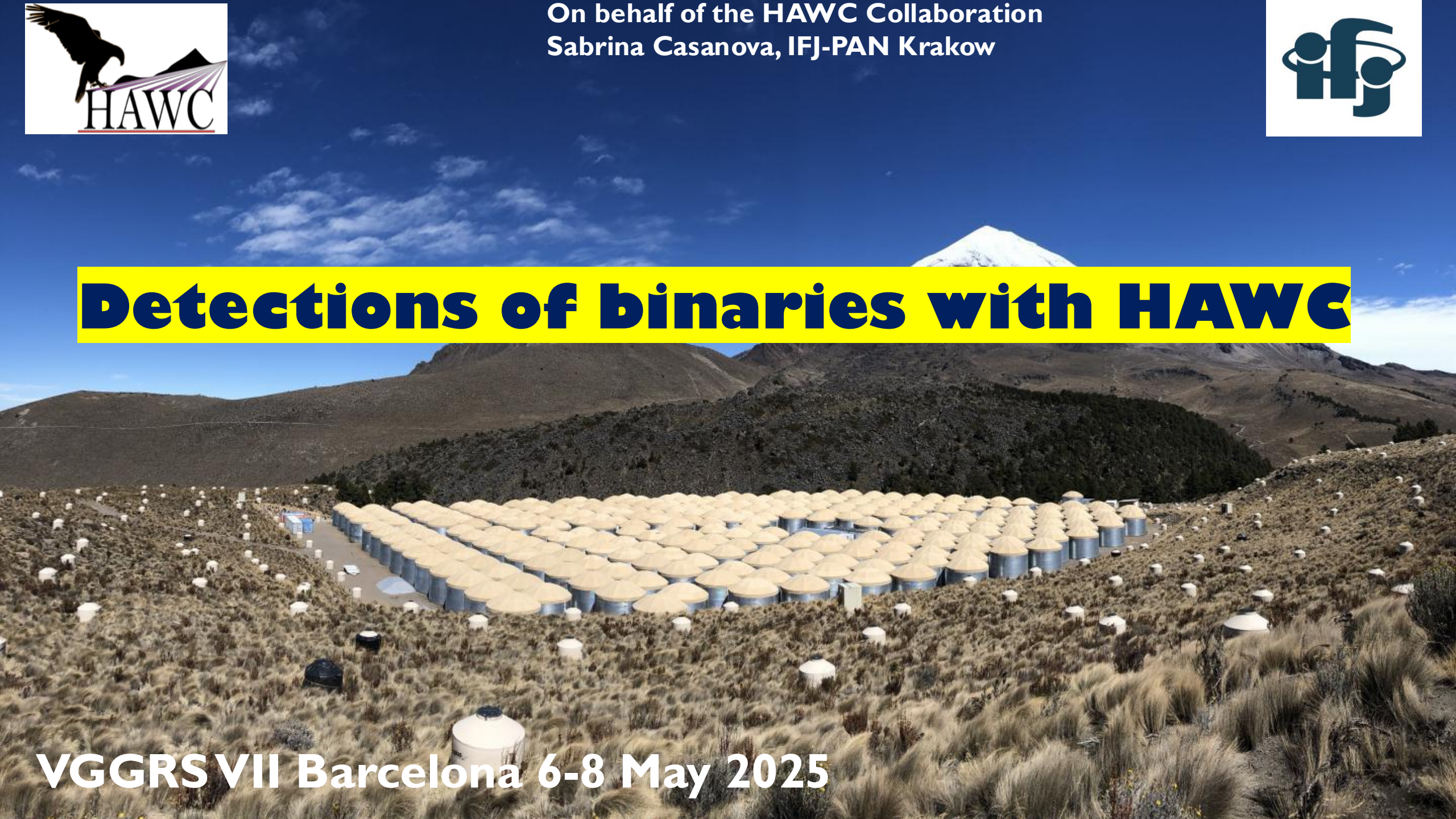
On behalf of the HAWC Collaboration
Sabrina Casanova, IFJ-PAN Krakow

Detections of binaries with HAWC



VGGRS VII Barcelona 6-8 May 2025

Outline

- HAWC Observatory
- HAWC micro-quasars
  - ✓SS 433
  - ✓V4641 Sgr
- LS 5039
- Conclusions and Outlook

HAWC Site

- HAWC is located on the flanks of the Sierra Negra volcano near Puebla
- 4,100 meters (13,500 feet) above the sea level

High-Altitude Water Cherenkov Gamma-Ray Observatory

Pico de Orizaba
Puebla, Mexico (19°N)

Inaugurated **March 2015**.

Instantaneous FOV 2sr

Daily FOV 8sr (66% of the sky)

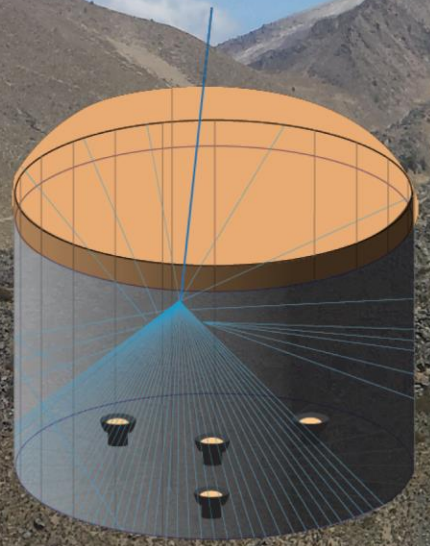
Energy range: 100s GeV to 100s TeV

Observing >95% of the time

Angular resolution 0.2° – 1°

345 outriggers since 2018

300 ×



5m tall, 7.3 m diameter
~200,000 L of water

4 PMTs facing upwards collect Cherenkov light produced by secondary particles

22,000 m²

T-rex for scale

HAWC Water Cherenkov detectors and detection technique

Steel frame construction

Large plastic bag container

3900 Water trucks filling the tanks

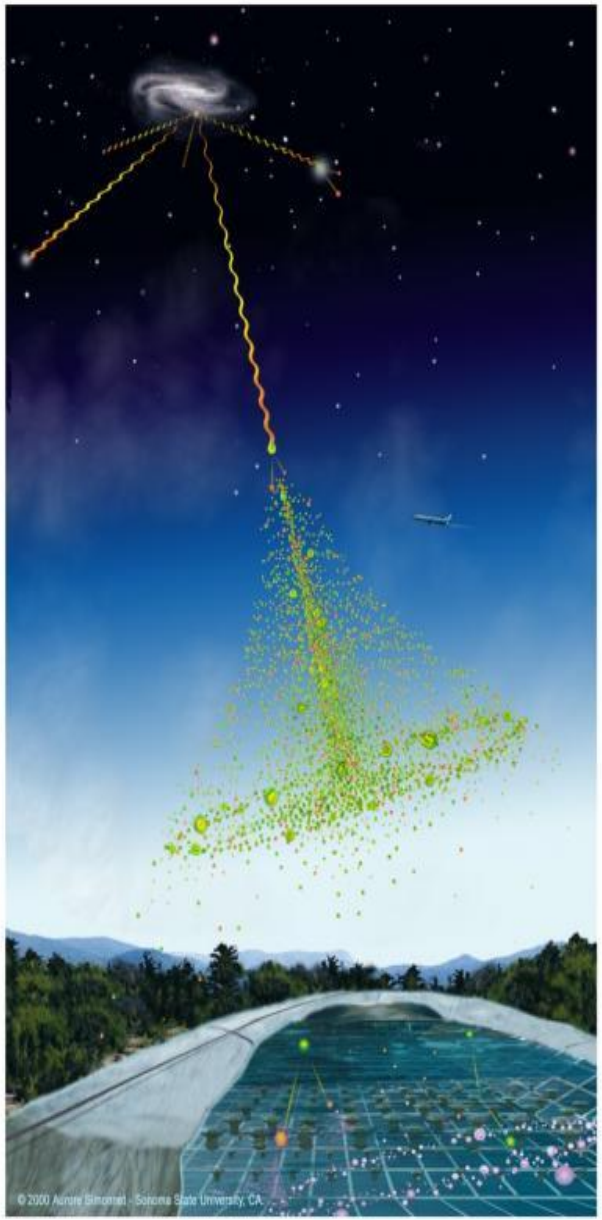
8-inch 10-inch PMTs

WCDs with 200,000 l of purified water.

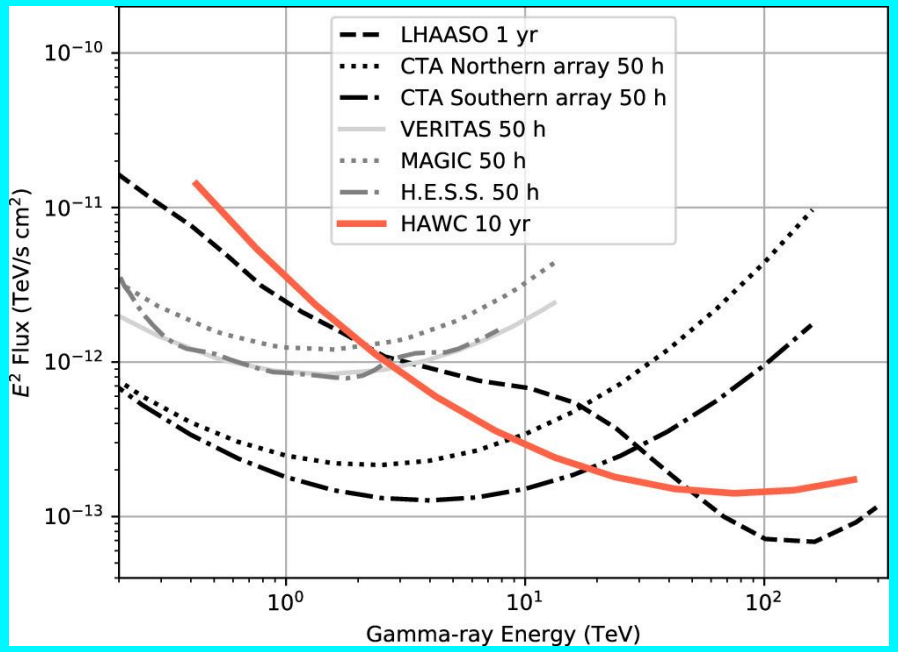
Particles from the shower induce Cherenkov light in water detected by 4 PMTs.

Measure: time and light level in each PMT

Reconstruct: core, energy, direction and background rejection

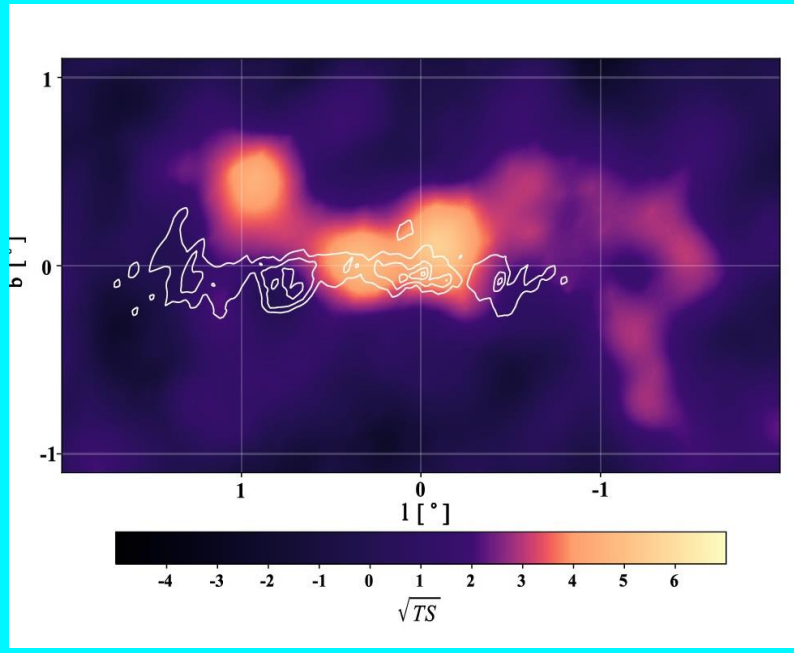


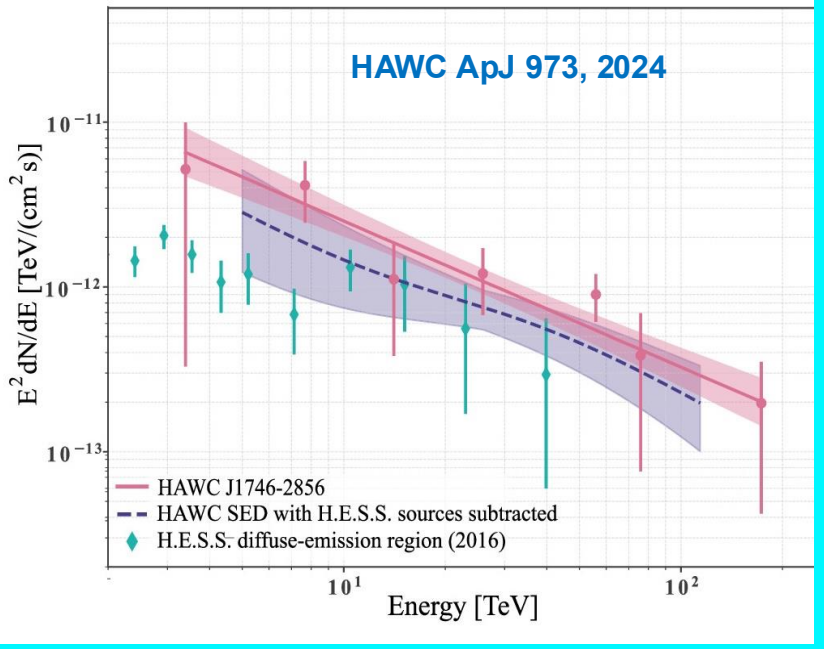
Pass 5 sensitivity



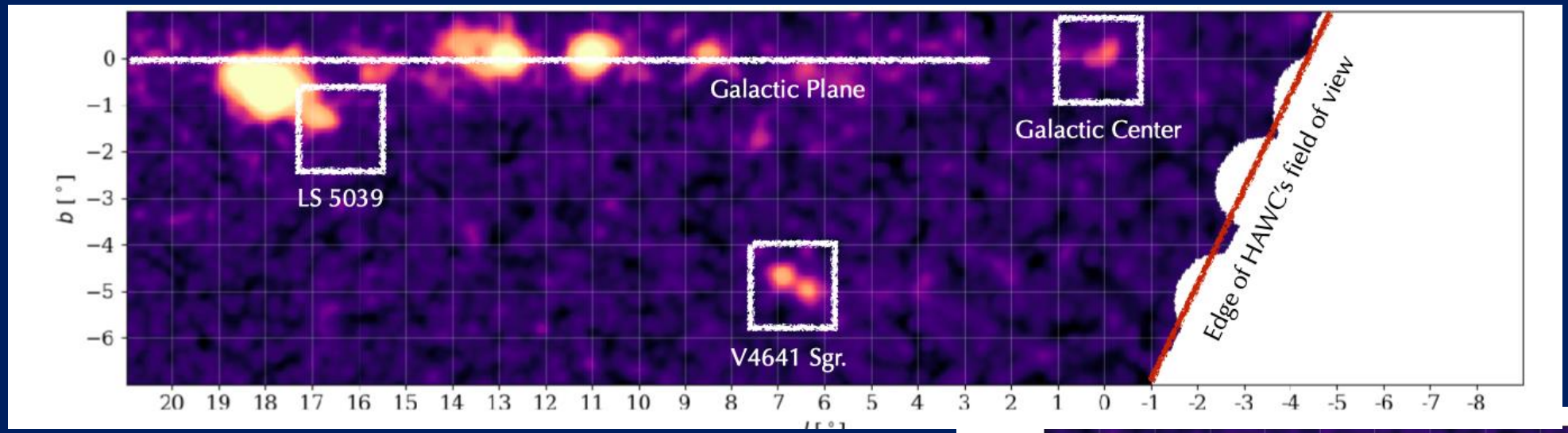
HAWC ApJ 972, 2024

- Improved background rejection
- Better angular resolution
- Improved sensitivity at 100s GeV

