



# **Follow-Up Results on Jet Interaction Regions of SS 433 Using Data from HAWC**

**Chang Dong Rho & Hao Zhou**

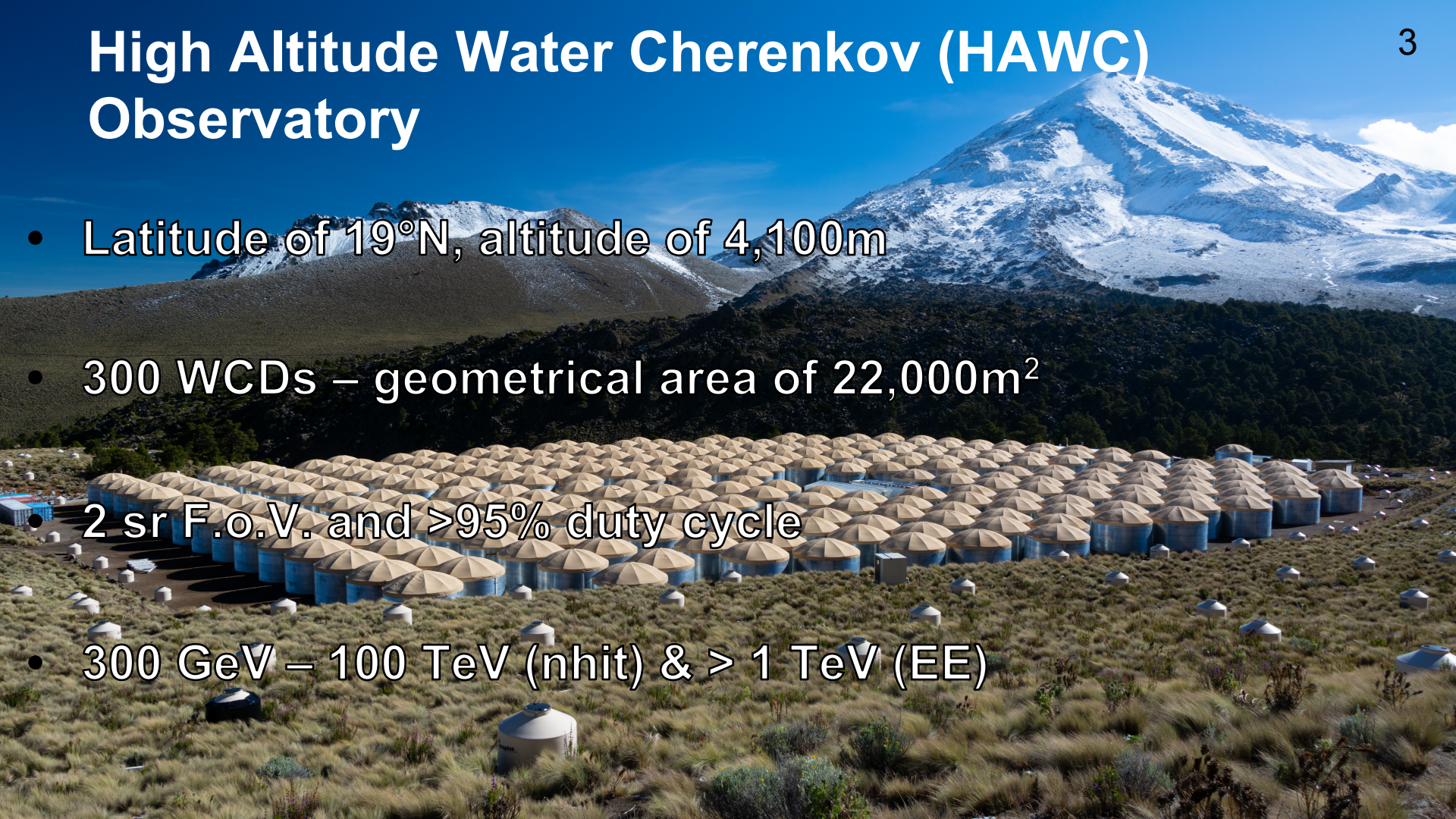
# Overview

- Introduction to HAWC.
- SS 433 results recap (1,017 days).
- Theoretical interpretation.
- New follow-up SS 433 results (1,038 days; new energy estimator).

