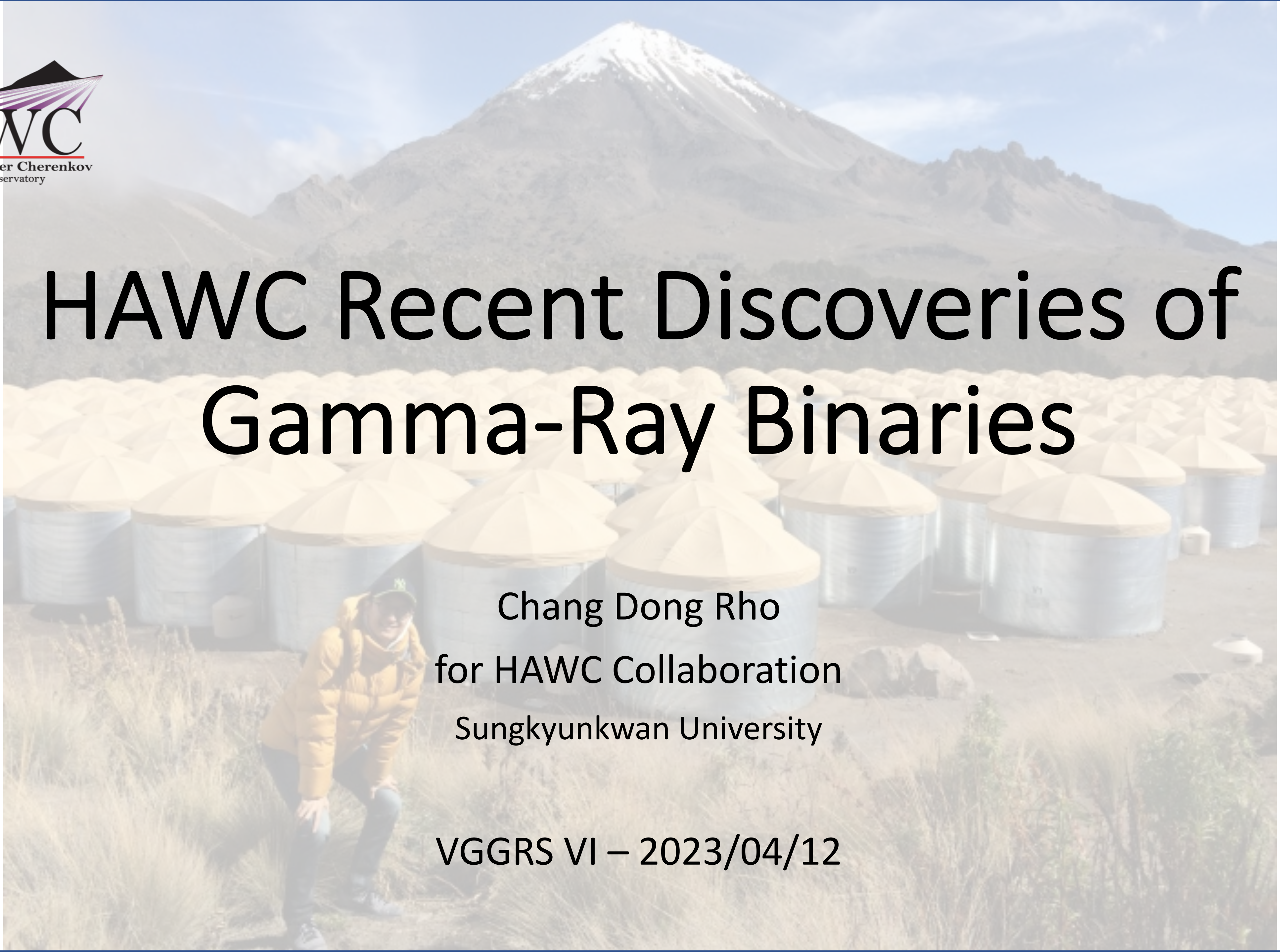

HAWC Recent Discoveries of Gamma-Ray Binaries

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for HAWC Collaboration
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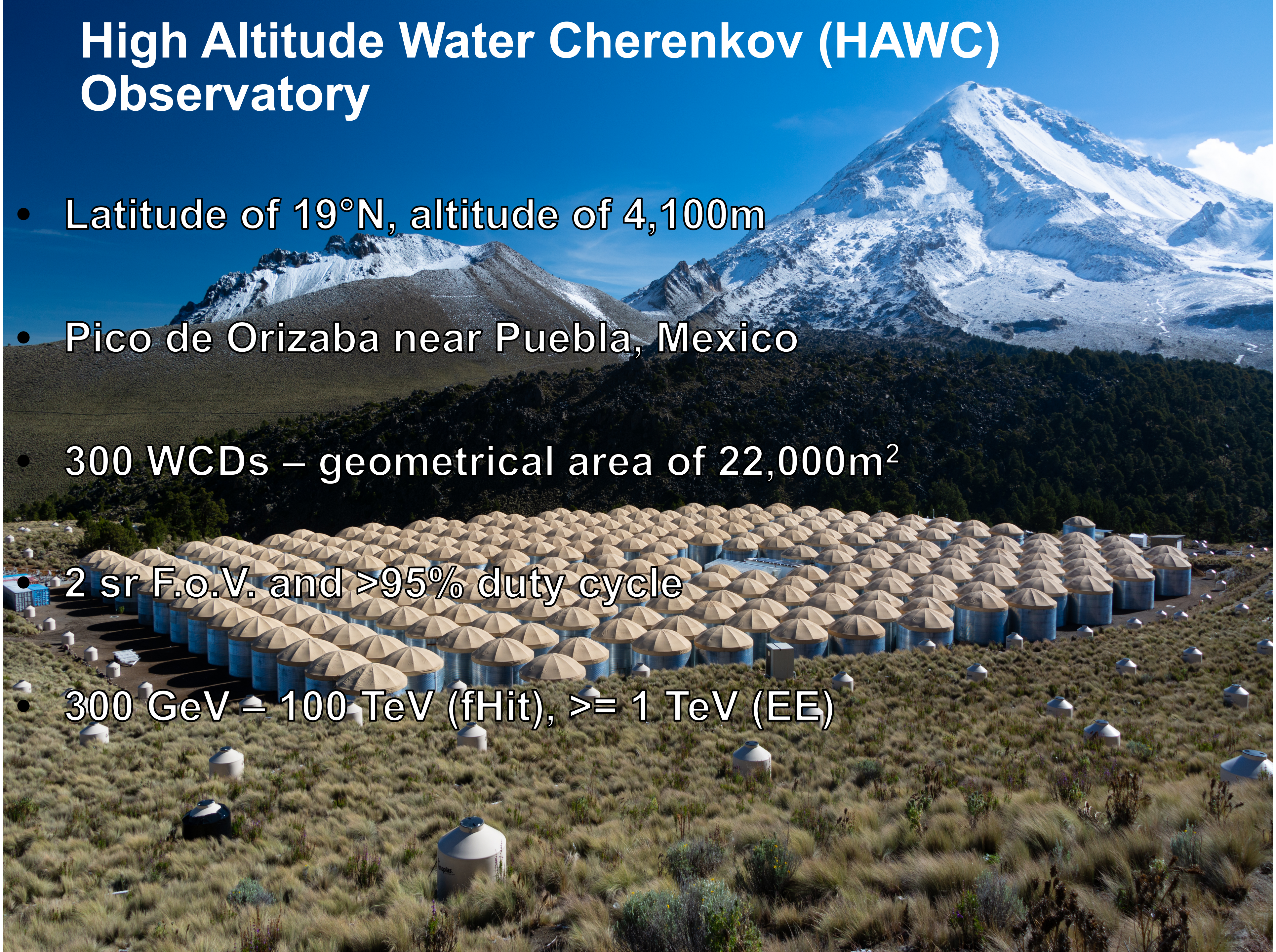
VGGRS VI – 2023/04/12

Overview

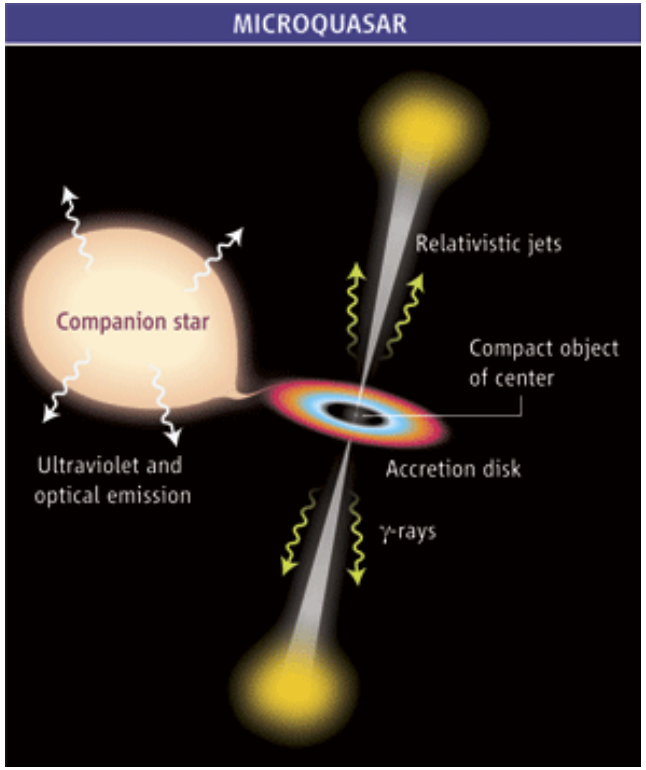
- Introduction to HAWC
- Gamma-ray binary systems
- Old key results on binaries from HAWC
- Recent highlight results on gamma-ray binaries from HAWC

