Observation of the Galactic Center PeVatron Beyond 100 TeV with HAWC

Sohyoun Yun-Cárcamo (yunsoh@umd.edu)

11th Fermi Symposium

Observation of the Galactic Center PeVatron Beyond 100 TeV with HAWC

Sohyoun Yun-Cárcamo (yunsoh@umd.edu)

Graduating next Spring, looking for a job :)

11th Fermi Symposium

Observation of the Galactic Center PeVatron Beyond 100 TeV with HAWC

Sohyoun Yun-Cárcamo (yunsoh@umd.edu)

Special thanks to Dezhi Huang, Rishi Babu, and Jason Fan

11th Fermi Symposium

HAWC Result

We present the first detection of gamma rays with energies >100 TeV from the Galactic Center (GC) with HAWC data.

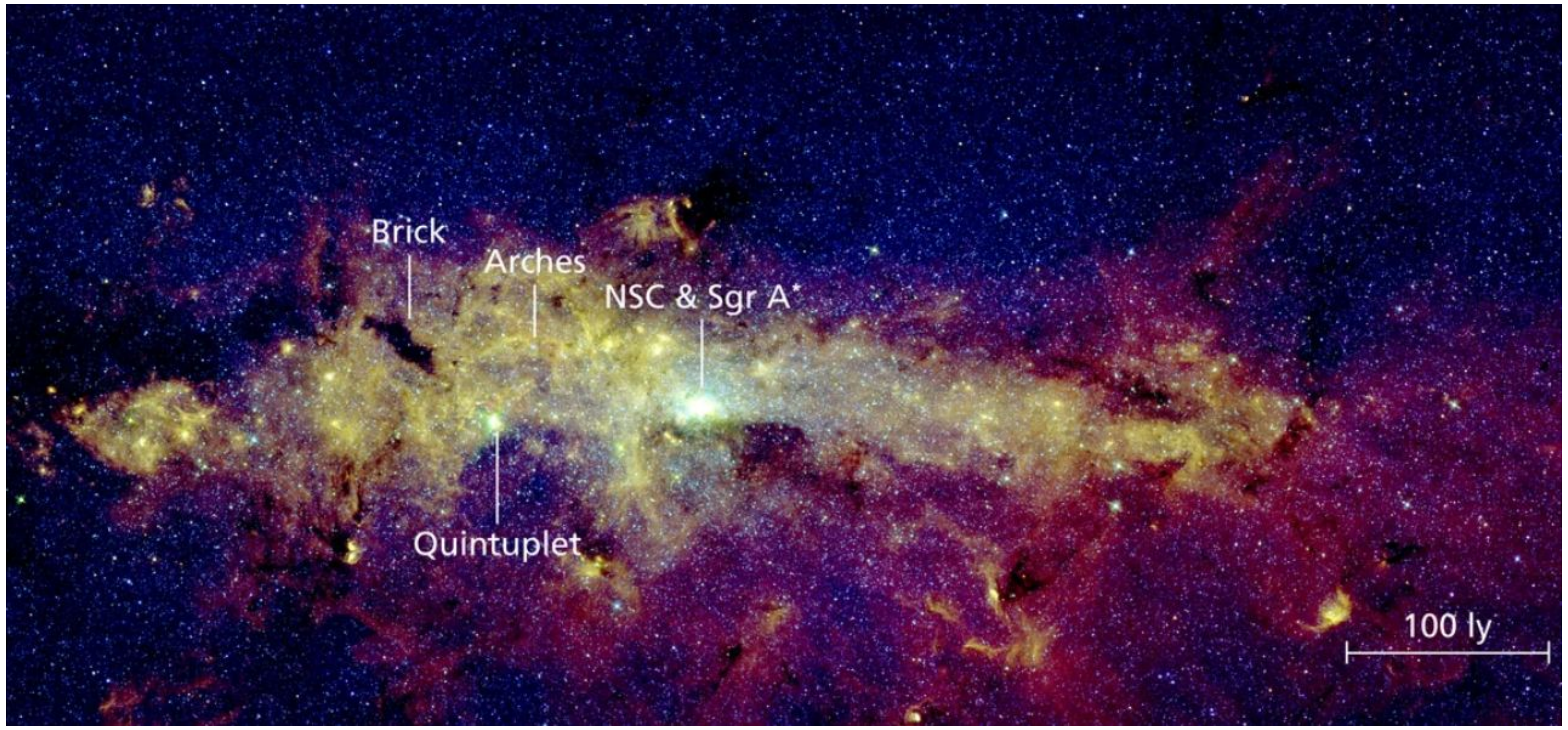


Figure 2: The Central Molecular Zone (CMZ). Credit: Henshaw / MPIA

HAWC Result

We present the first detection of gamma rays with energies >100 TeV from the Galactic Center (GC) with HAWC data.

Results suggest that the gamma rays originate from interaction of protons from the Central Molecular Zone (CMZ) and PeV protons freshly accelerated within the GC region.

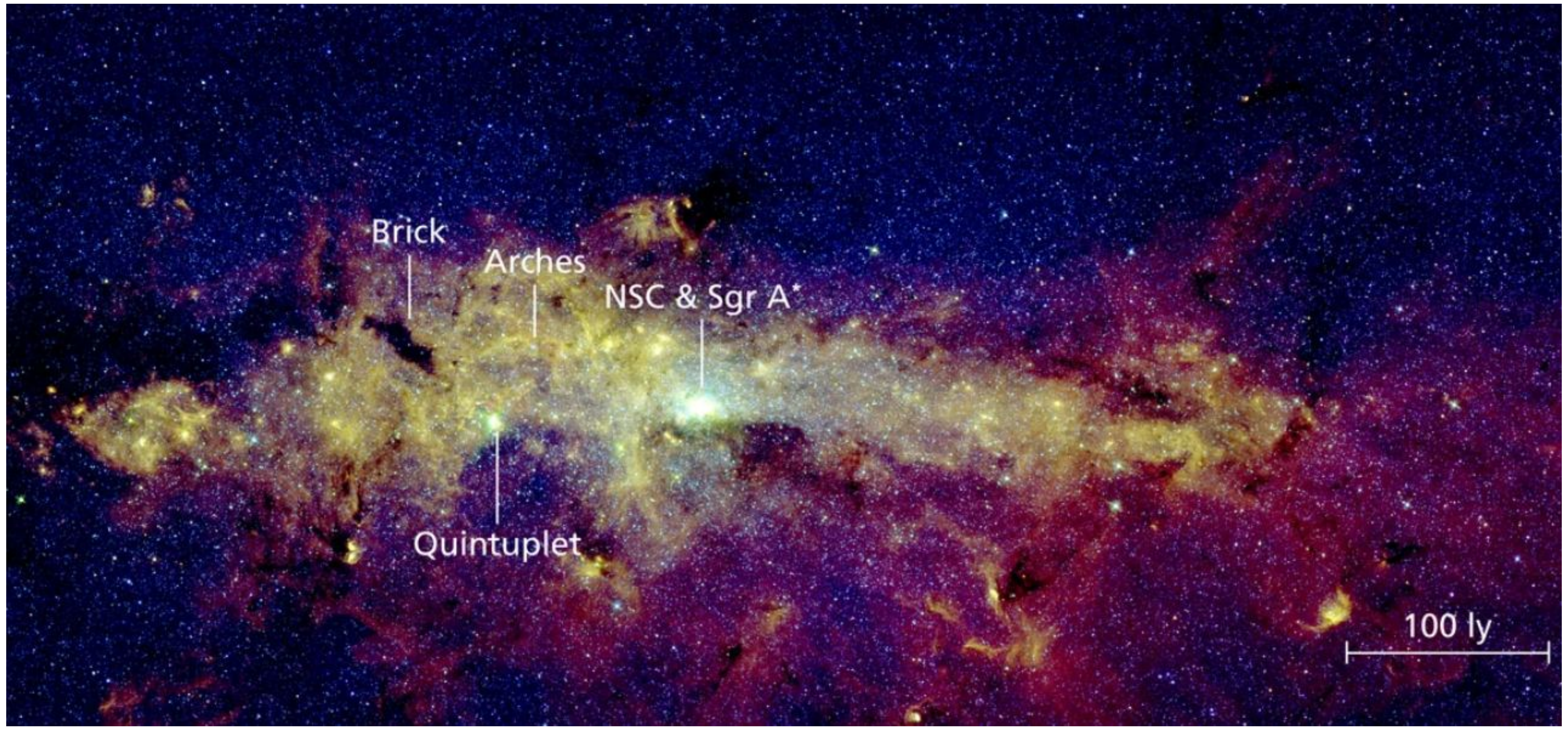


Figure 2: The Central Molecular Zone (CMZ). Credit: Henshaw / MPIA

HAWC Result

We present the first detection of gamma rays with energies >100 TeV from the Galactic Center (GC) with HAWC data.

Results suggest that the gamma rays originate from interaction of protons from the Central Molecular Zone (CMZ) and PeV protons freshly accelerated within the GC region.

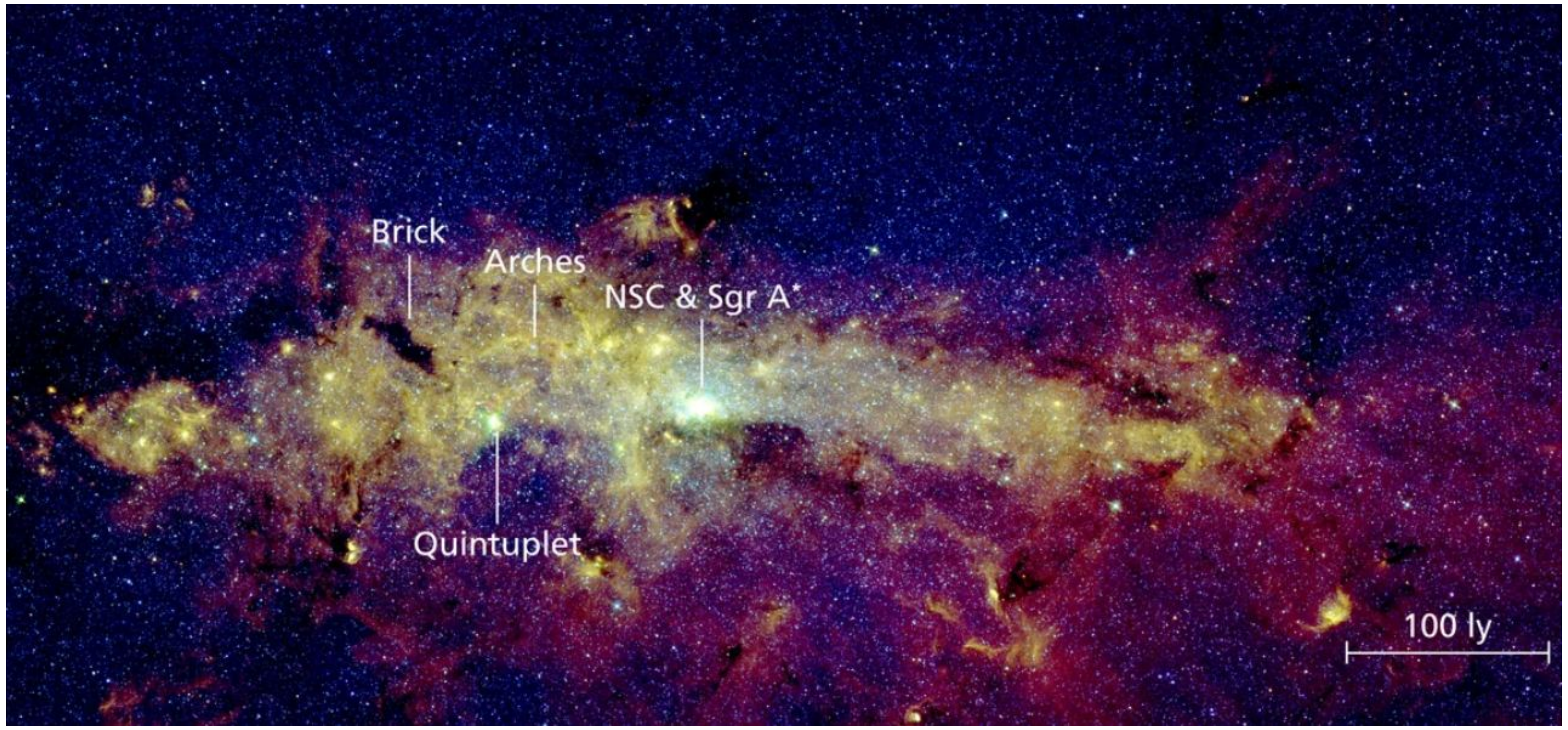


Figure 2: The Central Molecular Zone (CMZ). Credit: Henshaw / MPIA

Dear Ms. Yun-Cárcamo,

arXiv:2407.03682

Congratulations on the acceptance of the above manuscript into The Astrophysical Journal Letters.

Figure 1: A *me* for tank size scale.

HAWC is located on the flanks of the Sierra Negra volcano, Mexico at an altitude of 4100 meters (13,500 feet).

The main array is composed of 300 water Cherenkov tanks.

