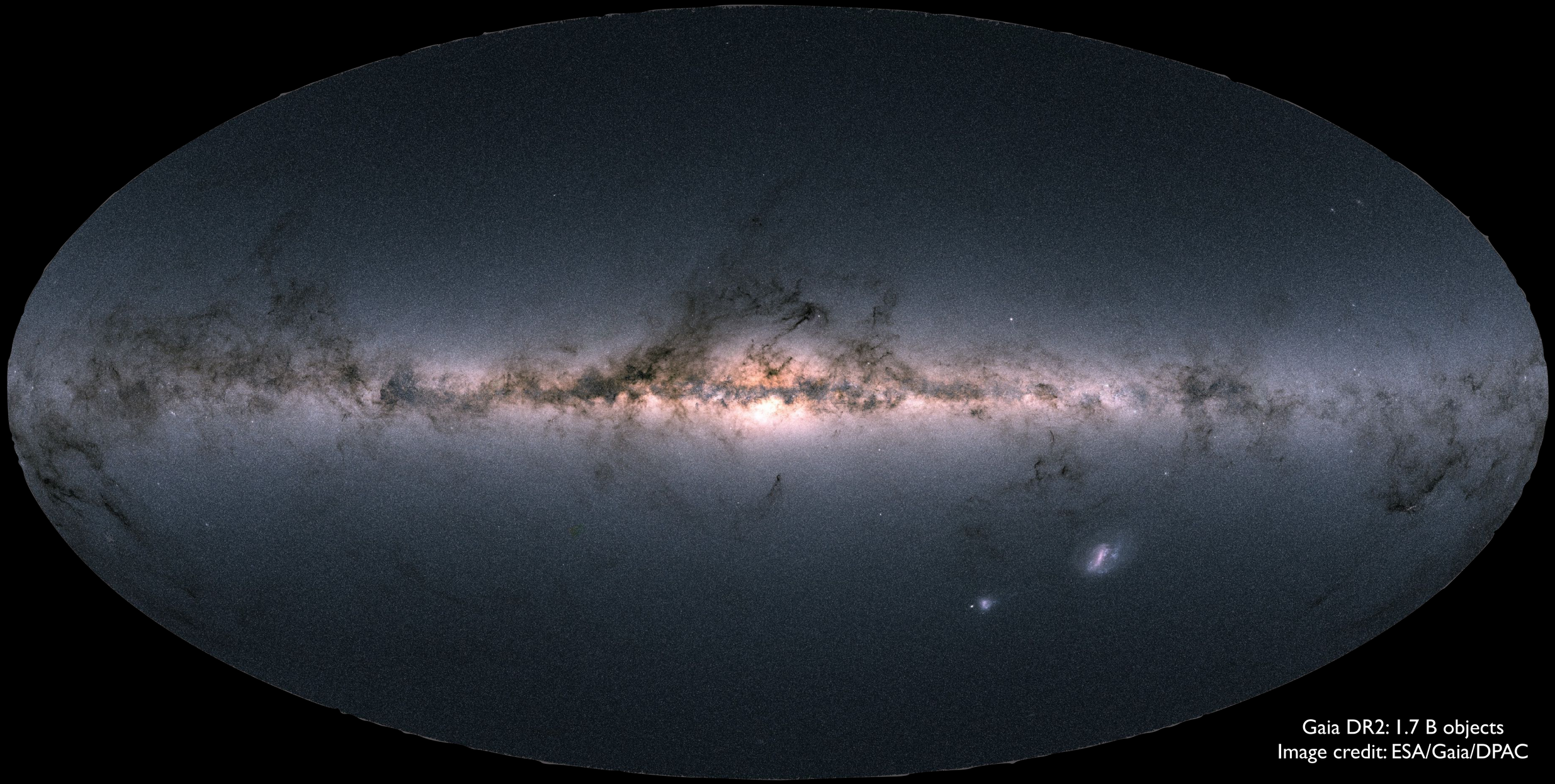
Slide from V. Baghmanyan

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/or contact us if you want more information!***
  - E.g.: D. Hooper and T. Linden, 2018, arXiv:1803.0408

