HAWC results on binary systems

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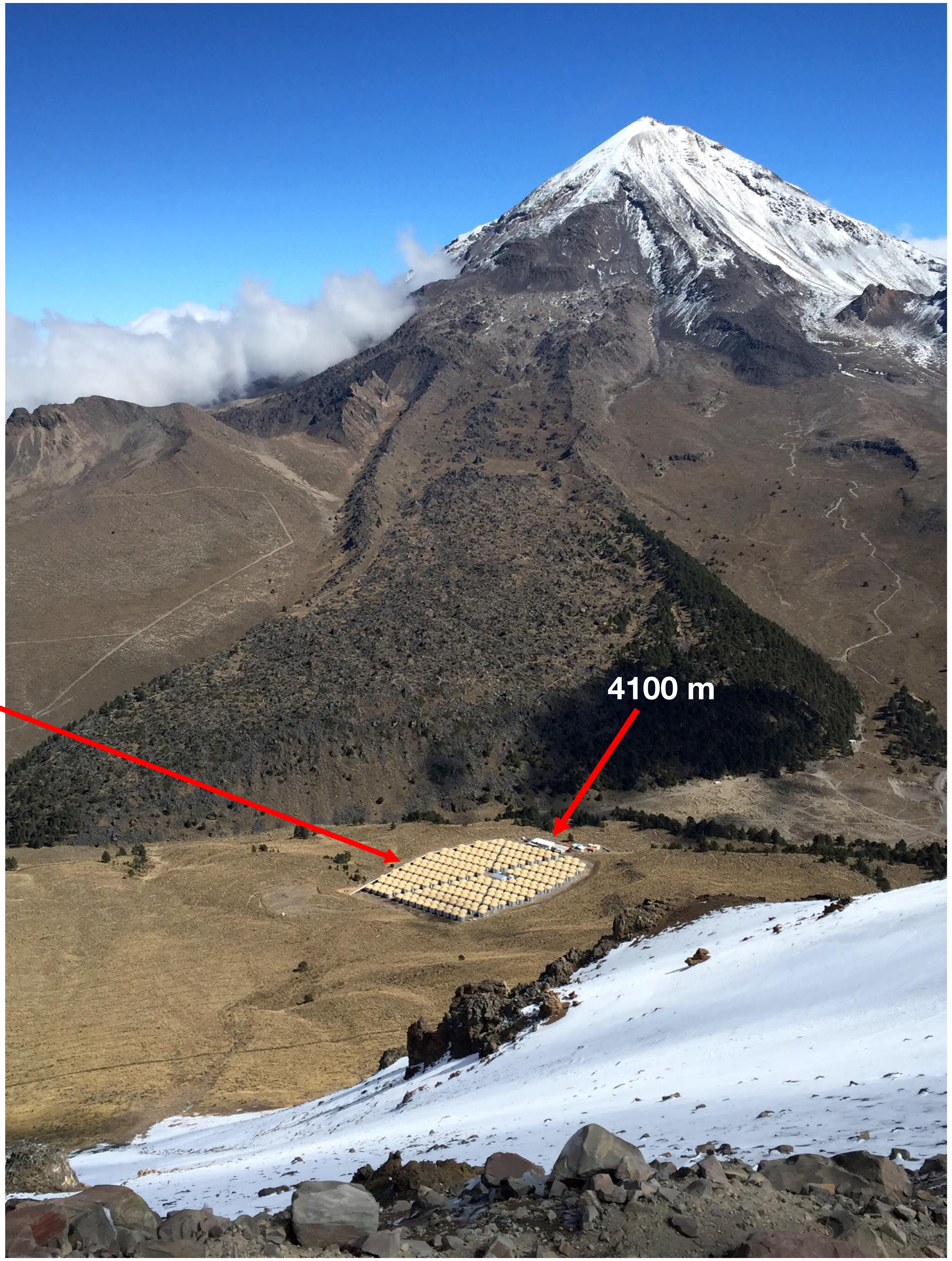
Outline

- The HAWC Observatory
- Binary candidates in HAWC FOV
- Multi TeV emission from the lobes of SS 433
- Recent studies of SS 433 with Fermi-LAT compared to HAWC results
- Conclusions and Outlook

The HAWC observatory



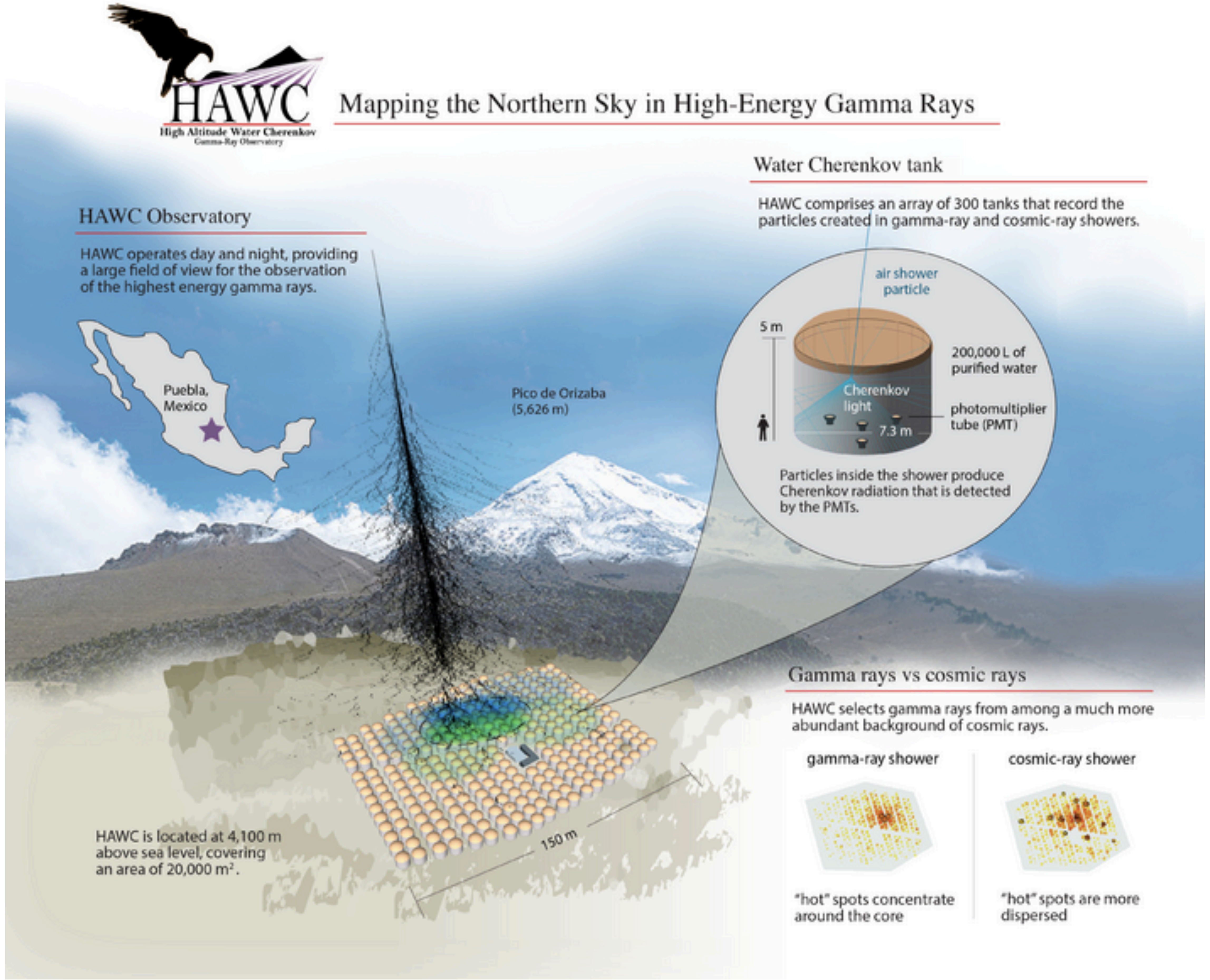
Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.

