



On behalf of the HAWC Collaboration
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Detecting Micro-quasars with HAWC



CDY online seminar 13.11.2024

Outline

- HAWC Observatory
- The CR paradigm
- 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)**

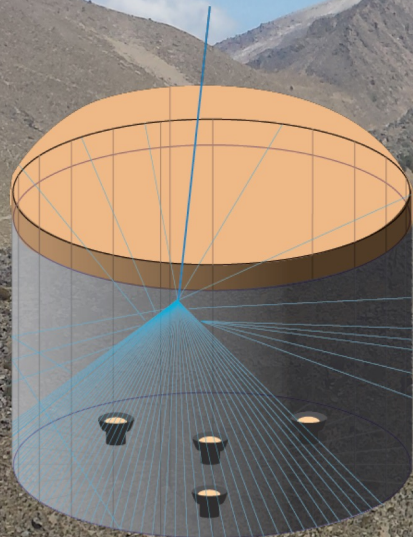
Energy range: 100s GeV to
100s TeV

Observing $>95\%$ of the time

Angular resolution $0.2^{\circ} - 1^{\circ}$

345 outriggers since 2018

300 ×

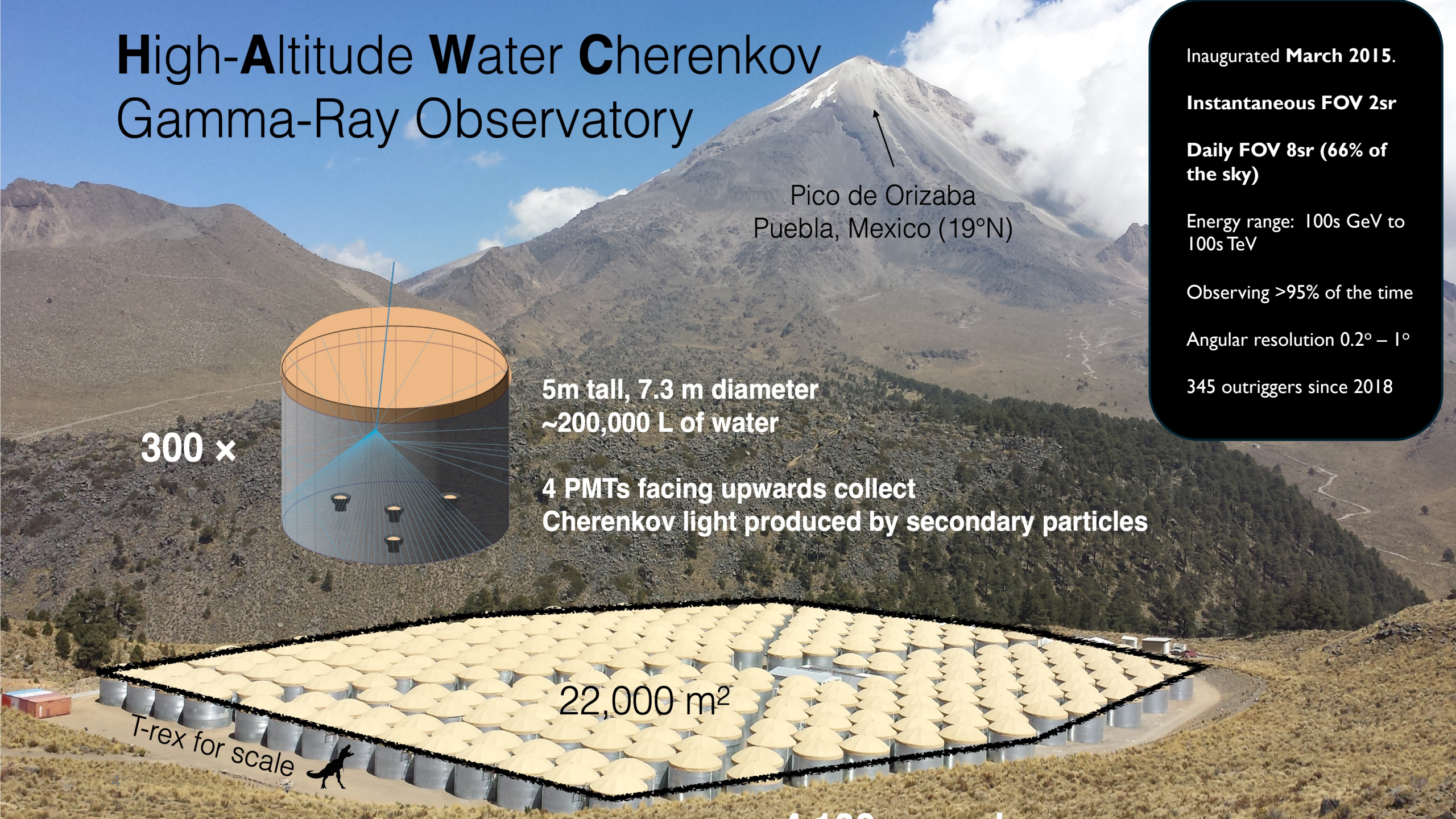


5m tall, 7.3 m diameter
~200,000 L of water

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.

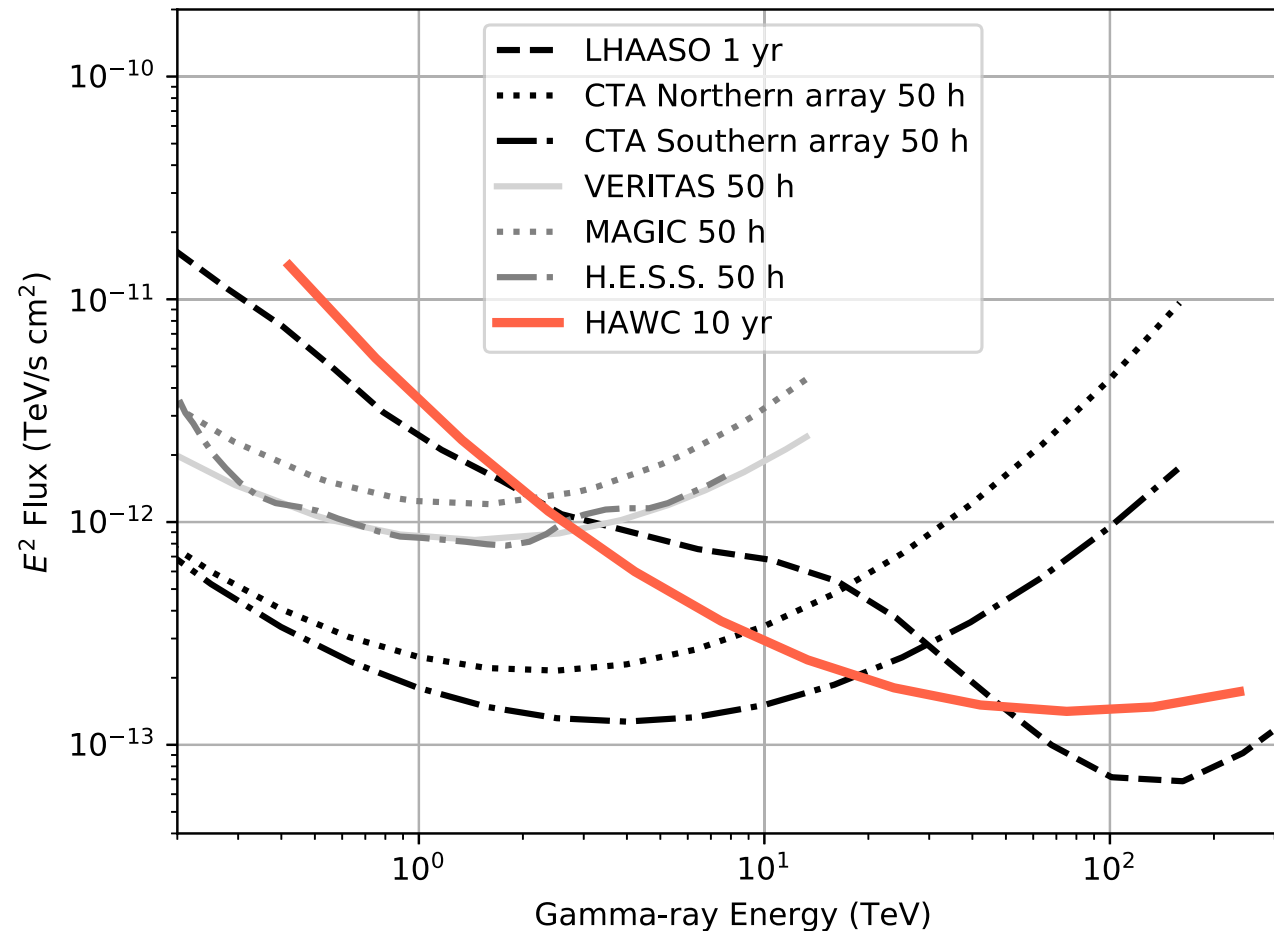
Particles from the shower induce Cherenkov light in water, detected by 4 PMTs.

Measure: time and light level in each PMT

Reconstruct: core, energy, direction and background rejection



Pass 5 sensitivity



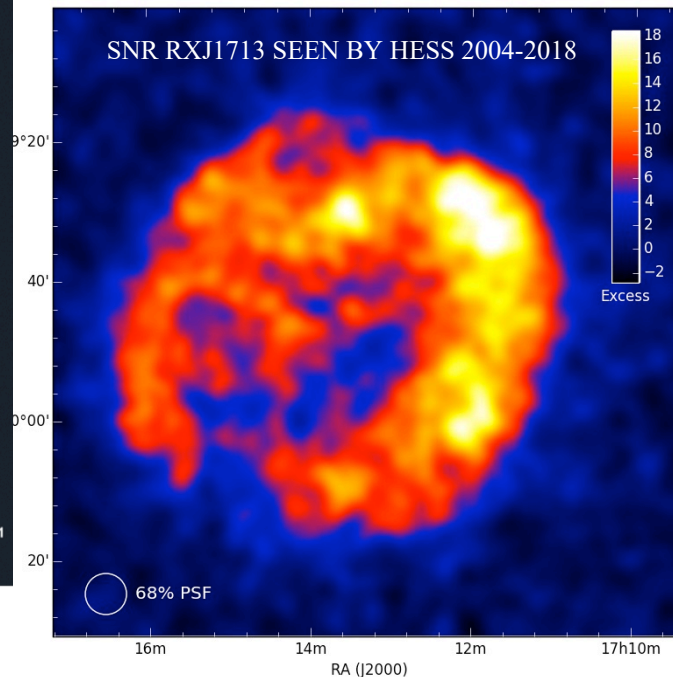
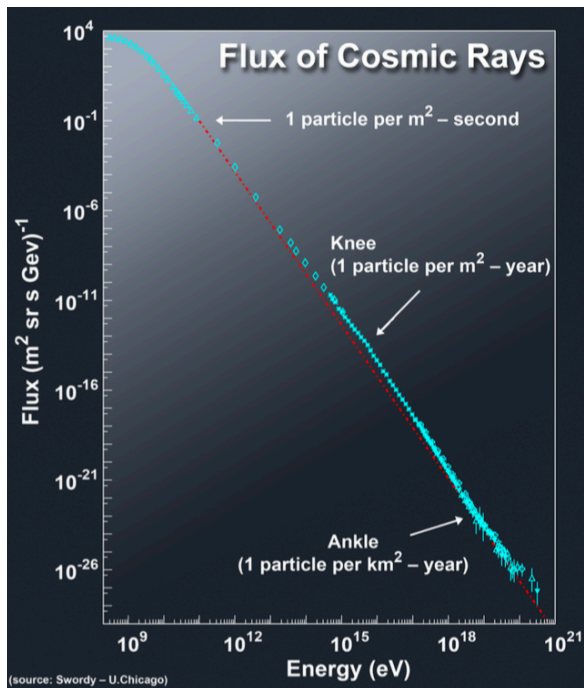
Improved background rejection

Better angular resolution

Improved sensitivity at hundred GeVs

Once upon a time the SNR paradigm

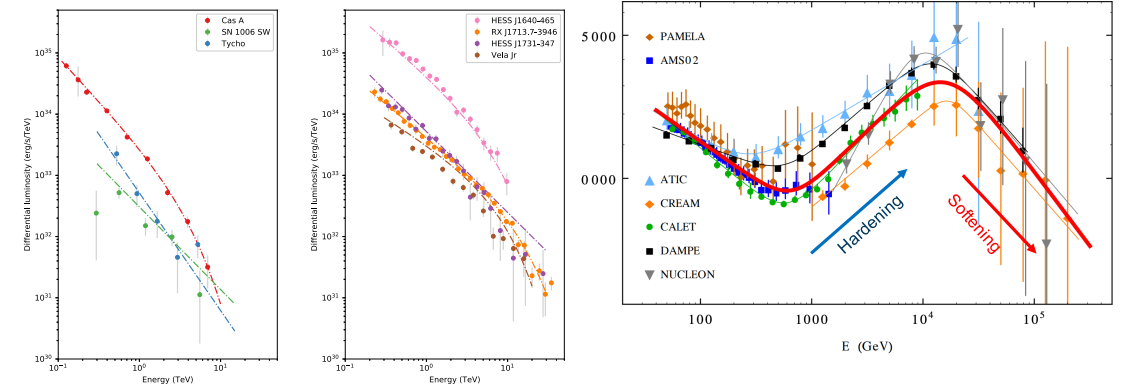
- Research focus : Local CR spectrum
- Featureless CR PL spectrum up to PeVs
- SNRs major CR contributors – energy budget and DSA theory working well in SNR shocks



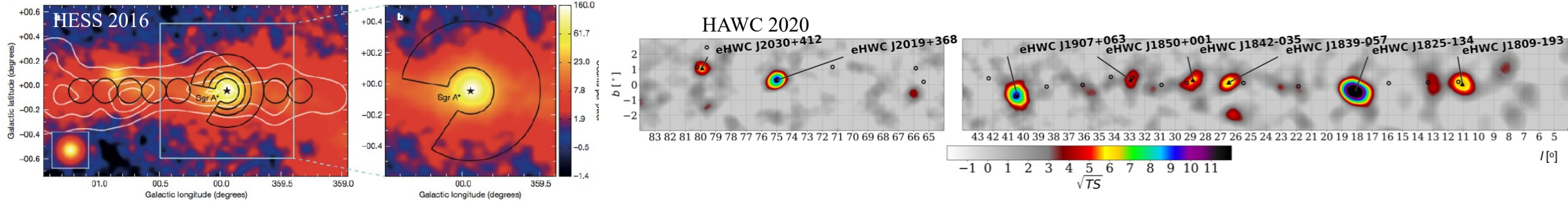
Challenges

- Cutoffs at few TeV in SNRs – CRs up to 100 TeVs
- Including B amplification from CRs - CRs up to 100 TeV
- High precision measurements reveal multiple features in local CR spectrum

