The Unexpected TeV Emitters in the Galactic Plane

Ke Fang

University of Wisconsin-Madison

Sugar 2024, Madison, WI

October16, 2024

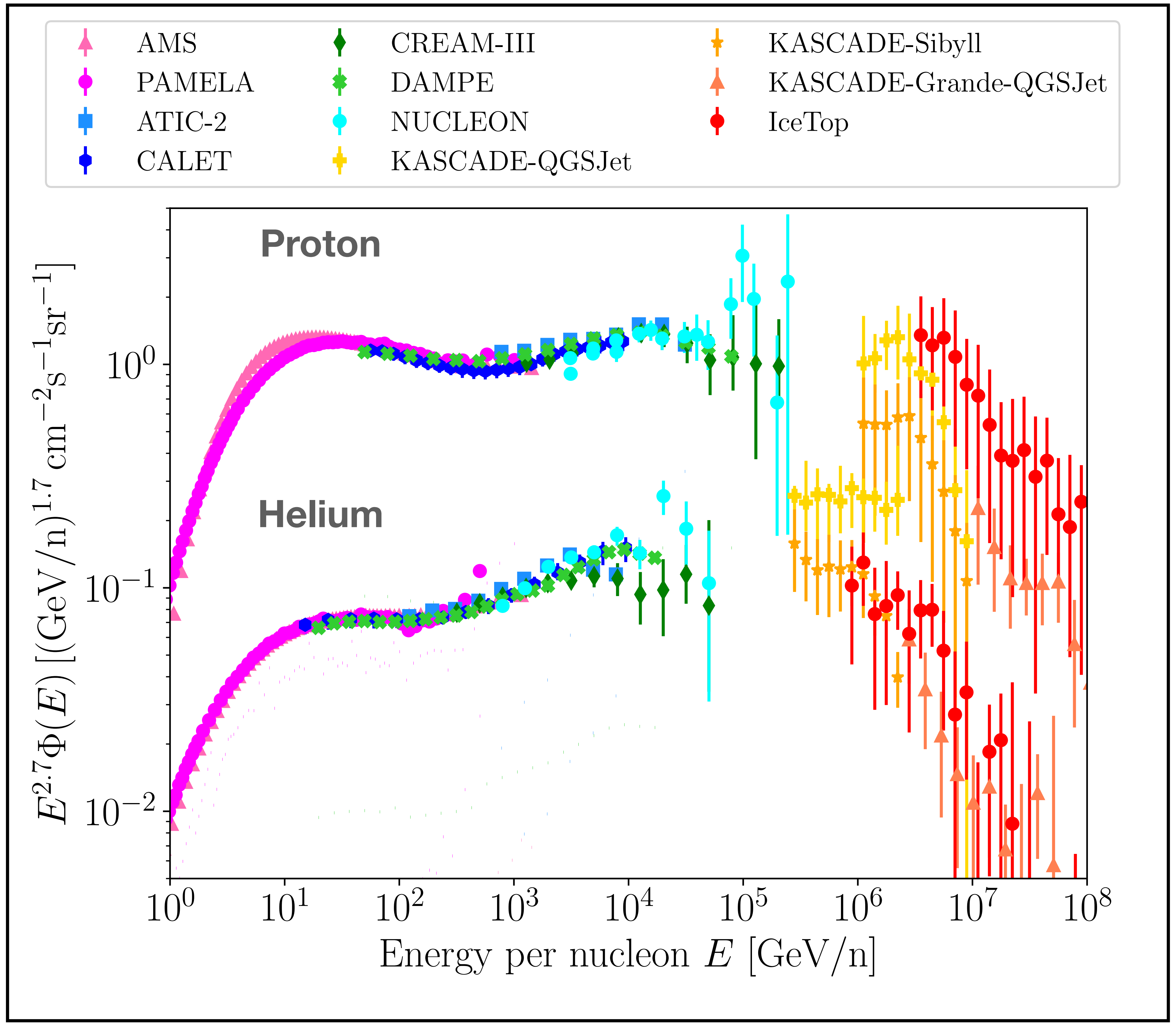
\

- The sky viewed with 100 TeV photons — γ
- Gamma-ray-obscured sources — ν γ

- **The sky viewed with 100 TeV photons** γ
- Gamma-ray-obscured sources ν γ

The PeVatron

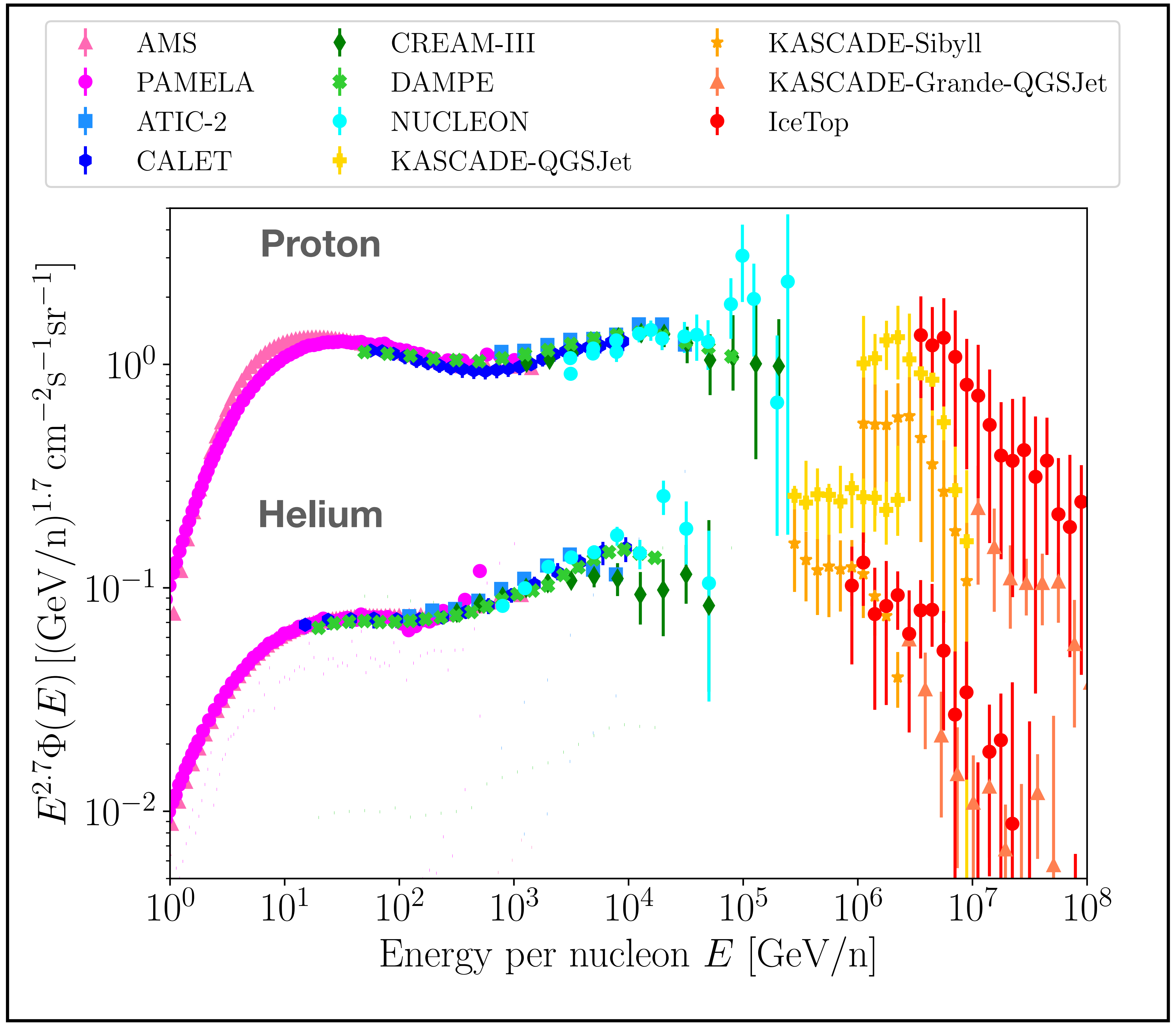
From P. Blasi's talk:
Definition of a PeVatron: "A PeVatron is a source that is able to accelerate particles with a spectrum that shows a substantial suppression with respect to its low energy power law extrapolation in the region of PeV energies"



The PeVatron

From P. Blasi's talk:
Definition of a PeVatron: "A PeVatron is a source that is able to accelerate particles with a spectrum that shows a substantial suppression with respect to its low energy power law extrapolation in the region of PeV energies"

Strictly: a PeVatron is an object that accelerates **protons** to the PeV range with a **hard (slope ~ 2) spectrum**

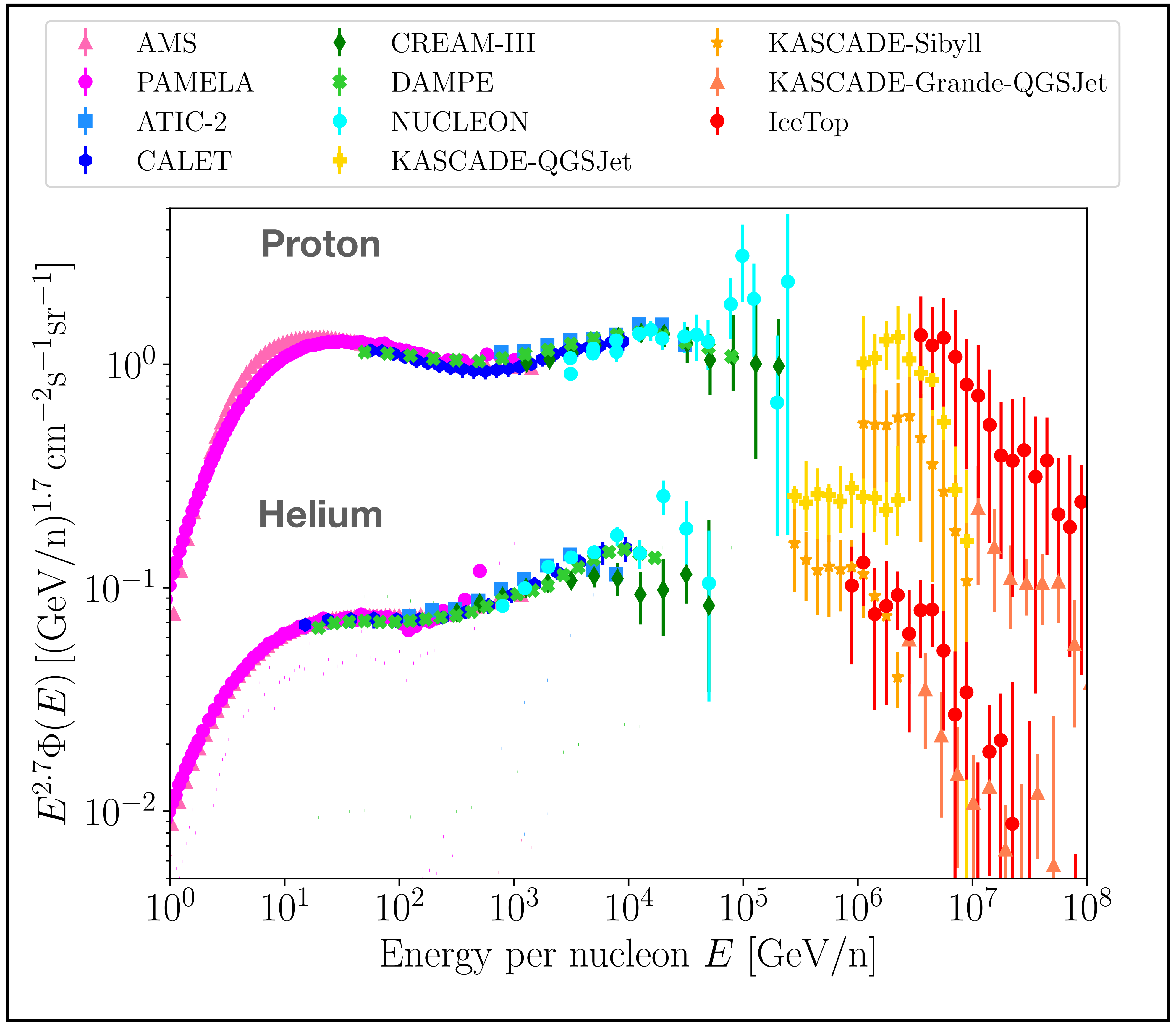


The PeVatron

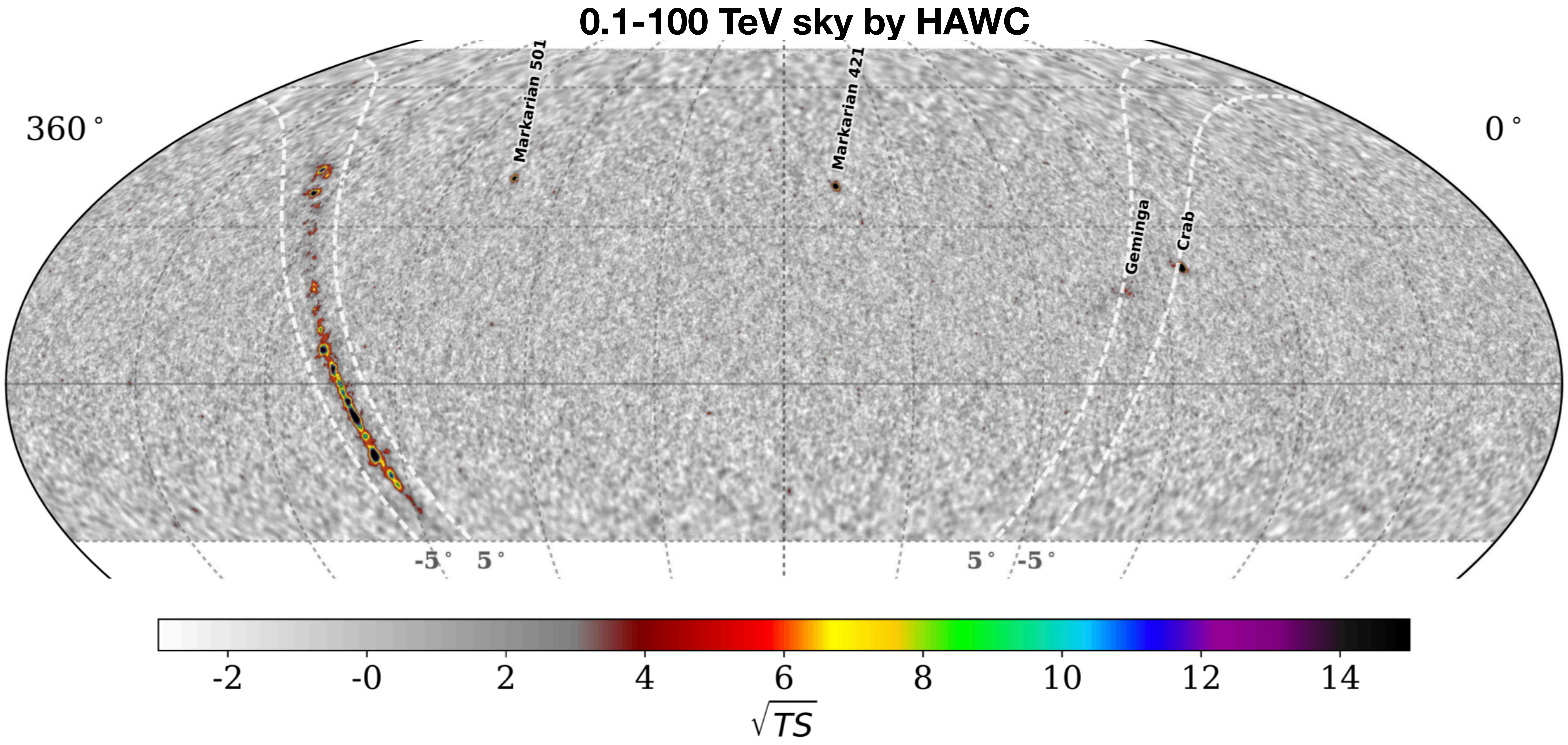
From P. Blasi's talk:
Definition of a PeVatron: "A PeVatron is a source that is able to accelerate particles with a spectrum that shows a substantial suppression with respect to its low energy power law extrapolation in the region of PeV energies"

Strictly: a PeVatron is an object that accelerates **protons** to the PeV range with a **hard (slope ~ 2) spectrum**

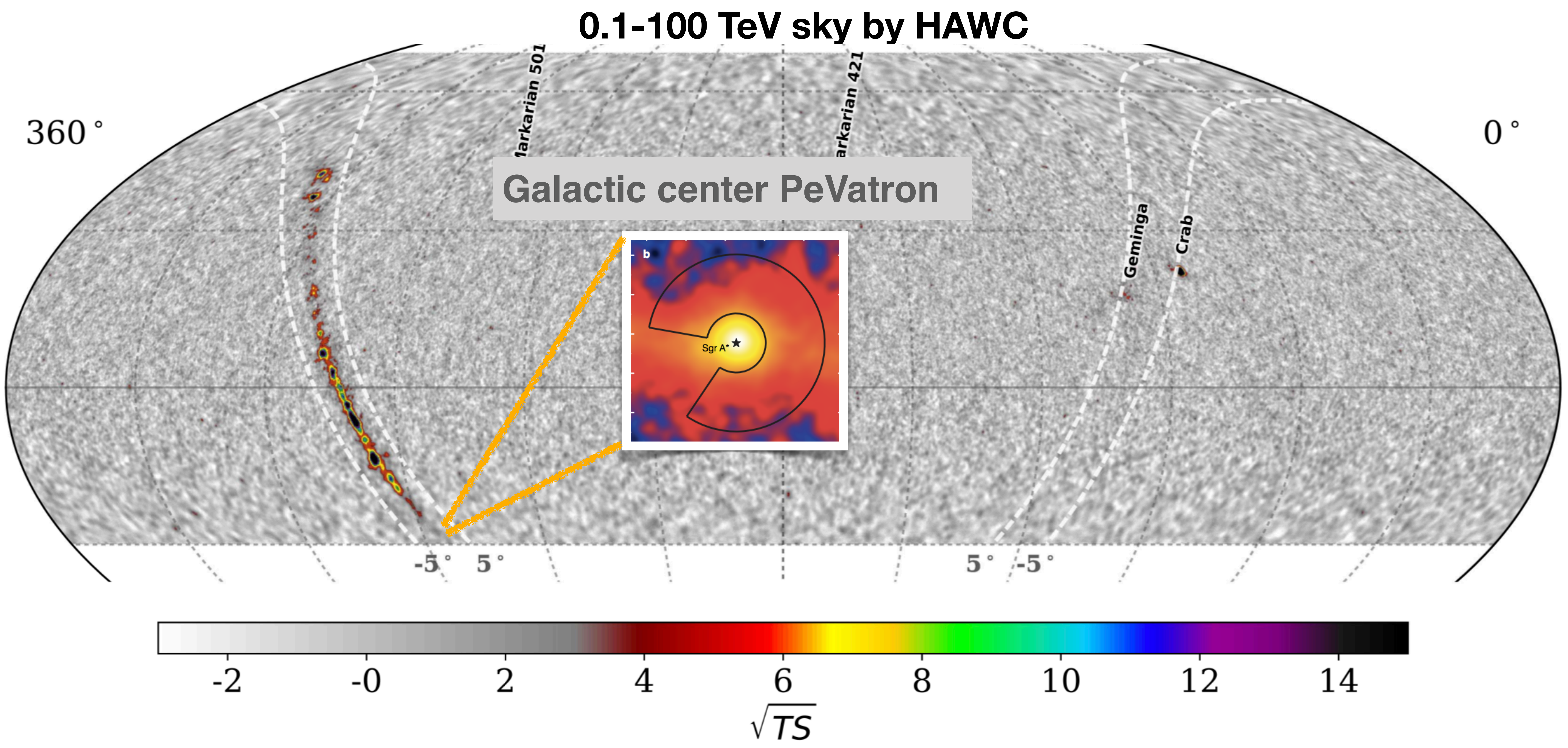
Broadly: an object that accelerates either leptons or hadrons to the PeV range



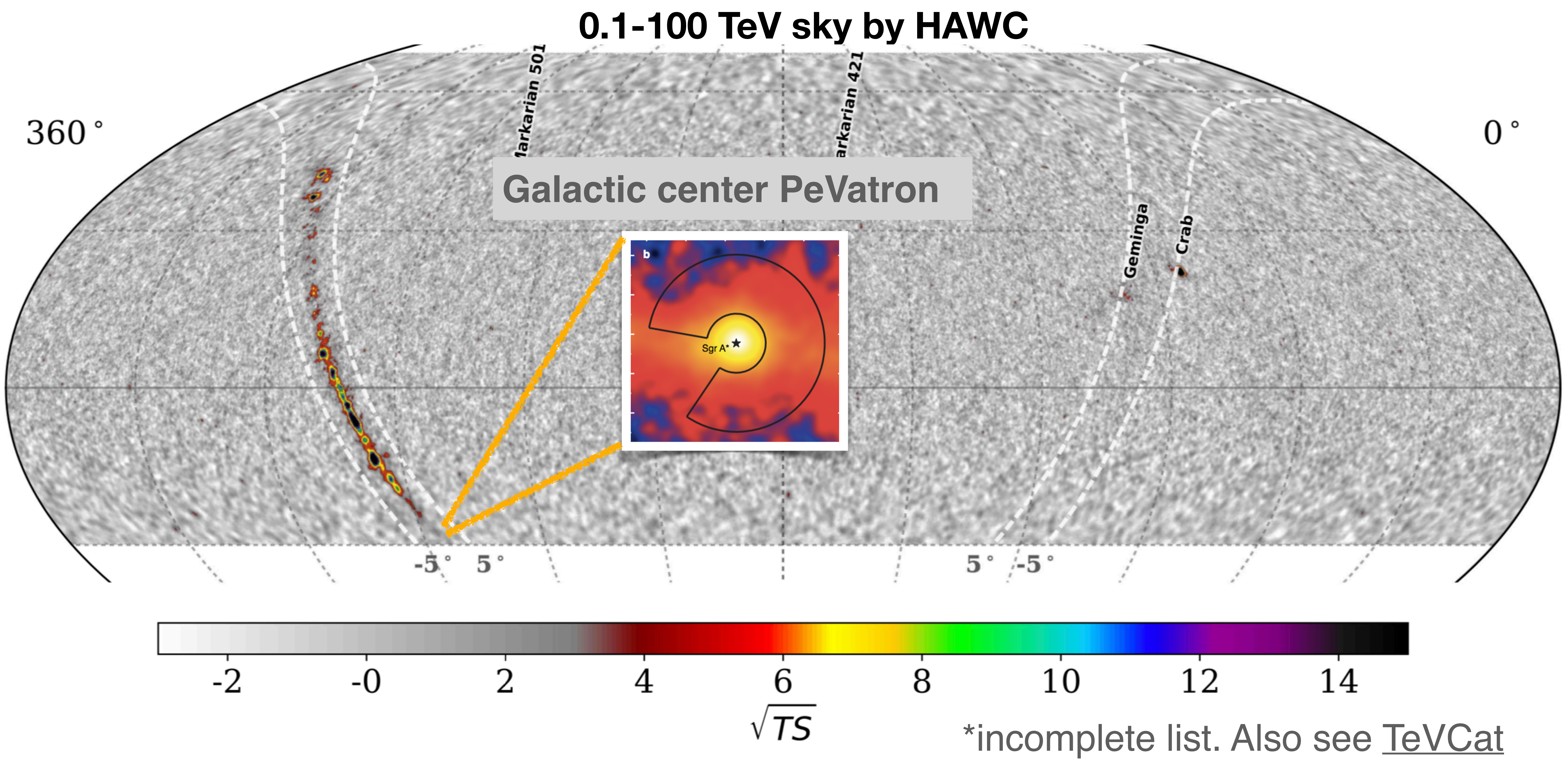
PeVatron in 2016



PeVatron in 2016



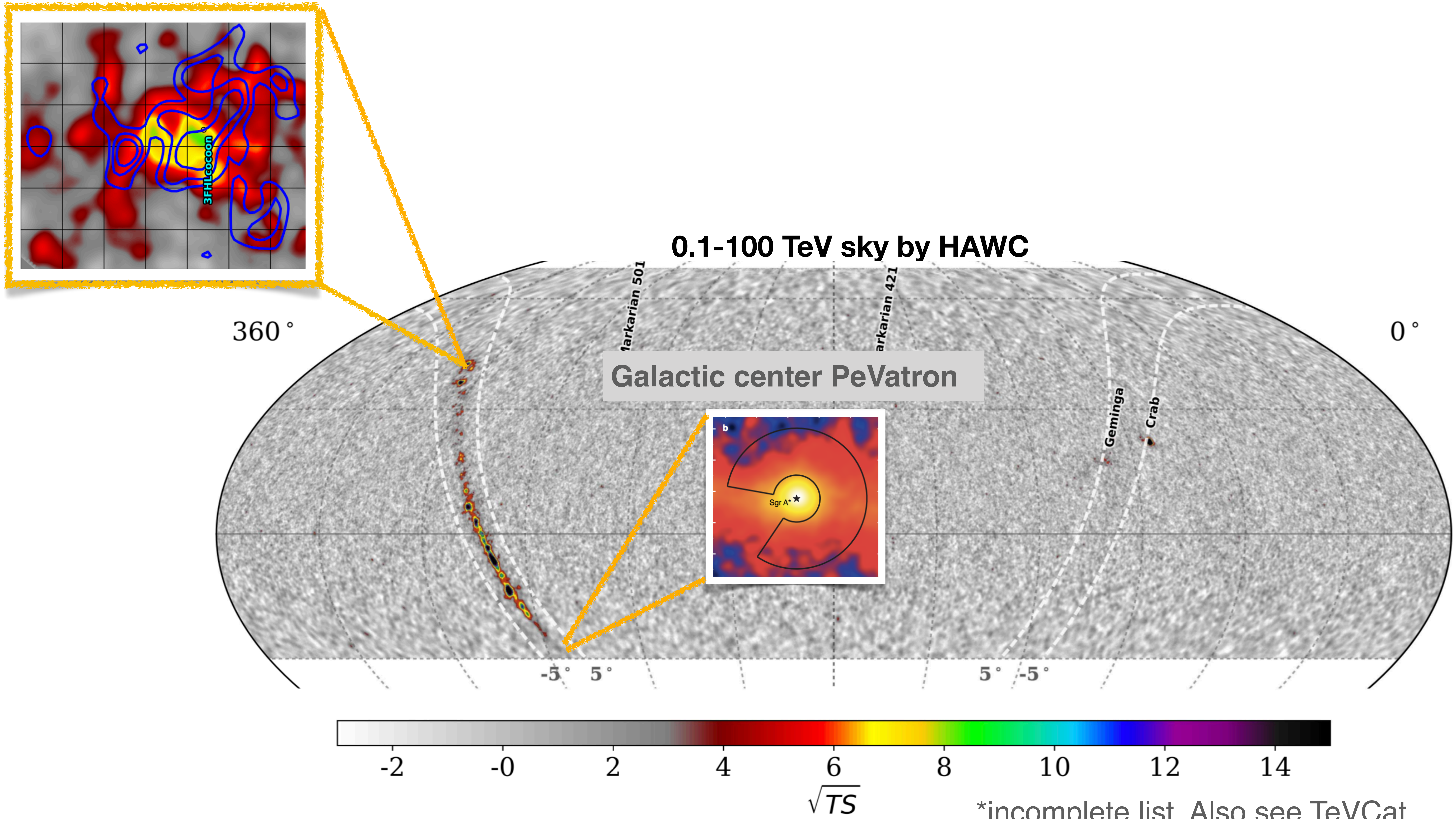
PeVatron Zoo* in 2024



*incomplete list. Also see TeVCat

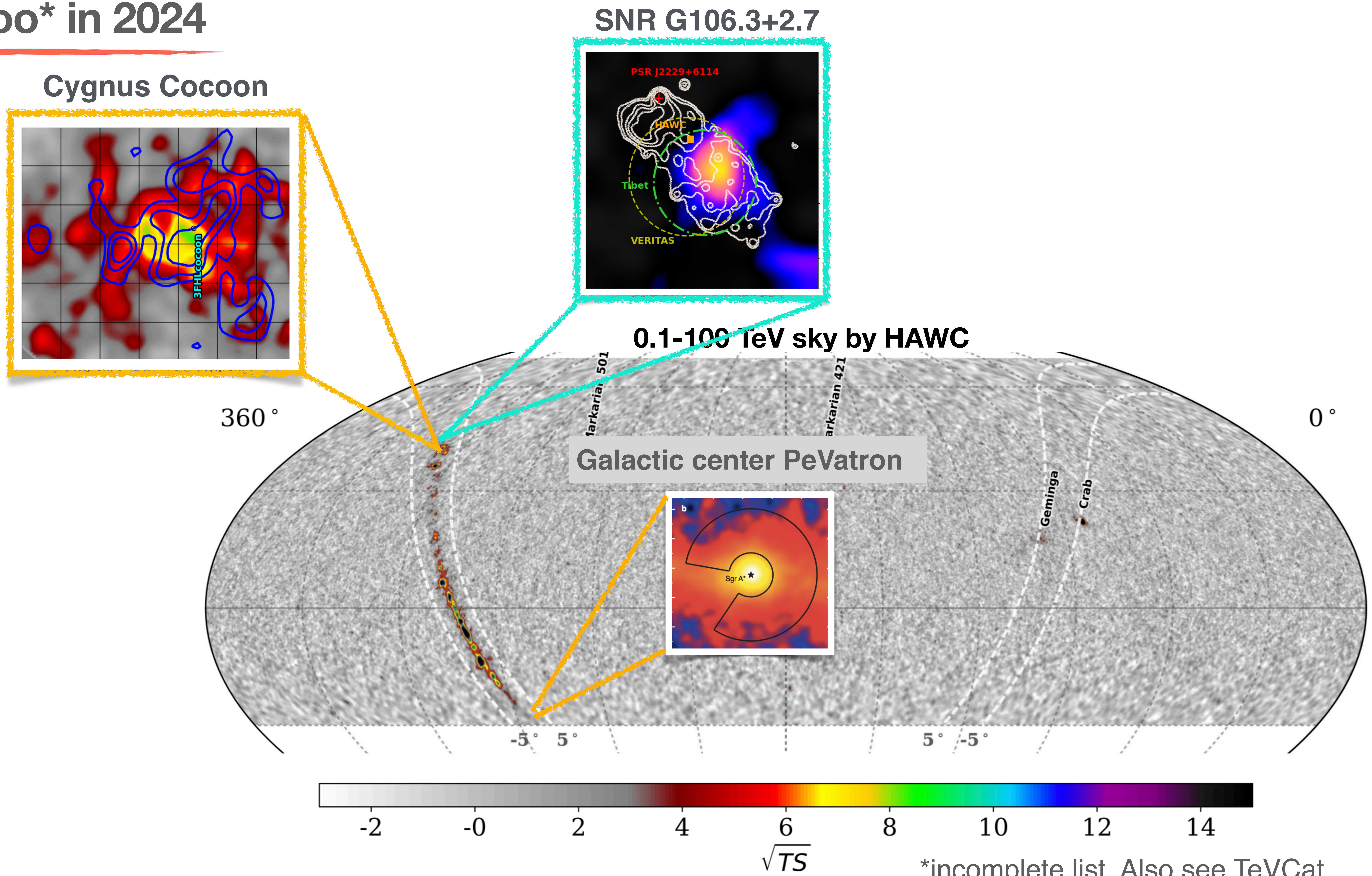
PeVatron Zoo* in 2024

Cygnus Cocoon



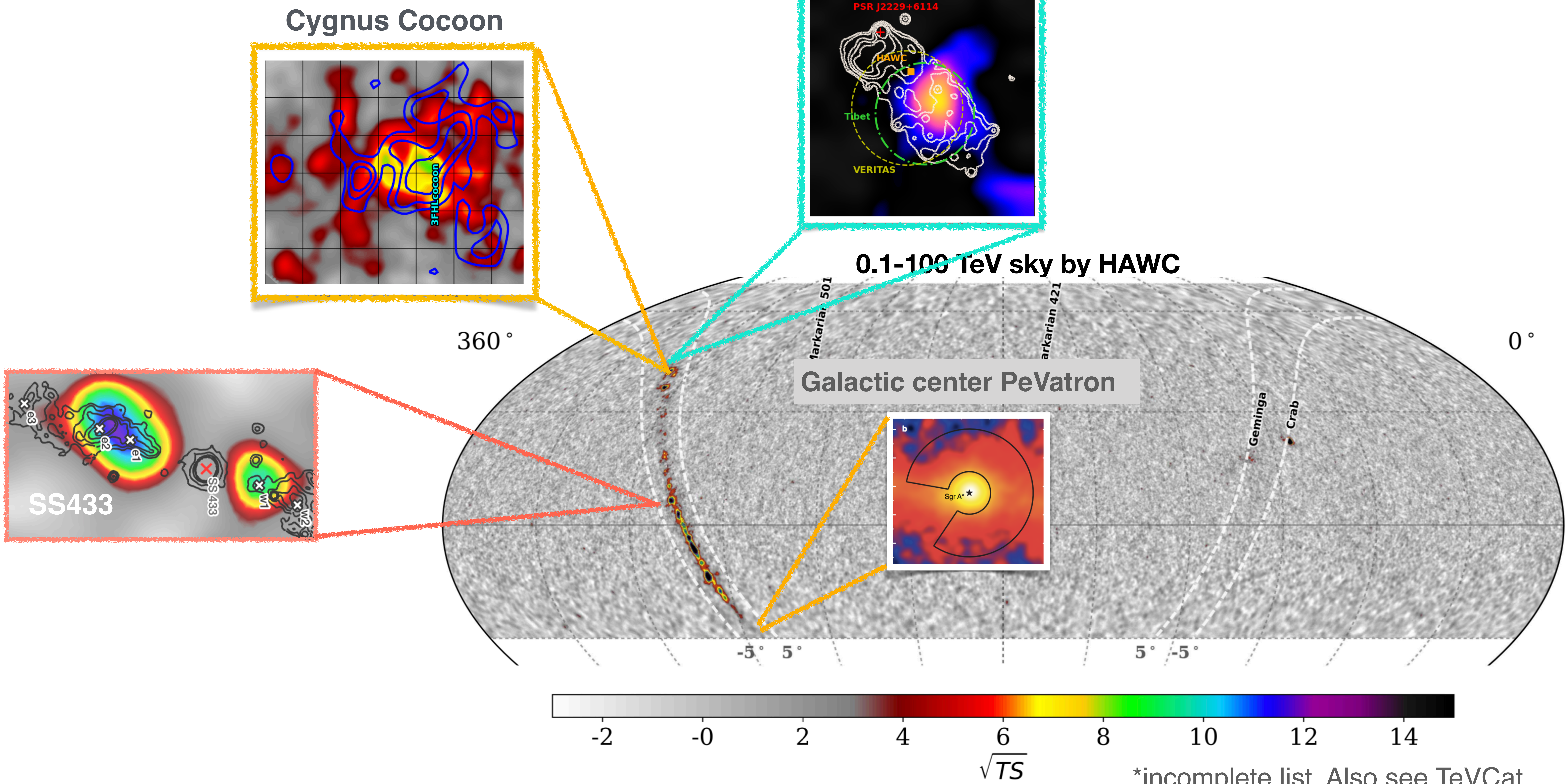
*incomplete list. Also see TeVCat

PeVatron Zoo* in 2024



*incomplete list. Also see TeVCat

PeVatron Zoo* in 2024

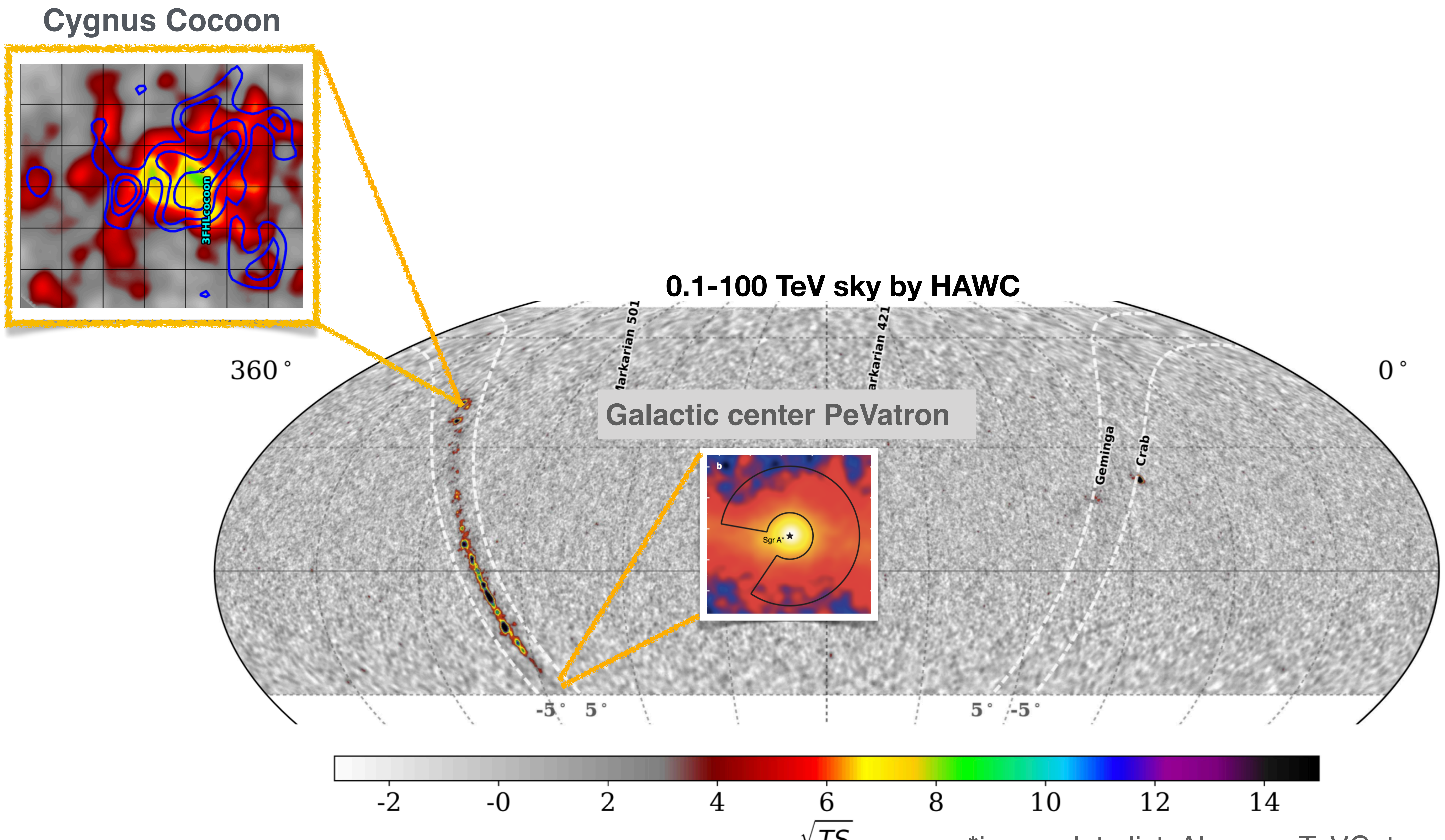


*incomplete list. Also see TeVCat

PeVatron Zoo* in 2024

*incomplete list. Also see TeVCat

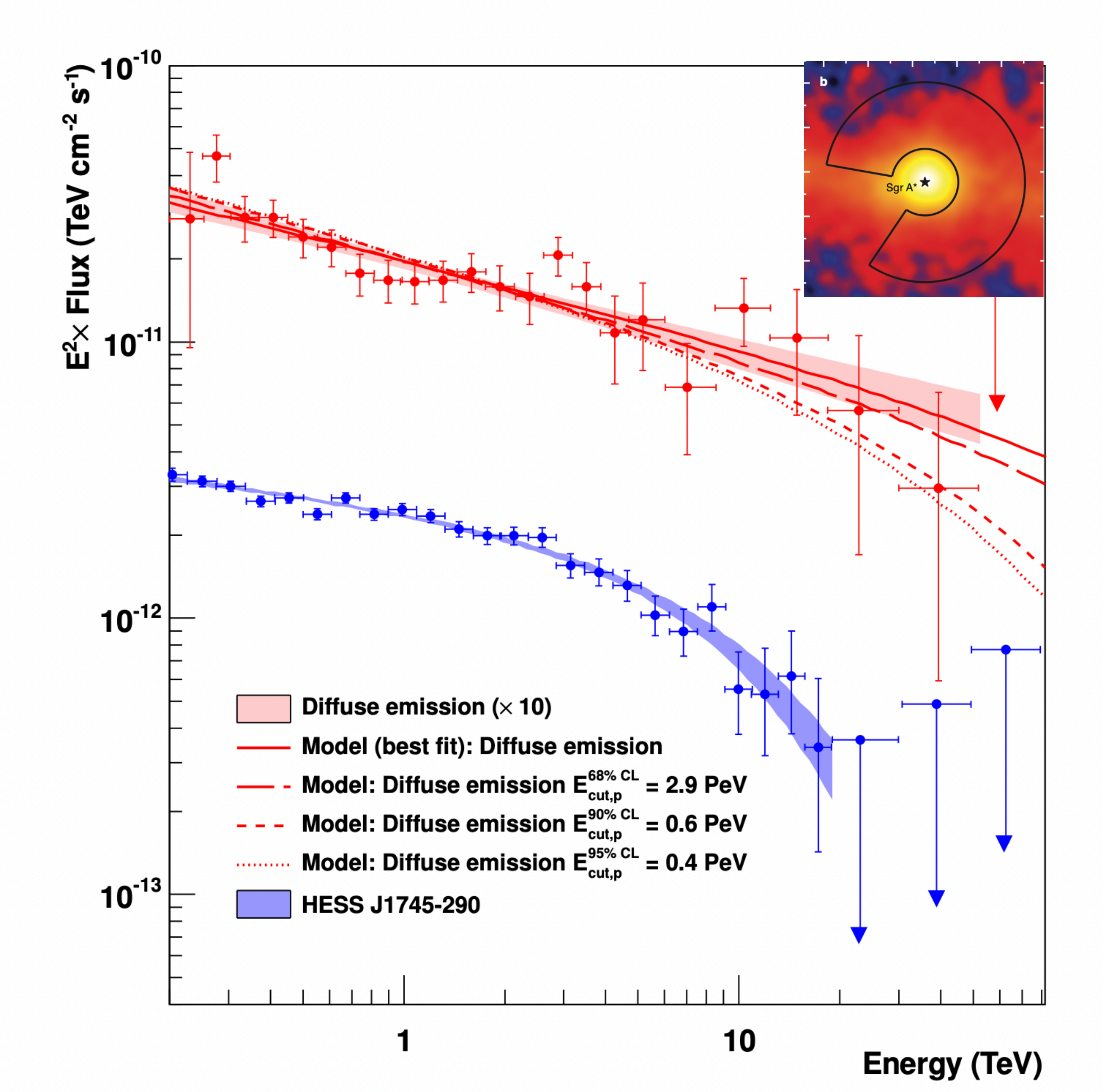
PeVatron Zoo* in 2024



*incomplete list. Also see TeVCat

Galactic Center

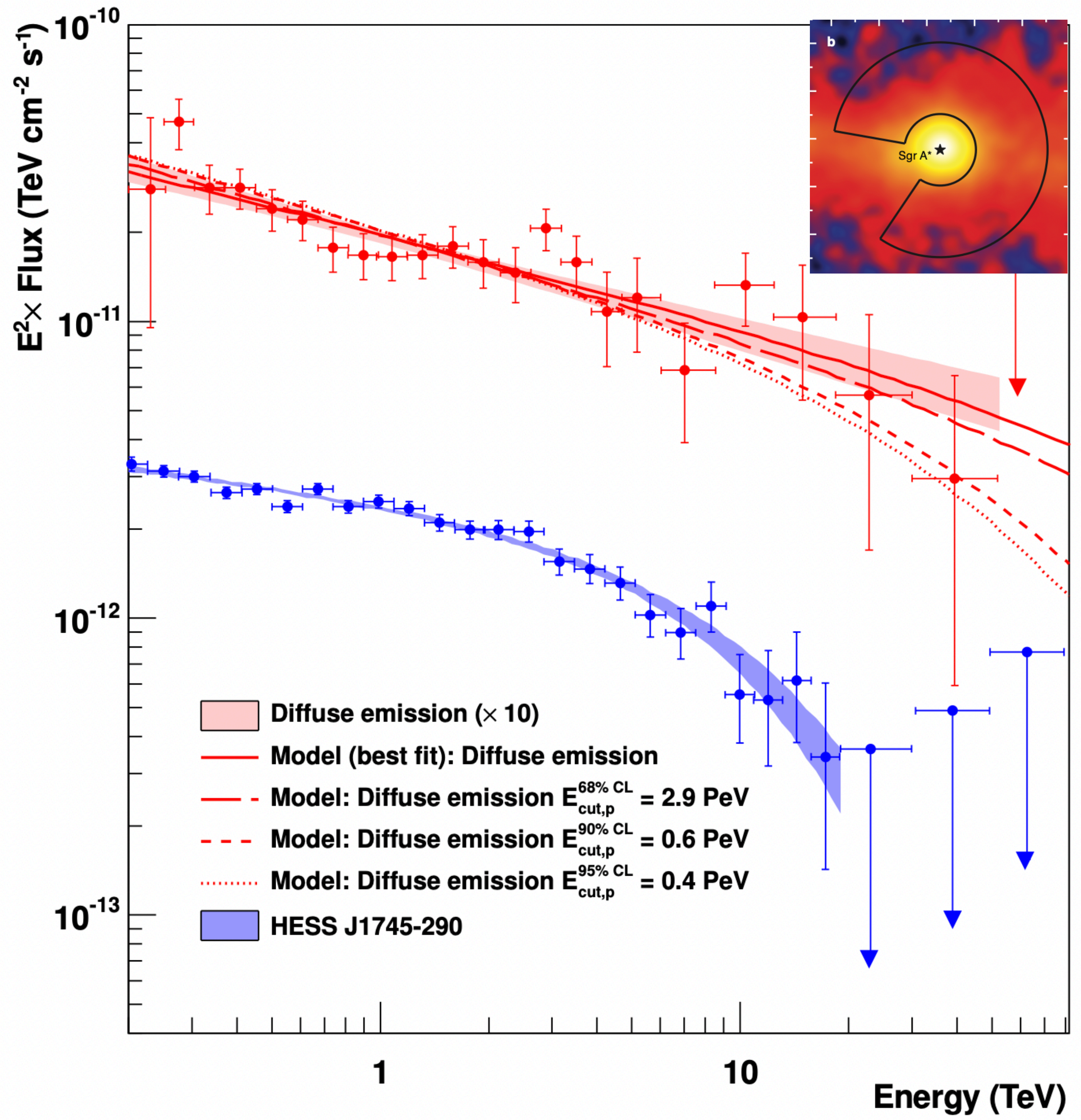
H.E.S.S. Nature (2016)



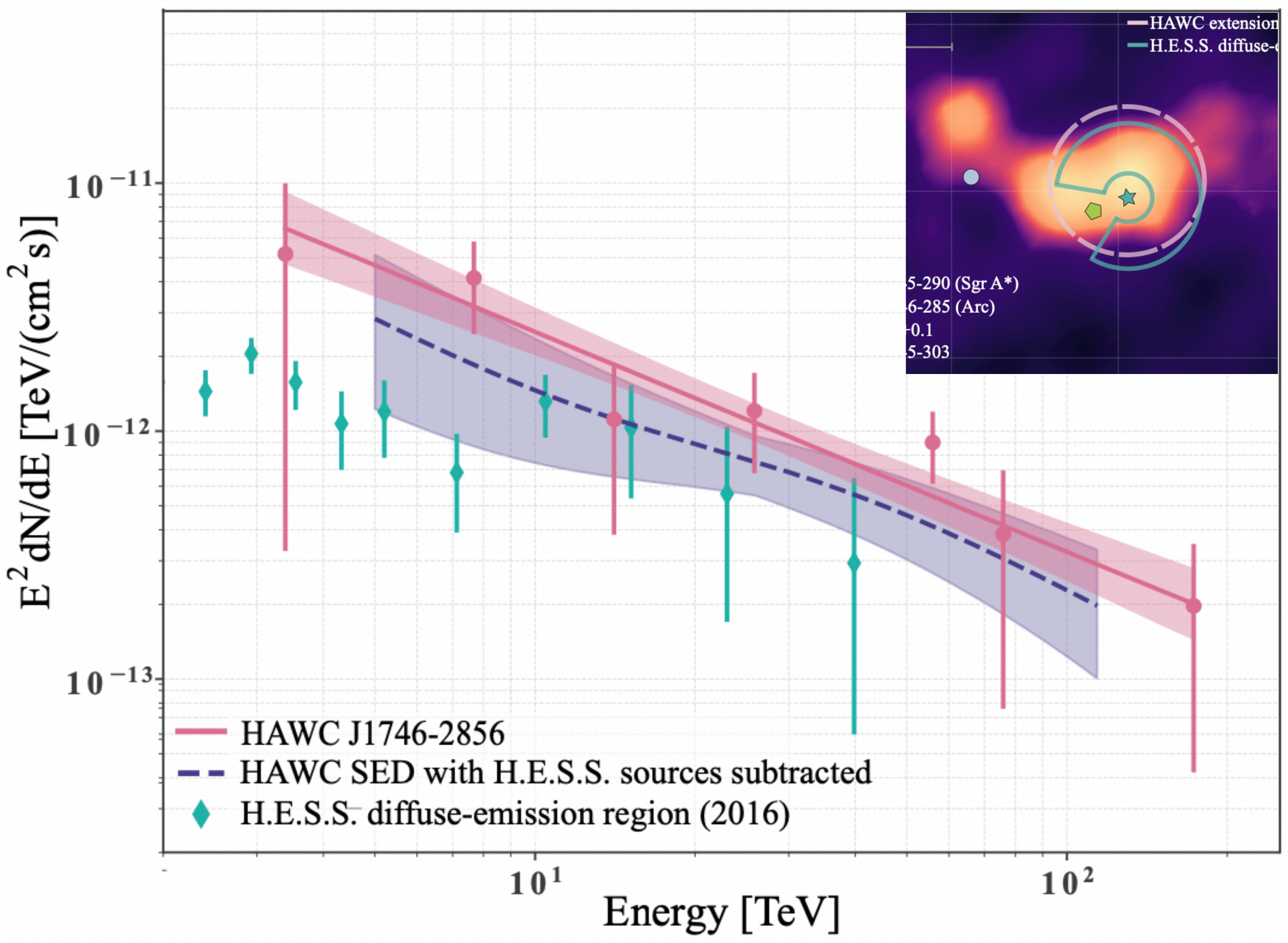
H.E.S.S. Collaboration, *Nature (2016);*
HAWC Collaboration, *ApJL (2024)*

Galactic Center

H.E.S.S. Nature (2016)



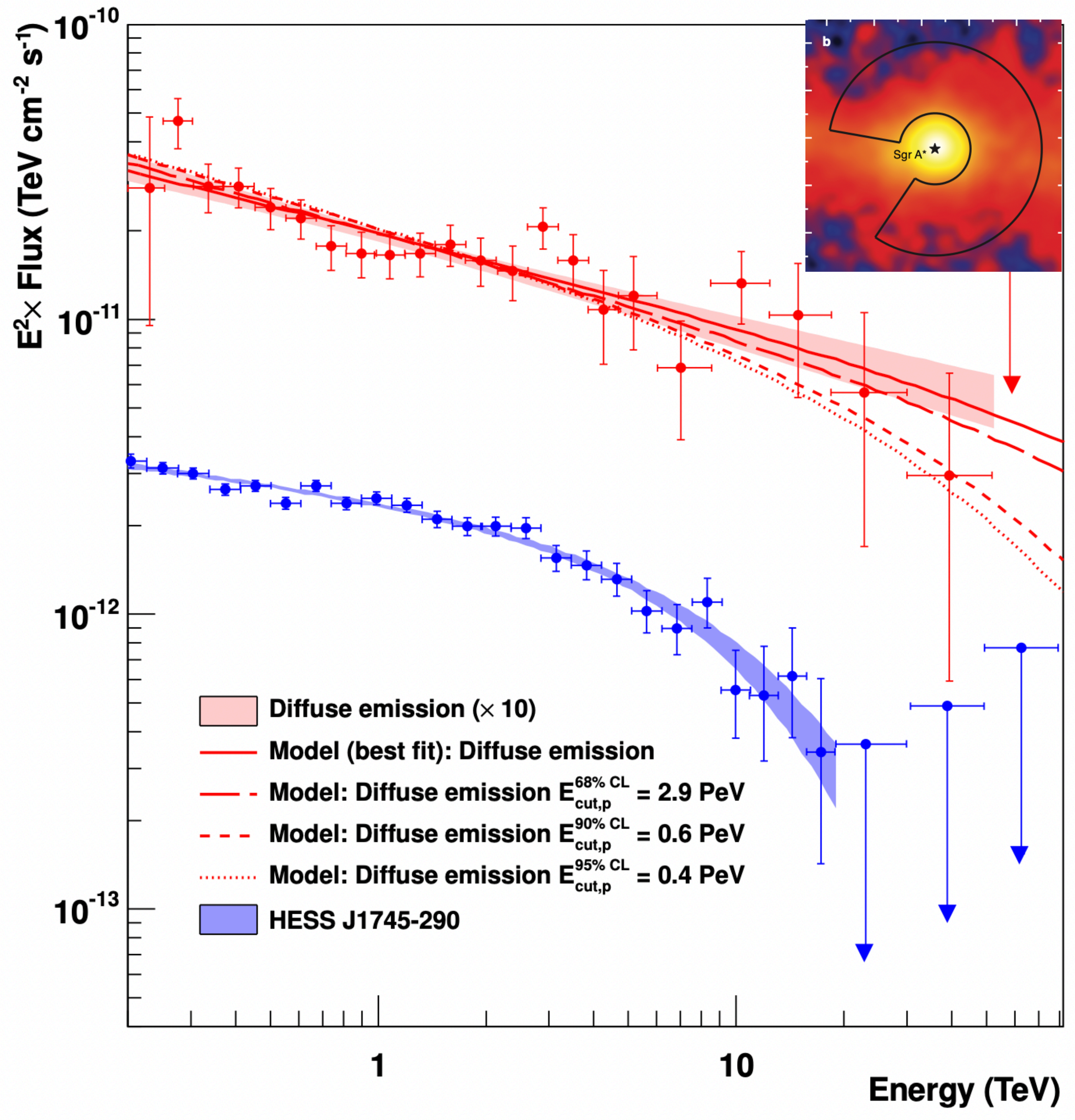
HAWC ApJL (2024)



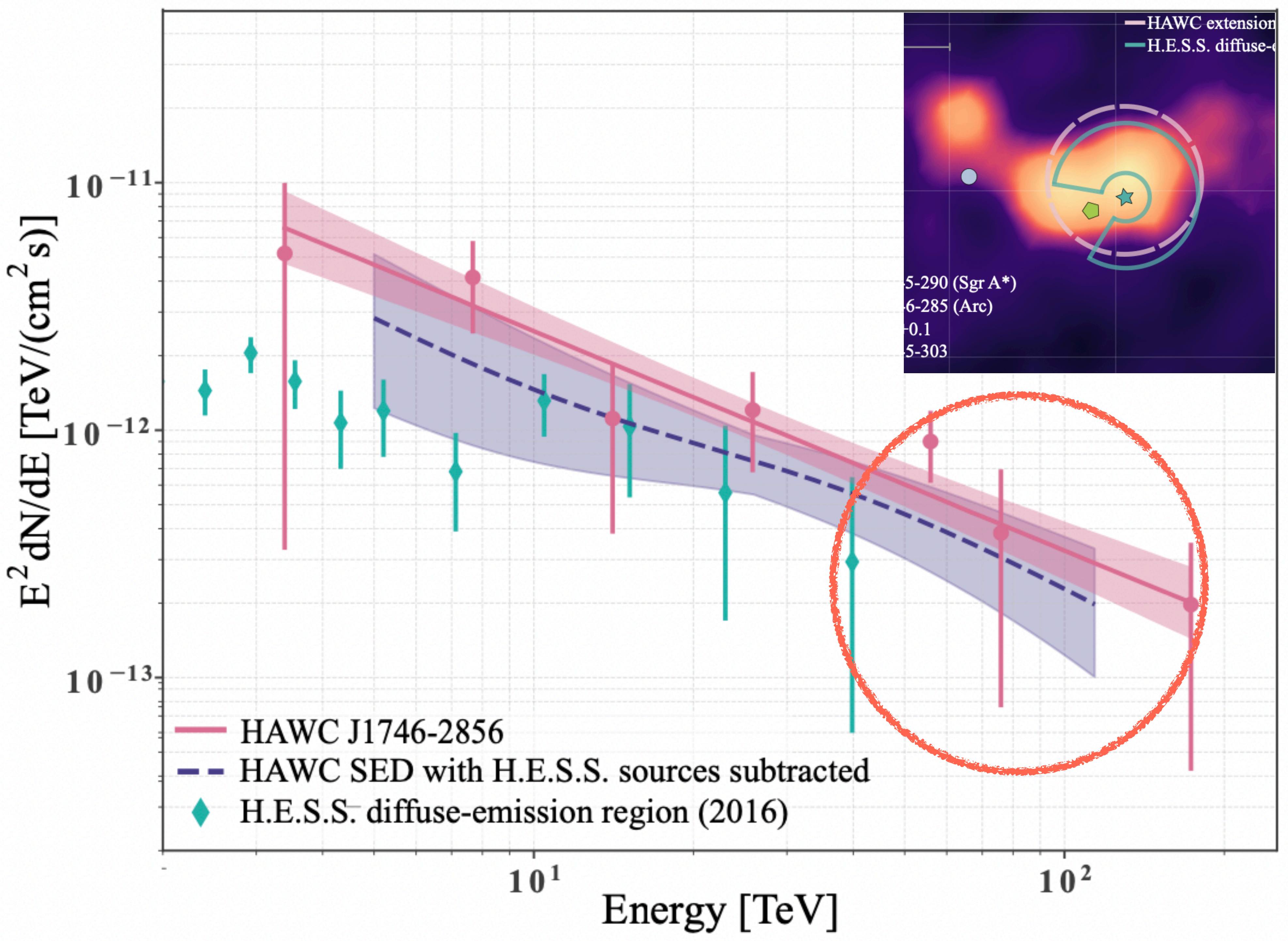
H.E.S.S. Collaboration, *Nature (2016);*
HAWC Collaboration, *ApJL (2024)*

Galactic Center

H.E.S.S. Nature (2016)



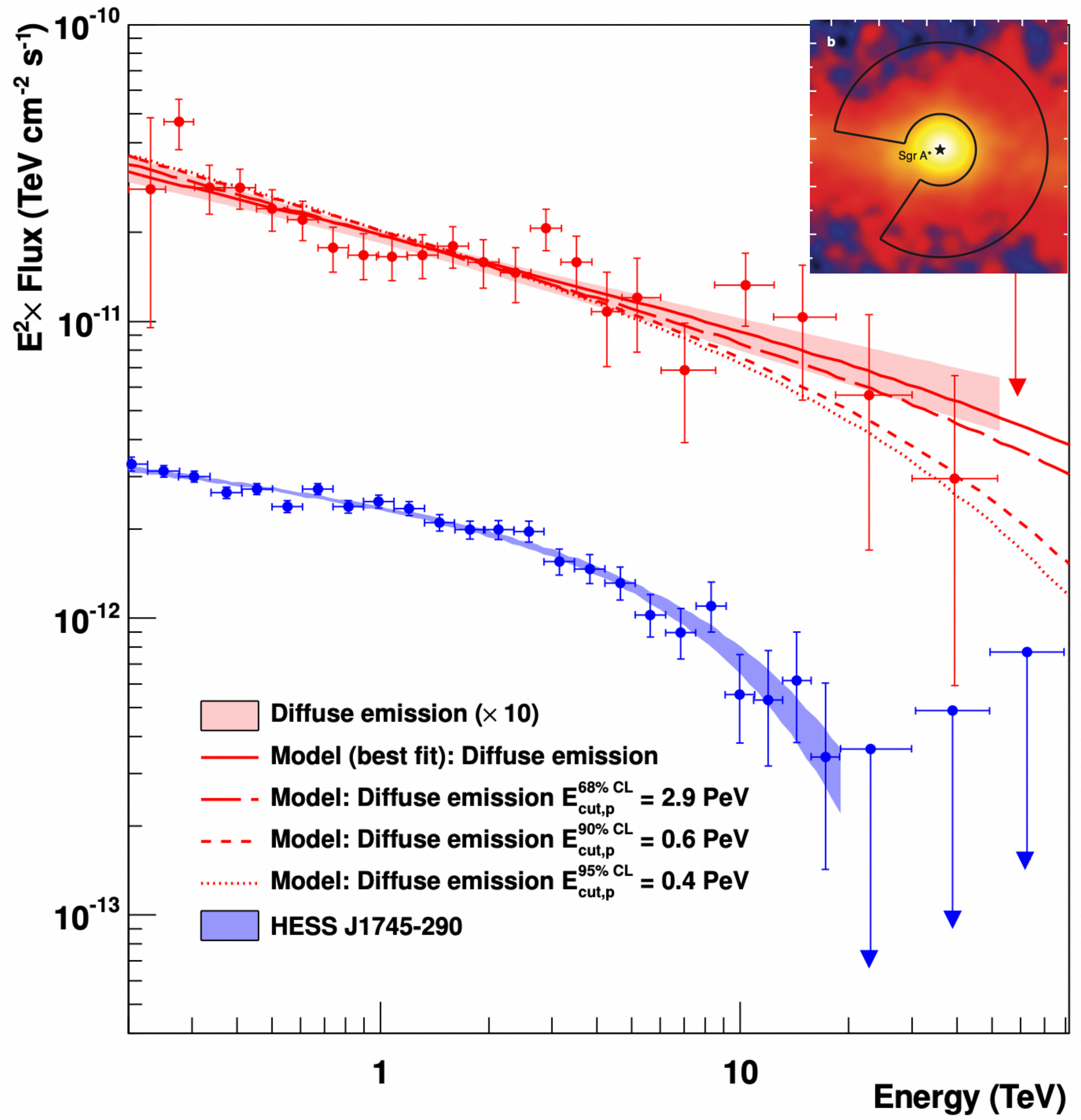
HAWC ApJL (2024)



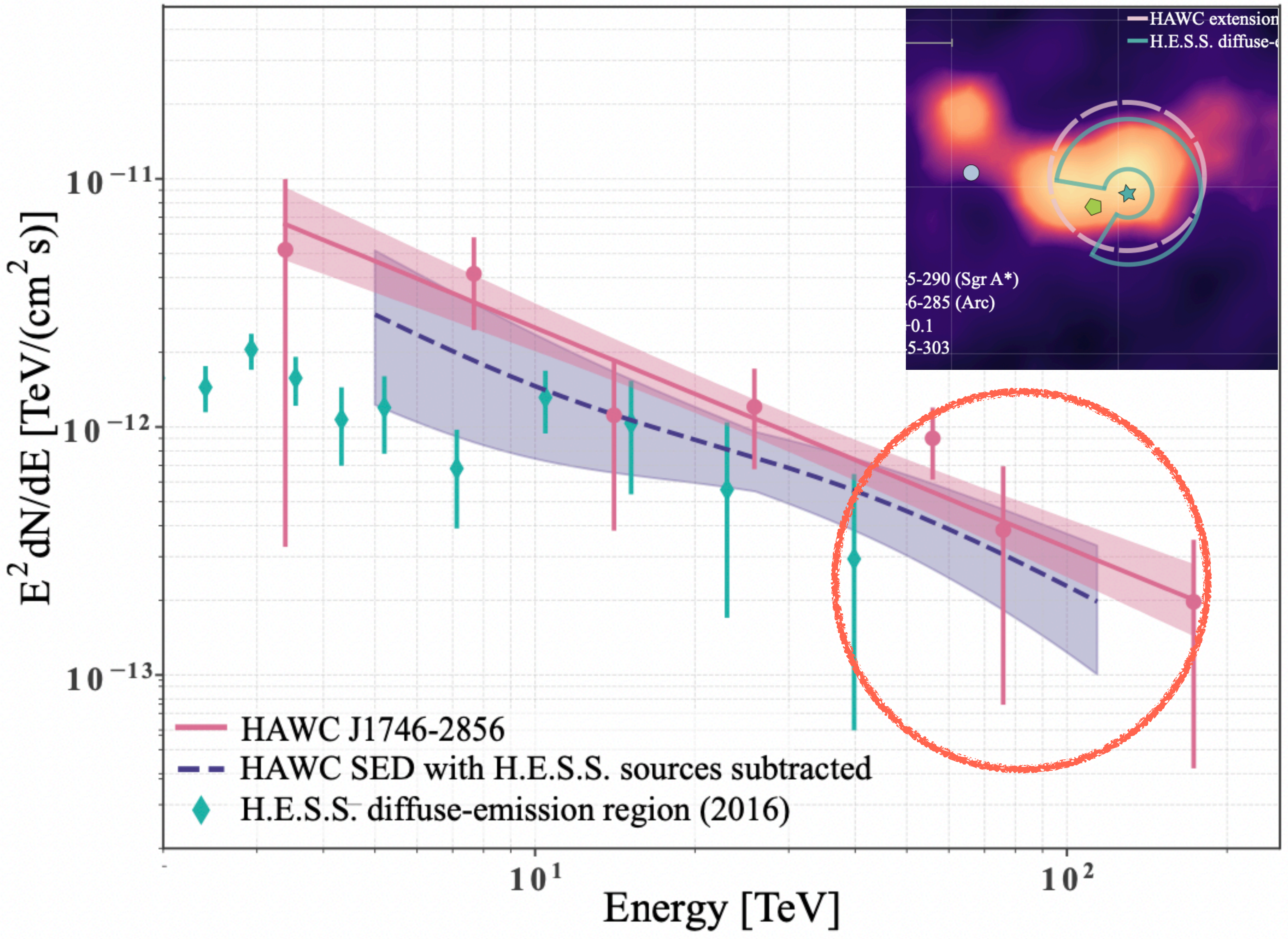
H.E.S.S. Collaboration, *Nature (2016);*
HAWC Collaboration, *ApJL (2024)*

Galactic Center

H.E.S.S. Nature (2016)



HAWC ApJL (2024)

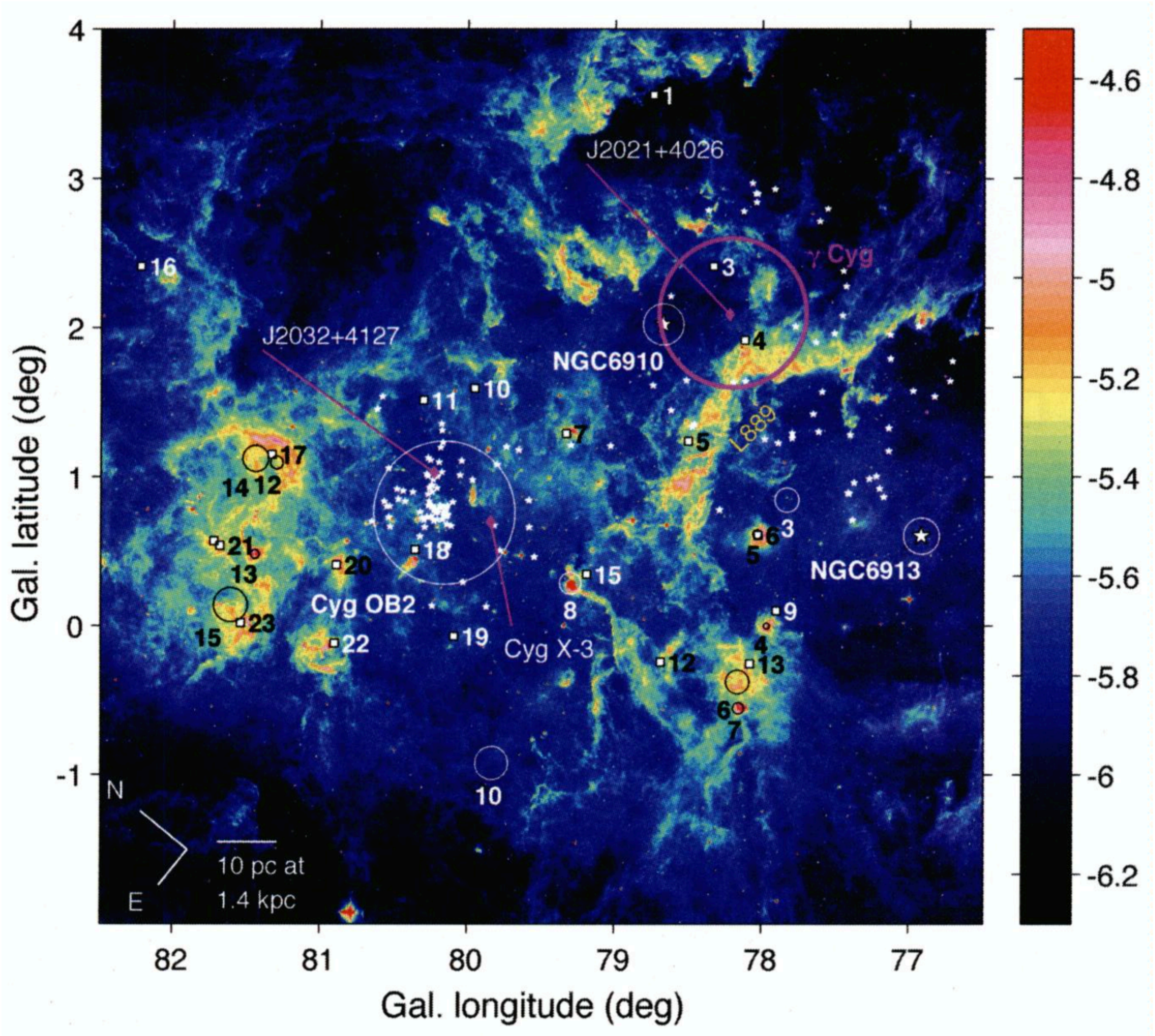


- Electron cooling time $\approx 13\,(E/100\,\mathrm{TeV})^{-1}\,\mathrm{yr} = 4\,\mathrm{pc}$, too short to populate the 10-100 pc emission region
- The detection of emission to energies >100 TeV thus **strongly disfavors the leptonic scenario**

H.E.S.S. Collaboration, *Nature (2016);*
HAWC Collaboration, *ApJL (2024)*

Cygnus Cocoon

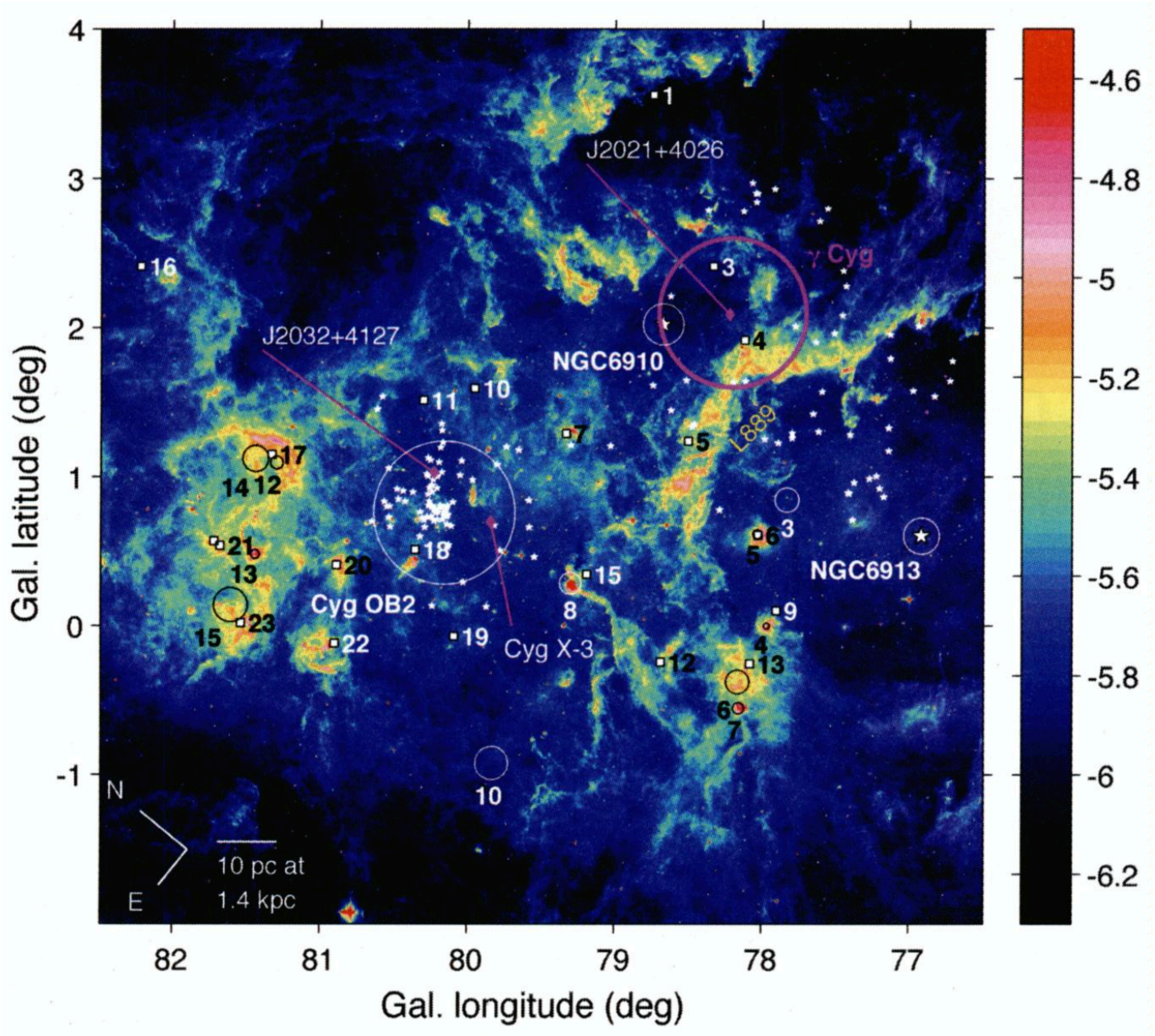
IR



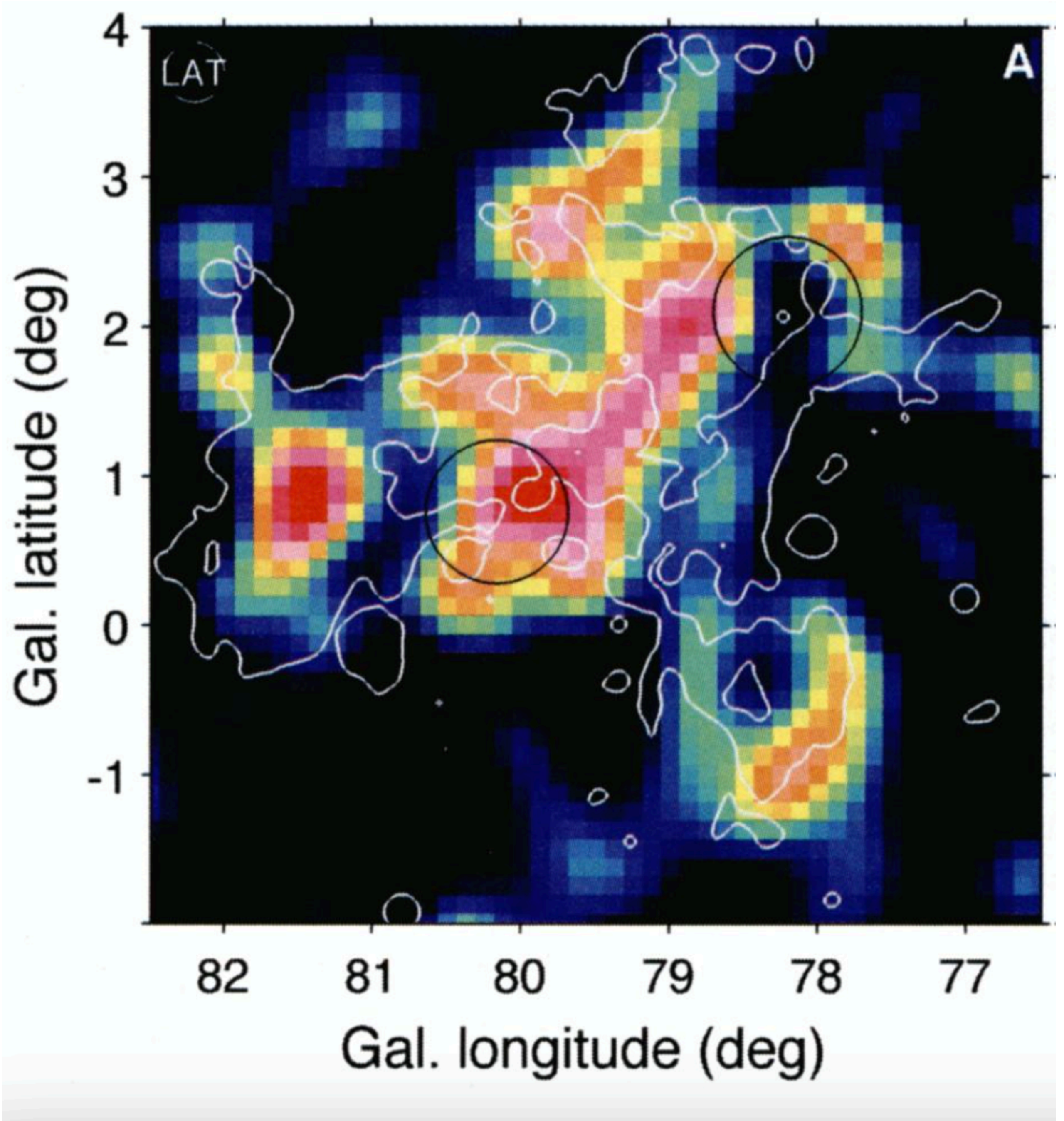
Fermi-LAT Collaboration, *Science (2011); Astiasarain et al A&A (2023)*
HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

