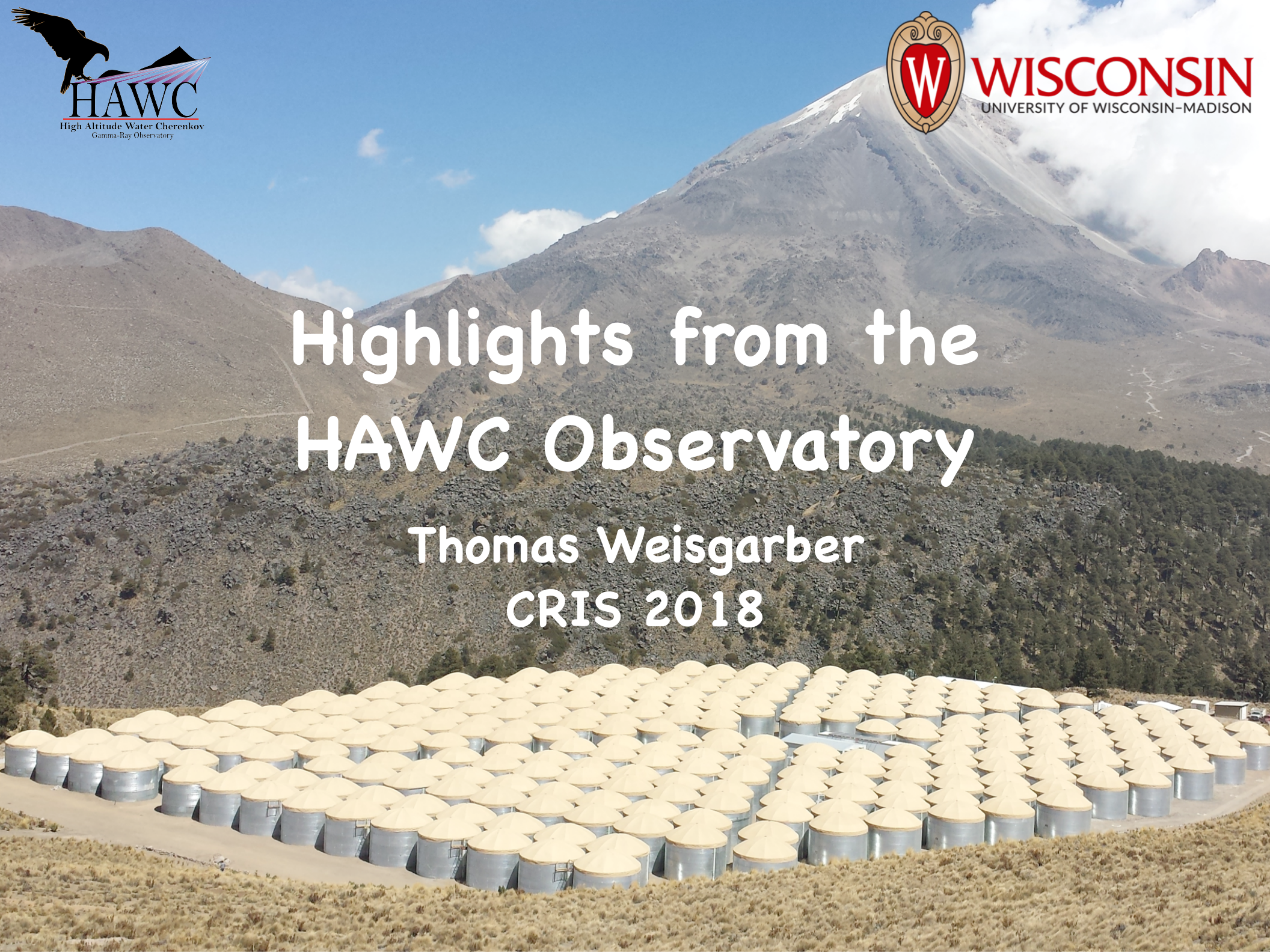

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON
Highlights from the
HAWC Observatory
Thomas Weisgarber
CRIS 2018

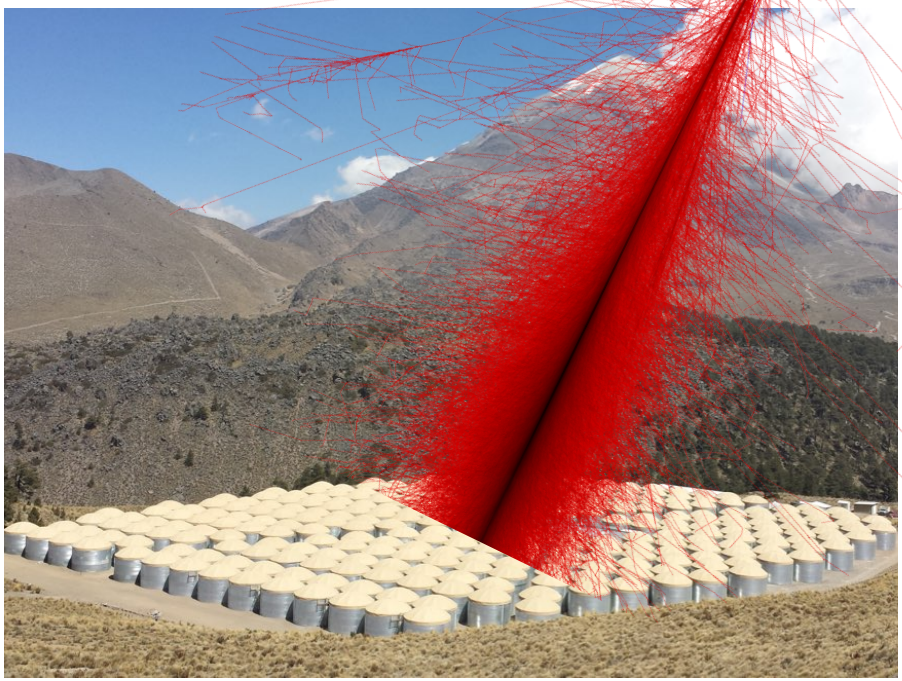
Overview

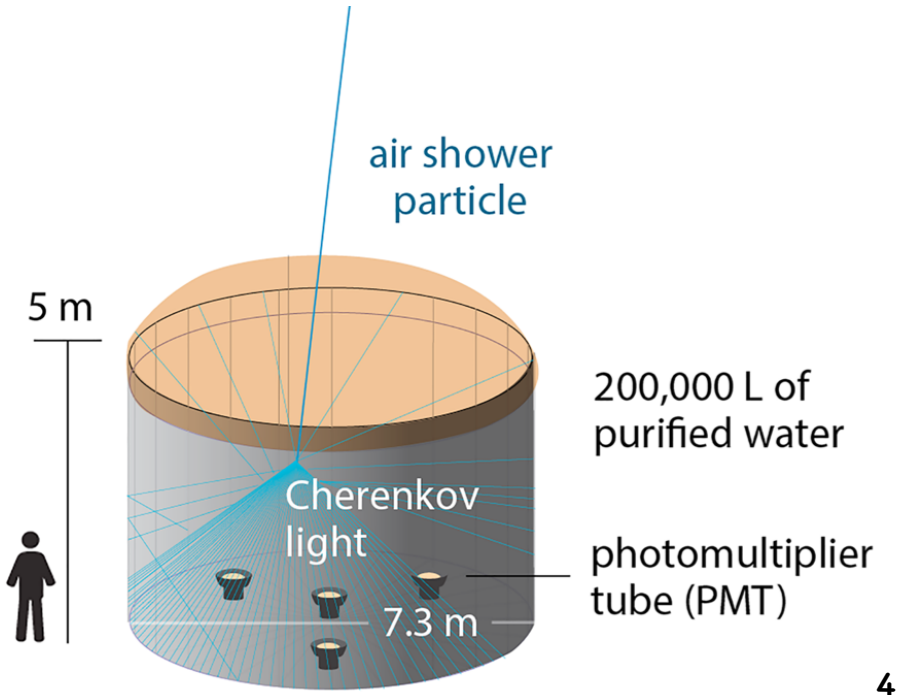
- HAWC design and sensitivity
  - HAWC view of the gamma-ray sky
- Galactic cosmic ray accelerators
- Extragalactic sources of gamma rays
- HAWC in the multimessenger era
- The future of ground arrays

HAWC design and sensitivity

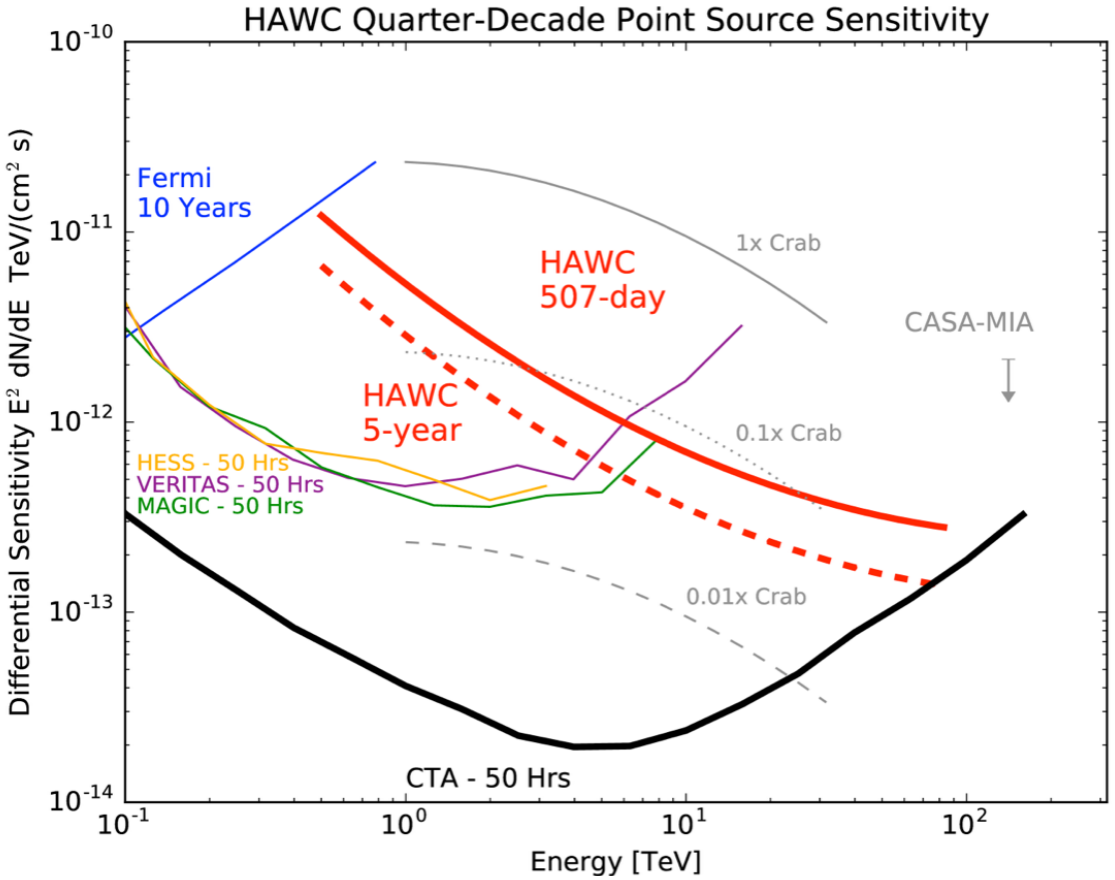
Introduction to HAWC

- High Altitude Water Cherenkov
- 4100 m above sea level at 19° N
- 300 close-packed optically isolated water Cherenkov detectors
- Detects air showers from gamma rays and cosmic rays above 100 GeV
- Wide field (2 sr) survey instrument
- Near-100% duty cycle
- Fully operational as of March 2015

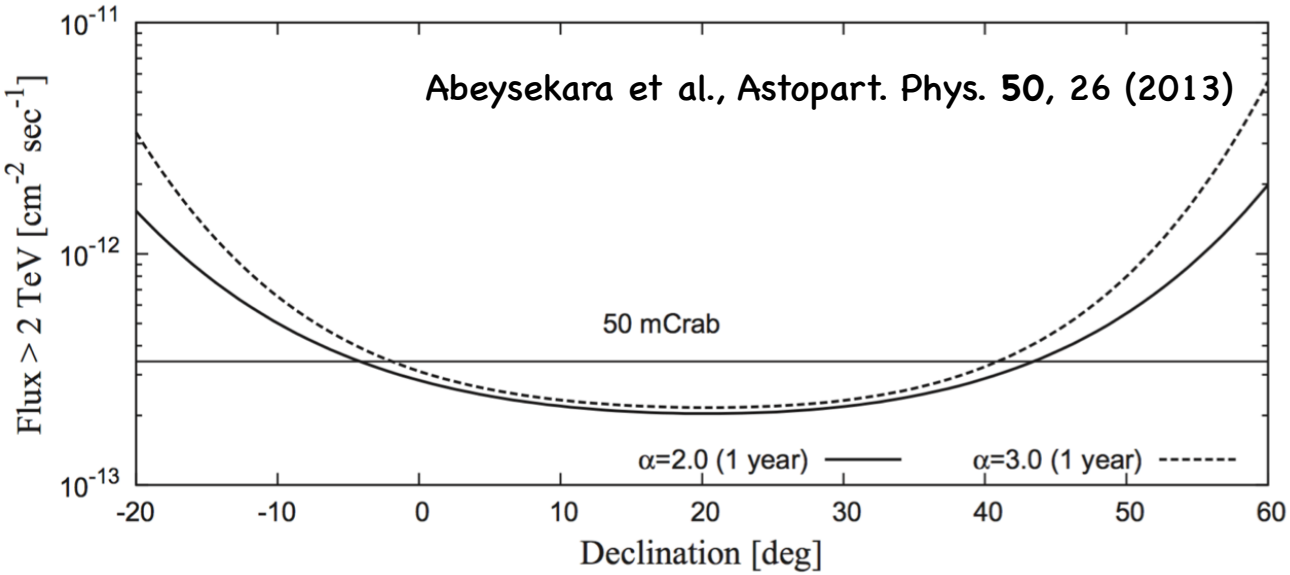




Gamma-ray sensitivity

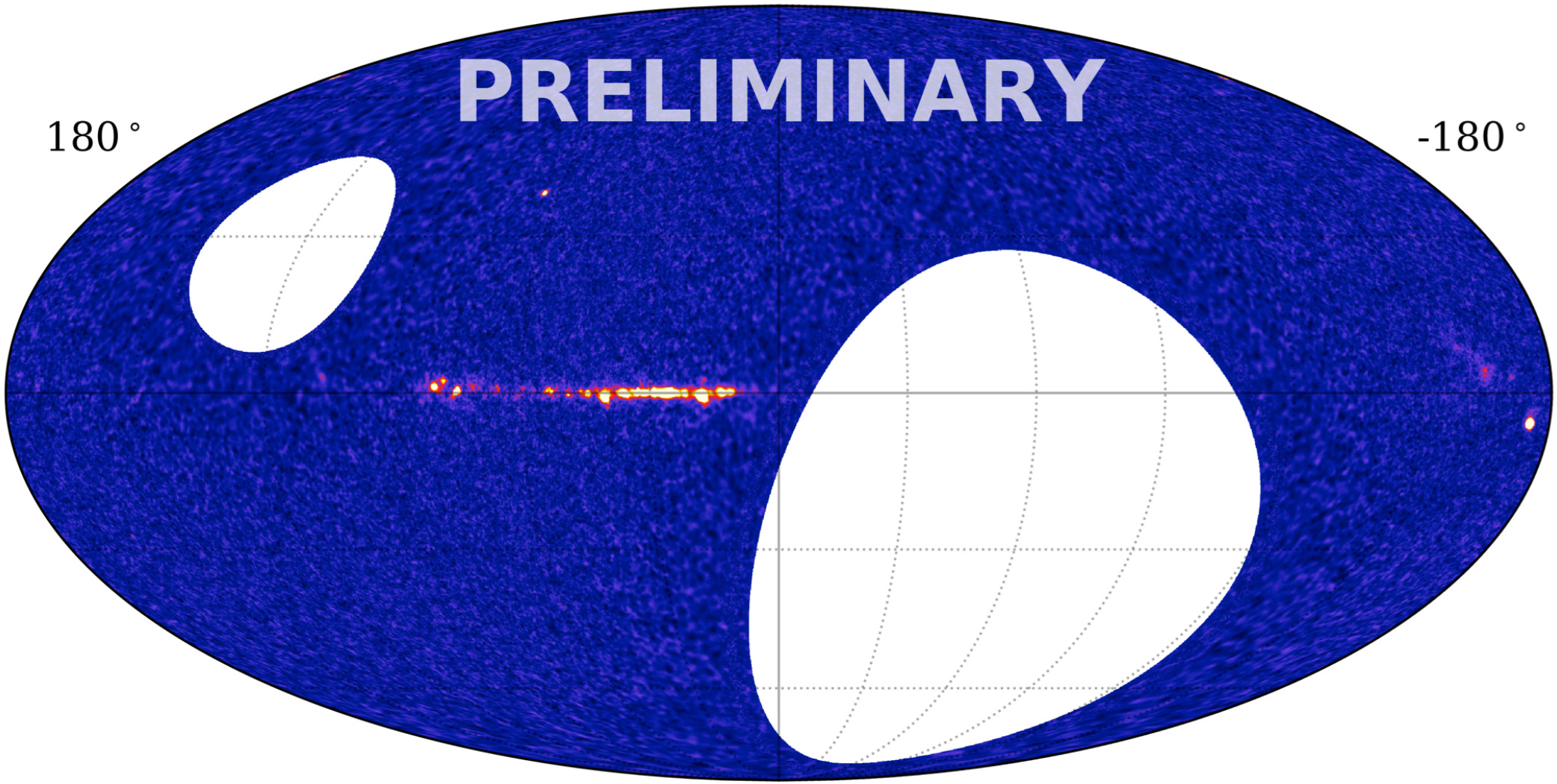


- HAWC separates gamma rays from hadrons based on air shower morphology
- HAWC sensitivity applies to a large fraction of all sources over the sky
- Complementary to pointed observations by IACTs
- HAWC is the most sensitive existing instrument above 10 TeV



HAWC view of the gamma-ray sky

- HAWC significance map in Galactic coordinates
- 1017 days of livetime from November 2014 to December 2017



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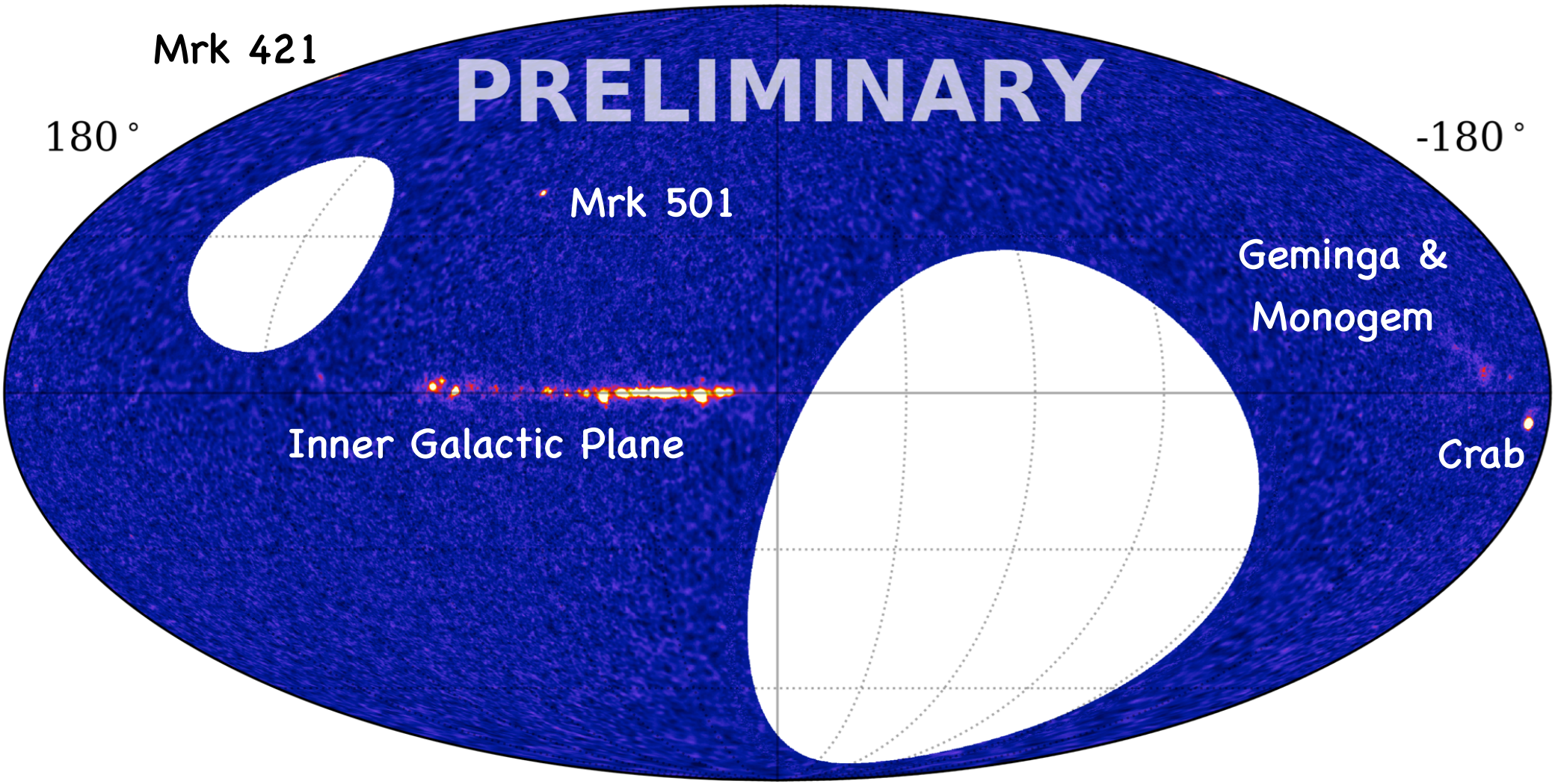
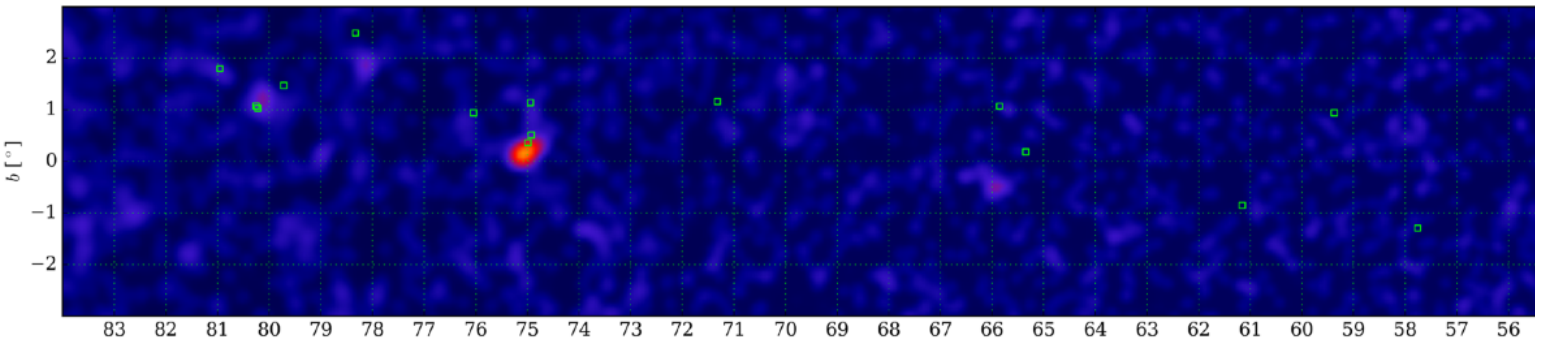
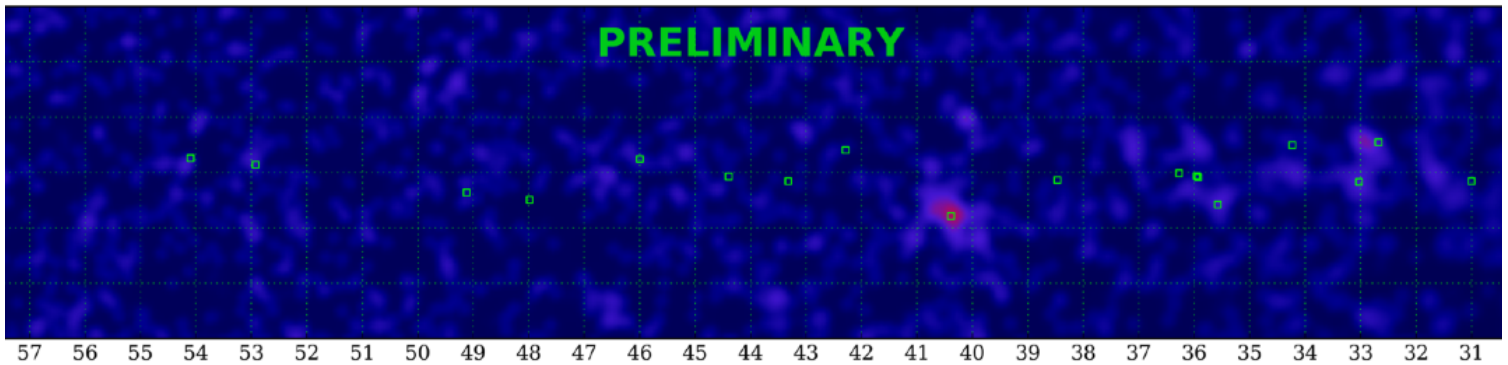