HAWC detects secondary particles from gamma/cosmic rays with primary energies between 100s GeV and 100s TeV.

In 24 hours it surveys 2/3 of the sky.

The High-Altitude Water Cherenkov Gamma-Ray Observatory

Figure 1: A *me* for tank size scale.

HAWC is located on the flanks of the Sierra Negra volcano, Mexico at an altitude of 4100 meters (13,500 feet).

The main array is composed of 300 water Cherenkov tanks.

HAWC detects secondary particles from gamma/cosmic rays with primary energies between 100s GeV and 100s TeV.

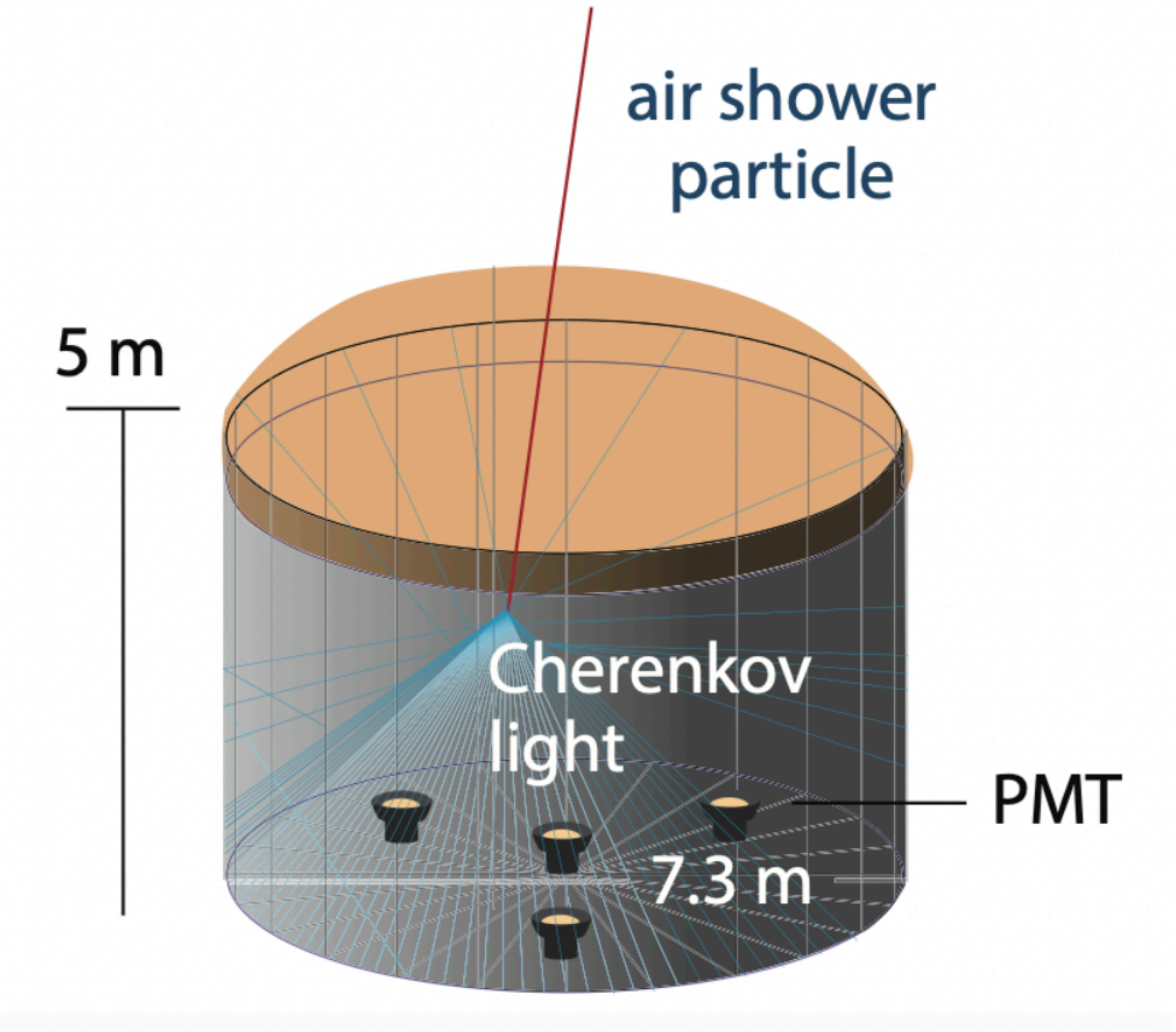
In 24 hours it surveys 2/3 of the sky.

Why now and not before?

Performance improvements > 37° zenith and > 70 TeV (check ApJ, 972:144 (15pp), 2024 September 10):

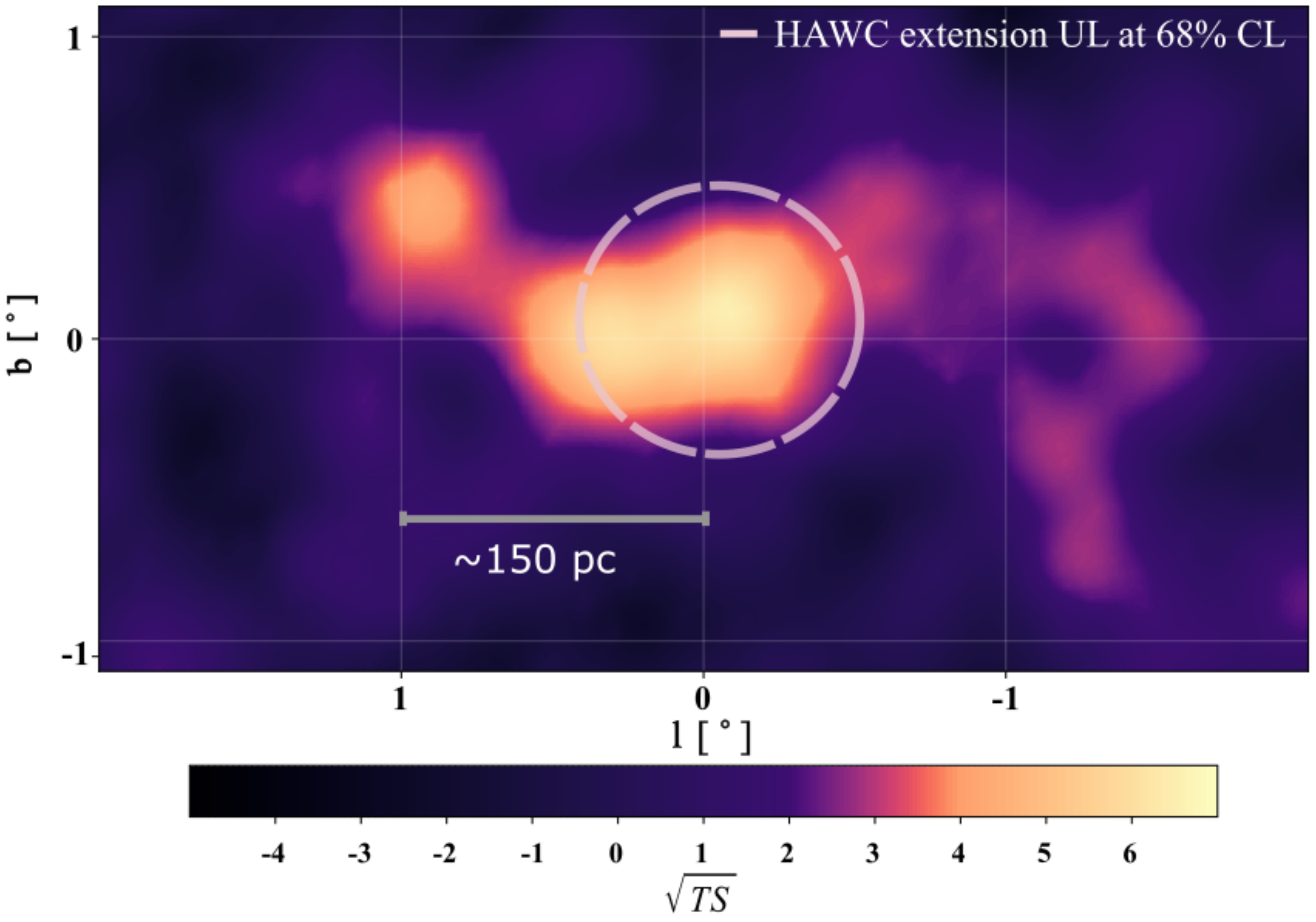
- The angular resolution improved by a factor of four.
- Factor of four improvement in background rejection compared to previous HAWC publications.

Using 2546 days of HAWC data, we detect gamma-ray emission from the GC region (max. zenith of 48°) with a maximum significance of 6.5σ above the background.



