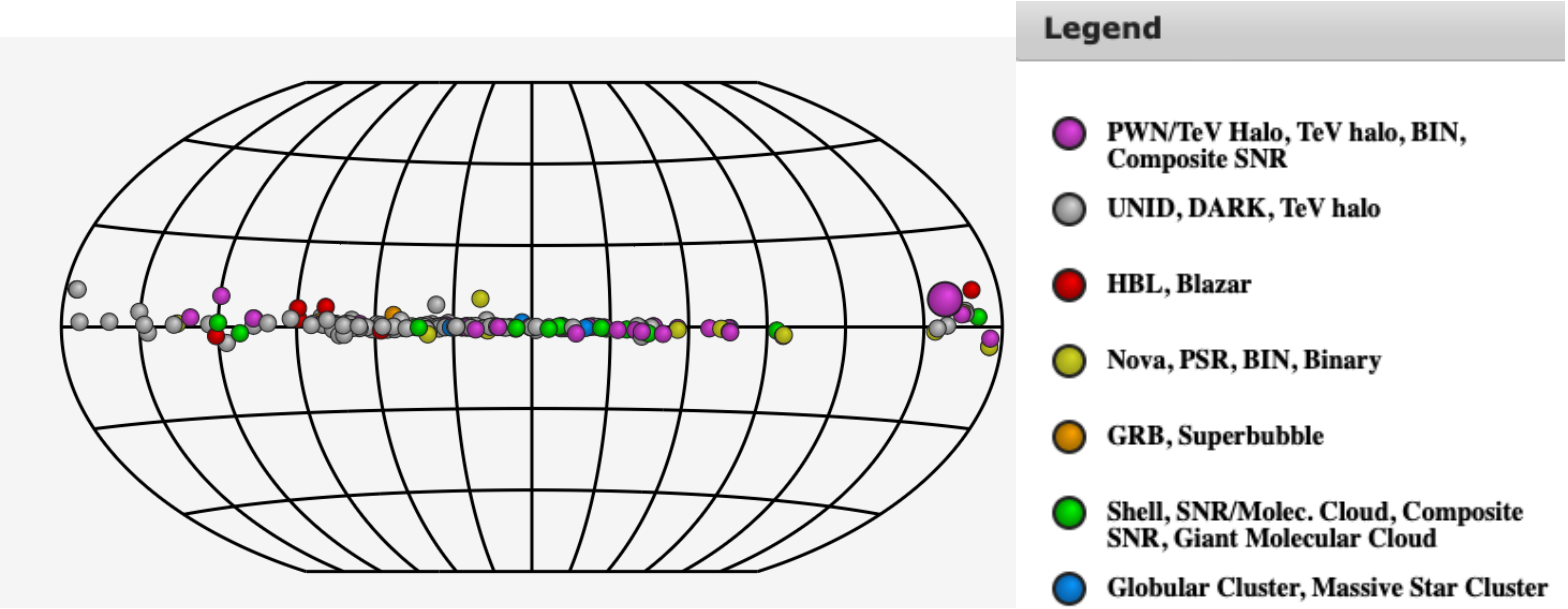
HAWC Galactic Sources

Jordan Goodman for the
HAWC Collaboration
SUGAR Conf. October 2024

TeVCat Galactic Sources



The HAWC Collaboration

USA

Mexico

United States
University of Maryland
Los Alamos National Laboratory
University of Wisconsin
University of Utah
University of New Hampshire
Pennsylvania State University
University of New Mexico
Michigan Technological University
NASA/Goddard Space Flight Center
Georgia Institute of Technology
Michigan State University
University of Rochester

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 Chiapa
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

The HAWC Site

Latitude: 18°59.7’N
Longitude: 97°18.6’W


HAWC
Pico de Orizaba
“Citlaltepetl”
5610m (18,400 ft)
Sierra Negra
“Tliltepetl”
4582m (15,000 ft)

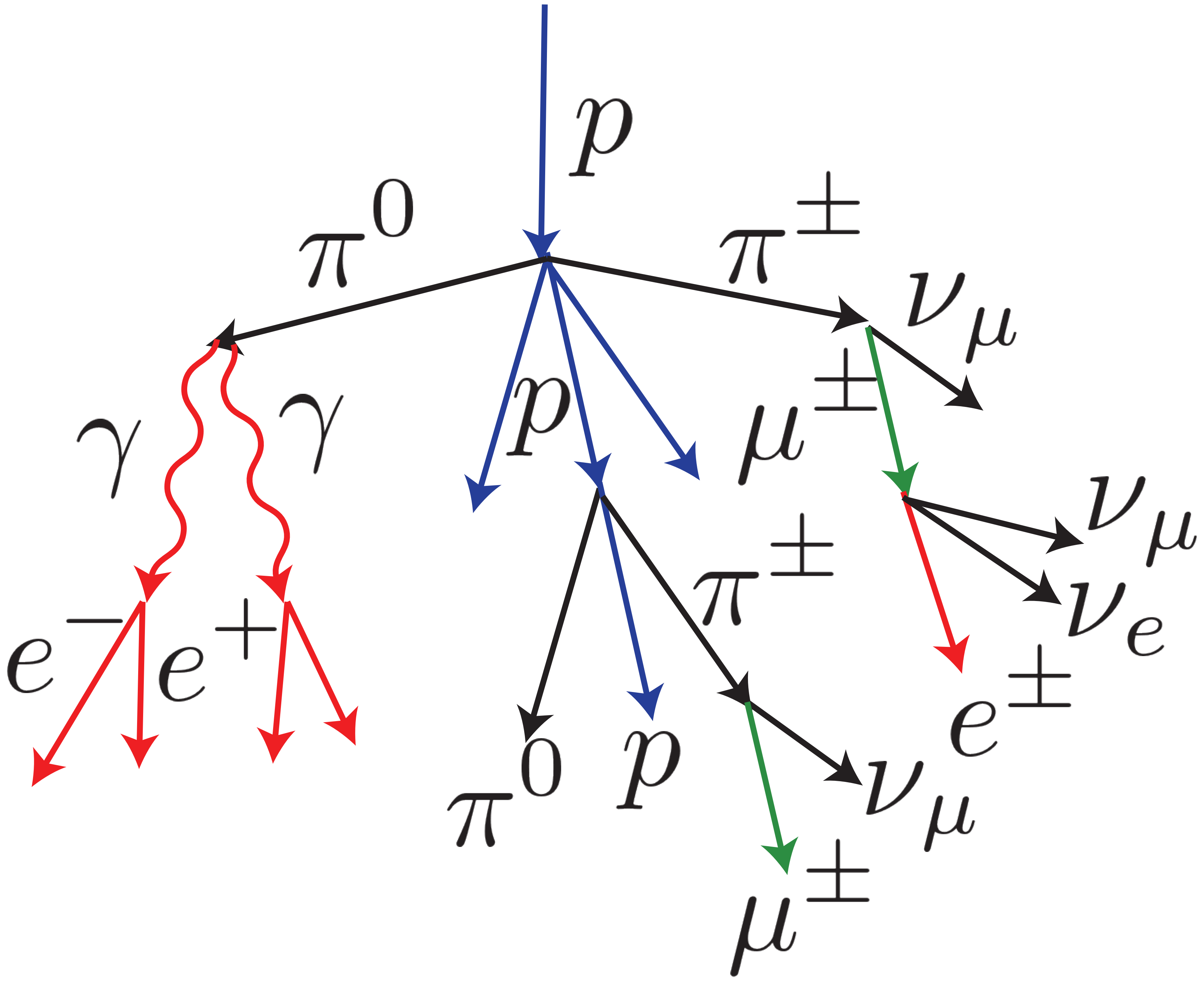

Pico de Orizaba
5636 m a.s.l.
Sierra Negra
Alfonso Serrano
Large Millimetric Telescope
4640 m a.s.l.
HAWC
4100 m a.s.l.

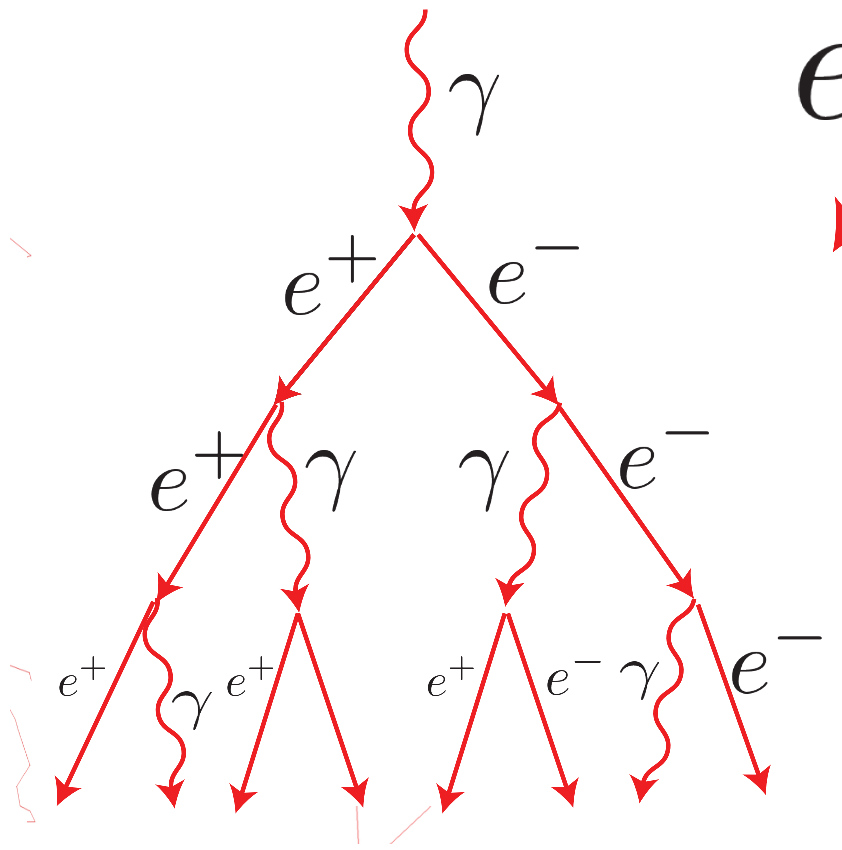
HAWC: High Altitude Water Cherenkov Observatory

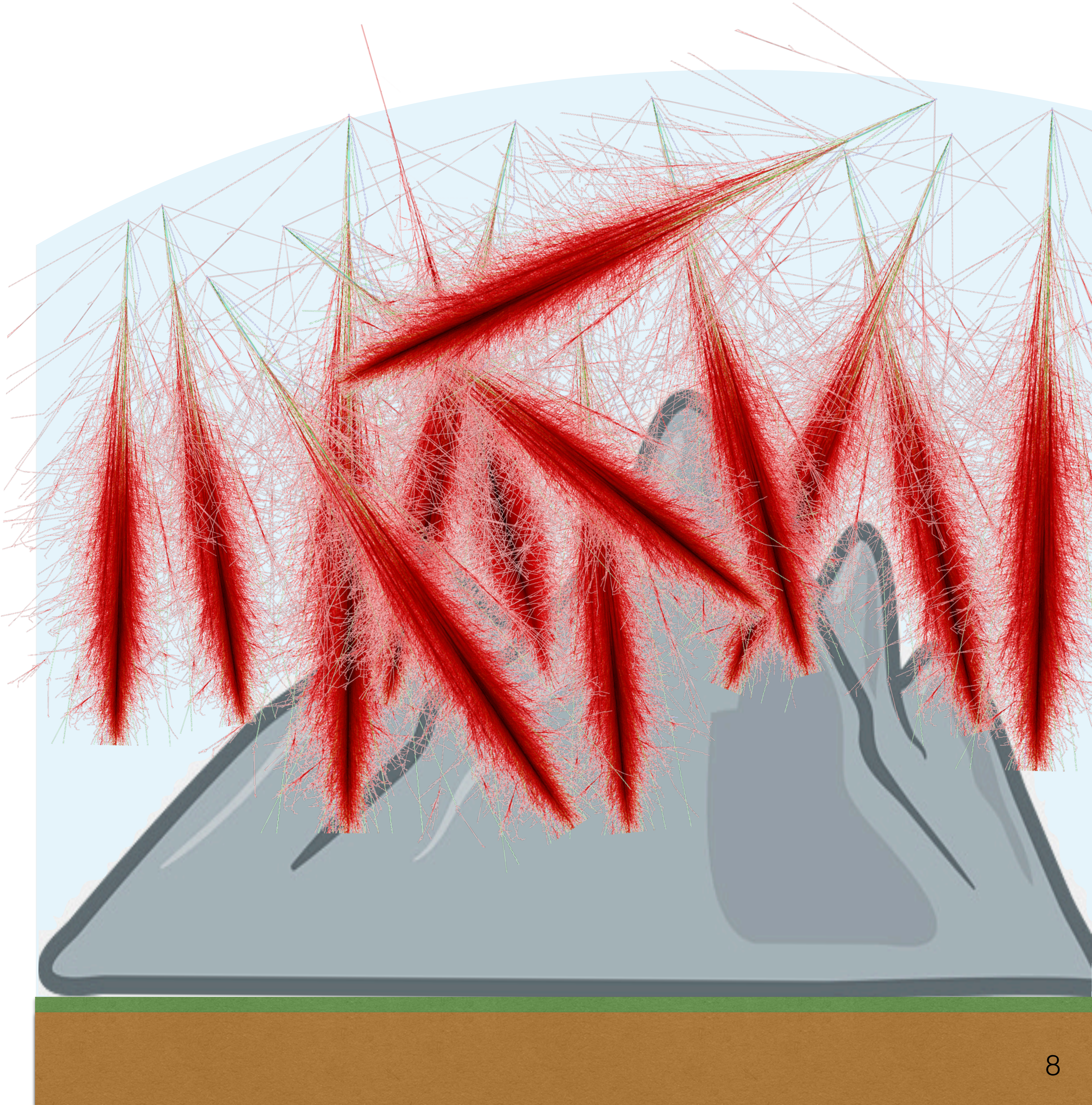
- 300 close-packed optically isolated water Cherenkov detectors
- Full detector inaugurated March 2015
- Funding from a combination of US and Mexican agencies
- High energy extension: Outrigger array, since summer 2018
- Takes data with >95 on time
- ~5 trillion triggers to date - 7PB of data

The cosmic ray background

- Charged particles more abundant than γ-rays
- They produce similar showers



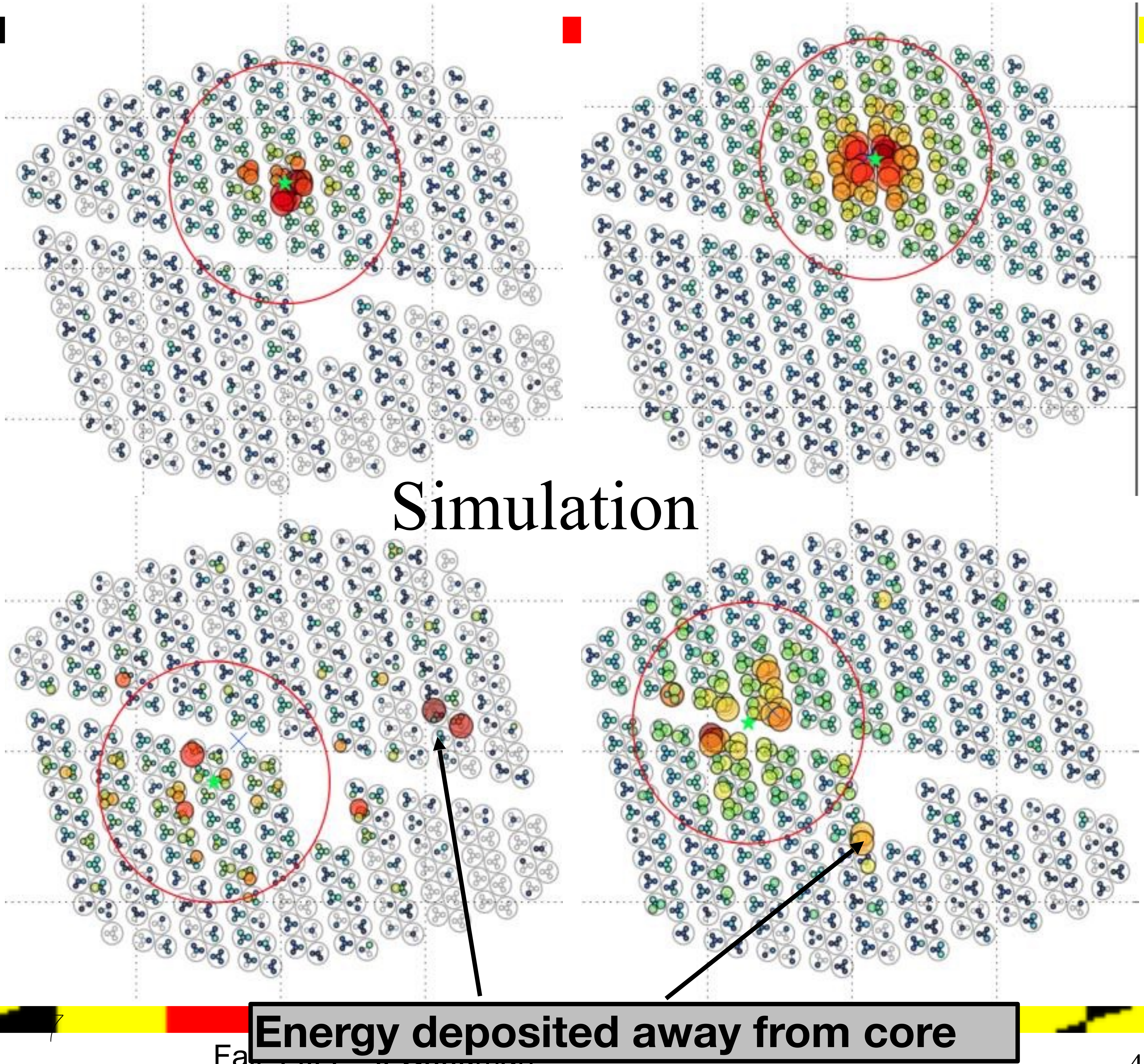




Gamma Hadron Separation (MC)

Gammas

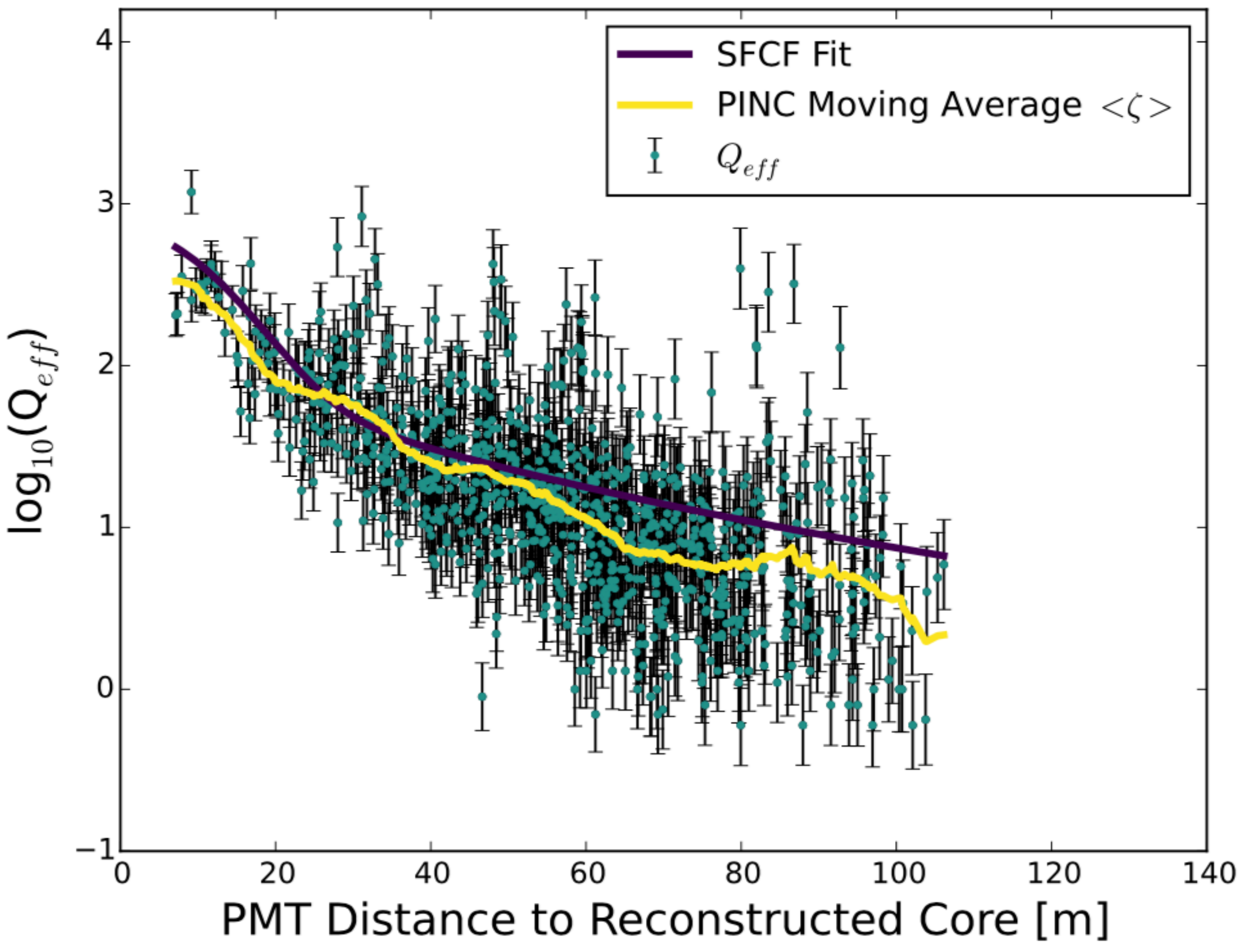
Protons



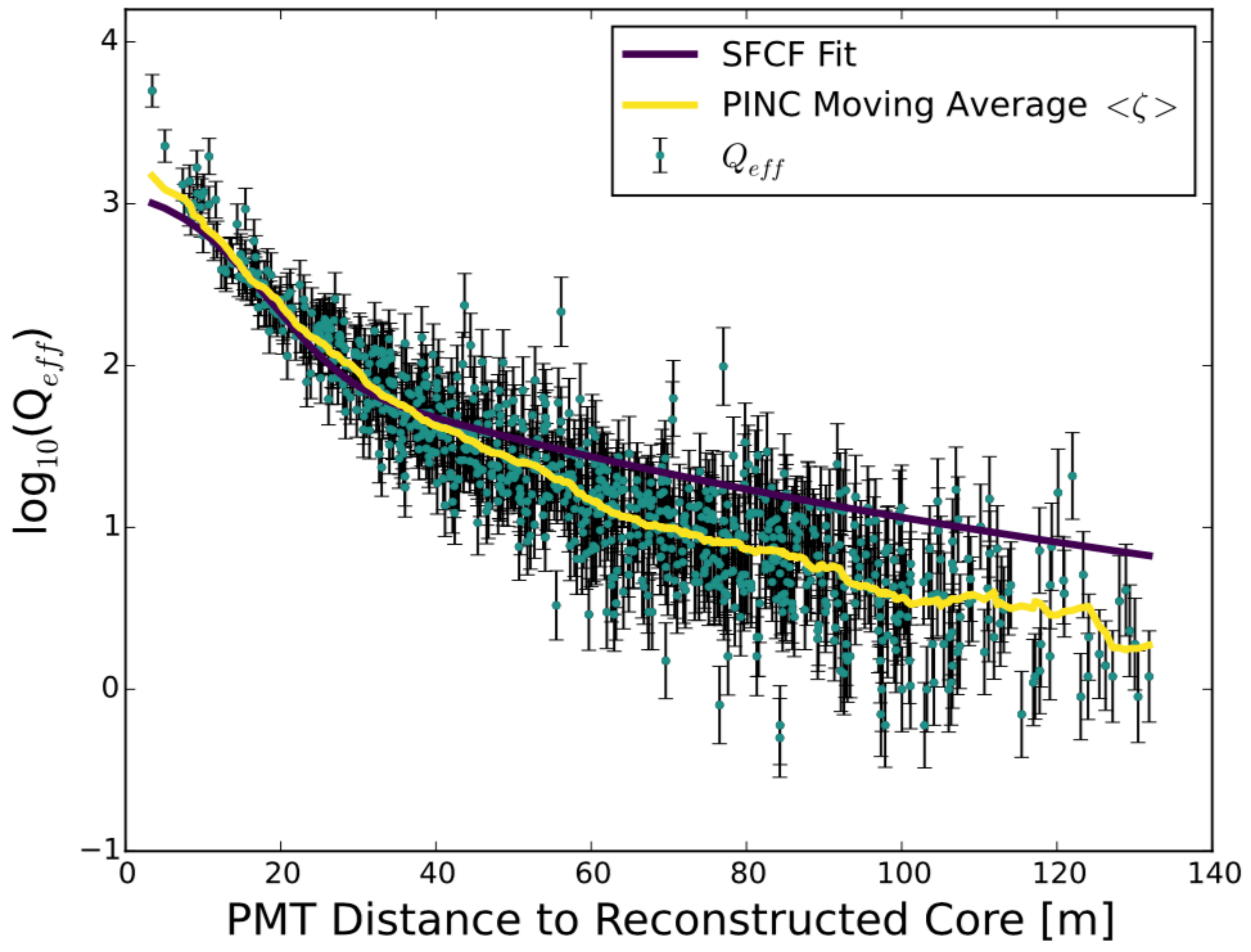
Shower reconstruction

- 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

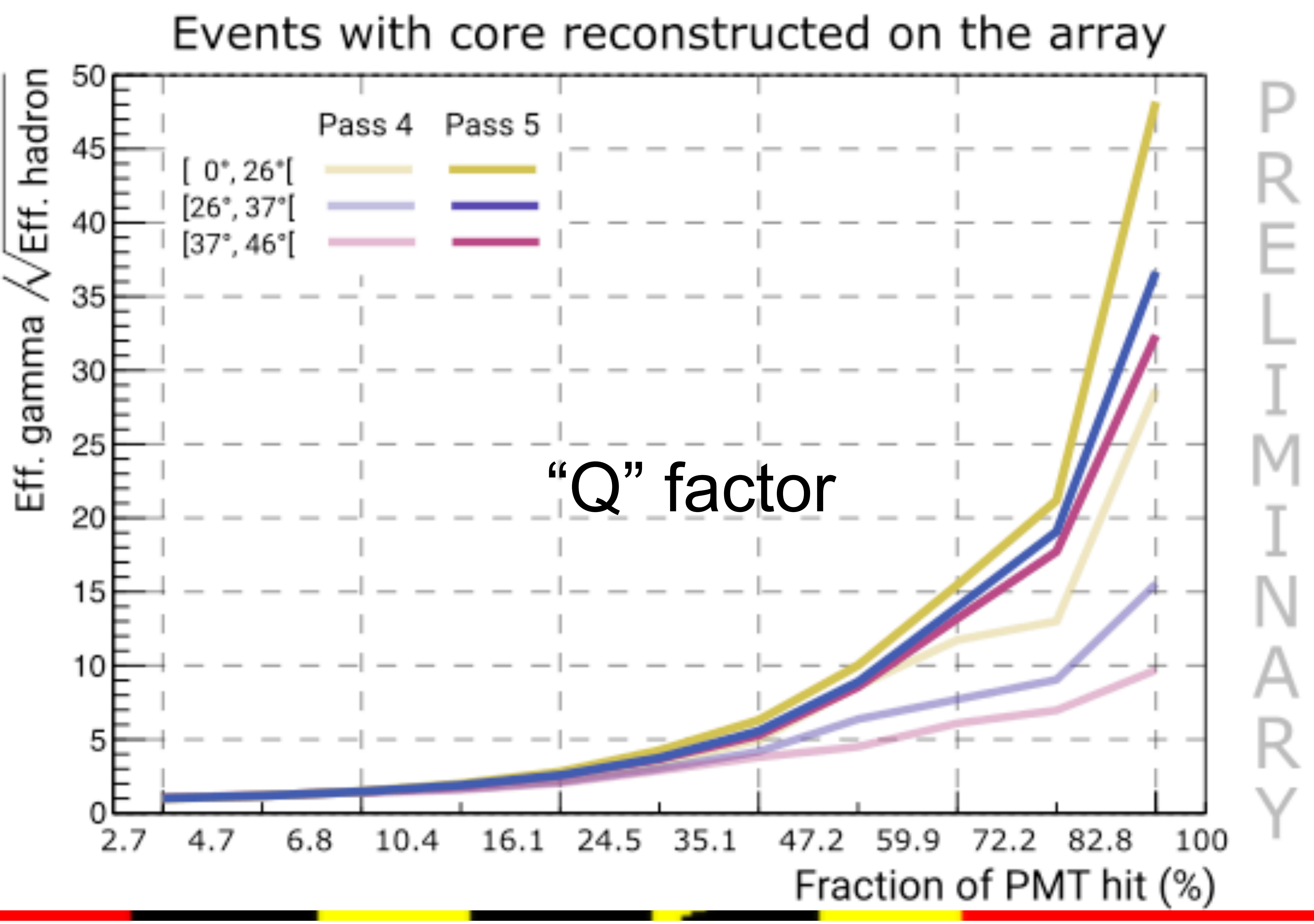


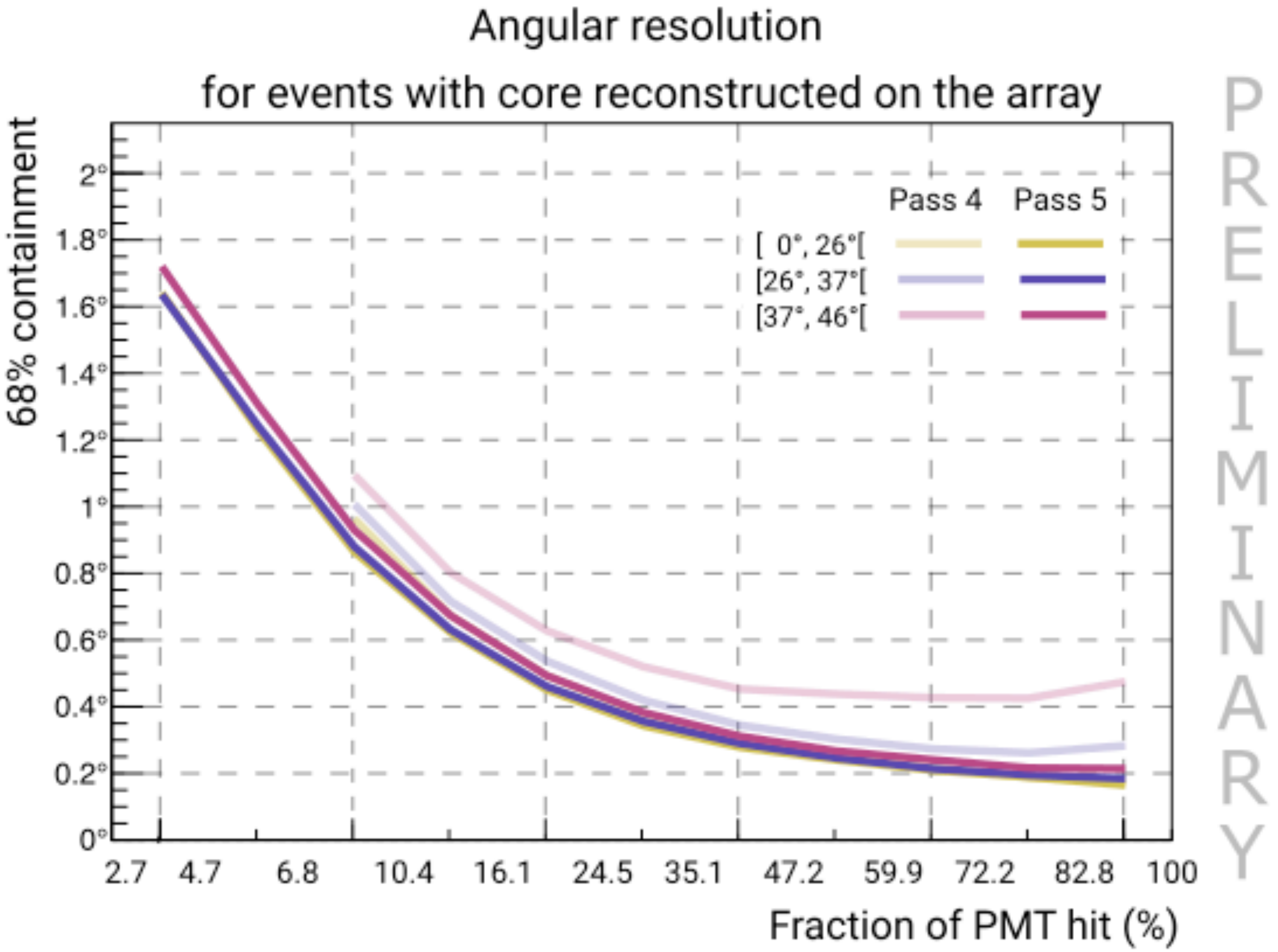
Smooth: gamma-like



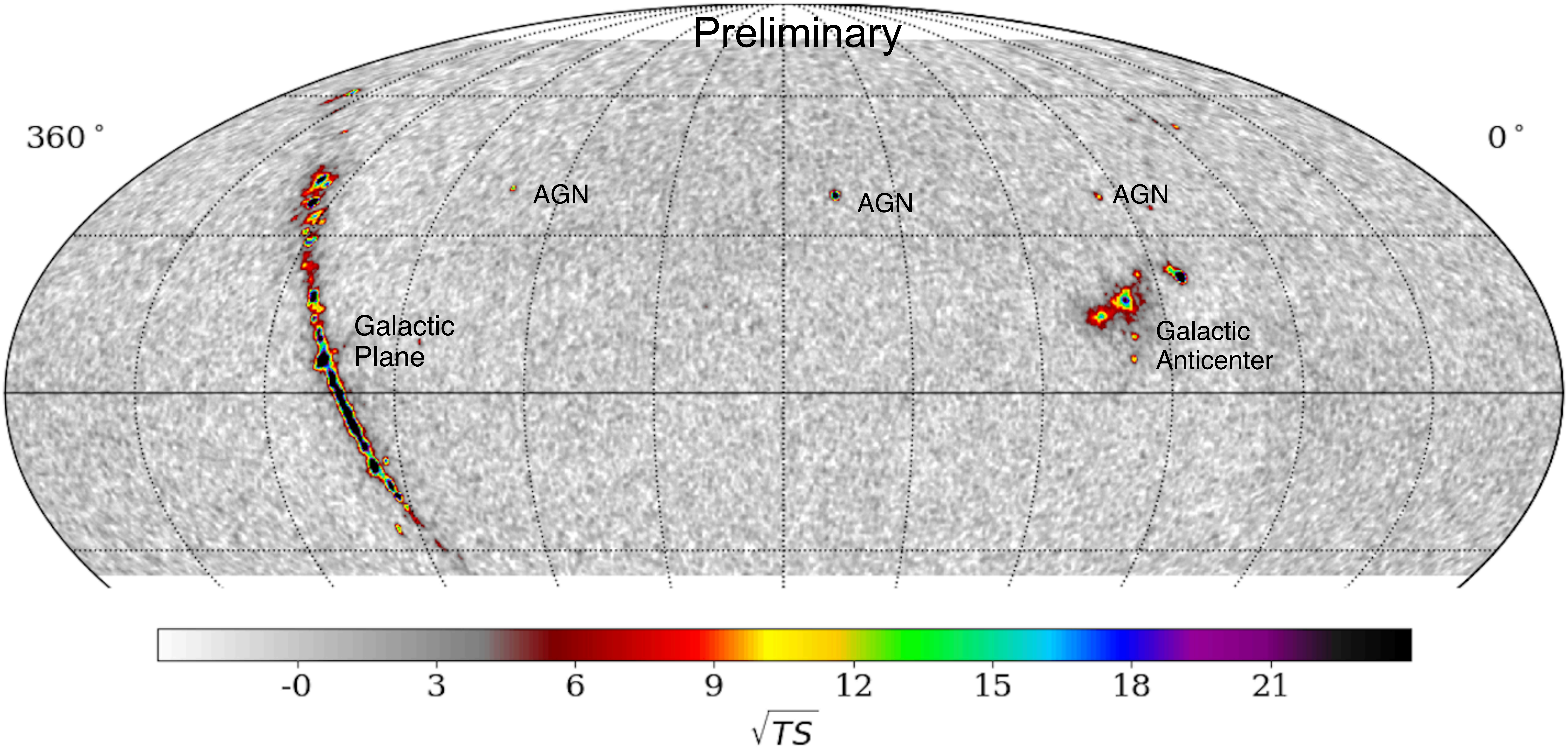
"Pass 5" - Improved Reconstruction

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

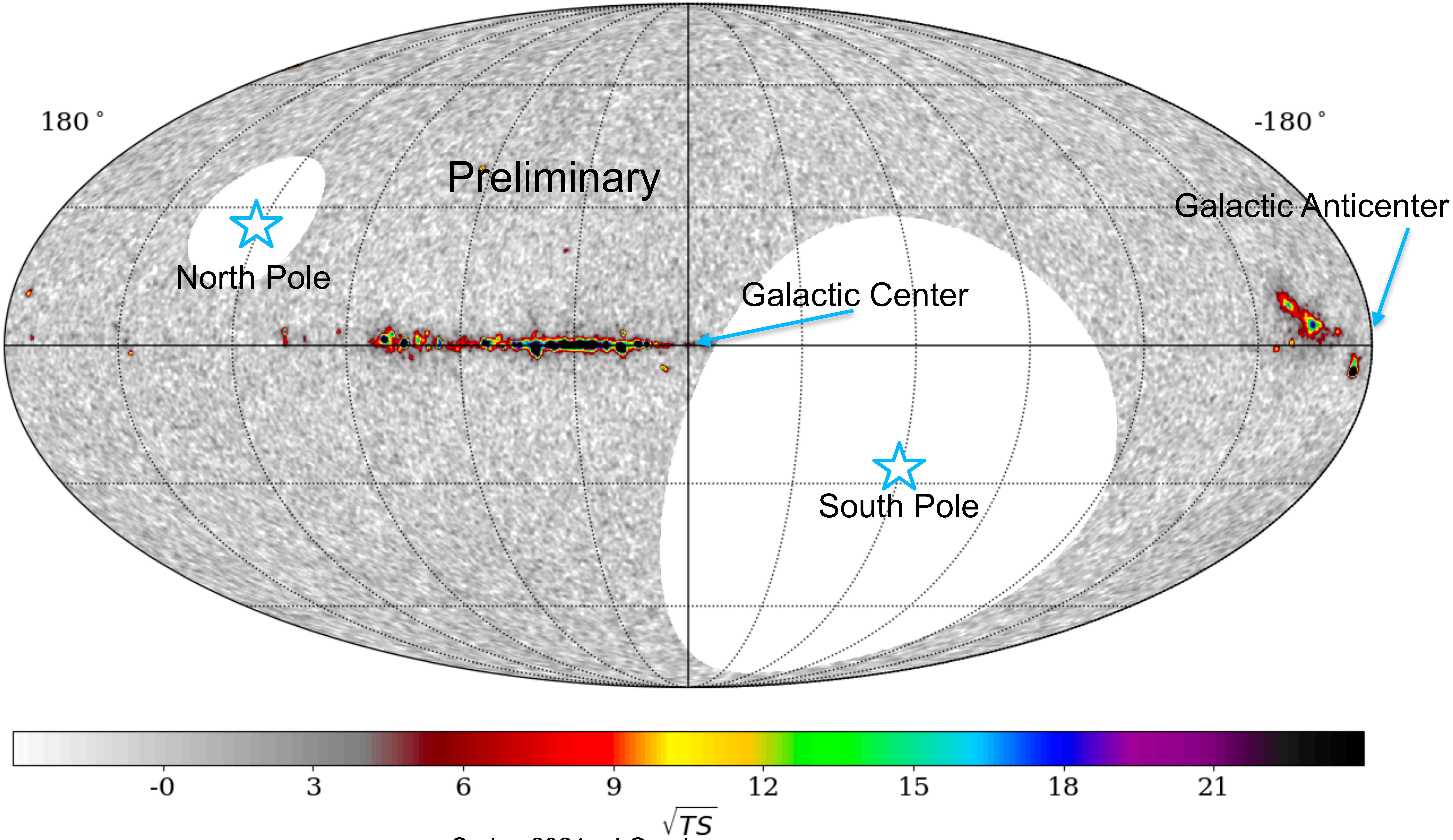




HAWC Sky Map 3040 Days of Data - Pass 5



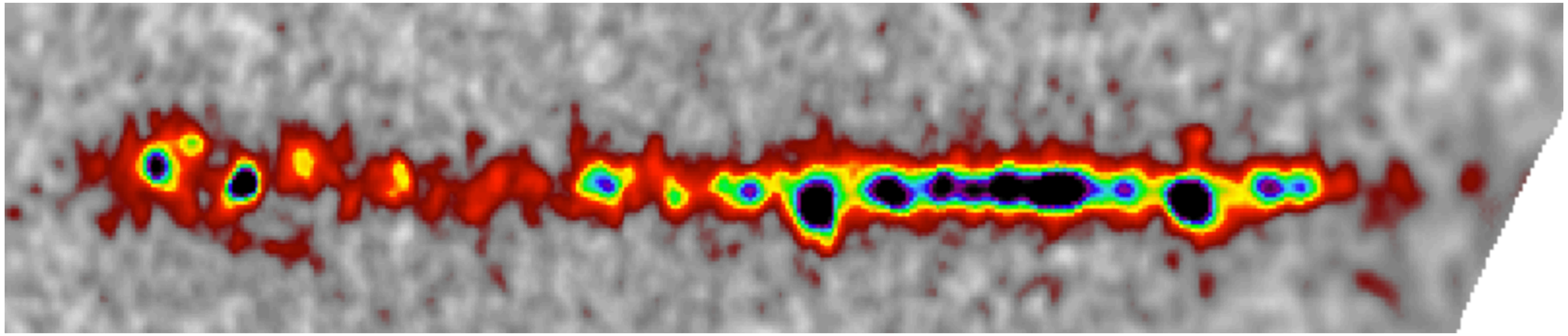
HAWC Sky Map 3040 Days of Data - Pass 5



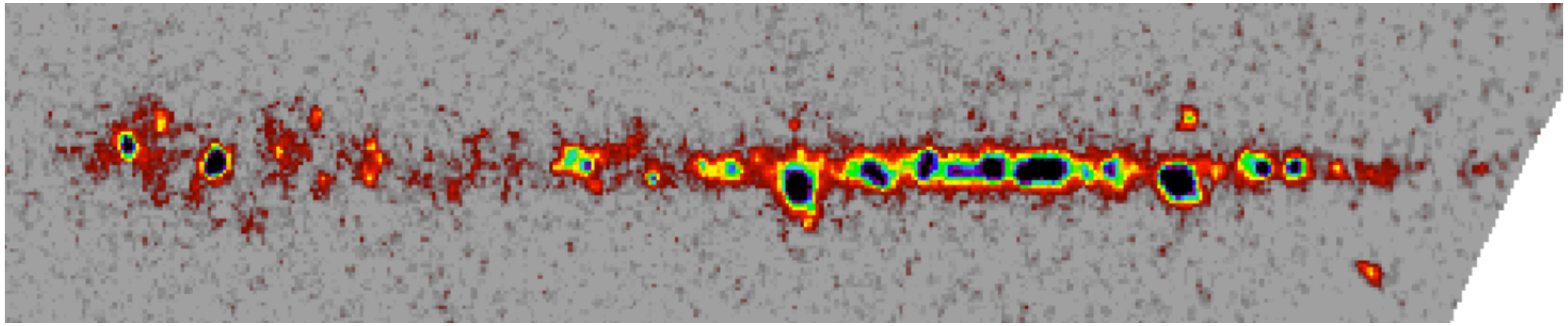
Spring 2024 - J Goodman

Pass 4 (1523d) vs Pass 5 (2090d)