# High Altitude Water Cherenkov (HAWC) Observatory

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- Latitude of  $19^{\circ}\text{N}$ , altitude of  $4,100\text{m}$
- 300 WCDs – geometrical area of  $22,000\text{m}^2$
- 2 sr F.o.V. and  $>95\%$  duty cycle
- 300 GeV – 100 TeV (nhit) &  $> 1\text{ TeV}$  (EE)

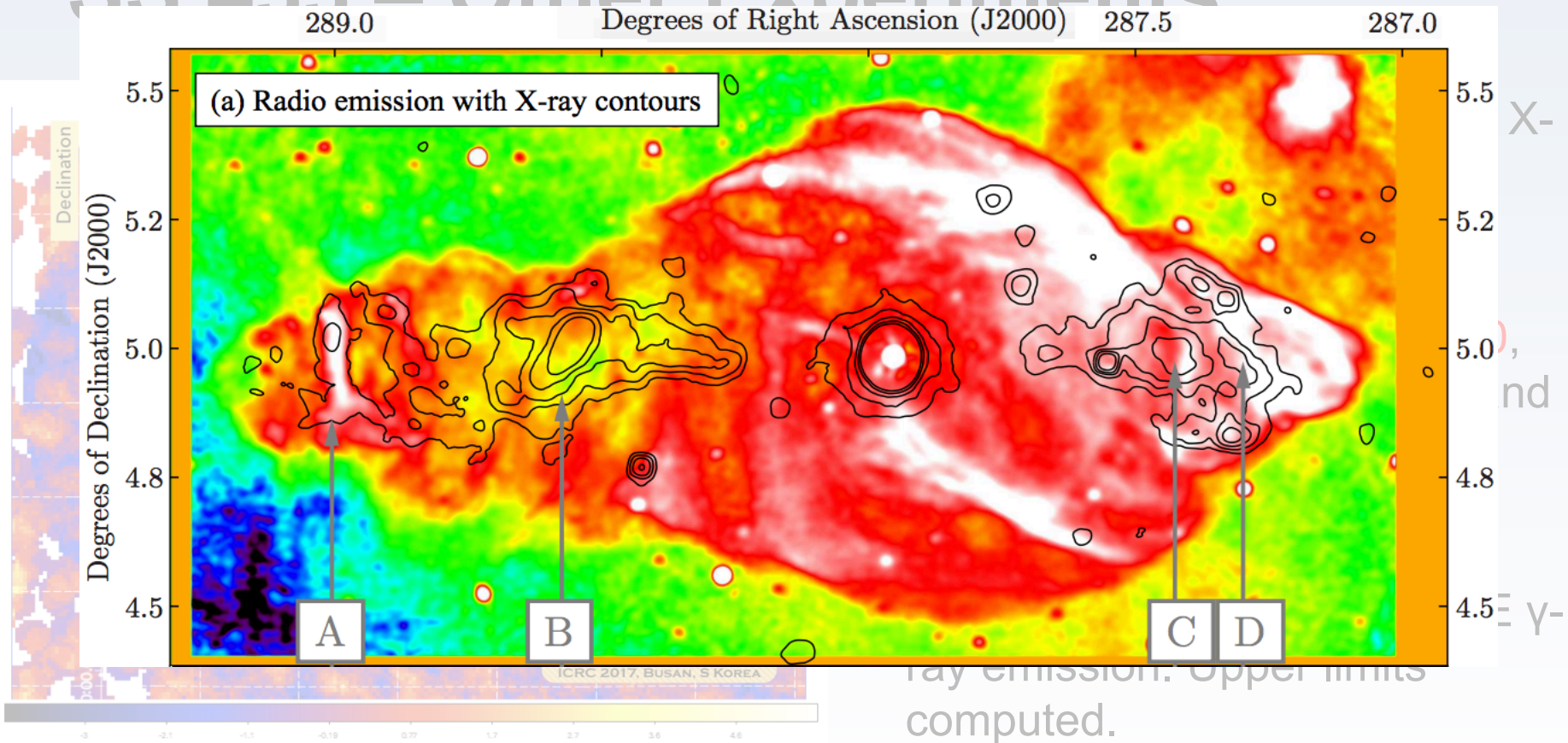








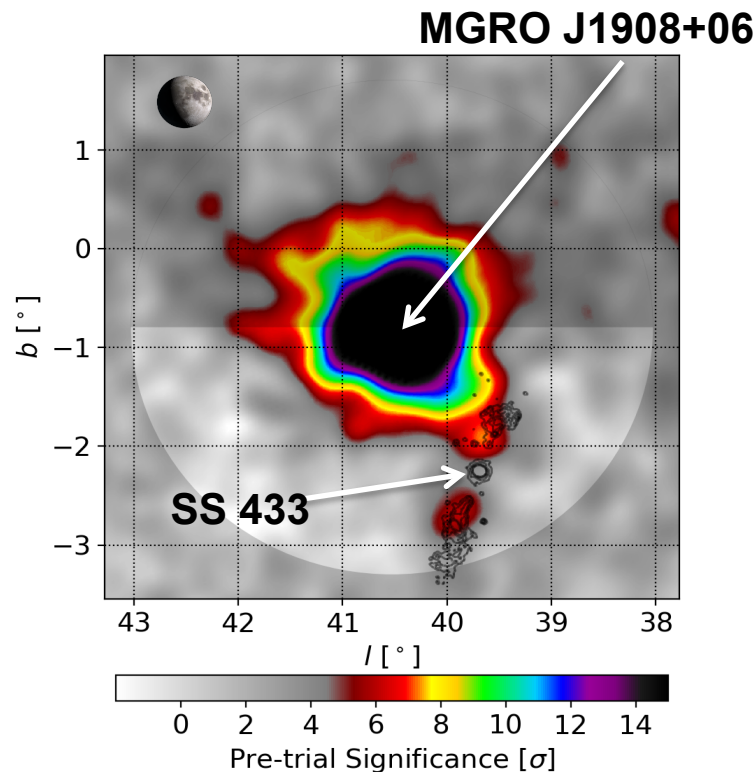