High Altitude Water Cherenkov (HAWC) Observatory

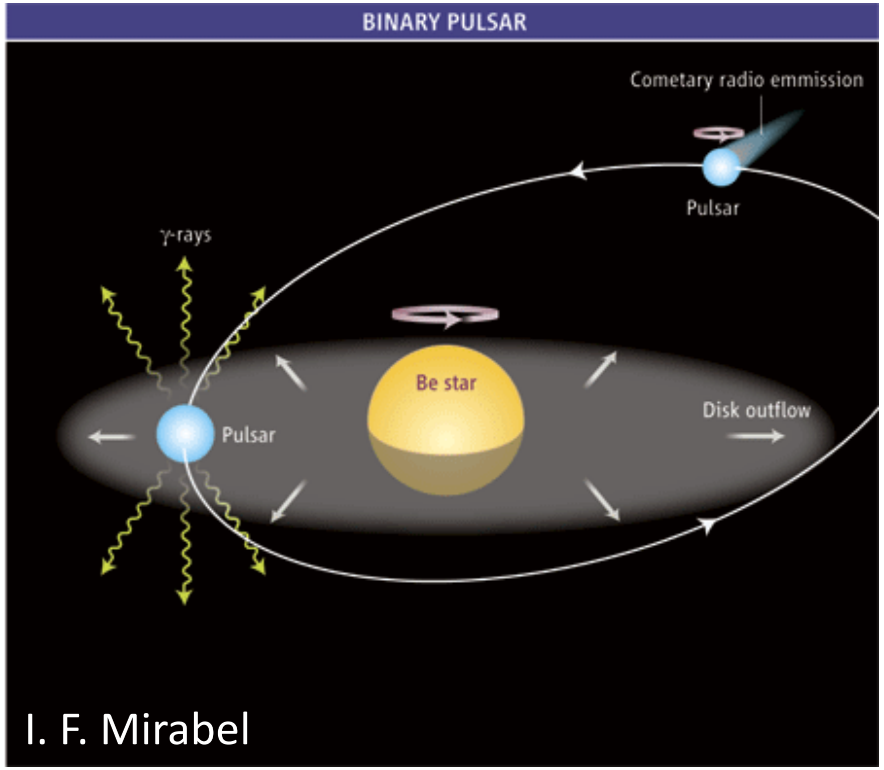


- Latitude of 19°N, altitude of 4,100m
- Pico de Orizaba near Puebla, Mexico
- 300 WCDs – geometrical area of 22,000m^2
- 2 sr F.o.V. and >95% duty cycle
- 300 GeV – 100 TeV (fHit), >= 1 TeV (EE)

Gamma-Ray Binary Models



Accretion powered microquasar



I. F. Mirabel

Rotation powered pulsar binary

- “Gamma-ray binaries” are systems composed of a compact object and a massive star, in orbit around their barycenter, exhibiting periodic orbital modulation in flux. Also, have non-thermal emission peaking above 1 MeV in their spectra.
- But, today we will also discuss interesting TeV gamma-ray excess we have observed that are associated with known binary systems.
- Two most prevalent models
- Three binaries: **SS 433; LS 5039; V4641 Sgr**

Past Key Results

SS 433 – General Information

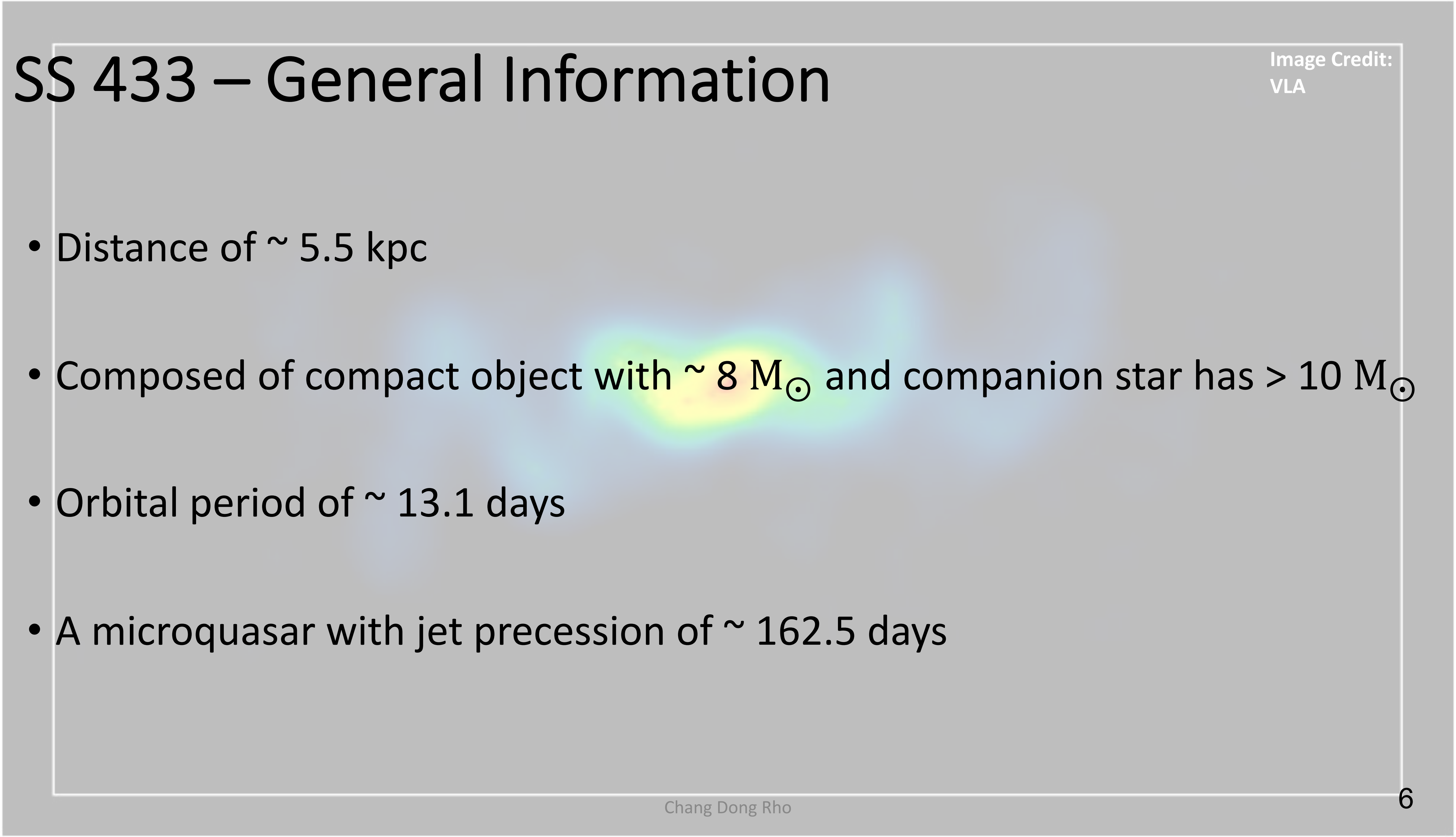
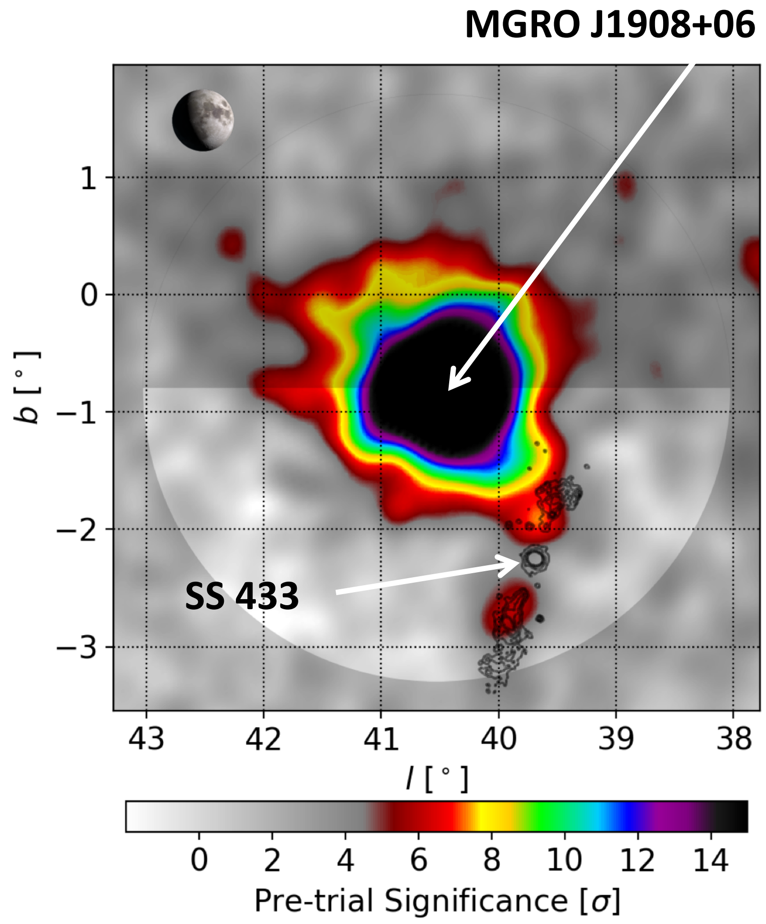