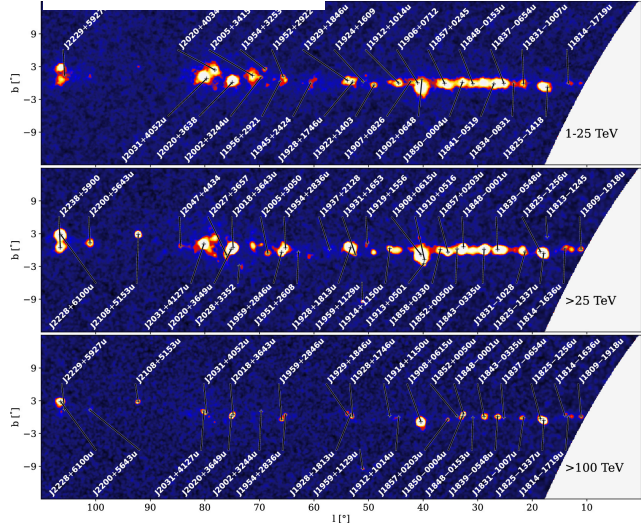
Aharonian+2019



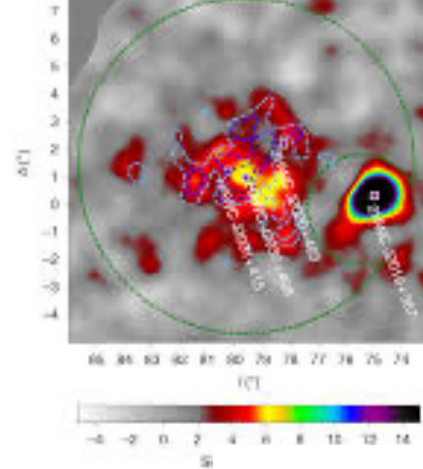
Reformulating the CR paradigm



LHAASO 2024

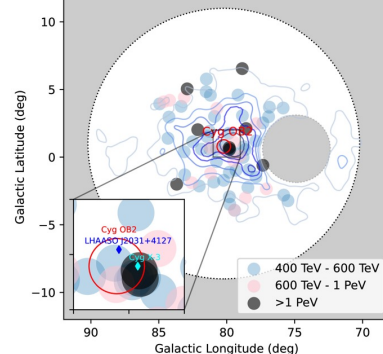


HAWC 2021

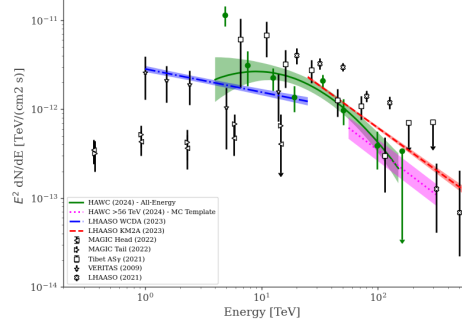


- Several classes of PeVatrons and superPeVatrons - revealed with γ s
- Research focus: investigate classes of CR sources: study confinement, acceleration and escape
- SNRs still viable CR sources but major contributors ?

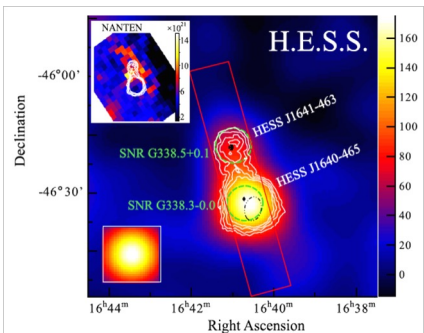
LHAASO 2023



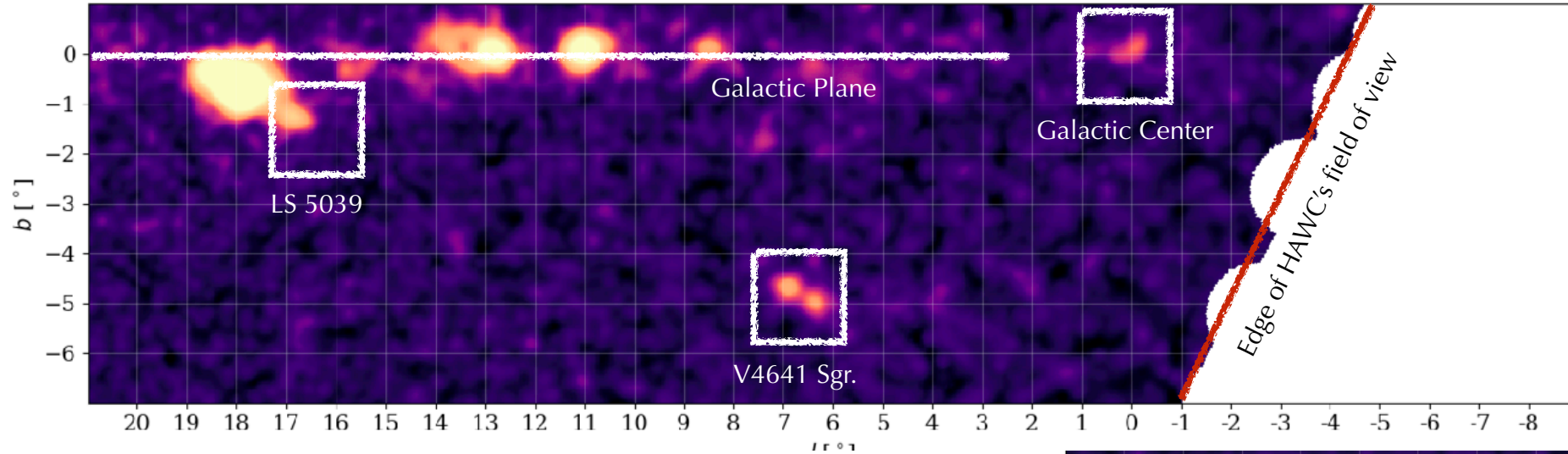
HAWC 2024



Last discovery : micro-quasars !

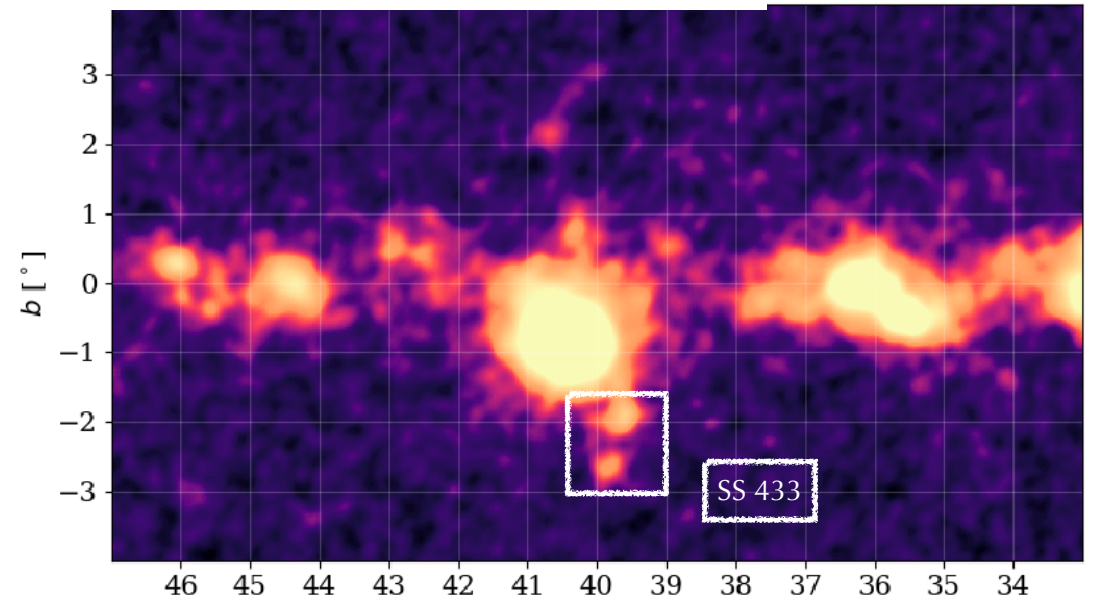


Looking for binaries with HAWC



Xiaojie Wang

	Distance (kpc)	Companion star mass ($M_{\odot}$)	Compact star mass ($M_{\odot}$)	Orbital period (days)	Orbital axis inclination ($^{\circ}$)
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

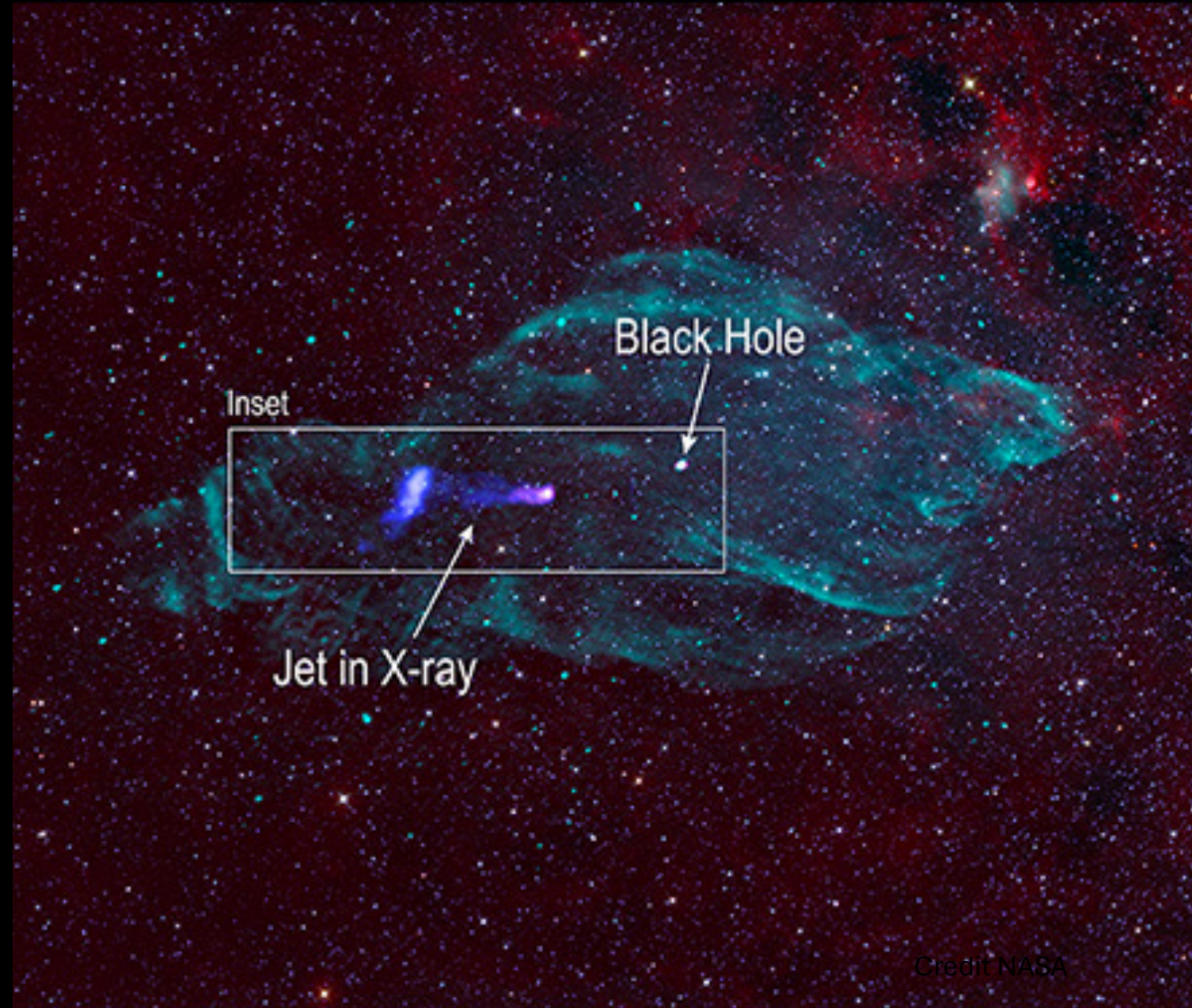
Barion loaded SS433 jet : 10^{39-40} erg/s

SS433 jet speed roughly $c/4$

Most powerful jets in the Galaxy terminate at 40 pc distance in W50 nebula and produce western and eastern X-ray lobes

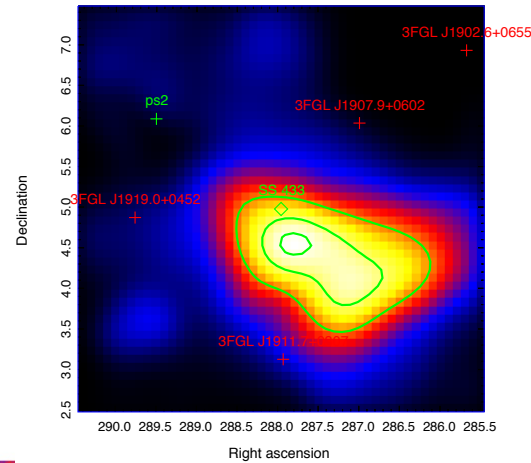
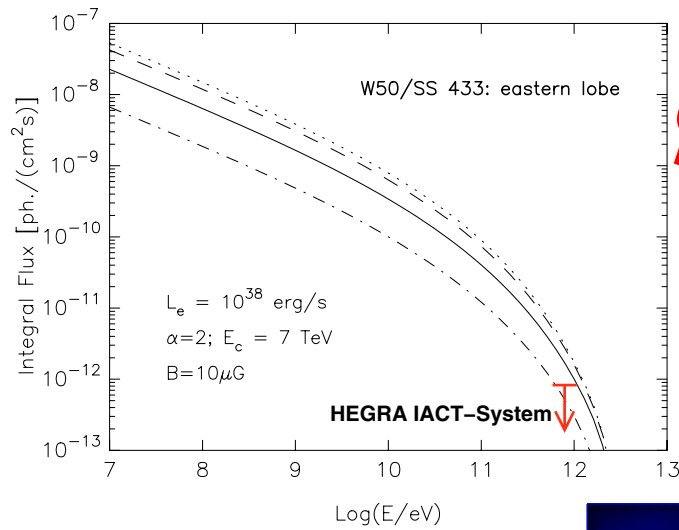
Particle acceleration & GeV-TeV radiation predicted at the lobes

Credit: NRAO/AUI/NSF, K. Golap, M. Goss;
NASA's Wide Field Survey Explorer (WISE)



Credit NASA

SS 433 with Fermi and IACTs

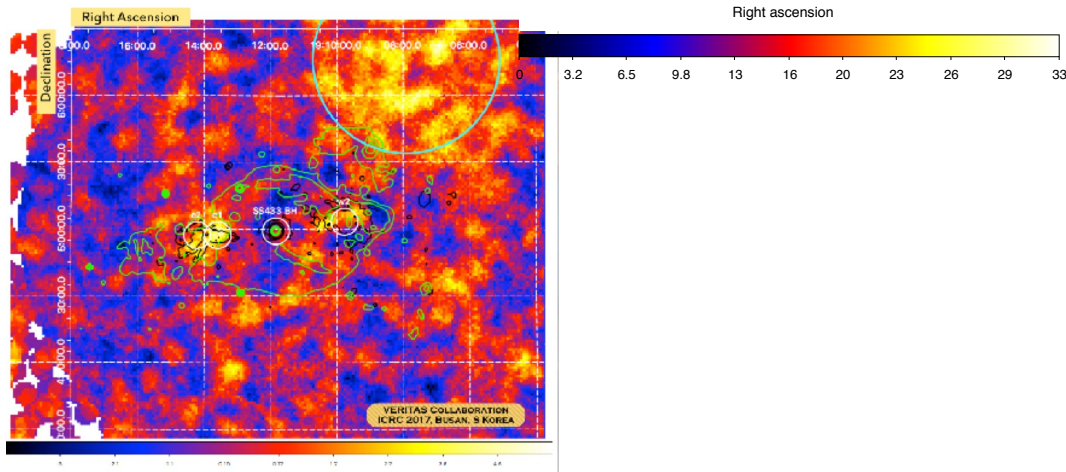


HEGRA set upper limits on the emission from e3 (Aharonian+, 2005)