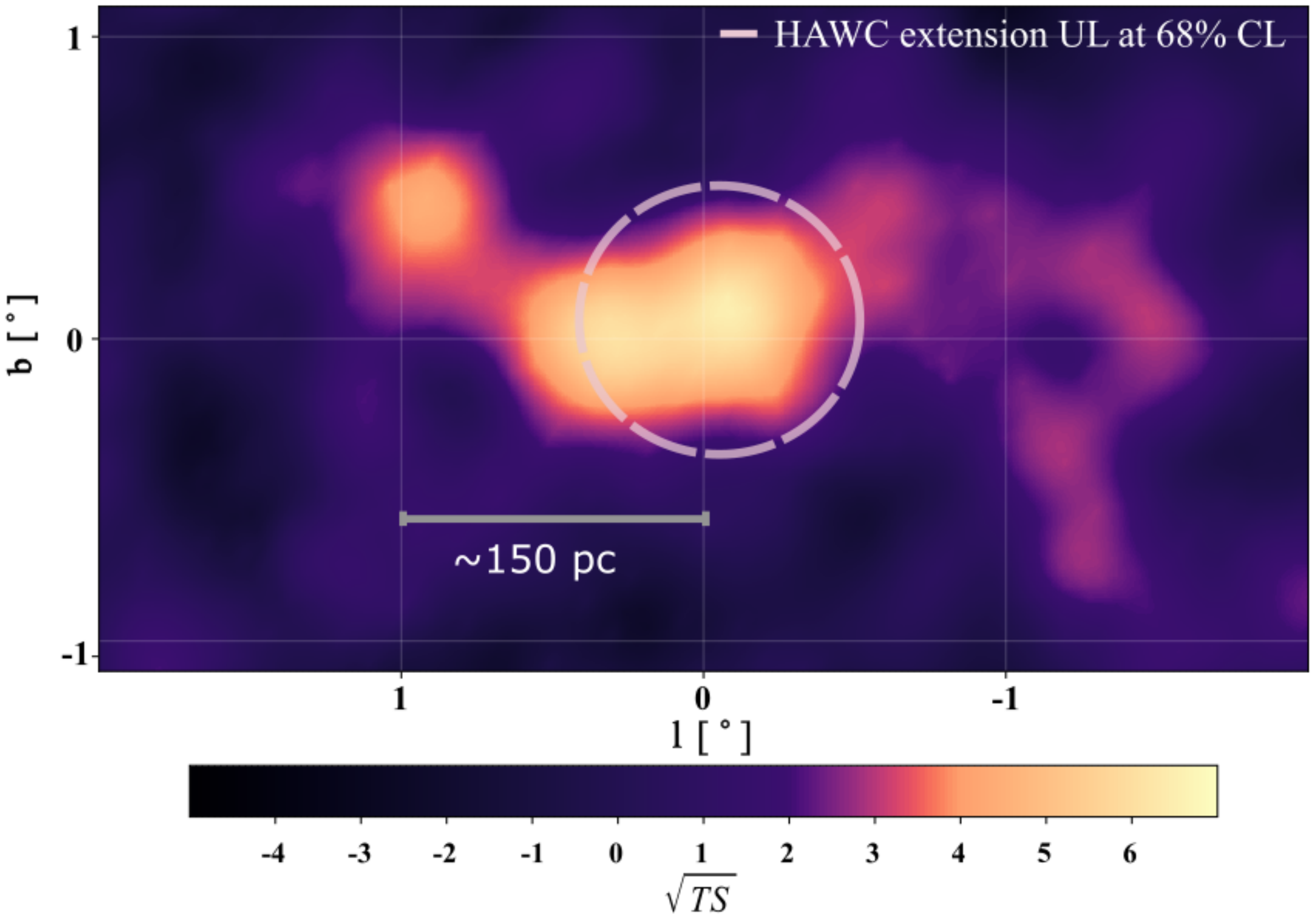
HAWC observation and modeling

Point source

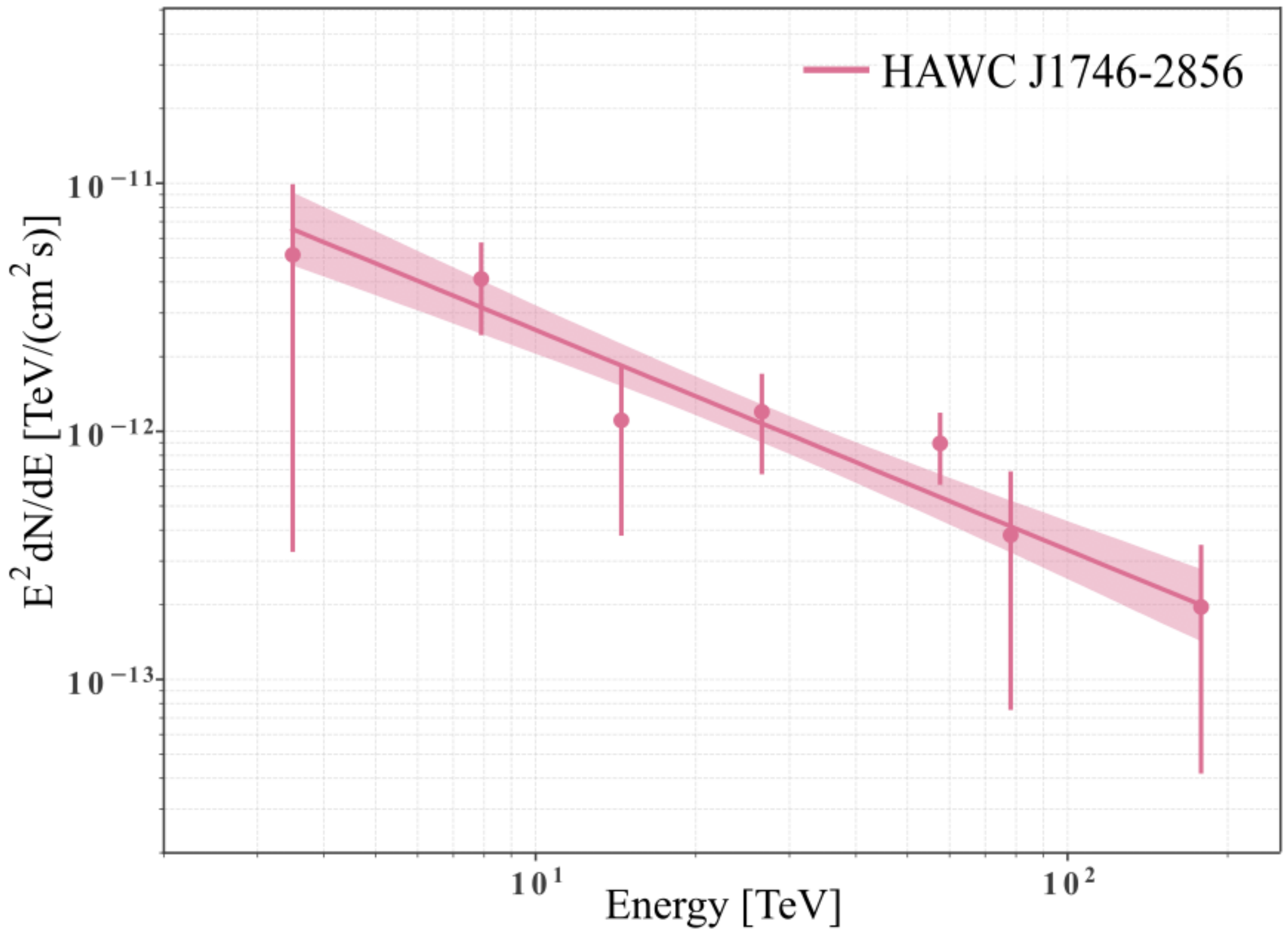


HAWC observation and modeling

Point source

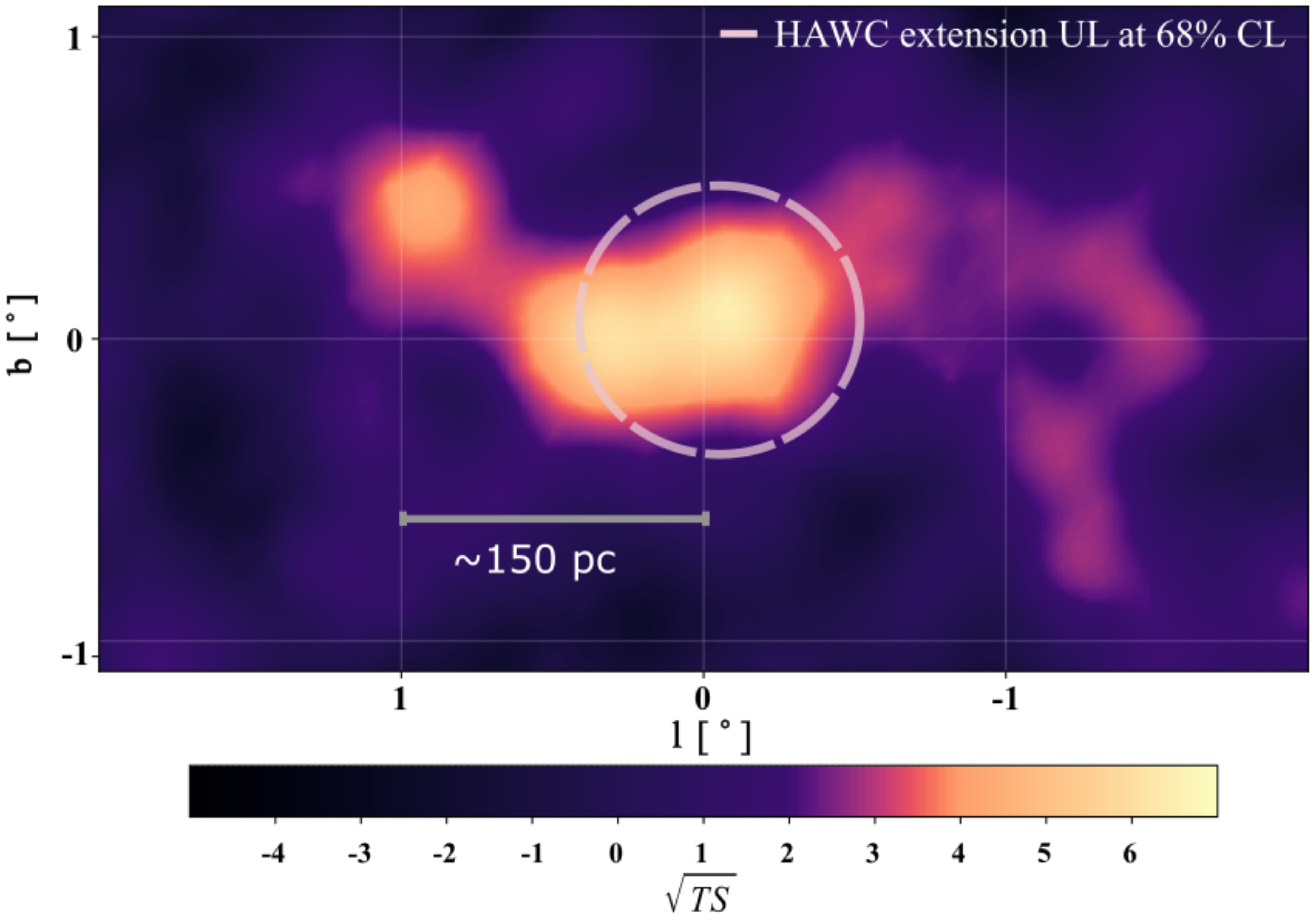


Power Law

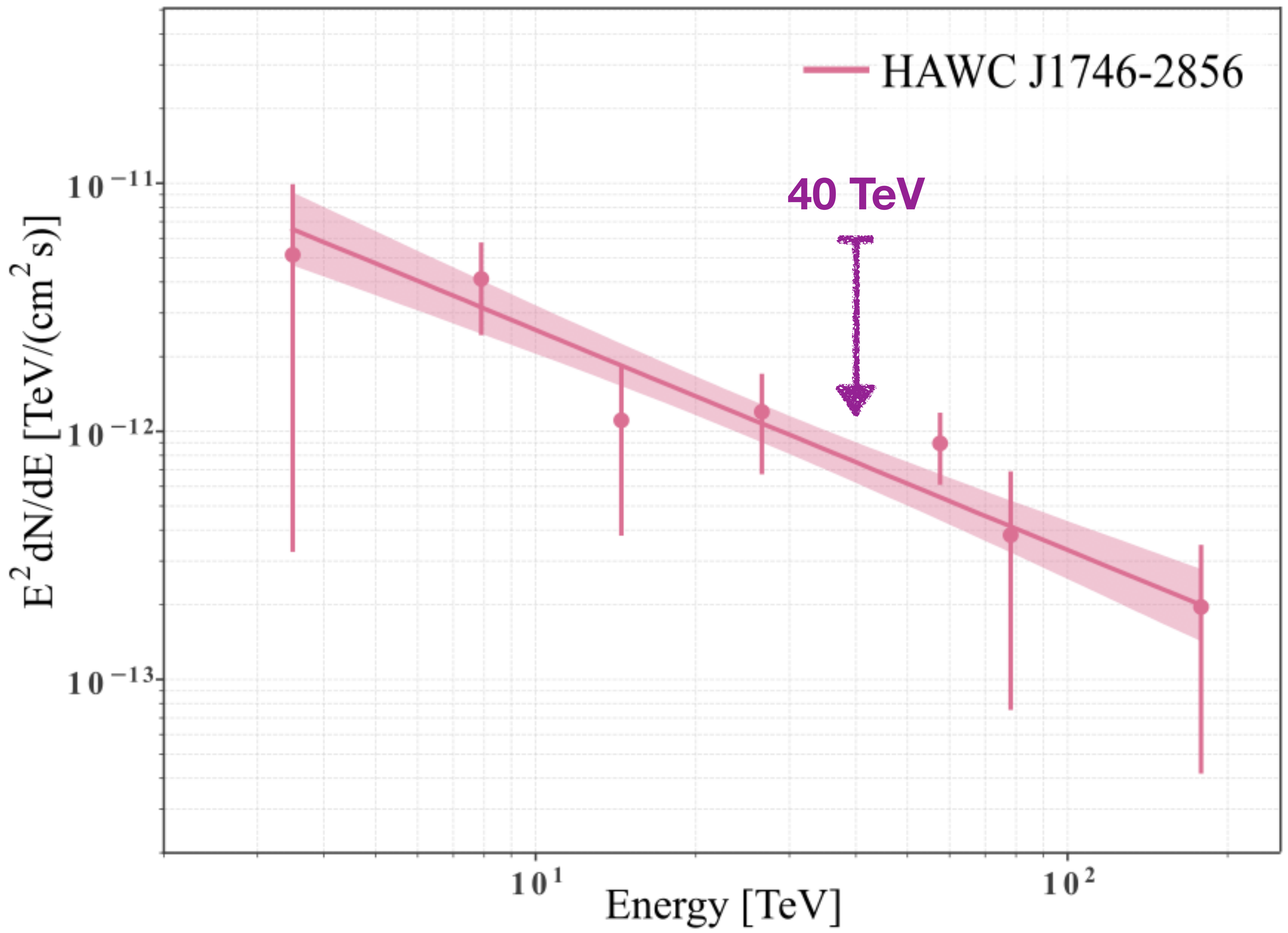


HAWC observation and modeling

Point source