Pass 4

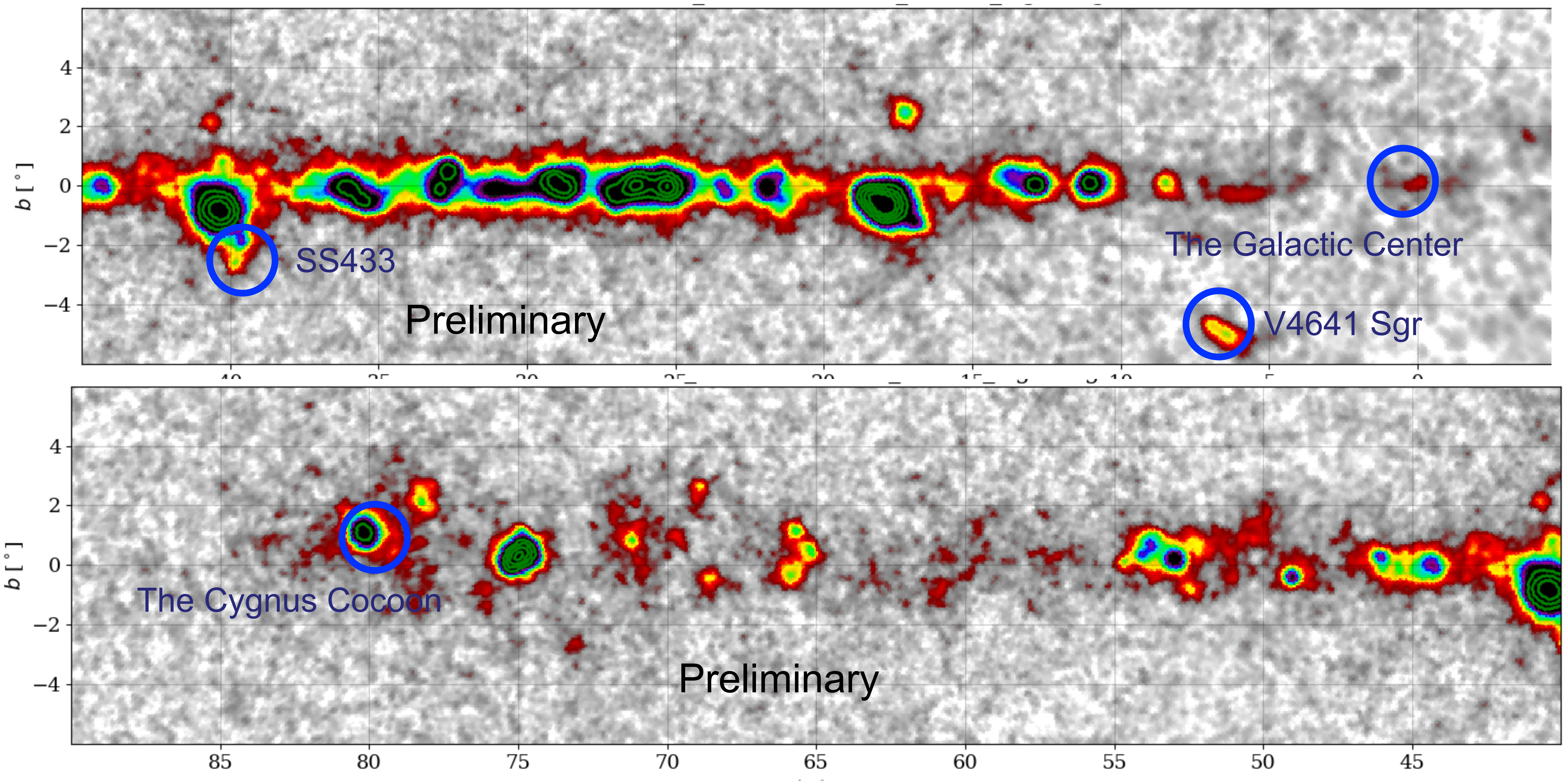


Pass 5




Pass 6 is coming

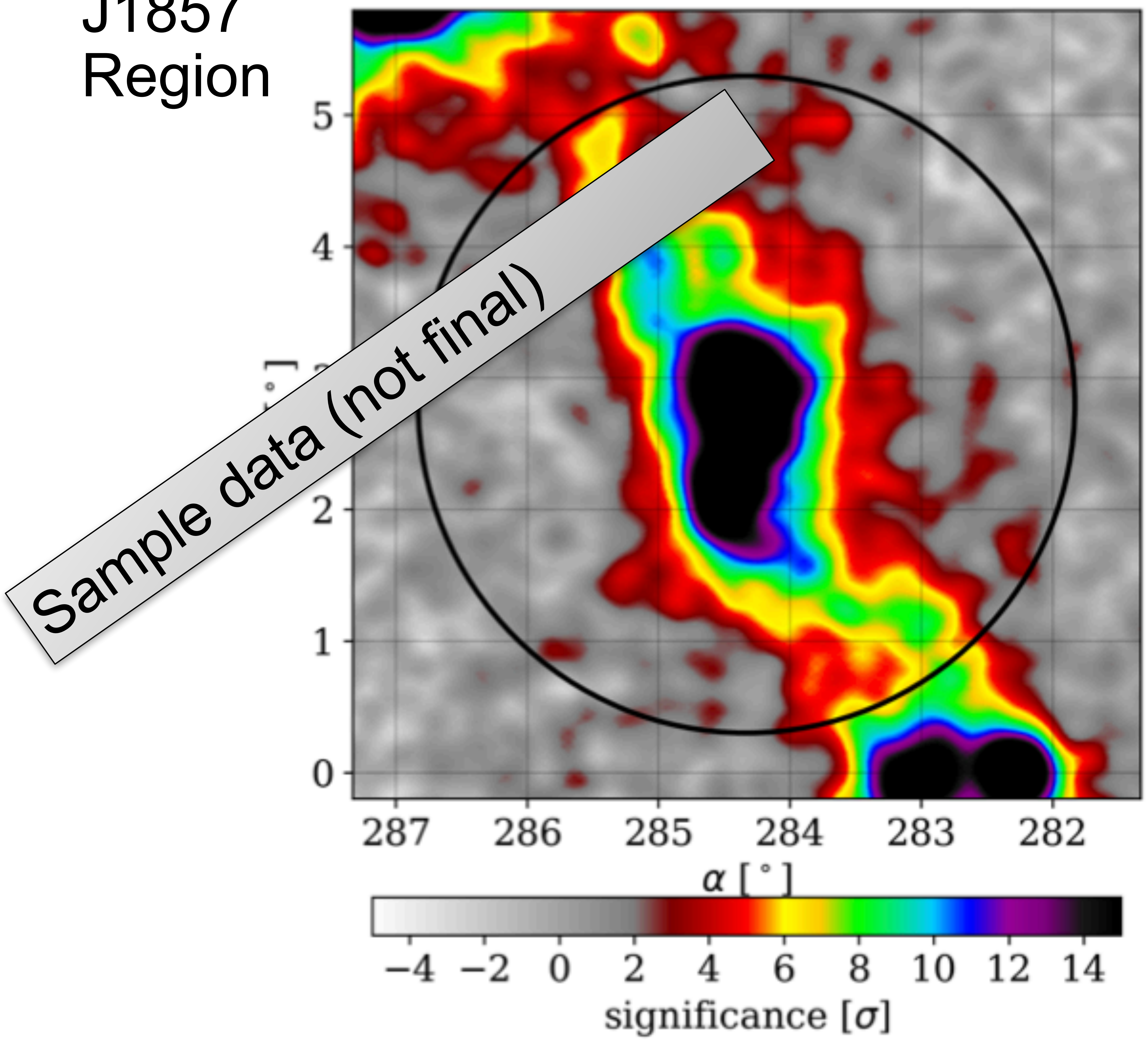
Pass 5 - 3040 Day Map



How do you make a catalog

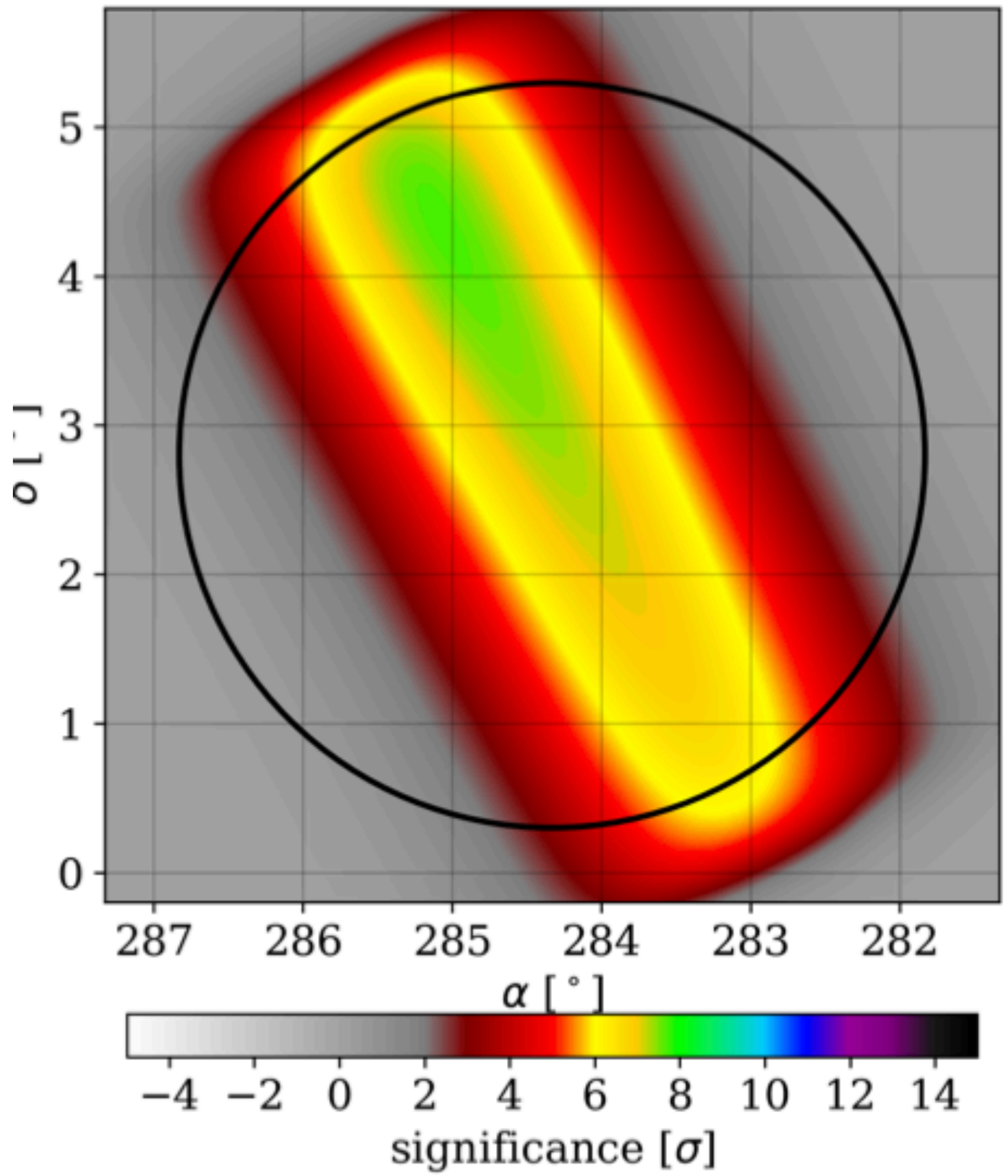
- Confused Region of the sky
- How do you decided what's a source?
- Need a well defined process
-

J1857 Region



How do you make a catalog

- Model a background diffuse/unresolved Sources (DBE)
- Use Hermes/Galprop, etc
-

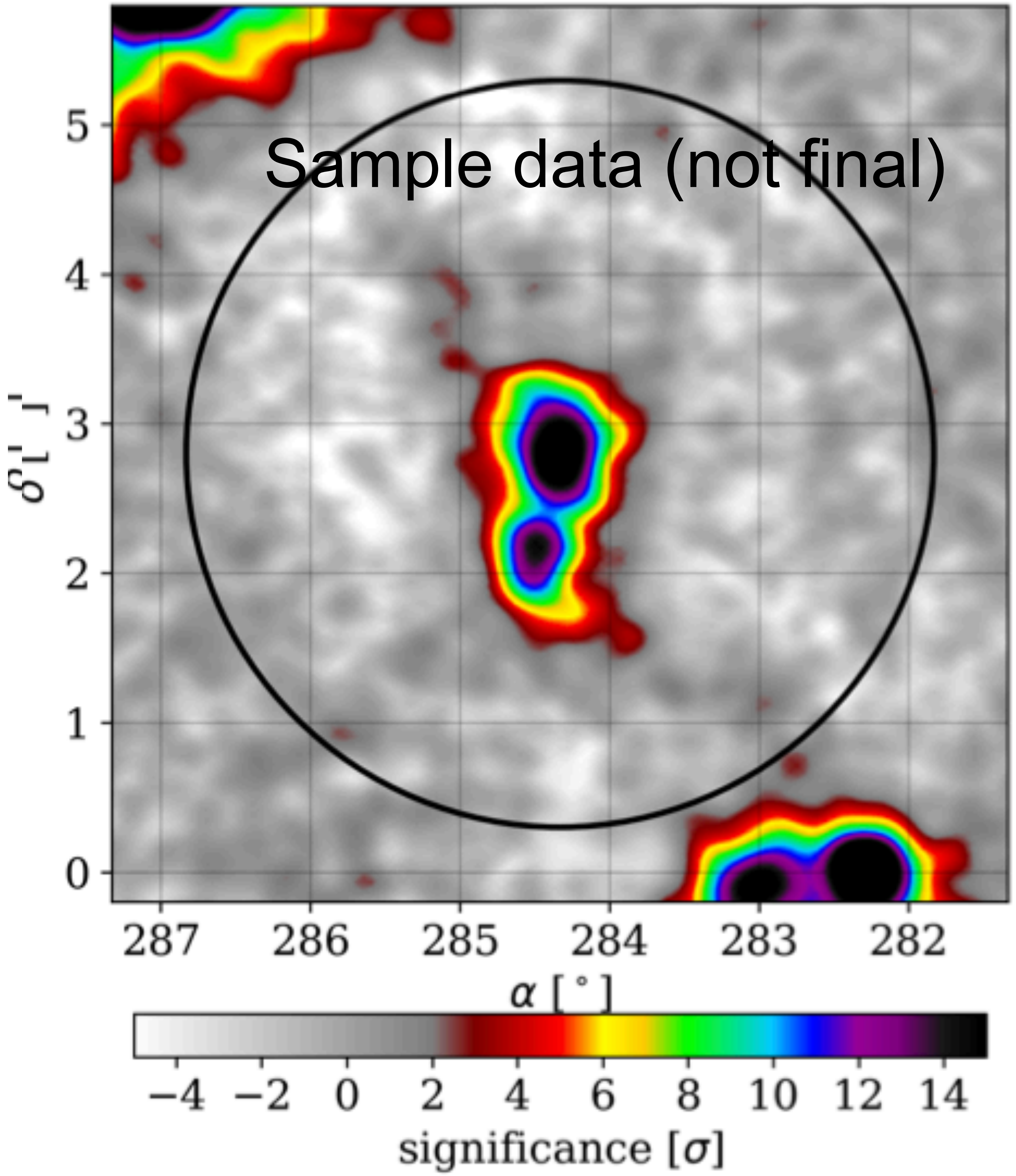


How do you make a catalog

- Subtract the background
- Now start adding the hottest sources

Model	Total -log(likelihood)	ΔTS
only DBE	16909.436	
DBE + 1 point	16711.242	396.388
DBE + 2 point	16586.572	[illegible]340
DBE + 3 point	16548.508	[illegible].128
DBE + 4 point	16524.69[illegible]	47.636
DBE + 5 point	1649[illegible]	51.368
DBE + 6 point	1[illegible]26	33.962
DBE + 7 point	[illegible]68.363	27.326
DBE + 8 p[illegible]	16453.416	29.894
DBE + [illegible]	16438.787	29.258
DBE + [illegible] point	16429.291	18.992

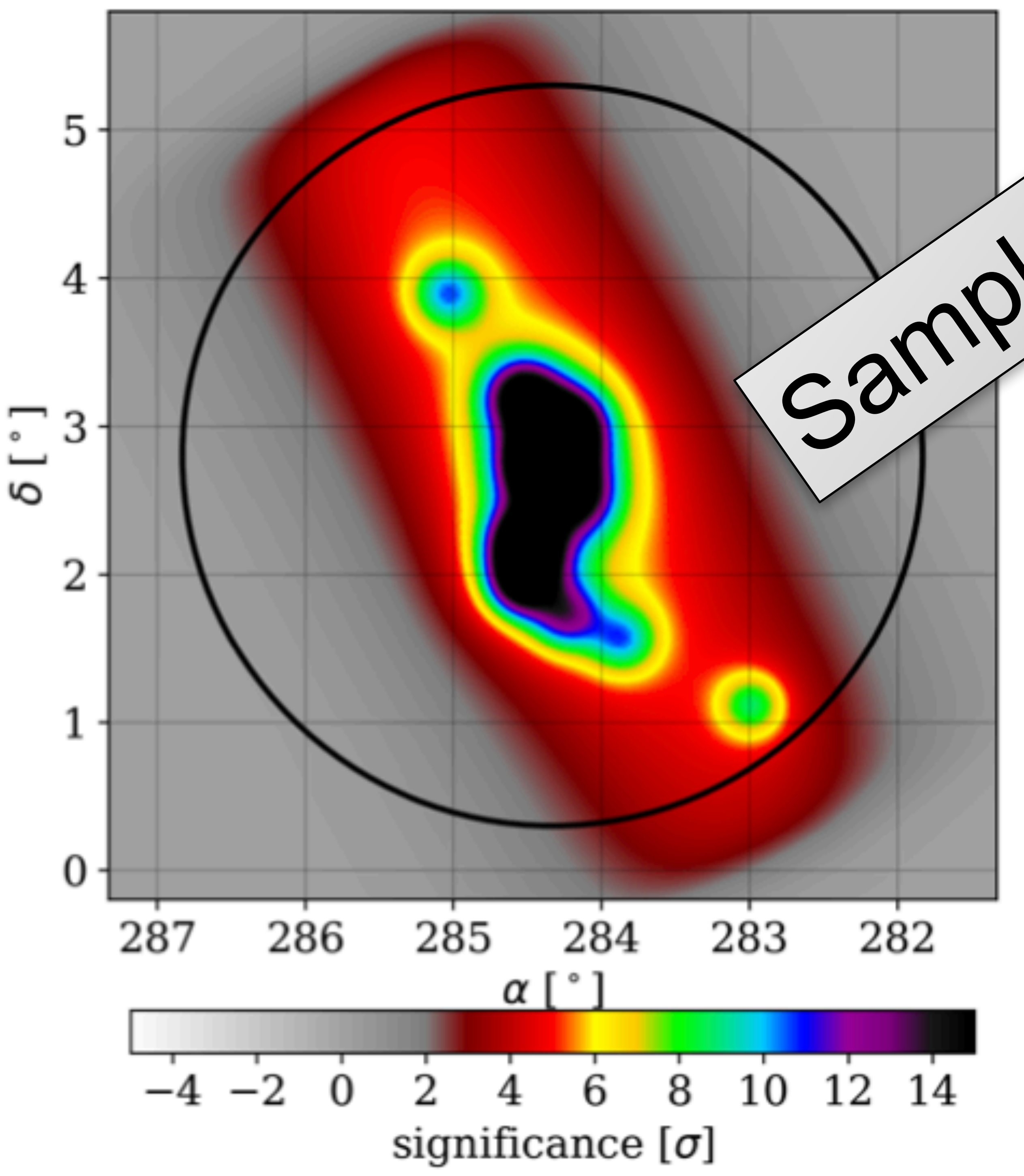
Sample data (not final)

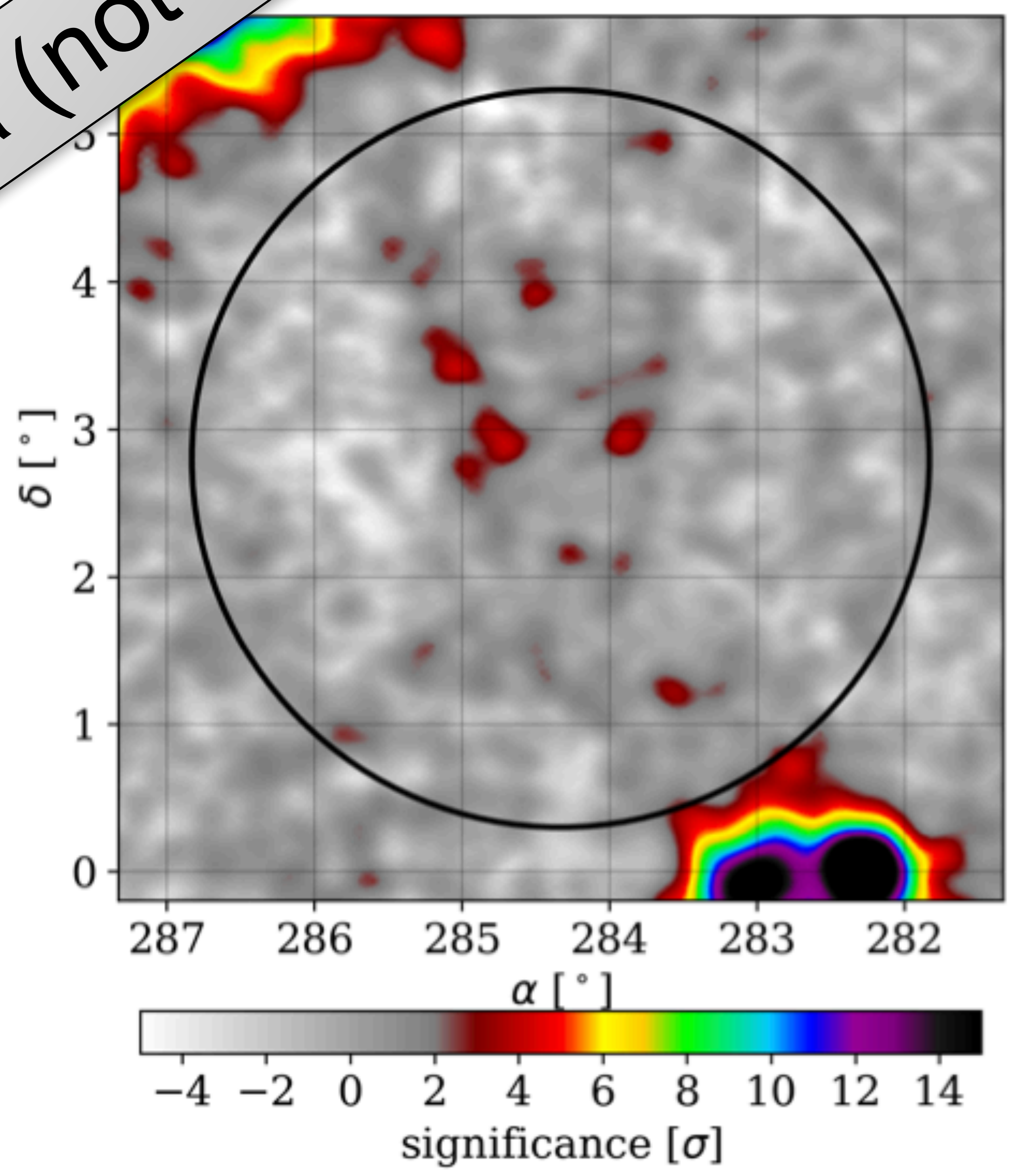


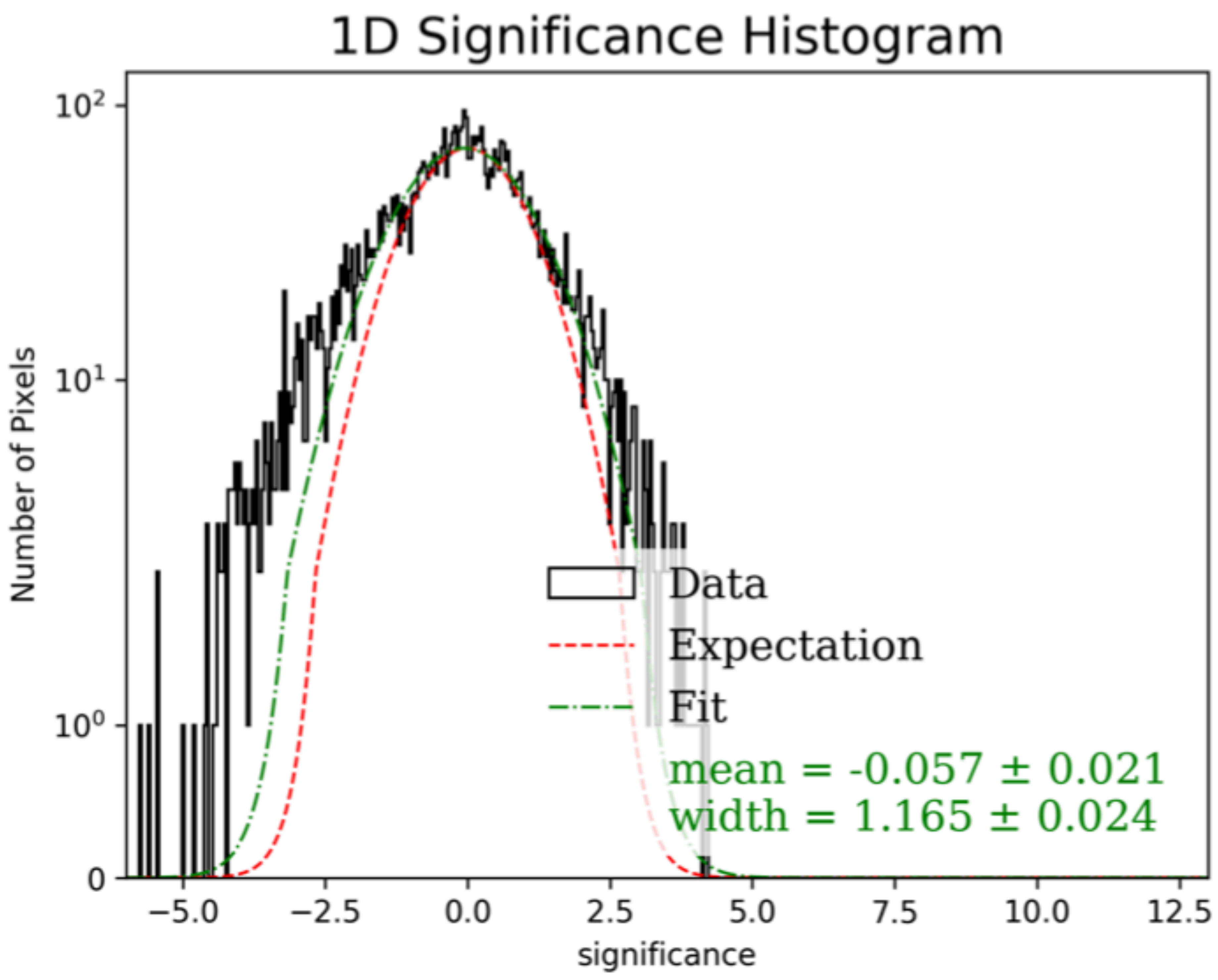
How do you make a catalog

- Subtract the result

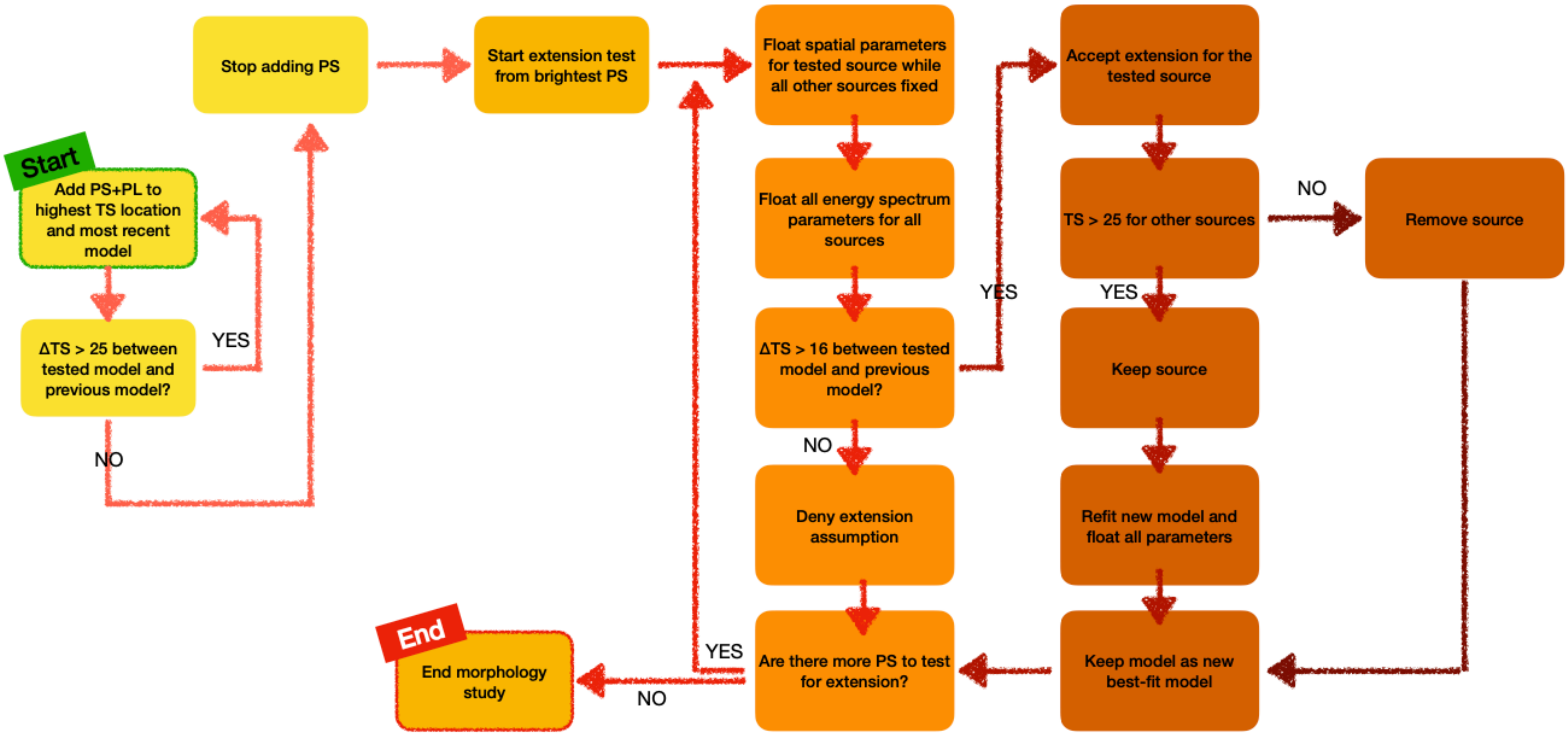
Sample data (not final)





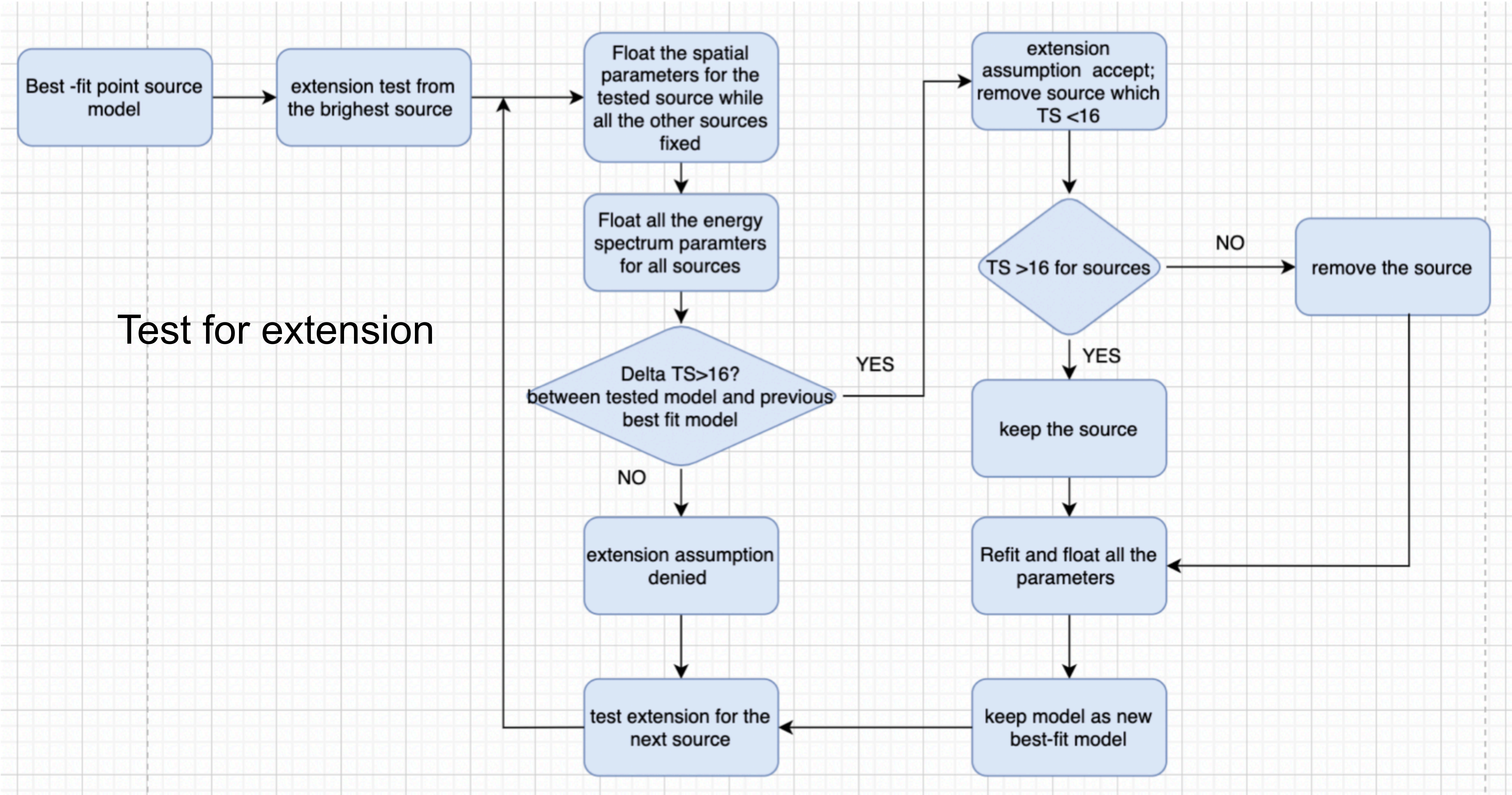


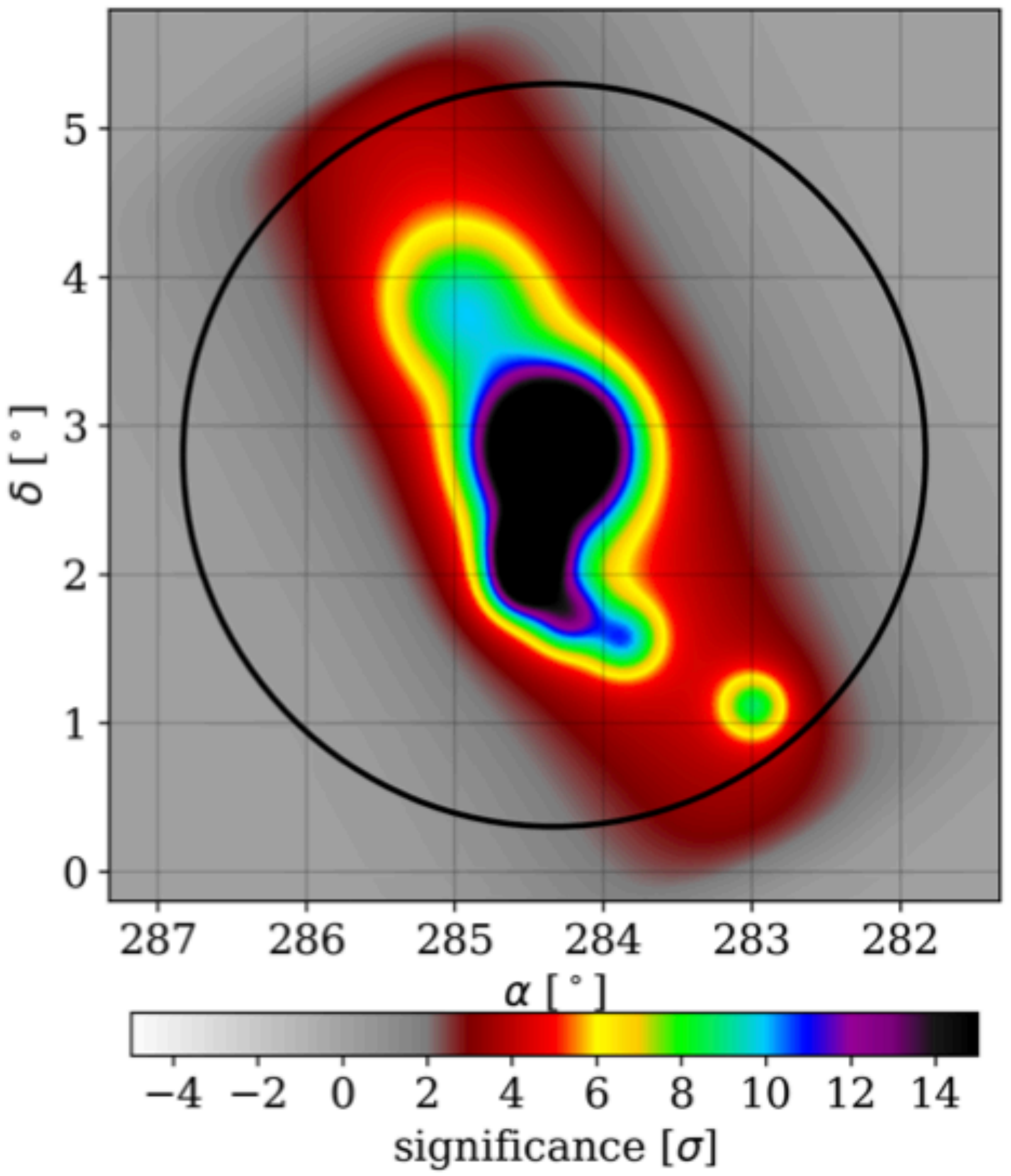
How do you make a catalog



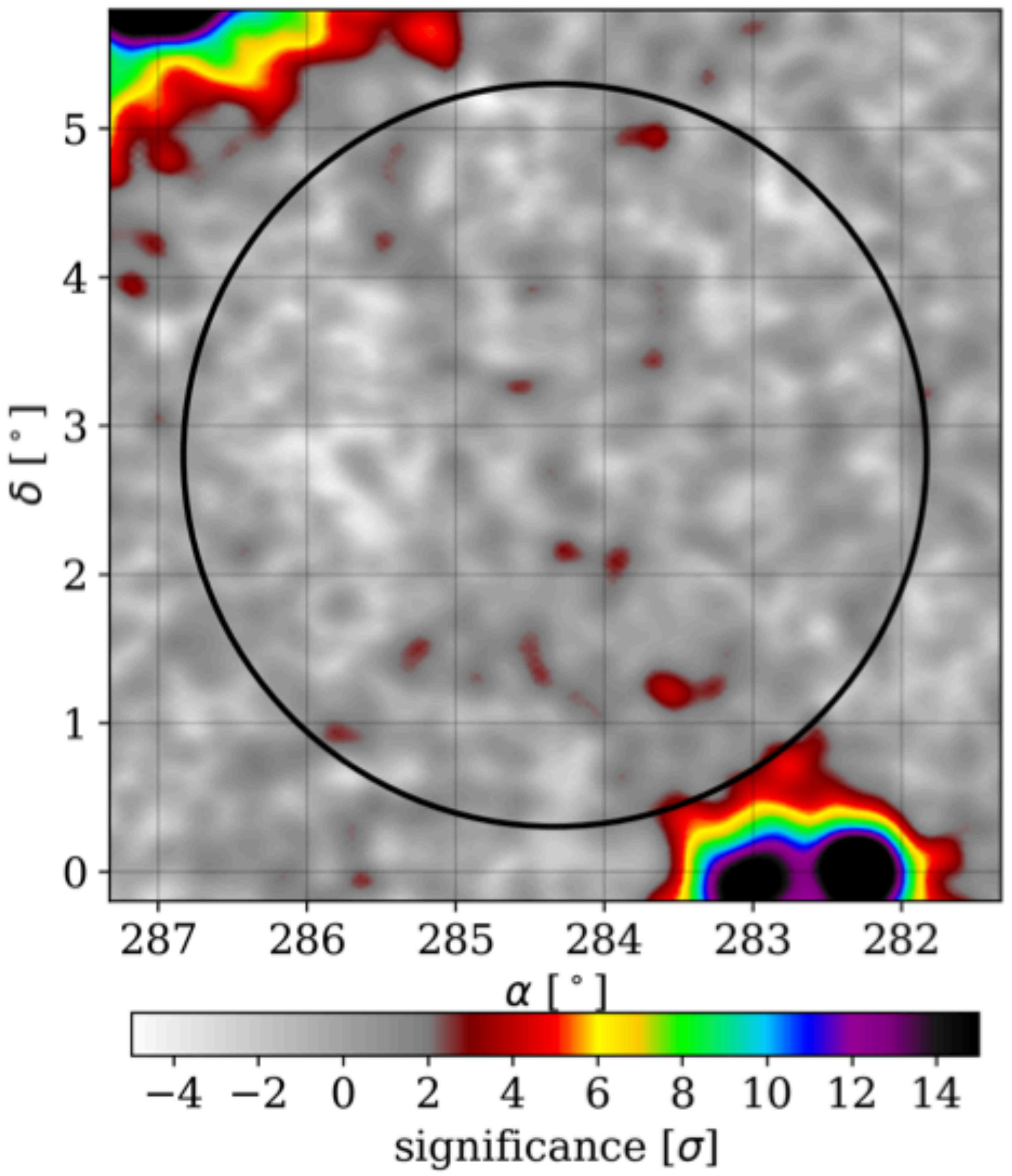
How do you make a catalog

Test for extension

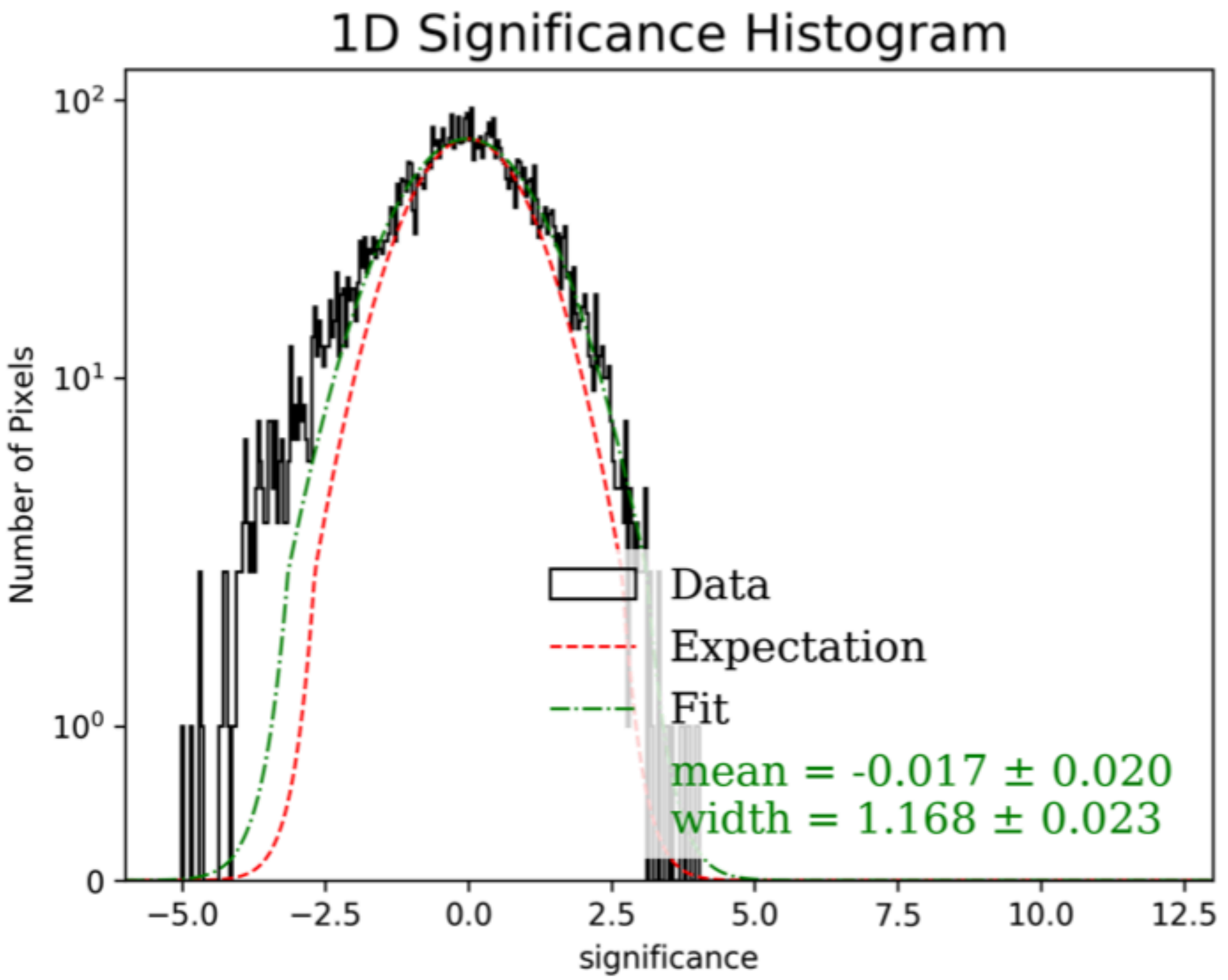




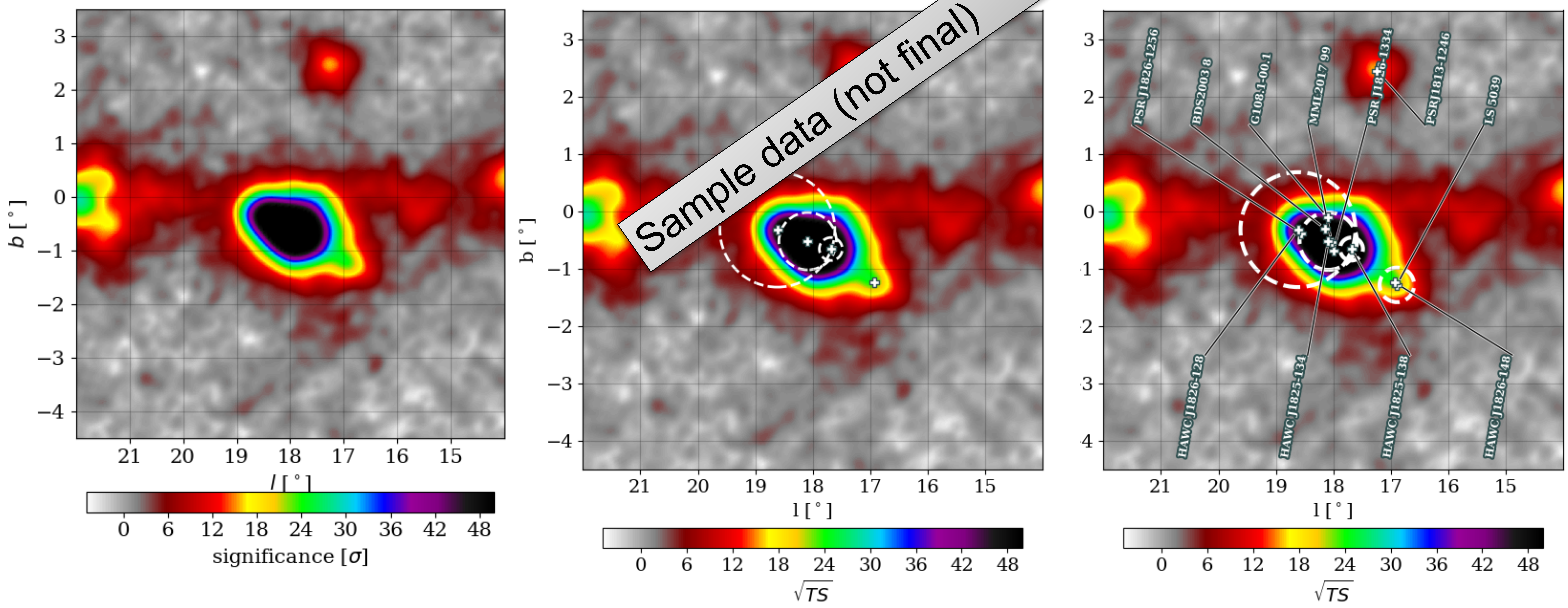
5
4
3
2
1
0
δ [°]
287
286
285
284
283
282
α [°]
−4 −2 0 2 4 6 8 10 12 14
significance [σ]