HAWC view of the gamma-ray sky

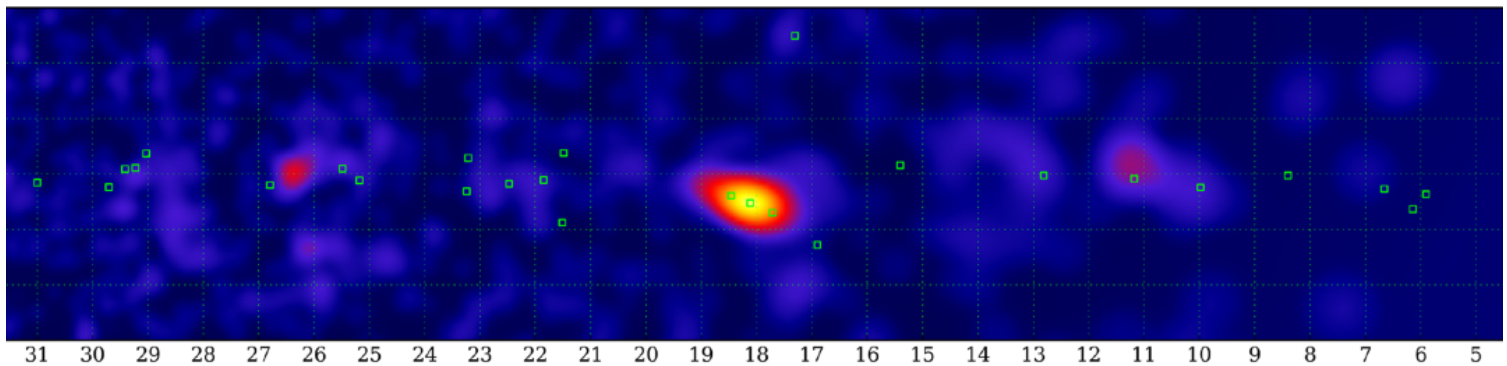
- HAWC offers the possibility of measuring high-energy cutoffs to study the highest energy Galactic cosmic ray accelerators

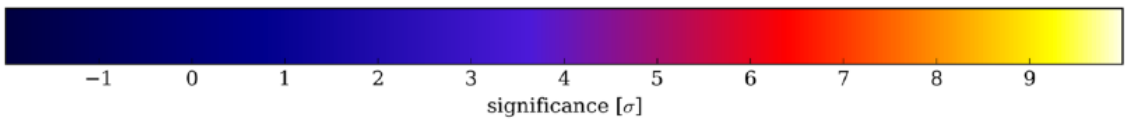


911 days livetime



Galactic Plane at energies > 56 TeV





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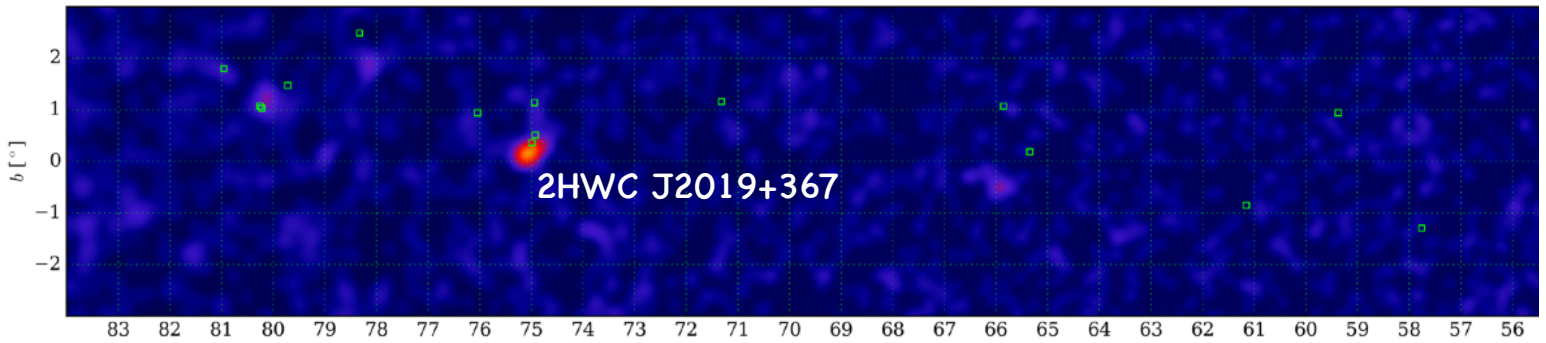

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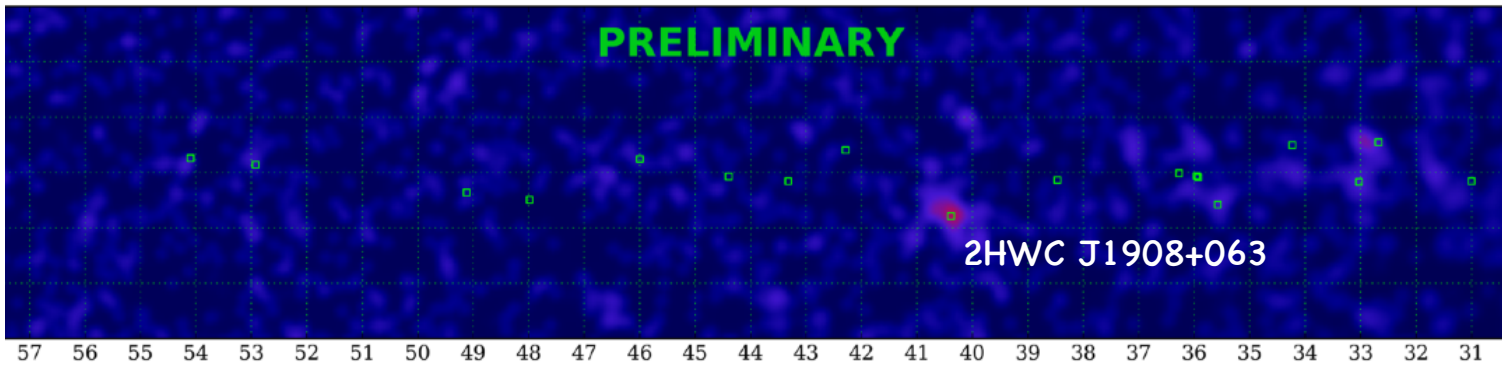

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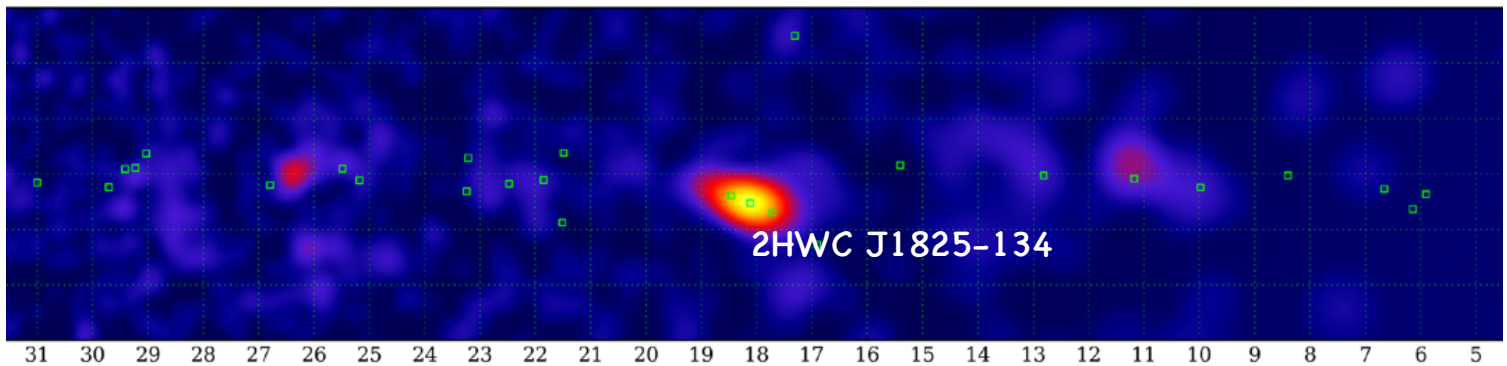

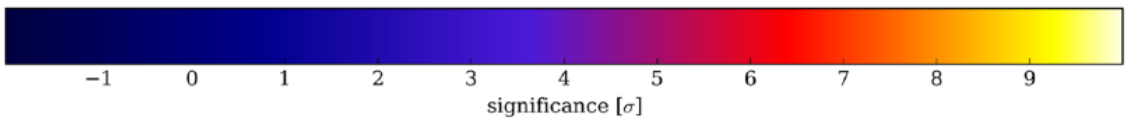

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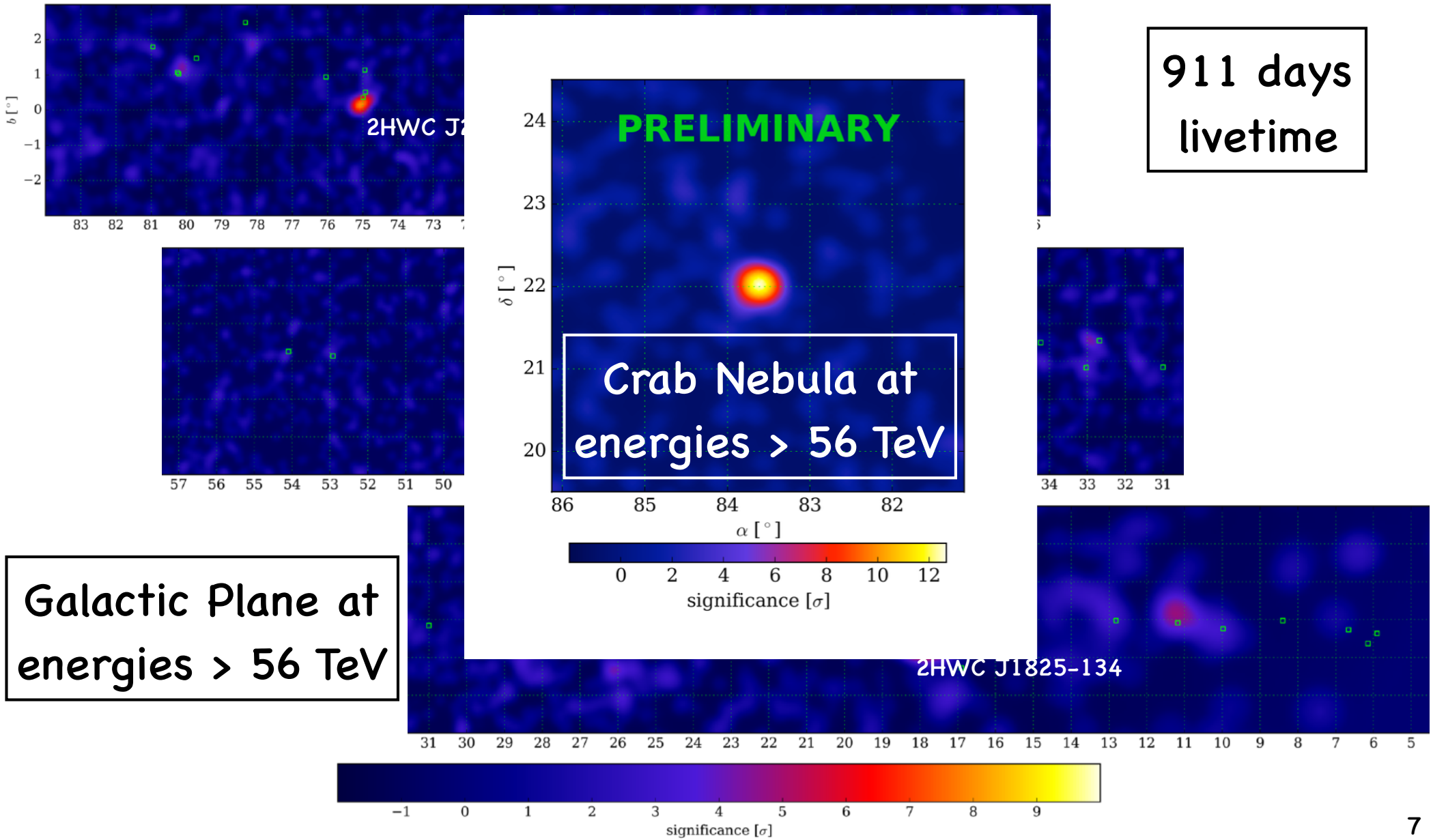
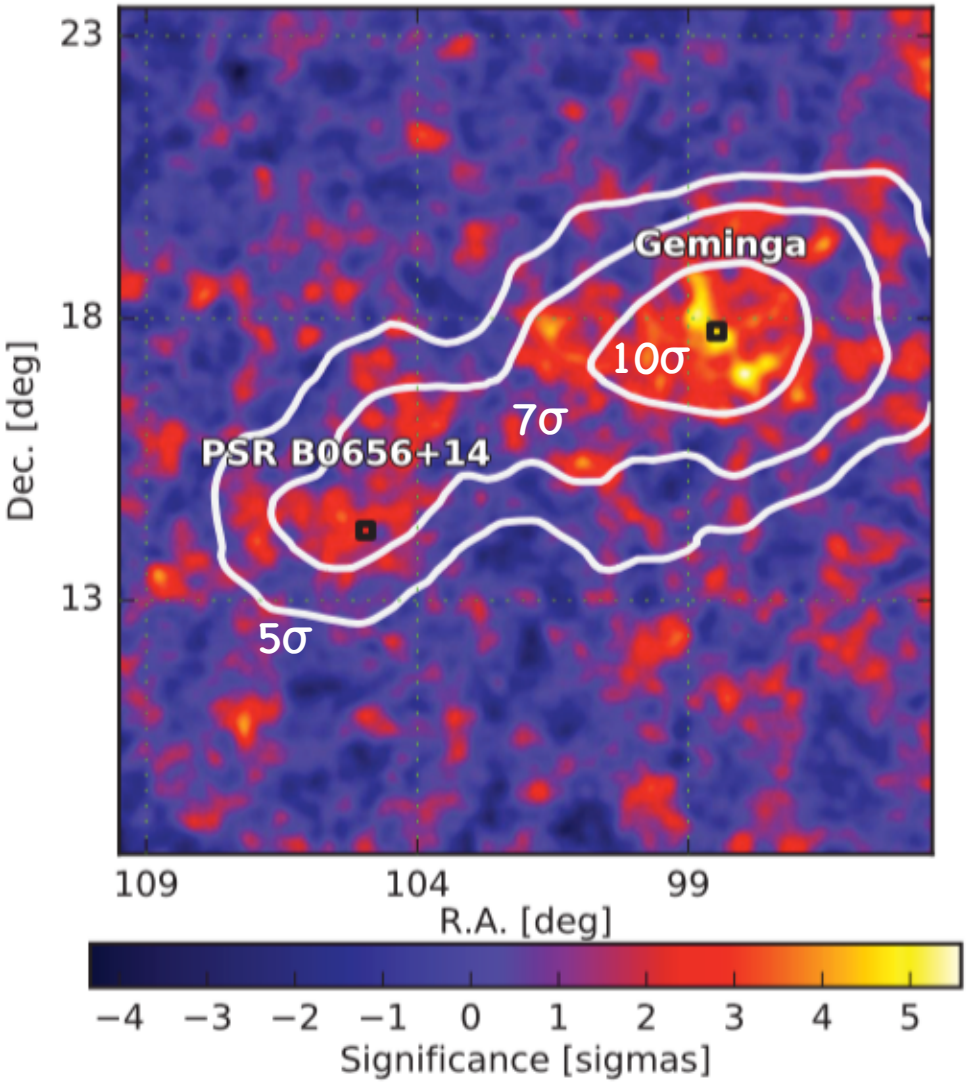
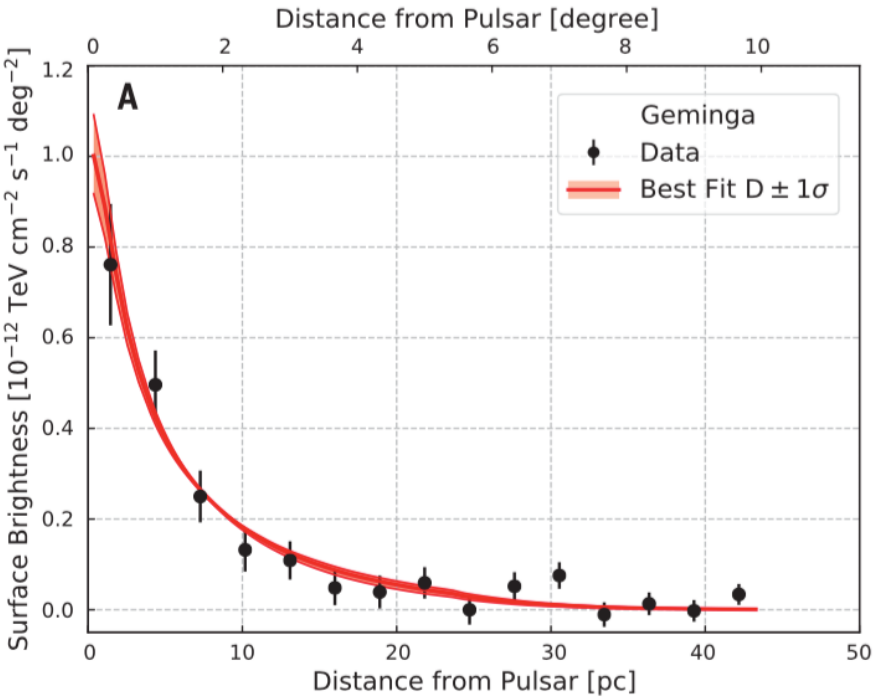


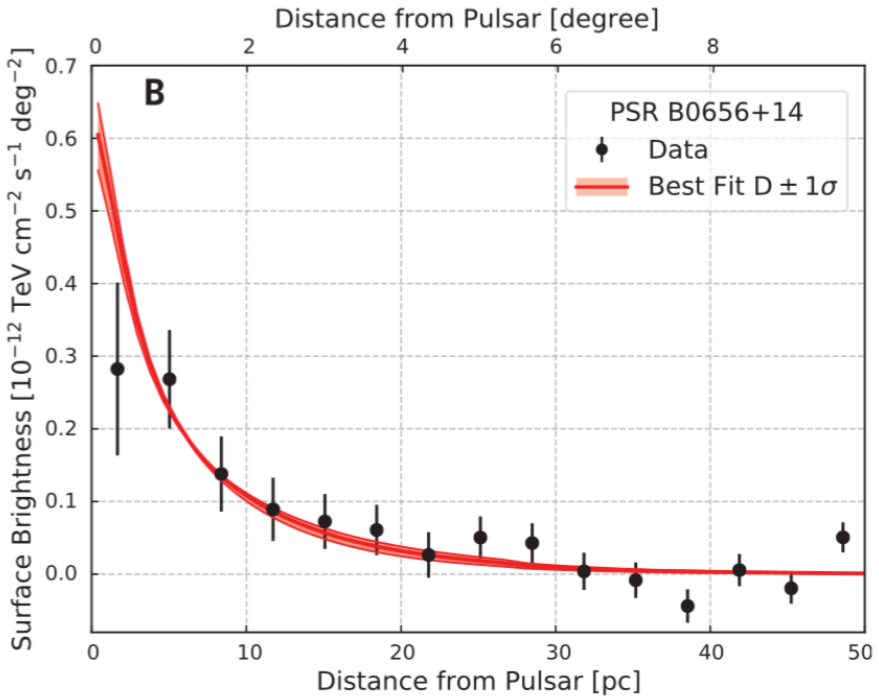
HAWC view of Galactic cosmic ray accelerators

Local accelerators: Geminga and Monogem



Abeysekara et al., Science **358**, 911 (2017)

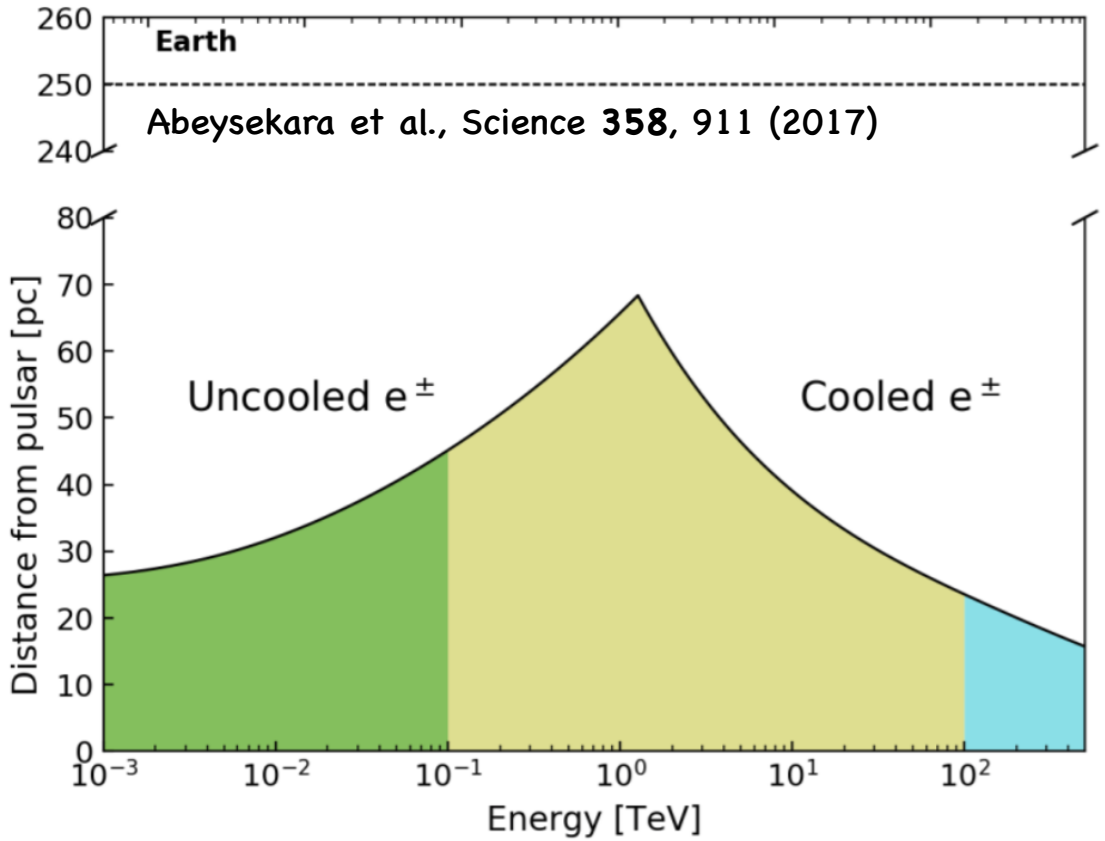




- Distance to Geminga: 250^{+120}_{-62} pc
- Distance to Monogem 288^{+33}_{-27} pc