Image Credit: VLA

- Distance of ~ 5.5 kpc
- Composed of compact object with ~ 8 $M_\odot$ and companion star has > 10 $M_\odot$
- Orbital period of ~ 13.1 days
- A microquasar with jet precession of ~ 162.5 days

SS 433 – 1017 day HAWC Dataset

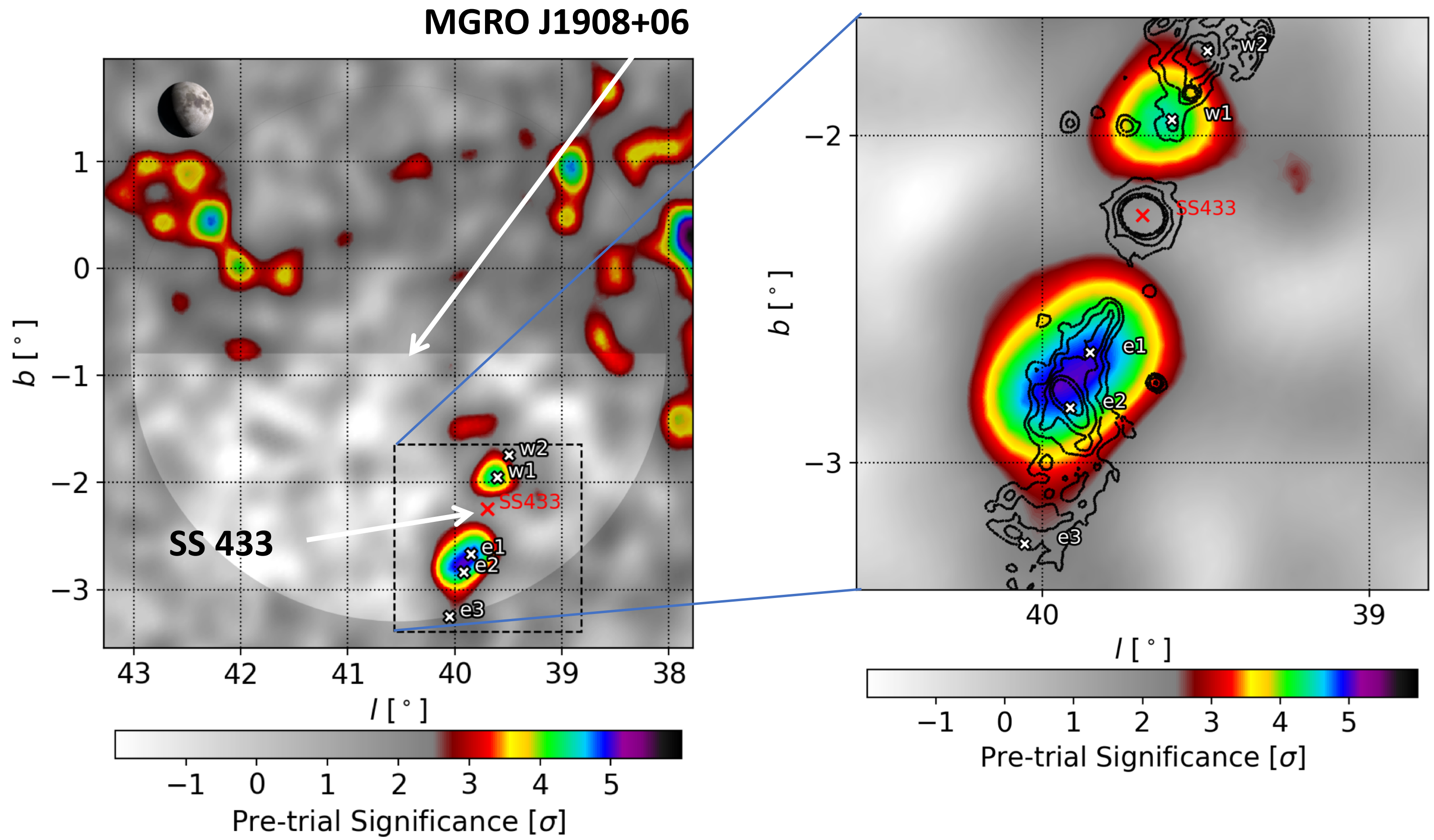


- In 2018, HAWC saw two hot spots to the either side of the known location of SS 433, spatially in coincidence with the X-ray contours

- Lobes positioned very close to J1908, so the two SS 433 lobes (point) & J1908 (extended) fitted simultaneously

- Semi-circular RoI to reduce contamination from GDE

SS 433 – 1017 day HAWC Dataset

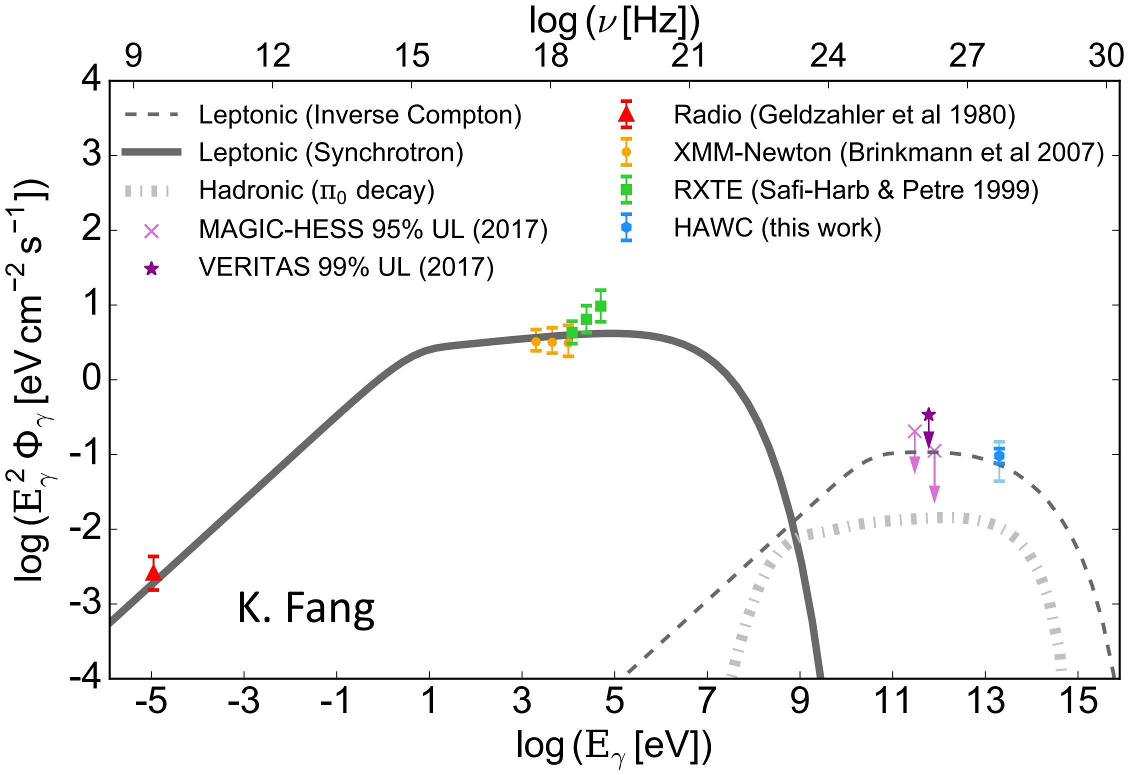


- Used nested models: H_1(J1908 + lobes) – H_0(J1908) to separate the lobes from J1908

- Hotspots outside the RoI can be ignored (Galactic Plane)

- “The nested fit of east and west lobes gives 5.4σ post-trial with HAWC’s 1,017 days of dataset at e1 and w1”

Broadband S.E.D. at e1



- Leptonic: radio + X-ray photons are produced via synchrotron emission in a magnetic field. TeV γ rays observed by HAWC are produced via IC of CMB by the same population of e^-.

