Recent Results from The HAWC Gamma Ray Observatory

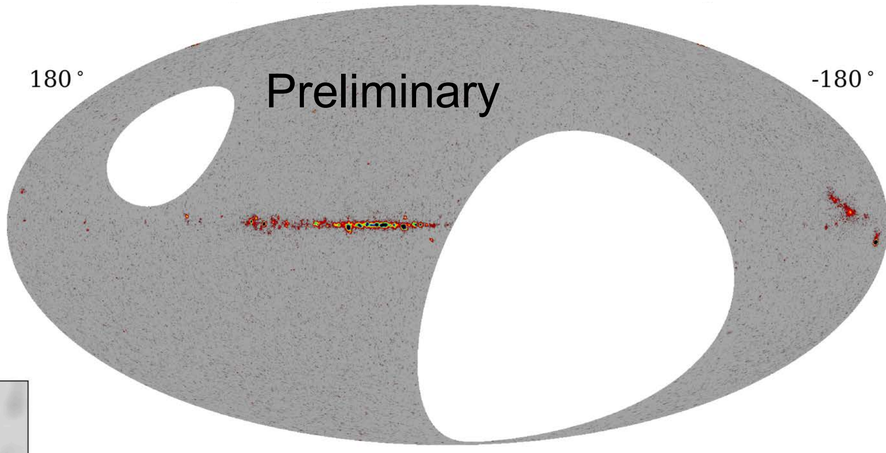
Jordan Goodman for the
HAWC Collaboration
Lake Louise 2024

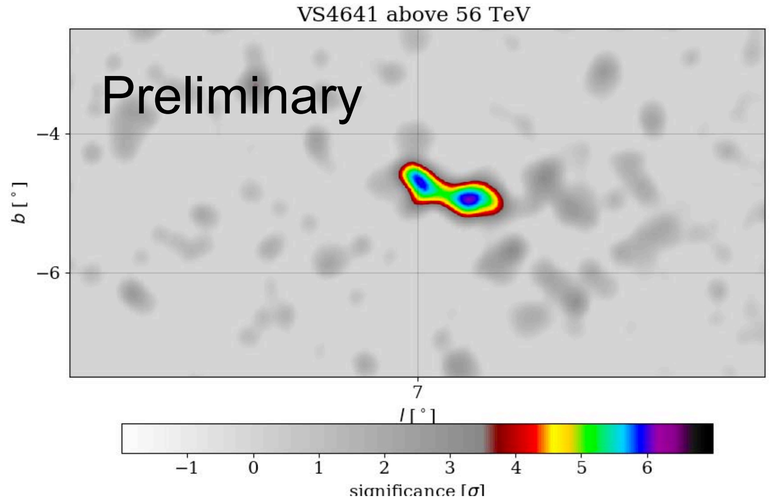
The High Altitude Water Cherenkov (HAWC) Observatory

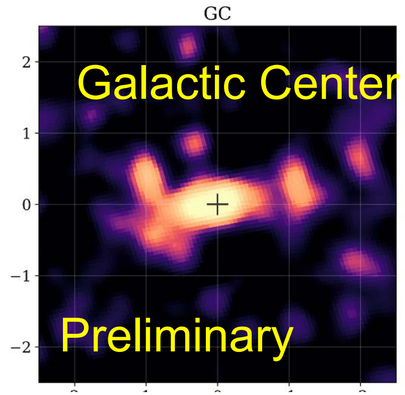
- Why study high energy gamma rays from space?
  - Gamma rays travel in straight lines from the production site of the highest energy charged particles which are bent by magnetic fields
  - We want to understand the origin of the high energy cosmic rays and their acceleration mechanism
- What astrophysical process accelerates particles to PeV energies?
  - Shock acceleration in extreme astronomical processes - pulsar winds, supernova remnants, jets from black holes, binary systems, active galaxies…
- What produces high energy gamma rays?
  - High energy pions from hadronic collisions with matter near the source
  - High energy electrons inverse Compton scattering off of x-rays or CMB photons
  - 100 TeV gamma rays from PeV electrons or hadrons

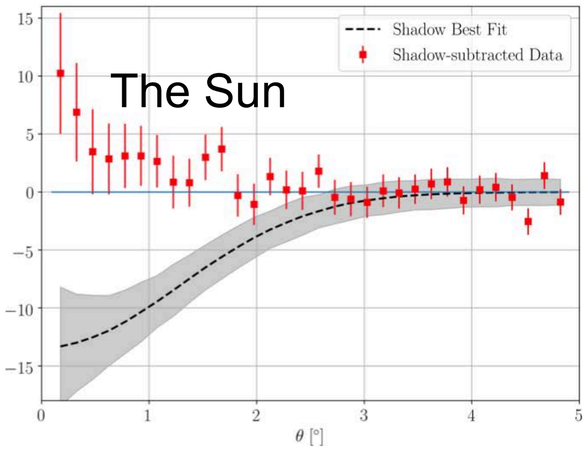
HAWC - Recent Results

- Updated sky maps:
  - Improved resolution & gamma/hadron rejection
- Highest Energy Sky
- TeV Halos
- Binaries (micro-quasars)
  - SS 433
  - V4641 SGR (new)
- Galactic Center
- TeV Gamma rays from the Sun
- AGN results
- Cosmic Ray Spectra
- Dark Matter and LIV Limits









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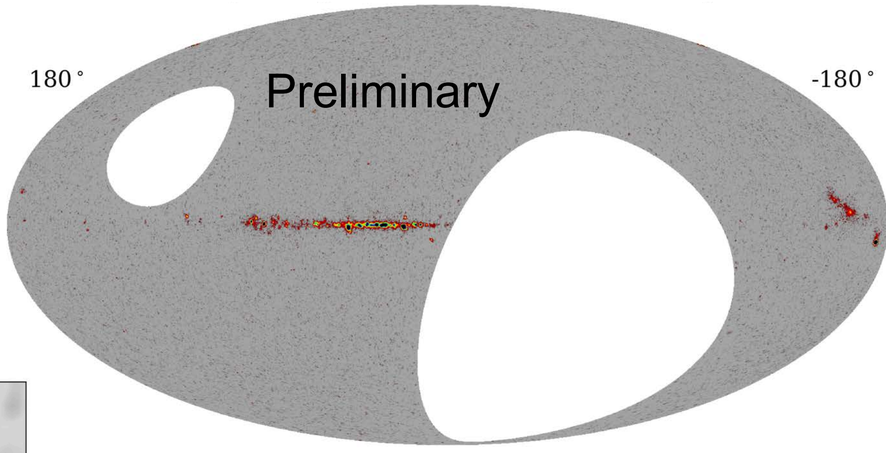
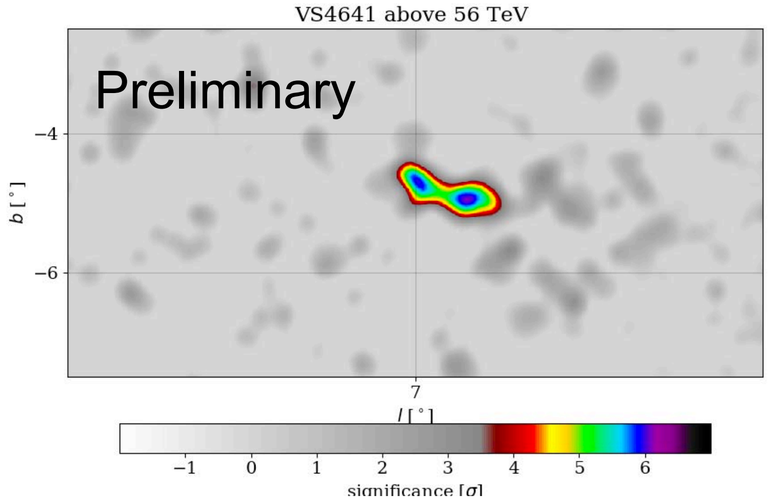
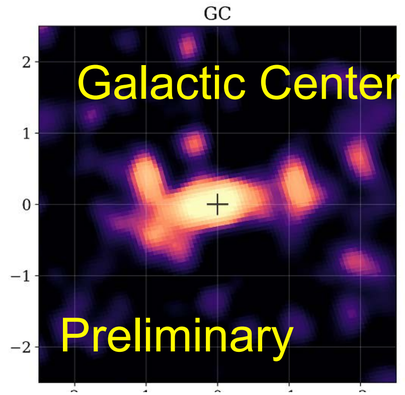
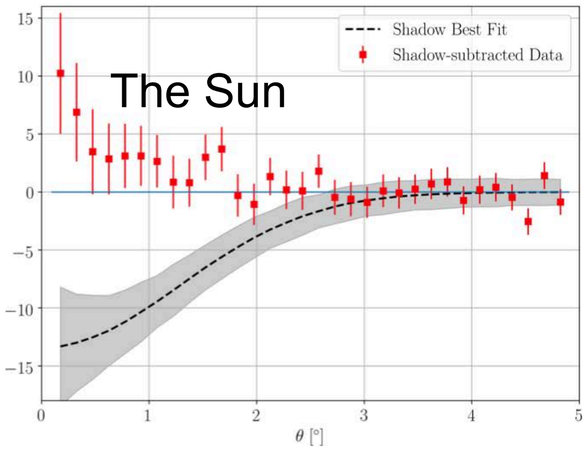