## SS 433 – Other Experiments



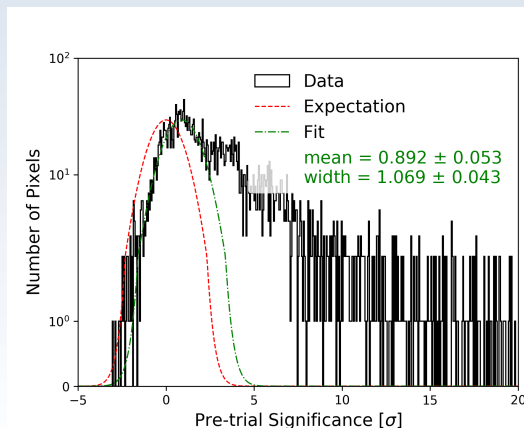
ray emission. Upper limits  
computed.

# HAWC – SS 433 in 1017d of Data

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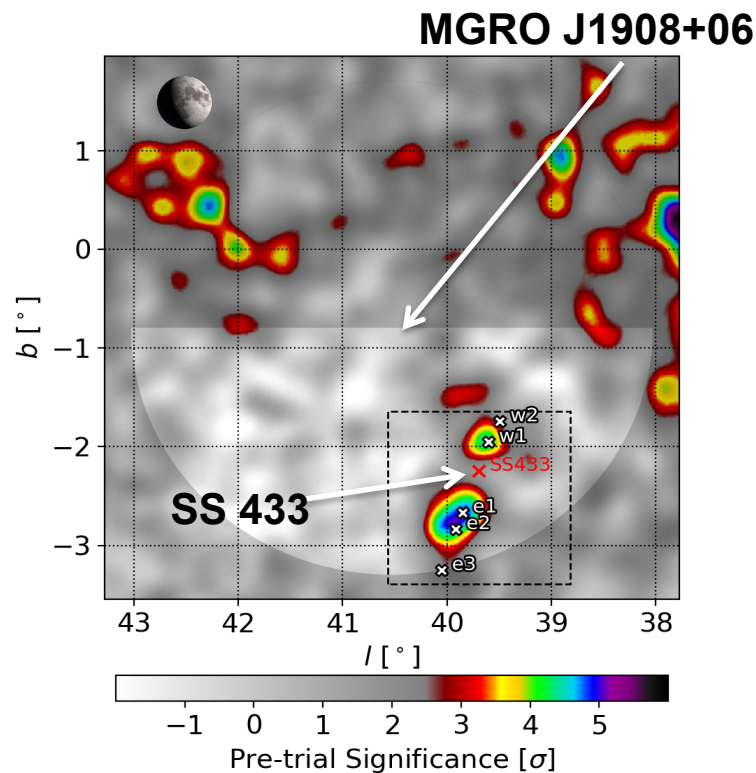


- HAWC sees **two hot spots**, spatially in coincidence with X-ray contours.
- Two SS 433 lobes & J1908 fitted simultaneously.
- **Semi-circular RoI** to reduce contamination from GDE.