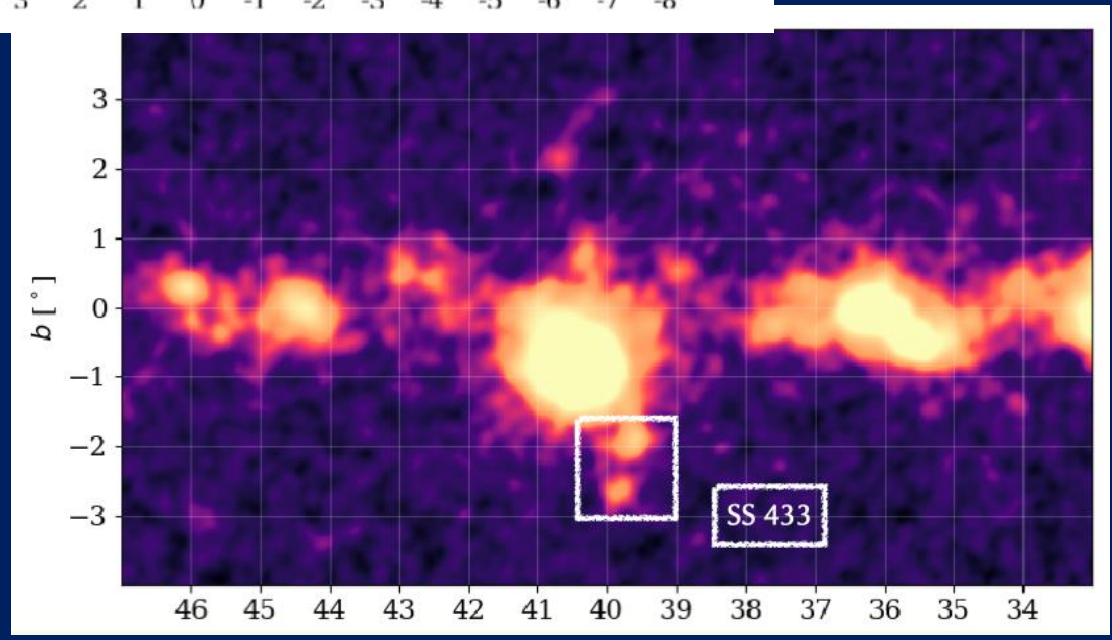




Looking for binaries with HAWC



	Distance (kpc)	Companion star mass ($M_\odot$)	Compact star mass ($M_\odot$)	Orbital period (days)	Orbital axis inclination (°)
V4641 Sgr	6.2 ± 0.7	2.9 ± 0.4	6.4 ± 0.6	2.817 ± 0.002	72. 3 ± 4.1
SS433	~ 5.5	>10	8	13.082	79
LS5039	~2.5	22.9 +3.4 -1.3	3.7 +1.3 -1.0	3.90603 ± 0.00017	24.9 ± 2.8



SS433 Lobes

Binary observed in radio-X-rays

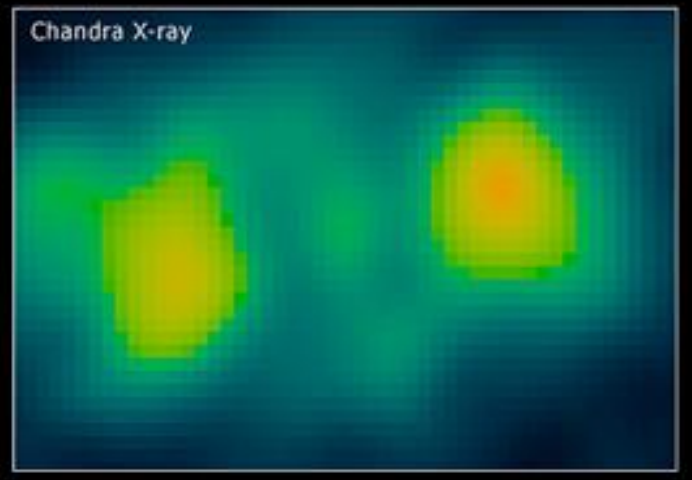
Supergiant > 10 $M_\odot$ and 8 $M_\odot$ compact object, BH or NS

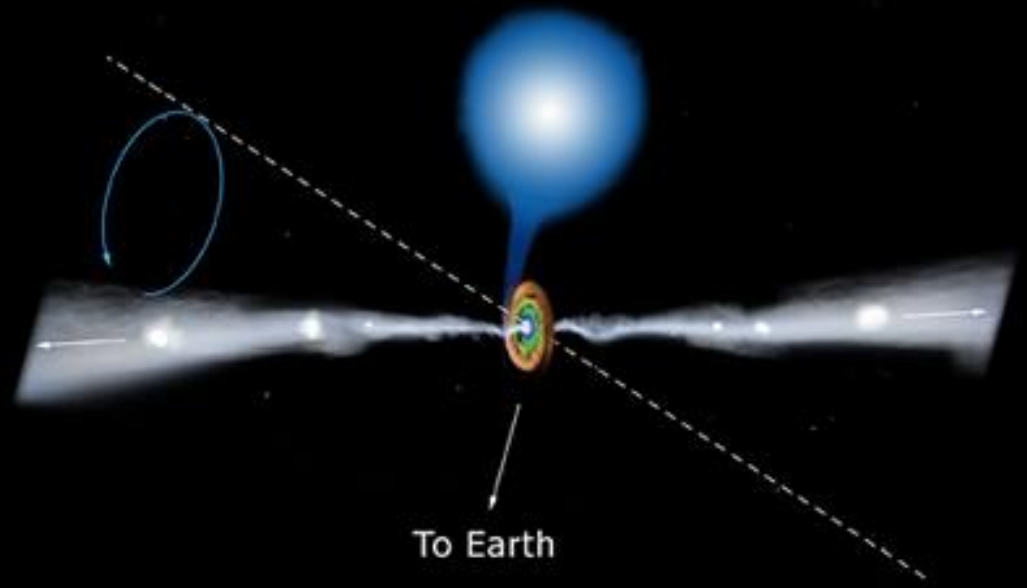
Accretion believed to be super Eddington

$10^{39\text{-}40}$ erg/s barion-loaded jets terminate at 40 pc distance in W50 nebula and produce western and eastern X-ray lobes

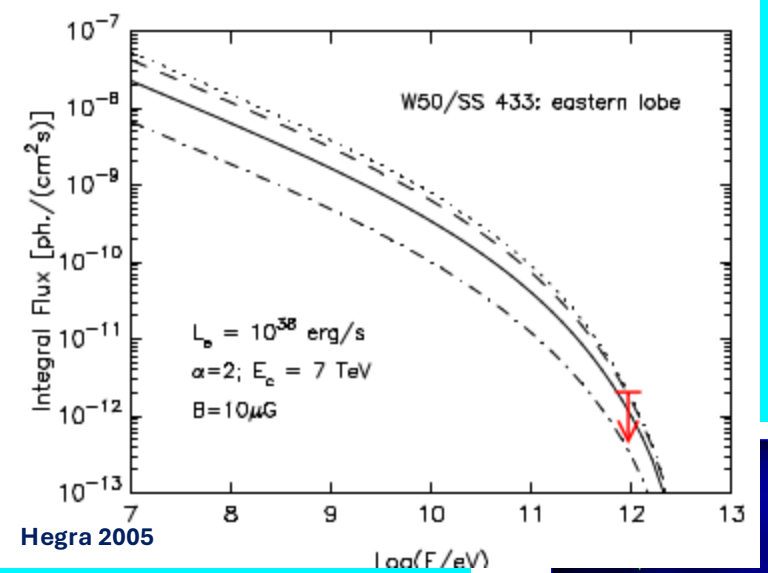
Jet speed roughly c/4

Particle acceleration & GeV-TeV radiation predicted

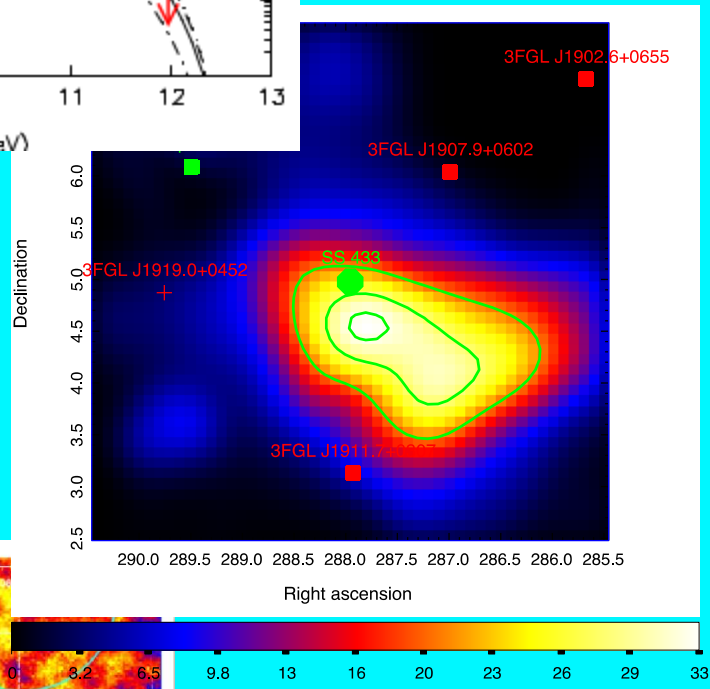


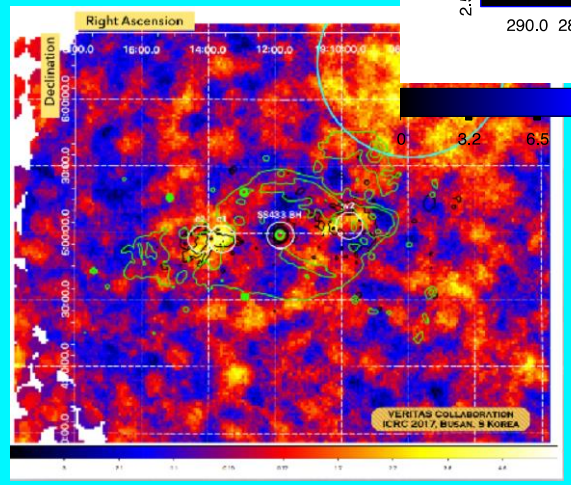


SS 433 with Fermi and IACTs



Hegra 2005





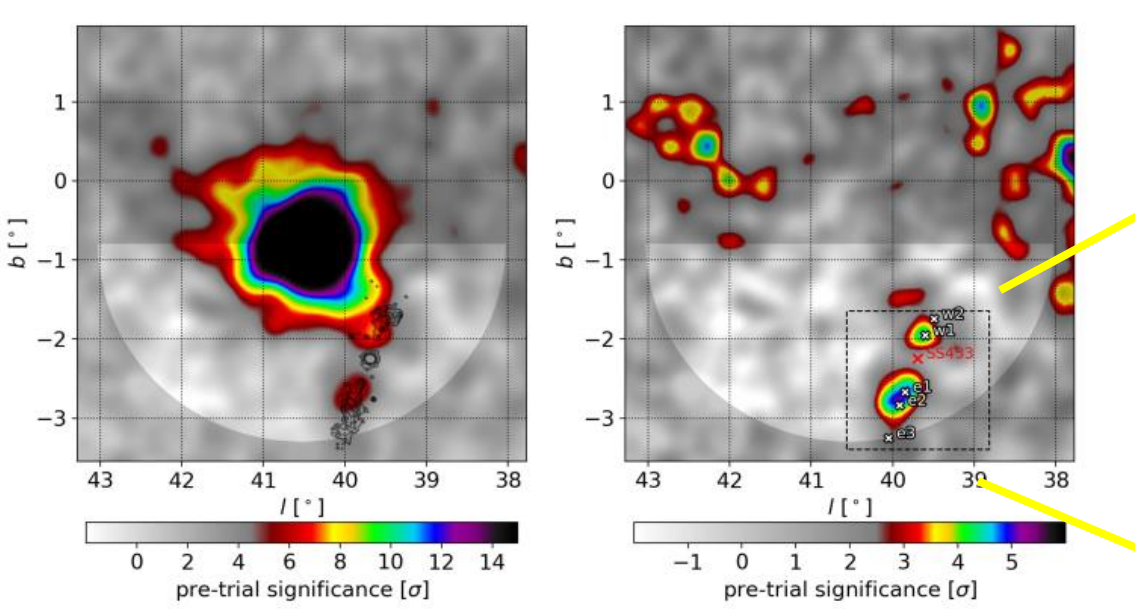
HEGRA set upper limits on the emission from e3 (Aharonian+, 2005)

Fermi-LAT analysis revealed a persistent emission between 250 MeV and 800 MeV, possibly due to proton-proton interaction close to SS433(Bordas+,2015)

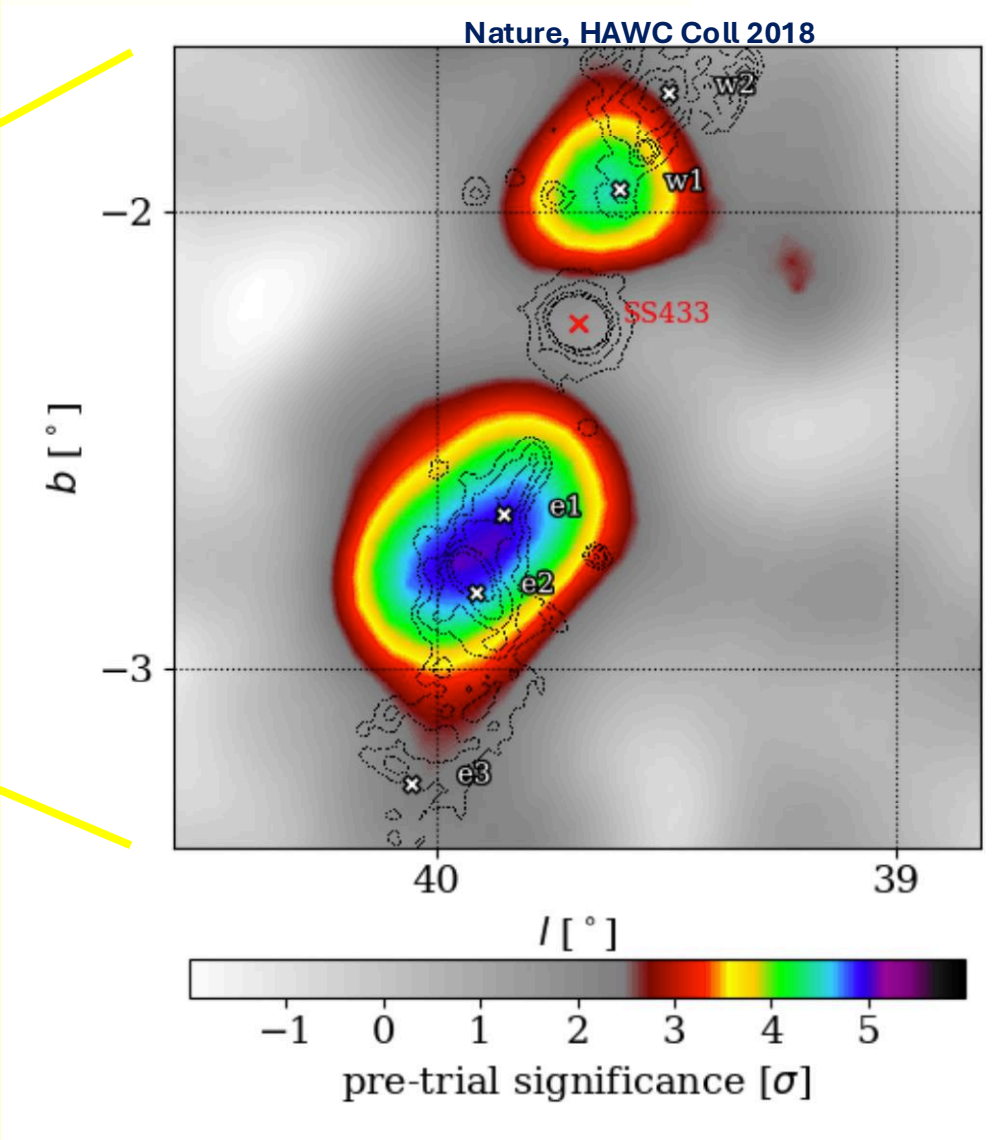
VERITAS has 4 σ pre trial at termination regions at the X-ray lobe

Combined HESS-MAGIC produced only upper limits.