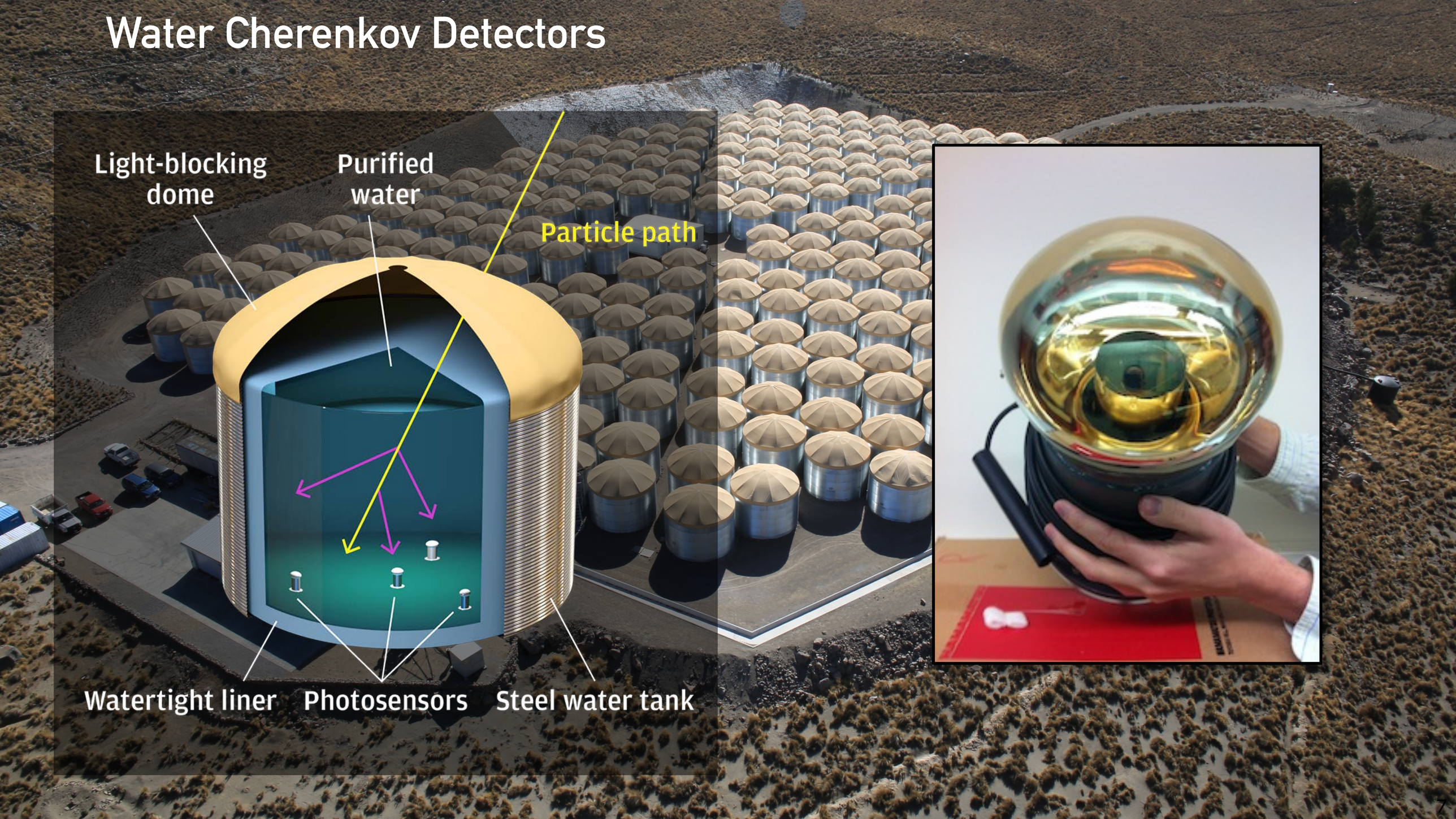




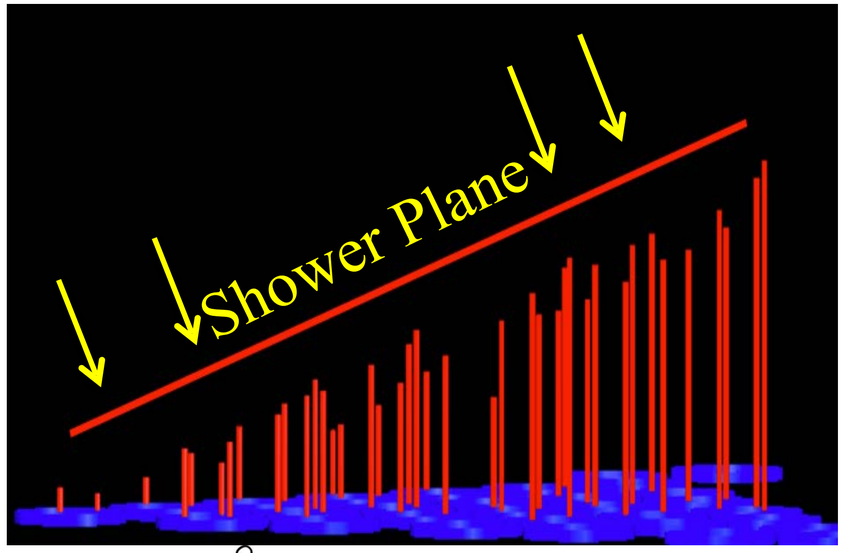

HAWC
V2
V1

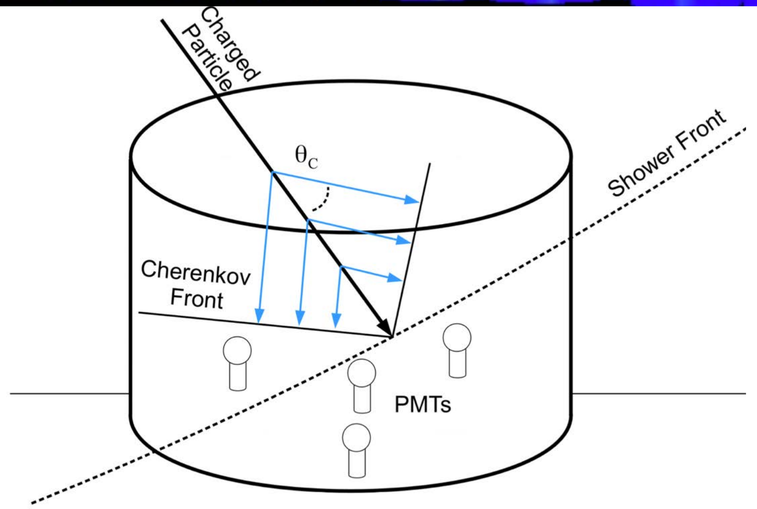
- 300 close-packed optically isolated water Cherenkov detectors
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, since summer 2018
- Takes data with >95 on time
- ~8 trillion triggers to date - 10PB of data