Cygnus Cocoon

IR



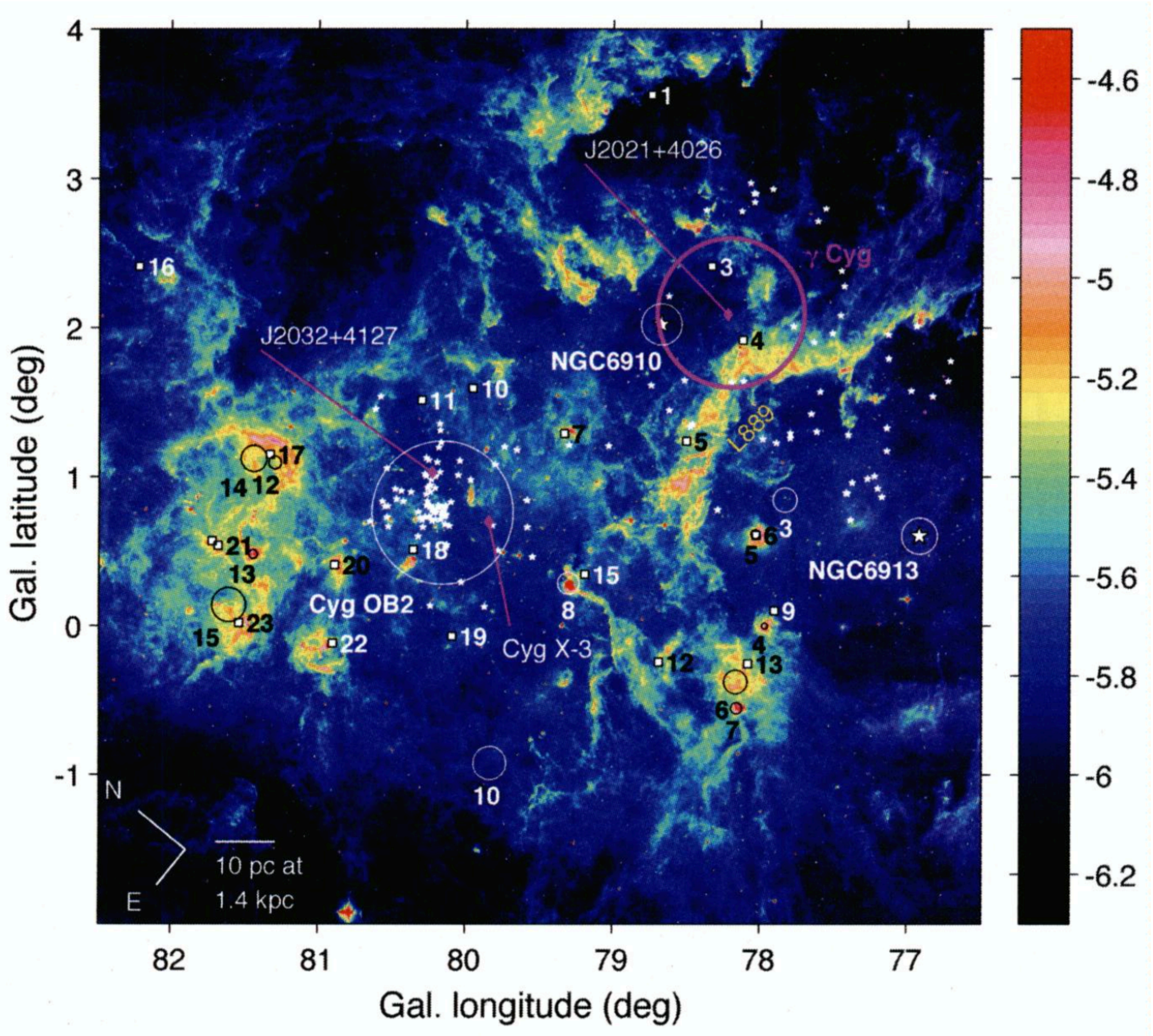
0.1-100 GeV



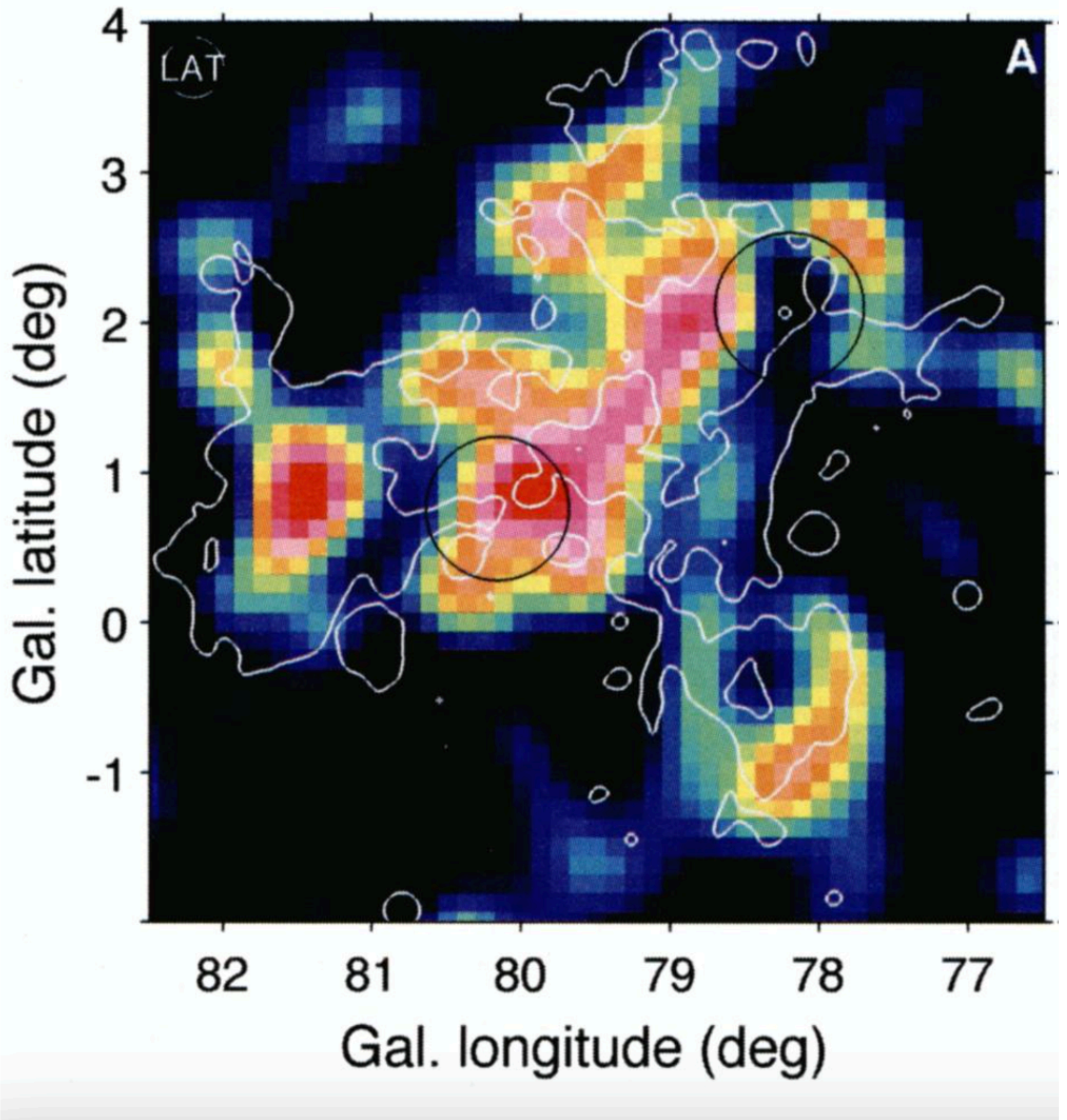
Fermi-LAT Collaboration, *Science (2011); Astiasarain et al A&A (2023)*
HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

Cygnus Cocoon

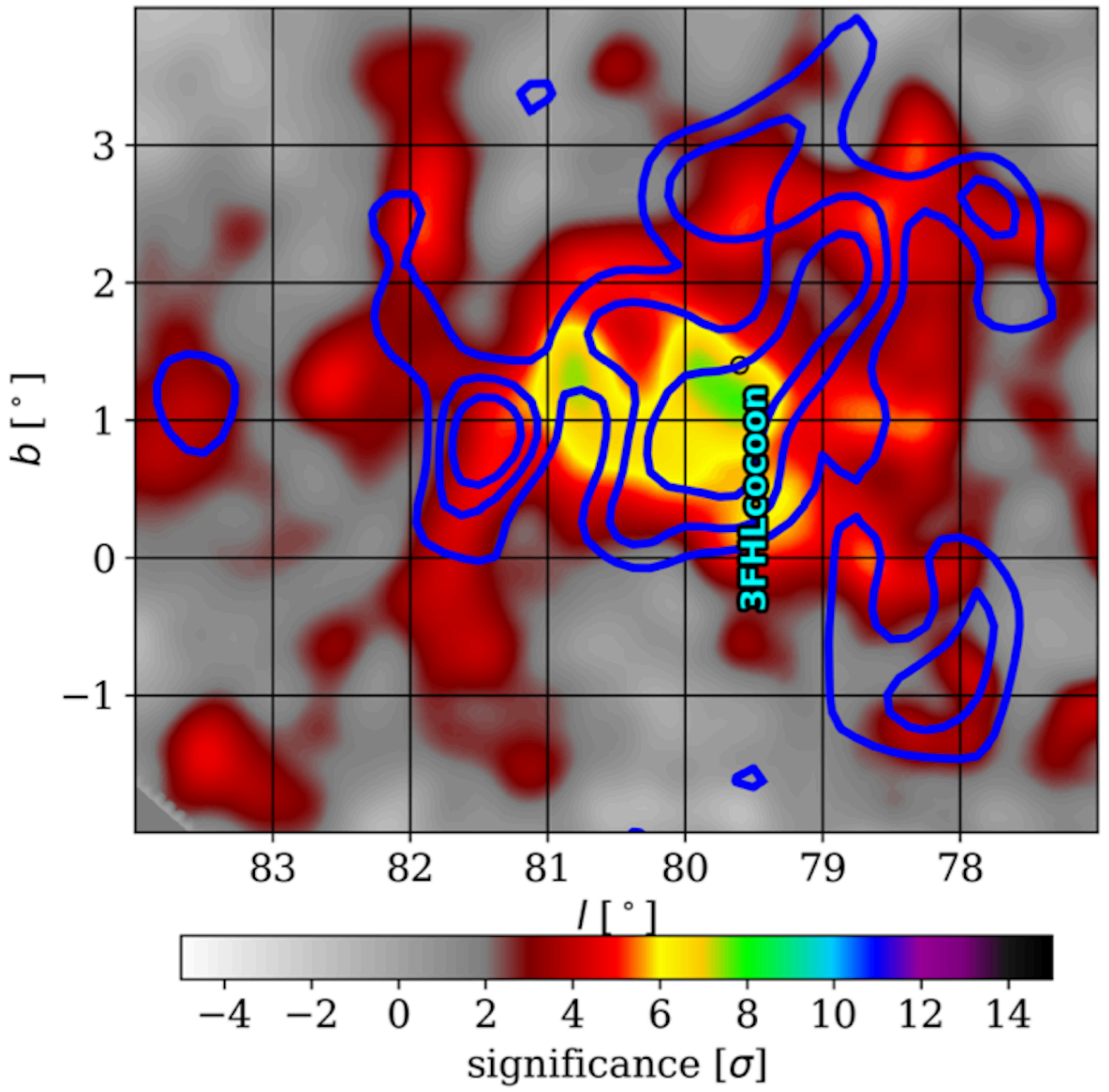
IR



0.1-100 GeV



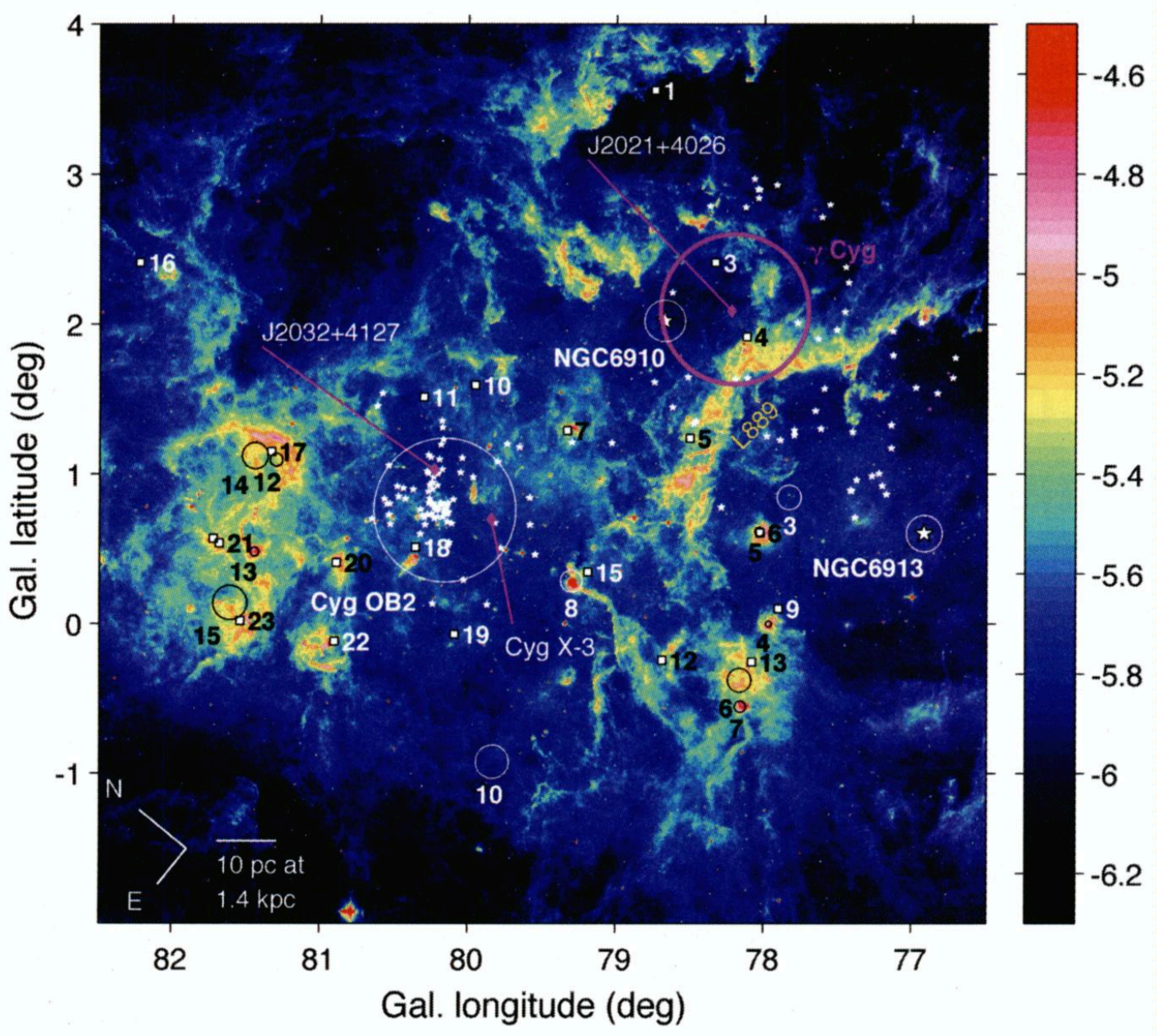
1-100 TeV



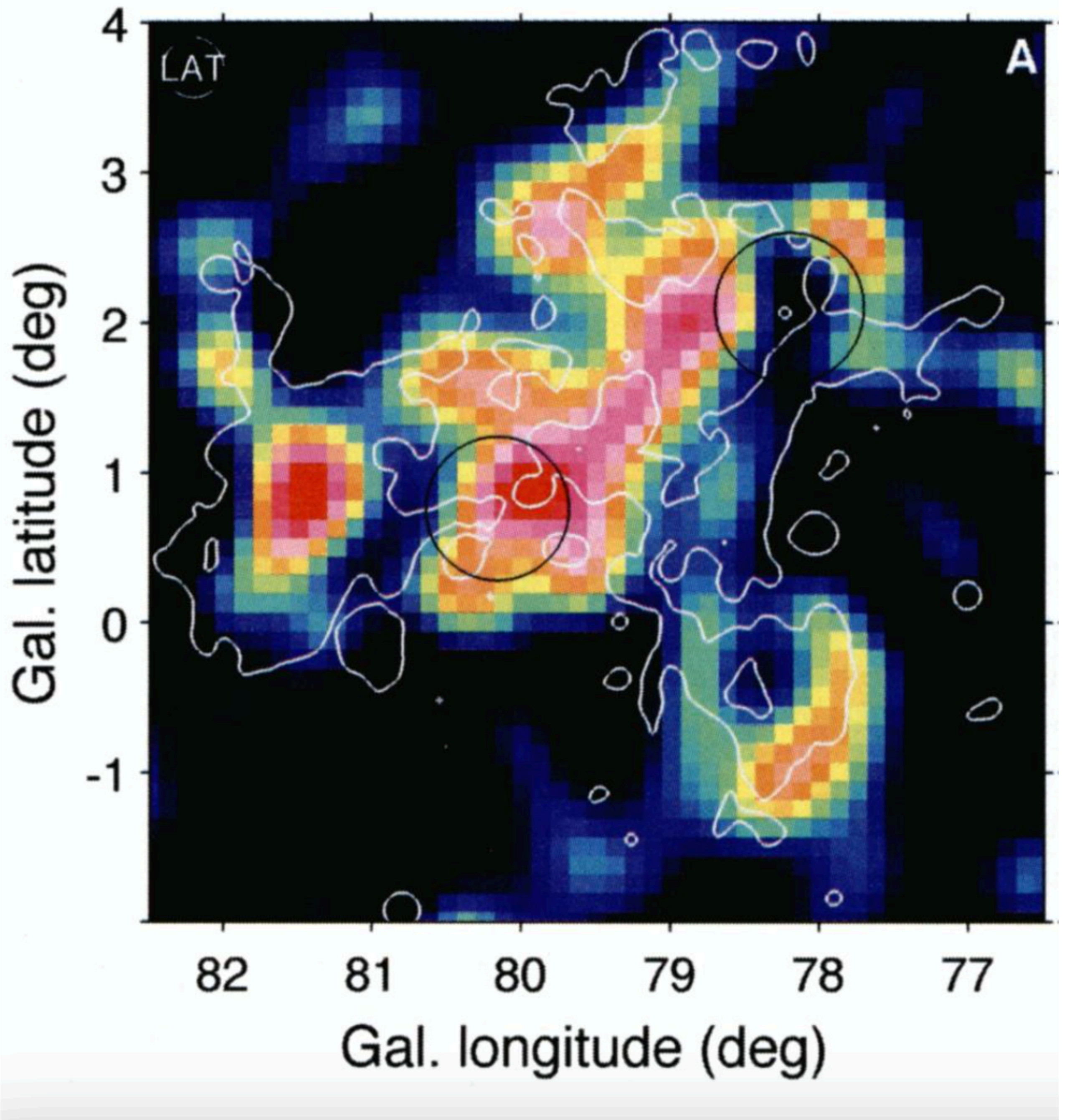
Fermi-LAT Collaboration, *Science (2011); Astiasarain et al A&A (2023)*
HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

Cygnus Cocoon

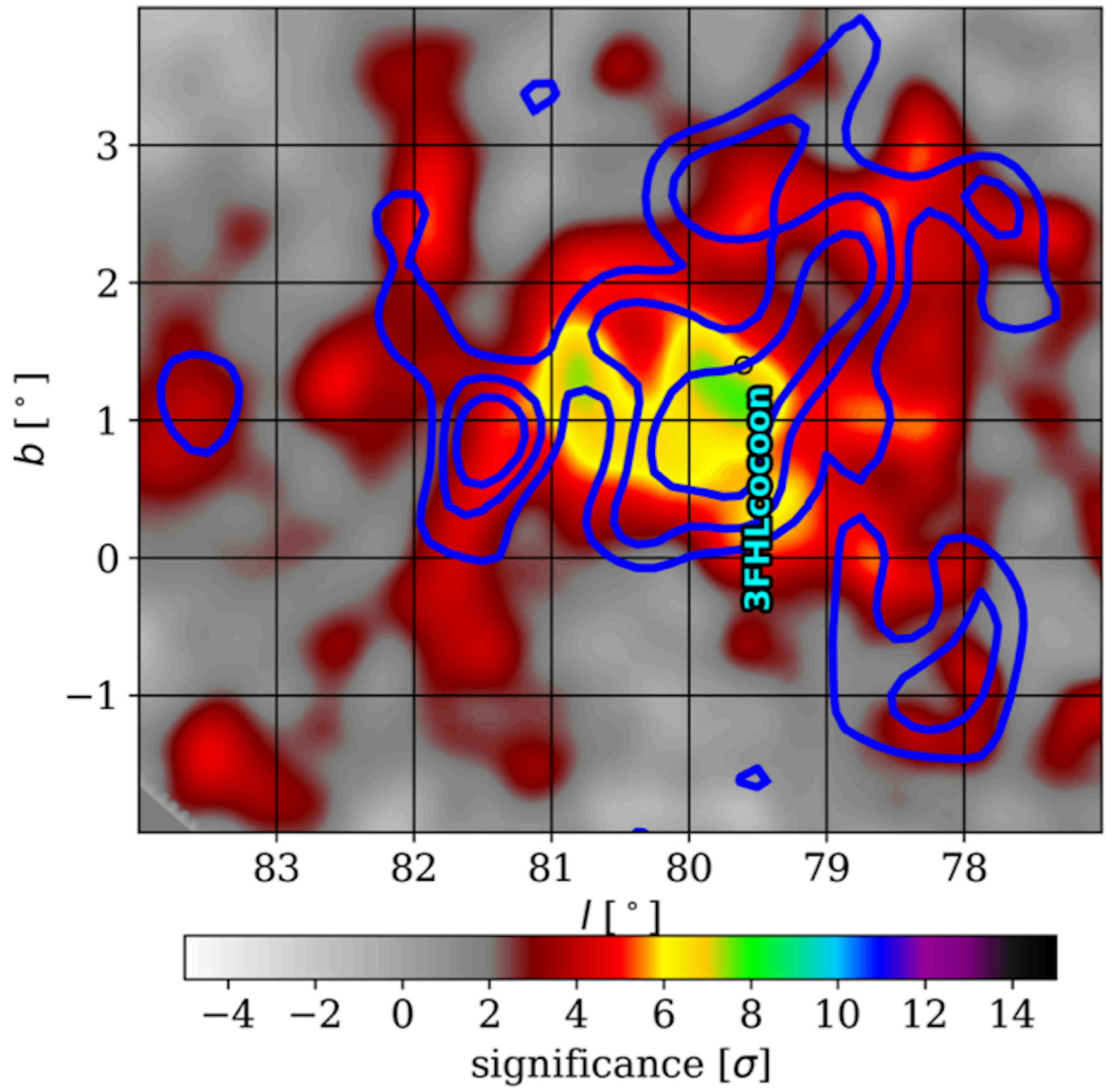
IR



0.1-100 GeV



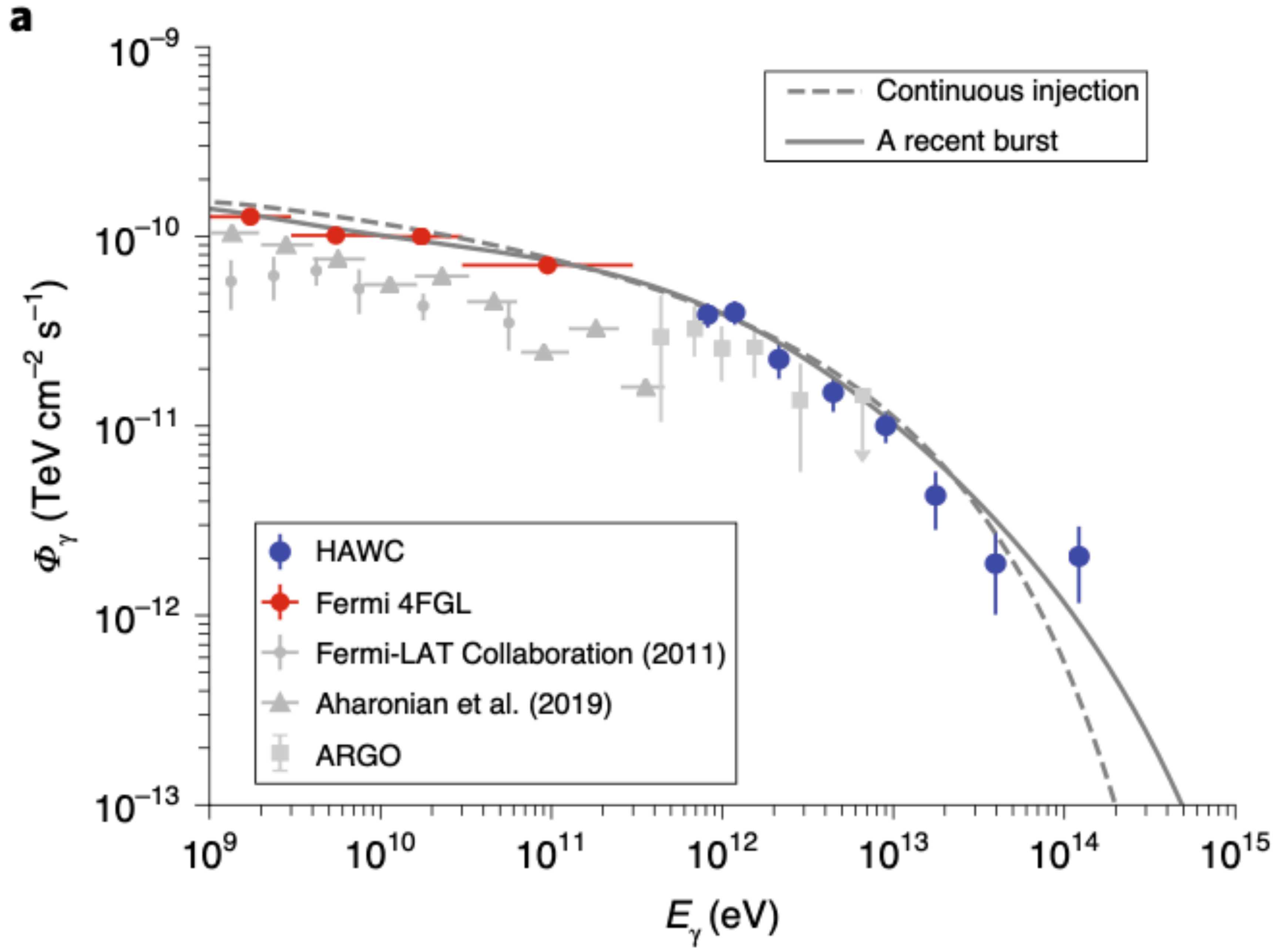
1-100 TeV



- Gamma-rays from 0.1 GeV to 100 TeV trace infrared emission, likely from proton gas interaction

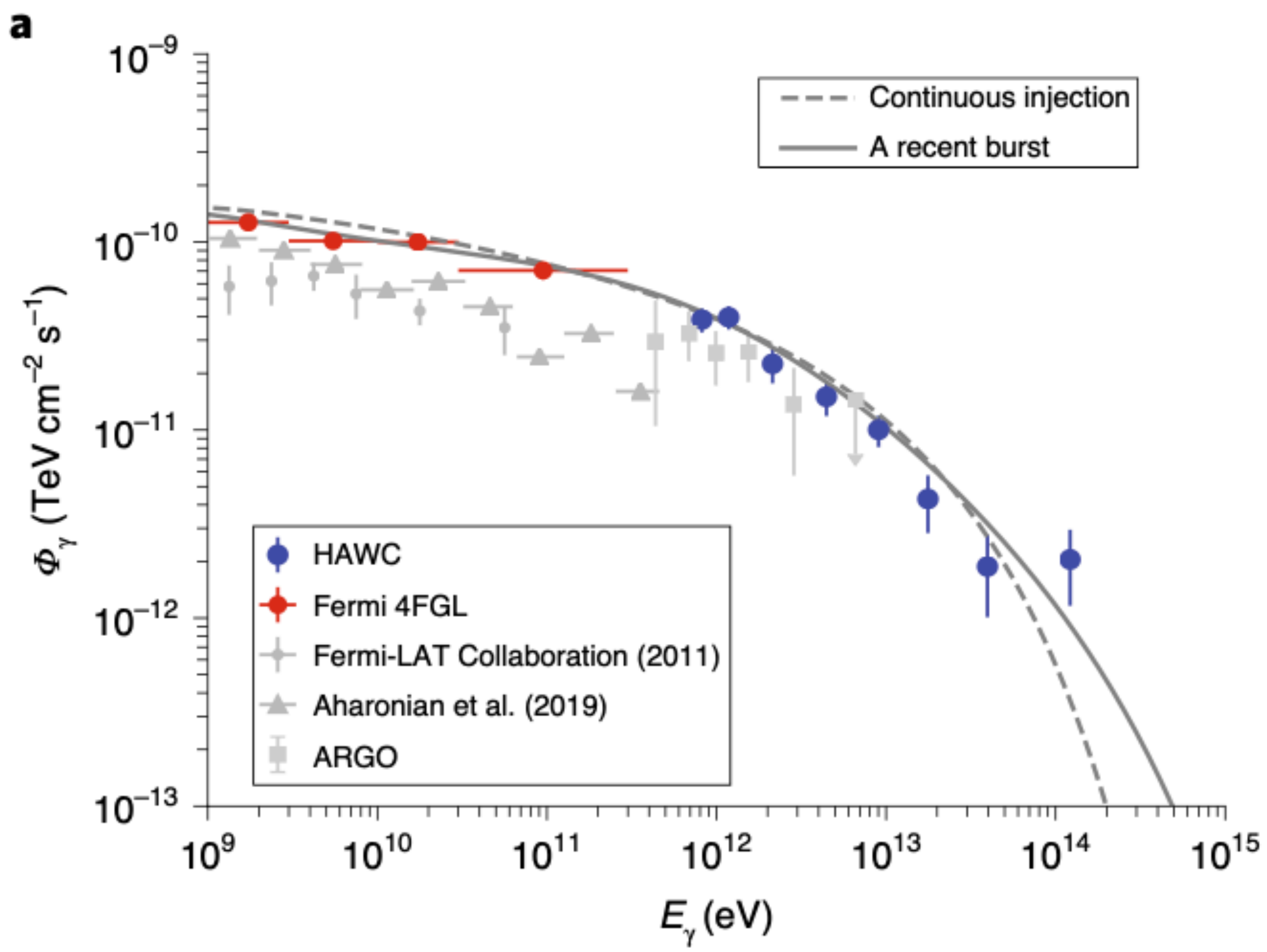
Fermi-LAT Collaboration, *Science (2011); Astiasarain et al A&A (2023)*
HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

Cygnus Cocoon



HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

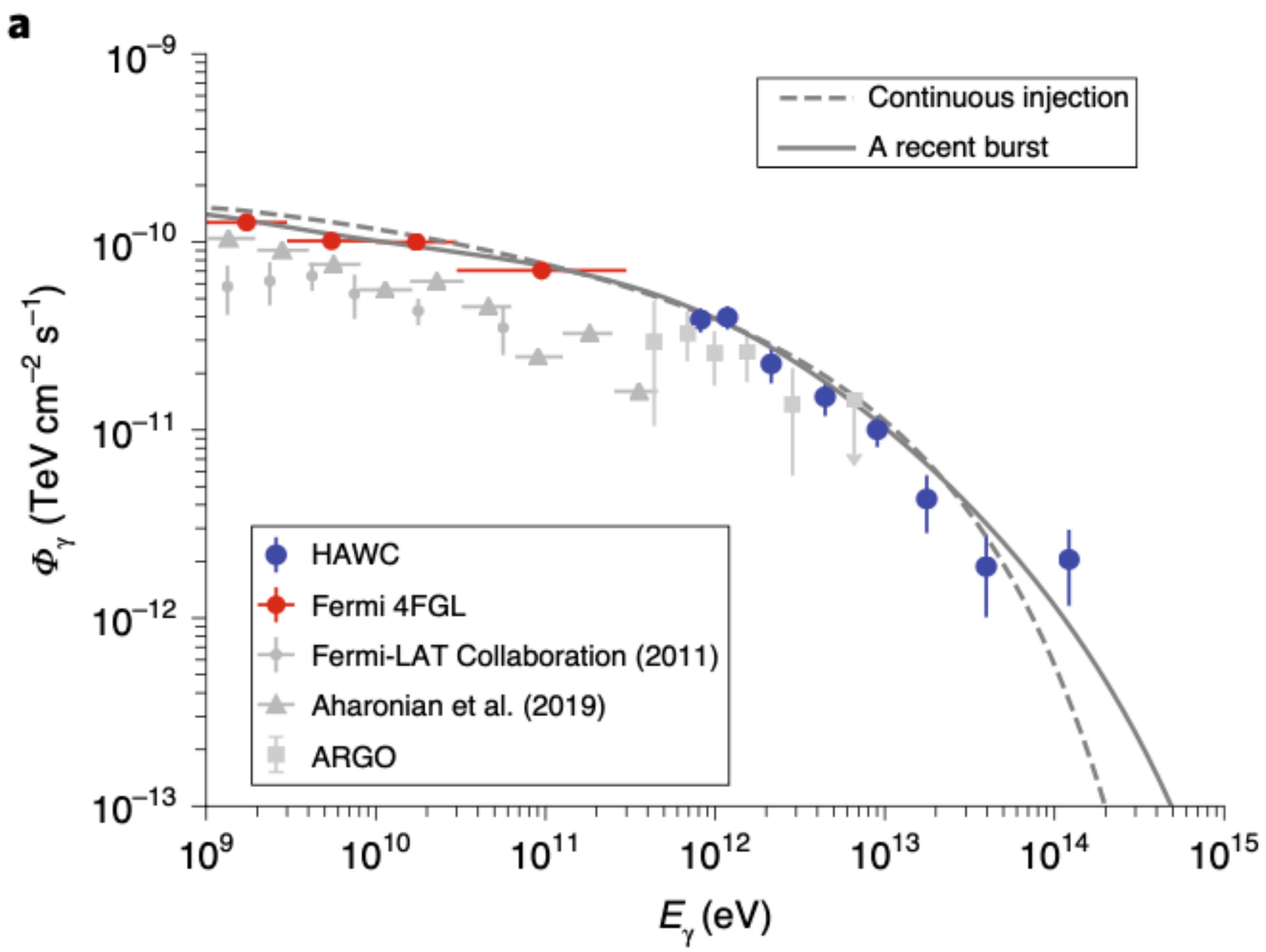
Cygnus Cocoon



- Gamma rays are likely from protons accelerated by stellar winds

HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

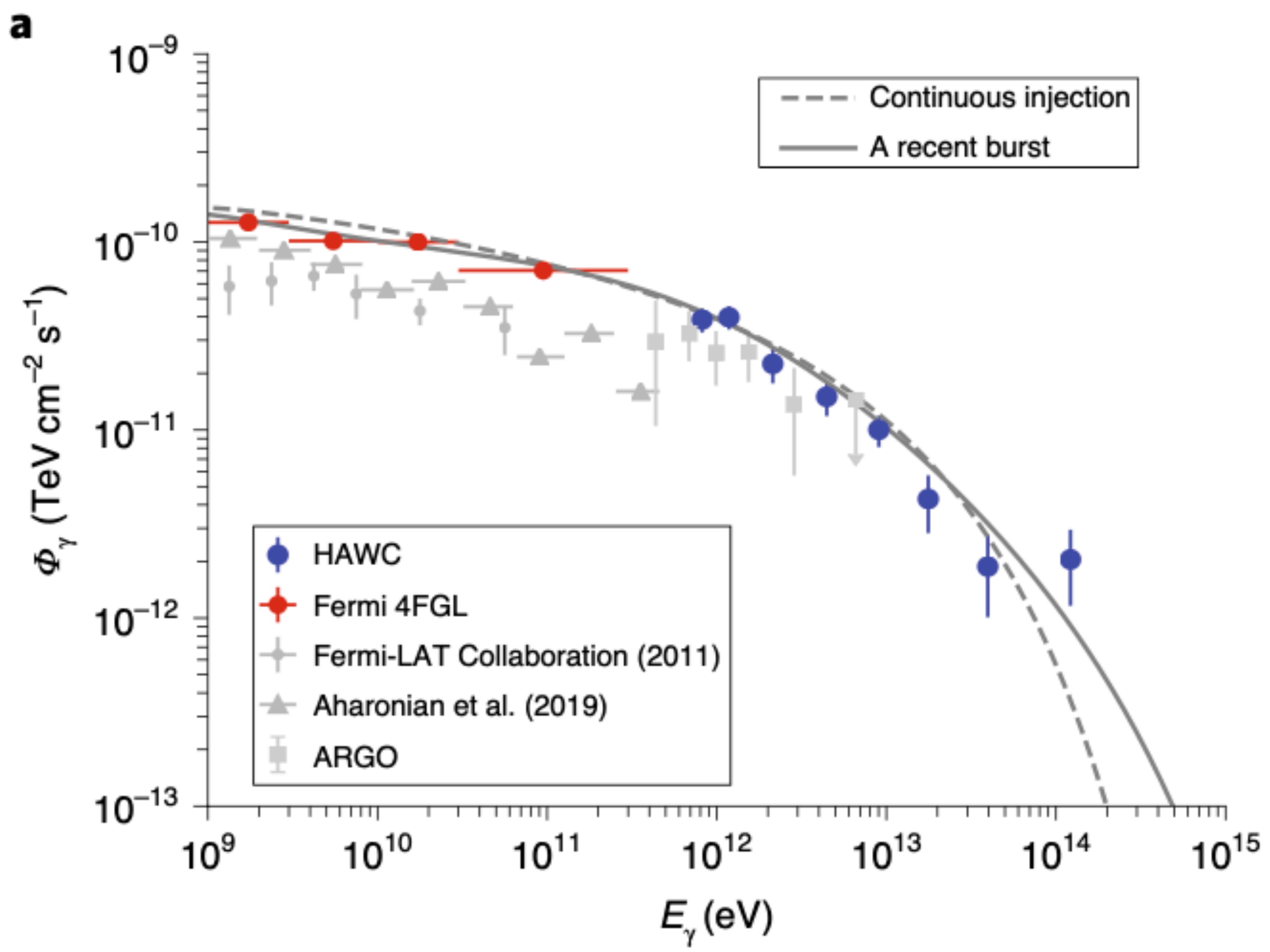
Cygnus Cocoon



- Gamma rays are likely from protons accelerated by stellar winds

HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

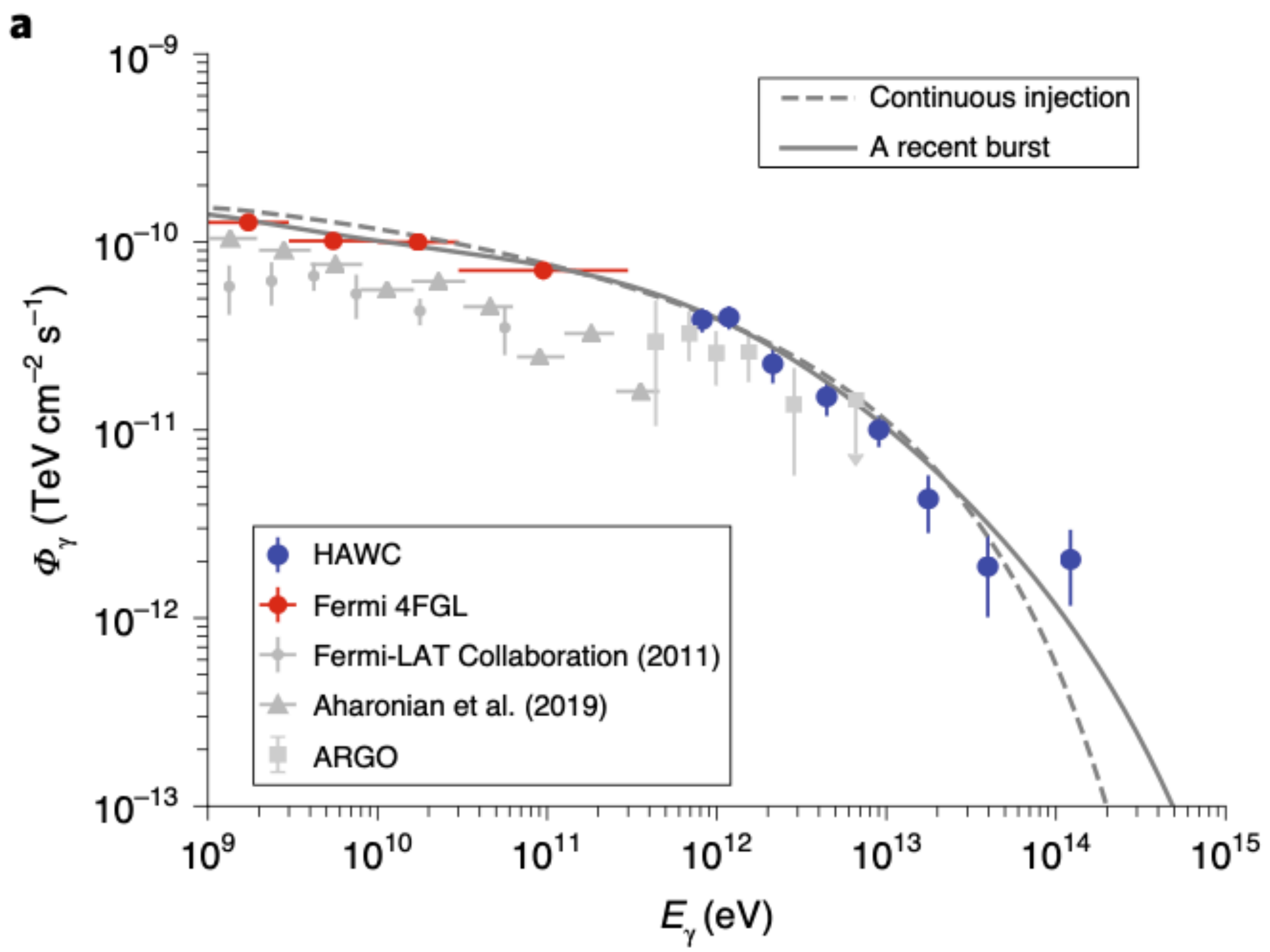
Cygnus Cocoon



- Gamma rays are likely from protons accelerated by stellar winds
- **Continuous injection scenario:** steady injection of **sub-PeV** protons to the cocoon over Myrs

HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

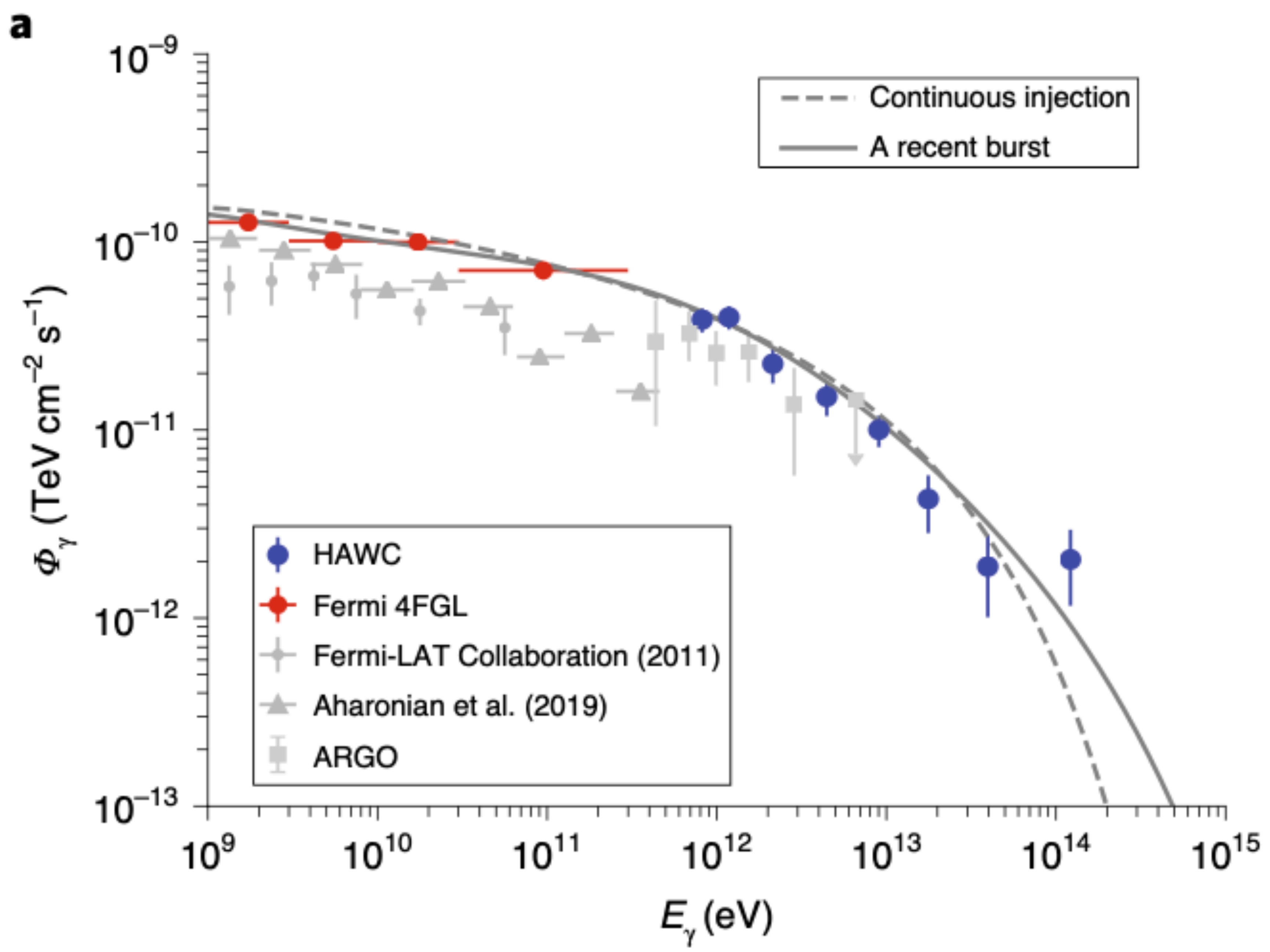
Cygnus Cocoon



- Gamma rays are likely from protons accelerated by stellar winds
- **Continuous injection scenario:** steady injection of **sub-PeV** protons to the cocoon over Myrs

HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

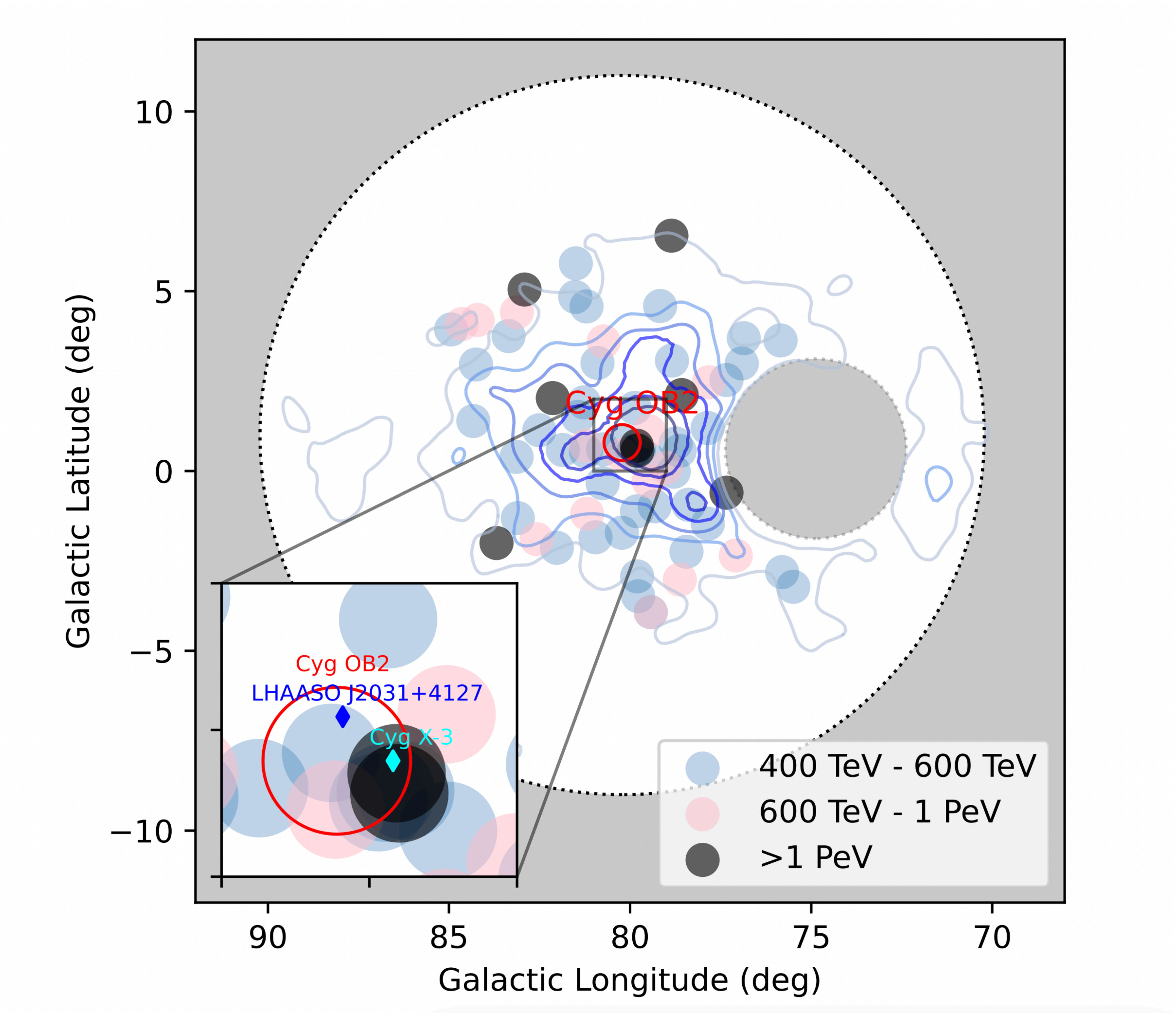
Cygnus Cocoon



- Gamma rays are likely from protons accelerated by stellar winds
- **Continuous injection scenario:** steady injection of **sub-PeV** protons to the cocoon over Myrs
- **Recent burst scenario**: a recent injection of **> PeV** protons; spectral turnover due to leak of high-energy particles

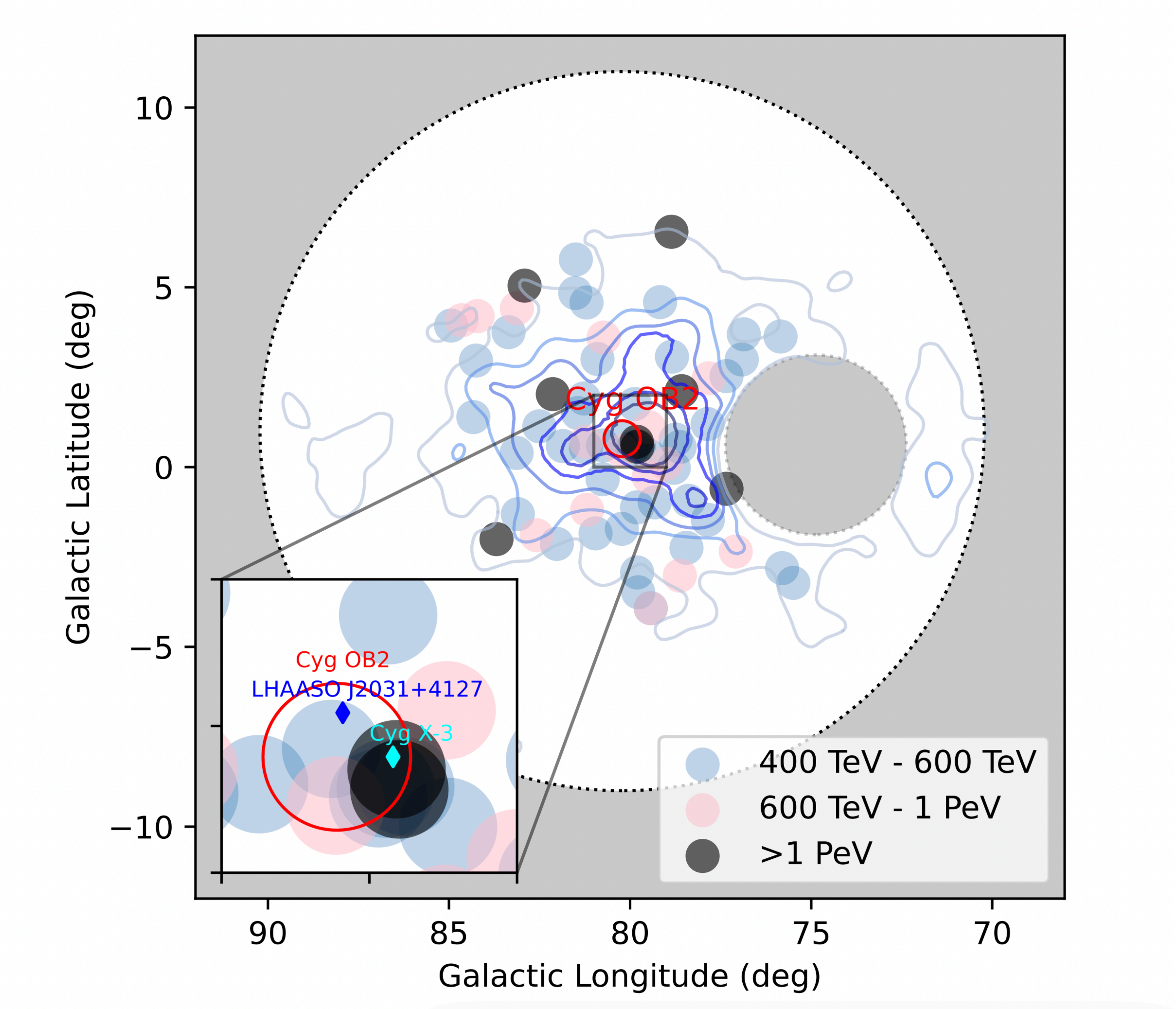
HAWC Collaboration (**KF** as corresponding author), *Nature Astronomy (2021)*

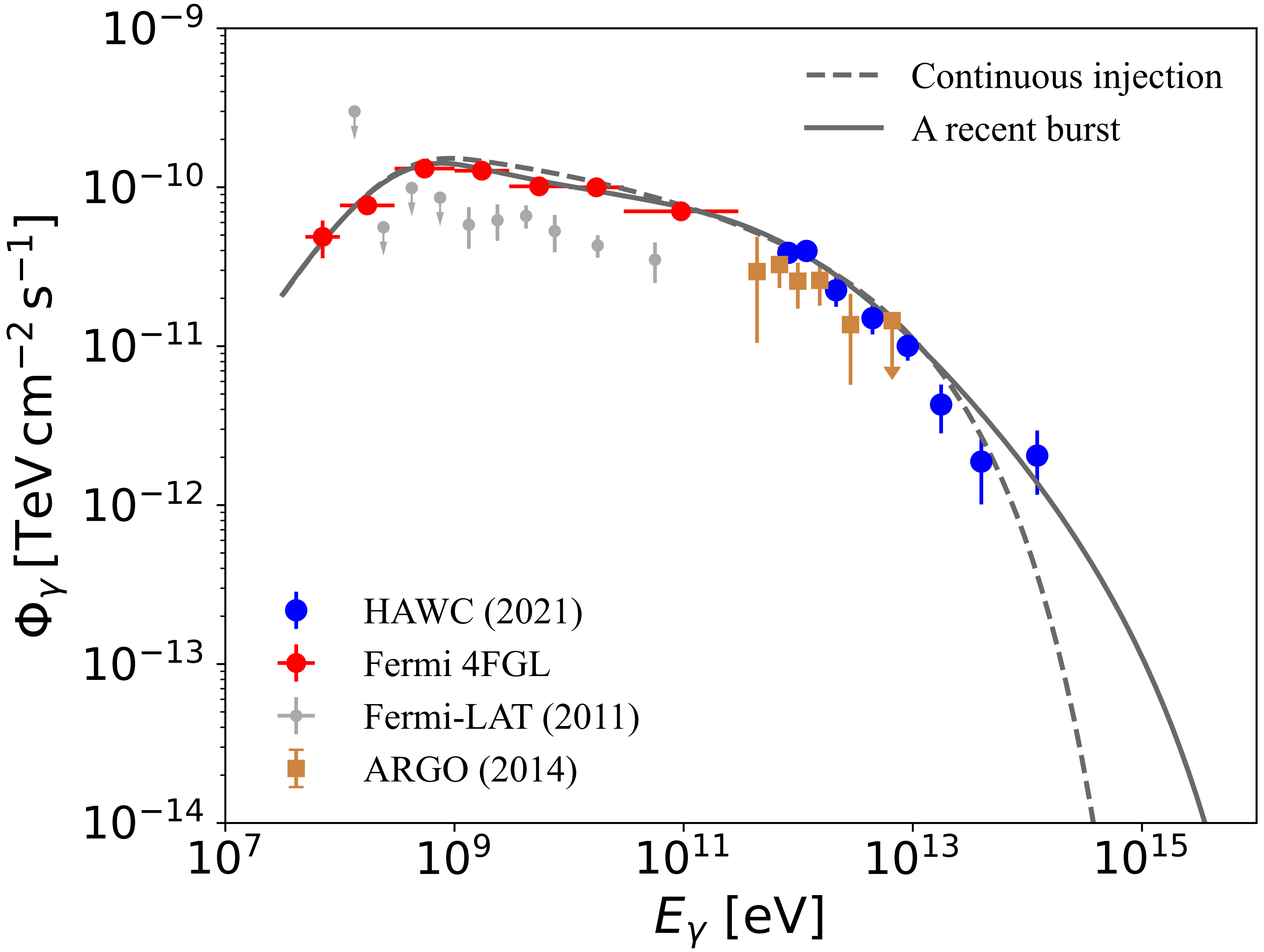
Cygnus Cocoon



LHAASO Collaboration, Science Bulletin (2024)
KF & Halzen, 2404.15944

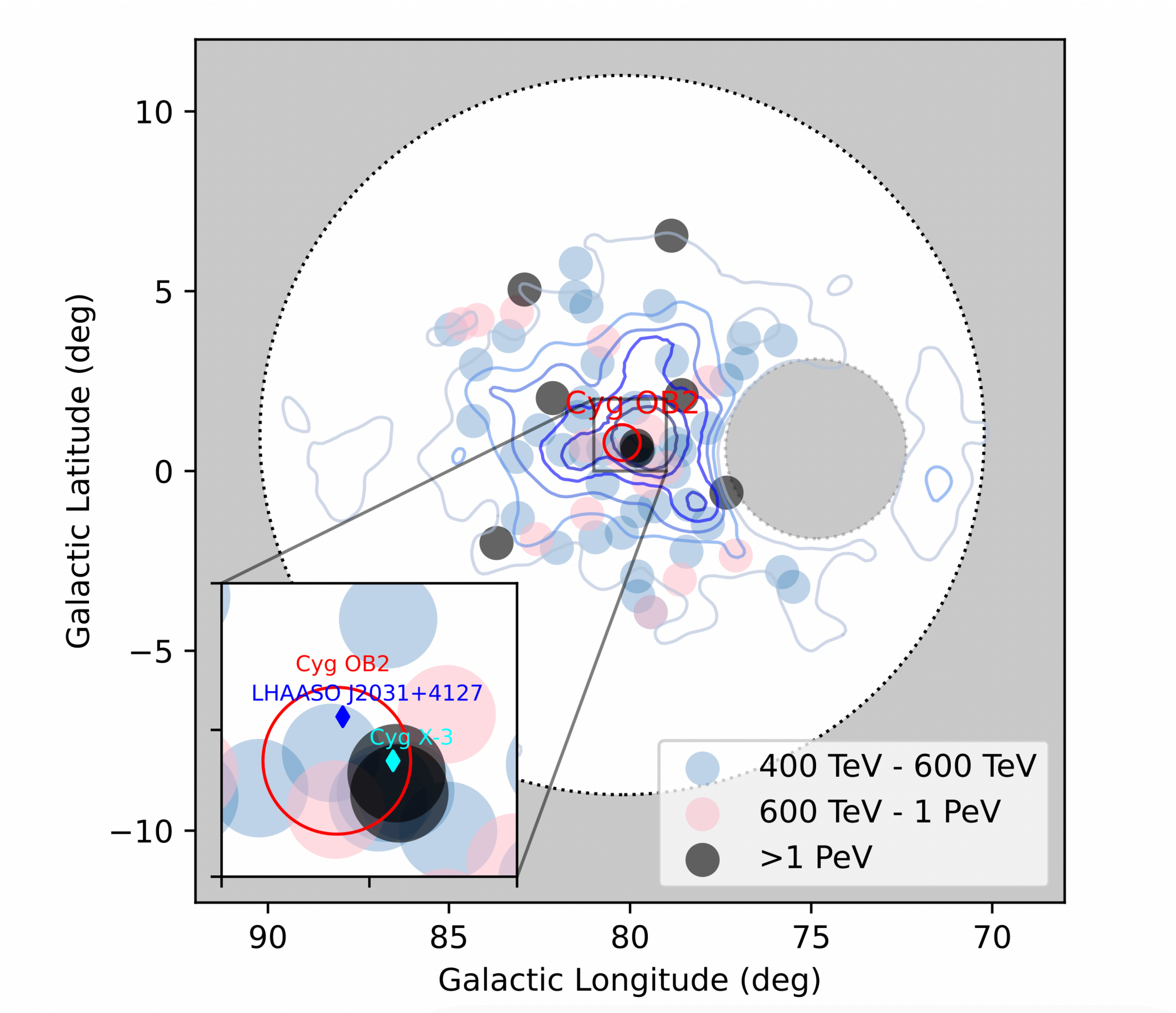
Cygnus Cocoon

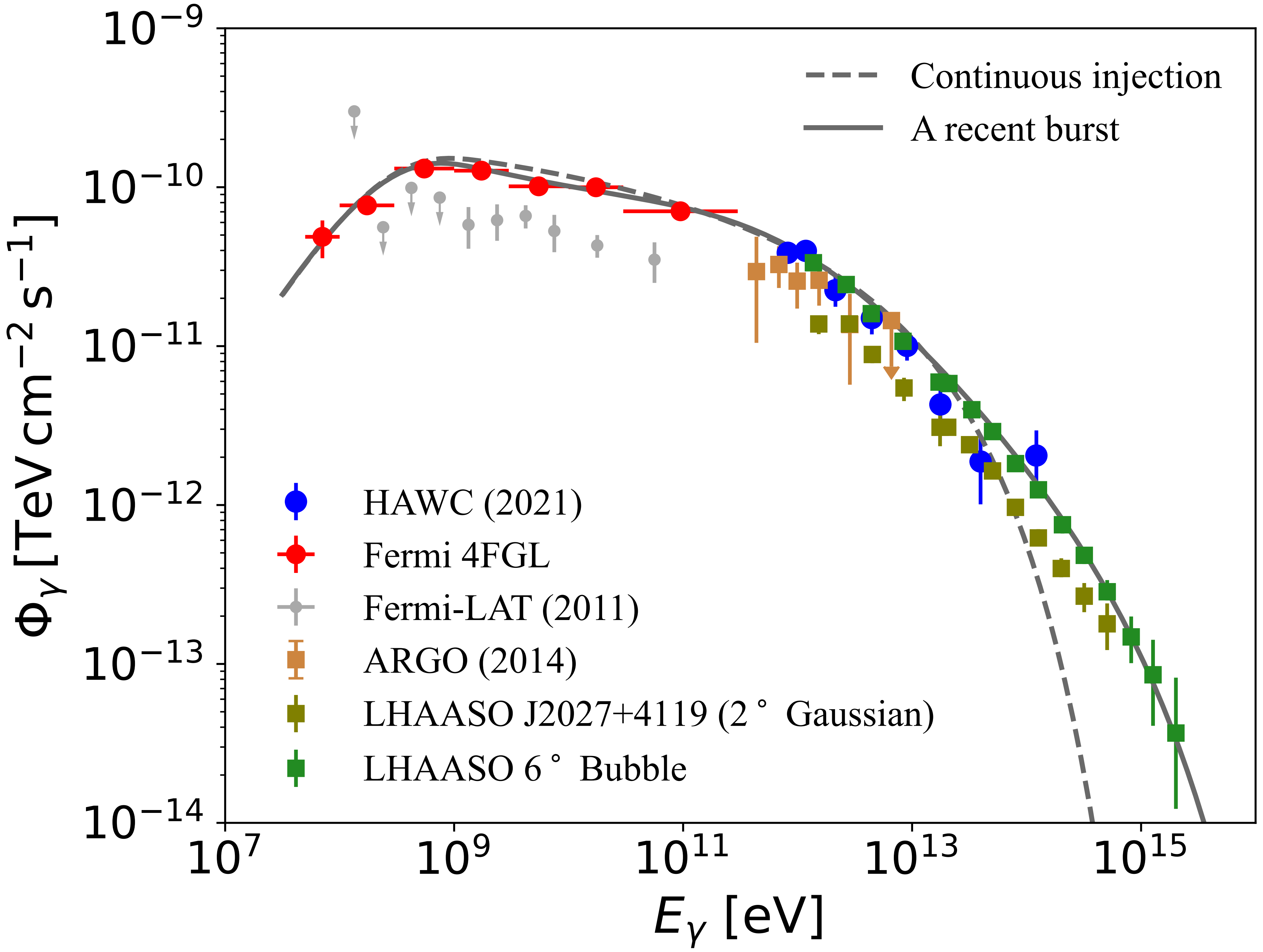




LHAASO Collaboration, Science Bulletin (2024)
KF & Halzen, 2404.15944

Cygnus Cocoon

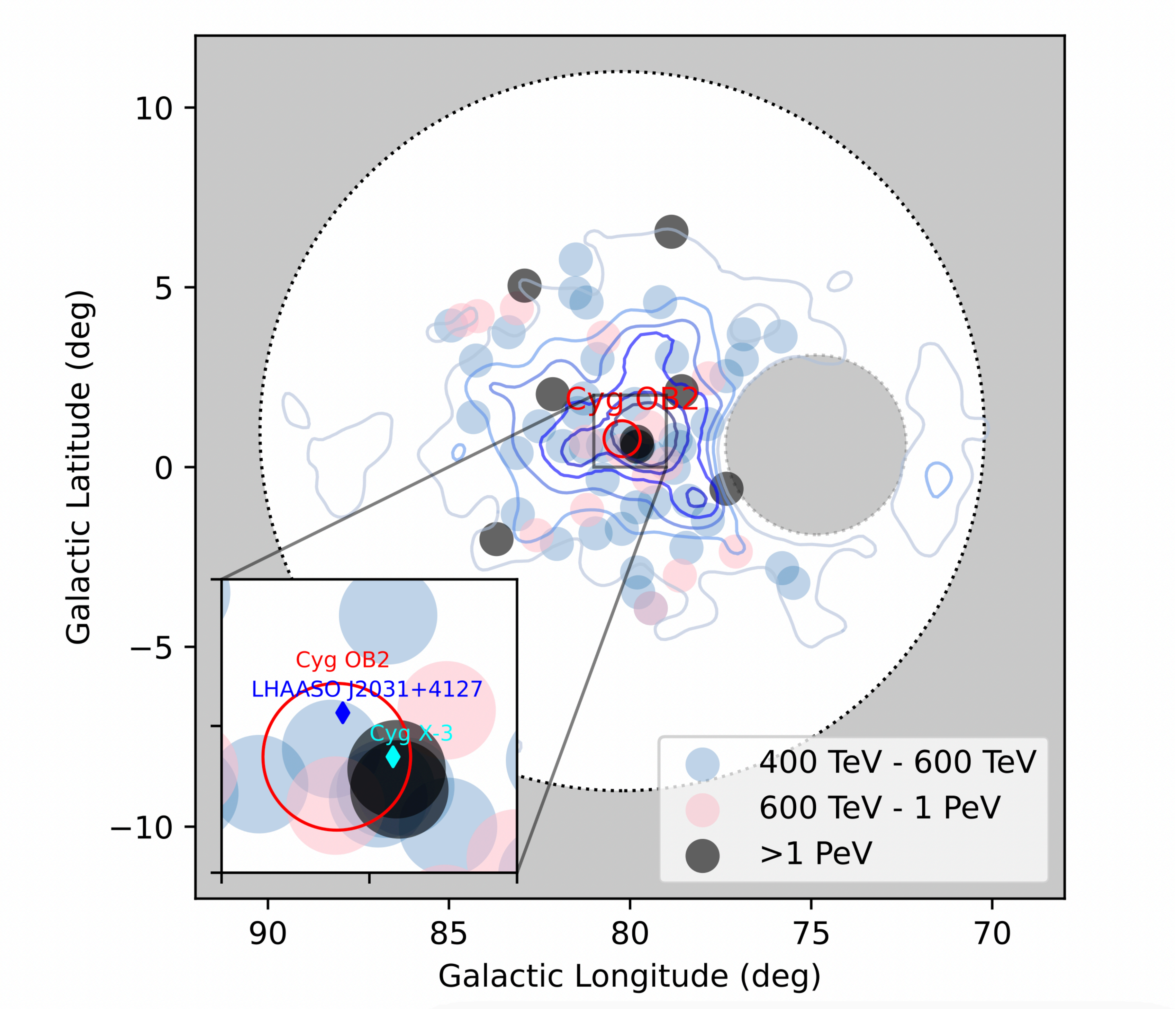


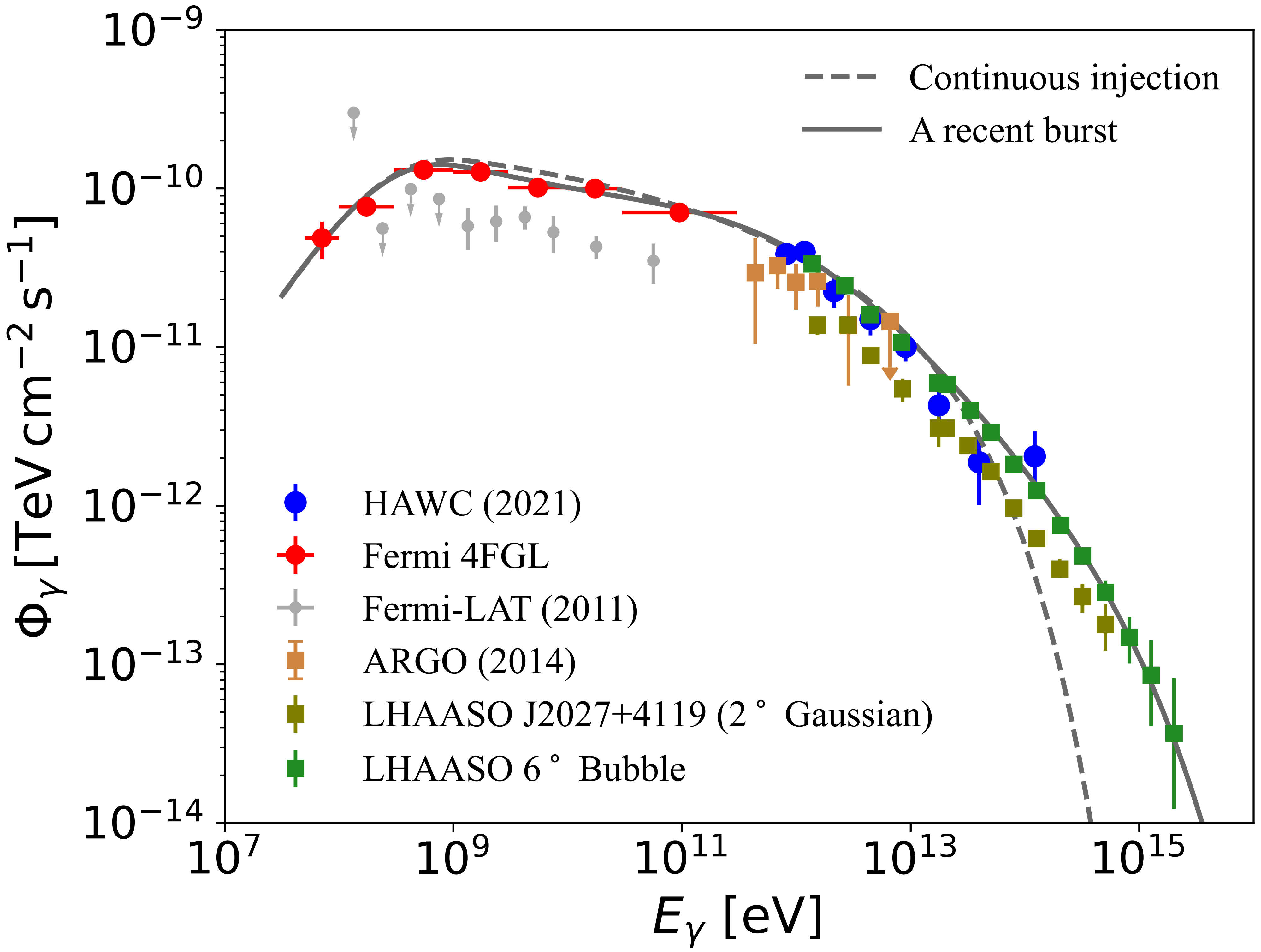


LHAASO Collaboration, Science Bulletin (2024)