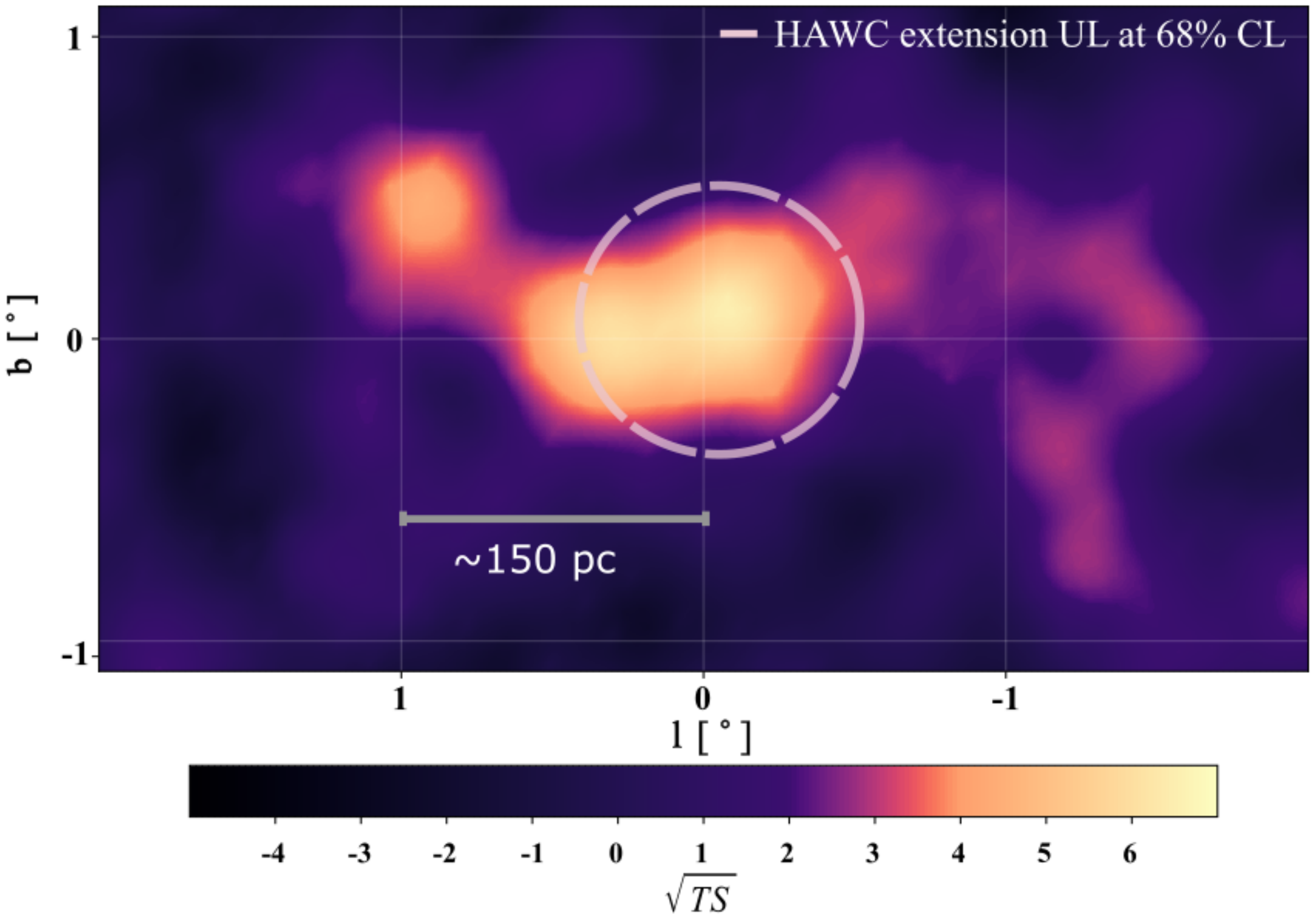


Power Law

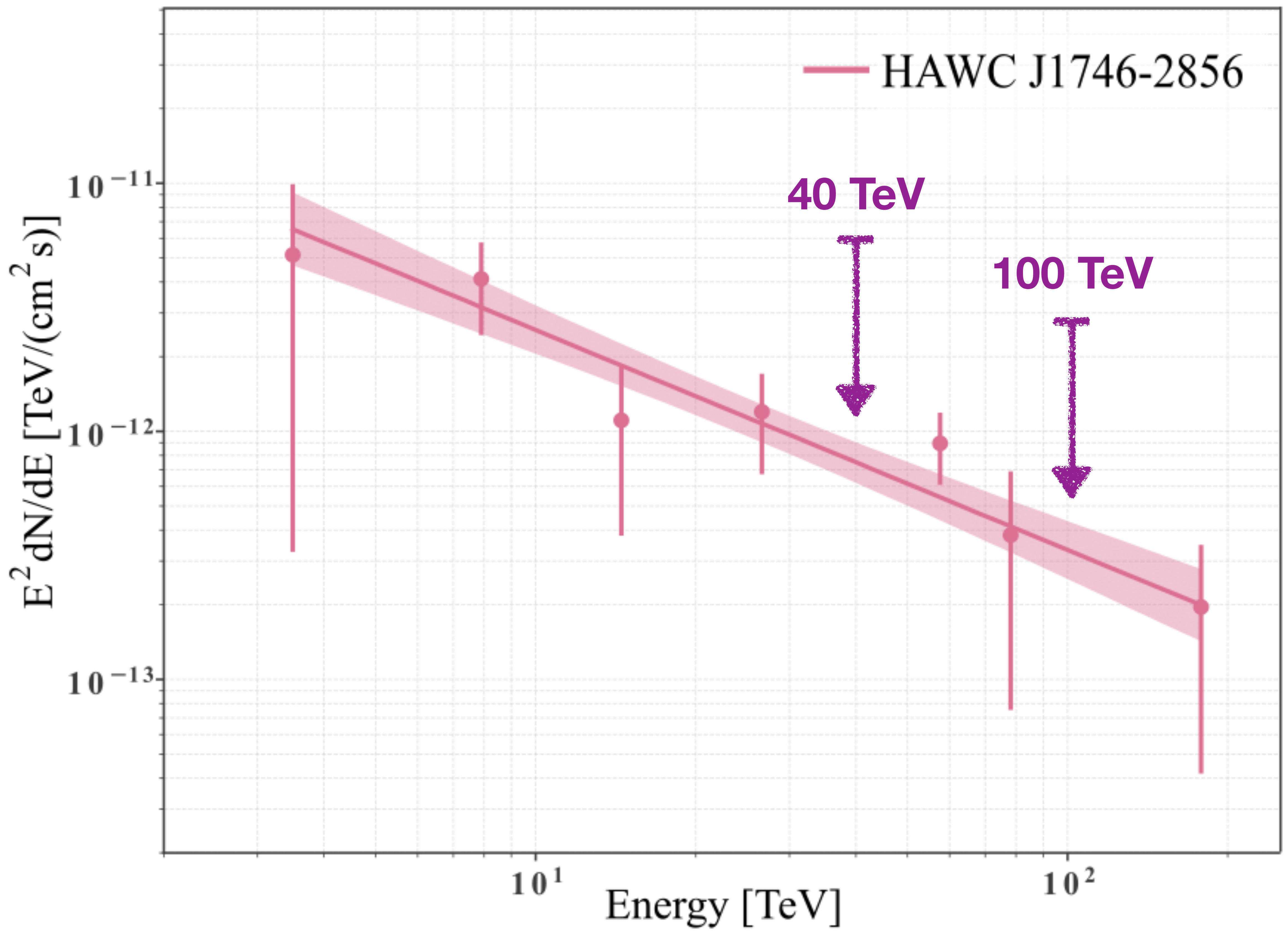


HAWC observation and modeling

Point source

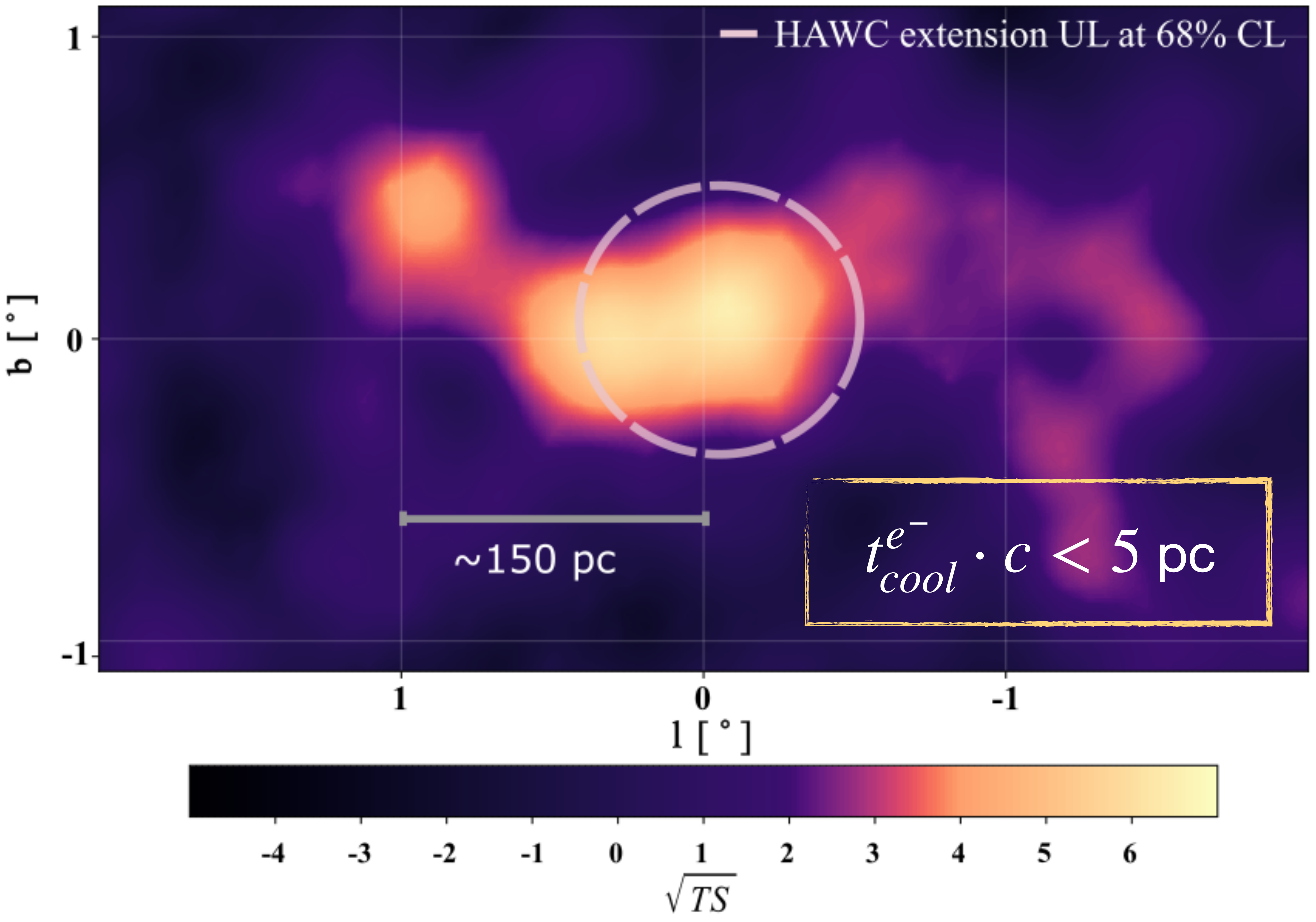


Power Law

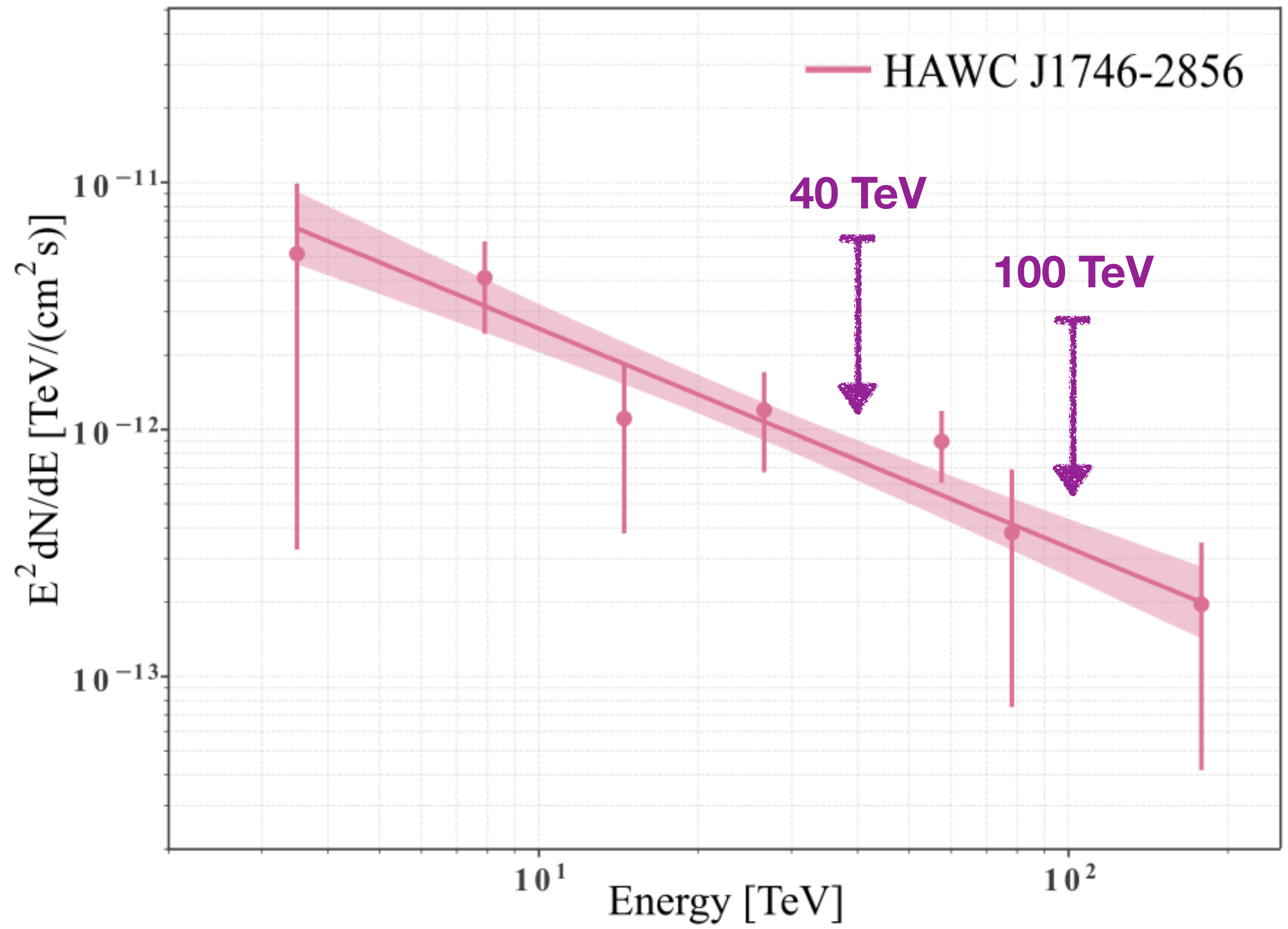


HAWC observation and modeling

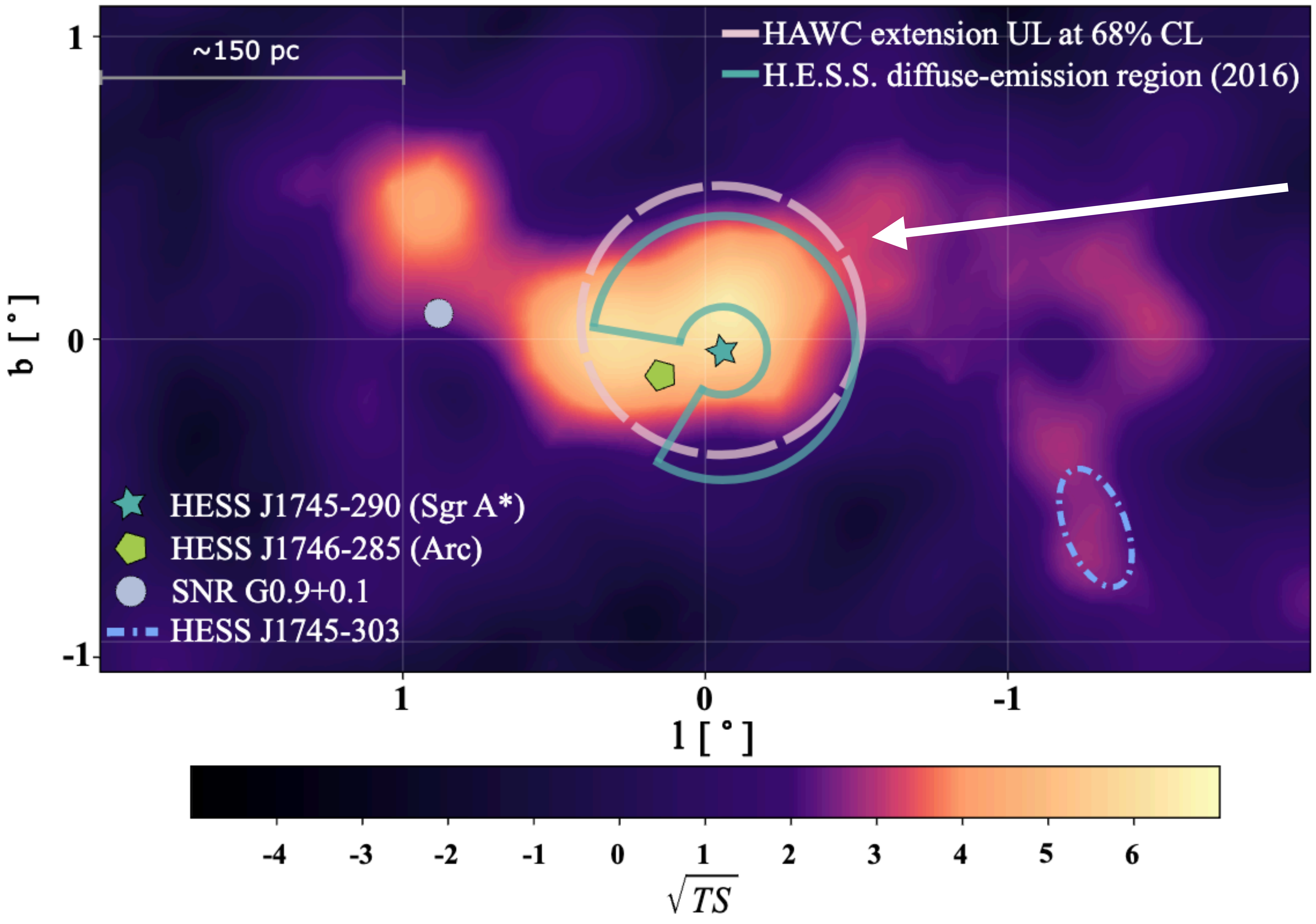