5
4
3
2
1
0
δ [°]
287
286
285
284
283
282
α [°]
−4 −2 0 2 4 6 8 10 12 14
significance [σ]

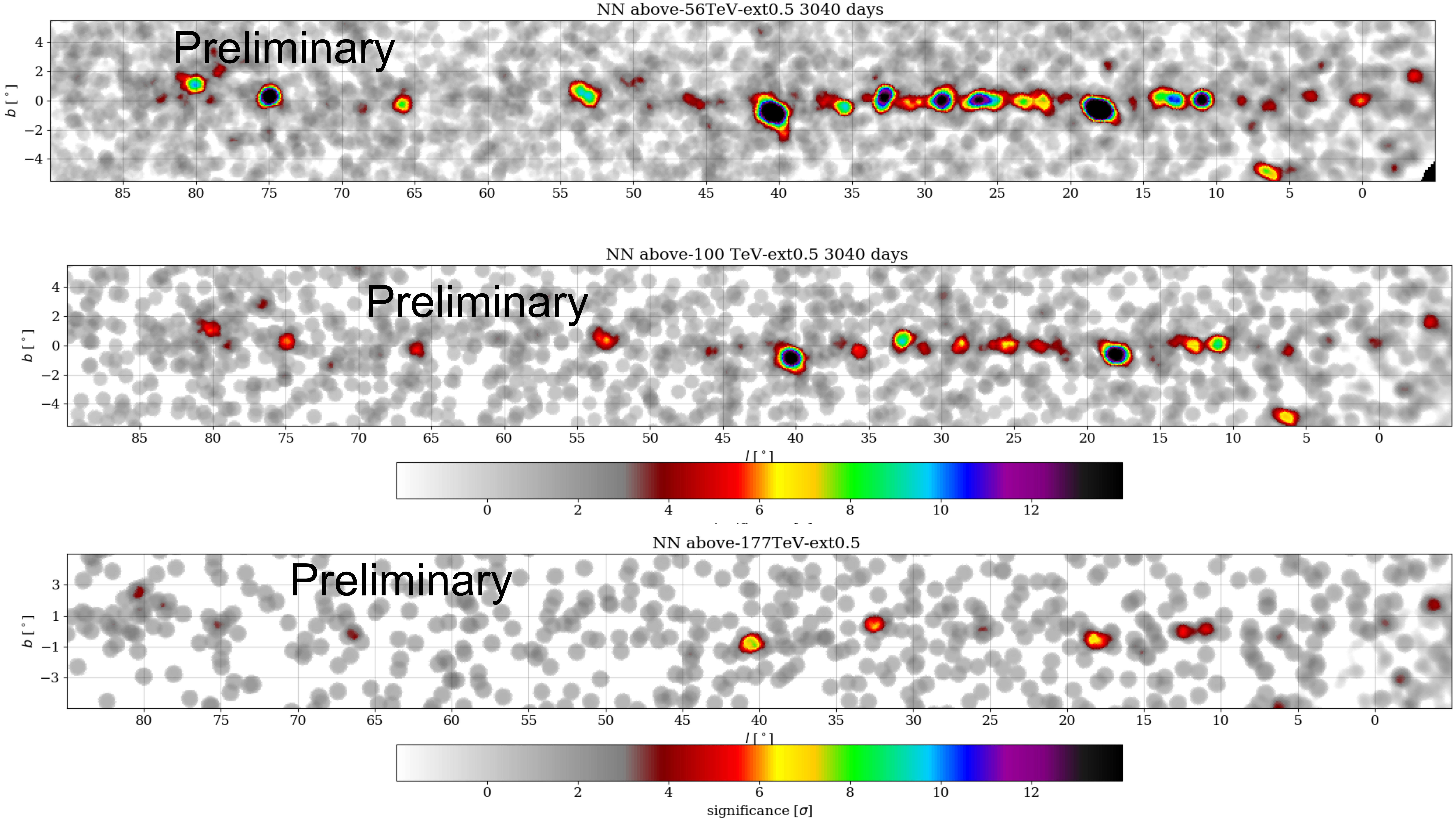


1D Significance Histogram
Number of Pixels
Data
Expectation
Fit
mean = -0.017 ± 0.020
width = 1.168 ± 0.023
−5.0 −2.5 0.0 2.5 5.0 7.5 10.0 12.5
significance


Sample data (not final)
b [°]
l [°]
significance [σ]
√TS
PSRJ1826-1256
BDS2003 8
G108.1-00.1
MML2017 99
PSR J1826-1334
PSRJ1813-1246
LS 5039
HAWC J1826-128
HAWC J1825-134
HAWC J1825-138
HAWC J1826-148

Pushing to the highest energies

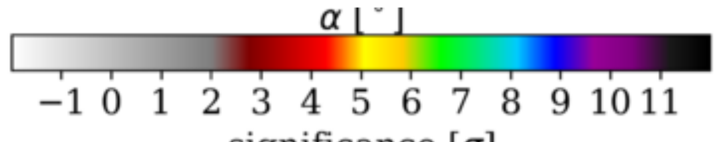
0.5° Extended Source Analysis



>56 TeV

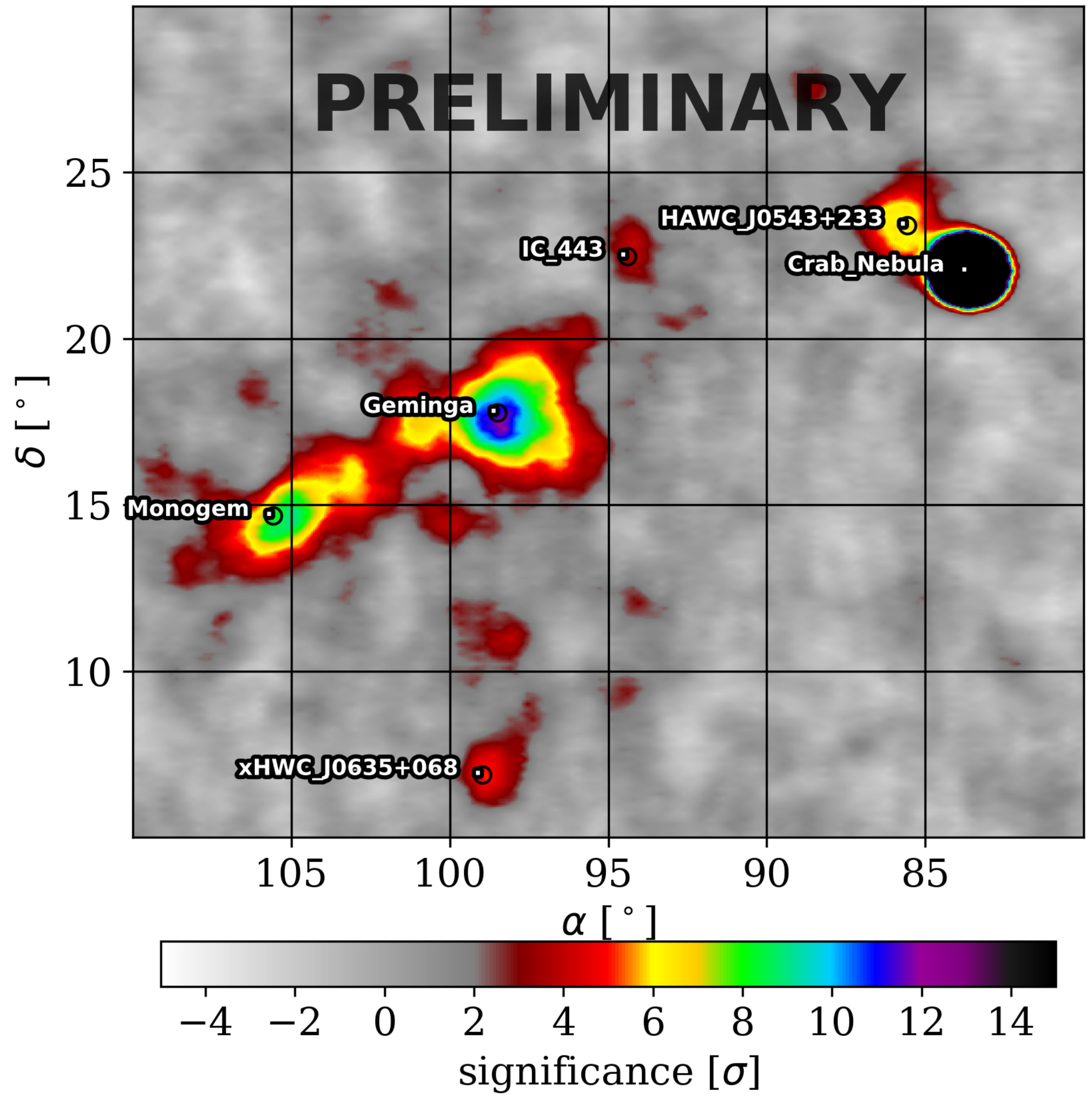
>100 TeV

>177 TeV



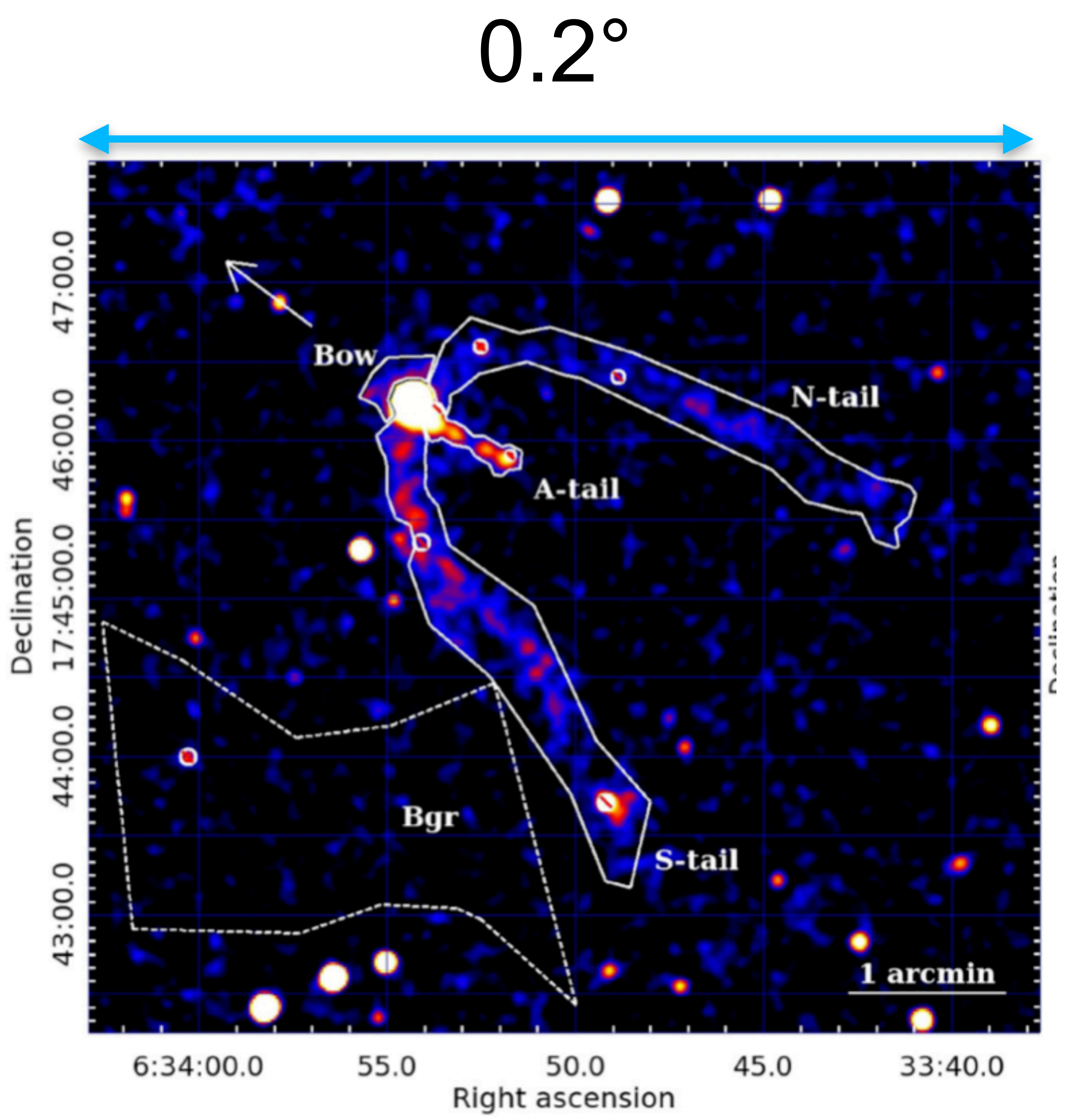
The Galactic Anti-Center

- 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



Geminga - PWN

- Geminga is one of the brightest GeV sources in the northern sky
- It's a middle-aged 340kyr, pulsar T=0.237s
- It's close to earth - 250^{+250}_{-62} pc
- X-Ray PWN seen to be very small
- First seen in TeV by Milagro at 40 TeV
- HAWC also sees energies above 25TeV
- Very extended in the TeV - ~5 degrees across
- Not easily seen by IACTs



Where do these gammas come from?

- Inverse Compton Scattering
  - Off of what?
- HAWC sees gammas above 25 TeV from these sources
  - These must come from >100 TeV electrons
  - At these energies the Compton Cross section is suppressed for scattering off of IR or optical photons
    - Why?

Compton Scattering Cross Section

- Thompson cross section (non-relativistic)

$$\sigma_T = \frac{8\pi}{3} r_e^3$$

r_e is the classical radius of the electron

- This applies when the photon energy in the rest frame of the electron is $<< m_e c^2$
- If the photon energy is $> m_e c^2$ you need to use the relativistic formulation

Klein Nishina Scattering

$$\sigma = 2\pi \int_0^\pi \frac{d\sigma}{d\Omega} \sin\theta d\theta$$
$$= \ldots\ldots$$
$$= \frac{3}{4}\sigma_T \left[\frac{1+x}{x^3}\left(\frac{2x(1+x)}{1+2x} - \ln(1+2x)\right) + \frac{1}{2x}\ln(1+2x) - \frac{1+3x}{(1+2x)^2}\right]$$

where

$$x \equiv \frac{h\nu_i}{m_e c^2}$$

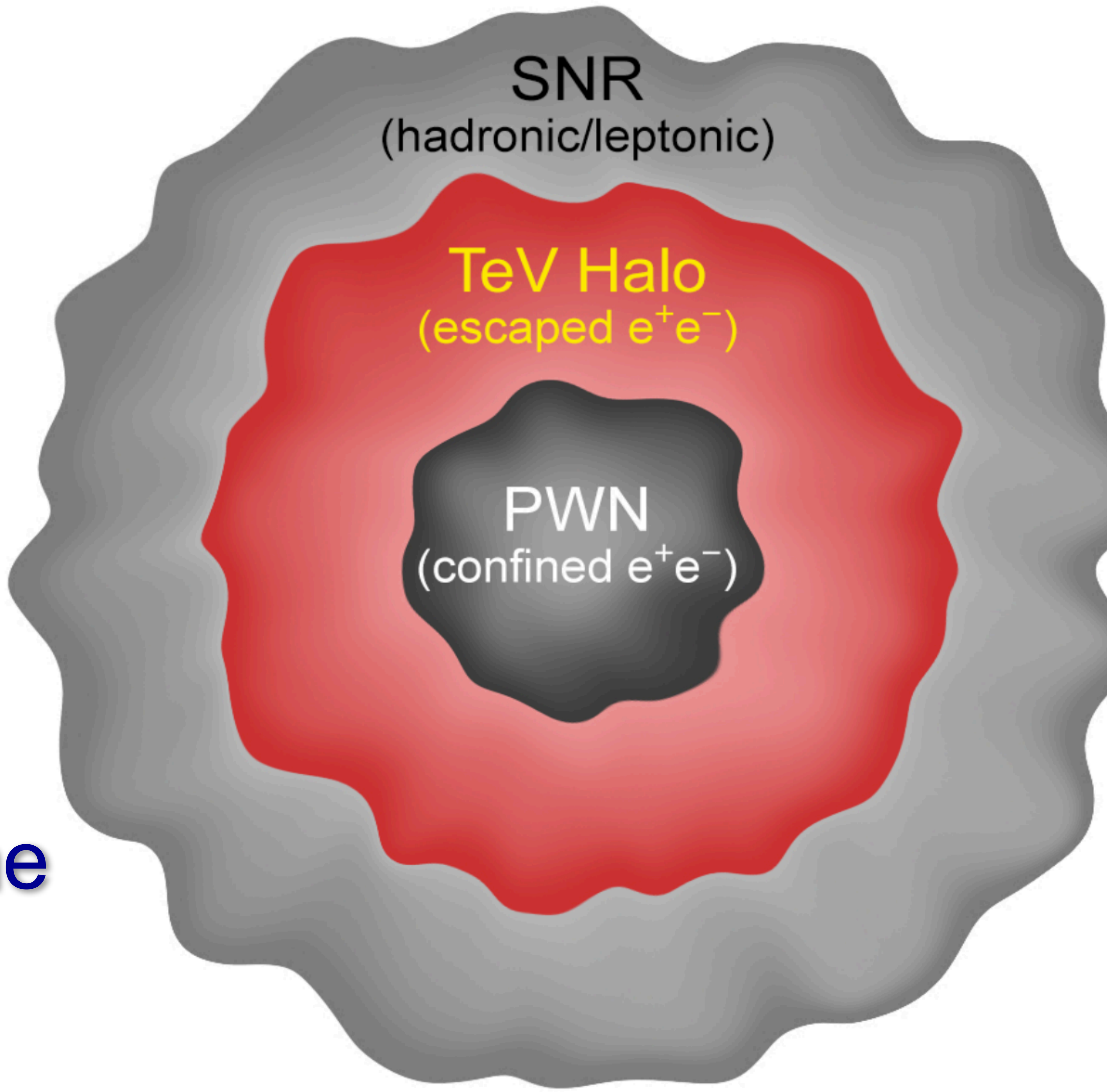
Limits:

$$\sigma(x) \simeq \sigma_T (1 - 2x + \ldots) \quad \text{for} \quad x \ll 1 \quad \text{(Thomson)}$$

$$\sigma(x) \simeq \frac{3}{8}\sigma_T \frac{1}{x}\left(\ln 2x + \frac{1}{2}\right) \quad \text{for} \quad x \gg 1 \quad \text{(extreme KN)}$$

TeV Halos

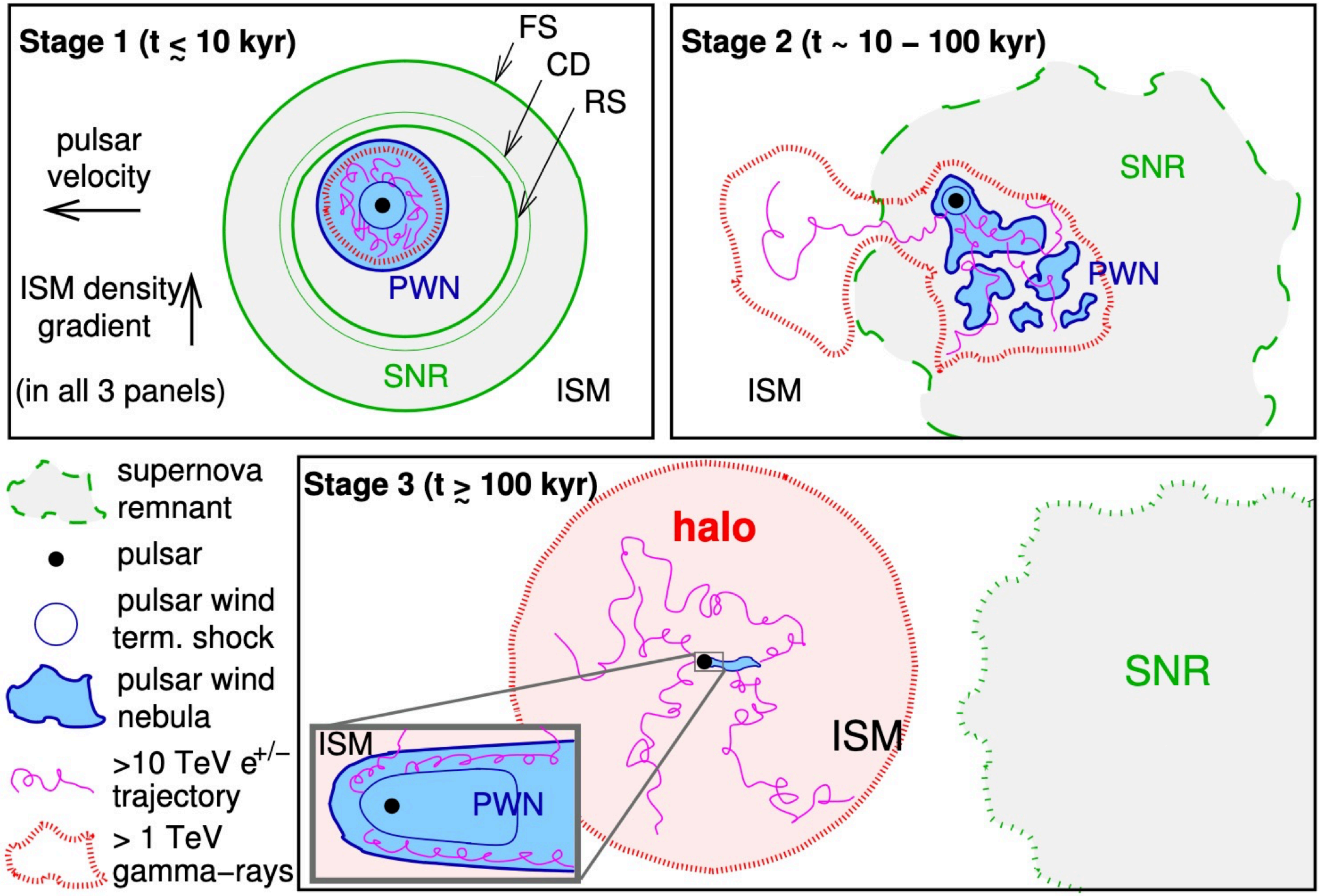
- The x-ray emission is from synchrotron radiation, where the B field is enhanced by the pulsar to 10 to 20 μG
- For the highest energy electrons above ~100 TeV the only thing you can scatter off of is the CMB because its energy is so low (KN effect)
  - We know what the CMB is everywhere
- So we measure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



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

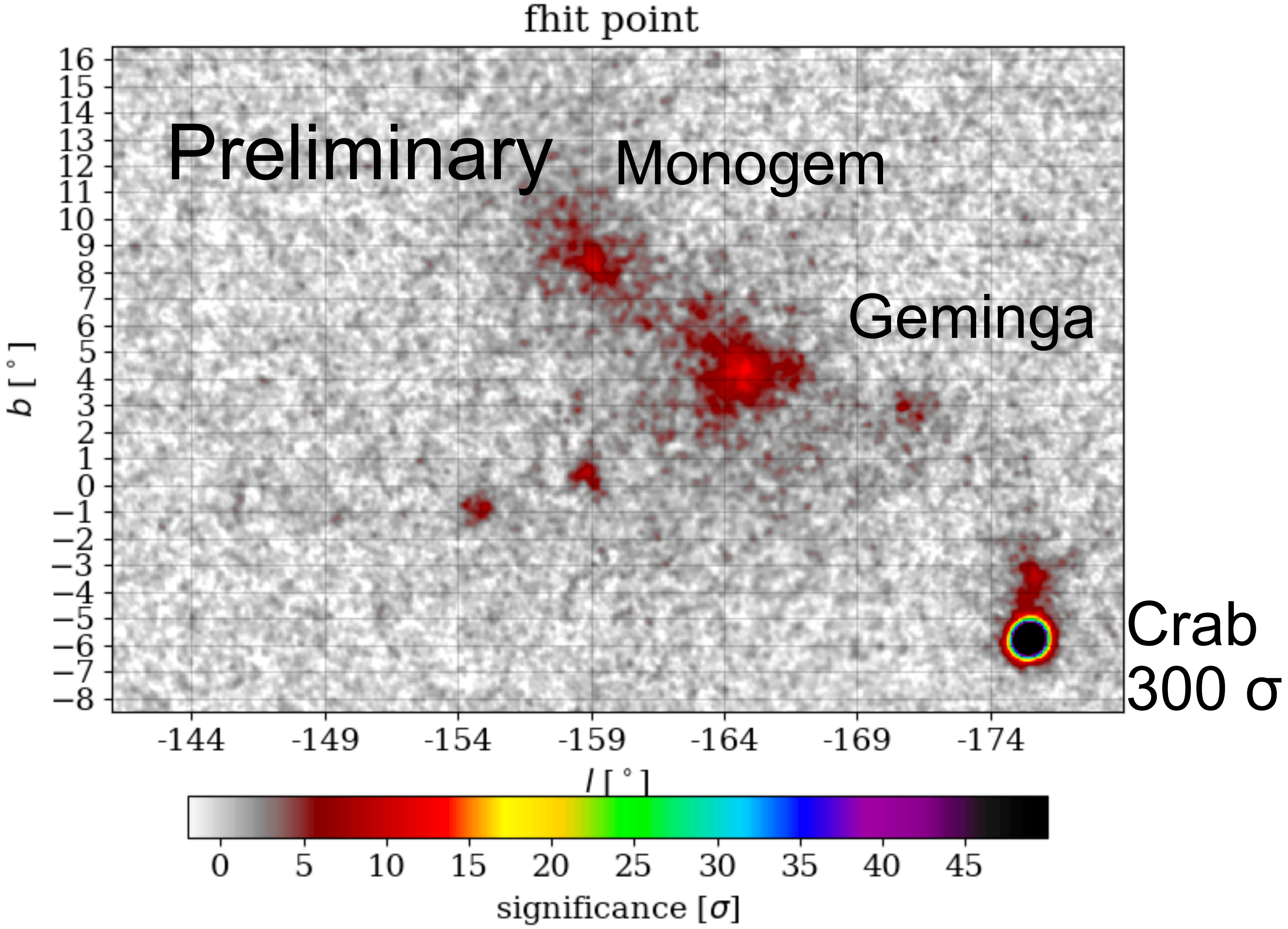
TeV Halos

- **Powered by spin-down of middle-aged pulsar**
- **Extended TeV emission beyond the PWN to 10s of pc**