KF & Halzen, 2404.15944

Cygnus Cocoon

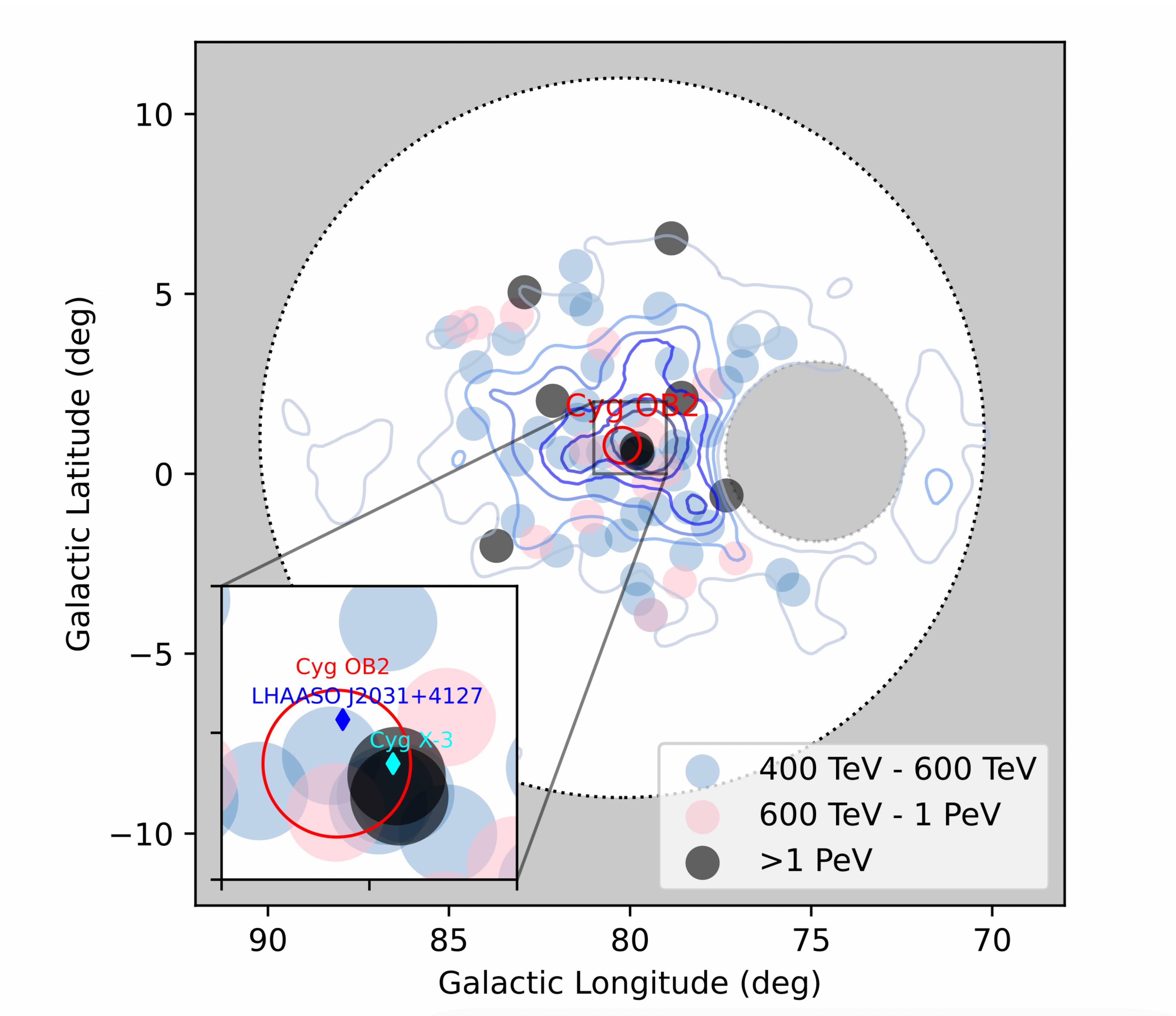


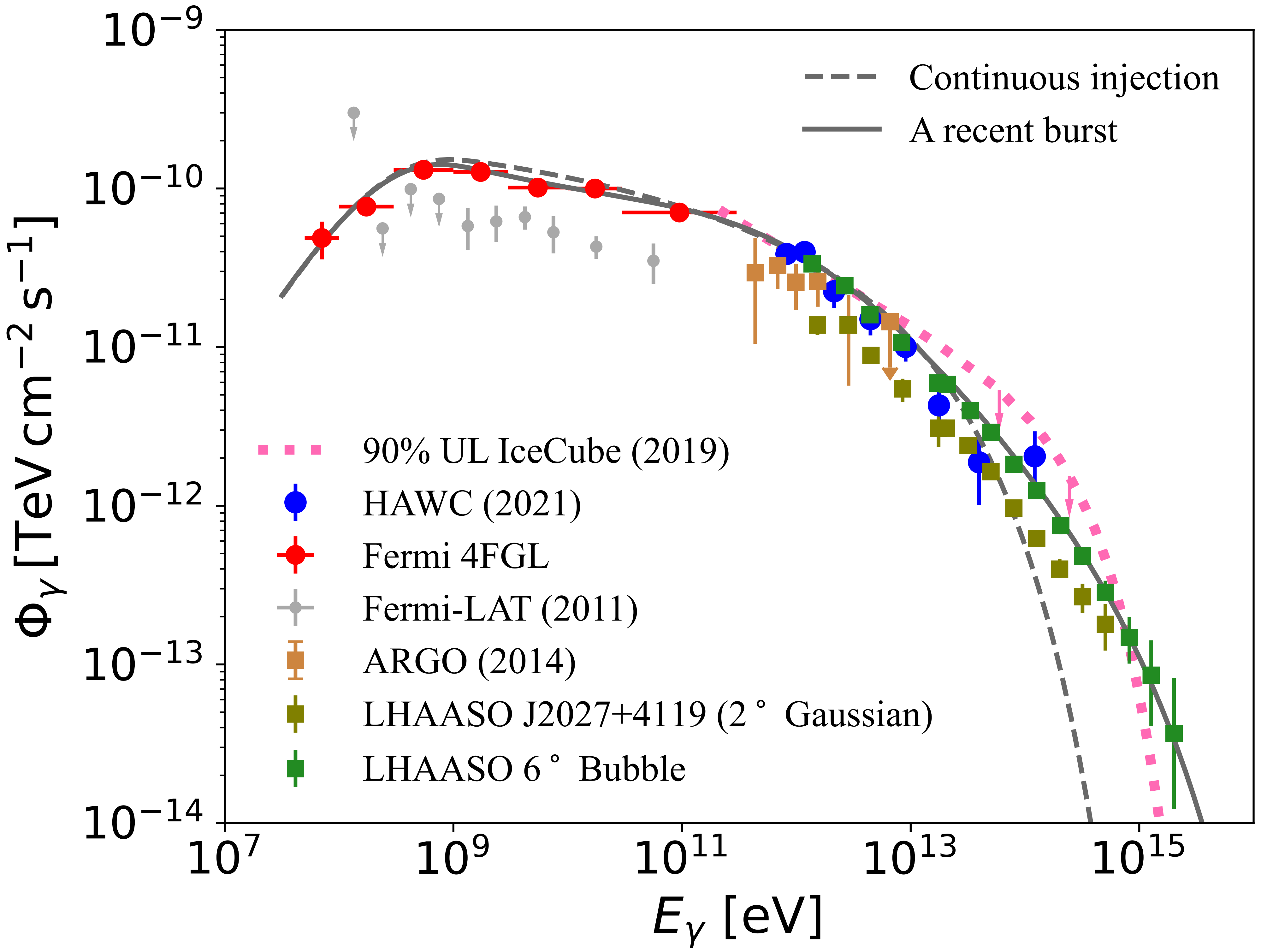


- 0.1-1 PeV gamma-ray observation indicates a “super-PeVatron”

LHAASO Collaboration, Science Bulletin (2024)
KF & Halzen, 2404.15944

Cygnus Cocoon



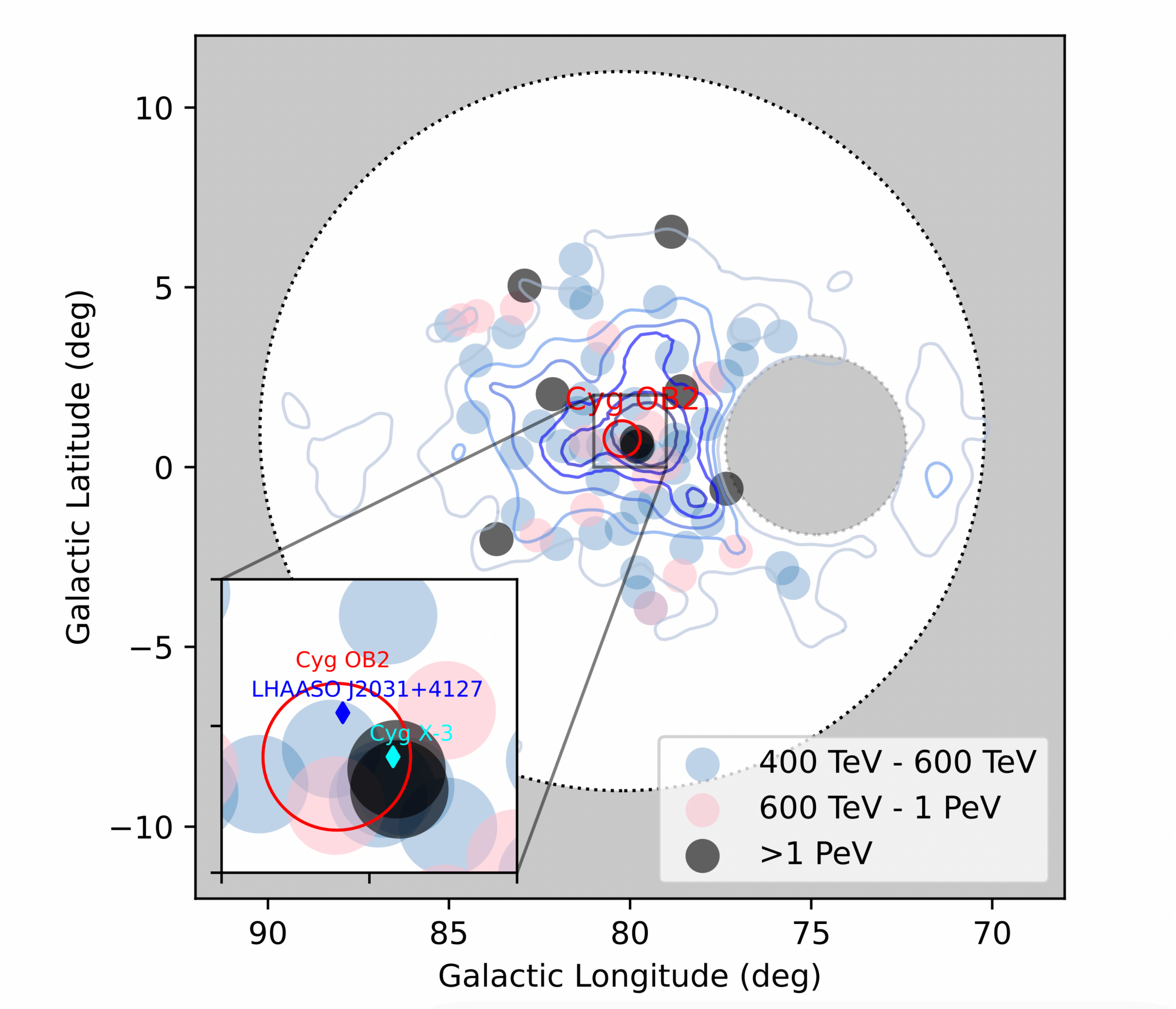


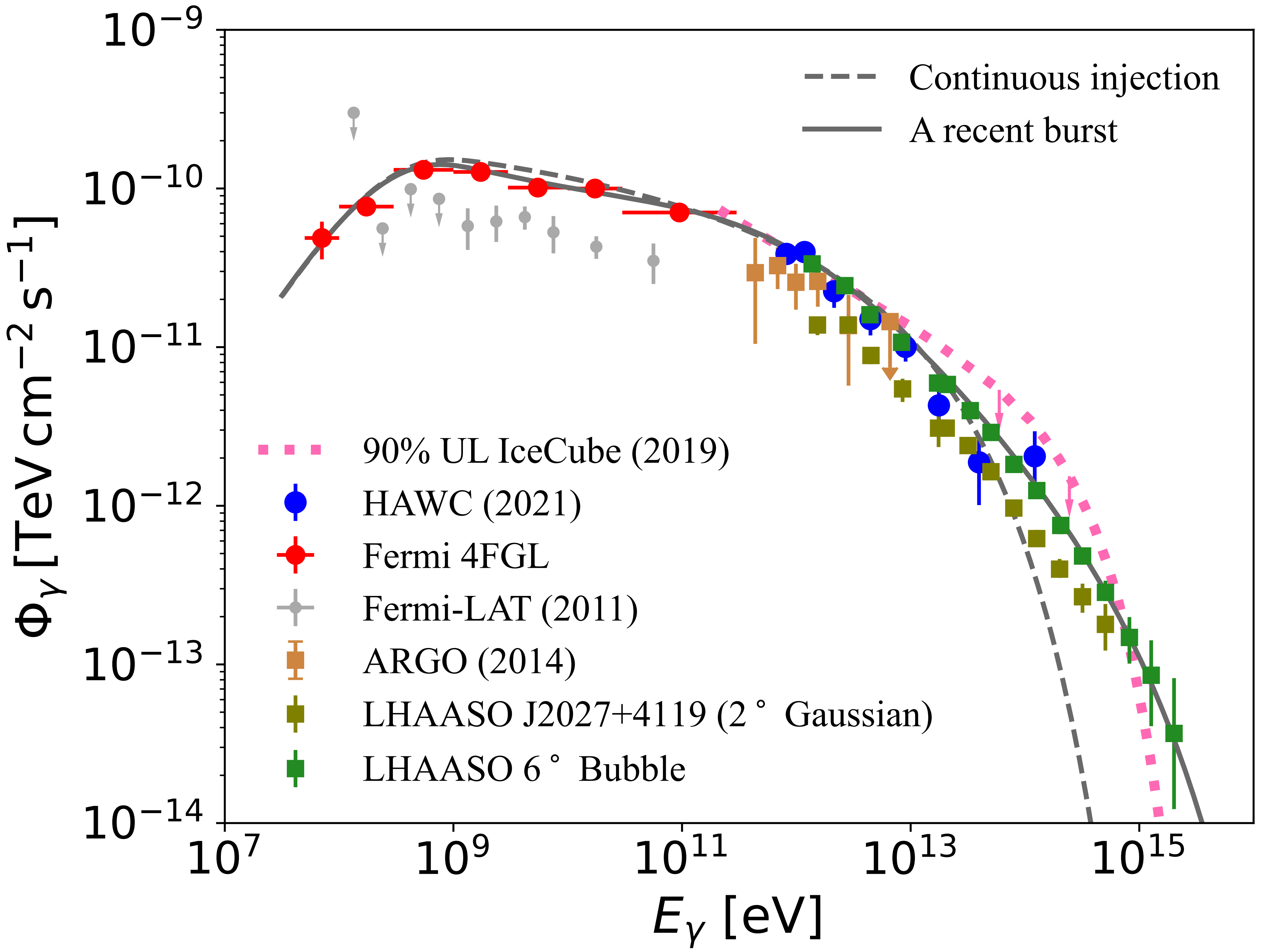
- 0.1-1 PeV gamma-ray observation indicates a “super-PeVatron”

LHAASO Collaboration, Science Bulletin (2024)
KF & Halzen, 2404.15944

Cygnus Cocoon

ICECUBE
NEUTRINO OBSERVATORY

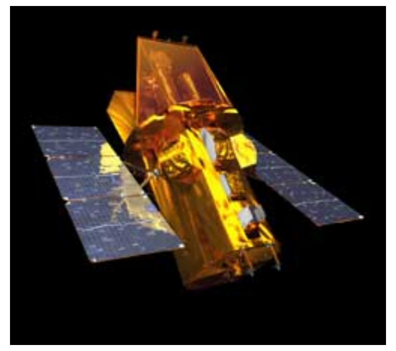


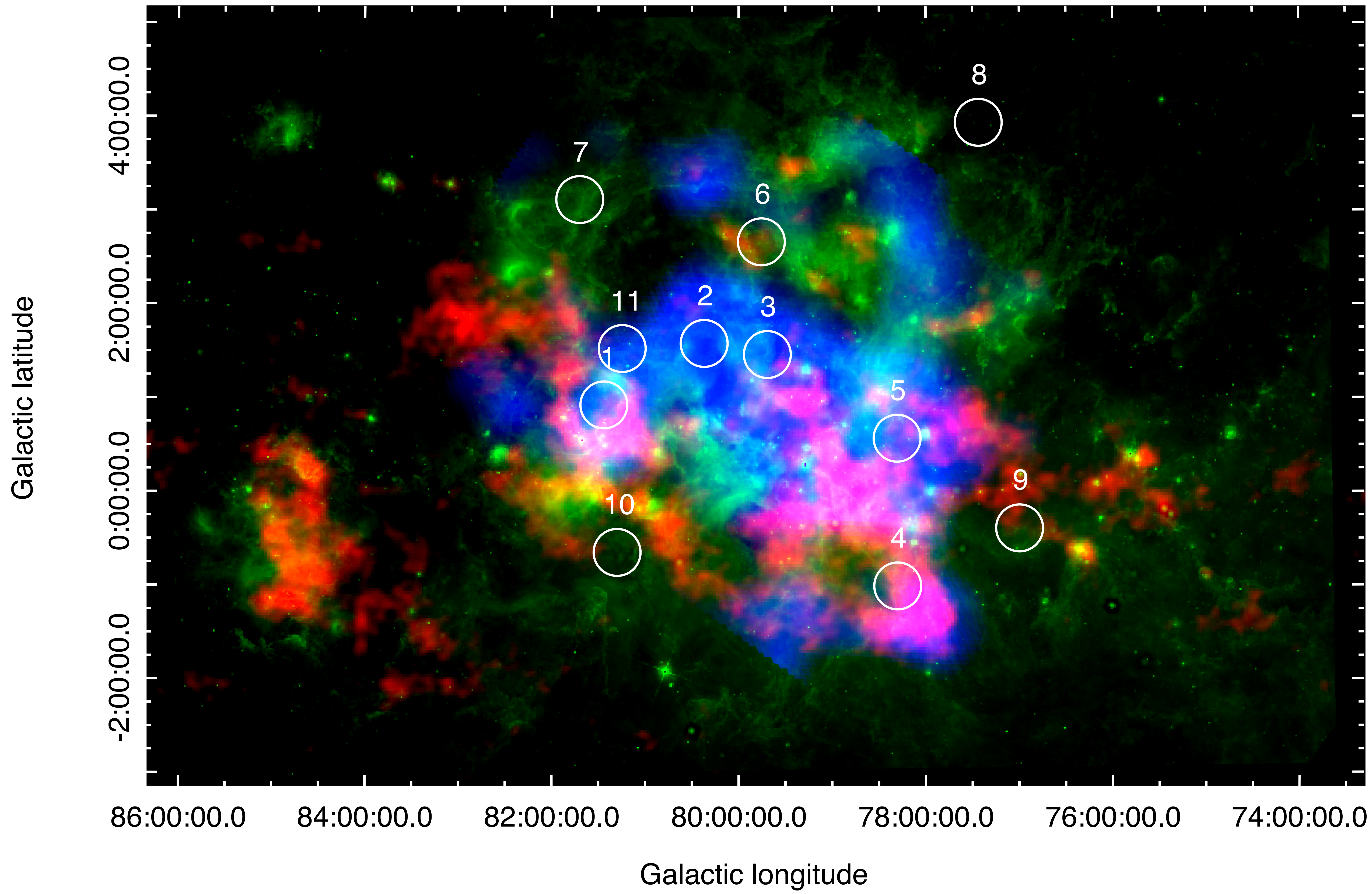


- 0.1-1 PeV gamma-ray observation indicates a “super-PeVatron”
- Plausible neutrino source

LHAASO Collaboration, Science Bulletin (2024)
KF & Halzen, 2404.15944

Cygnus Cocoon: Leptonic Emission?

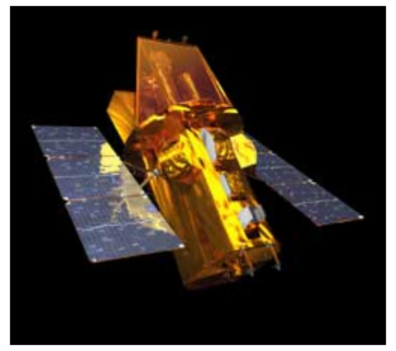


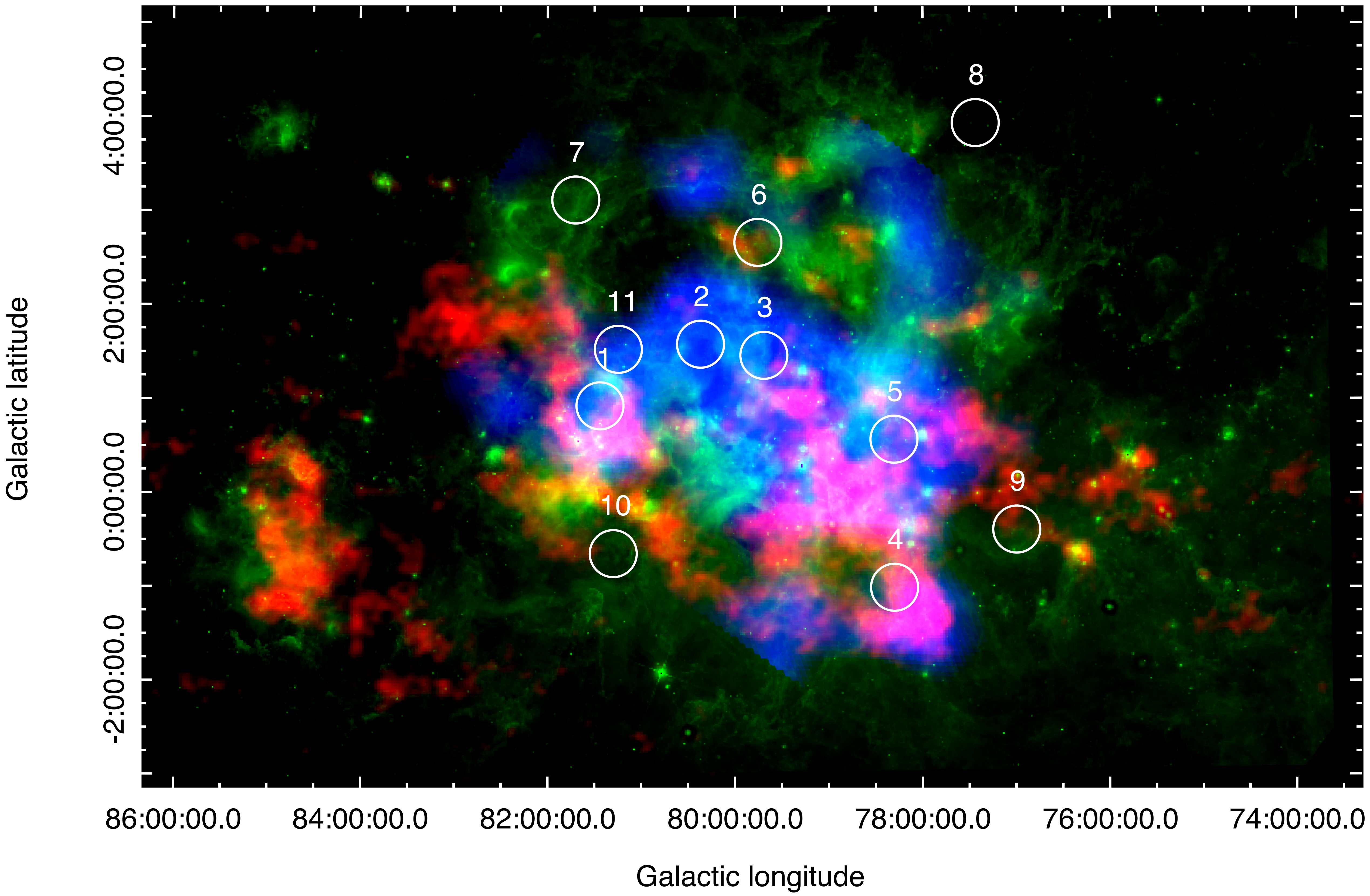


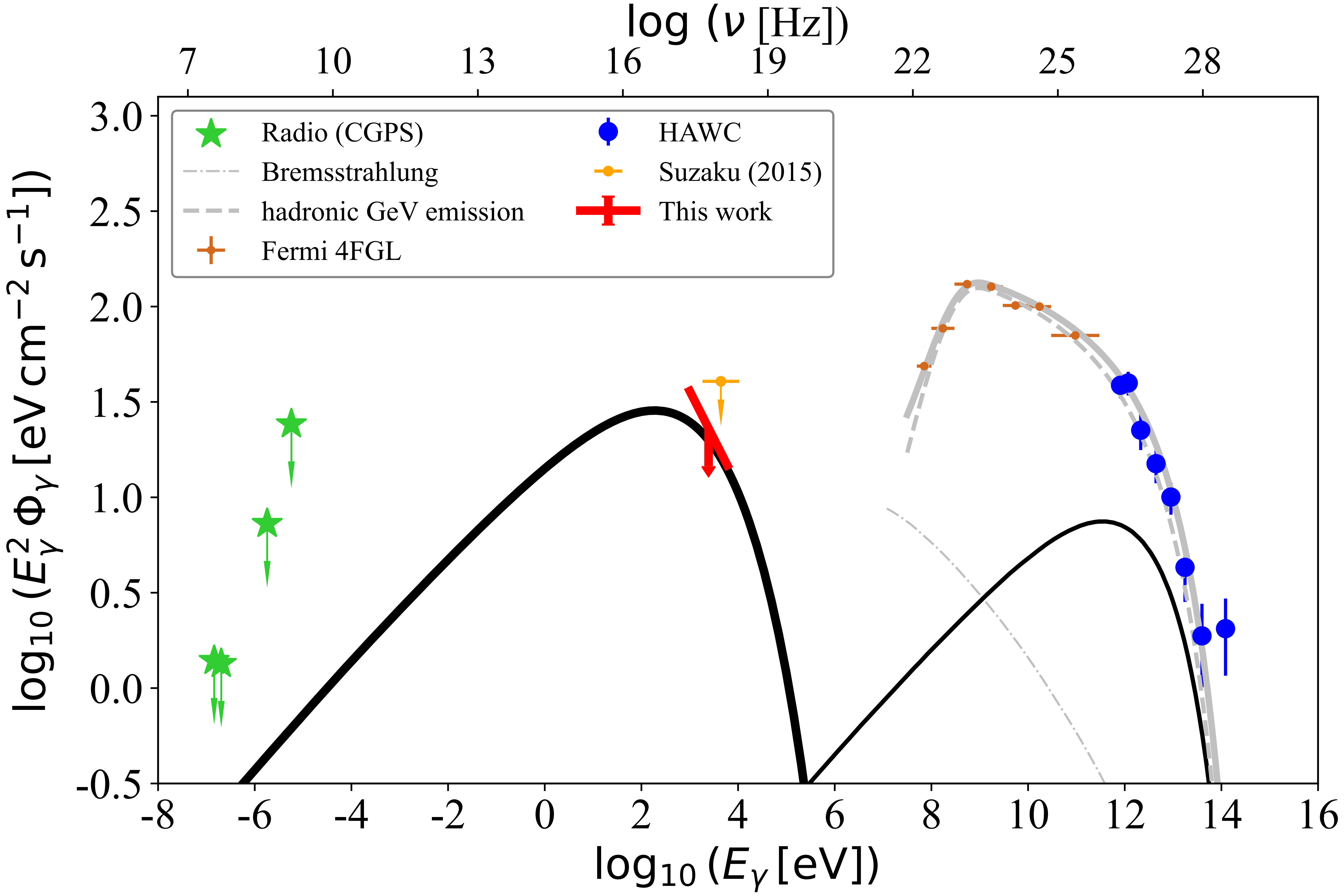
- **X-ray follow-up with Swift-XRT** (110 ks observations of 11 sites inside and around the Cocoon)
- Constrained X-ray emission by relativistic electrons

Swift Guest Investigator Program Cycle 17
Guevel et al, *ApJ 2211.07617*

Cygnus Cocoon: Leptonic Emission?





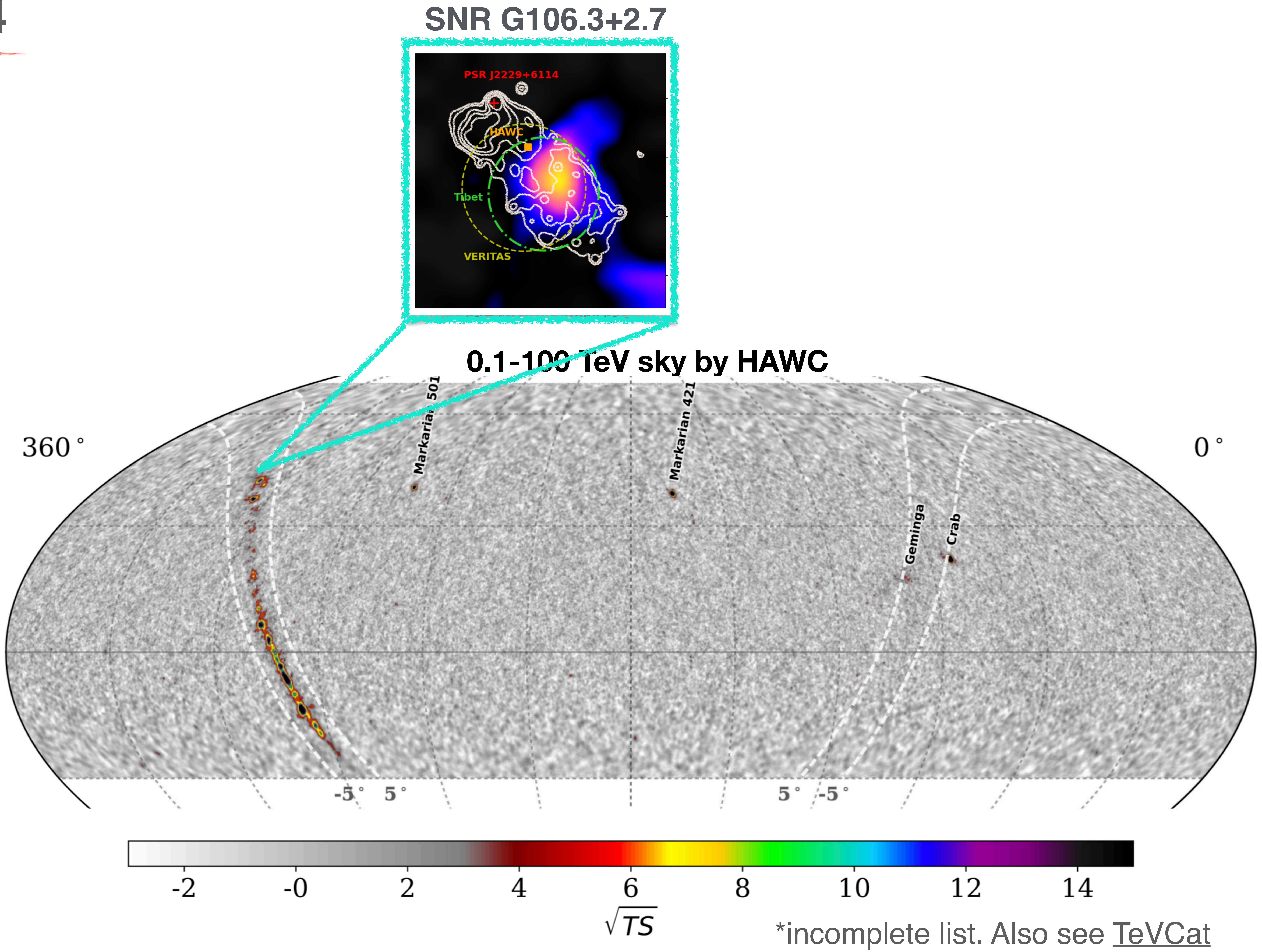


- **X-ray follow-up with Swift-XRT** (110 ks observations of 11 sites inside and around the Cocoon)
- Constrained X-ray emission by relativistic electrons

Swift Guest Investigator Program Cycle 17

Guevel et al, *ApJ 2211.07617*

PeVatron Zoo* in 2024

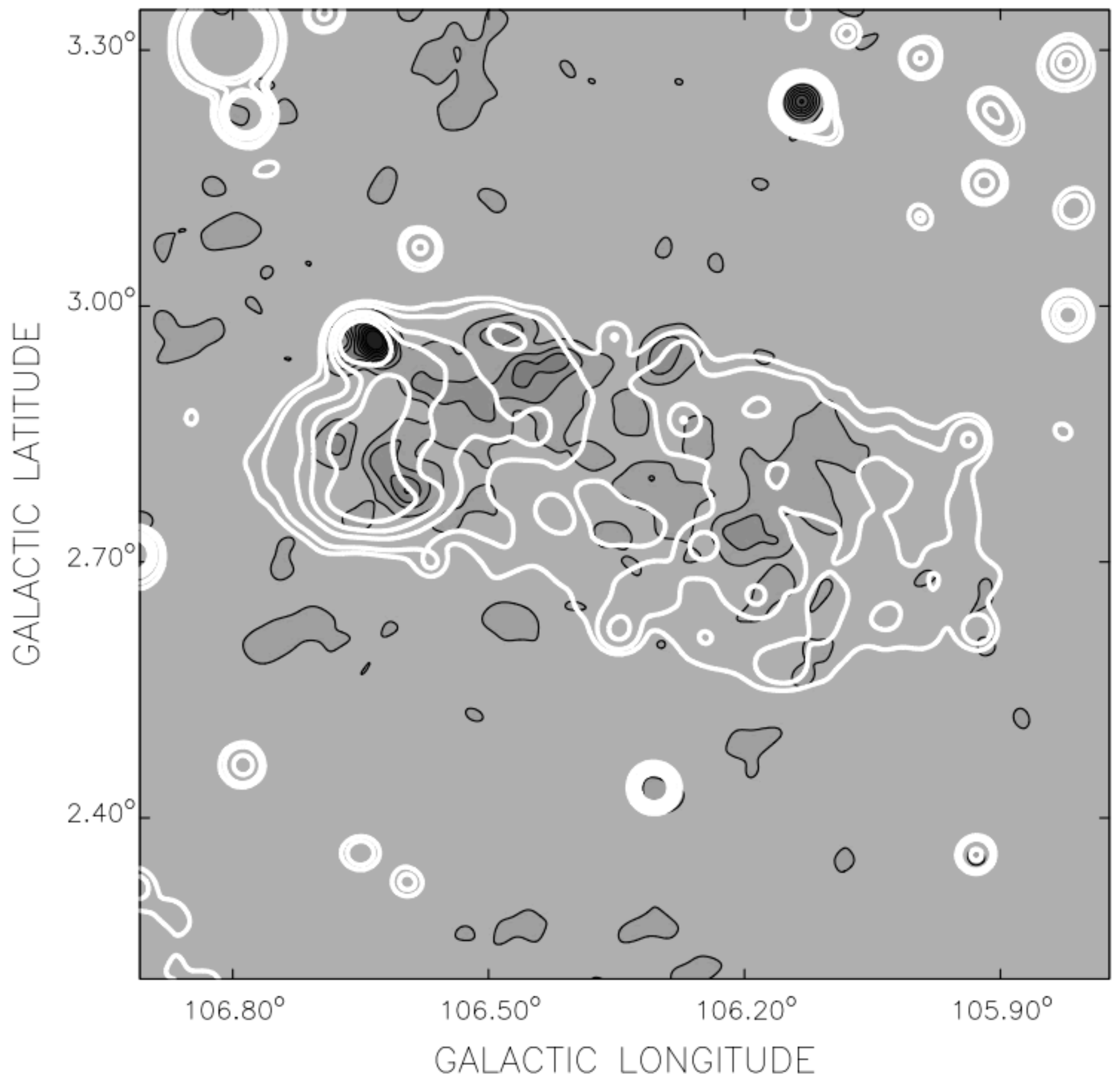


*incomplete list. Also see TeVCat

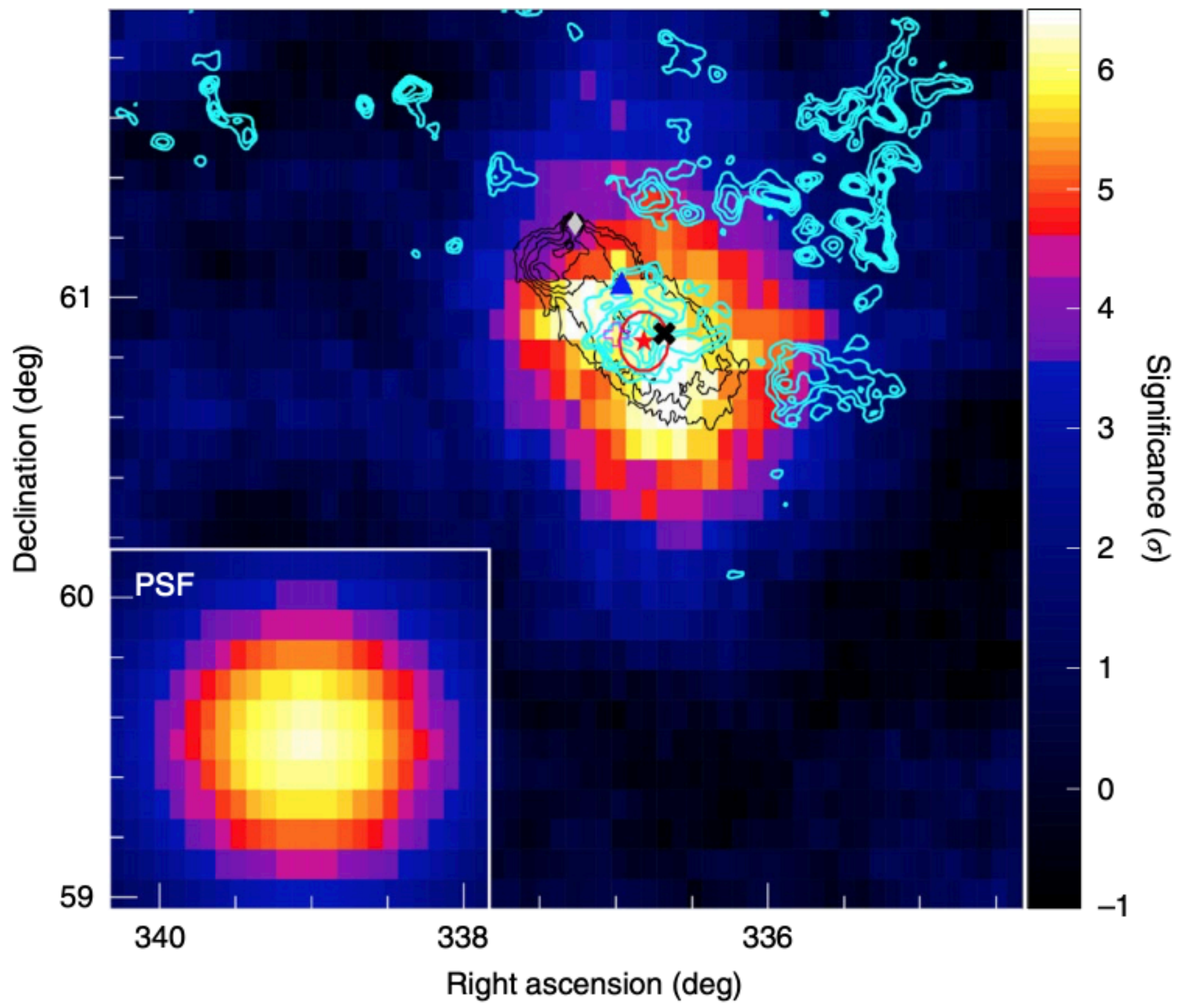
Supernova Remnant G106.3+2.7

Supernova Remnant G106.3+2.7

Radio (1420 MHz)
Kothes et al *ApJ* (2001)



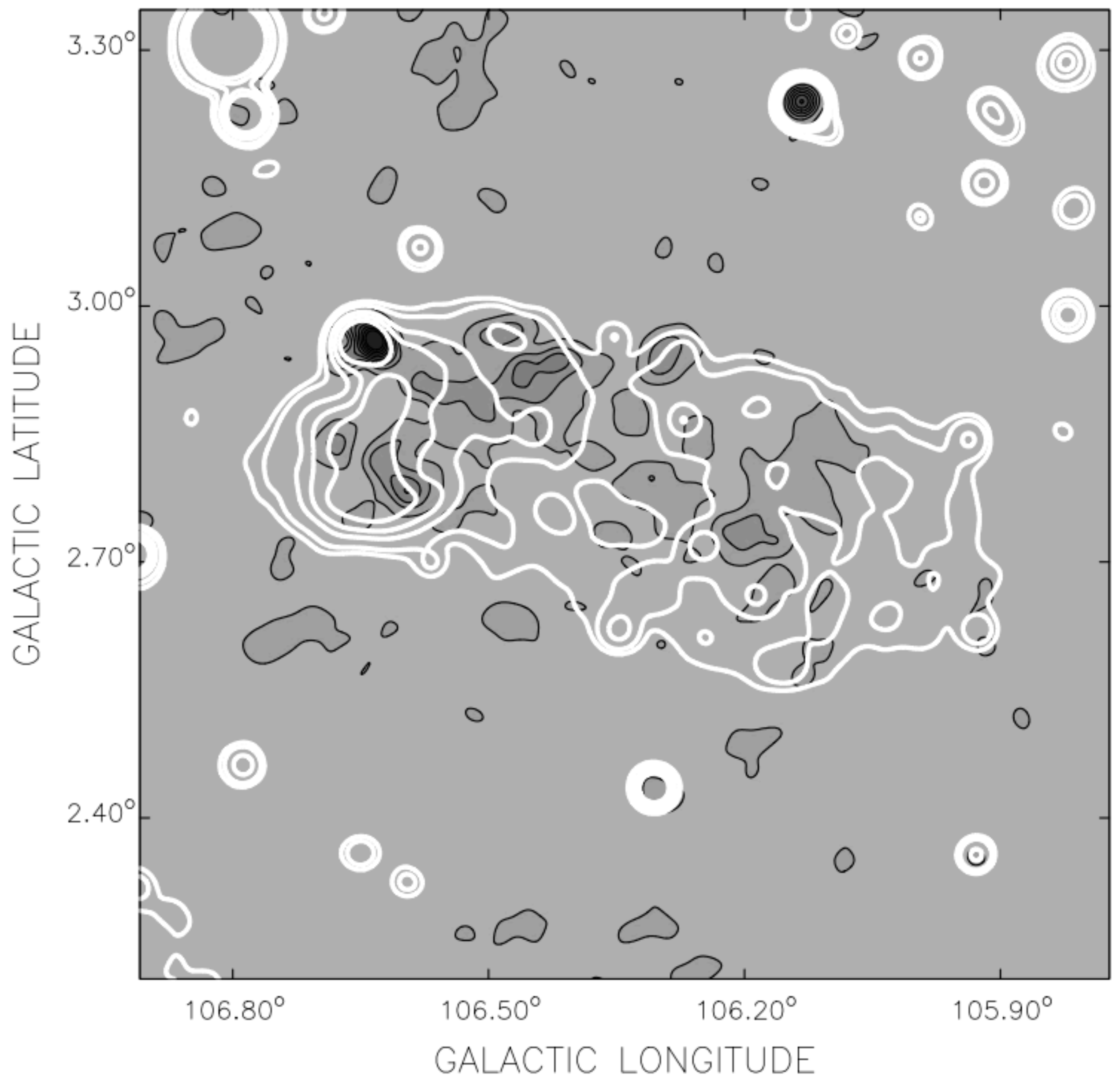
1-100 TeV
Tibet ASγ Coll. *Nature Astro.* (2021)



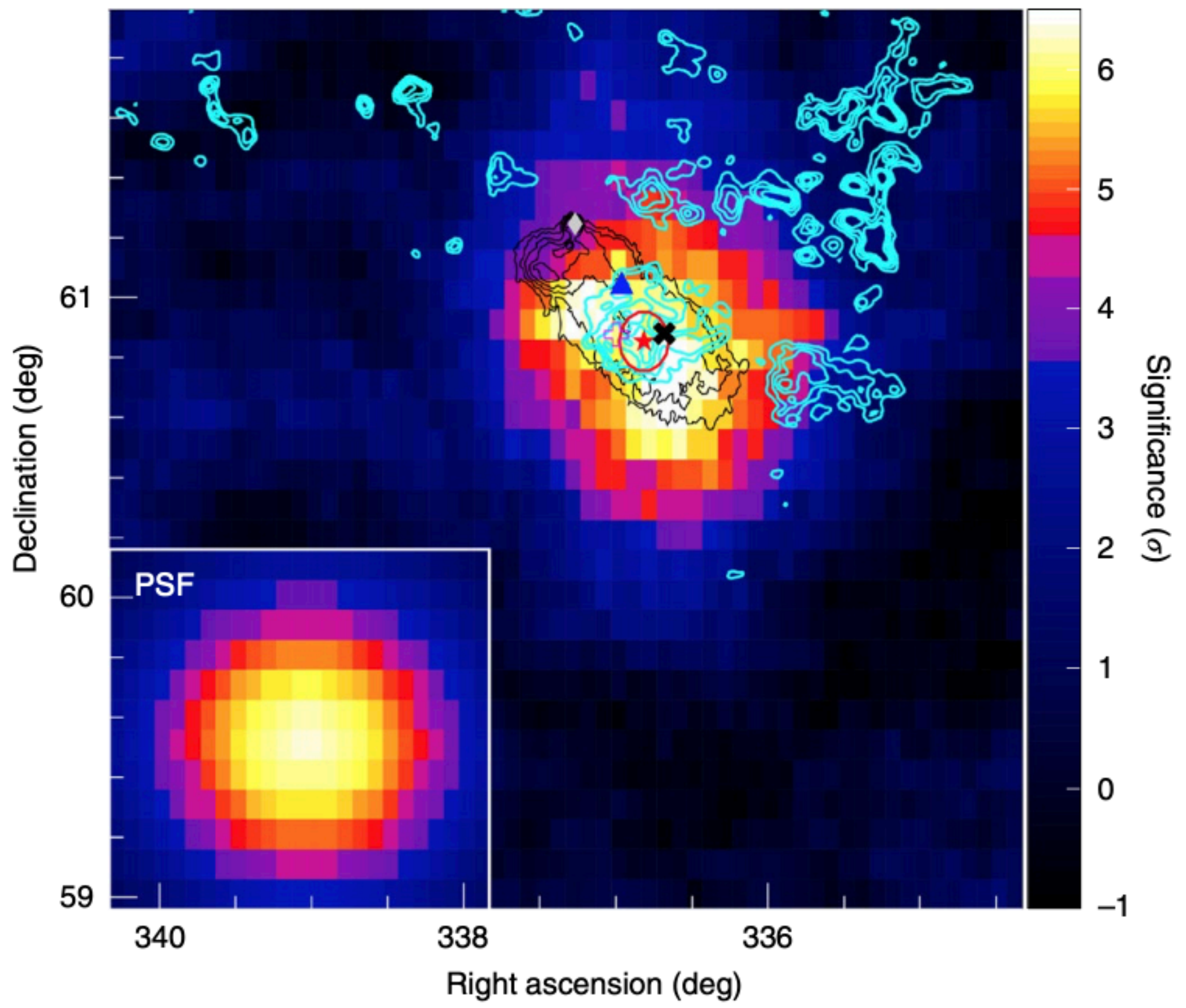
- **Observed in radio, X-ray, and TeV gamma-ray** (VERITAS, HAWC, Tibet, LHAASO)
- Gamma-ray emitting site closes to a molecular cloud

Supernova Remnant G106.3+2.7

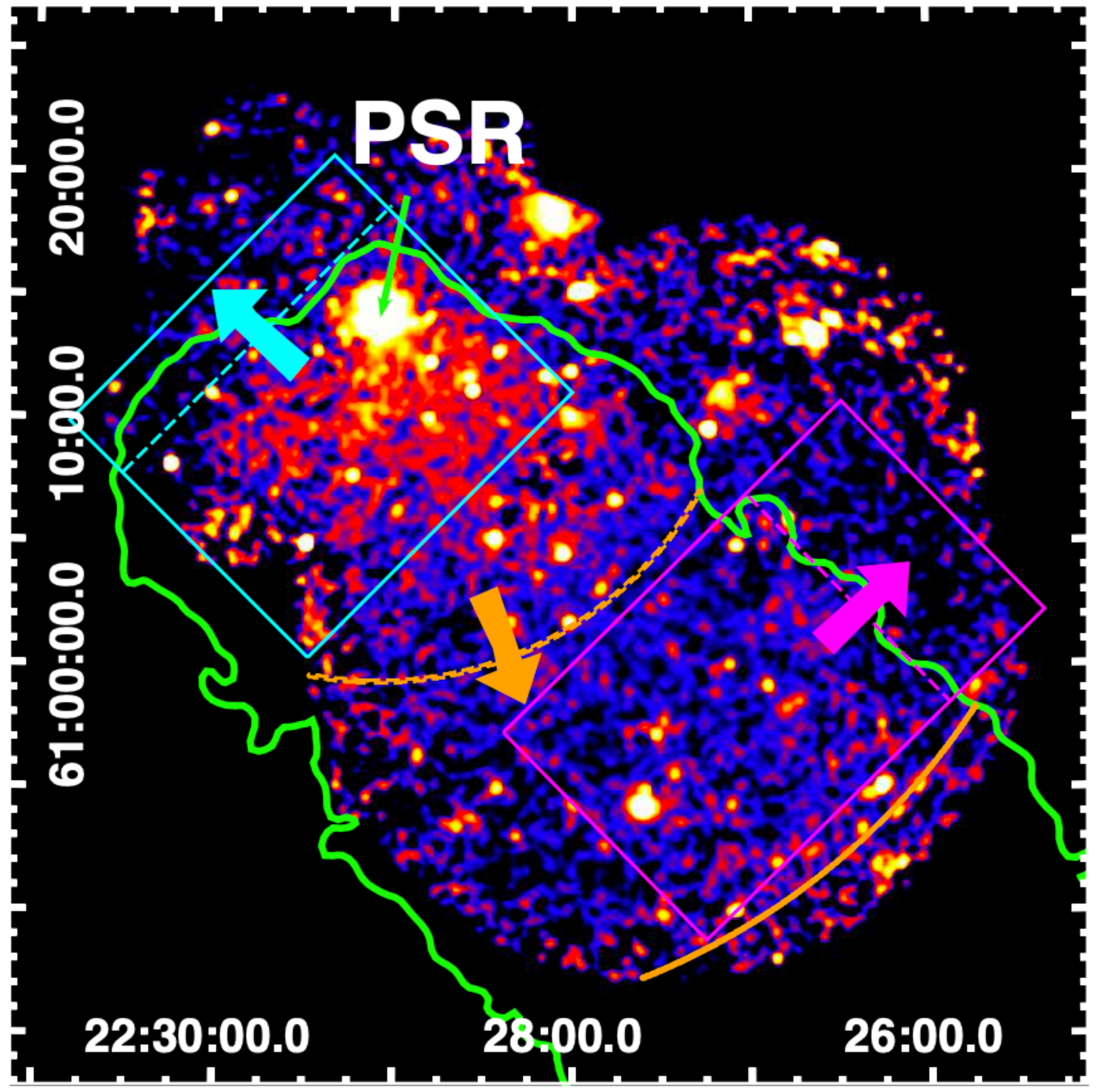
Radio (1420 MHz)
Kothes et al *ApJ* (2001)



1-100 TeV
Tibet ASγ Coll. *Nature Astro.* (2021)



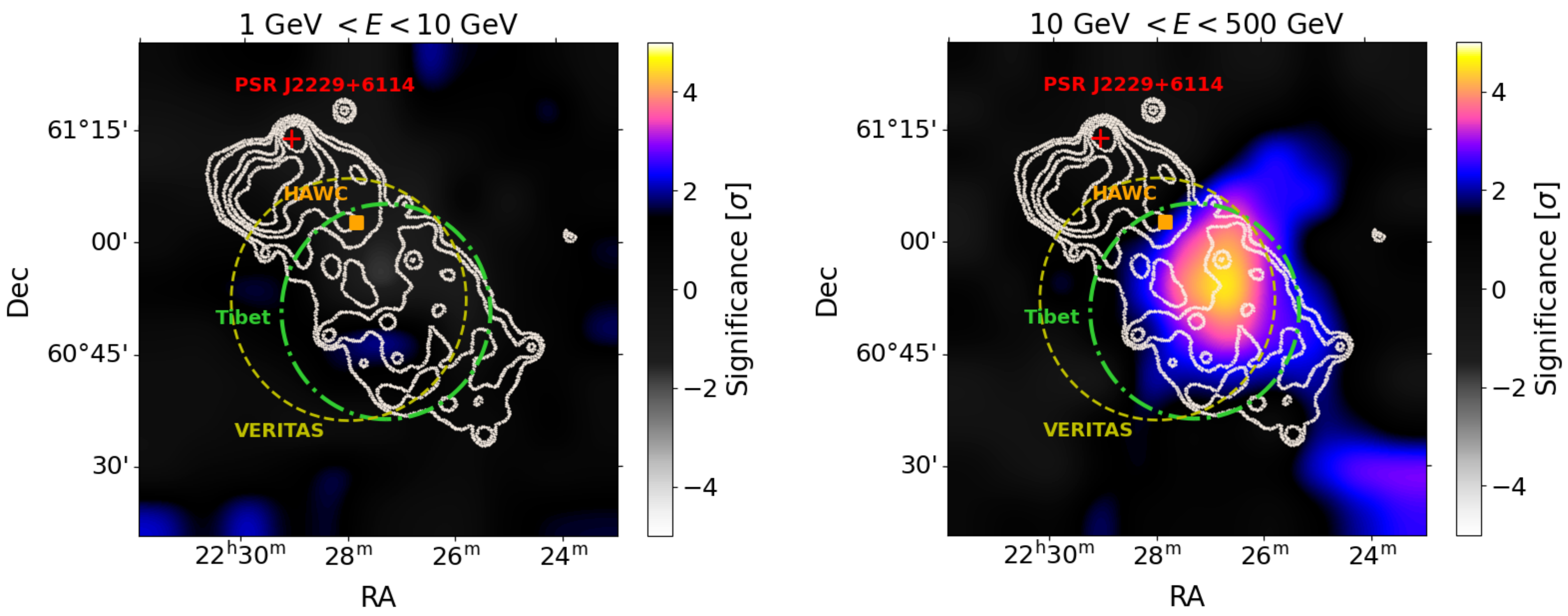
2-10 keV
Ge et al *the Innovation* (2021)



- **Observed in radio, X-ray, and TeV gamma-ray** (VERITAS, HAWC, Tibet, LHAASO)
- Gamma-ray emitting site closes to a molecular cloud
- Gamma-ray spectrum may be explained by either proton or electron emission

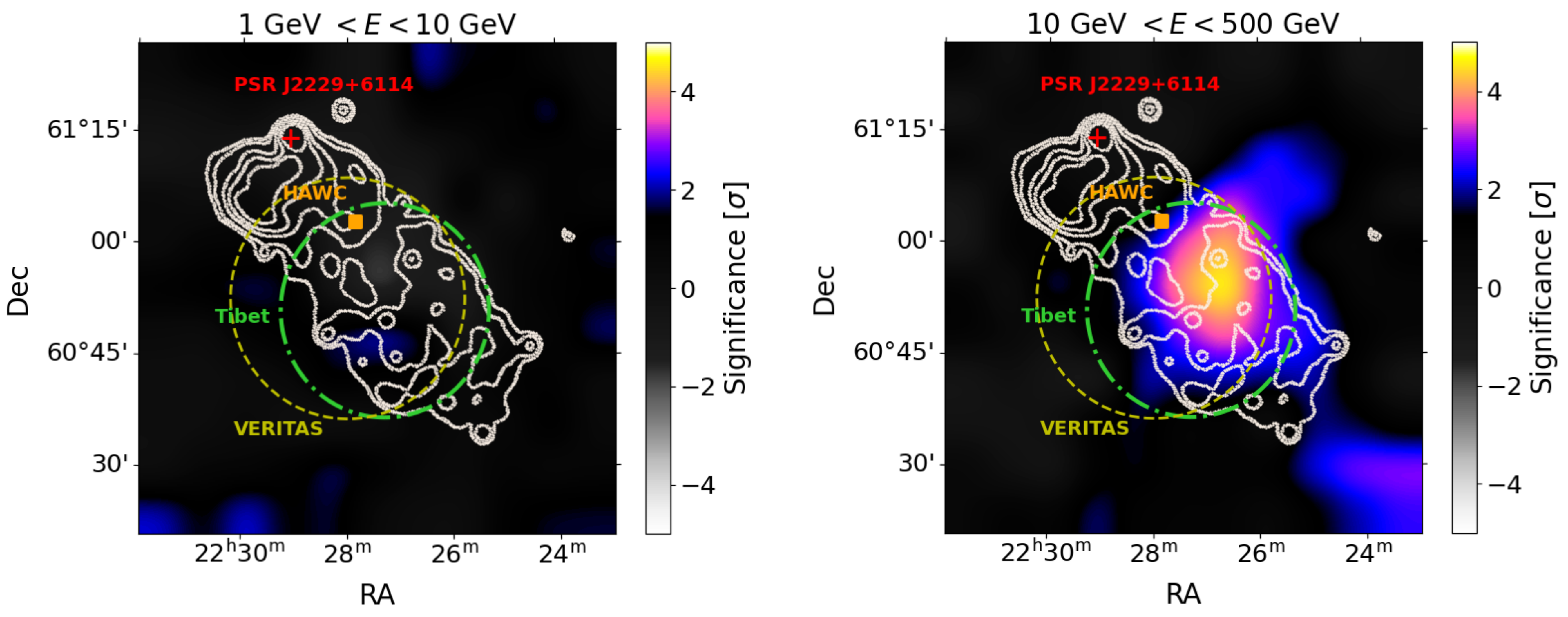
Ke Fang

Supernova Remnant G106.3+2.7



KF, Kerr, Blandford, Fleischhack, Charles, *PRL (2022) Editor's Suggestion*

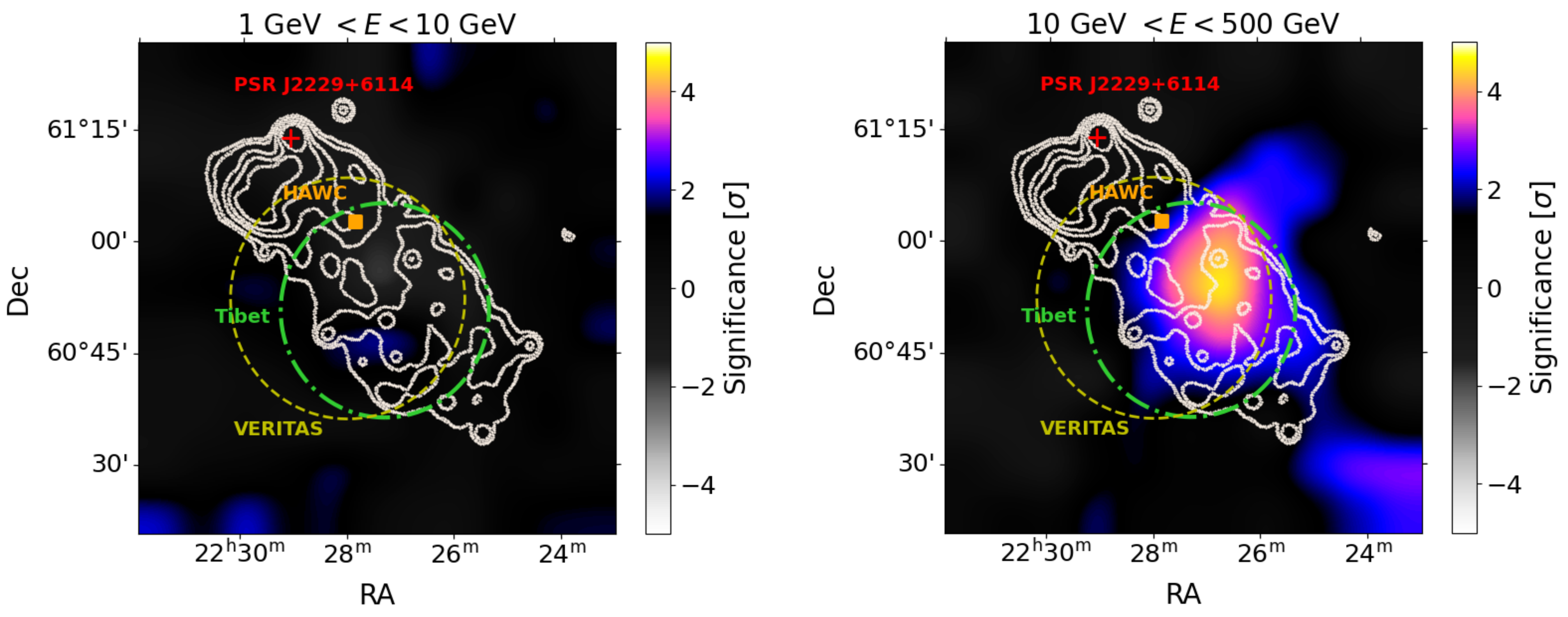
Supernova Remnant G106.3+2.7



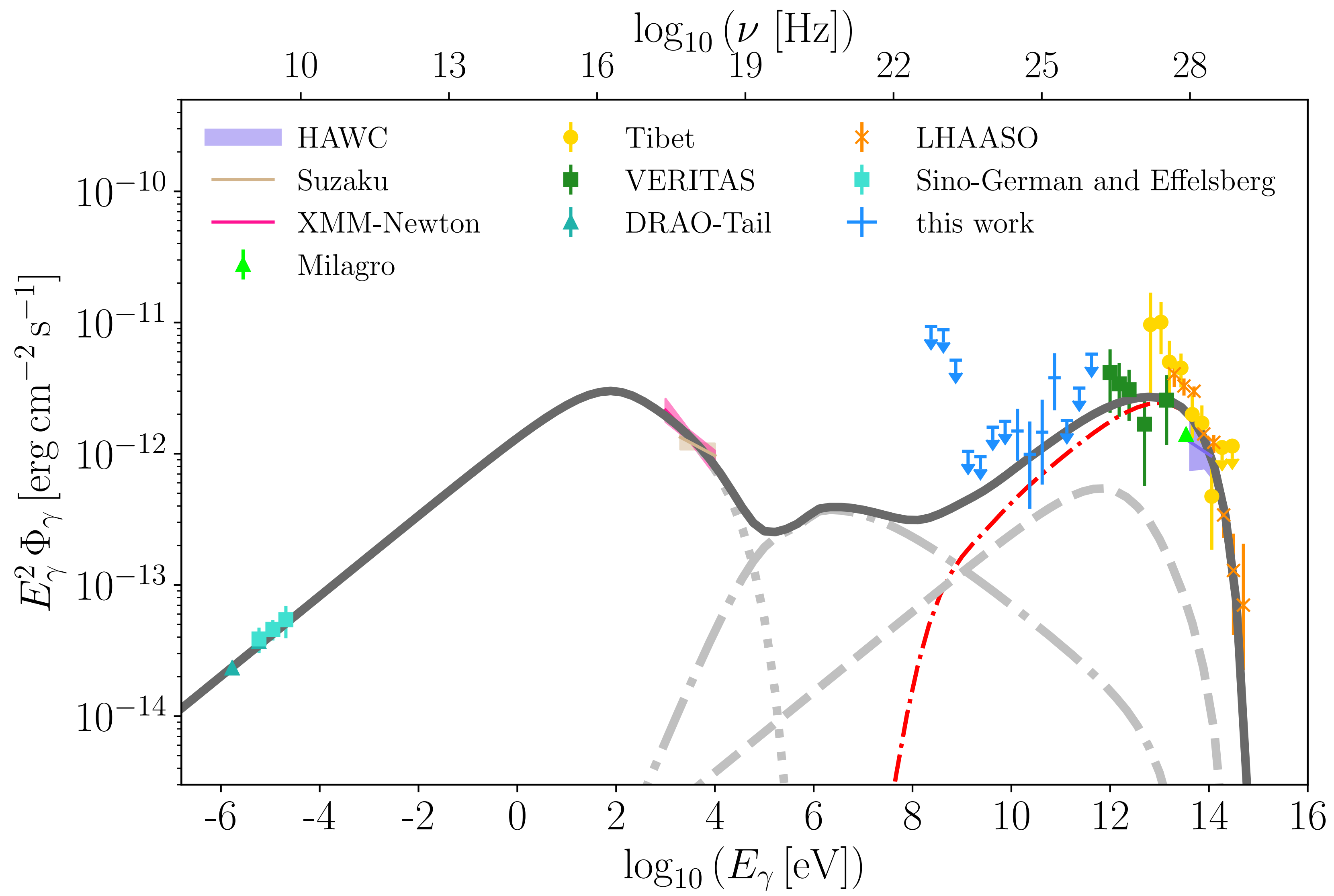
- Emission above 10 GeV is observed, consistent with TeV measurements; no emission found below 10 GeV

KF, Kerr, Blandford, Fleischhack, Charles, *PRL (2022) Editor's Suggestion*

Supernova Remnant G106.3+2.7



Electron + Proton

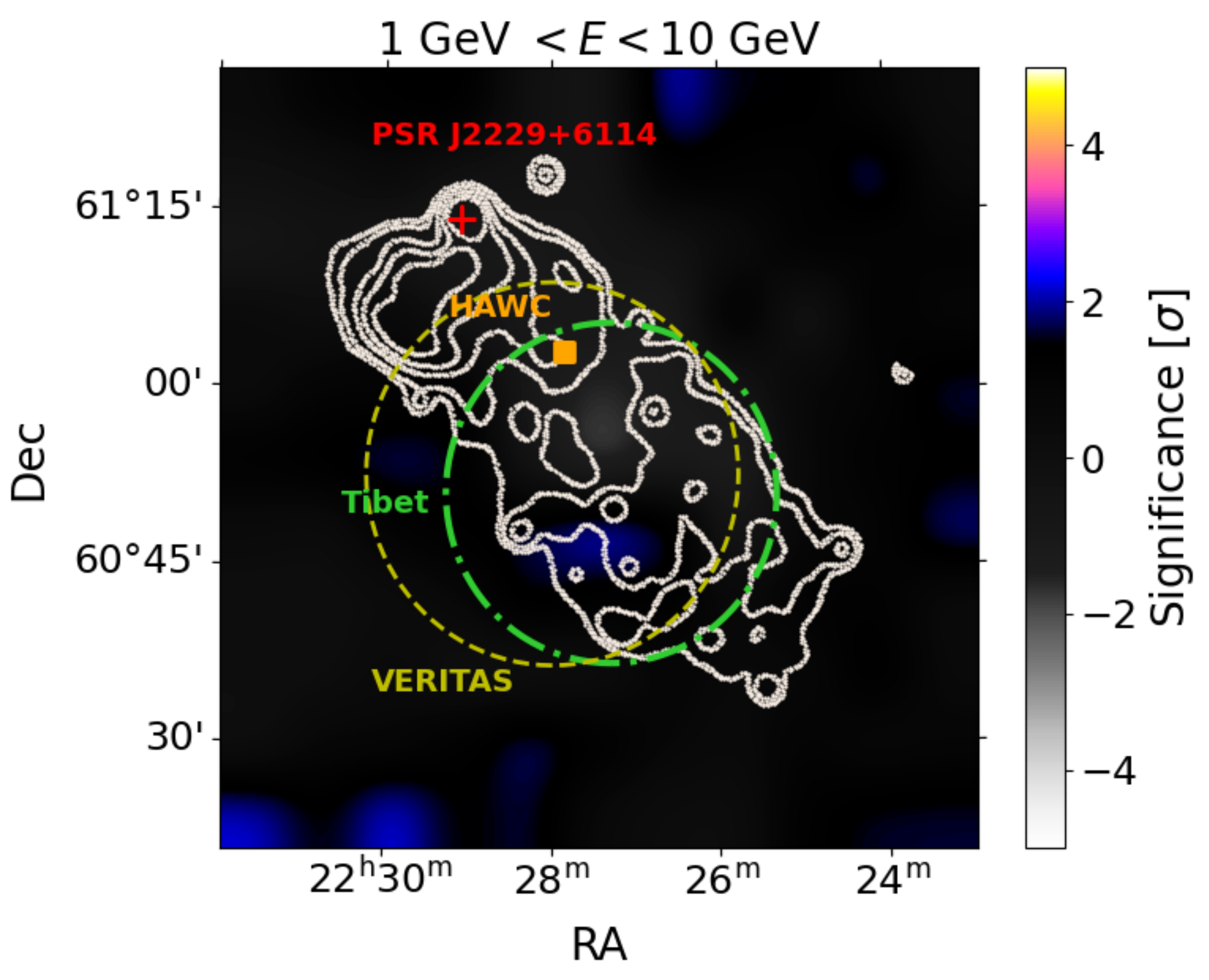


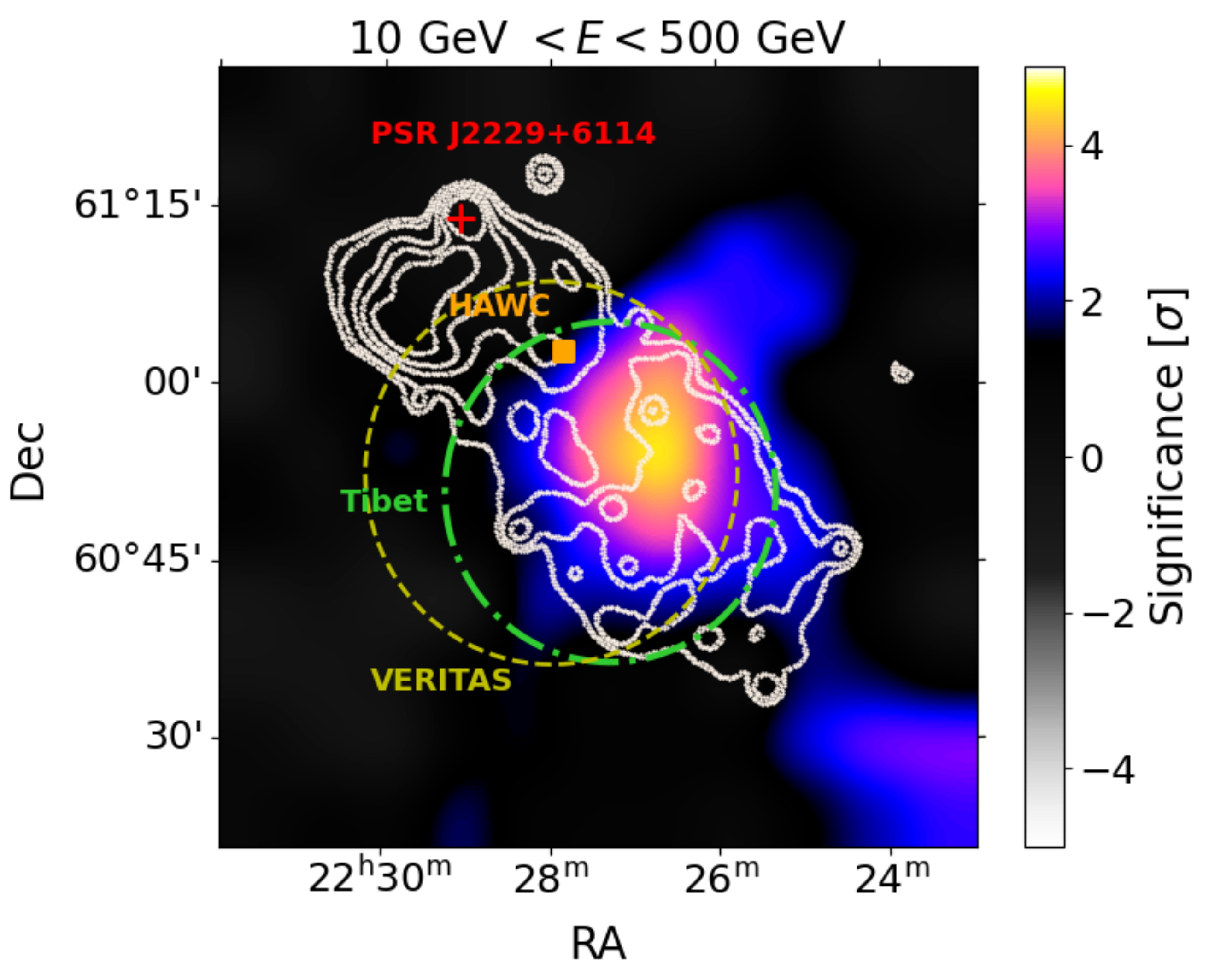
Best-fit proton maximum energy = 0.9 PeV

- Emission above 10 GeV is observed, consistent with TeV measurements; no emission found below 10 GeV
- **Model with proton contribution is favored at >5 σ significance**

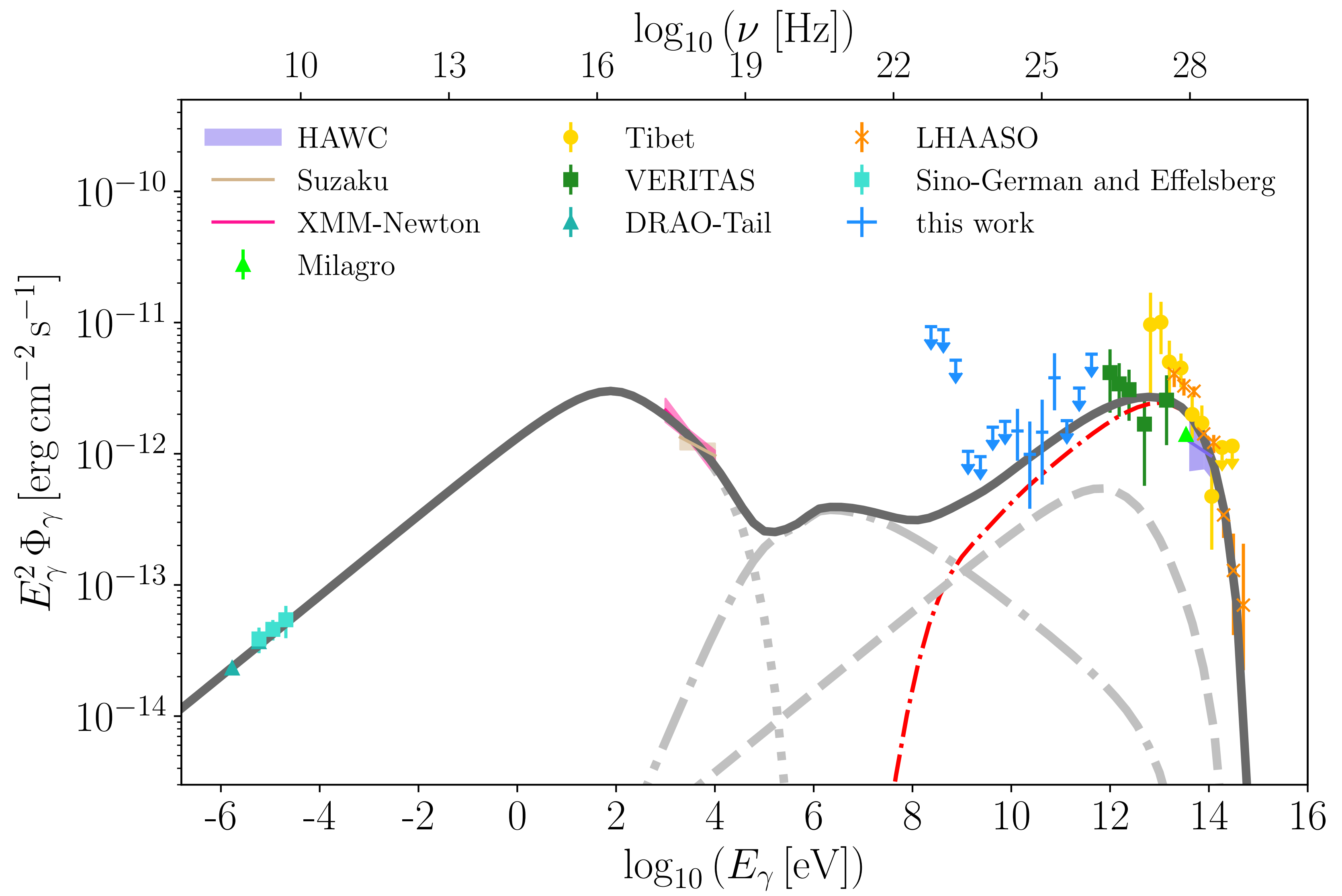
KF, Kerr, Blandford, Fleischhack, Charles, *PRL (2022) Editor's Suggestion*

Supernova Remnant G106.3+2.7





Electron + Proton



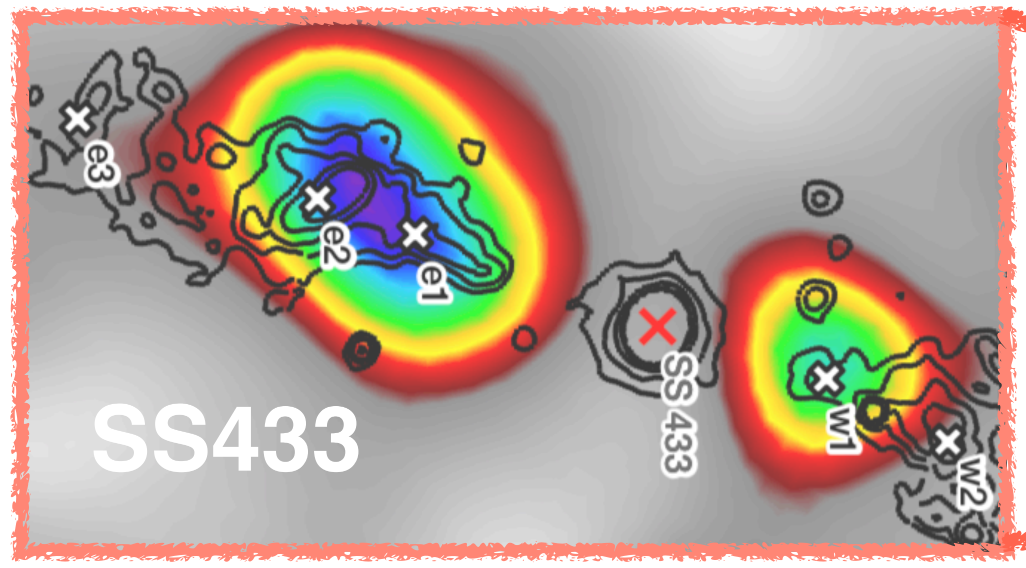
Best-fit proton maximum energy = 0.9 PeV