Key Points

- Leptonic model does a good job of explaining the gamma ray emission, requires ~0.03% of jet power -> electron acceleration.

- HAWC observation disfavors hadronic-only scenario because:
  1. Hadronic-only scenario can hardly meet the energy budget; ~100% of jet energy -> accelerating protons to explain the observed gamma-ray emission.
  2. Protons should have spread to a few degrees before emitting gamma rays.

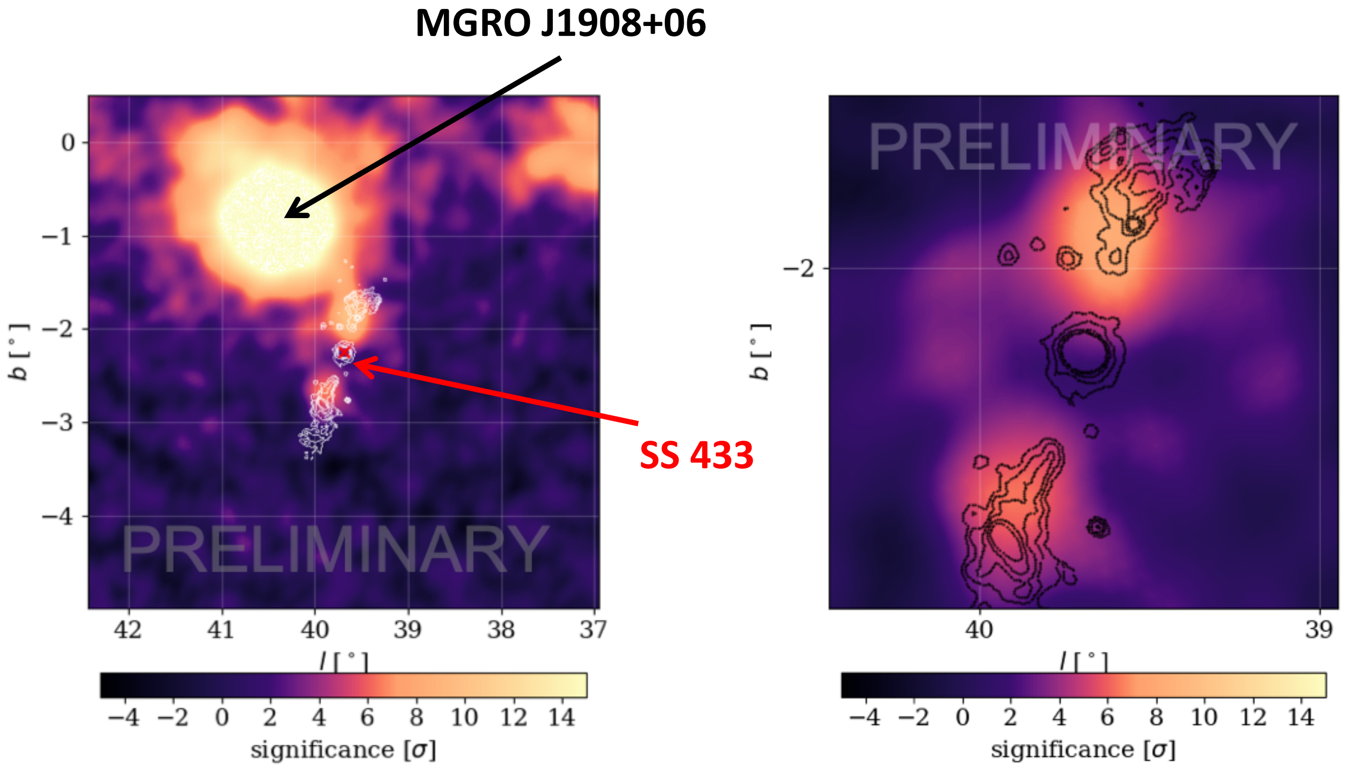
- Acceleration is occurring at the jet interaction, not in the central binary:
  1. Emission region is ~40 pc from central binary.
  2. Diffusion length scale is ~35 pc at these energies, assuming ISM diffusion coefficient (which may be much too large in this region).
  3. Advection length scale is ~4 pc.

❖ Note: We are not ruling out cosmic-ray acceleration entirely, but data do not support a purely hadronic origin for the gamma rays.

Nature **562,** 82–85 (2018).
https://doi.org/10.1038/s41586-018-0565-5

Recent Results!

Follow-Up Analysis on SS 433 – 1910 days



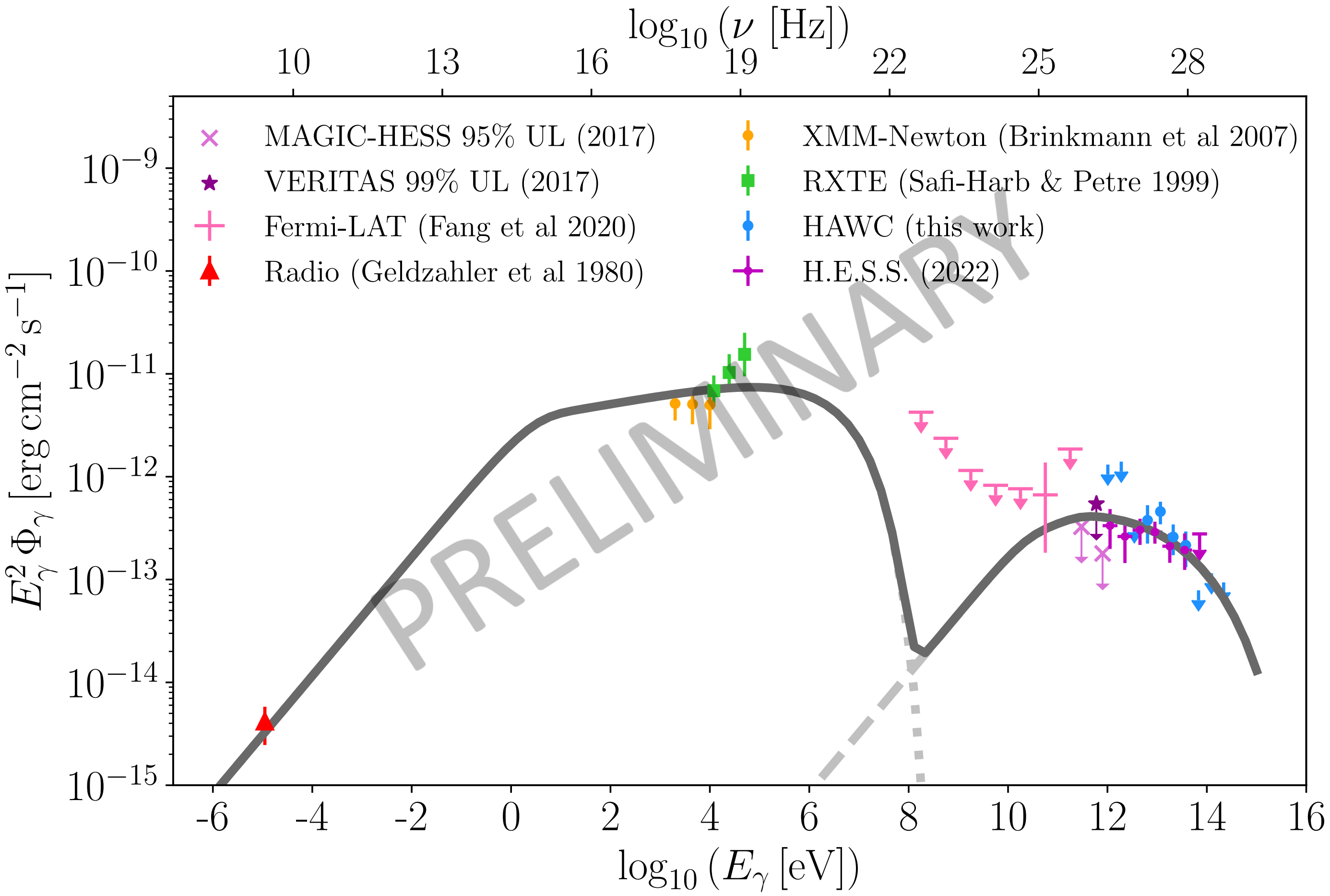
MGRO J1908+06

SS 433

East and west lobes now at 7σ and 9σ, respectively!