SS-433 Lobes with HAWC



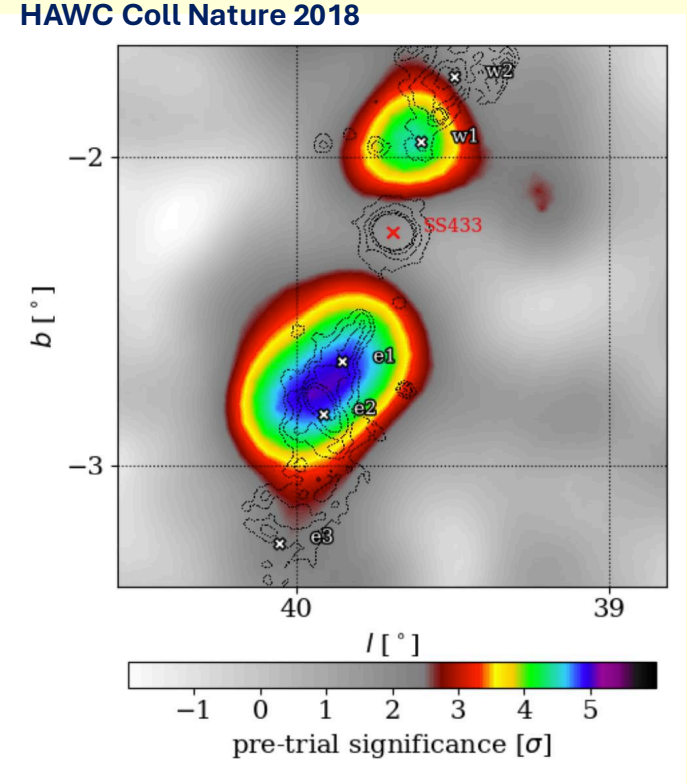
Nature, HAWC Coll 2018



- The first micro-quasar HAWC detected
- 1017 days of HAWC observations
- Post-trial 5.4 σ
- Emission coincident with e1 and w1

SS-433 lobes with HAWC

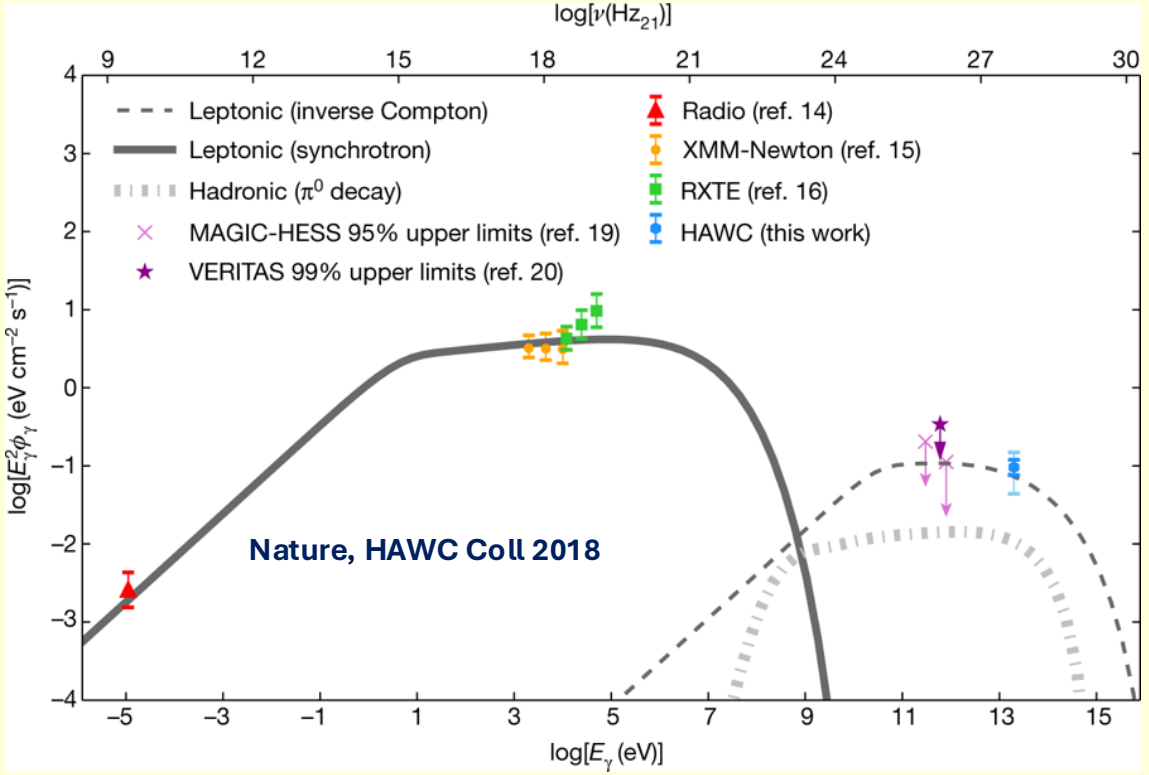
HAWC Coll Nature 2018



- HAWC emission → powerful jets accelerate particles beyond 100 TeV
- Combining γ and X-rays B~16 μG
- Emission region is ~40 pc from central binary > Diffusion length scale ~35 pc > advection length scale is ~4 pc → Acceleration is occurring in the jets, not in the central binary:

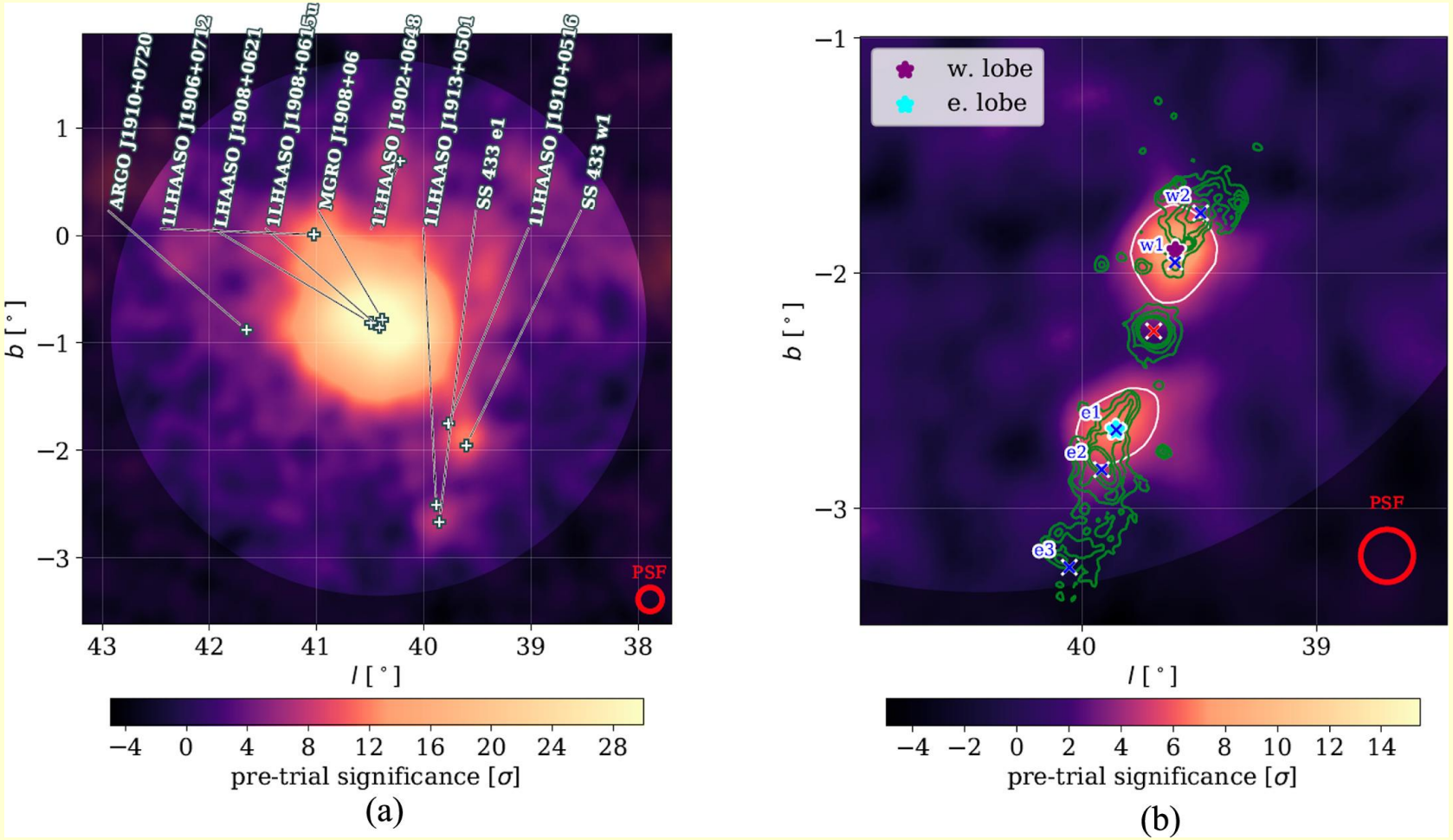
Energy Budget :
~0.5% of jet power into electron acceleration

~100% of jet energy over 30000 yr lifetime for accelerating protons of at least 250 TeV if n=0.1 cm^{-3}

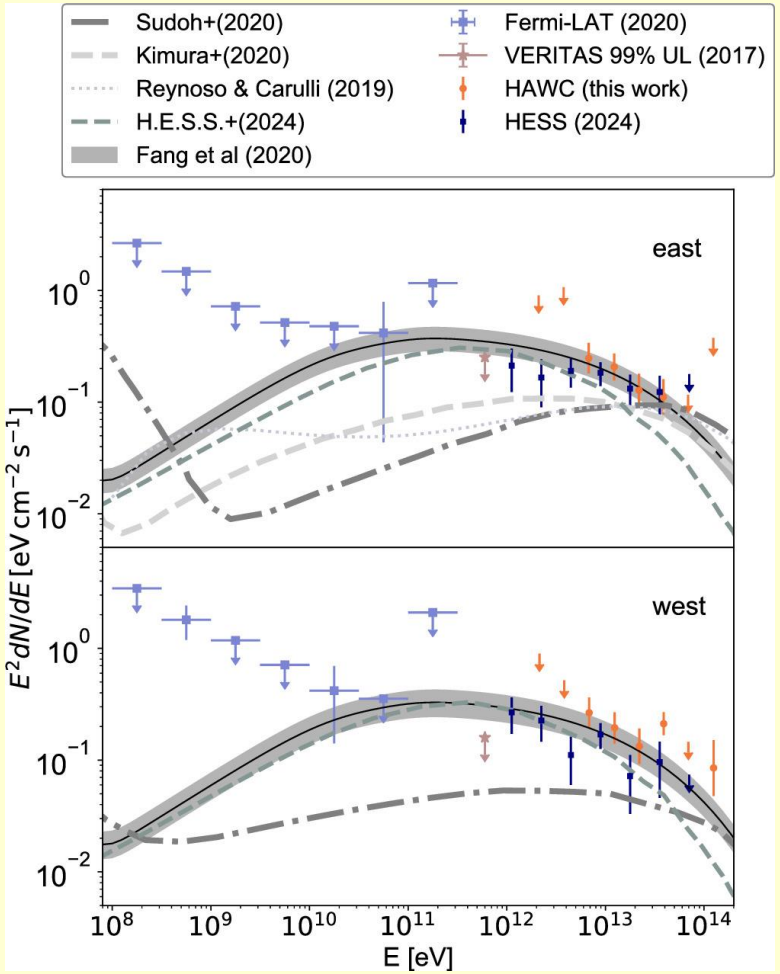


SS 433 lobes again

HAWC ApJ 2024

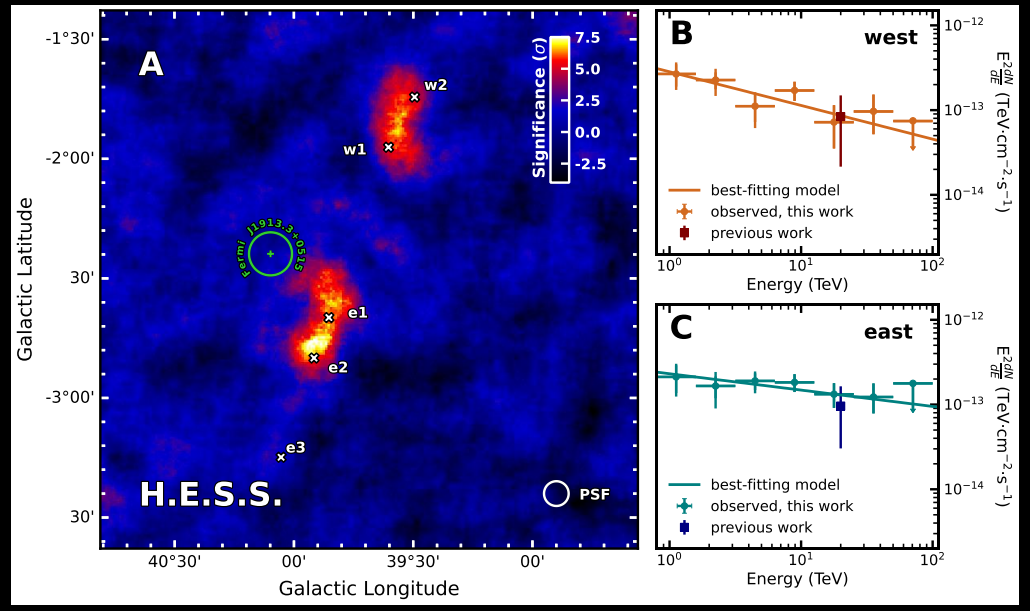


Spectra of the lobes

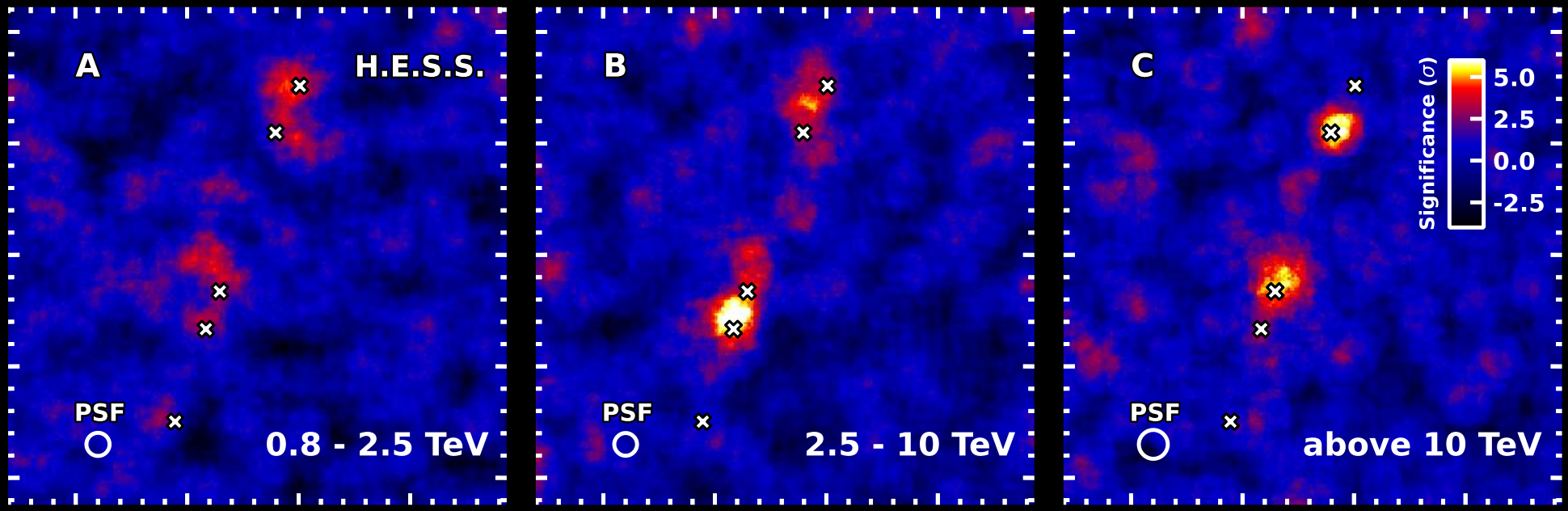


- 1922 days of data
- Better Reconstruction
- Increased significance
- Individual lobe analysis and spectra