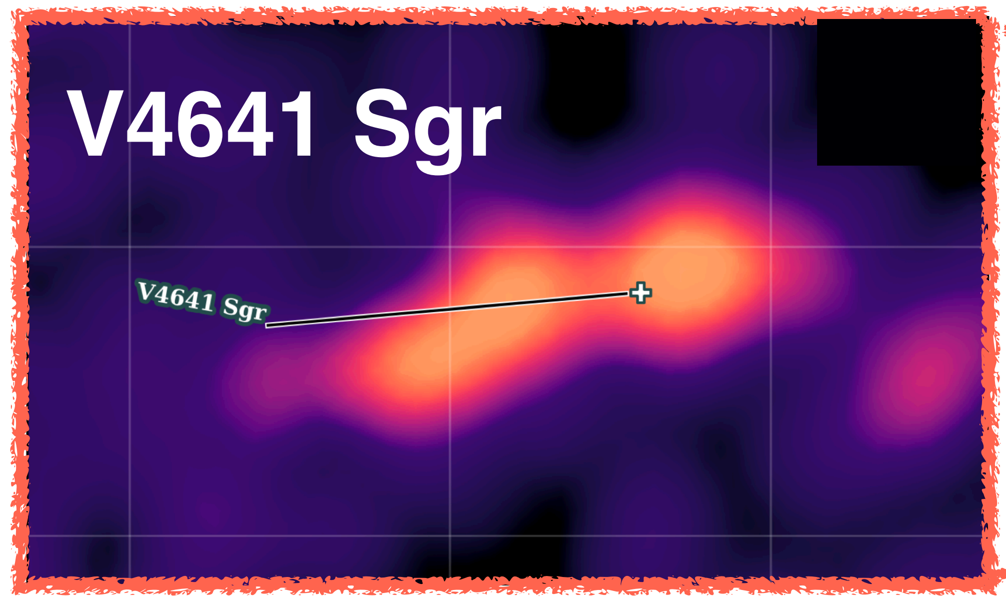
- Emission above 10 GeV is observed, consistent with TeV measurements; no emission found below 10 GeV
- **Model with proton contribution is favored at >5 σ significance**

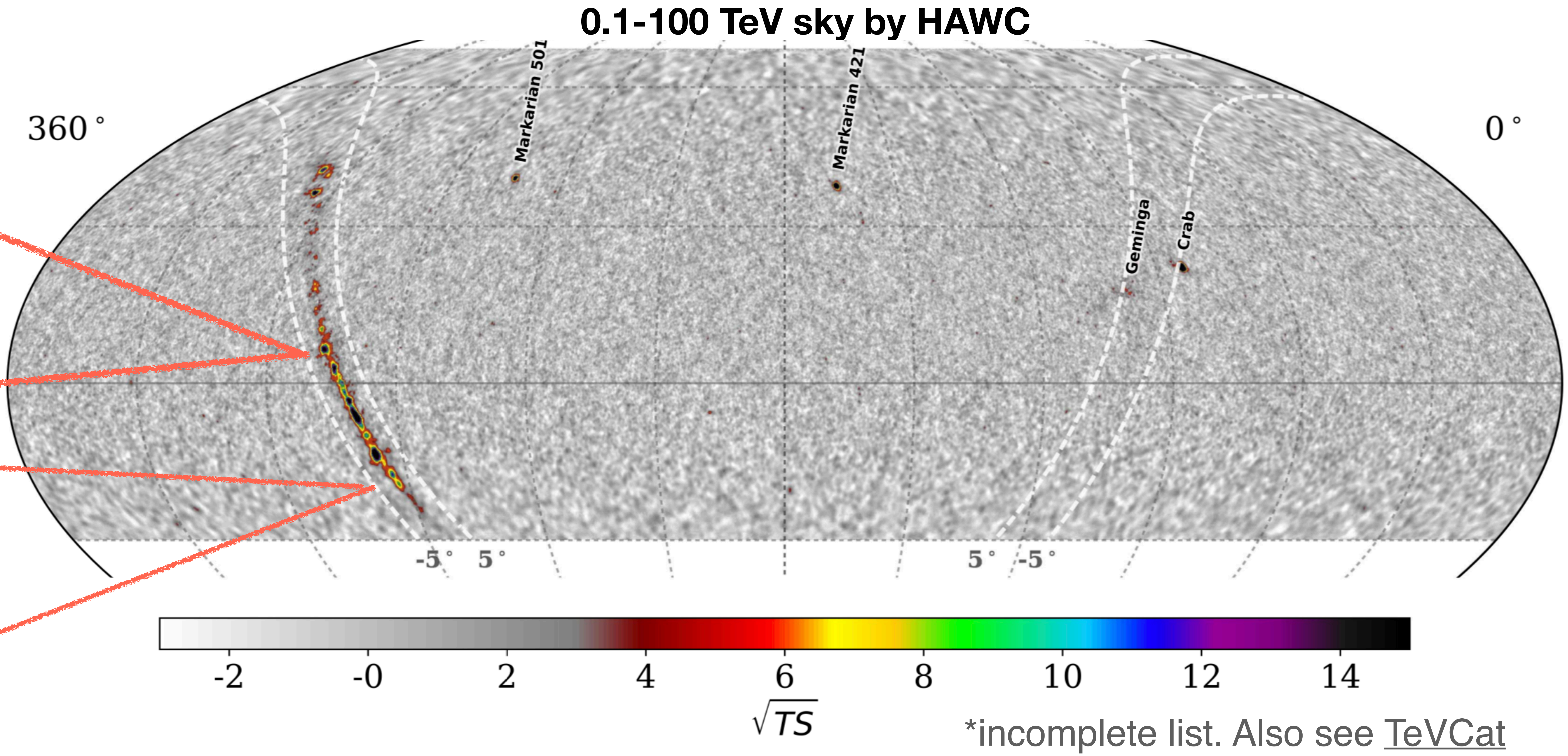
first PeVatron SNR candidate; very hard proton spectrum

KF, Kerr, Blandford, Fleischhack, Charles, *PRL (2022) Editor's Suggestion*

PeVatron Zoo* in 2024





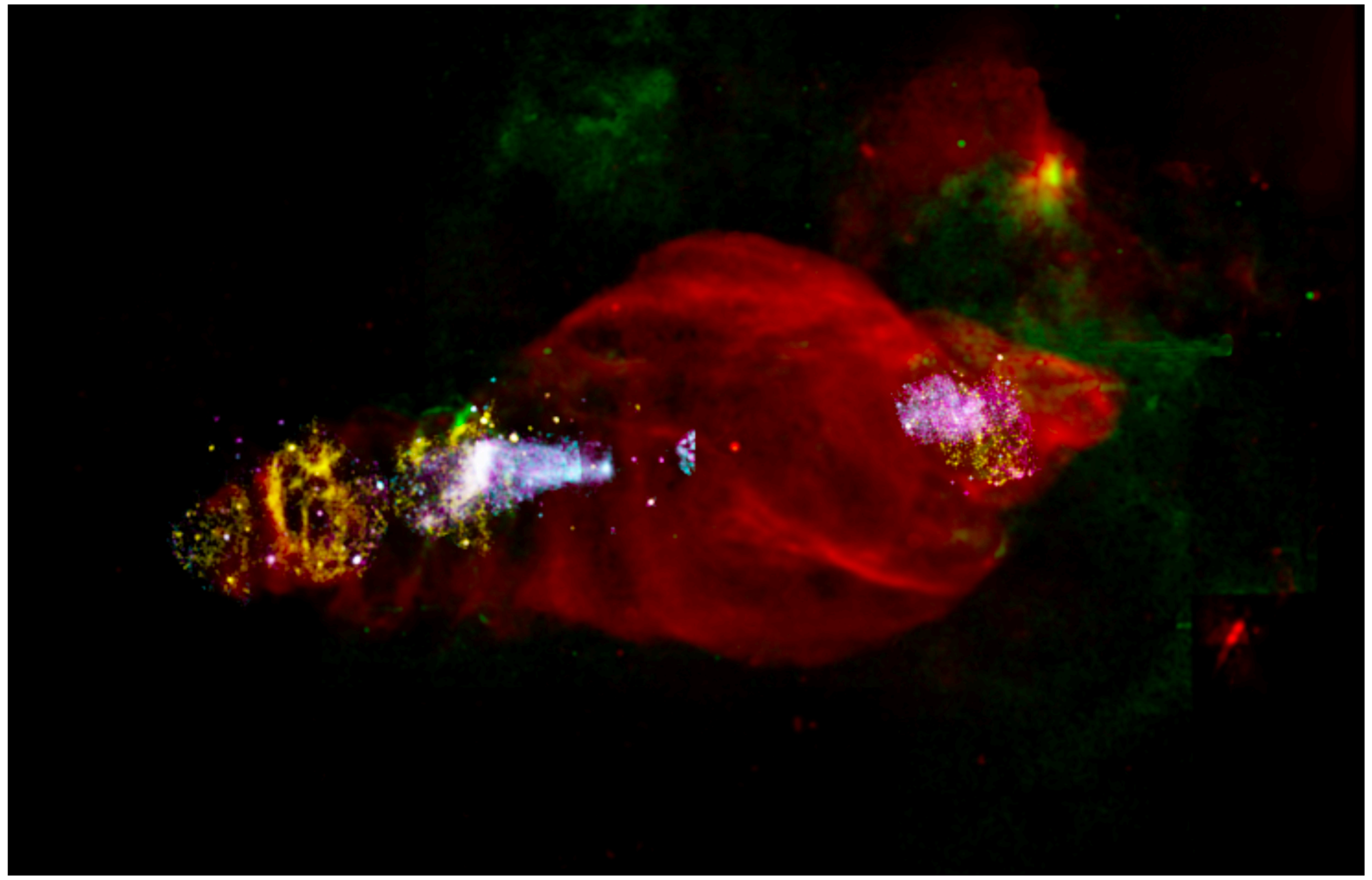


*incomplete list. Also see TeVCat

The Microquasar SS 433

Safi-Harb et al with **KF**, *ApJ* (2022)

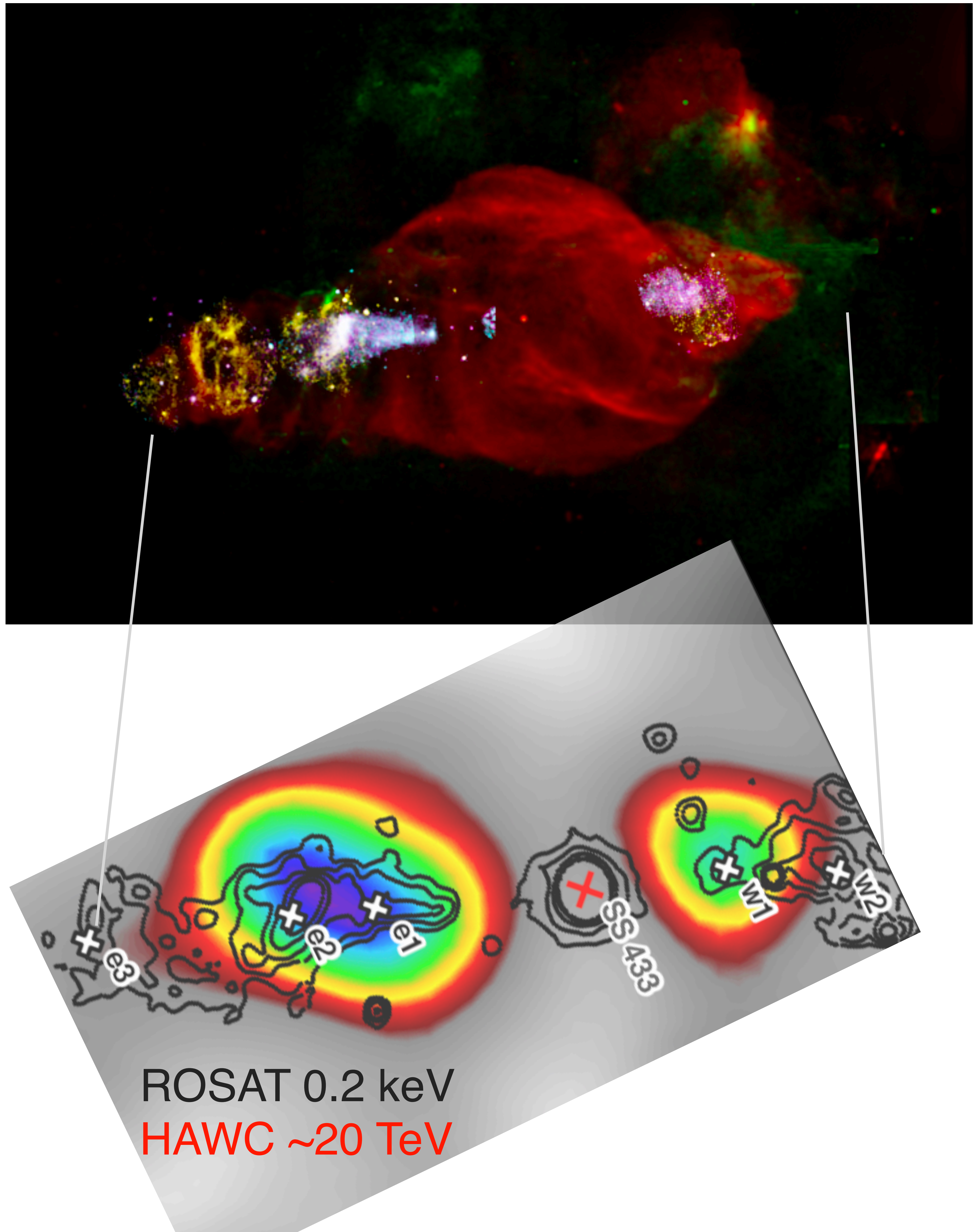
The Microquasar SS 433



HAWC Collaboration, *Nature* (2018)
KF as main author

The Microquasar SS 433

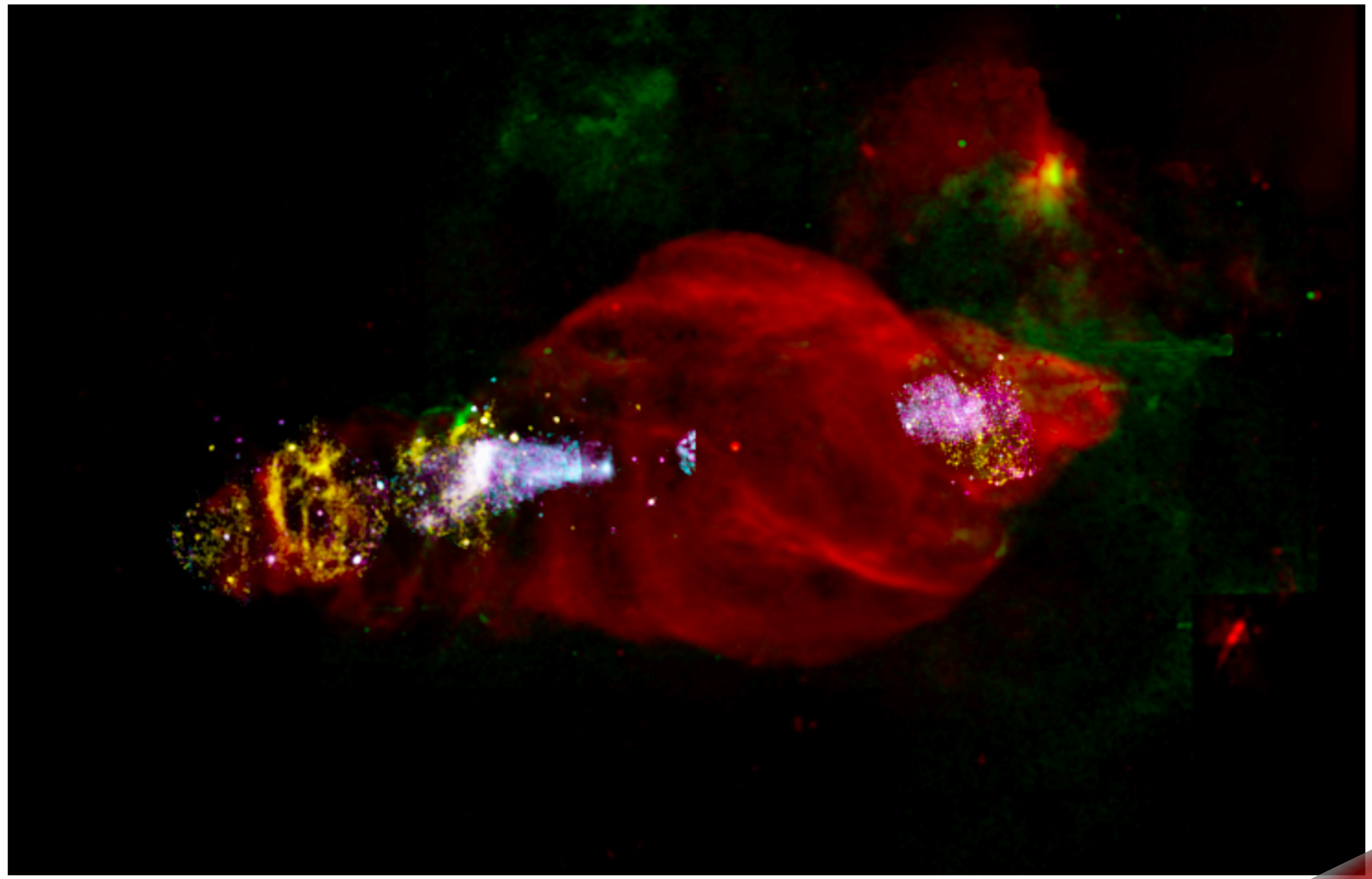
HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory



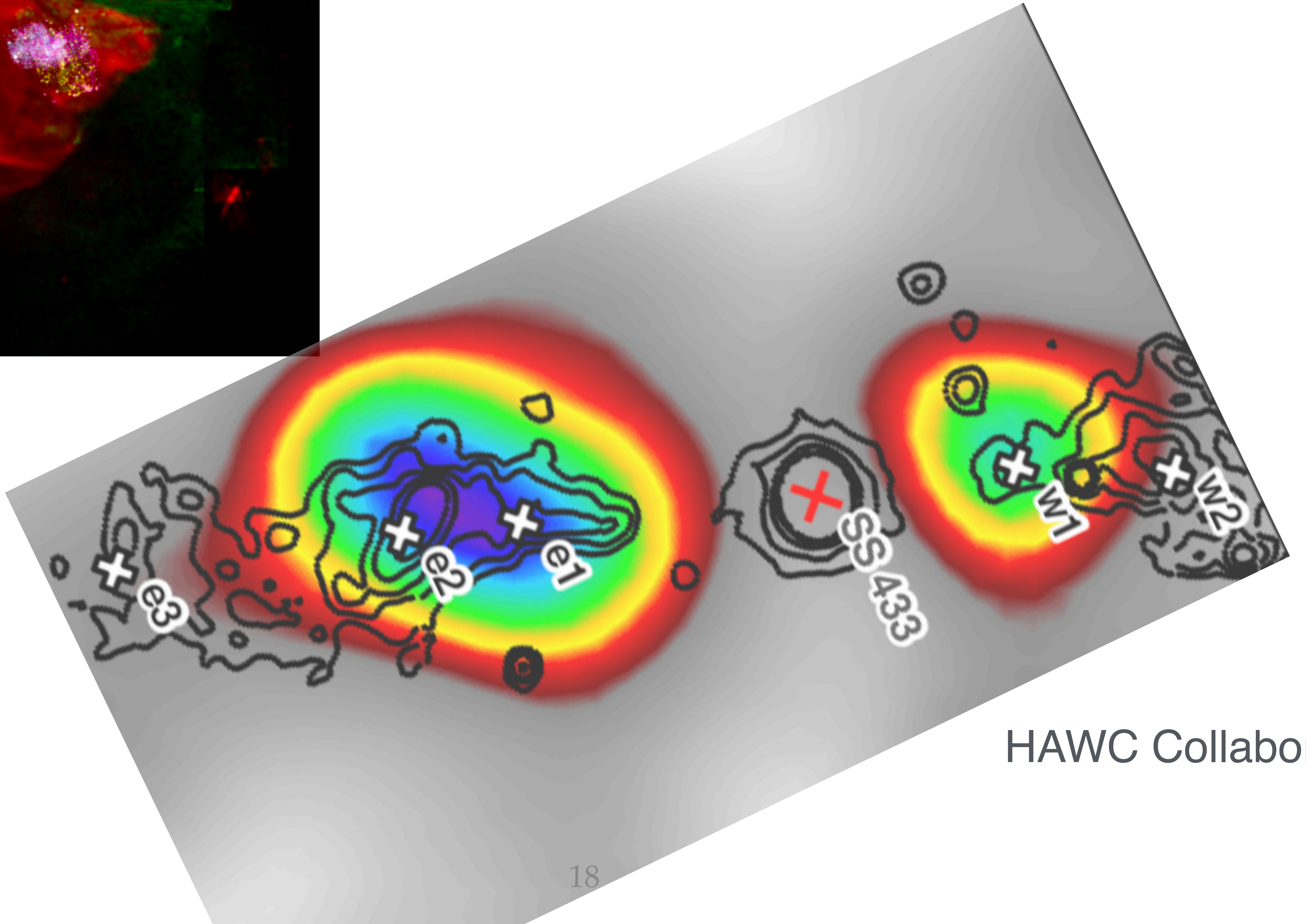
- **Point-like TeV gamma-rays in both lobes** detected by HAWC

HAWC Collaboration, *Nature* (2018)
KF as main author

The Microquasar SS 433



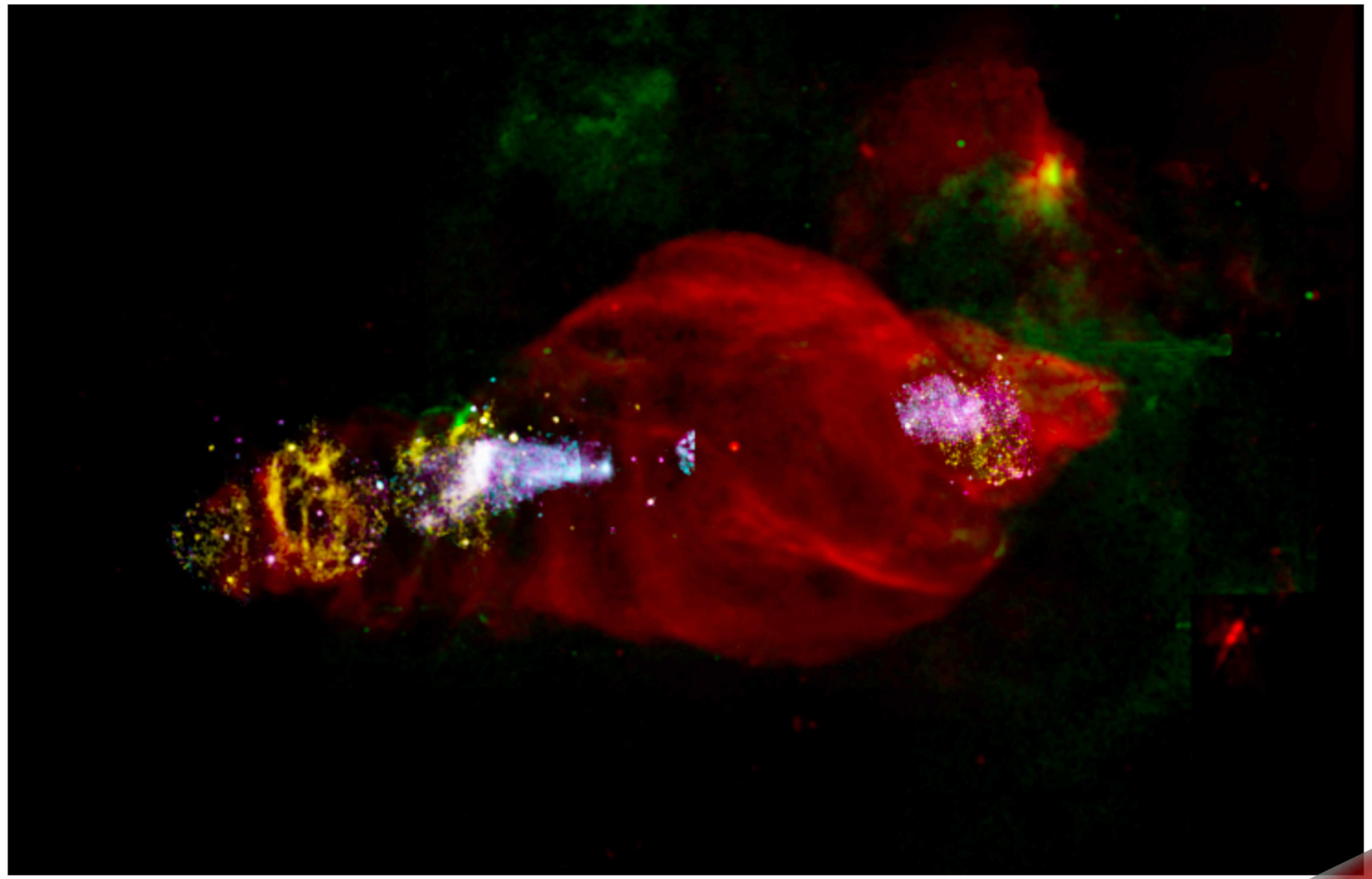
- **Point-like TeV gamma-rays in both lobes** detected by HAWC



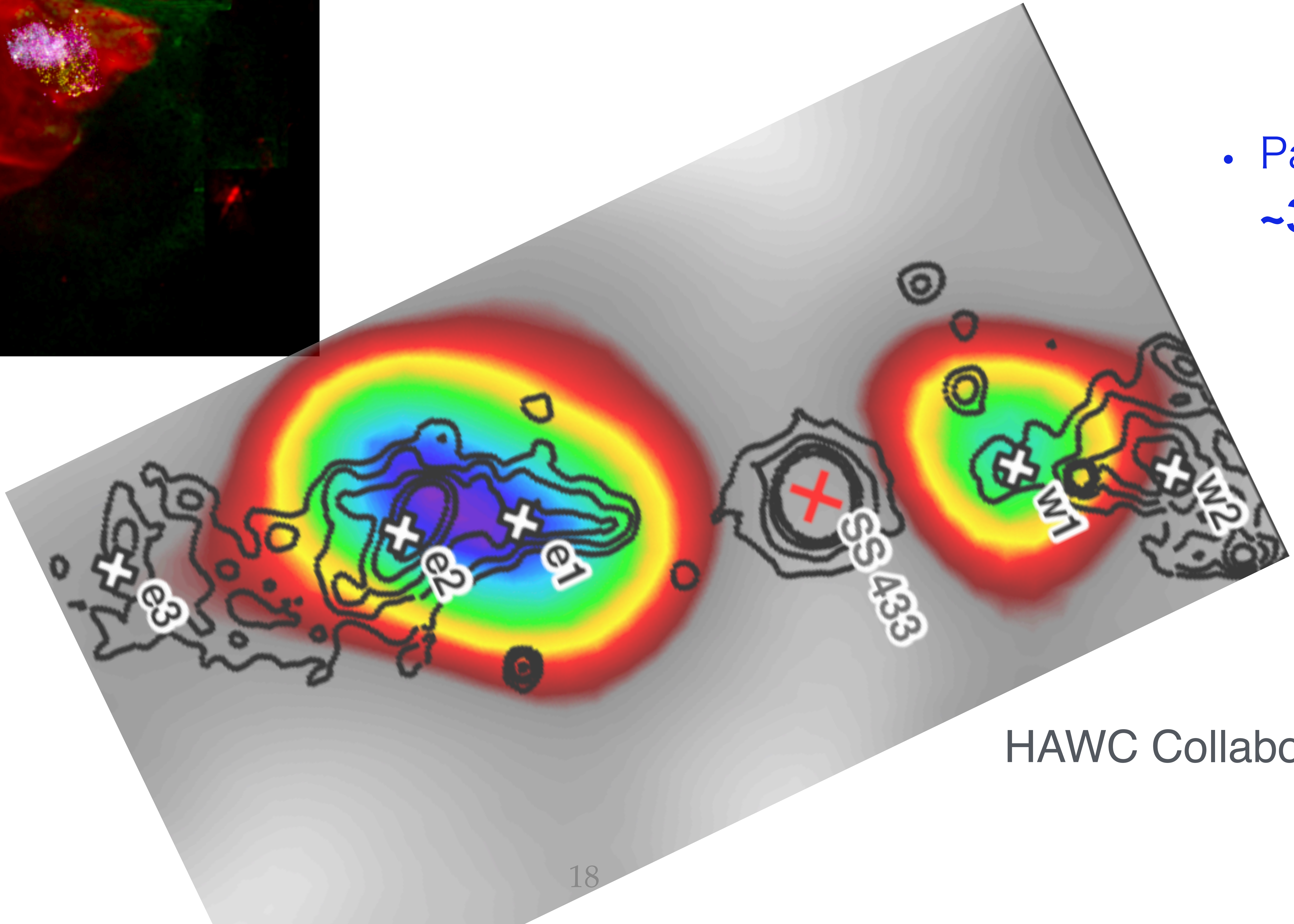
HAWC Collaboration, *Nature* (2018)
KF as main author

ROSAT 0.2 keV
HAWC ~20 TeV

The Microquasar SS 433



- **Point-like TeV gamma-rays in both lobes** detected by HAWC

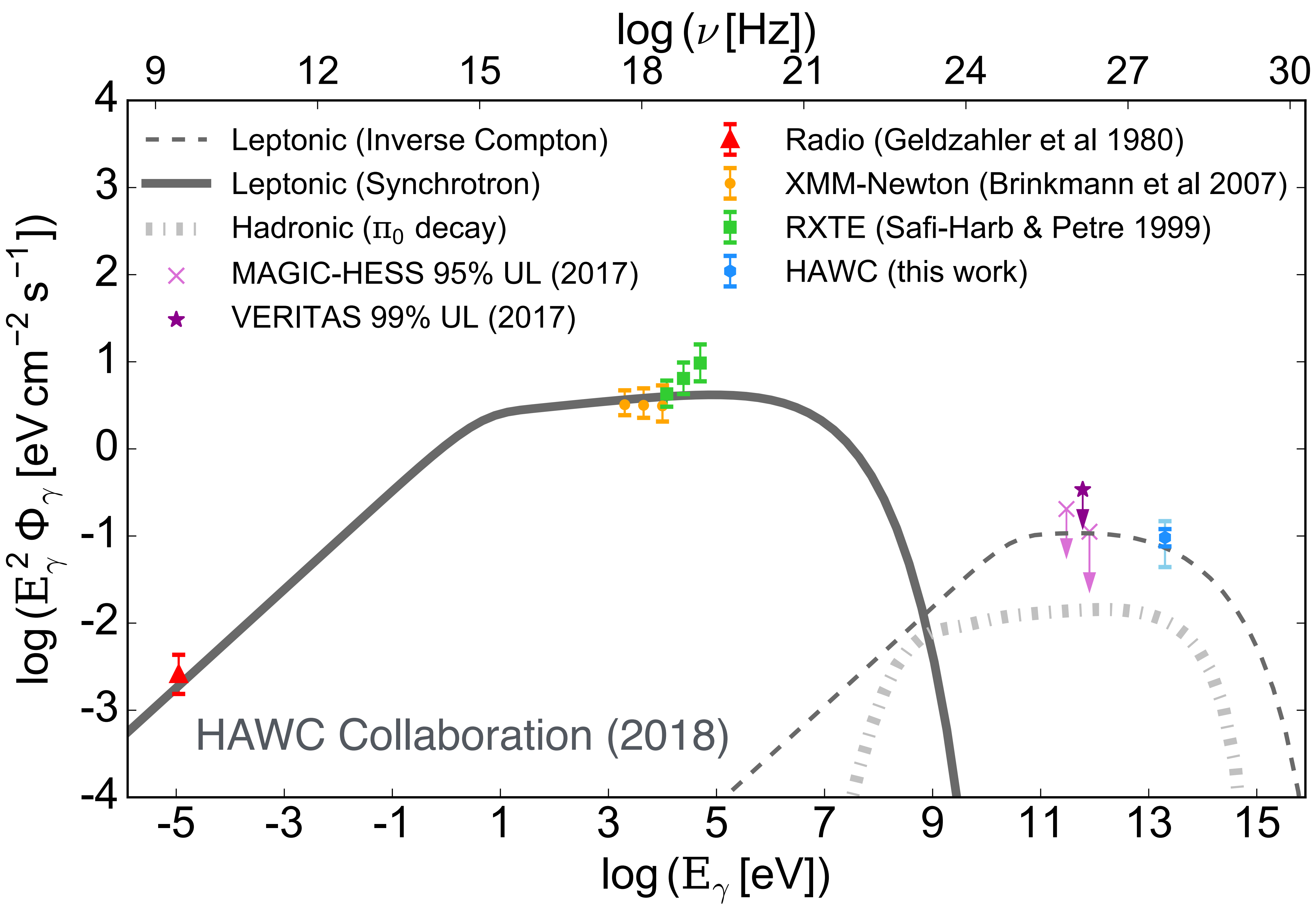


- Particle acceleration sites **~30 pc away from hole**

ROSAT 0.2 keV
HAWC ~20 TeV

HAWC Collaboration, *Nature* (2018)
KF as main author

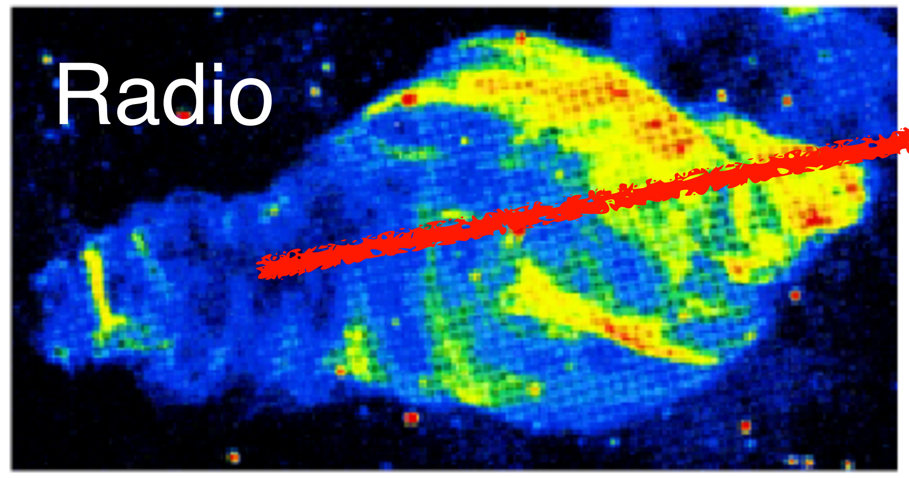
SS 433 jets

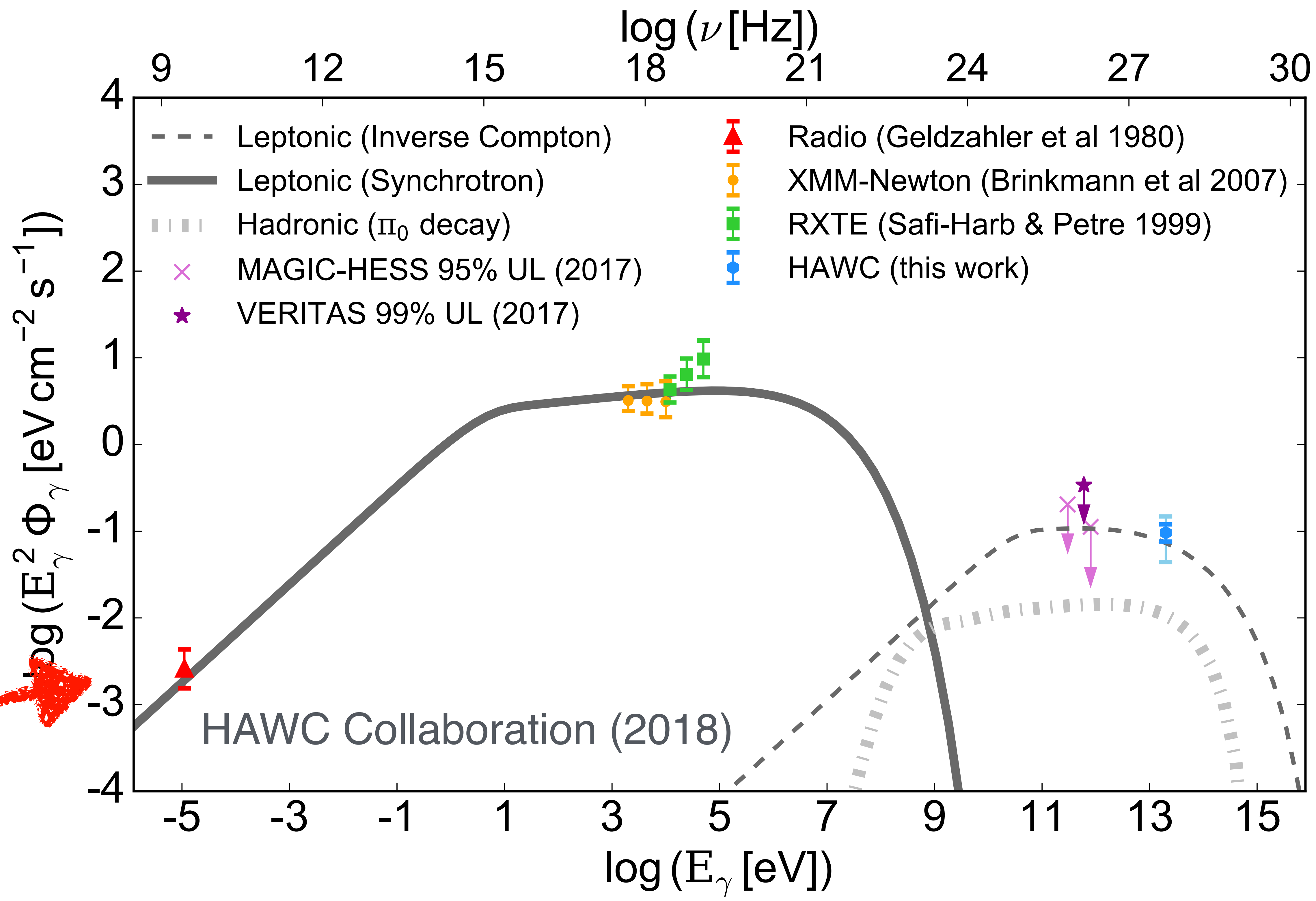


HAWC Collaboration, *Nature* (2018)

KF, Charles, Blandford, ApJL (2020)

SS 433 jets

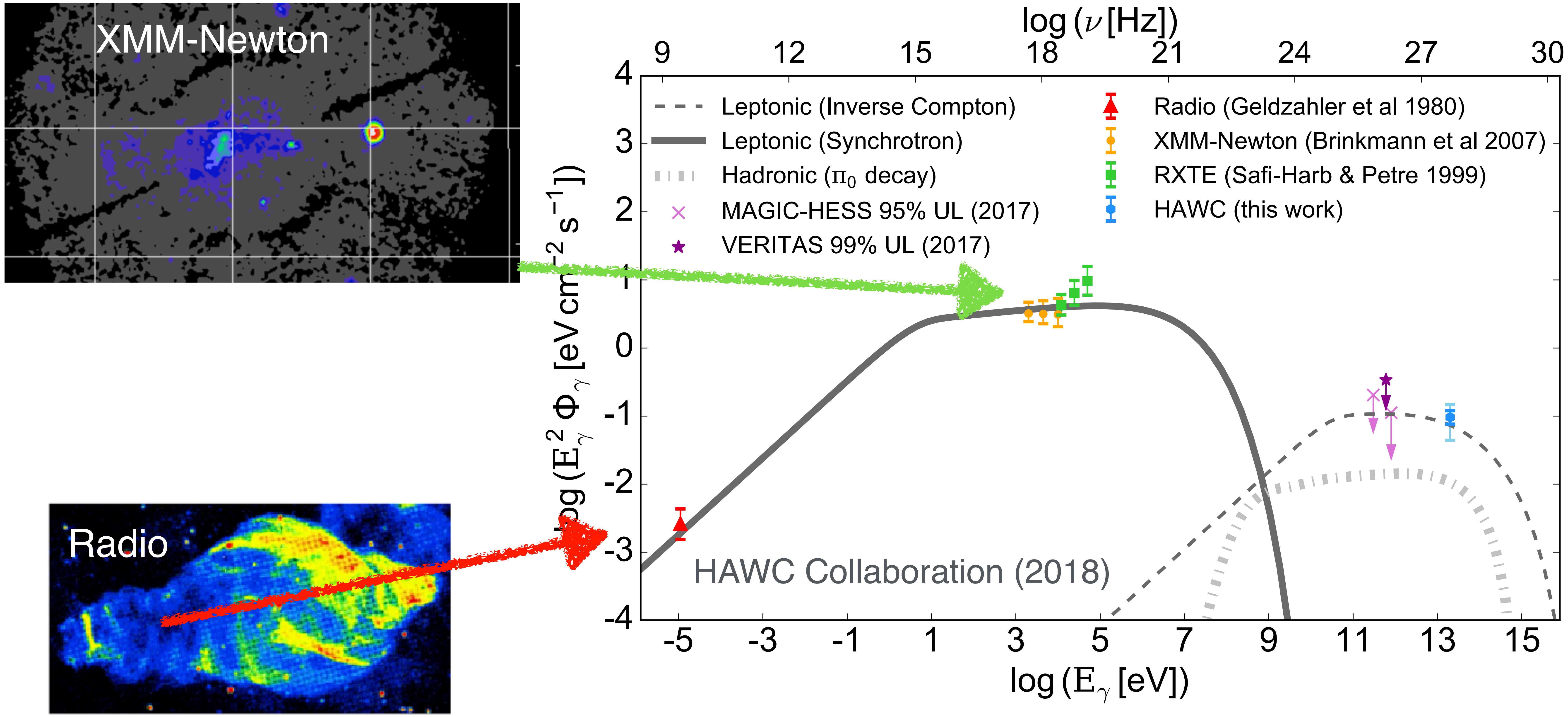




HAWC Collaboration, *Nature* (2018)

KF, Charles, Blandford, ApJL (2020)

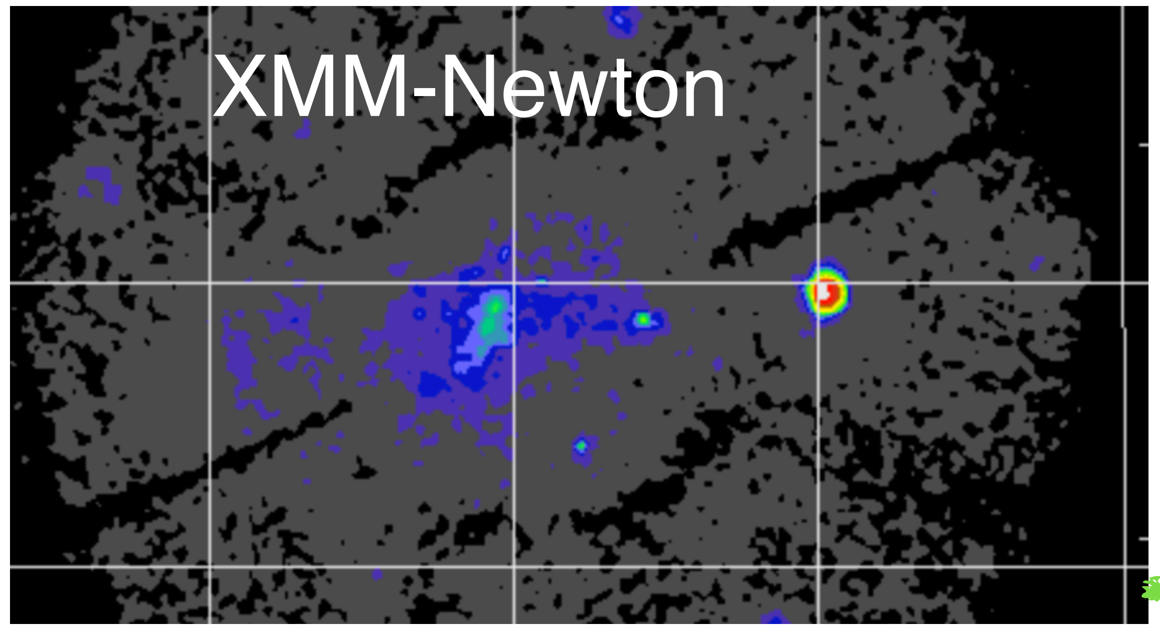
SS 433 jets

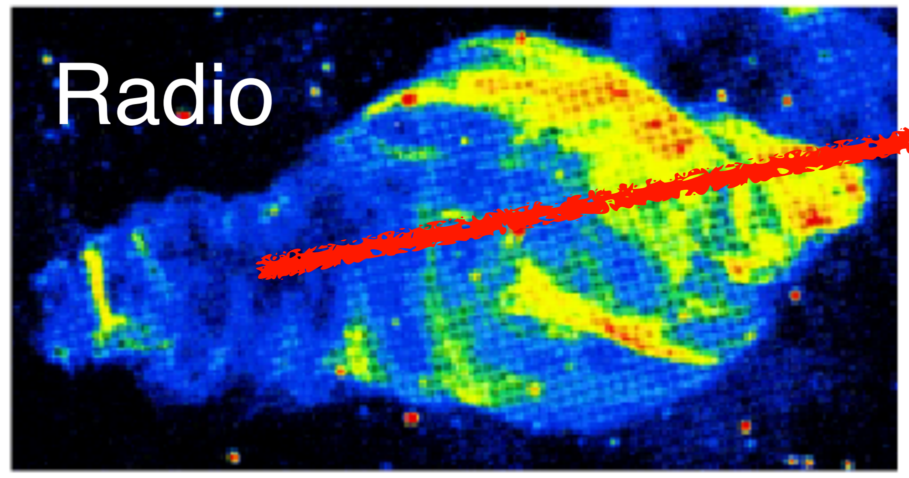


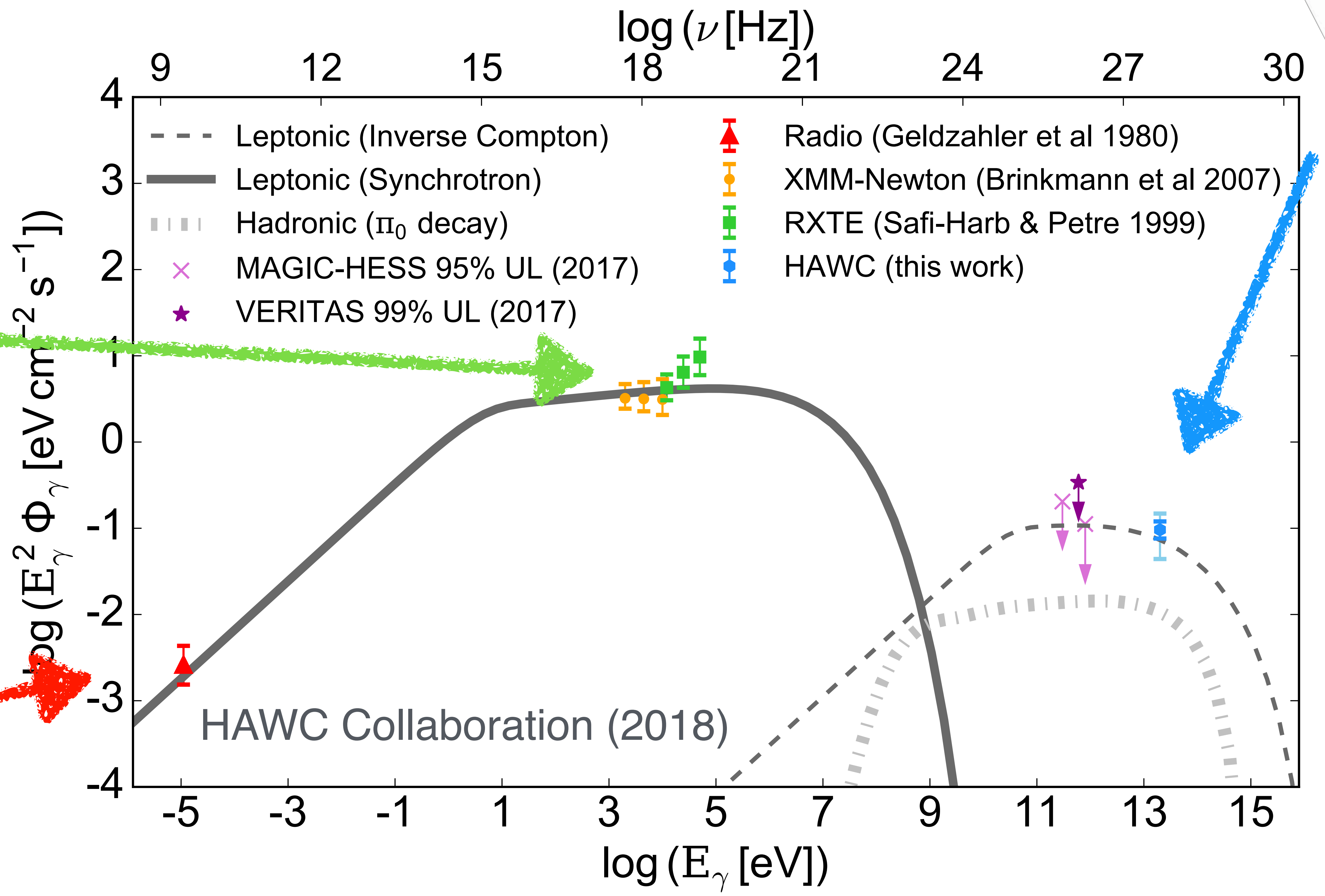
HAWC Collaboration, *Nature* (2018)

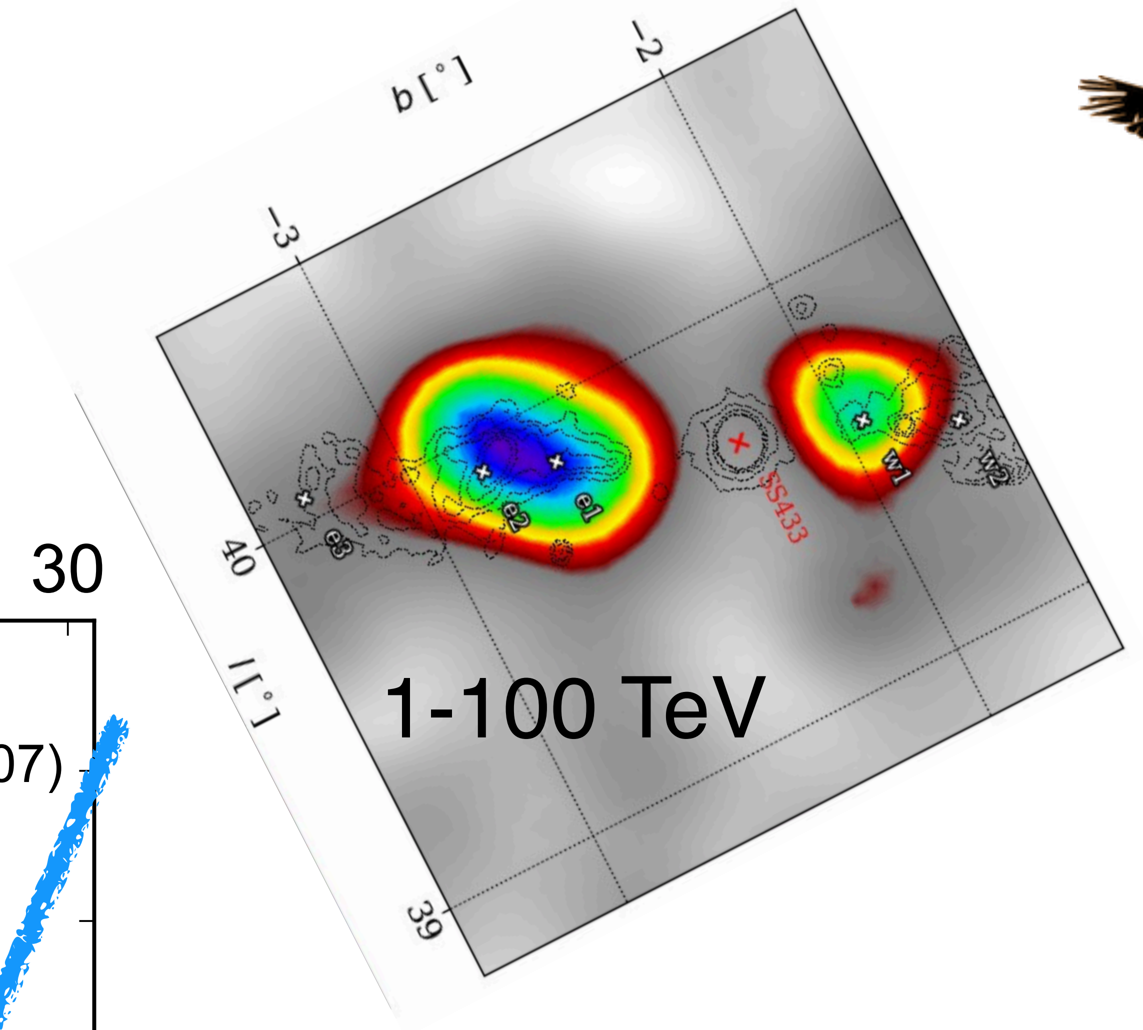
KF, Charles, Blandford, ApJL (2020)

SS 433 jets





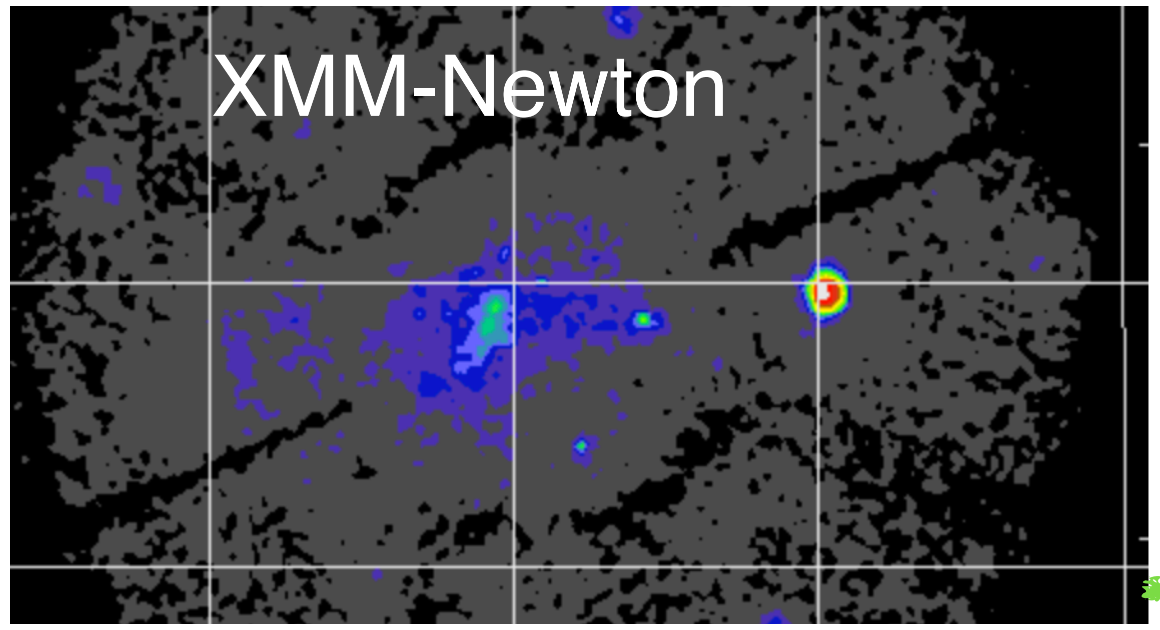


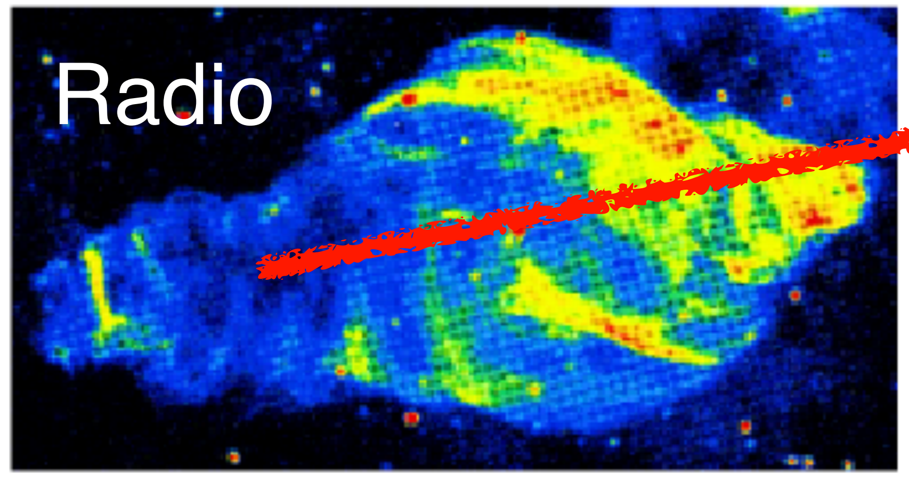


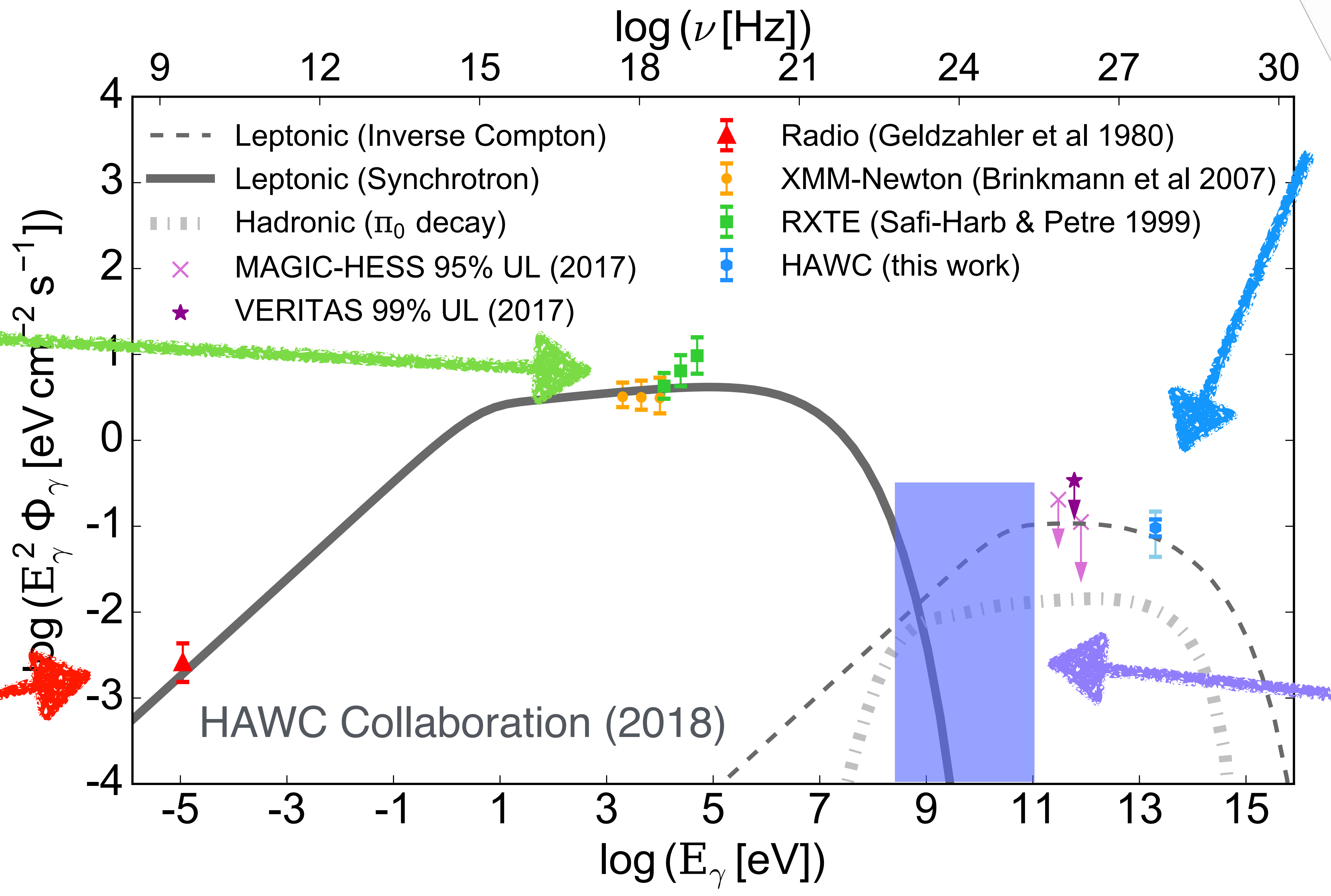
HAWC Collaboration, *Nature* (2018)

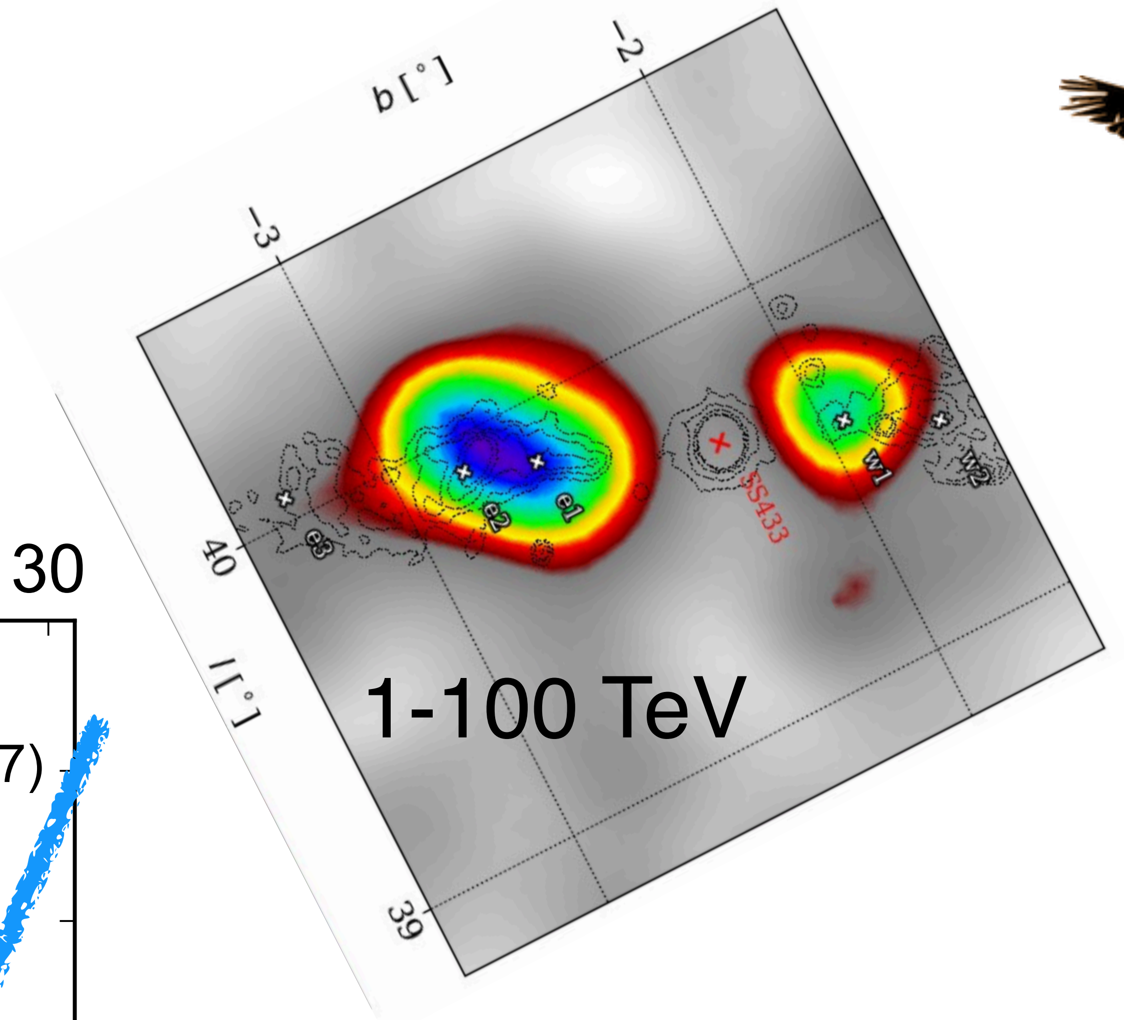
KF, Charles, Blandford, ApJL (2020)

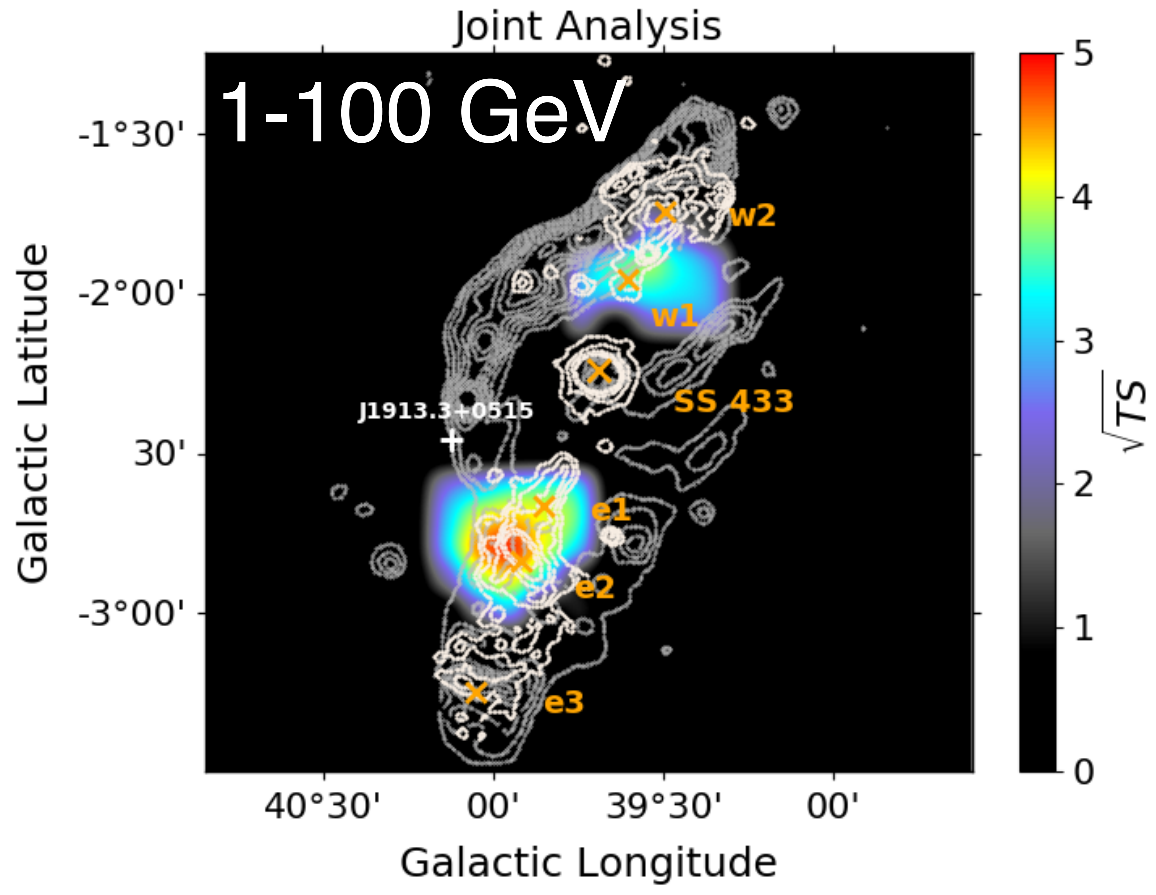
SS 433 jets







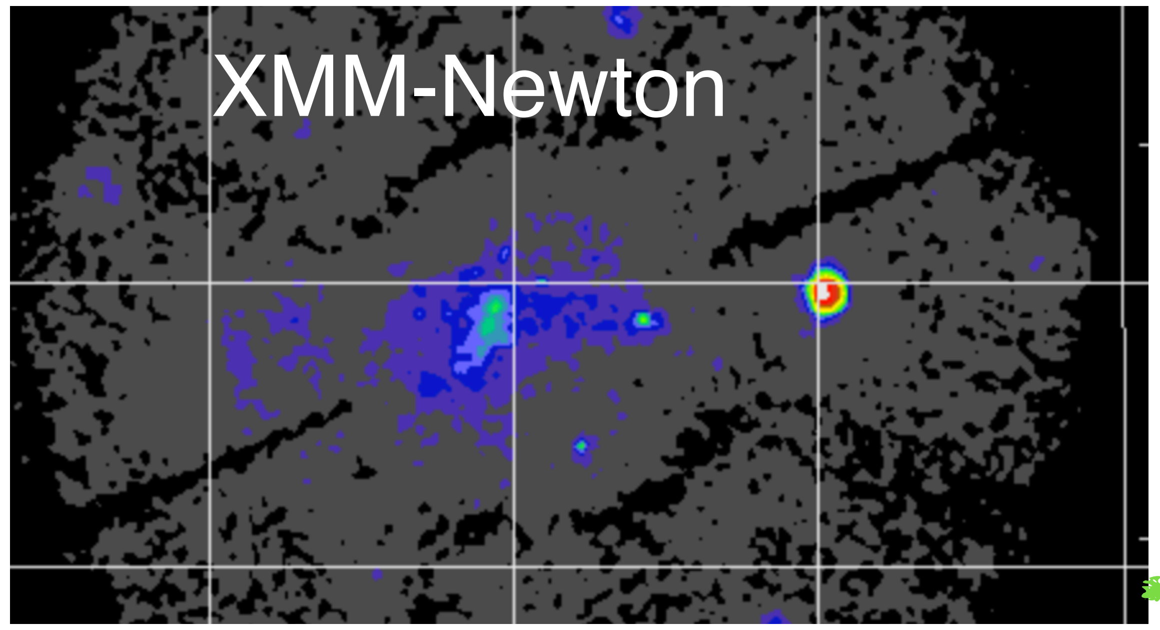


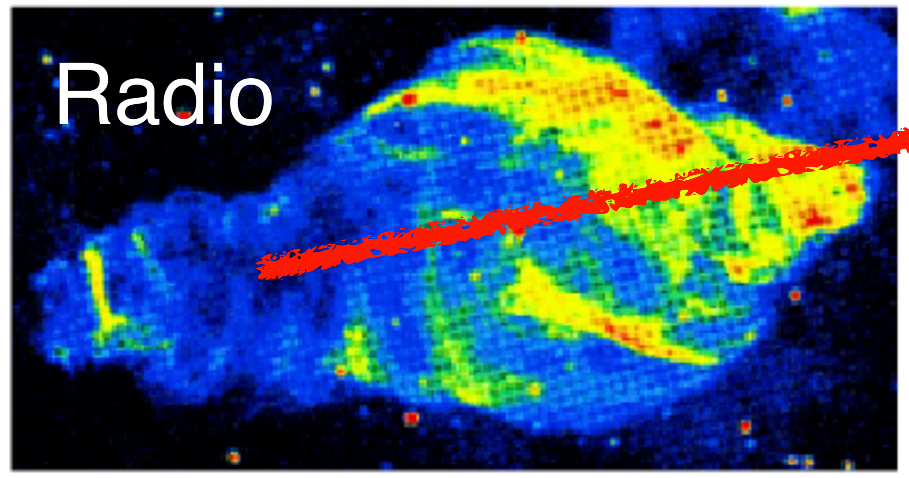


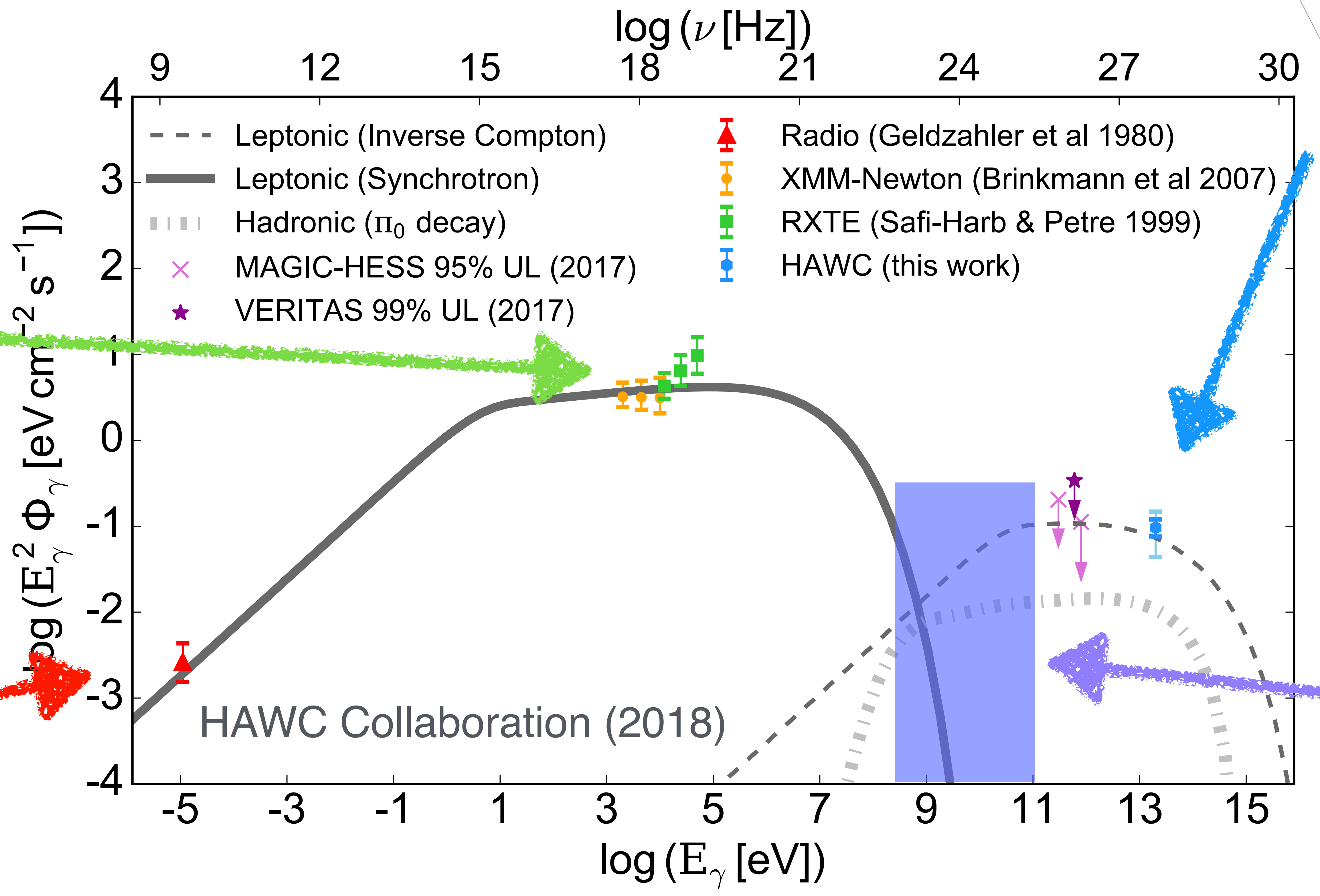
HAWC Collaboration, *Nature* (2018)