Water Cherenkov Detectors



Angle Reconstruction



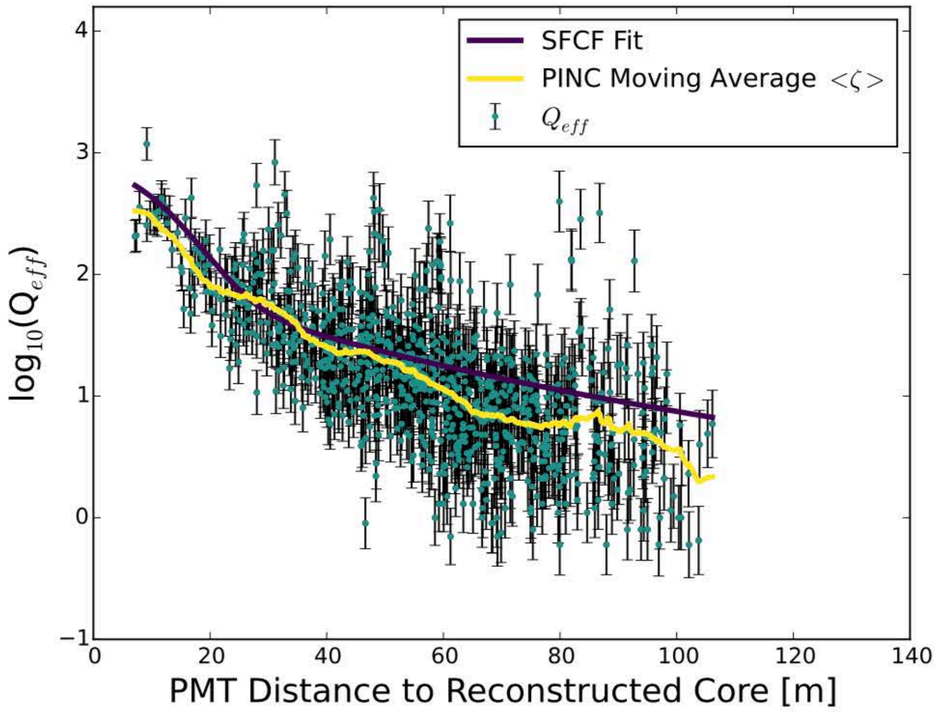


Photons convert to e+e- in the water

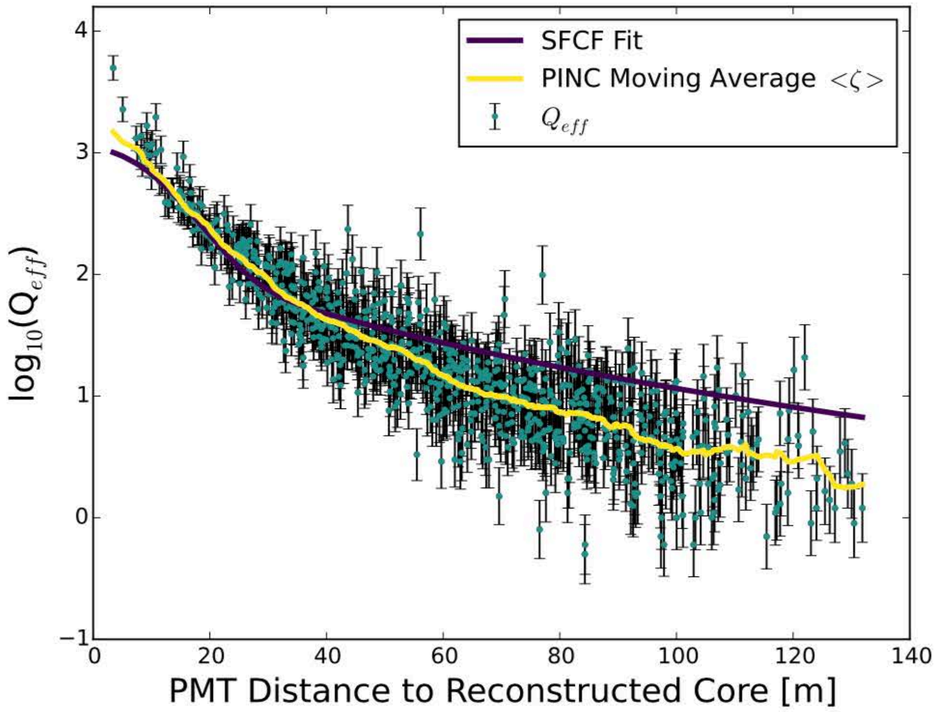
Shower reconstruction

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

Clumpy: hadron-like

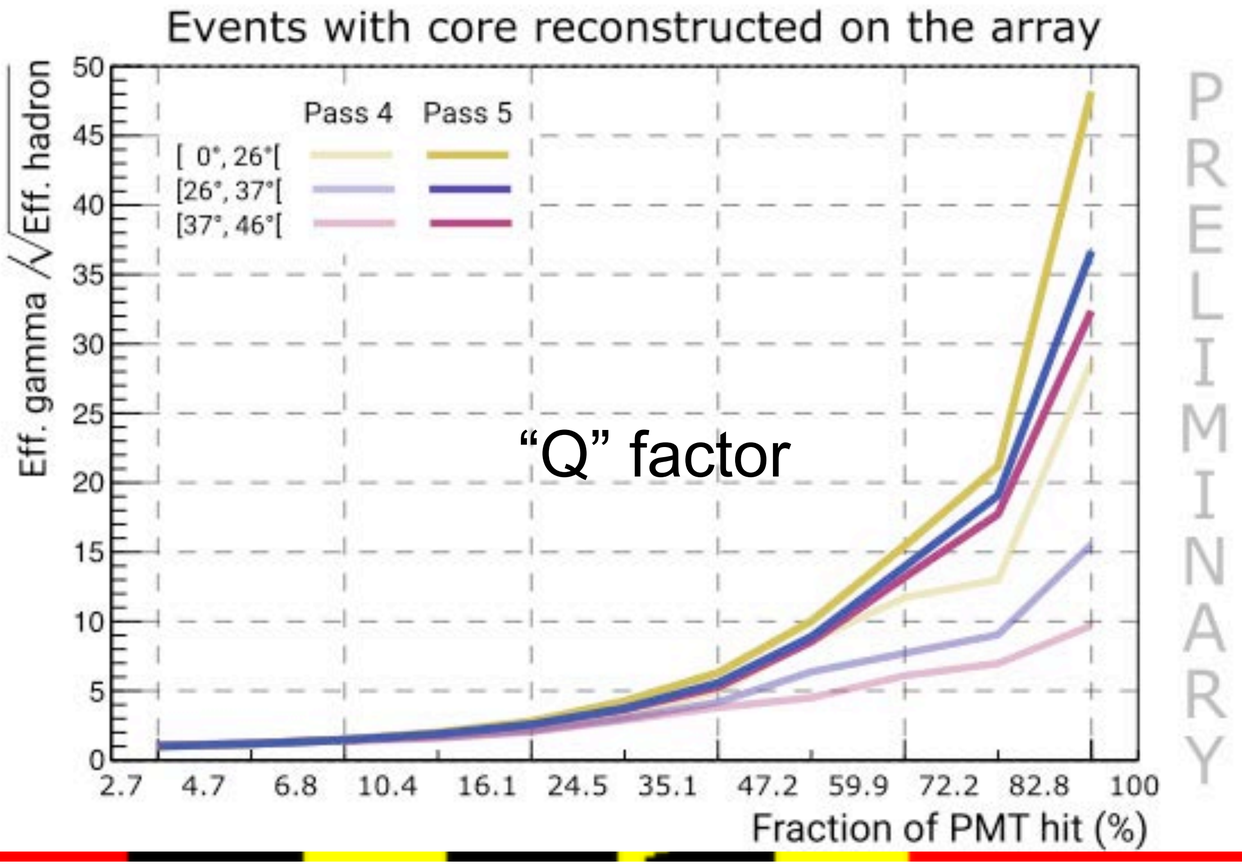


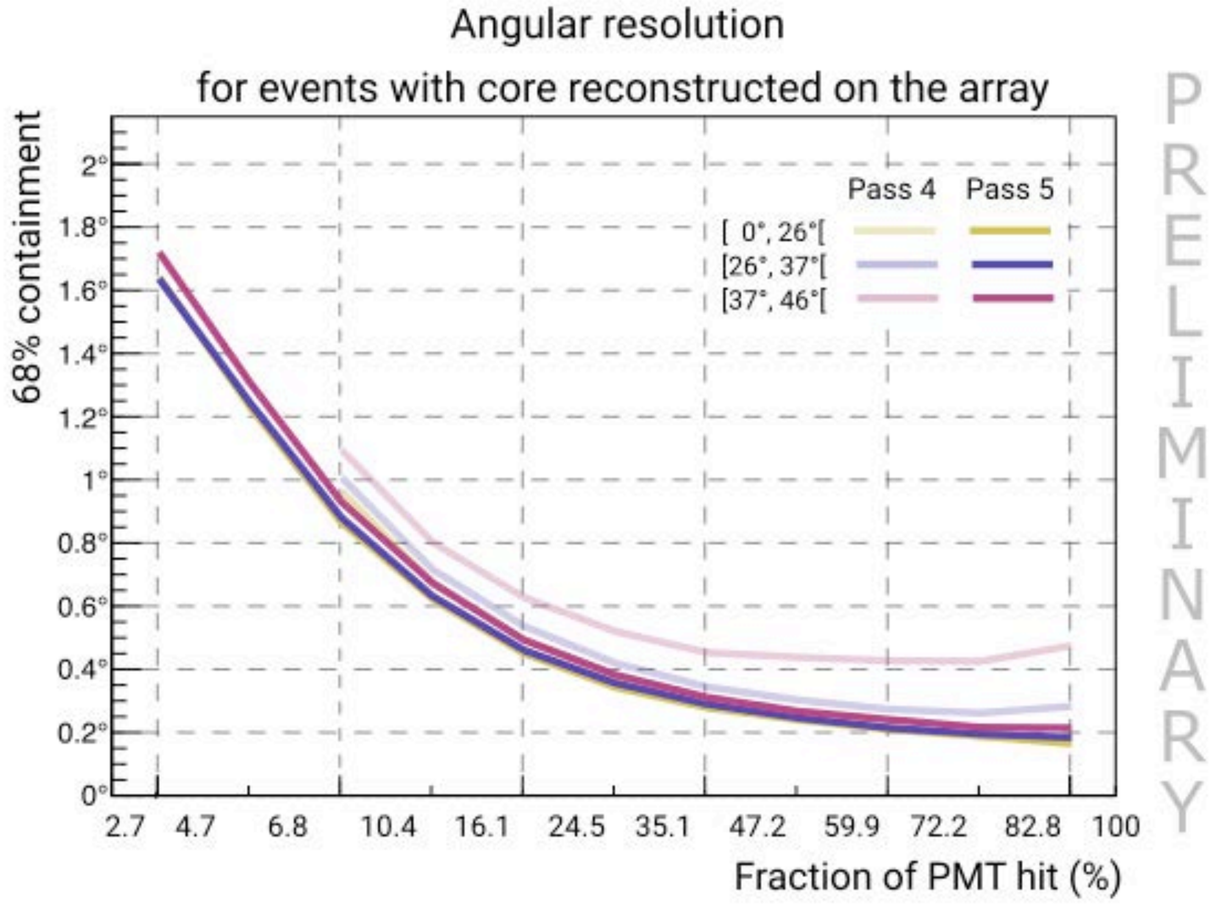
Smooth: gamma-like



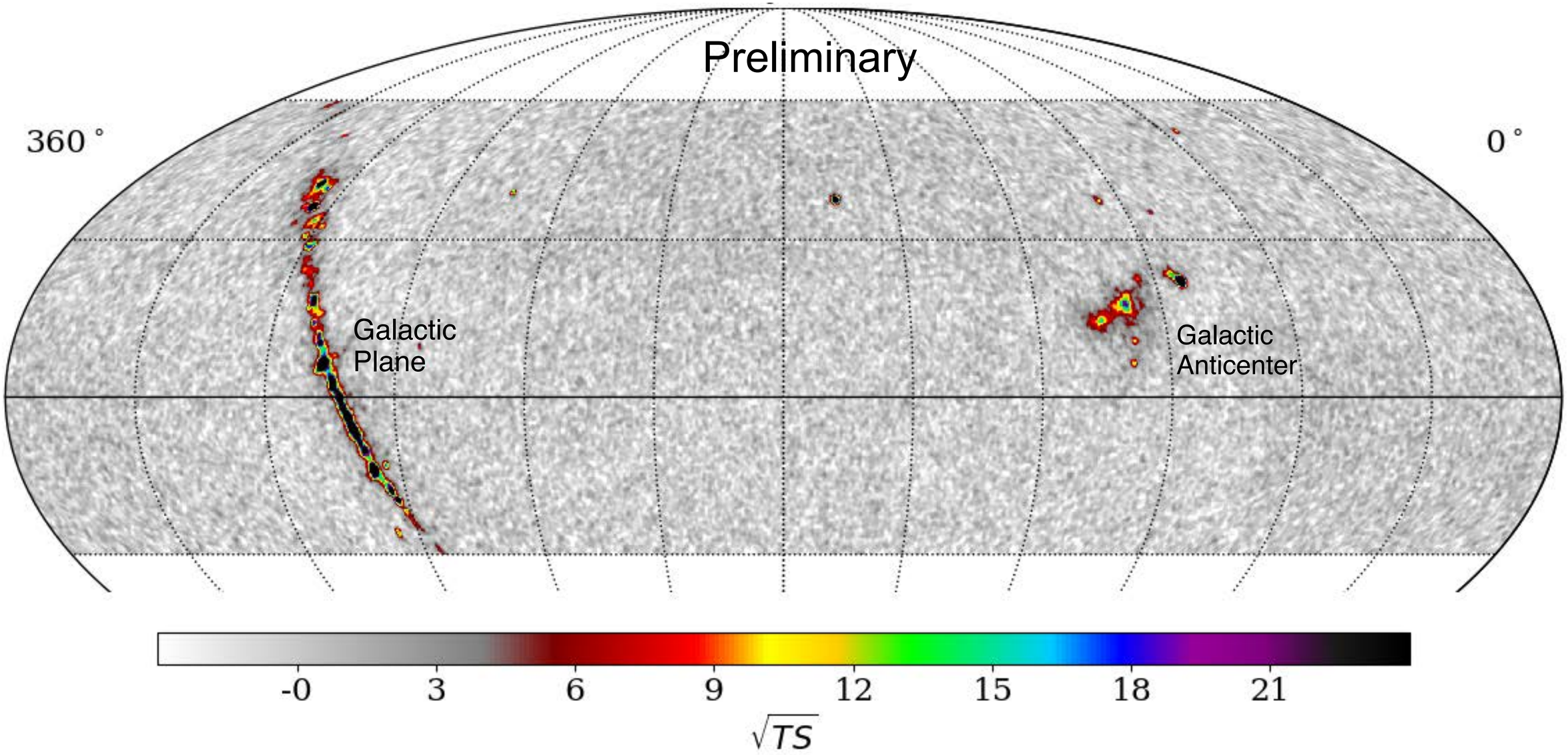
“Pass 5” - Improved Reconstruction

- Large Events - Much improved background rejection (better than 10^4)
- Better Angular Resolution - ~0.15^o
- Wider FOV - Previous 45^o - now ~55^o





HAWC Sky Map 2770 Days of Data - Pass 5



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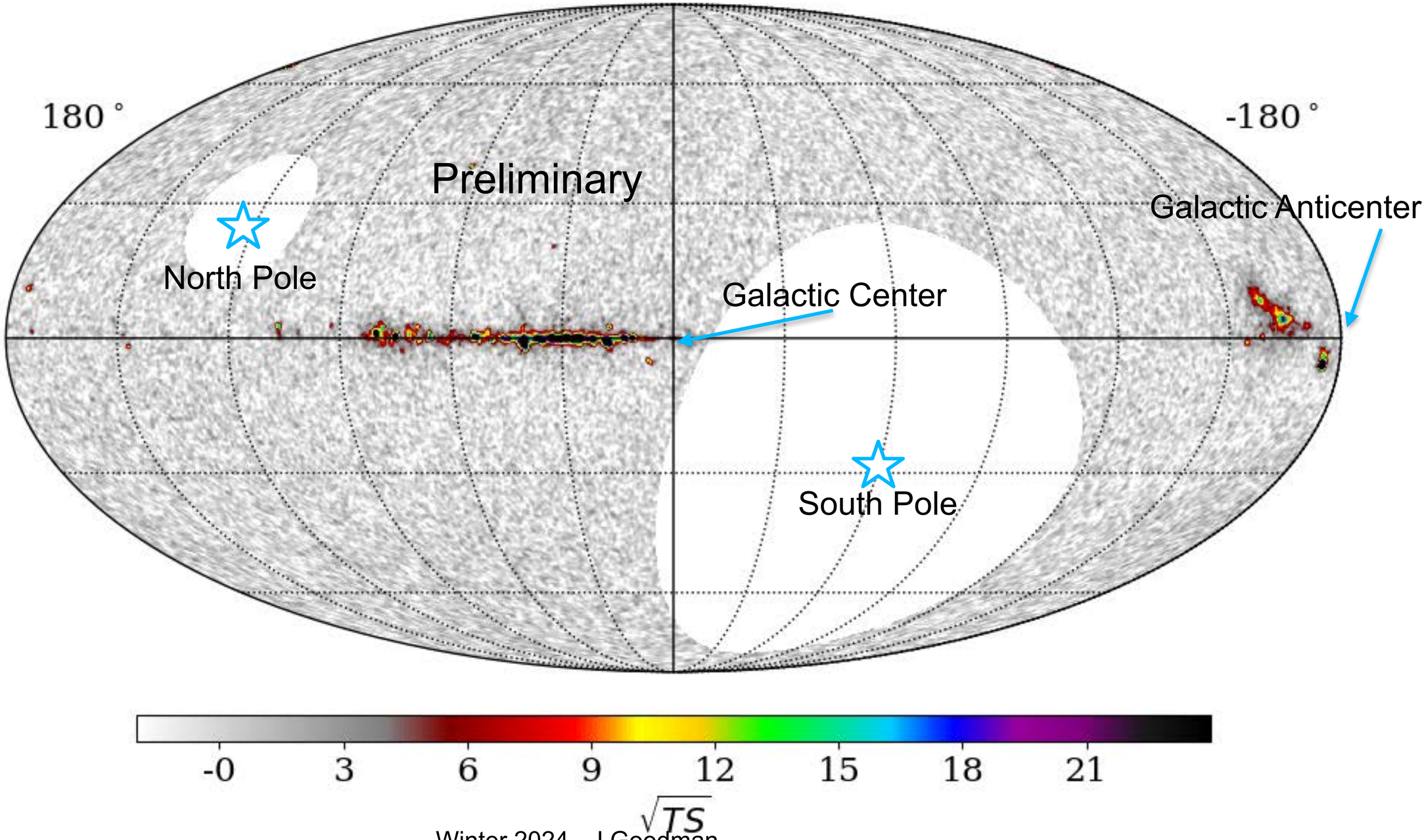
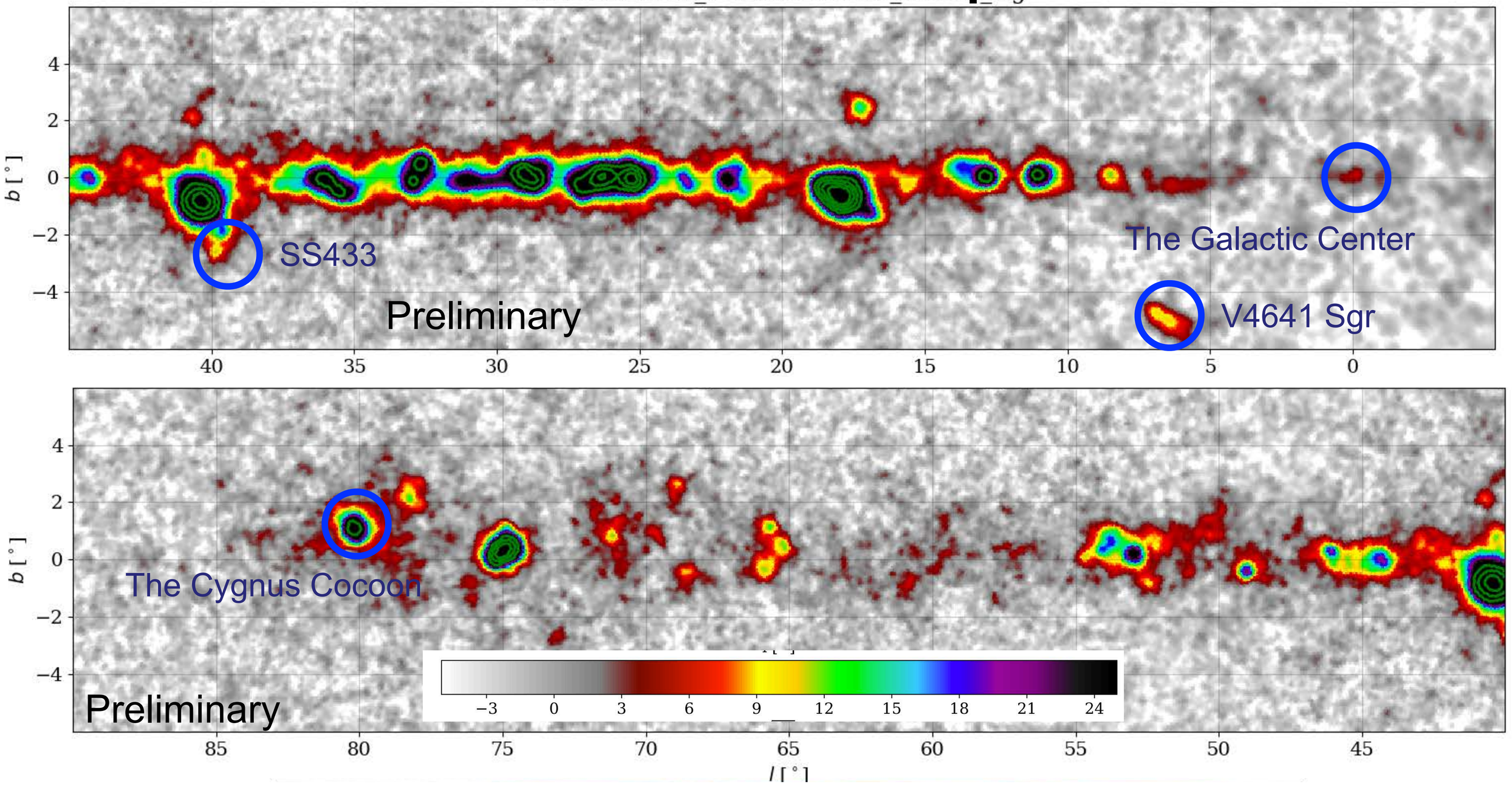
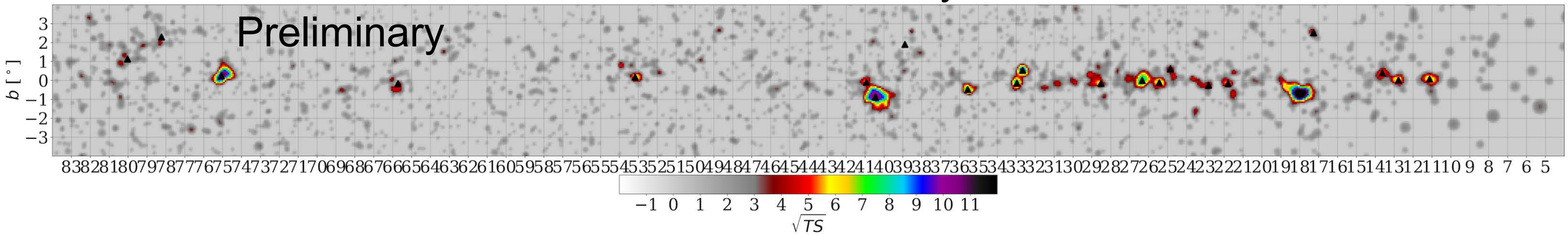