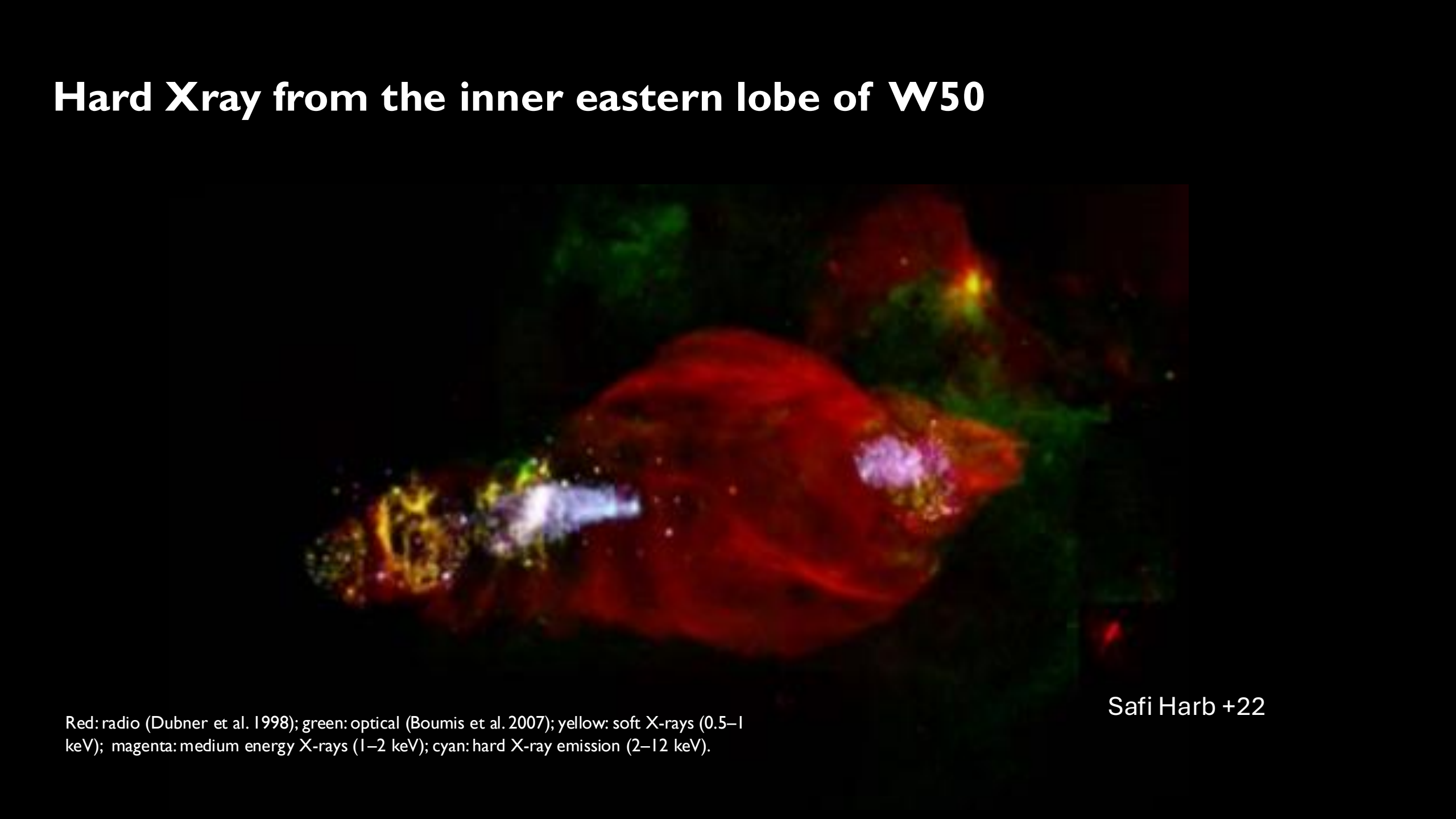
SS 433 energy - dependent morphology



HESS Coll Science 2024



Hard Xray from the inner eastern lobe of W50

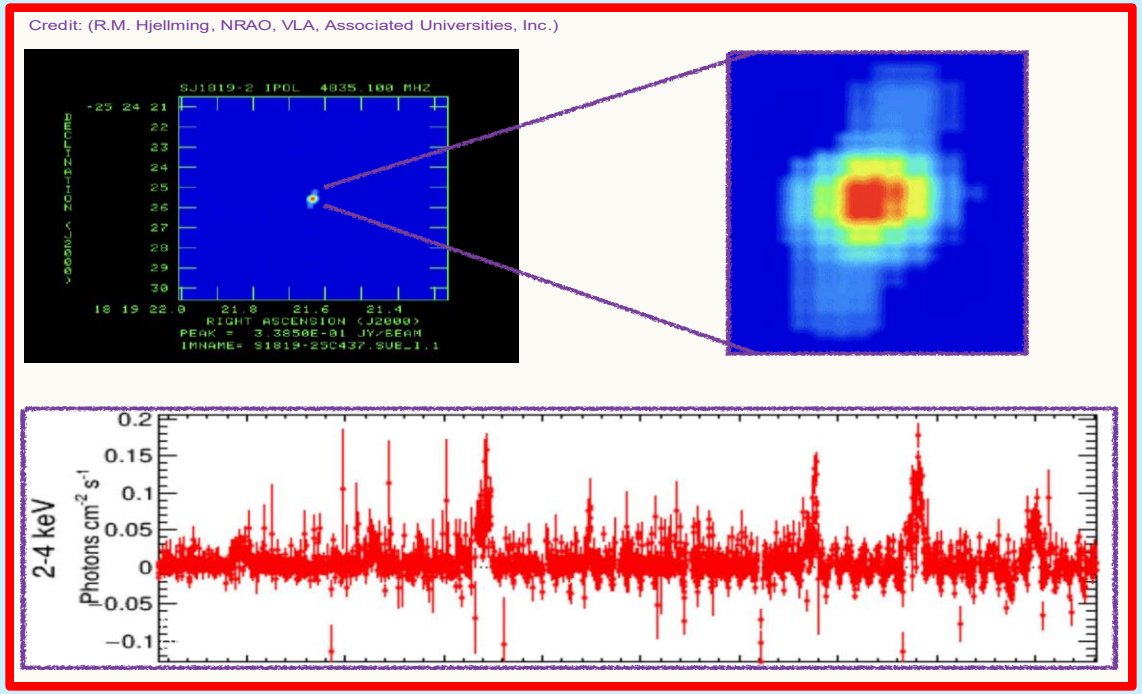


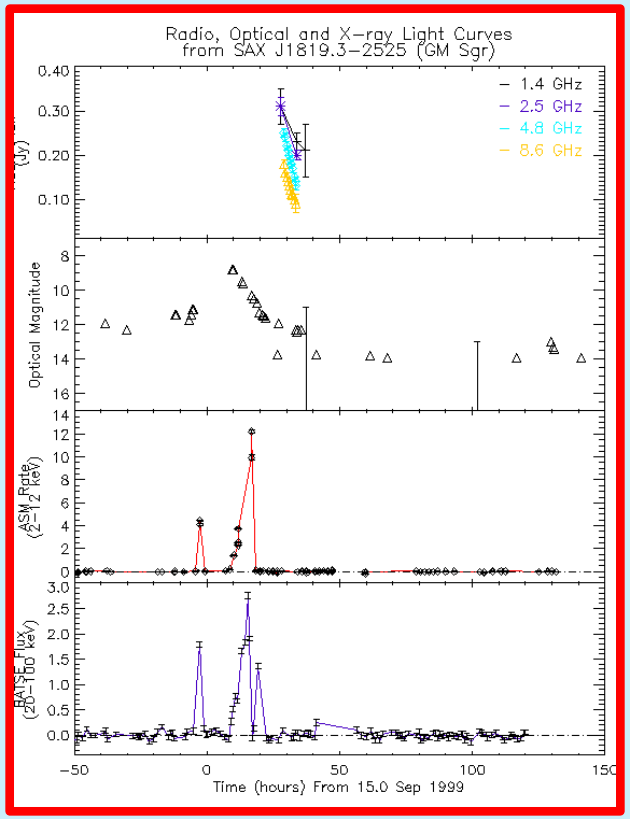
Red: radio (Dubner et al. 1998); green: optical (Boumis et al. 2007); yellow: soft X-rays (0.5–1 keV); magenta: medium energy X-rays (1–2 keV); cyan: hard X-ray emission (2–12 keV).

Safi Harb +22

V4641 Sgr

- Transient X-ray binary first detected flares in 1999
- X-ray flux reached 12.2 Crab in 8 hr
- Arcsec radio jets inclined < 16° (VLA)
- Low Mass Xray Binary :Black-hole 6.4 $M_\odot$ - B-star companion 2.9 $M_\odot$
- Orbital period 2.8 d, distance 6.2 kpc
- Super-Eddington accretion – $L_{Eddington} \sim 10^{39}$erg
- Superluminal jets - apparent expansion speed 9.5c

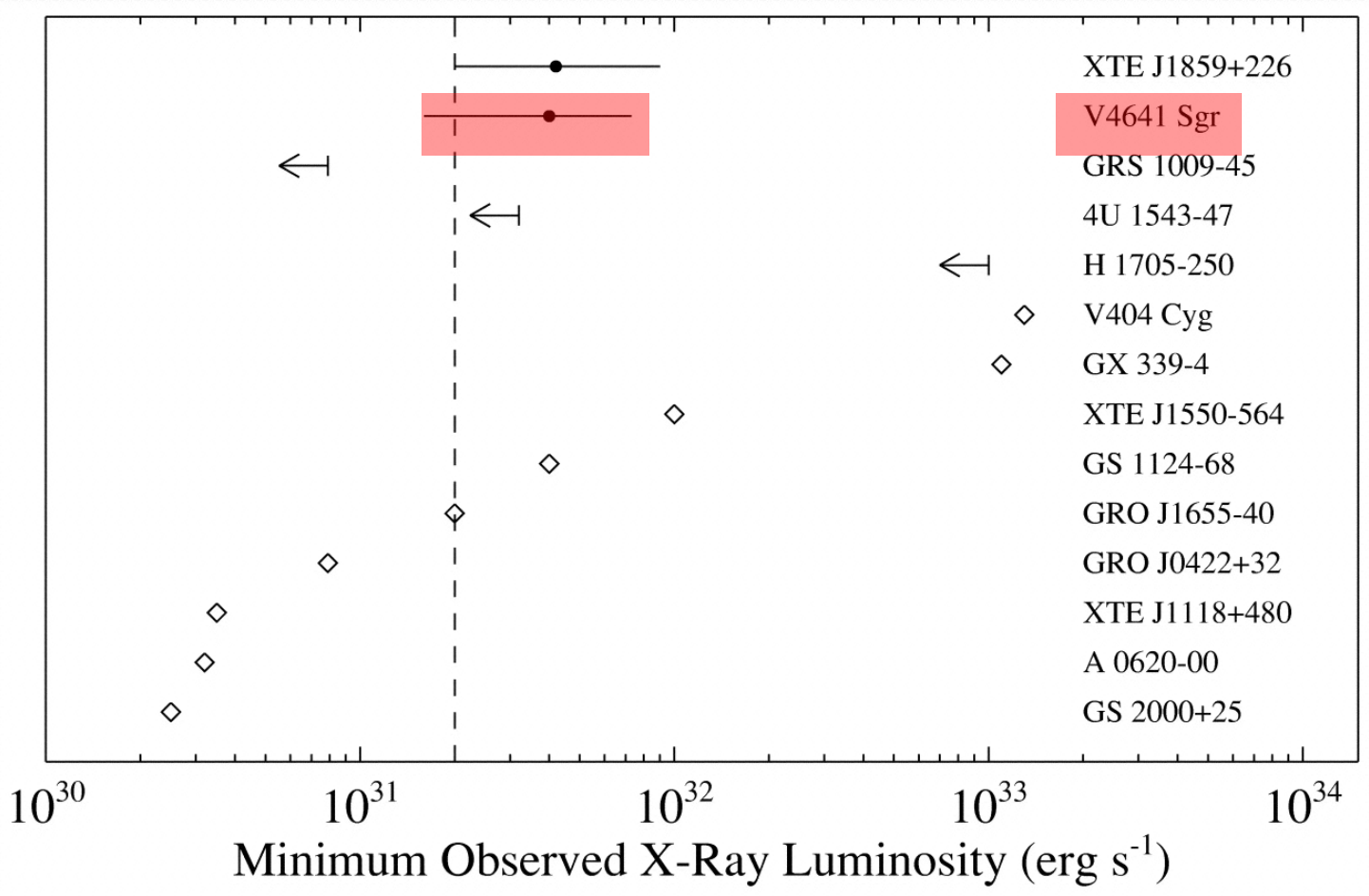




- Luminous Jet-like radio structure of 0,25" within 1 day after an X-ray burst in 1999 (VLA)
- Long time monitoring by MAXI