Diffusion of particles from Geminga/Monogem

- HAWC constrains the diffusion coefficient at 20-30 pc from the pulsars
- If this continues to Earth, electrons and positrons cannot reach us
- However, a spatially varying diffusion coefficient can explain the positron excess measured by PAMELA, Fermi, and AMS
- Future updated HAWC analysis of the energy-dependent morphology may help resolve the situation



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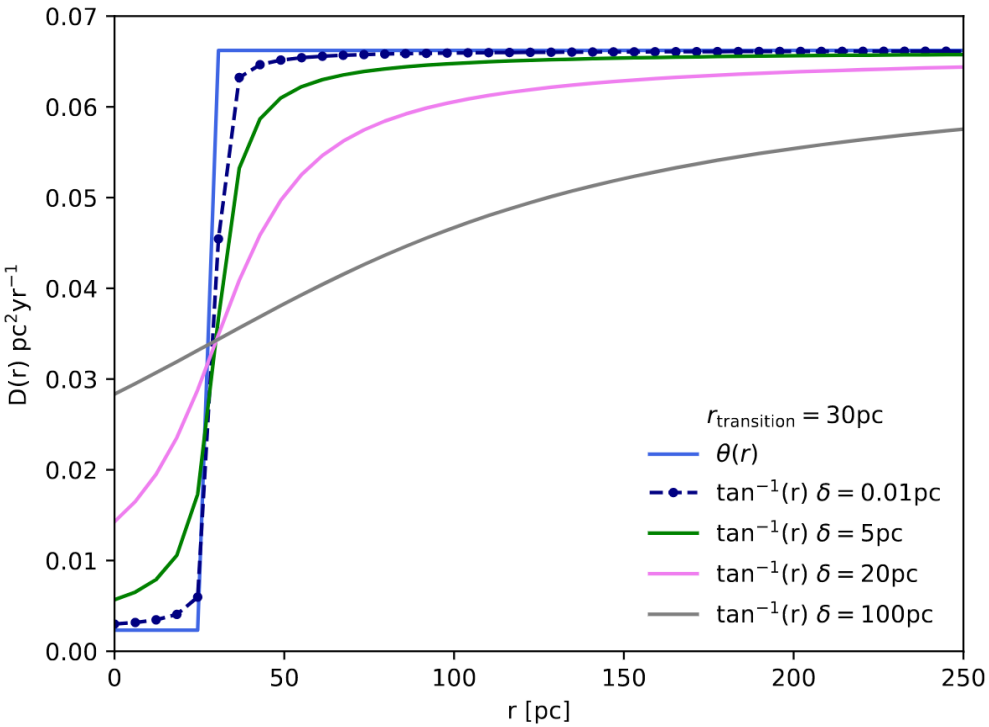
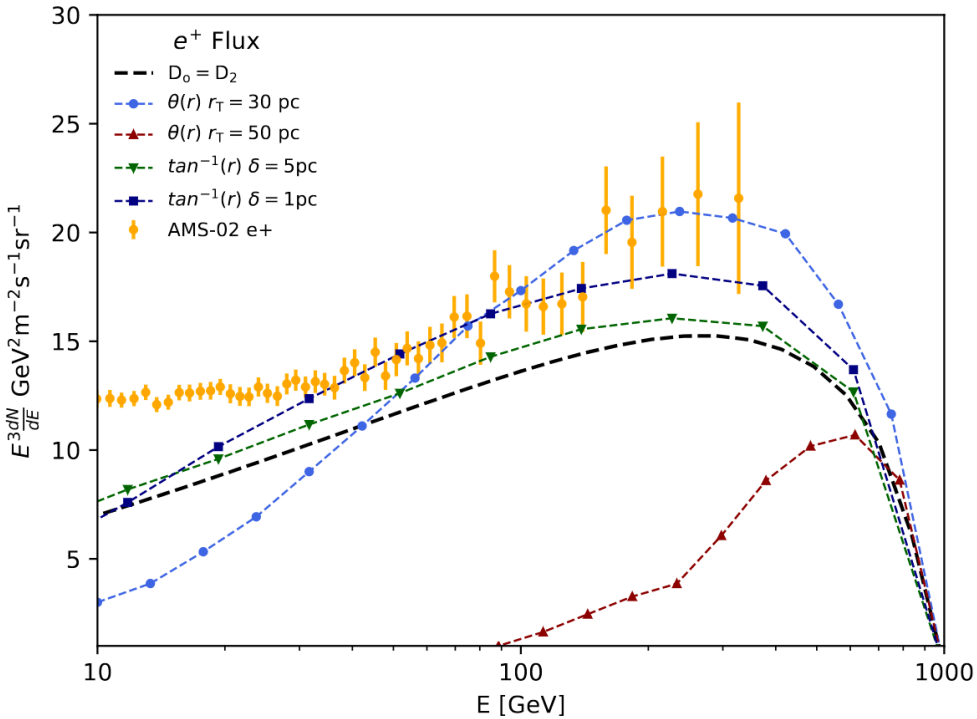
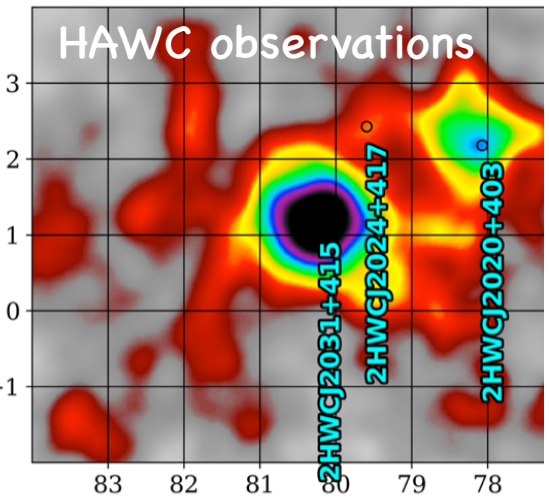


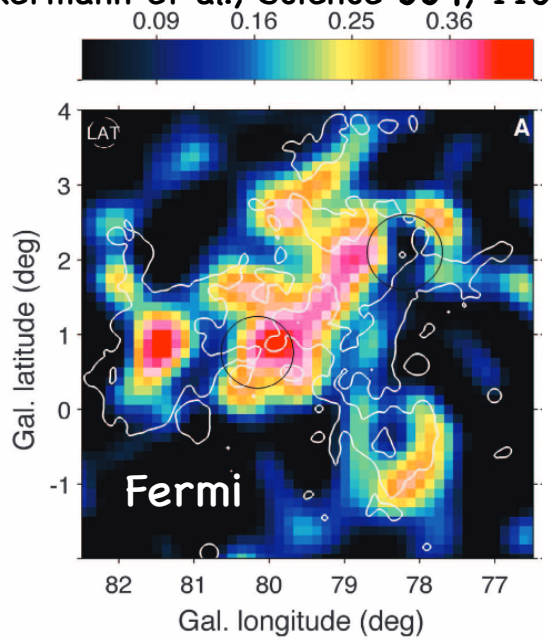


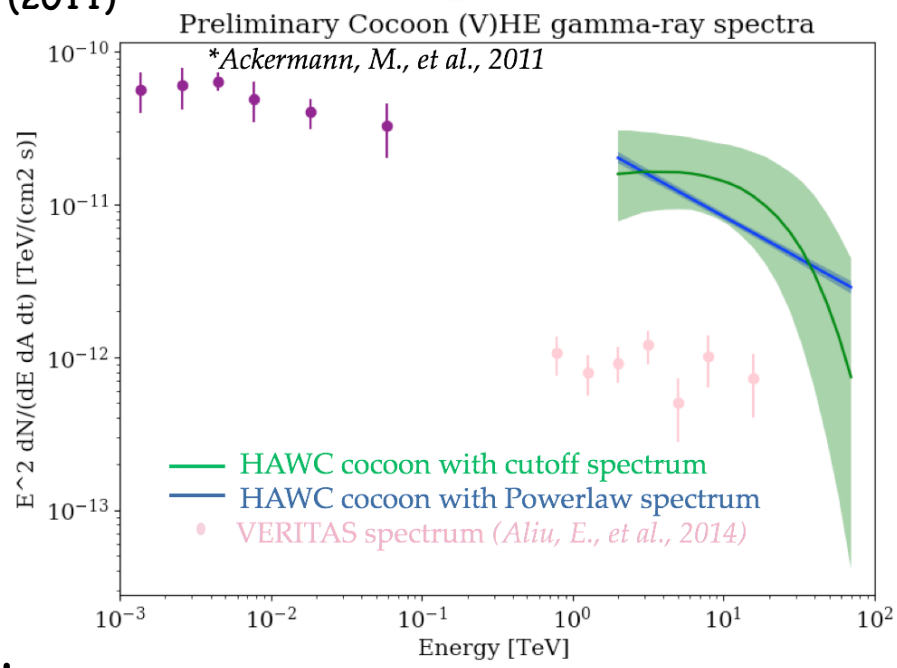
Profumo et al., arXiv:1803.09731 (2018)

Cygnus "cocoon" of recently accelerated cosmic rays

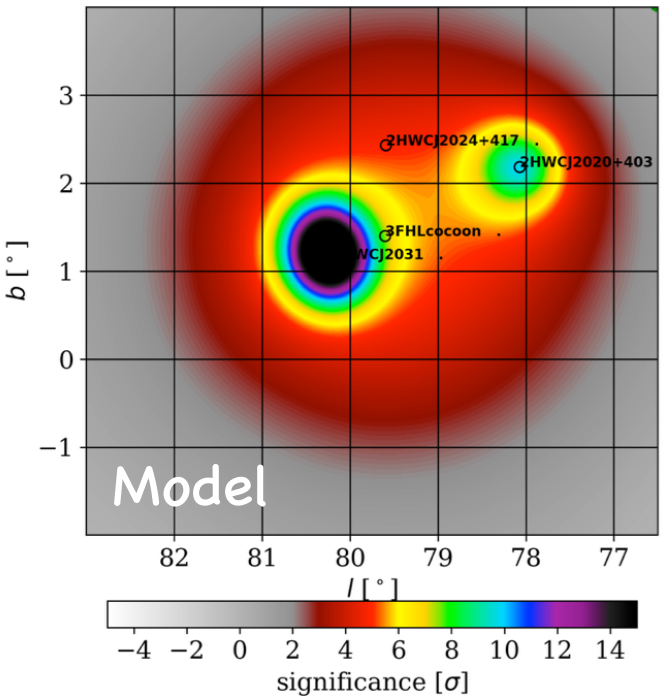
Ackermann et al., Science **334**, 1103 (2011)







- Complicated region, with an extended PWN, an SNR, and recently accelerated "cocoon" of cosmic rays discovered by Fermi in GeV
- VERITAS observations set the PWN model
- Fit the SNR with a point-source model
- HAWC fit to the cocoon using a Gaussian profile favors a power law with a cutoff over a simple power law model
- HAWC cocoon flux matches Fermi extrapolation



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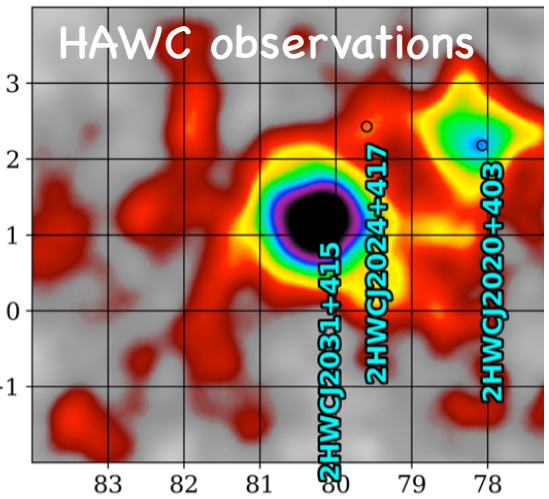

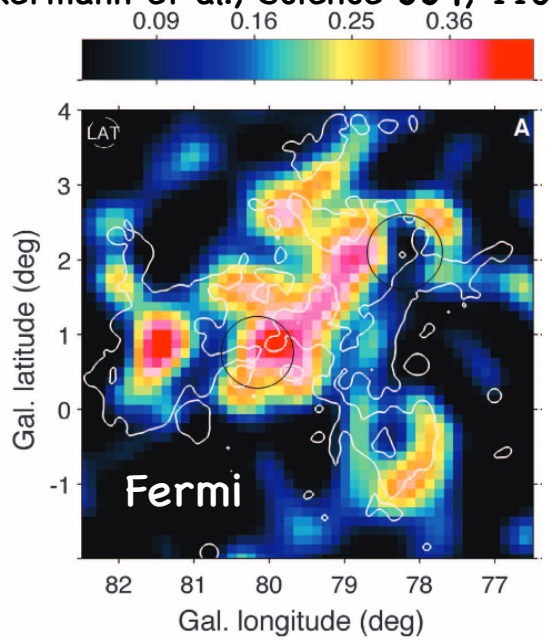

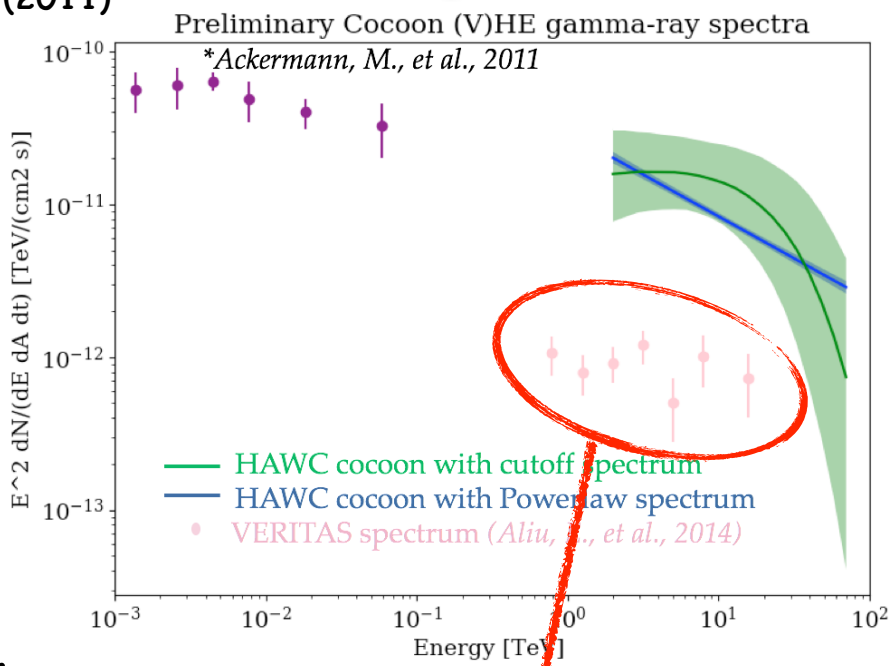

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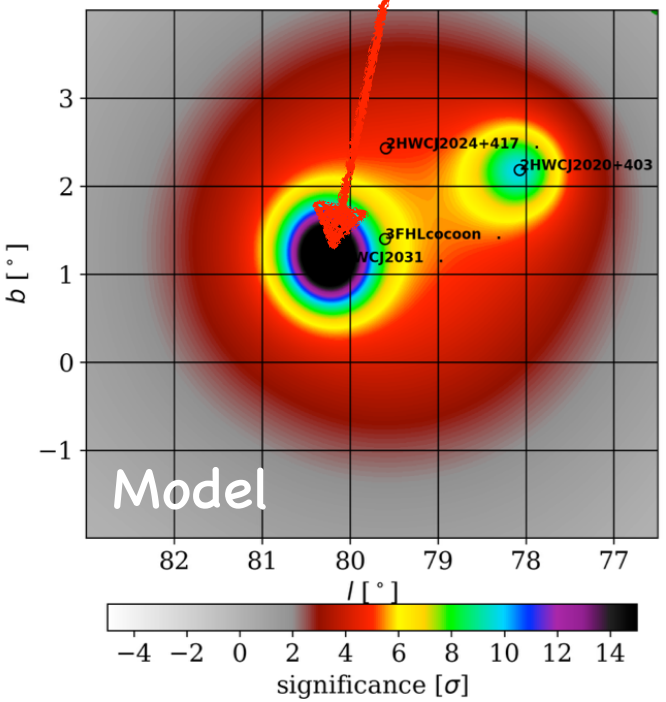
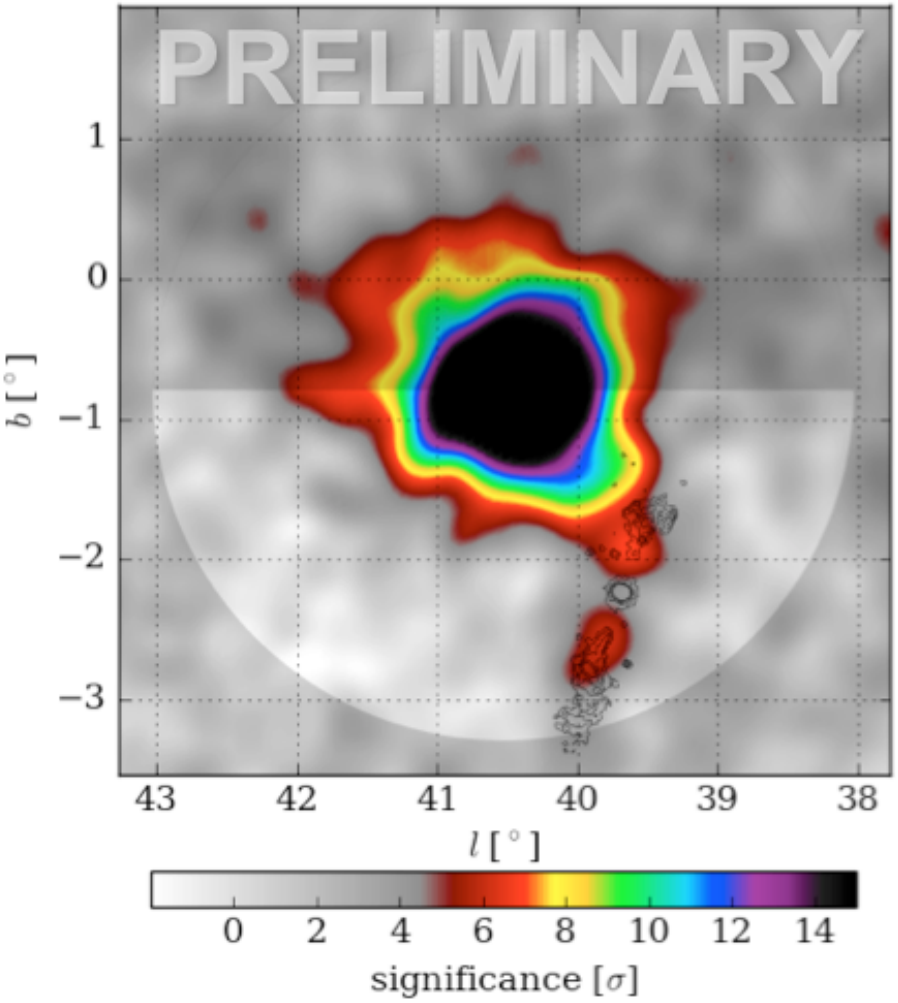
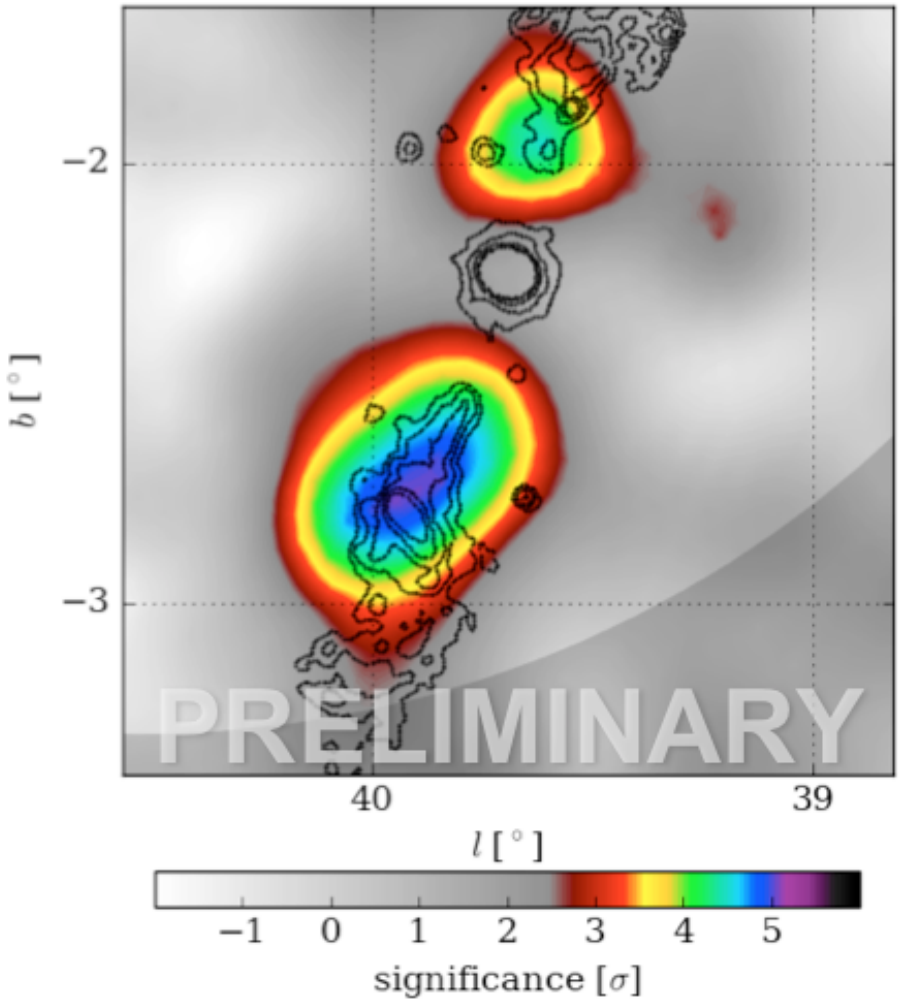


SS 433

- Microquasar with jets oriented nearly perpendicular to the line of sight
- Bulk speed of the jets is around c/4
- Located in the shadow of very strong and extended MGRO J1908+06
- VHE detection coincident with beginning of radio lobes where jets terminate
- Modeling supports a leptonic interpretation due to energetics requirements