Point source



Power Law



HAWC observation and modeling

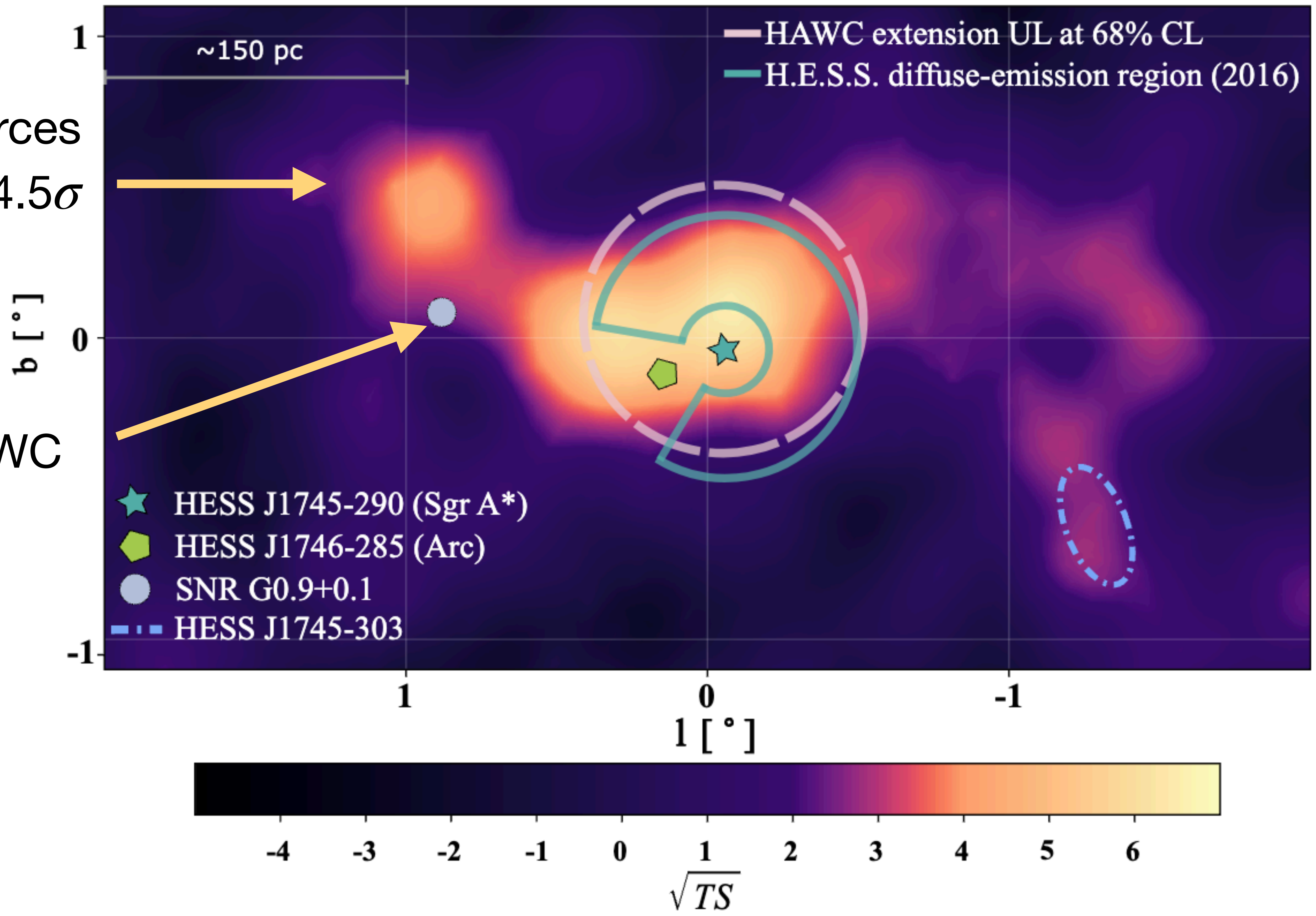


HAWC source coincident with two H.E.S.S. point sources and “pacman” diffuse region

HAWC observation and modeling

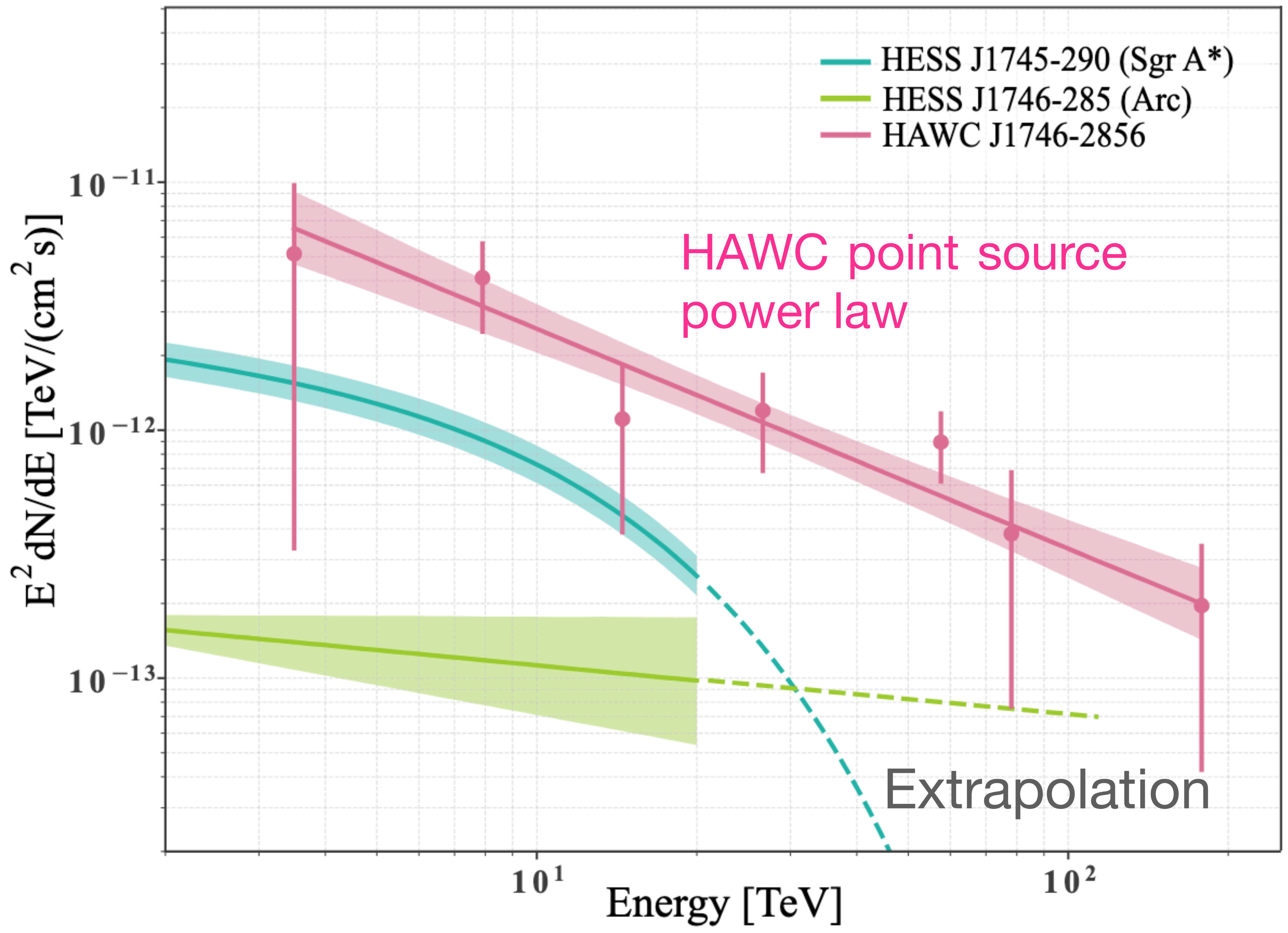
No known sources coincident with 4.5σ blob