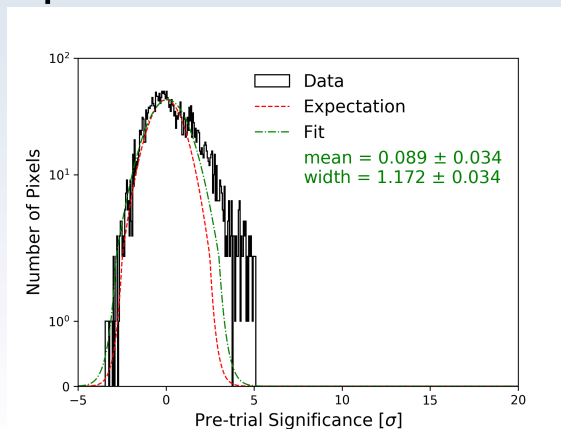


# HAWC – SS 433 in 1017d of Data

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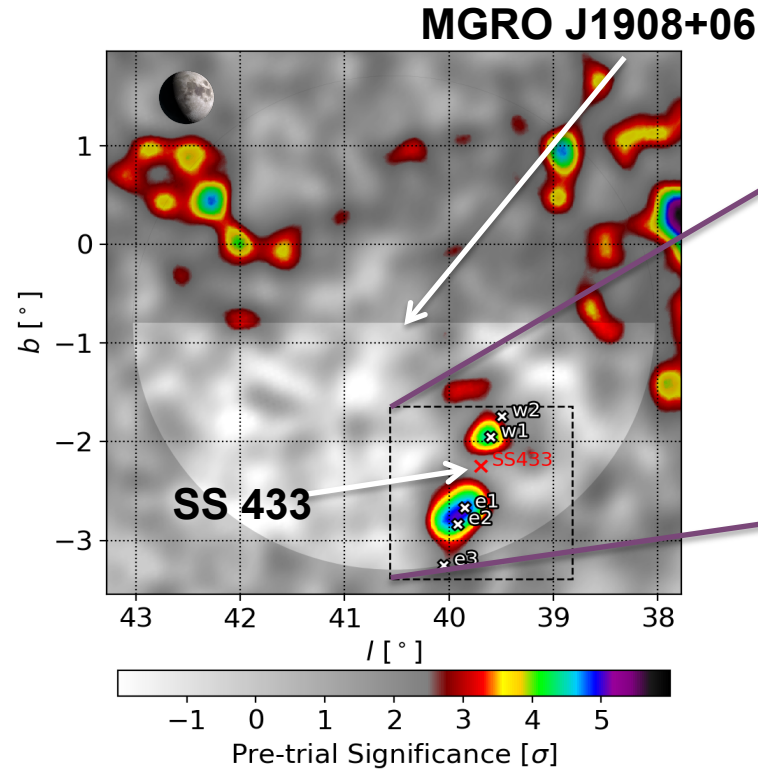
- Used nested models to separate the emission of **lobes** from **J1908**.
- Hotspots outside the **RoI** can be ignored (Galactic Plane).
- The pre-trial significance distribution shows improvement after subtraction.



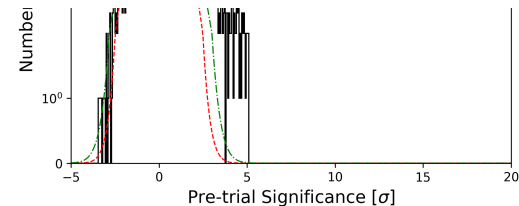
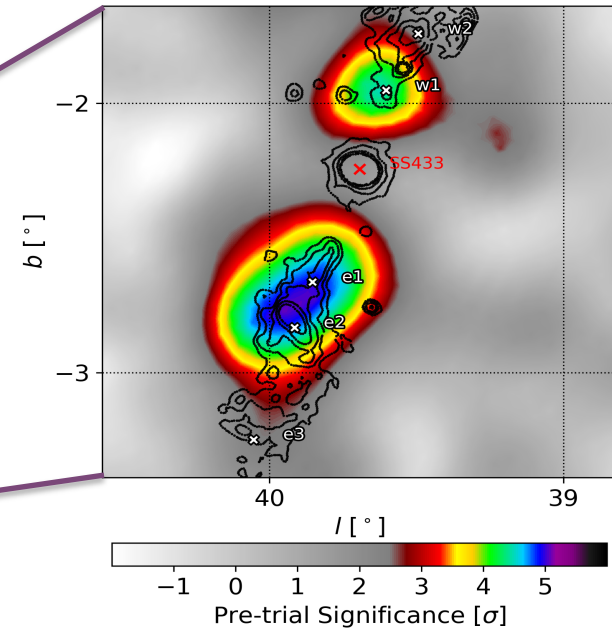


# HAWC – SS 433 in 1017d of Data

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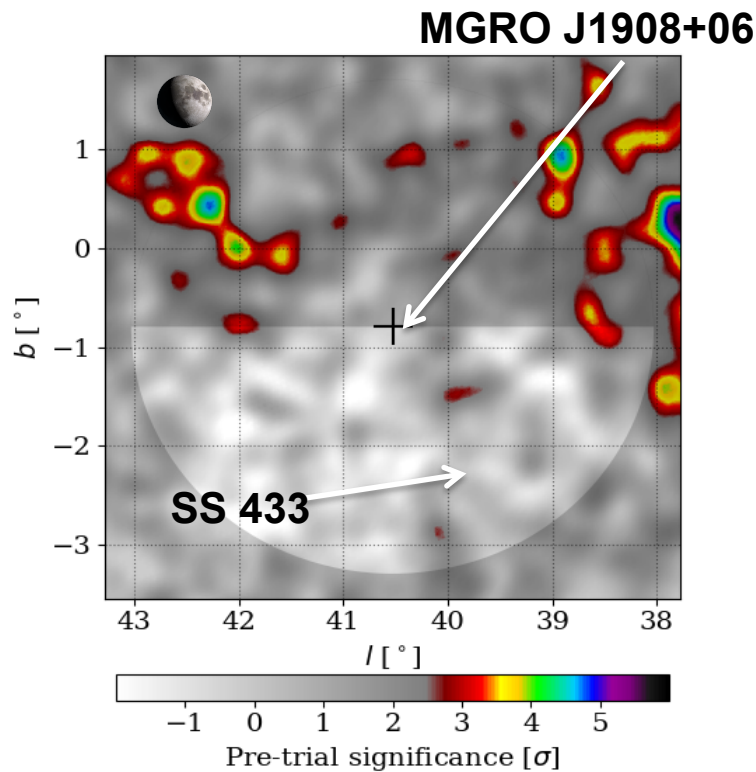