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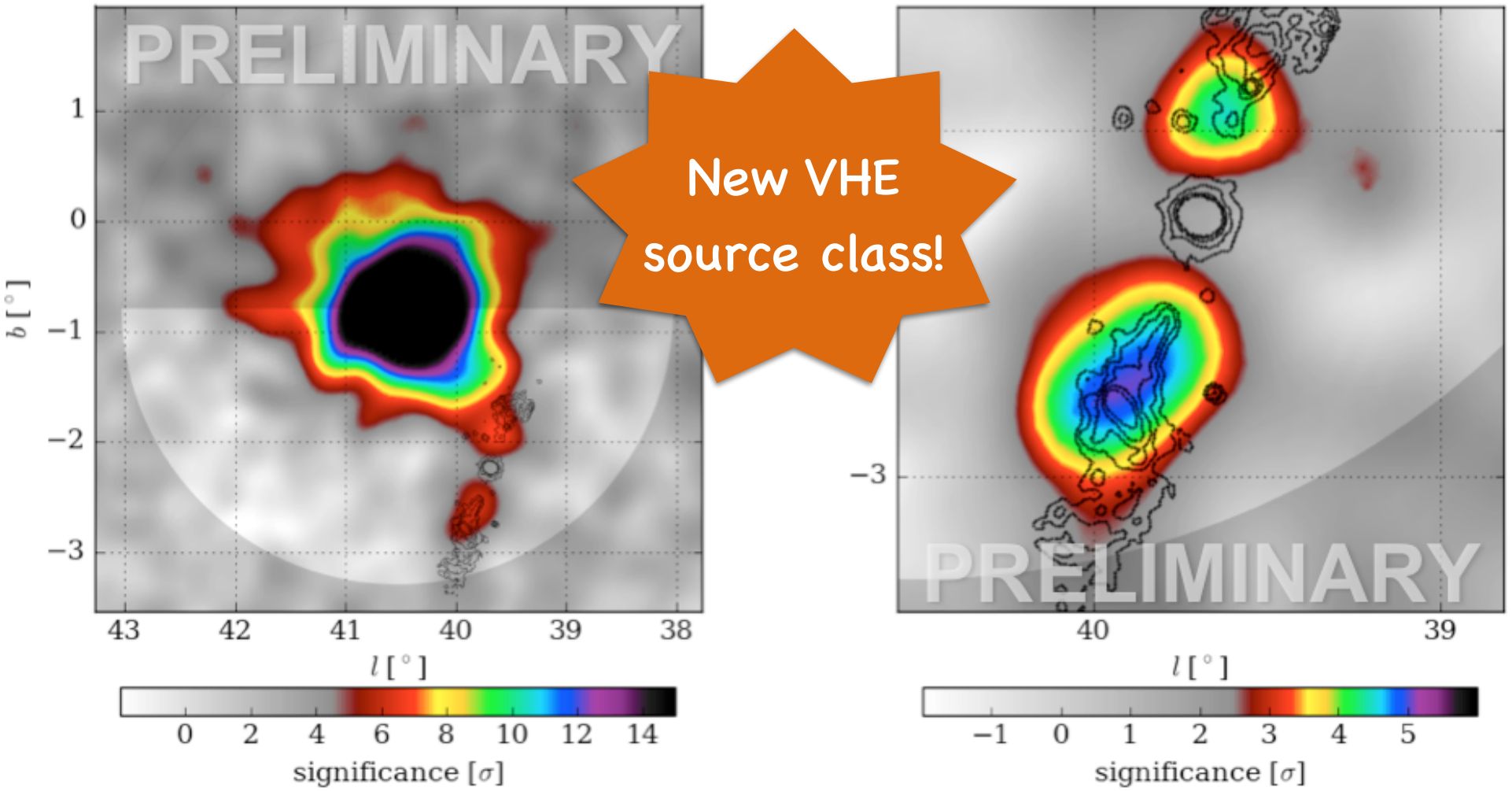
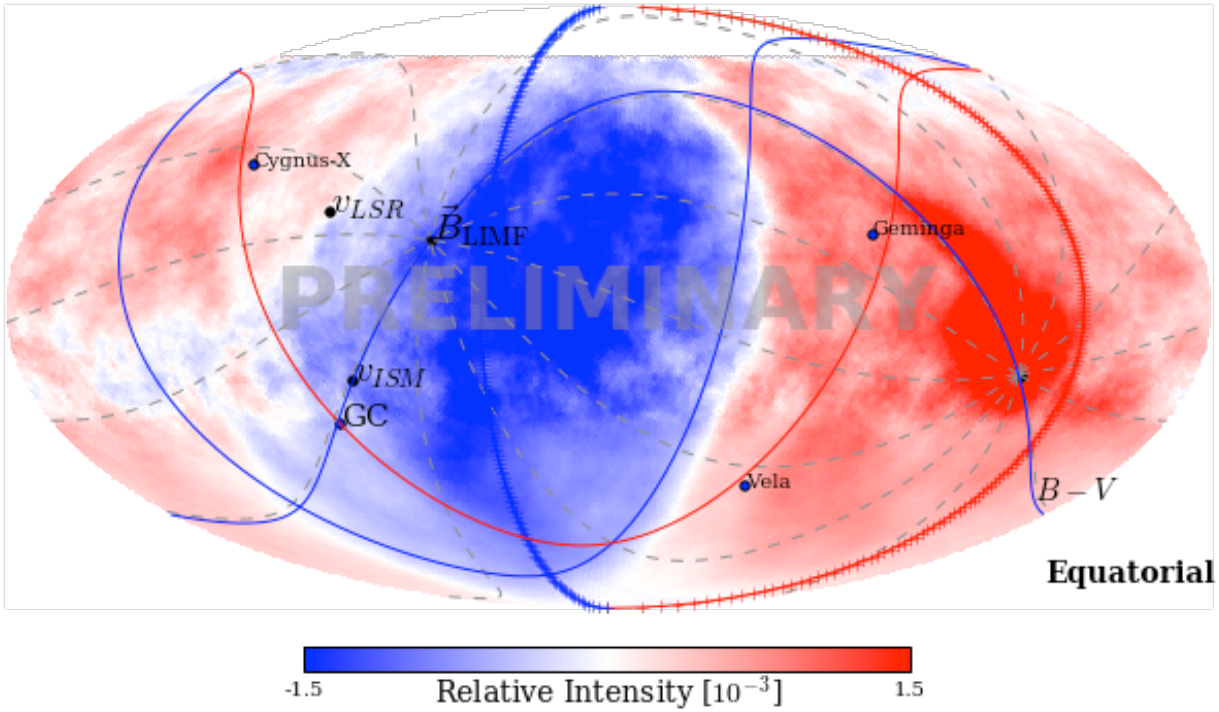
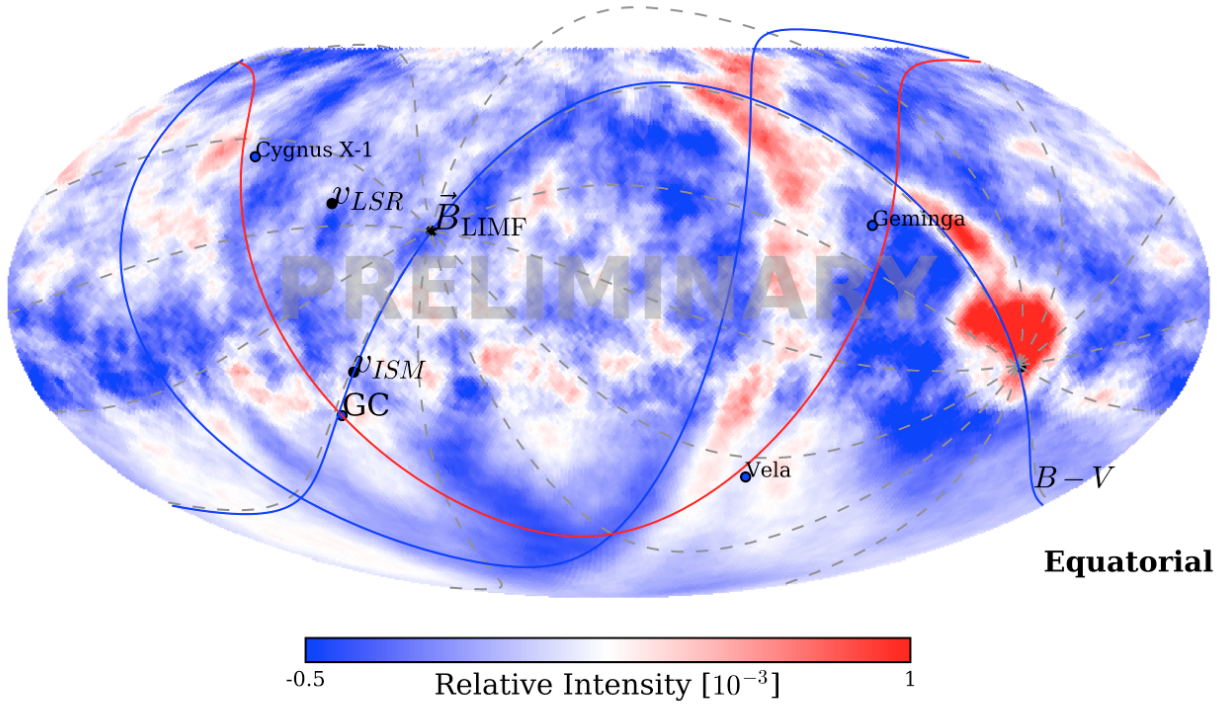


Cosmic ray anisotropy

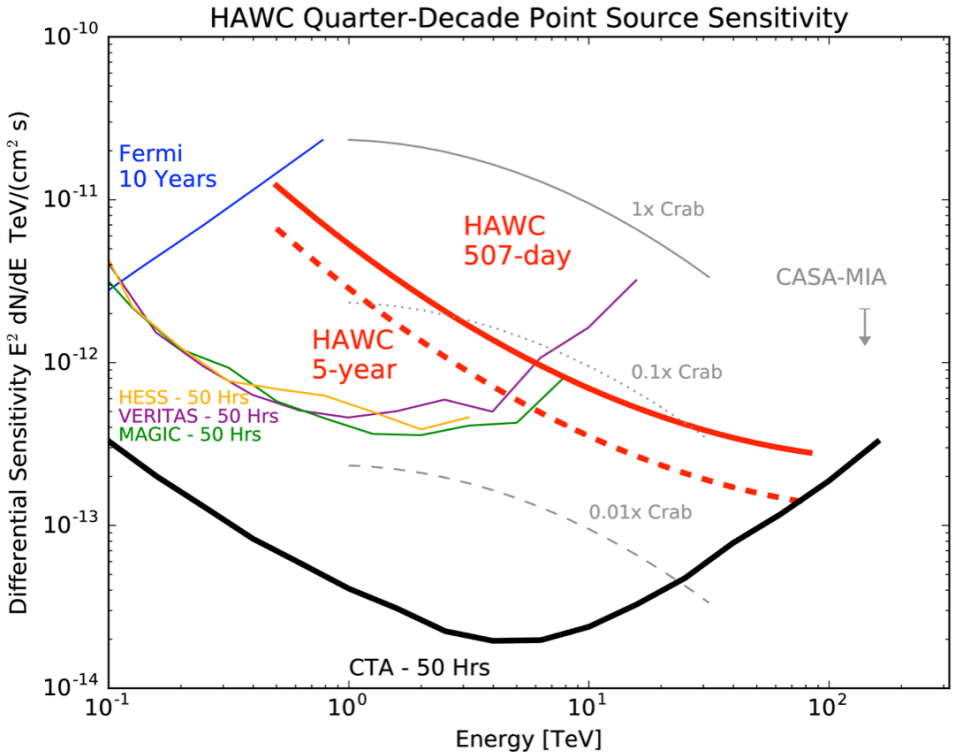


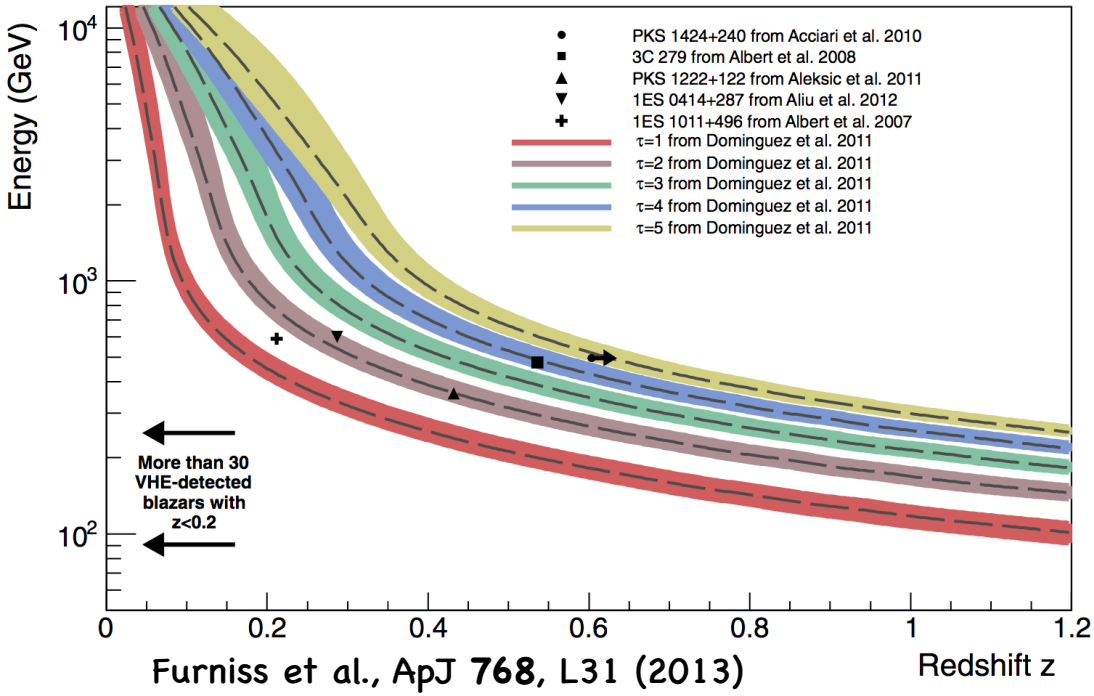


- Large-scale (top) and small-scale (bottom) anisotropy in the cosmic ray arrival direction distribution, jointly fit by HAWC and IceCube
- Median energy is approximately 10 TeV
- Apparent alignment between dipole anisotropy and local magnetic field
- Possible connection to local sources complicated by unknown diffusion coefficient, heliospheric effects

HAWC view of extragalactic sources

The challenges of extragalactic sources

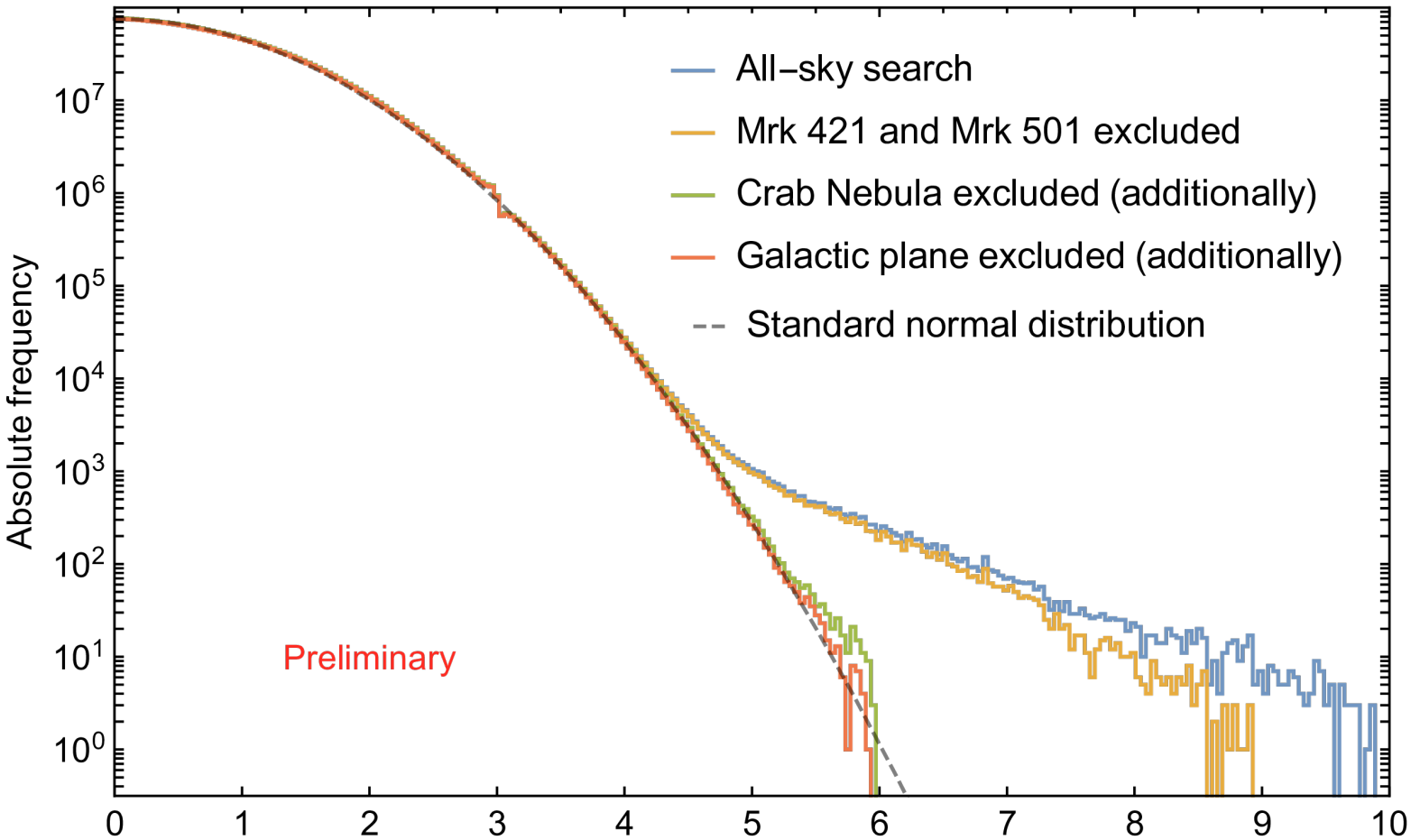




- HAWC sensitivity below 1 TeV is considerably worse than that of IACTs
- Attenuation of gamma rays on the extragalactic background light strongly limits the flux above 1 TeV for distant sources

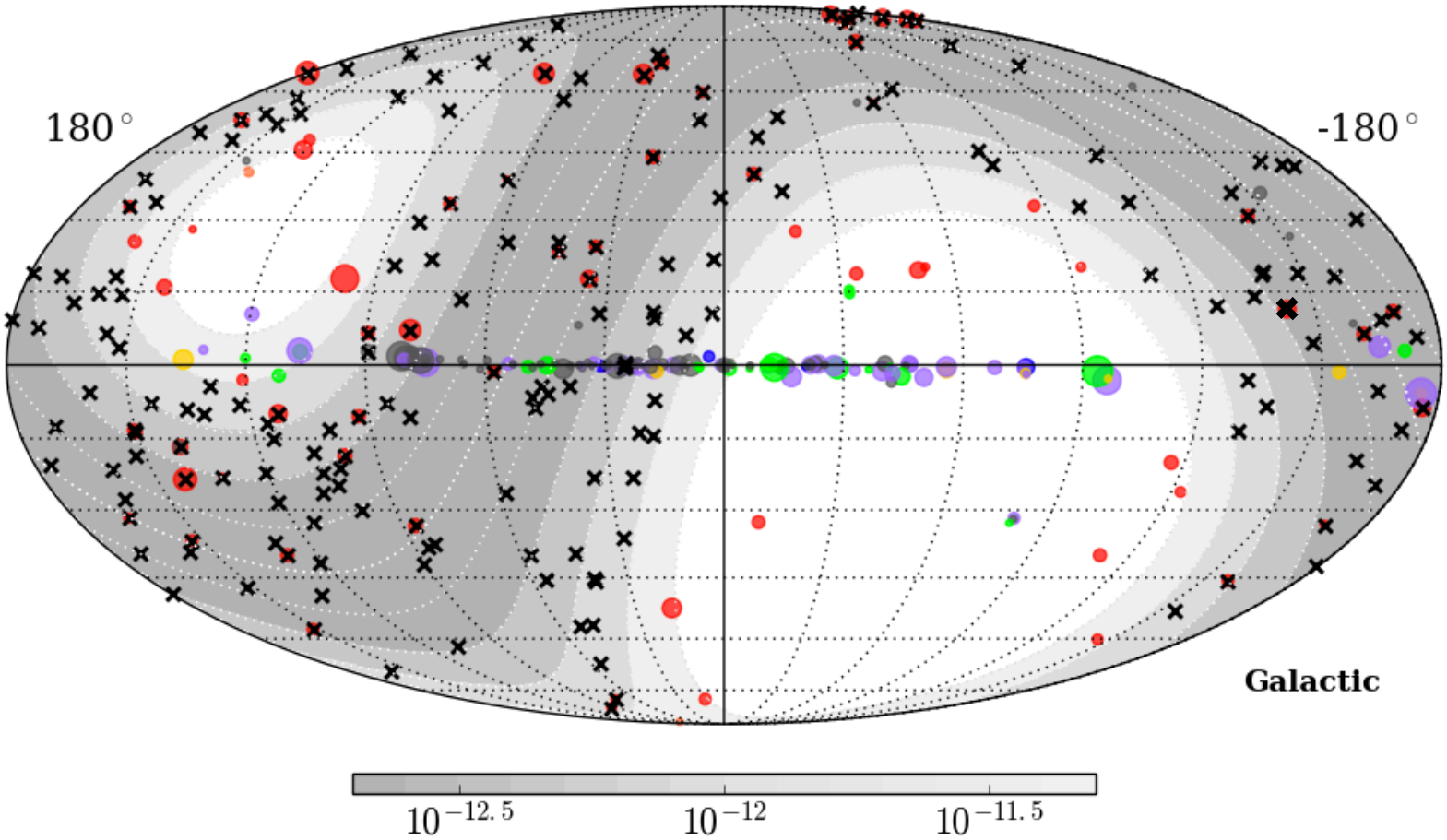
Daily search

- No significant steady extragalactic sources other than Mrk 421 and Mrk 501
- Search on time scale of 1 day reveals no significant extragalactic sources in 768 days