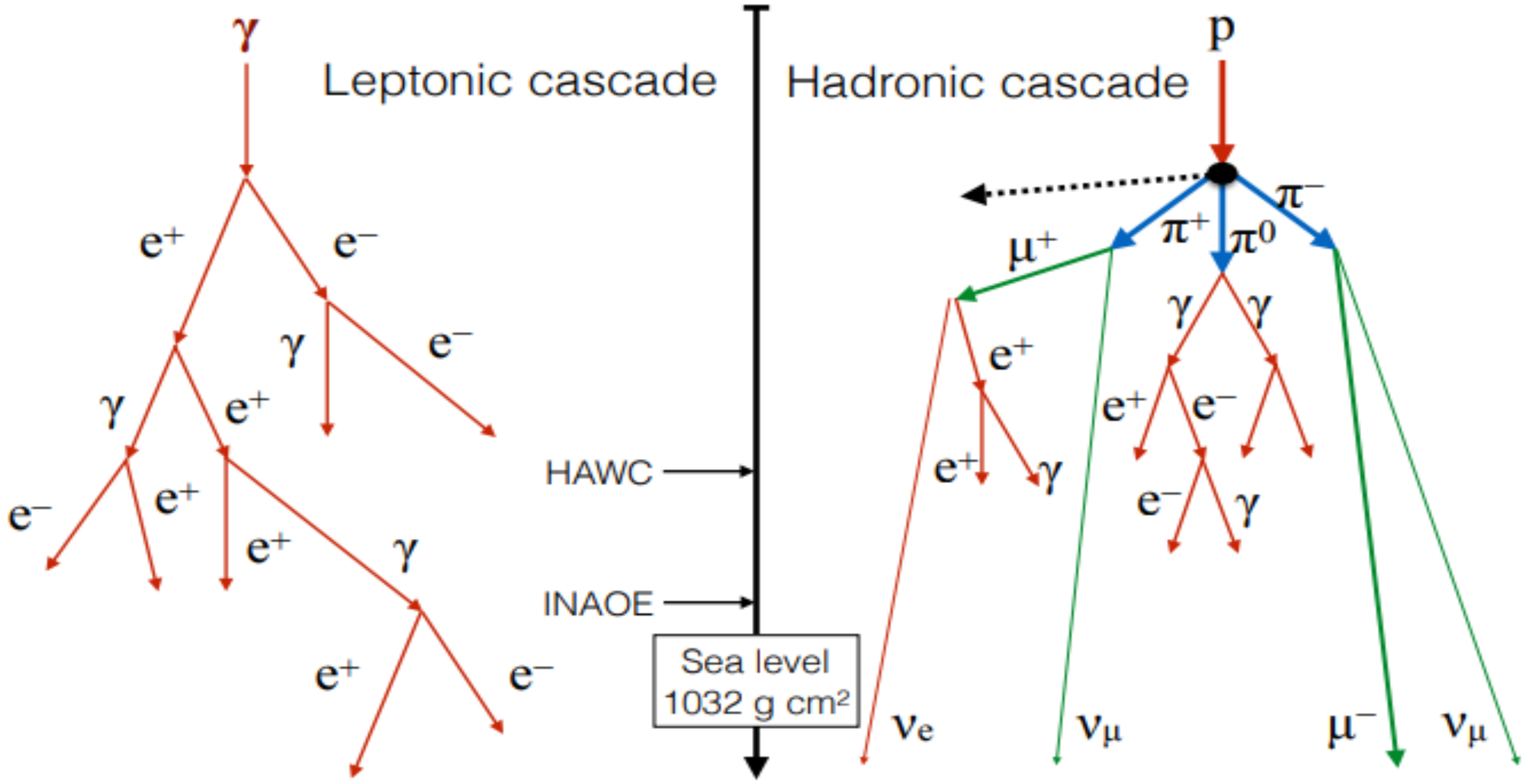
Instantaneous FOV 2 sr. (15%) and daily 8sr (66%).

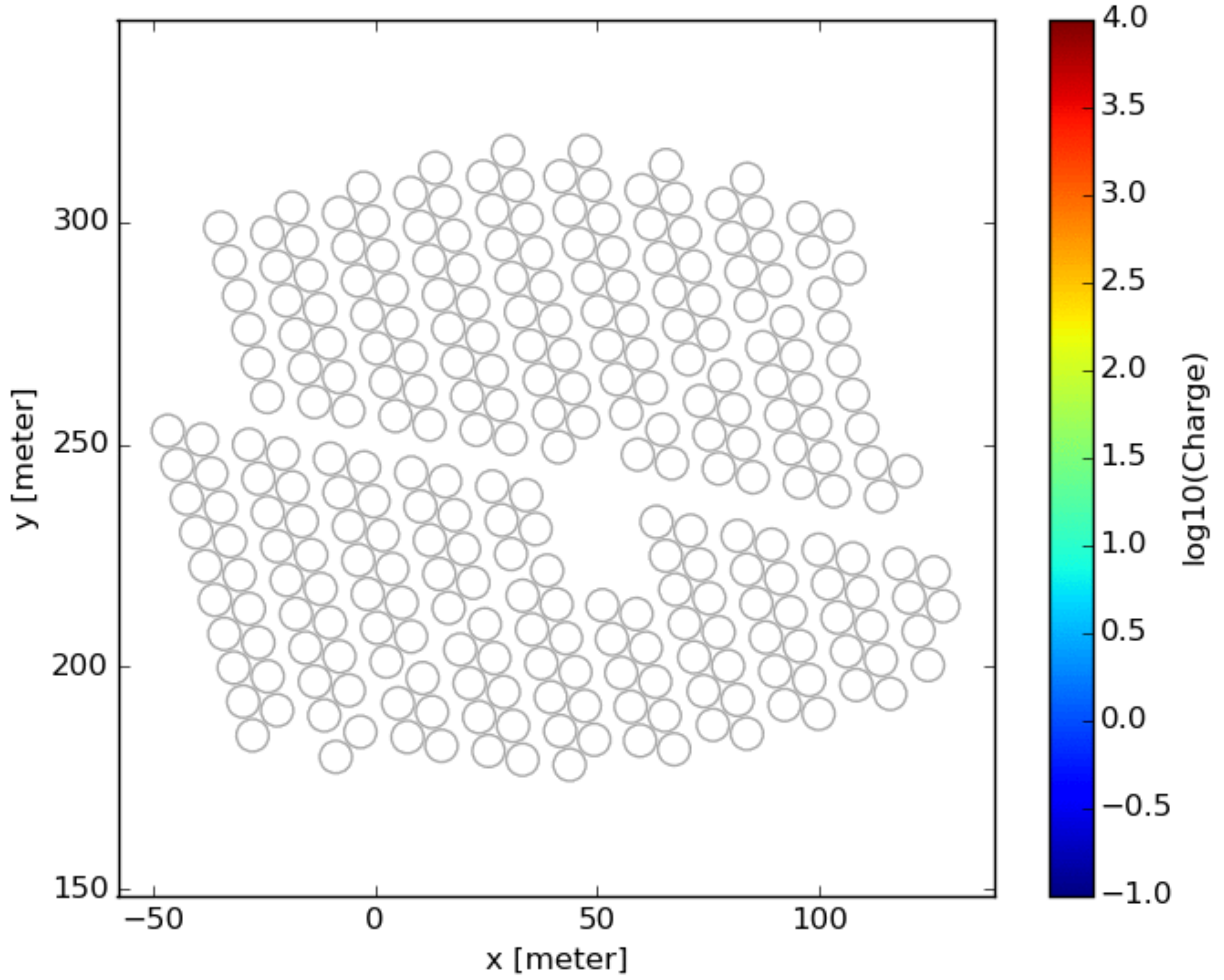
Duty cycle >90%.