Pass 5 - 2770 map

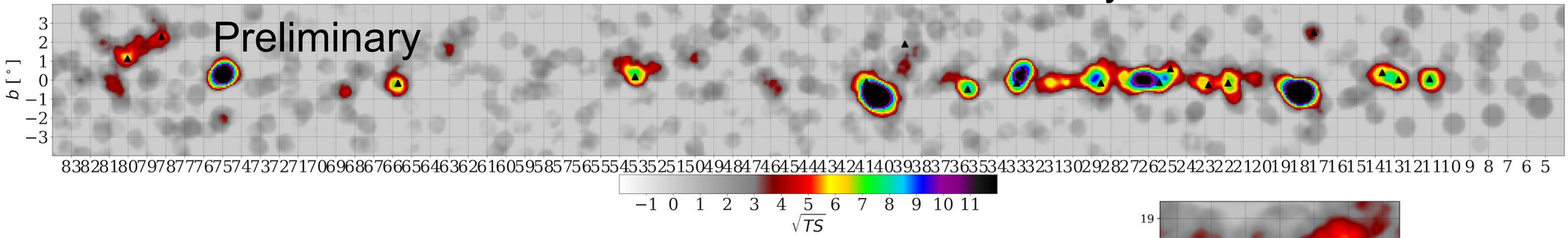


Pushing to the highest energies (>56 TeV)

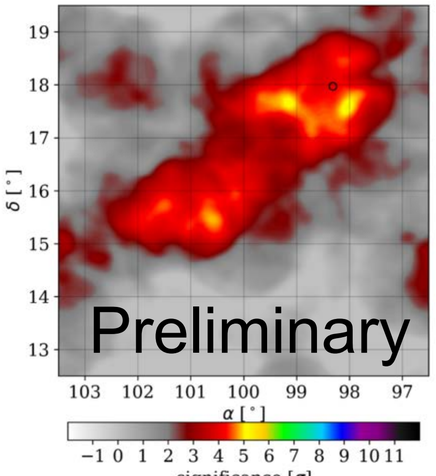
Point Source Analysis



0.5° Extended Source Analysis



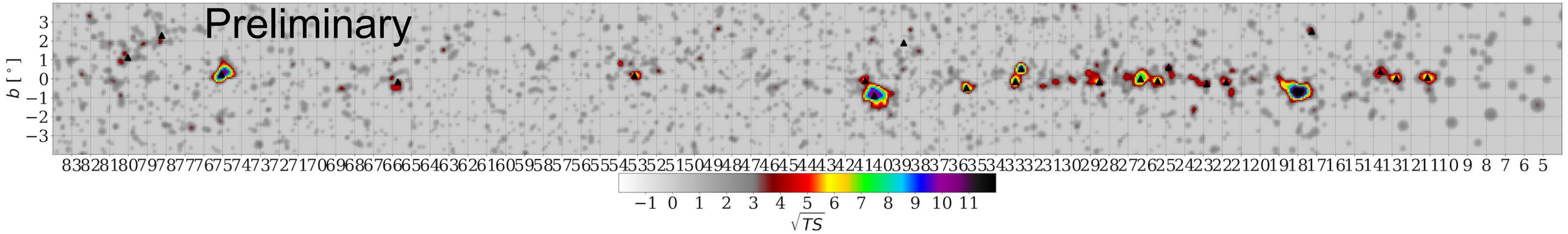
- Pass 5 - 25 sources are identified above 56 TeV (compared to 9 in Pass 4)
- Most high energy sources appear to be extended



Geminga >56 TeV TeV Halo

Pushing to the highest energies (>100 TeV)

Point Source Analysis



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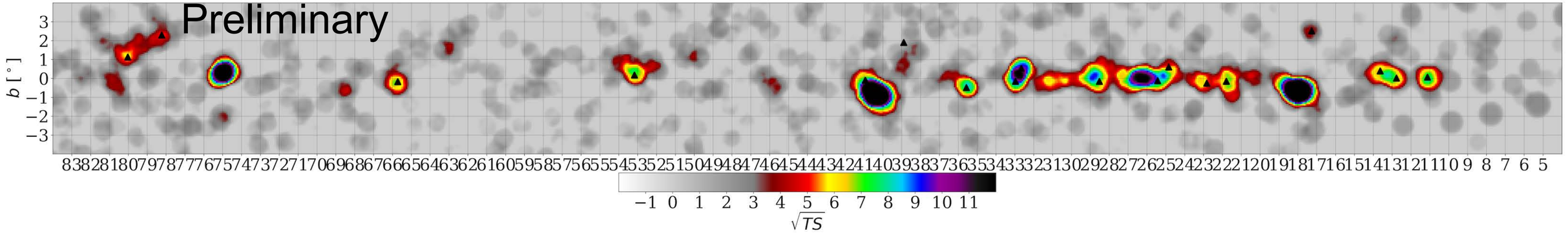
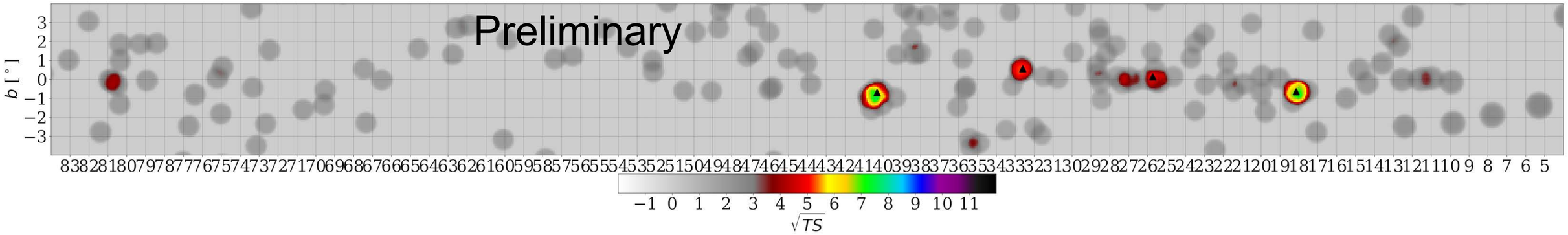


- Pass 5 - 18 sources are identified above 100 TeV (compared to 3 in Pass 4)
- Most high energy sources appear to be extended, but Crab is point-like

Pushing to the highest energies (>177 TeV)

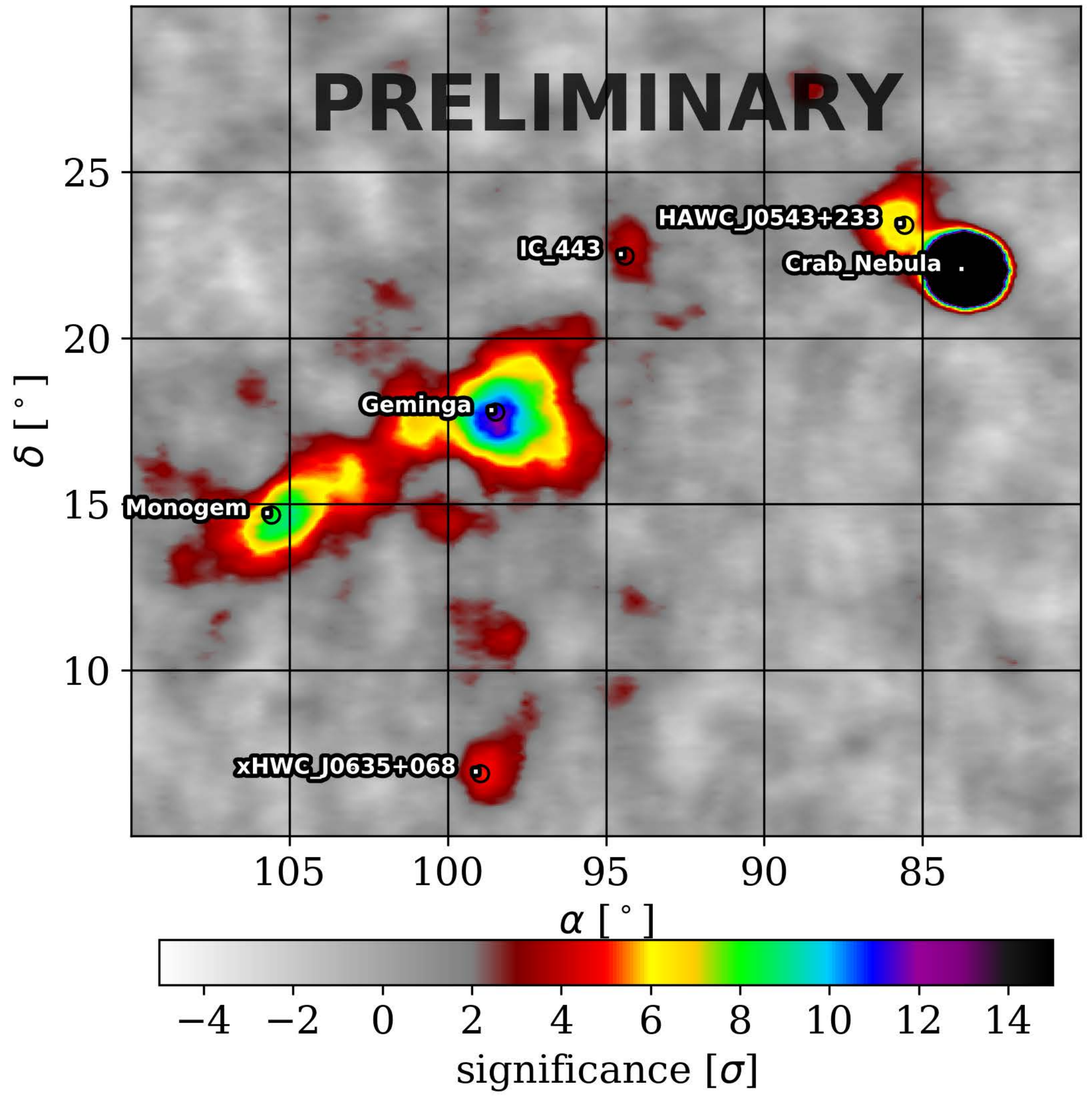
0.5° Extended Source Analysis



- Pass 5 - 4 sources are identified above 177 TeV (compared to 0 in Pass 4)
- Most high energy sources appear to be extended