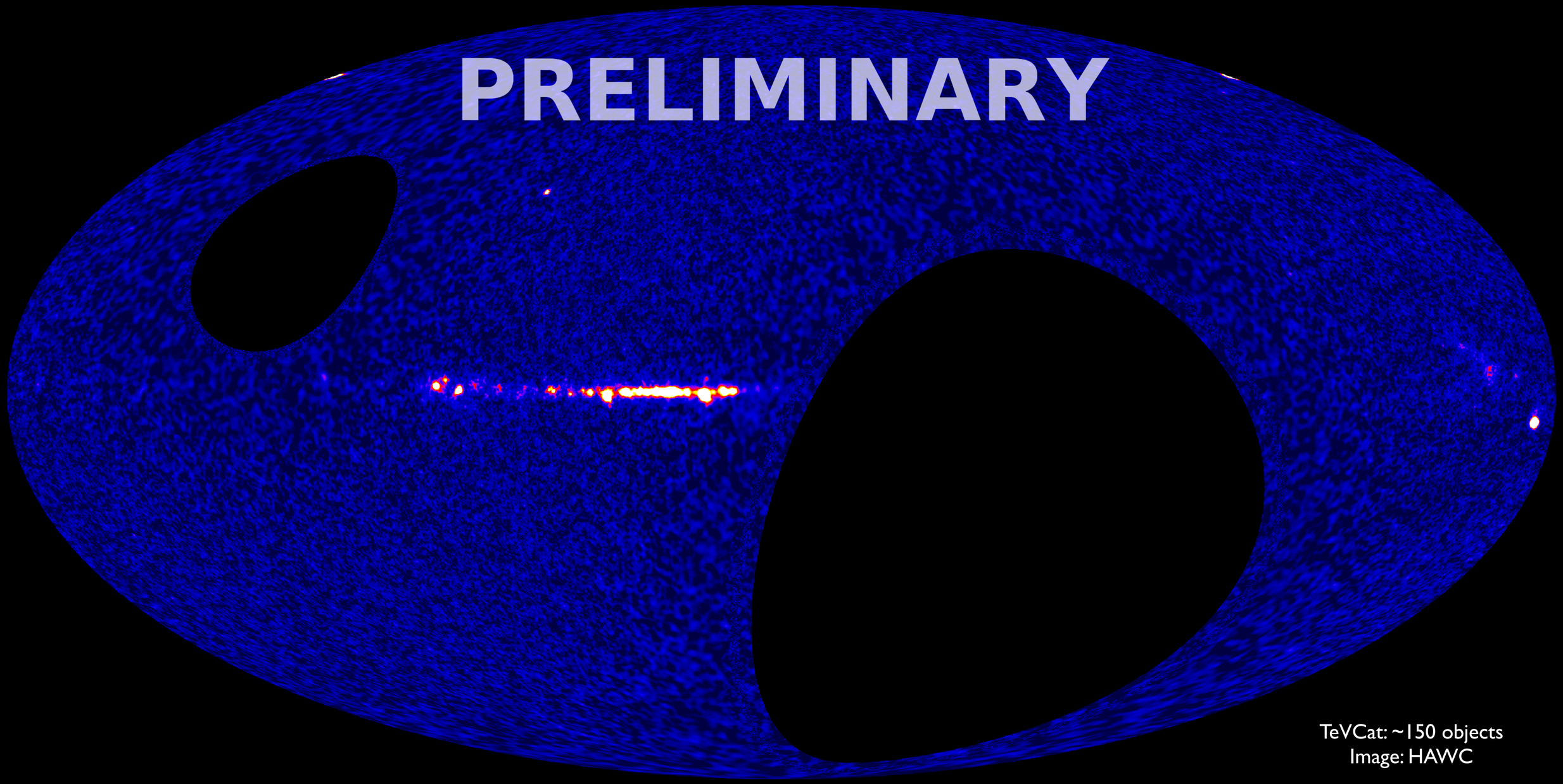


Sky — visible wavelength: billions of sources