SNR below HAWC sensitivity



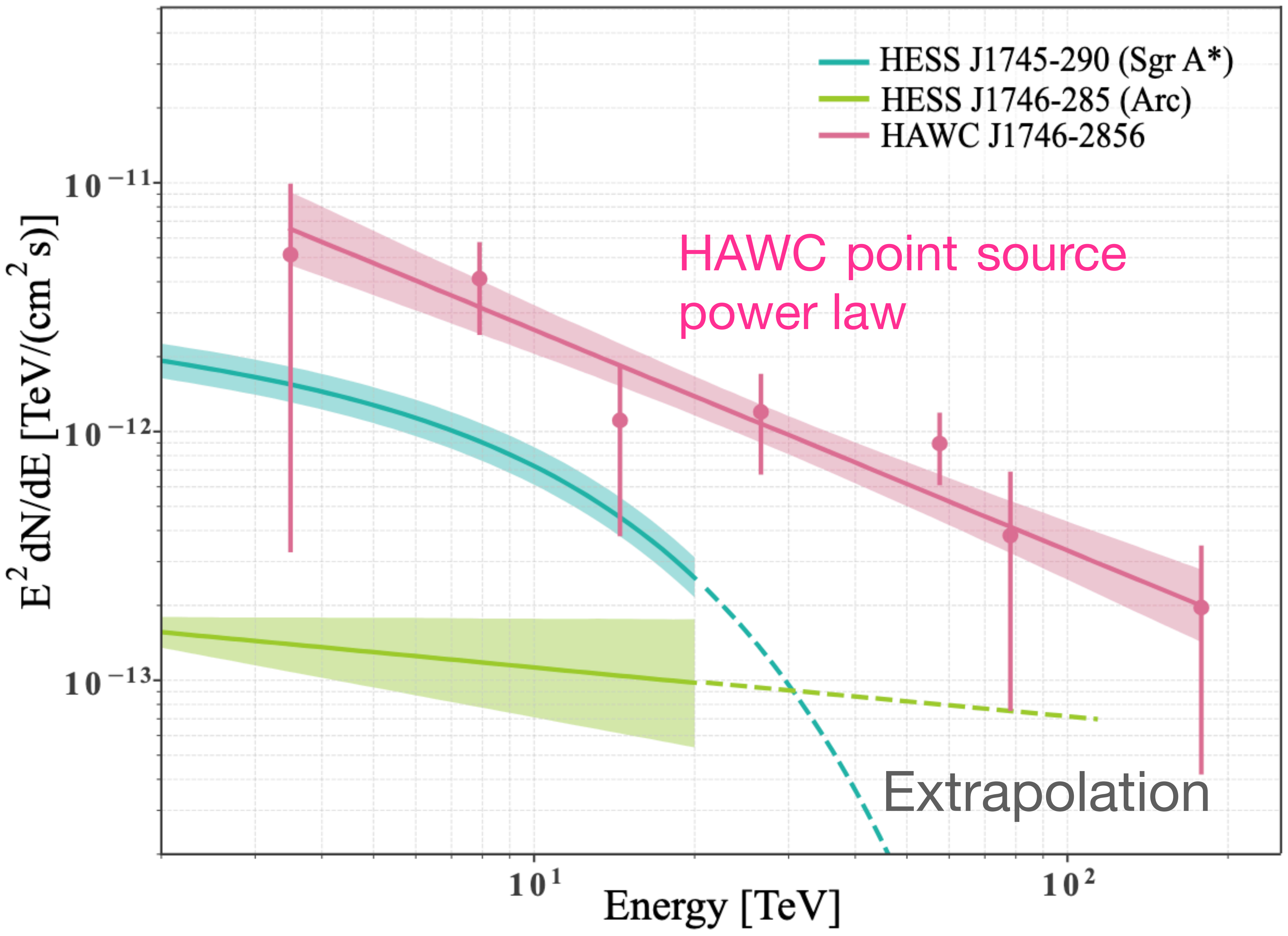
HAWC observation and modeling

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

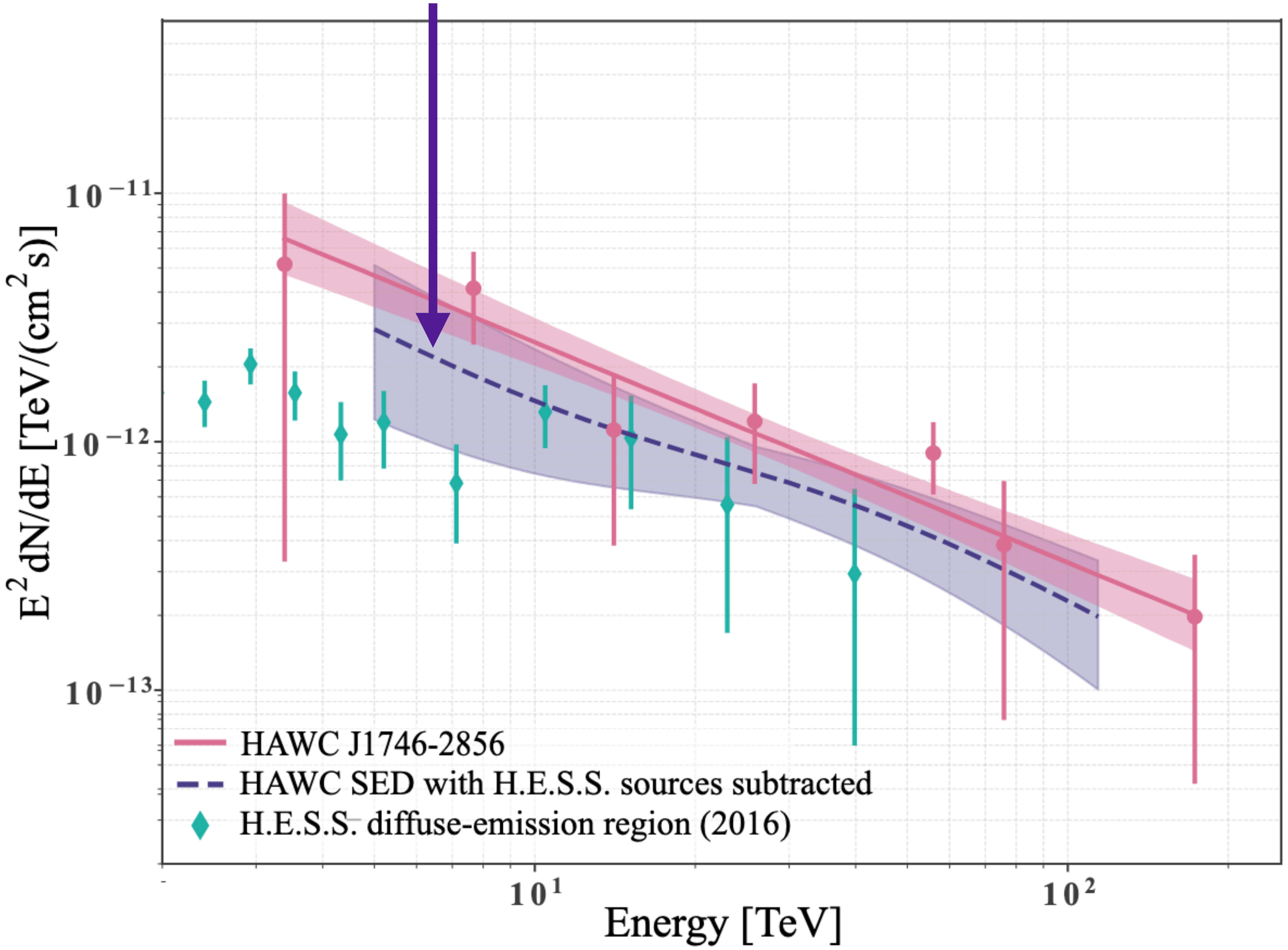


HAWC observation and modeling

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

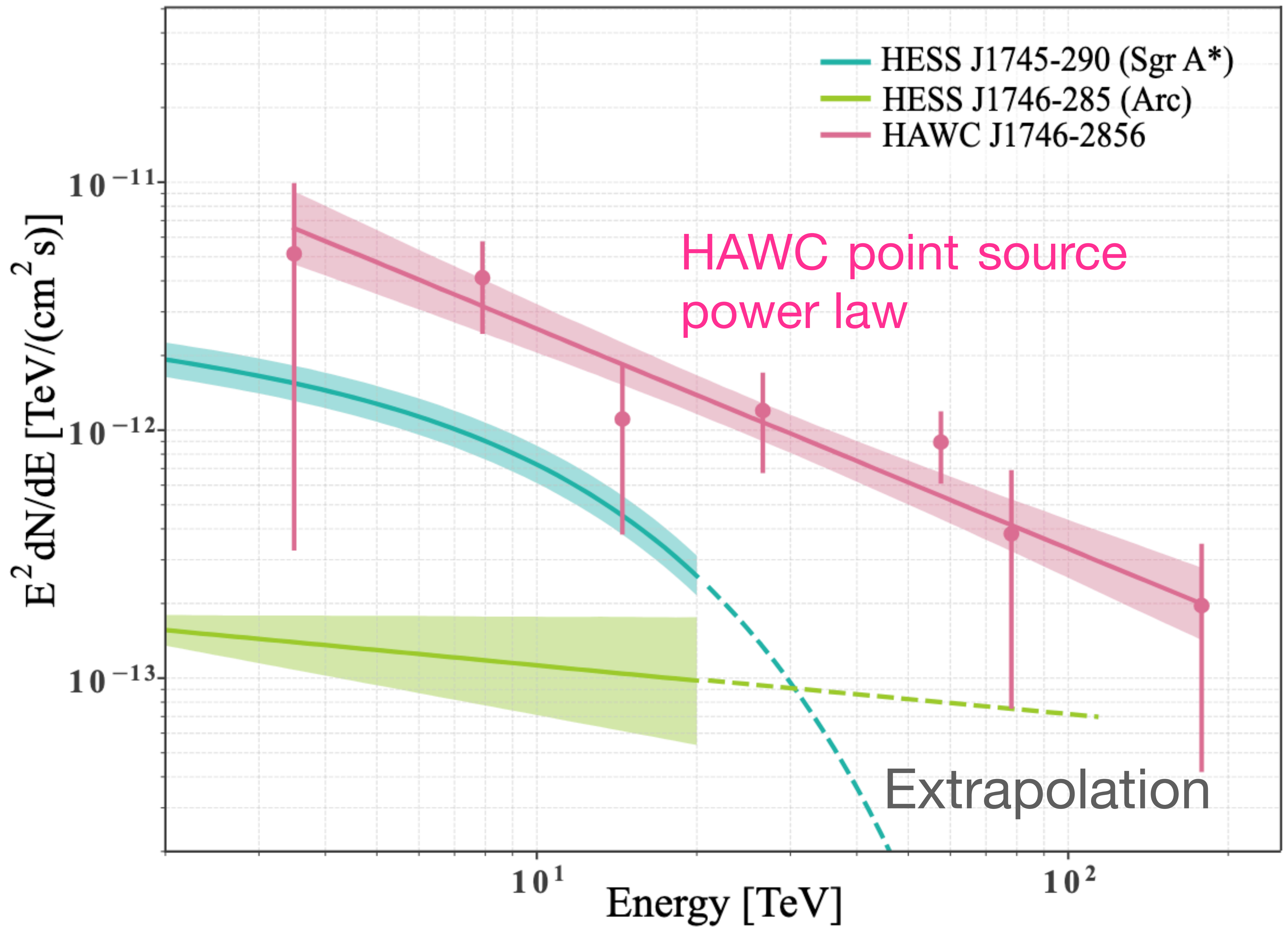


HAWC power law with H.E.S.S. sources subtracted.

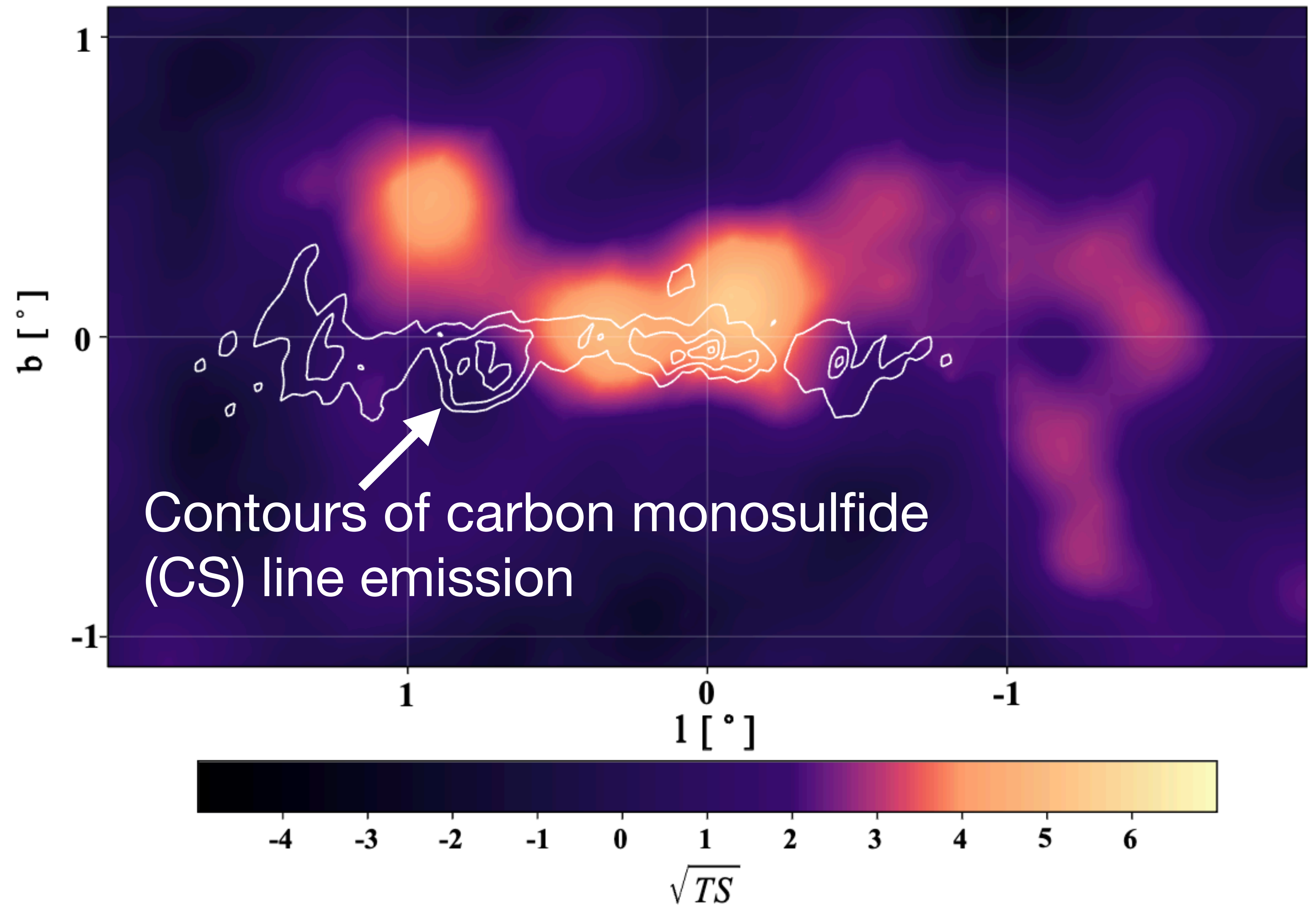


HAWC observation and modeling

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



Residual after subtracting the estimated excess of the H.E.S.S. point sources from HAWC data