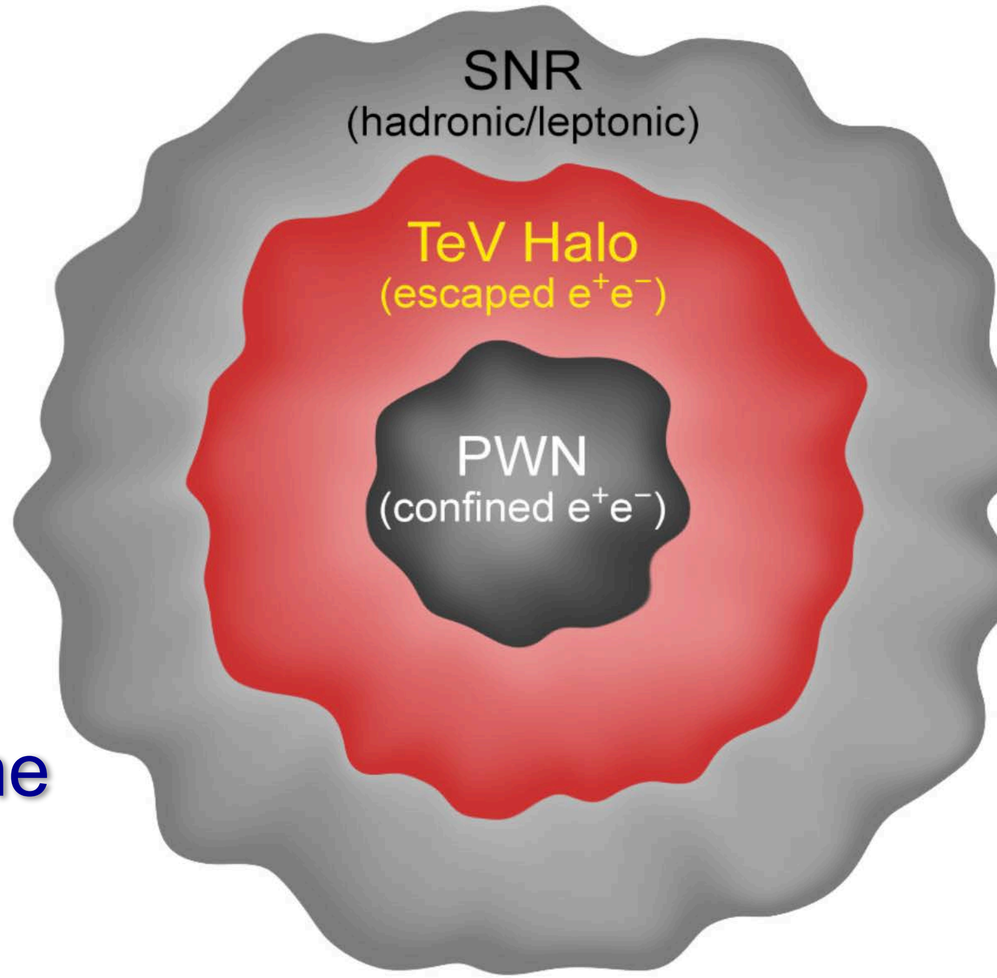
The Galactic Anti-Center

- New class of sources
  - Highly extended hard spectrum sources surrounding PWN
  - Labeled TeV Halos because their extension is much larger than the PWN
  - In the outer galaxy where there is little source confusion
  - Geminga and PSR B0656+14
    - Two middle-aged close-by PWN
    - Very extended in the sky
    - Thought to be a possible source of the positron excess



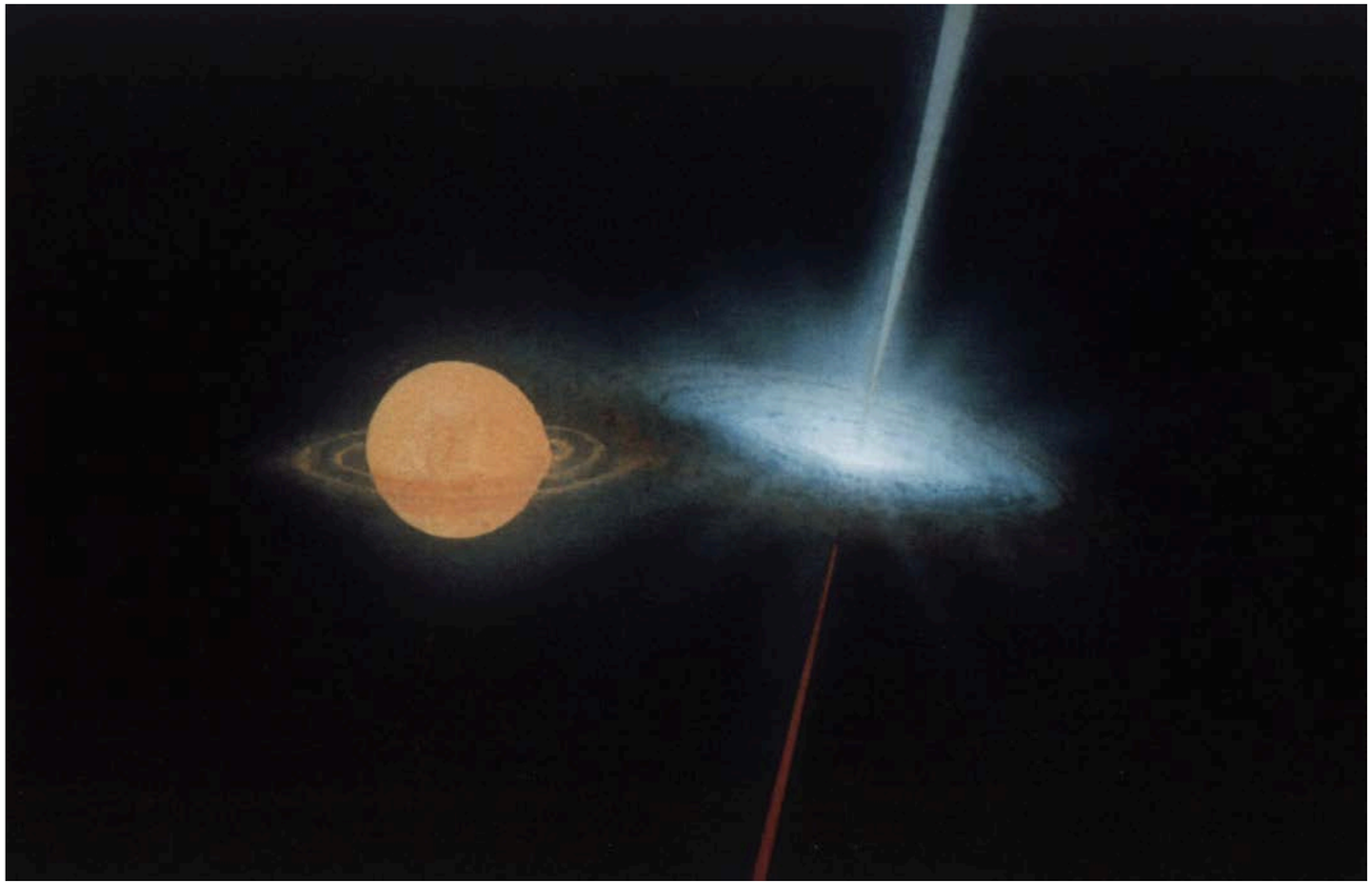
TeV Halos

- The x-ray emission is from synchrotron radiation, where the B field is enhanced by the pulsar to 10 to 20 μG
- For the highest energy electrons above ~100 TeV the only thing you can scatter off of is the CMB because its energy is so low (KN effect)
  - We know what the CMB is everywhere
- So we measure very extended objects in the TeV called TeV halos



Sudoh, T., Linden, T., & Beacom, J. F. 2019, arXiv:1902.08203.

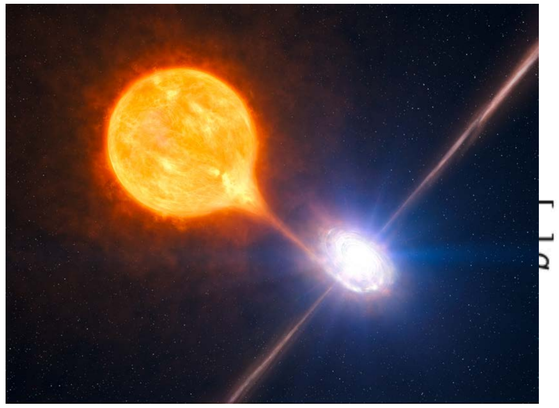
Microquasars

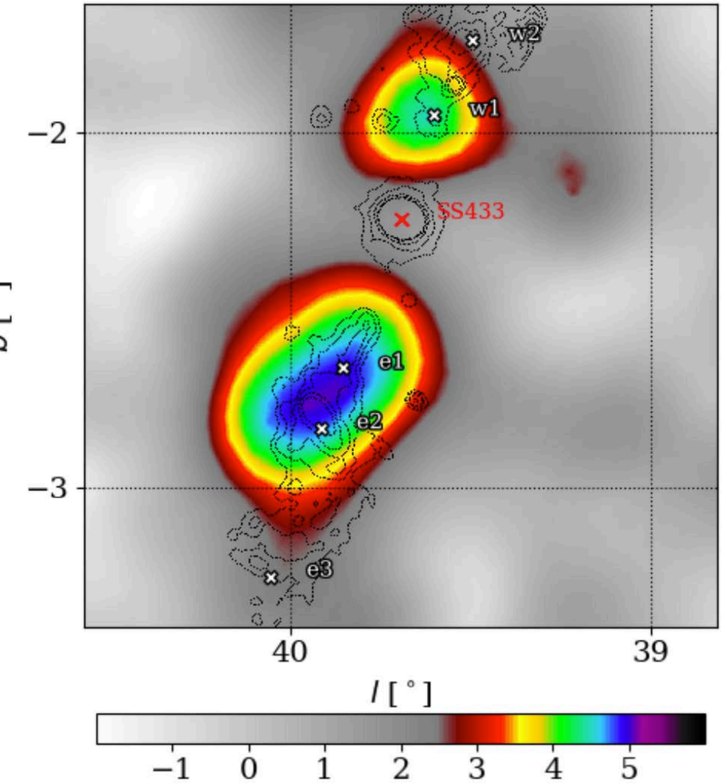


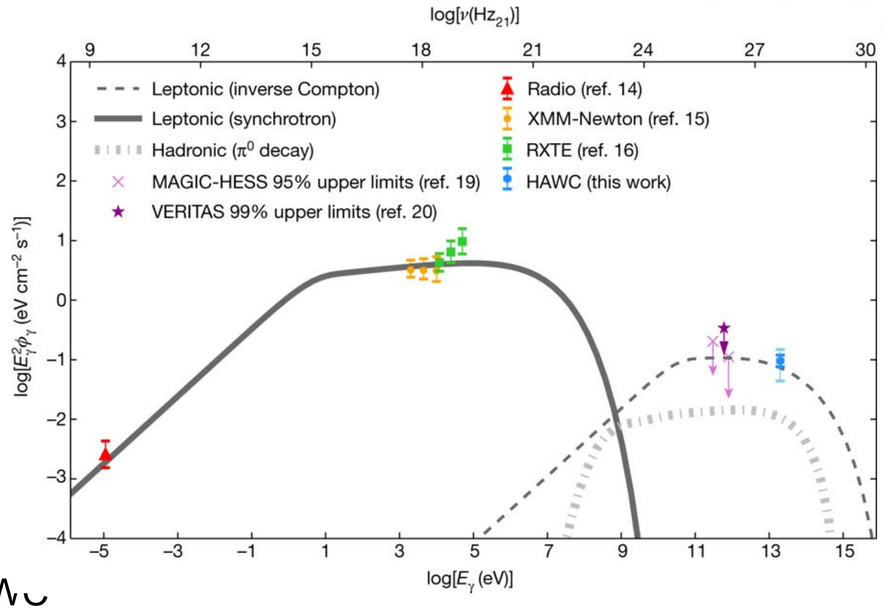
Possible an A-type supergiant and a very extended disk around a black hole.

Microquasar SS-433

- 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 (Cen A & Fornax)