300 WCDs covering 22,000 m2 area.

The structure and principles of operation







- The interactions of cosmic ray or photon with a nucleus from the air produces a shower of secondary particles.
- Cherenkov light produced by secondary particles, passed through the water in the tanks, is detected with PMTs.
- Event reconstruction

1. Obtain the shower core position
2. Fit the shower direction
3. Estimate the shower energy by computing event size, PMT charge, etc.

Scientific objectives

- Primary cosmic-ray studies between 1 TeV and 1 PeV
- Studies of Galactic (pulsars, cosmic ray anisotropy, **binaries**) and extragalactic γ-ray sources
- Monitoring of TeV γ-ray transients and hard-spectrum sources
- Multi-wavelength studies with Fermi, Swift and IACTs telescopes
- Multi-messenger following ups on triggers from Neutrino telescopes and GW observatories
- Search for dark matter sources

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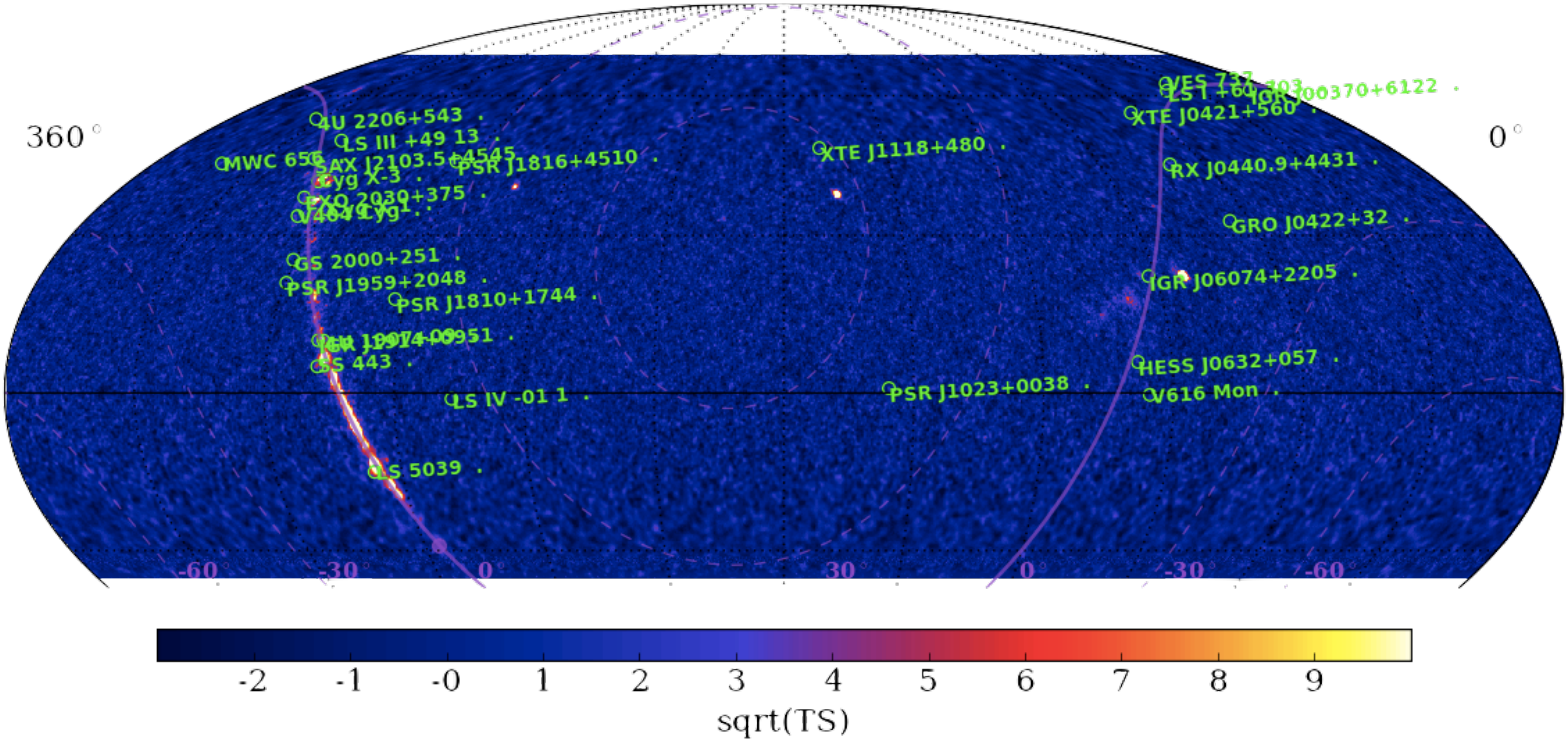
Binary candidates in HAWC 1017d map