Chandra Observations of V4641 Sgr in quiescent state

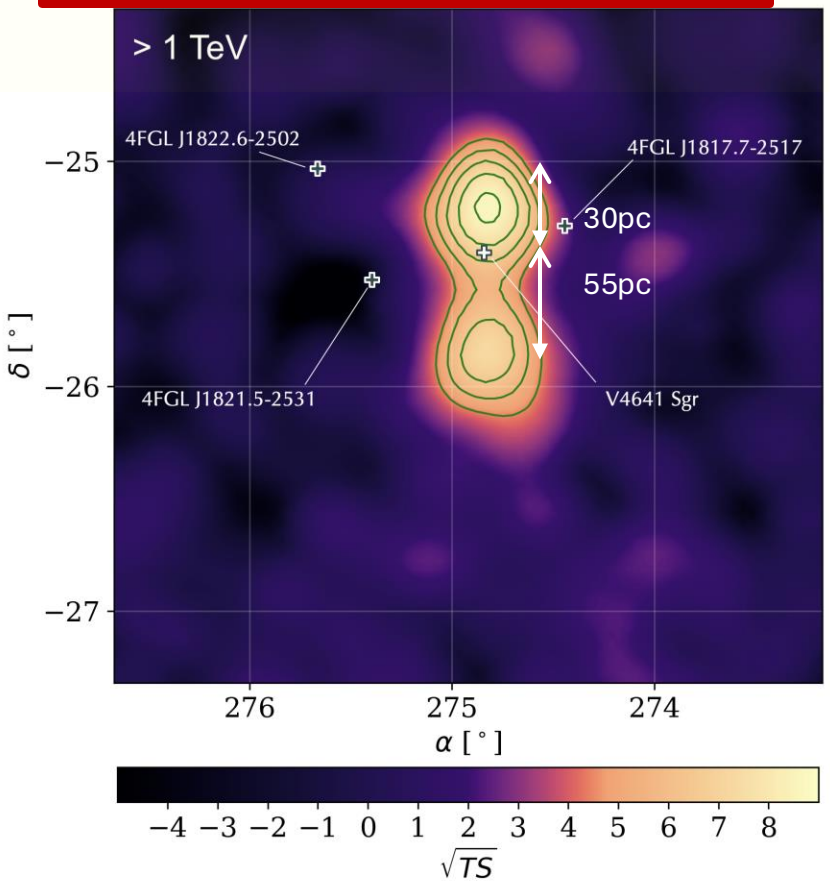
Tomsick et al, 2003

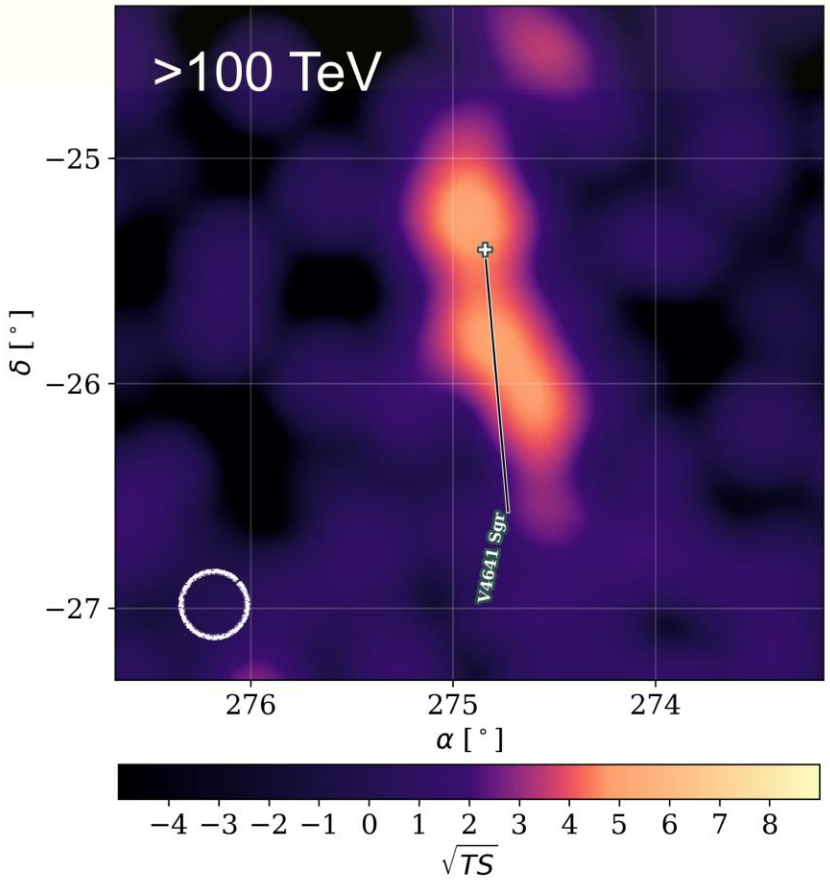


- X-ray observations focused on X-ray outbursts happening roughly every two years
- What about quiescent state ?
- Quiescent state 0.3- 8 keV luminosity 4.0×10^{31} $(d/7\ \mathrm{kpc})^2$ ergs s^{-1} (Tomsick+2003)
- In optical wavelengths V4641 Sgr 85% quiescent state and 15% active state (MacDonald+2014)

VHE Photons coincident with V4641 Sgr

HAWC Collaboration, Nature 2024

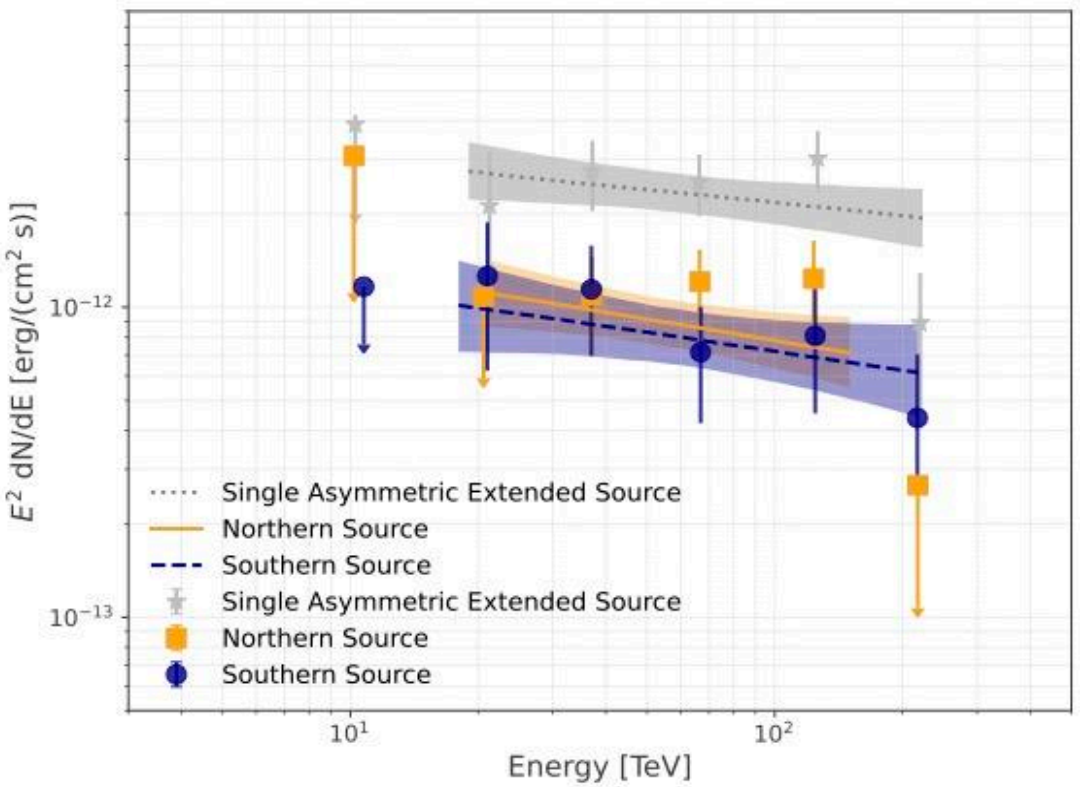




- 2400 days obs
- High zenith angle for HAWC - 45◦ off zenith
- 8.8σ above 1 TeV and 5.2σ above 100 TeV – > 100 TeV 23 photons after background subtracted – 14 background

Spectra and morphology of the lobes

HAWC Collaboration, Nature 2024



Model	−logLikelihood	BIC	AIC
One Point Source	60733	121520	121473
One Asymmetric Extended Source	60694	121485	121403
Two Point Sources	60694	121498	121404

- Morphology: two sources (8,1 σ and 6.8 σ) or a roughly 70 pc extended one
- PL spectra up to 220 TeV
- No time flux variations
- No other TeV gamma-ray counterpart
- 800 TeV photons detected with LHAASO

Origin of the emission

- Electrons of at least 200 TeV at the termination shocks
- PeV protons at the termination shocks where jets impact ISM

$$t_{acc} \approx 10 D_B(E_e)/v_{sh}^2$$

$$t_{cooling} \approx 600 (E_e/200\ \mathrm{TeV})^{-1} (B/10\ \mu\mathrm{G})^{-2}\ \mathrm{yr}$$

$$v_{sh}/c > 0.02 (E_e/200\ \mathrm{TeV}) (B/10\ \mu\mathrm{G})^{1/2}$$

$$t_{esc} \approx R^2/(2D) \approx 1{,}000/\eta\ \mathrm{years}$$

$$D(200\ \mathrm{TeV}) \approx \eta 10^{30}\ \mathrm{cm^2\ s^{-1}}$$

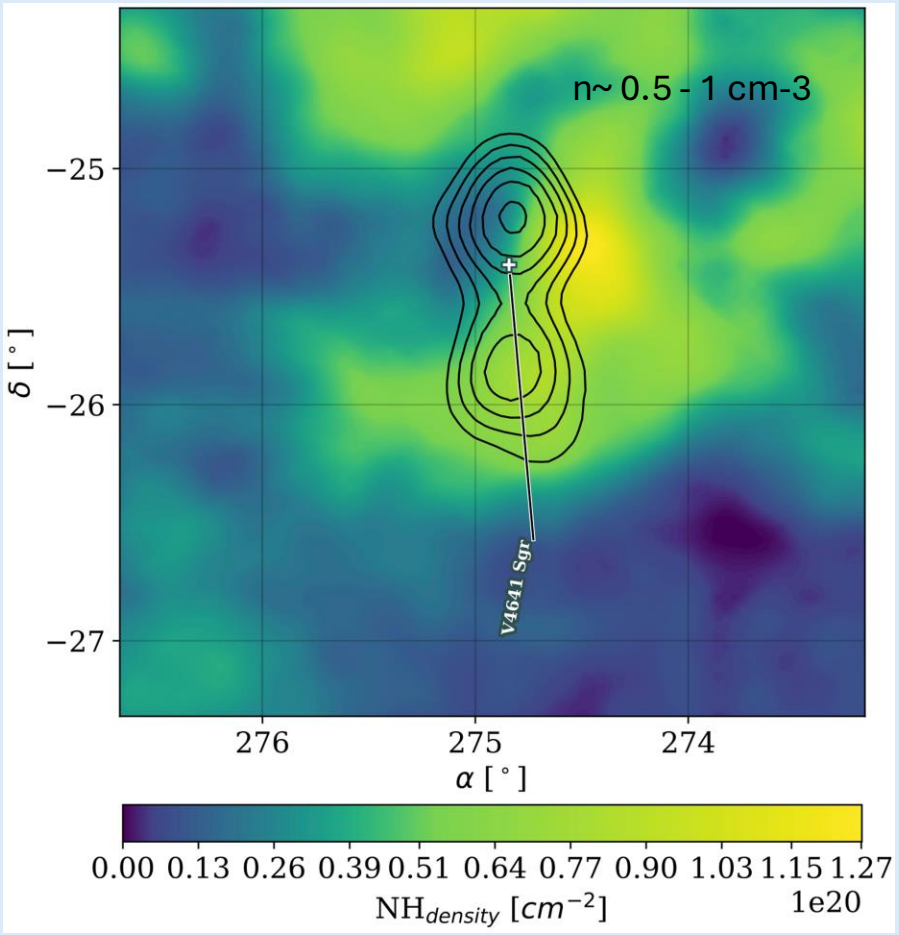
$$\dot{W}_p(E_p > 1\ \mathrm{PeV}) = L_\gamma \frac{t_{pp}}{t_{esc}}$$

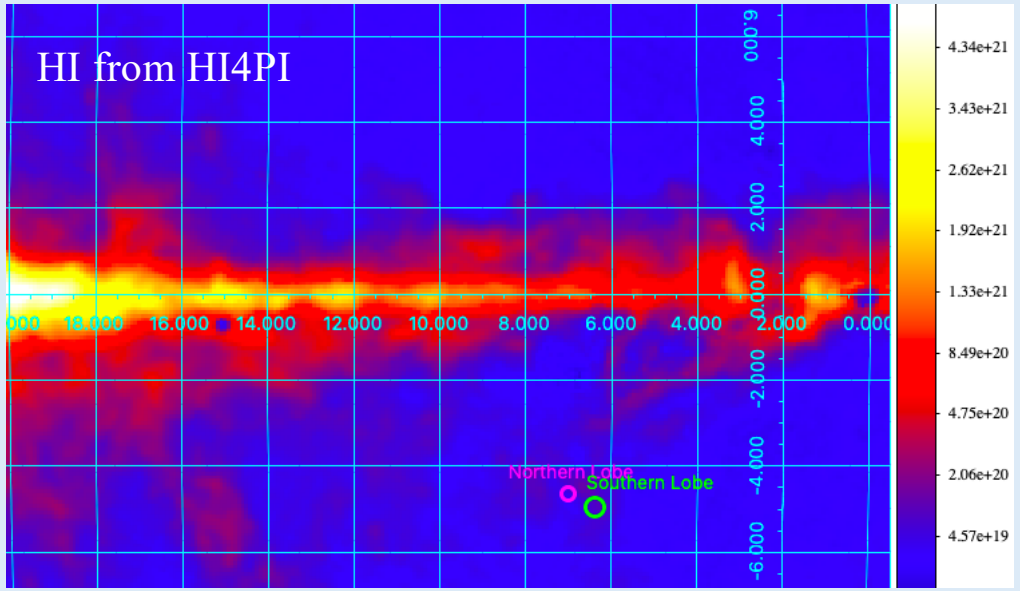
$$\simeq 10^{39} \eta \left(\frac{L_\gamma}{10^{34}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{D_0}{3\times 10^{30}\ \mathrm{cm^2\ s^{-1}}}\right)\left(\frac{n}{1\ \mathrm{cm^{-3}}}\right)^{-1}\ \mathrm{erg\ s^{-1}}$$

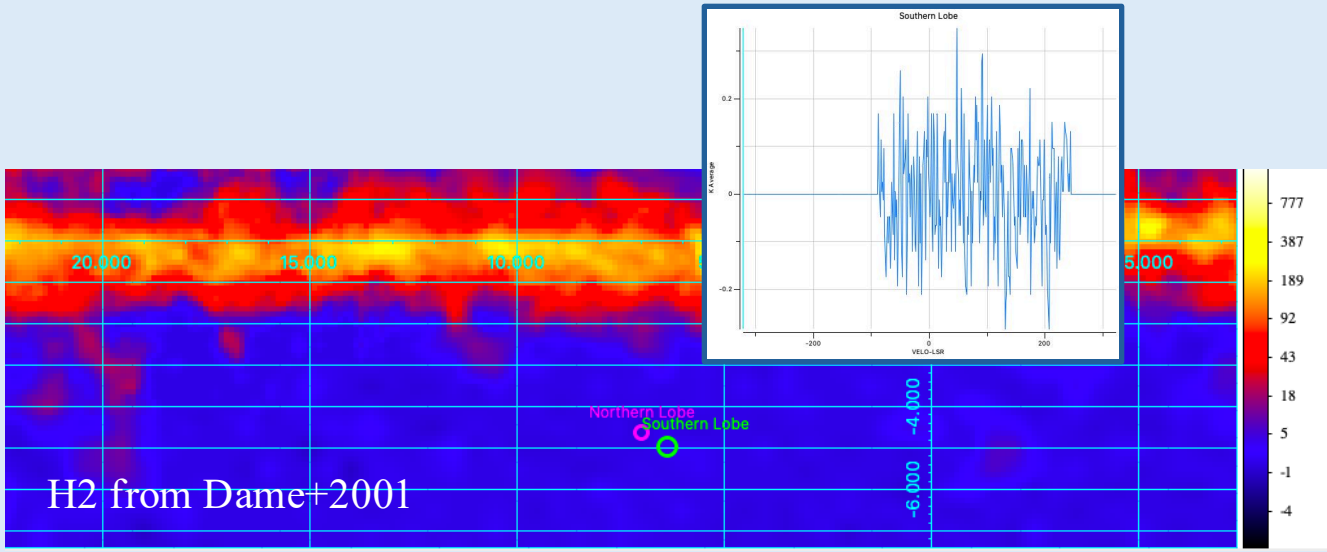
$W_p \approx 1 \times 10^{50}$ Total budget in protons > 1 GeV if n = 1 $\mathrm{cm^{-3}}$