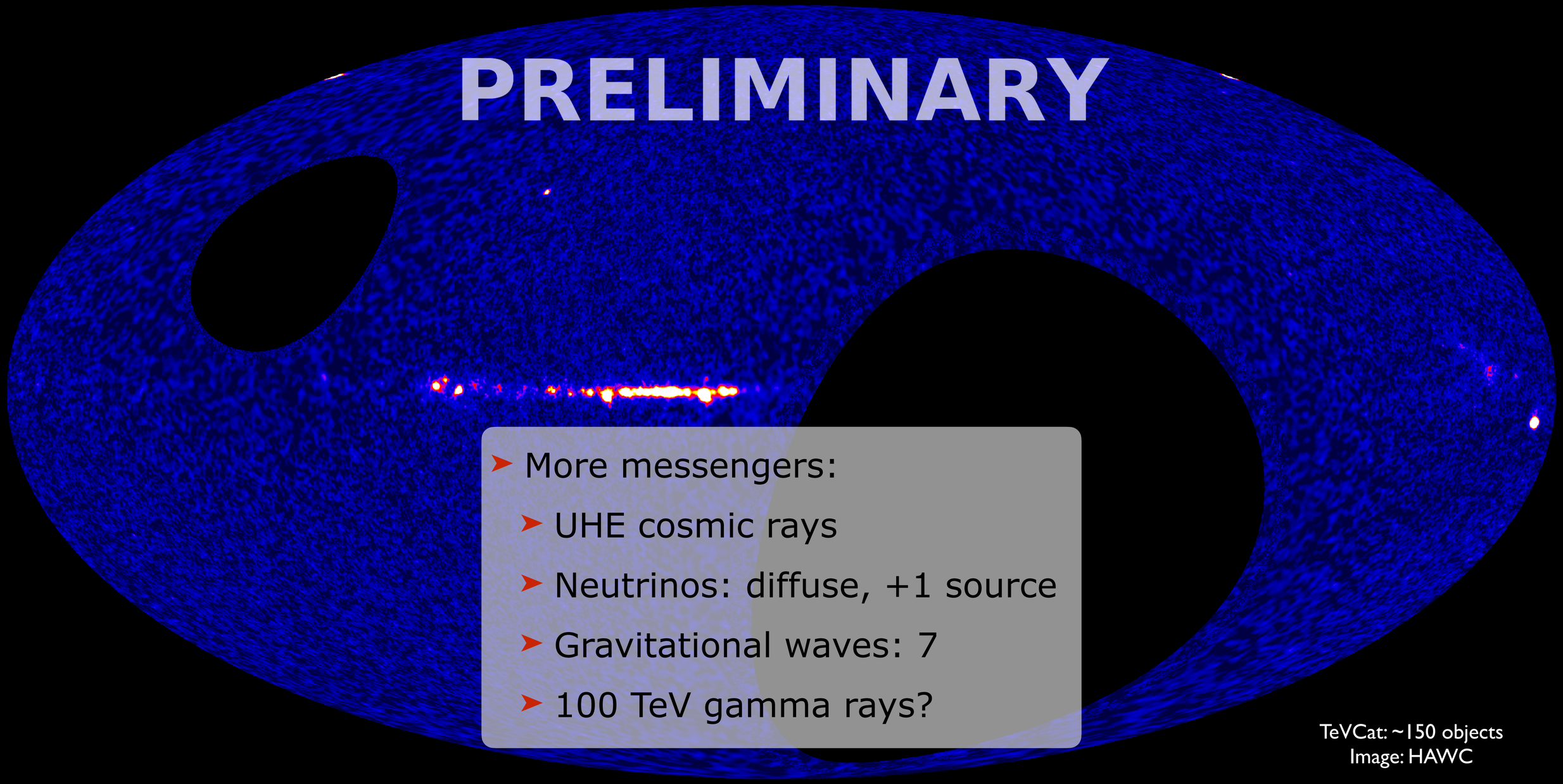
Gaia DR2: 1.7 B objects
Image credit: ESA/Gaia/DPAC