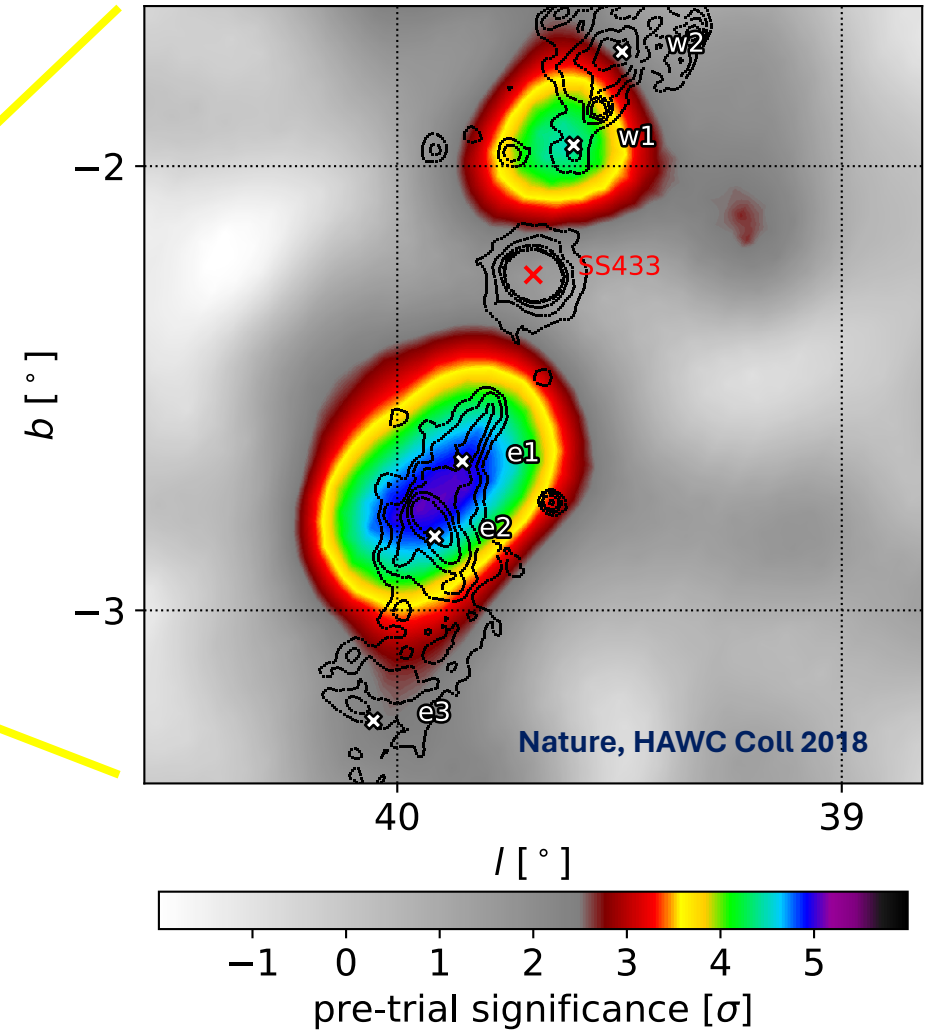
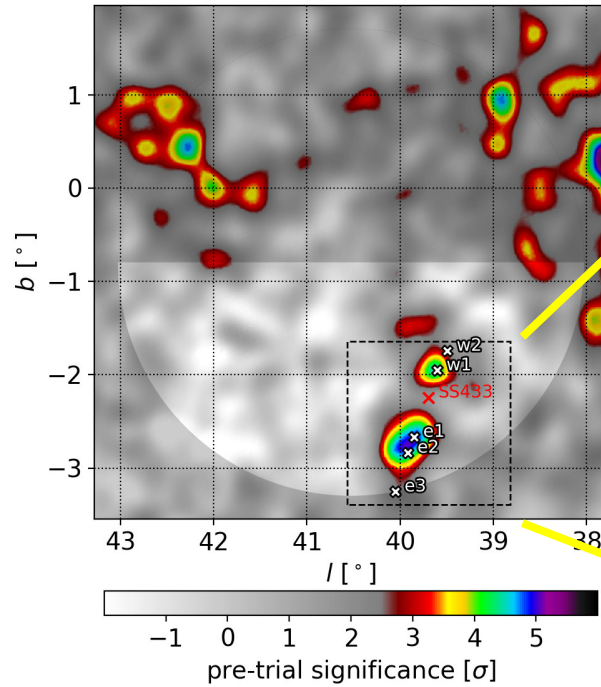
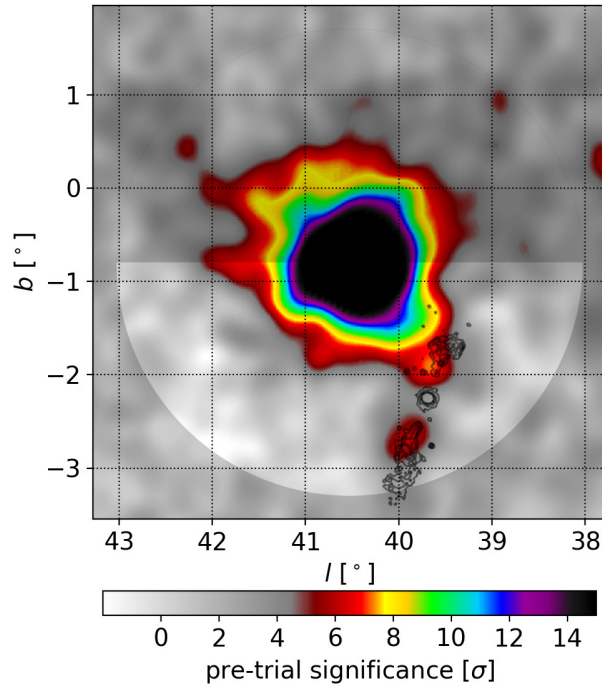
Fermi-LAT analysis revealed a persistent emission between 250 MeV and 800 MeV, possibly due to proton-proton interaction close to SS433 (Bordas+, 2015)

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

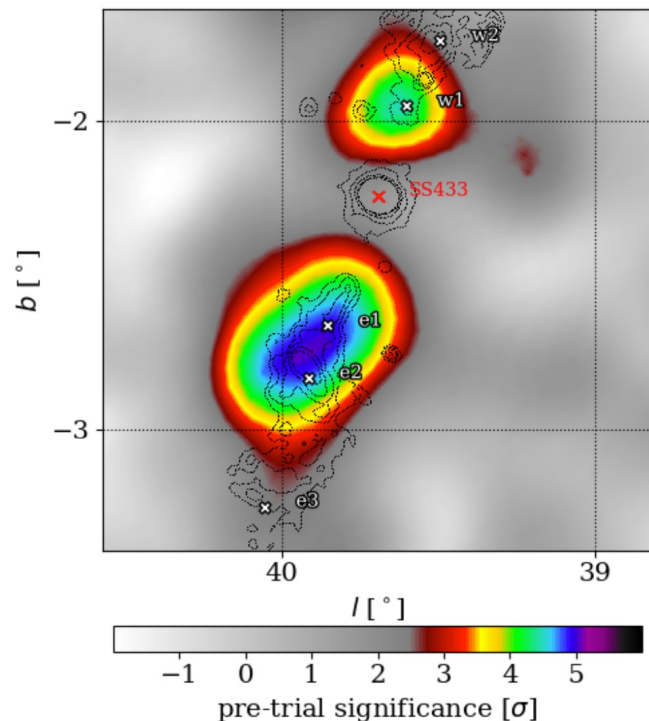
Combined HESS-MAGIC produced only upper limits.



SS-433 Lobes with HAWC



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



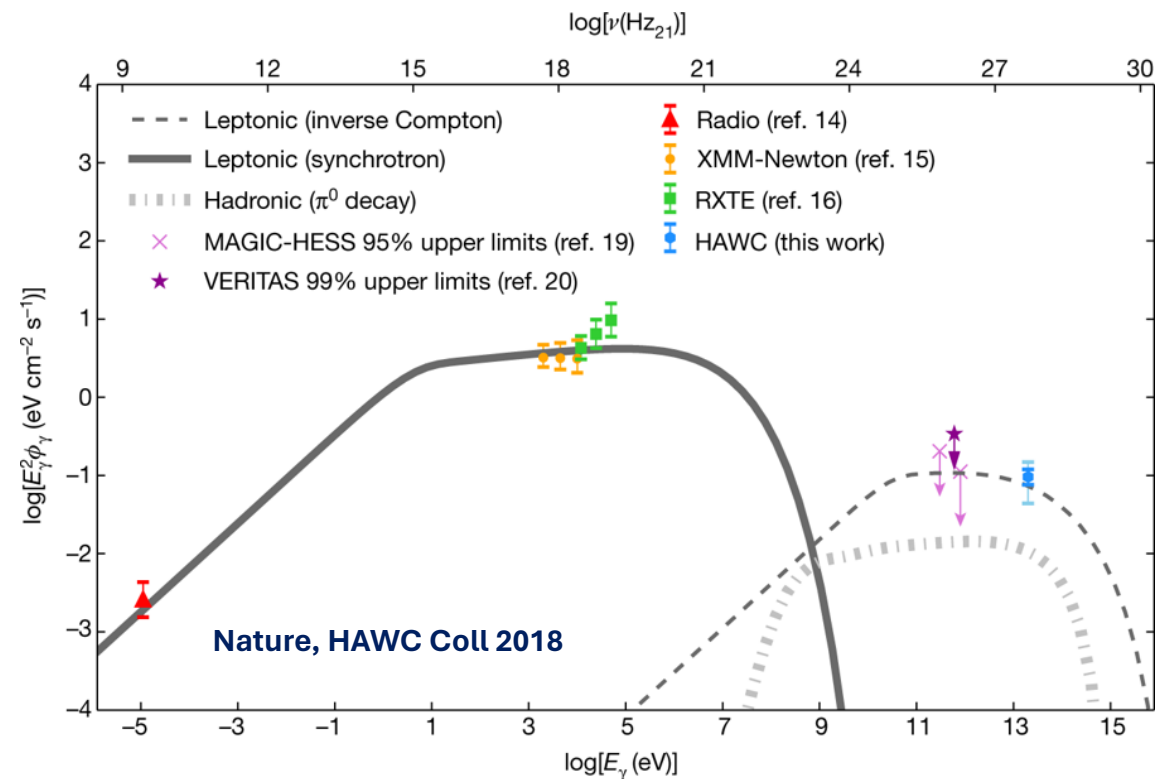
SS-433 lobes with HAWC

- HAWC emission shows that powerful jets accelerate particles beyond 100 TeV
- Combining γ and X-rays $B \sim 16 \mu\text{G}$

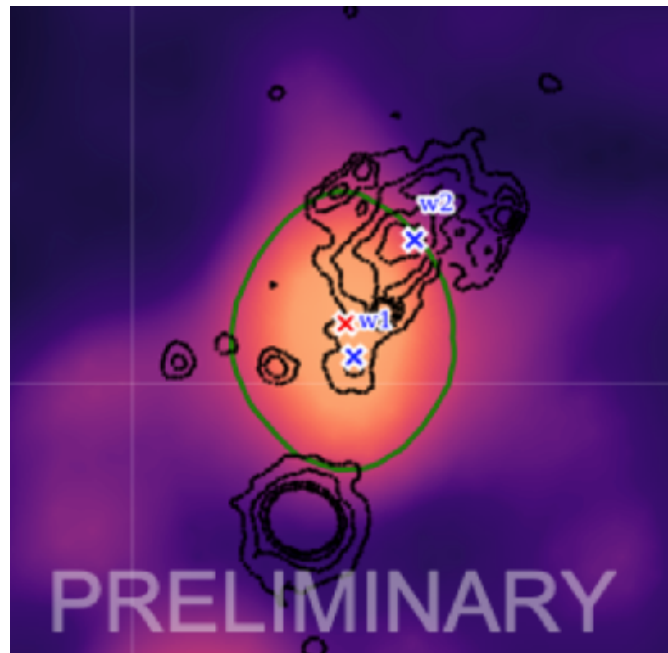
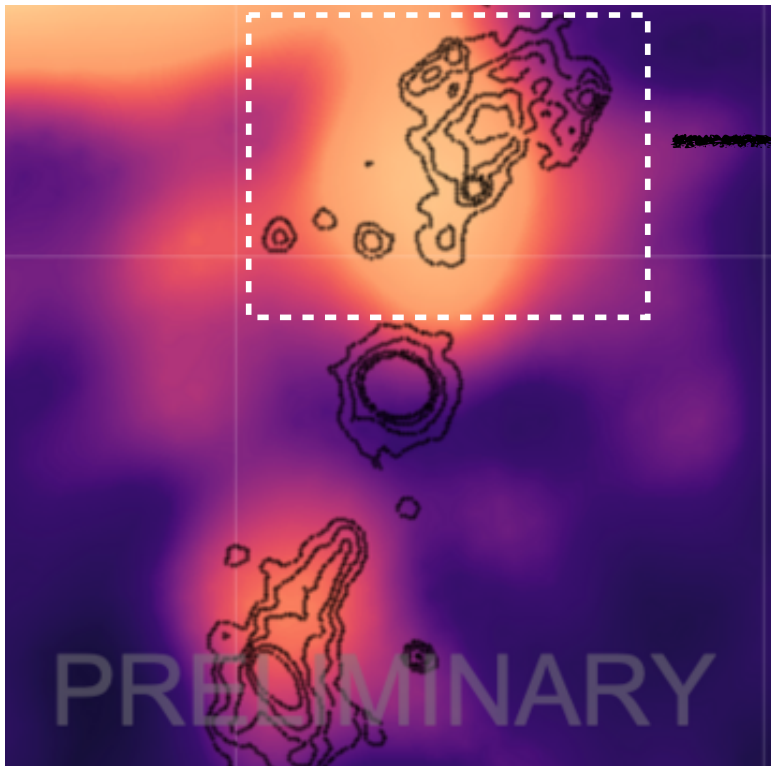
Energy Budget :

$\sim 0.5\%$ of jet power into electron acceleration

$\sim 100\%$ of jet energy over 30000 years lifetime of SS 433 for accelerating protons of at least 250 TeV if $n=0.1 \text{ cm}^{-3}$