28 XRBs with short orbital periods and 3 known γ-ray binaries (LS I +61 303, LS 5039 and HESS J0632+057).

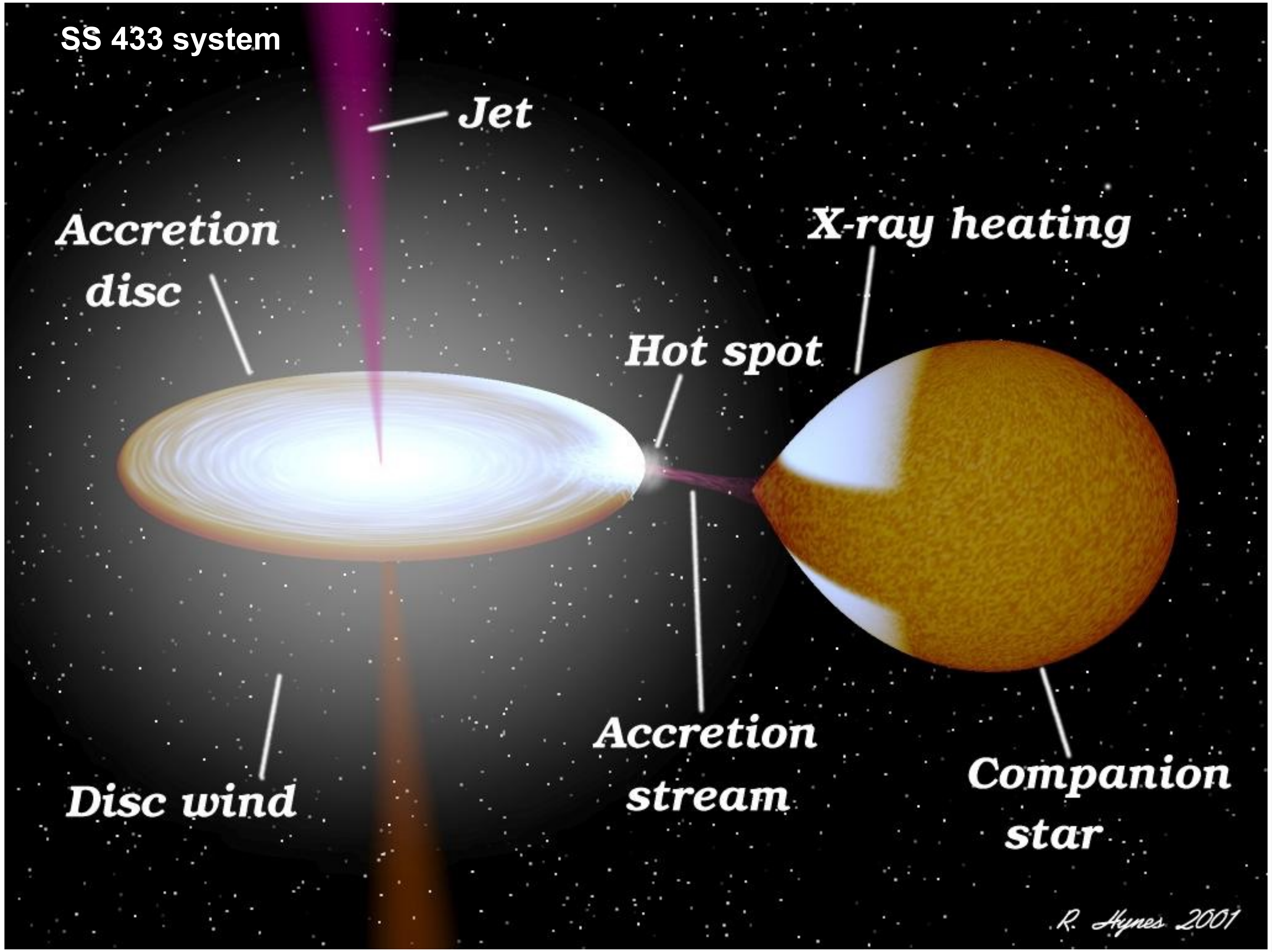
Short periods (<1 month), <10 kpc from Earth.

Table of binary candidates

Source	RA	Dec	Type	d [kpc]	τ [day]	TS	Signif. [post-trial]	Dif Flux @ 7 TeV [TeV^{-1} cm^{-2} s^{-1}]
IGR J00370+6122	00:37	$+61°21'$	HMXB	3.4	15.67	3.6	-0.2σ	$7.65 \cdot 10^{-15}$
V662 Cas	01:18	$+65°17'$	HMXB	6.5	11.60	0.0	0.0σ	$4.13 \cdot 10^{-14}$
IGR J01363+6610	01:36	$+66°11'$	HMXB	2.0	–	1.8	-0.0σ	$2.46 \cdot 10^{-14}$
IGR J01583+6713	01:58	$+67°13'$	XB	4.1	–	0.3	0.0σ	$8.44 \cdot 10^{-14}$
VES 737	02:20	$+63°01'$	Bin	5.0	–	1.3	0.0σ	$4.81 \cdot 10^{-14}$
LS I +61 303	02:40	$+61°13'$	HMXB	2.0	26.50	0.7	-0.0σ	$1.40 \cdot 10^{-14}$
XTE J0421+560	04:19	$+55°59'$	HMXB	2.0	19.41	0.0	0.0σ	$1.05 \cdot 10^{-14}$
GRO J0422+32	04:21	$+32°54'$	LMXB	2.0	0.21	1.3	0.0σ	$3.33 \cdot 10^{-15}$
RX J0440.9+4431	04:40	$+44°31'$	HMXB	2.9	–	4.8	0.5σ	$4.39^{+4.09}_{-3.43} \cdot 10^{-15}$
IGR J06074+2205	06:07	$+22°05'$	HMXB	4.5	–	0.3	-0.0σ	$1.34 \cdot 10^{-15}$
V616 Mon	06:22	$-00°20'$	LMXB	1.1	0.33	0.1	-0.0σ	$2.53 \cdot 10^{-15}$
HESS J0632+057	06:32	$+05°48'$	HMXB	1.6	315 ± 5	3.2	0.1σ	$2.06^{+2.39}_{-1.94} \cdot 10^{-15}$
PSR J1023+0038	10:23	$+00°53'$	LMXB	1.3	–	5.3	0.7σ	$3.13^{+2.83}_{-2.28} \cdot 10^{-15}$
XTE J1118+480	11:18	$+48°02'$	LMXB	1.7	0.17	4.9	0.6σ	$5.57^{+5.20}_{-4.37} \cdot 10^{-15}$
LS IV -01 1	17:07	$-01°05'$	Star	0.3	–	0.1	-0.0σ	$2.58 \cdot 10^{-15}$
PSR J1810+1744	18:10	$+17°41'$	MSP	2.0	–	1.2	0.0σ	$2.89 \cdot 10^{-15}$
PSR J1816+4510	18:16	$+45°10'$	MSP	4.0	0.36	0.2	0.0σ	$4.96 \cdot 10^{-15}$
LS 5039	18:26	$-14°50'$	HMXB	2.9	3.90	210.5	14.3σ	$6.83^{+1.03}_{-1.01} \cdot 10^{-14}$
4U 1907+09	19:09	$+09°49'$	HMXB	4.0	8.37	13.4	2.7σ	$4.22^{+2.42}_{-2.32} \cdot 10^{-15}$
SS 433	19:12	$+04°59'$	XB	5.5	13.10	19.2	3.6σ	$5.21^{+2.48}_{-2.40} \cdot 10^{-15}$
IGR J1914+0951	19:14	$+09°52'$	HMXB	5.0	13.56	88.6	9.0σ	$1.11^{+0.25}_{-0.25} \cdot 10^{-14}$
Cyg X-1	19:58	$+35°12'$	HMXB	2.2	5.60	5.0	0.6σ	$2.81^{+2.58}_{-2.19} \cdot 10^{-15}$
PSR J1959+2048	19:59	$+20°48'$	Bin	2.5	–	2.6	0.0σ	$3.43 \cdot 10^{-15}$
GS 2000+251	20:02	$+25°14'$	LMXB	2.7	0.35	0.0	0.0σ	$2.07 \cdot 10^{-15}$
V404 Cyg	20:24	$+33°52'$	LMXB	2.4	6.47	1.3	0.0σ	$3.61 \cdot 10^{-15}$
EXO 2030+375	20:32	$+37°38'$	HMXB	5.0	46.02	16.7	3.2σ	$5.60^{+2.85}_{-2.82} \cdot 10^{-15}$
Cyg X-3	20:32	$+40°57'$	HMXB	7.0	0.20	98.9	9.6σ	$1.73^{+0.37}_{-0.36} \cdot 10^{-14}$
LS III +49 13	20:56	$+49°40'$	BH	0.1	–	0.5	-0.0σ	$4.13 \cdot 10^{-15}$
SAX J2103.5+4545	21:03	$+45°45'$	HMXB	6.5	12.68	0.1	0.0σ	$5.26 \cdot 10^{-15}$
4U 2206+543	22:07	$+54°31'$	HMXB	2.6	9.57	2.2	-0.0σ	$4.20 \cdot 10^{-15}$
MWC 656	22:42	$+44°43'$	HMXB	2.6	–	0.5	0.0σ	$5.49 \cdot 10^{-15}$