Sky — TeV gamma-rays: ~150 sources



TeVCat: ~150 objects
Image: HAWC

Sky — TeV gamma-rays: ~150 sources



- More messengers:
  - UHE cosmic rays
  - Neutrinos: diffuse, +1 source
  - Gravitational waves: 7
  - 100 TeV gamma rays?

TeVCat: ~150 objects
Image: HAWC

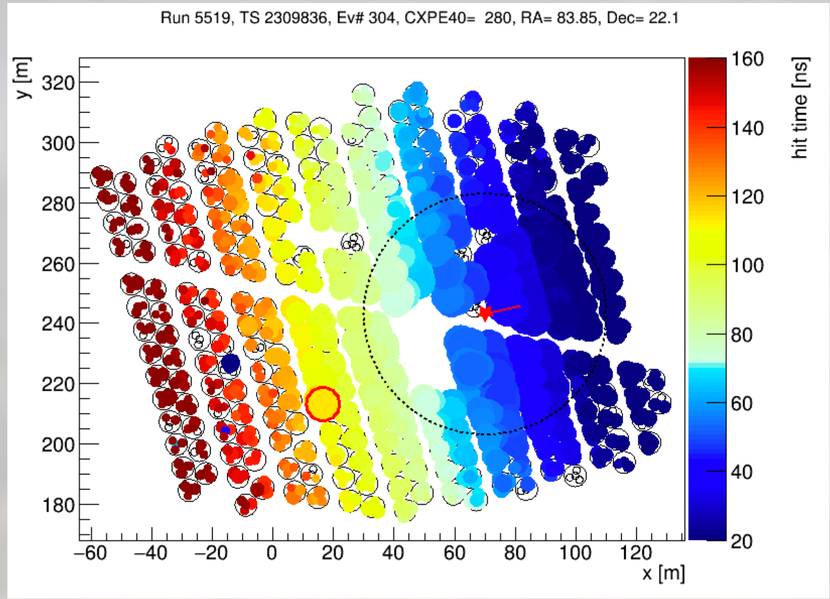
Tank Construction

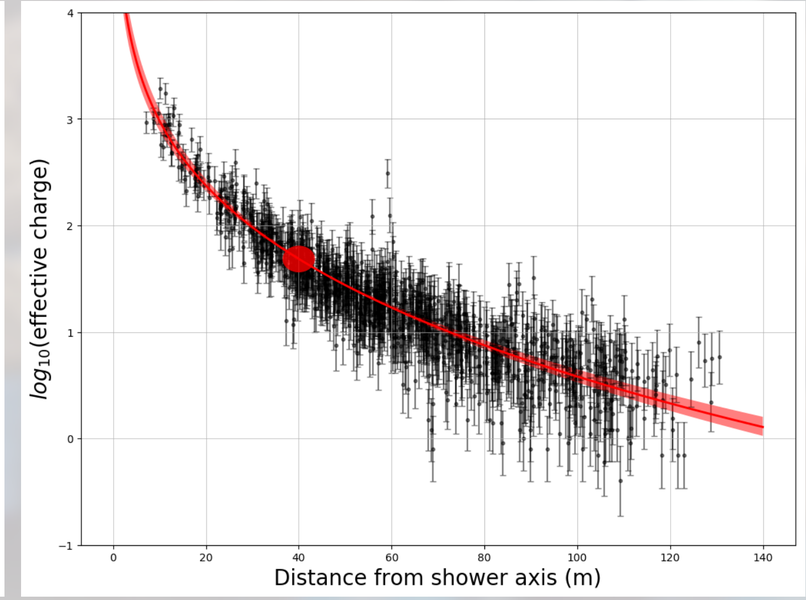
- .....