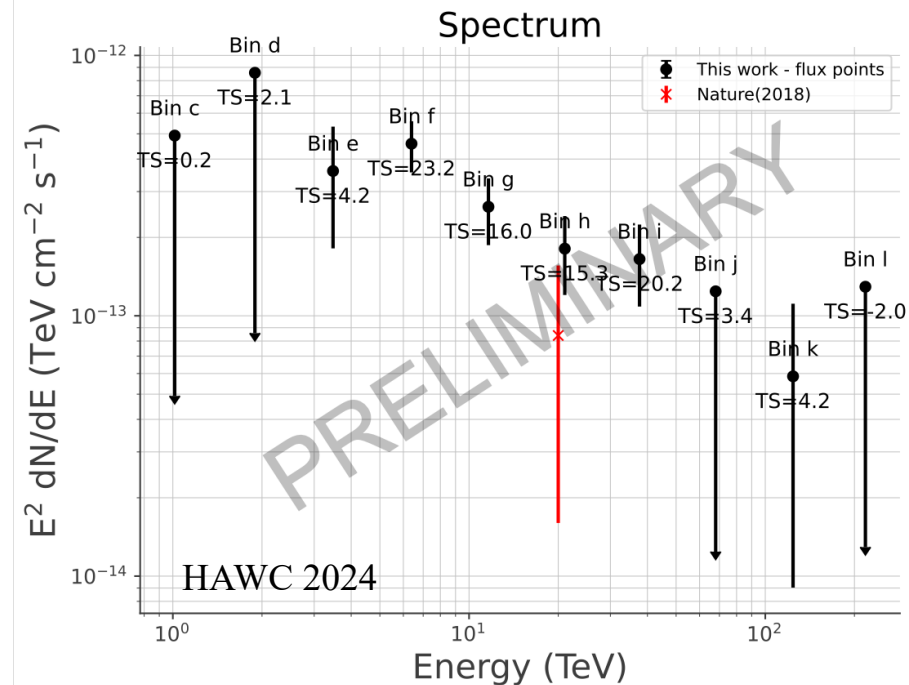


SS 433 lobes with Pass5

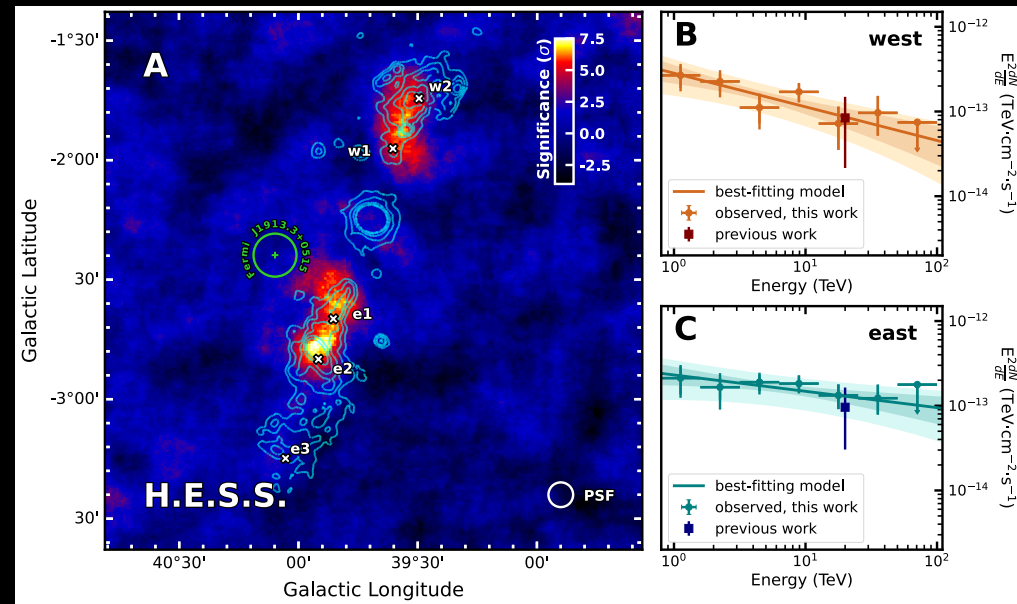


- 1922 days of data
- Better Reconstruction
- Increased significance
- Individual analysis
- Lobe spectra reach 100 TeV

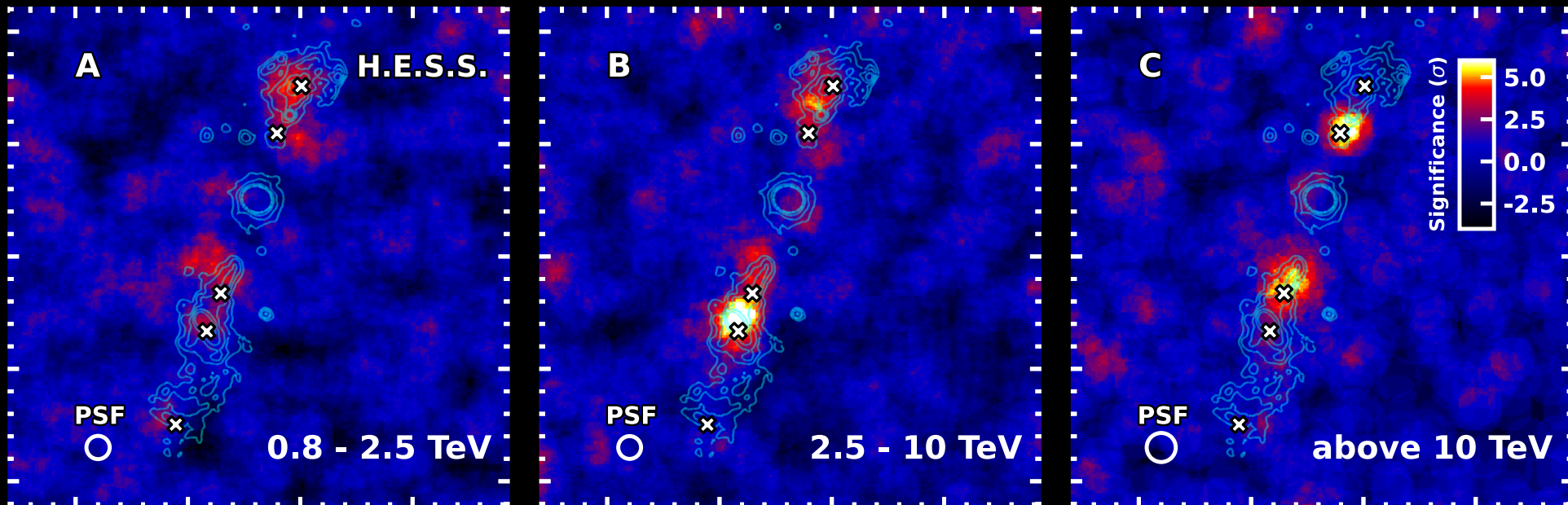
Spectrum of the west lobe



SS 433 energy - dependent morphology



HESS Coll Science 2022



Hard Xray obs of the inner eastern lobe of W50

Safi-Harb+22

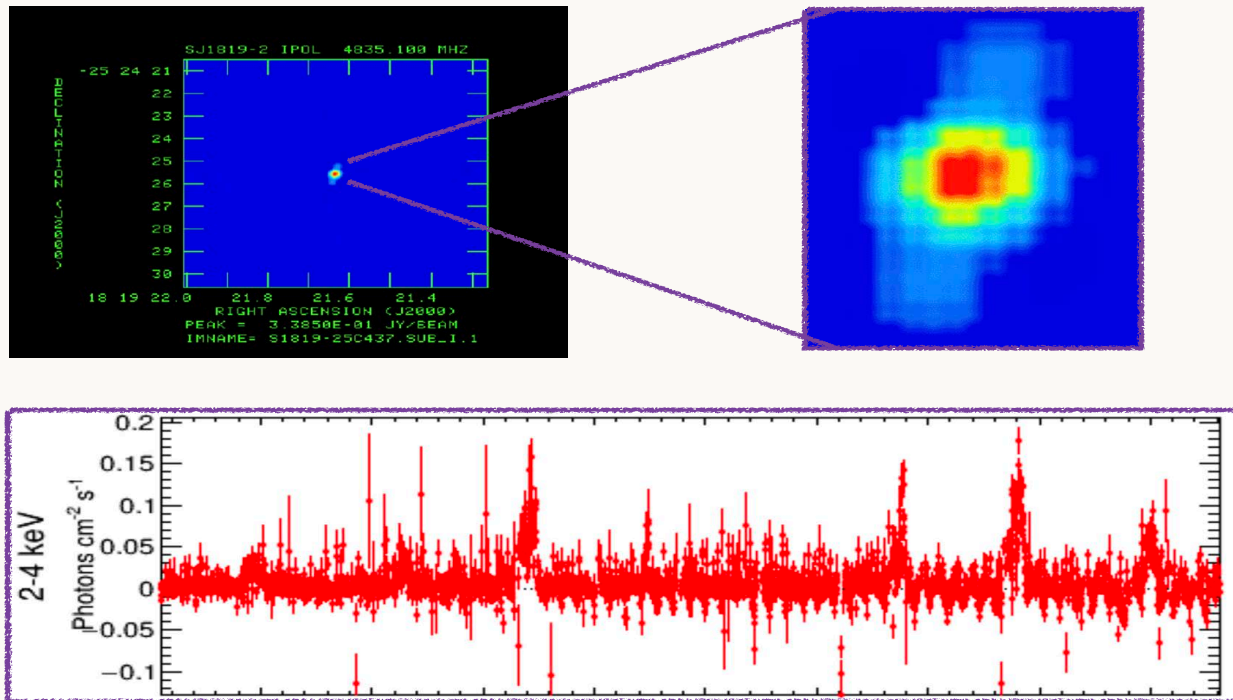


Red: radio (Dubner et al. 1998); green: optical (Boumis et al. 2007); yellow: soft X-rays (0.5–1 keV); magenta: medium energy X-rays (1–2 keV); cyan: hard X-ray emission (2–12 keV).

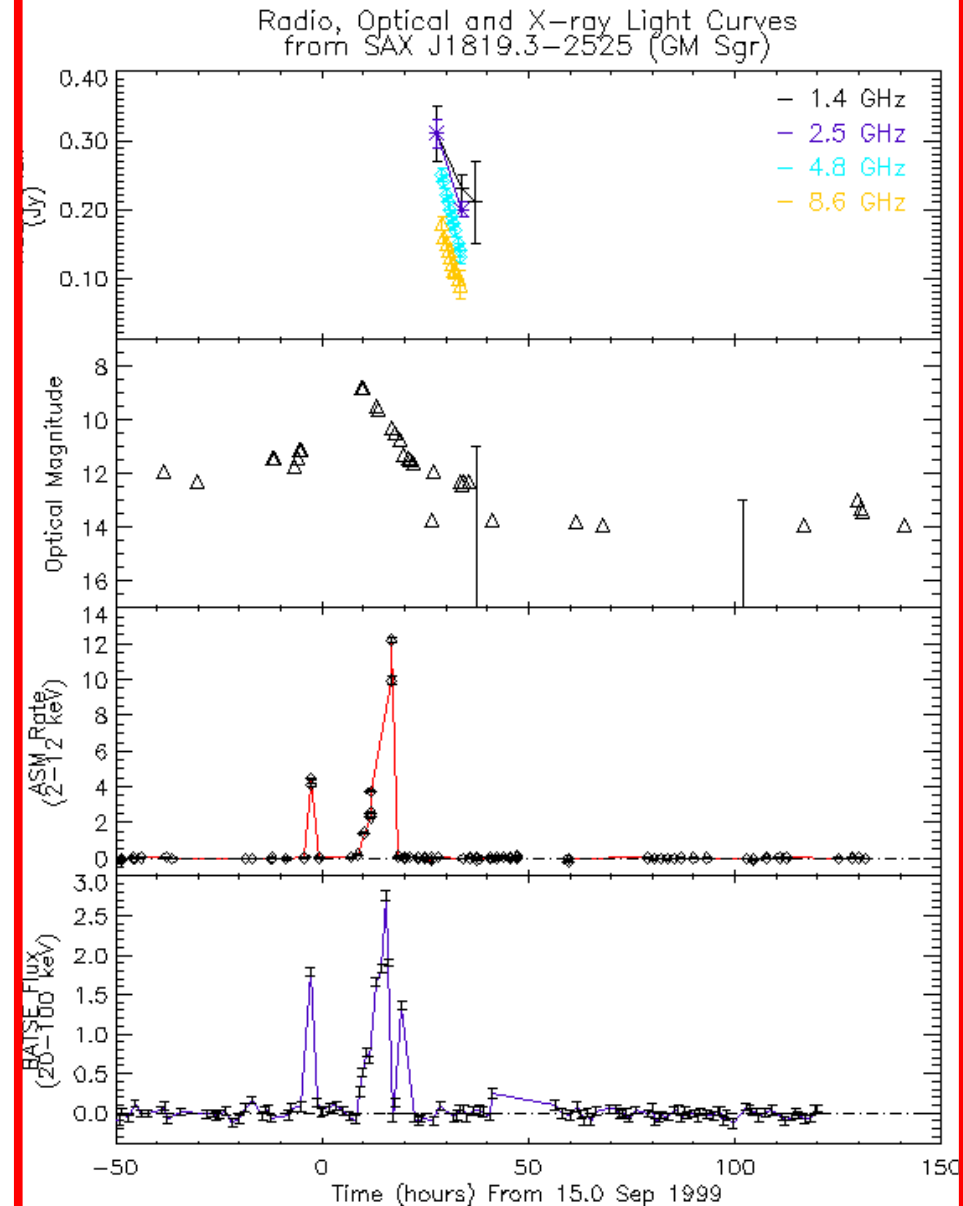
See seminar by Samar

- Transient X-ray binary first detected flares in 1999
- X-ray flux reached 12.2 Crab in 8 hr
- Arcsec radio jets inclined $< 16^\circ$ (VLA)
- Black-hole $6.4 M_\odot$ (MacDonald+2014)
- B-star companion $2.9 M_\odot$
- Orbital period 2.8 d, distance 6.2 kpc
- Super-Eddington accretion – $L_{\text{Eddington}} \sim 10^{39} \text{ erg}$
- Superluminal jets - apparent expansion speed $9.5c$

Credit: (R.M. Hjellming, NRAO, VLA, Associated Universities, Inc.)