Gas density

HAWC Collaboration, Nature 2024







Observations & Observational Proposal

X-rays

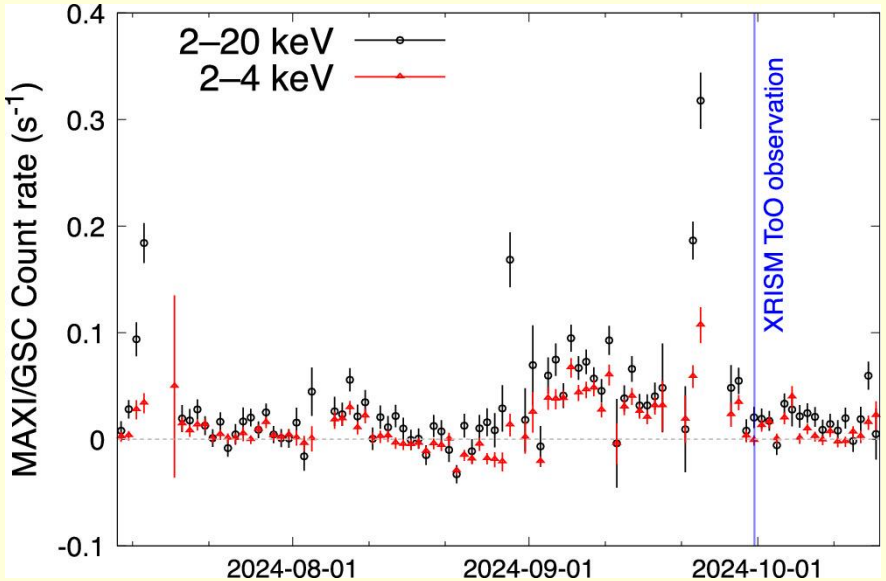
- MAXI/GSC announcement of renew BH activity AteL #16804
- INTEGRAL obs from 2024-09-07 at 16:44 until 2024-09-08 at 22:16 UTC. AteL #16881
- XRISM (ToO 12 ks on 2024-09-07 covering 60% UHE emission)
- Nustar proposal (P.I. Kaya and Naomi)
- Chandra proposal (P.I. Kaya and Naomi)

Radio Observations

- Observations with APEX (P.I. Eduardo, Daniel)
- Observations with Nobeyama (P.I. Naomi)

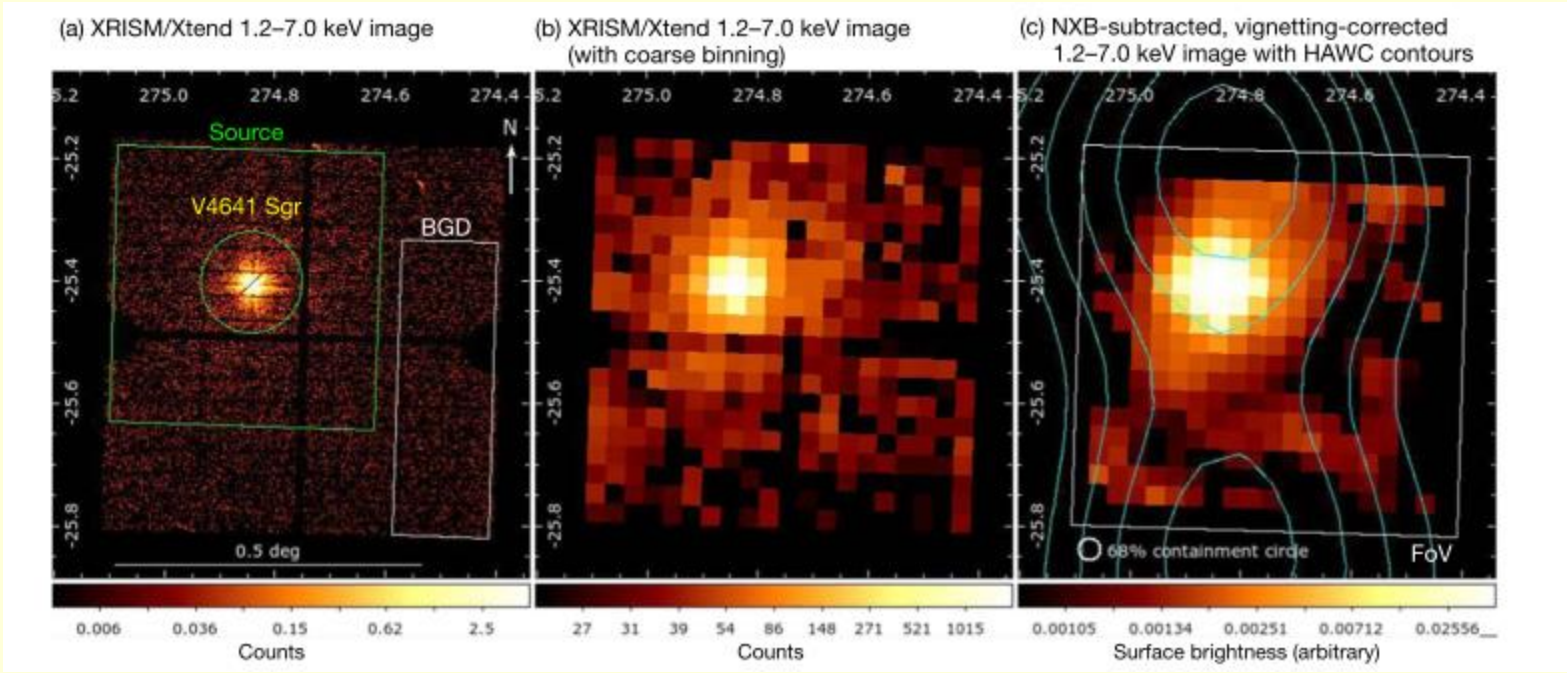
XRISM discovers extended X-ray emission

XRISM 12.2 ks



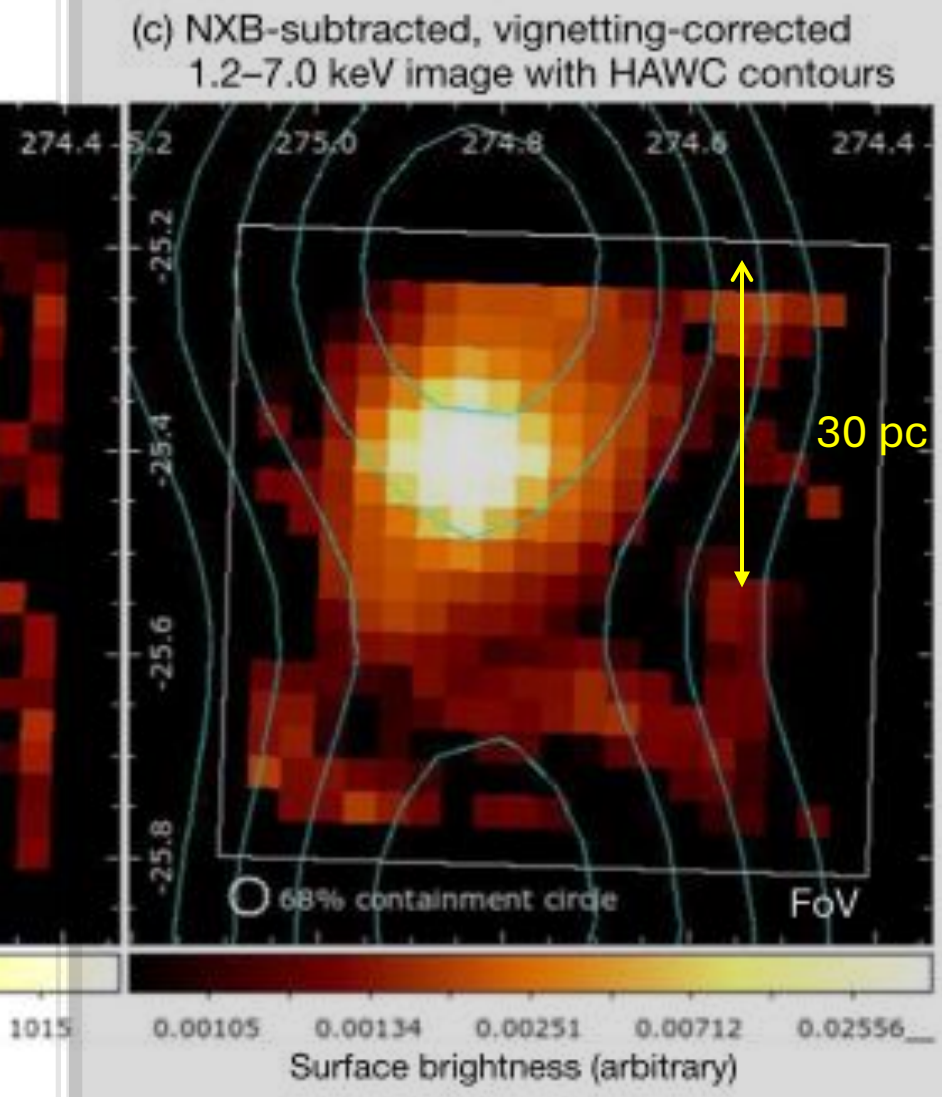
Negroro et al, 2024

Susuki et al, 2025



Extended emission either thermal
or non-thermal emission
If thermal constraint on gas density

Extended Xray from V4641 Sgr region



$$\frac{L_\gamma}{L_X} \rightarrow B \sim 10\ \mu G$$

$$t_{cool} \approx 100\ yr \left(\frac{E_e}{1PeV}\right)^{-1} \left(\frac{B}{10\mu G}\right)^{-2}$$

$$R_{diff} = \sqrt{2\ D(1PeV) t_{cool}}$$

$$\sim 80\ pc \left(\frac{\eta\ D(1PeV)}{10^{31} cm^2 s^{-1}}\right)^{1/2} \left(\frac{E_e}{1PeV}\right)^{-1/2} \left(\frac{B}{10\mu G}\right)^{-1}$$

Xray extension ~ (13± 5) pc $\rightarrow \eta < 1\ or\ B > 10\ \mu G$

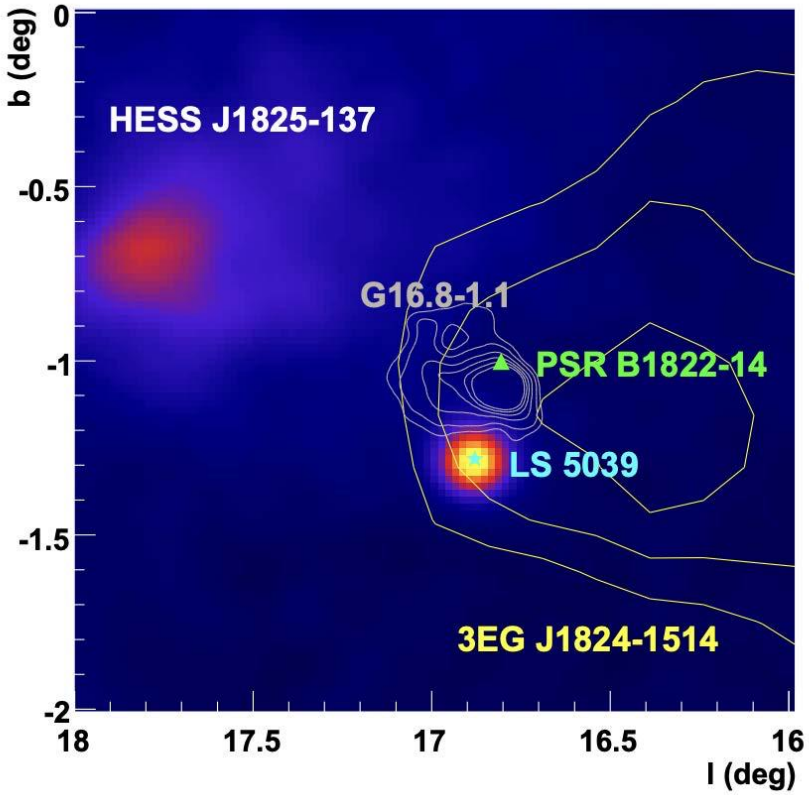
Susuki et al, 2025

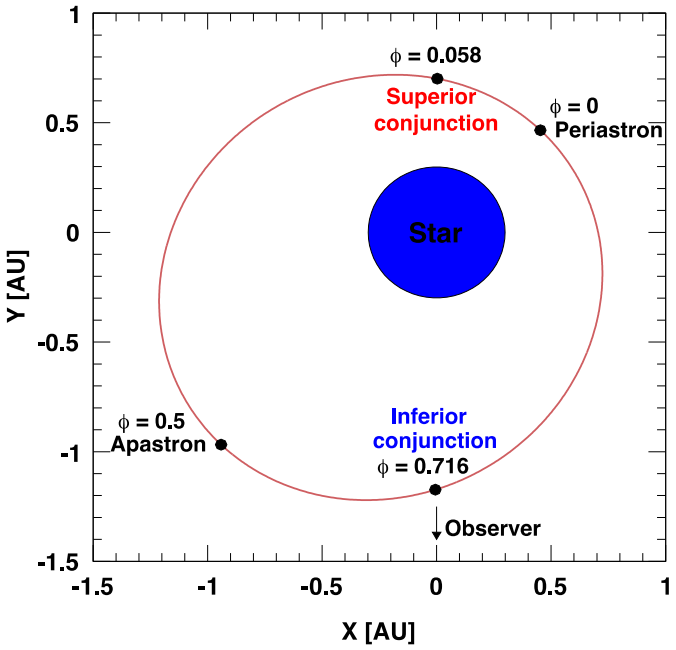
Summary of HAWC microquasars

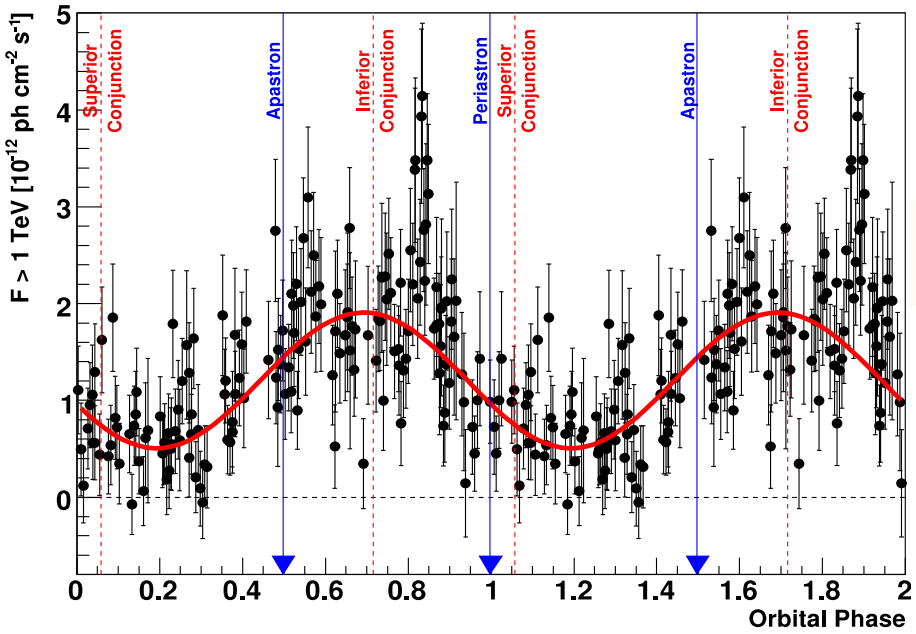
- Accretion
  - SS 433 : likely super-Eddington
  - V4641 Sgr: super-Eddington
- Jets
  - SS 433 : most powerful jets known in the Galaxy ~$10^{39\text{-}40}$ erg/s
  - V4641 Sgr : superluminal jets
- BH activity
  - SS 433 : persistent BH activity
  - V4641 Sgr : powerful outbursts – intermittent BH activity ~ every 2 yr

- Hard Spectra up to 100-200 TeVs
- Morphology of the emission
  - SS 433 : lobes
  - V4641 Sgr : lobes or extended source ?
- Similar acceleration locations
- Origin of the emission
  - SS 433 : sub-PeV electrons accelerated at termination shocks. Barion loaded jet, proton energy budget 3 x10^{50} erg ~ 100% Edd
  - V4641 Sgr : sub-PeV electrons accelerated at termination shocks – – Extension of diffuse Xray emission 10pc – Energy budget for hadronic emission : few objects as V4641 Sgr could explain the local PeV CR flux

- Accretion driven or interaction pulsar - star winds
- Distance = 3.5 kpc
- 23 M_o O6.5V star and 3.7 M_o compact object
- mildly eccentric 3.9 day orbit.
- From radio to TeV energies.
- Flux and spectral modulation as a function of its orbital period.