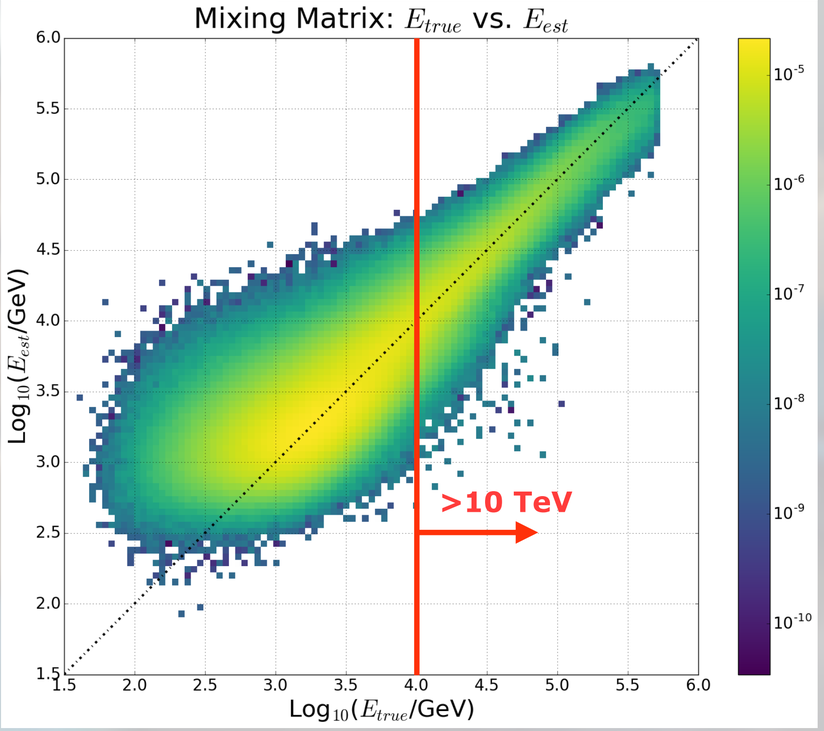
HAWC Construction

Pushing to the highest energies: New energy reconstruction

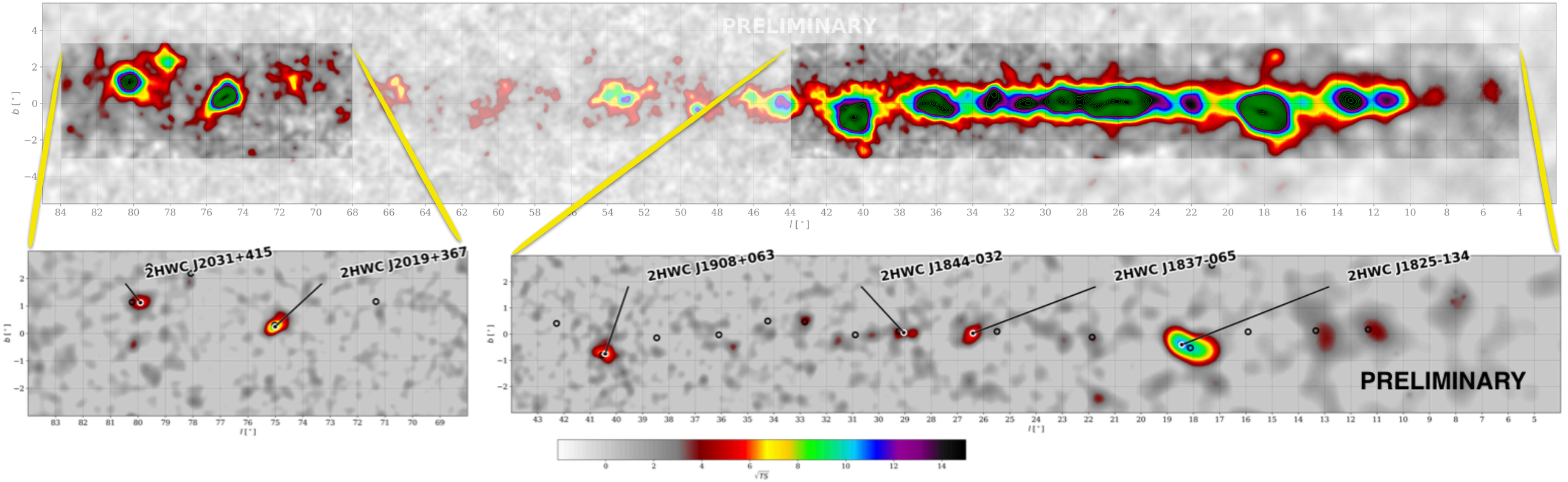
- So far, use the number of PMT seeing light as energy proxy. 10 and 50 TeV events are not differentiated.