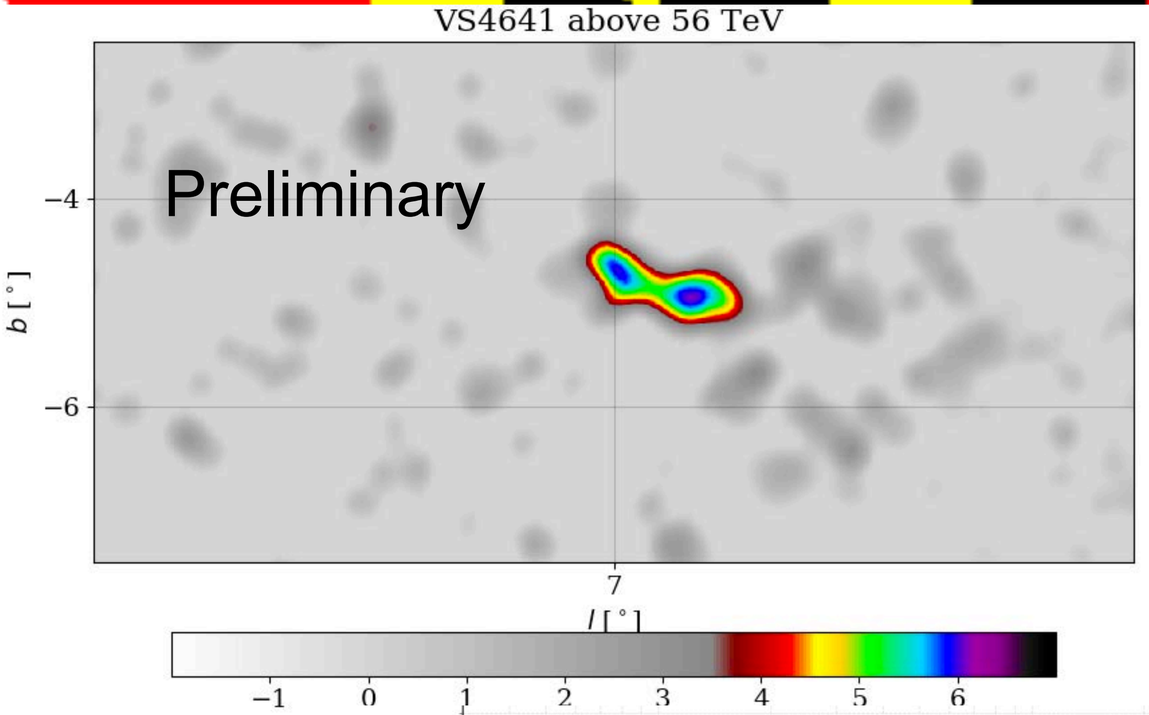


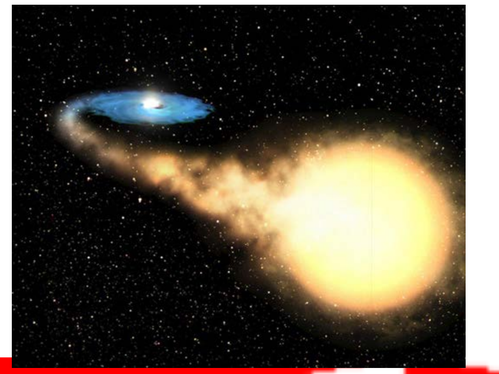


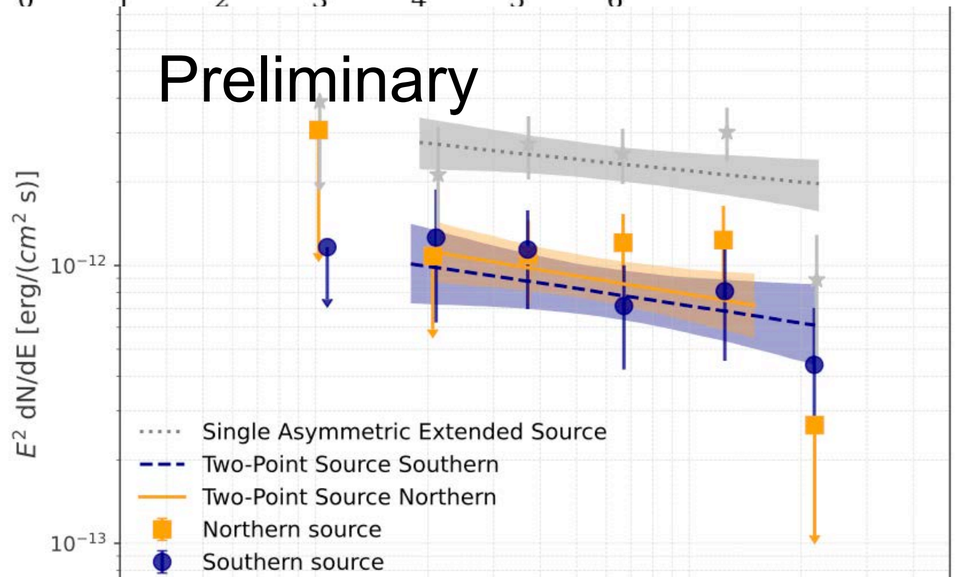
Published in Nature Oct 4, 2018

V4641 Sgr - Binary System

- Newly discovered TeV micro-quasar by HAWC.
- We measure photon energies from 300 GeV to above 100 TeV, with no sign of a cutoff above 200 TeV.
- The source is surrounded by a bubble of very high energy emission with a size of roughly ~ 100 pc, much more extended than the radio jet.
- If hadronic this indicates that micro-quasars could be PeVatrons.







THE ASTROPHYSICAL JOURNAL, 382:652–666, 1991 December 1

SIGNATURES OF COSMIC-RAY INTERACTIONS ON THE SOLAR SURFACE

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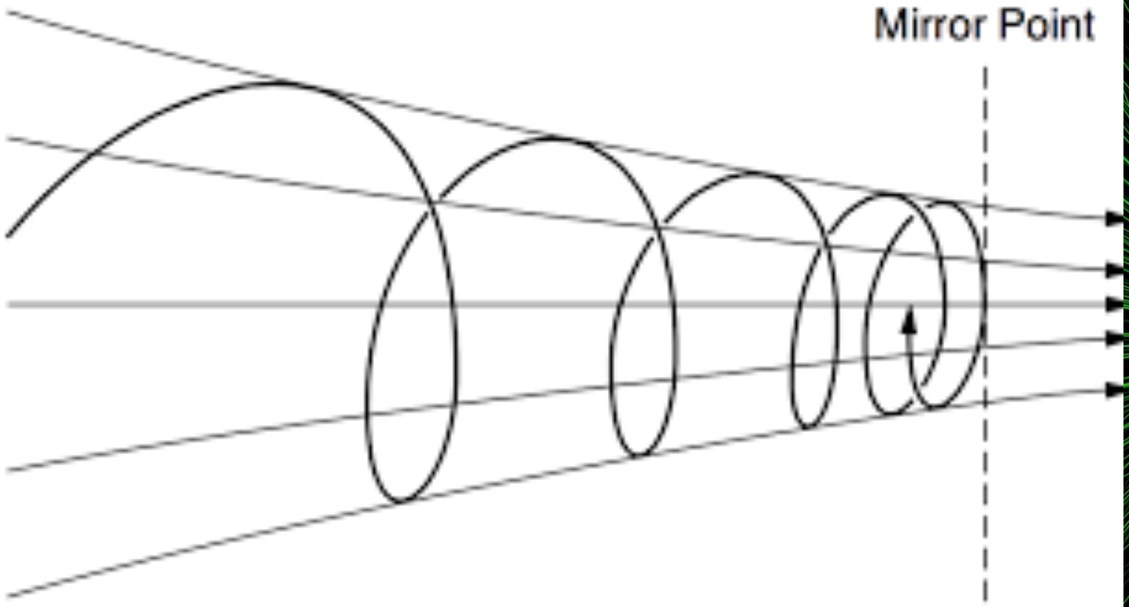
Received 1991 March 21; accepted 1991 June 5

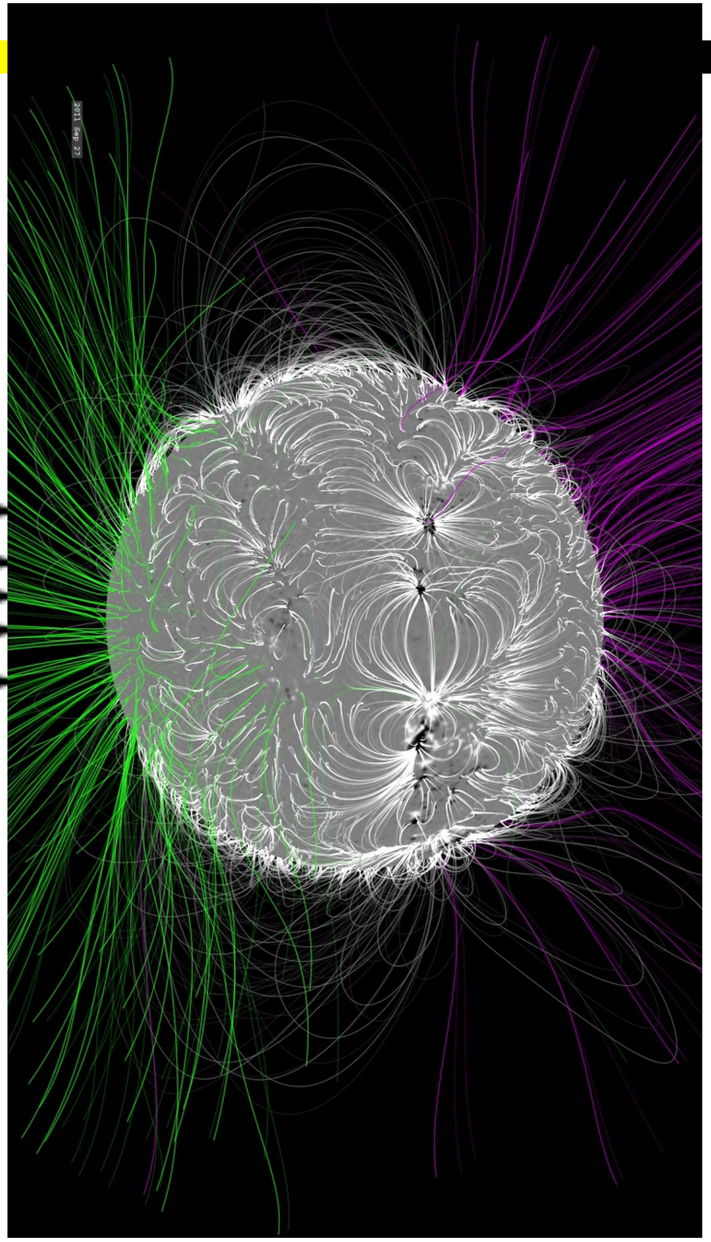
ABSTRACT

We estimate the fluxes of neutrinos, gamma rays, antiprotons, neutrons, and antineutrons that result from collisions of high-energy Galactic cosmic rays with the solar atmosphere. The results are sensitive to assumptions about cosmic-ray transport in the magnetic fields of the inner solar system. The high-energy photon flux should be observable by the Gamma Ray Observatory. The neutrino flux should produce less than one event per year in the next generation of neutrino telescopes. The antiproton flux is unobservable against the Galactic background. The neutron and antineutron fluxes are detectable only if neutrons produced in terrestrial cosmic-ray events may be discriminated against.

Subject headings: cosmic rays: general — gamma rays: general — neutrinos — Sun: activity

- Charged cosmic rays ~TeV energies mirror off the Sun's magnetic field

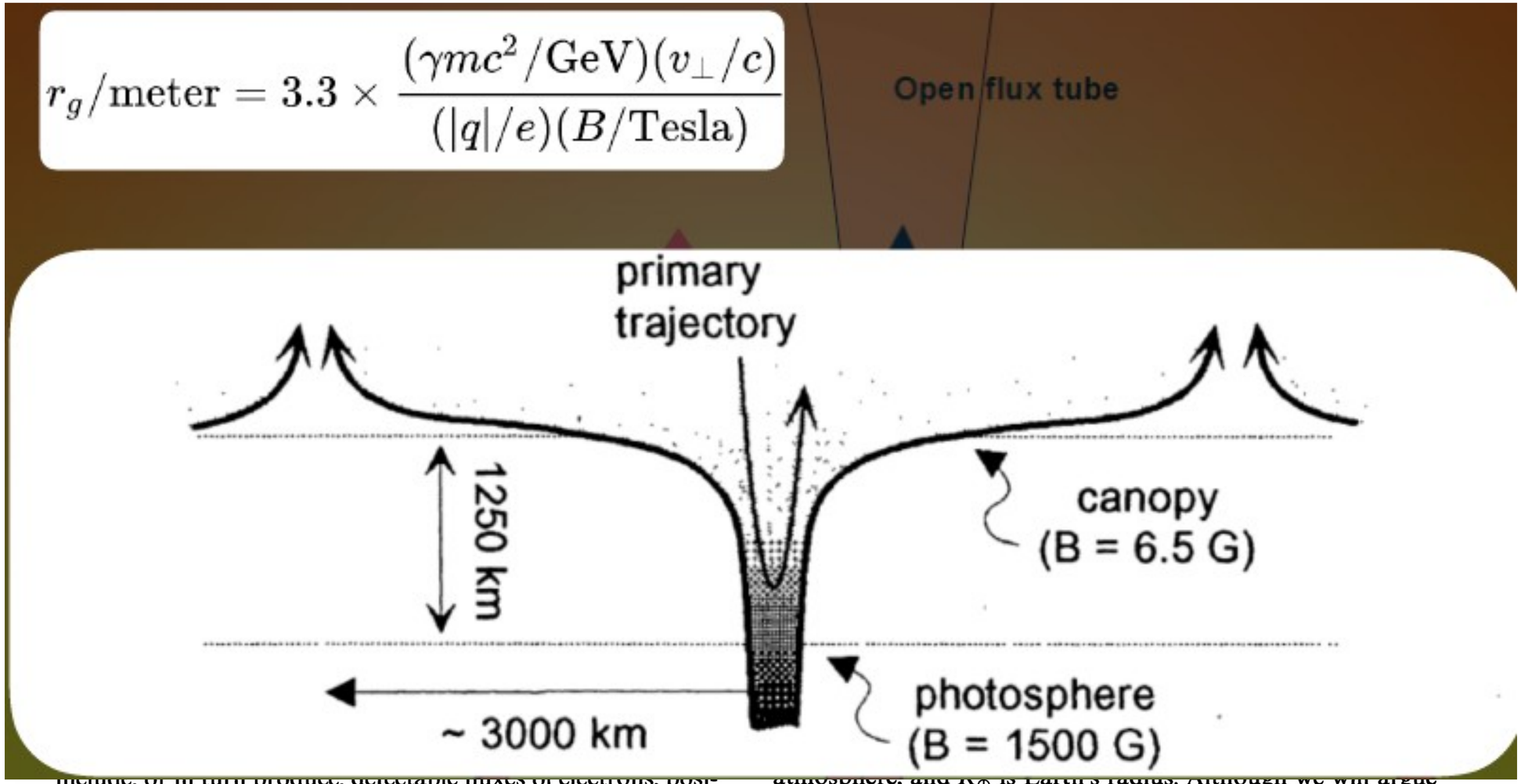




- When they come back out they interact in the corona producing gamma rays, etc

How?

$$r_g/\mathrm{meter} = 3.3 \times \frac{(\gamma mc^2/\mathrm{GeV})(v_\perp/c)}{(|q|/e)(B/\mathrm{Tesla})}$$