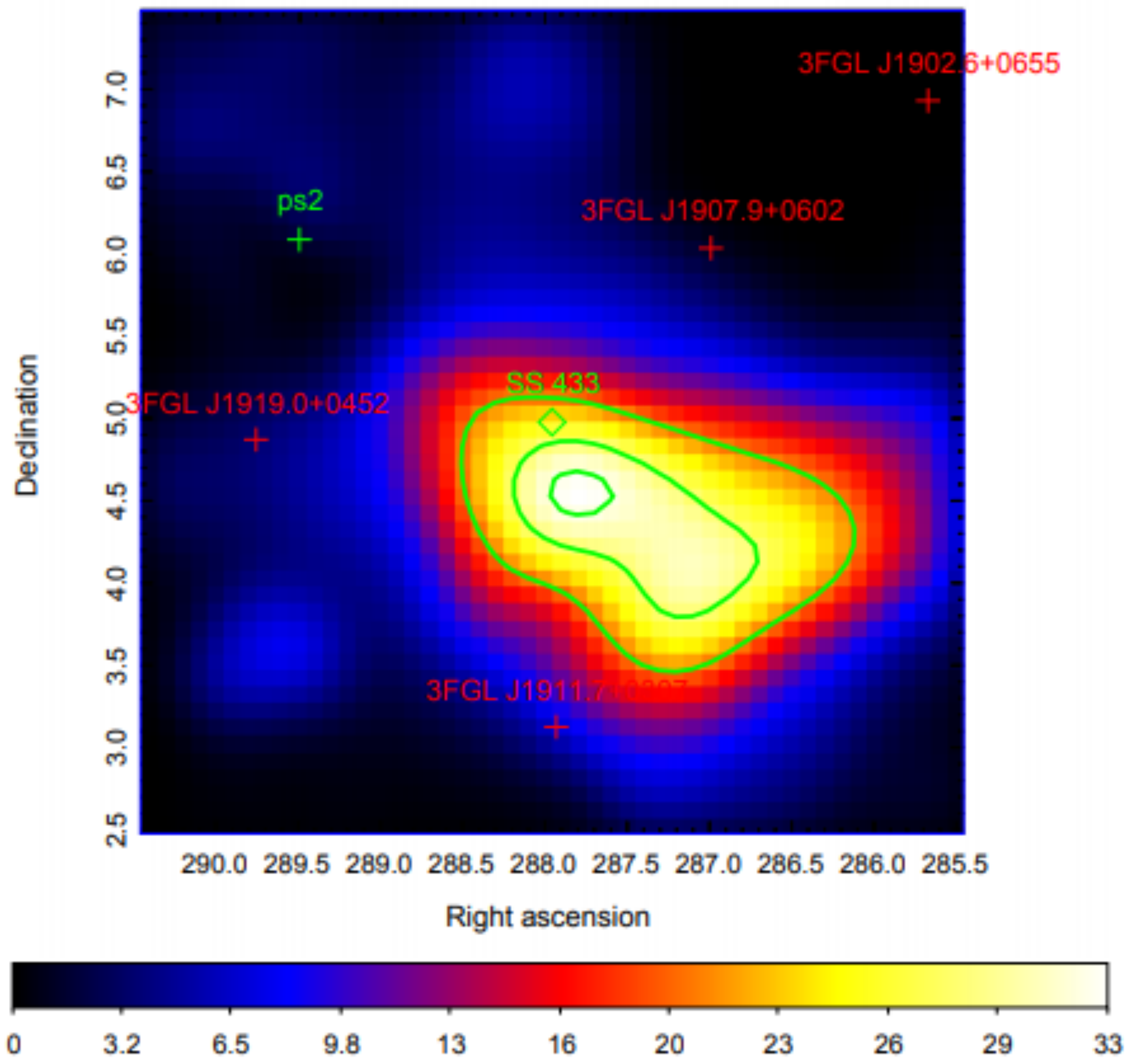
- Calculated TS after fitting a power law with a fixed idex of -2.7 and Epiv at 7 TeV.
- Source confusion for objects in the Galactic Plane is an issue.
- Micro-quasar LS 5039 was isolated from confused region using multi-source fits, but HAWC does not yet have 5σ observation.

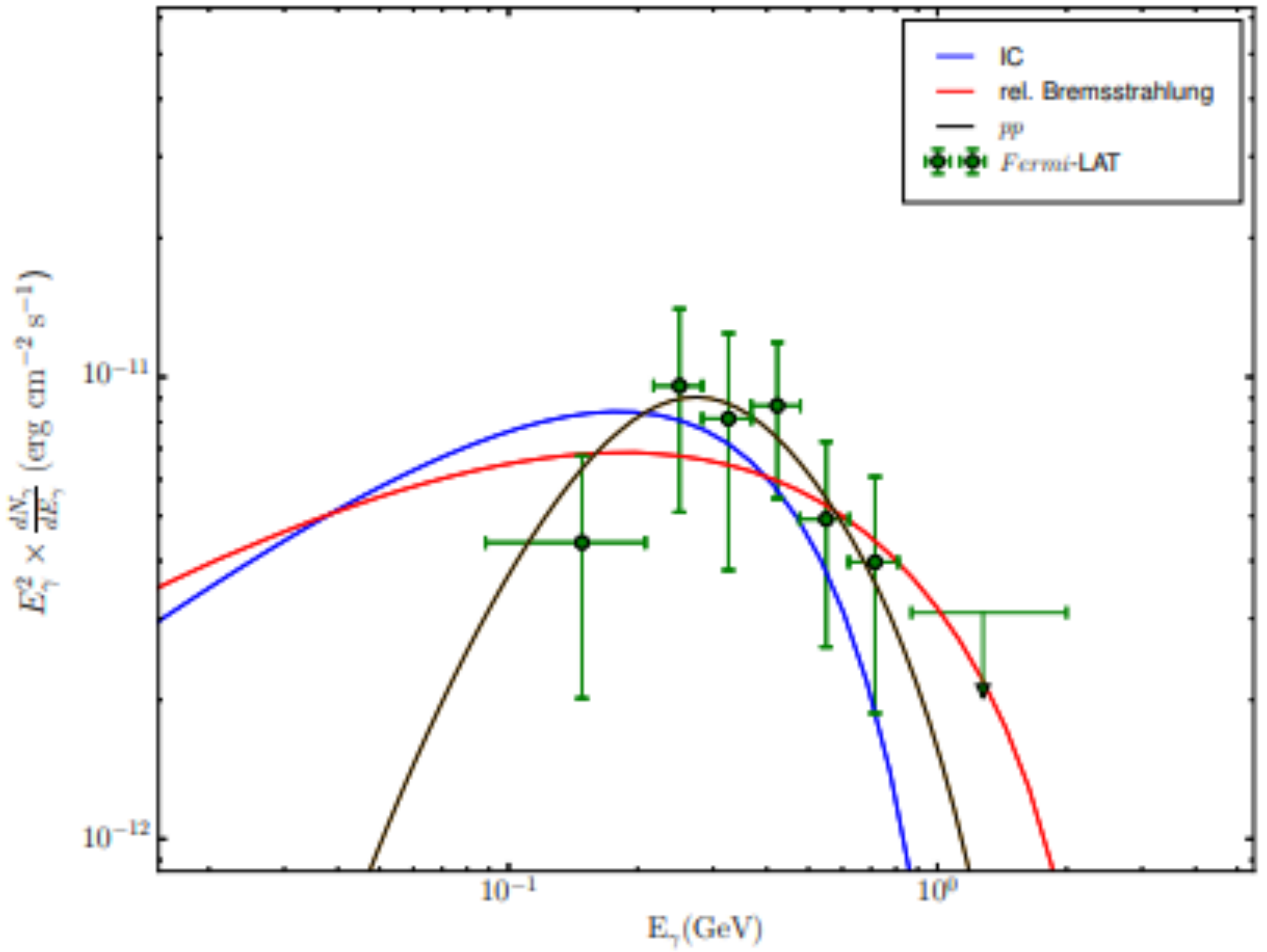
Micro-quasars as sources of GeV/TeV gamma-rays: SS 433