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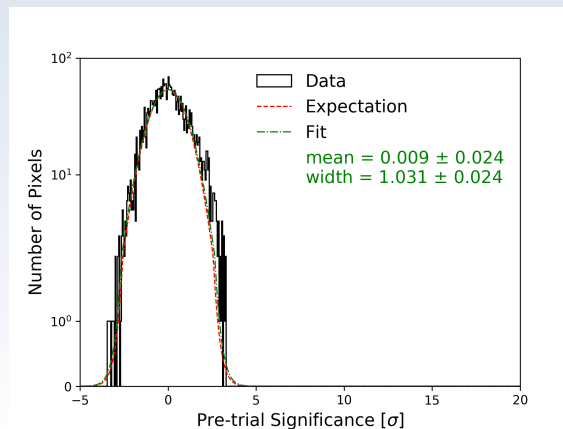


# HAWC – SS 433 in 1017d of Data

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- Residual significance distribution is **zero-mean Gaussian**, consistent with background-only distribution.
- “The nested fit of east and west lobes gives  $5.4\sigma$  post-trial with HAWC’s 1,017 days of dataset at e1 and w1”.



# Key Issues

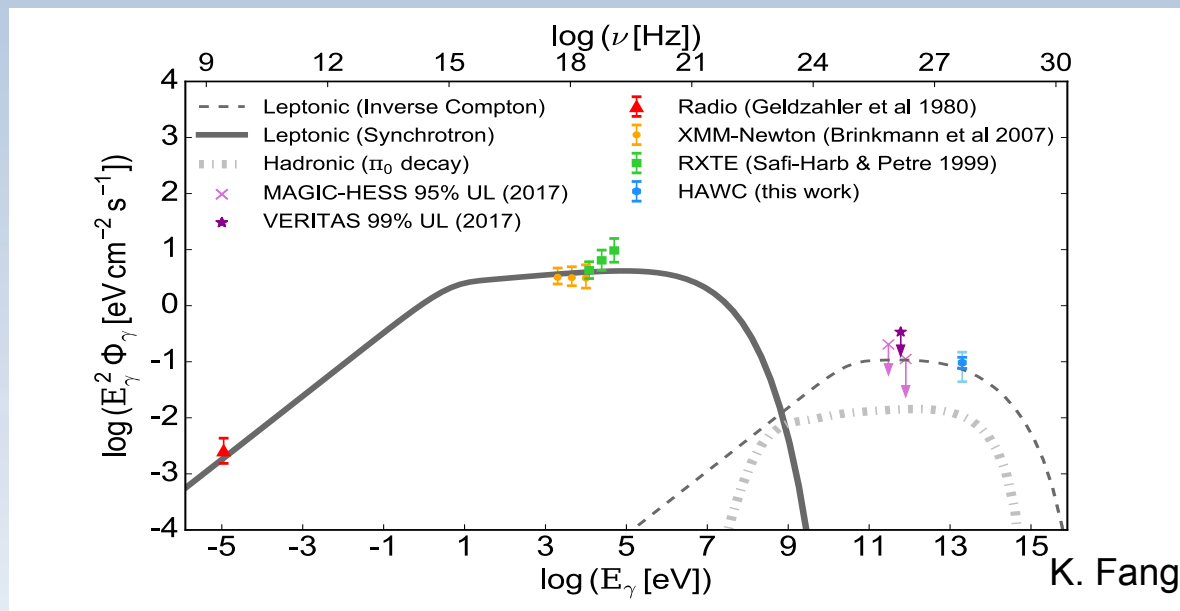
This is the first time astrophysical jets have been spatially resolved at such high energies. But there still are questions:

- **Composition and spectrum** of the particles generating the gamma rays: hadronic ( $\pi^0$  decay) or leptonic (IC) origin?
- **Acceleration site**: near binary or jet interaction regions?
- **Acceleration mech.**: magnetic fields or standing shocks?