- **New energy estimators** (neural network, ground parameter) using signal amplitude, zenith angle, etc.
- Break degeneracy, increase energy dynamic range.
- **Best performance above 10 TeV**,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





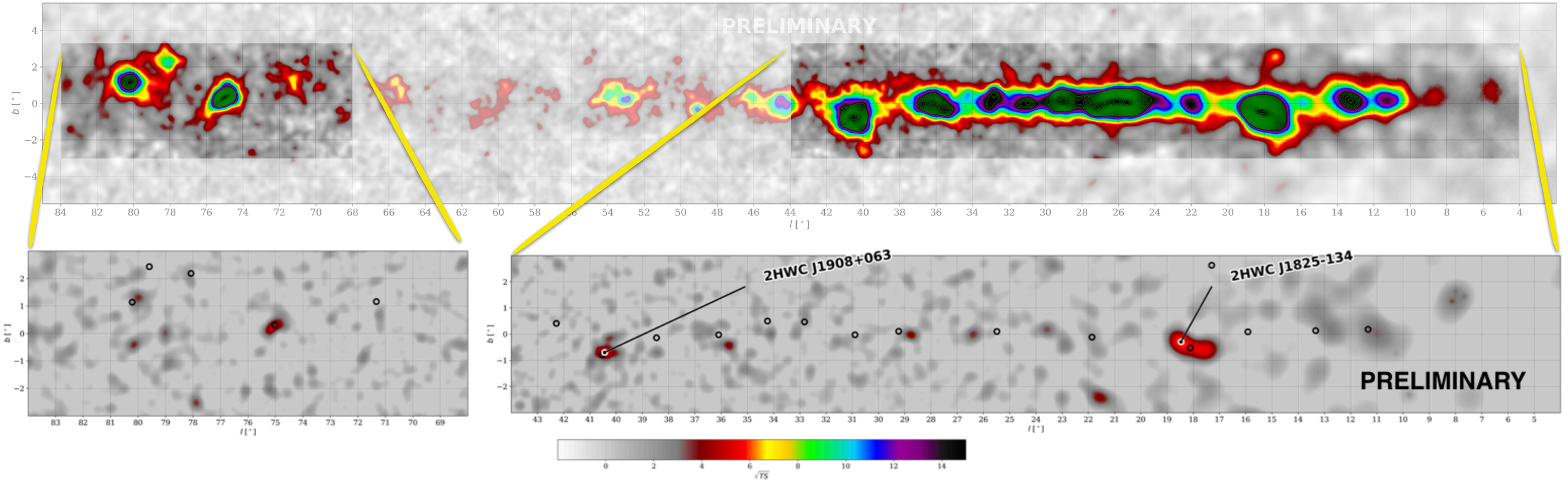


Pushing to the highest energies (E_{reco} > 56 TeV)