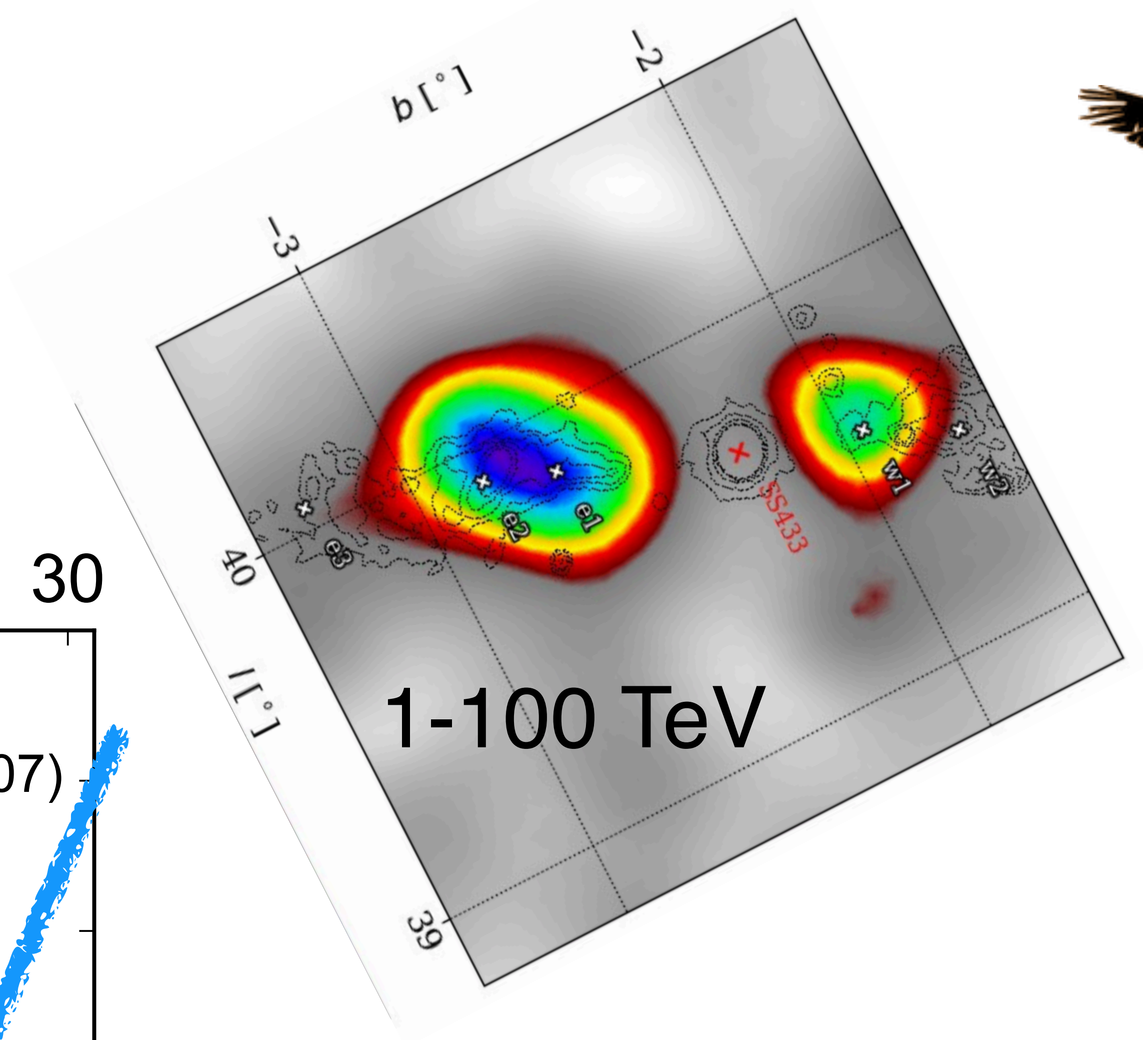
KF, Charles, Blandford, ApJL (2020)

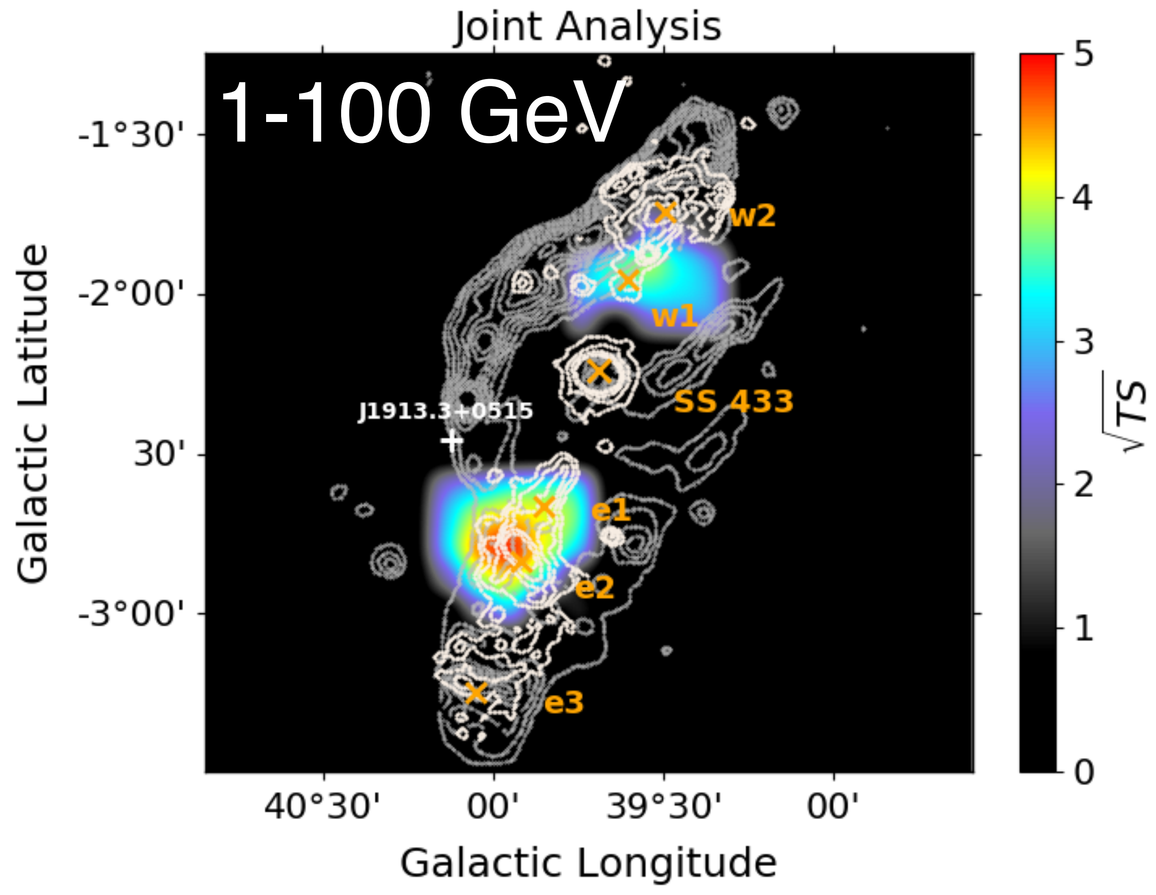
SS 433 jets









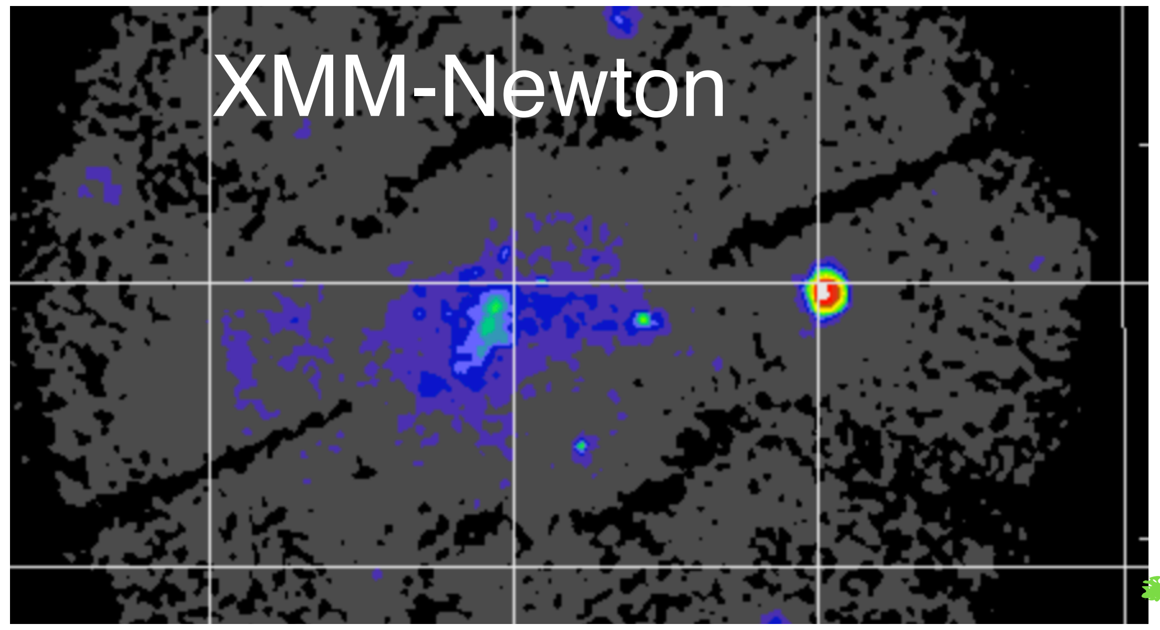


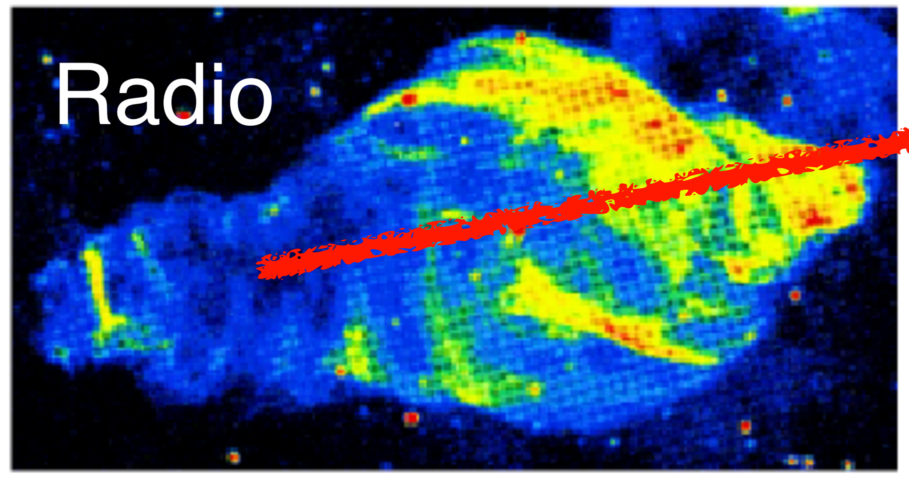
GeV-to-TeV Gamma-ray emission can be explained by inverse Compton emission by **relativistic electrons that cool efficiently**

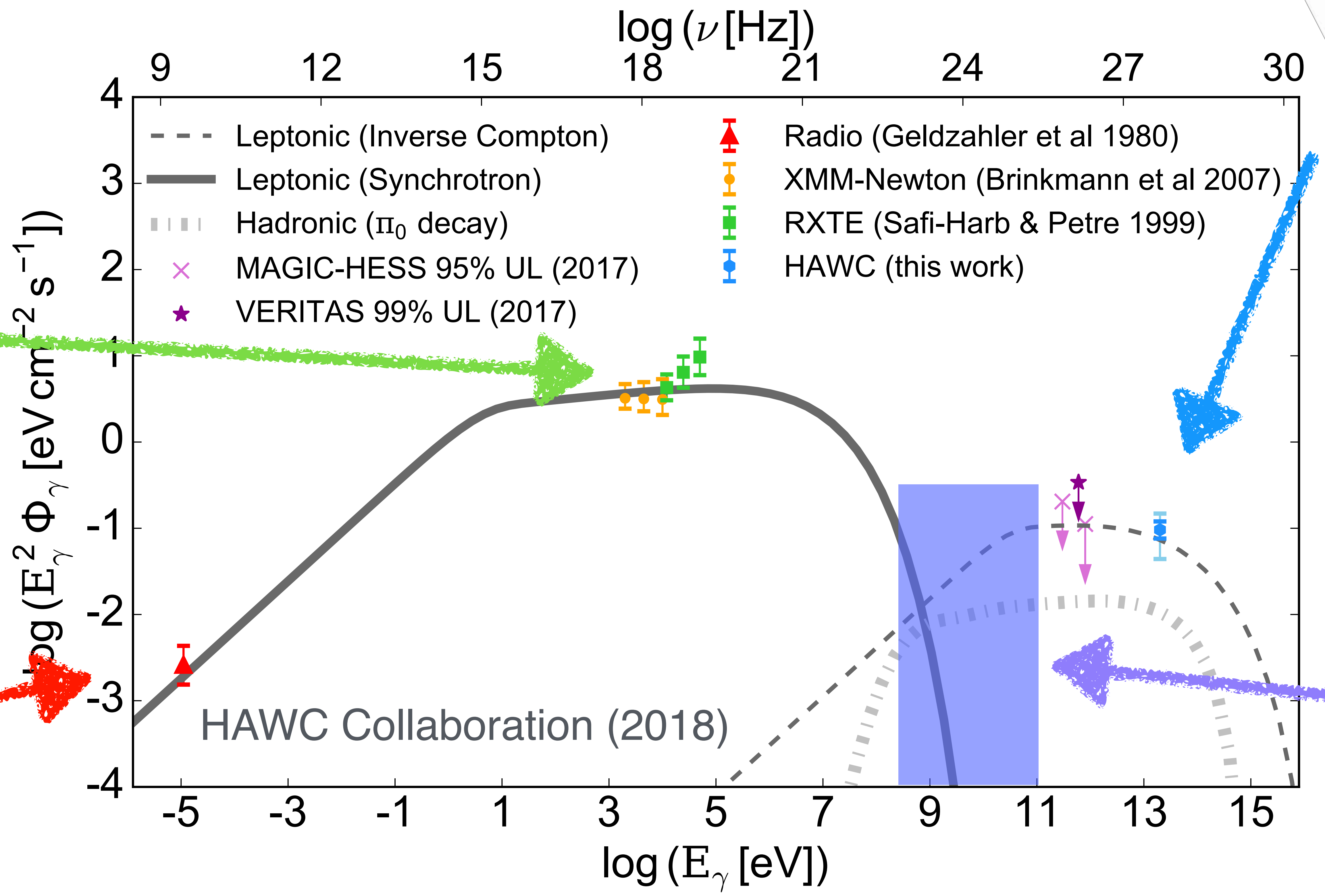
HAWC Collaboration, *Nature* (2018)

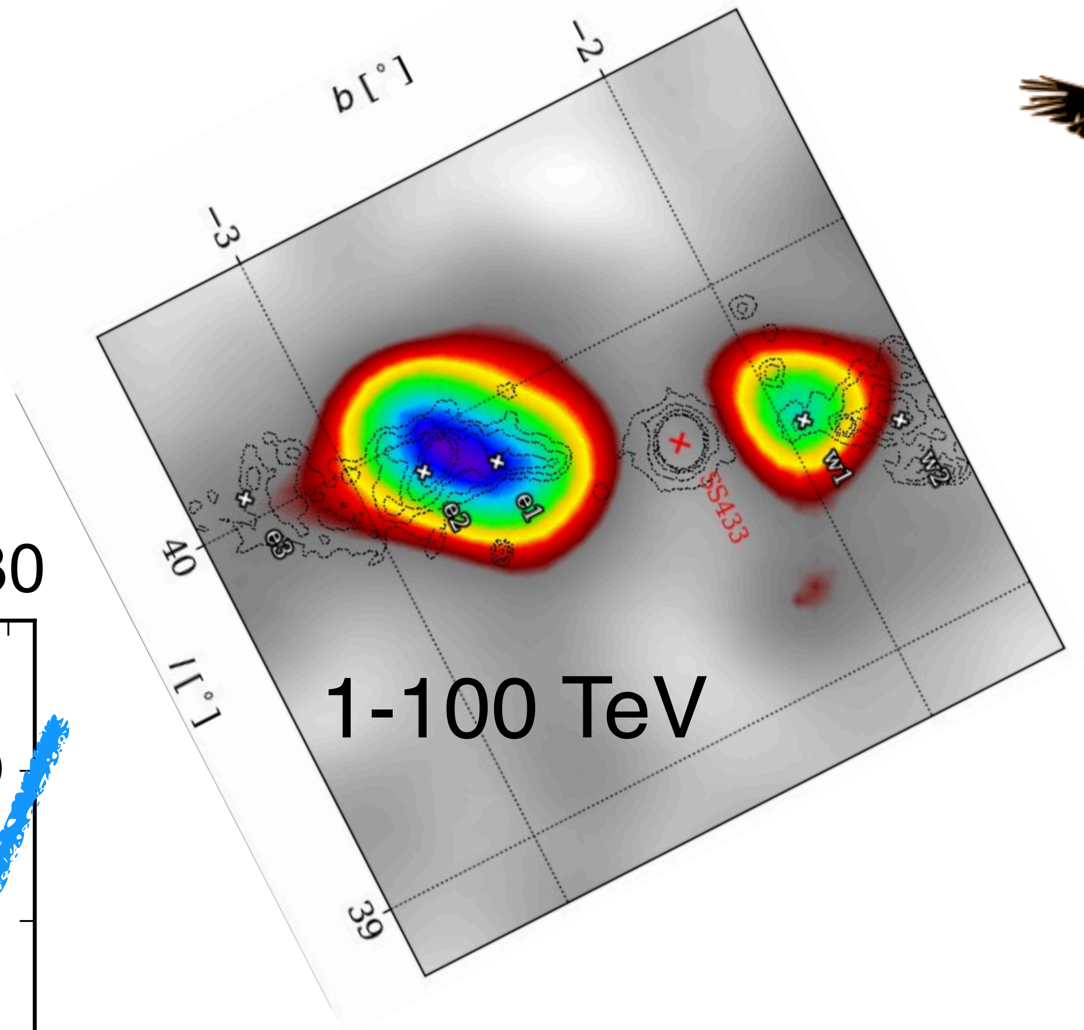
KF, Charles, Blandford, ApJL (2020)

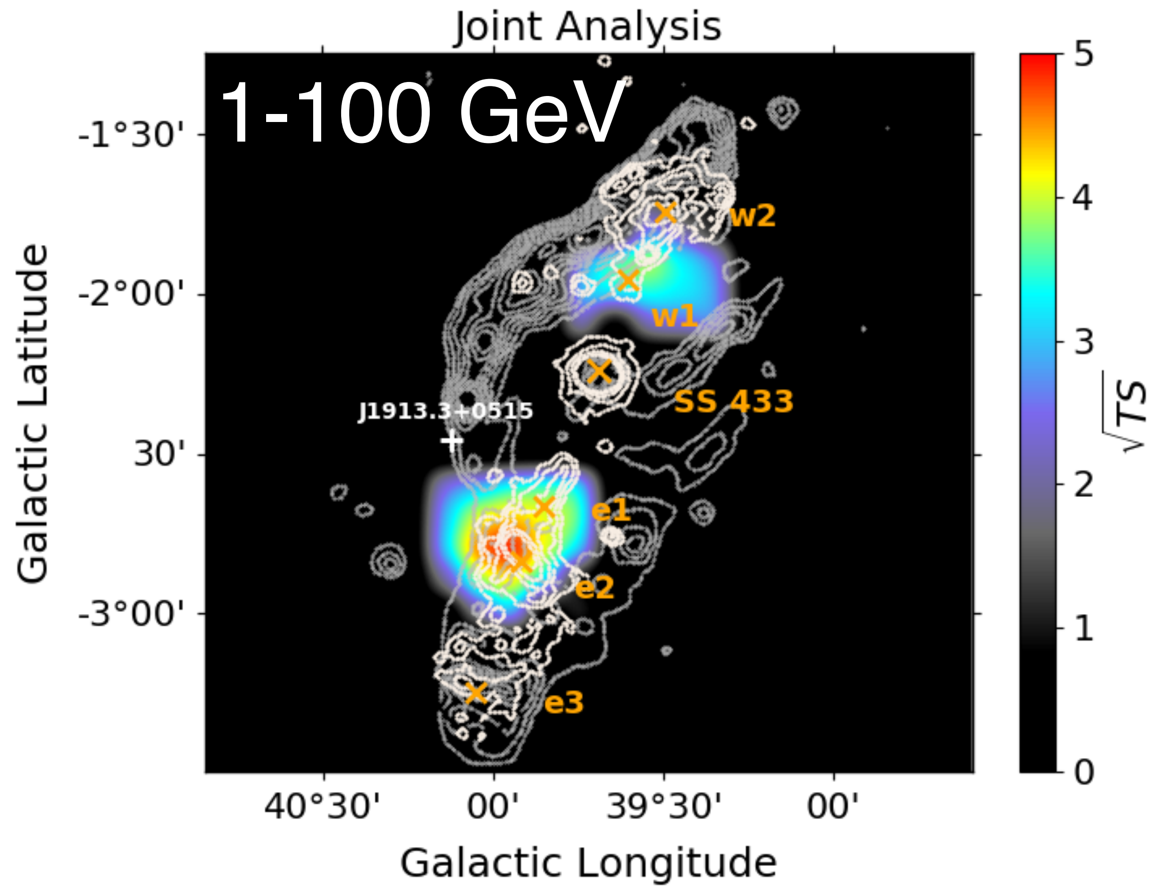
SS 433 jets











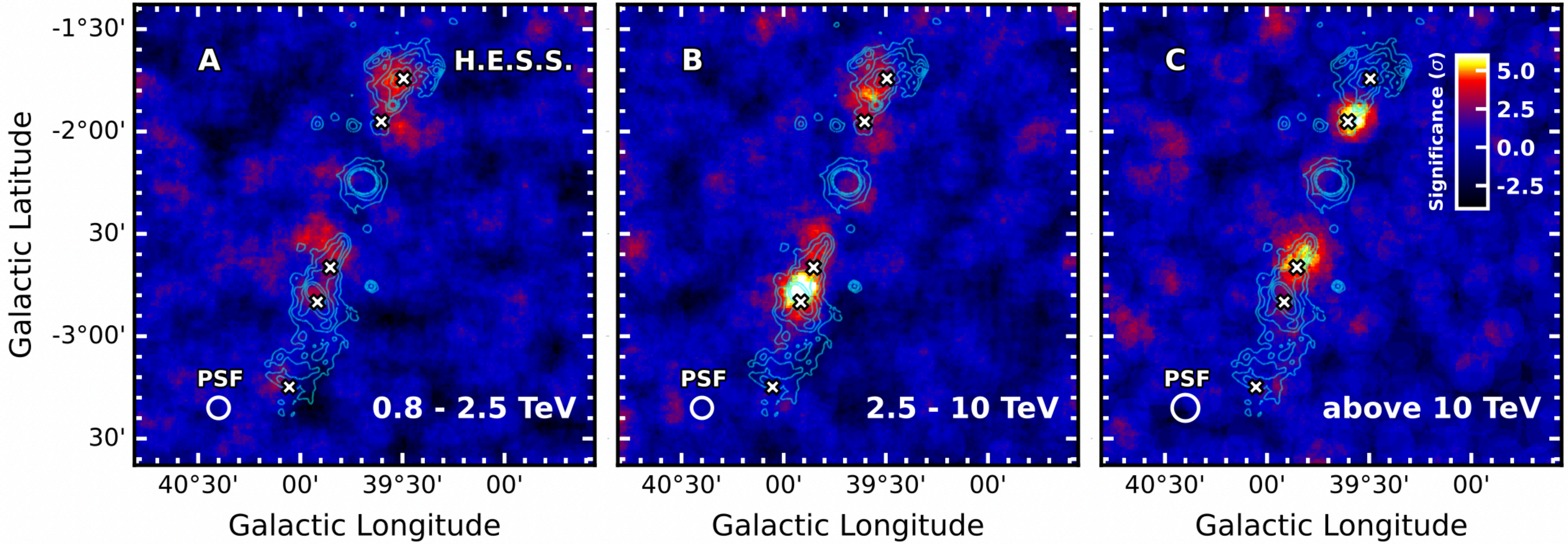
GeV-to-TeV Gamma-ray emission can be explained by inverse Compton emission by **relativistic electrons that cool efficiently**

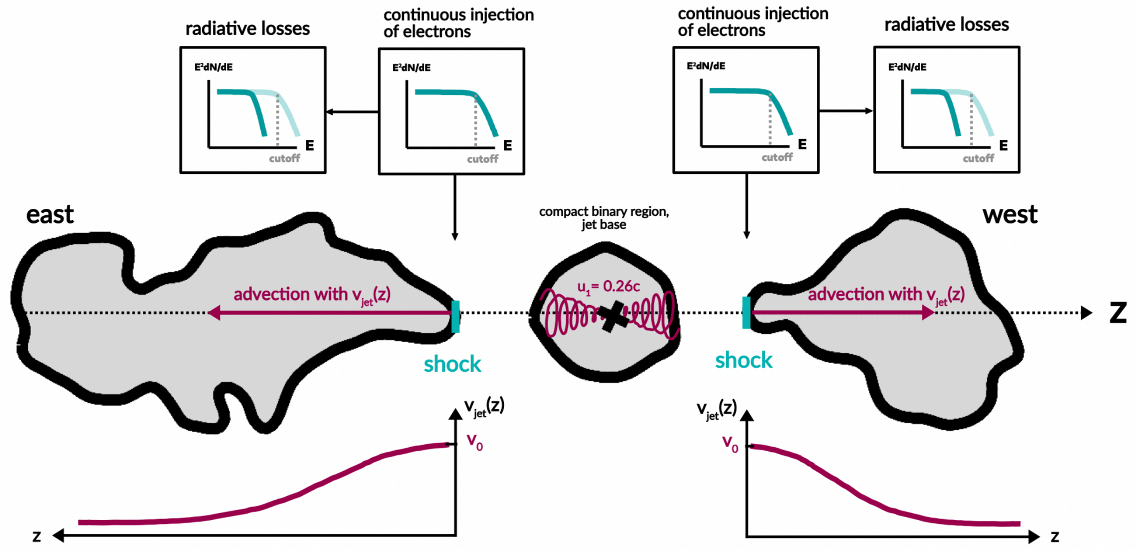
Not a hadronic PeVatron, but shows jets accelerating 100 TeV electrons

HAWC Collaboration, *Nature* (2018)

KF, Charles, Blandford, ApJL (2020)

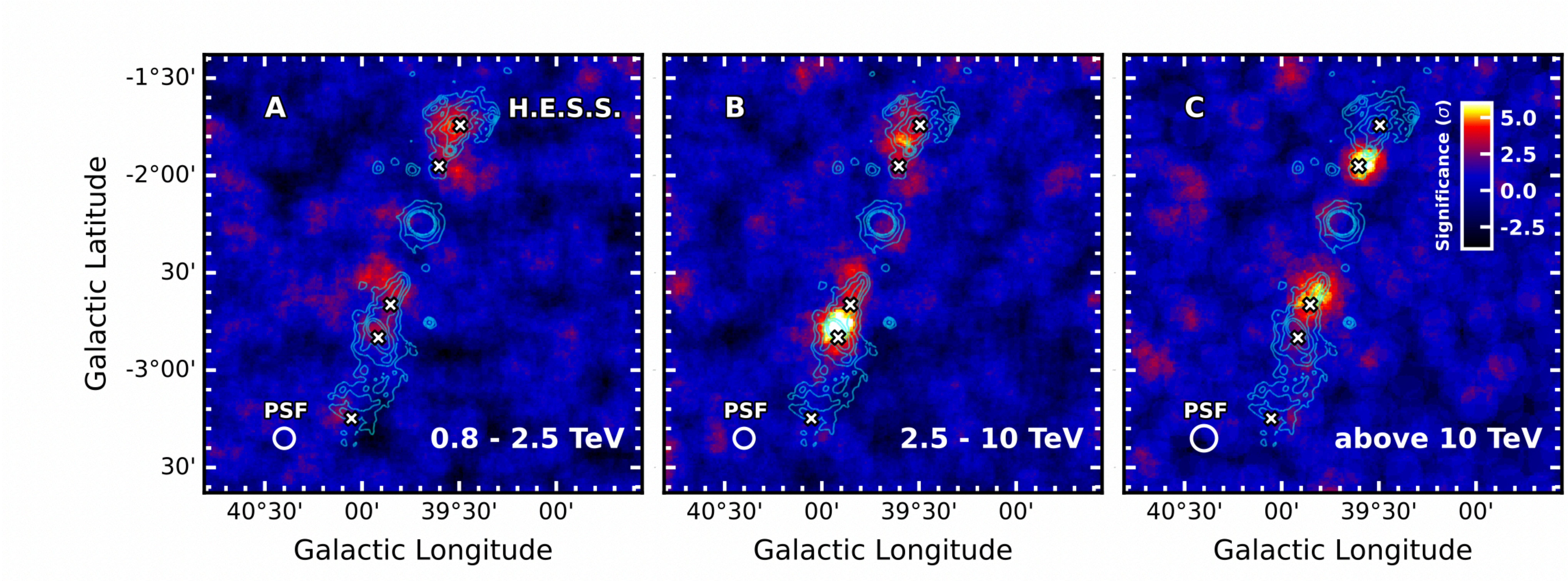
SS 433 / W50: H.E.S.S. results



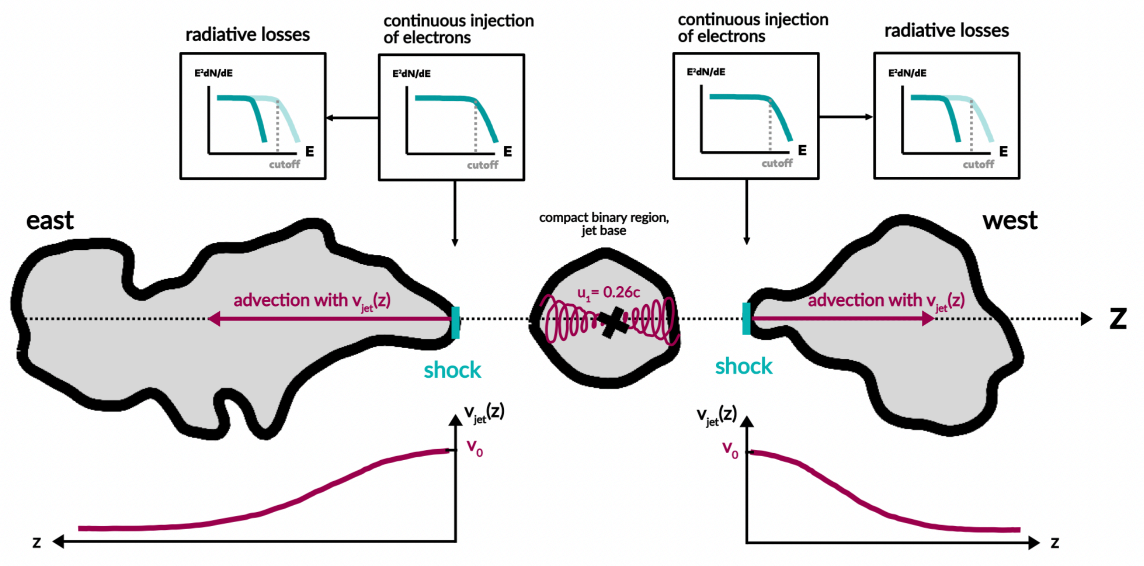


H.E.S.S. Collaboration, *Science* (2024)

SS 433 / W50: H.E.S.S. results

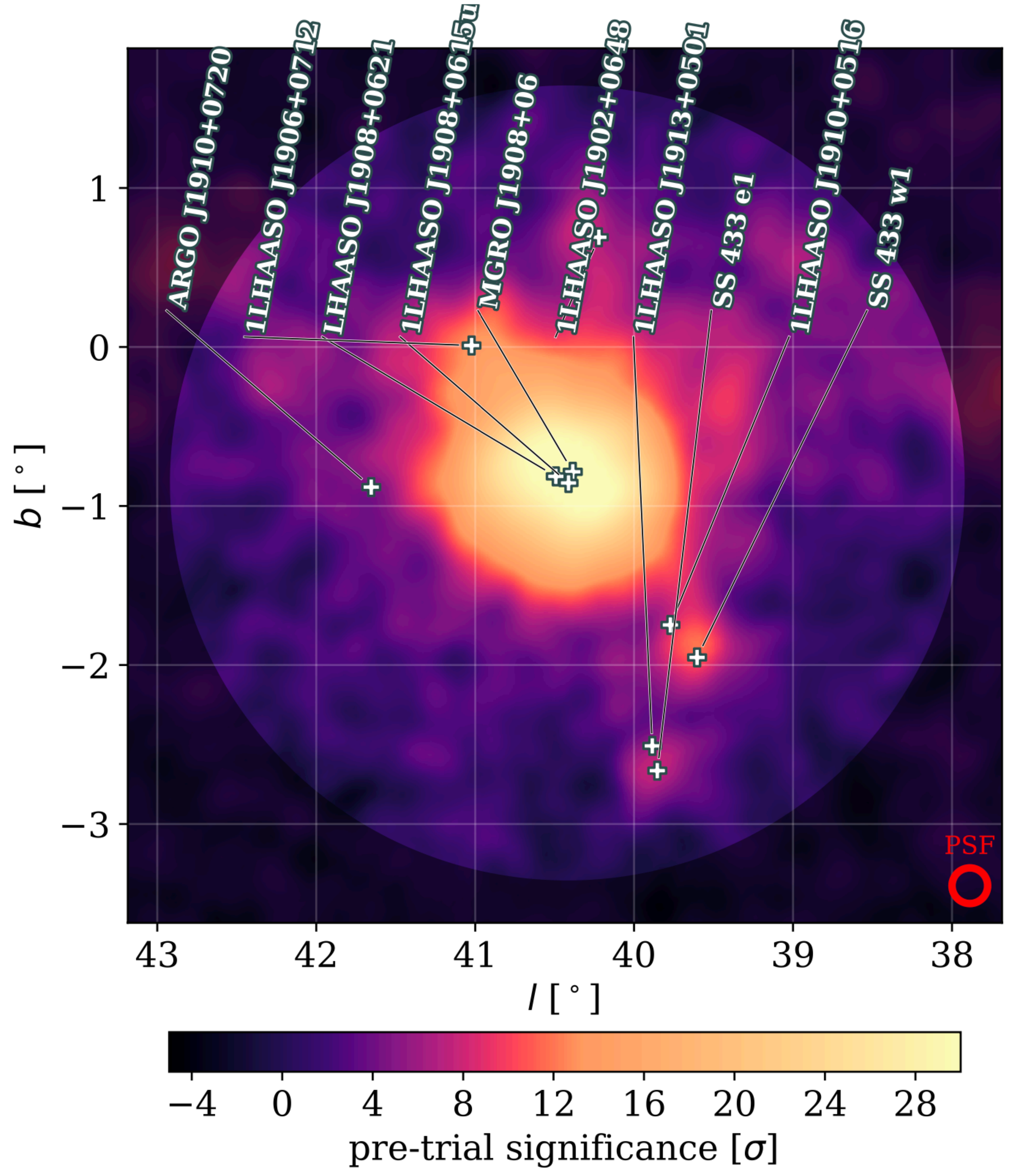


- **Gamma-ray emission sites vary slightly in energy bands**
- Explained as shock velocity changes



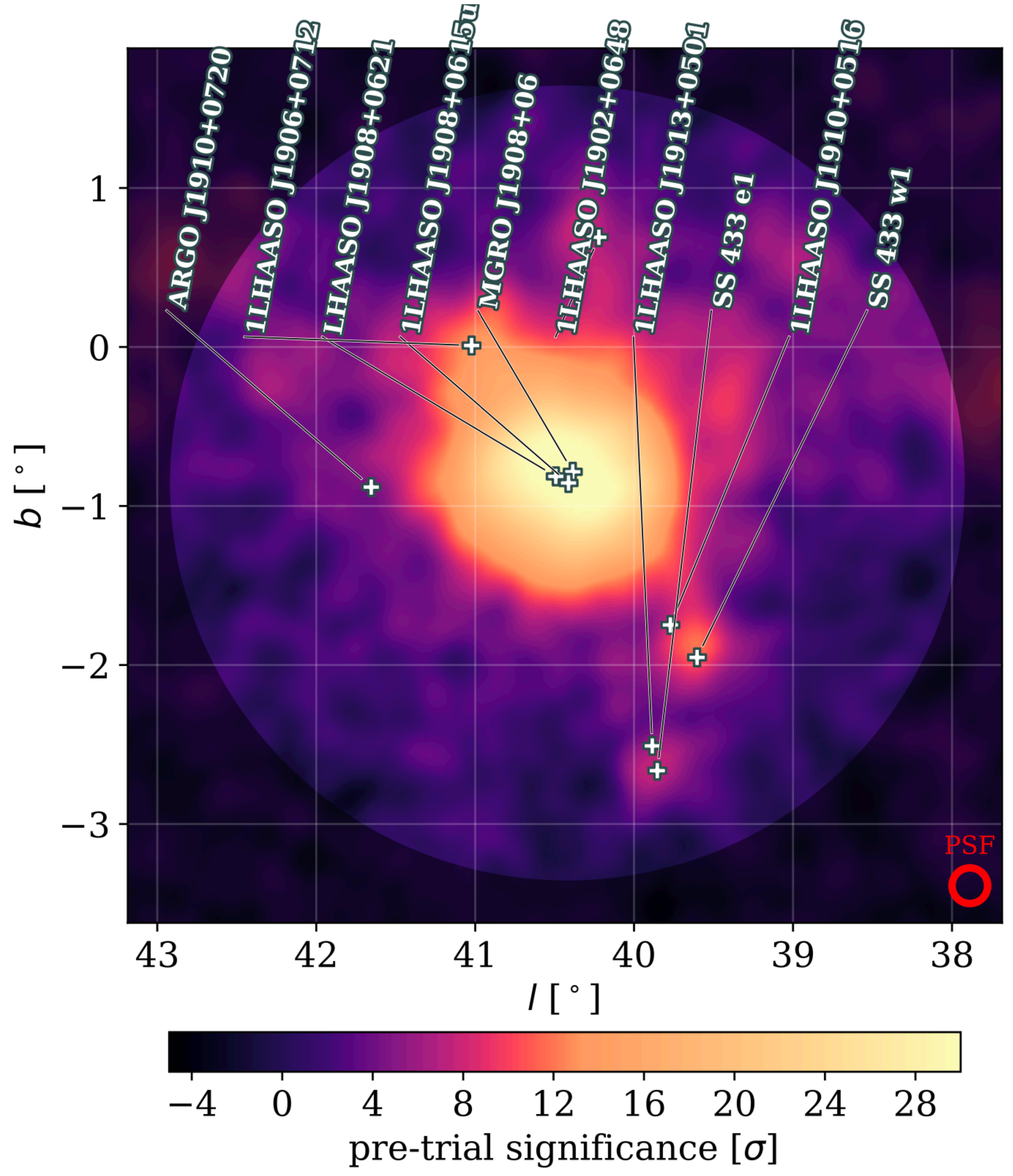
H.E.S.S. Collaboration, *Science* (2024)

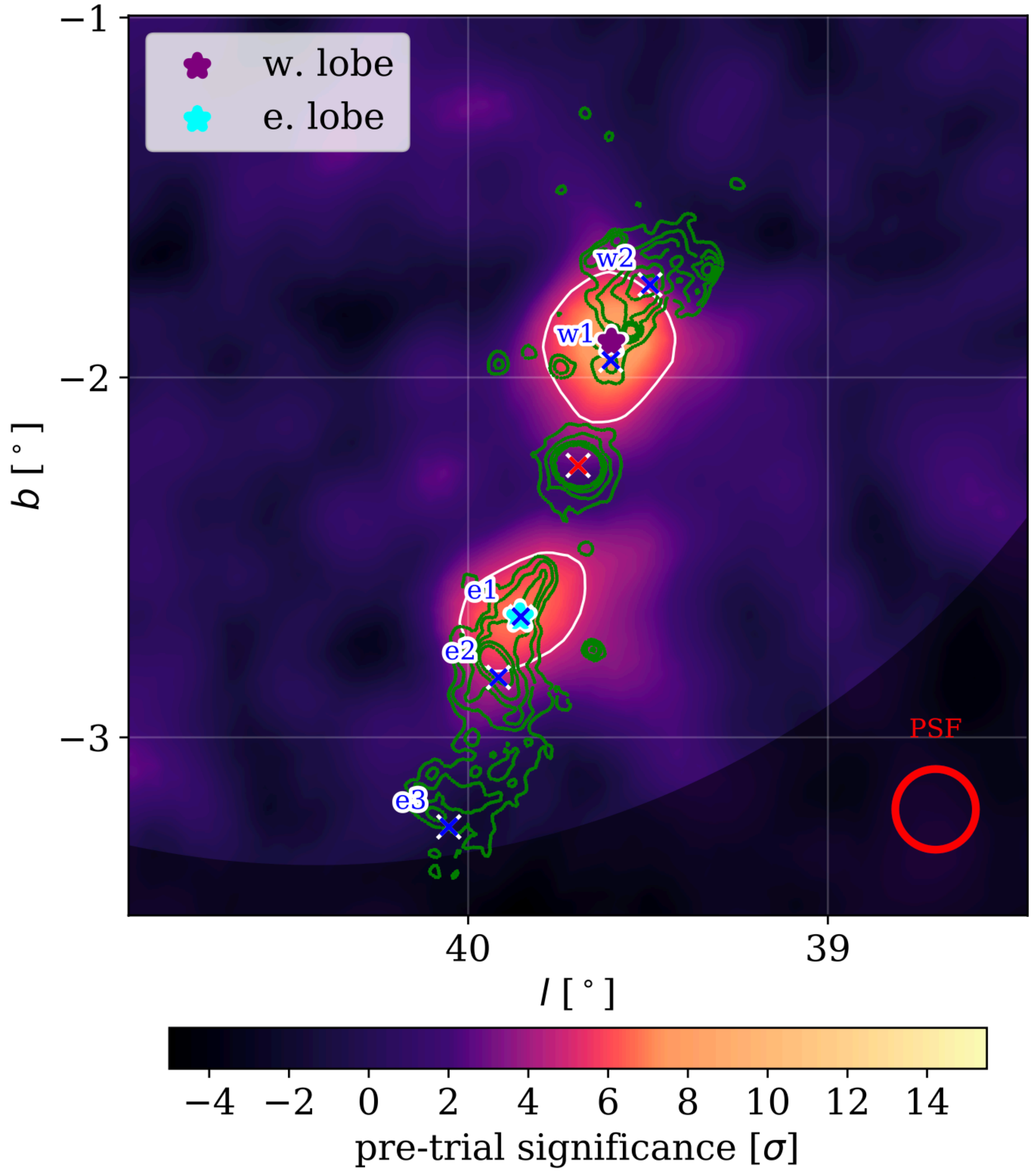
SS 433 / W50: HAWC 2024 results



HAWC Collaboration (**KF** as corresponding author), *ApJ (2024)*

SS 433 / W50: HAWC 2024 results

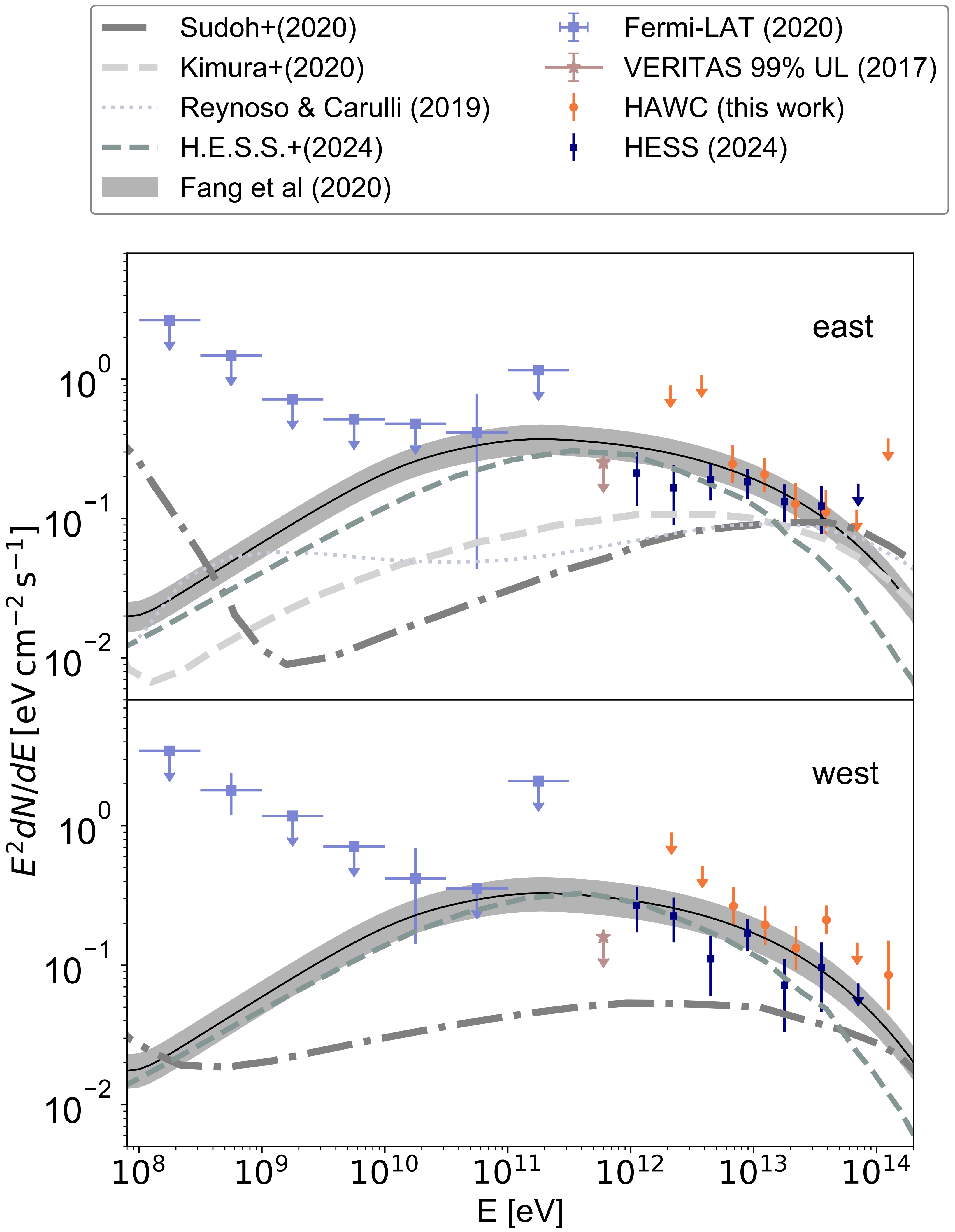




- SS 433 observed with a systematic analysis approach, confirming 2018 results

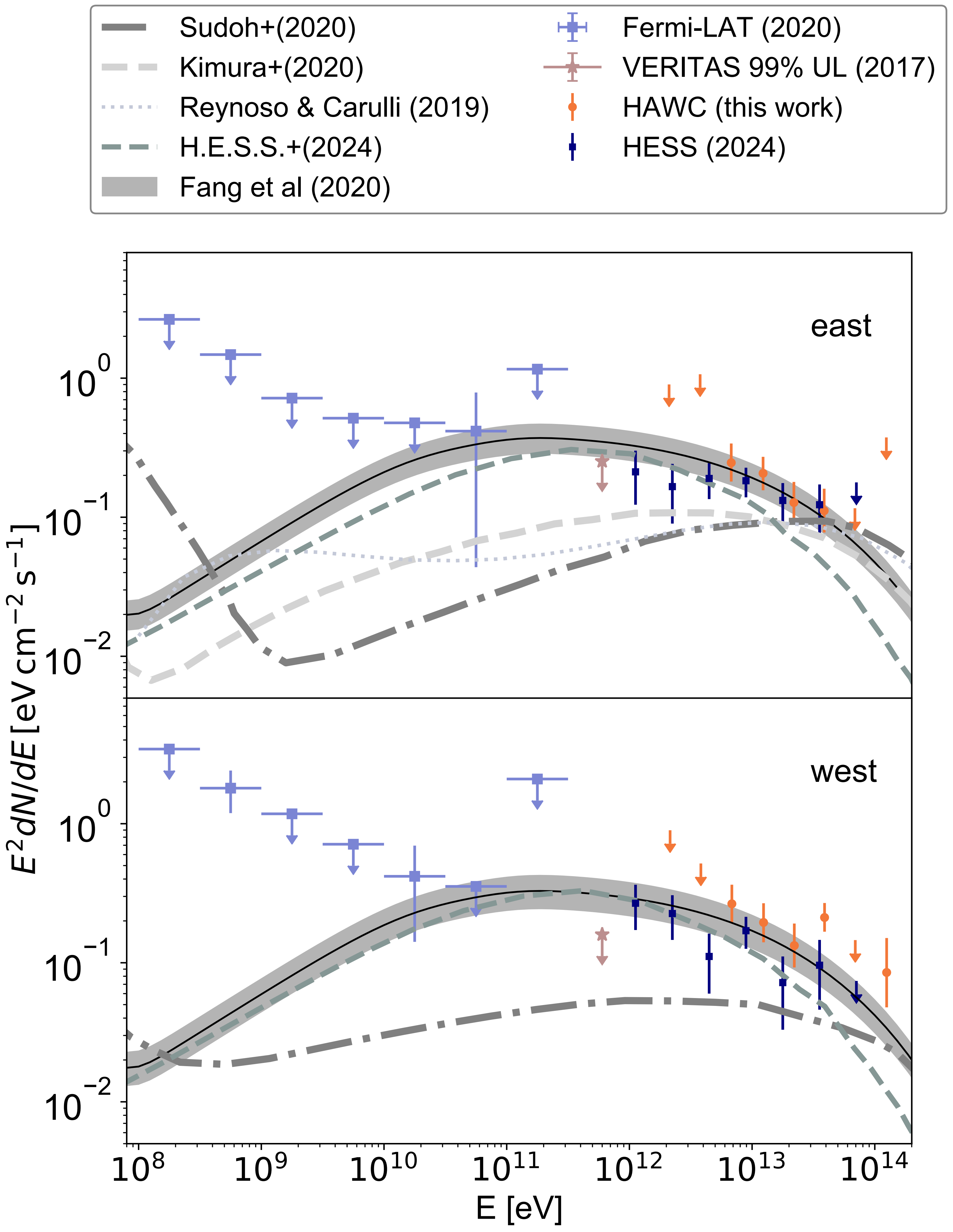
HAWC Collaboration (**KF** as corresponding author), *ApJ (2024)*

SS 433 / W50: HAWC 2024 results



HAWC Collaboration, *ApJ* (2024)
LHAASO Collaboration, 2410.08988

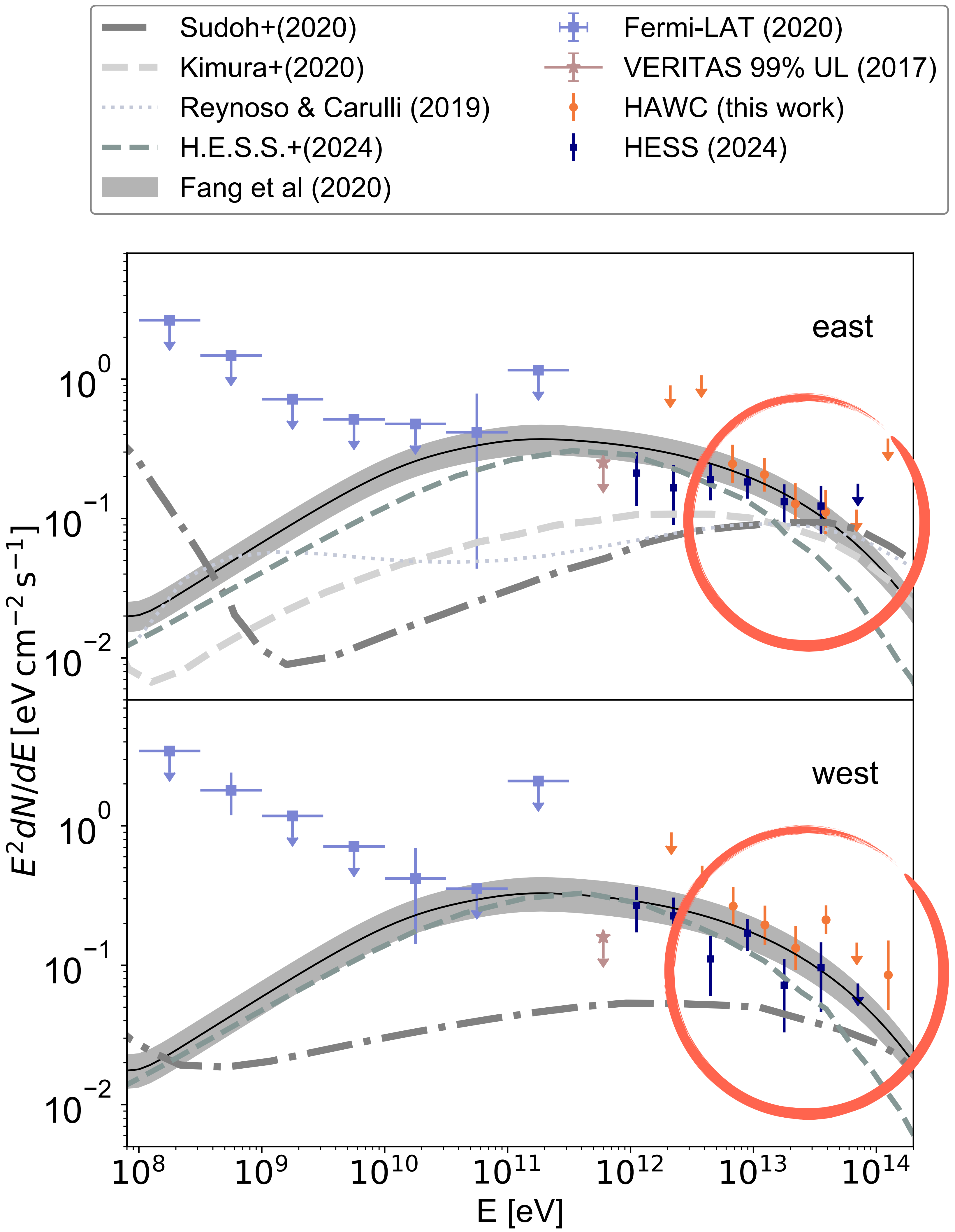
SS 433 / W50: HAWC 2024 results



- Need new models to fit the data!

HAWC Collaboration, *ApJ* (2024)
LHAASO Collaboration, 2410.08988

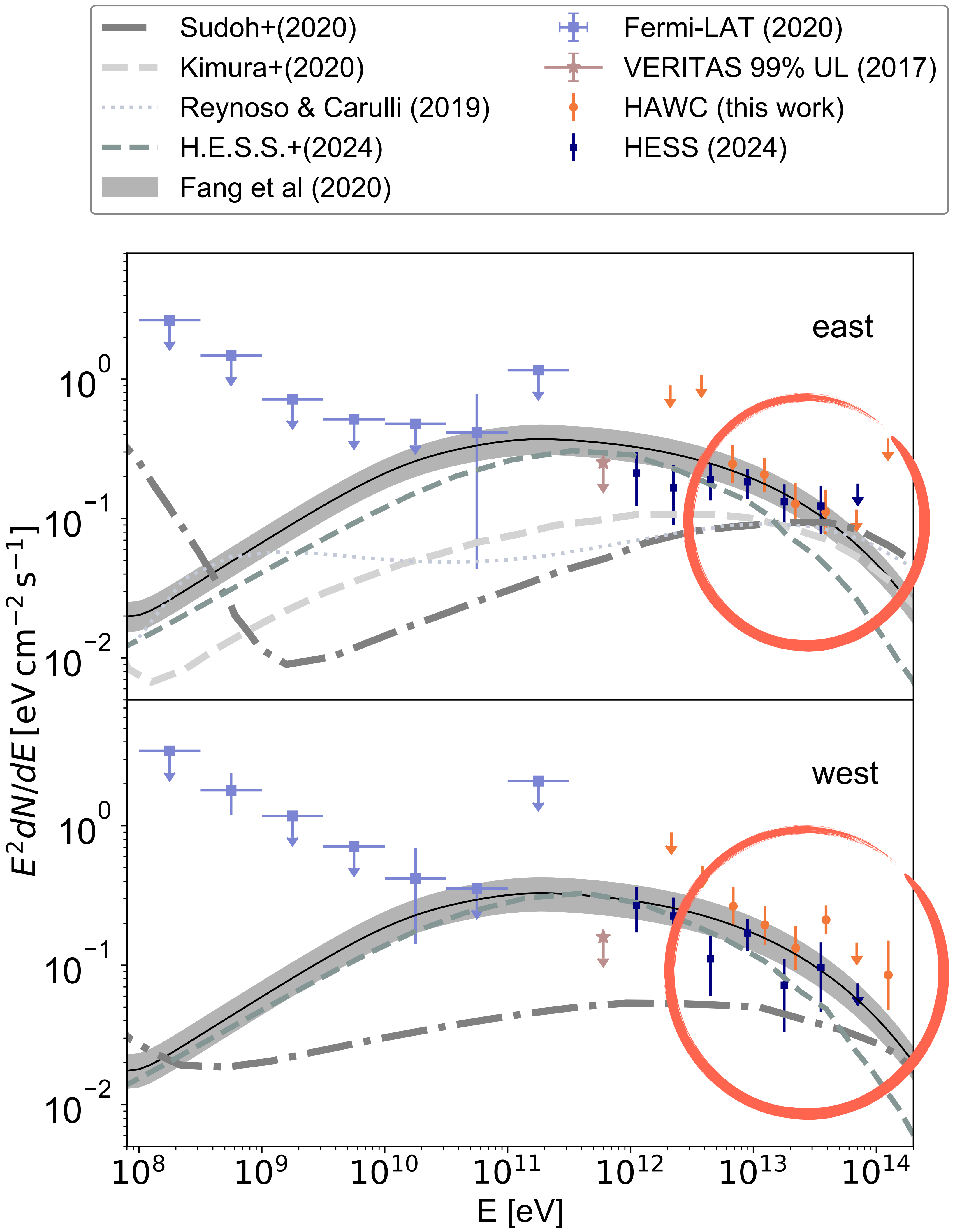
SS 433 / W50: HAWC 2024 results



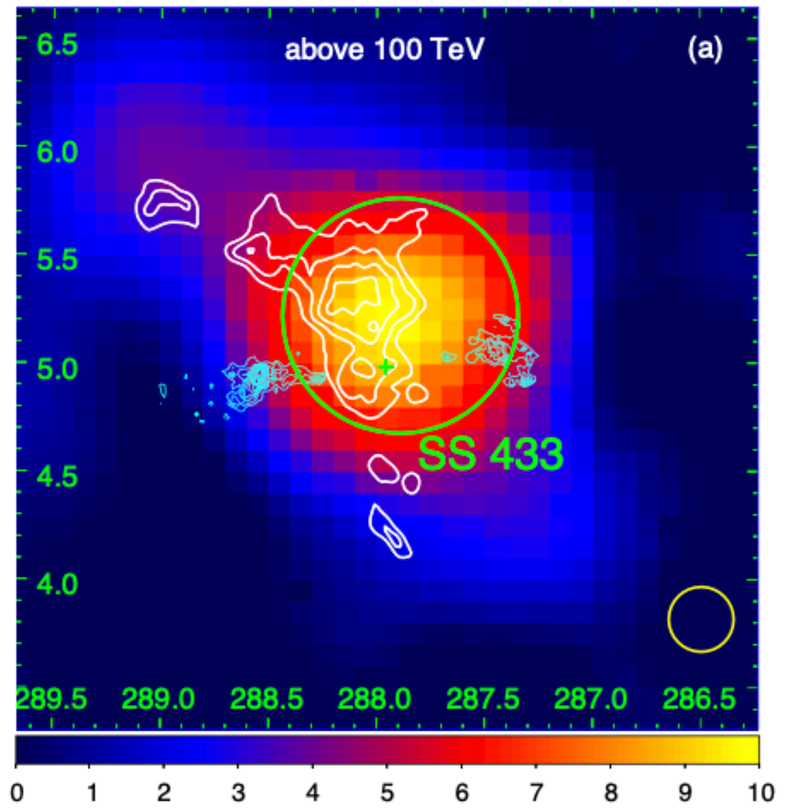
- Need new models to fit the data!
- HAWC and H.E.S.S. data above 10 TeV could indicate a **failure of one-zone leptonic models**

HAWC Collaboration, *ApJ* (2024)
LHAASO Collaboration, 2410.08988

SS 433 / W50: HAWC 2024 results



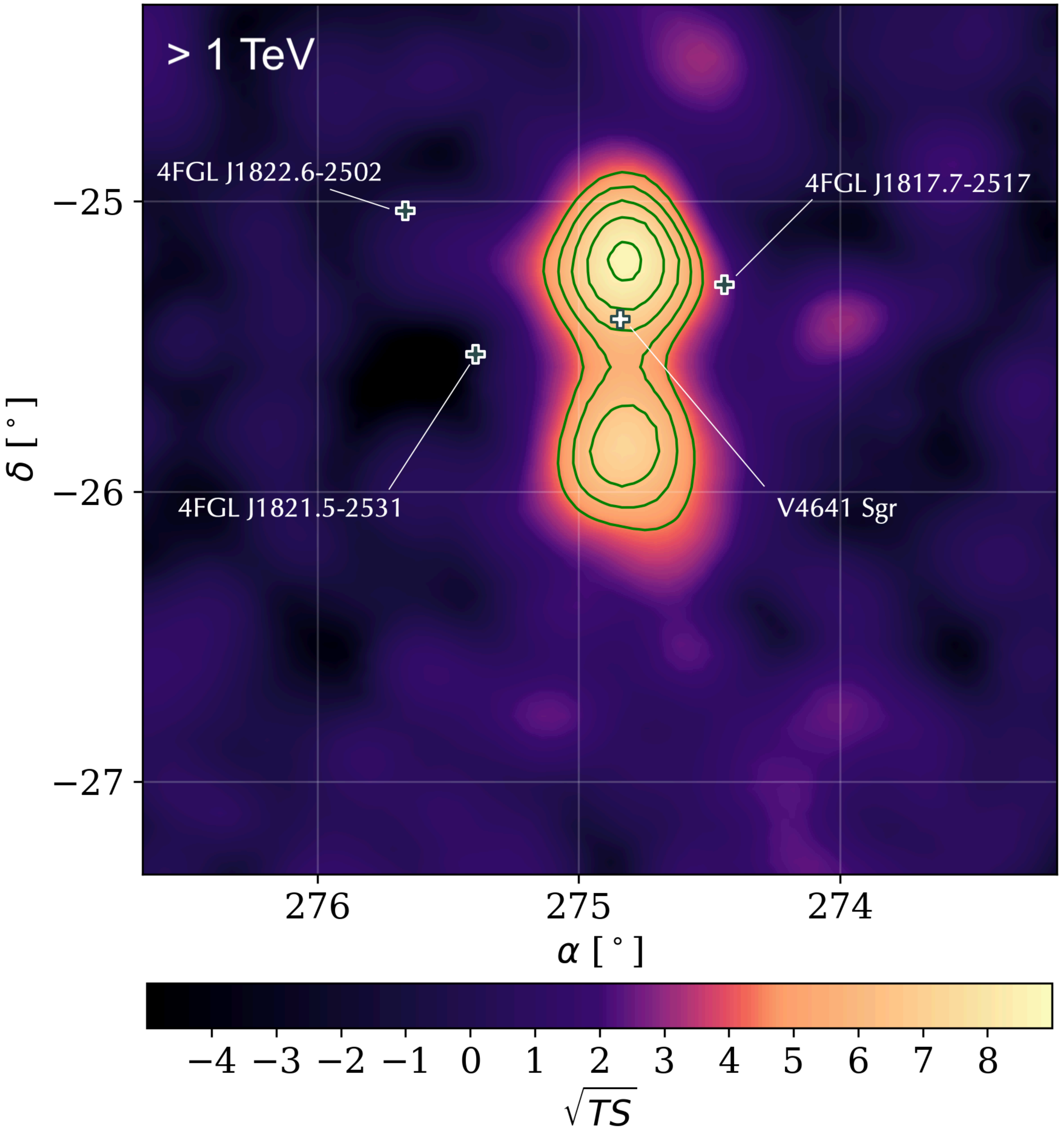
- Need new models to fit the data!
- HAWC and H.E.S.S. data above 10 TeV could indicate a **failure of one-zone leptonic models**
- Also suggested by **LHAASO observation above 100 TeV**



HAWC Collaboration, *ApJ* (2024)
LHAASO Collaboration, 2410.08988

V4641 Sagittarii

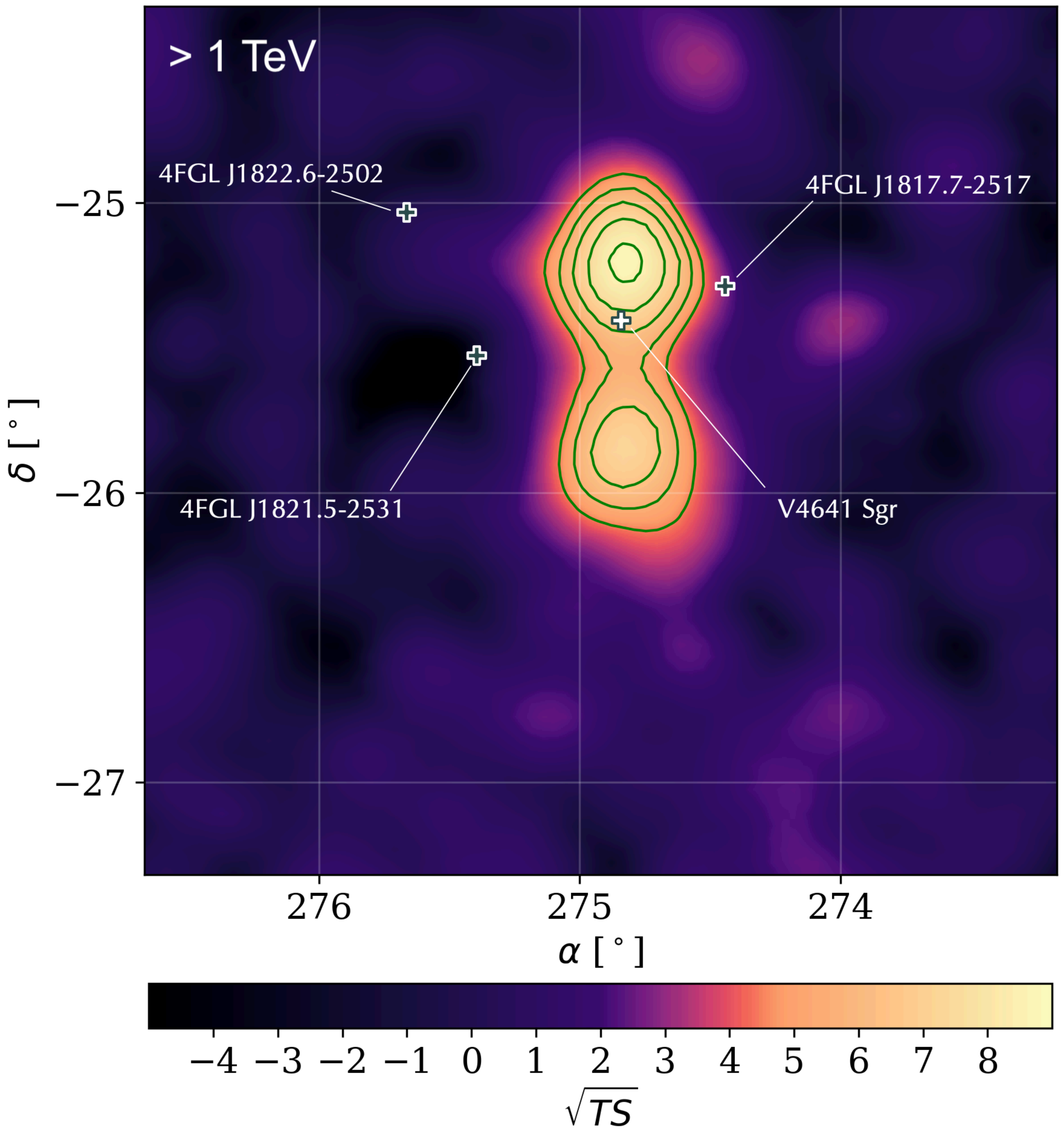
https://doi.org/10.1038/s41586-024-07995-9



HAWC Collaboration, *Nature* (2024)
KF as a correspondent author

V4641 Sagittarii

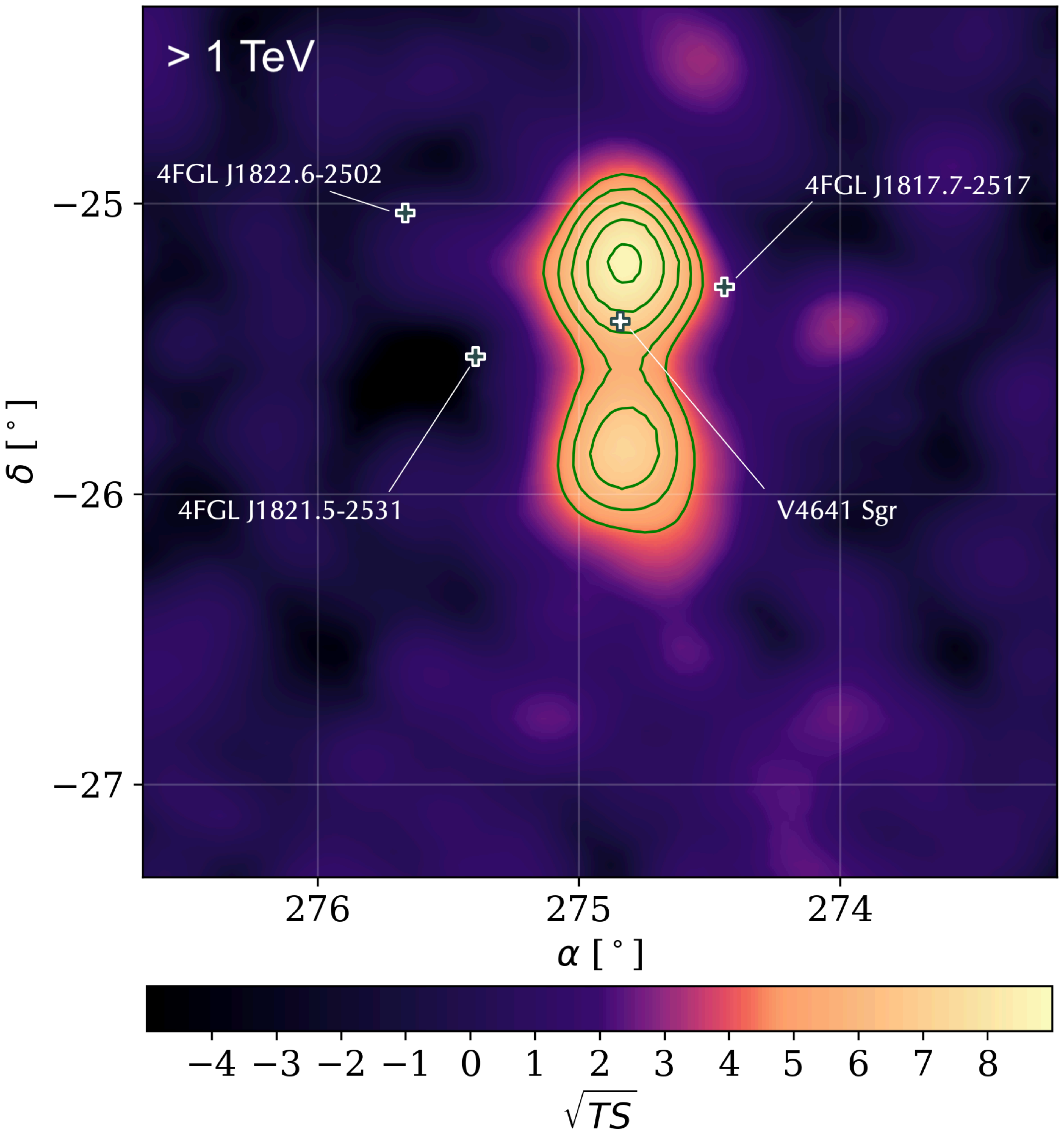
https://doi.org/10.1038/s41586-024-07995-9



HAWC Collaboration, *Nature* (2024)
KF as a correspondent author

V4641 Sagittarii

https://doi.org/10.1038/s41586-024-07995-9



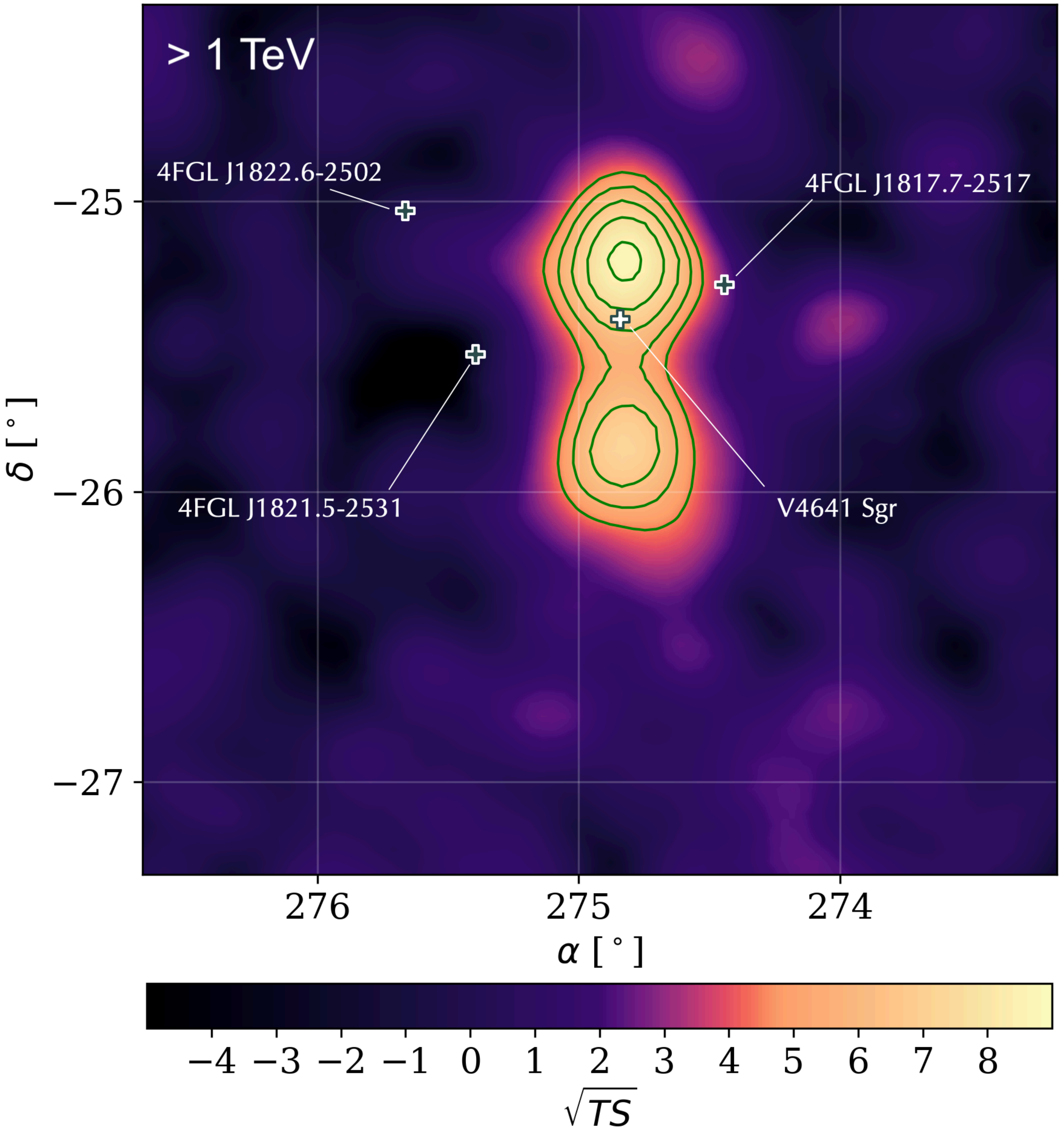
- X-ray binary with a 3-10 solar mass black hole. Super-Eddington flares in radio and likely X-ray

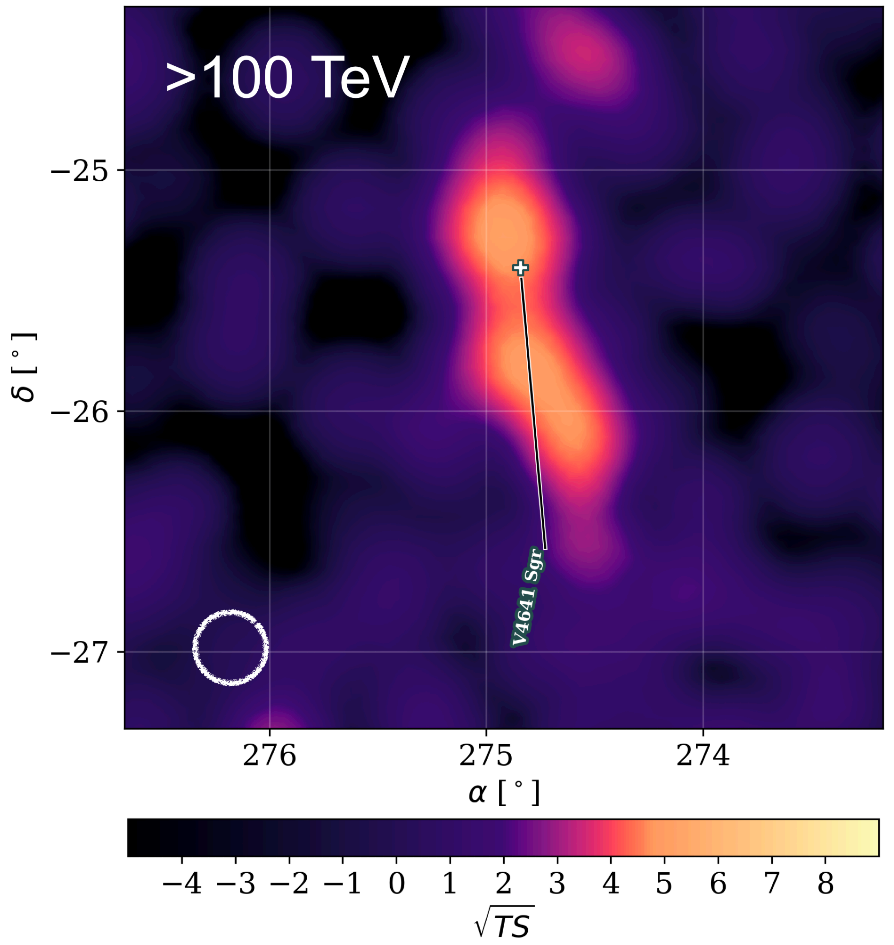
HAWC Collaboration, *Nature* (2024)
KF as a correspondent author