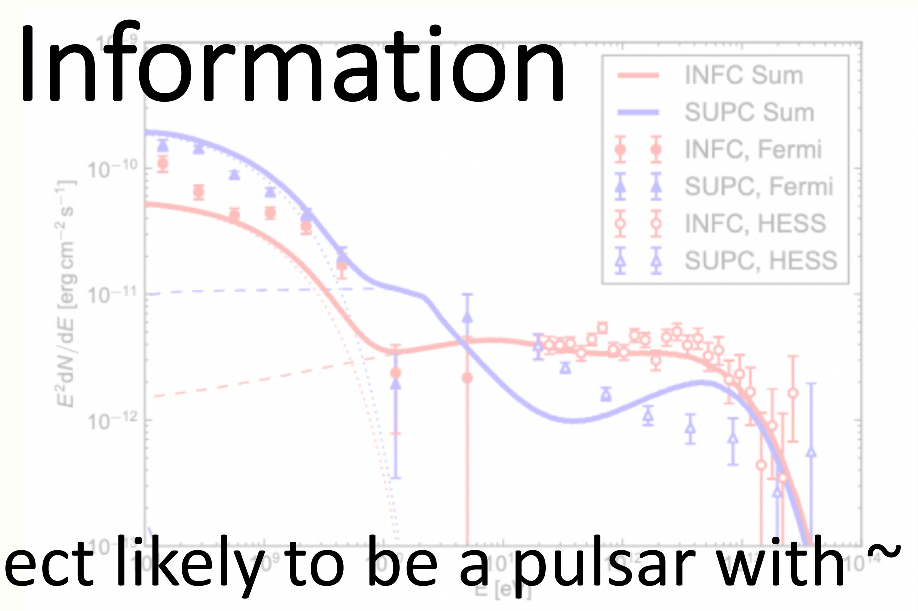
- Brighter lobes, more evident separation from J1908
- Jet lobes now significant enough for individual analyses including spectral studies
- The maximum photon energy is now at 50 TeV as opposed to 25 TeV in 2018
- Working on a paper right now for east lobe. West lobe also coming soon

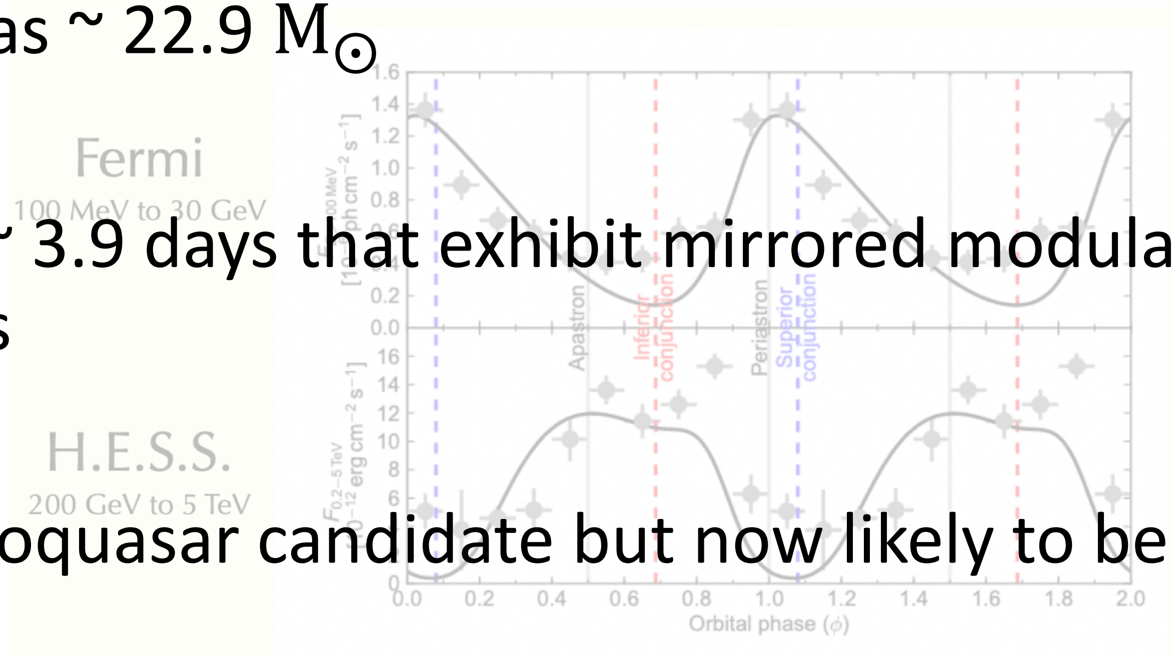
Follow-Up Analysis on SS 433 – 1910 days



- HAWC now has multiple data points with spectral information
- New results from H.E.S.S. and Fermi-LAT have also been added to SED
- Solid line is for the fitted leptonic model (synchrotron + inverse Compton) with electron cooling
- Conclusion still consistent with our previous results (2018)

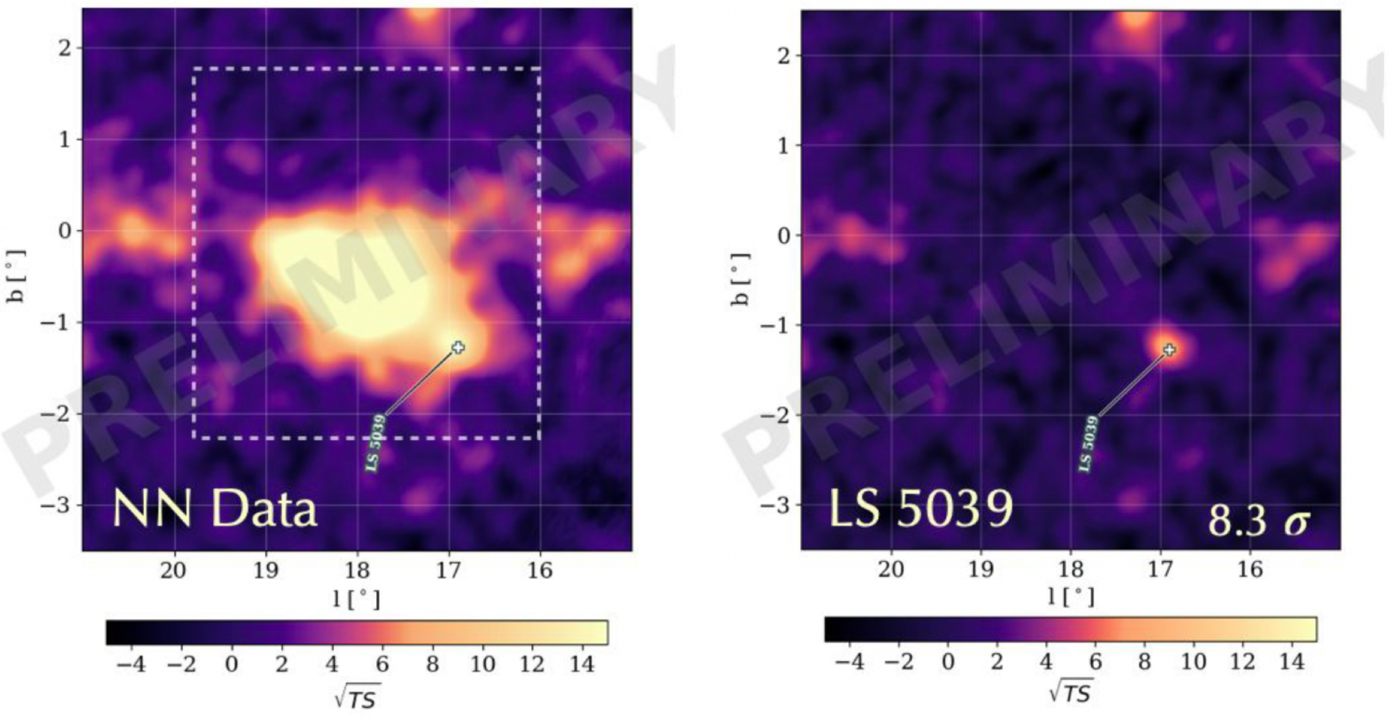
LS 5039 – General Information





- Distance of ~ 2.5 kpc
- Composed of compact object likely to be a pulsar with ~ 3.7 $M_\odot$ and companion star has ~ 22.9 $M_\odot$
- Orbital period of ~ 3.9 days that exhibit mirrored modulation between GeV and TeV emissions
- It has been a microquasar candidate but now likely to be a pulsar binary