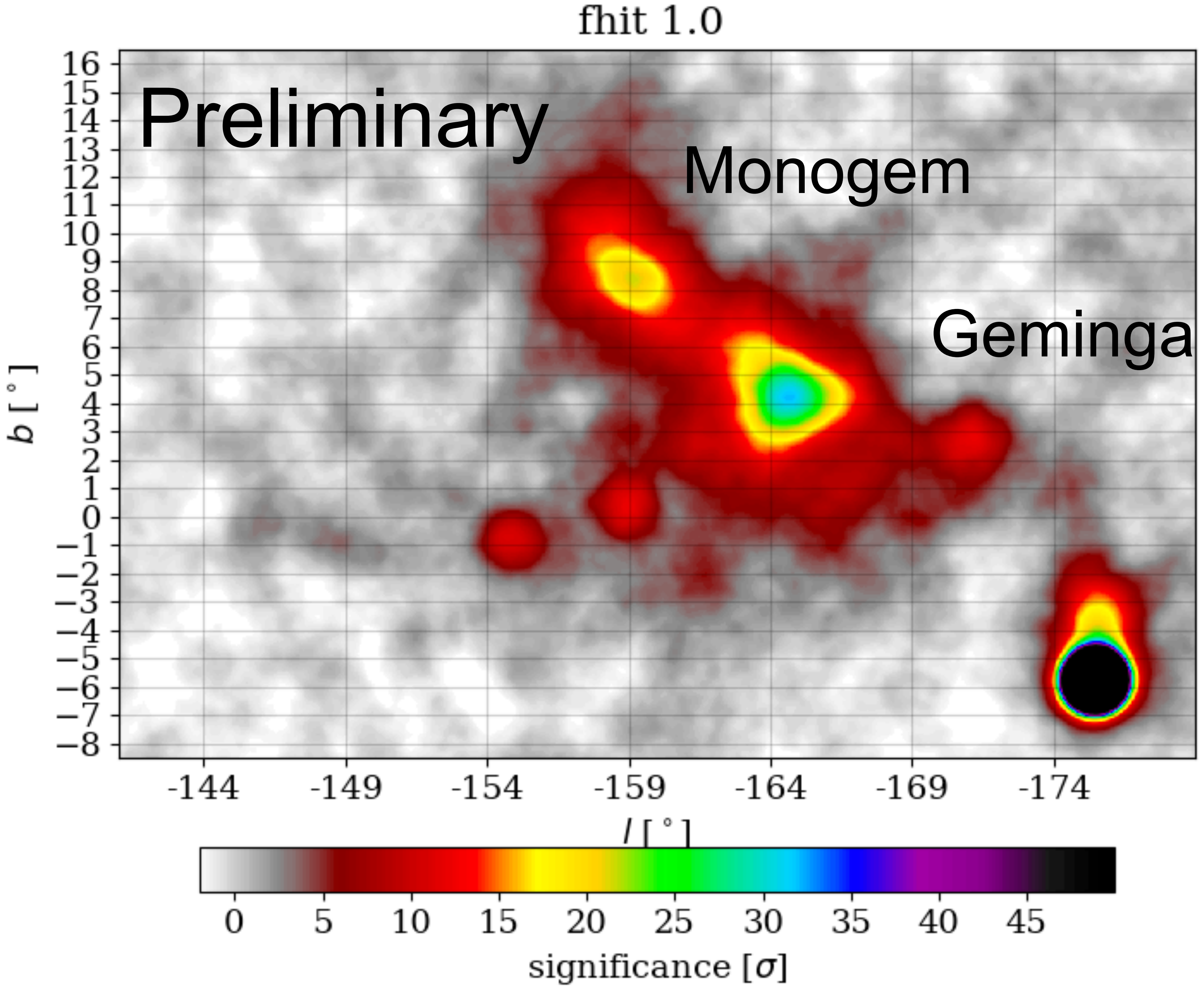


Giacinti et al. 2020

Outer Galaxy 3040 days



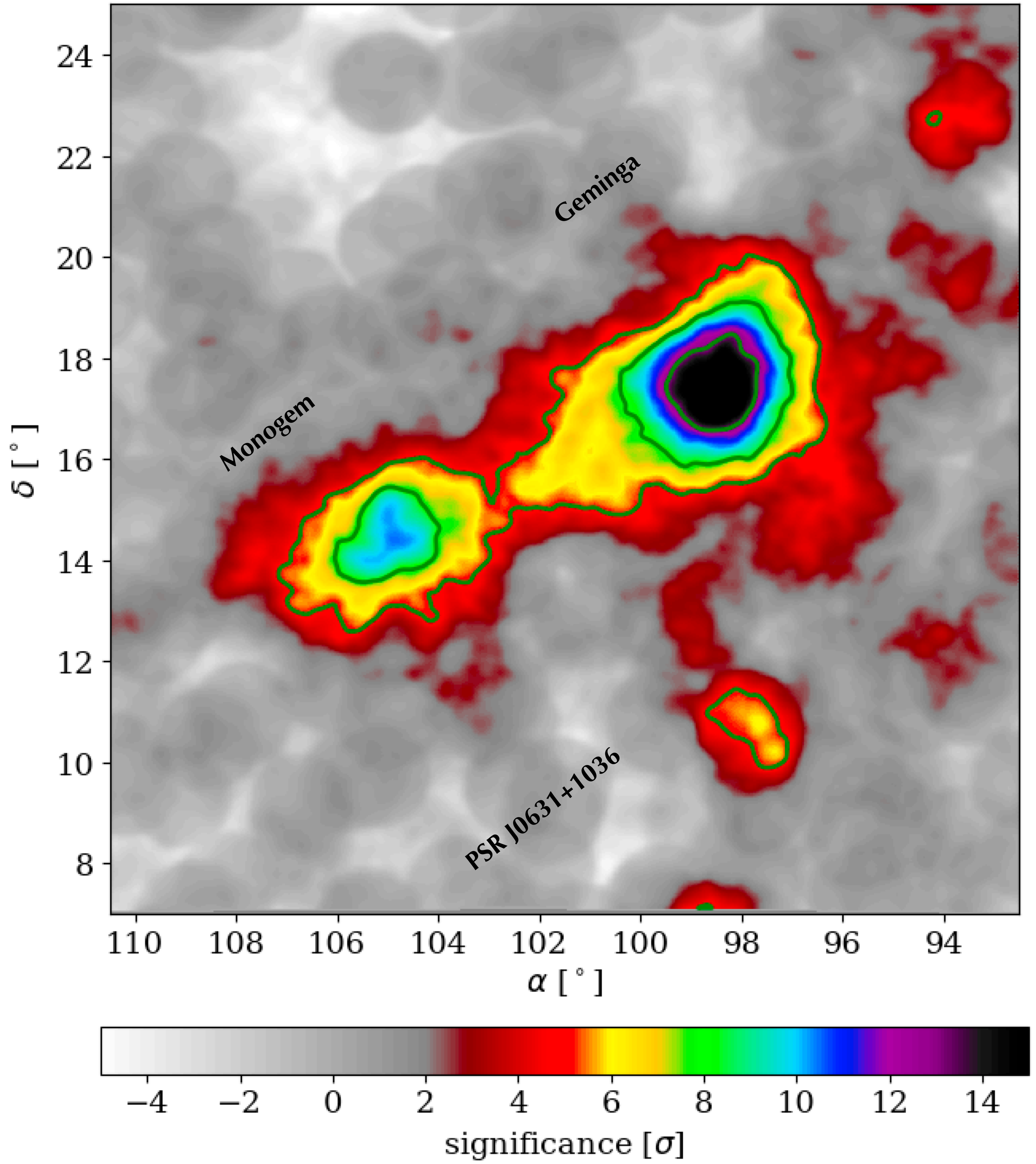
Point Source

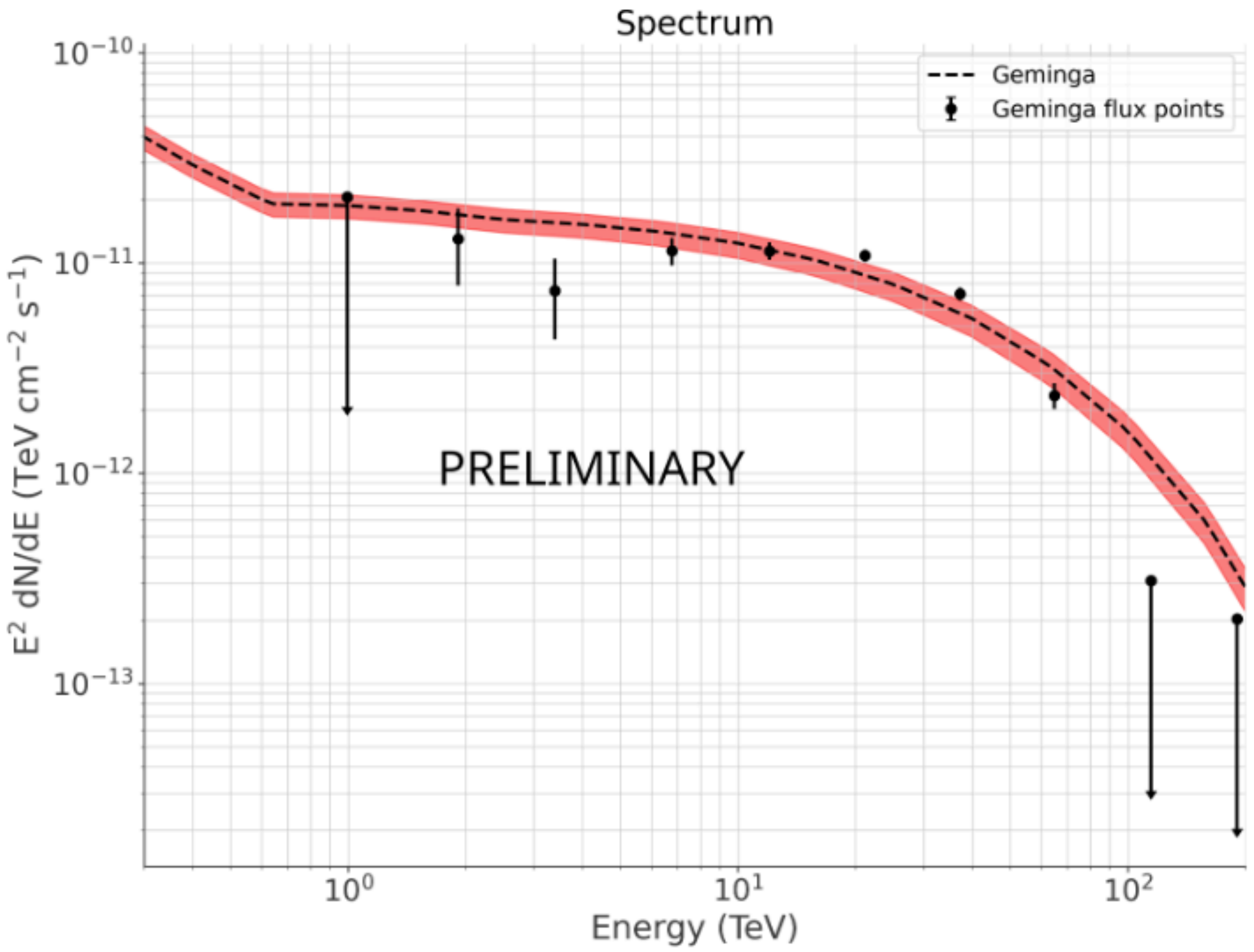


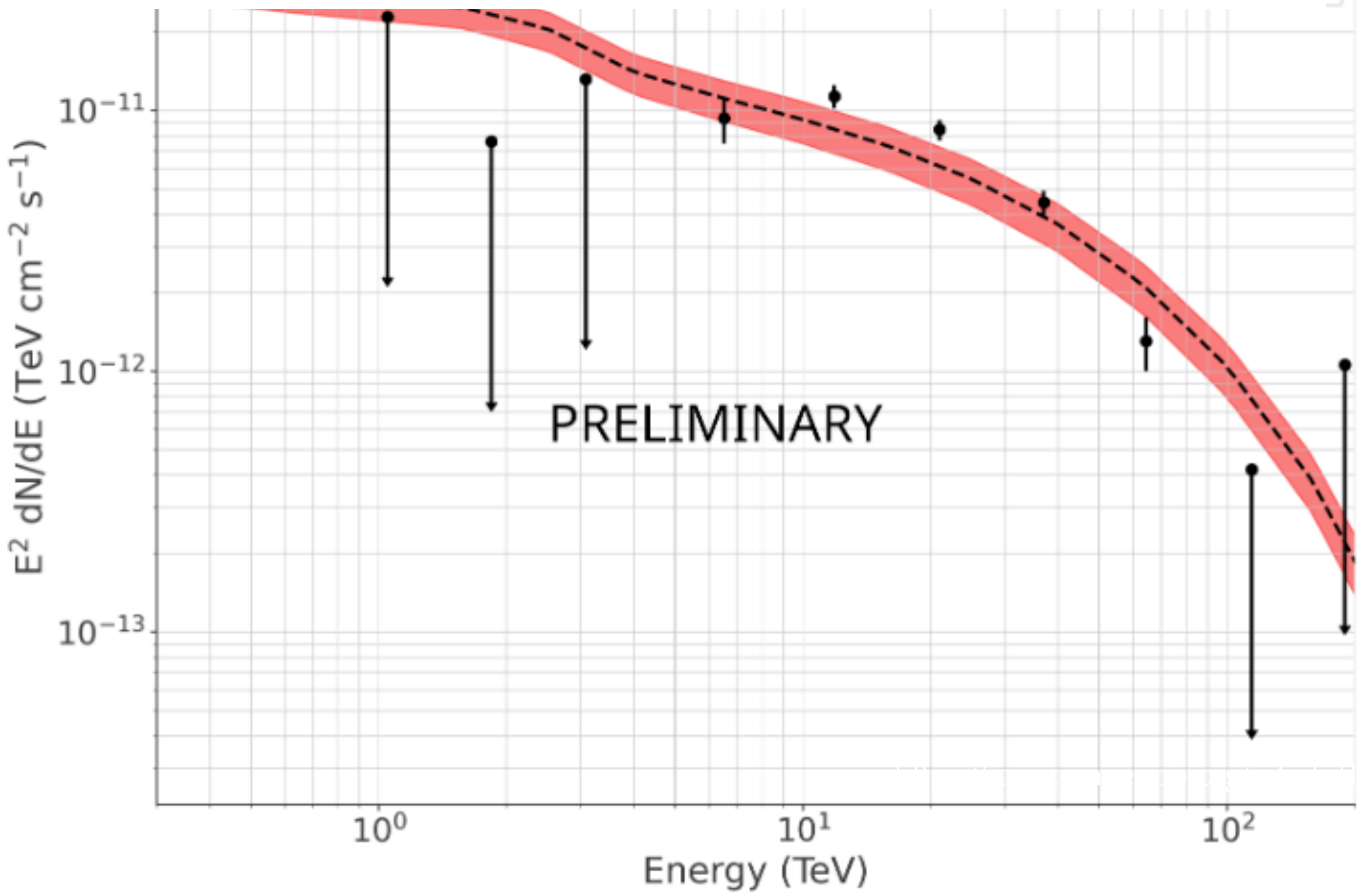
1 degree analysis

Preliminary

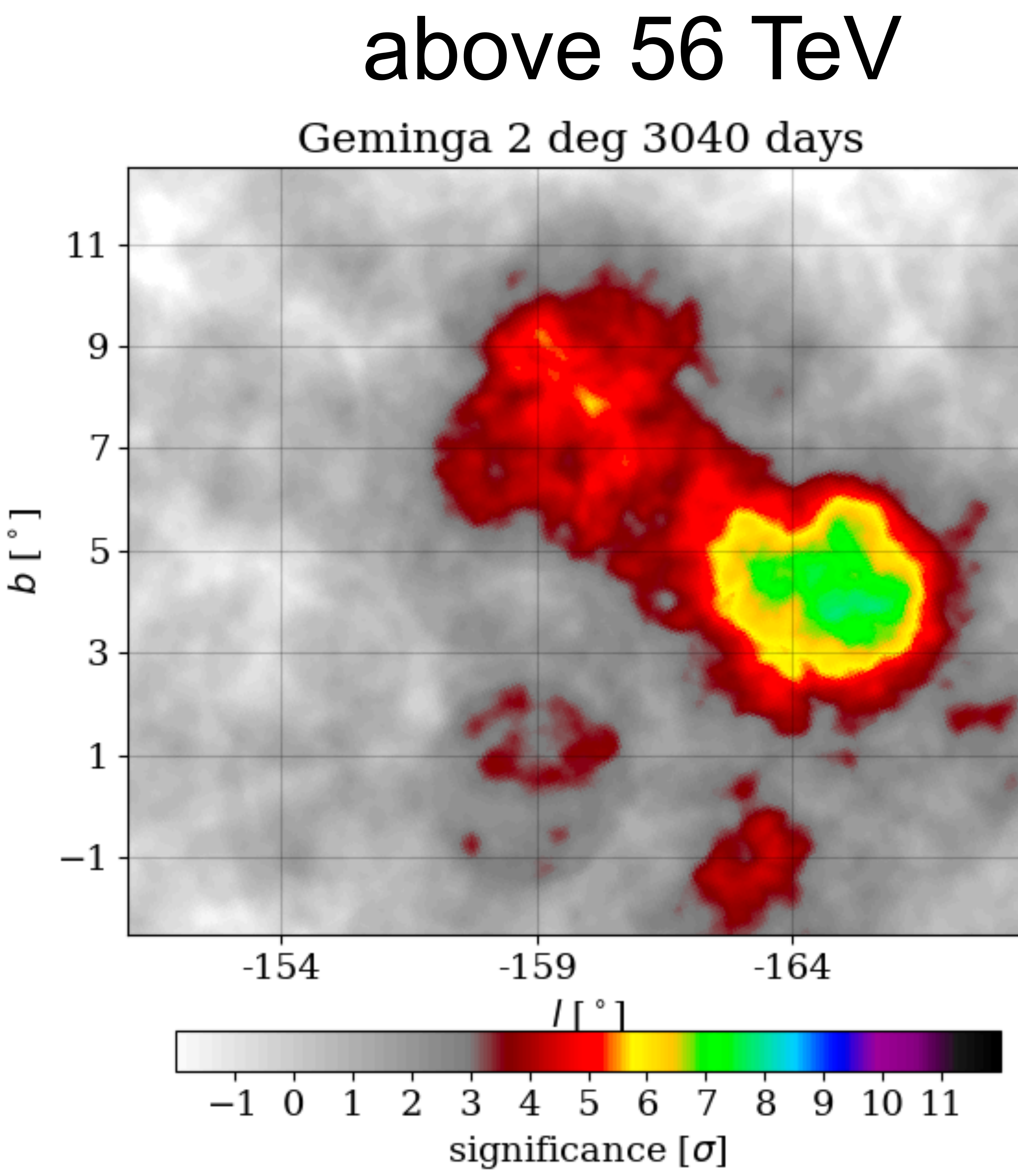
New From Pass 5

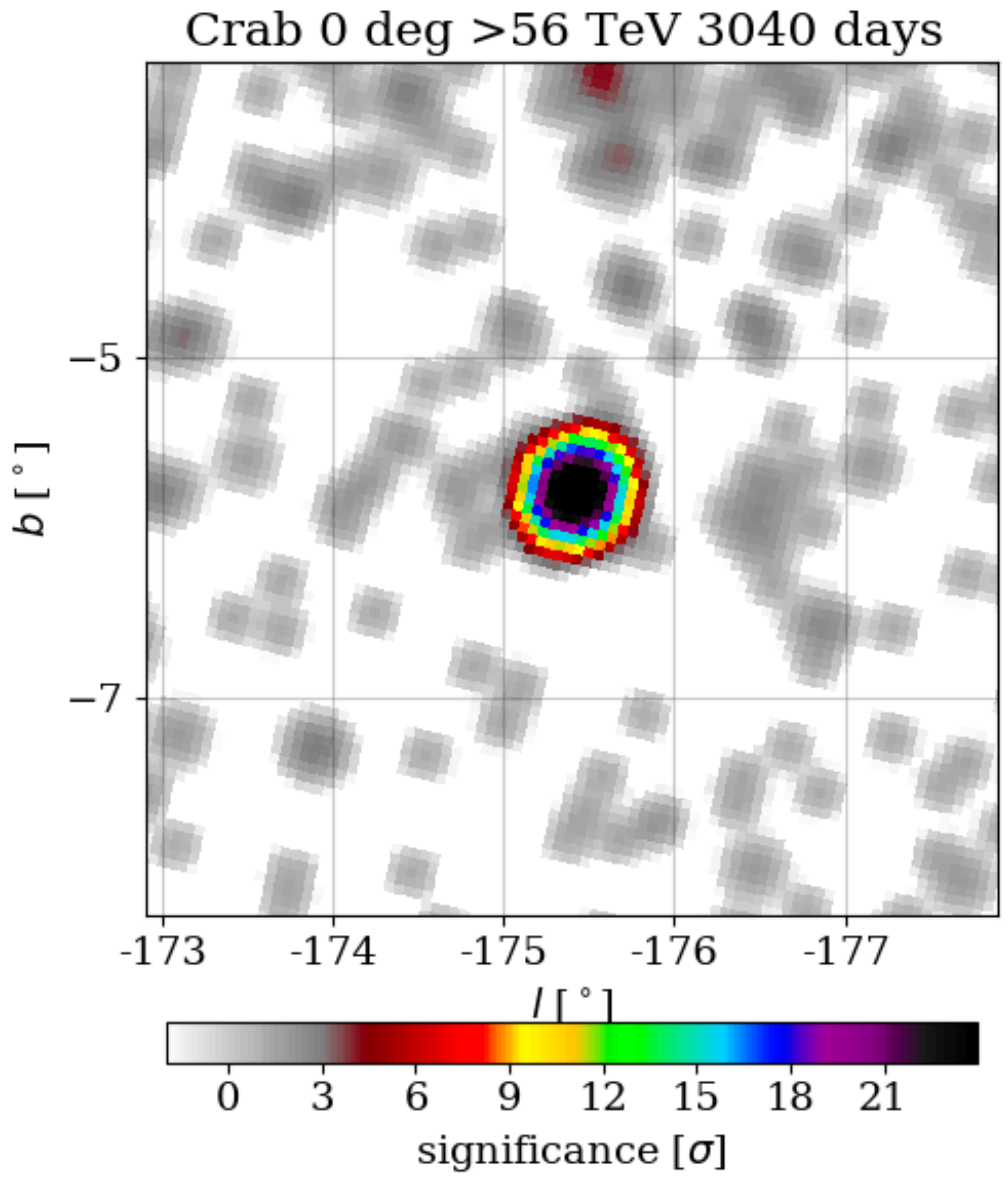




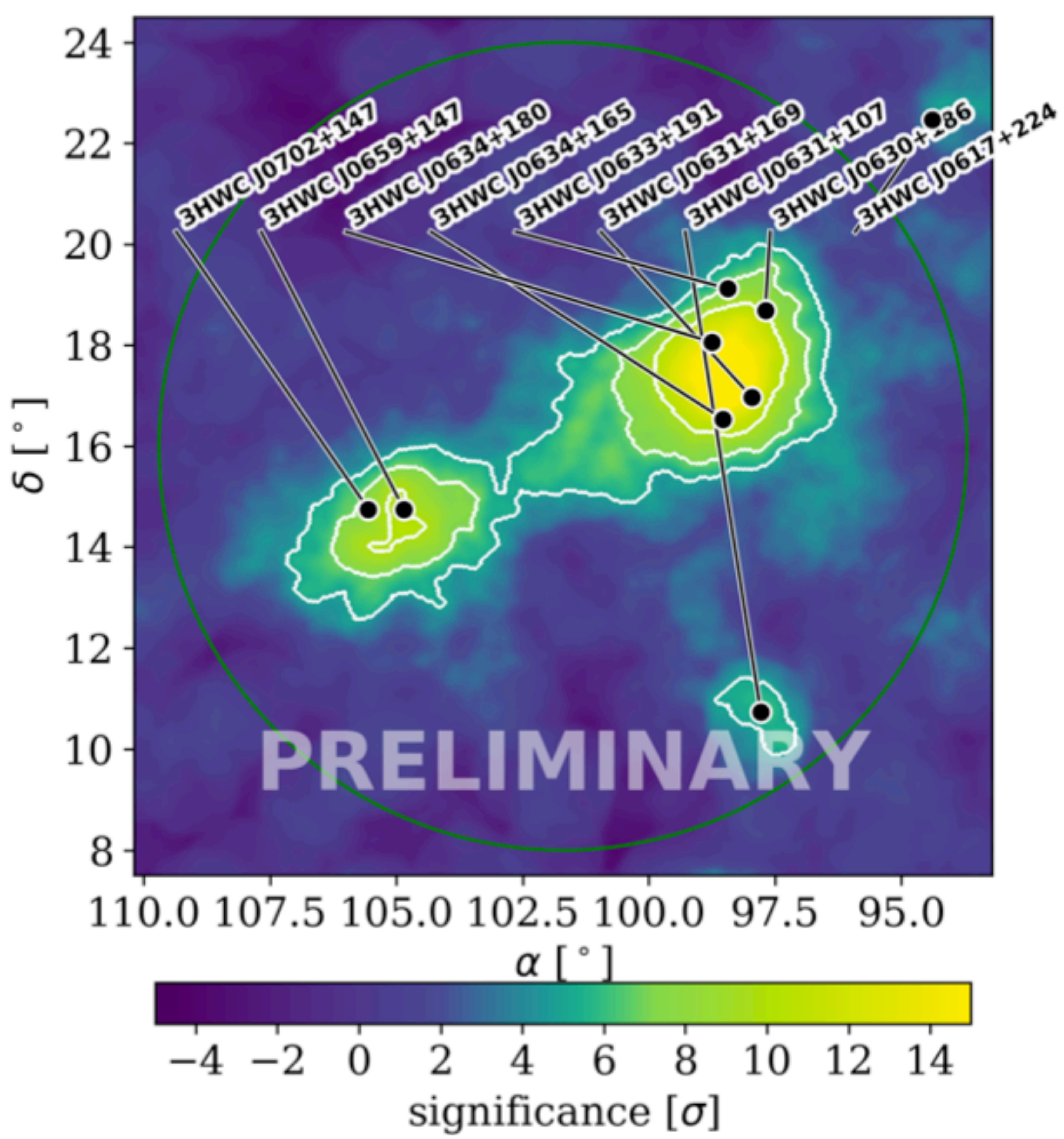


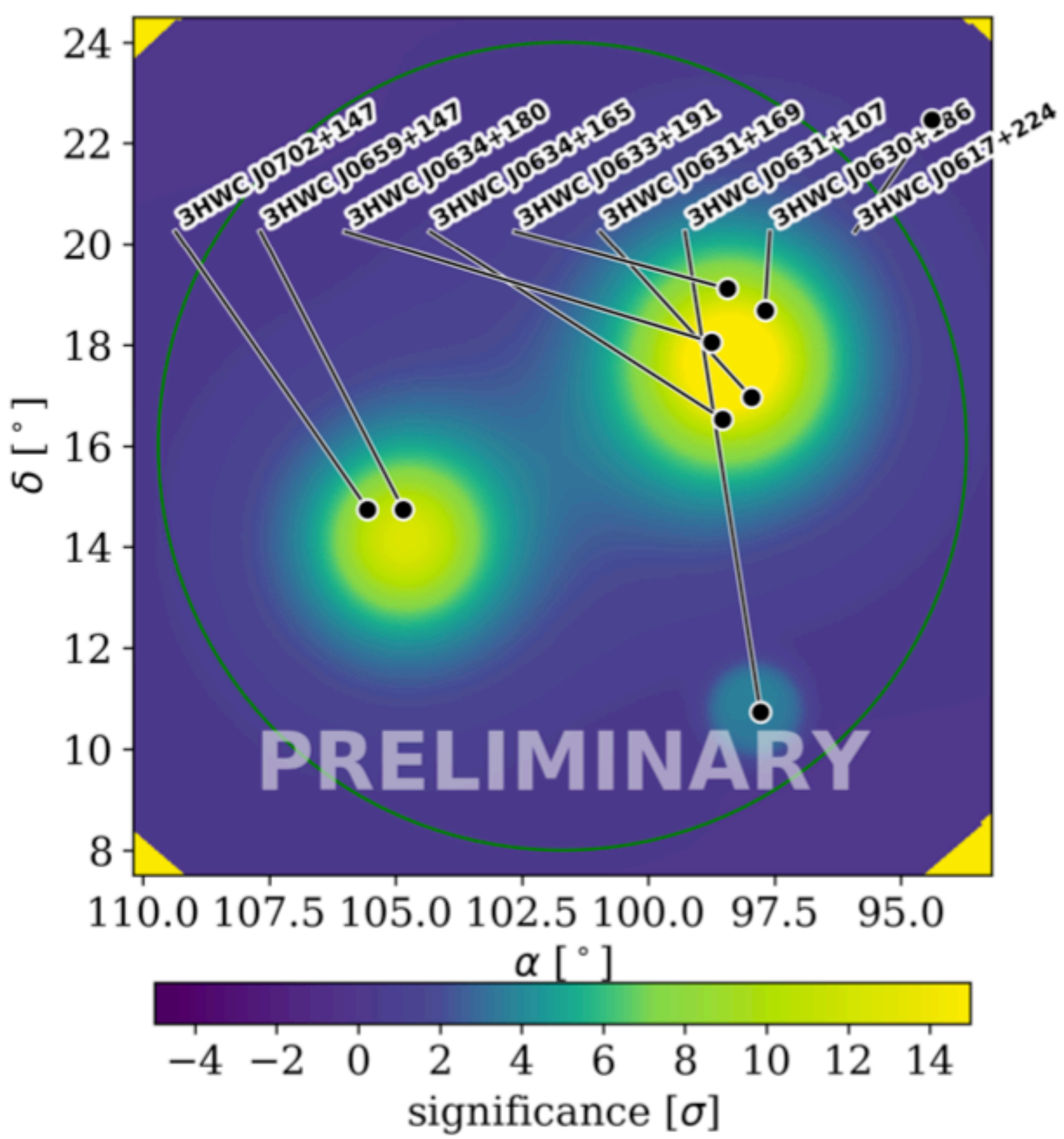
Geminga/Mongem + Crab Above 56 TeV





Geminga and Monogem in Pass 5





Geminga in Pass 5

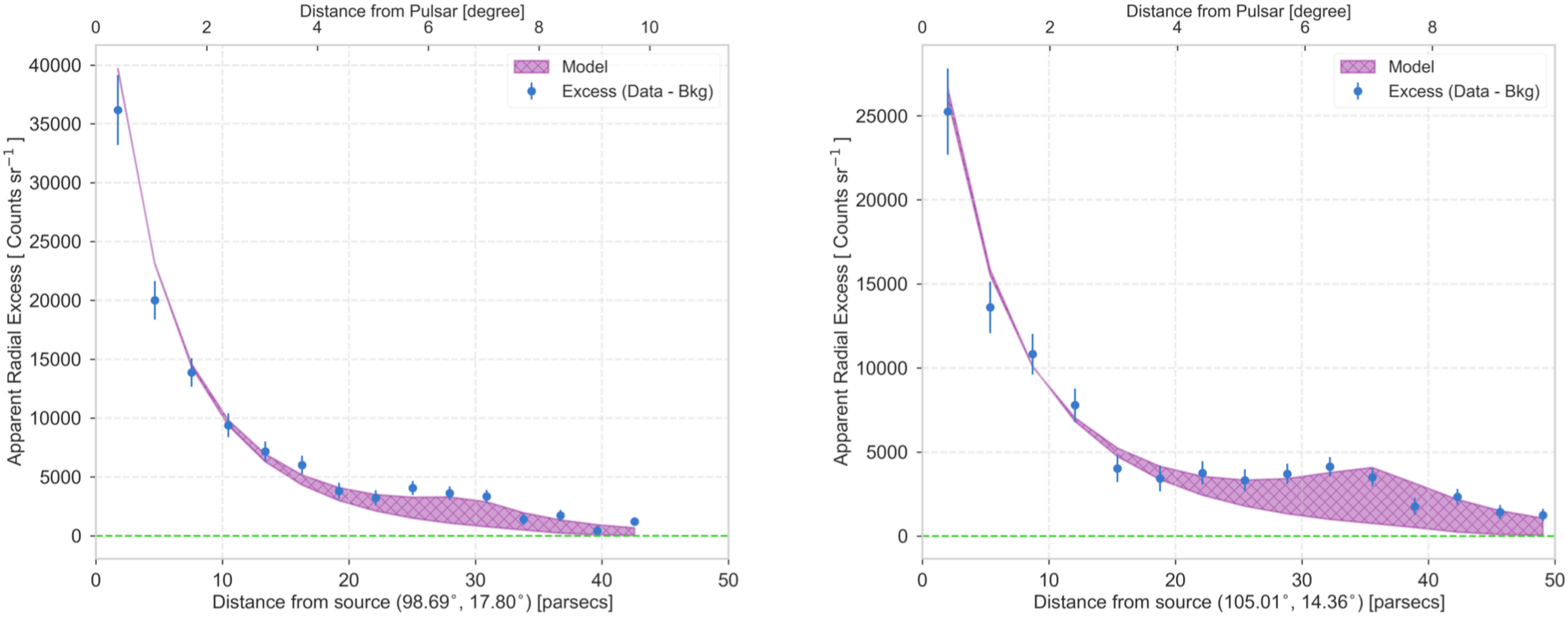
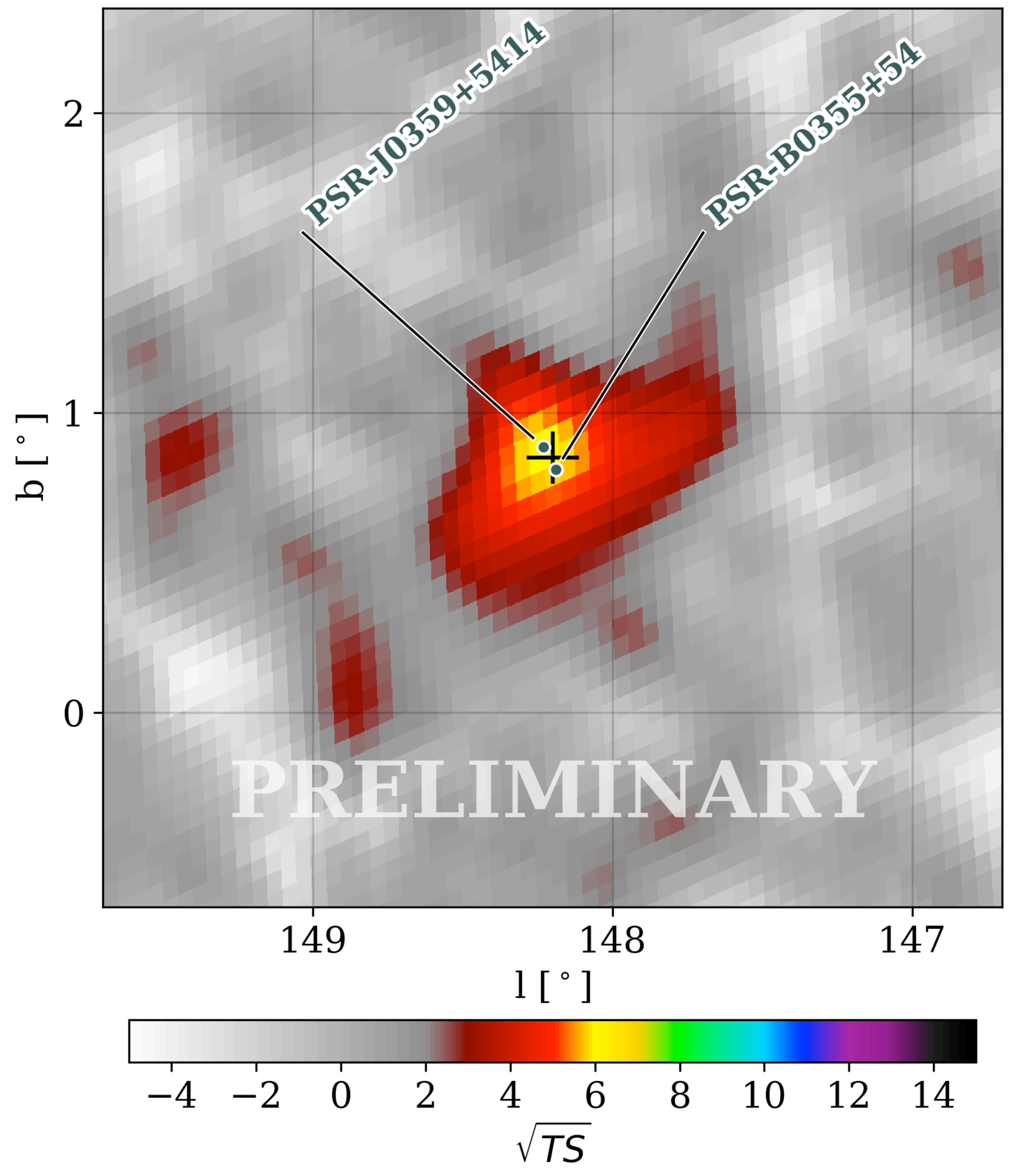
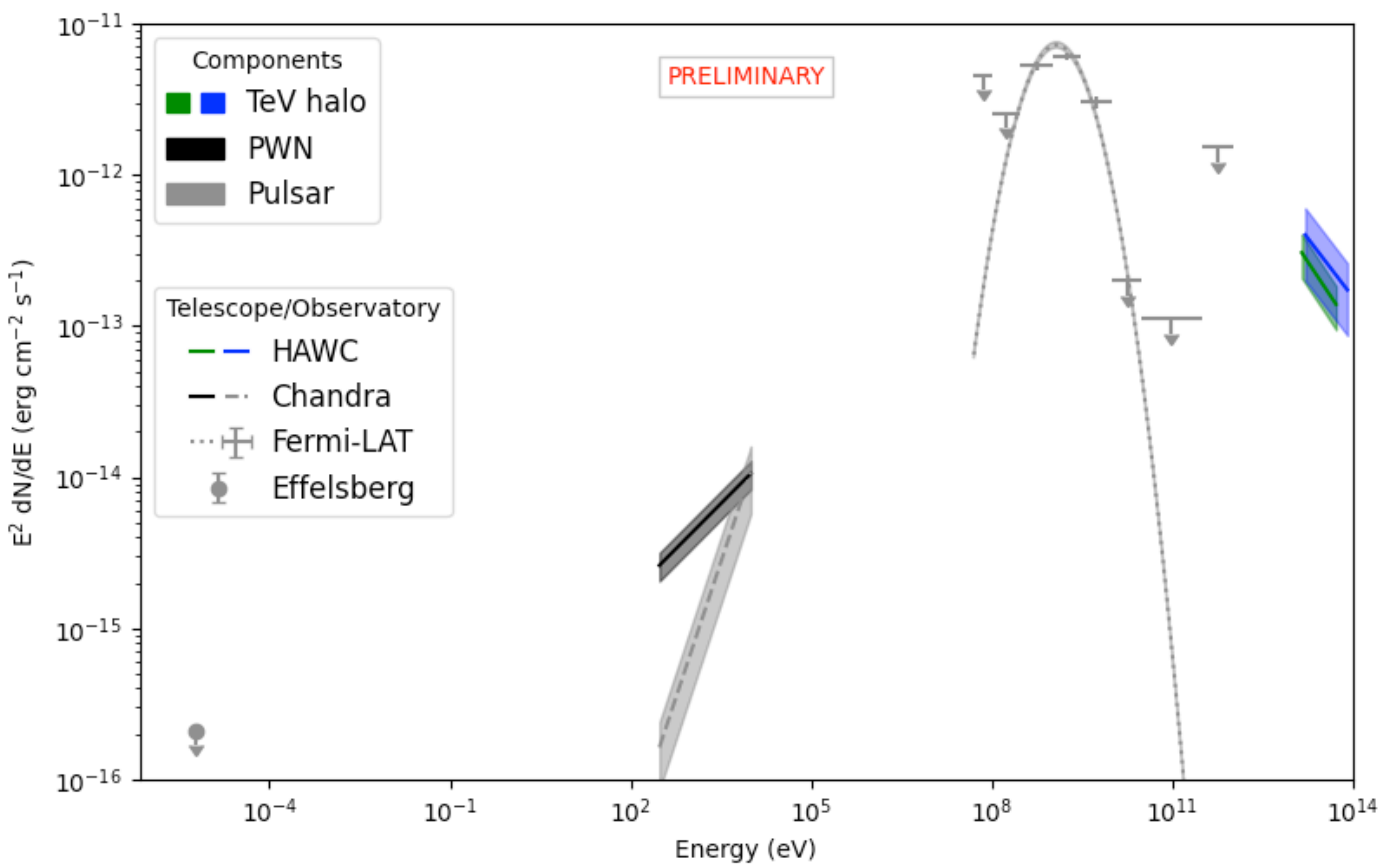


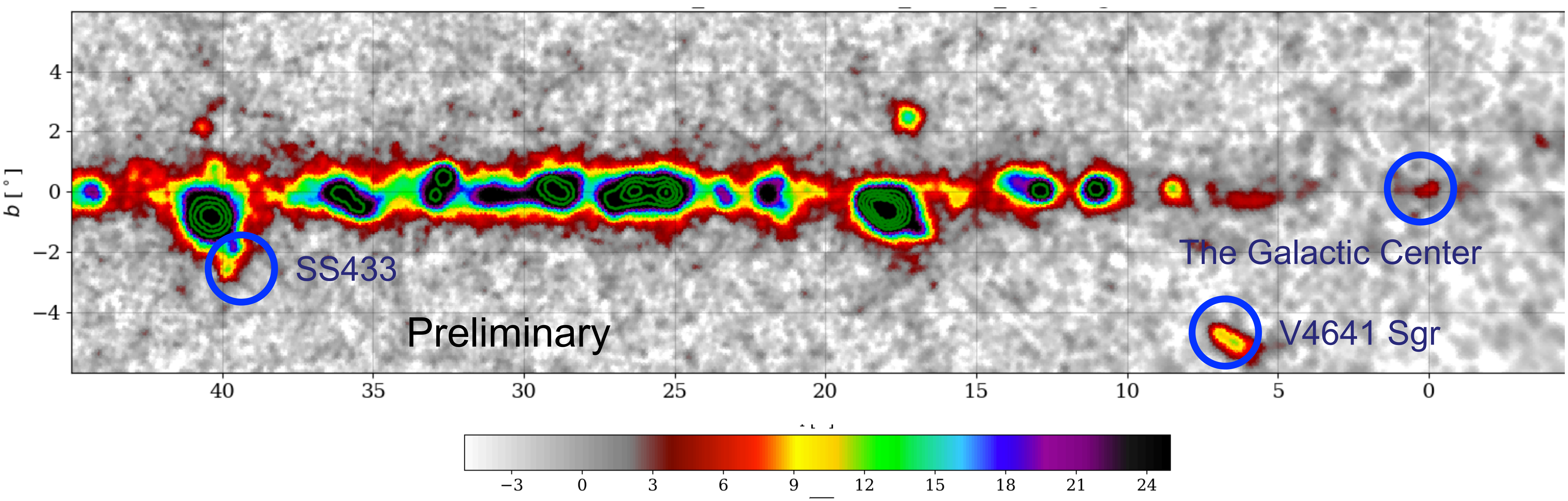
Figure: The purple band shows the contamination of neighboring pulsar.

PWN Halos - PSR J0359+5414

- PSR J0359+5414 - Newly discovered TeV Halo
- Outer galaxy, isolated
- Age = 75kyr
- High Spin-down power: 10^{36} ergs/s

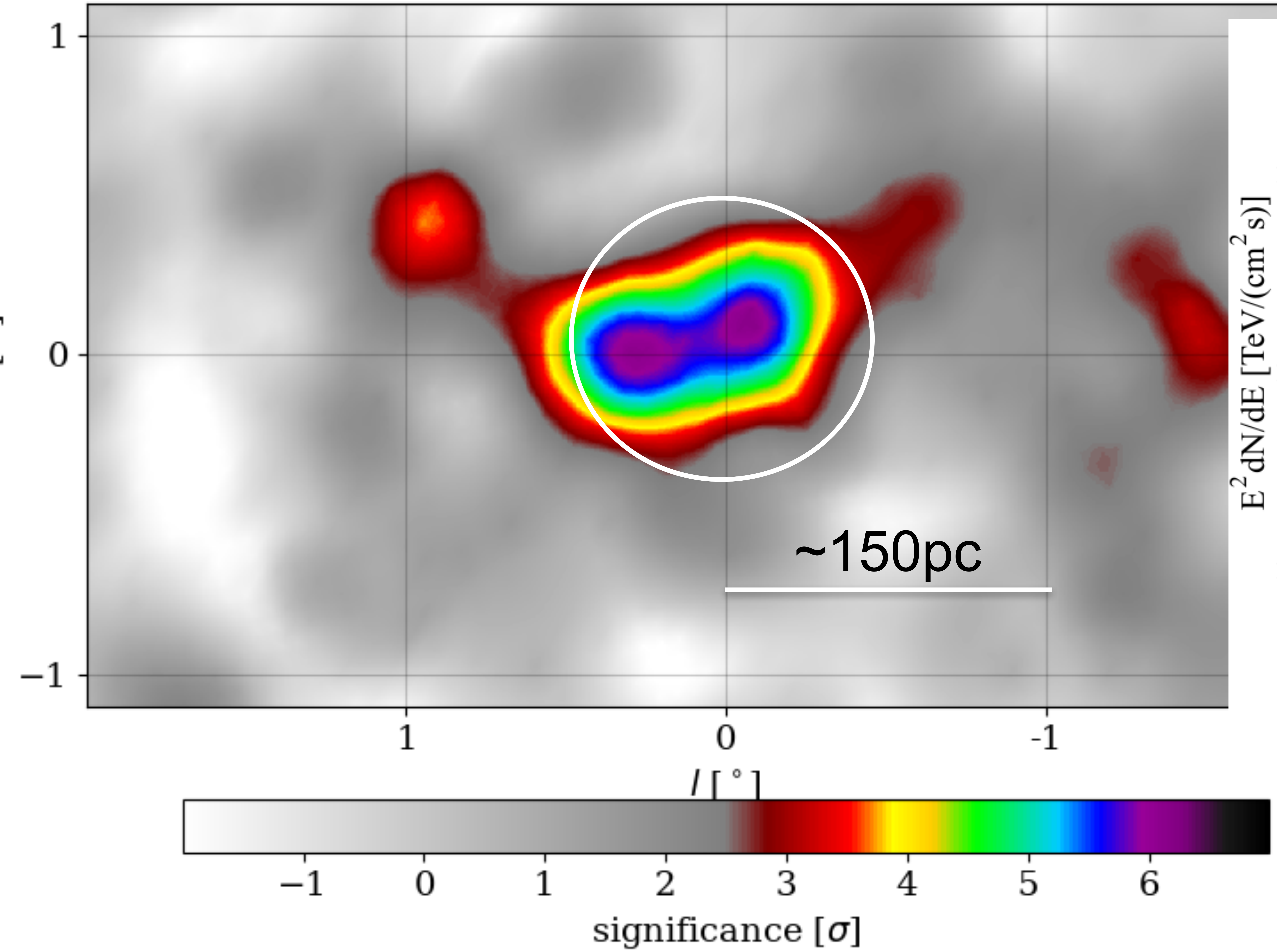


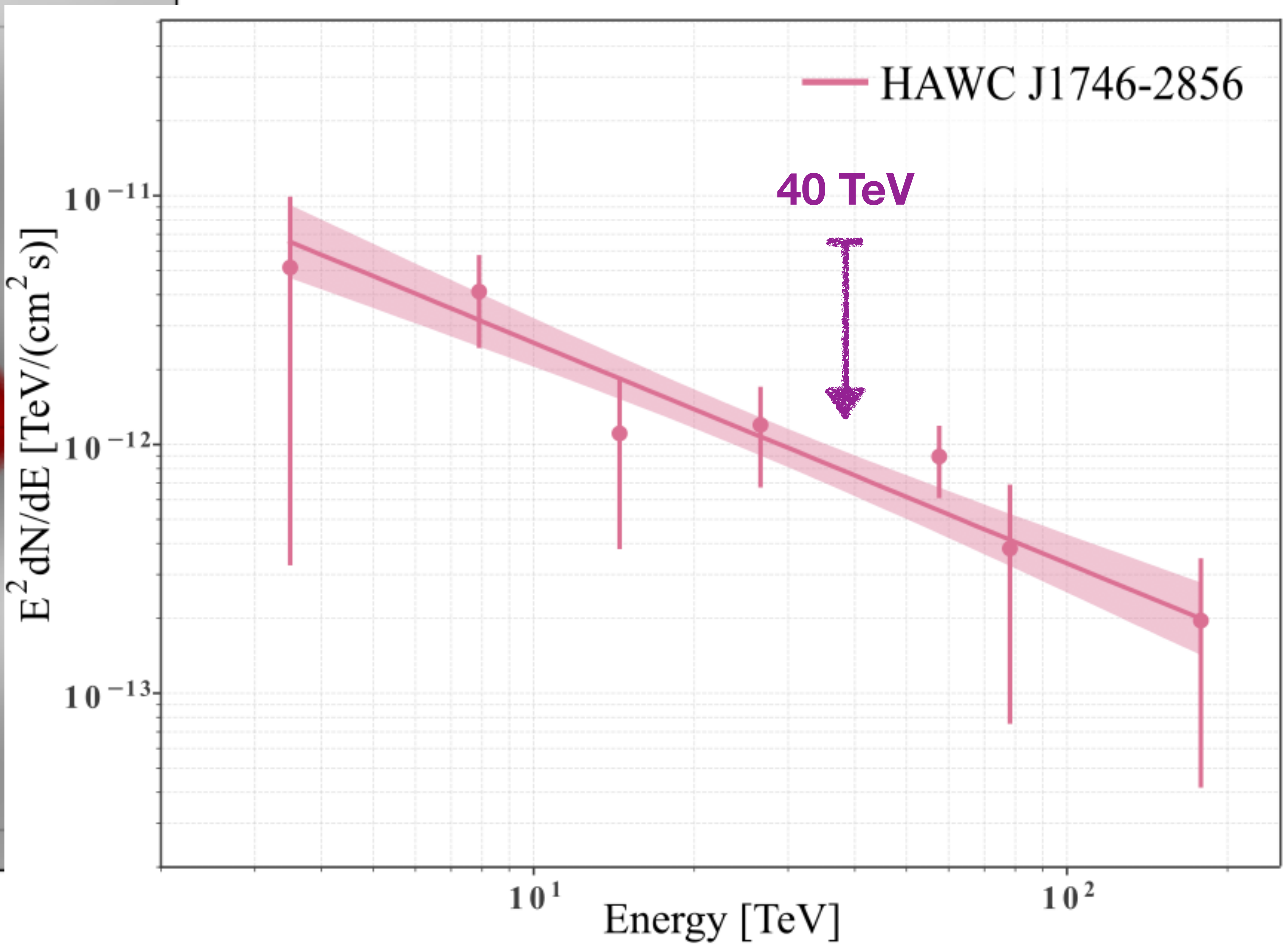




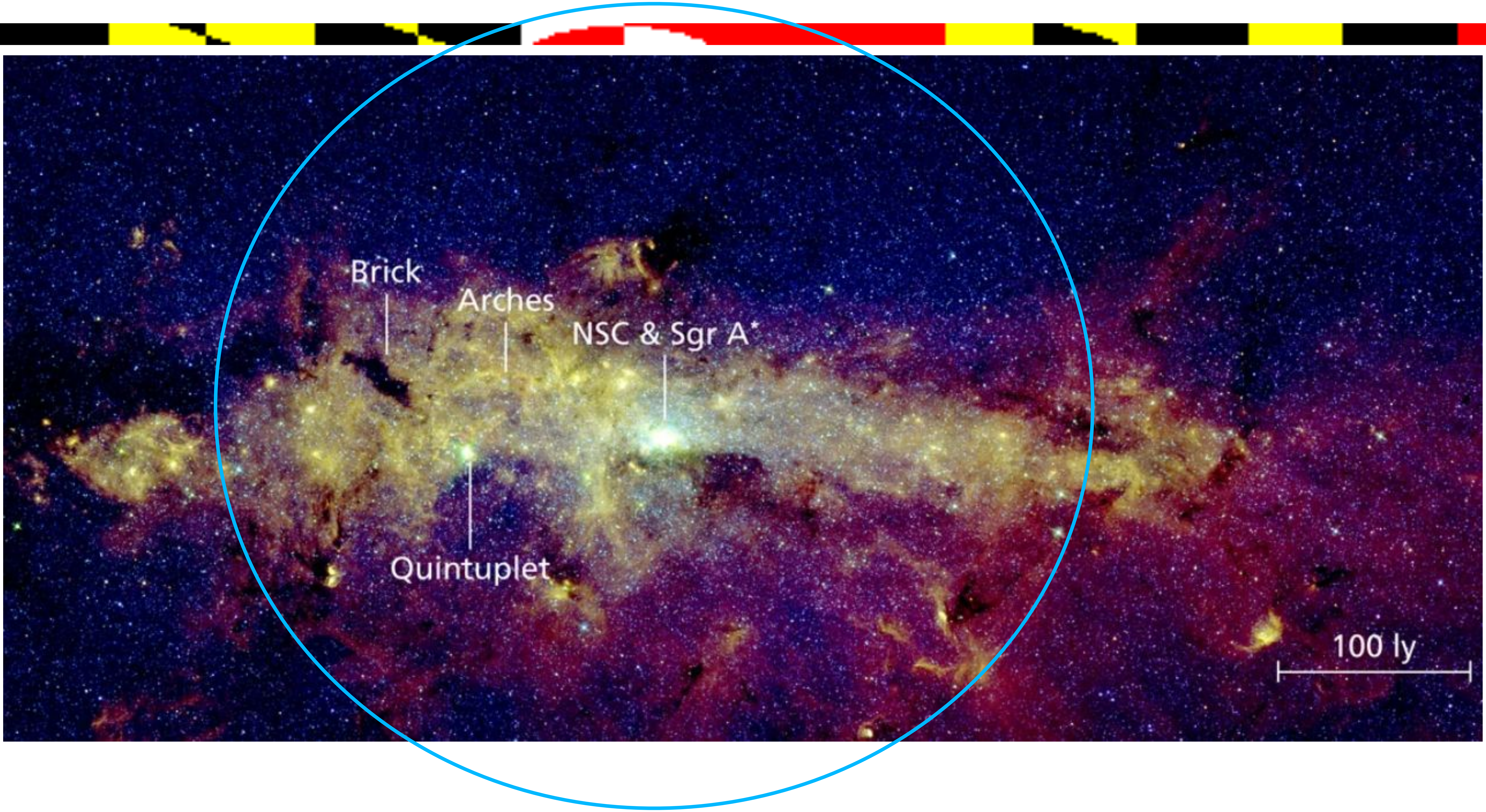
SS433
Preliminary
The Galactic Center
V4641 Sgr
b [°]