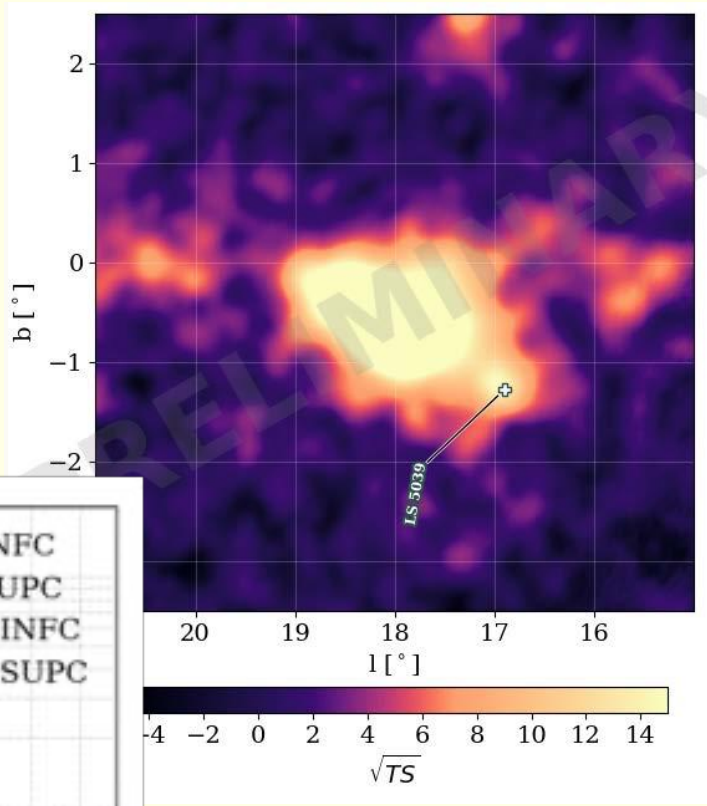


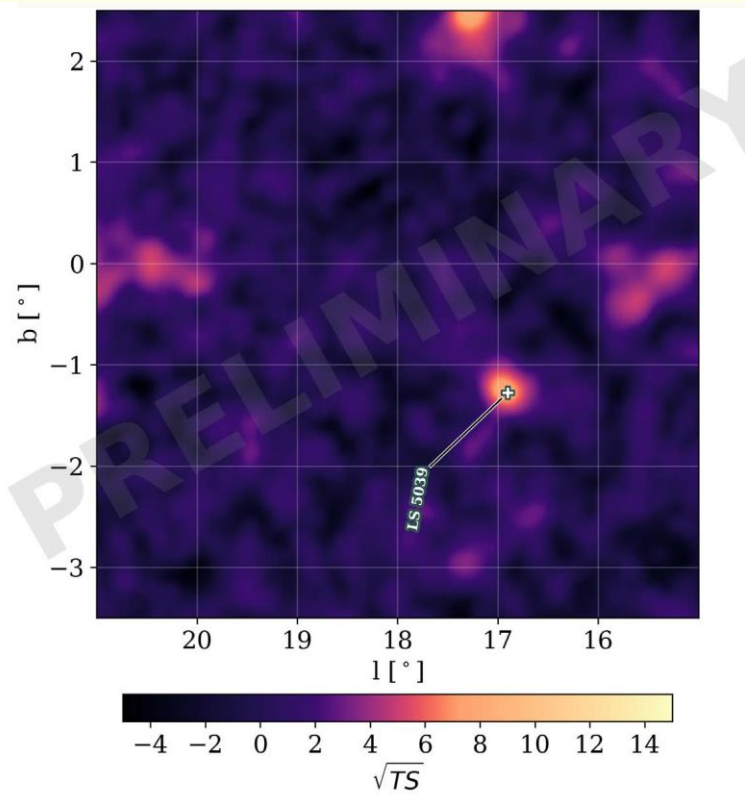
(Aharonian et al. 2005)

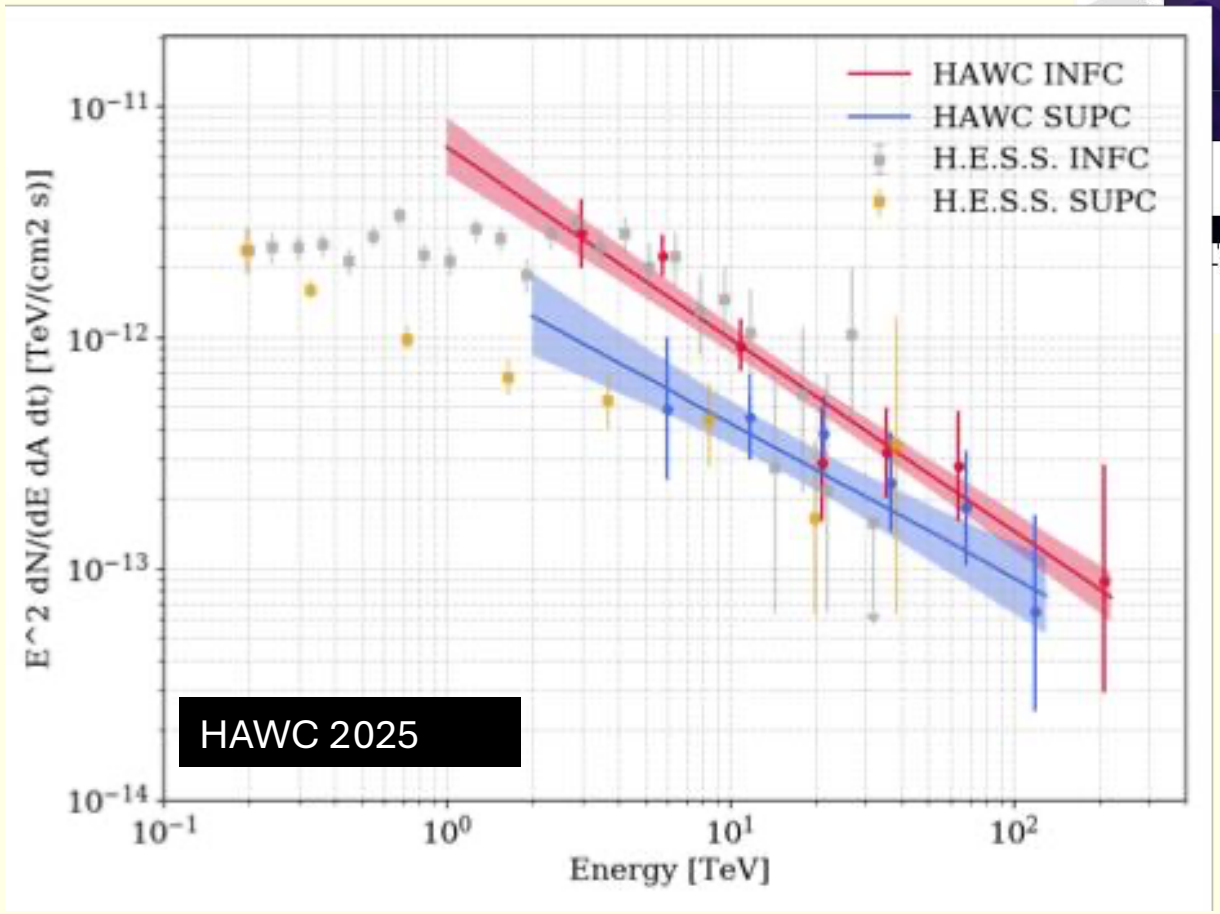
H.E.S.S. 2007 Astrophys Space Sci (2007) 309: 277–284

LS 5039

LS 5039 with HAWC



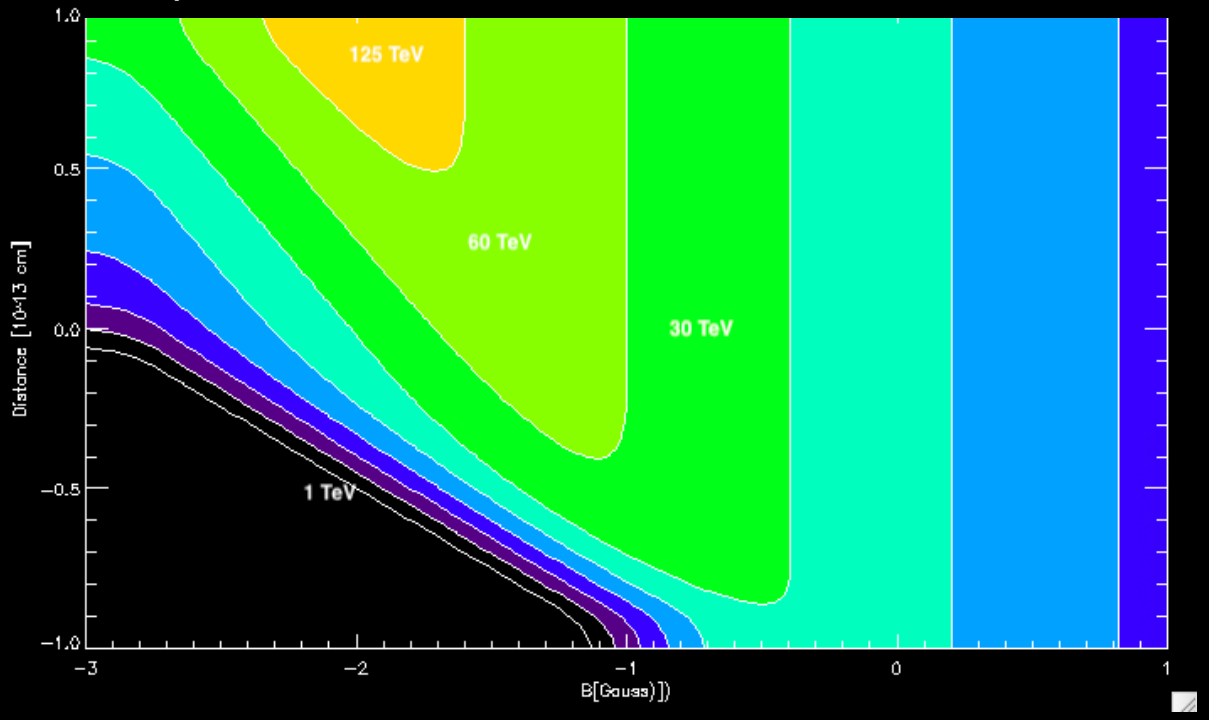




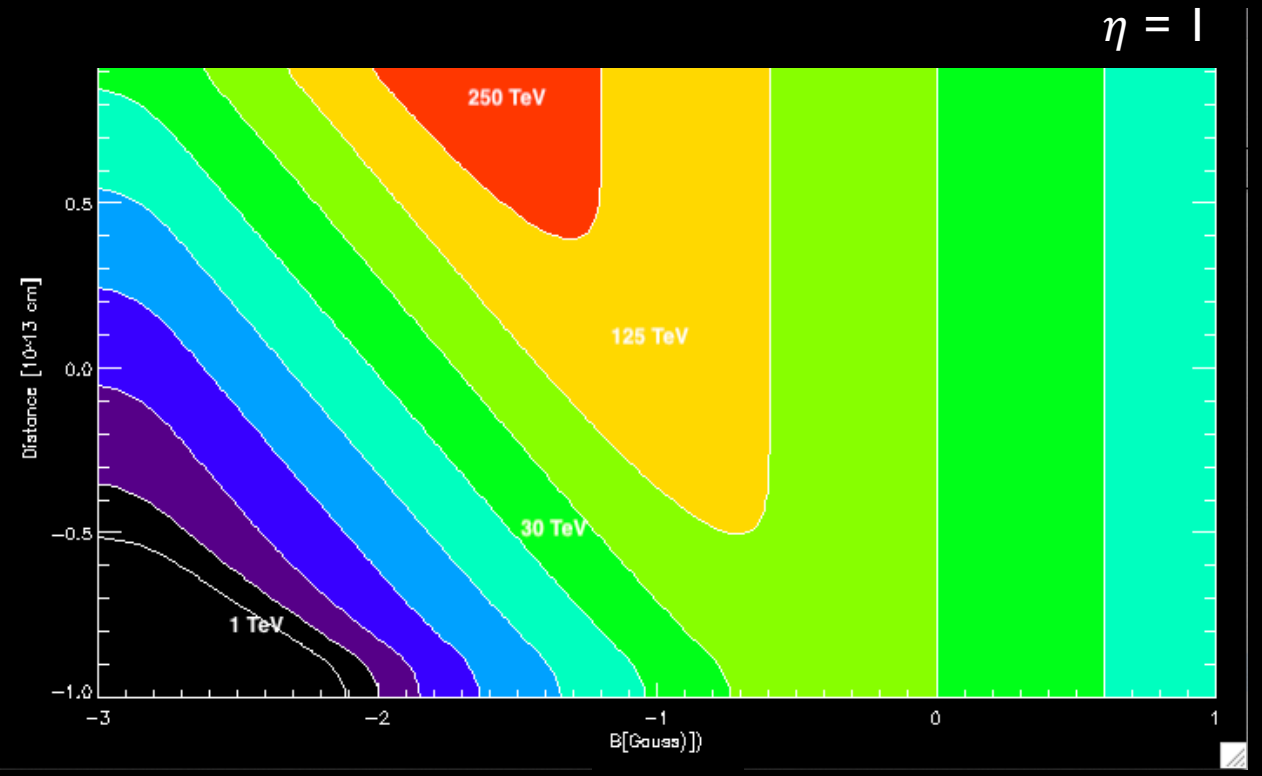
- 1910 days of data
- Simultaneously likelihood fit with diffuse emission and background sources
- 8 σ
- PL preferred up to at least 100 TeV
- ~5σ modulation between 2 and 118 TeV → likely the emission up to the highest energy originates close to the binary

Maximum acceleration energy in LS 5039

$\eta = 10$



$\eta = 1$



$\eta \gtrsim 10$ **B < 0.1 G** **d $\gg 10^{13}$ cm**

$\eta \sim 1 \rightarrow$ **B $\lesssim$ 0.1 G**

- HAWC emission detected up to 118 TeV → B-field, acceleration efficiency and acceleration location in LS 5039
- Difficult to accelerate electrons up to hundreds TeV within the binary
- Maybe room for pp or pγ ?