# Broadband Spectral Energy Distrib. of e1

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- Leptonic: TeV  $\gamma$  rays observed by HAWC are produced via IC of CMB by the **same**  $e^-$ .
- Multiwavelength spectral fit (solid + dashed line) of leptonic scenario assumes

$$\frac{dN}{dE} \propto E^{-\alpha} \exp\left(\frac{-E}{E_{\max}}\right),$$

in a magnetic field  $B$  for an injected flux of electrons. We inferred  $E_{\max} > 1$  PeV.

# Key Points

- **Leptonic model** does a good job of explaining the gamma ray emission, requires  **$\sim 0.03\%$  of jet power  $\rightarrow$  electron acceleration**.
- HAWC observation **disfavors** hadronic-only scenario because:
  1. Hadronic-only scenario can hardly meet the energy budget;  **$\sim 100\%$  of jet energy  $\rightarrow$  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  $\sim 40$  pc from central binary.
  2. Diffusion length scale is  $\sim 35$  pc at these energies, assuming ISM diffusion coefficient (which may be much too large in this region).
  3. Advection length scale for electrons is  $\sim 4$  pc.

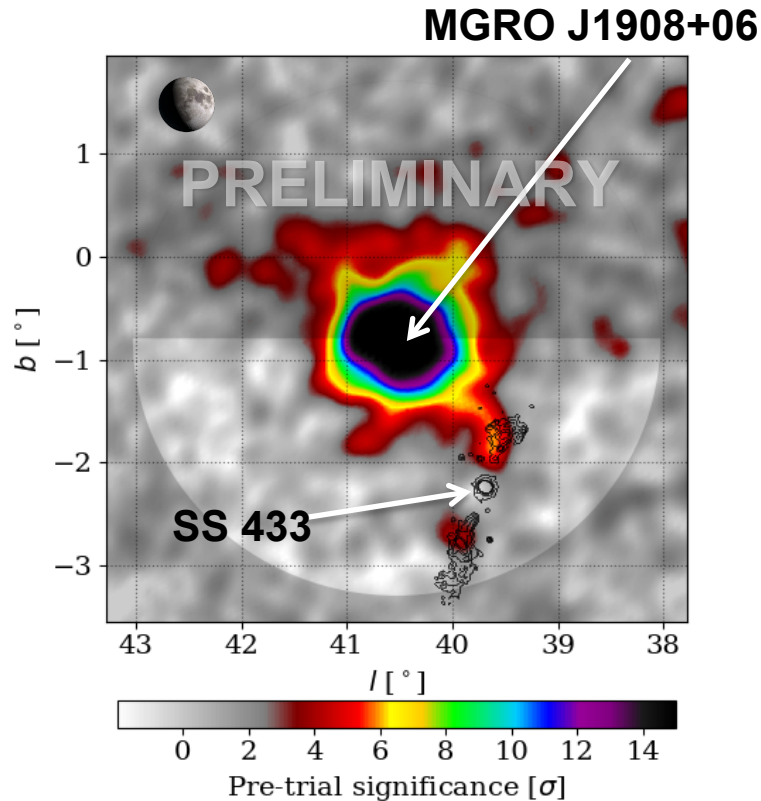
# Acceleration Mechanism

How does SS 433 produce  $\sim$  PeV electrons?

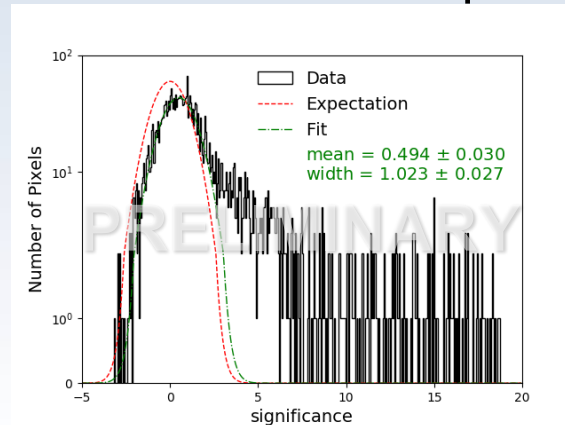
- **Acceleration in magnetic fields:**  
**Possible up to a few hundred TeV.** Above that, acceleration time exceeds synchrotron cooling time for 16  $\mu$ G fields.
- **Acceleration in standing shocks (Fermi acceleration):**  
**Can reach PeV energies.** But, no multiwavelength evidence for large shocks in the interaction regions.
- Explaining the emission from SS 433 is a challenge for current acceleration models!