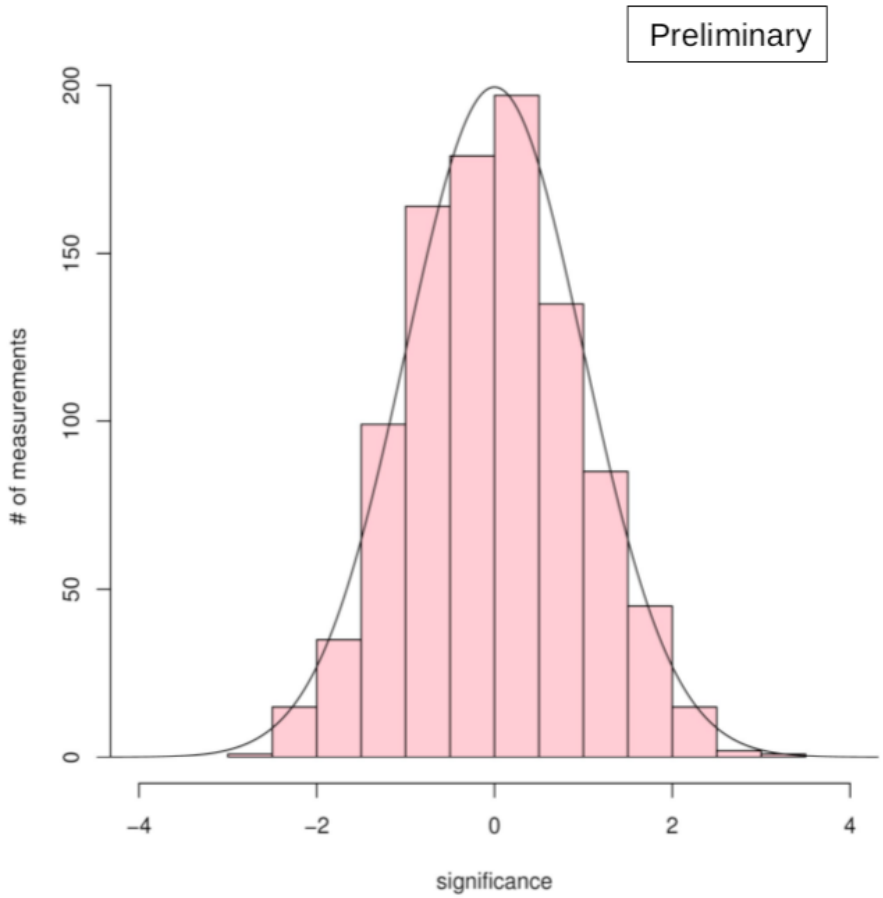
Searches for other blazars

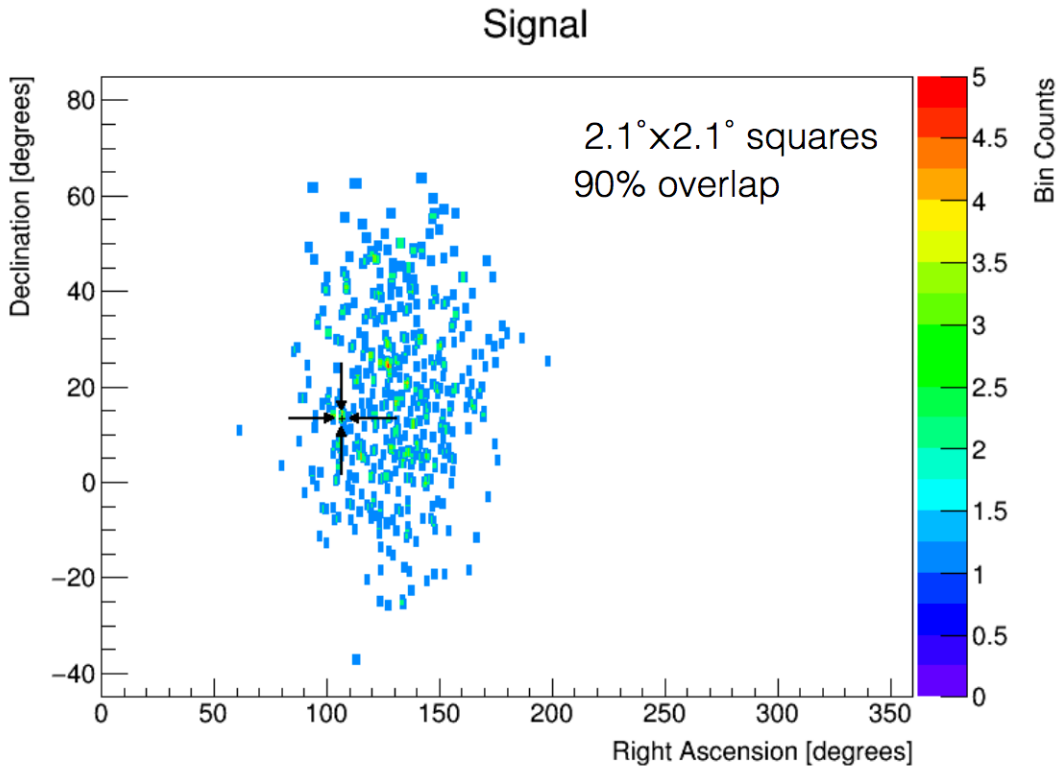
- HAWC real-time flare monitor searches for flares on time scales as short as 2 minutes, observing 187 sources in HAWC's sky coverage, divided into 4 categories:
  - Mrk 421 and Mrk 501: 2 sources
  - TeVCat extragalactic: 44 sources
  - 2FHL extragalactic objects with z < 0.3: 22 sources
  - other 2FHL extragalactic objects or of unknown type: 119 sources



GRBs

- 93 GRBs have occurred within the HAWC field of view
- For long GRBs, consider 10 time windows ranging from 0 to 10xT_{90}
- For short GRBs, consider time windows ranging from 0 to 20 seconds
- No significant emission from any time window
- HAWC also runs a real-time GRB search covering time scales up to 100 seconds

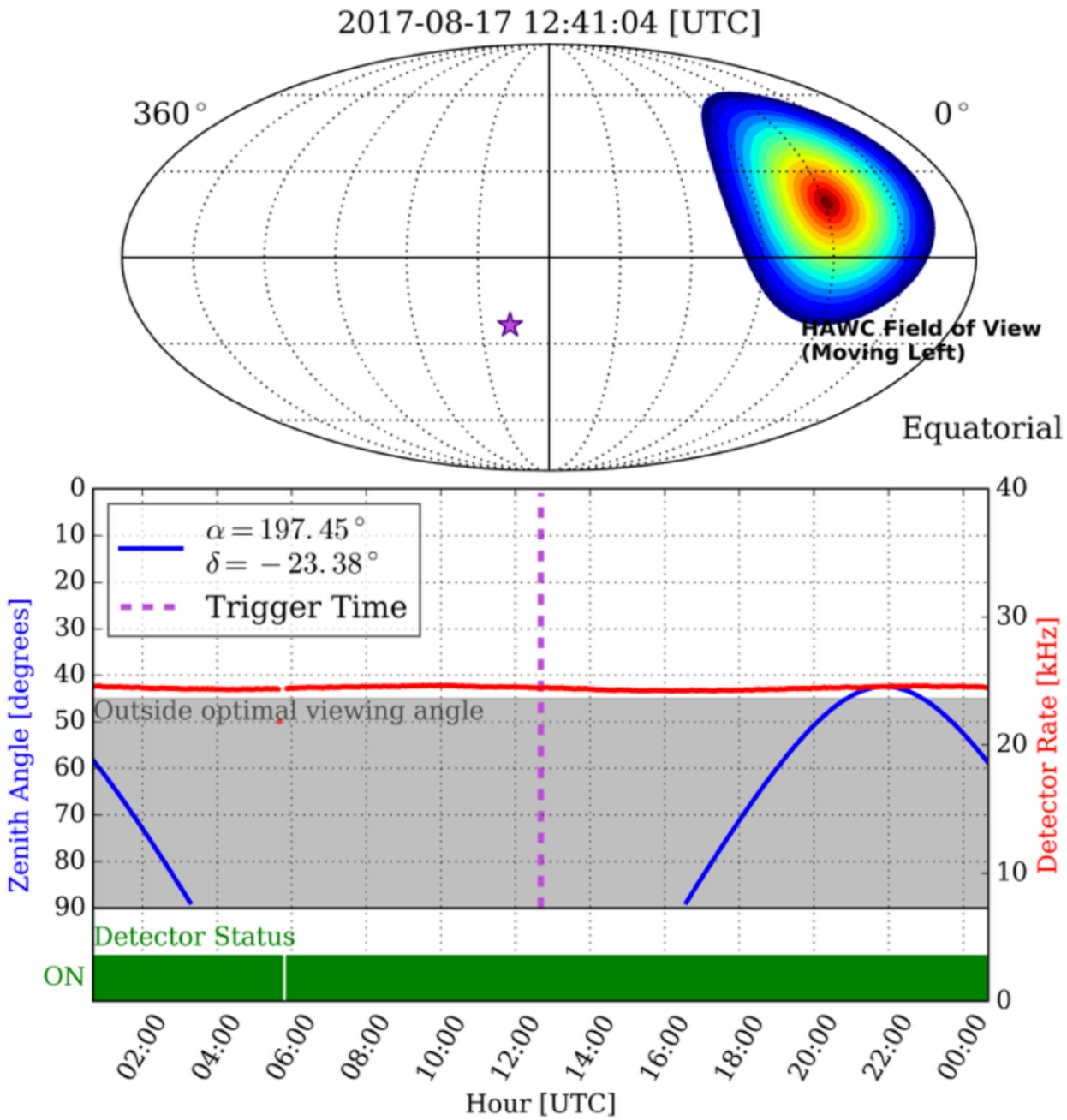




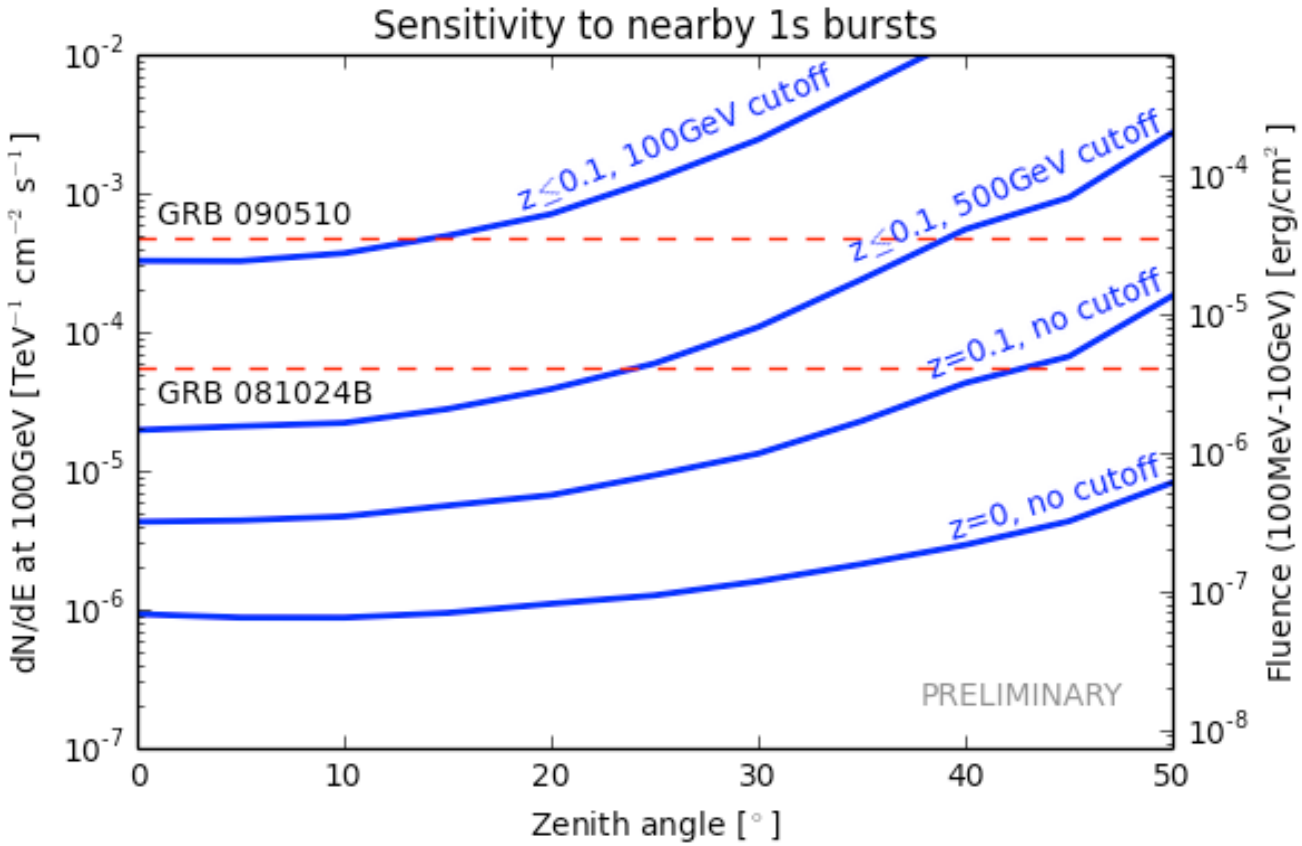
HAWC in the multimessenger era

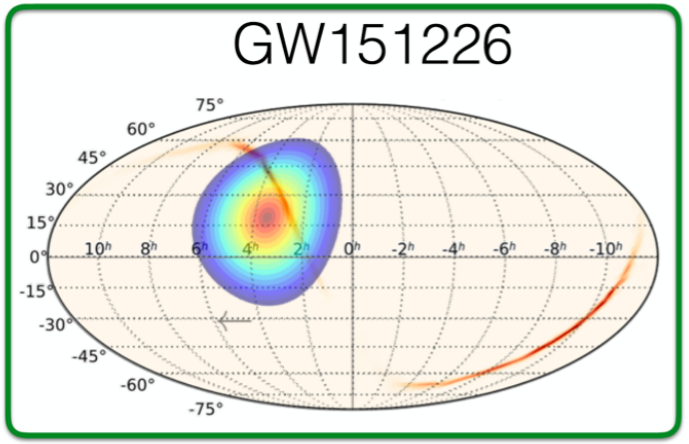
Limits on GW 170817

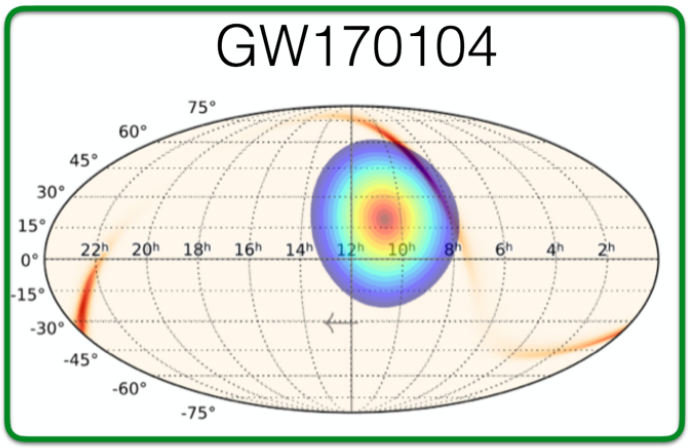
- GW 170817 was consistent with binary neutron star coalescence
- Electromagnetic counterpart detected from radio to gamma rays
- Location entered the HAWC field of view approximately 9 hours after the event
- Due to low declination, the HAWC energy threshold is quite high and HAWC has poor sensitivity
- 90% CL upper limit of 1.7×10^{-10} erg cm^{-2} s^{-1} between 4 and 100 TeV



HAWC and gravitational waves

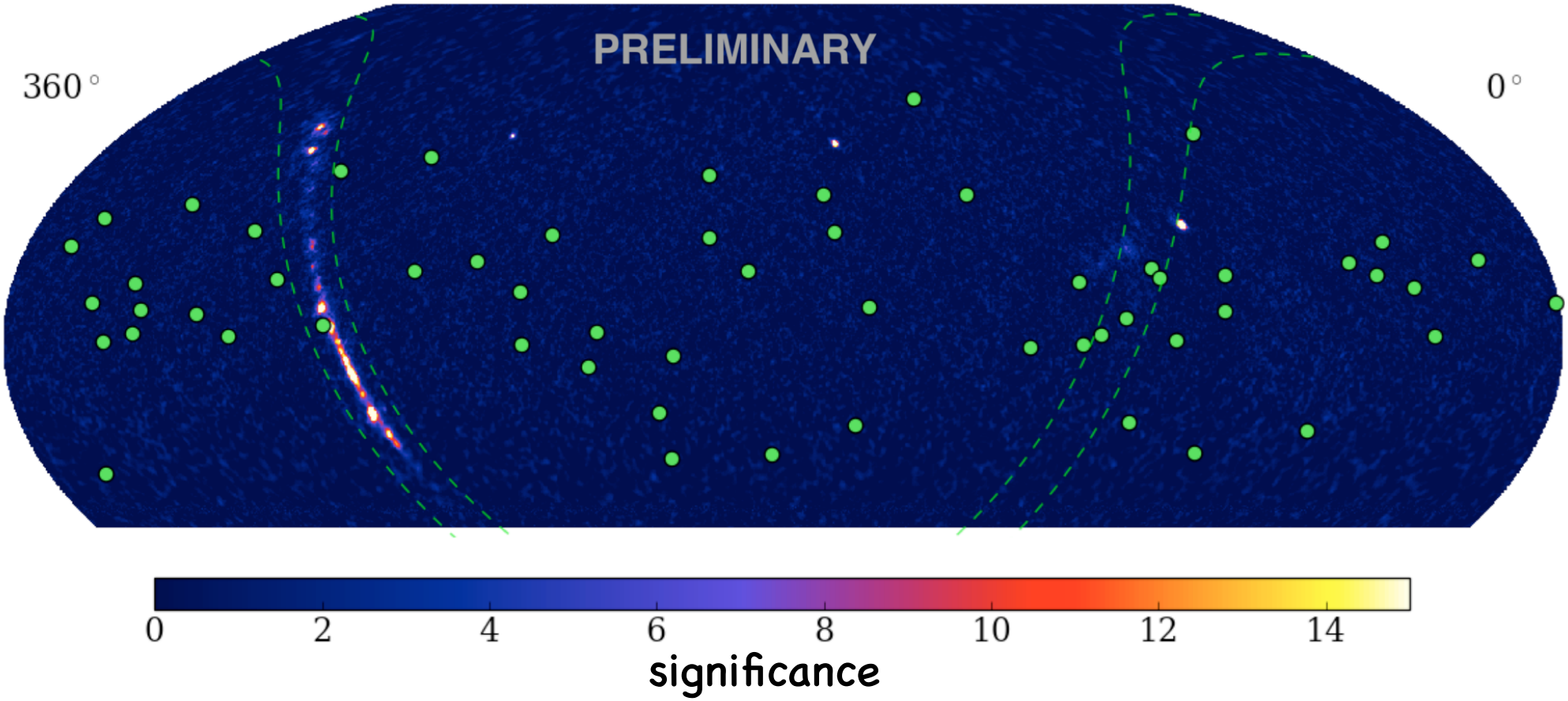






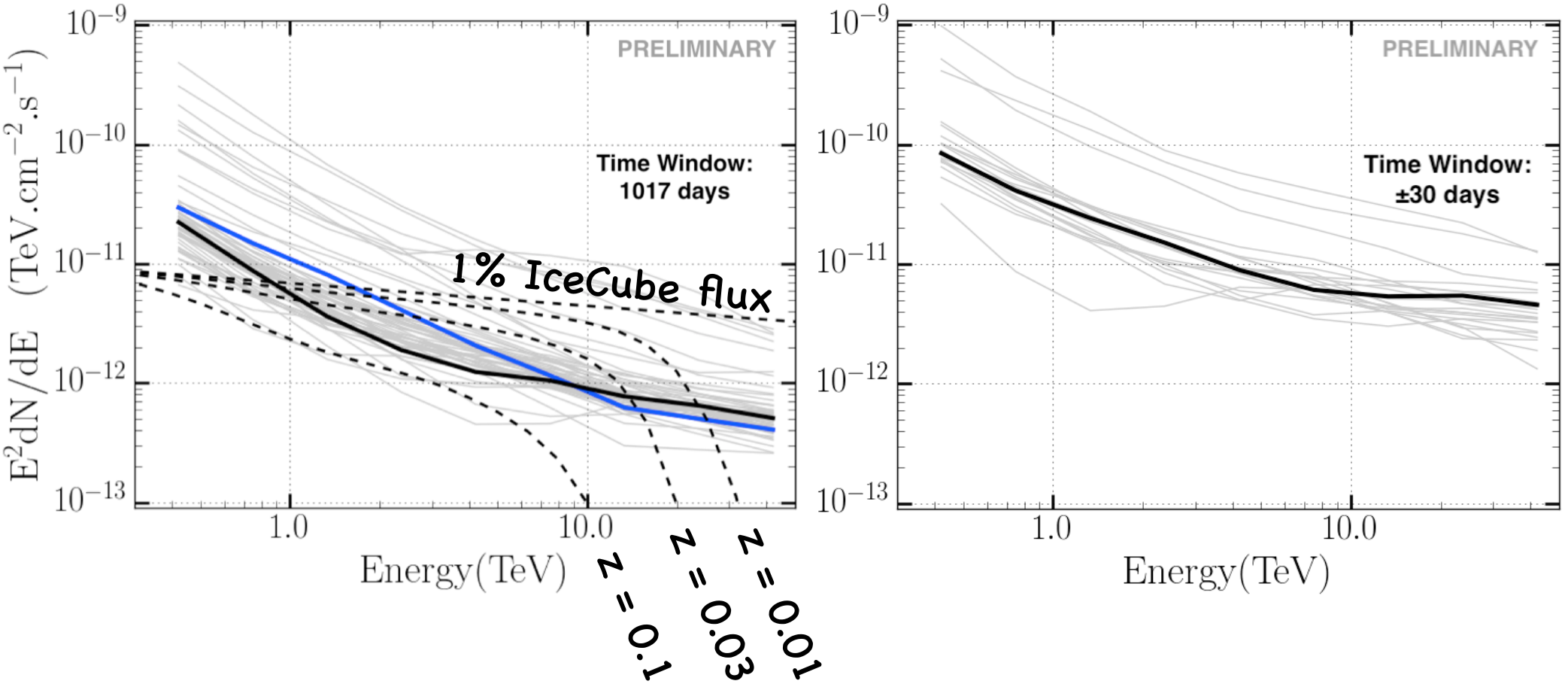
- Two GW events occurred with some instantaneous overlap with the HAWC field of view
- No significant emission observed in the error bands
- Possible to perform simultaneous follow-up observations even if alert is delayed, due to survey mode
- Sensitivity of HAWC to bursts lasting 1 second comparable to known GRB fluences

HAWC limits on IceCube tracks



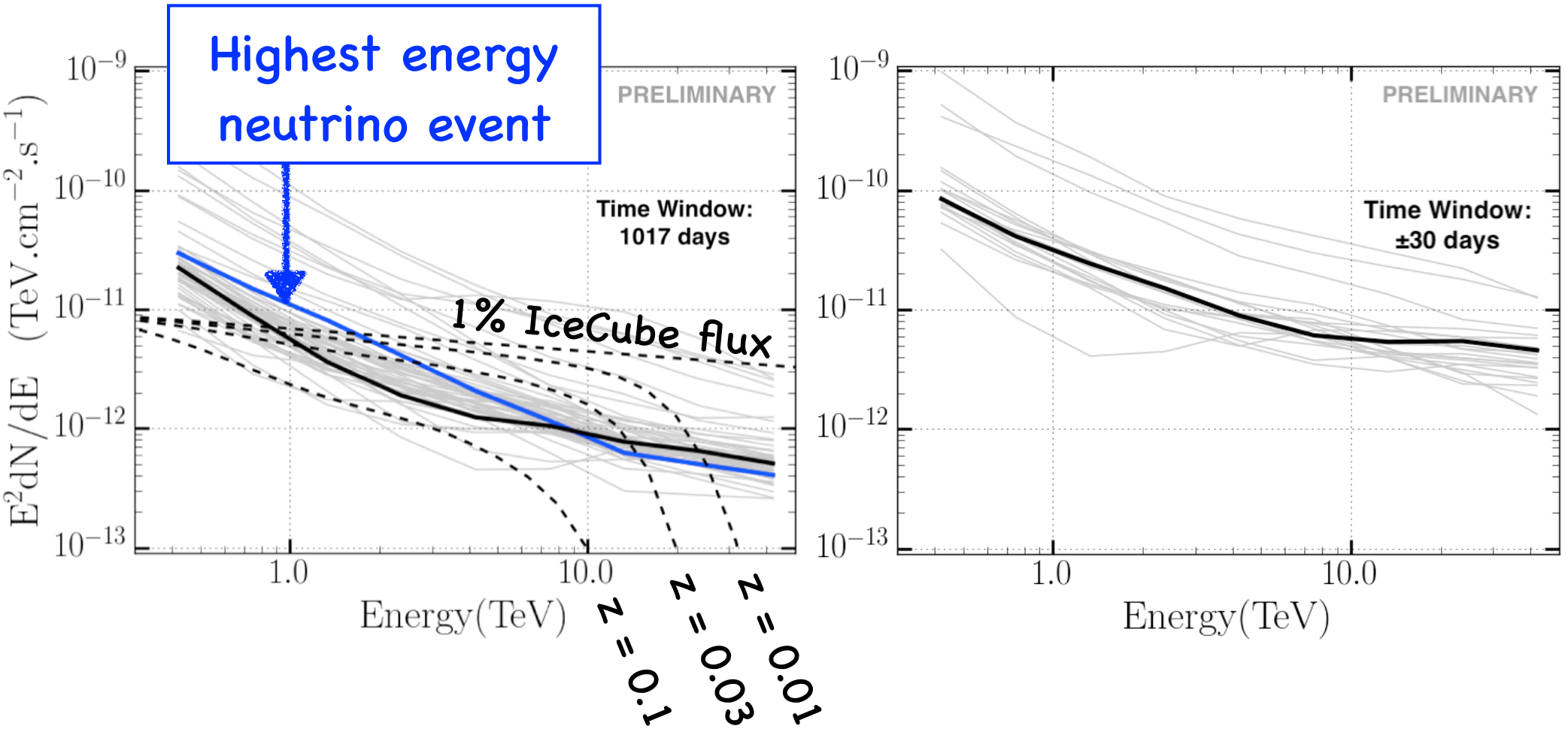
- Expect that the processes (proton-proton, proton-gamma, etc.) producing high-energy neutrinos will also produce high-energy gamma rays
- Selected 57 neutrinos from IceCube observations
- Limited to track-type events in the nominal HAWC declination range (-26° to +64°)
- Distribution of events on the sky clearly supports an extragalactic origin