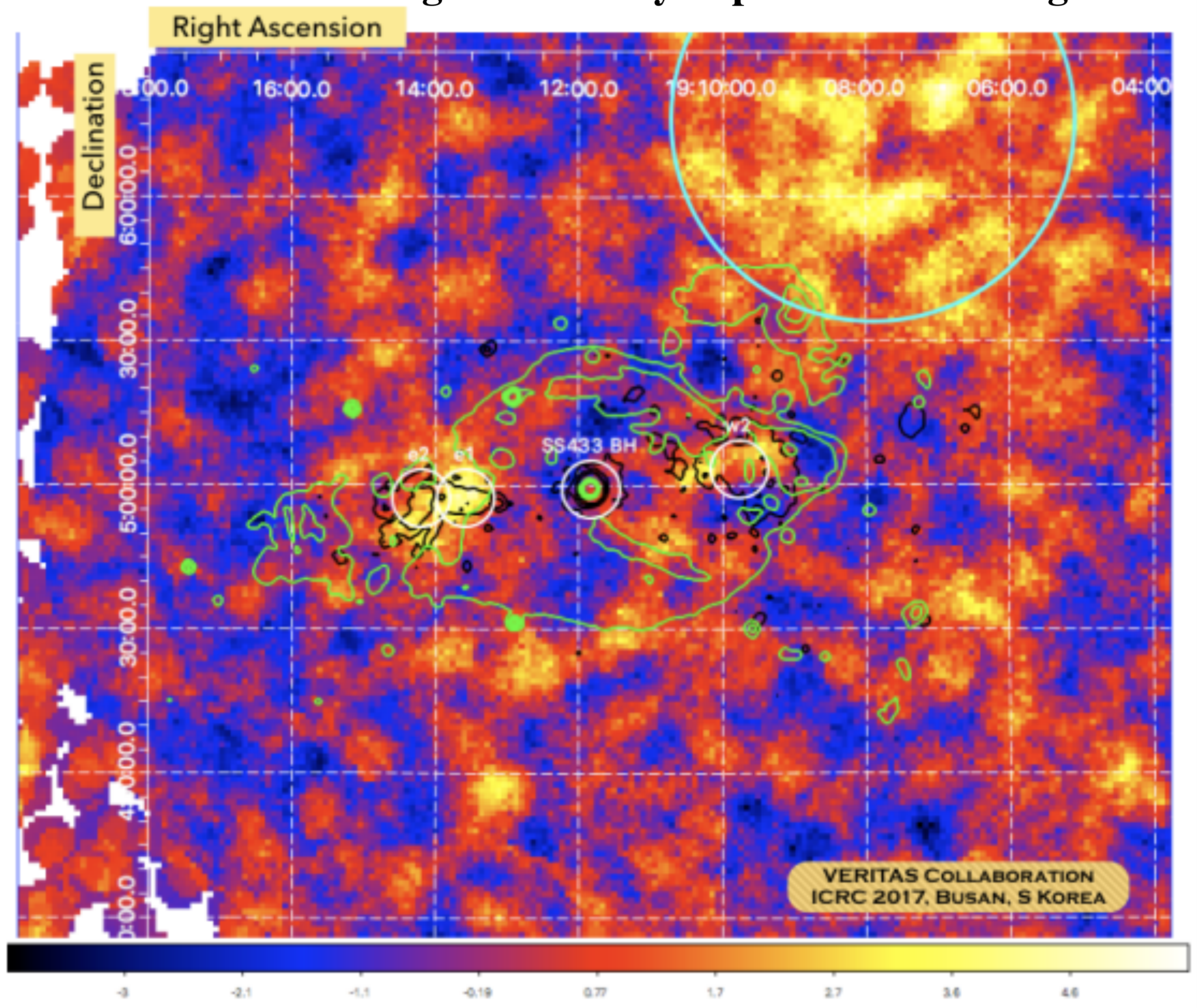
- Micro-quasars are binary stellar systems where the remnant of a star that has collapsed to form a dark and compact object is gravitationally linked to a star that still produces light, and around which it makes a closed orbital movement.
- SS 433 is a binary star consisting of an early type supergiant 30 solar masses star and a compact object (neutron star or black hole). Material from the normal star is falling toward the compact object, either as the result of a strong stellar wind, or through Roche lobe overflow.
- Two jets, the most powerful known in the Galaxy, extend perpendicular to the line of sight and terminate in W50 nebula producing western and eastern X-ray lobes.
- SS433 jet : 10^39-10^40 erg/s
- SS433 jet speed roughly c/4
- Particle acceleration is believed to occur at the lobes where strong radiation is expected to be emitted at GeV/TeV energies