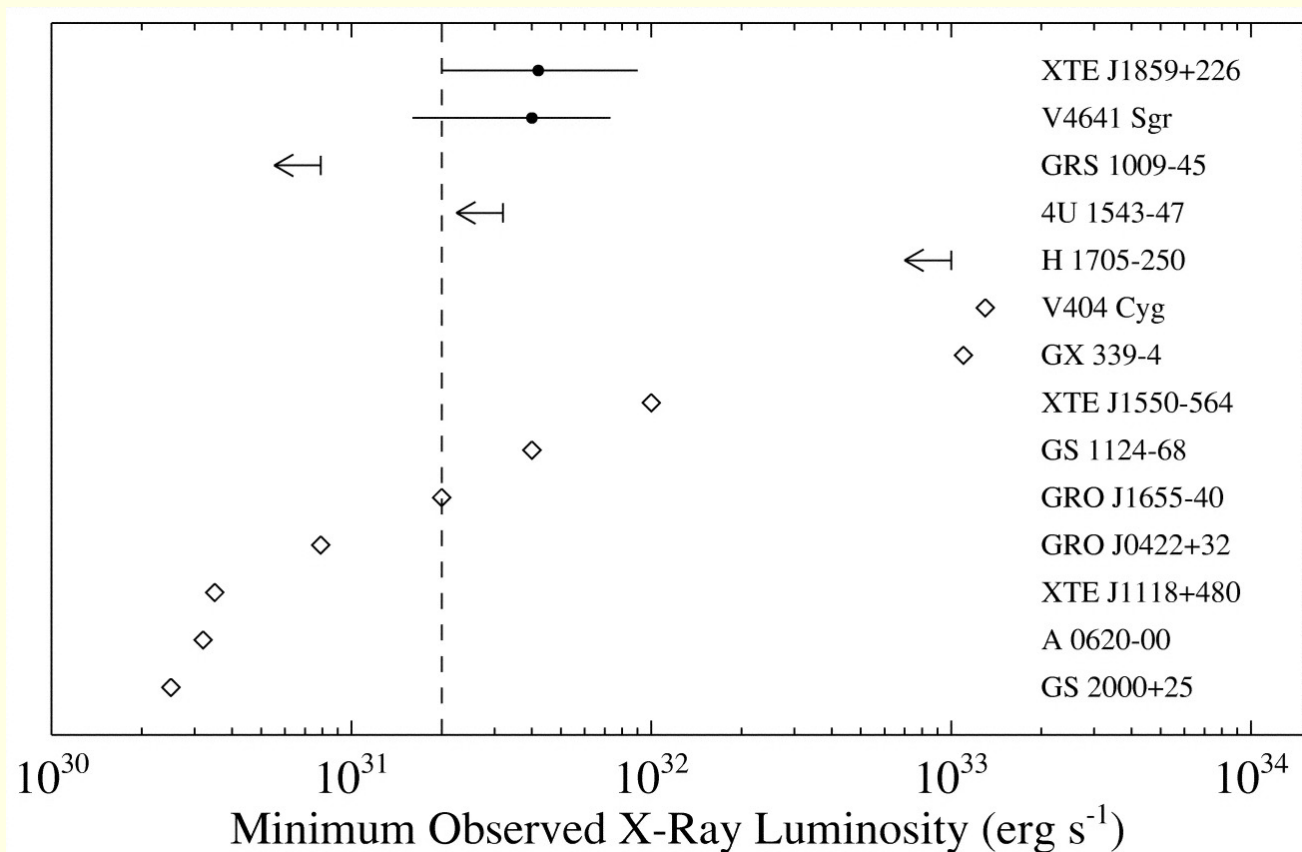


V4641 Sgr



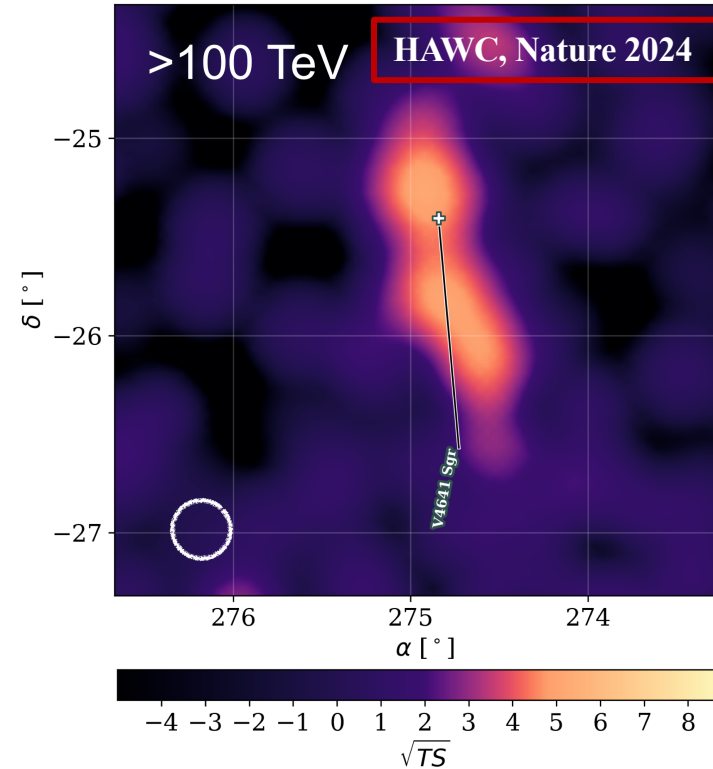
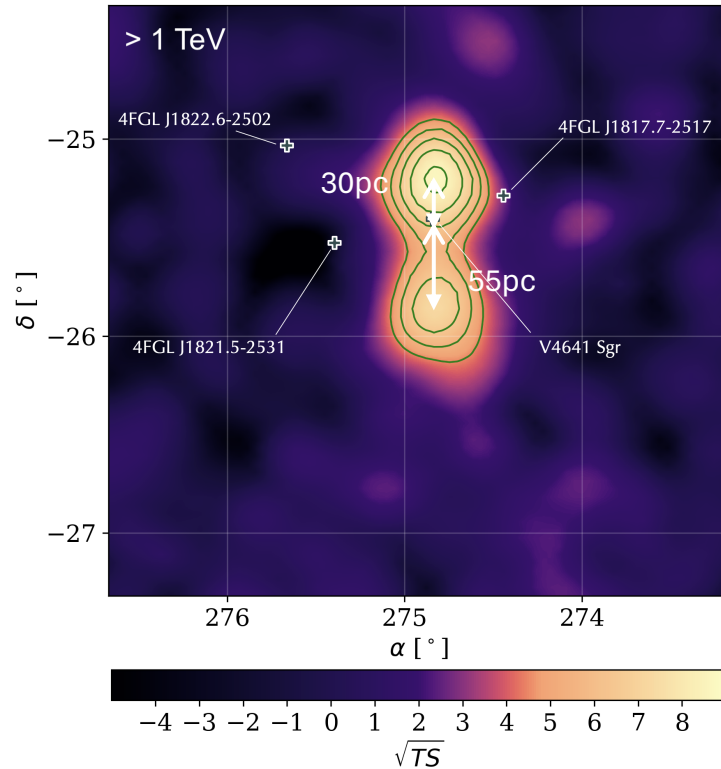
Chandra Observations of V4641 Sgr in quiescent state

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 $4.0 \times 10^{31} (d/7 \text{ kpc})^2 \text{ ergs s}^{-1}$ (Tomsick+2003)
- In optical wavelengths V4641 Sgr 85% quiescent state and 15% active state (MacDonald+2014)

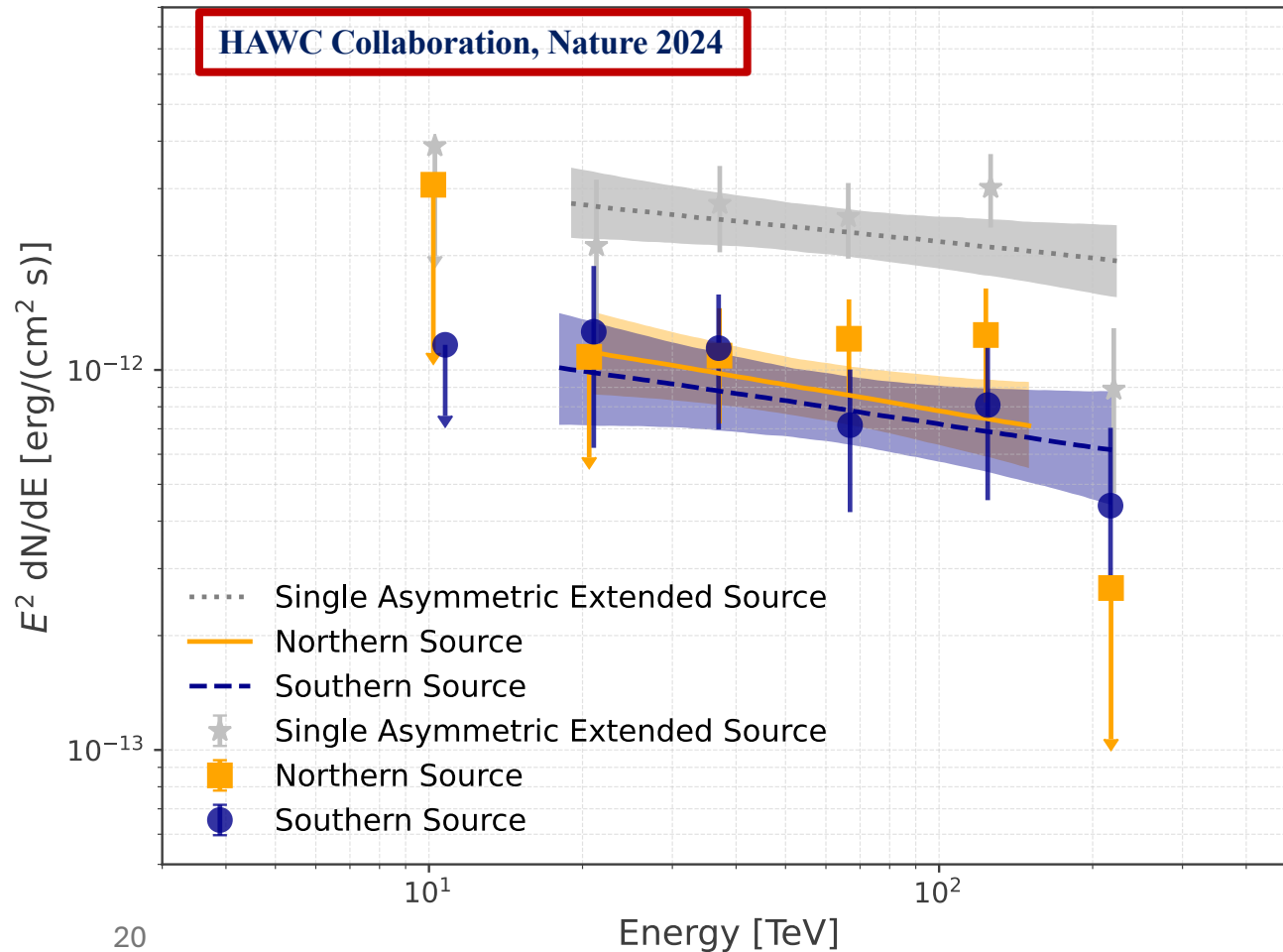
VHE Photons coincident with V4641 Sgr



- 2400 days obs
- High zenith angle for HAWC - 45° off zenith
- 8.8 σ above 1 TeV and 5.2 σ above 100 TeV

Spectra and morphology of the lobes

Source Name	R.A. [°]	Dec. [°]	$N_0 [\times 10^{-16} \text{cm}^{-2} \text{TeV}^{-1} \text{s}^{-1}]$	Index (α)	Extension upper limit at 95% CL [°]	Physical distance to the black hole (distance: 6.6 kpc)
Southern	274.82 ± 0.04	-25.87 ± 0.03	$2.4^{+0.6}_{-0.5}(\text{stat.})^{+0.2}_{-0.5}(\text{syst.})$	$-2.2 \pm 0.2(\text{stat.})^{+0.07}_{-0.02}(\text{syst.})$	0.23	$0.46^\circ \sim 55 \text{ pc}$
Northern	274.82 ± 0.03	-25.18 ± 0.02	$2.6^{+0.5}_{-0.4}(\text{stat.}) \pm 0.4(\text{syst.})$	$-2.2 \pm 0.2(\text{stat.})^{+0.07}_{-0.05}(\text{syst.})$	0.17	$0.23^\circ \sim 30 \text{ pc}$



- 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

Origin of the emission

- Electrons of at least 200 TeV at the termination shocks

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

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

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

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

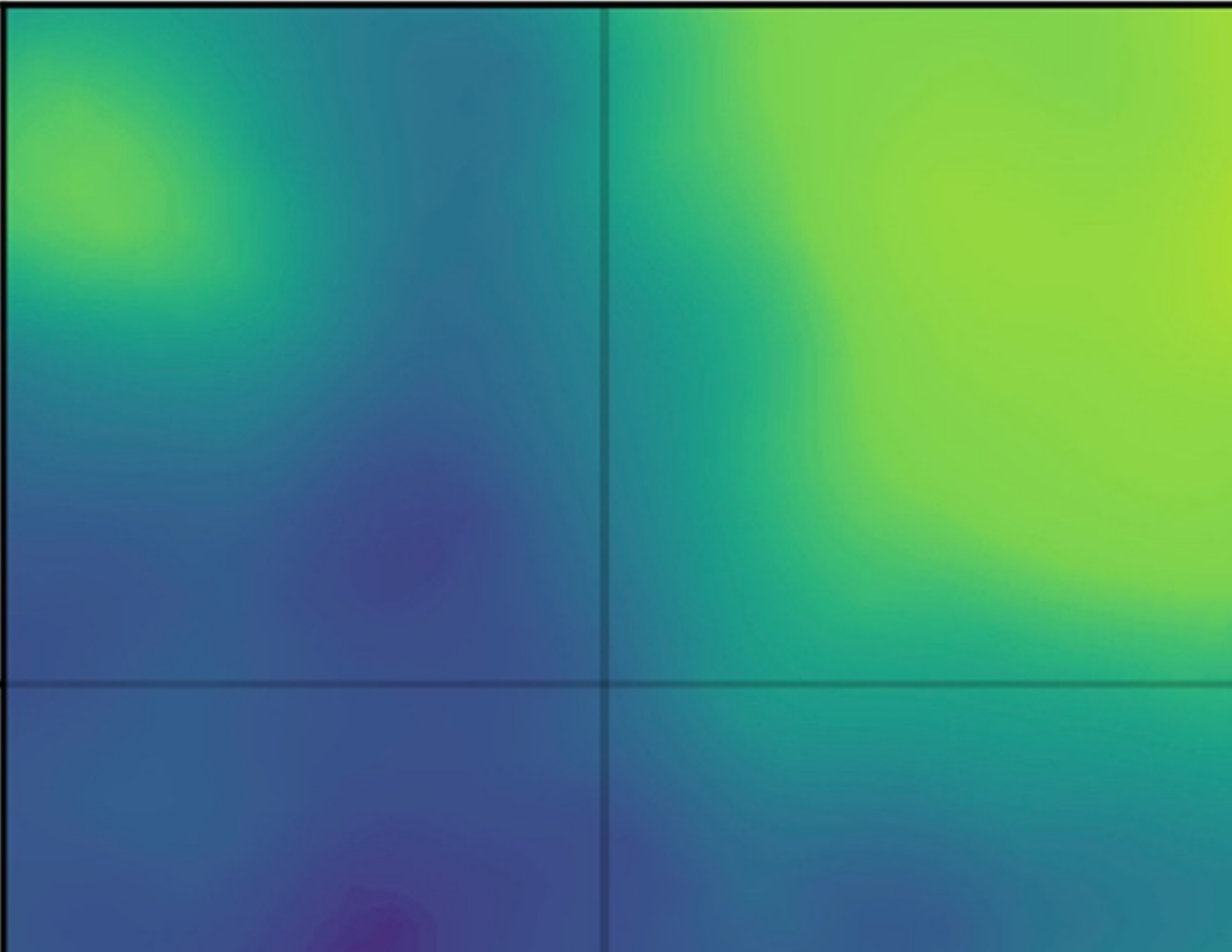
$$D(200 \text{ TeV}) \approx \eta 10^{30} \text{ cm}^2 \text{ s}^{-1}$$