Summary and outlook

SS 433

- Discovery of multi TeV gamma-rays from SS 433/W50
- Extension of the spectra of SS 433 lobes up to 100 TeV

V4641 Sgr

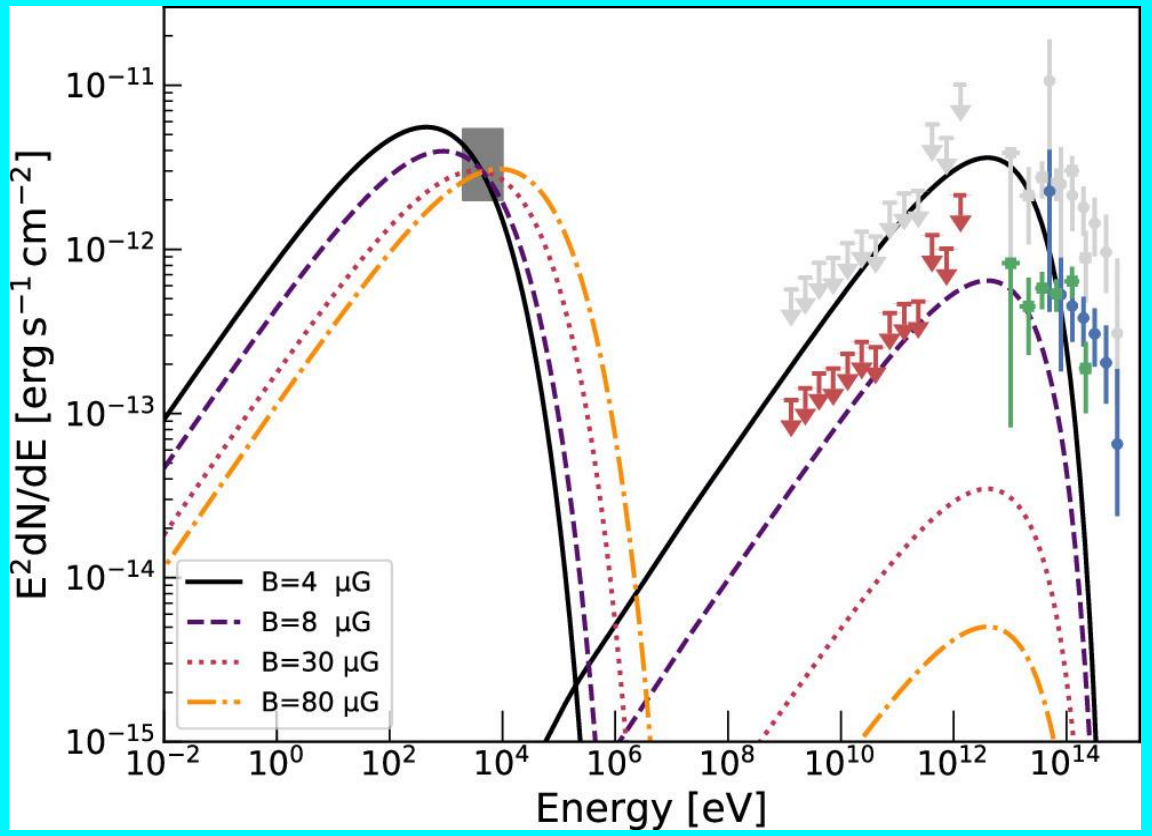
- Discovery of hundred TeV gamma-rays from V4641 Sgr
- Multiwavelength analysis of V4641 Sgr ongoing – First discovery of extended emission with XRISM

LS 5039

- Extension of the HESS modulated spectra up to 118 TeV

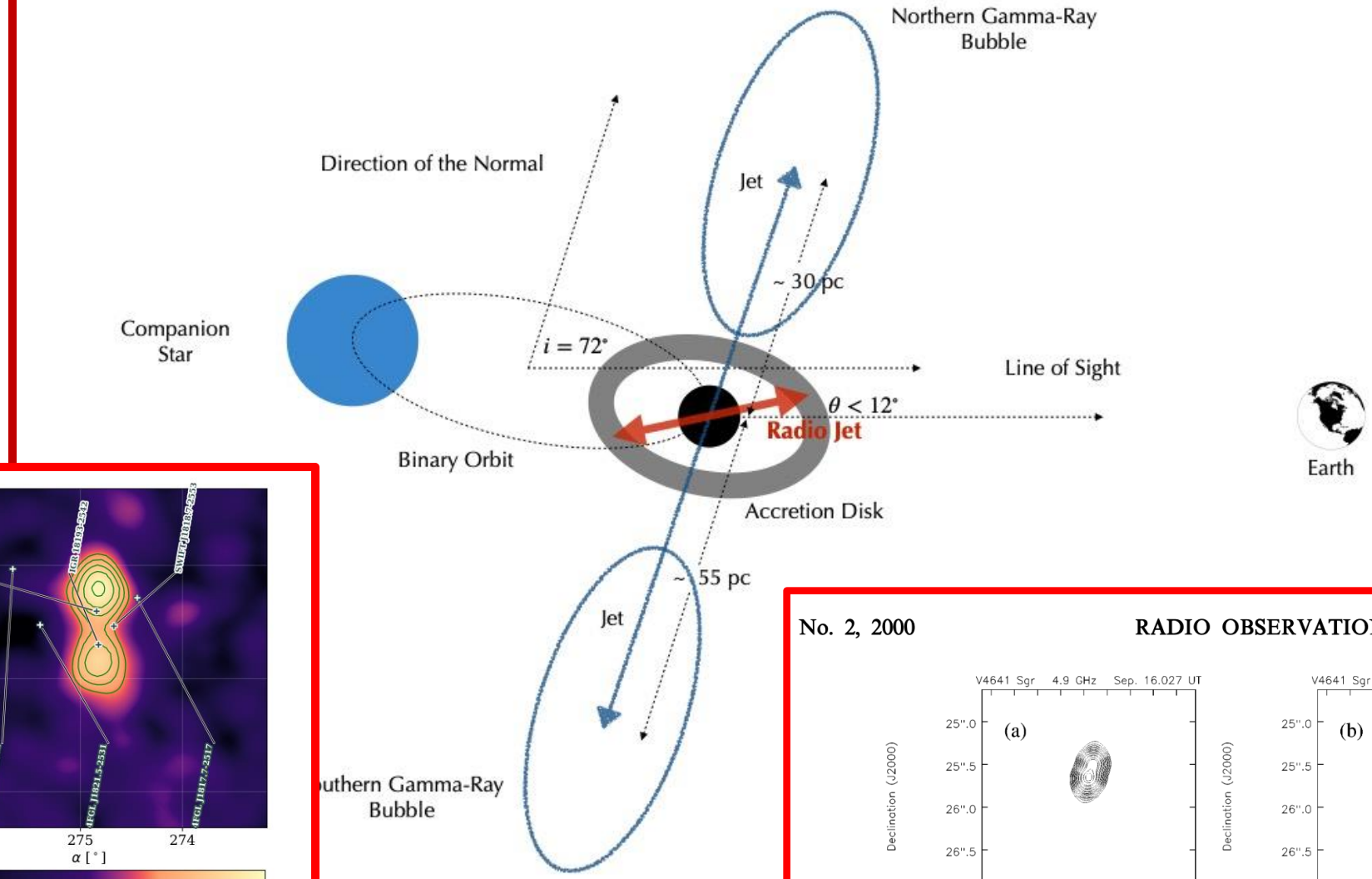
Many ongoing multiwavelength efforts.

XRISM discovers extended emission



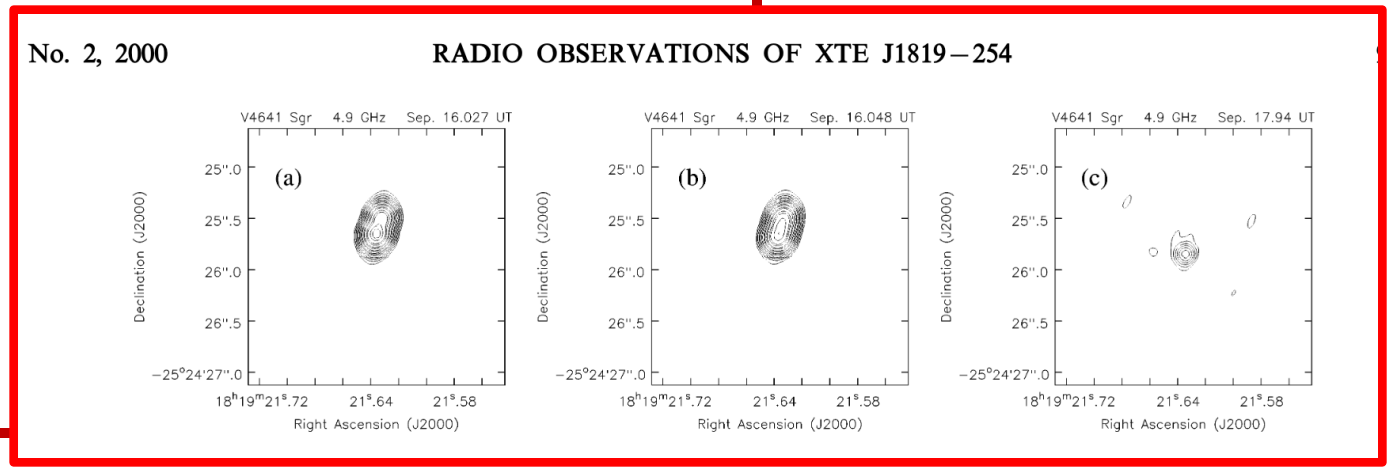
Susuki et al 2025

HAWC Collaboration, Nature 2024



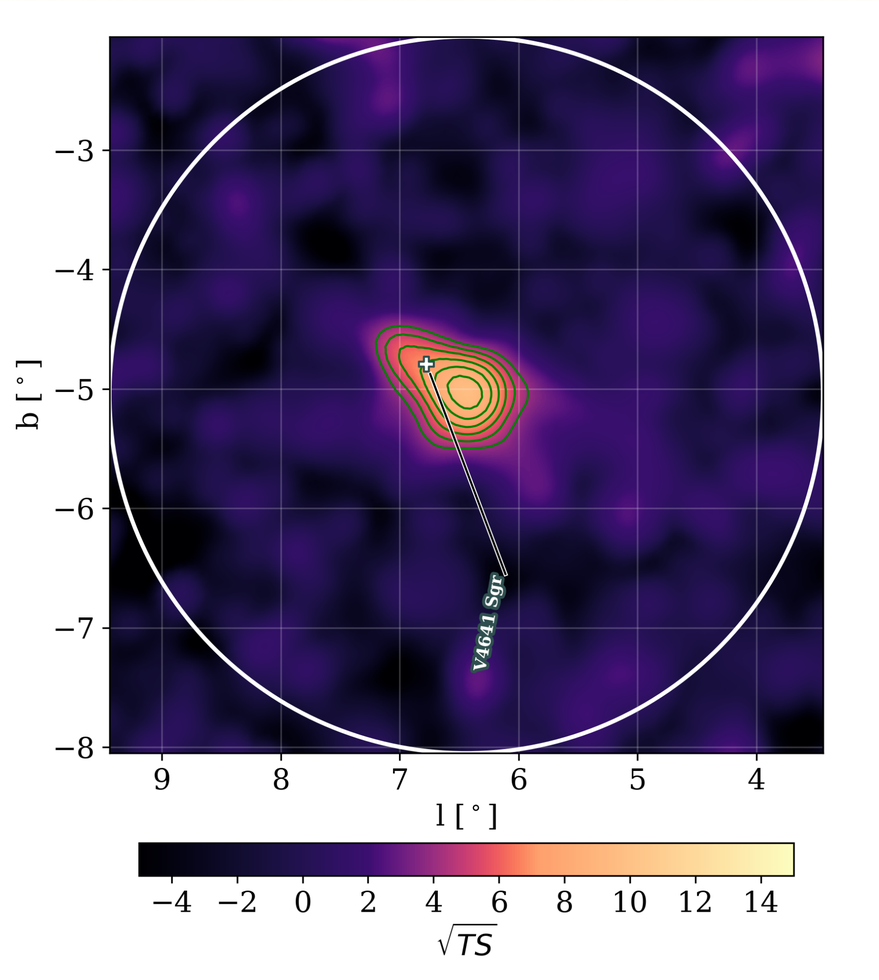
Arc-sec Radio jet-like structure in the outburst of 1999 (Hjellming et al, 2000)

100 pc persistent structure, HAWC 2022



DETAILS ON THE ANALYSIS OF V4641 SGR

SIGNIFICANCE MAP



ROI - 3deg

2321 days

Multi-source fitting - No diffuse emission

Contours from 4 to 9 sigmas

PSF (68% containment) between 0.28 to 0.18

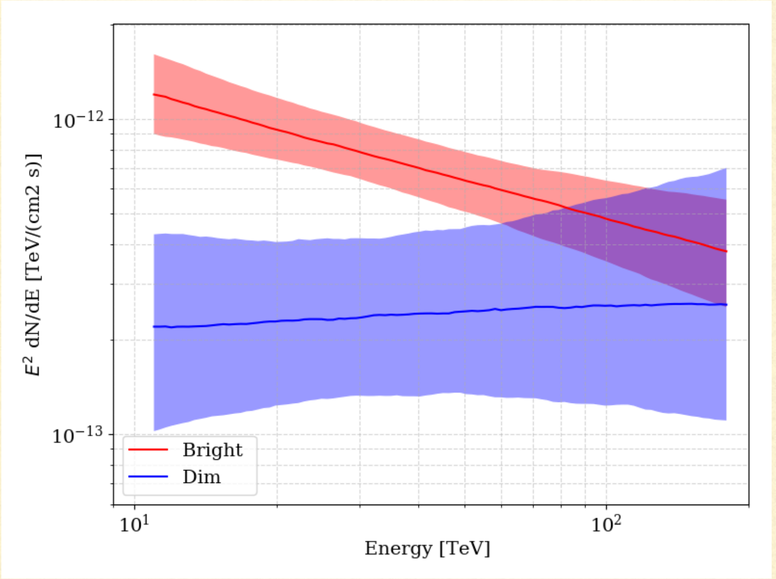
MORPHOLOGICAL STUDIES

Model	−logLikelihood	BIC	AIC
One Point Source	60733	121520	121473
One Asymmetric Extended Source	60694	121485	121403
Two Point Sources	60694	121498	121404

Lower BIC model preferred

Lower AIC model preferred

BIC and AIC penalize complexity



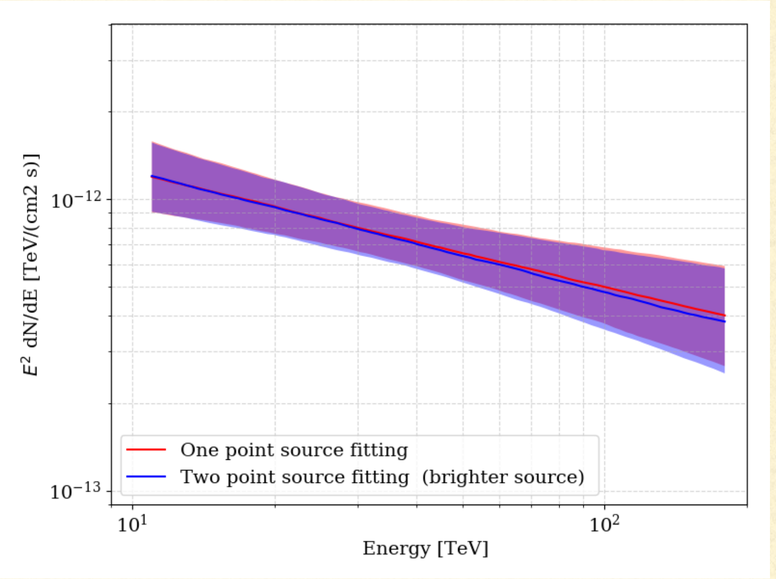


Figure 4: Spectrum energy distribution. Left: the best fit results from the two point source assumption; The red line represent the brighter lower source