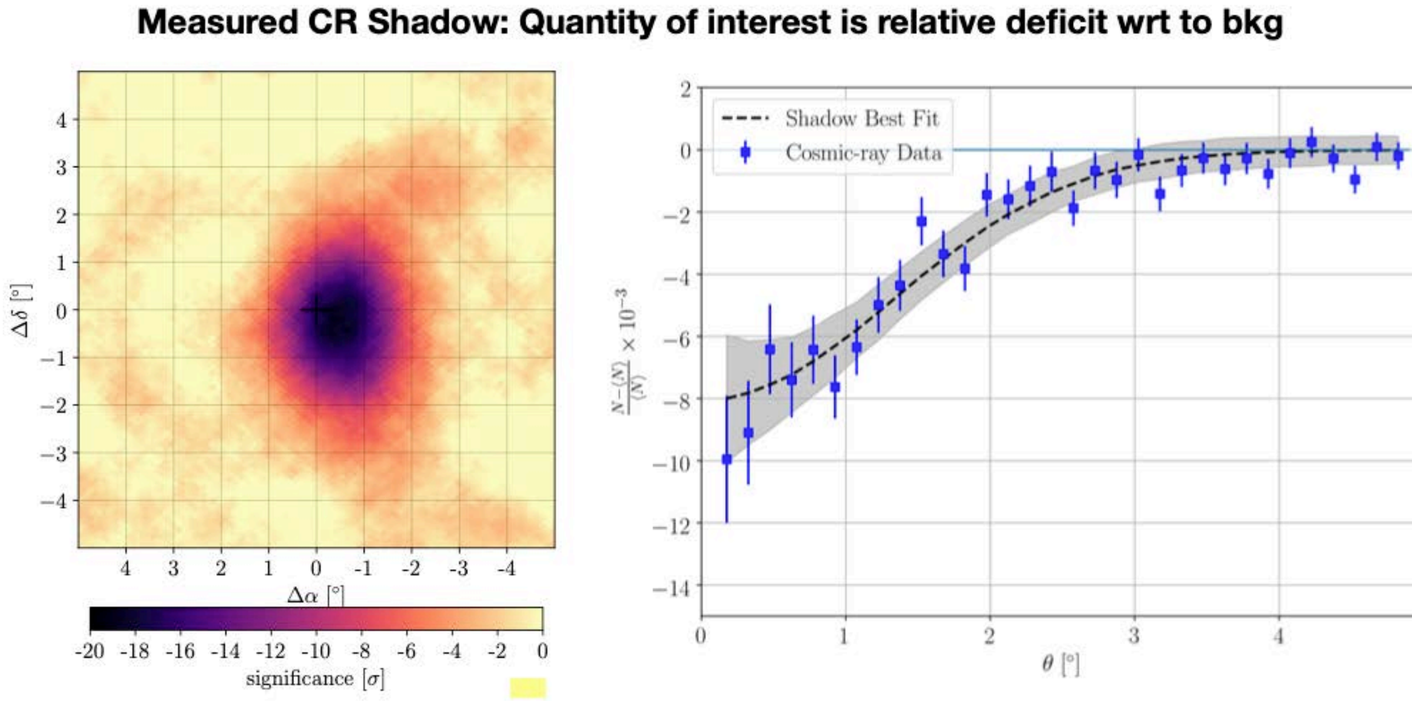


trons, muons, gamma rays, Čerenkov light, neutrons and other

otherwise, one might worry that a similar suppression occurs

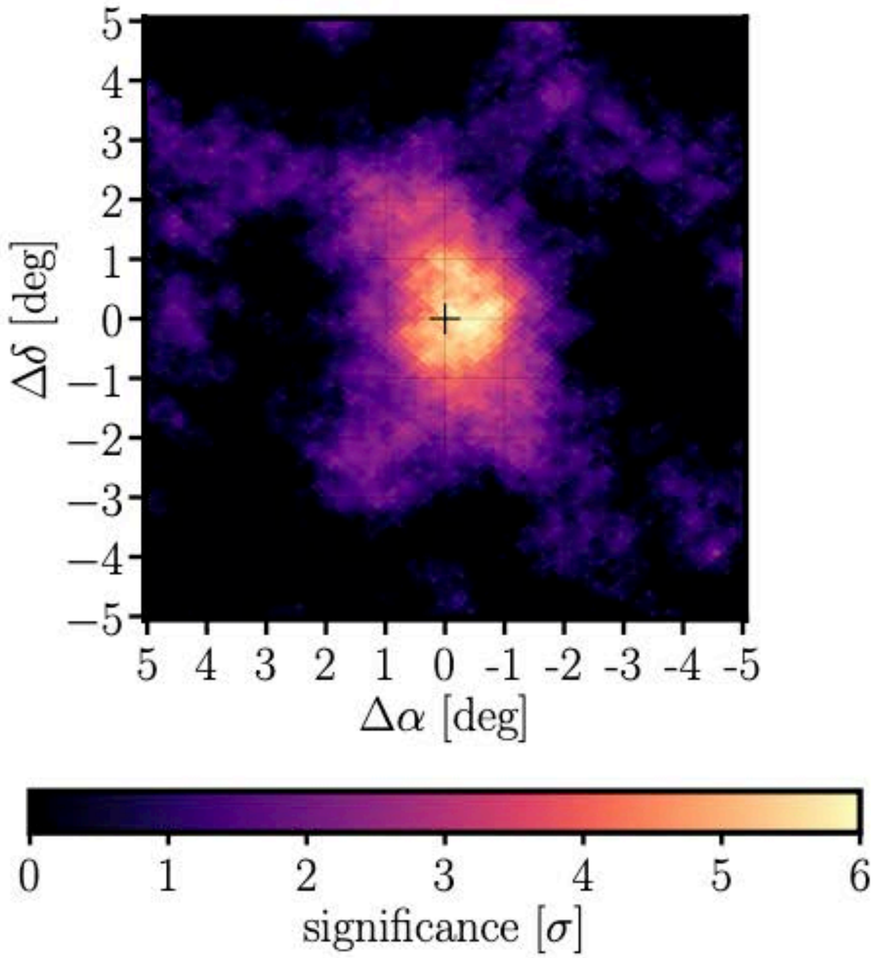
Sun Shadow

- We see the shadow of the Sun (and Moon) in charged Cosmic Rays
  - The deficit is slightly offset due to the Earth's magnetic field
- The Moon's shadow is steady but the Sun's varies with Solar magnetic field (11 yrs)
  - "Solar Max" is the sunspot max but corresponds to the minimum polar magnetic field and vice versa

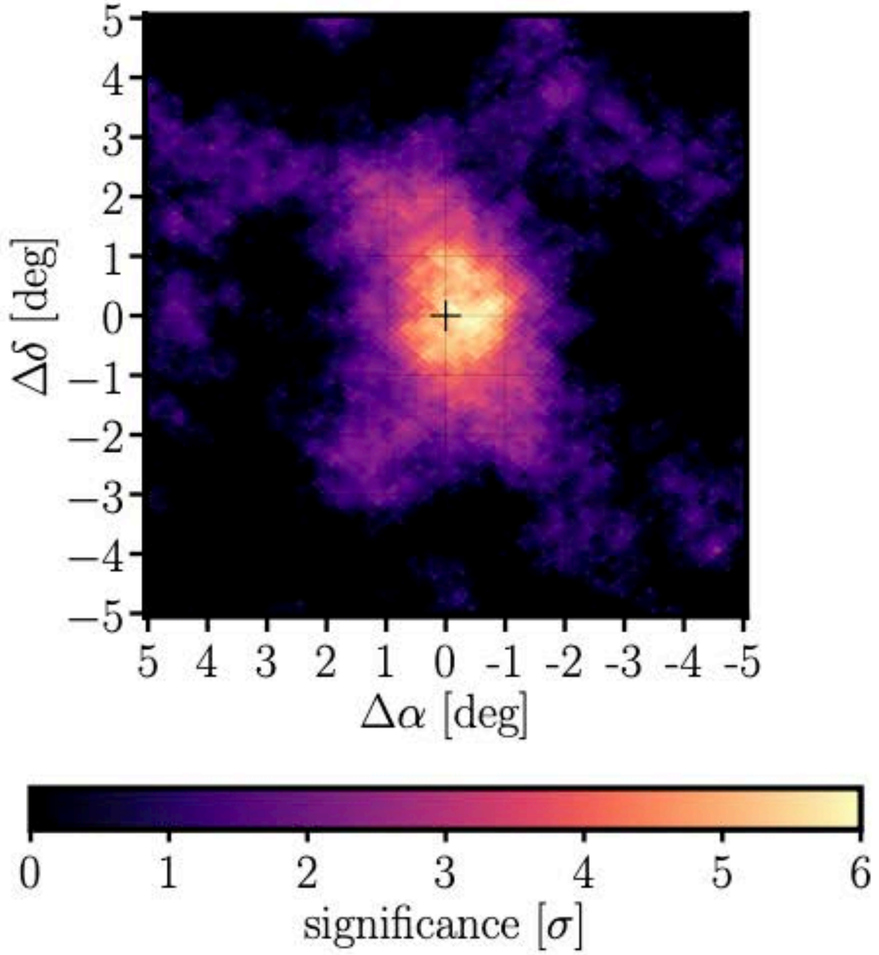


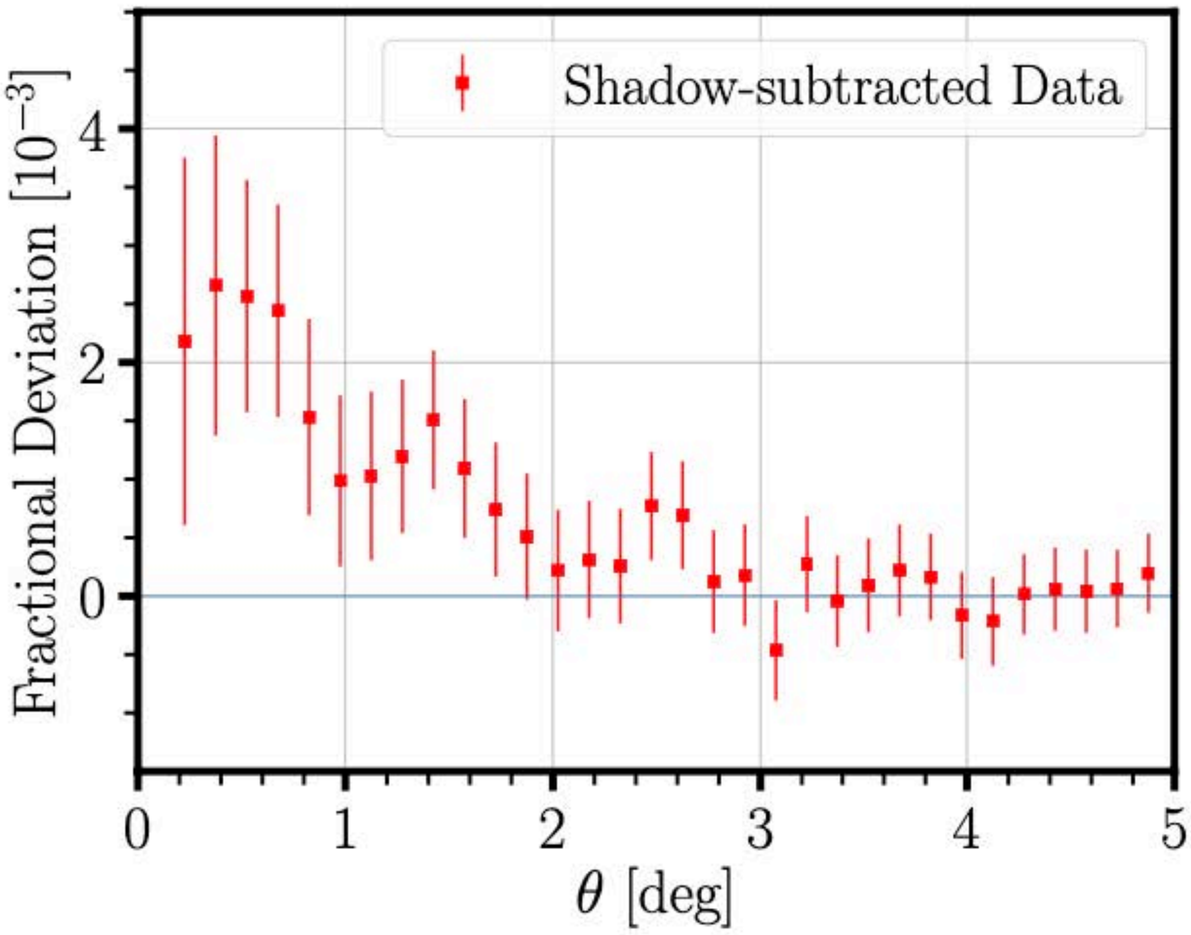
Sun Shadow

- We subtract the shadow and look for a gamma ray excess from the true position of the sun
  - Gamma rays are not deflected by the field
- We see a gamma ray excess!