- PeV protons at the termination shocks where jets impact ISM

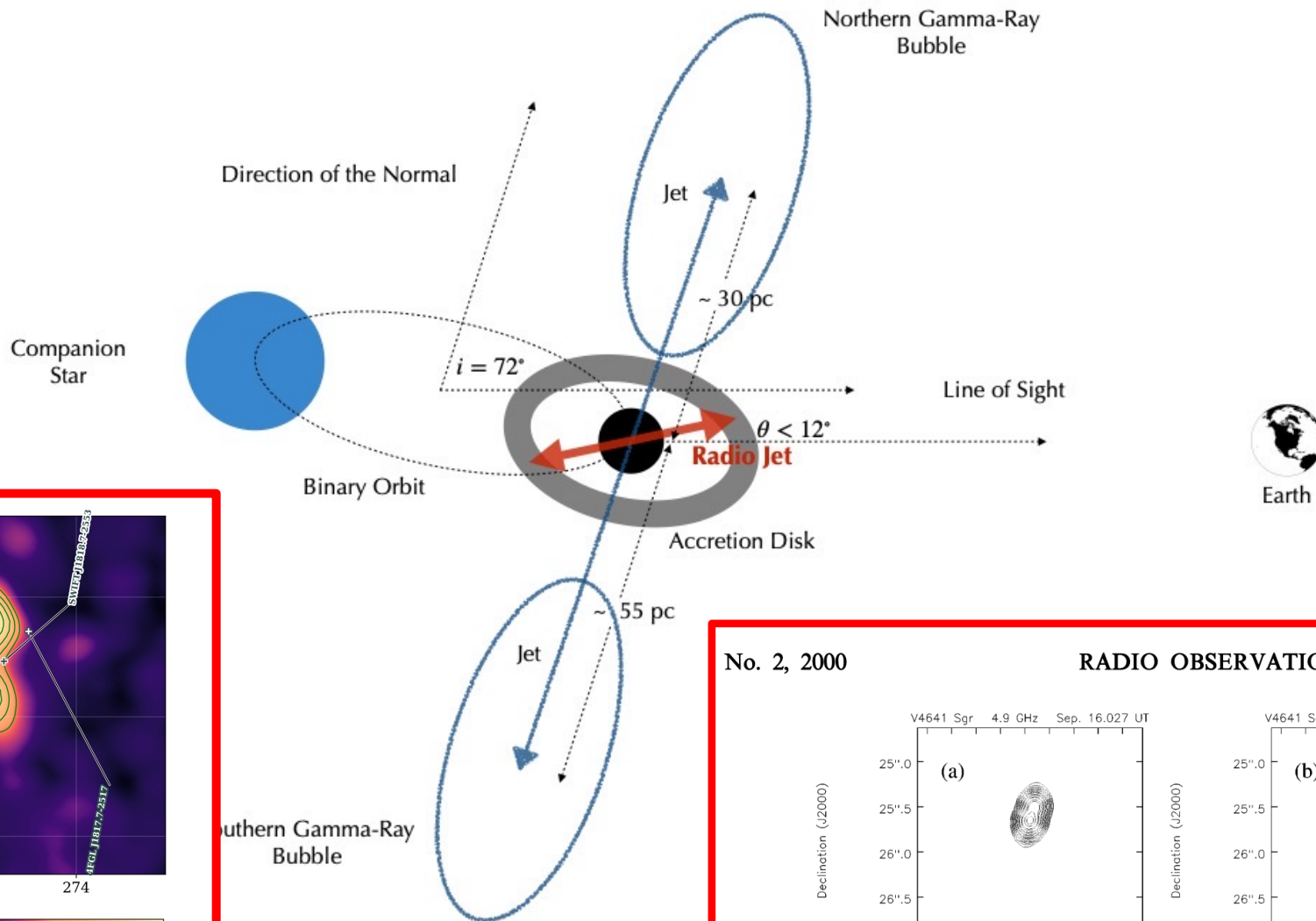
$$\begin{aligned} \dot{W}_p(E_p > 1 \text{ PeV}) &= L_\gamma \frac{t_{\text{pp}}}{t_{\text{esc}}} \\ &\simeq 10^{39} \eta \left(\frac{L_\gamma}{10^{34} \text{ erg s}^{-1}} \right) \left(\frac{D_0}{3 \times 10^{30} \text{ cm}^2 \text{ s}^{-1}} \right) \left(\frac{n}{1 \text{ cm}^{-3}} \right)^{-1} \text{ erg s}^{-1} \end{aligned}$$

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

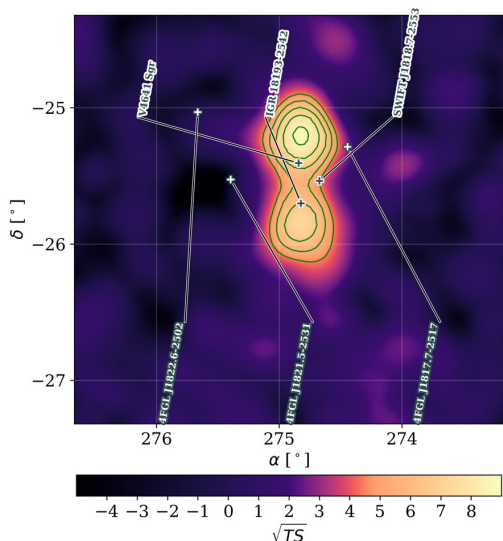
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HAWC Collaboration, Nature 2024

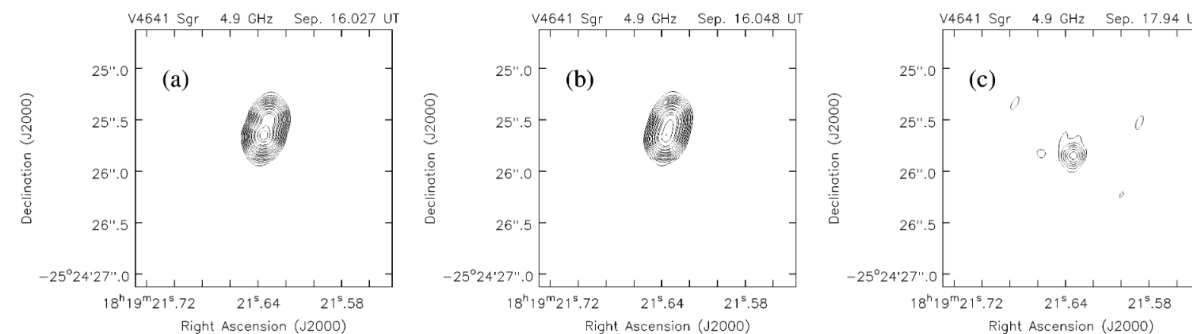


**Weather
and
Climate ?**



No. 2, 2000

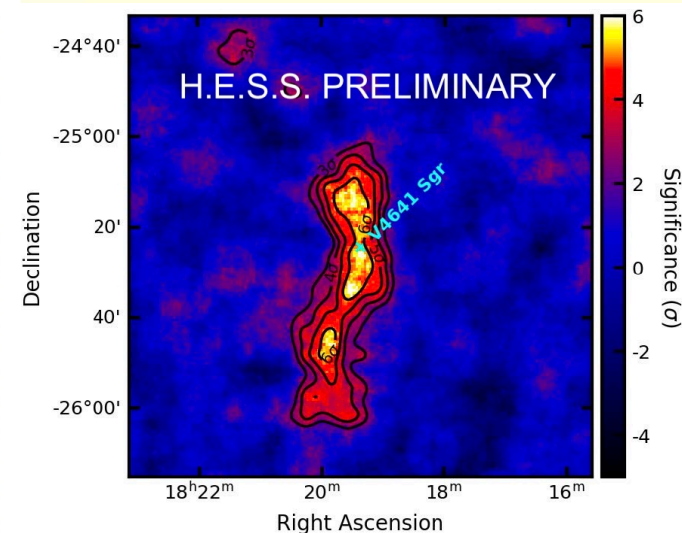
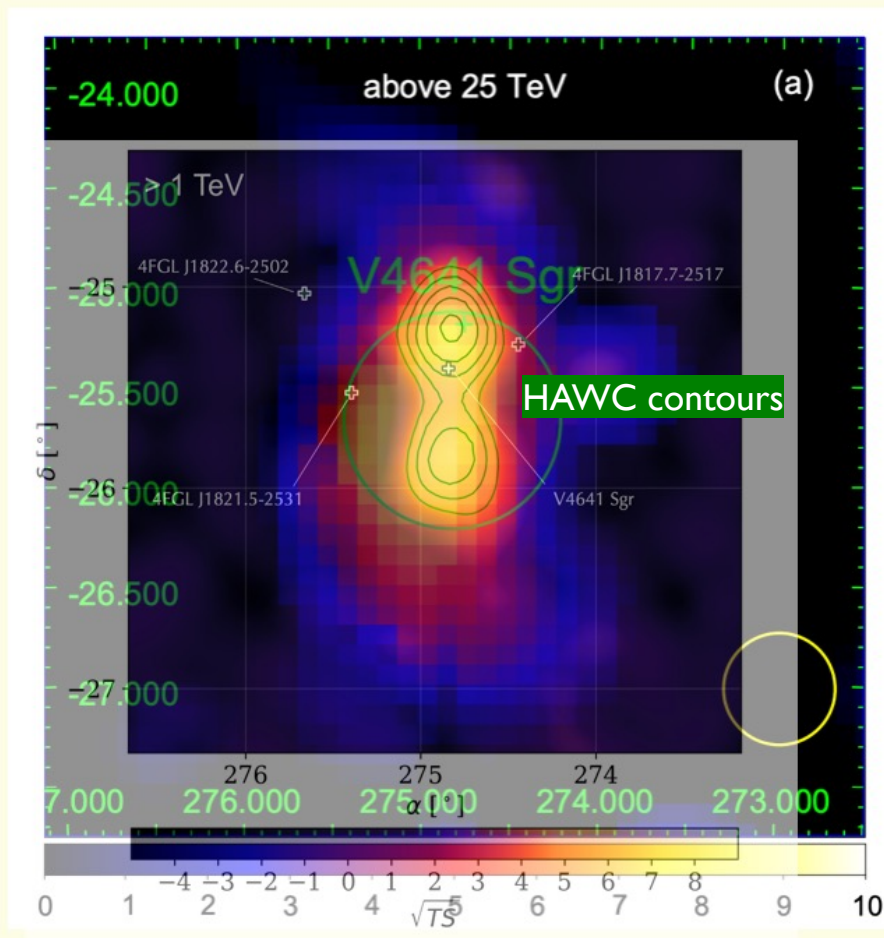
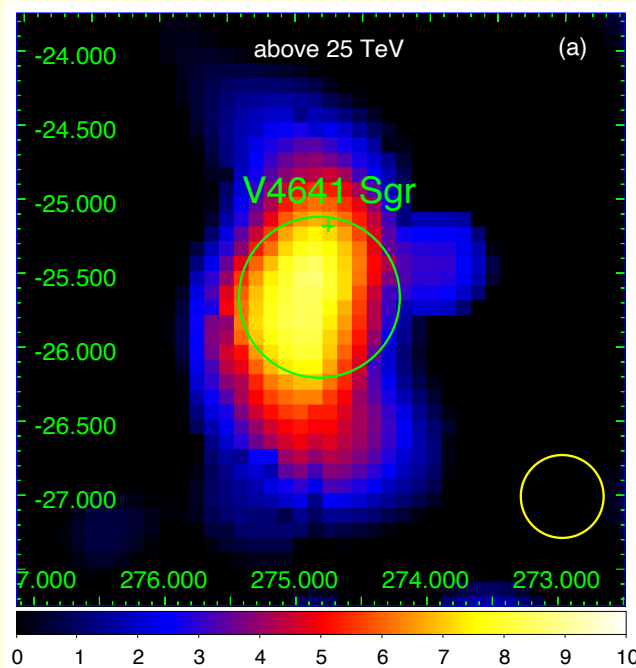
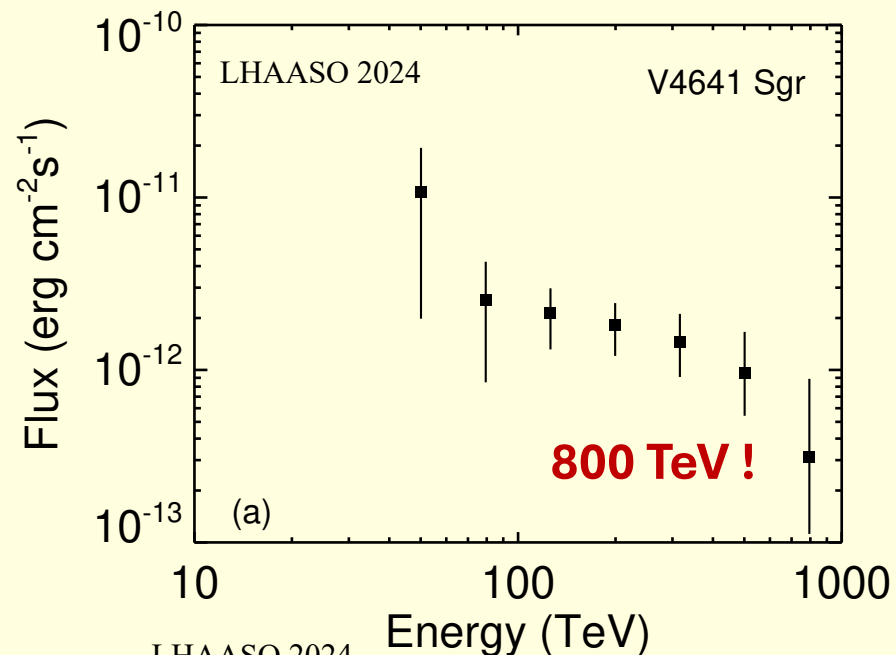
RADIO OBSERVATIONS OF XTE J1819-254