SS 433 with Fermi and IACTs



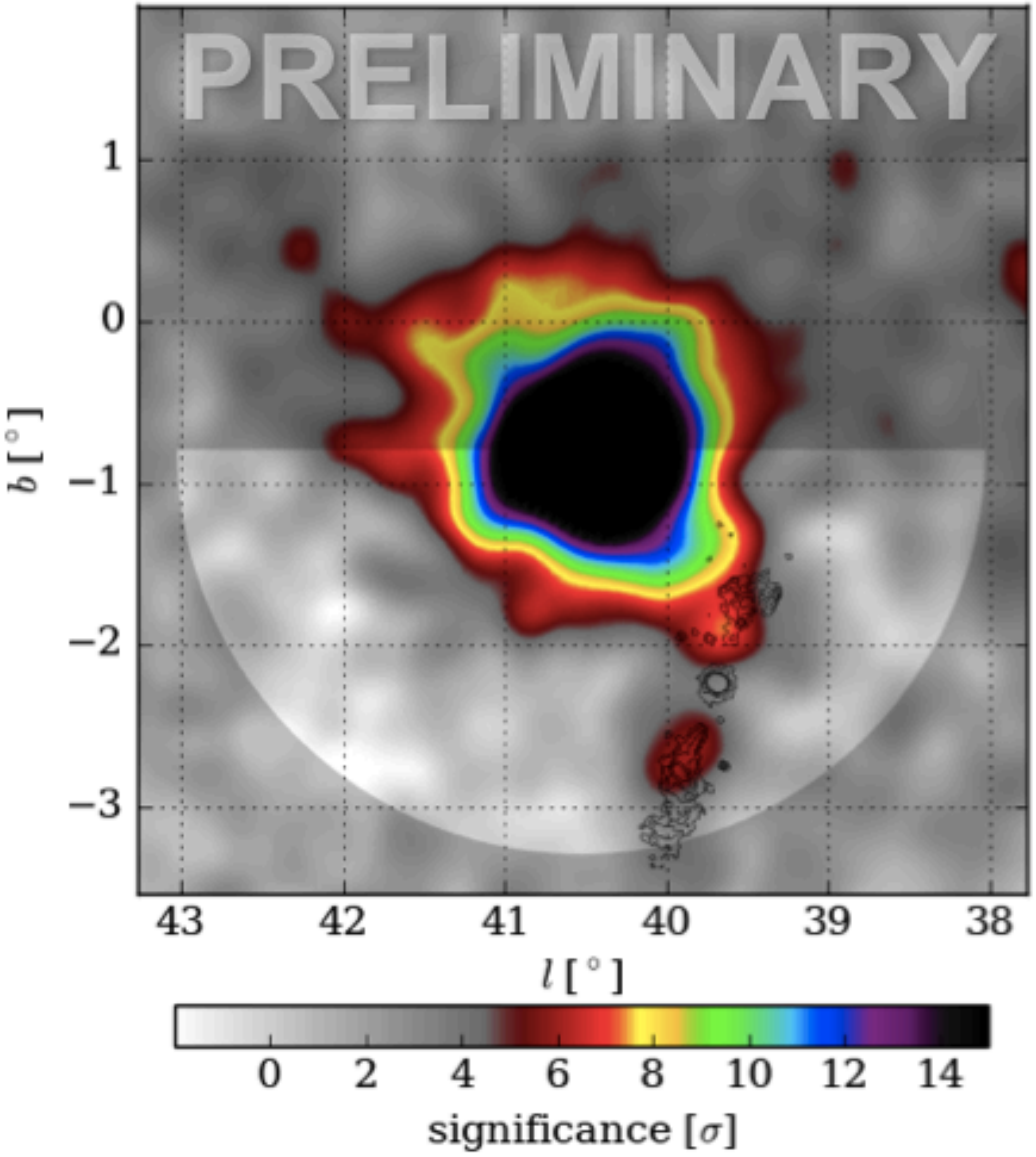


VERITAS significance skymap of the SS 433 region

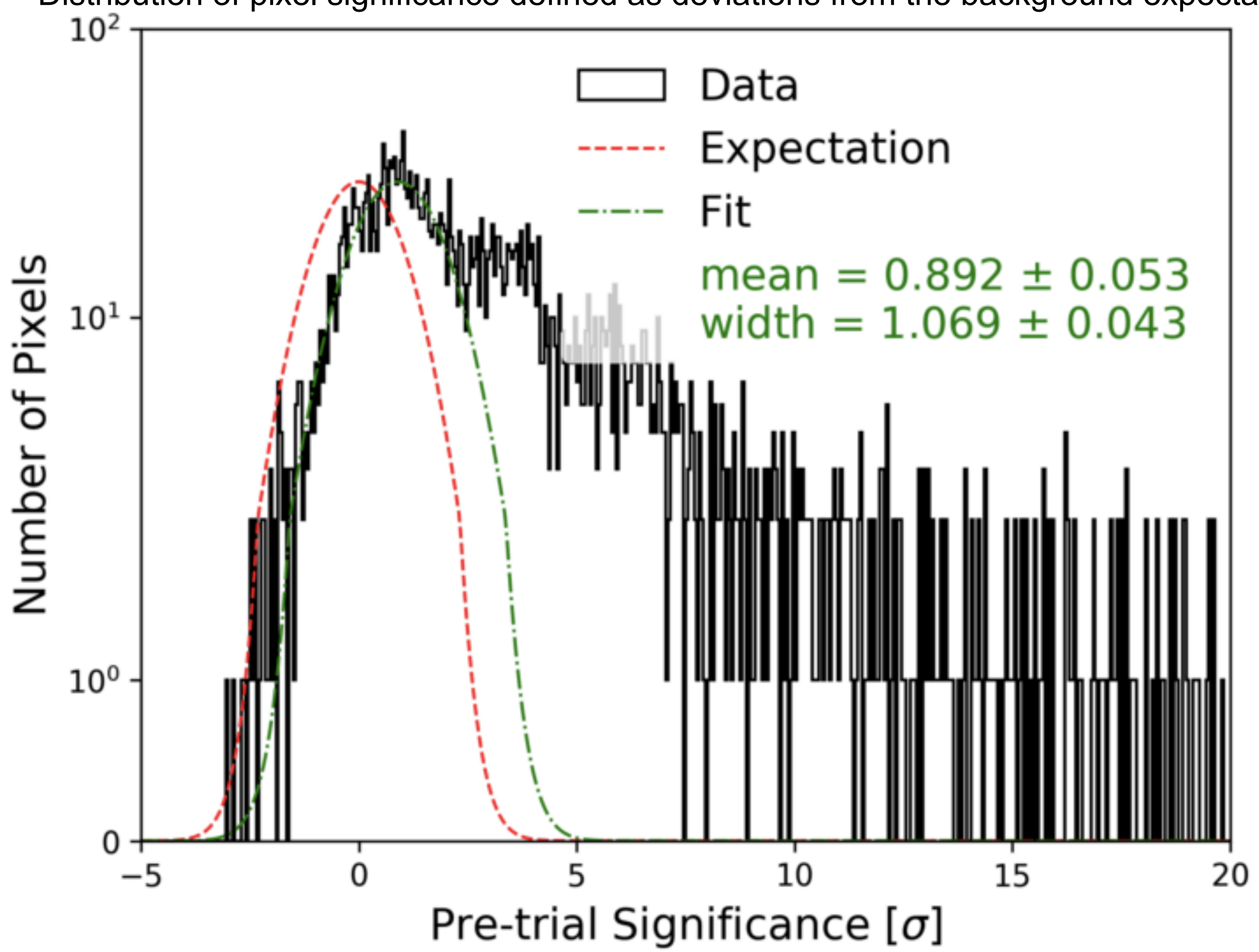


- Fermi-LAT analysis revealed a persistent gamma radiation between 250 MeV and 800 MeV, possibly due to proton-proton interaction close to SS433 (Bordas et al. 2015).
- The 70 hours (during 2009-2012) with VERITAS didn't detect significant emission from the location of the black hole or the jet termination regions (Payel Kar et al 2017).
- Combined HESS-MAGIC analysis produces only upper limits.