LS 5039 Analysis – 1910 days

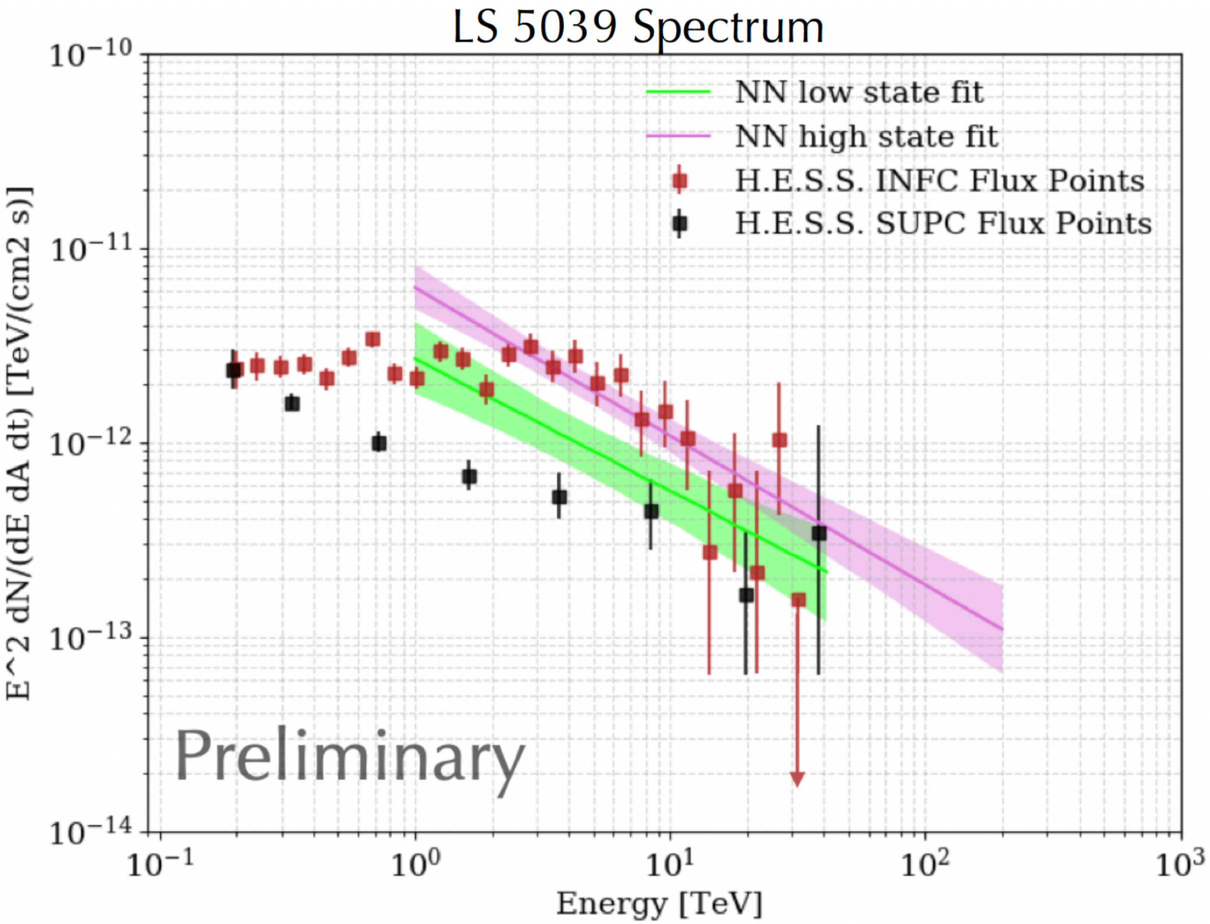


- Simultaneously fitted multiple sources to model the complex region (inside white box)

- Model includes diffuse background emission + background sources + LS 5039

- After subtracting all the other sources (residual map) -> point-like LS 5039 with 8.3σ

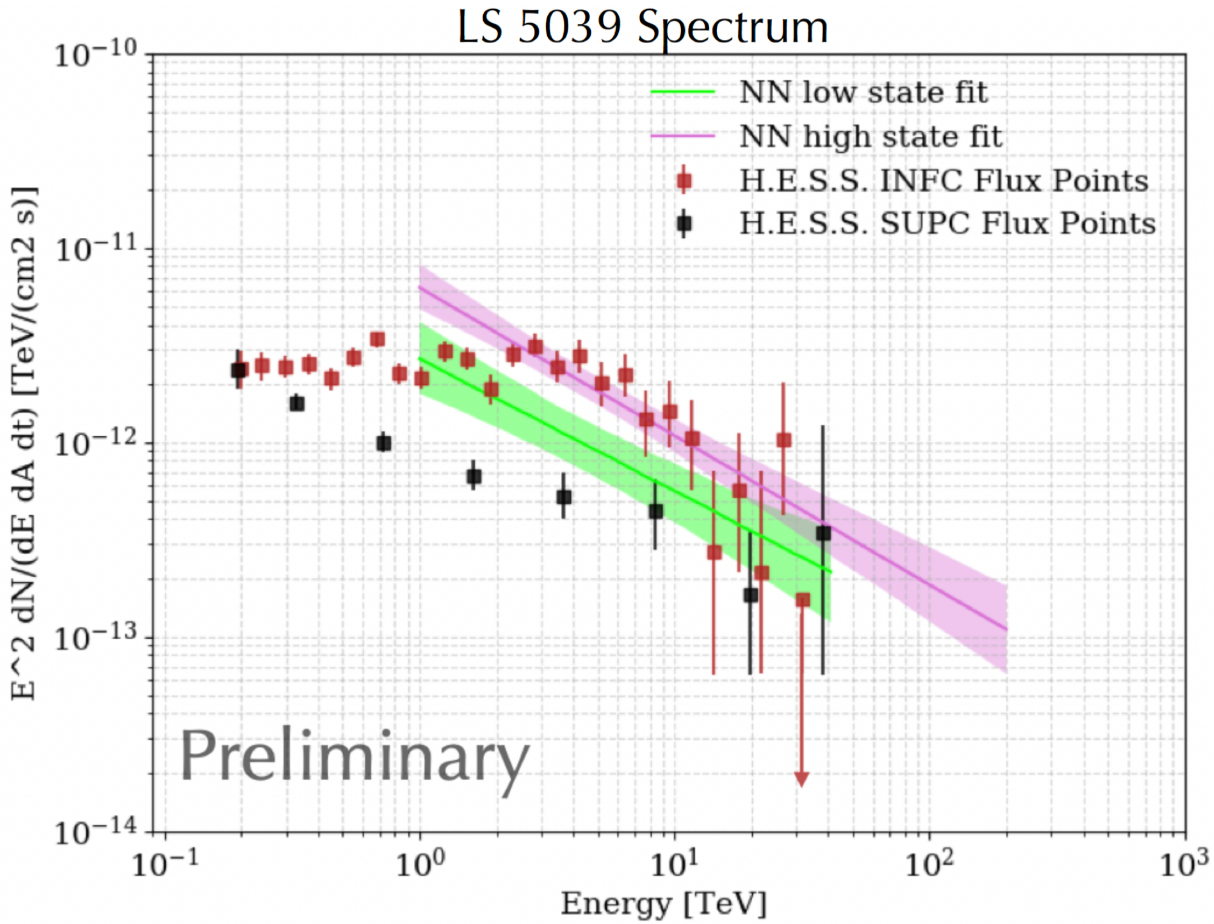
LS 5039 Analysis – 1910 days



Credits:H.E.S.S. data points A&A, 460 3 (2006) 743-749

- Using the timing information from the H.E.S.S. results, we have also divided the HAWC data into two sets corresponding to high states and low states
- First time HAWC sees flux modulations due to orbital motion of a binary system
- High state flux (INFC) ~ 2 times higher than low state flux (SUPC)
- Similar spectral indices
- The high-state spectrum seemingly continues up to 100 TeV without any evidence of a spectral cutoff