The Galactic Center

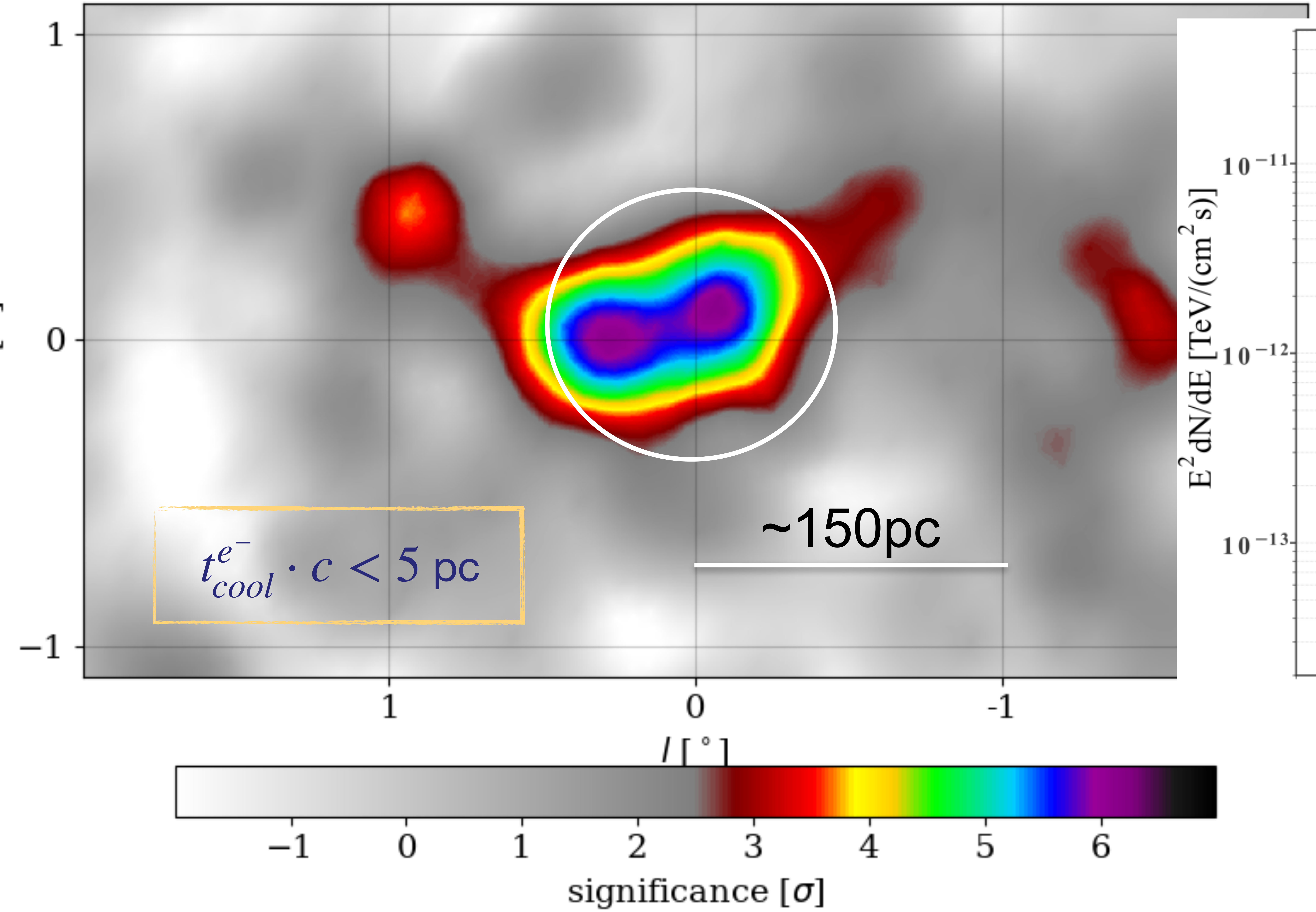


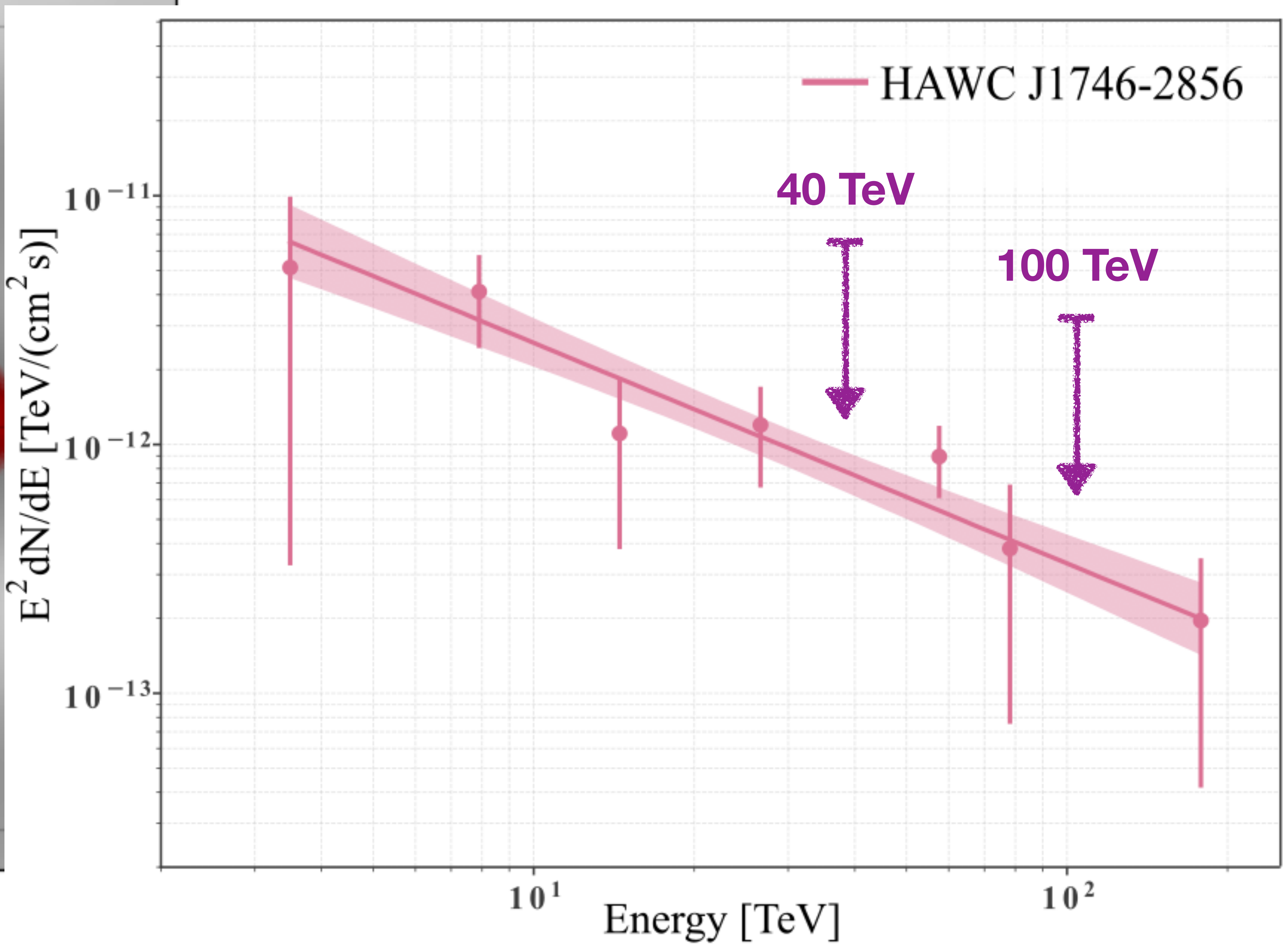


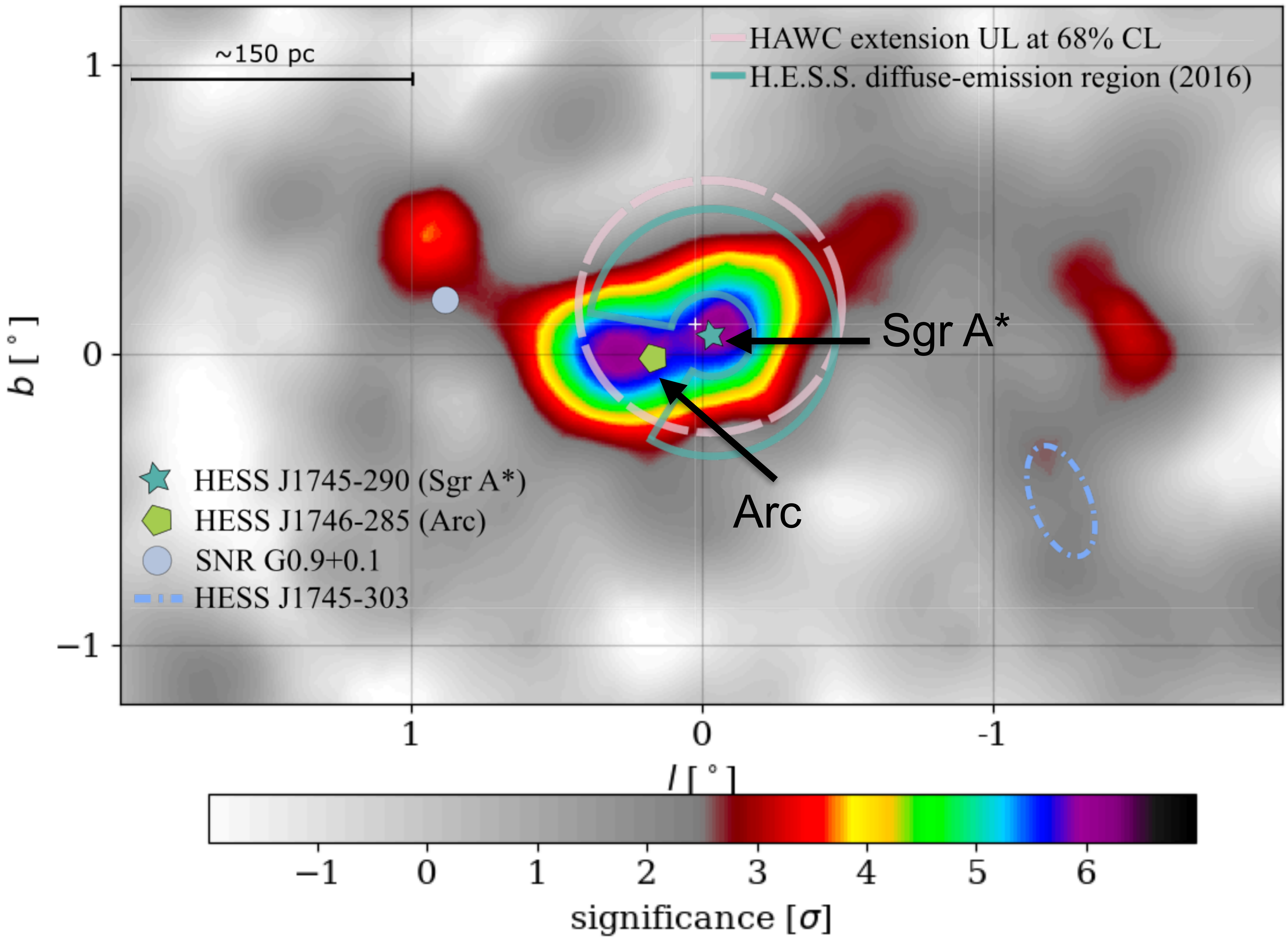
The Galactic Center



The Galactic Center



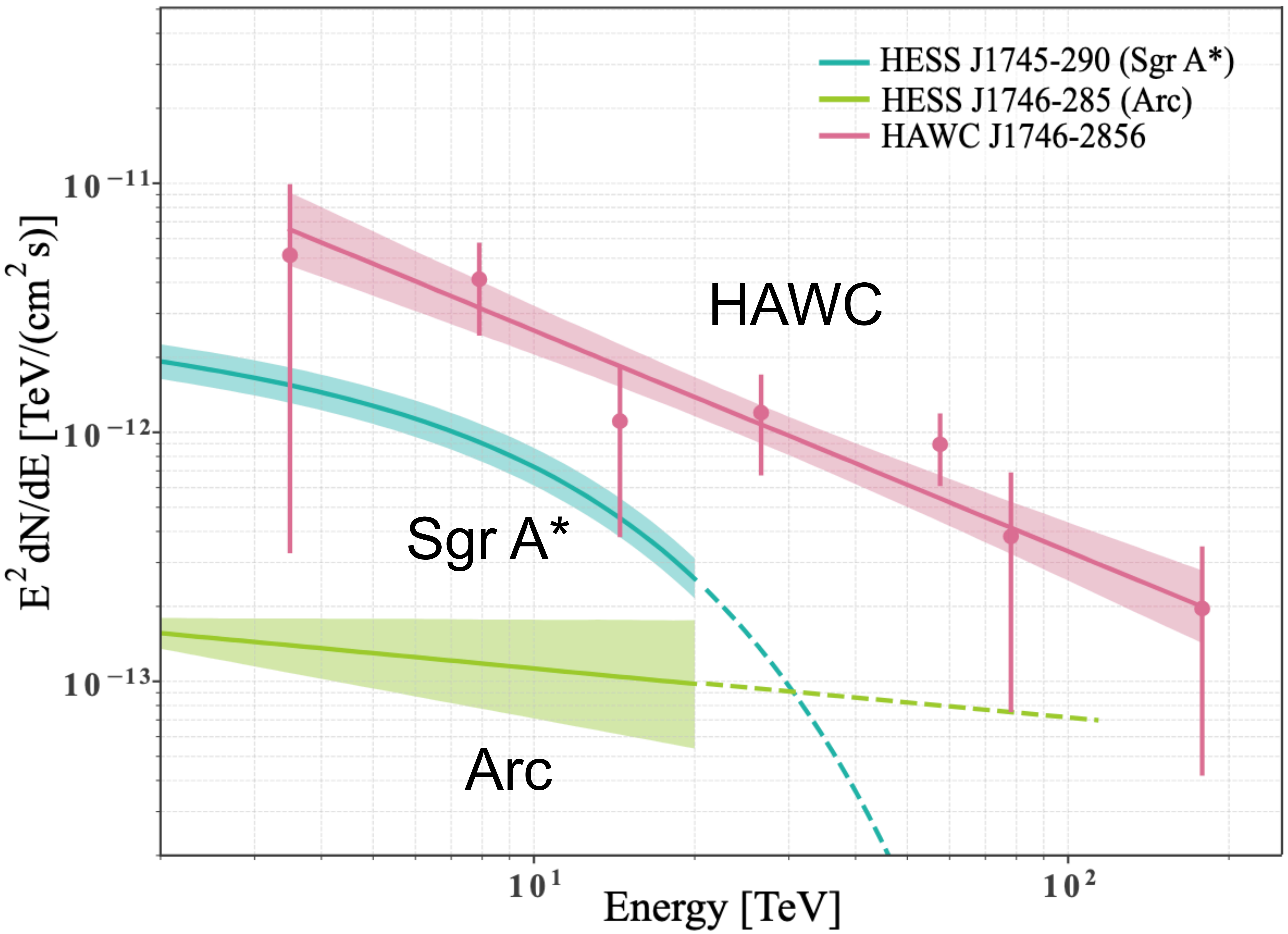




~150 pc
HAWC extension UL at 68% CL
H.E.S.S. diffuse-emission region (2016)
Sgr A*
Arc
HESS J1745-290 (Sgr A*)
HESS J1746-285 (Arc)
SNR G0.9+0.1
HESS J1745-303
b [°]
l [°]
1
0
−1
1
0
-1
−1
0
1
2
3
4
5
6
significance [σ]

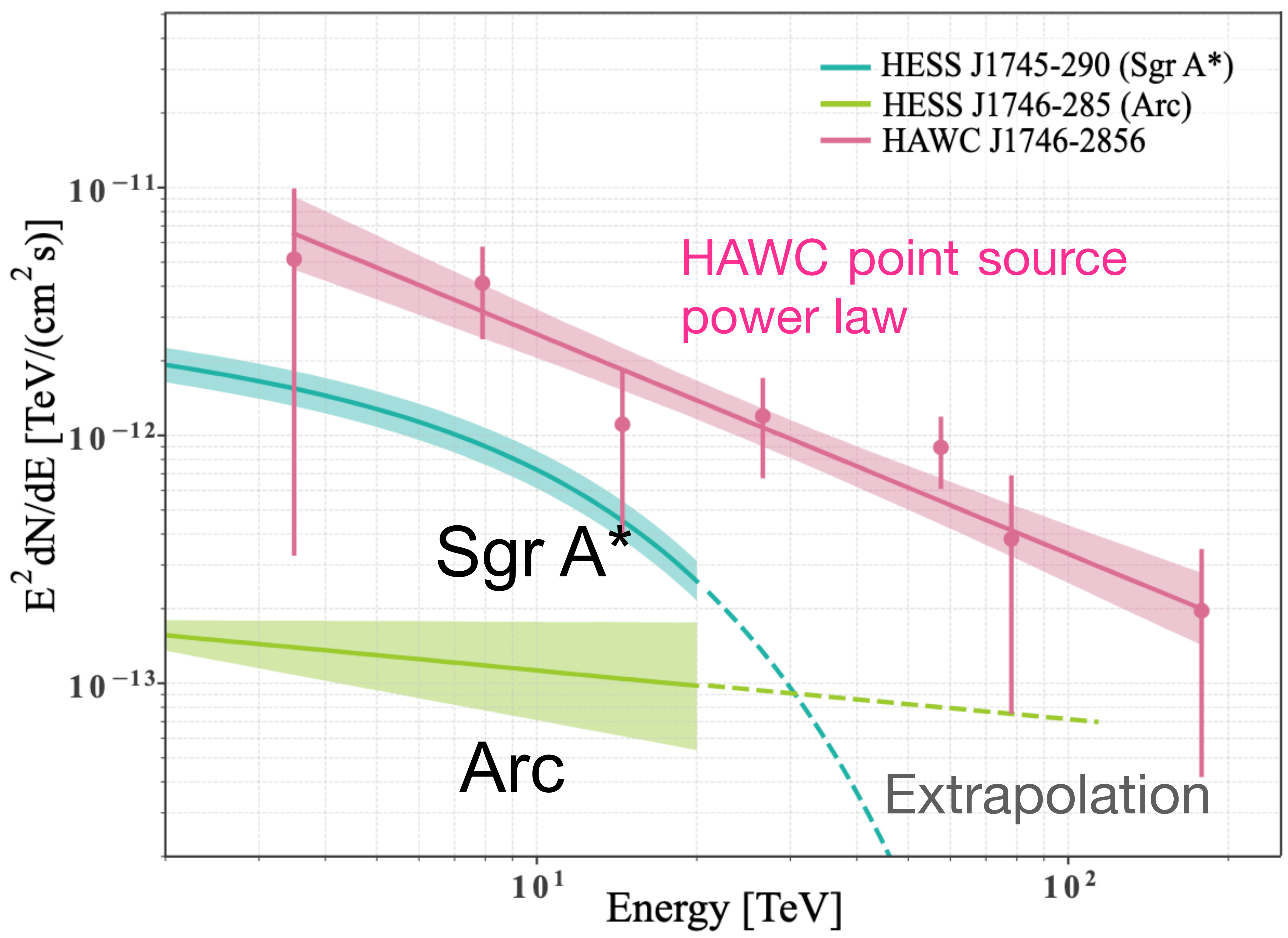
HAWC observation and modeling

HAWC cannot resolve H.E.S.S. point sources

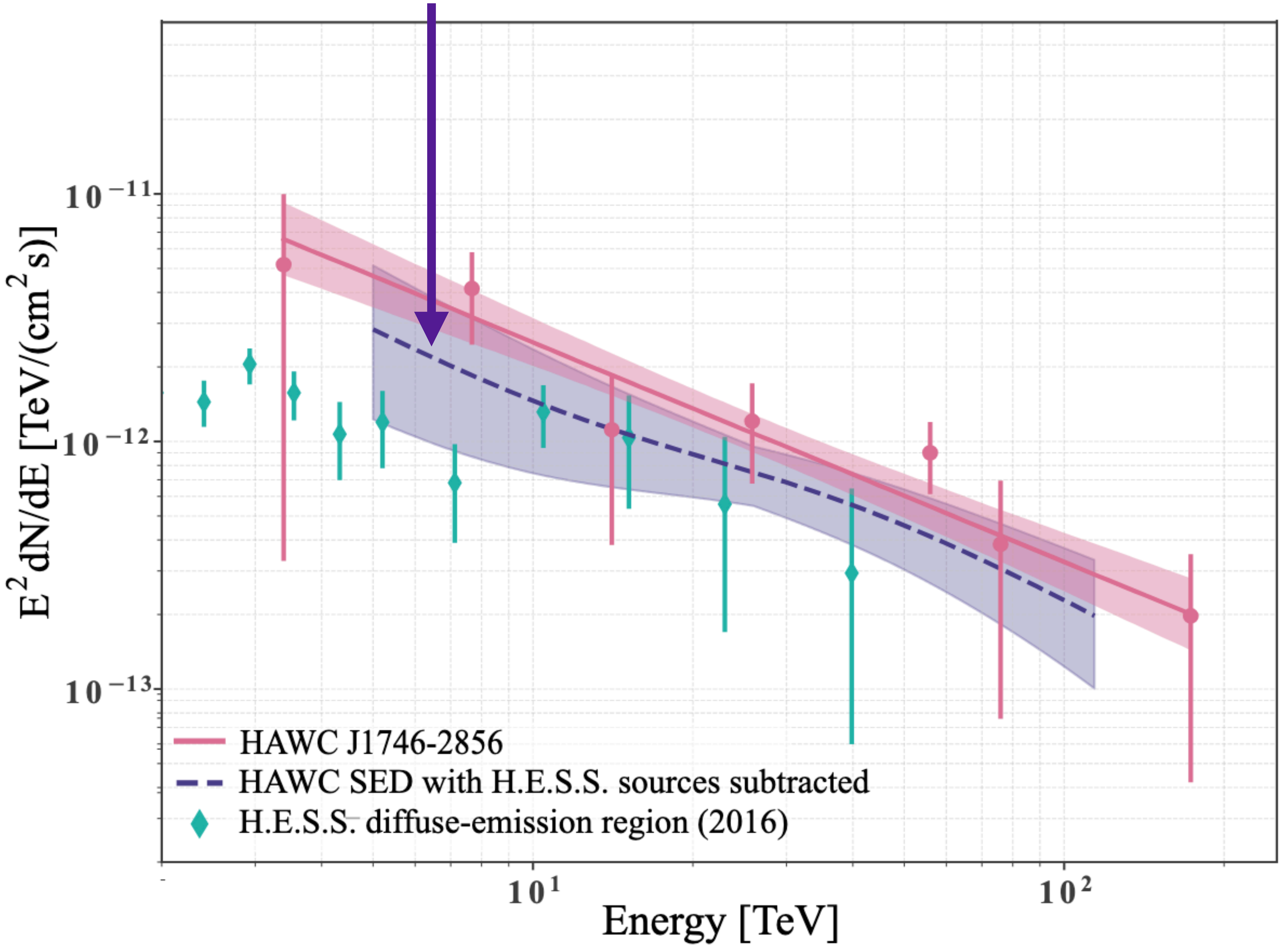


HAWC observation and modeling

HAWC cannot resolve H.E.S.S. point sources

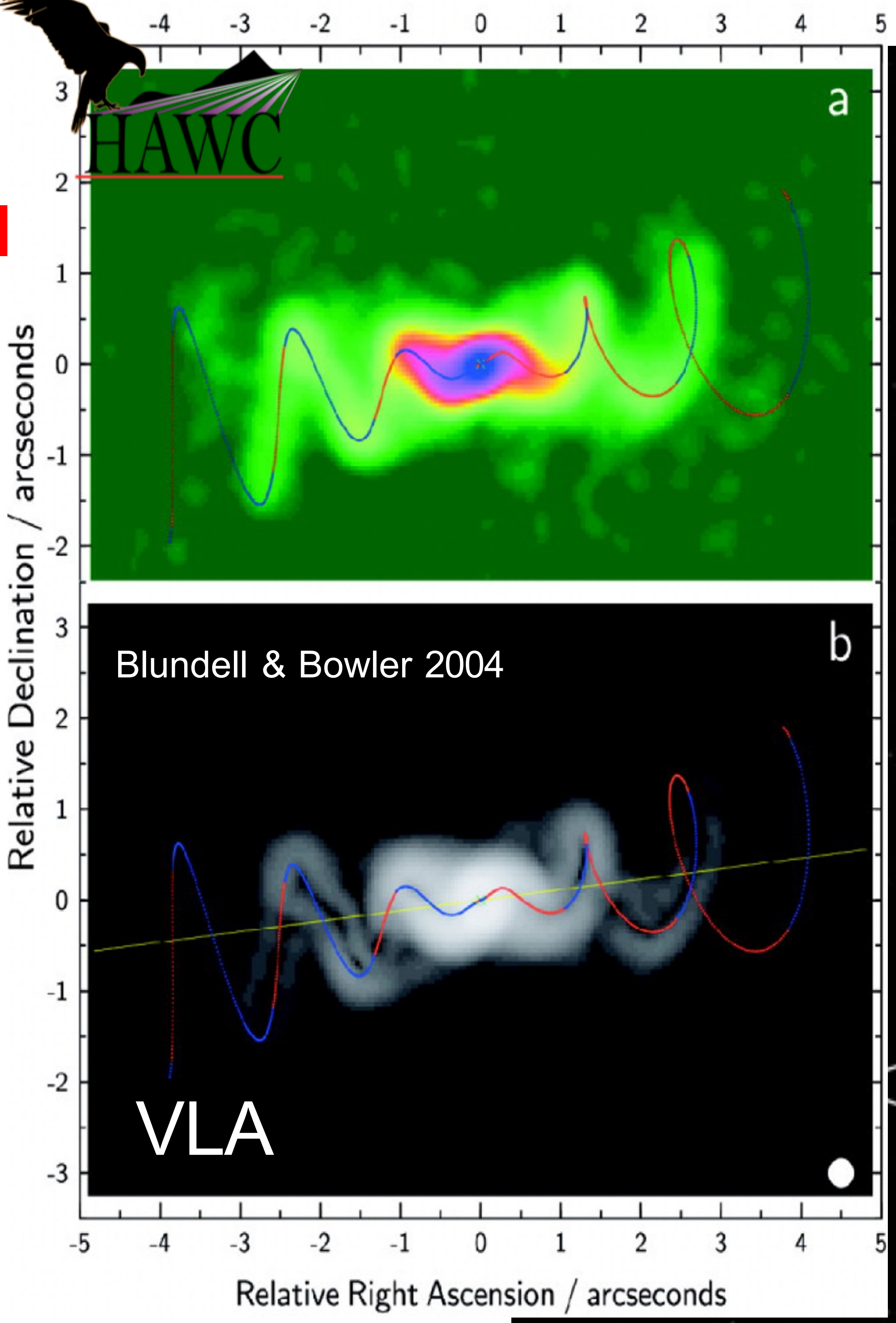


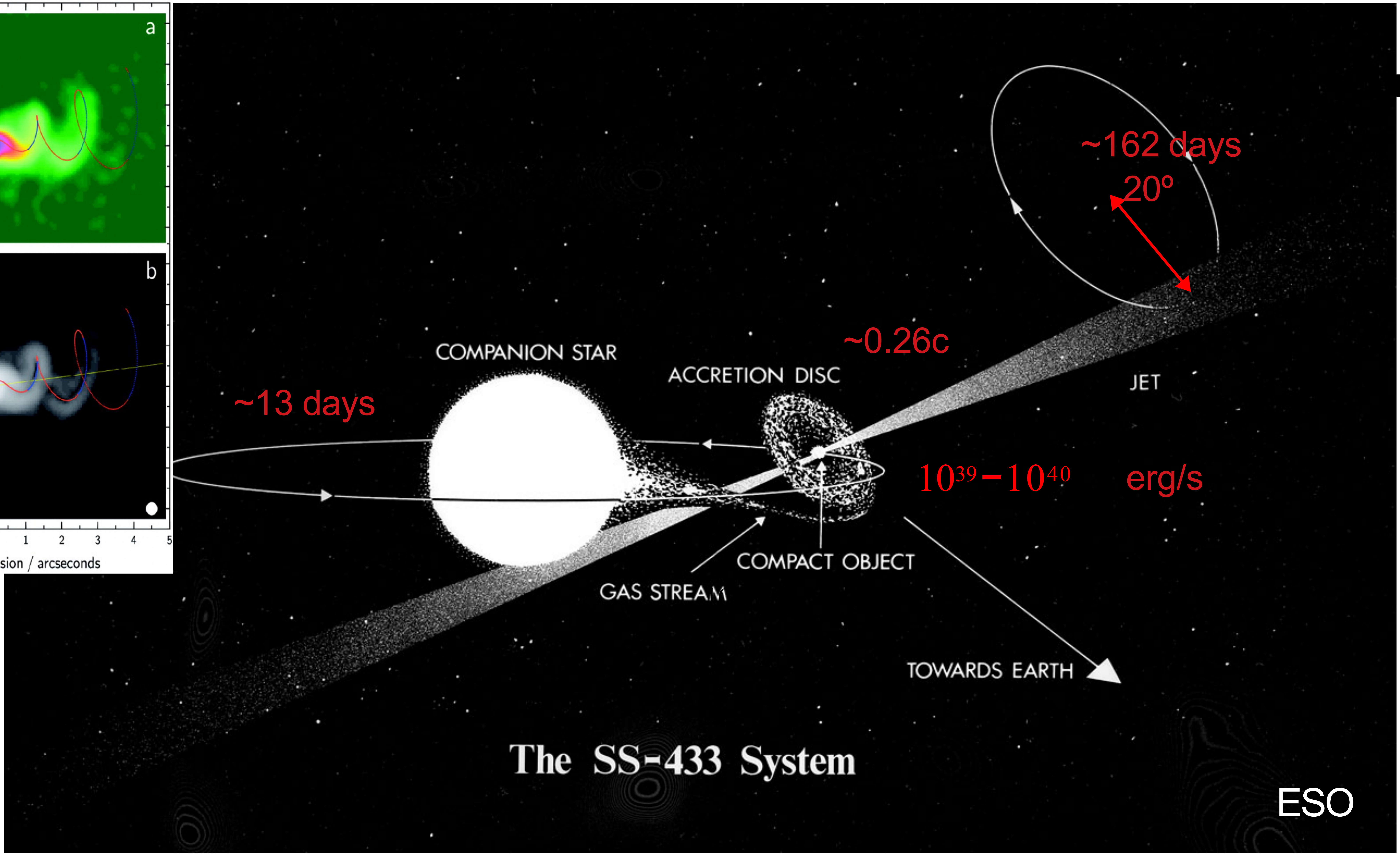
HAWC power law with H.E.S.S. sources subtracted.



Microquasars

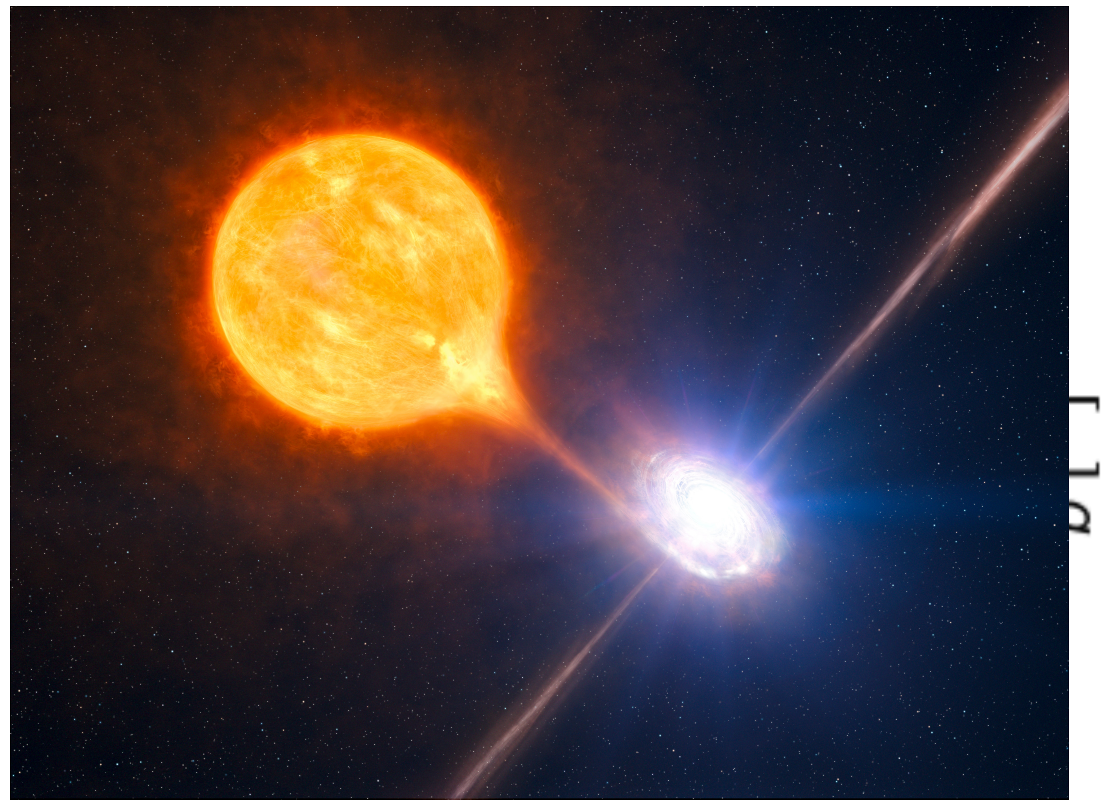
Possible an A-type supergiant and a very extended disk around a black hole.

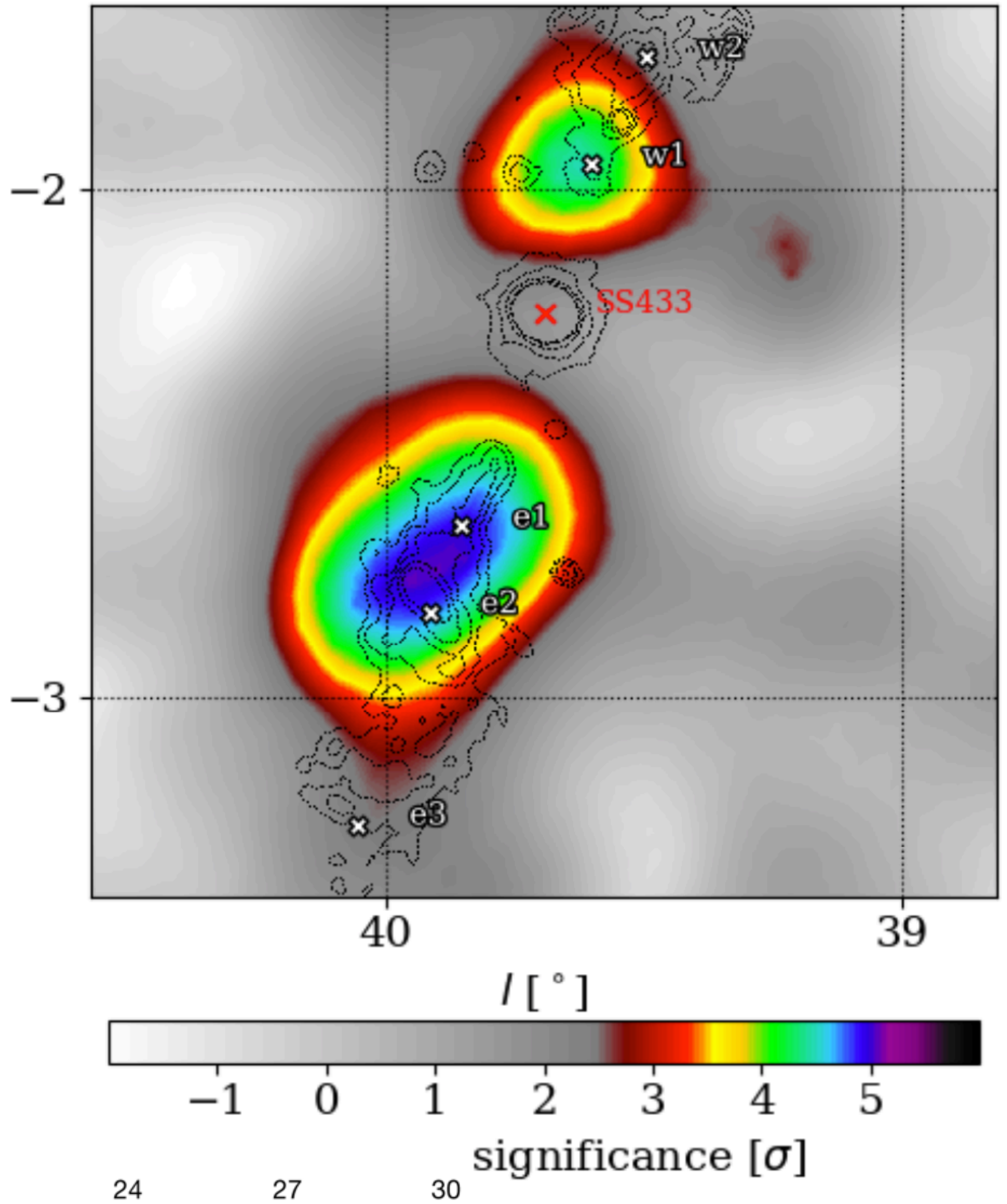

HAWC
a
b
Blundell & Bowler 2004
VLA
Relative Declination / arcseconds
Relative Right Ascension / arcseconds

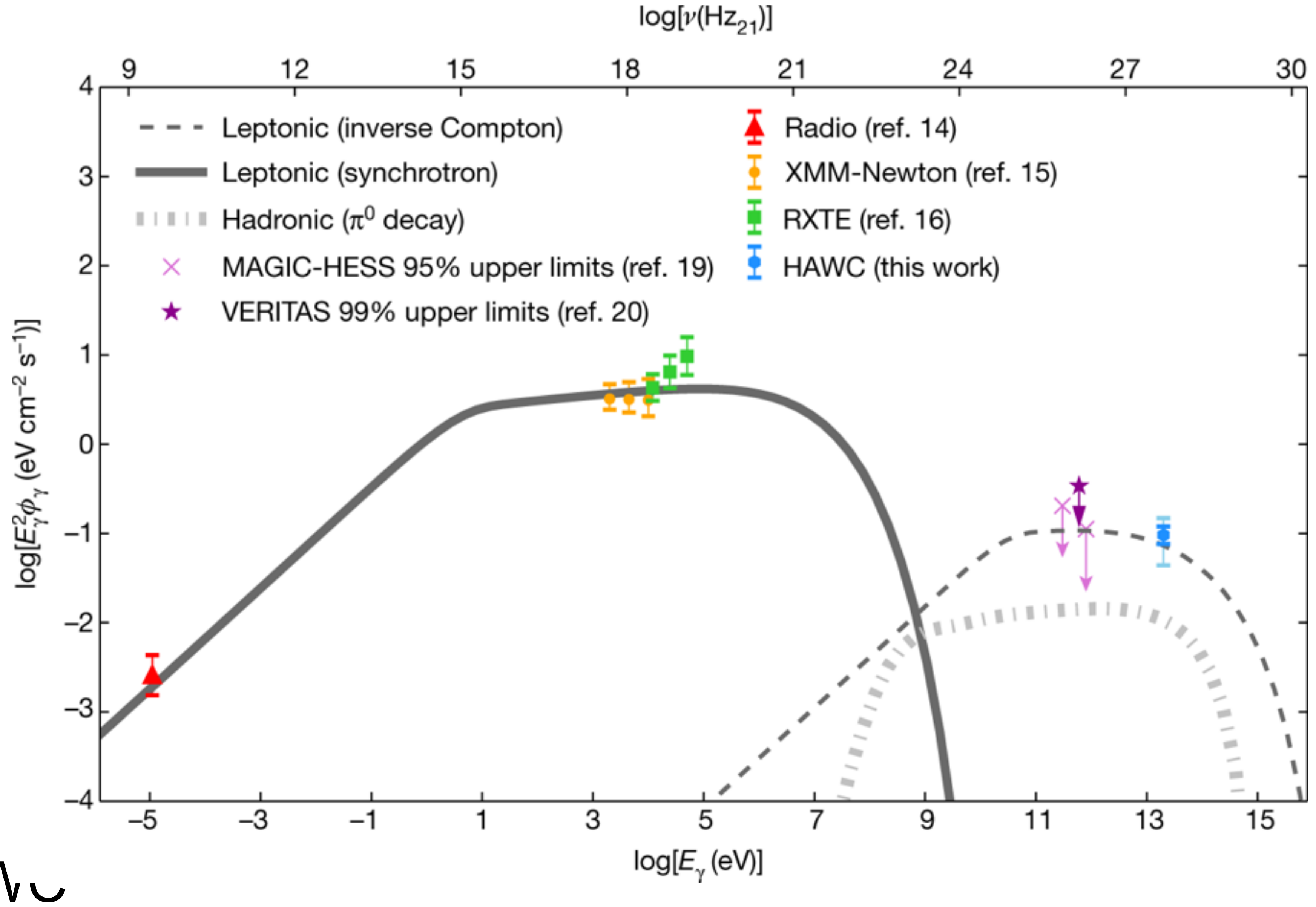

~162 days
20º
~0.26c
COMPANION STAR
ACCRETION DISC
JET
~13 days
$10^{39} - 10^{40}$ erg/s
COMPACT OBJECT
GAS STREAM
TOWARDS EARTH
The SS-433 System
ESO

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)