HAWC limits on IceCube tracks



- Upper limits constrain the extrapolation of the IceCube spectrum to lower energies, assuming proton-proton production of neutrinos
- Limits from both full HAWC observations to date and 60 days around each event (possible because of HAWC's wide field of view)
- Sources may be numerous, far away, or opaque to gamma rays
- Possible connection to TXS 0506+056 hints at blazars as potential sources

HAWC limits on IceCube tracks



- Upper limits constrain the extrapolation of the IceCube spectrum to lower energies, assuming proton-proton production of neutrinos
- Limits from both full HAWC observations to date and 60 days around each event (possible because of HAWC's wide field of view)
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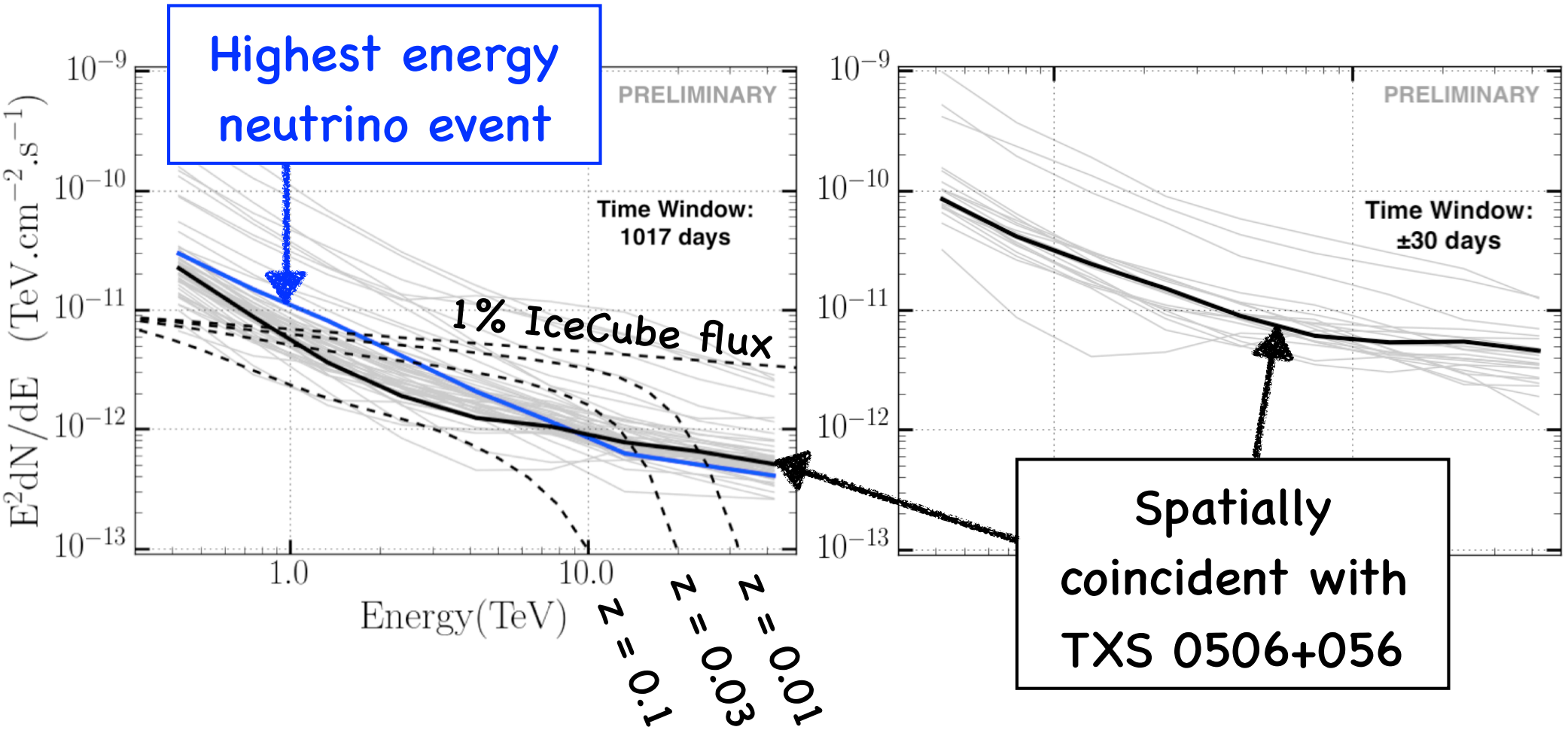

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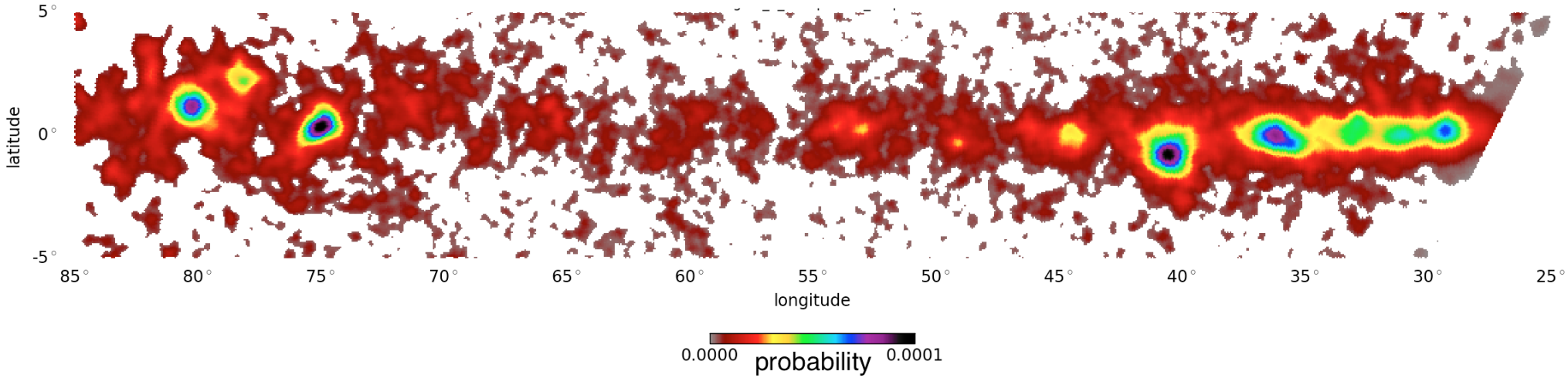
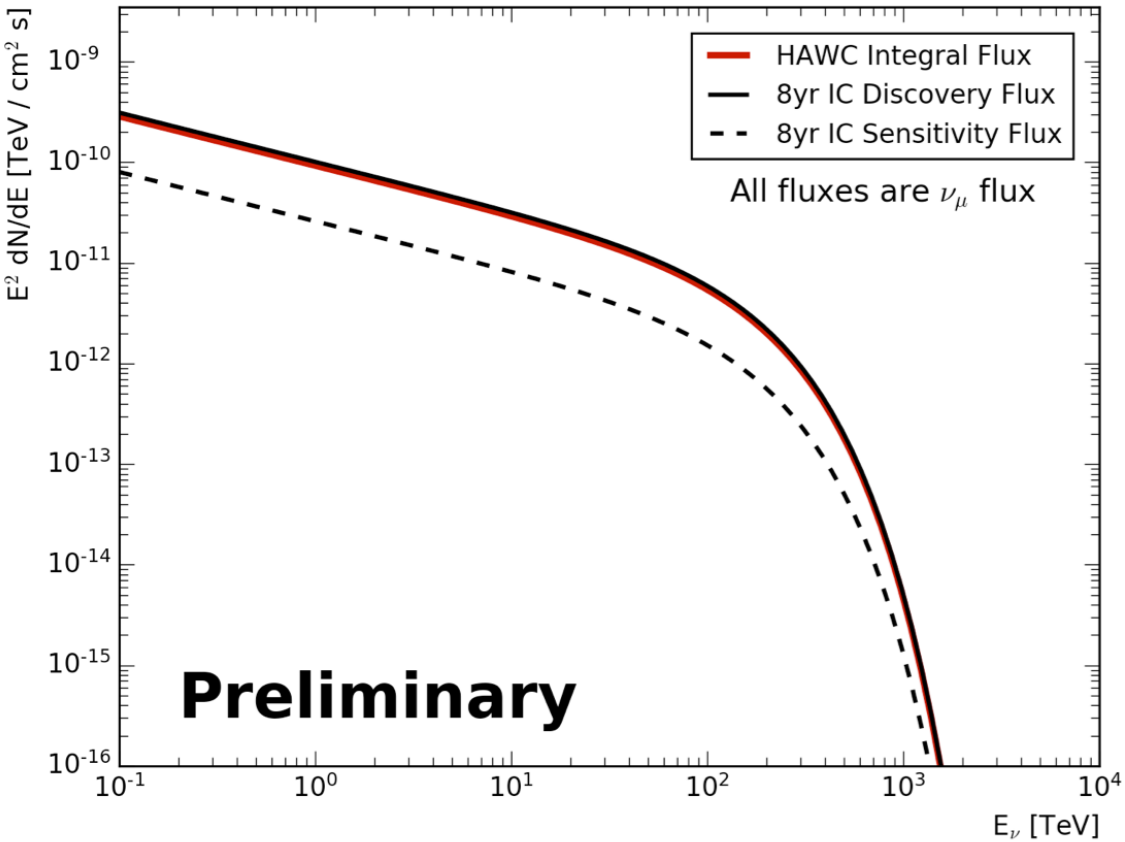
Galactic neutrino source search





- Use HAWC Galactic plane observations as a template for neutrino emission
- Assume 300 TeV cutoff consistent with knee of cosmic ray spectrum
- Integral flux prediction reaches the flux necessary to produce a 5σ detection in IceCube in 8 years
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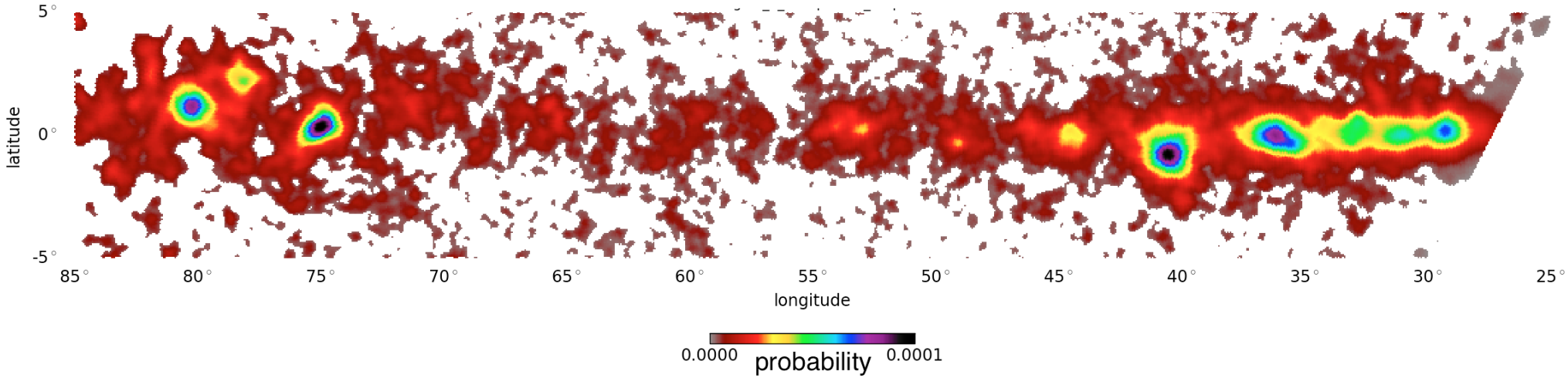

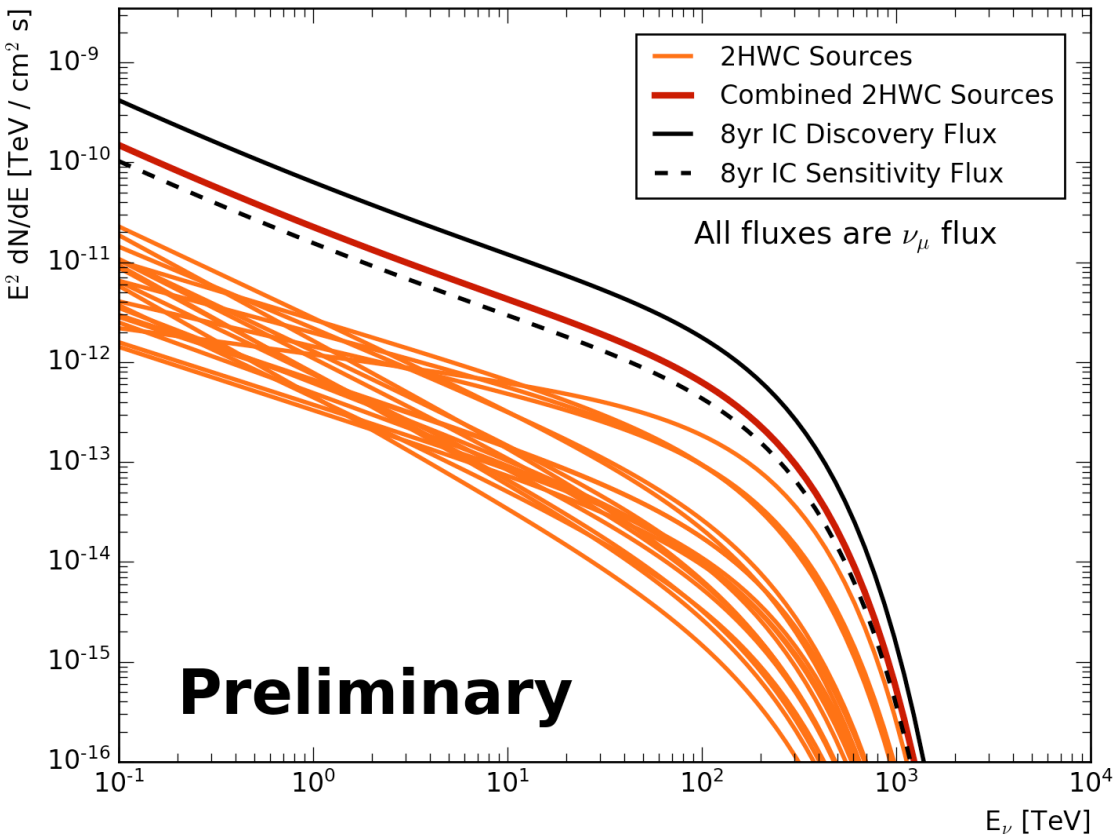

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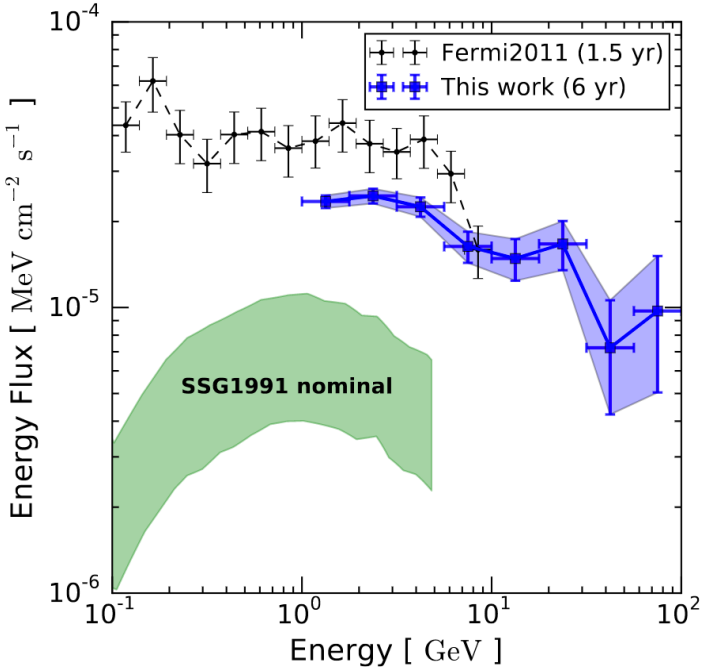
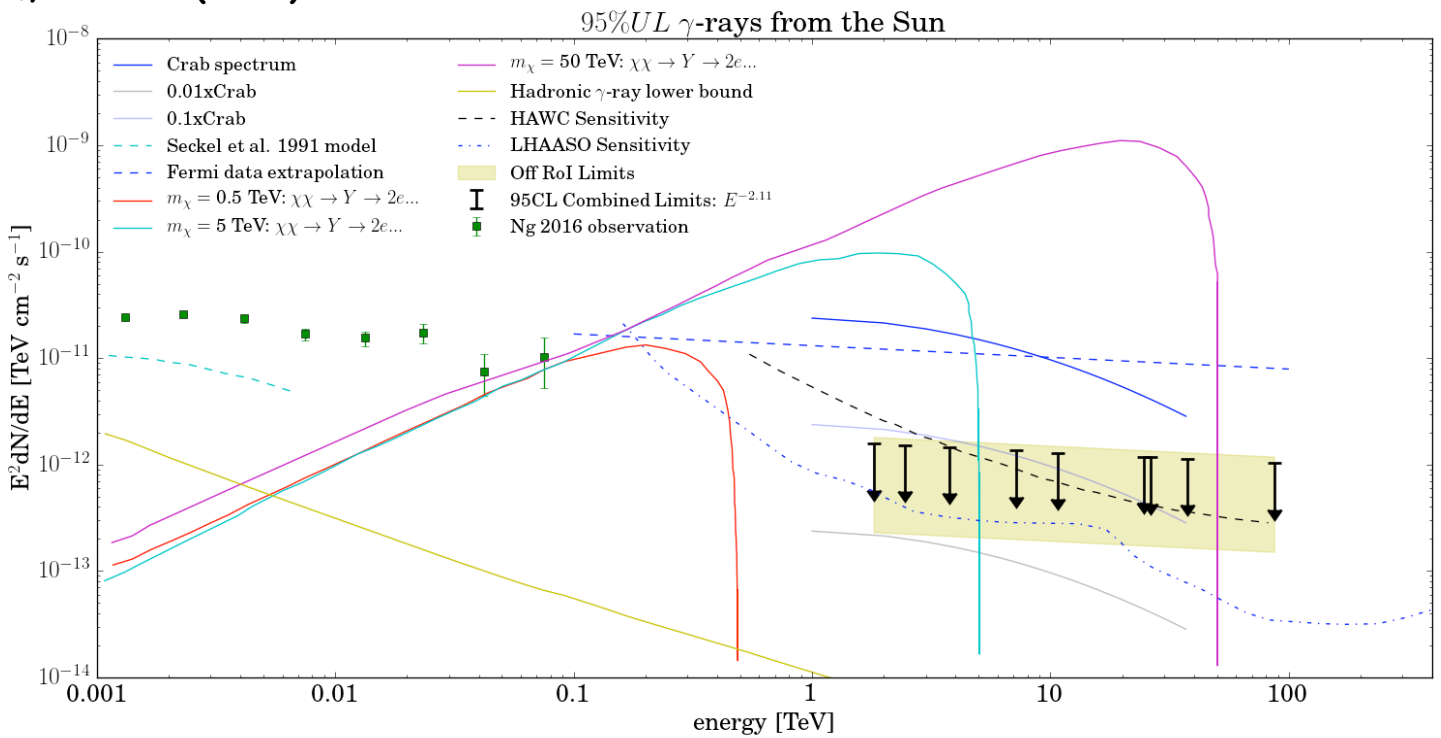
Observations of the sun

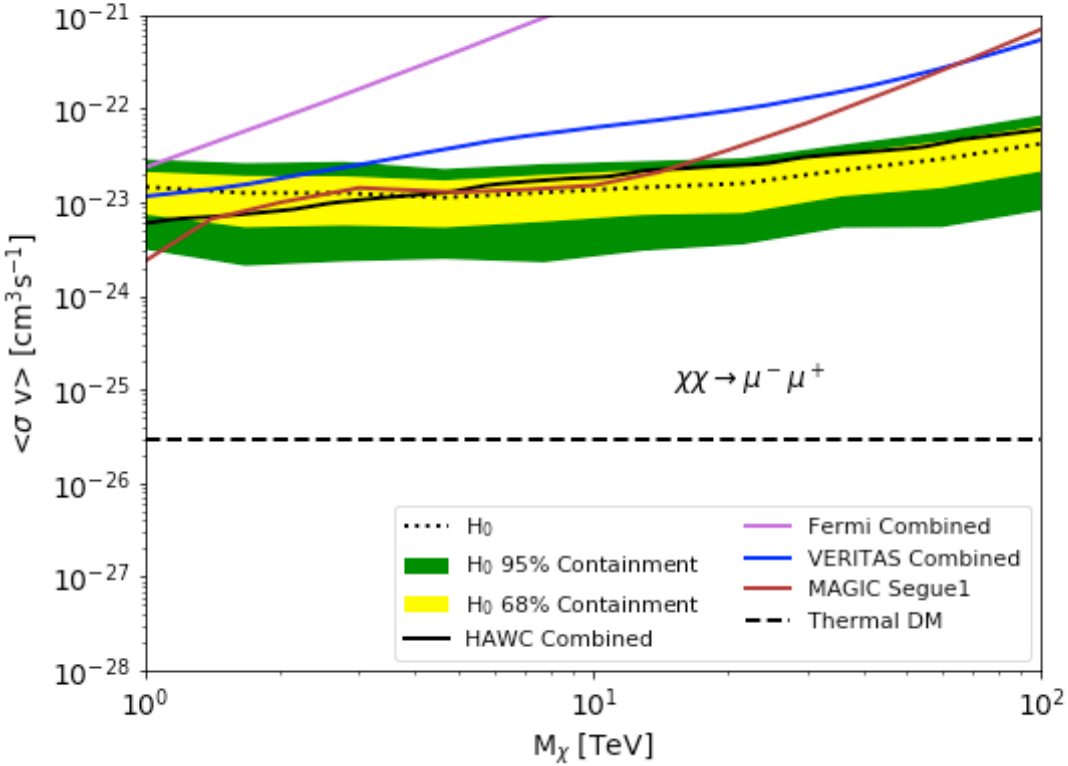


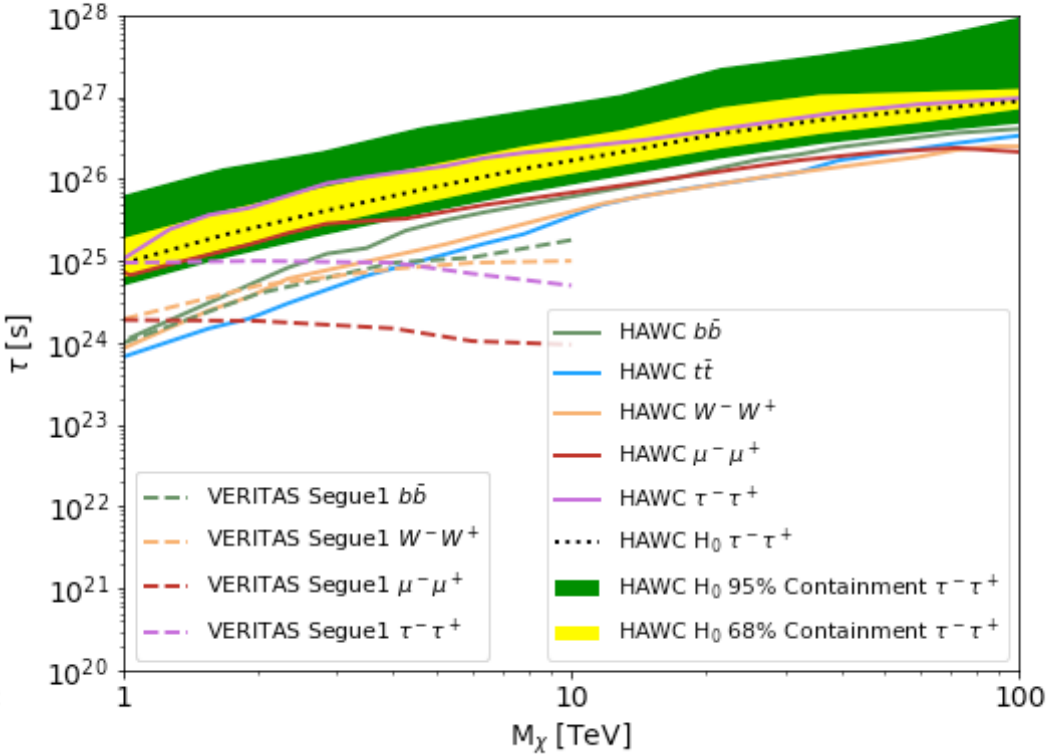
Ng et al., PRD 94, 023004 (2016)