LS 5039 Analysis – Interpretation

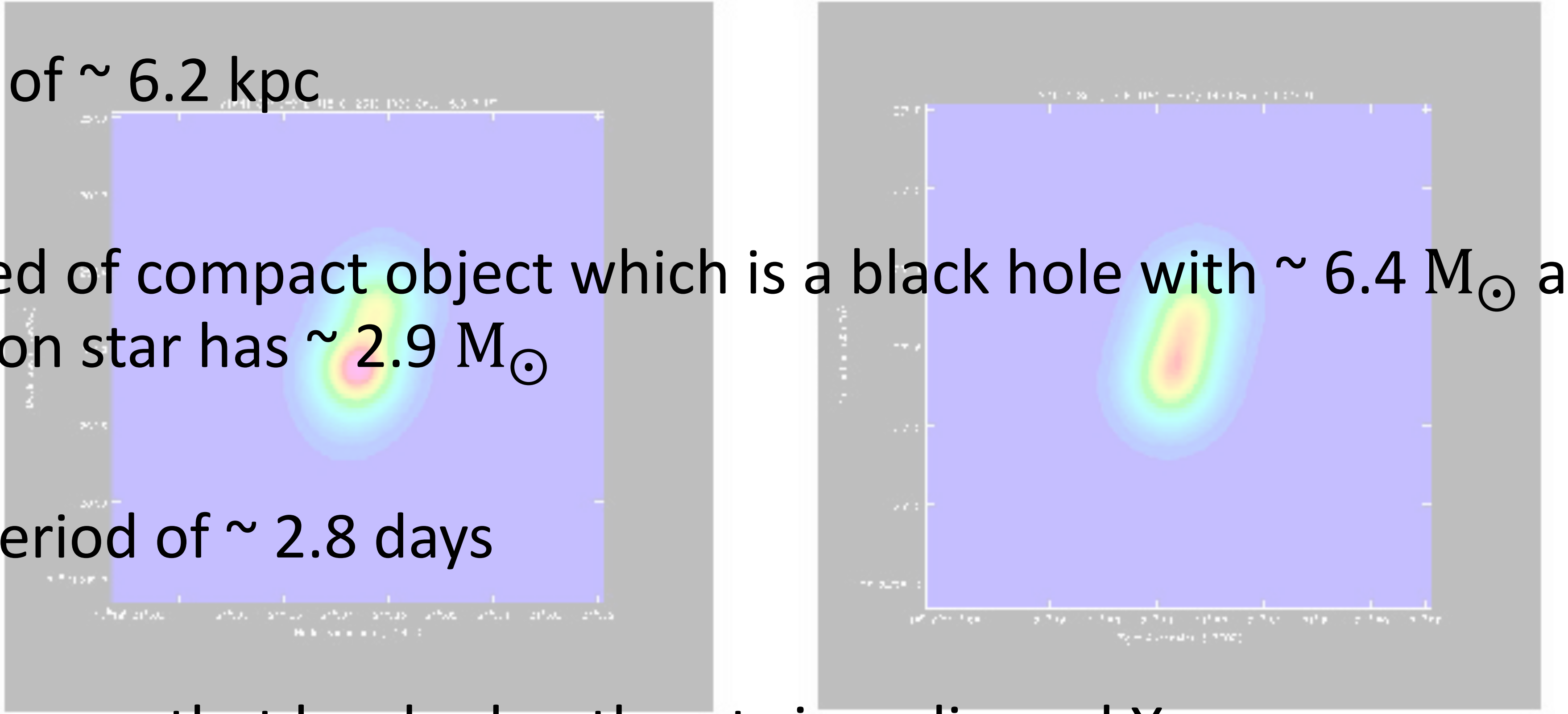


Credits:H.E.S.S. data points A&A, 460 3 (2006) 743-749

- Currently working on understanding the particle composition and acceleration mechanism
- We are in the process of writing a draft for a paper

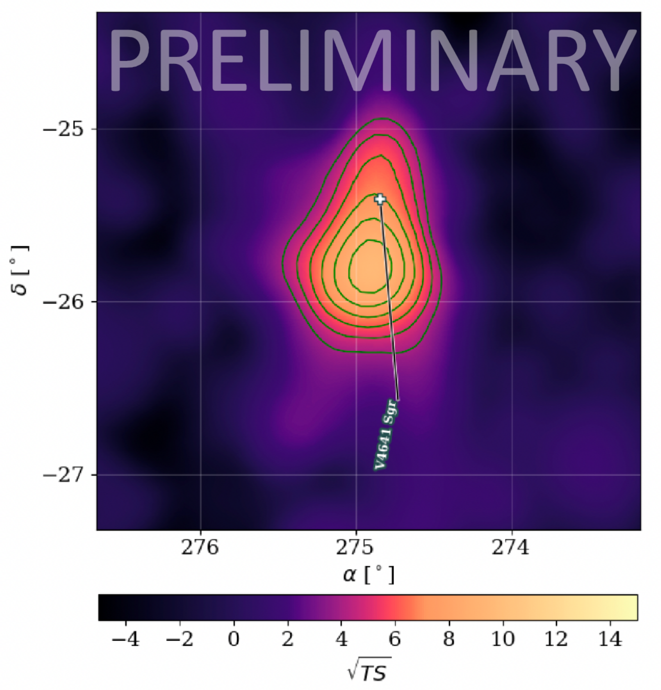
V4641 Sgr – General Information

Image Credit:
NRAO

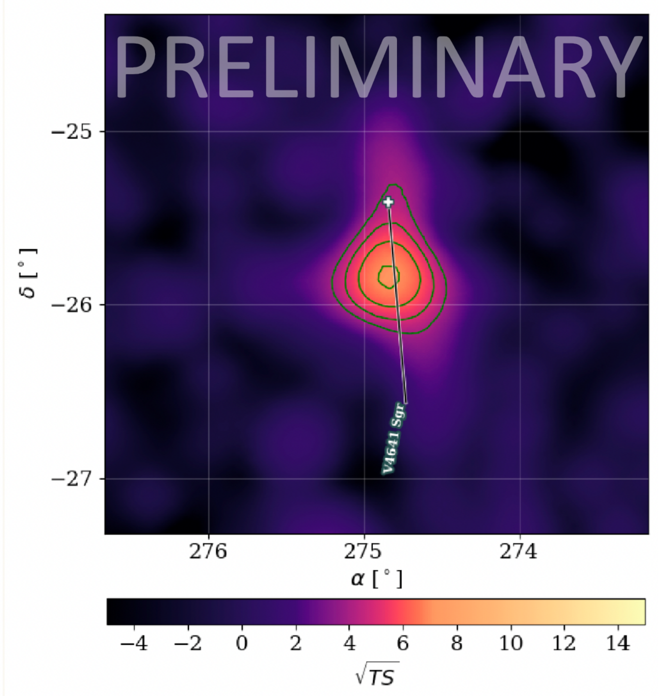


- Distance of ~ 6.2 kpc
- Composed of compact object which is a black hole with ~ 6.4 $M_\odot$ and companion star has ~ 2.9 $M_\odot$
- Orbital period of ~ 2.8 days
- A microquasar that has had outbursts in radio and X-rays

V4641 Sgr Analysis – 1910 days



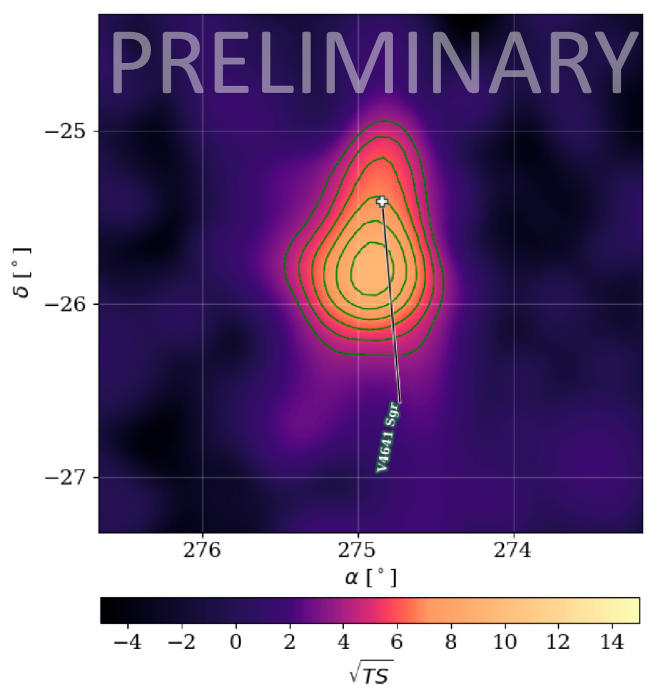
9.67 σ



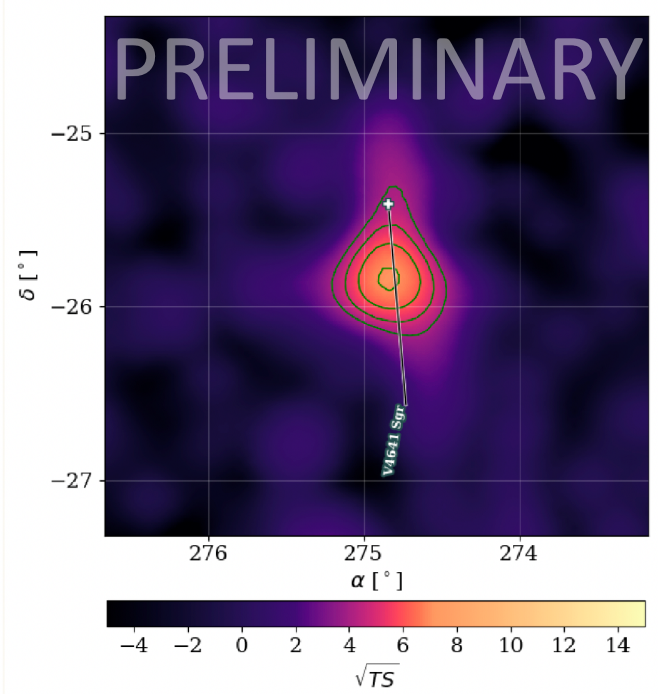
7.20 σ

- Recently detected off-plane excess
- 9.7σ above background, 7.2σ for $E > 25$ TeV
- This new source is coincident with a known X-ray binary (microquasar) V4641 Sgr
- Relatively easier to analyse since less source confusion

V4641 Sgr Analysis – Interpretation



$9.67\ \sigma$



$7.20\ \sigma$

- Spectral analyses are being carried out to study its properties + nature of the system
- Morphological analyses + one extended source vs. two point source models
- Jet emissions similar to SS 433?
- Manuscript with more details is being prepared

Time Dependent Analyses and Central Binary

- SS 433:
  - No significant excess from the central binary (only from the jet lobes)
  - No modulation in flux observed when using daily maps
  - No jet precession observed at the jet interaction regions. Even in an ideal low-density environment where the jets precess without any disruption, the phase should be lost by ~0.1 pc (Also the lobes are too fat!)