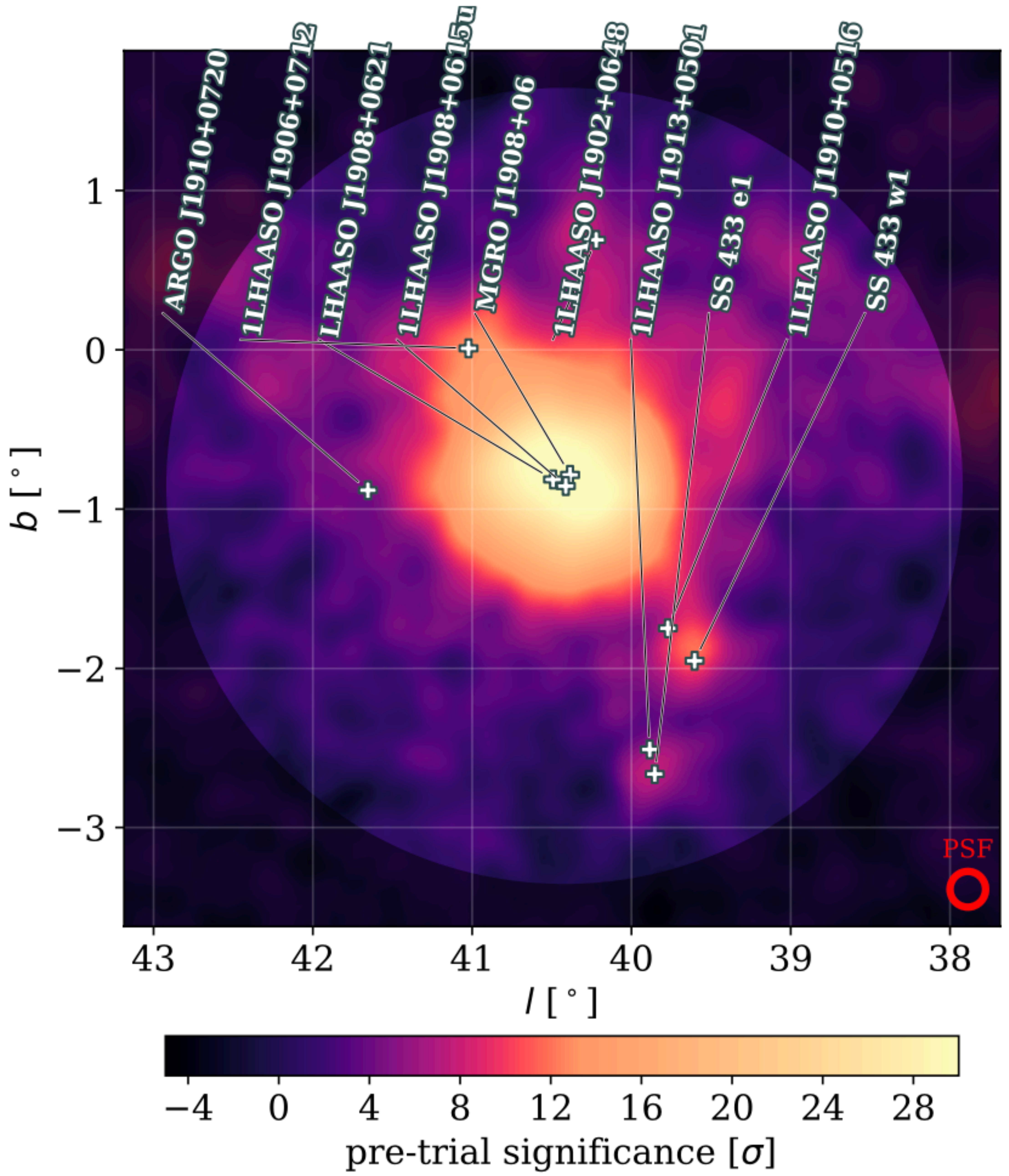


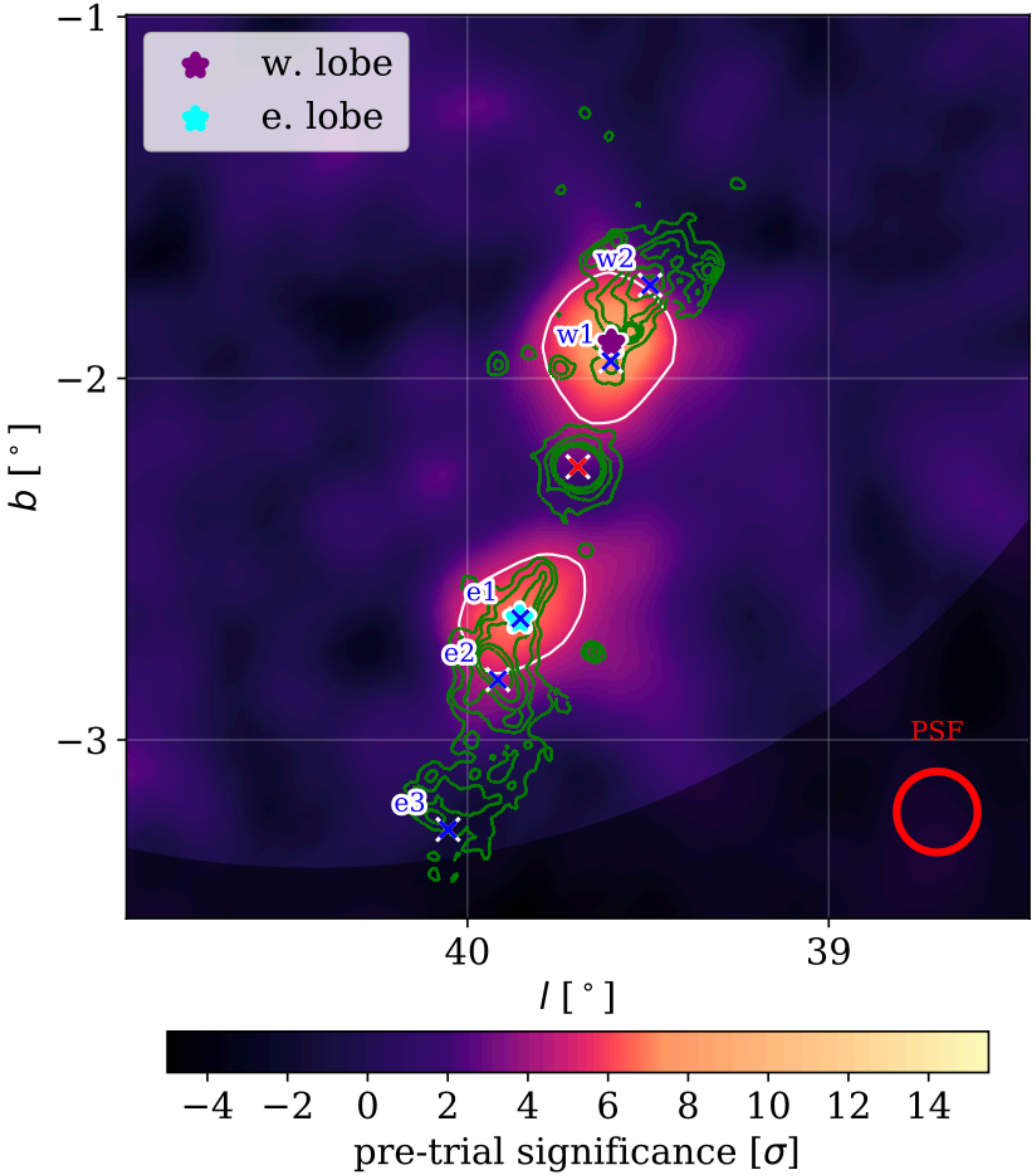




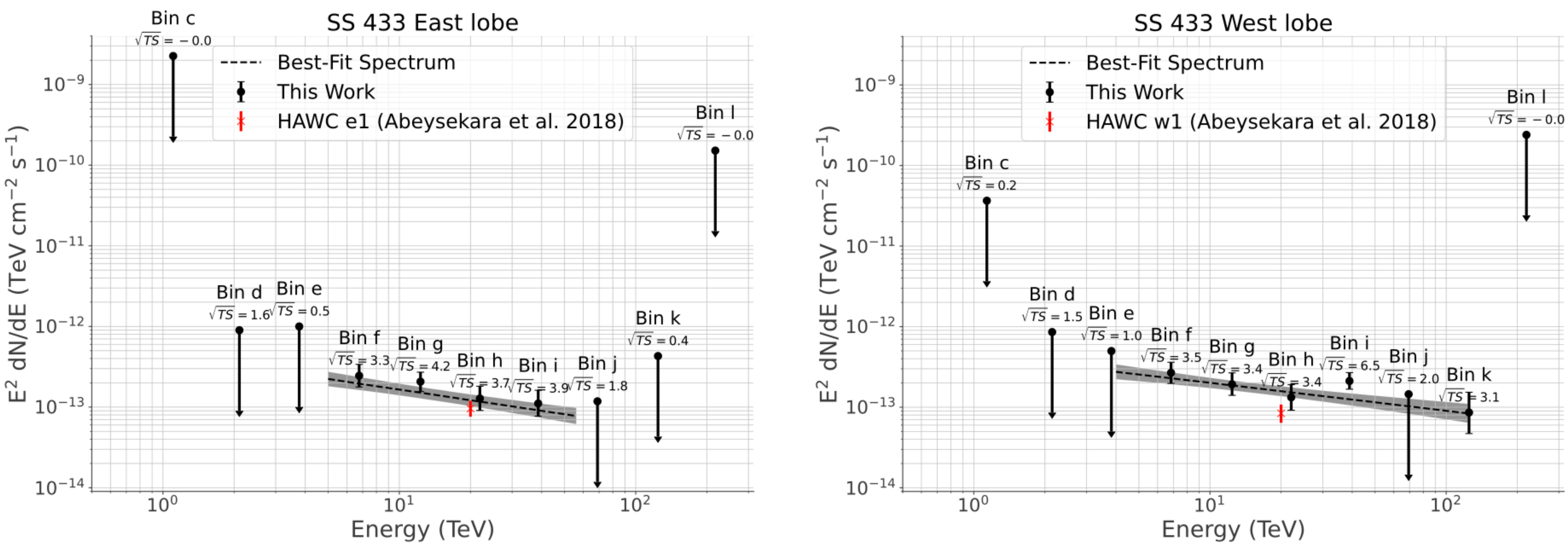
Published in Nature Oct 4, 2018

Updated results

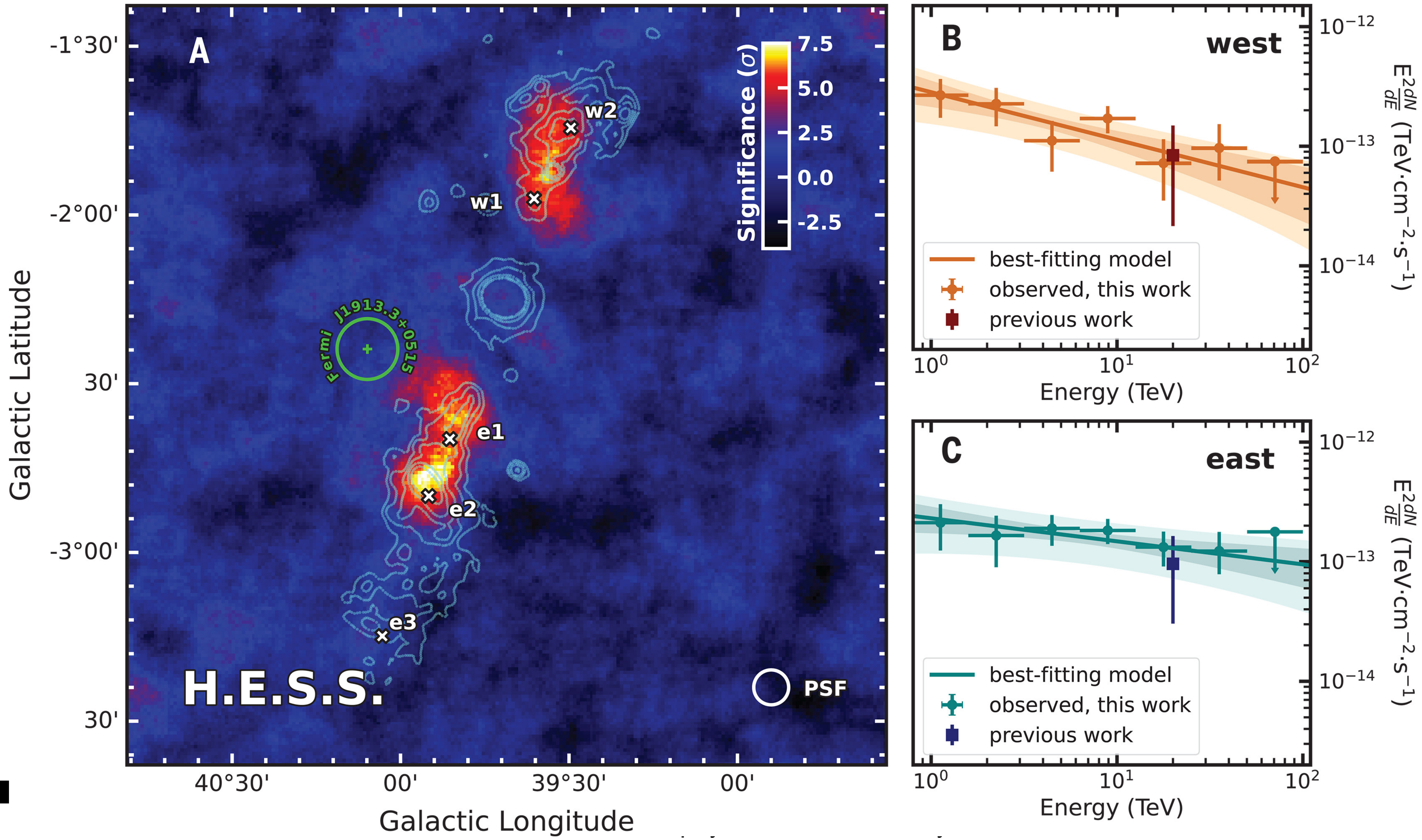


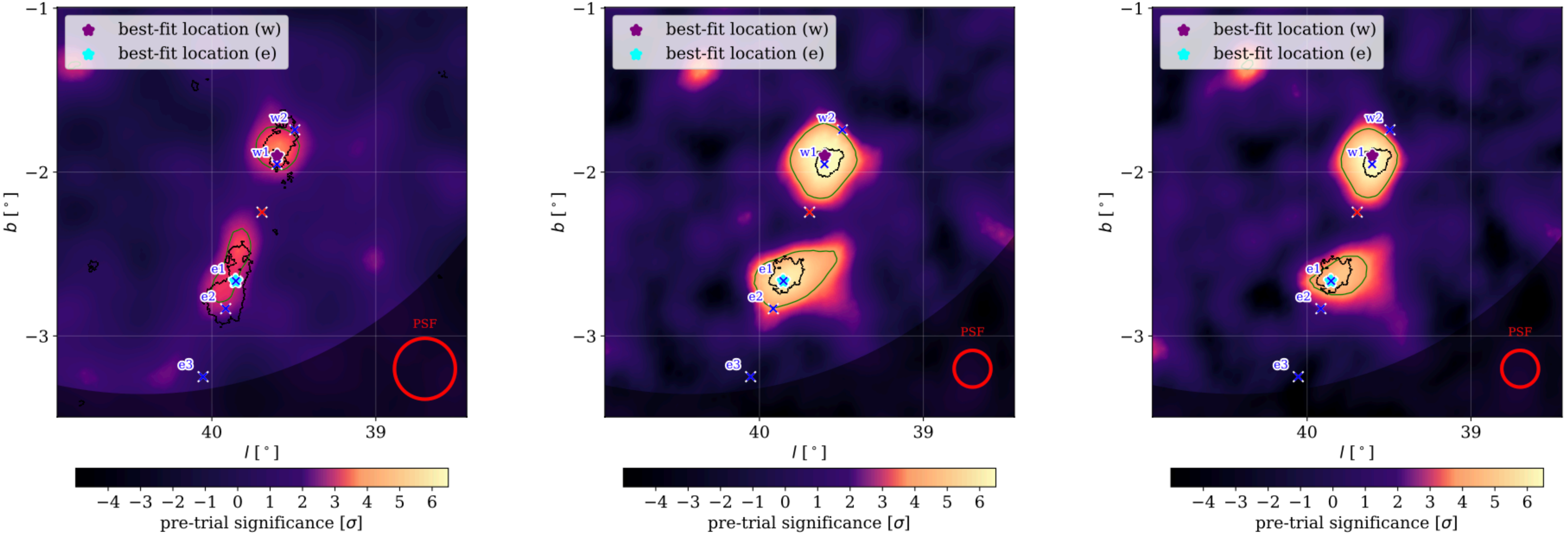


SPECTRAL STUDY OF SS 433

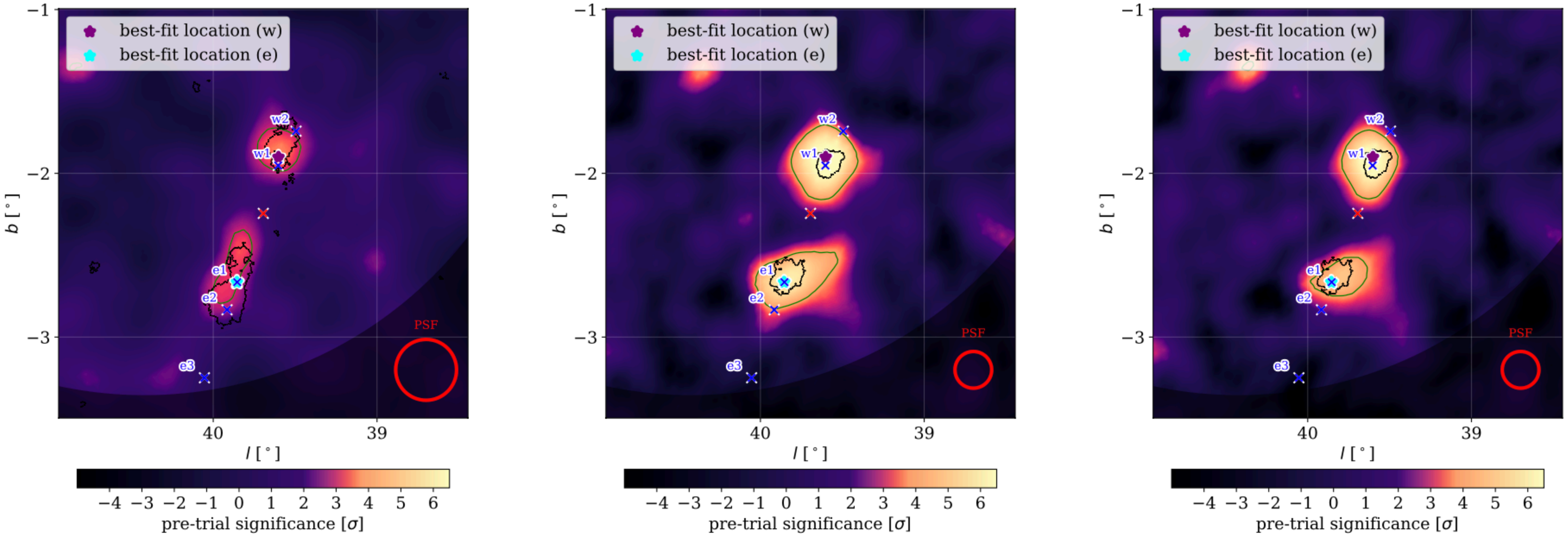


H.E.S.S. Results on SS433



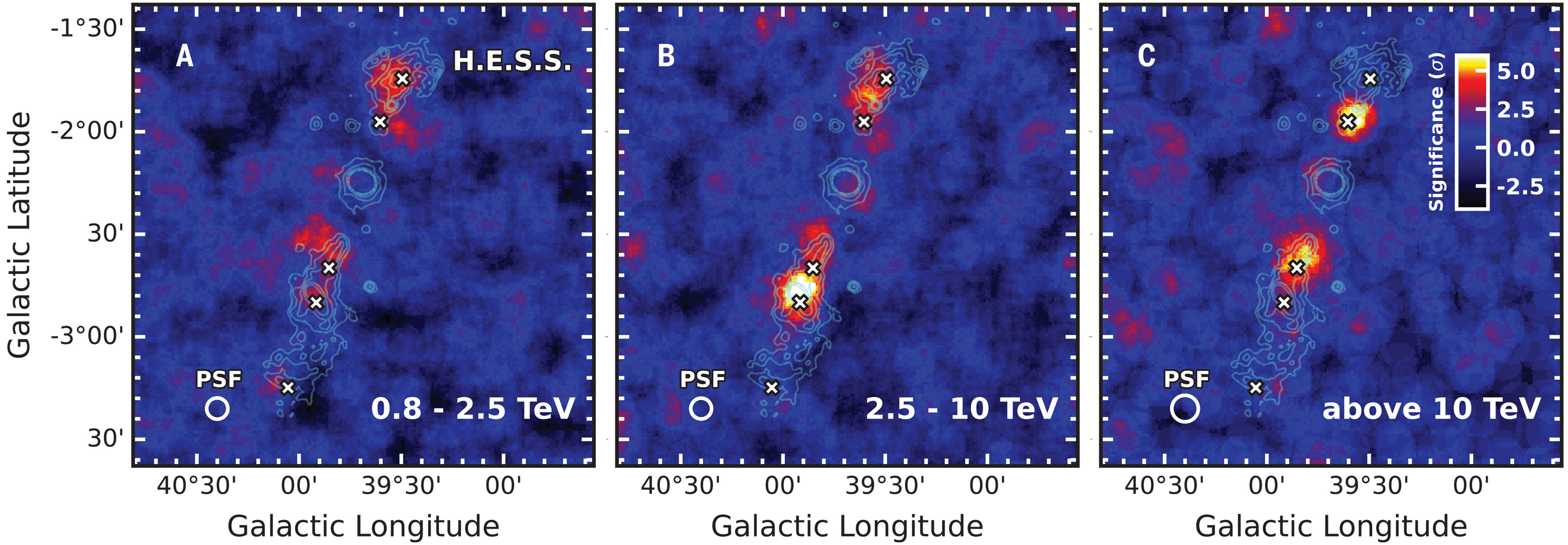


(a) 1 – 10 TeV (b) > 10 TeV (c) > 18 TeV



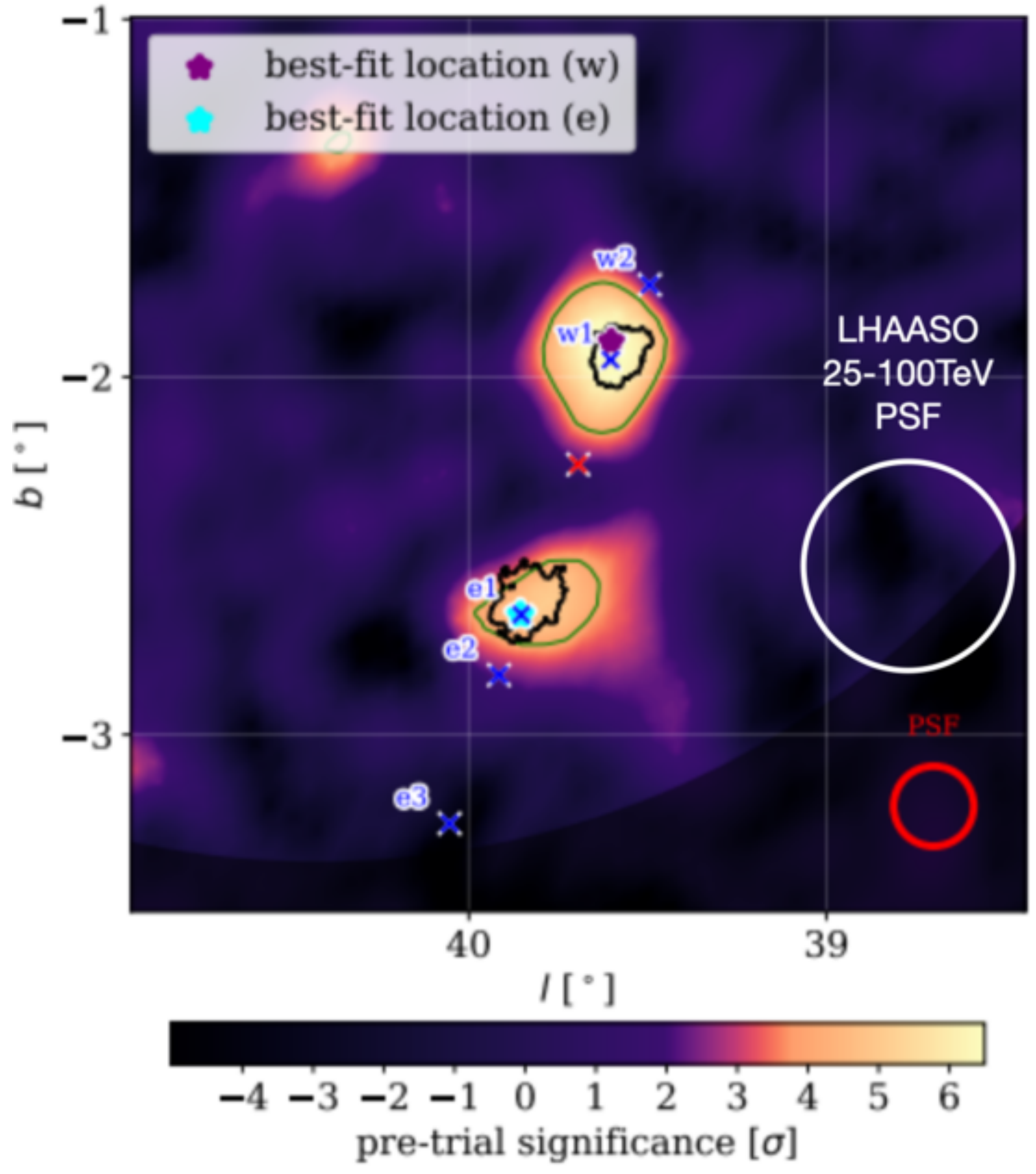
(a) 1 – 10 TeV (b) > 10 TeV (c) > 18 TeV

HAWC

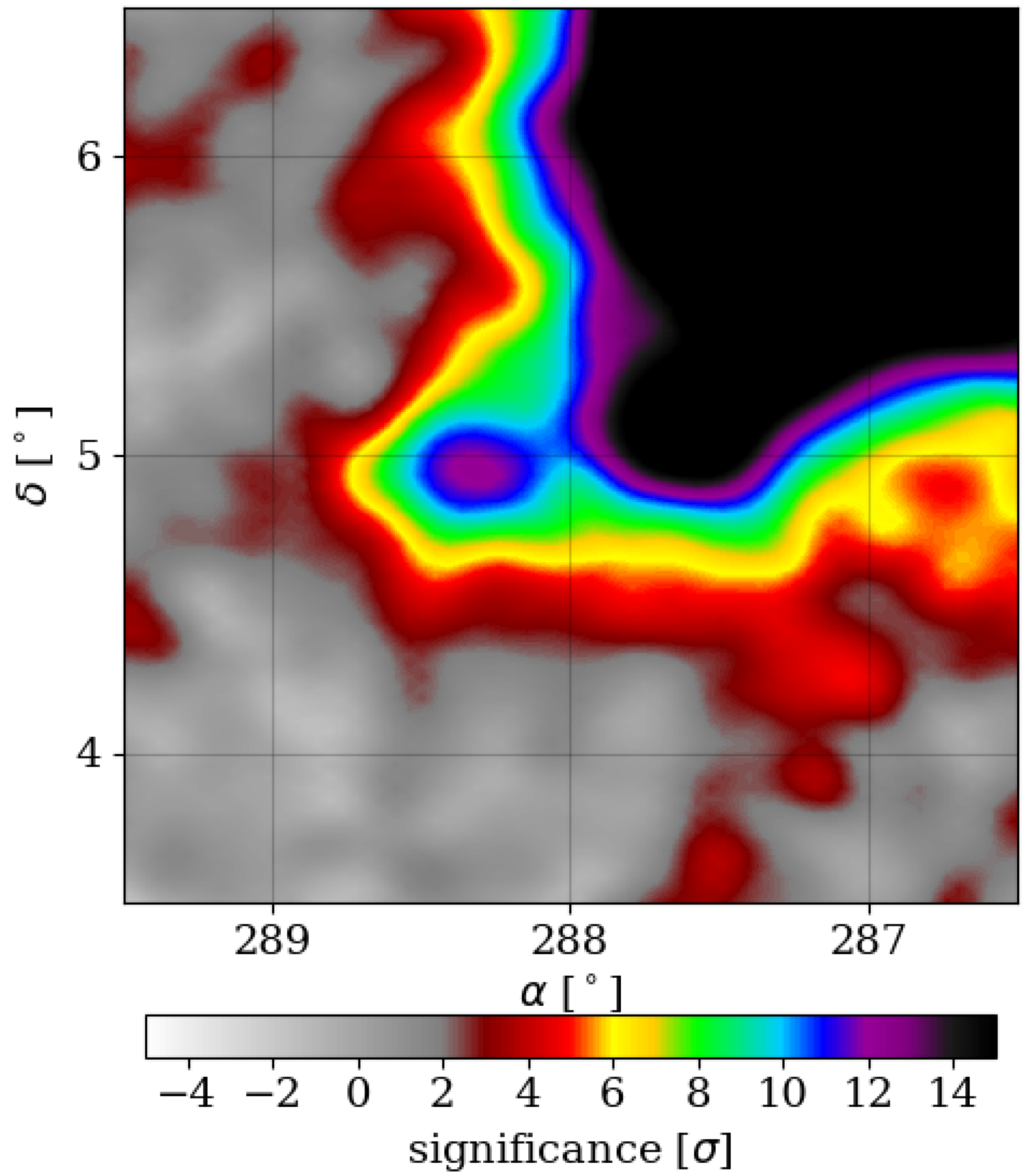


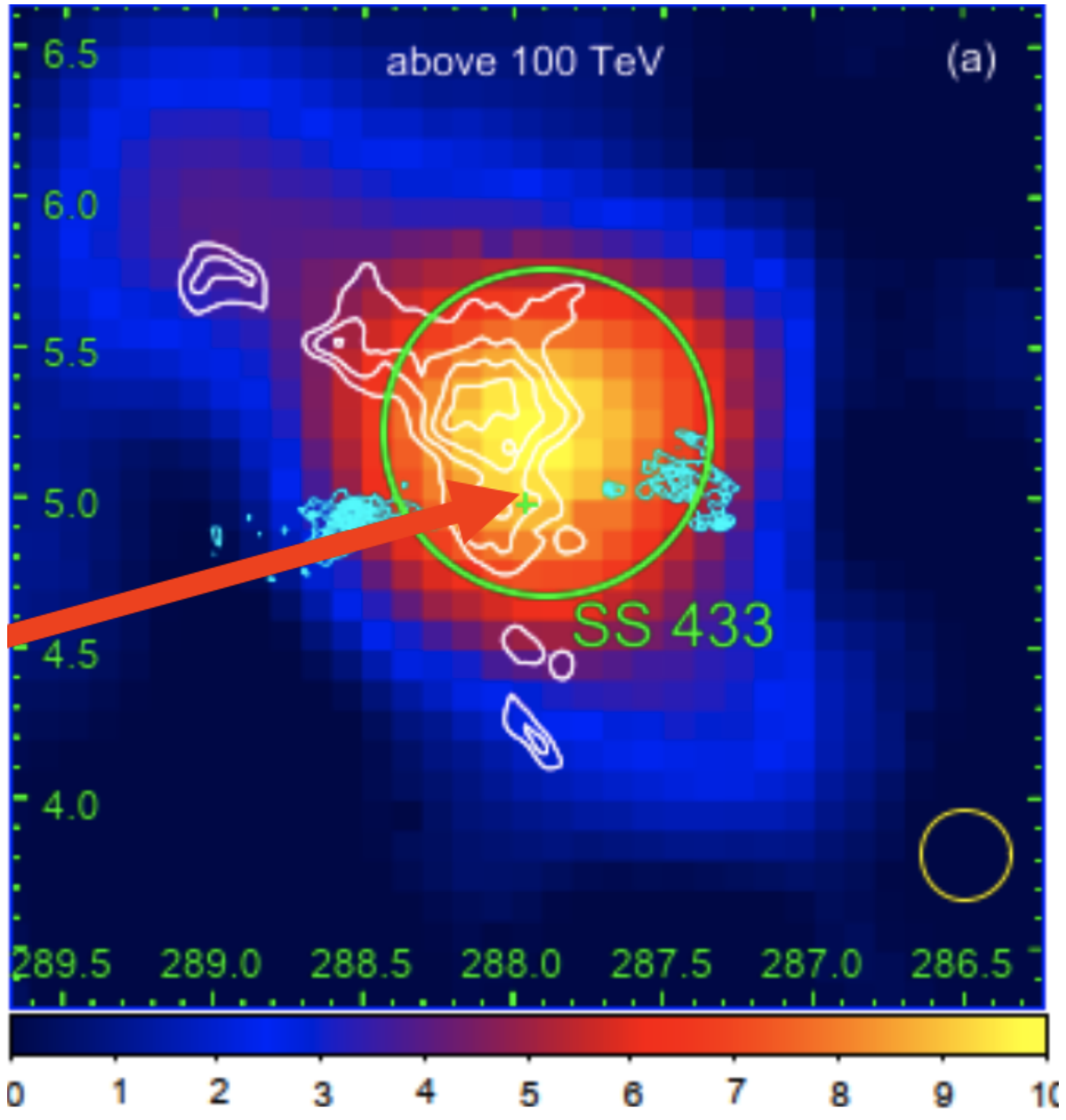
H.E.S.S

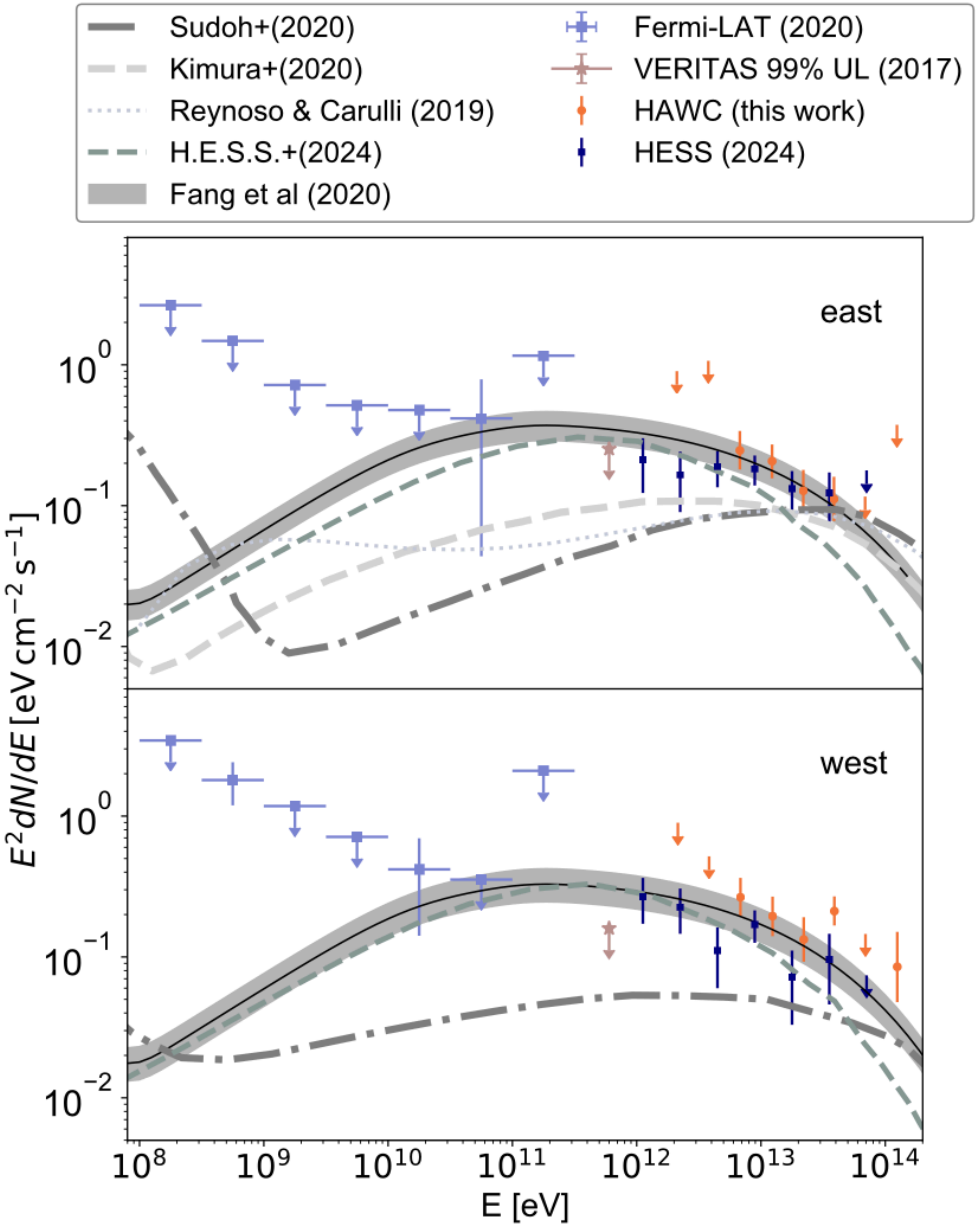
SS 433



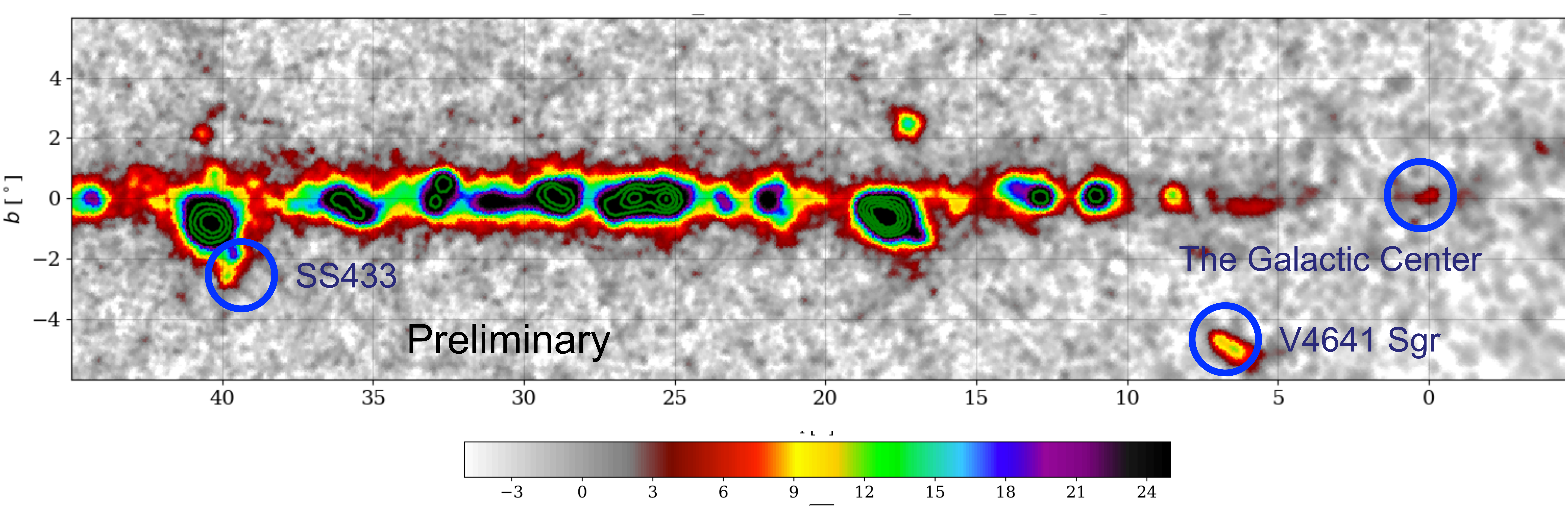
(c) > 18 TeV







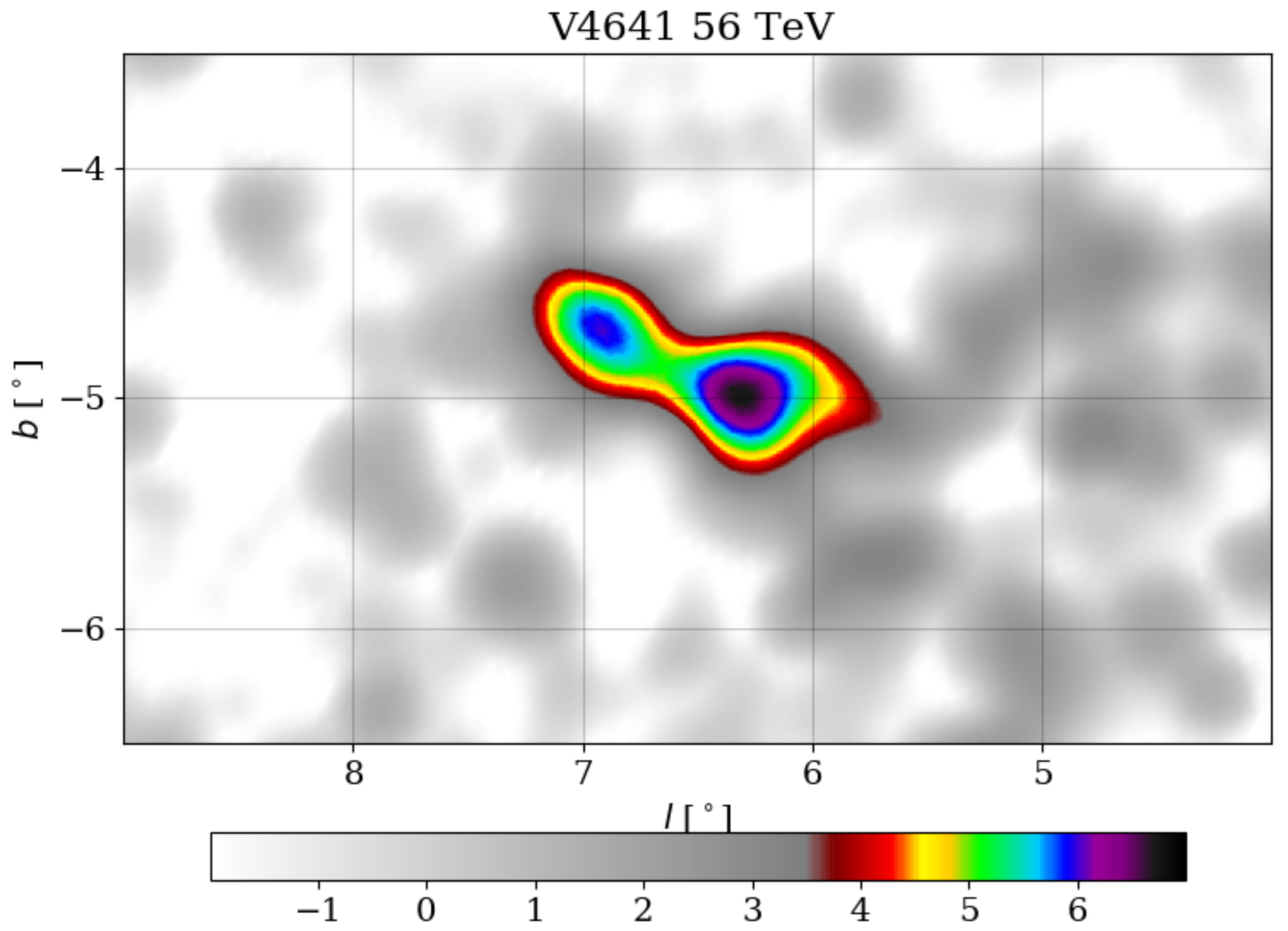
Because of the energy dependent morphology H.E.S.S. concludes these are electrons