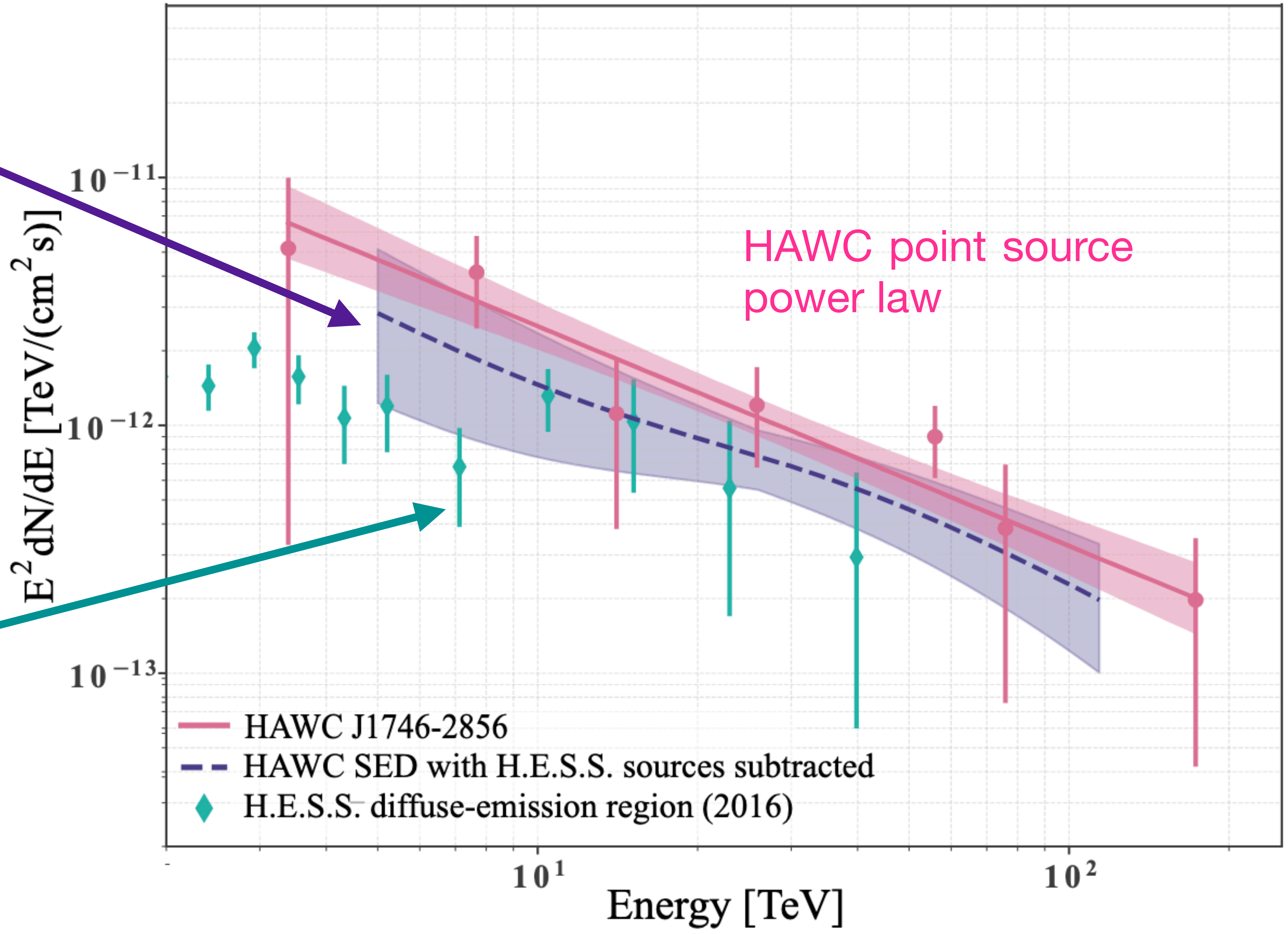


Main analysis results

HAWC power law with H.E.S.S. sources subtracted continues to 100 TeV without evidence of cutoff.

This is likely GC diffuse emission from PeV protons interacting with molecular clouds, and in small contribution, unresolved sources.

"Pacman" diffuse flux points for comparison



Hadronic origin and continuous injection

- The cooling time of protons is not a concern. It's actually the opposite!
- $t_{\text{escape}} \approx 100$ yr for 1 PeV protons -> proton source(s) are either very young or injecting protons into the CMZ in a recent burst.
- Only plausible explanation is that one or more sources quasi-continuously accelerate and inject high-energy protons into the CMZ at rates that exceed the escape rate.

Consistency checks

- The energy density of cosmic-ray protons using our measurement of the gamma-ray flux above 10 TeV is much larger than the local measurement by the Alpha Magnetic Spectrometer.

- And our estimated total energy budget of protons with energies >100 TeV is compatible with H.E.S.S. measurements.

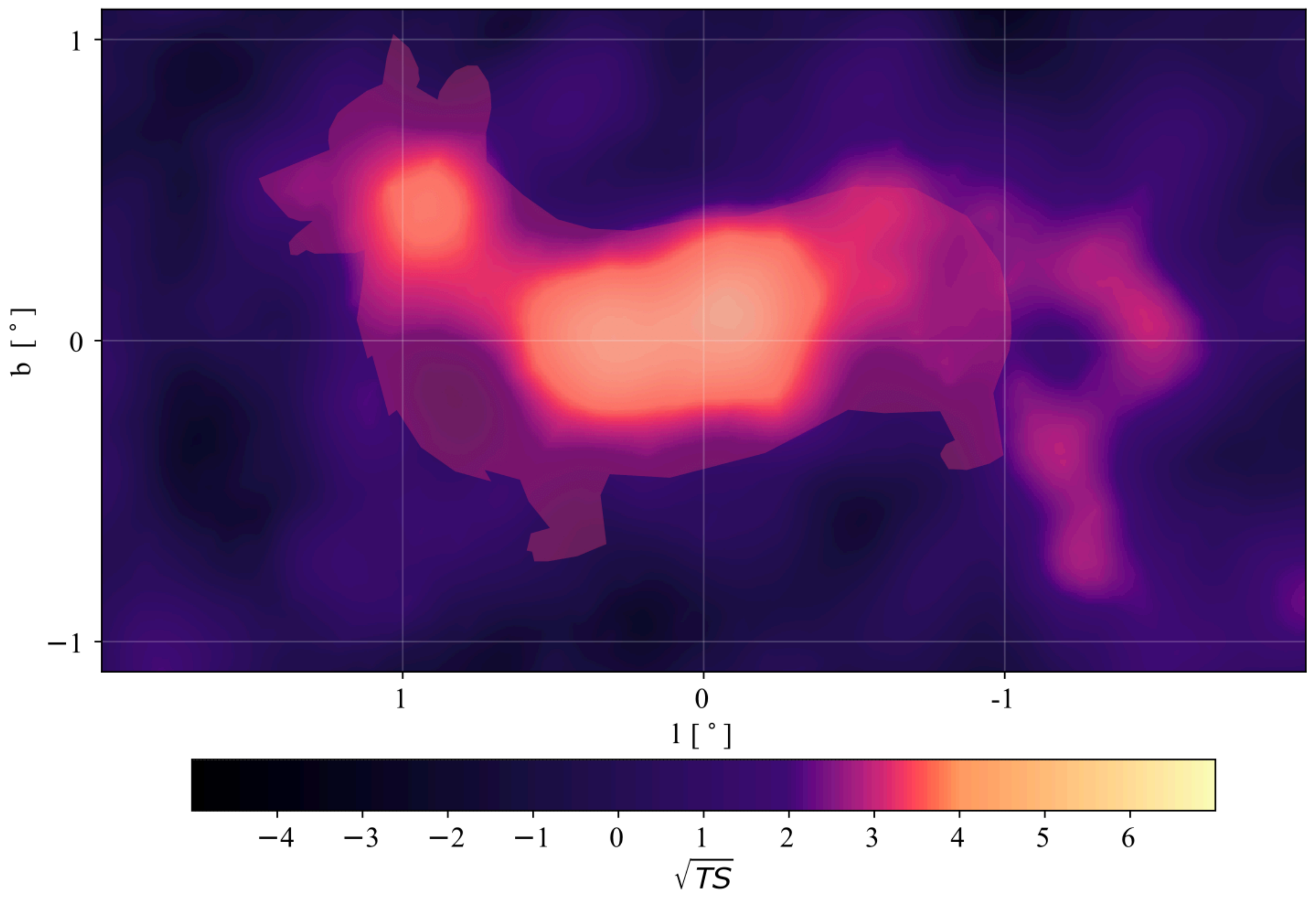
Conclusion

- We attribute the UHE gamma rays to the freshly accelerated proton CRs from the local accelerators within the GC region, which continuously inject protons with PeV energies.
- HAWC results confirm suggestion made with lower energy observations of the GC diffuse emission.
- However, we cannot resolve the specific PeVatron source.
- In coming years—CTA and SWGO could better constraint models of the CMZ.

Thank you!

The Galactic Corgi (GC)

Gamma rays



Optical

Dr. to be S. Yun-Cárcamo (yunsoh@umd.edu)

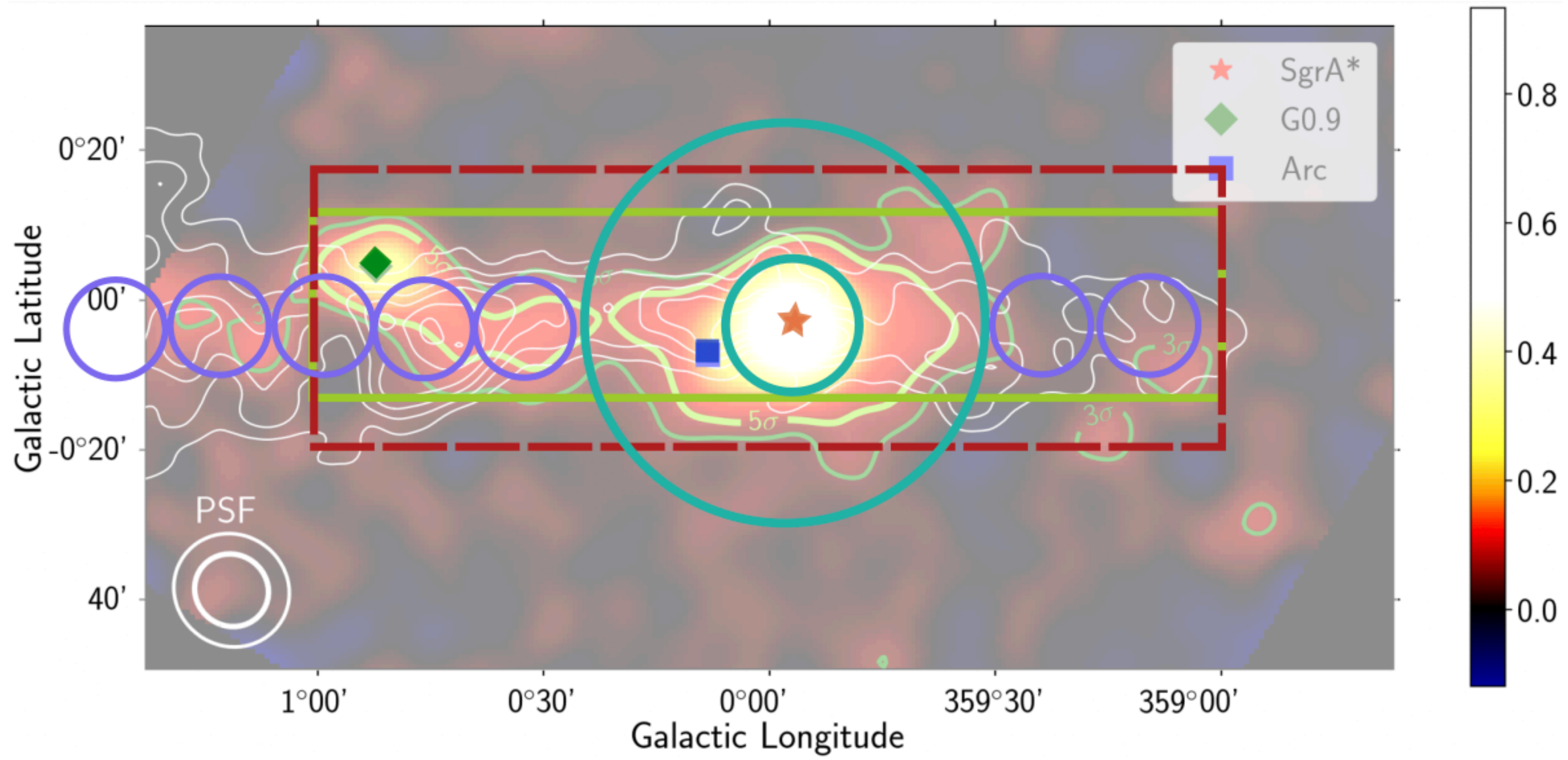
The End

BACK-UP slides

BACK UP

- H.E.S.S., MAGIC., and VERITAS have observed very high-energy (VHE) gamma rays spatially correlated to the CMZ up to 50 TeV without cutoff, suggesting a hadronic origin.