- Gamma rays expected from interaction of cosmic rays in the solar limb
- Fermi observations reveal time dependence and inconsistency with previous calculations treating diffusion between sun and Earth
- HAWC upper limits constrain extrapolation of Fermi observations to TeV energies
- HAWC observations also limit models of dark matter annihilation via semi-stable mediator



Limits on dark matter



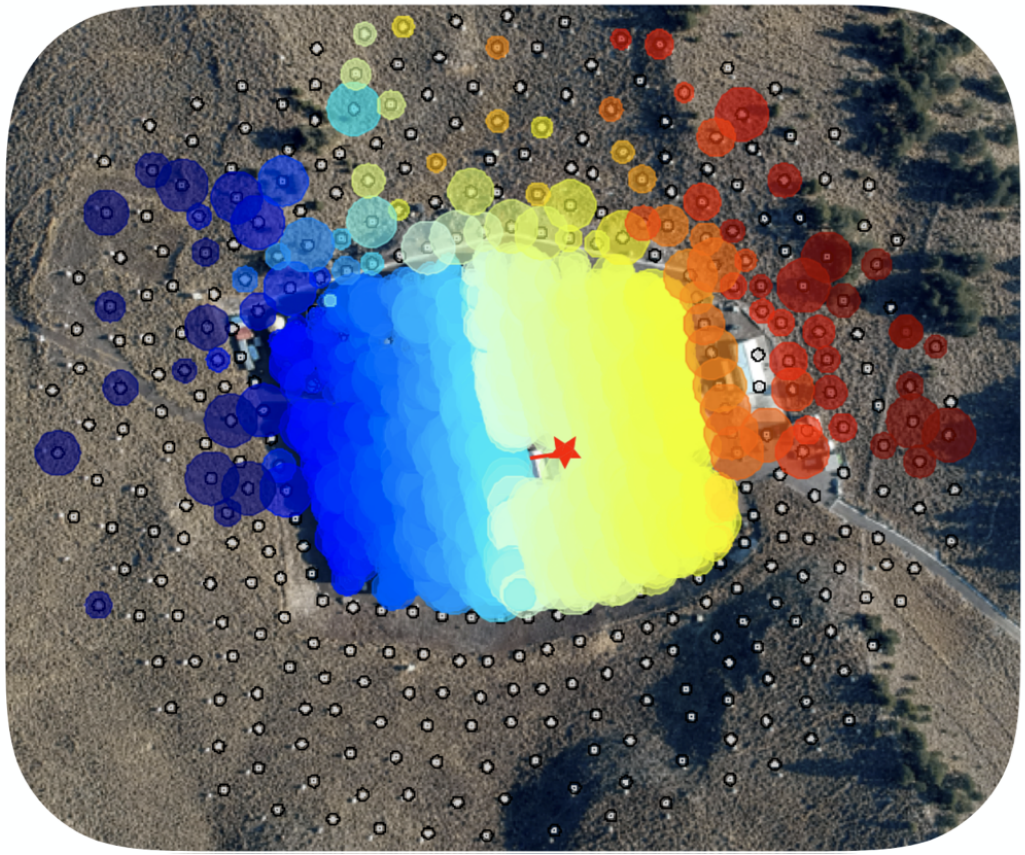


- HAWC observes 15 dwarf galaxies to search for dark matter annihilation or decay
- Annihilation limits competitive with IACTs and Fermi for dark matter masses above 1 TeV
- HAWC also limits the lifetime of dark matter particles to be larger than 10^{24} to 10^{26} seconds, depending on mass and decay channel

The future of ground-based gamma-ray astronomy

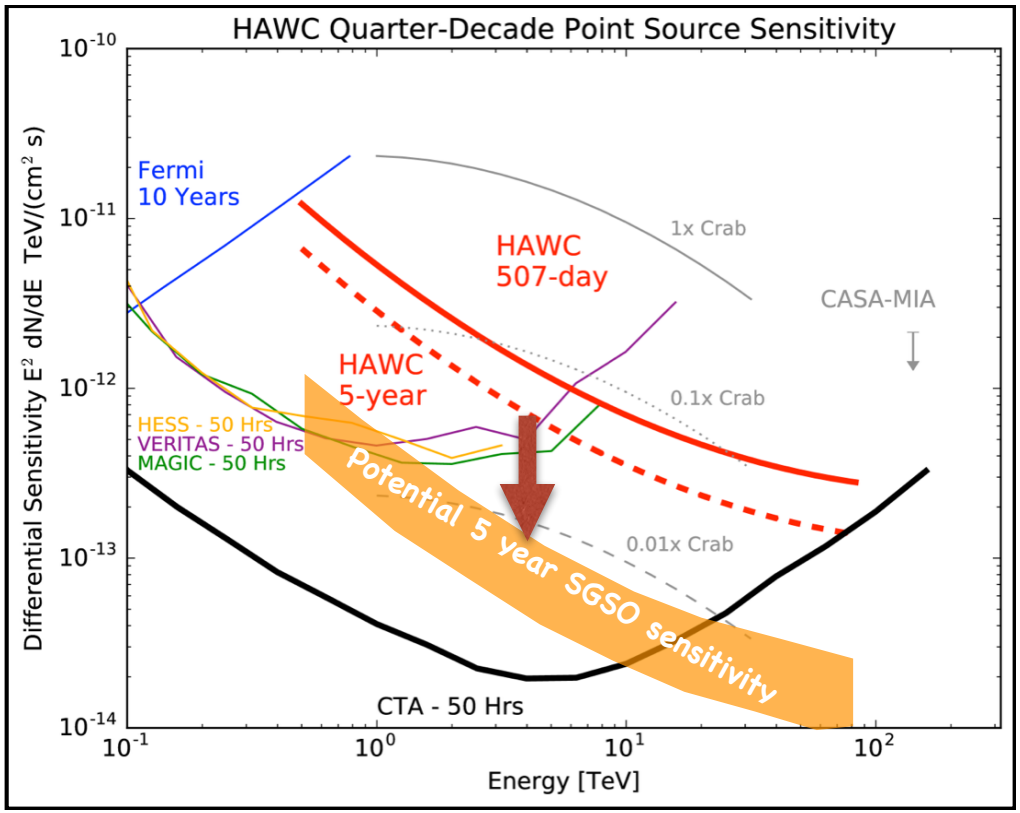
HAWC outriggers

- 350 smaller tanks in sparse array covering 3x area of HAWC
- Increase sensitivity at highest energies by a factor of 2 to 4
- All tanks currently deployed and filled with water, approximately 3/4 with PMTs connected and active
- Preliminary data taking has begun, full integration in a few months

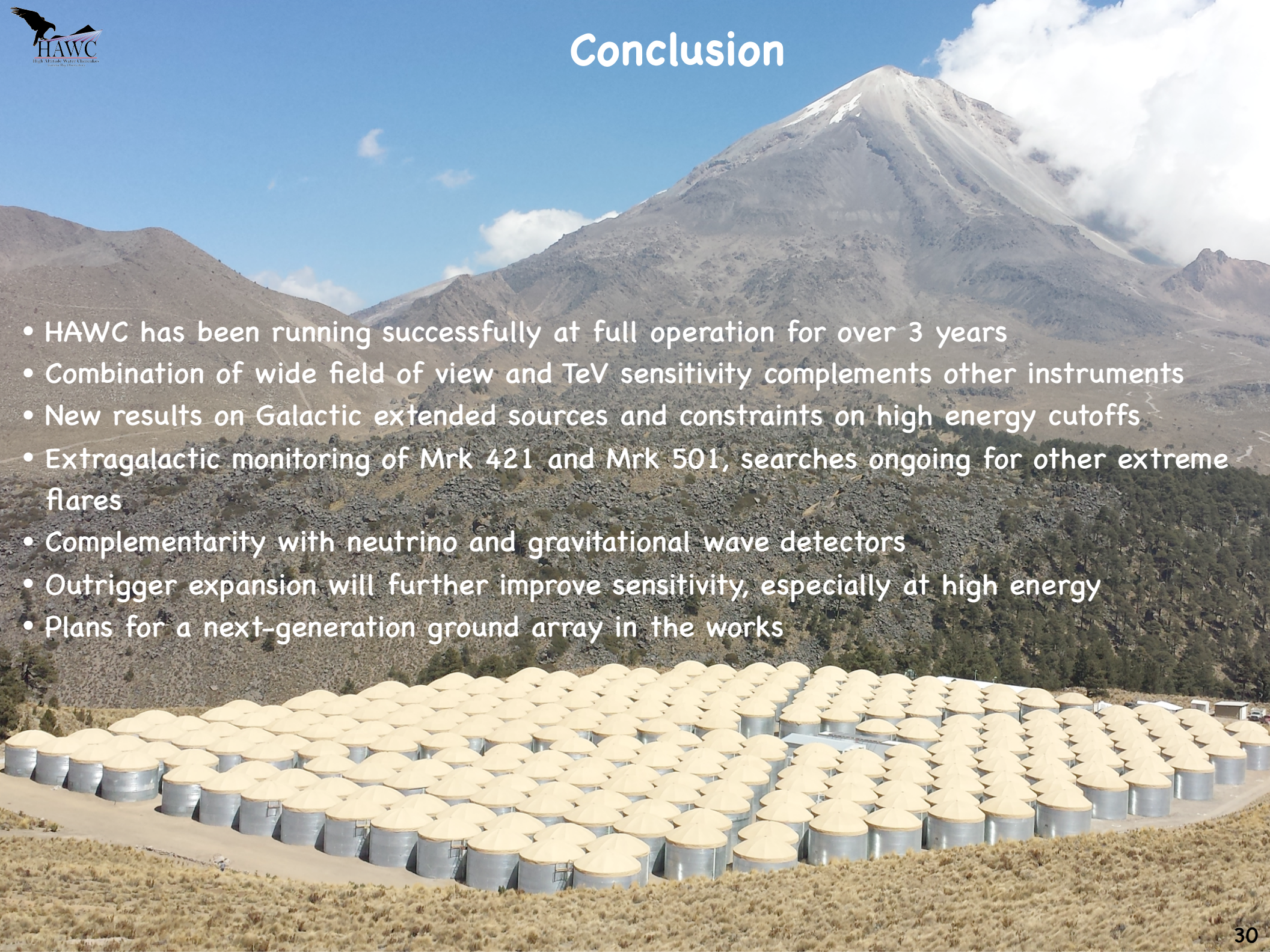


Southern Gamma-ray Survey Observatory

- Plans for a ground array in the southern hemisphere
- Complementary to CTA and LHAASO
- Higher altitude, larger instrumented area for lowering energy threshold, increasing overall sensitivity
- Several sites in South America being considered, most around 5000 m altitude
- https://www.sgso-alliance.org/SGSOWiki/doku.php?id=sgso_members



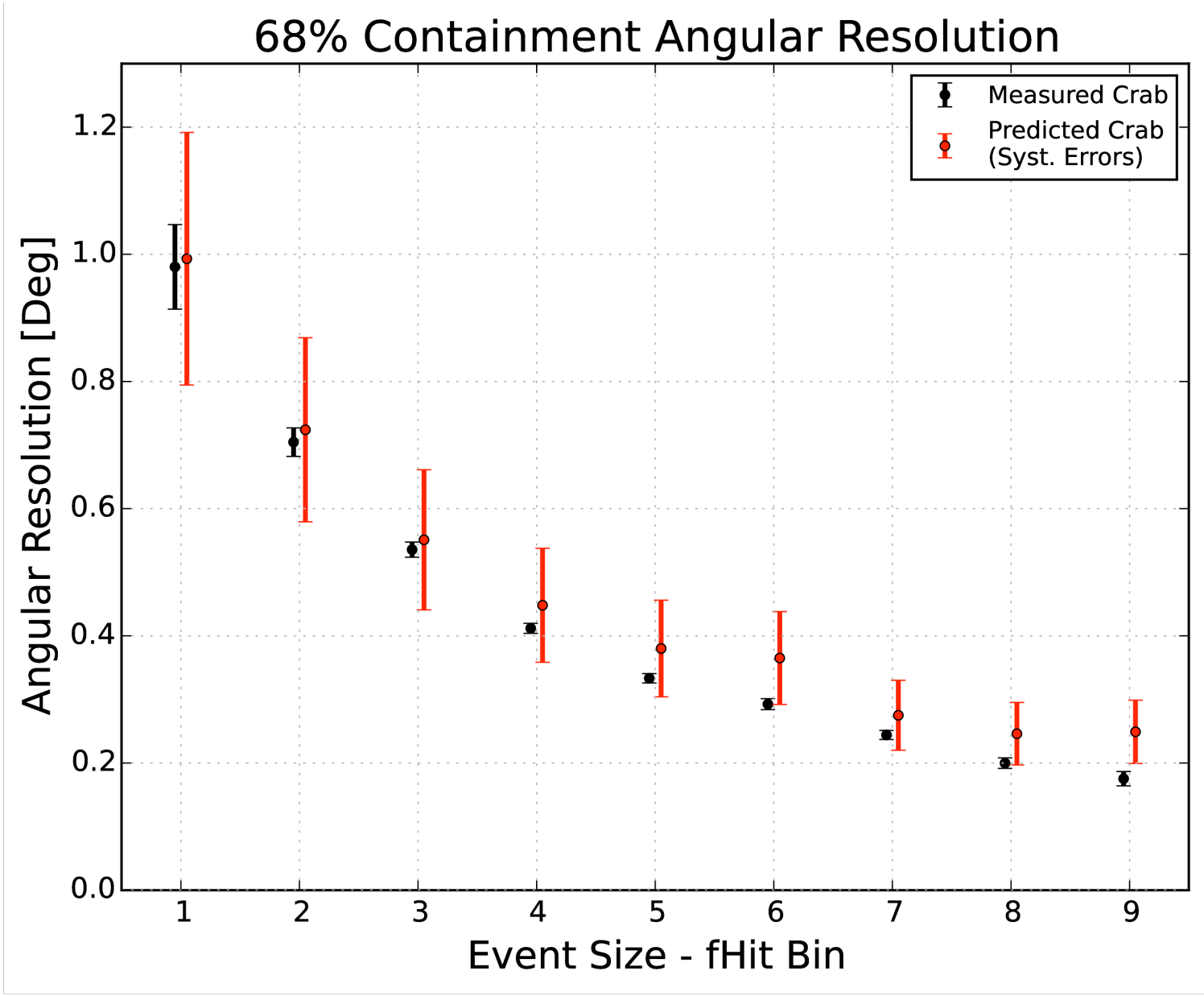
Conclusion



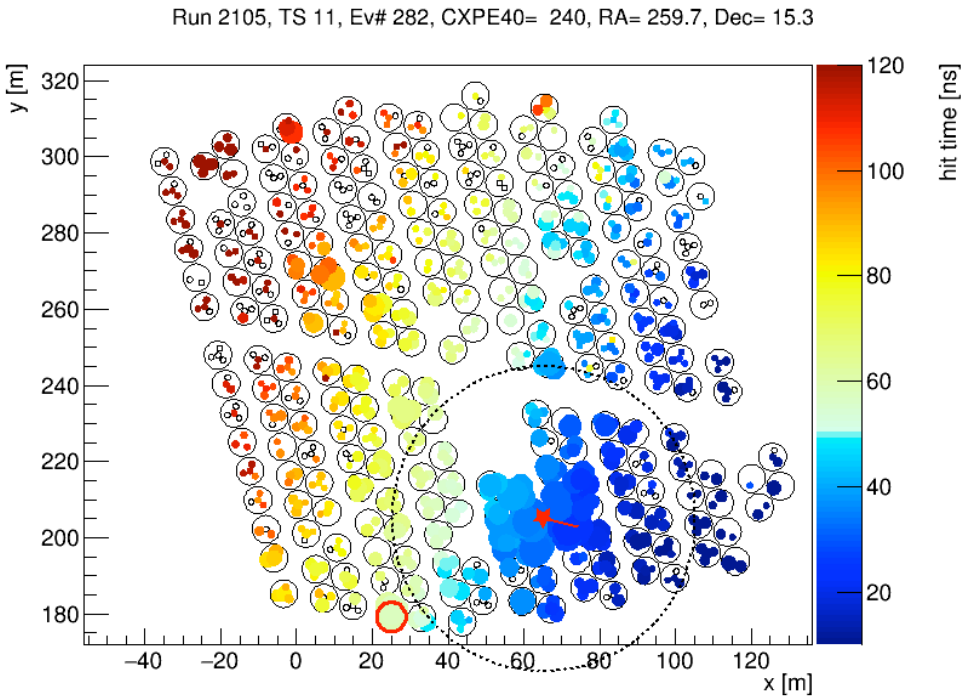
- HAWC has been running successfully at full operation for over 3 years
- Combination of wide field of view and TeV sensitivity complements other instruments
- New results on Galactic extended sources and constraints on high energy cutoffs
- Extragalactic monitoring of Mrk 421 and Mrk 501, searches ongoing for other extreme flares
- Complementarity with neutrino and gravitational wave detectors
- Outrigger expansion will further improve sensitivity, especially at high energy
- Plans for a next-generation ground array in the works

Backup

HAWC angular resolution

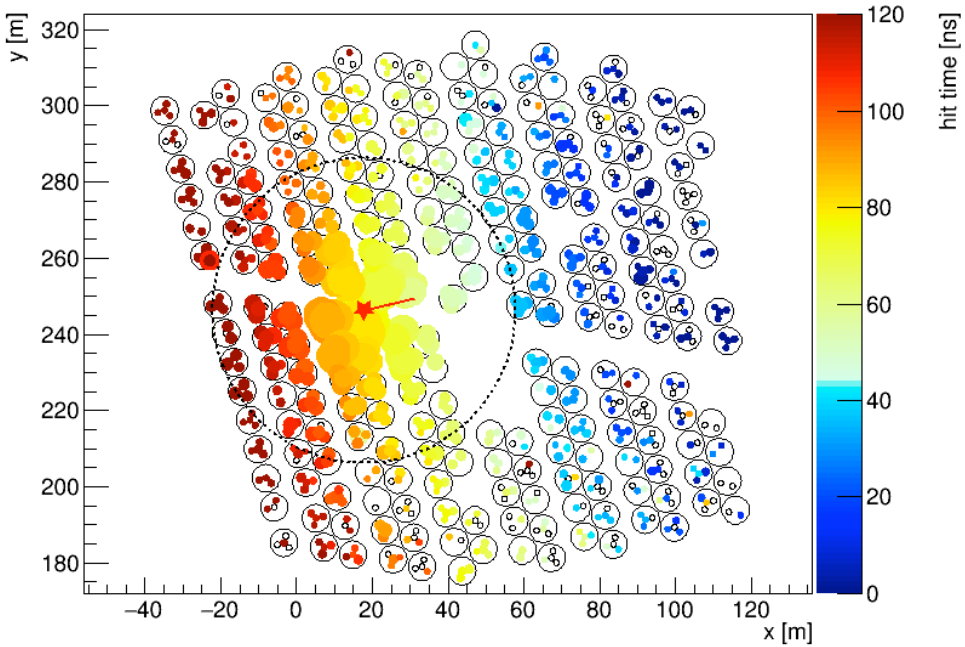


Gamma/hadron separation



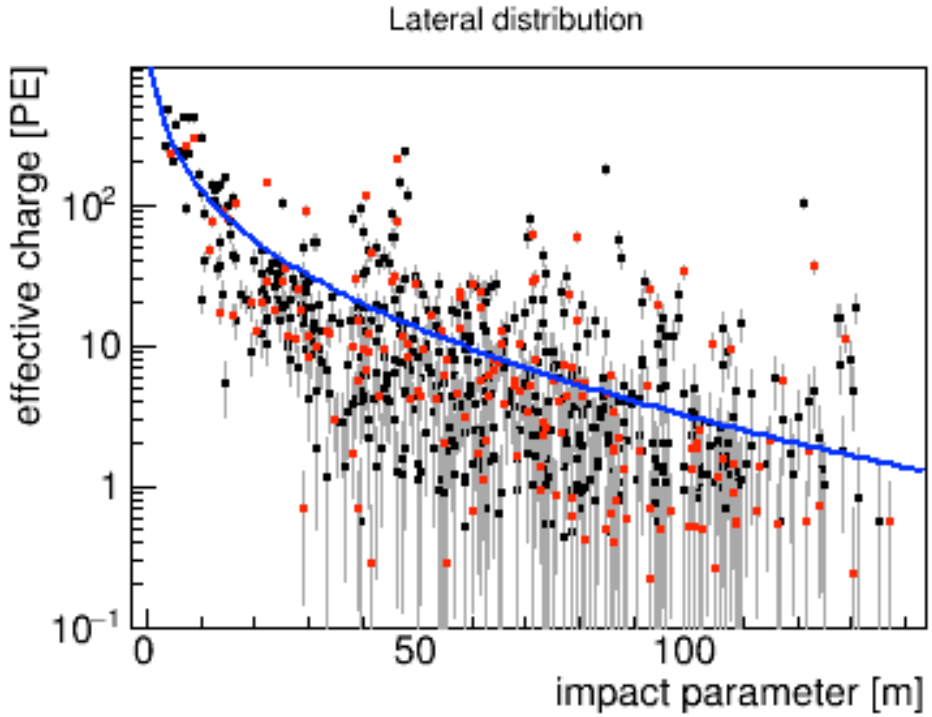
Background cosmic ray event

- Hadronic interactions create local depositions of charge far from shower core due to high transverse momentum of pions
- In contrast, lateral distribution of charge at ground level is smooth for electromagnetic showers