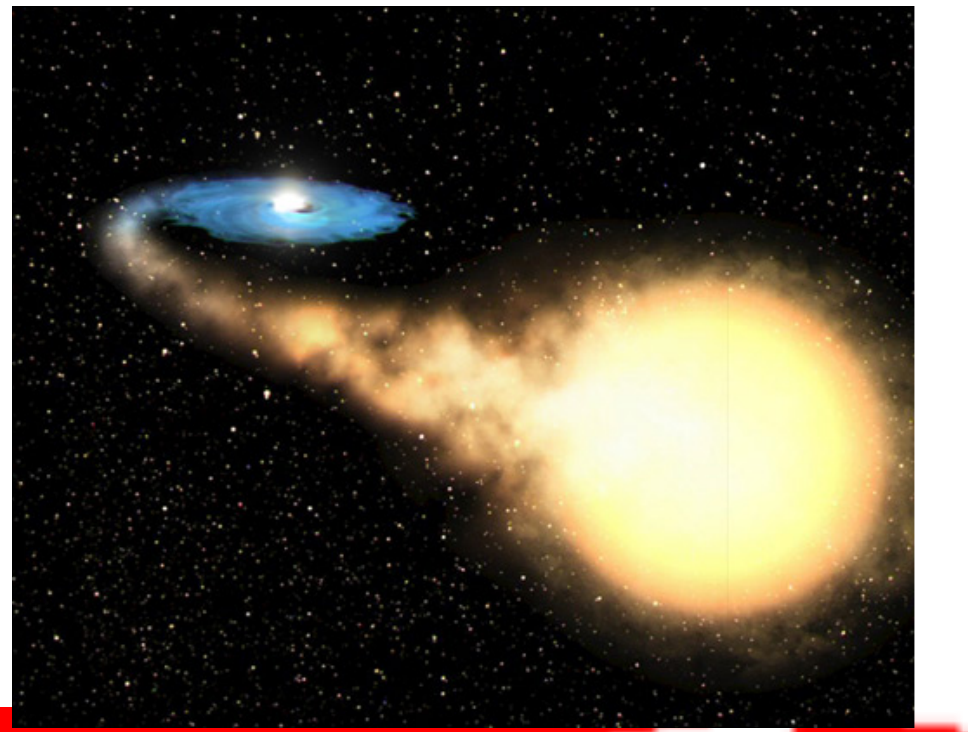


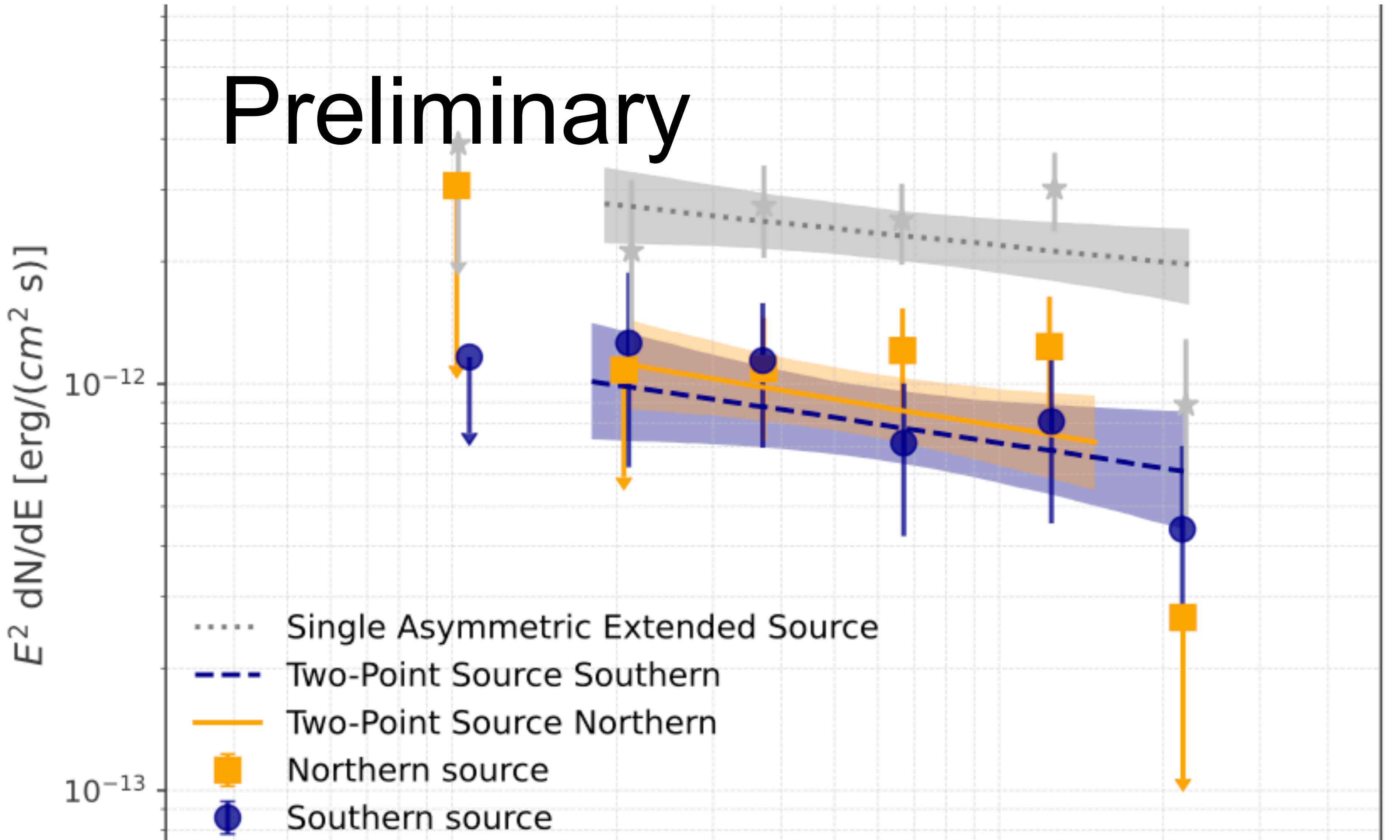
SS433
The Galactic Center
V4641 Sgr
Preliminary
b [°]

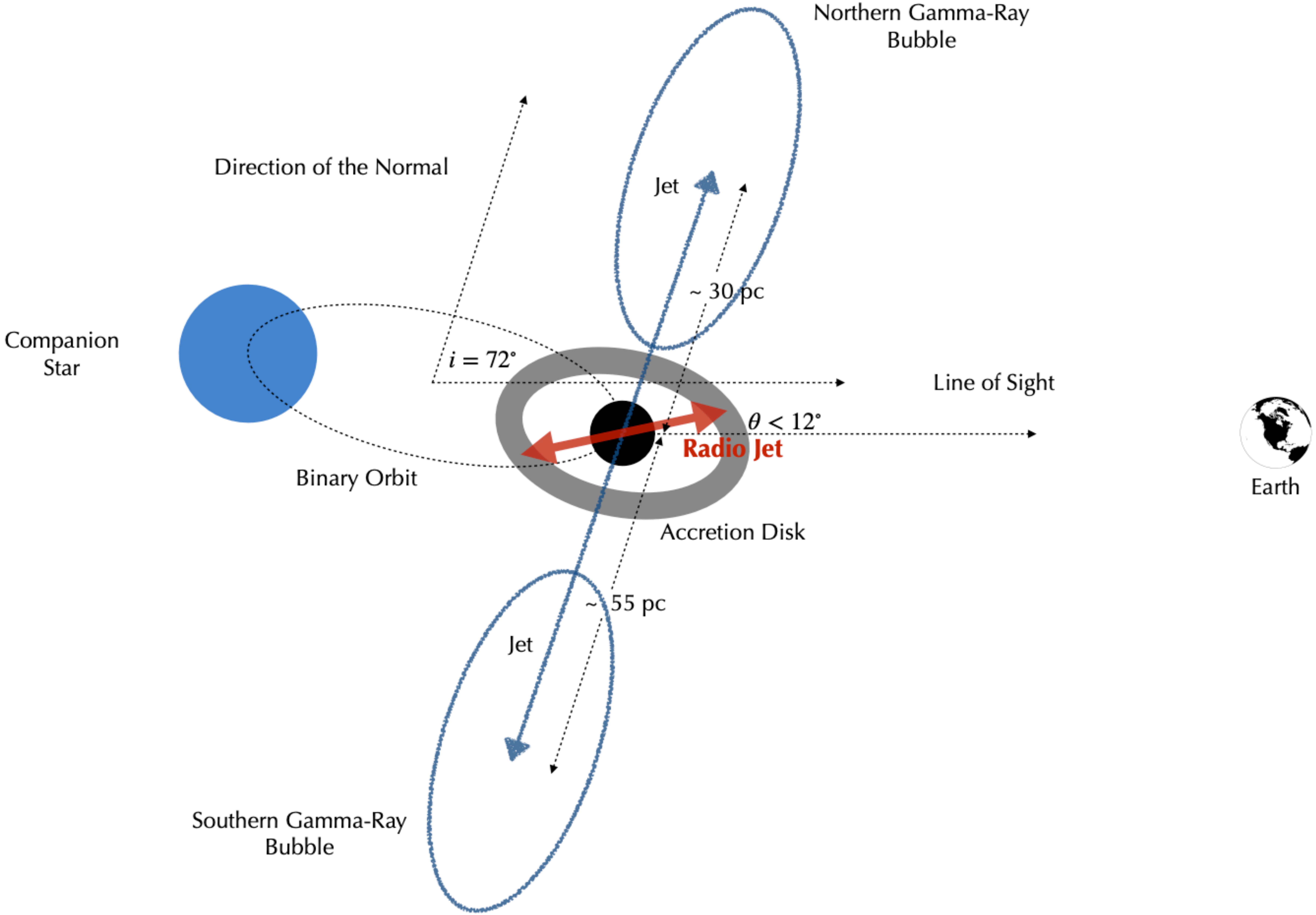
V4641 Sgr - Binary System

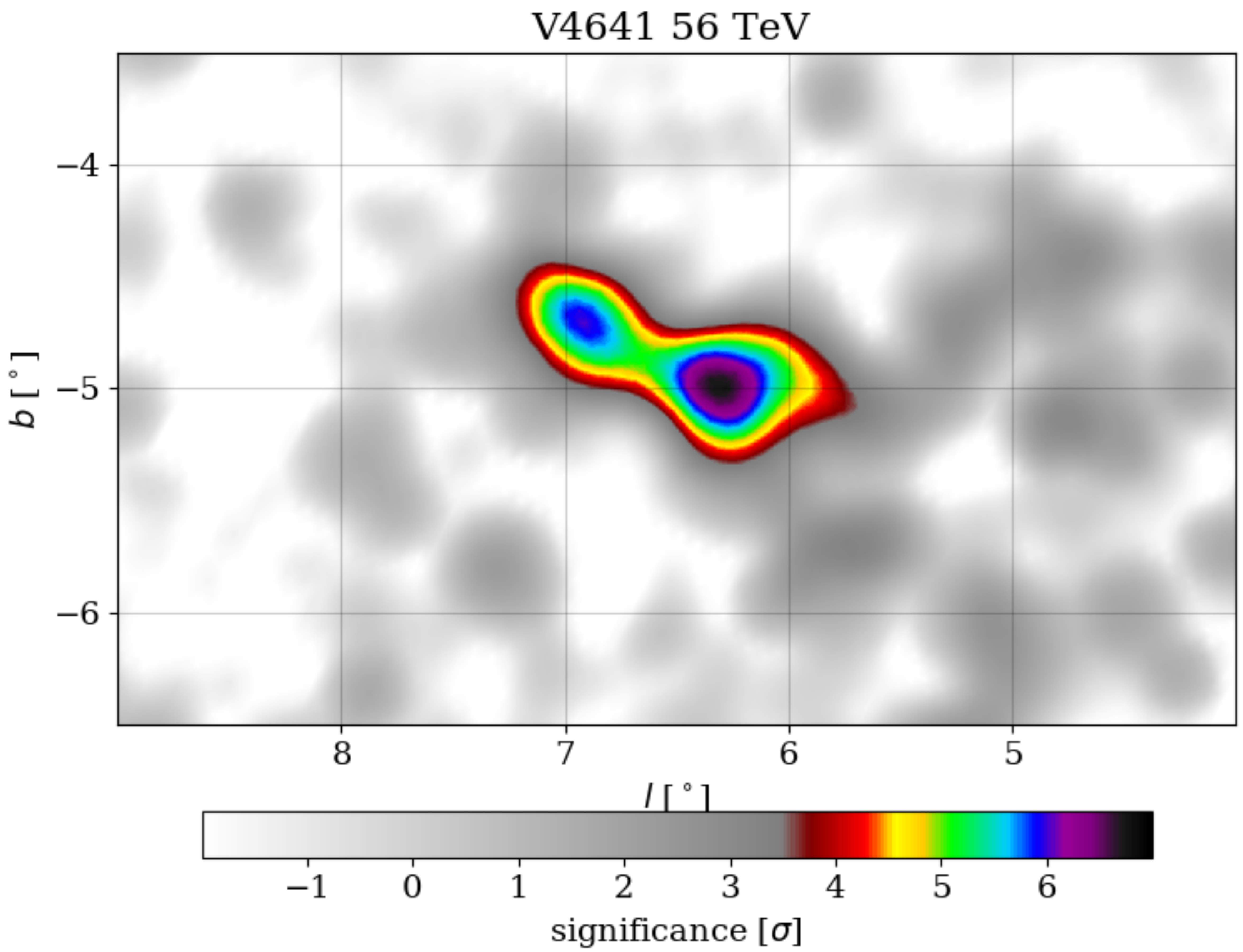
- Newly discovered TeV micro-quasar by HAWC.
- We measure photon energies from 300 GeV to above 100 TeV, with no sign of a cutoff above 200 TeV.
- The source is surrounded by a bubble of very high energy emission with a size of roughly ~ 100 pc, much more extended than the radio jet.
- If hadronic this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

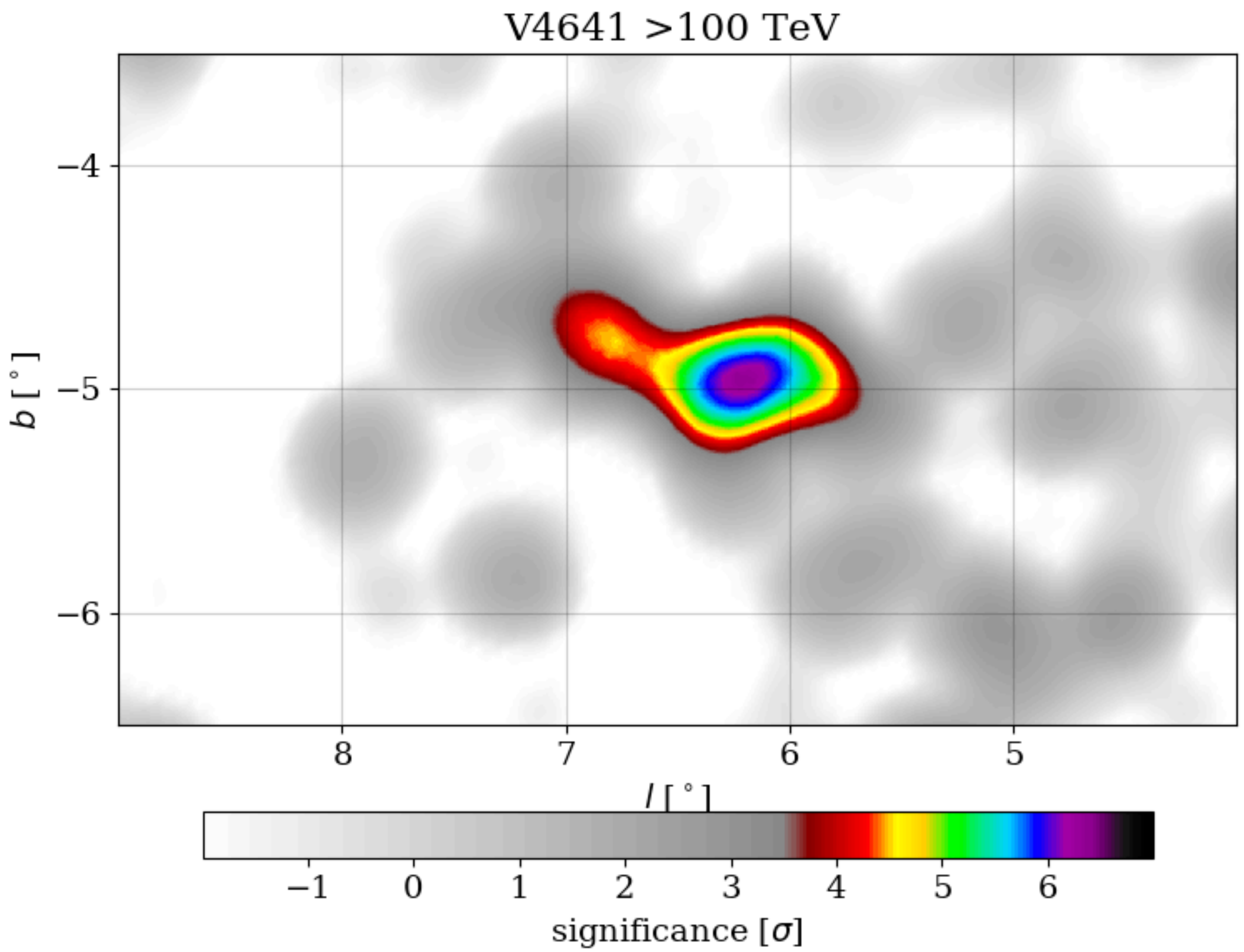




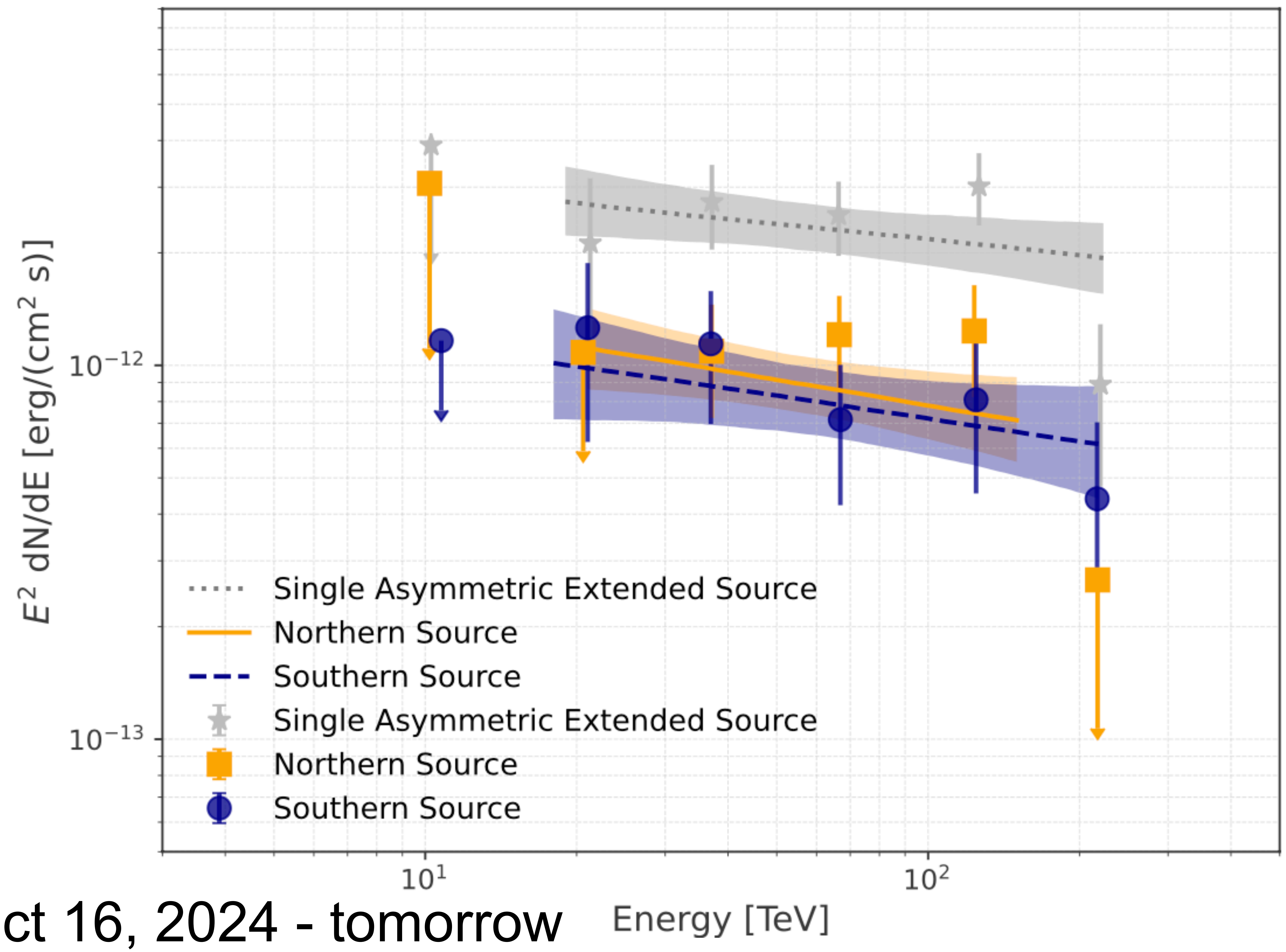



Northern Gamma-Ray Bubble
Direction of the Normal
Jet
~ 30 pc
Companion Star
i = 72°
Line of Sight
θ < 12°
Radio Jet
Earth
Binary Orbit
Accretion Disk
~ 55 pc
Jet
Southern Gamma-Ray Bubble

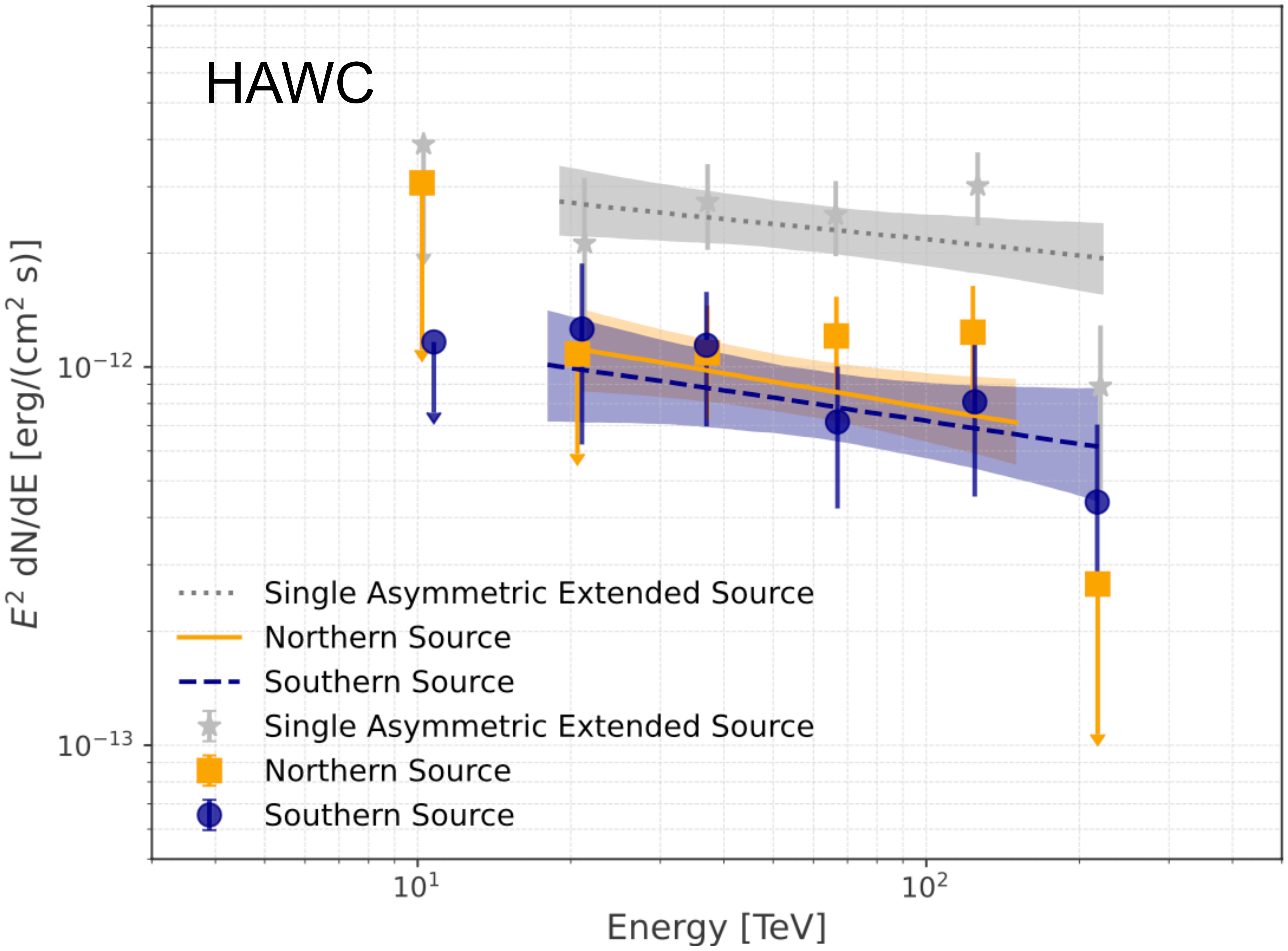

V4641 56 TeV
−4
−5
−6
b [°]
8
7
6
5
l [°]
−1
0
1
2
3
4
5
6
significance [σ]

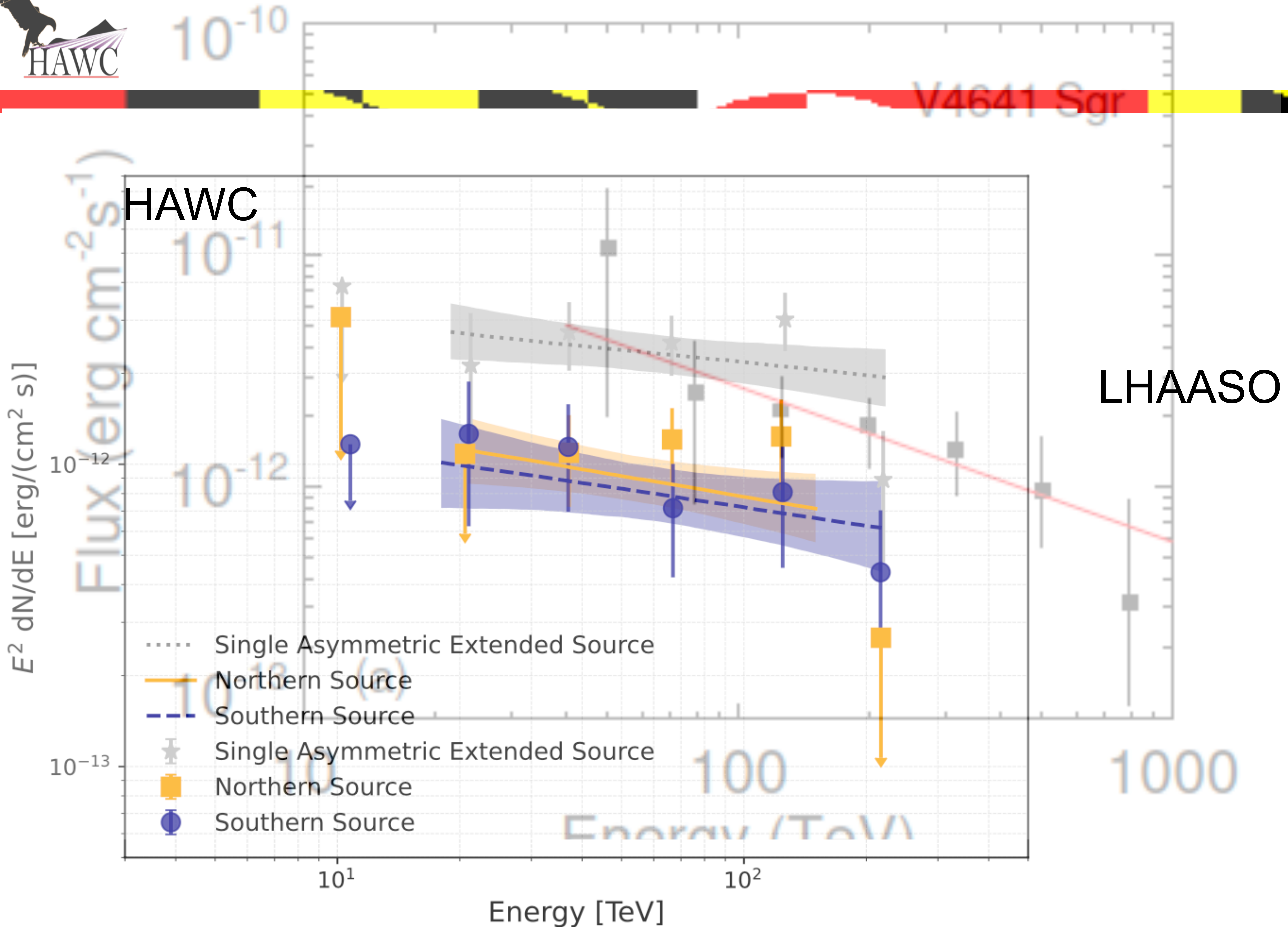

V4641 >100 TeV
−4
−5
−6
b [°]
8
7
6
5
l [°]
−1
0
1
2
3
4
5
6
significance [σ]

- Highest Energy HAWC photon 217 TeV
- 100+ TeV photons indicates that microquasars could be protonic PeVatrons
- LHAASO archive paper shows that matched the combined HAWC spectrum but extended with some steepening to 800 TeV

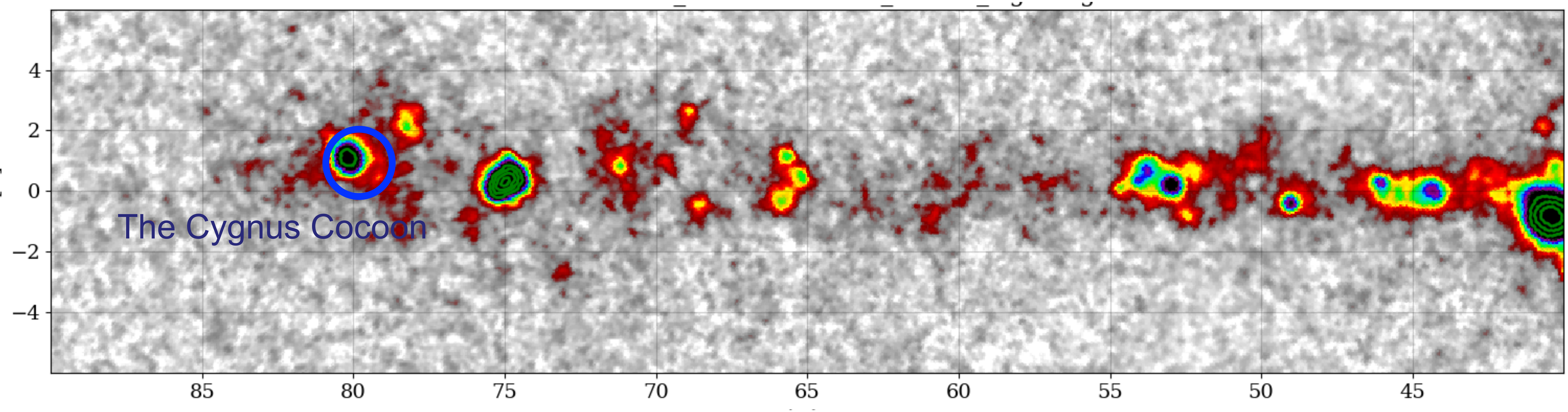


To be published in Nature Oct 16, 2024 - tomorrow


HAWC
Single Asymmetric Extended Source
Northern Source
Southern Source
Single Asymmetric Extended Source
Northern Source
Southern Source
10^{-12}
10^{-13}
10^{1}
10^{2}
Energy [TeV]
E^2 dN/dE [erg/(cm^2 s)]

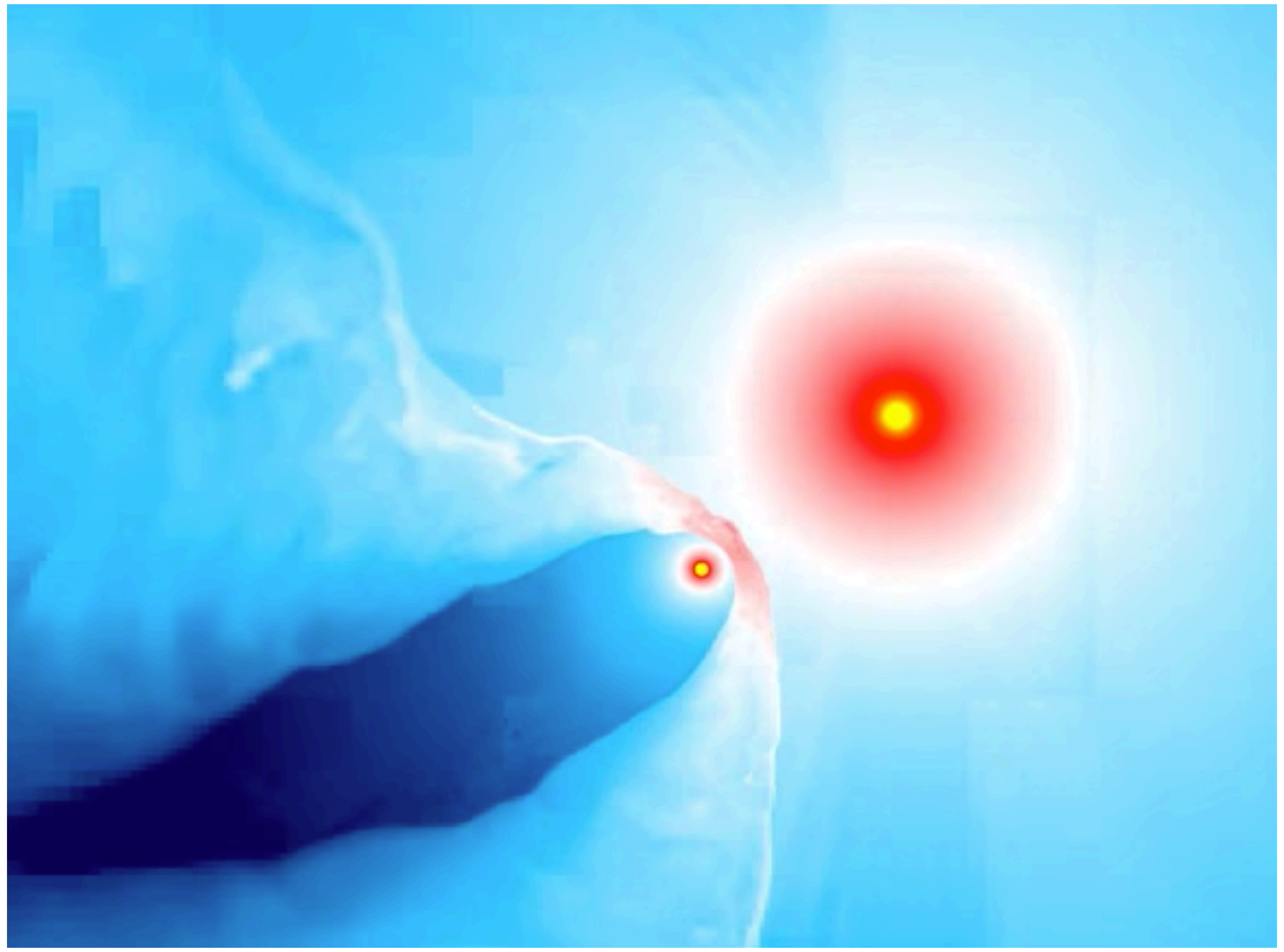


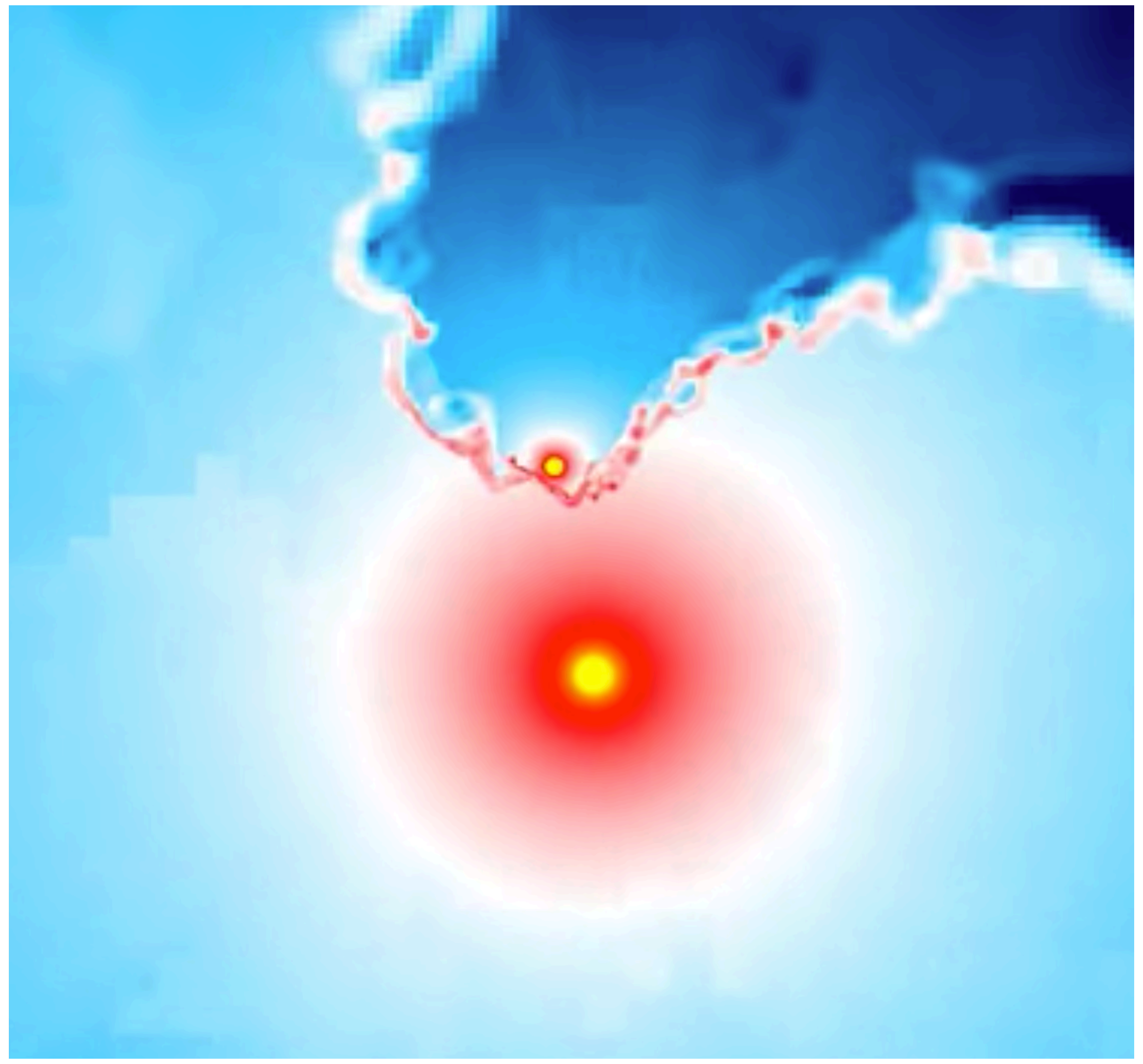
HAWC
LHAASO
V4641 Sgr
Single Asymmetric Extended Source
Northern Source
Southern Source
Single Asymmetric Extended Source
Northern Source
Southern Source
Energy [TeV]
E² dN/dE [erg/(cm² s)]
Flux (erg cm⁻² s⁻¹)
Energy (TeV)


The Cygnus Cocoon
4
2
0
−2
−4
85
80
75
70
65
60
55
50
45

CR Origin: Star Forming Regions (SFR)

- No evidence of particle acceleration in **SNRs** beyond 100s of TeV
- **Can SFRs provide this energy via e.g. collective star winds?**
- **Candidate: OB2 association in Cygnus Region**
  - *Fermi detection at GeV* (Ackermann et al., ***Science*** 334, 2011, '*The Cocoon'*)
- ***Cygnus OB2 is an OB association that is home to some of the most massive and most luminous stars known***
  - ***It is hidden behind a massive dust cloud known as the Cygnus Rift, which obscures many of the stars in it. This means that despite its large size, it is hard to determine its actual properties.***
- ***Including* two Massive stars orbiting tightly**
  - **Steller Winds collide producing x-rays**
  - **These can influence star formation and possibly accelerate particles**

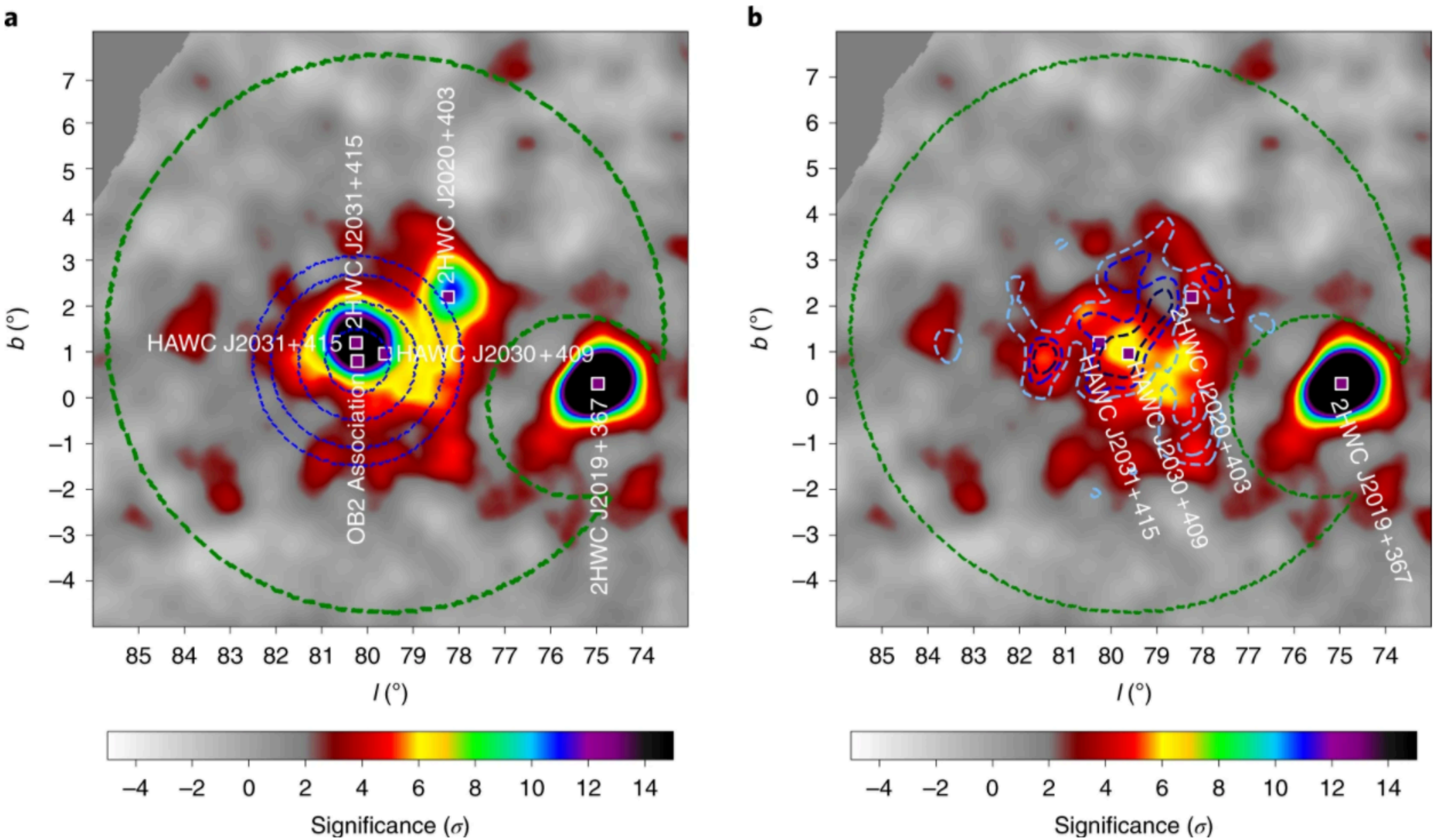




HAWC

Fig. 1: Significance map of the Cocoon region before and after subtraction of the known sources at the region.

From: HAWC observations of the acceleration of very-high-energy cosmic rays in the Cygnus Cocoon



Cygnus Cocoon

- HAWC reported observations of 1–100 TeV γ rays coming from the ‘Cygnus Cocoon’, which is a superbubble that surrounds a region of massive star formation.
- These γ rays are likely produced by 10–1,000 TeV freshly accelerated cosmic rays that originate from the enclosed star-forming region Cyg OB2.
- Until now it was not known that such regions could accelerate particles to these energies. The measured flux likely originates from hadronic interactions.