V4641 Sagittarii

https://doi.org/10.1038/s41586-024-07995-9

- X-ray binary with a 3-10 solar mass black hole. Super-Eddington flares in radio and likely X-ray
- **Elongated emission extends to > 100 TeV**

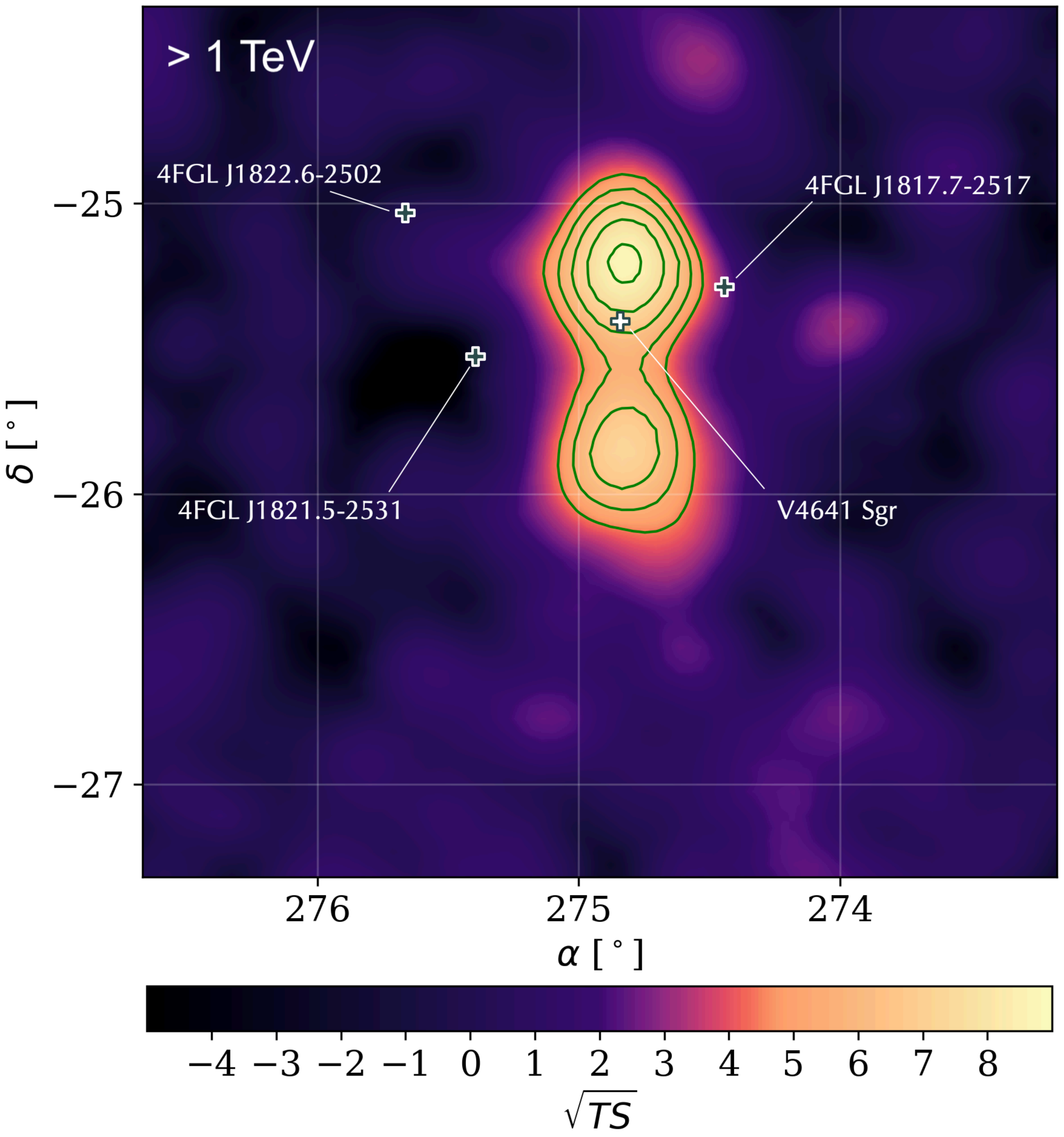




HAWC Collaboration, *Nature* (2024)
KF as a correspondent author

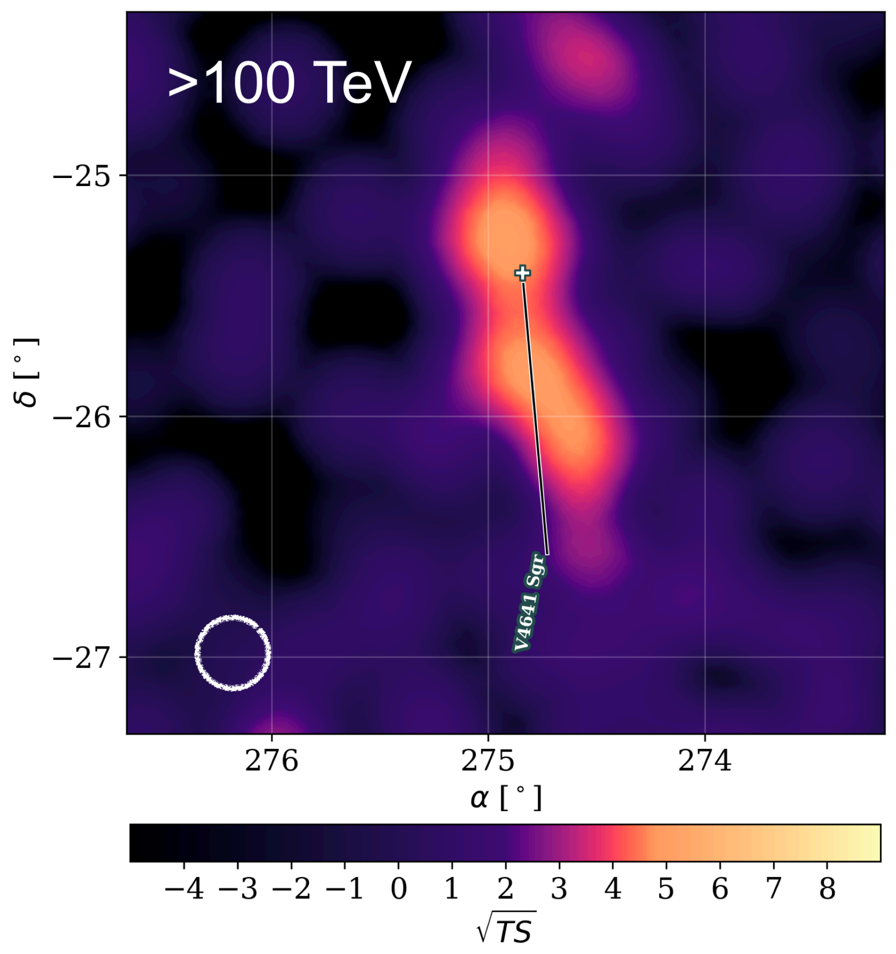
V4641 Sagittarii

https://doi.org/10.1038/s41586-024-07995-9



- X-ray binary with a 3-10 solar mass black hole. Super-Eddington flares in radio and likely X-ray
- **Elongated emission extends to > 100 TeV**
- Observation consistent with Jet size

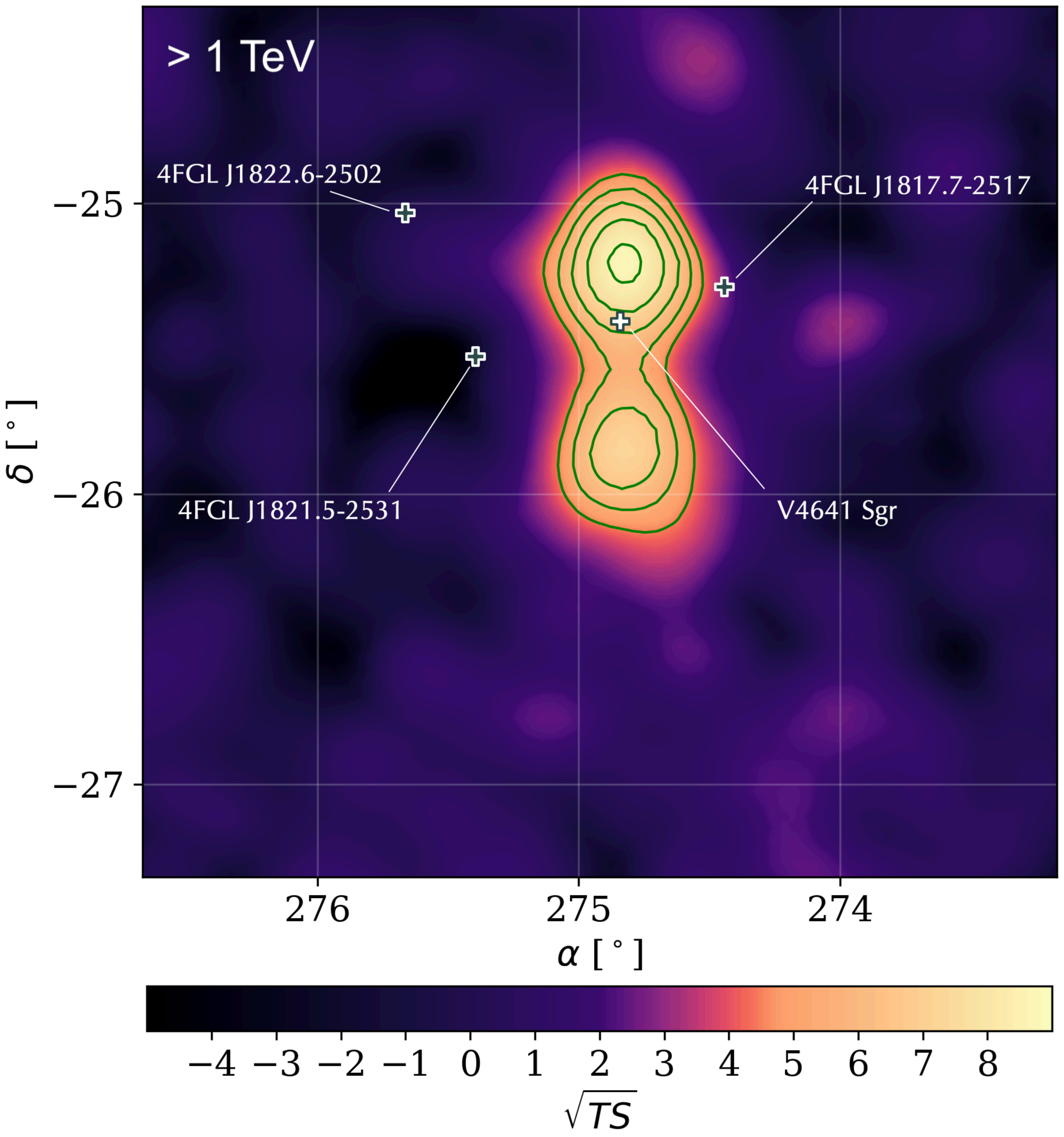
$$R \sim (L_{\rm jet}/n_0 m_p)^{1/5} t^{3/5} \sim 100\,{\rm pc}$$



HAWC Collaboration, *Nature* (2024)
KF as a correspondent author

V4641 Sagittarii

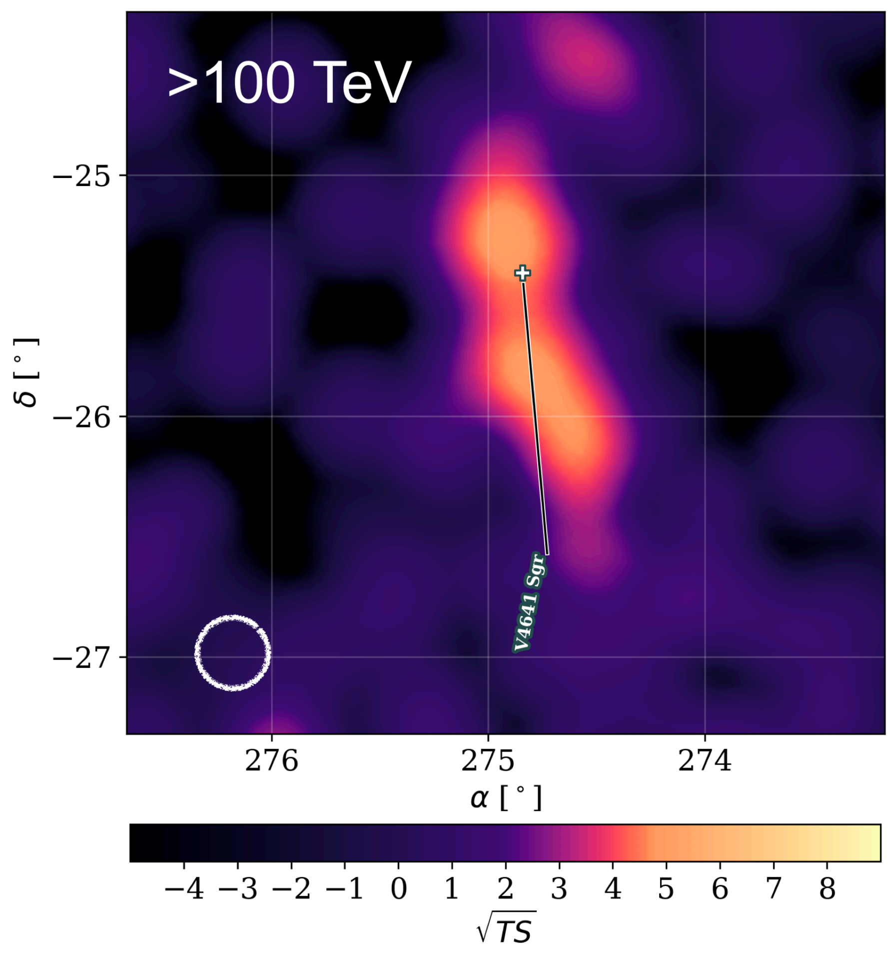
https://doi.org/10.1038/s41586-024-07995-9



- X-ray binary with a 3-10 solar mass black hole. Super-Eddington flares in radio and likely X-ray
- **Elongated emission extends to > 100 TeV**
- Observation consistent with Jet size

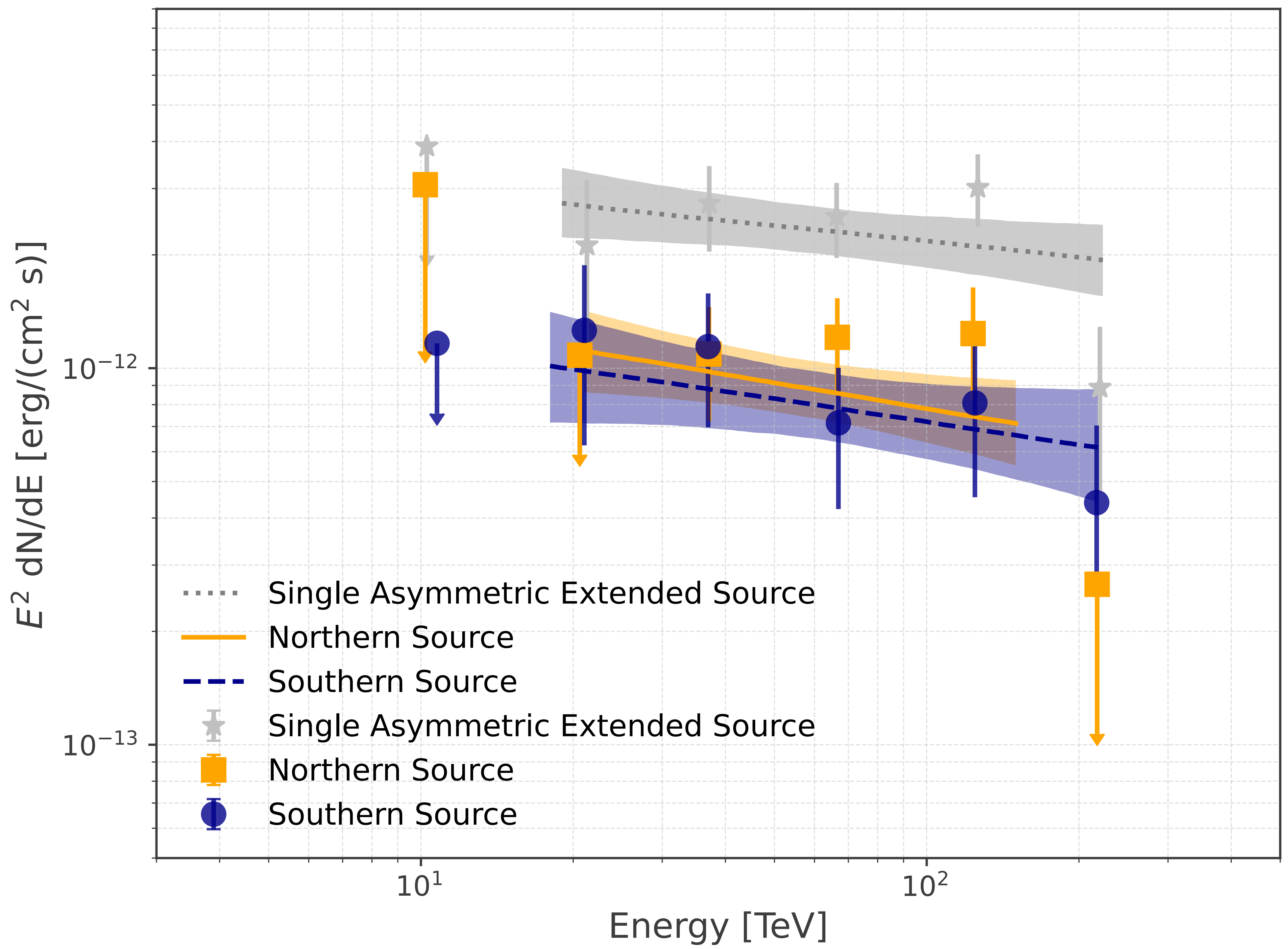
$$R \sim (L_{\rm jet}/n_0 m_p)^{1/5} t^{3/5} \sim 100\,{\rm pc}$$

- Adds to SS 433 as the **second Galactic microquasar with large-scale jets**



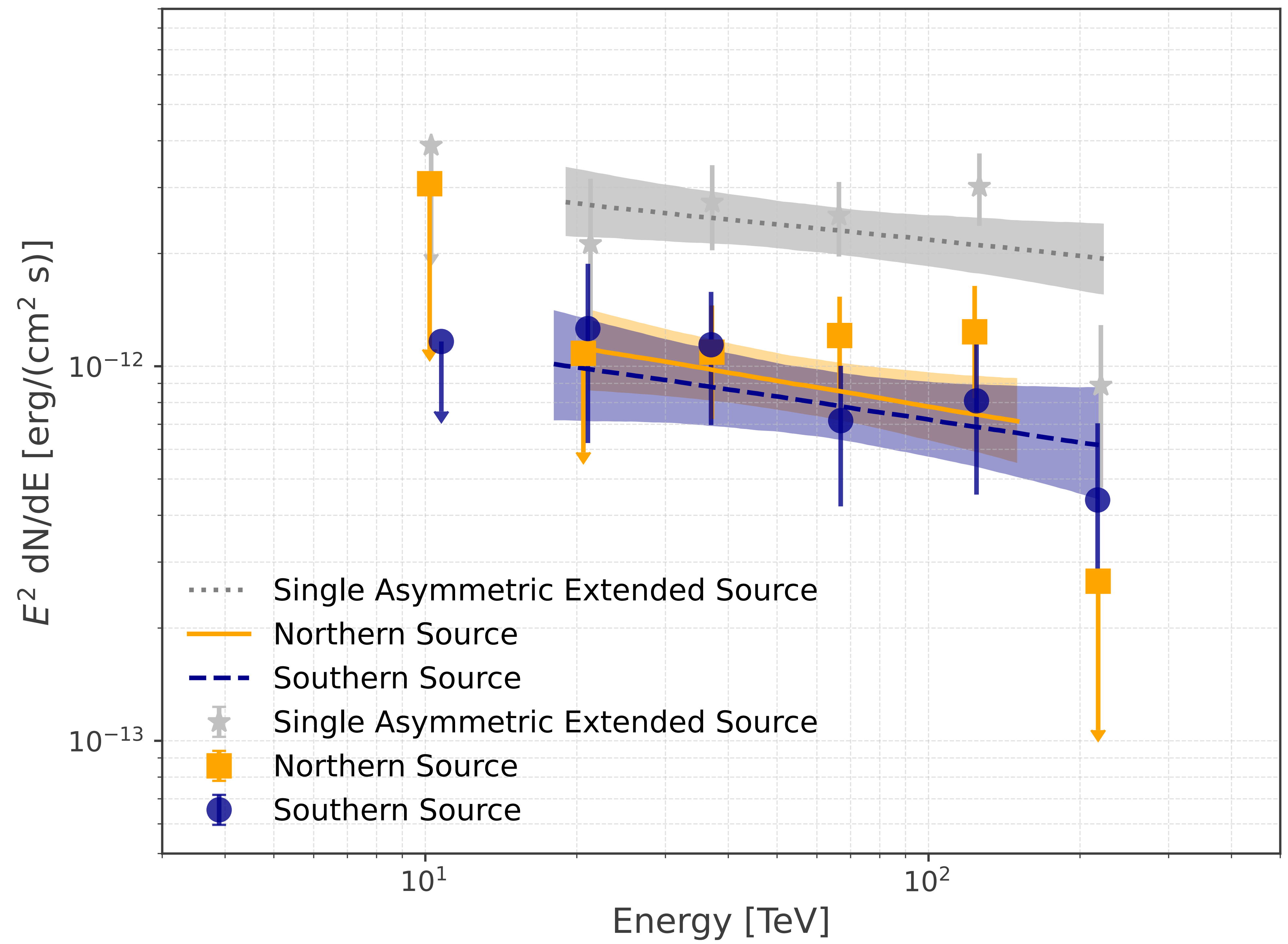
HAWC Collaboration, *Nature* (2024)
KF as a correspondent author

V4641 Sagittarii: PeVatron perspective



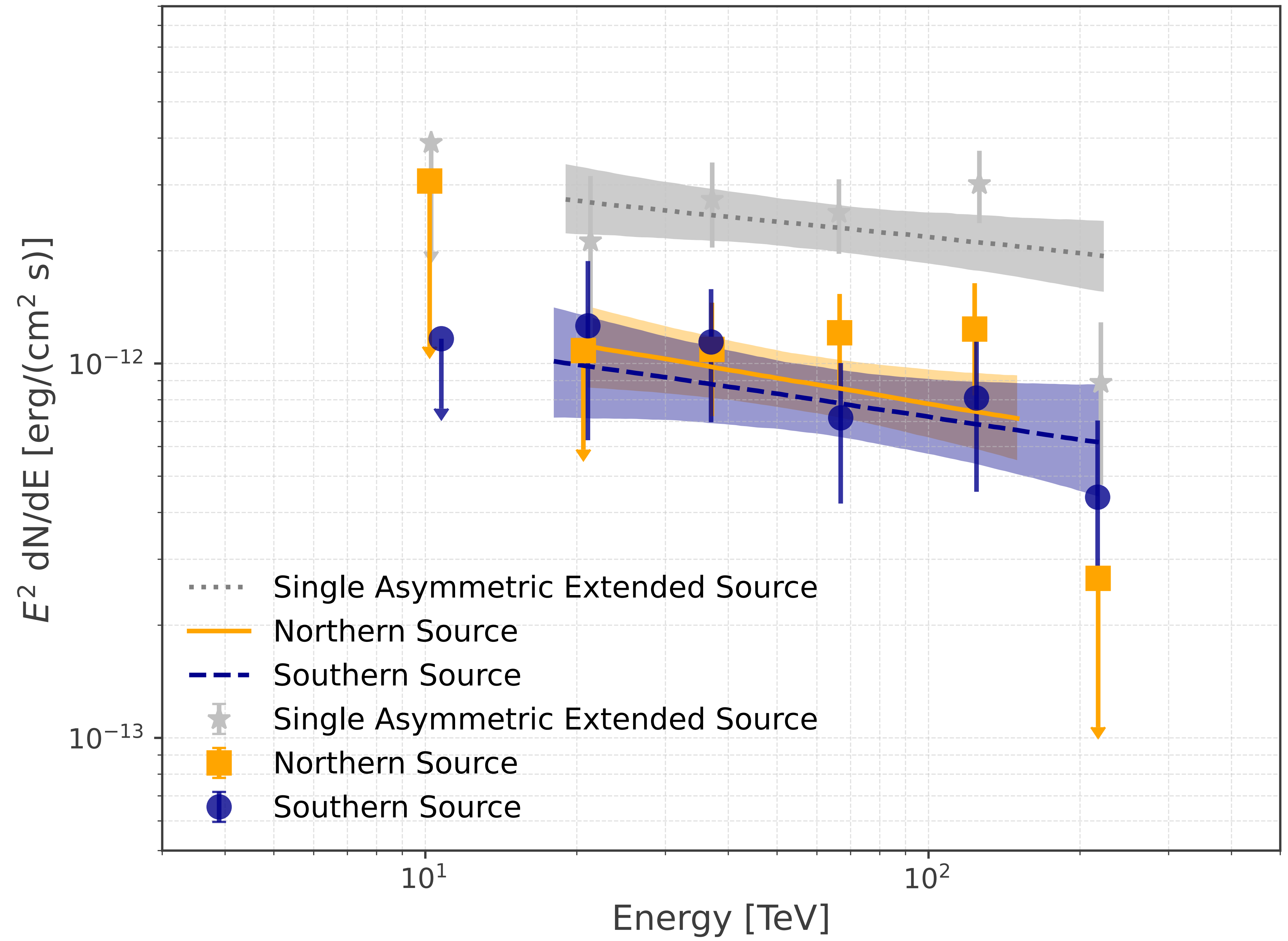
HAWC Collaboration, *Nature* (2024)

V4641 Sagittarii: PeVatron perspective



HAWC Collaboration, *Nature* (2024)

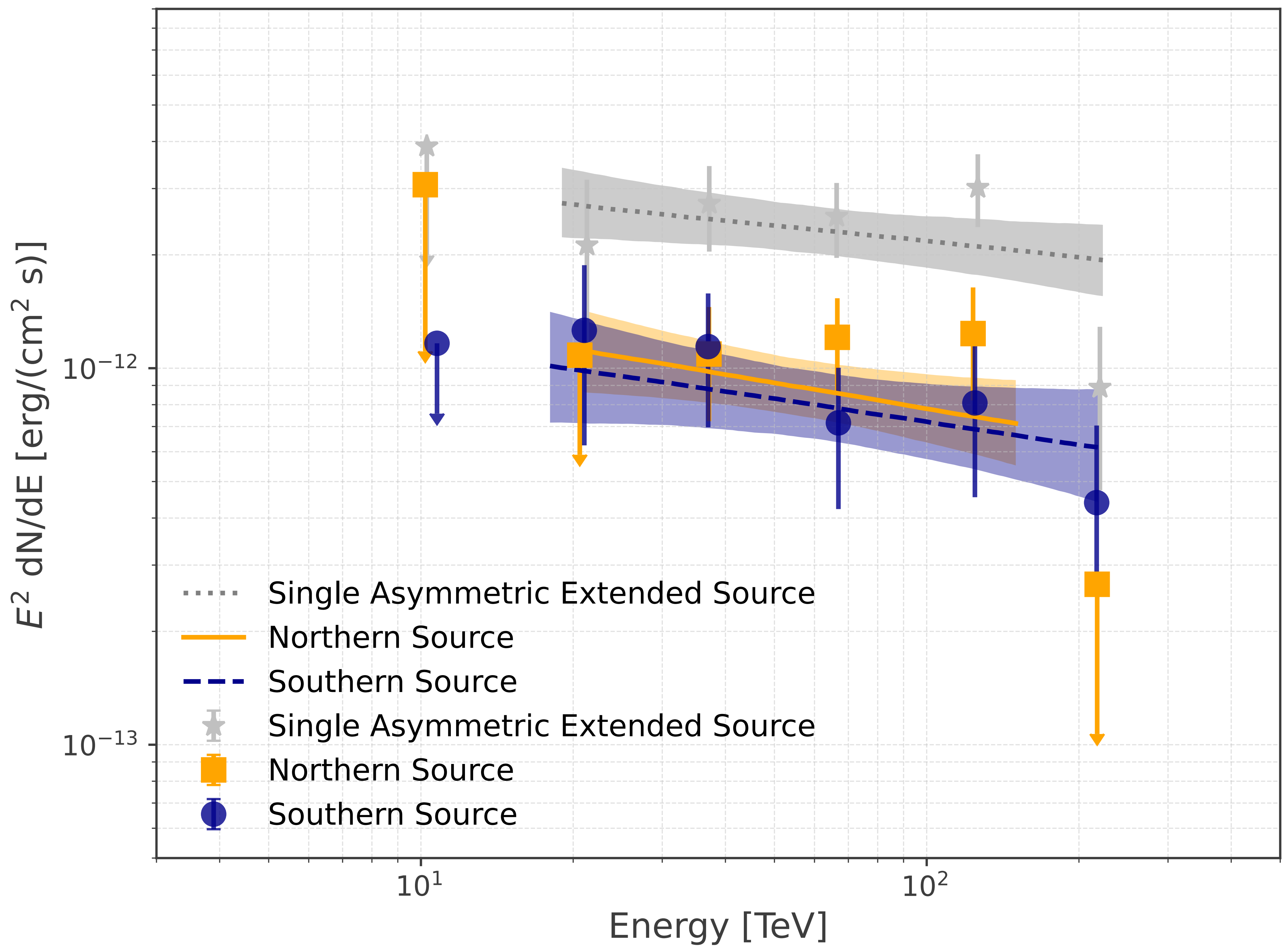
V4641 Sagittarii: PeVatron perspective



- $dN/dE_\gamma \propto E_\gamma^{-2.2}$. Among the **hardest source** ever detected by air shower gamma-ray observatories

HAWC Collaboration, *Nature* (2024)

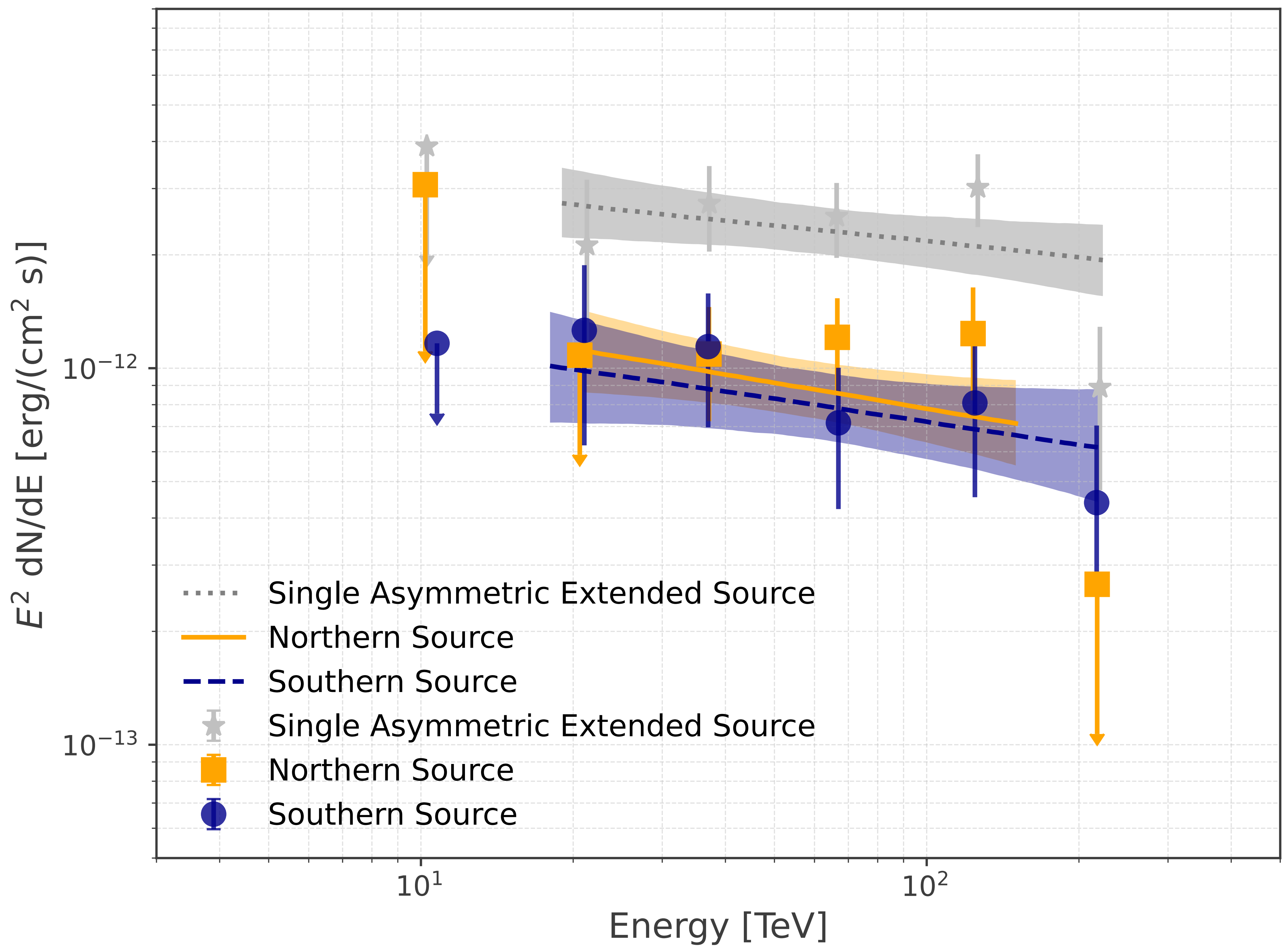
V4641 Sagittarii: PeVatron perspective



- $dN/dE_\gamma \propto E_\gamma^{-2.2}$. Among the **hardest source** ever detected by air shower gamma-ray observatories

HAWC Collaboration, *Nature* (2024)

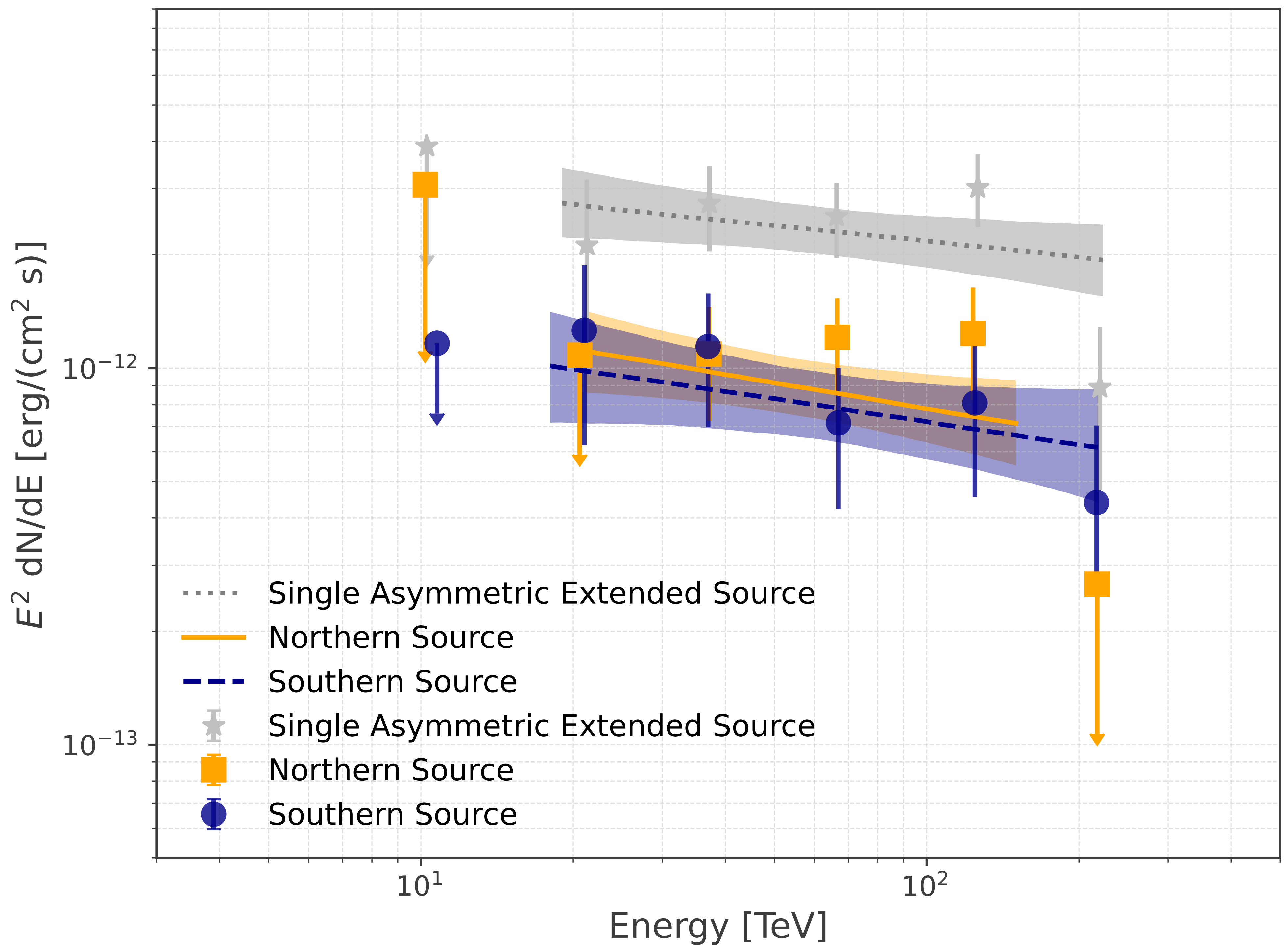
V4641 Sagittarii: PeVatron perspective



- $dN/dE_\gamma \propto E_\gamma^{-2.2}$. Among the **hardest source** ever detected by air shower gamma-ray observatories
- **pp interaction may explain the emission** with $L_p \ll L_{\rm Edd}$

HAWC Collaboration, *Nature* (2024)

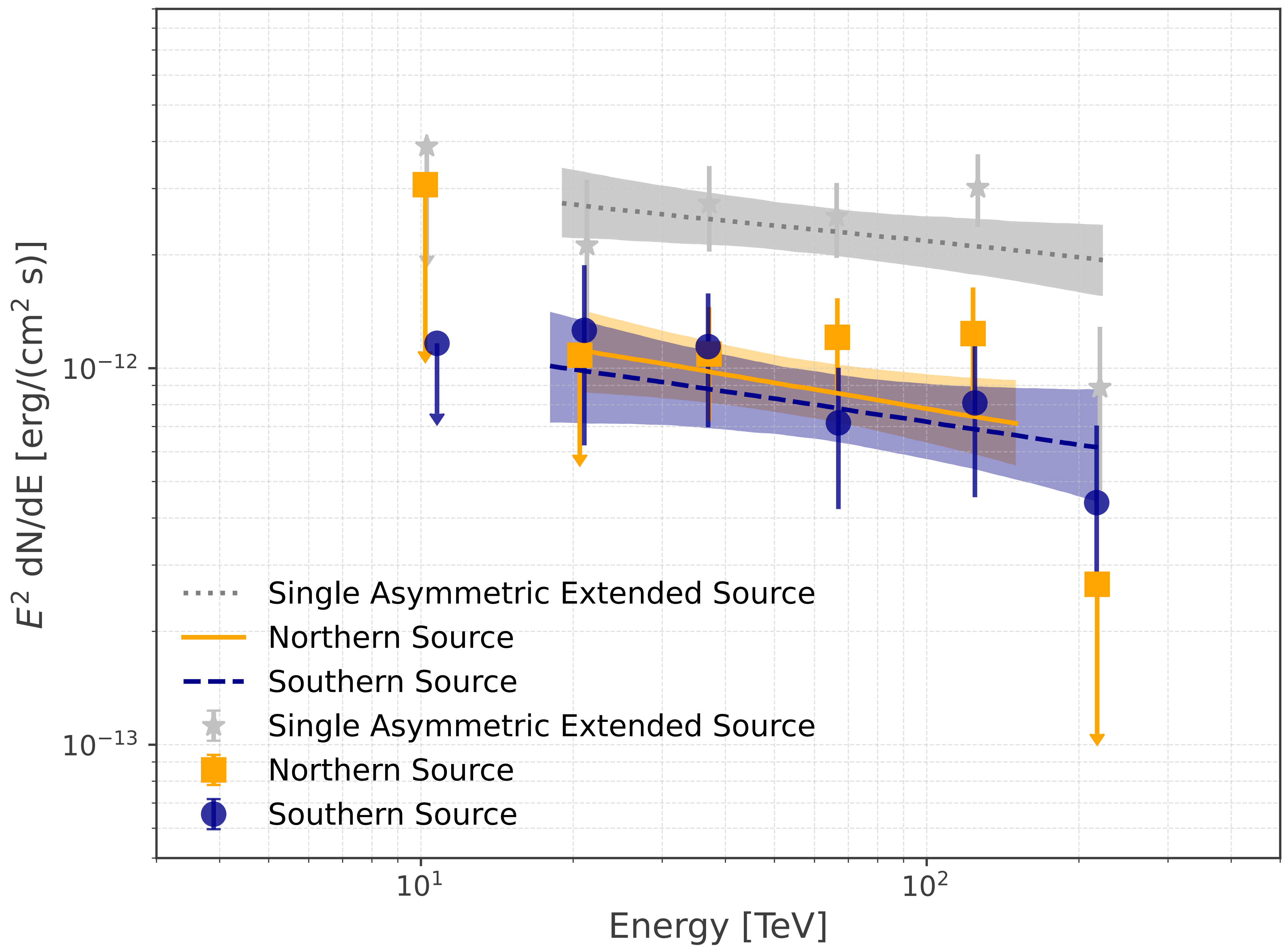
V4641 Sagittarii: PeVatron perspective



- $dN/dE_\gamma \propto E_\gamma^{-2.2}$. Among the **hardest source** ever detected by air shower gamma-ray observatories
- **pp interaction may explain the emission** with $L_p \ll L_{\rm Edd}$

HAWC Collaboration, *Nature* (2024)

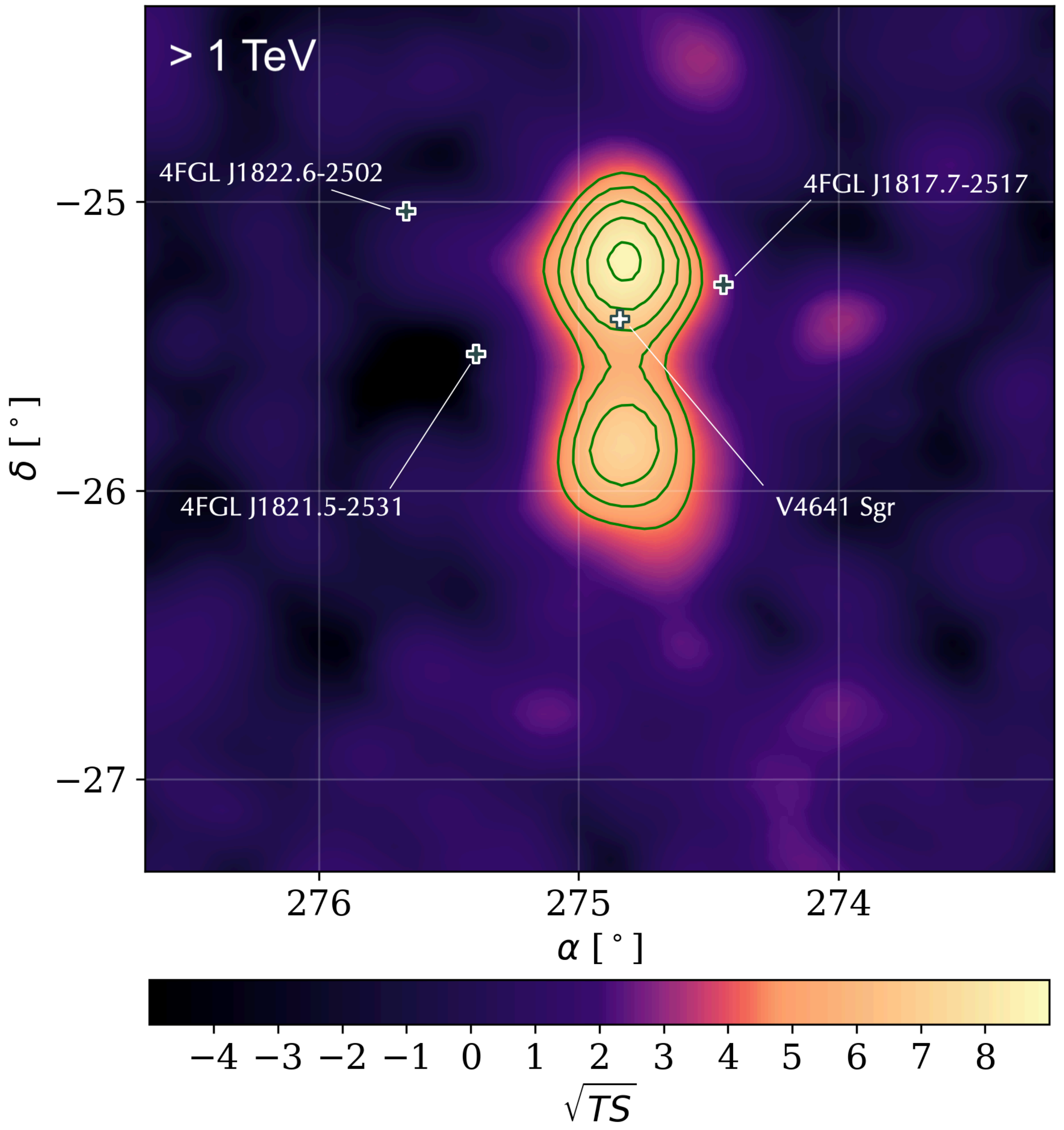
V4641 Sagittarii: PeVatron perspective

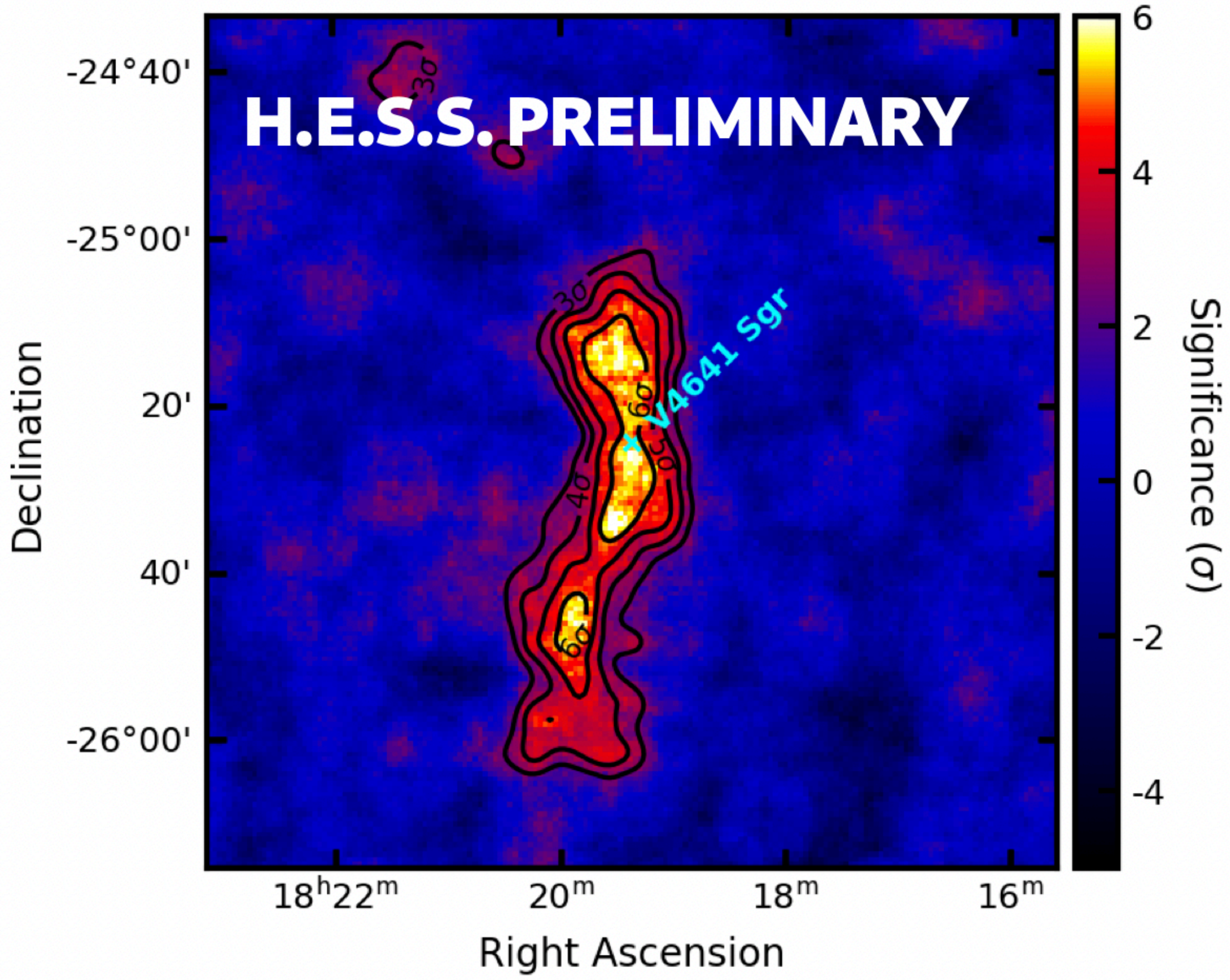


- $dN/dE_\gamma \propto E_\gamma^{-2.2}$. Among the **hardest source** ever detected by air shower gamma-ray observatories
- **pp interaction may explain the emission** with $L_p \ll L_{\rm Edd}$
- A leptonic scenario is challenging as 100 TeV electrons can hardly diffuse over 100 pc. It also requires fast acceleration

HAWC Collaboration, *Nature* (2024)

V4641 Sagittarii: H.E.S.S. followup

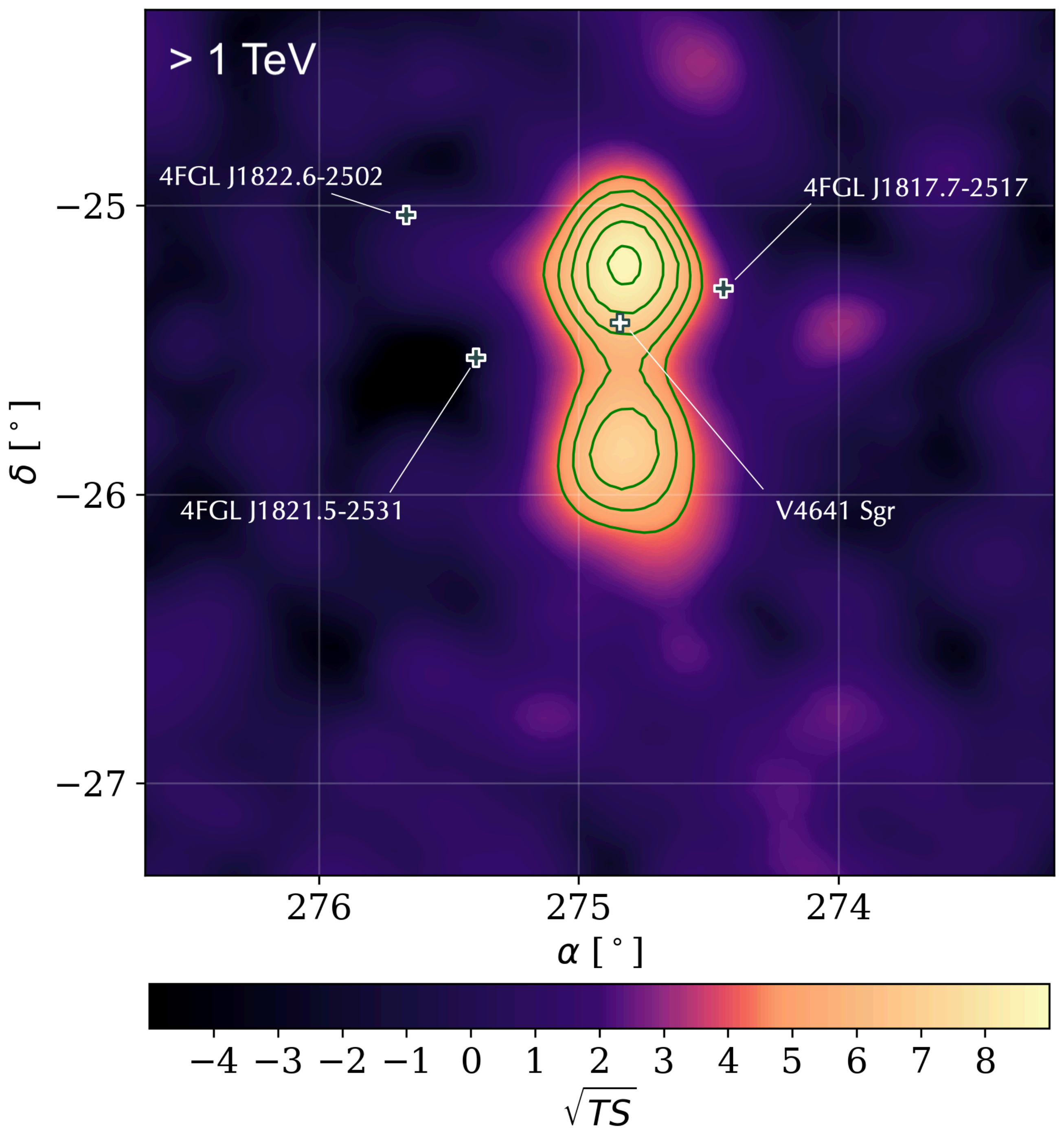


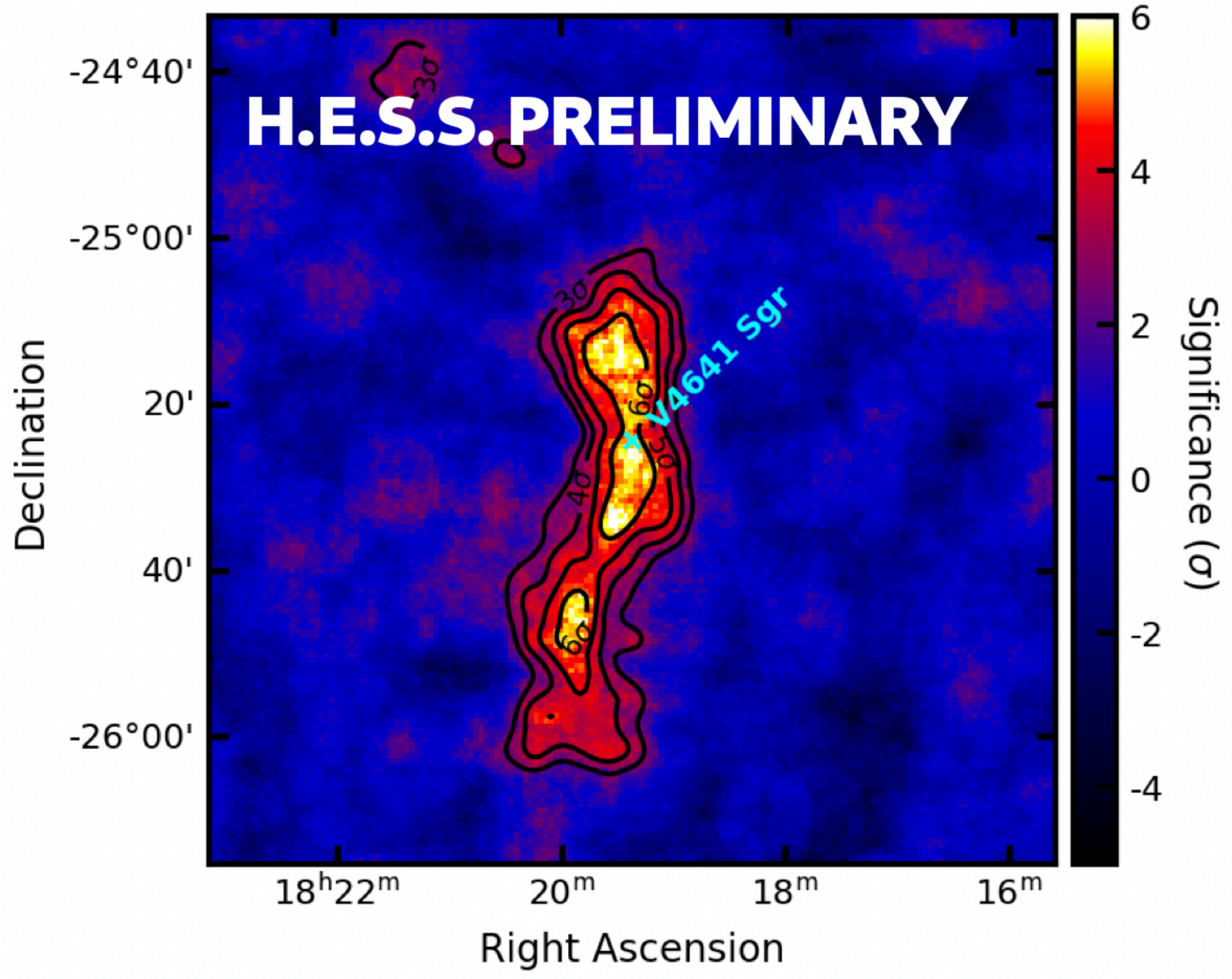


Olivera-Nieto Gamma2024

- Seen by H.E.S.S. with ~115 hours of total observation time
- Harder spectrum (<2)
- Detected up to 800 TeV by LHAASO
- More multi-wavelength/multi-messenger followup coming

V4641 Sagittarii: H.E.S.S. followup



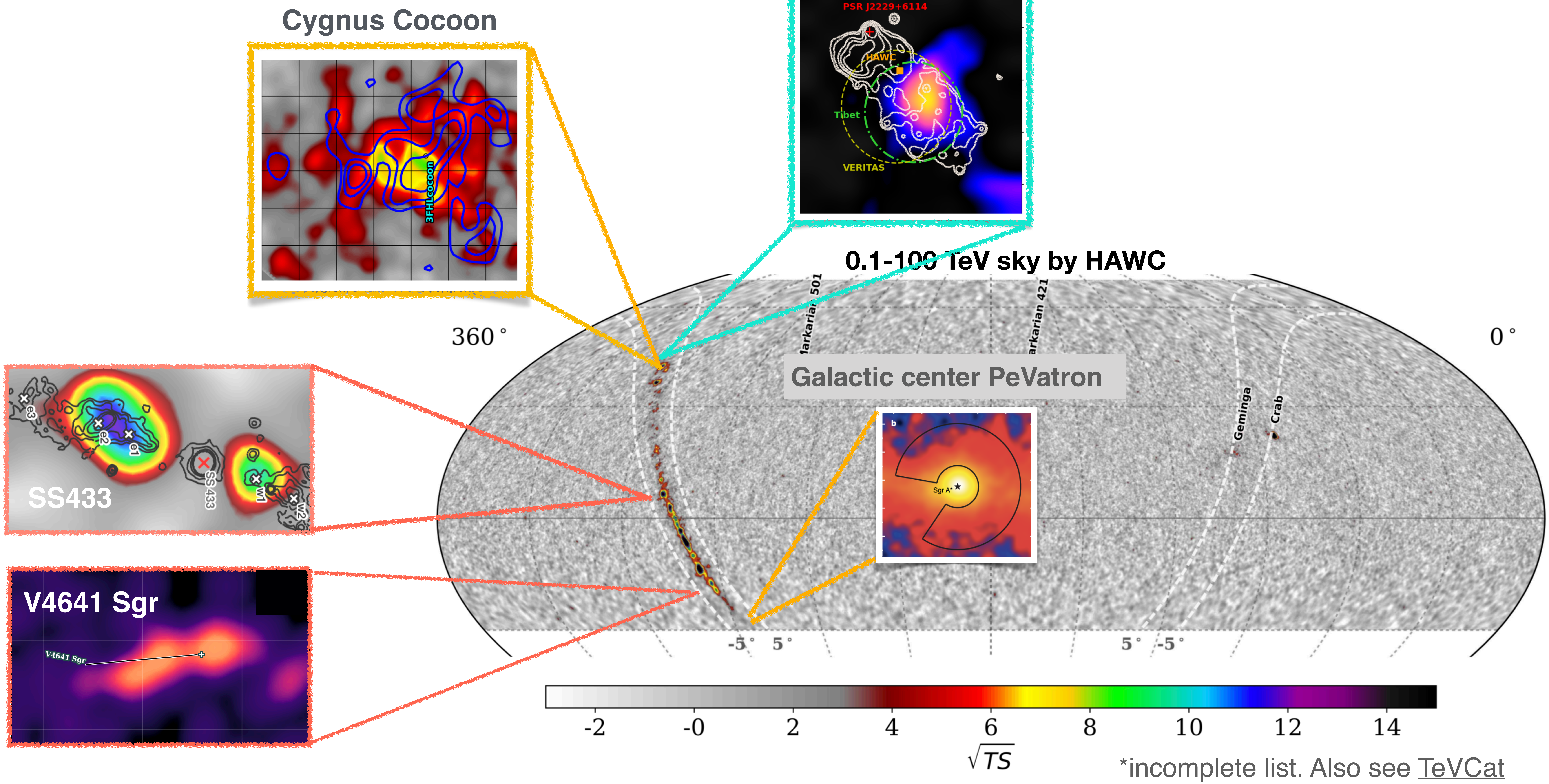


Olivera-Nieto Gamma2024

- Seen by H.E.S.S. with ~115 hours of total observation time
- Harder spectrum (<2)
- Detected up to 800 TeV by LHAASO
- More multi-wavelength/multi-messenger followup coming

- Shock acceleration in regions where jets passing pre-existing clumps?
- Reconnection in jets?
- Cavity in jets?

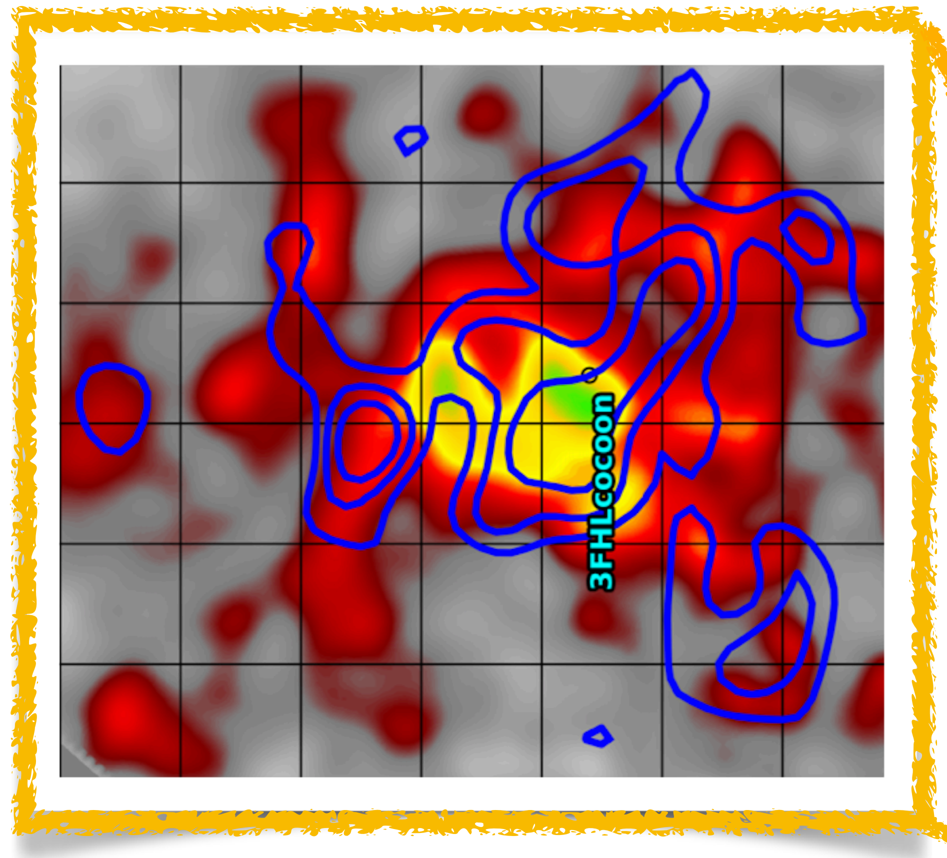
PeVatron Zoo* in 2024



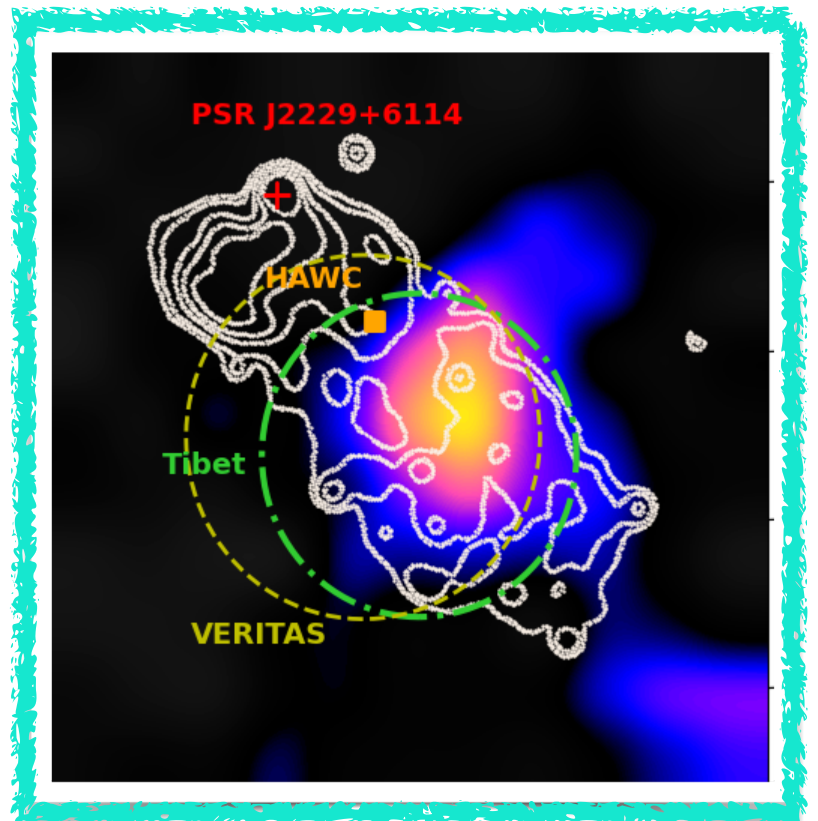
*incomplete list. Also see TeVCat

PeVatron Zoo* in 2024

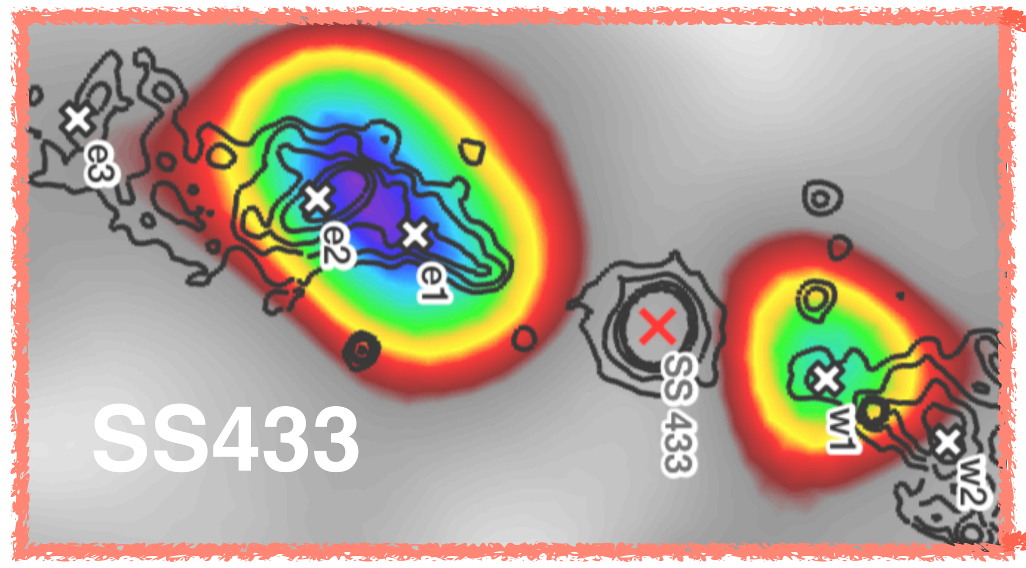
Cygnus Cocoon

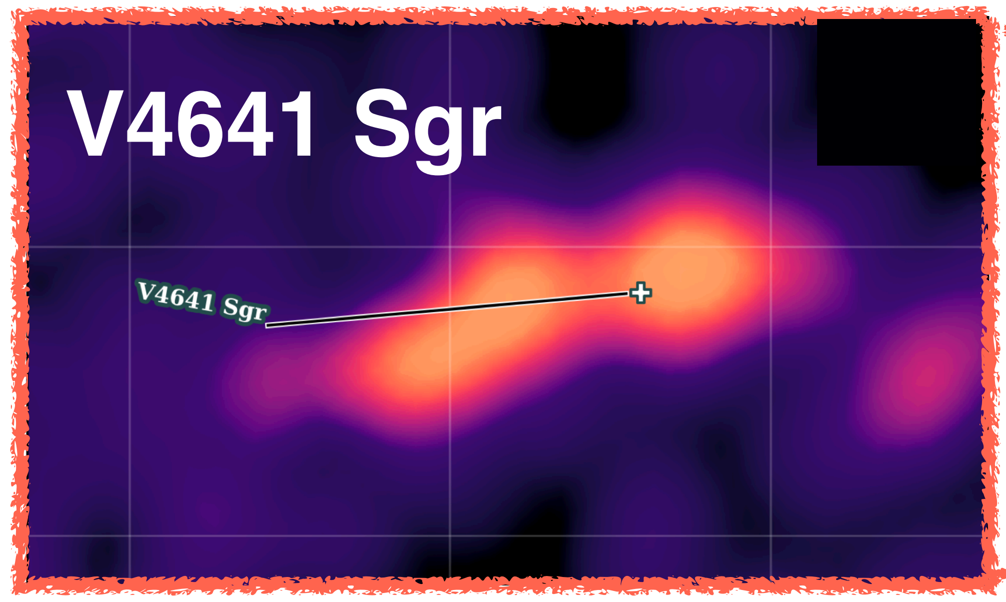


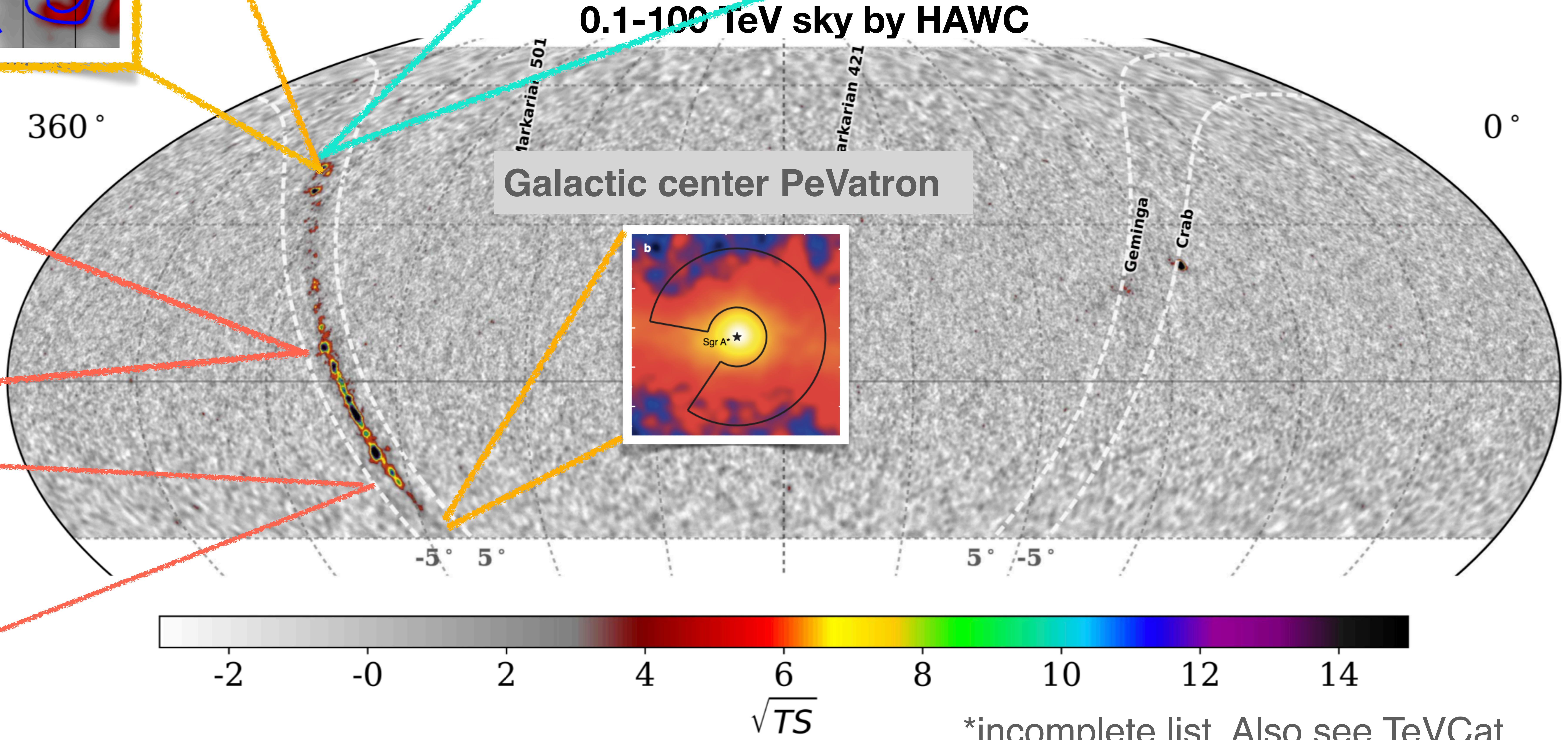
SNR G106.3+2.7



New source classes + expected source class but unexpected look at TeV-PeV

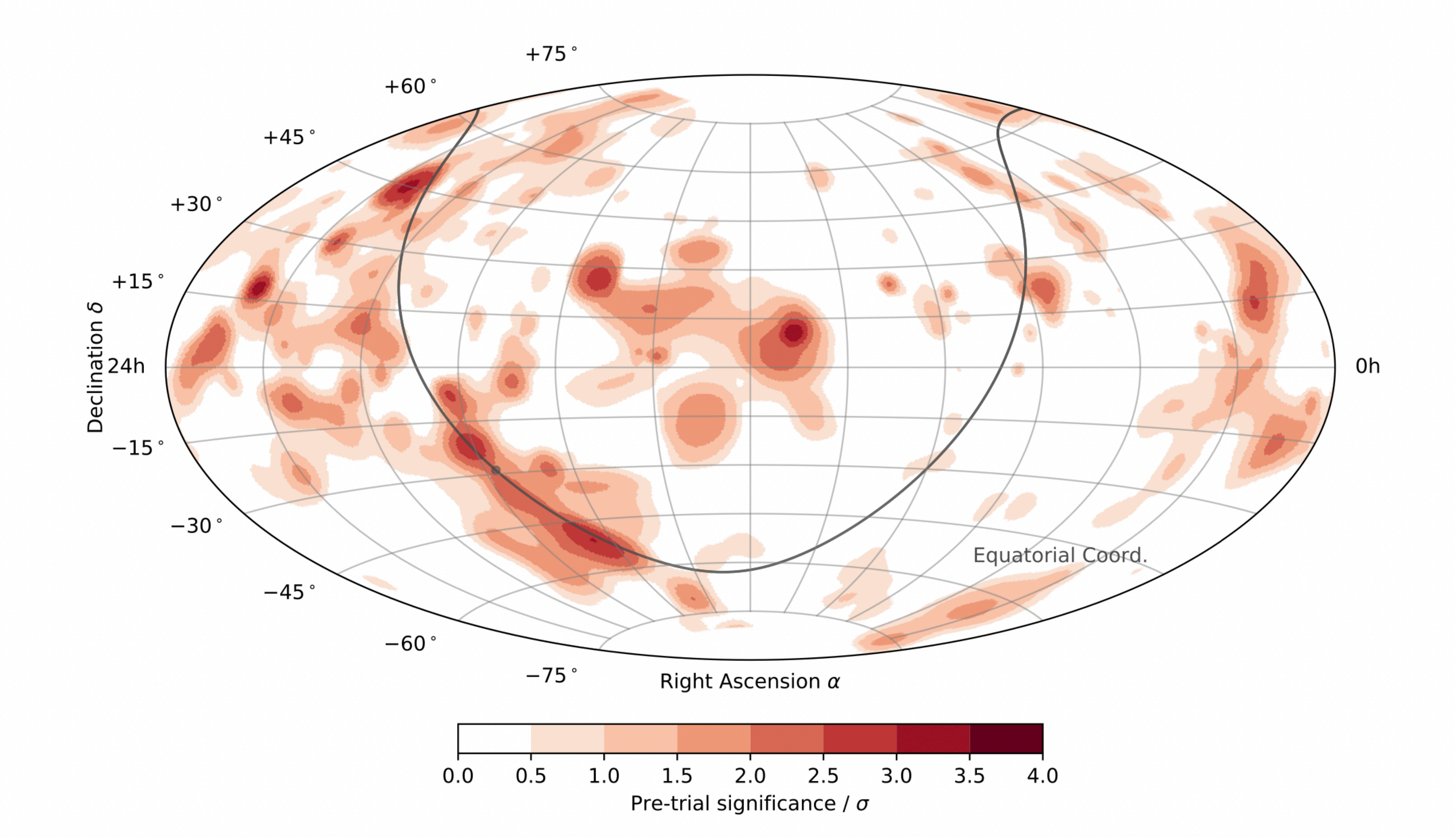






*incomplete list. Also see TeVCat

PeVatron Zoo* in 2024: Neutrino efforts

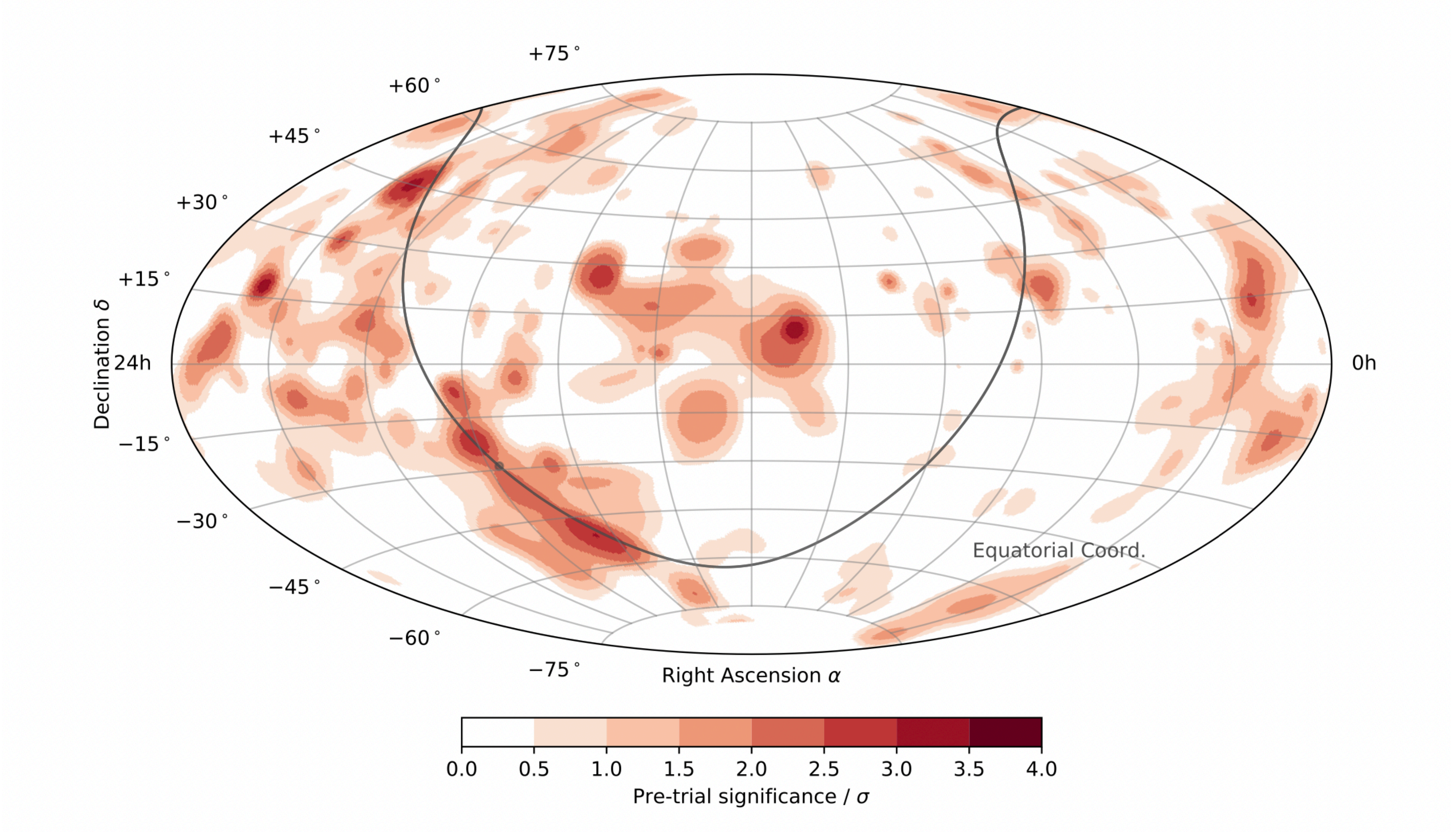


Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	

IceCube Collaboration, *Science* (2023)

KF & Halzen, 2404.15944

PeVatron Zoo* in 2024: Neutrino efforts



Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8\,^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	

IceCube Collaboration, *Science* (2023)

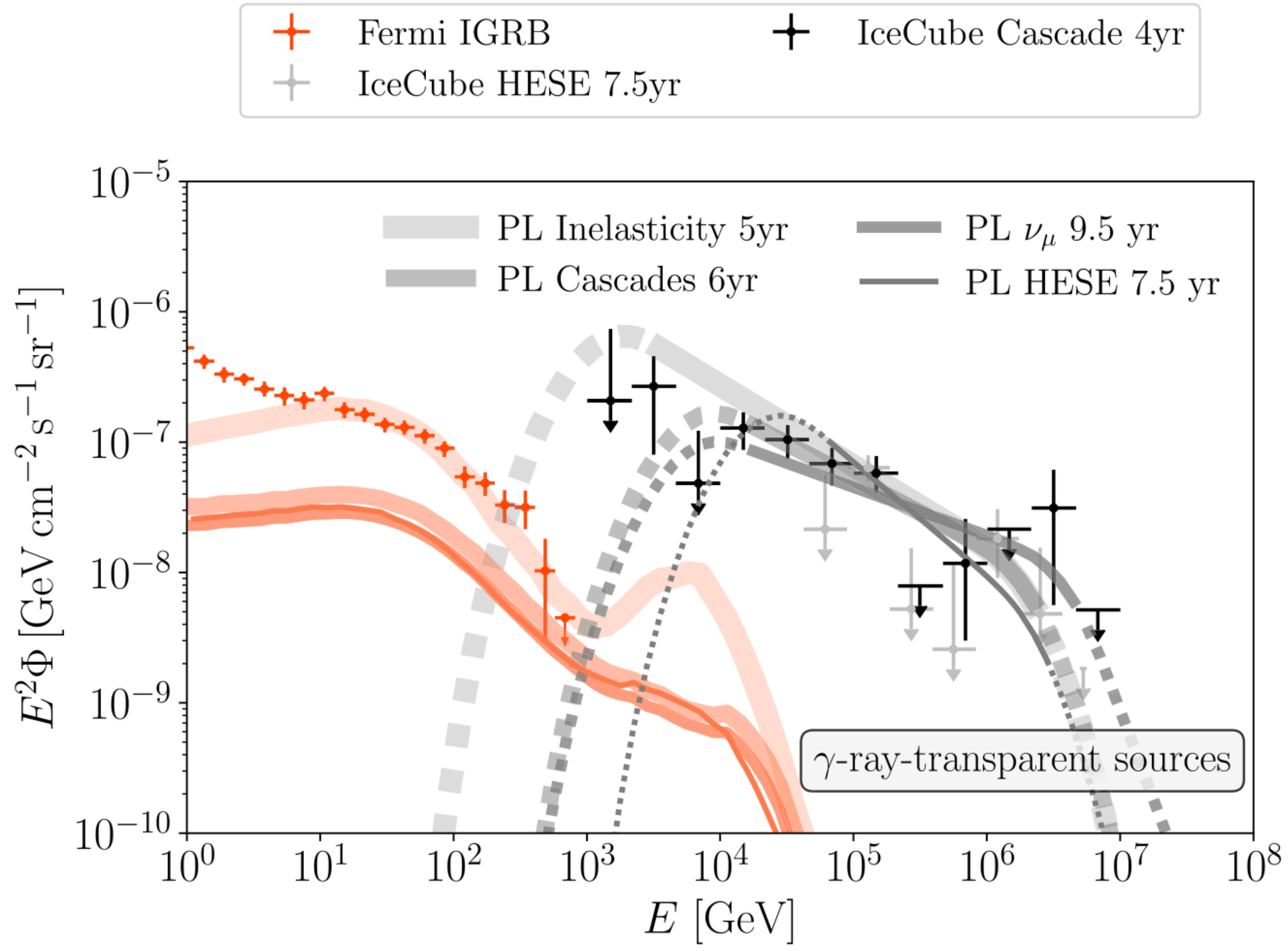
- **Enhanced data & selection**
  - New event selection in the Southern sky (ESTES)
  - Multi-flavor combined sample
- **Various source classes**:
  - XRBs (7.5 years of tracks)
  - PWNe (9.5 years of point-source data)
  - LHAASO UHE sources (11 yr tracks)
  - Extended gamma-ray sources (10 yr tracks)
- **Joint search in gamma-ray data**
  - IceCube & HAWC

KF & Halzen, 2404.15944

- The sky viewed with 100 TeV photons γ
- **Gamma-ray-obscured sources** ν γ

Extragalactic neutrino sources are likely gamma-ray-opaque!