- LS 5039:
  - Significant excess from the central binary
  - No modulation in flux observed when using daily maps
  - But, the comparison between high states and low states yielded significant difference between two datasets

- V4641 Sgr:
  - No modulation in flux observed when using daily maps
  - No significant results from comparing with known outbursts
  - Hot spot slightly off of the known location of the central binary similar to SS 433

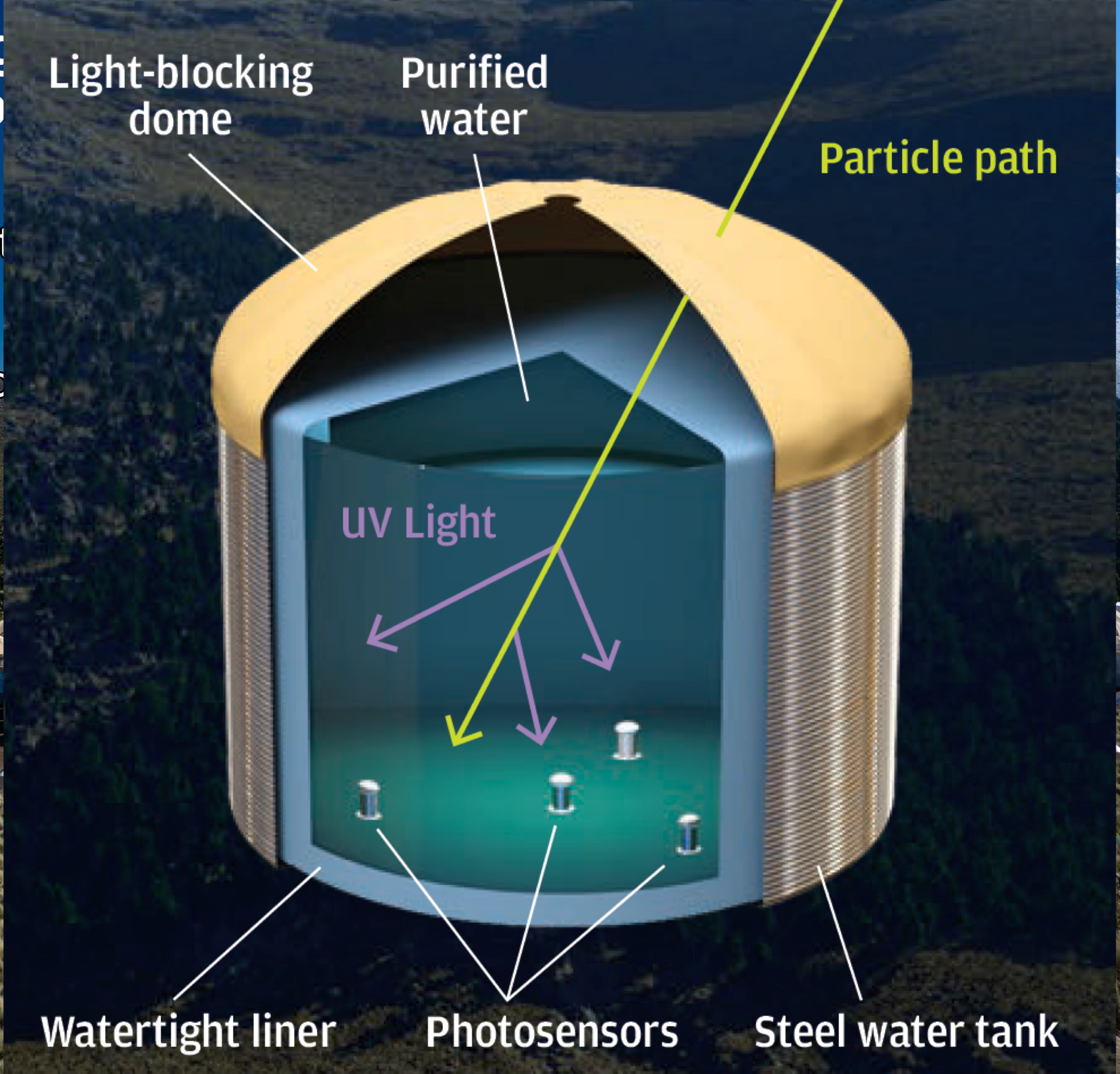
Summary

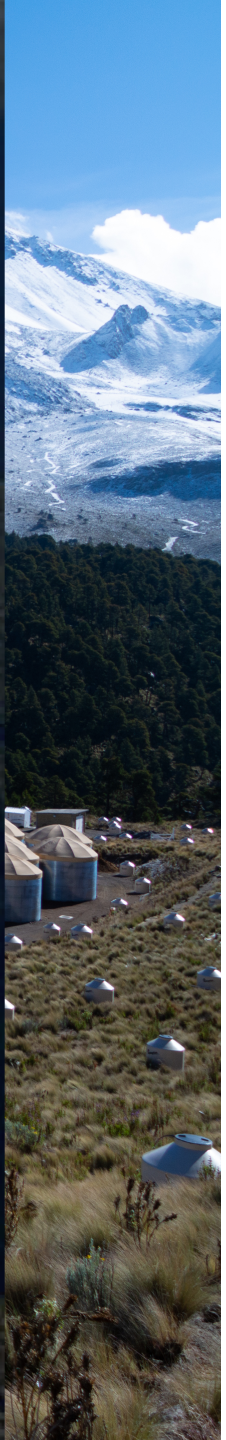
- HAWC is well-suited to search for TeV gamma-ray binaries due to its high uptime and wide field-of-view
- However, time dependent analyses with daily maps have not been yielding significant results
- With increased amount of accumulated data, HAWC now sees significant emission from three unique binary systems
- Two separate jet emissions from SS 433, high-states + low-states from LS 5039, elongated significant emission from V4641 Sgr

Back Up

Hig
Ob

- Latit
- Pico
- 300
- 2 sr
- 300





Acceleration Mechanism

How does SS 433 produce ~1 PeV electrons?

- **Acceleration in magnetic fields:**
  Possible up to a few hundred TeV. Above that, acceleration time exceeds synchrotron cooling time for 16 μG fields.

- **Acceleration in standing shocks (Fermi acceleration):**
  Can reach PeV energies. But, there is no multiwavelength evidence for large shocks in these interaction regions.

- Explaining the emission from SS 433 jets is a challenge with existing acceleration models!

High-Mass Microquasar Analysis – 1523 days

- Flux upper limits on each microquasar (LS 5039, SS 433 (central binary location), Cyg X-1, Cyg X-3)
- Jet powered: 95% credible interval of jet emission efficiency above 1 TeV

$$\boxed{\epsilon_\gamma^{\mathrm{UL}} = 5.4 \times 10^{-6}}$$

- Magnetic field: Lower limit on the magnetic field strength

$$\boxed{B^{\mathrm{LL}} = 22 \left(\frac{\epsilon_{\mathrm{syn}}}{10\,\%}\right)^{1/2} \mathrm{G}}$$

Astrophys.J.Lett. 912 (2021) 1, L4

Scenario I – jet powered

- We assume γ-ray luminosity proportional to jet power $L_\gamma = \epsilon_\gamma \, L_{\rm jet}$.

- γ-ray flux for scenario I is given by

$$\Phi_\gamma = \frac{\epsilon_\gamma}{4\pi}\boxed{\frac{L_{\rm jet}}{D^2}} K_p \left(\frac{E}{E_{\rm piv}}\right)^{-p}$$

Contribution Factor

- The 95% credible interval of jet emission efficiency above 1 TeV is

$$\boxed{\epsilon_\gamma^{\rm UL} = 5.4 \times 10^{-6}}$$

with a best fit spectral index of $p = 2.2$

Astrophys.J.Lett. 912 (2021) 1, L4

Scenario II – powered by magnetic field

- The inverse-Compton and synchrotron fluxes are connected by energy densities of magnetic field and radiation field of donor star.

$$\frac{F_{\rm syn}}{F_{\rm IC}} \approx \frac{u_B}{u_0\, f_{\rm KN}}$$

- γ-ray flux for scenario II is given by

Contribution Factor

$$\Phi_\gamma = \frac{\boxed{F_{\rm syn}\, u_0\, f_{\rm KN}}}{u_B} K_p \left(\frac{E}{E_{\rm piv}}\right)^{-p}$$

Scenario II – powered by magnetic field

- Lower limit on the magnetic field strength is derived to be

$$\boxed{B^{\mathrm{LL}} = 22 \left(\frac{\epsilon_{\mathrm{syn}}}{10\,\%} \right)^{1/2} \mathrm{G}}$$

ϵ_{syn} = fraction of observed X-ray and MeV gamma-ray flux due to synchrotron emi

- Strong *B* field found by our stacking analysis suggests that the X-ray to MeV gamma-ray flux is not dominated by synchrotron radiation of VHE electrons.

Astrophys.J.Lett. 912 (2021) 1, L4