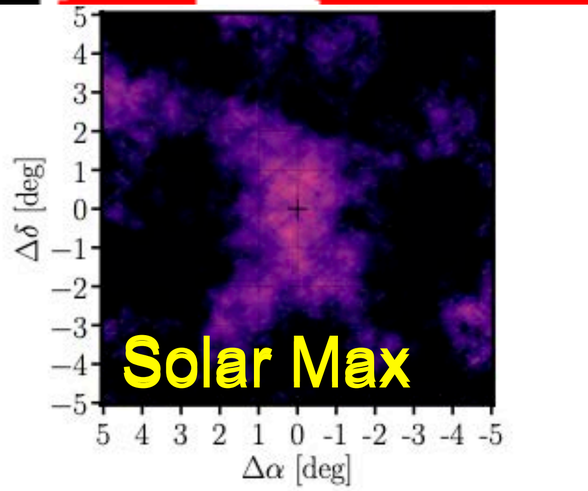
The Sun in Gamma Rays

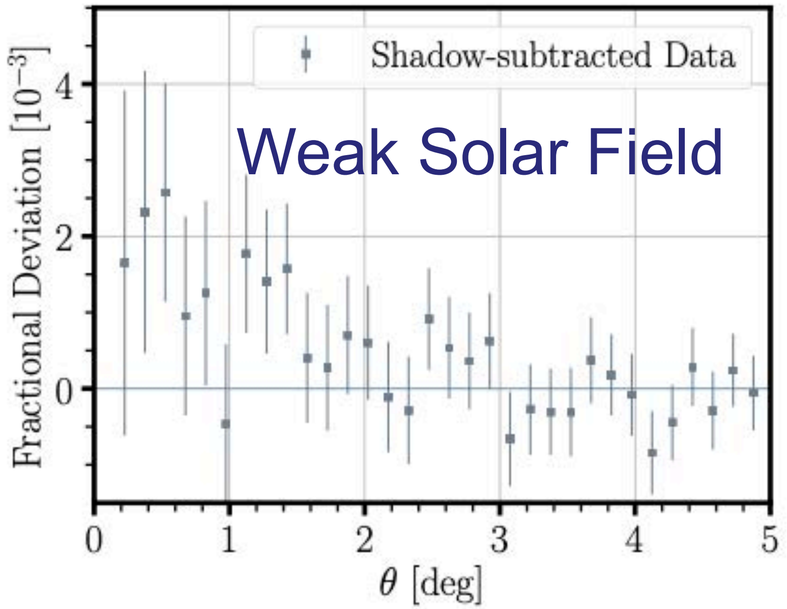


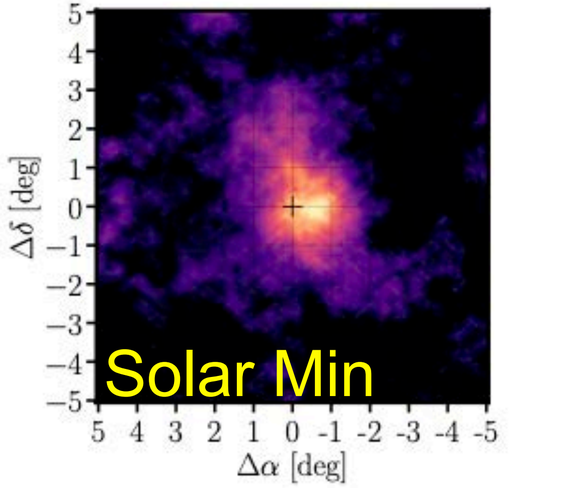


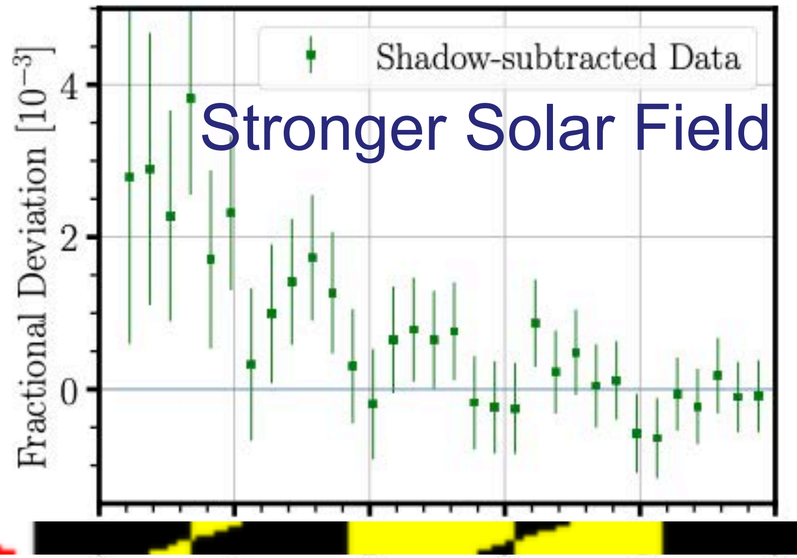
The Sun

At solar minimum, the toroidal field is at minimum strength, sunspots are relatively rare and the **poloidal field is at maximum** strength.



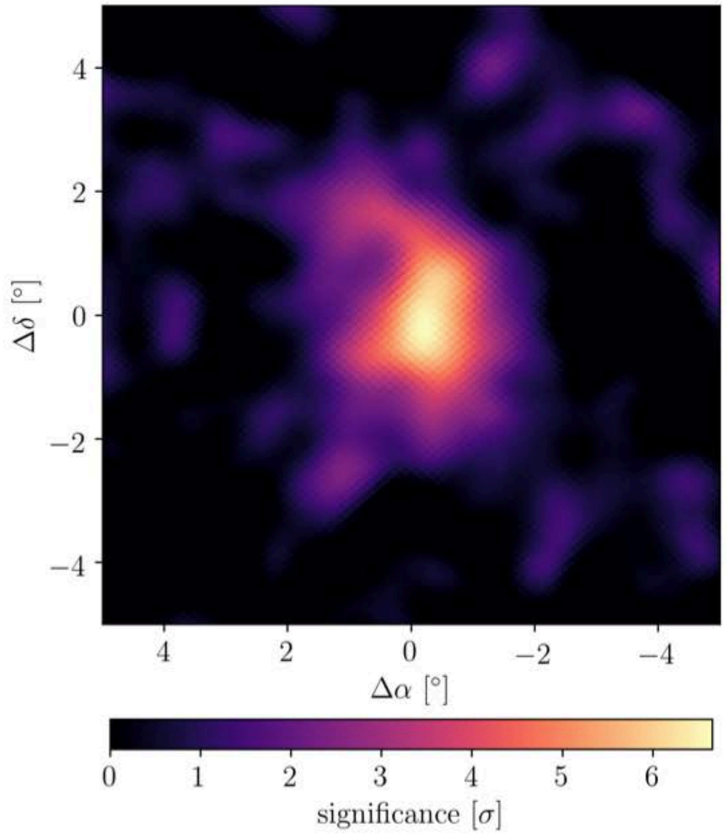






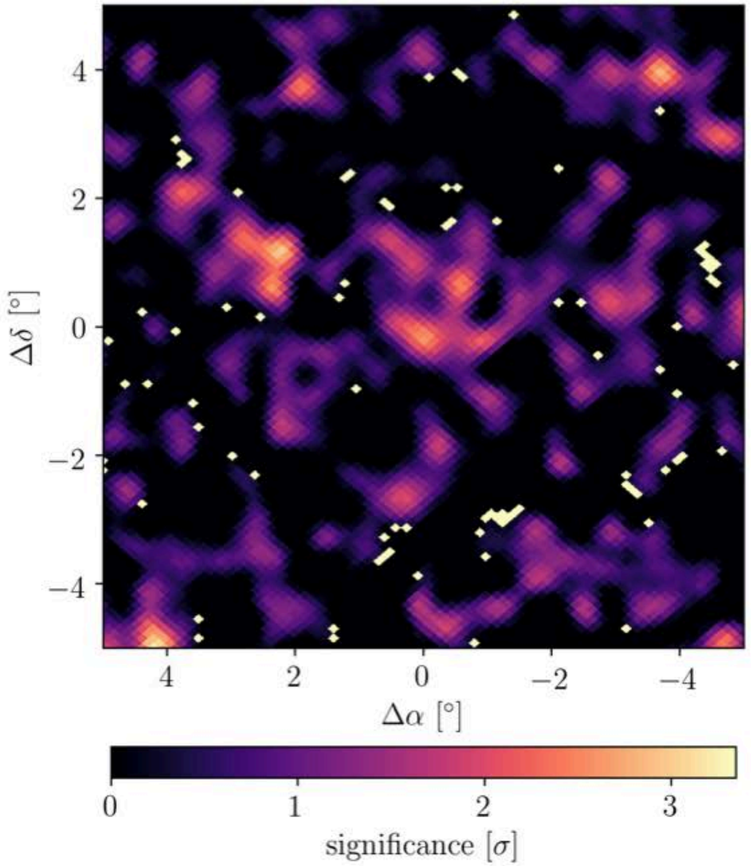
The Sun

Lower Energy <~ 3 TeV



Bins 2-4

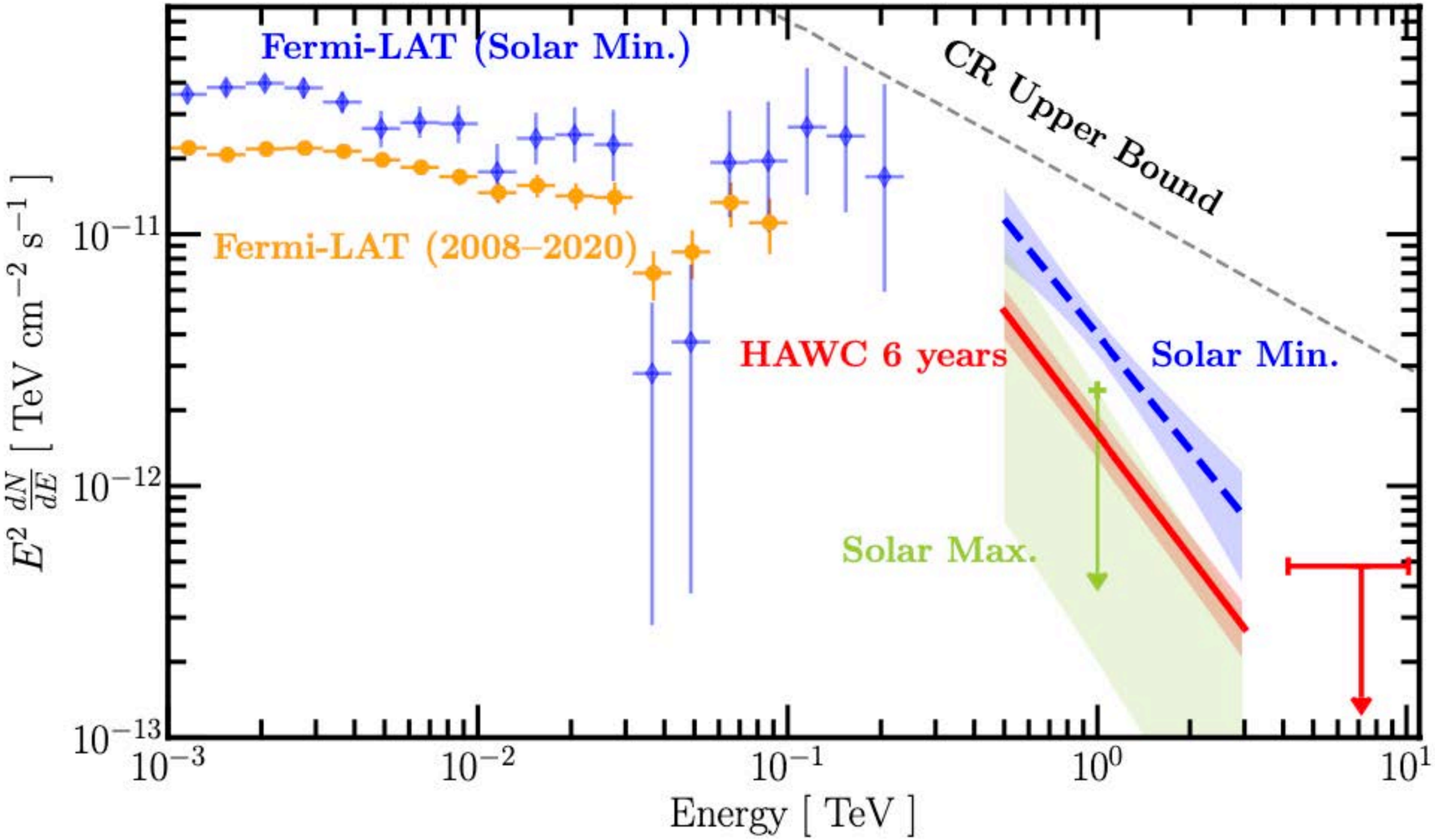
Higher Energy >~ 3 TeV



Bins 5-8

The Sun

Phys. Rev. Lett. **131**, 051201 – Published 3 August 2023



The Future

SWGO

The Southern Wide-field Gamma-ray Observatory