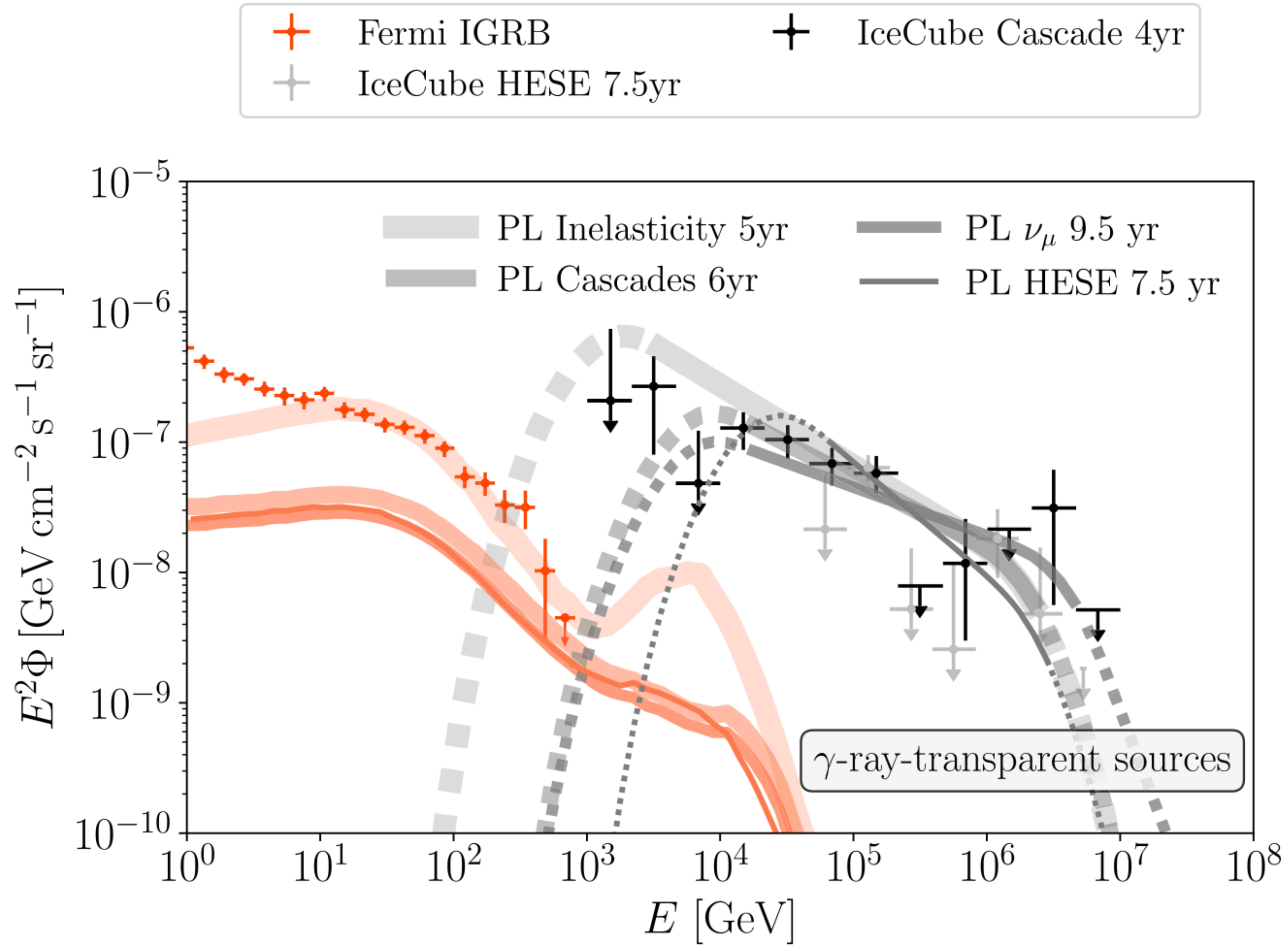
Diffuse Emission



Murase, Guetta, Ahlers PRL (2016)
Capanema et al PRD (2020), JCAP (2021)
KF, Gallagher, Halzen, ApJ (2022)

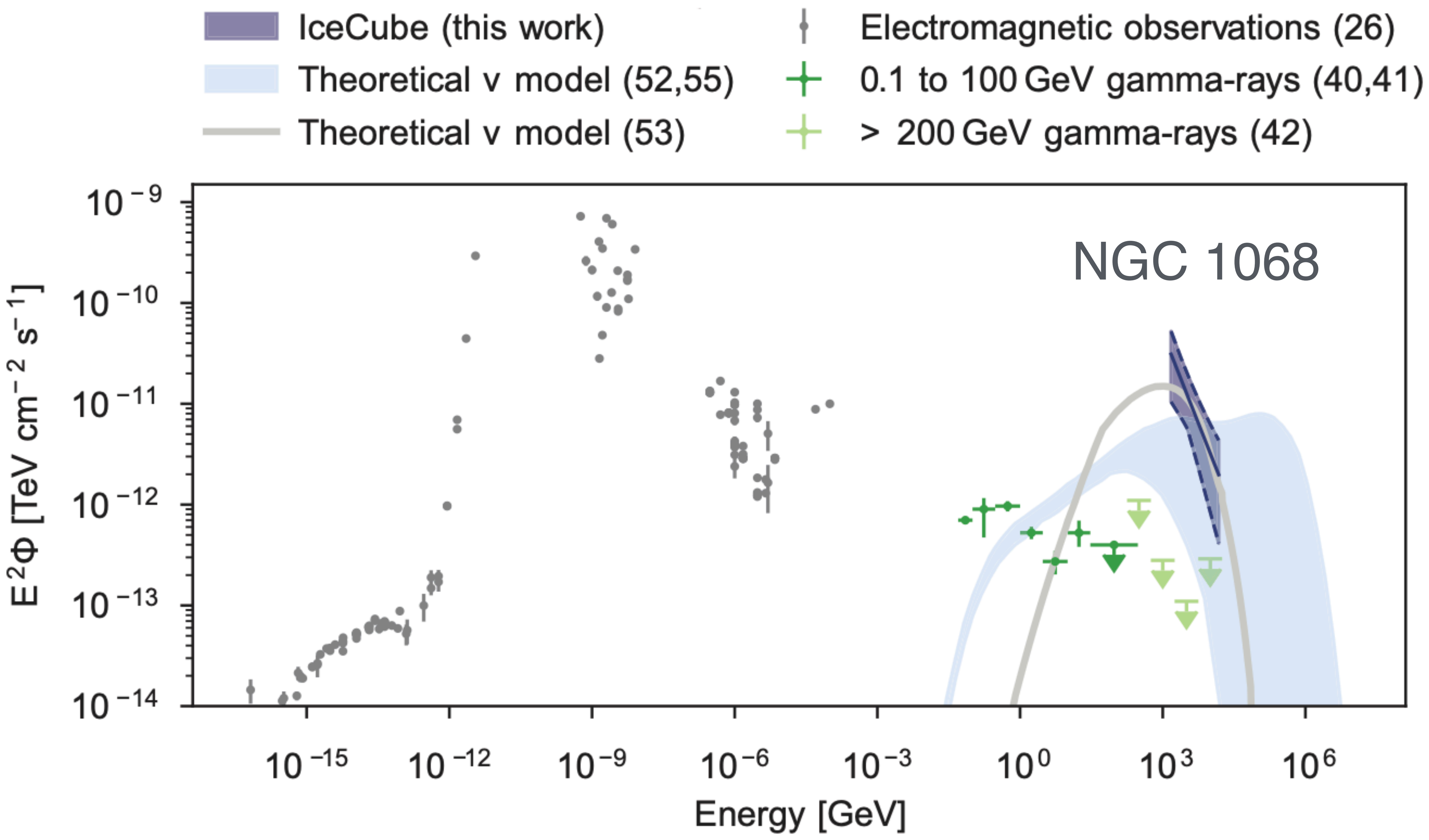
Extragalactic neutrino sources are likely gamma-ray-opaque!

Diffuse Emission



Murase, Guetta, Ahlers PRL (2016)
Capanema et al PRD (2020), JCAP (2021)
KF, Gallagher, Halzen, ApJ (2022)

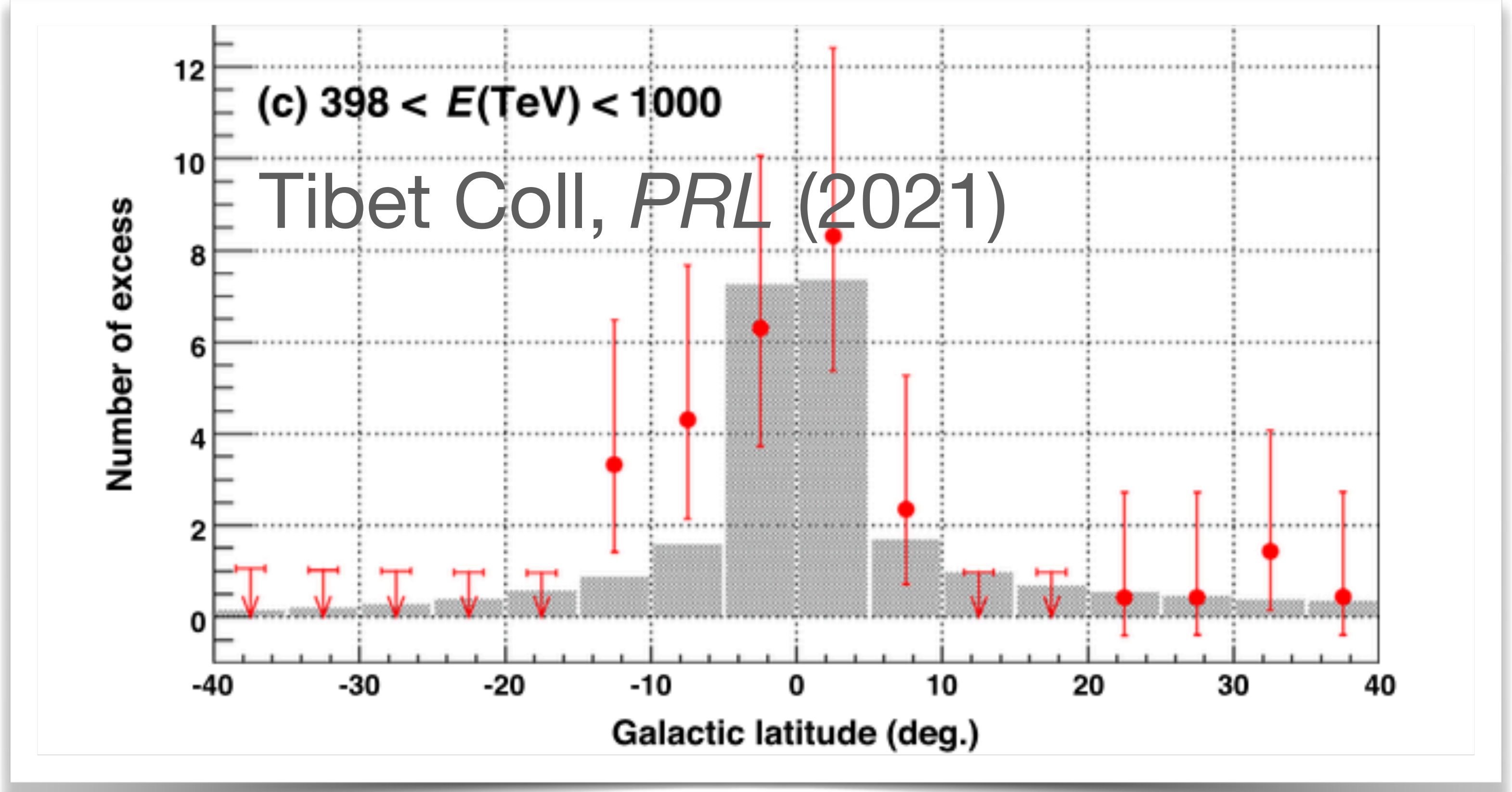
Individual Source

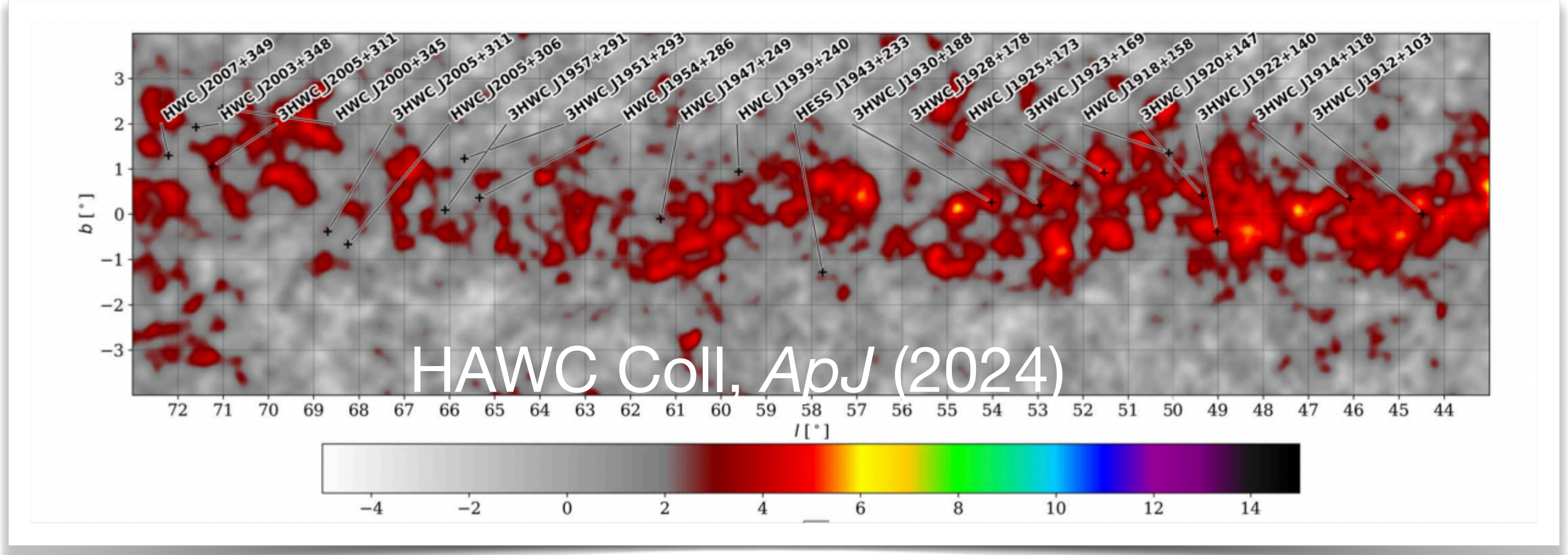


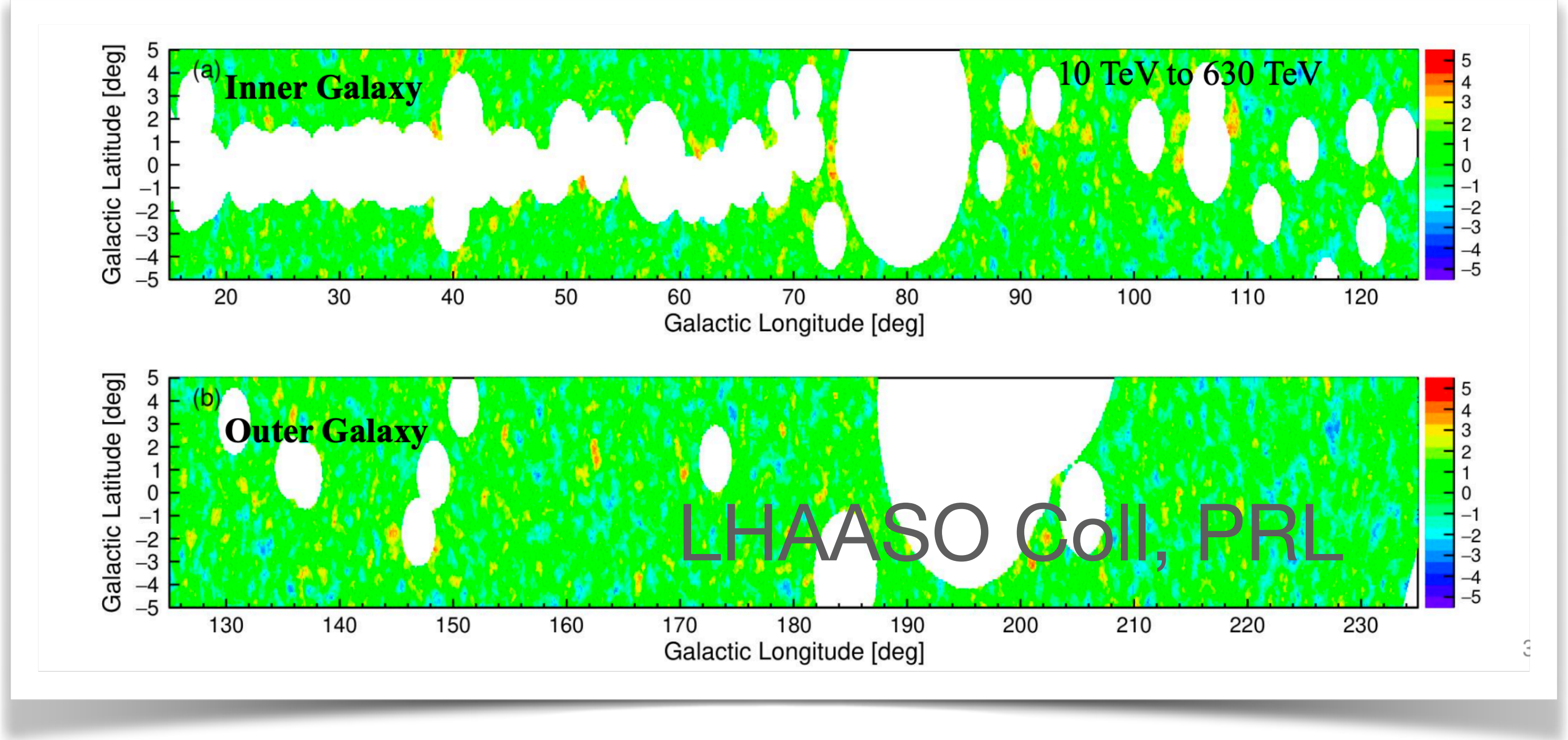
IceCube Collaboration, Science (2022)

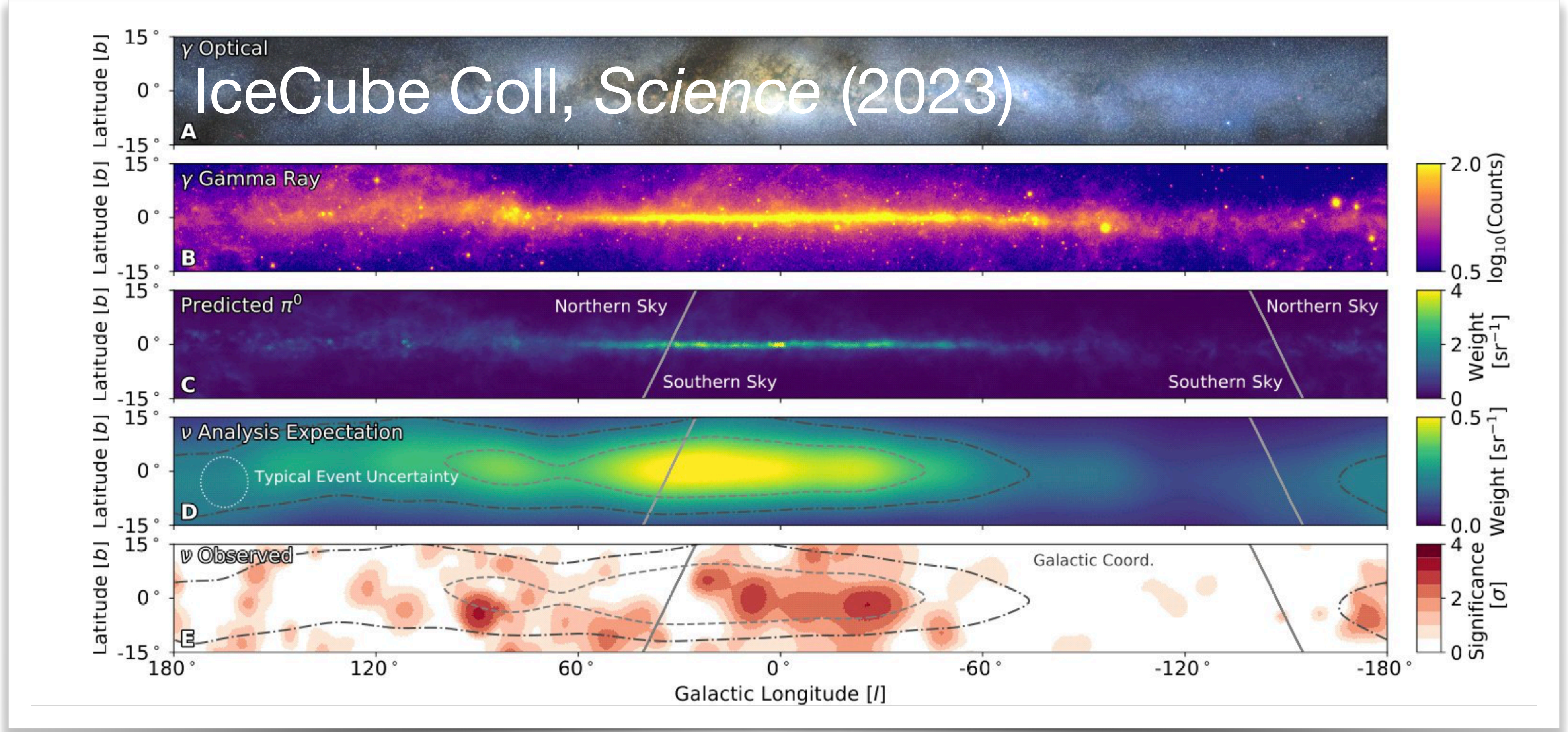
IceCube Collaboration, 2406.06684, 2406.07601

TeV to PeV multi-messenger emission by the Galactic Plane

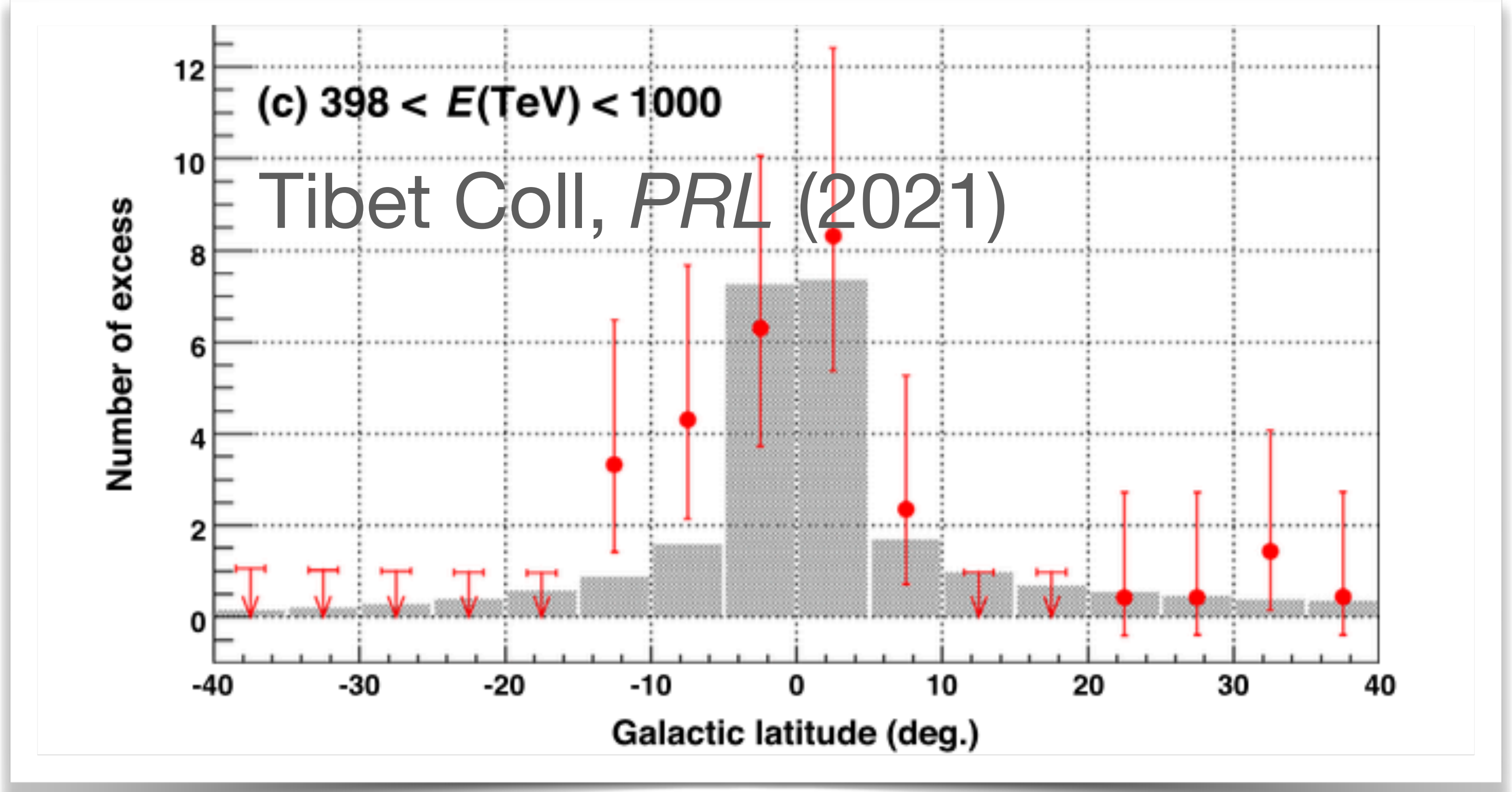


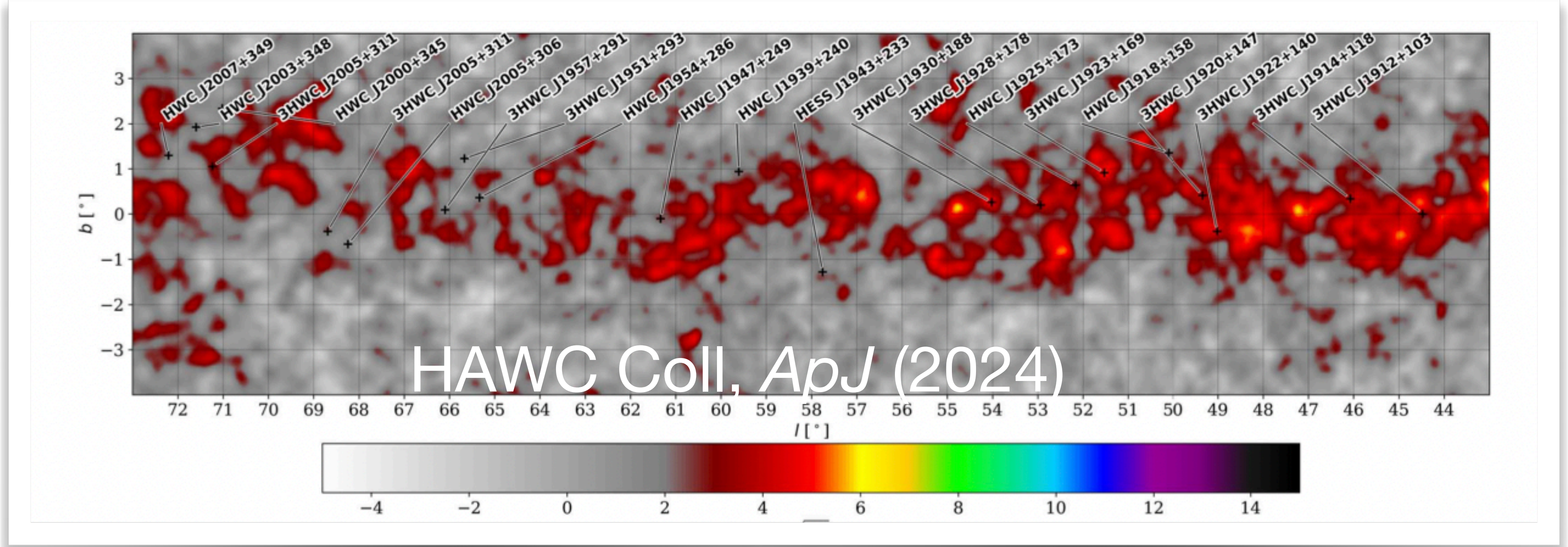


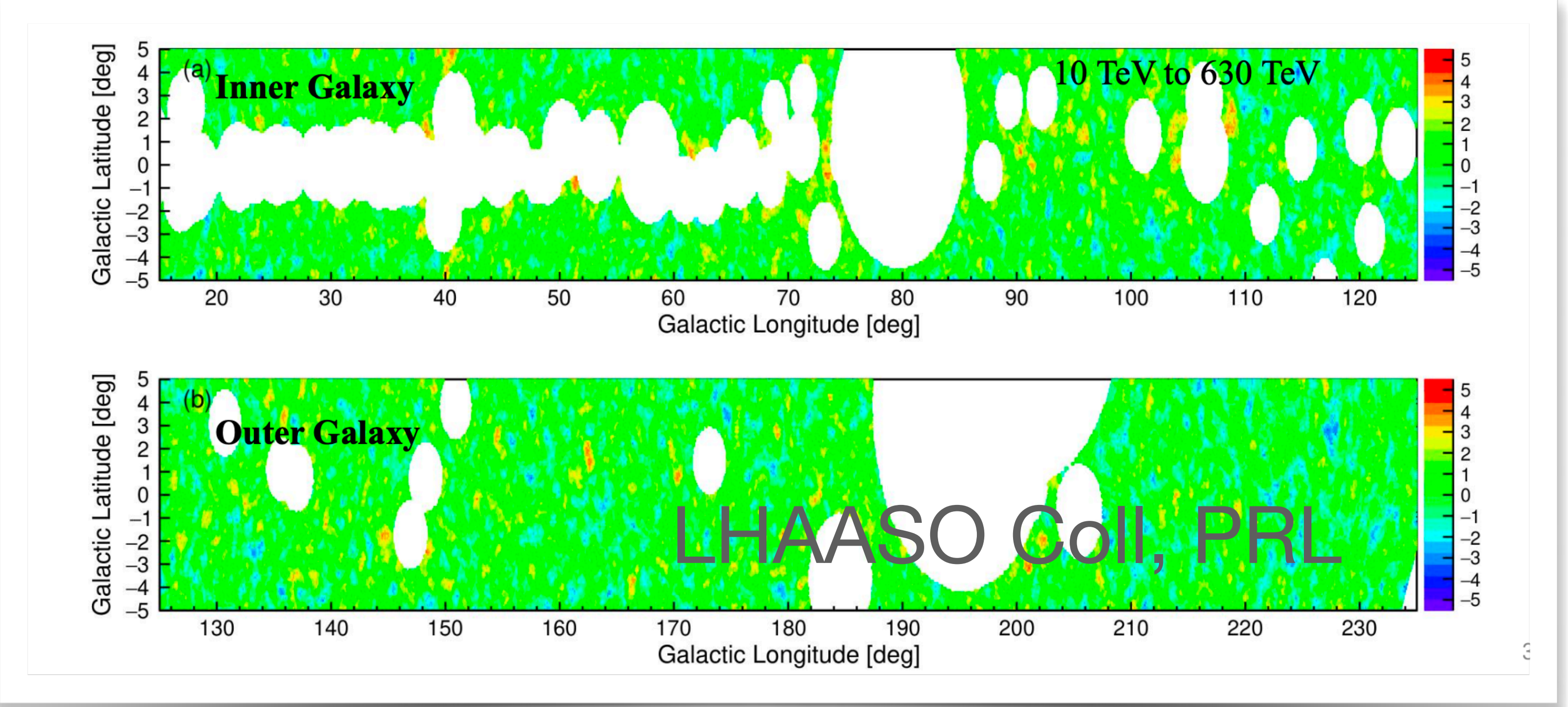


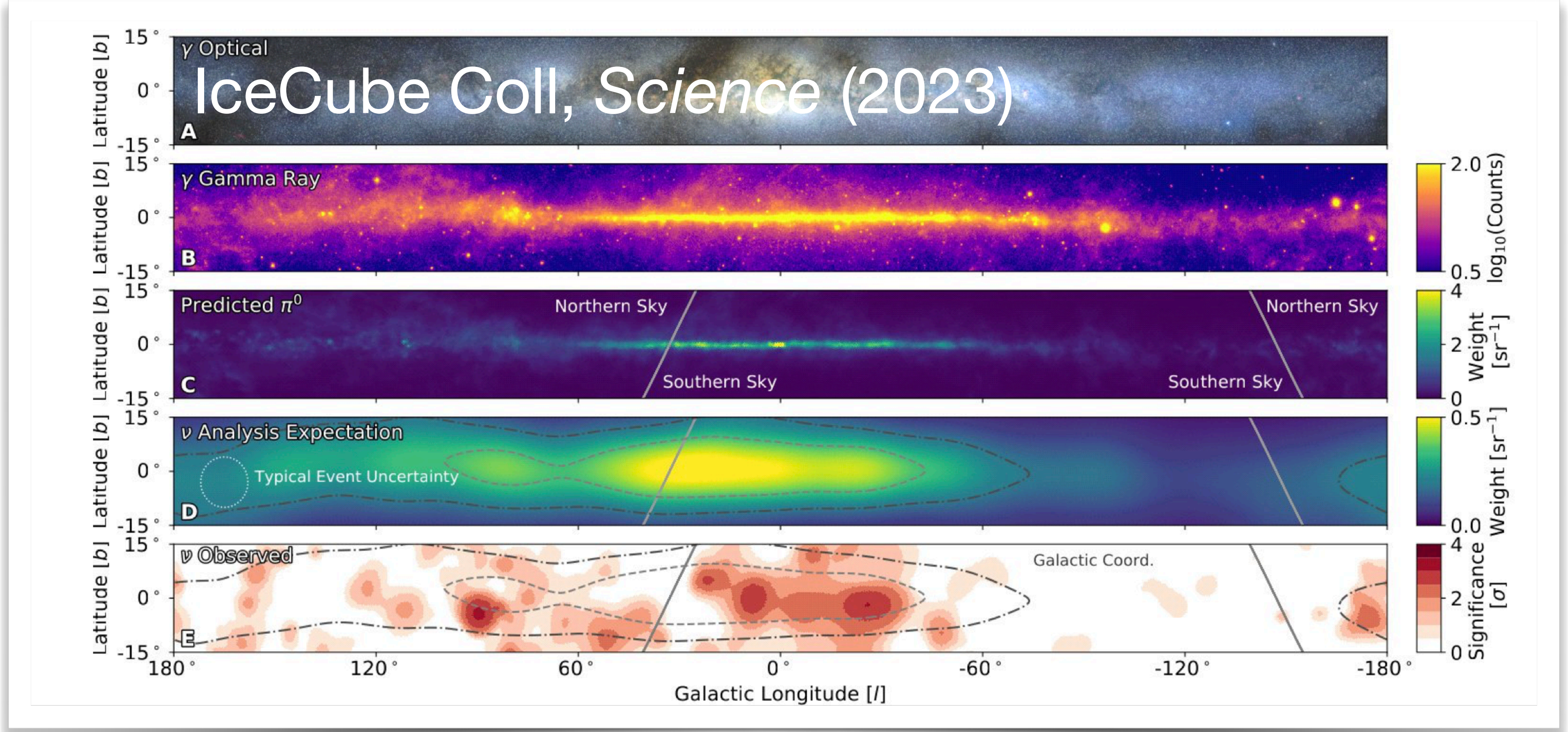


TeV to PeV multi-messenger emission by the Galactic Plane







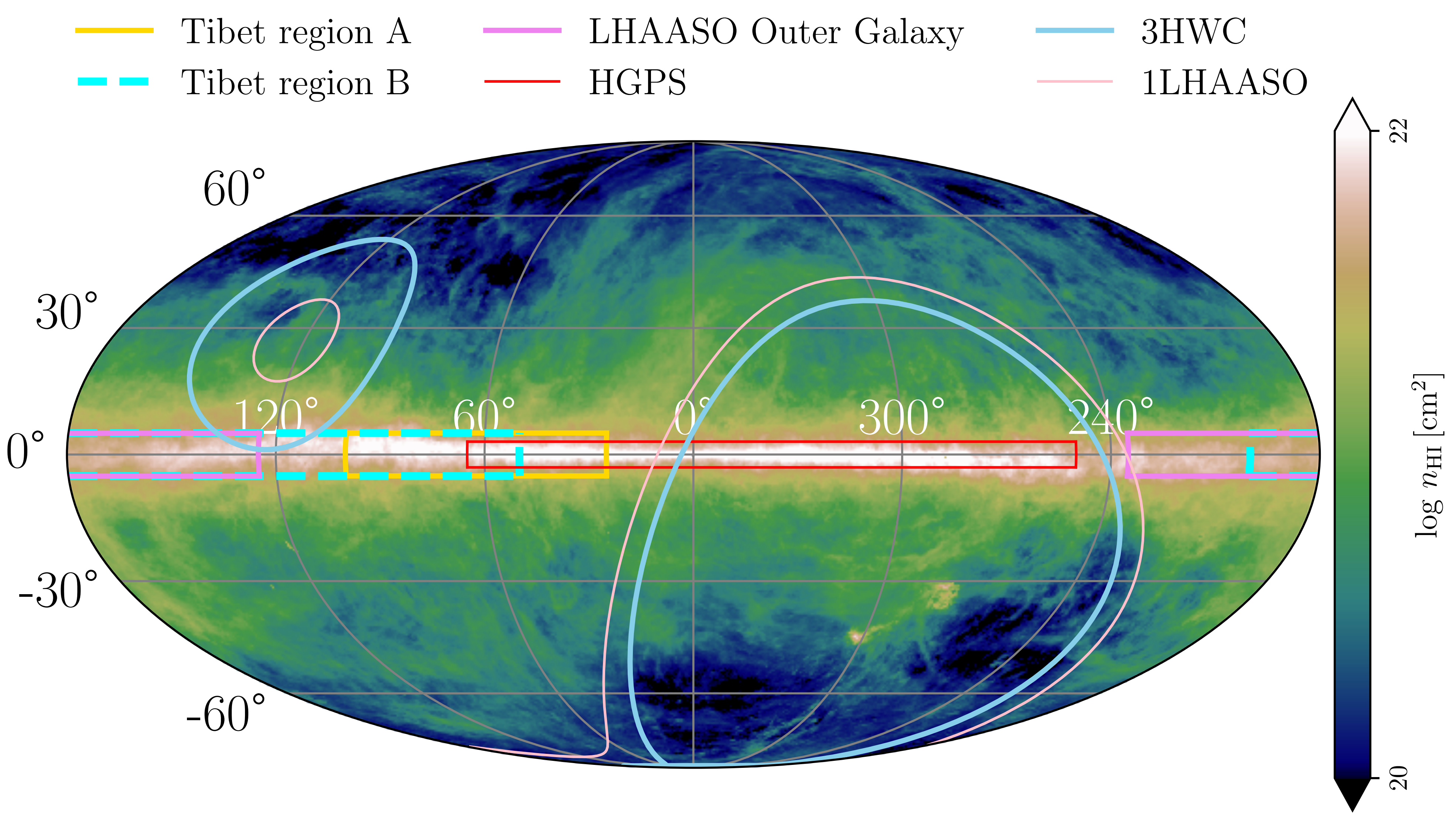


What does the neutrino Galactic plane flux imply for Galactic PeVatrons?