- They have also measured gamma-ray emission up to 20 TeV from two point sources in the region: Sgr A* (HESS J1745-290) and the radio arc HESS J1746-285, but only H.E.S.S. was able to model the diffuse emission to isolate this source's spectrum.

- 

H.E.S.S. 2016 diffuse region
HESS 2018 diffuse region
VERITAS diffuse region
MAGIC diffuse region

Image Credit: MAGIC collaboration 2020.

Frequently asked questions: how do you subtract significance?

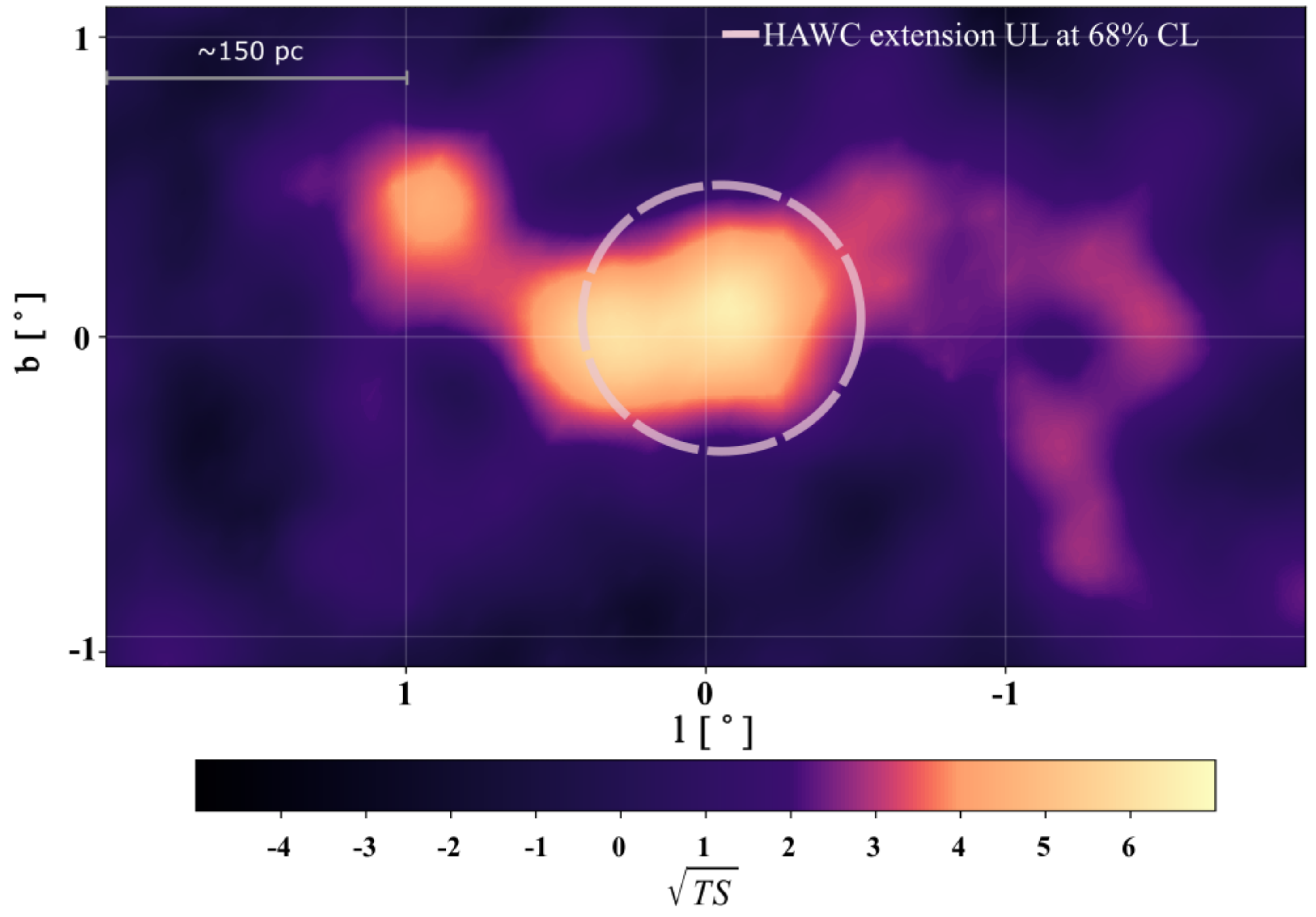
The predicted event count is calculated by convolving a model file with H.E.S.S. sources reported best-fit parameters with the HAWC instrument response function.

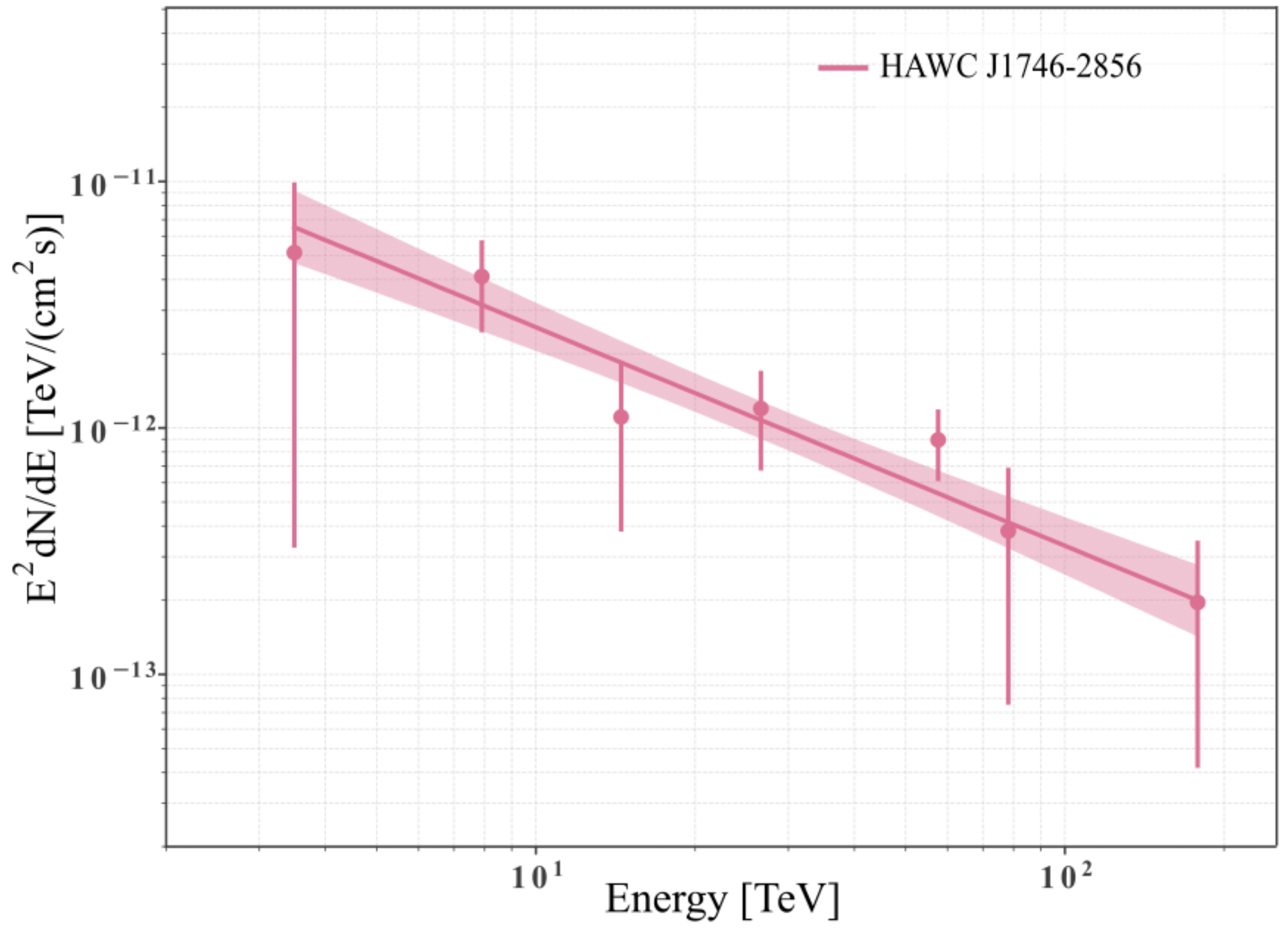
HAWC observation and modeling

The best fit to the data is a point source with a simple-power-law spectrum.

We calculated an upper limit of minimum energy at 6 TeV, and lower limit of maximum energy at 114 TeV, both at the 68% confidence level (CL).

Above 100 TeV, nearly 100 events pass gamma/hadron separation cuts.





Parameter estimated	Best fit	Statistical uncertainties	Systematic uncertainties
RA (°)	266.28	± 0.05	+0.09, −0.06
Dec (°)	−28.94	± 0.04	+0.03, −0.02
Flux norm. (ϕ) $\times 10^{-15}$ (TeV cm^{2}s)$^{-1}$	1.5	± 0.30	+0.08, −0.13
Index (γ)	−2.88	± 0.15	−0.1

Frequently asked questions: did you try other models?

- No strong preference was found when performing the fit to extended source models, hence the simplest model was chosen.
- Adding curvature to the spectrum did not significantly improve the test statistic.
- We do not model the diffuse background emission because for it to significantly impact the results, one would need to assume that the cosmic-ray sea's flux is nearly a factor of ten higher at the Galactic Center. Contradicting the widely accepted premise that the cosmic-ray sea is rather uniform in the Galaxy.

Origin of gamma rays with energies > 100 TeV

- *Leptonic scenario*: upscattering of low-energy photons by electrons with energies beyond 100 TeV.
- Electrons drastically lose energy by synchrotron emission so that they can only travel < 5 pc even at the speed of light, however the central molecular zone extends to ~ 100s of pcs

$$t_{\mathrm{cooling}} \approx 13\,\mathrm{yr} \left(\frac{E_{\mathrm{e}}}{100\mathrm{TeV}}\right)^{-1} \left(\frac{B}{100\,\mu\mathrm{G}}\right)^{-2} \approx 13\,\mathrm{yr}\,.$$

Therefore, the HAWC observation strongly disfavors a leptonic scenario.

Origin of gamma rays with energies > 100 TeV

- *Hadronic scenario*: the collision of relativistic protons (~1 PeV) with the surrounding dense ambient gas (neutral pion decay)

- The escape time for 1 PeV protons, assuming the Galactic plane characteristic diffusion coefficient

$$t_{\mathrm{escape}} \approx \frac{r^2}{2D} \approx 100 \left(\frac{r}{40\,\mathrm{pc}}\right)^2 \left(\frac{E_{\mathrm{p}}}{1\,\mathrm{PeV}}\right)^{-0.3} \mathrm{yr}\,,$$

- This escape time is much shorter than the age of the Galaxy, implying that the proton source(s) are either very young or injecting protons into the CMZ in a recent burst. Therefore, the only plausible explanation is that one or more sources quasi-continuously accelerate and inject high-energy protons into the CMZ at rates that exceed the escape time.

Consistency checks

- We calculated the energy density of cosmic-ray protons using our measurement of the gamma-ray flux above 10 TeV and show that is larger than the local measurement by the Alpha Magnetic Spectrometer (AMS; 1×10^{-3} eV/cm^3)

$$w_{\rm p}(\geq 10 E_\gamma) = 1.8 \times 10^{-2} \left(\frac{\eta_N}{1.5}\right)^{-1} \left(\frac{L_\gamma(E_\gamma \geq 10\ \text{TeV})}{10^{34}\ \text{erg/s}}\right) \left(\frac{M}{10^6 M_\odot}\right)^{-1} \text{eV/cm}^3 \approx 8.1 \times 10^{-3}\ \text{eV/cm}^3$$

- We calculated the total energy budget of protons with energies >100 TeV using HAWC observations and show that it is compatible with H.E.S.S. measurements ($2.1 \times 10^{49} n^{-1}$ erg)

$$W_p \approx L_\gamma(E_\gamma \geq 10\ \text{TeV})\, t_{\rm pp} \approx 3.53 \times 10^{49} n^{-1}\ \text{erg}$$