High-confidence gamma ray event

Gamma/hadron separation



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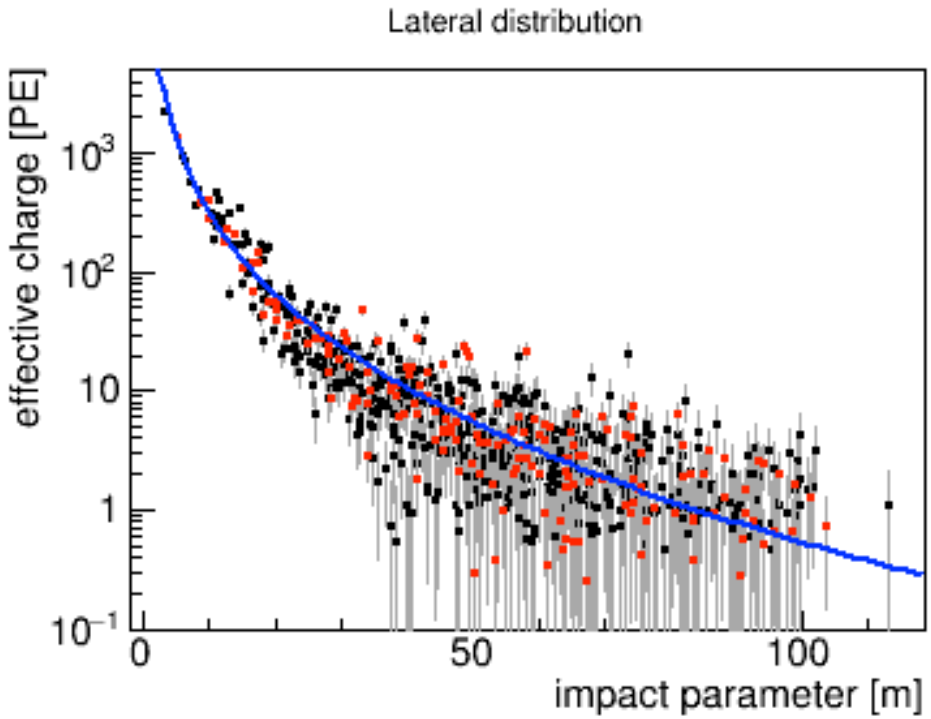

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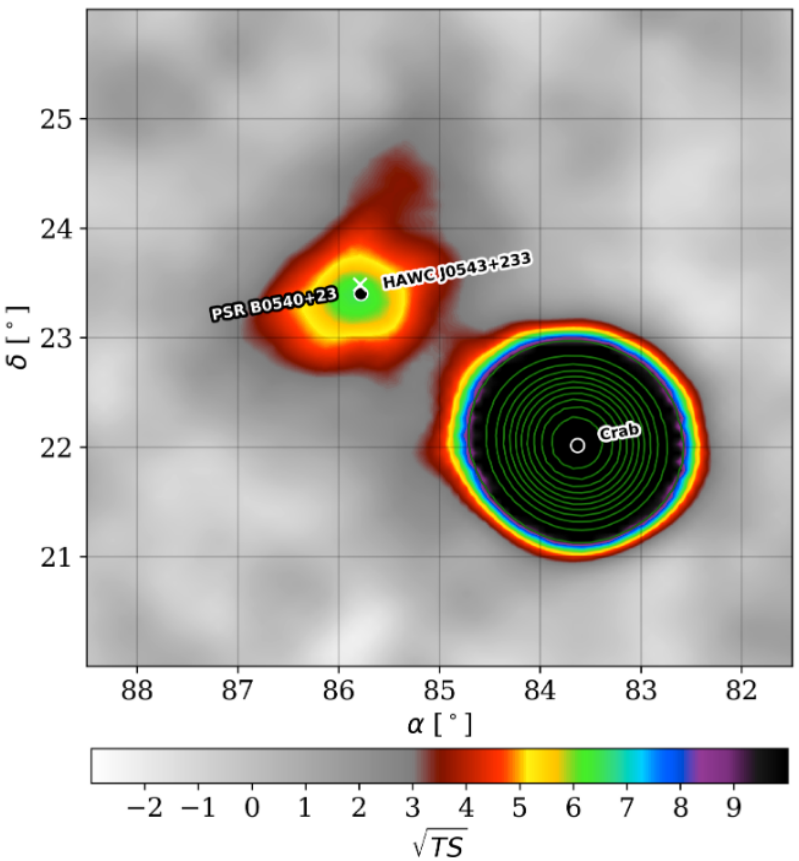
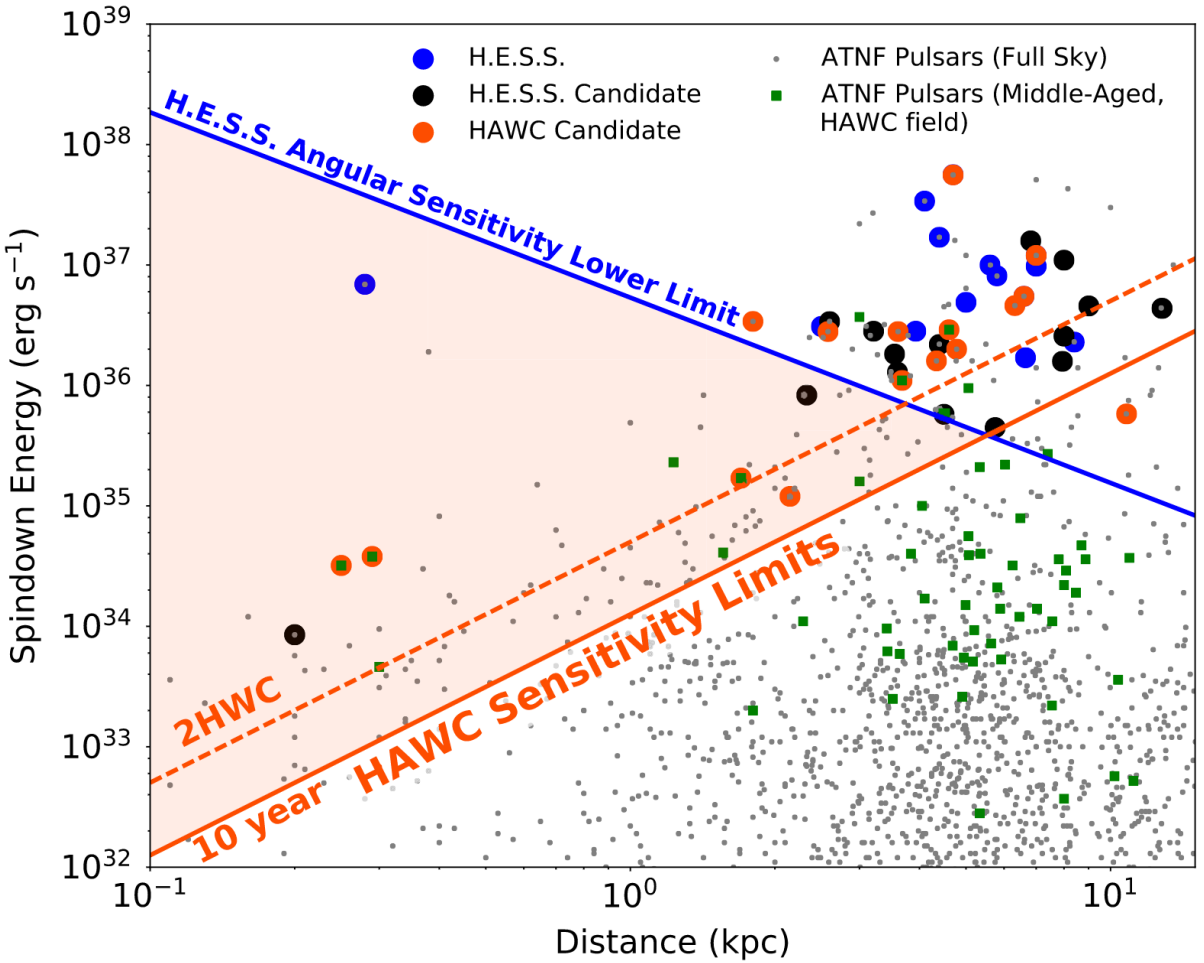
High-confidence gamma ray event

Local extended sources

- HAWC opens a new window to study local pulsar populations
- Connection between spindown power and VHE luminosity
- Recently discovered TeV emission from PSR B0540+23 near Crab Nebula
- Possibility to locate "hidden" pulsars via their TeV emission





Linden et al., PRD **96**, 103016 (2017)

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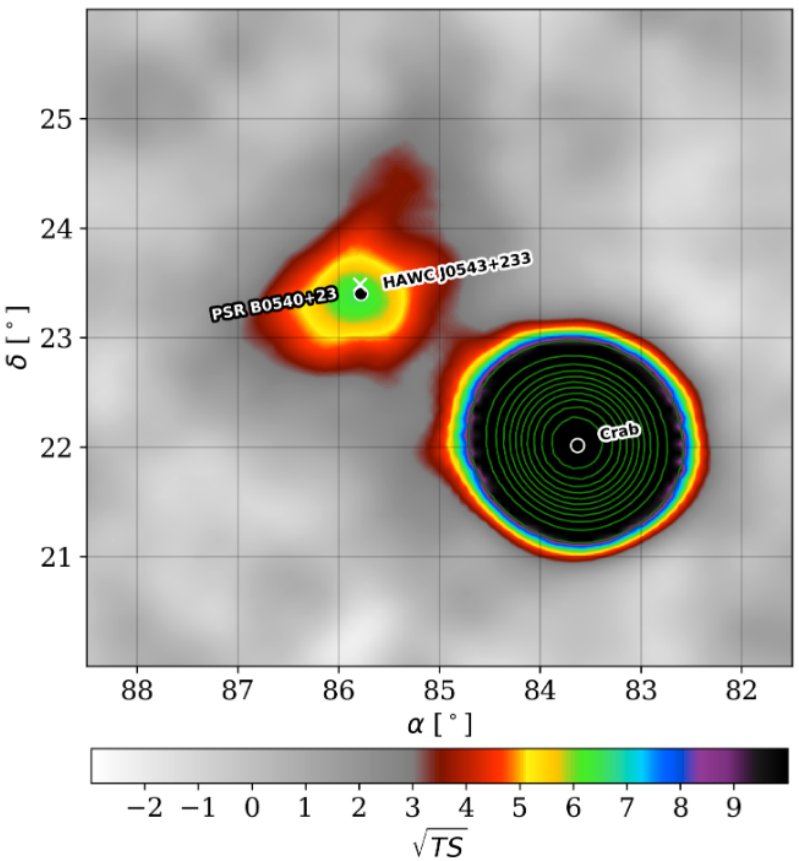
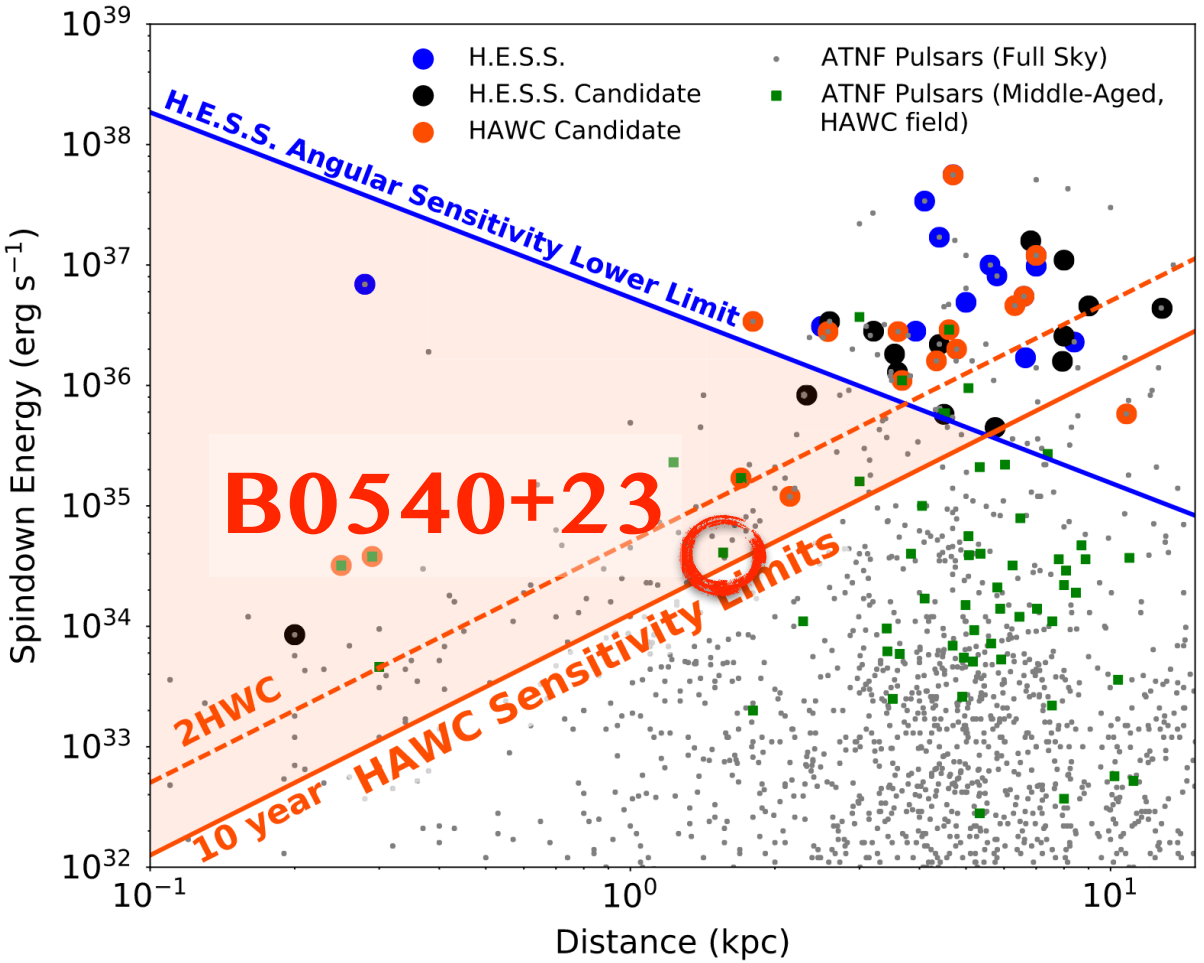
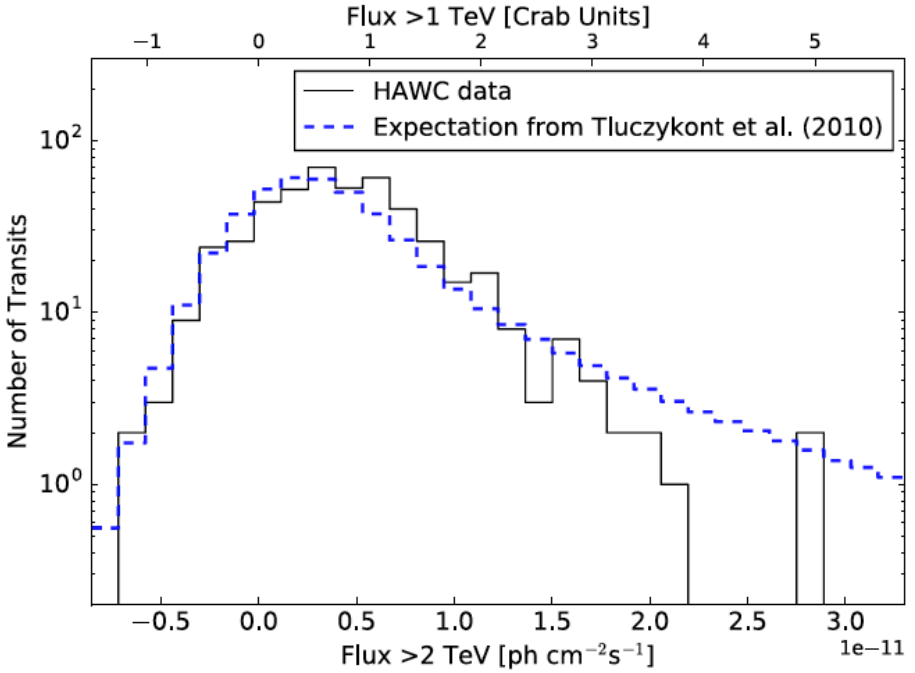


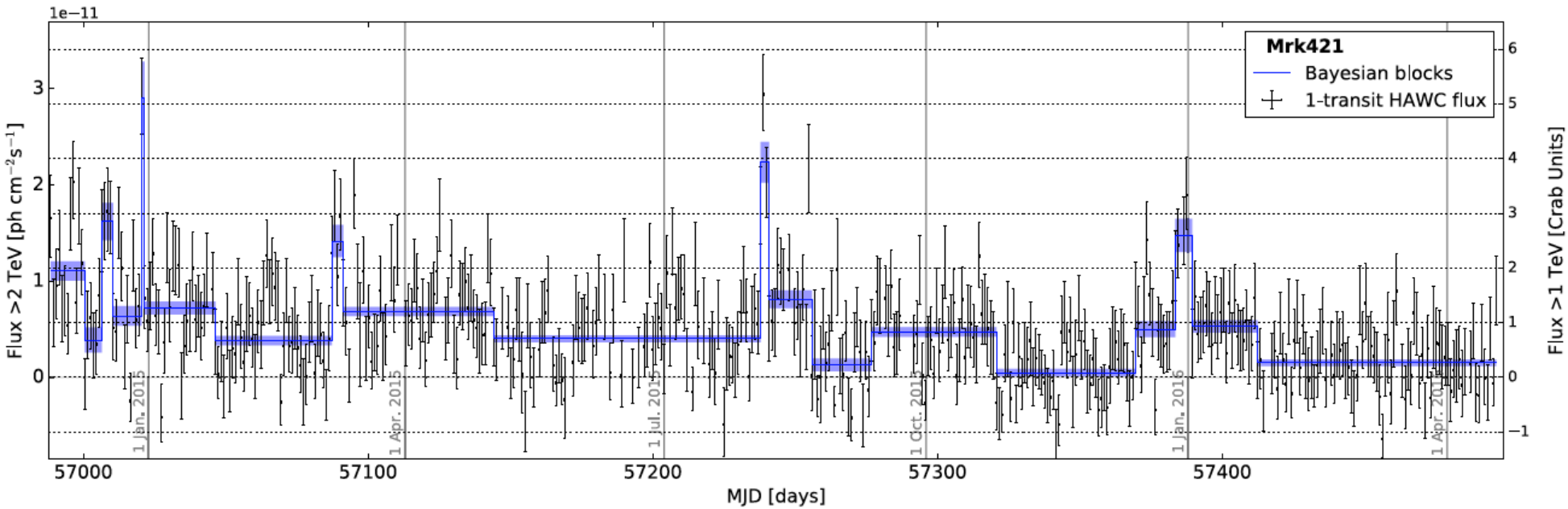


Linden et al., PRD **96**, 103016 (2017)

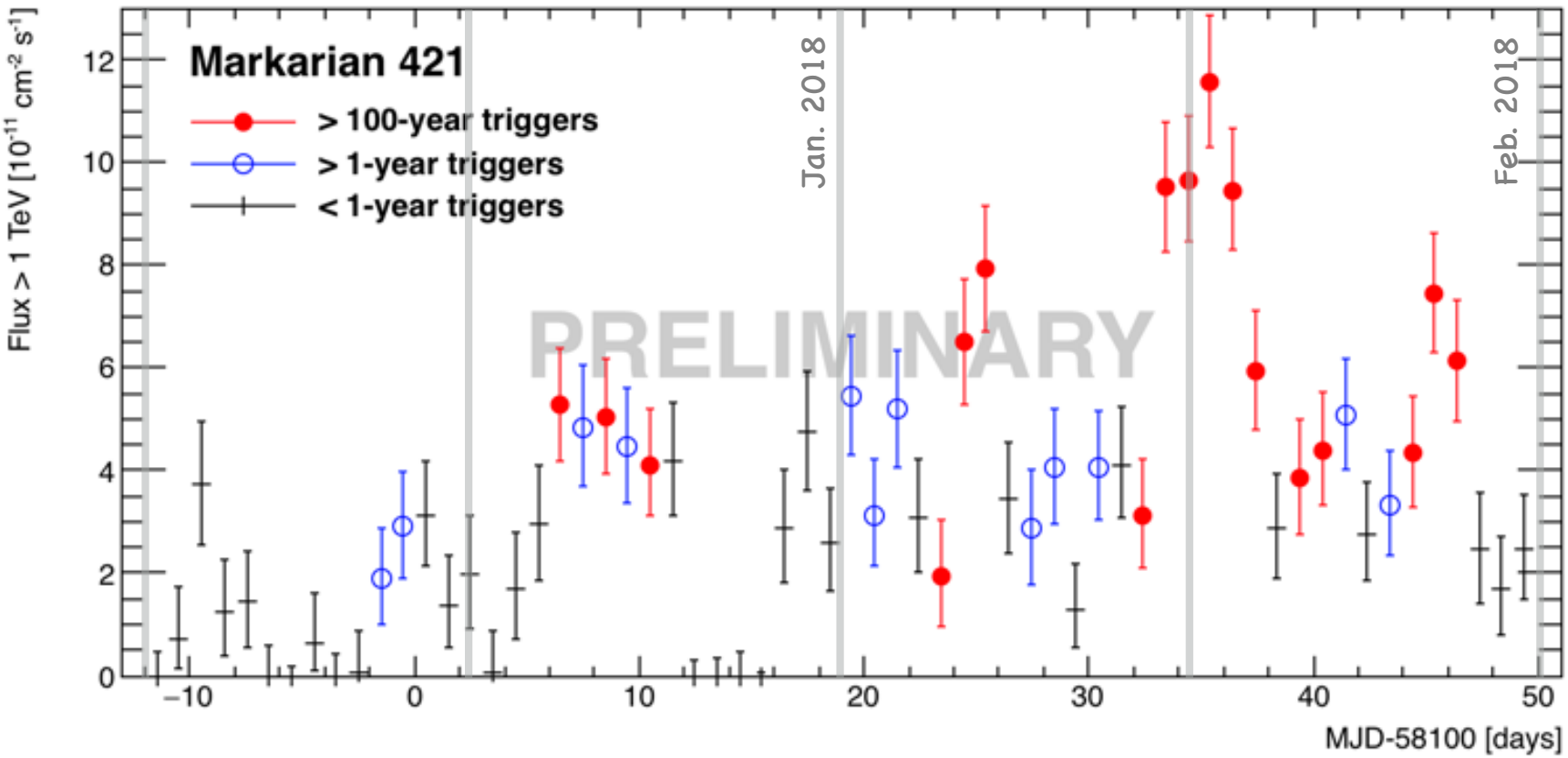
Markarian flares

- To date, Mrk 421 and Mrk 501 are the only extragalactic sources detected by HAWC (z = 0.03)
- Light curves show high degree of variability, as expected for blazars
- 1.5 years of HAWC observations of Mrk 421 are inconsistent with expectation from 10 years of IACT data
  - Difference in activity?
  - IACT bias for observing flares?





Flare monitor verification on Mrk 421



- Correlation between high-confidence triggers from the flare monitor and flux from offline analysis in recent Mrk 421 activity
- Coordinated observations with IACTs, other wavelengths can lead to in-depth understanding of particle acceleration mechanisms during flares
- Alerts presently sent to VERITAS, MAGIC, HESS, FACT, Fermi