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

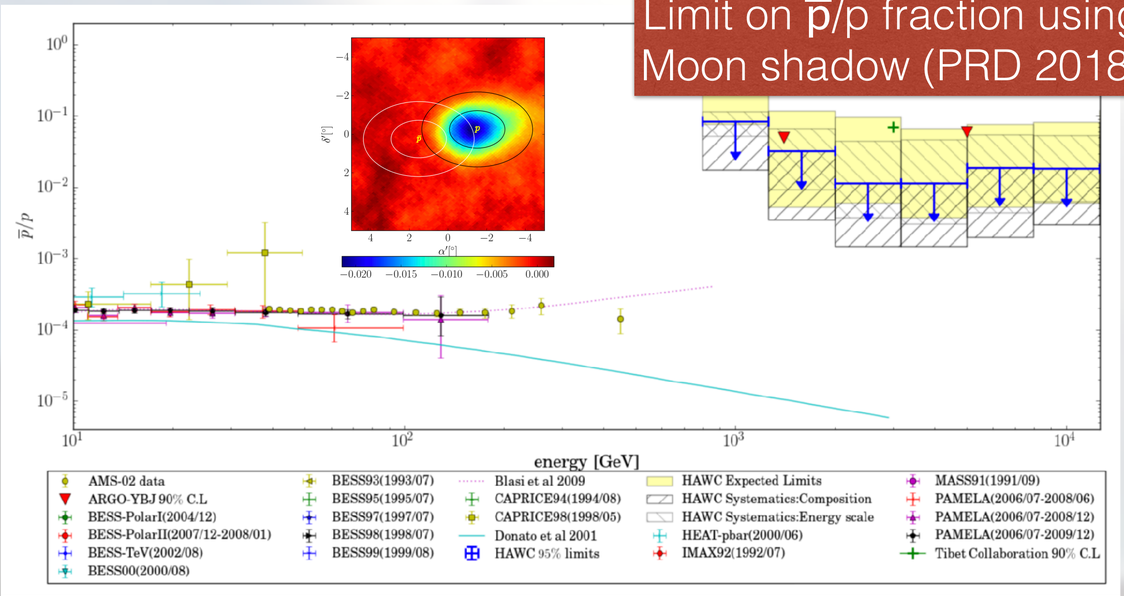
Pushing to the highest energies (E_{reco} > 100 TeV)