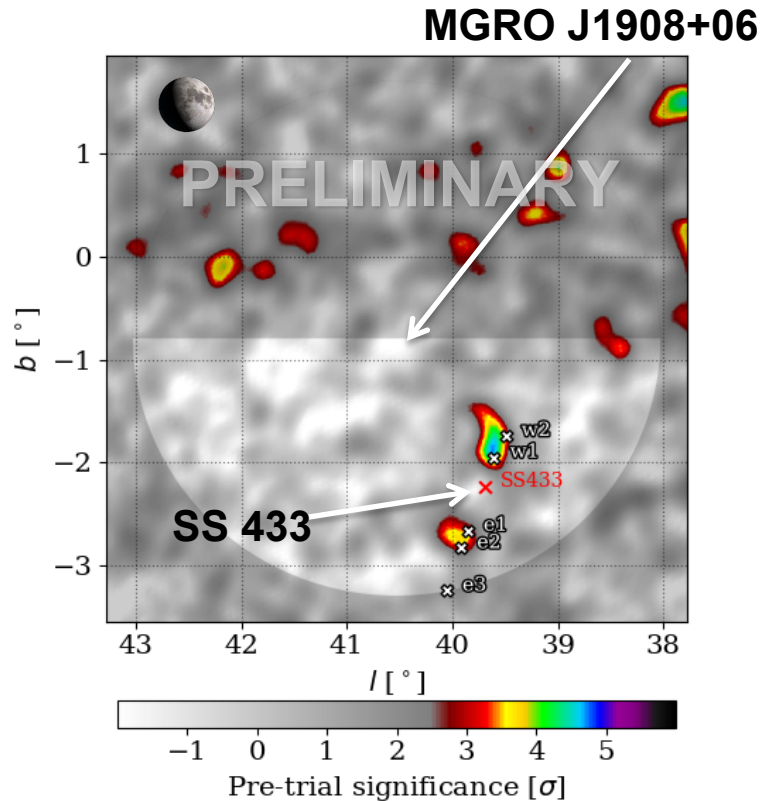
# HAWC – SS 433 Energy Estimator (1,038d) 14



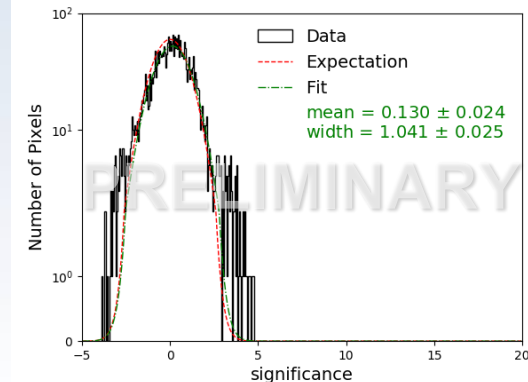
- Same analysis as 1,017 days.
- Both J1908 and the SS 433 lobes show much weaker significance.
- On-array vs. on+off-array.
- West lobe looks more independent.



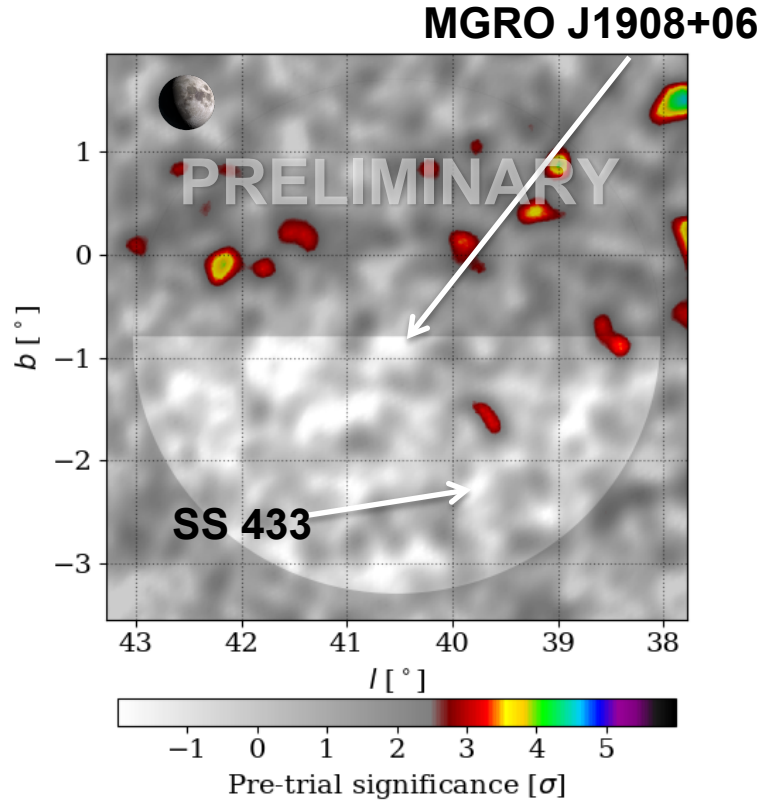
# HAWC – SS 433 Energy Estimator (1,038d) 15



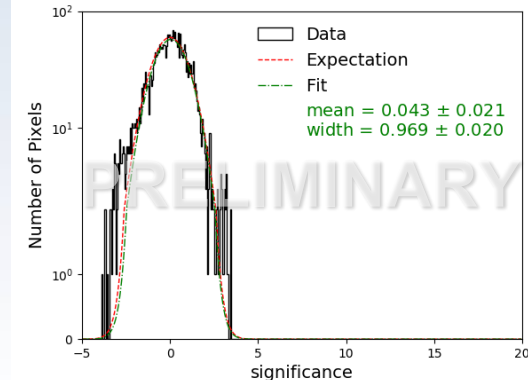
- Used nested models to separate the emission of lobes from J1908.
- Hotspots outside the RoI once again (Galactic Plane).
- Lobes are still there. Stronger west lobe but weaker east lobe.