HAWC

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

SIGNATURES OF COSMIC-RAY INTERACTIONS ON THE SOLAR SURFACE

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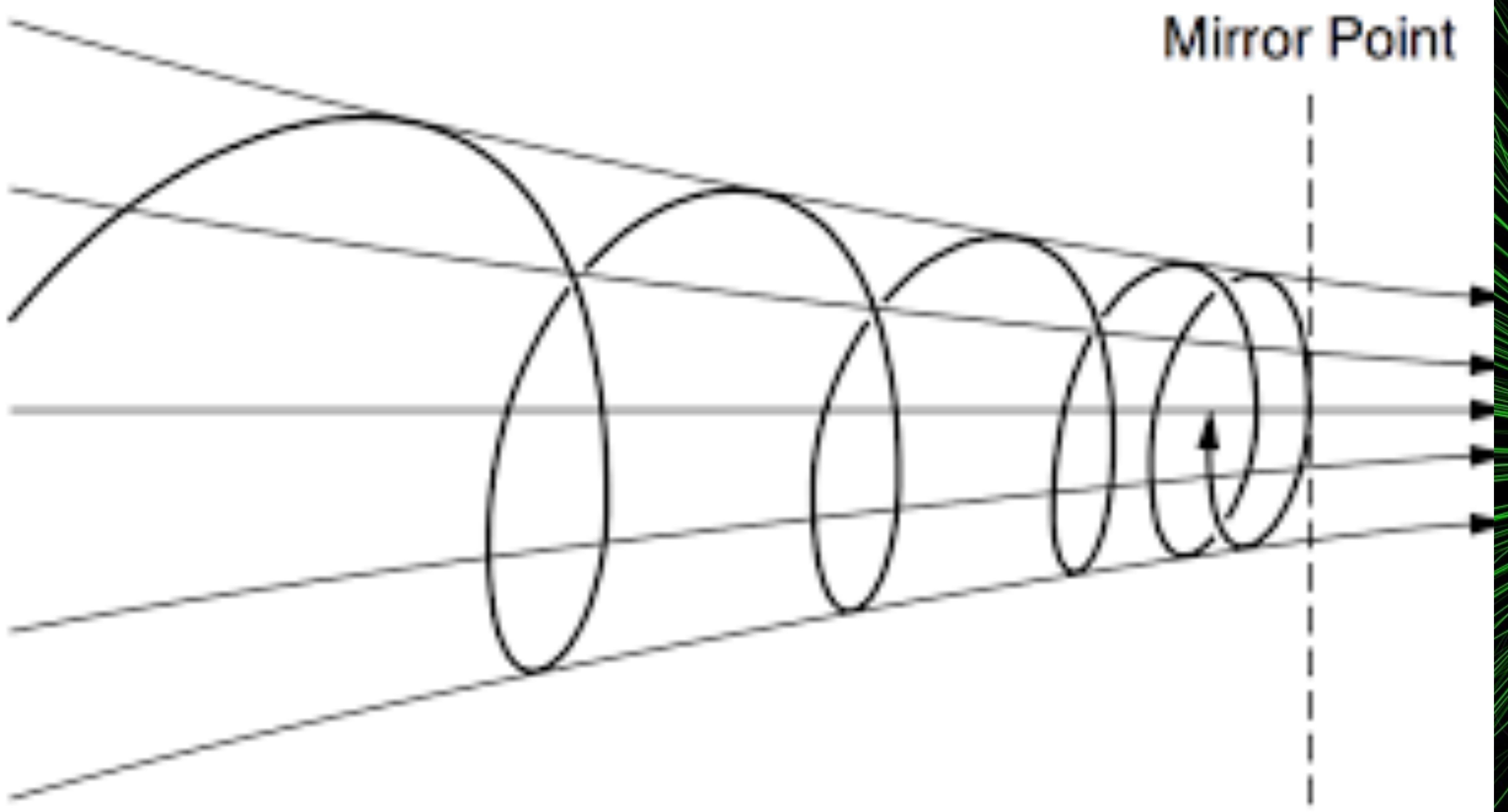
Bartol Research Institute, University of Delaware, Newark, DE 19716
Received 1991 March 21; accepted 1991 June 5

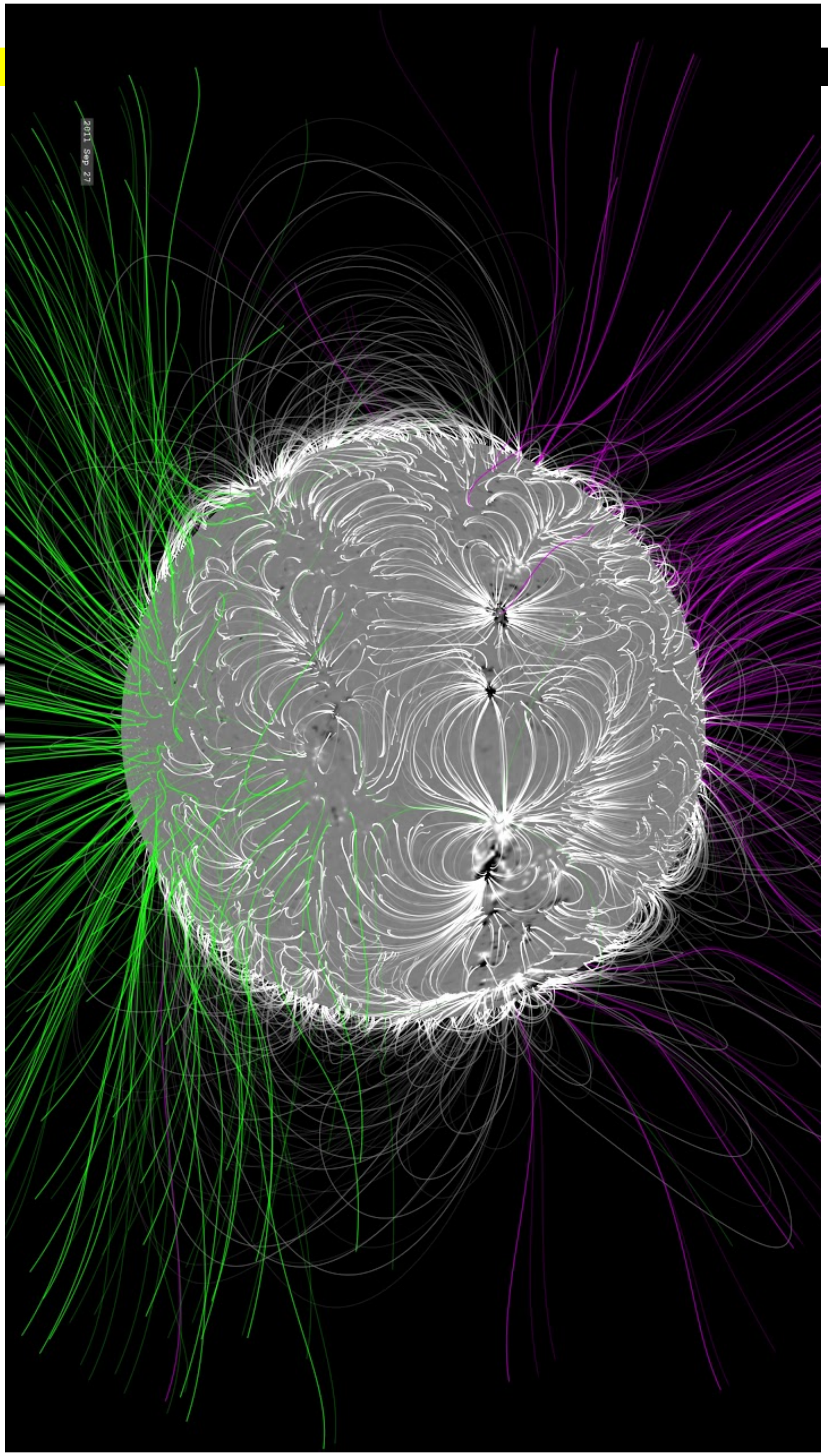
ABSTRACT

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

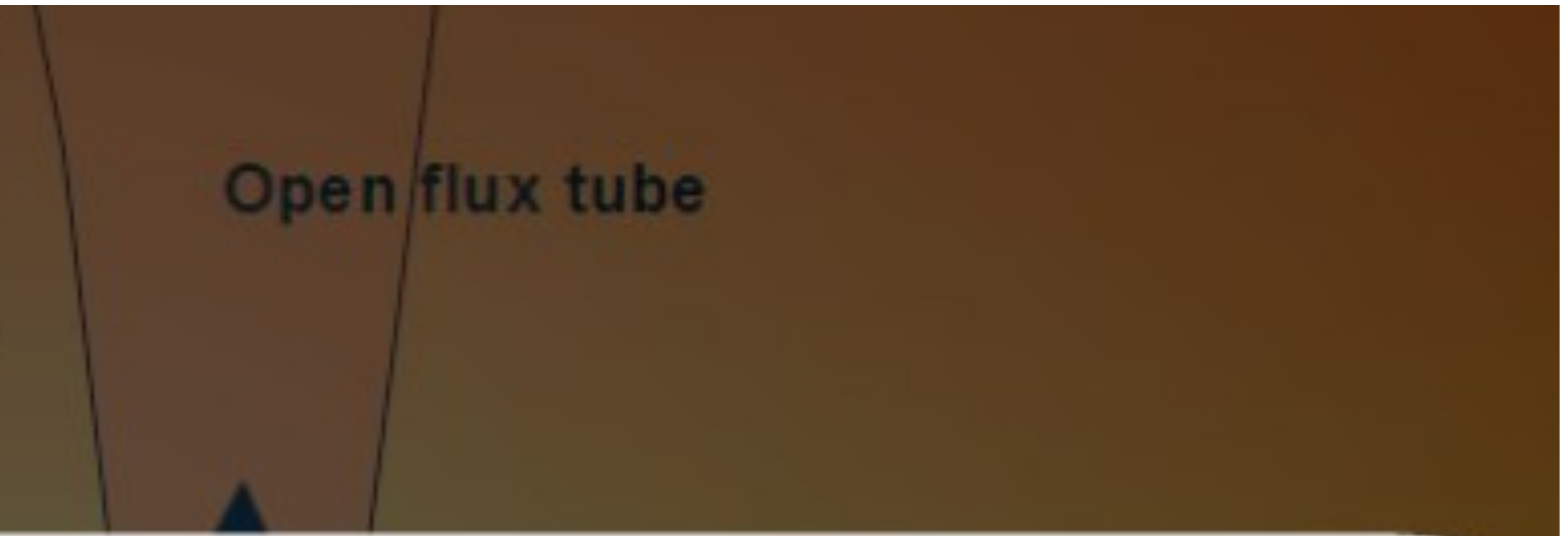


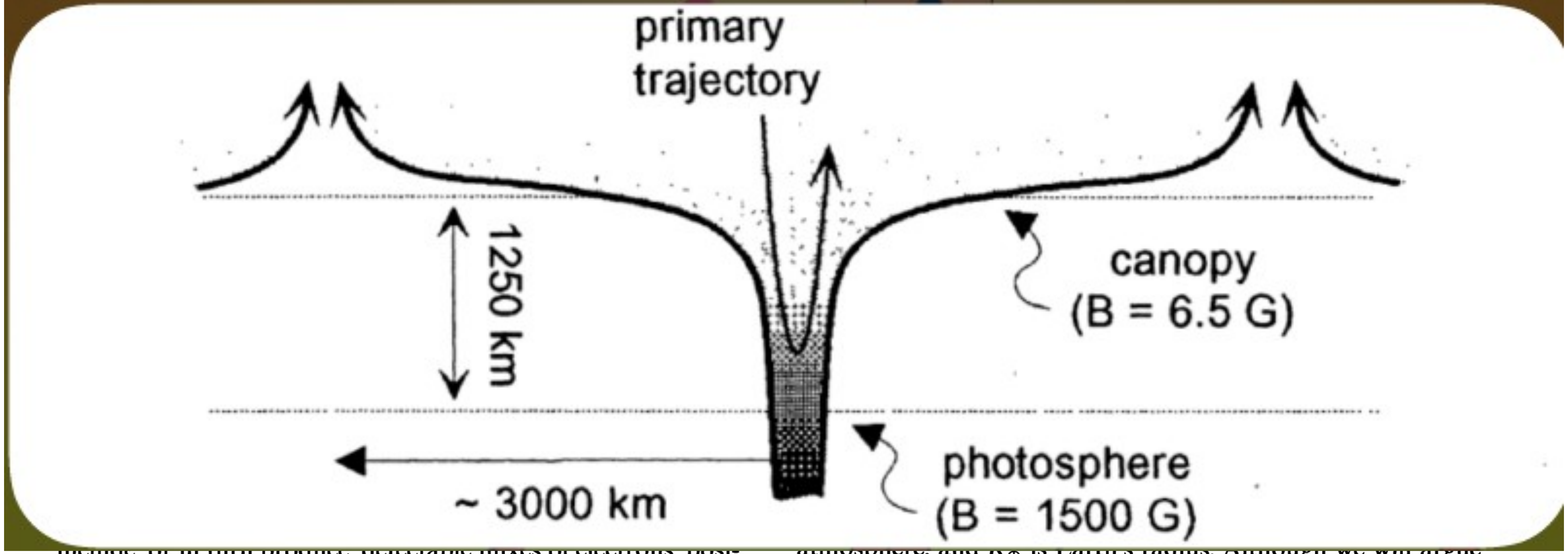


- When they come back out they interact in the corona producing gamma rays, etc

How?

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





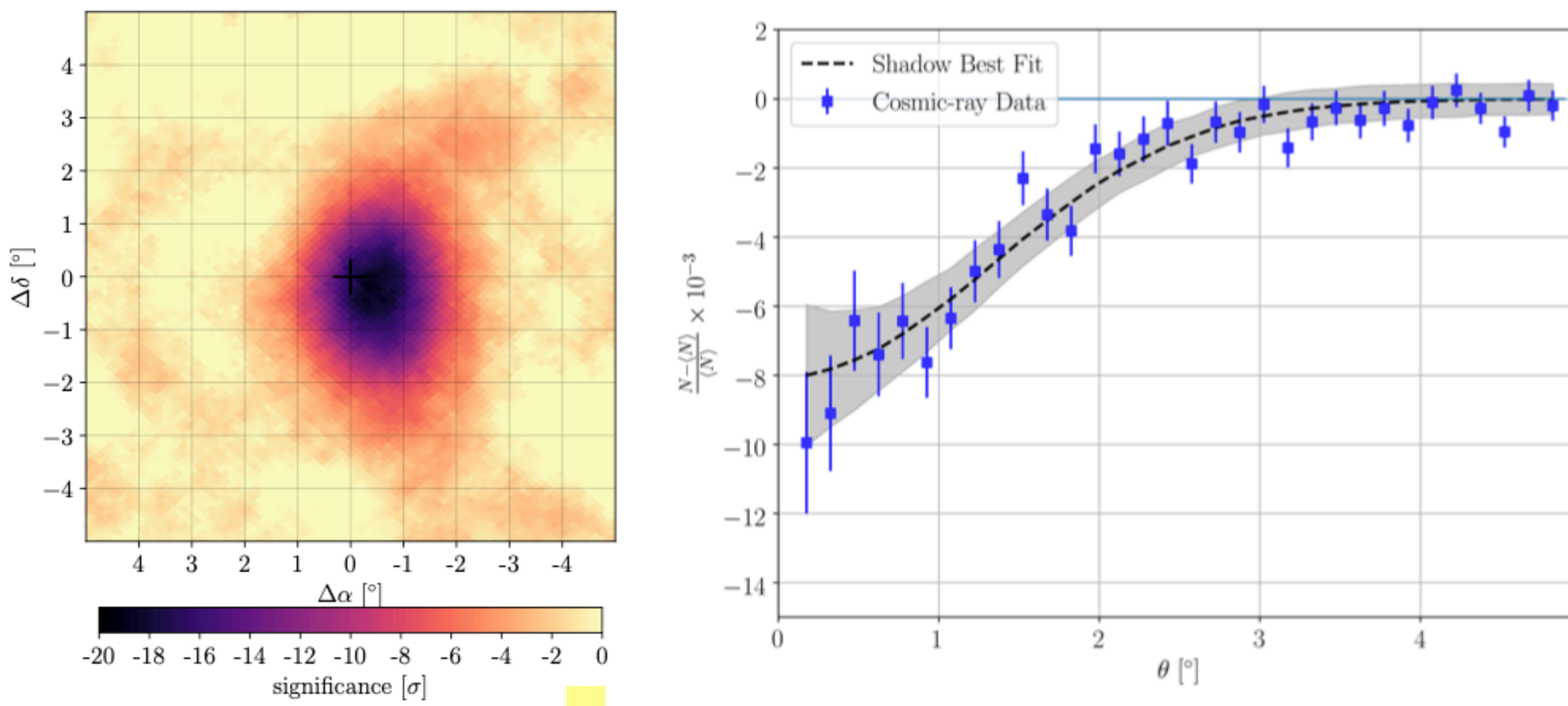
trons, muons, gamma rays, Čerenkov light, neutrons and other

otherwise, one might worry that a similar suppression occurs

Sun Shadow

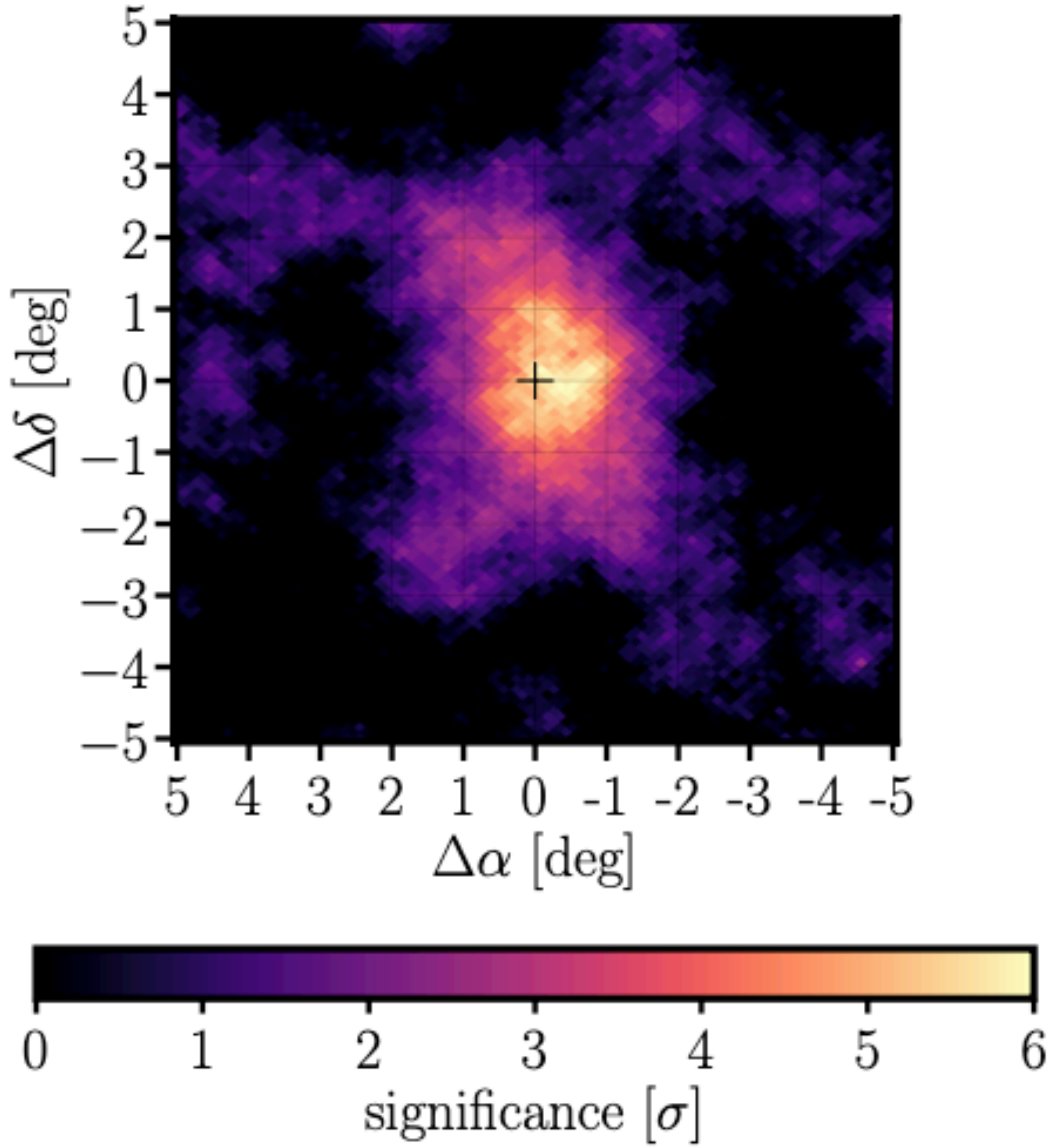
- We see the shadow of the Sun (and Moon) in charged Cosmic Rays
  - The deficit is slightly offset due to the Earth's magnetic field
- The Moon's shadow is steady but the Sun's varies with Solar magnetic field (11 yrs)
  - "Solar Max" is the sunspot max but corresponds to the minimum polar magnetic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

Measured CR Shadow: Quantity of interest is relative deficit wrt to bkg

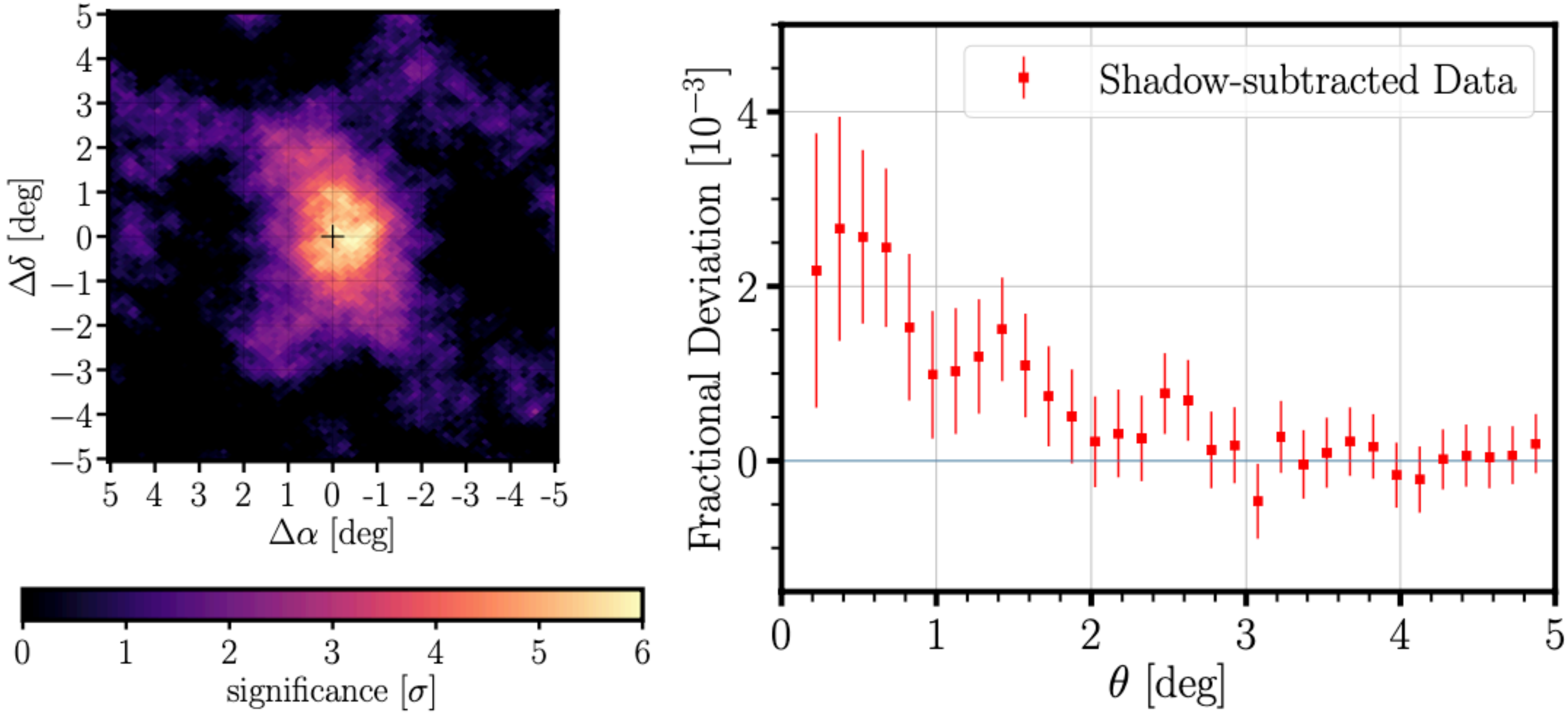


Sun Shadow

- 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!

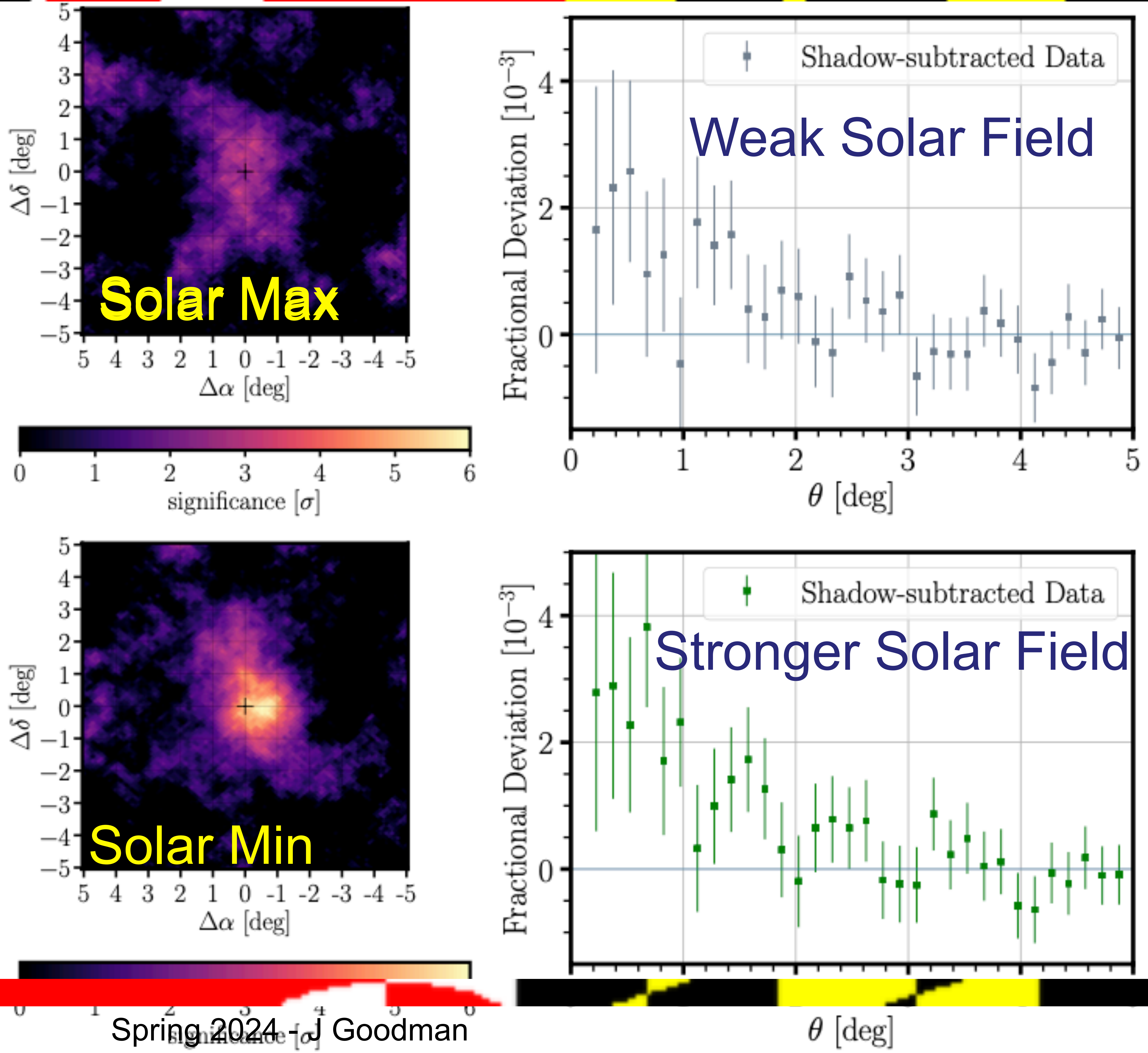


The Sun in Gamma Rays



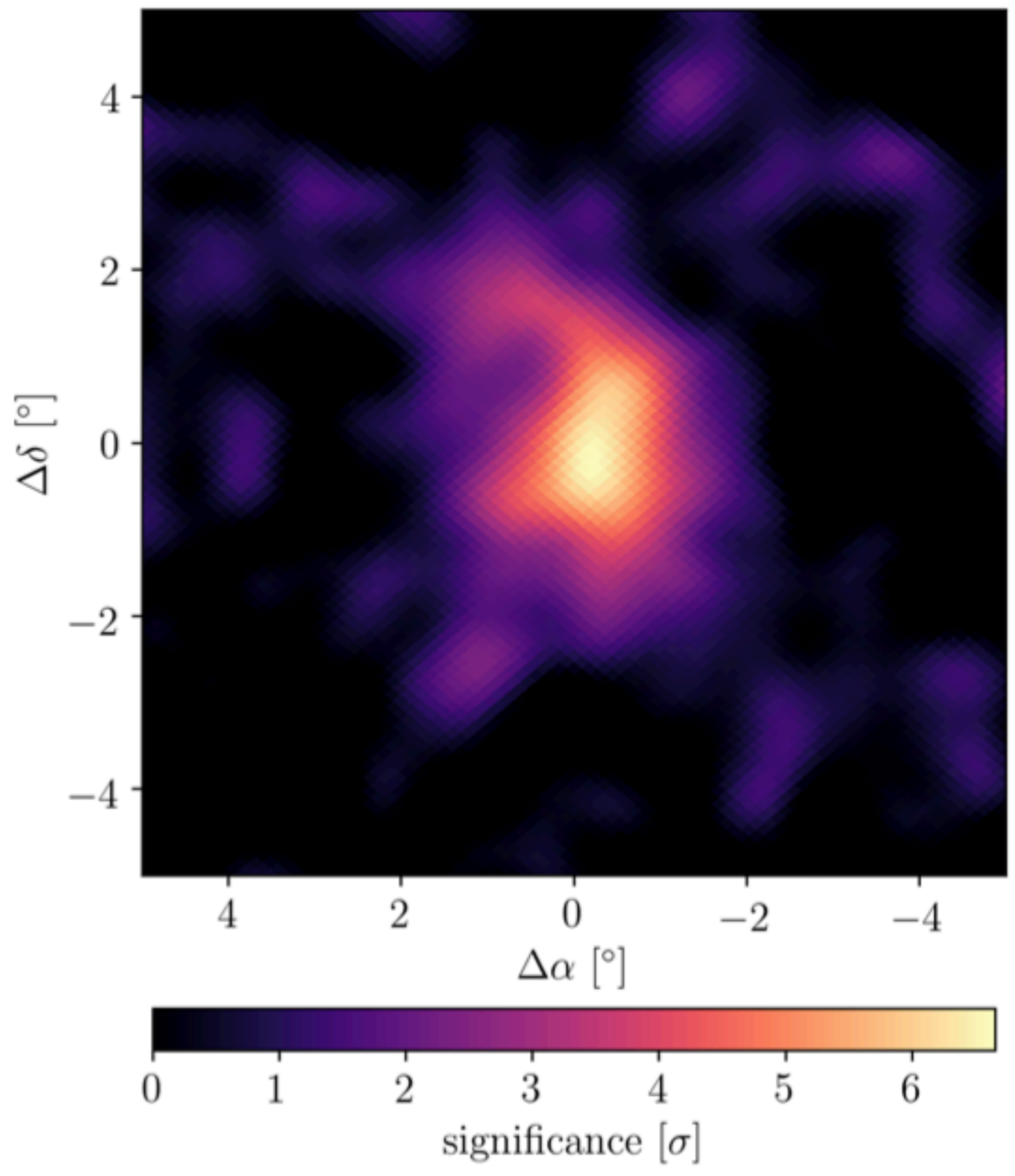
The Sun

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



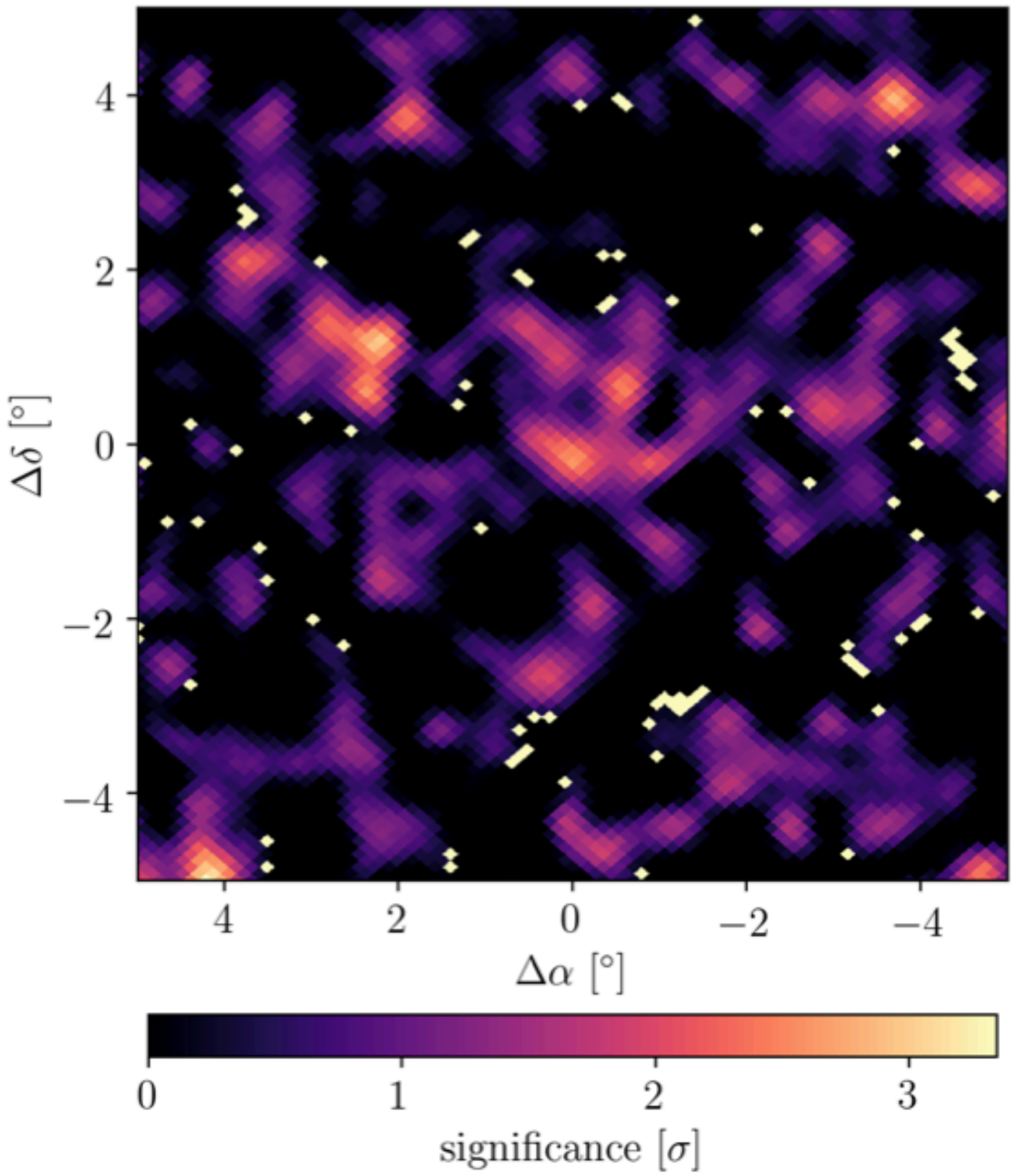
The Sun

Lower Energy <~ 3 TeV



Bins 2-4

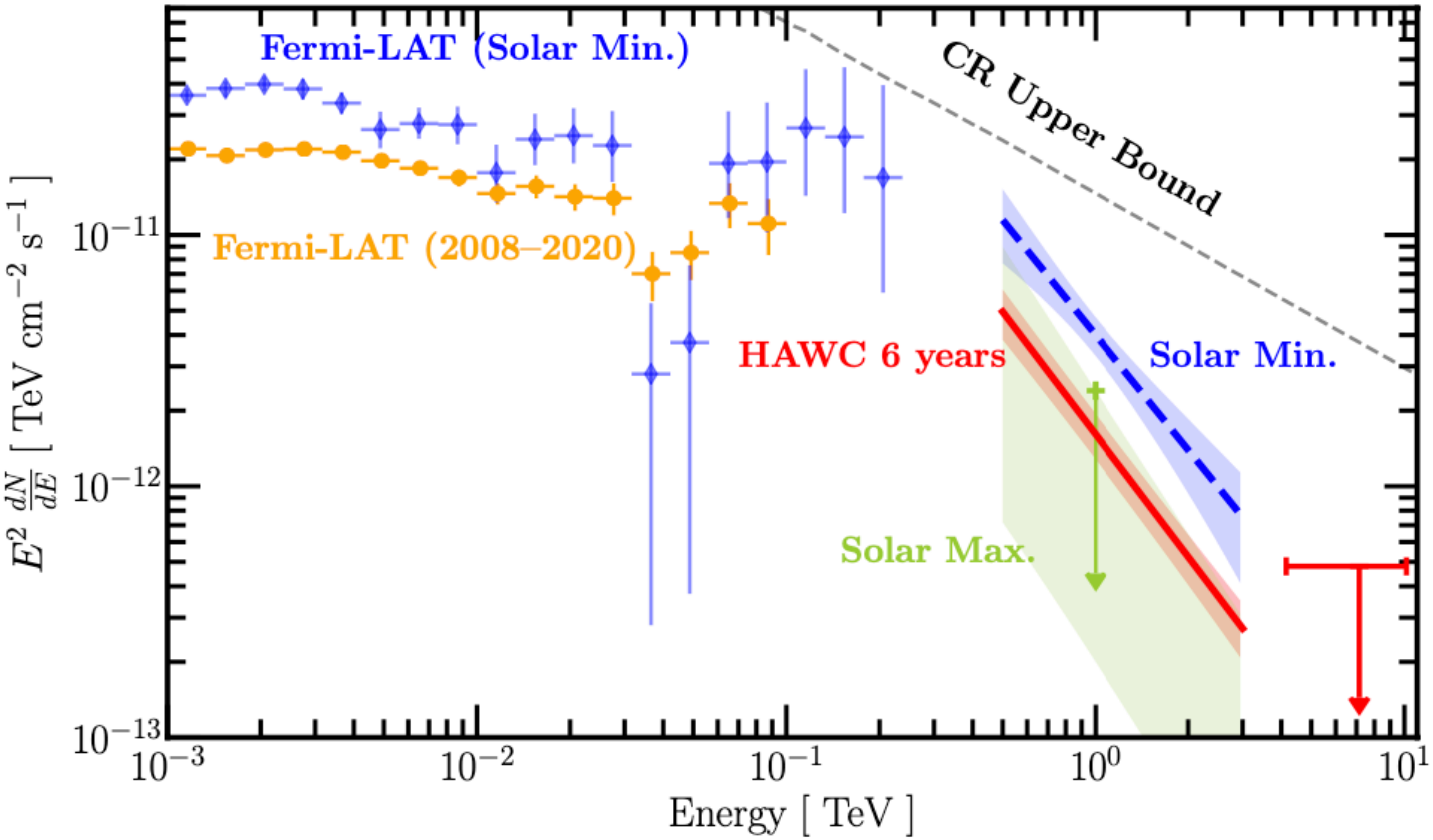
Higher Energy >~ 3 TeV



Bins 5-8

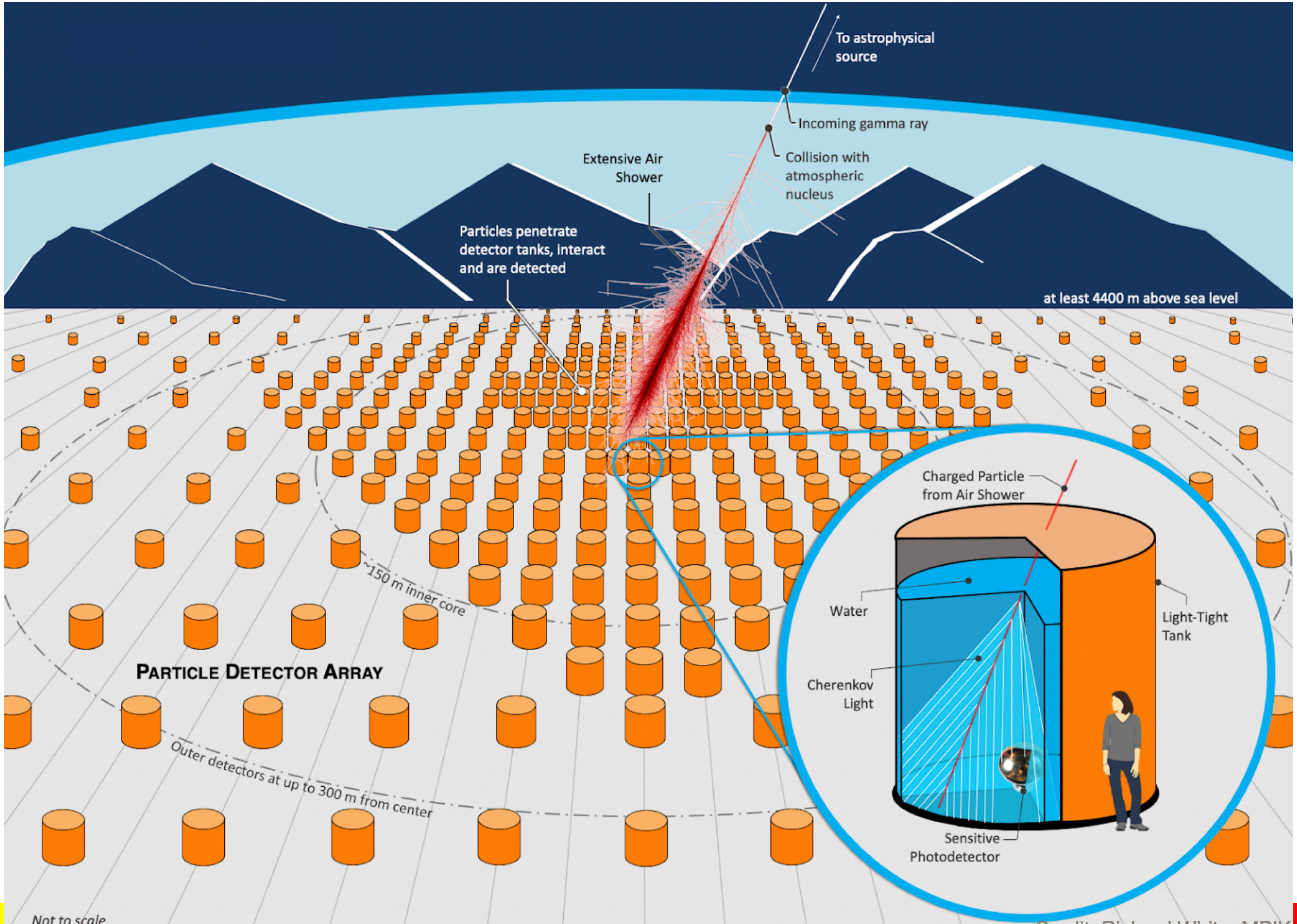
The Sun

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



The Future

SWGO
The Southern Wide-field Gamma-ray Observatory



Credit: Richard White, MPIK