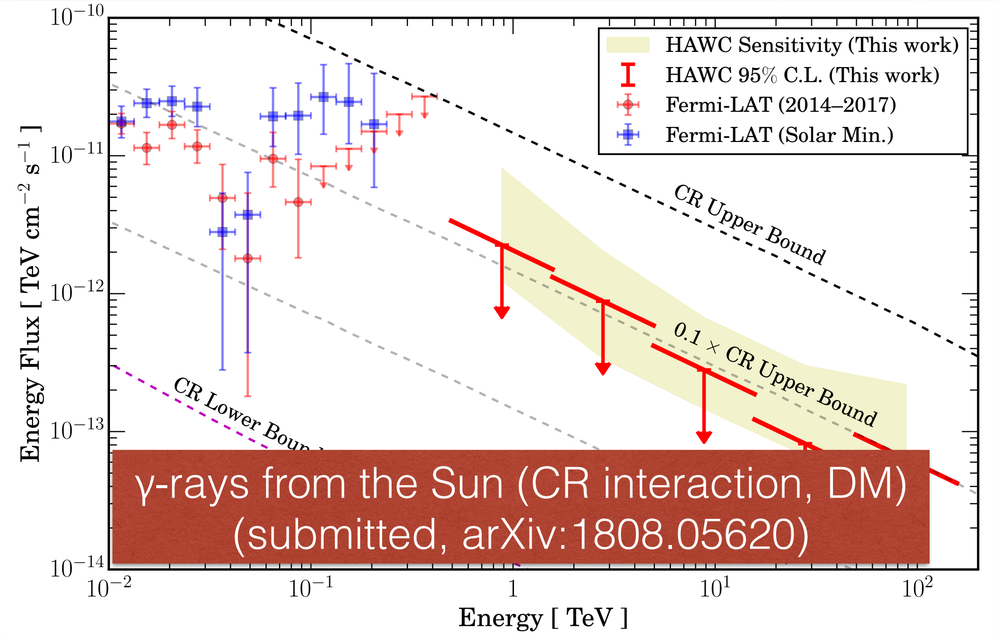


- Preliminary! Caveats: Reconstructed energy (bin migration), systematics studies ongoing.
  - Acceleration mechanisms: hadronic?
  - Correlation with neutrinos?
  - Prospects for testing Lorentz Invariance Violation.

Cosmic rays

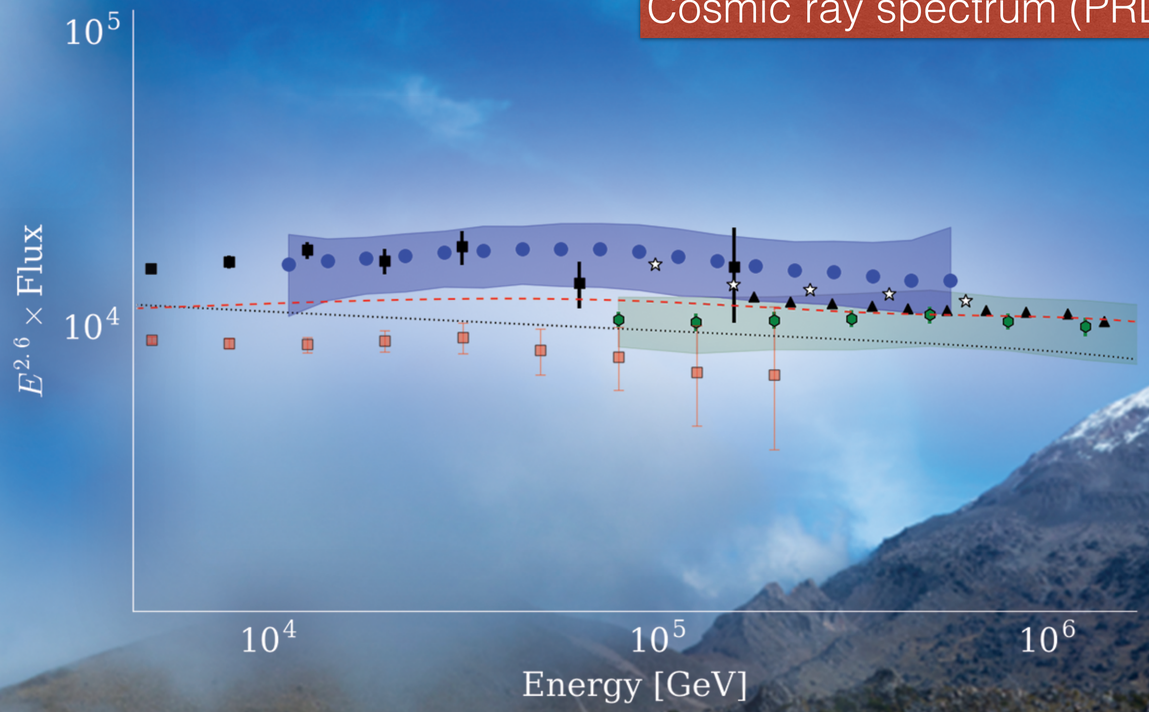
Limit on $\bar{p}/p$ fraction using Moon shadow (PRD 2018)





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