Comparing ν and γ observations

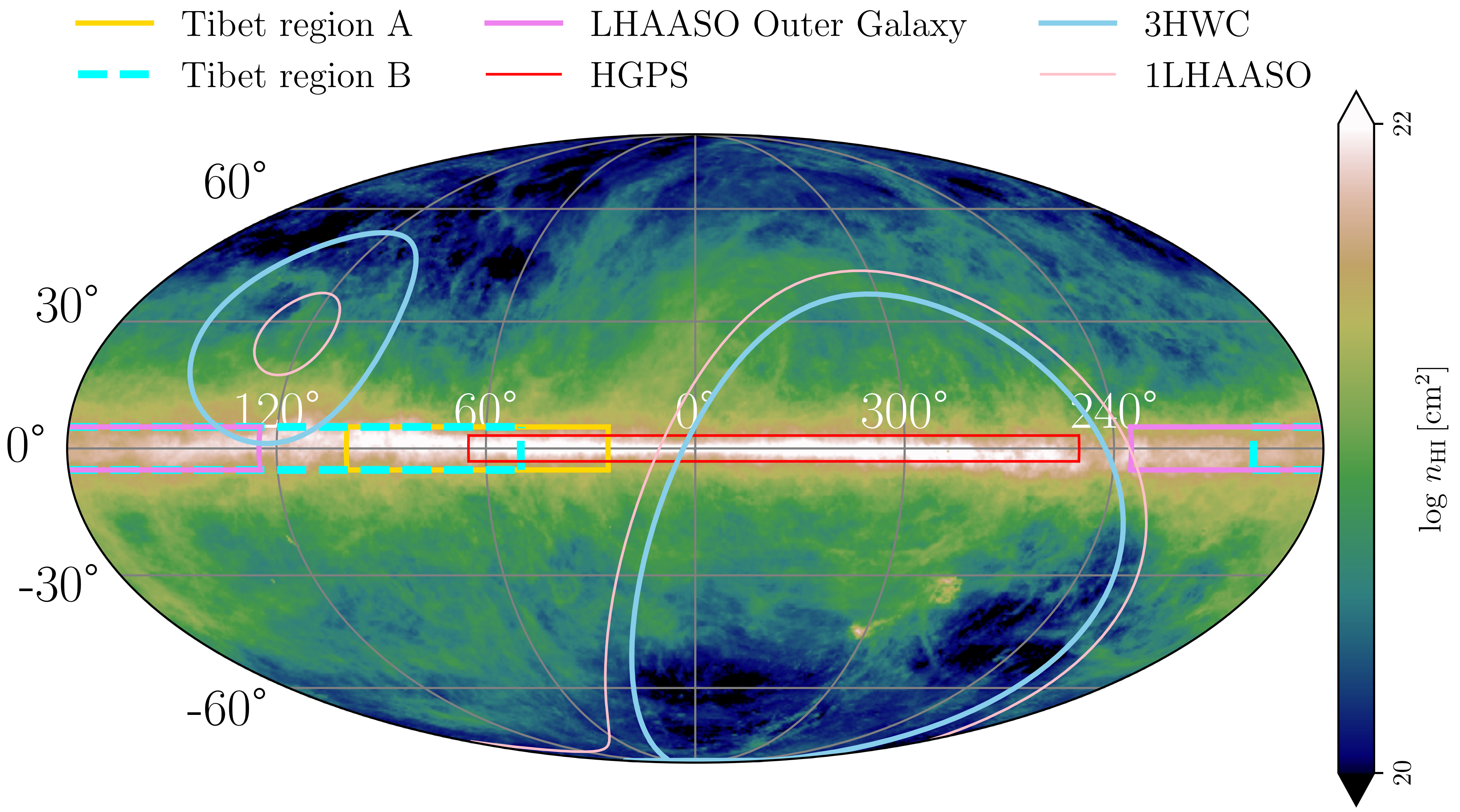
KF & Murase *ApJ (2021)*

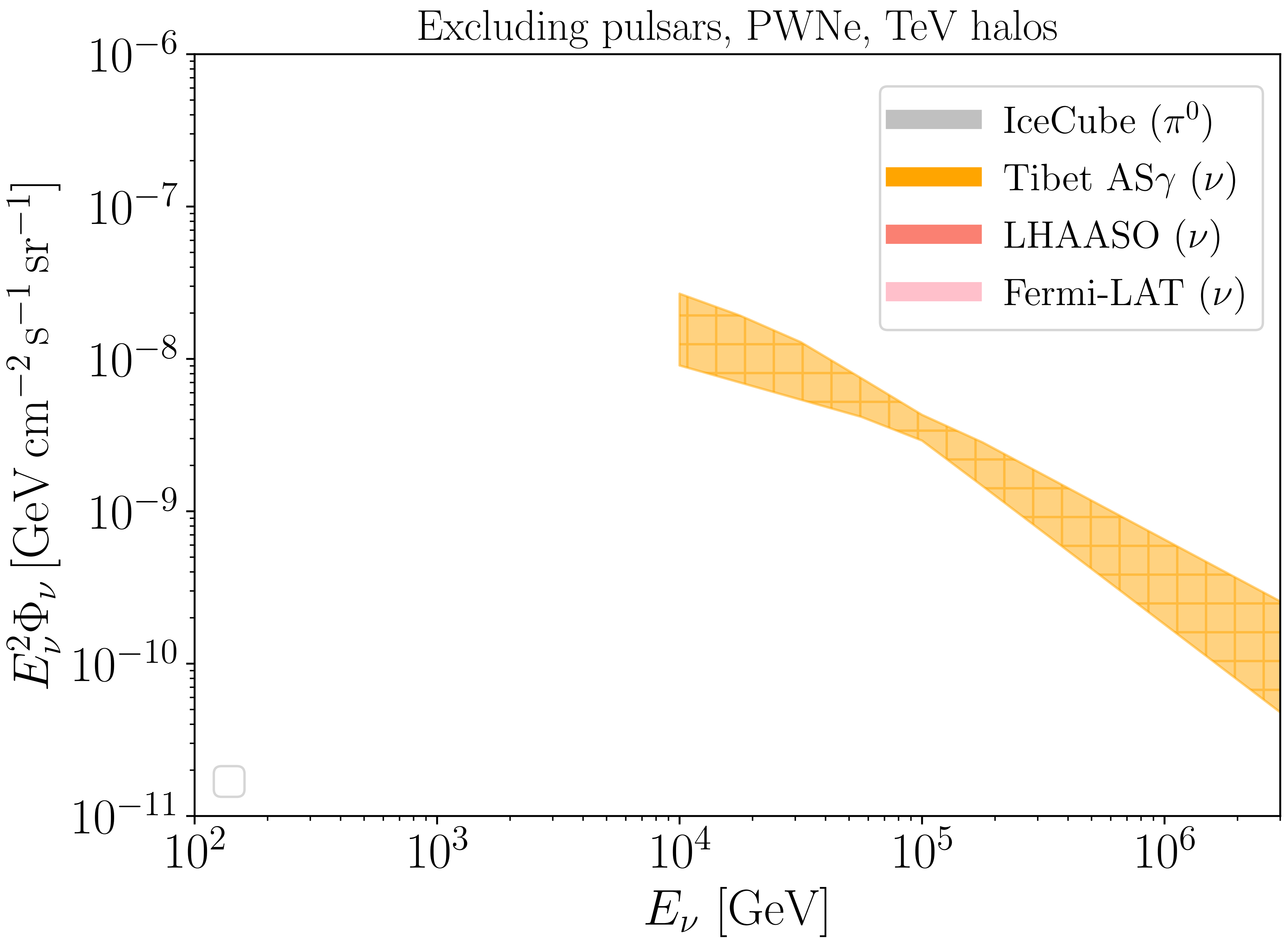
Comparing ν and γ observations



KF & Murase *ApJ (2021)*

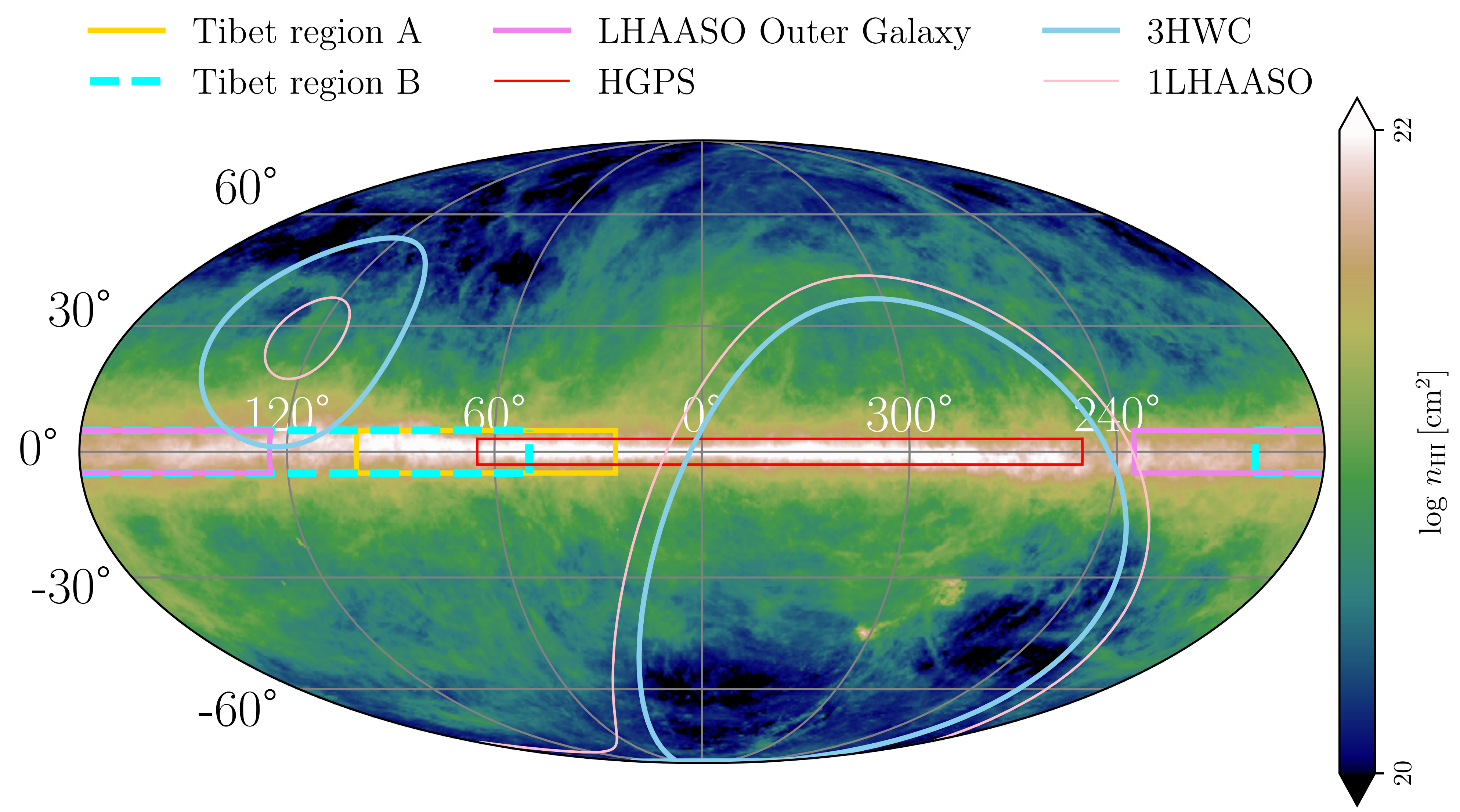
Comparing ν and γ observations

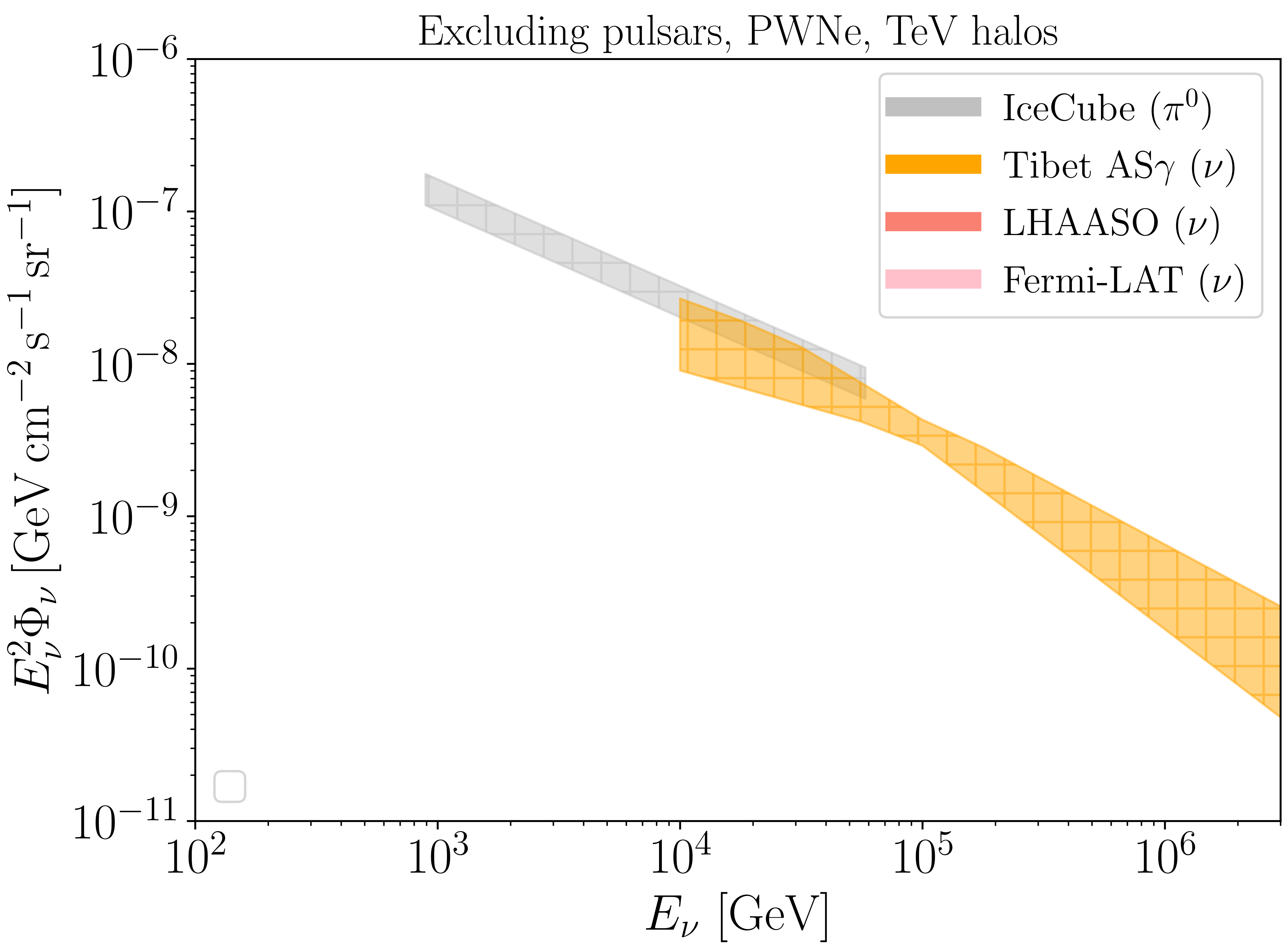




KF & Murase *ApJ (2021)*

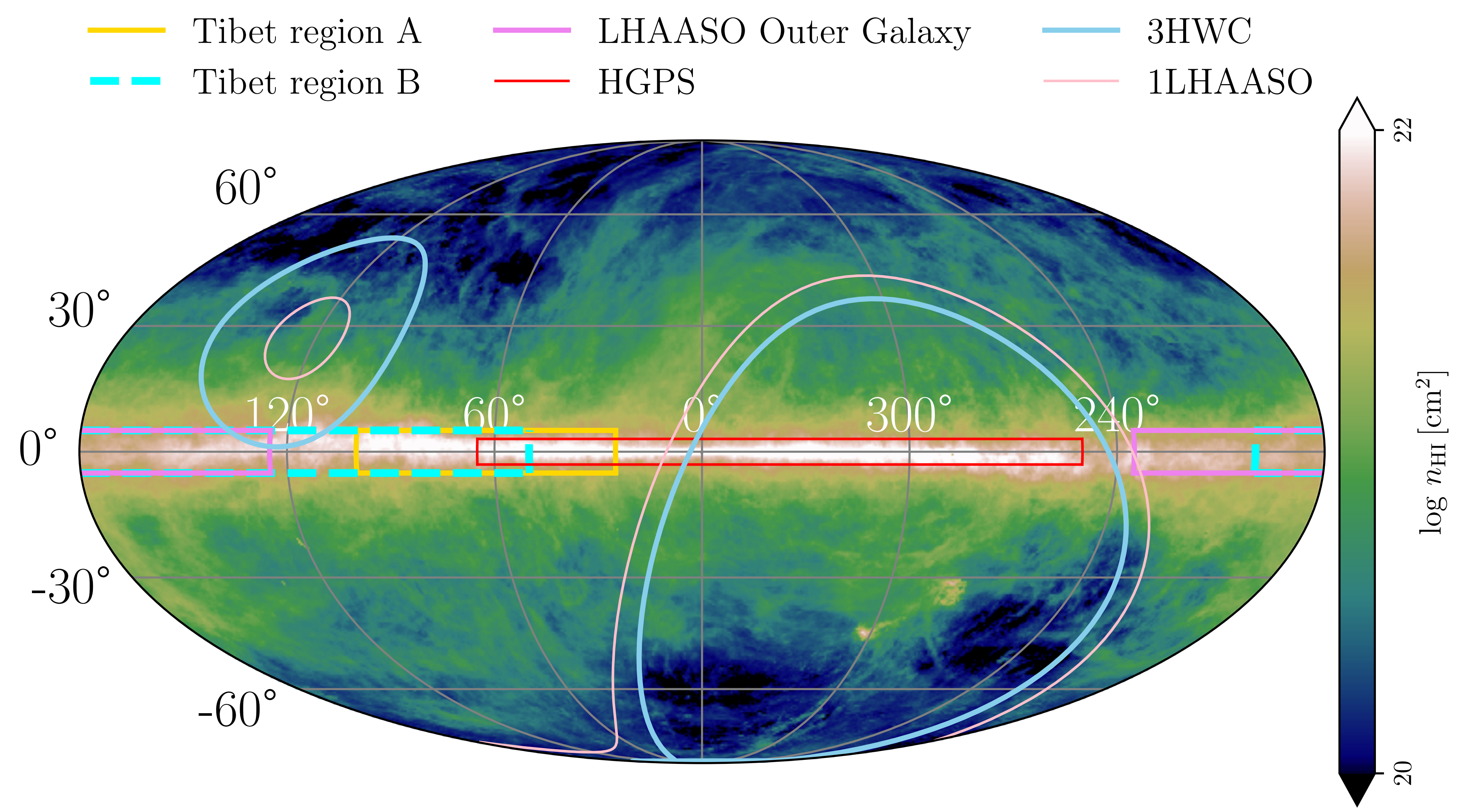
Comparing ν and γ observations

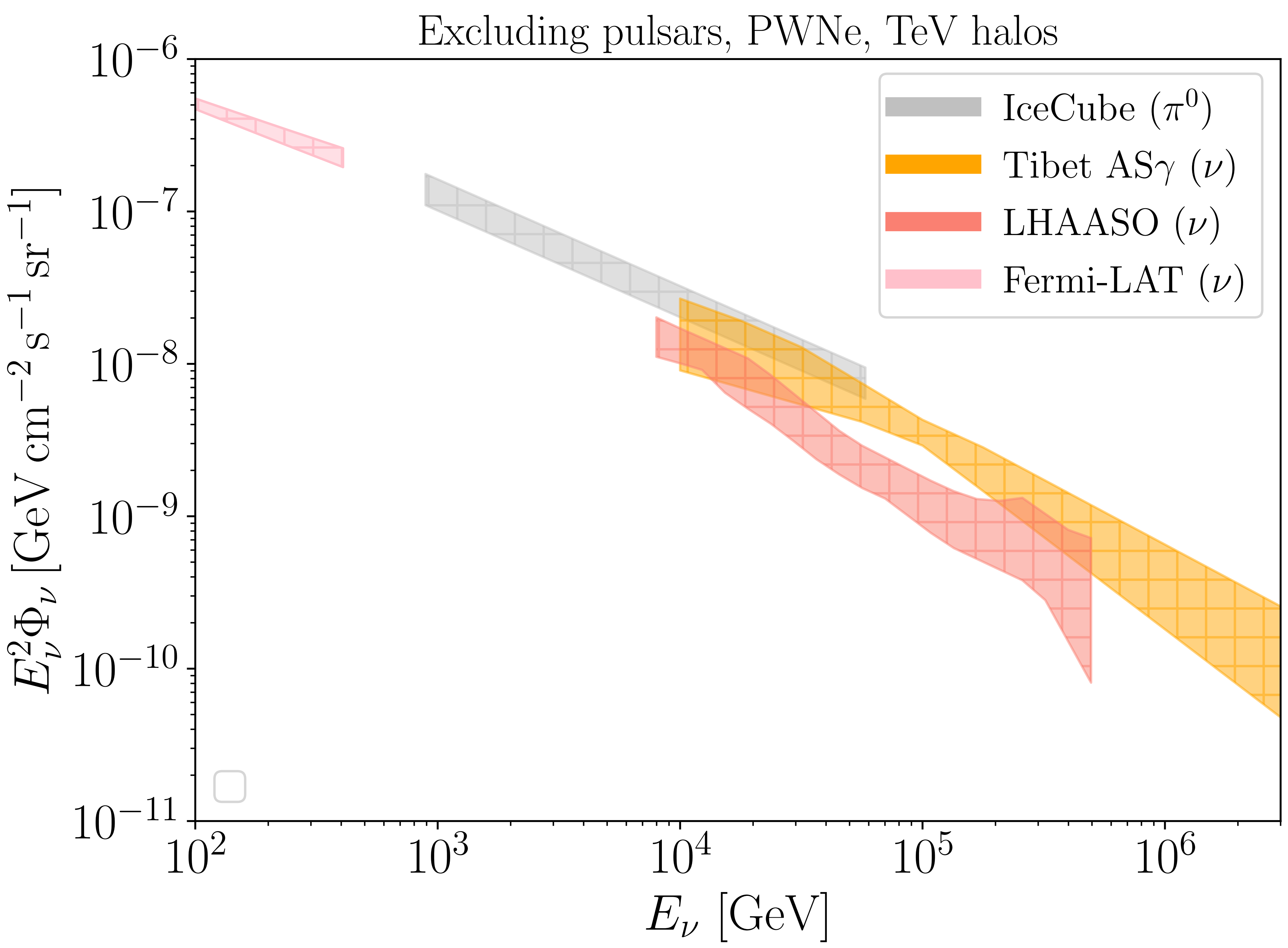




KF & Murase *ApJ (2021)*

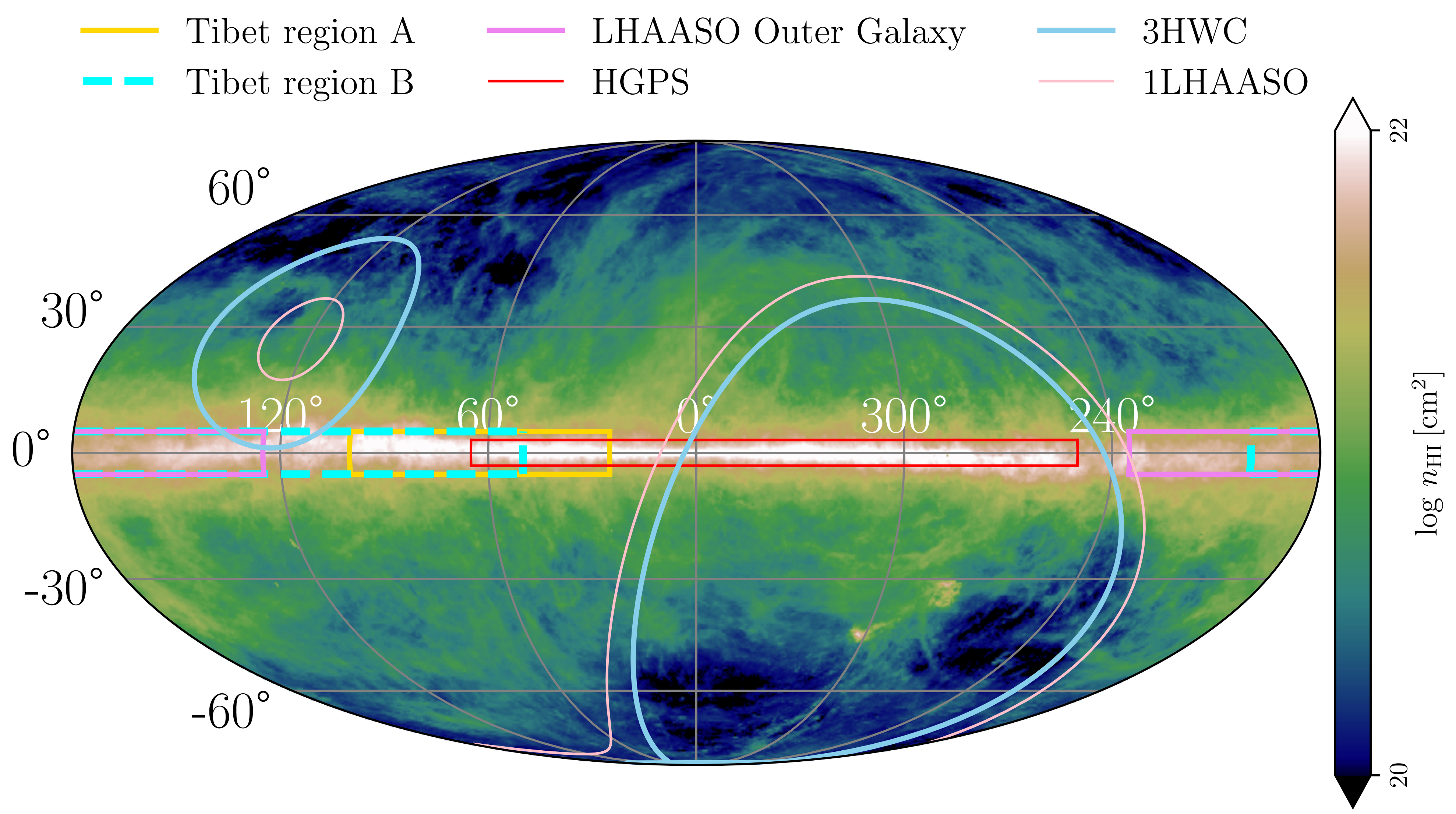
Comparing ν and γ observations

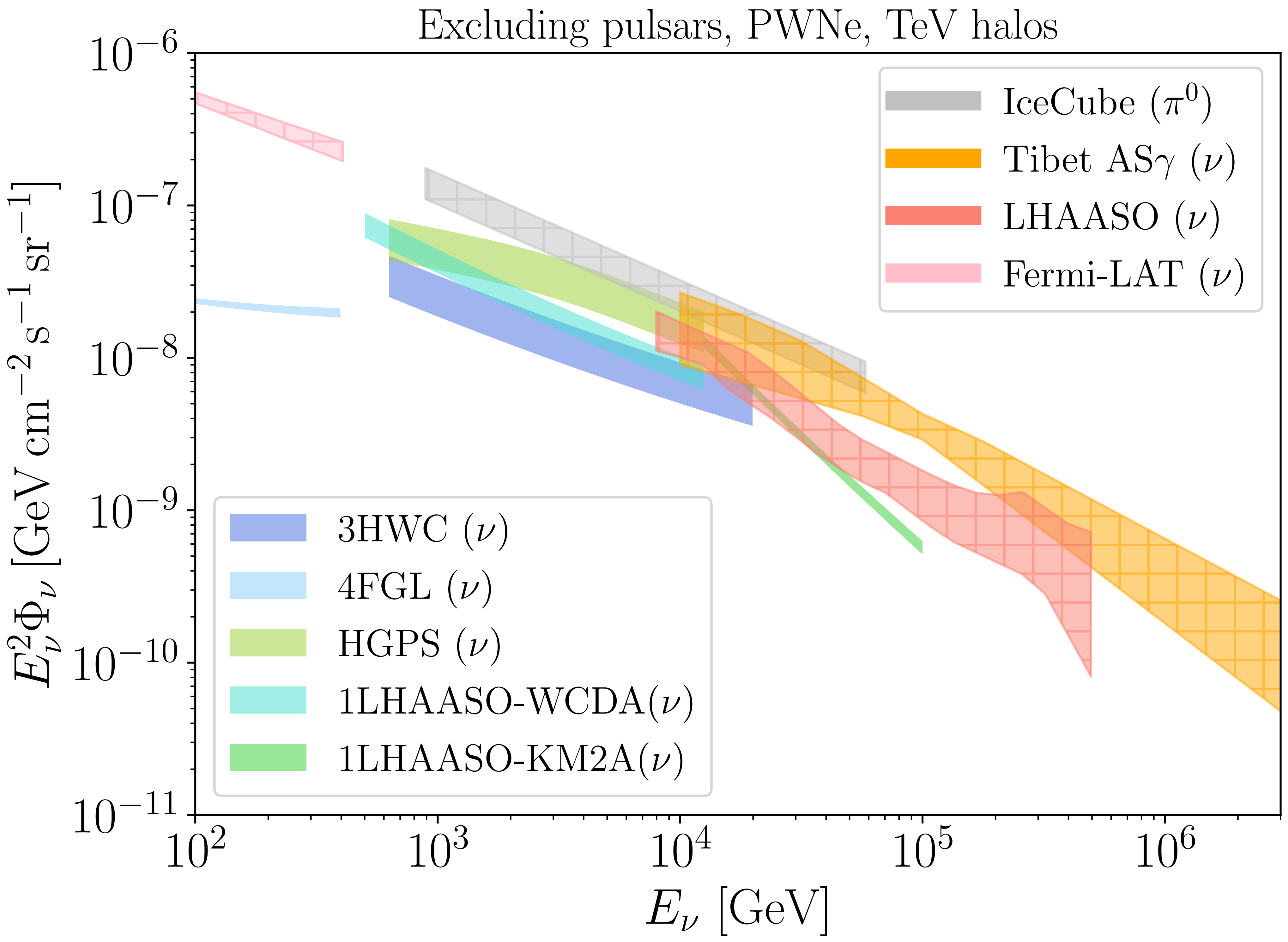




KF & Murase *ApJ (2021)*

Comparing ν and γ observations

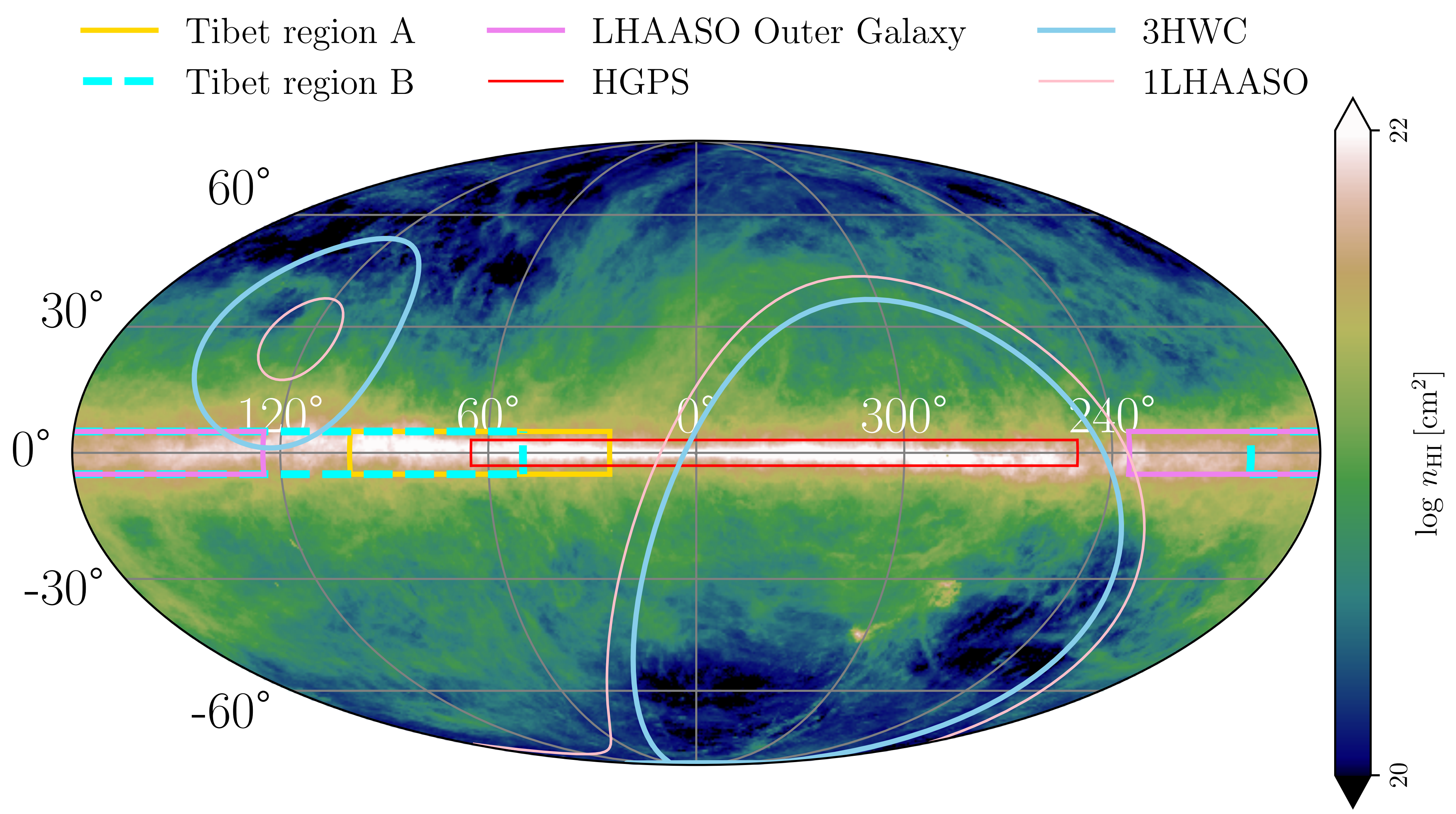


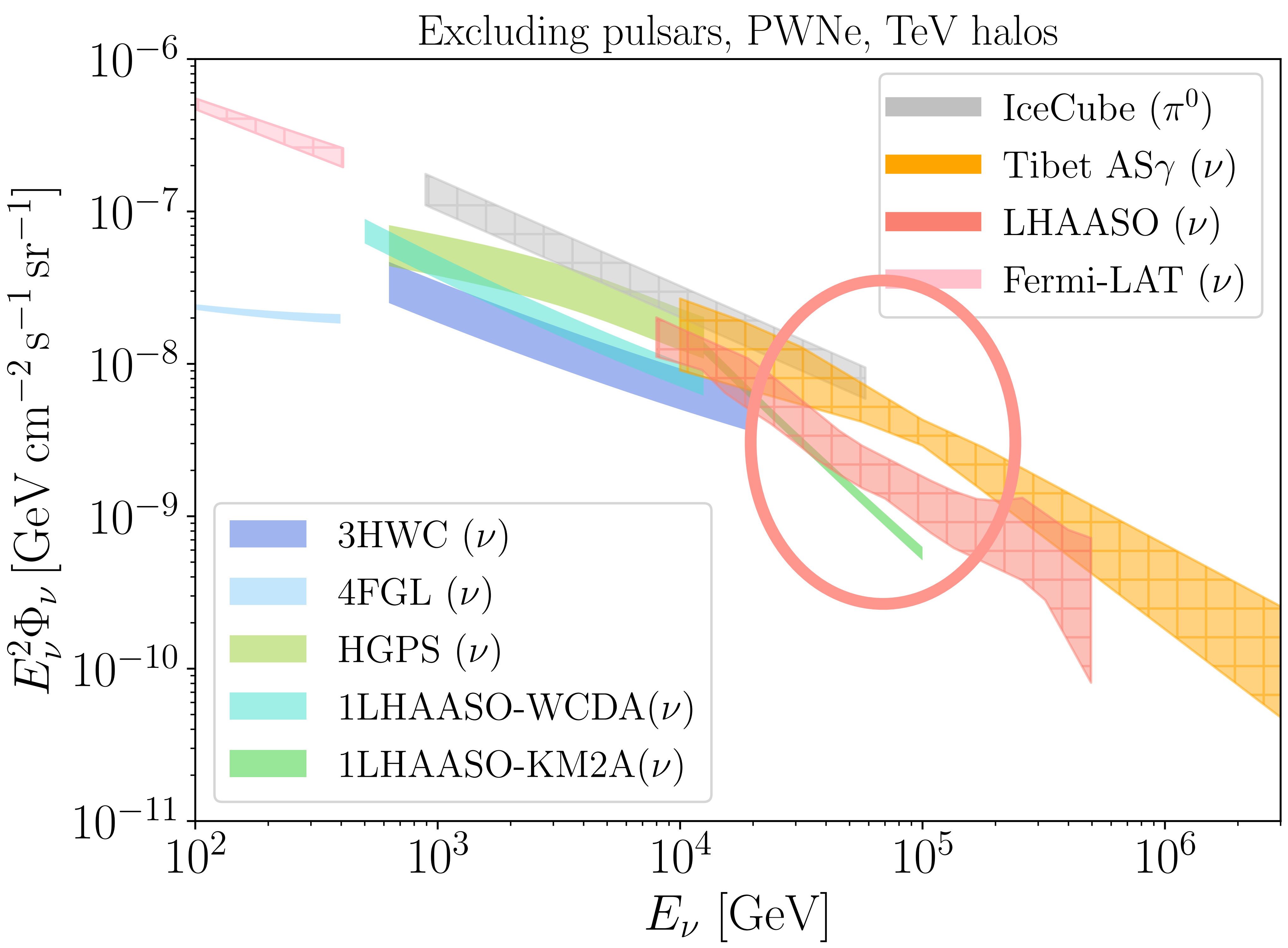


KF & Murase *ApJ (2021)*

KF & Murase ApJL *(2023)*

Comparing ν and γ observations





Above ~30 TeV, gamma-ray emission is **dominated by hadronic process** and/or there exists
a population of gamma-ray-obscured neutrino emitters

KF & Murase *ApJ (2021)*
KF & Murase ApJL *(2023)*

Coronal Neutrino Emission: Dependence on the Compactness

$$\ell = \frac{L_X}{R} \frac{\sigma_T}{m_e c^3}$$

Coronal Neutrino Emission: Dependence on the Compactness

$$\ell = \frac{L_X}{R}\frac{\sigma_T}{m_e c^3}$$

KF &, Halzen, Heinz, Gallagher *2410.02119*

Coronal Neutrino Emission: Dependence on the Compactness

$$\ell = \frac{L_X}{R}\frac{\sigma_T}{m_e c^3}$$

Acceleration

$$\sigma_{\pm} = \frac{B^2}{4\pi n_e m_e c^2} = \frac{\xi_B}{2\pi\,\tau_T}\ell$$

$$u_B = \xi_B\, u_X$$

$$n_e \approx \tau_T/\sigma_T R$$

KF &, Halzen, Heinz, Gallagher *2410.02119*

Coronal Neutrino Emission: Dependence on the Compactness

$$\ell = \frac{L_X}{R}\frac{\sigma_T}{m_e c^3}$$

Acceleration

$$\sigma_\pm = \frac{B^2}{4\pi n_e m_e c^2} = \frac{\xi_B}{2\pi\,\tau_T}\ell$$

$$u_B = \xi_B u_X$$

$$n_e \approx \tau_T/\sigma_T R$$

Interaction

$$\tau_{p\gamma} \propto \frac{m_e c^2}{\epsilon_X}\frac{\sigma_{p\gamma}}{\sigma_T}\ell$$

$$\tau_{pp} \propto \frac{n_p}{n_e}\frac{\sigma_{pp}}{\sigma_T}\tau_T$$

KF &, Halzen, Heinz, Gallagher *2410.02119*

Coronal Neutrino Emission: Dependence on the Compactness

$$\ell = \frac{L_X}{R}\frac{\sigma_T}{m_e c^3}$$

Acceleration

$$\sigma_\pm = \frac{B^2}{4\pi n_e m_e c^2} = \frac{\xi_B}{2\pi\,\tau_T}\ell$$

$$u_B = \xi_B\, u_X$$

$$n_e \approx \tau_T/\sigma_T R$$

Interaction

$$\tau_{p\gamma} \propto \frac{m_e c^2}{\epsilon_X}\frac{\sigma_{p\gamma}}{\sigma_T}\ell$$

$$\tau_{pp} \propto \frac{n_p}{n_e}\frac{\sigma_{pp}}{\sigma_T}\tau_T$$

- Particle acceleration and interaction timescales in the coronal region are tied to the compactness of the X-ray source

KF &, Halzen, Heinz, Gallagher *2410.02119*

Coronal Neutrino Emission: Dependence on the Compactness

$$\ell = \frac{L_X}{R}\frac{\sigma_T}{m_e c^3}$$

Acceleration

$$\sigma_{\pm} = \frac{B^2}{4\pi n_e m_e c^2} = \frac{\xi_B}{2\pi\,\tau_T}\ell$$

$$u_B = \xi_B\, u_X$$

$$n_e \approx \tau_T/\sigma_T R$$

Interaction

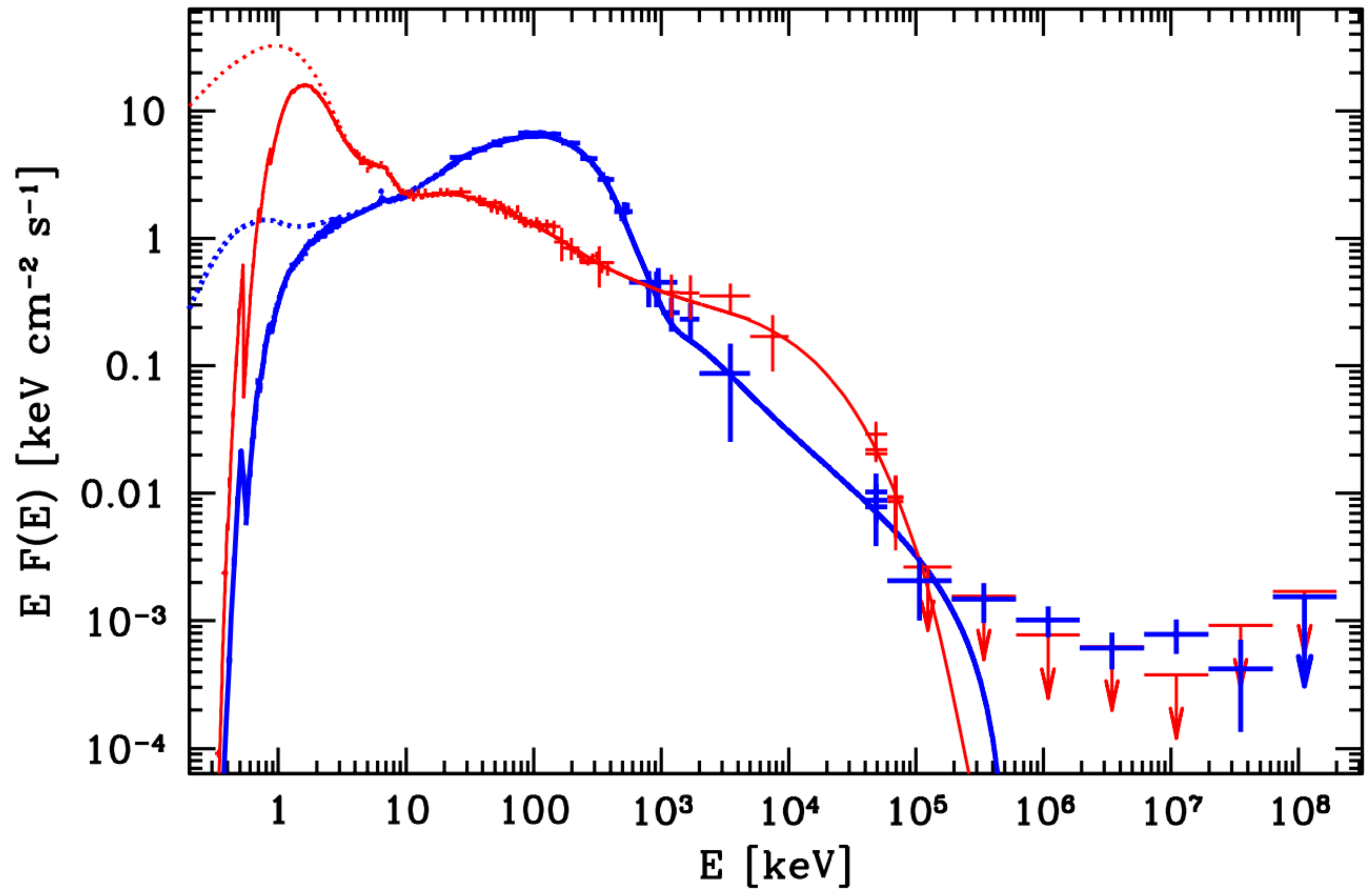
$$\tau_{p\gamma} \propto \frac{m_e c^2}{\epsilon_X}\frac{\sigma_{p\gamma}}{\sigma_T}\ell$$

$$\tau_{pp} \propto \frac{n_p}{n_e}\frac{\sigma_{pp}}{\sigma_T}\tau_T$$

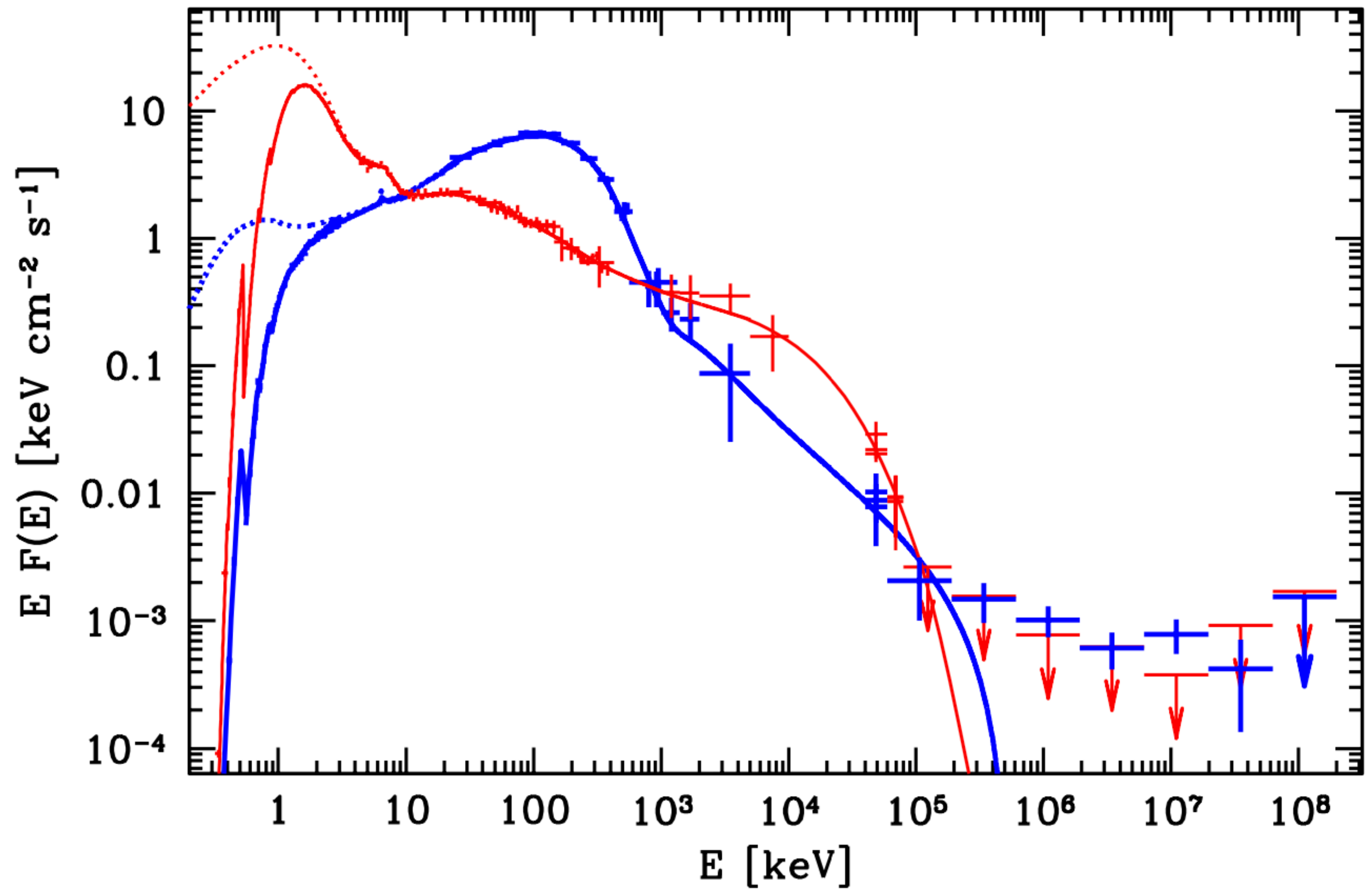
- Particle acceleration and interaction timescales in the coronal region are tied to the compactness of the X-ray source
- **Neutrino emission processes may similarly happen in the cores of active galactic nuclei and black hole XRBs**, despite of their drastically different masses and physical sizes.

KF &, Halzen, Heinz, Gallagher *2410.02119*

Galactic Black Hole Corona: Cygnus X-1 as an example

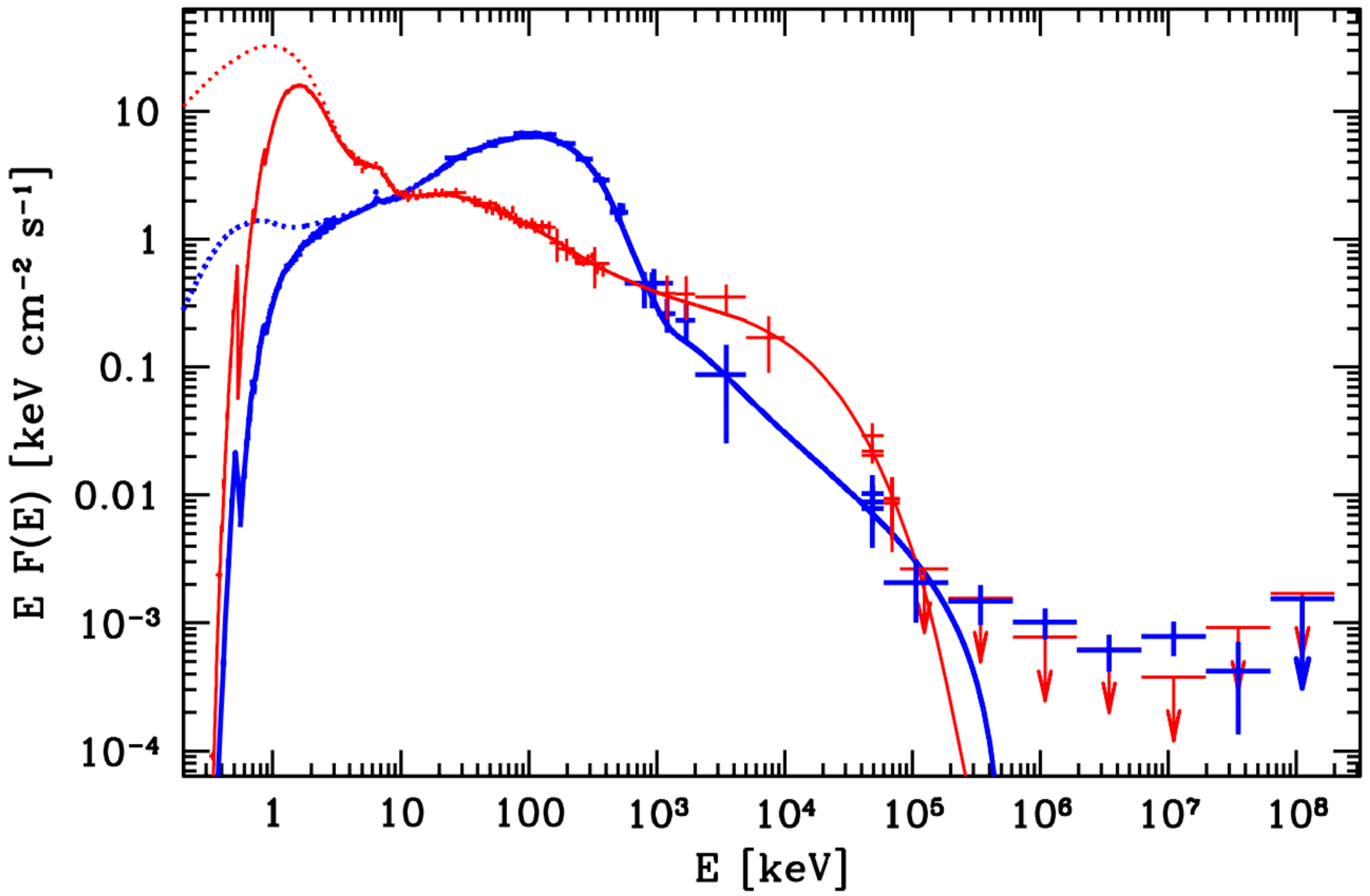


Galactic Black Hole Corona: Cygnus X-1 as an example



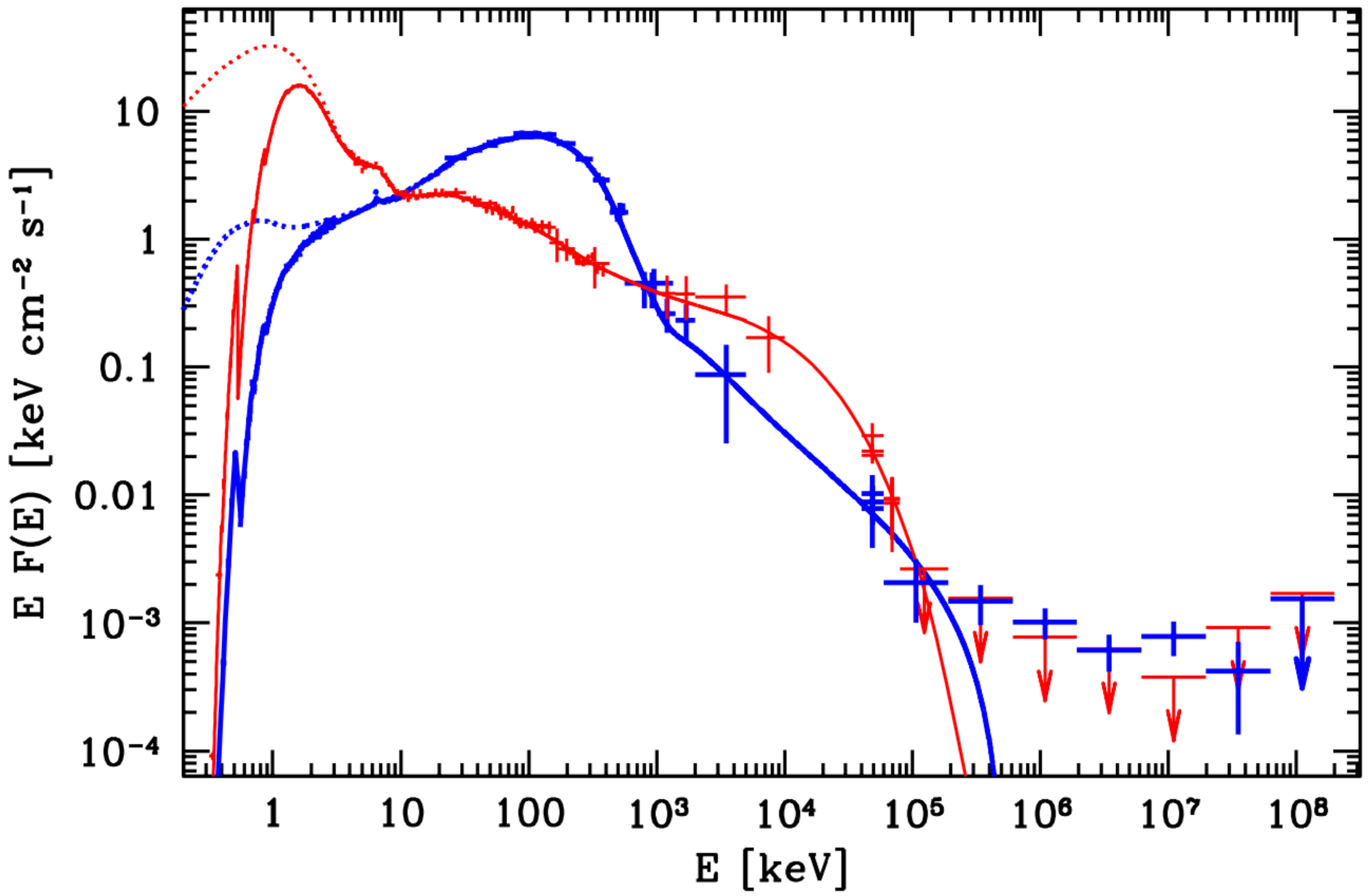
Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

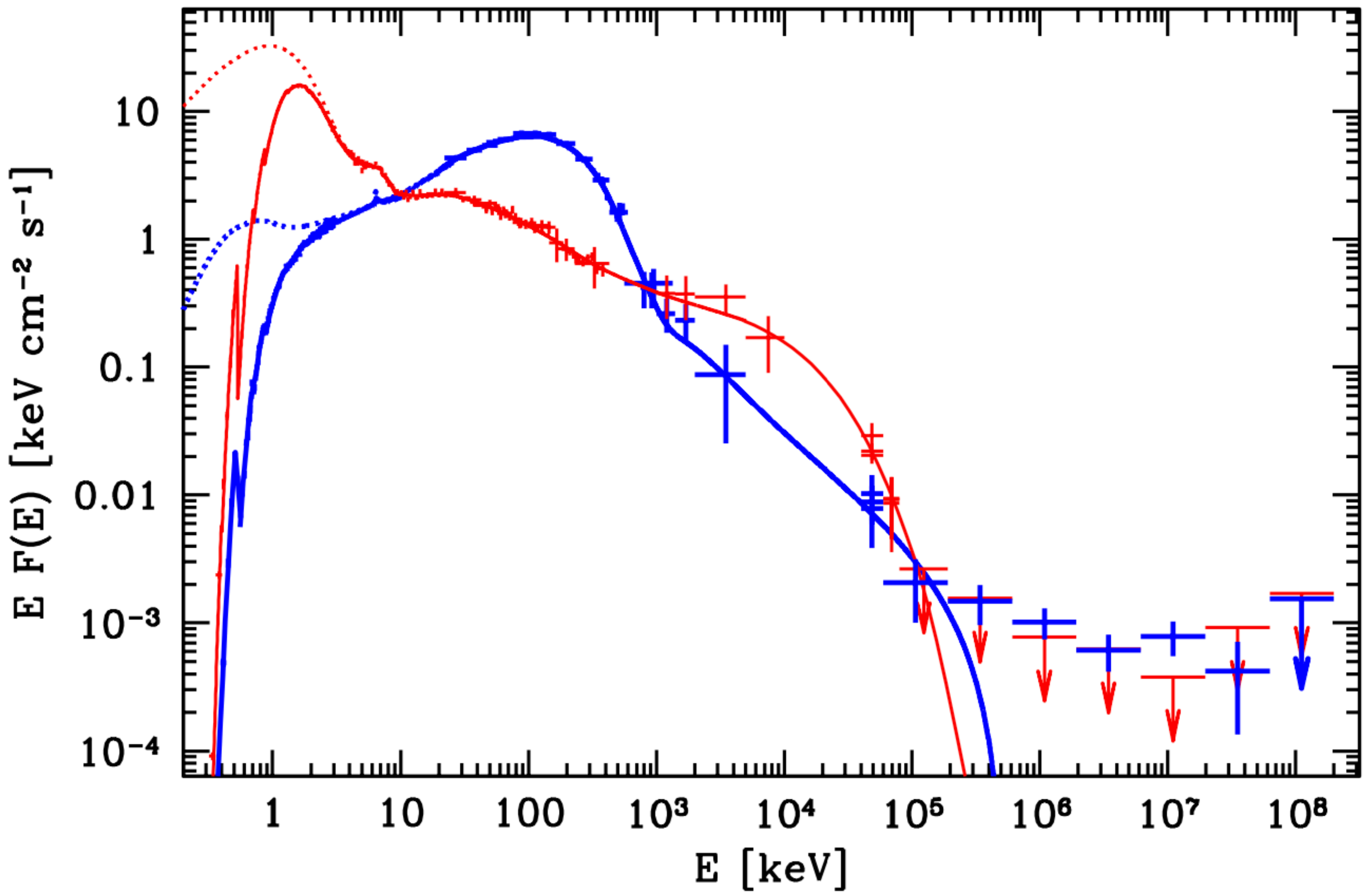
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states

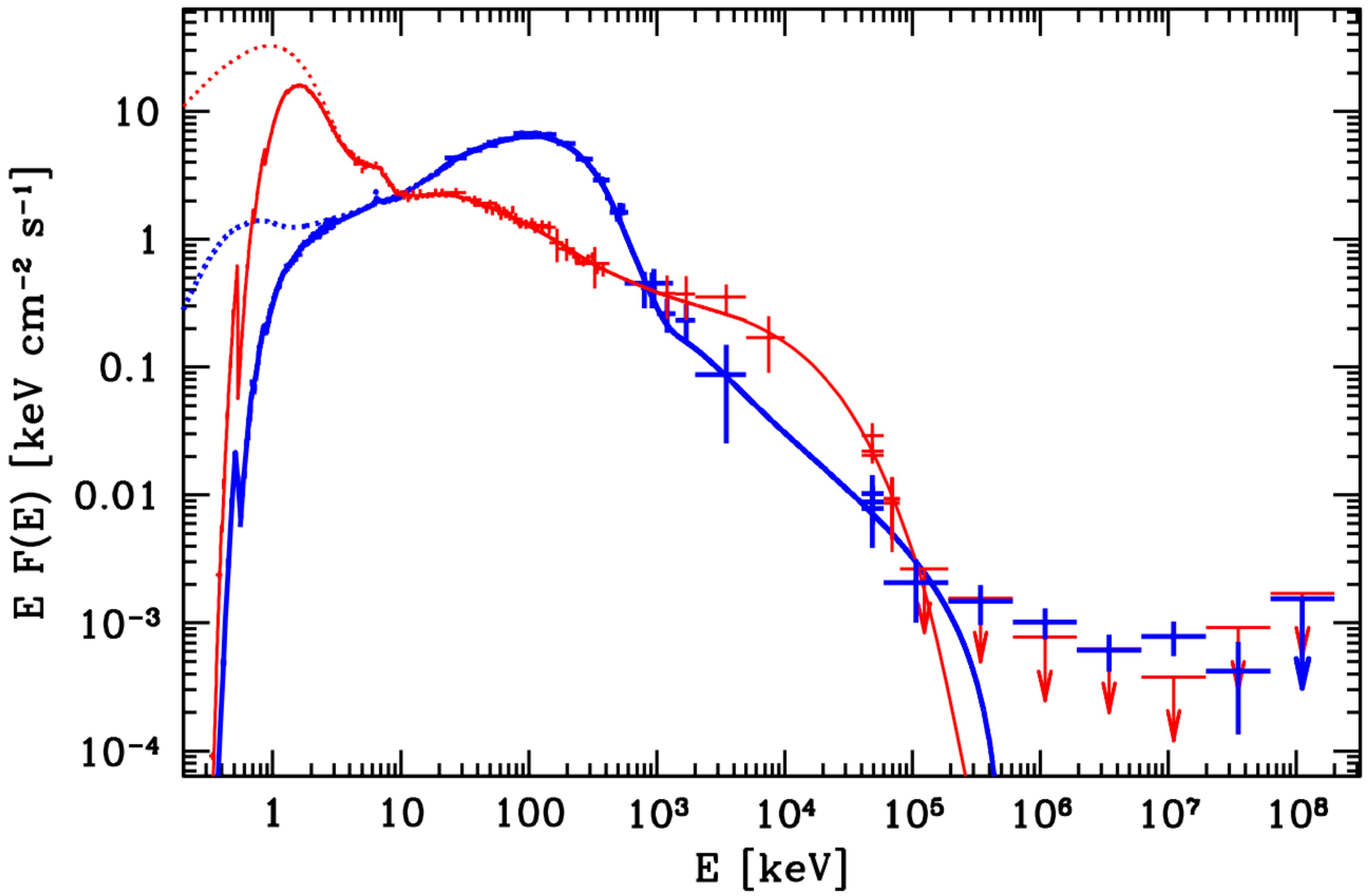
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states

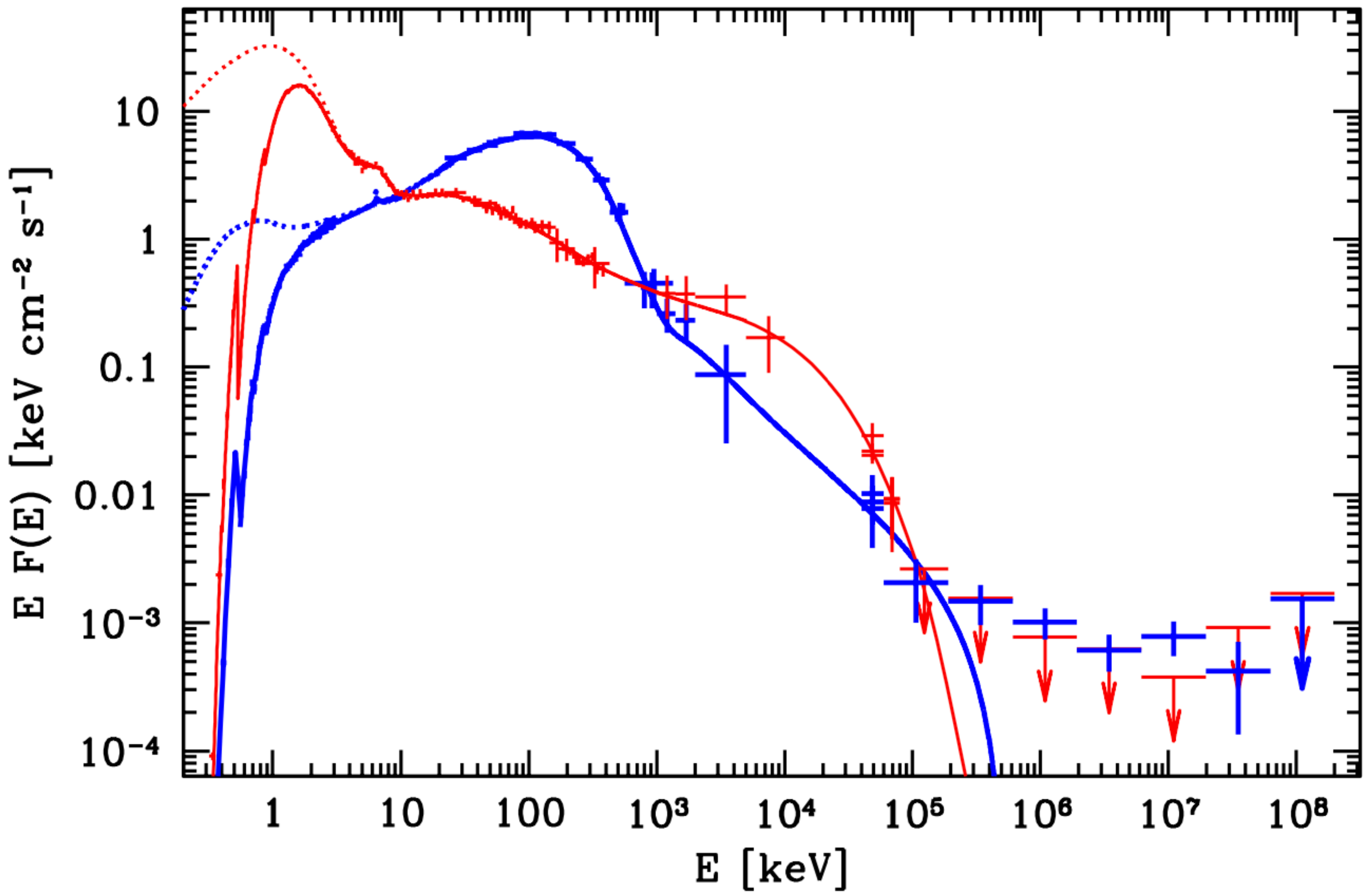
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states
- Transition of states due to **different accretion states**. In hard/soft state, coronal emission dominates at large/small radius

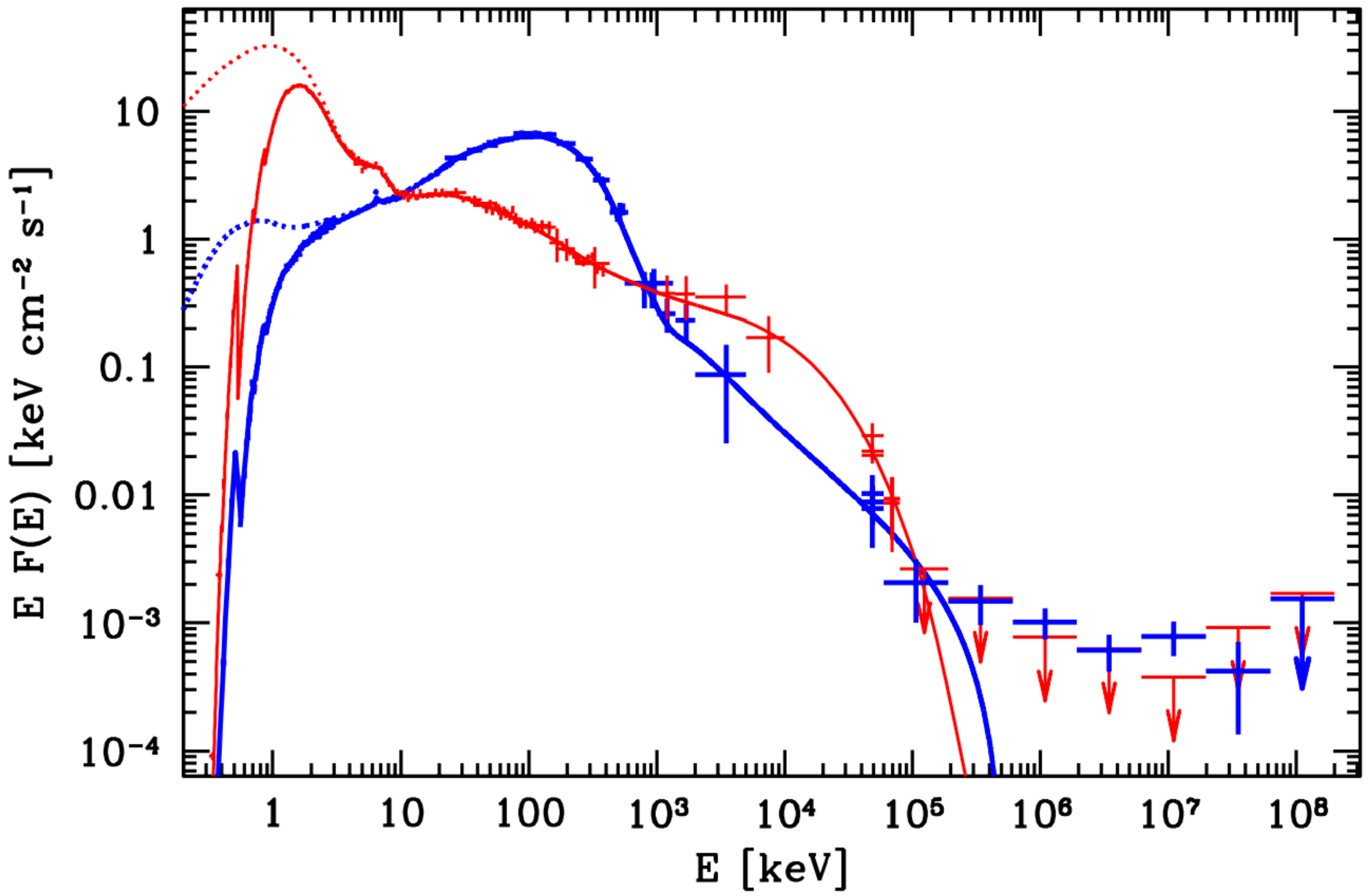
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states
- Transition of states due to **different accretion states**. In hard/soft state, coronal emission dominates at large/small radius

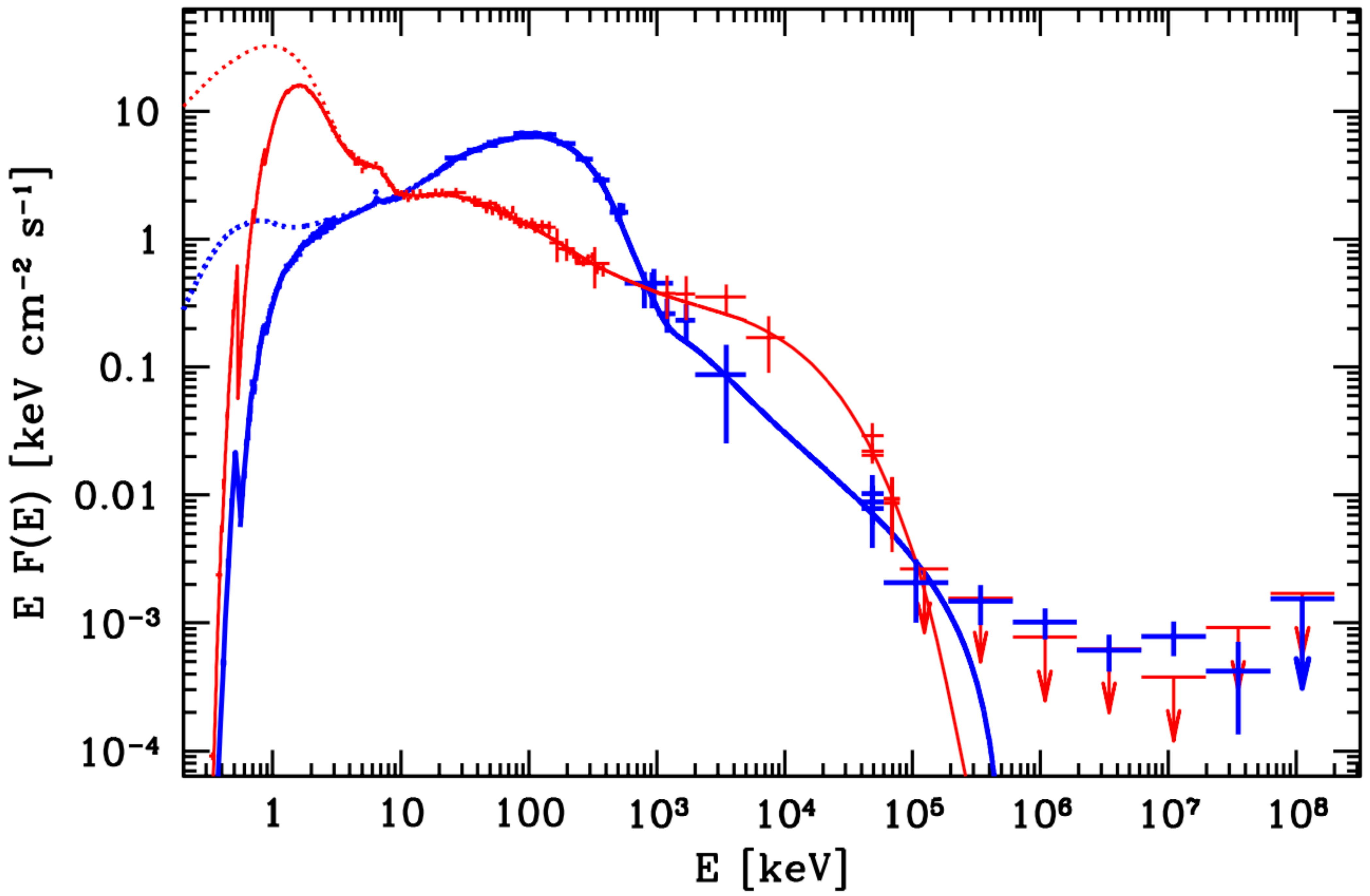
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states
- Transition of states due to **different accretion states**. In hard/soft state, coronal emission dominates at large/small radius
- Hard X-ray to MeV gamma-ray emission associated with corona

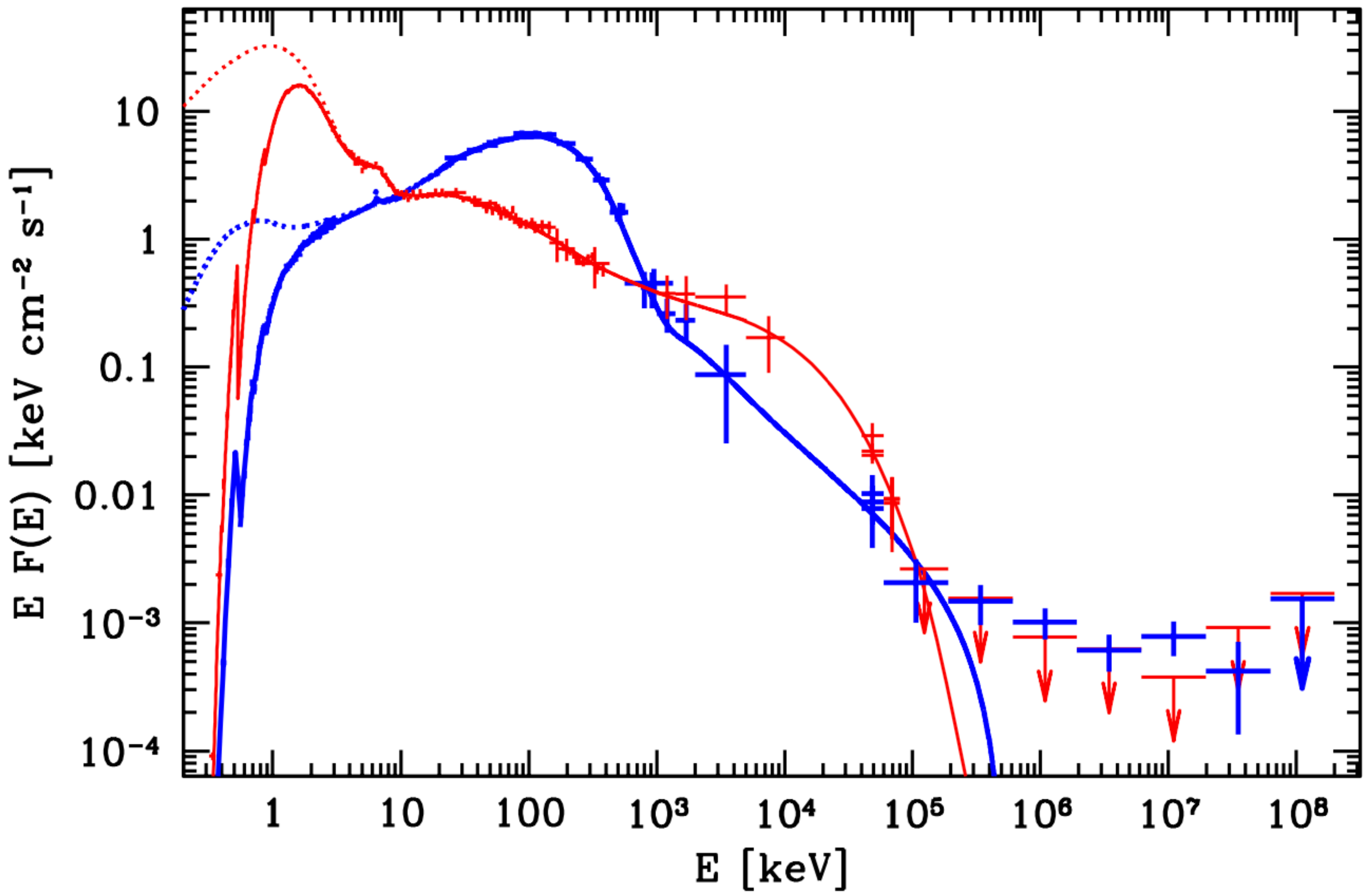
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states
- Transition of states due to **different accretion states**. In hard/soft state, coronal emission dominates at large/small radius
- Hard X-ray to MeV gamma-ray emission associated with corona

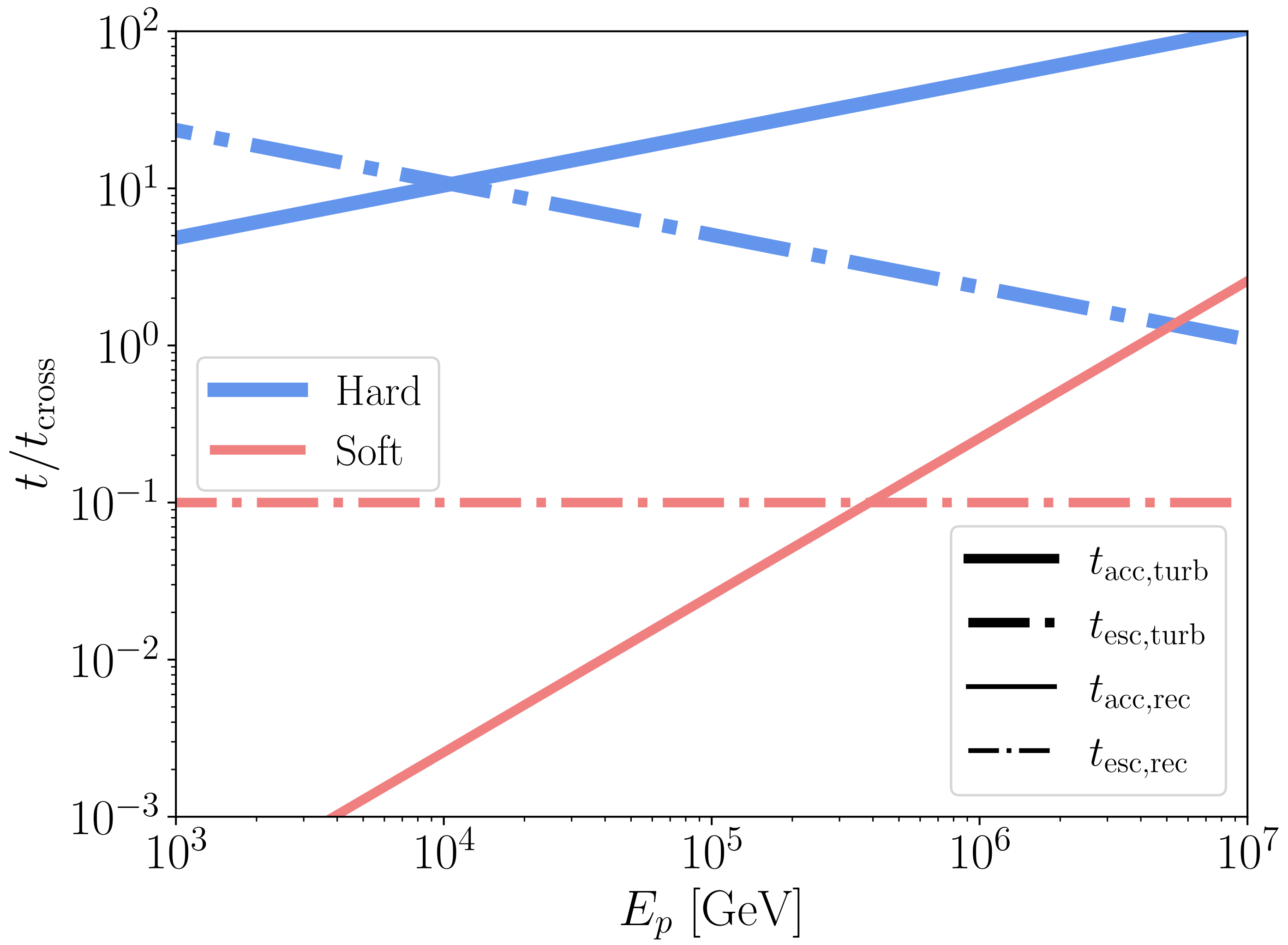
Galactic Black Hole Corona: Cygnus X-1 as an example



Zdziarski et al MNRAS (2017)
Krawczynski et al Science (2022)

- Hard and soft states
- Transition of states due to **different accretion states**. In hard/soft state, coronal emission dominates at large/small radius
- Hard X-ray to MeV gamma-ray emission associated with corona
- 1-100 GeV emission only in hard state; sub-GeV emission seen in both states. Origin unknown

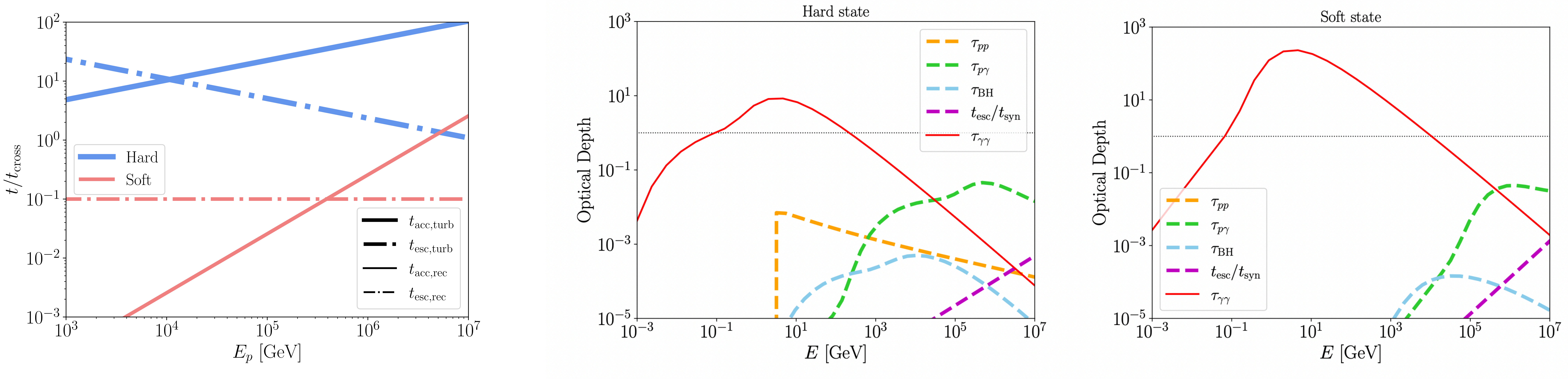
Galactic Black Hole Corona: Cygnus X-1 as an example



- Hard state: $R \sim 100\,R_g$, $\ell \sim 2$, $\sigma_\pm \sim 0.1$, turbulent acceleration
- Soft state: $R \sim 30\,R_g$, $\ell \sim 20$, $\sigma_\pm \sim 60$, magnetic reconnection
- In both states, coronal region is **opaque to gamma rays**. Soft state has $\tau_{\gamma\gamma} \gg 1$

KF &, Halzen, Heinz, Gallagher *2410.02119*

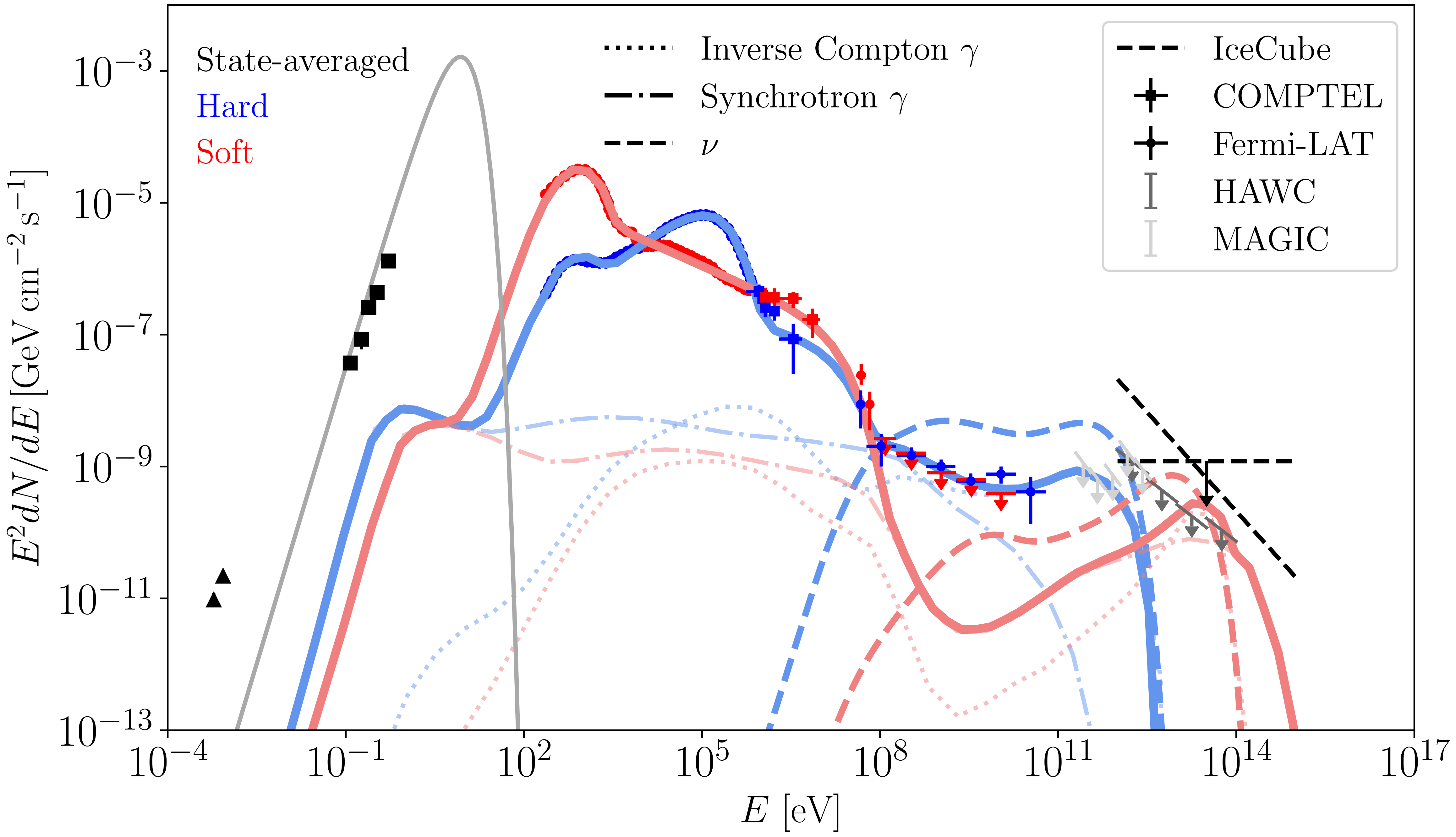
Galactic Black Hole Corona: Cygnus X-1 as an example



- Hard state: $R \sim 100\,R_g$, $\ell \sim 2$, $\sigma_\pm \sim 0.1$, turbulent acceleration
- Soft state: $R \sim 30\,R_g$, $\ell \sim 20$, $\sigma_\pm \sim 60$, magnetic reconnection
- In both states, coronal region is **opaque to gamma rays**. Soft state has $\tau_{\gamma\gamma} \gg 1$

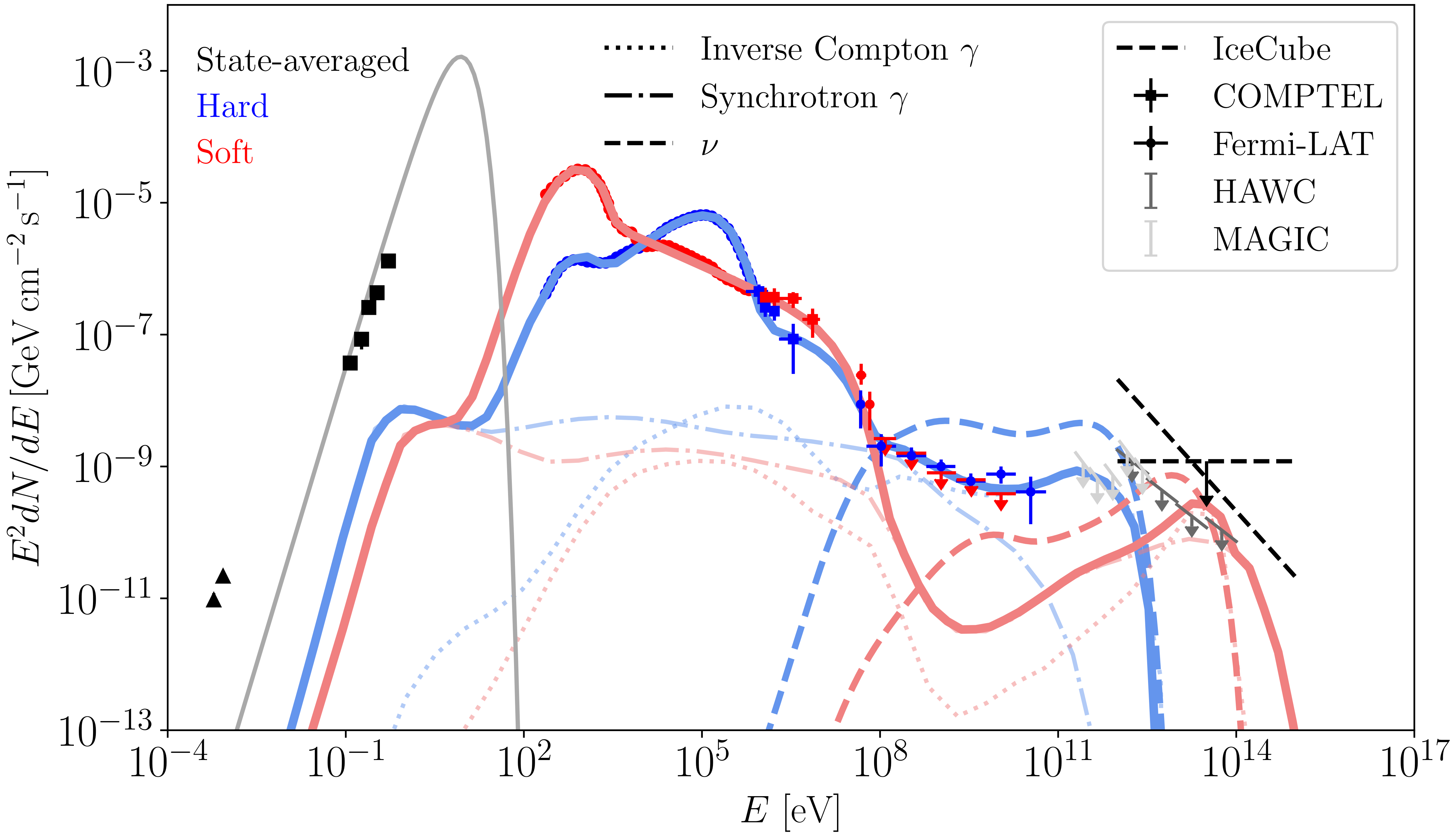
KF &, Halzen, Heinz, Gallagher *2410.02119*

Galactic Black Hole Corona: Cygnus X-1 as an example



KF &, Halzen, Heinz, Gallagher *2410.02119*

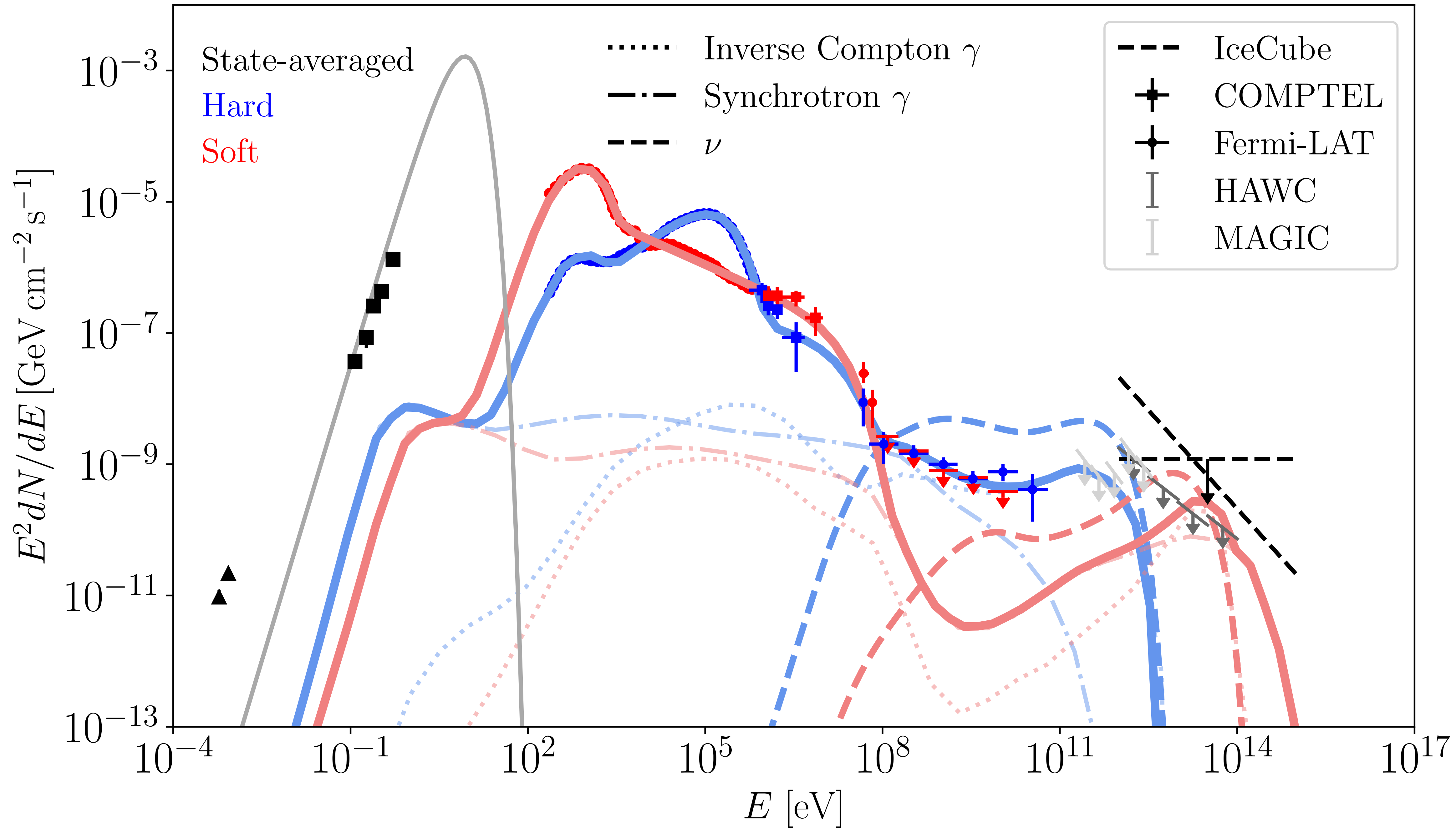
Galactic Black Hole Corona: Cygnus X-1 as an example



- Hadronic γ rays **cascade down** to sub-GeV energies in soft state and 0.1-100 GeV in hard state
- ν emission **detectable with future observations**

KF &, Halzen, Heinz, Gallagher *2410.02119*

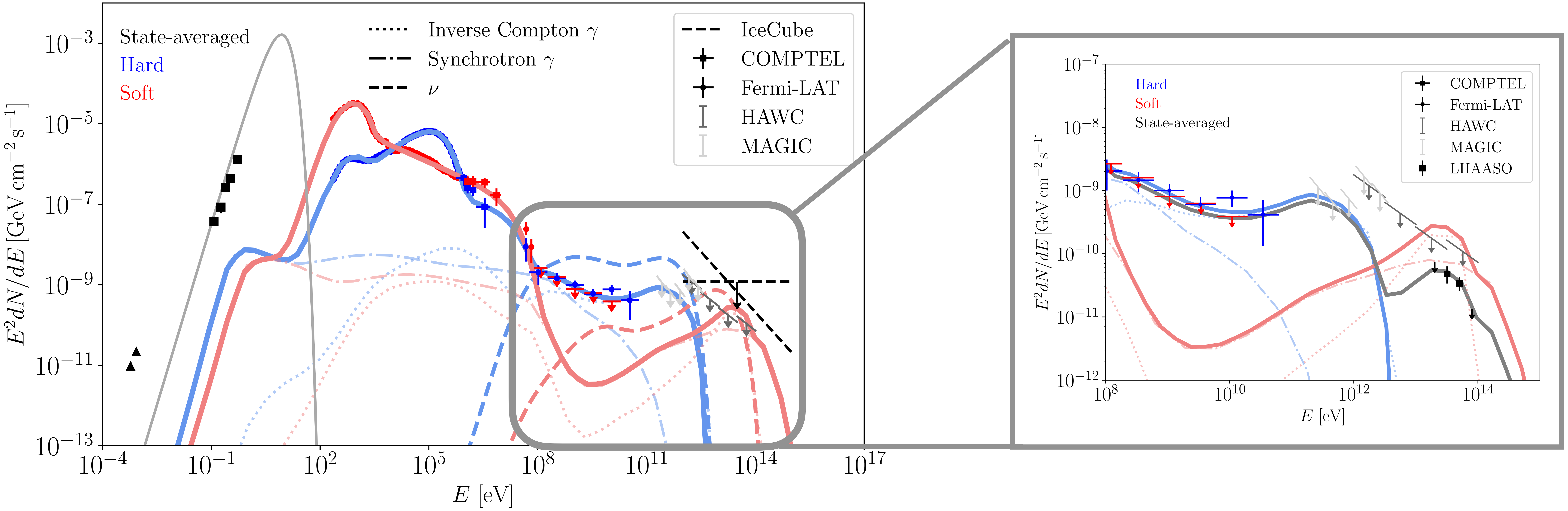
Galactic Black Hole Corona: Cygnus X-1 as an example



- Hadronic γ rays **cascade down** to sub-GeV energies in soft state and 0.1-100 GeV in hard state
- ν emission **detectable with future observations**
- State-averaged γ-ray flux is **consistent with TeV limits and LHAASO observation**

KF &, Halzen, Heinz, Gallagher *2410.02119*

Galactic Black Hole Corona: Cygnus X-1 as an example



- Hadronic γ rays **cascade down** to sub-GeV energies in soft state and 0.1-100 GeV in hard state
- ν emission **detectable with future observations**
- State-averaged γ-ray flux is **consistent with TeV limits and LHAASO observation**
- Galactic XRB coronal emission **could explain both Galactic cosmic-ray and neutrino flux**

KF &, Halzen, Heinz, Gallagher *2410.02119*

Summary

Summary

- Recent **gamma-ray observations** reveal new looks of the Milky Way, including its individual sources and diffuse emission

Summary

- Recent **gamma-ray observations** reveal new looks of the Milky Way, including its individual sources and diffuse emission

Summary

- Recent **gamma-ray observations** reveal new looks of the Milky Way, including its individual sources and diffuse emission

- The Galactic plane emission observed by IceCube indicates **a large population of hadronic sources**

Summary

- Recent **gamma-ray observations** reveal new looks of the Milky Way, including its individual sources and diffuse emission

- The Galactic plane emission observed by IceCube indicates **a large population of hadronic sources**

Summary

- Recent **gamma-ray observations** reveal new looks of the Milky Way, including its individual sources and diffuse emission
- The Galactic plane emission observed by IceCube indicates **a large population of hadronic sources**
- **X-ray binary coronae**, like their extragalactic big brothers, may work as gamma-ray-opaque neutrino emitters