# HAWC – SS 433 Energy Estimator (1,038d) 16



- Residual map after subtracting the lobes as well as J1908.
- Residual significance distribution is still consistent with background.





# Summary

- 1,017 day data published with Nature (Oct, 2018).
- Consistent with **leptonic model** with acceleration occurring at **jet interaction region**; acceleration mechanism not clear; hadronic model not completely ruled out.
- Follow-up results show reduced signif. for SS 433 lobes due to **on-array only** events **vs. on+off-array** events.
- With more data, we will find spectral constraints.

# Reference

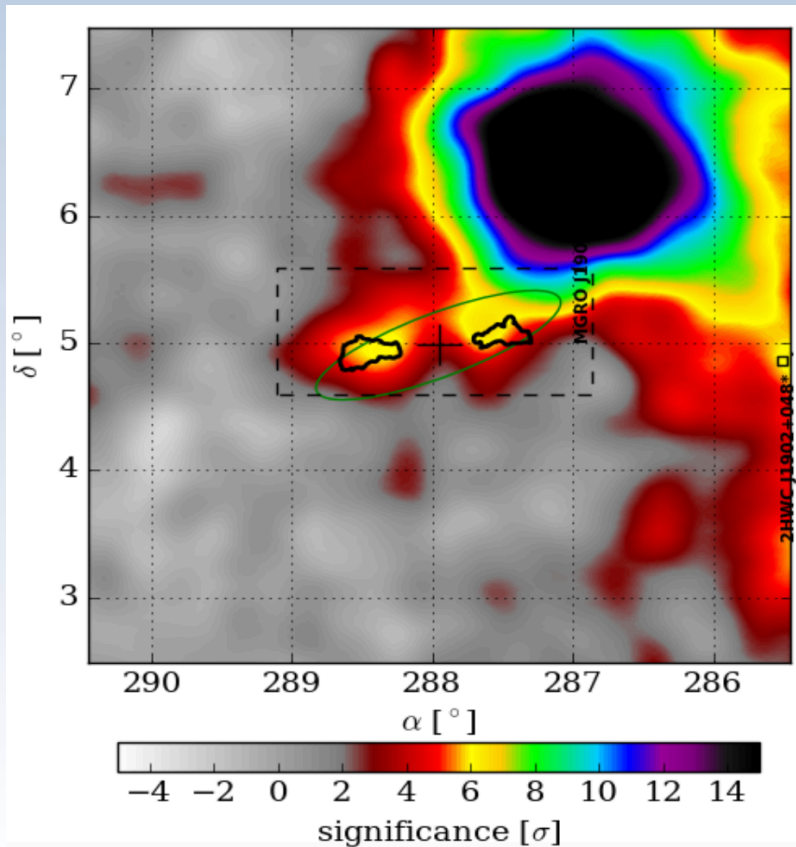
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**Back up**

# SS 433 – HAWC



- **HAWC**: Extended elliptical hotspot around location of **SS 433** in 17 month data.
- HAWC obs. interesting because searches for  $\gamma$ -ray emission from hotspots between 100 GeV and 10 TeV gave no detection.



# Fit Results fhit vs. ee

Lobe	Position (RA, Dec)	$dN/dE$ at 20 TeV [ $10^{-16} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ ]	TS
<b>Fractional hit bin results (published results).</b>			
e1	19:13:37 04°55'48"	$2.4^{+0.6+1.3}_{-0.5-1.3}$	41.2
w1	19:10:37 05°02'13"	$2.1^{+0.6+1.2}_{-0.5-1.2}$	
<b>Energy estimator (ground parameter; on-array only).</b>			
e1	19:13:37 04°55'48"	$2.5^{+1.1}_{-0.8}$	30.0
w1	19:10:37 05°02'13"	$3.5^{+1.2}_{-0.9}$	

# Precession & Central Engine

- HAWC does not see jet precession. Even in an ideal low-density environment where the jets precess without any disruption, the phase should be lost by  $\sim 0.04$  pc (Also the lobes are too fat!).
- Central binary:
  - No significant VHE gamma-ray emission from the central binary.
  - No periodic modulation in flux observed from the central engine.
- Therefore, SS 433 is not really a “gamma-ray binary”. It is a very special case!