100 pc persistent structure, HAWC 2022

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

V4641 Sgr with HESS and LHAASO

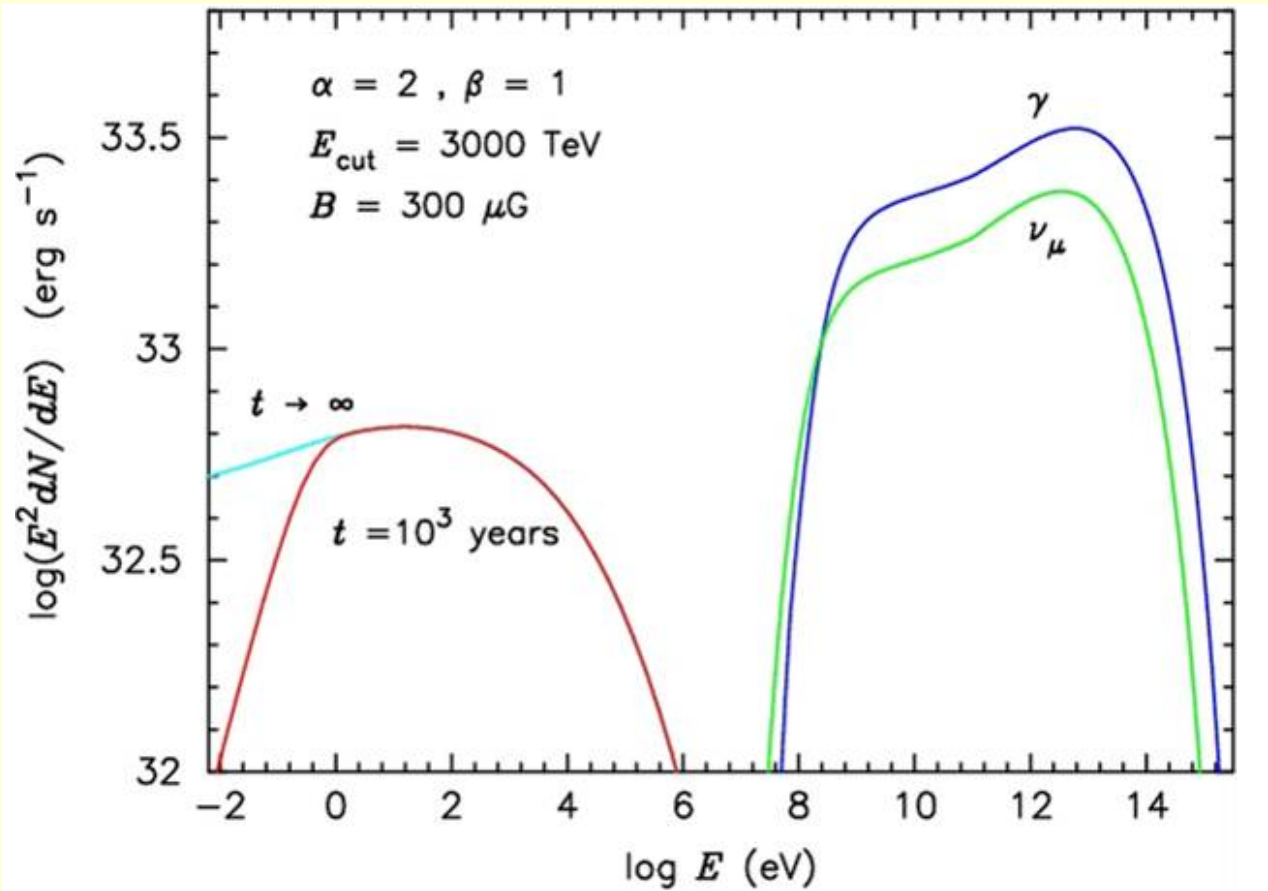


See previous talk by Laura

Photon energies close to 1 PeV!

See next talk by Ruoyu

Signatures of PeV CR factories



pp collisions

$\pi^0 \rightarrow \gamma\gamma$ Sub-PeV gamma-rays
 $\pi \rightarrow \mu\nu_\mu$ Sub-PeV neutrinos
 $\mu \rightarrow e\nu_e\nu_\mu$ Prompt hard X-ray (10-100 keV) synchrotron from secondary e^-

$$E^{-\alpha} \exp[-(E/E_0)^\beta]$$

$$t_{\text{synch}} \approx 15(B/100\mu\text{G})^{-3/2}(\epsilon/10\text{keV})^{-1/2} \text{ yr}$$

Current and planned observations

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 10ks on 2024-09-07 covering 60% UHE emission)

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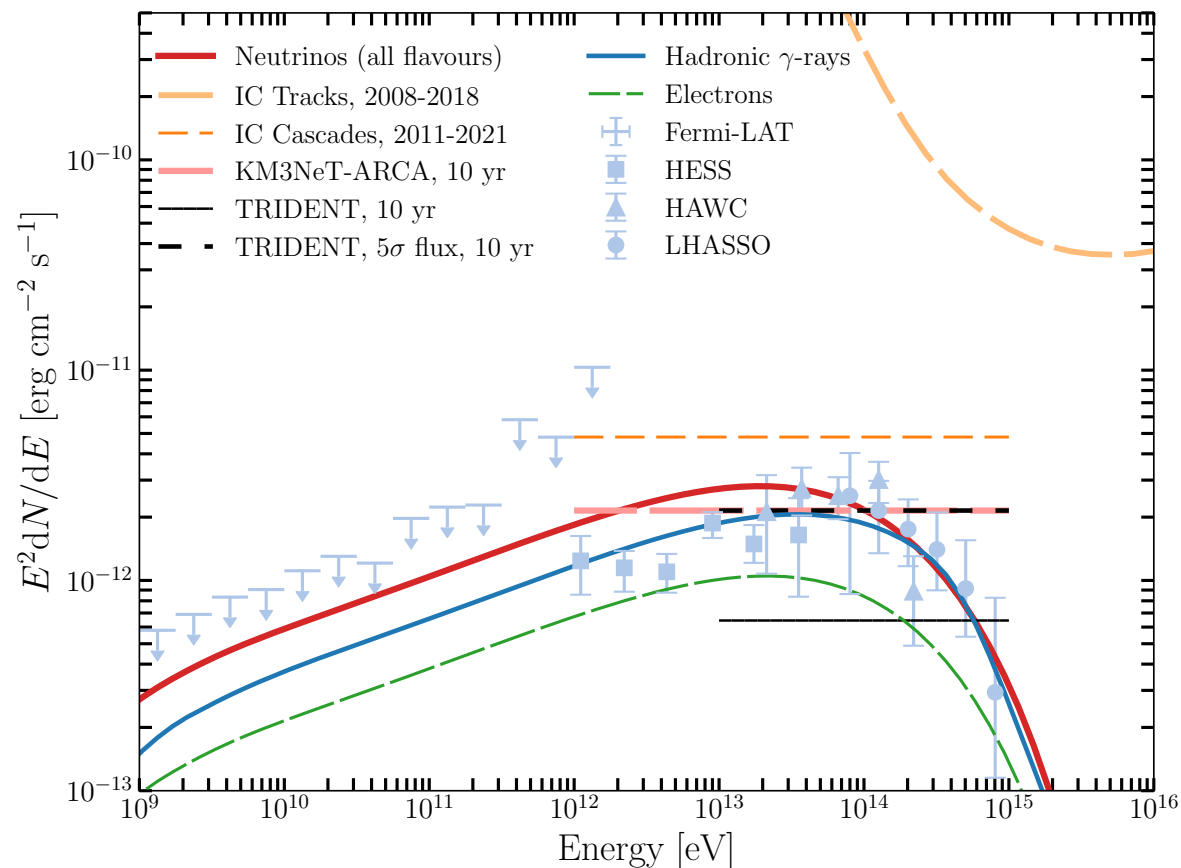
- XMM Newton proposal (P.I. X.Wang and K. Mori)

• Radio Observations

- Observations with APEX (P.I. Eduardo dela Fuente, Daniel Tafoya)
- Observations with Nobeyama (P.I. N.Fuji)

Expected neutrino fluxes

Neronov+2024

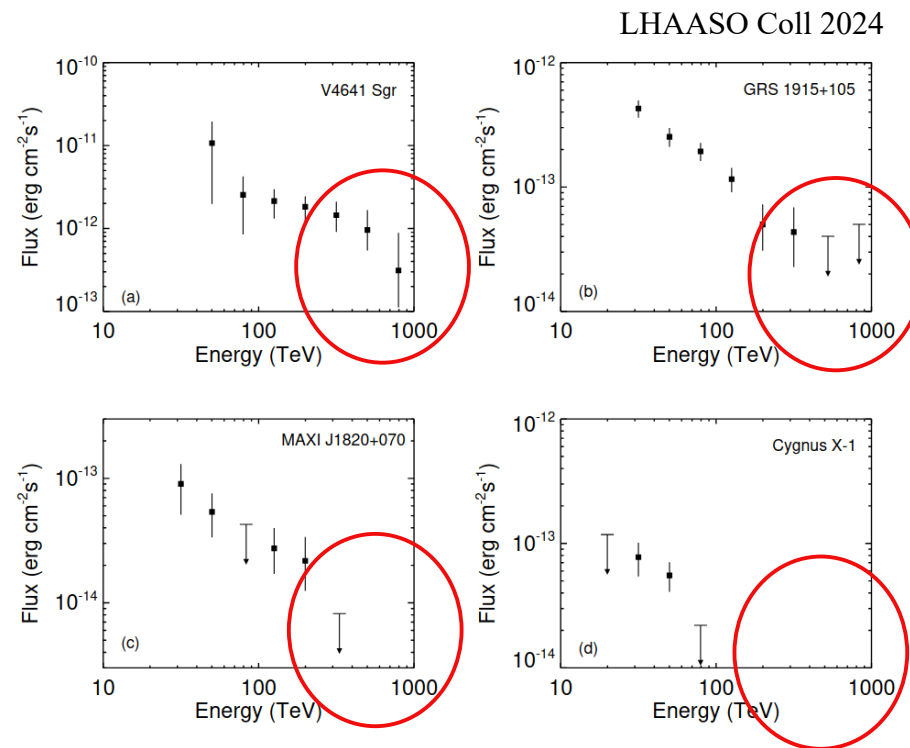
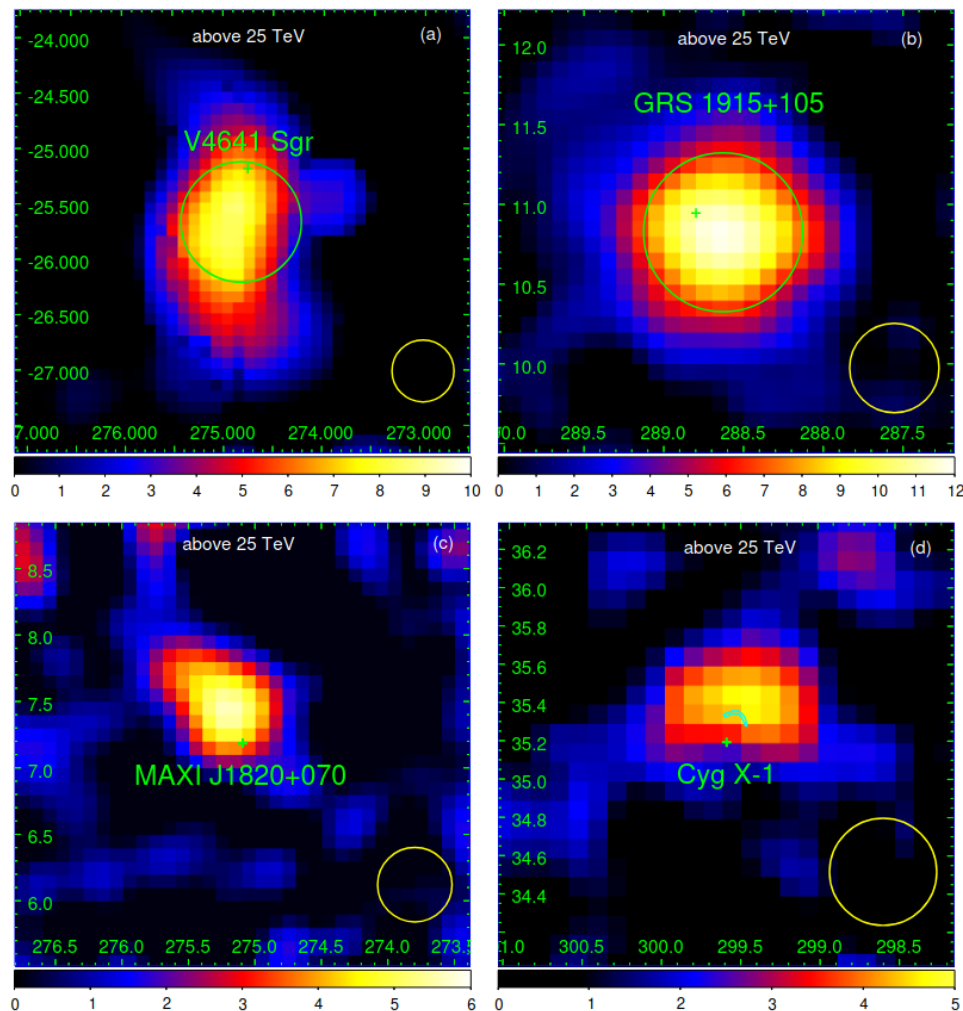


high-energy CR particles escaping from the micro-quasar along ordered field lines of the GMF colliding with ISM gas

Summary of HAWC microquasars

- Accretion
 - SS 433 : likely super-Eddington
 - V4641 Sgr: super-Eddington
- Jets
 - SS 433 : most powerful jets known in the Galaxy $\sim 10^{39-40}$ erg/s
 - V4641 Sgr : superluminal jets
- BH activity
 - SS 433 : persistent BH activity
 - V4641 Sgr : powerful outbursts – intermittent BH activity $\sim$ 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 3×10^{50} erg $\sim$ 100% Edd
 - V4641 Sgr : sub-PeV electrons accelerated at termination shocks – Energy budget for hadronic emission : few objects as V4641 Sgr could explain the local PeV CR flux

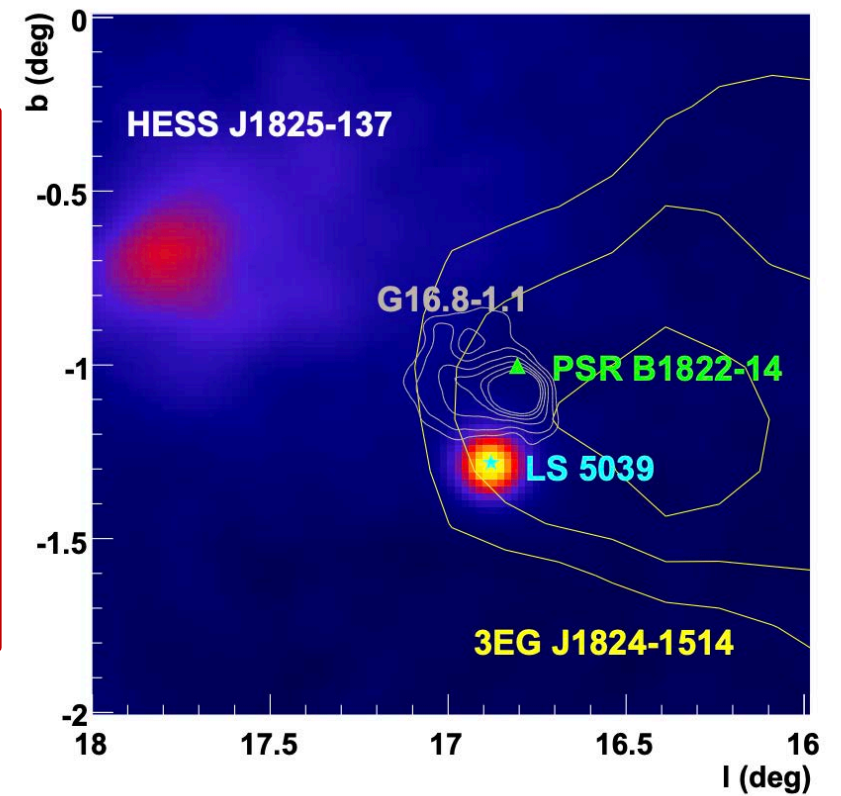
The LHAASO microquasar class



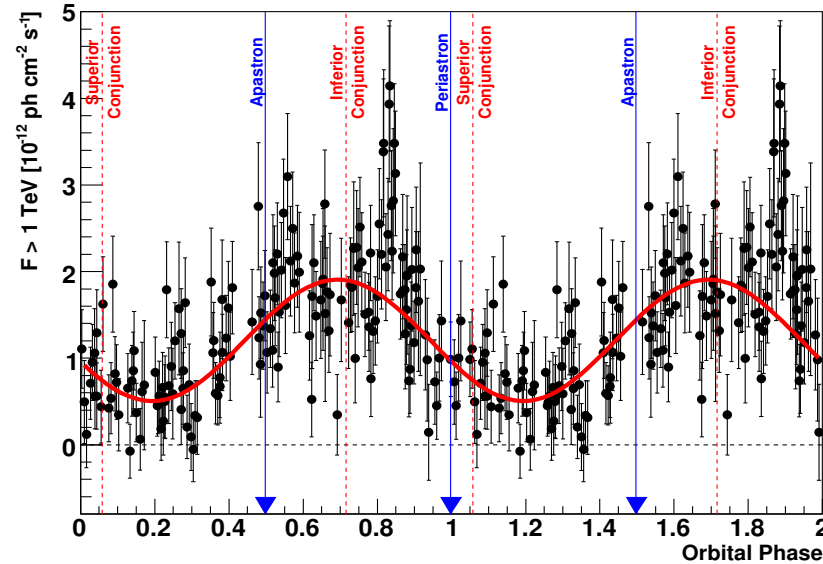
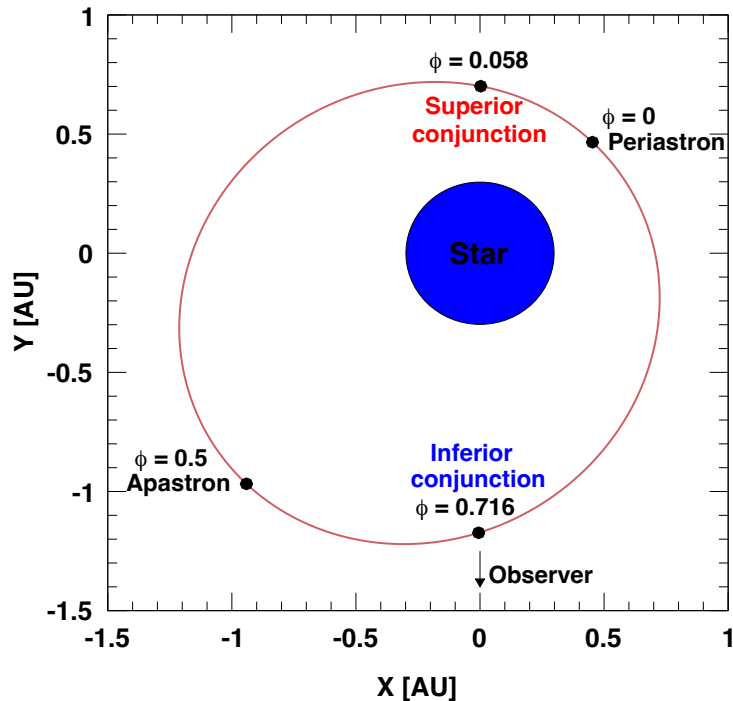
See next talk by Ruoyu

LS 5039

- Either microquasar with relativistic jet formation through matter accretion onto the compact object or acceleration resulting from the interaction between pulsar and star winds
- Distance = 3.5 kpc , O6.5V star and compact object with a mildly eccentric 3.9 day orbit. Mass companion star $23 M_{\odot}$, mass compact object = $3.7 M_{\odot}$
- From radio to TeV energies. Flux and spectral modulation as a function of its orbital period.

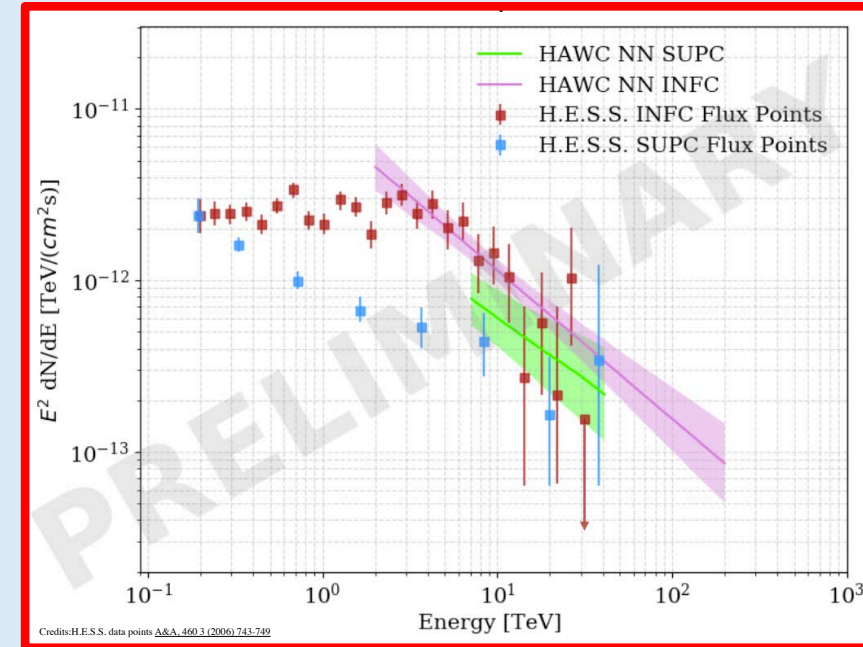
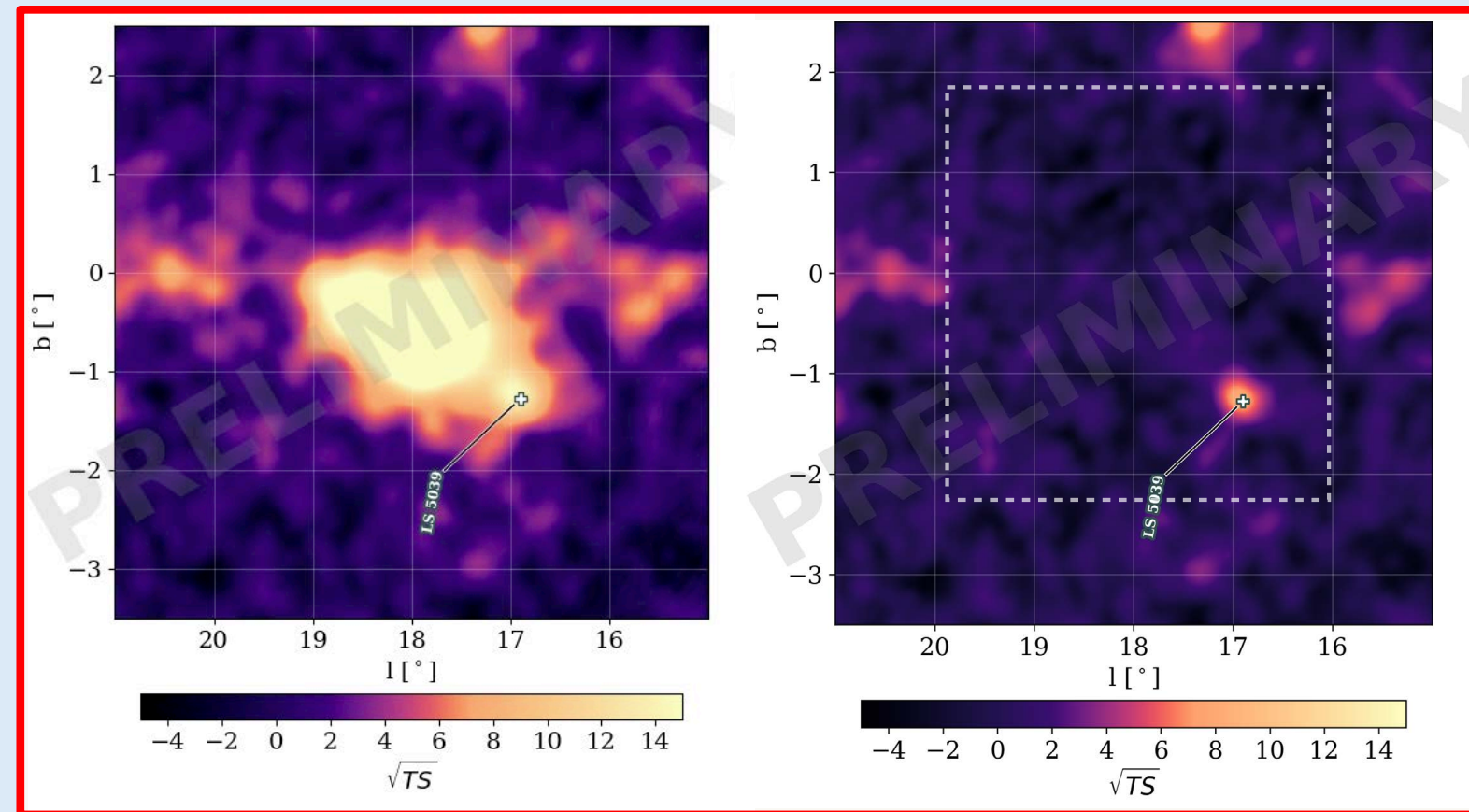


HESS Coll 2005-2007



(Aharonian et al. 2005)

LS5039 region with Pass 5

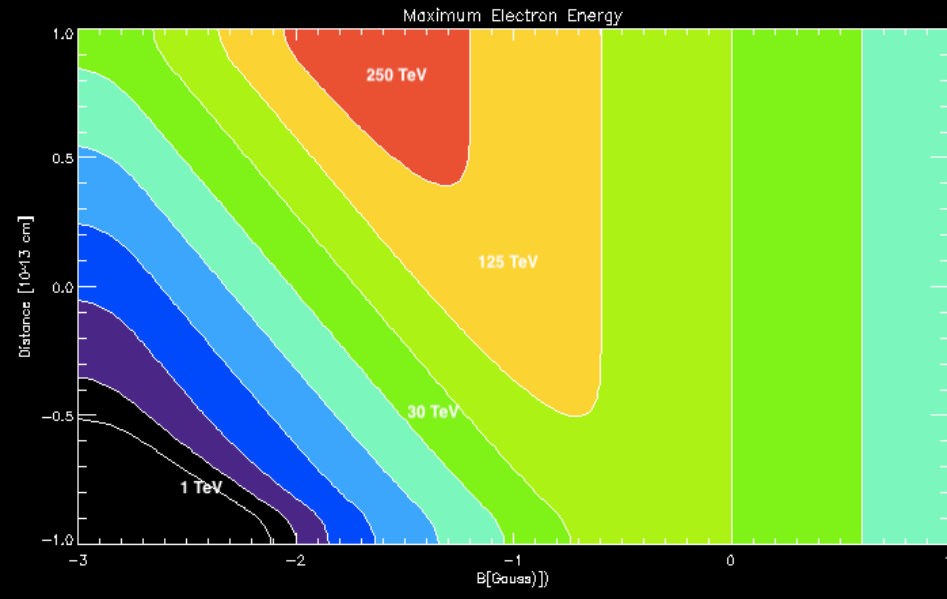


- 1910 days of data
- Simultaneously likelihood fit with diffuse emission and background sources
- About 8σ
- PL preferred up to at least 100 TeV

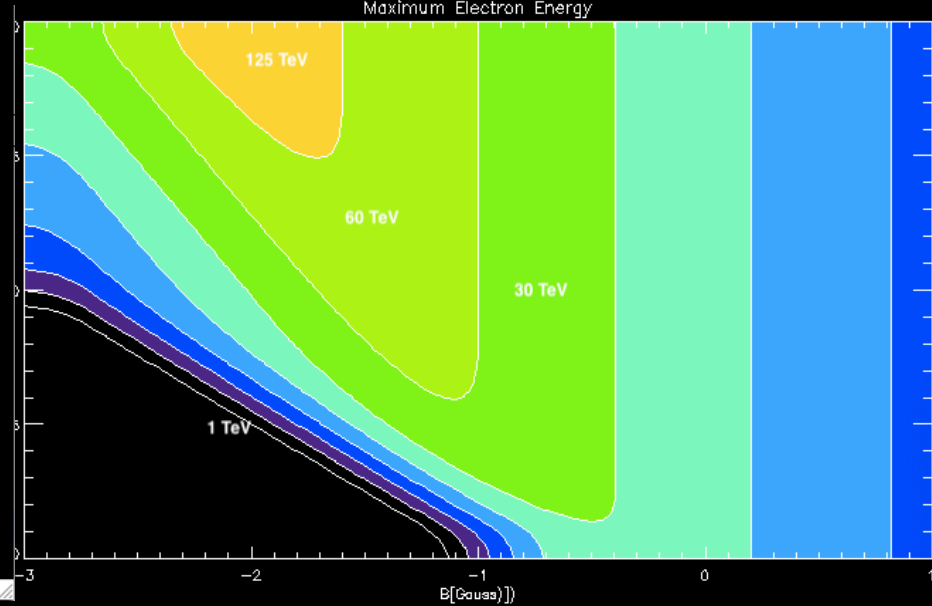
Dezhi Huang, ICRC 2023

Origin of the emission

$\eta = 1$



$\eta = 10$



- VHE emission can help constrain B-field, acceleration
- efficiency and acceleration location (see Khangulian+2008)
- Maybe room for pp or p γ ?

- IC off starlight photons proceeds in extreme KN regime, maximum E_{max}
 $t_{\text{acc}} = t_{\text{KN}}$
- maximum E_{max} from synchrotron
 $t_{\text{acc}} = t_{\text{syn}}$
- $r_L < \text{accelerator linear size}$

Acceleration efficiency
Location of the accelerator
B field

- $\eta < 10$
 $B < 10^{-1} \text{ G}$ $d > 10^{13} \text{ cm}$
- $\eta = 1$
 $B < 1 \text{ G}$

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

V464I Sgr

- Discovery of hundred TeV gamma-rays from V464I Sgr
- Multiwavelength analysis of V464I Sgr ongoing

LS 5039

- Extension of the HESS spectra up to 100 TeV

**Perspective for improving analysis of UHE photons with outrigger data.
Multiwavelength studies !
STAY TUNED !**



SS 433 : Origin of the emission

Leptonic model does a good job of explaining the gamma ray emission, requires $\sim 0.5\%$ of jet power going into electron acceleration.

In hadronic-only scenario protons of at least 250 TeV produce gamma in proton-proton interaction and secondary leptons radio and X-rays via synchrotron radiation.

Energy budget of 3×10^{50} erg $\sim 100\%$ of jet energy over 30000 year lifetime of SS 433 must go into accelerating protons to explain the observed gamma-ray emission. But do we really know the local gas density ?

Acceleration is occurring in the jets, not in the central binary:

1. Emission region is ~ 40 pc from central binary.
2. Diffusion length scale is ~ 35 pc at these energies, assuming ISM diffusion coefficient
3. Advection length scale is ~ 4 pc.