Region of SS 433 dominated by MGRO J1908+06

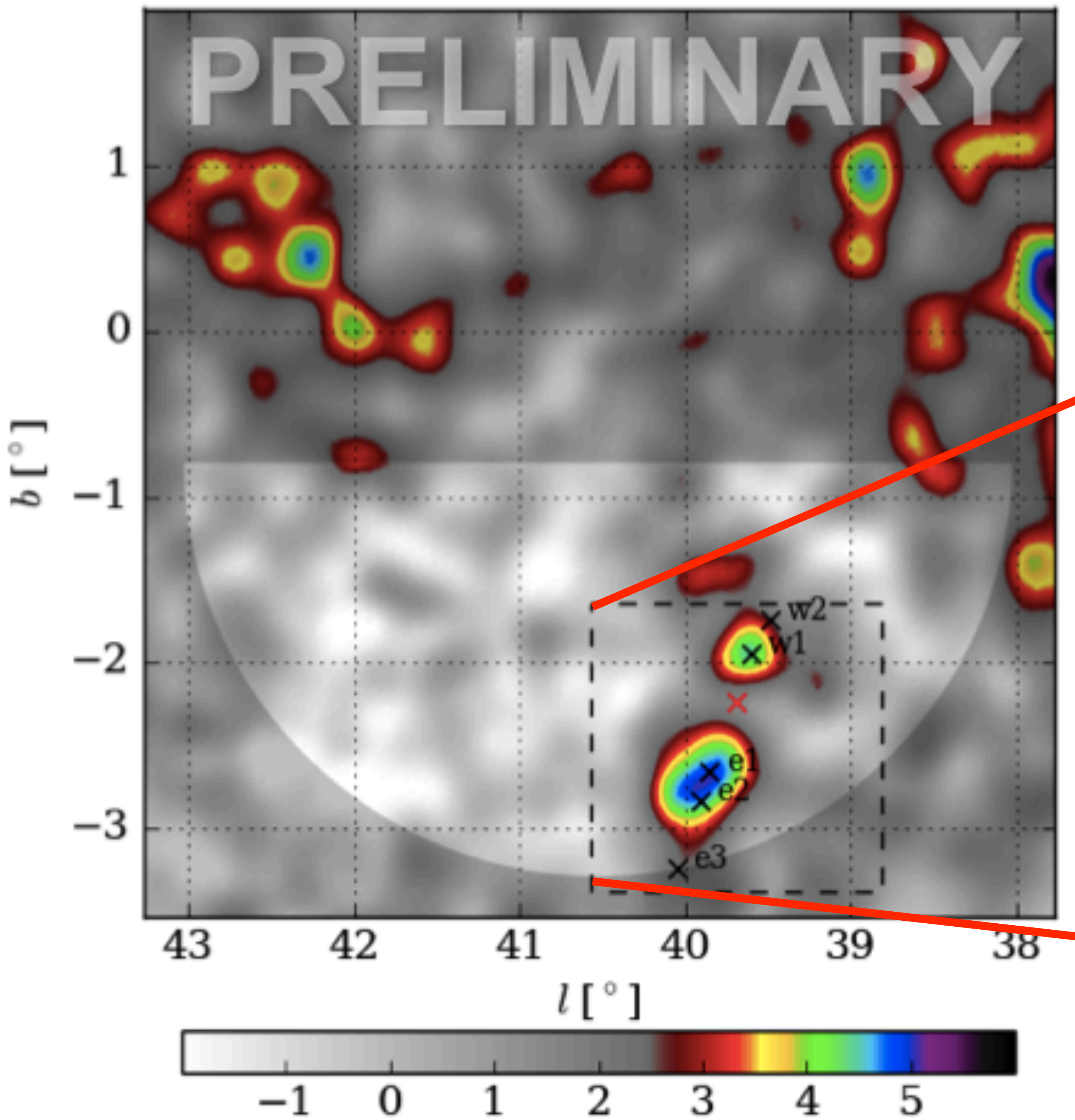


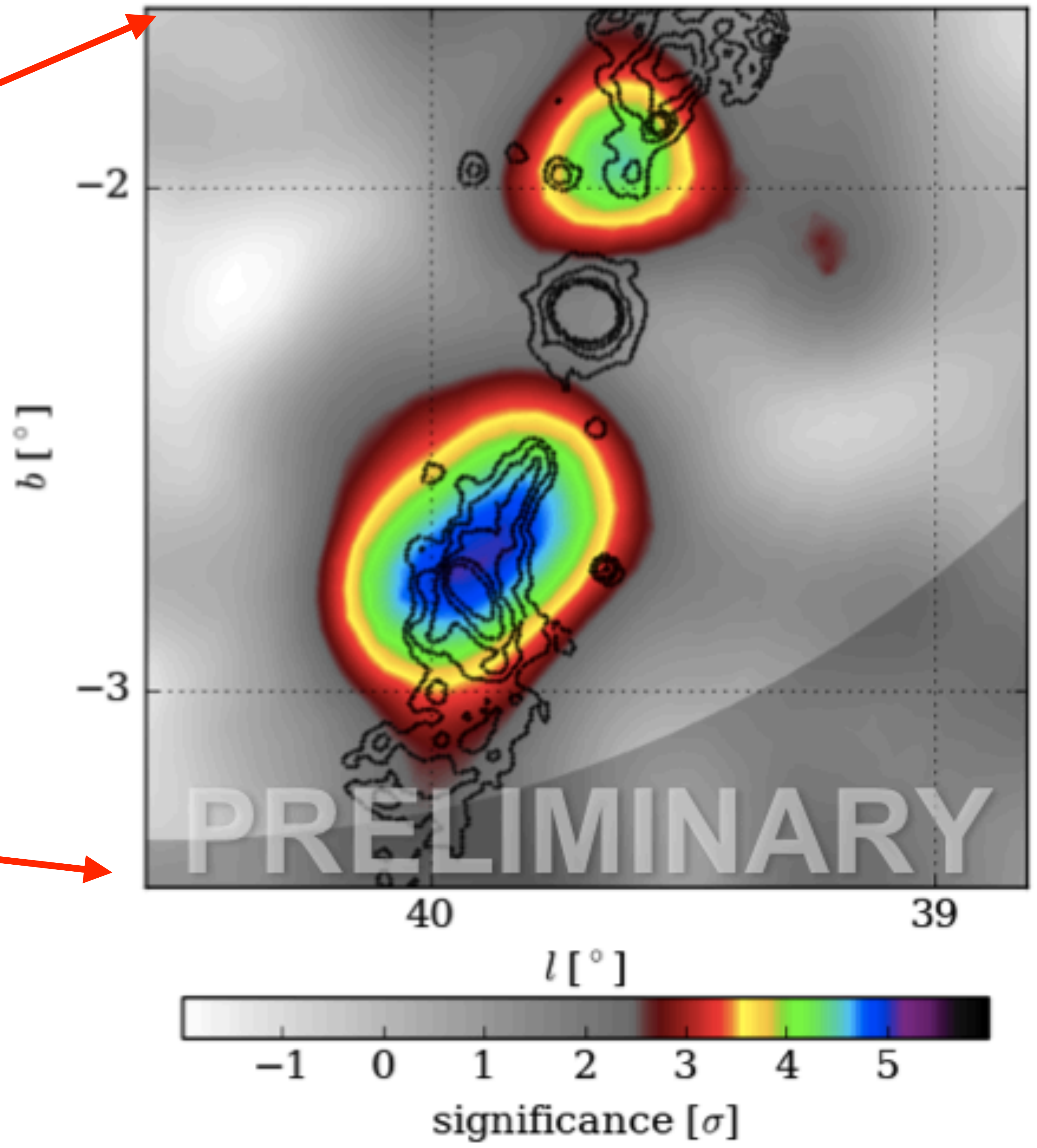
Distribution of pixel significance defined as deviations from the background expectation.

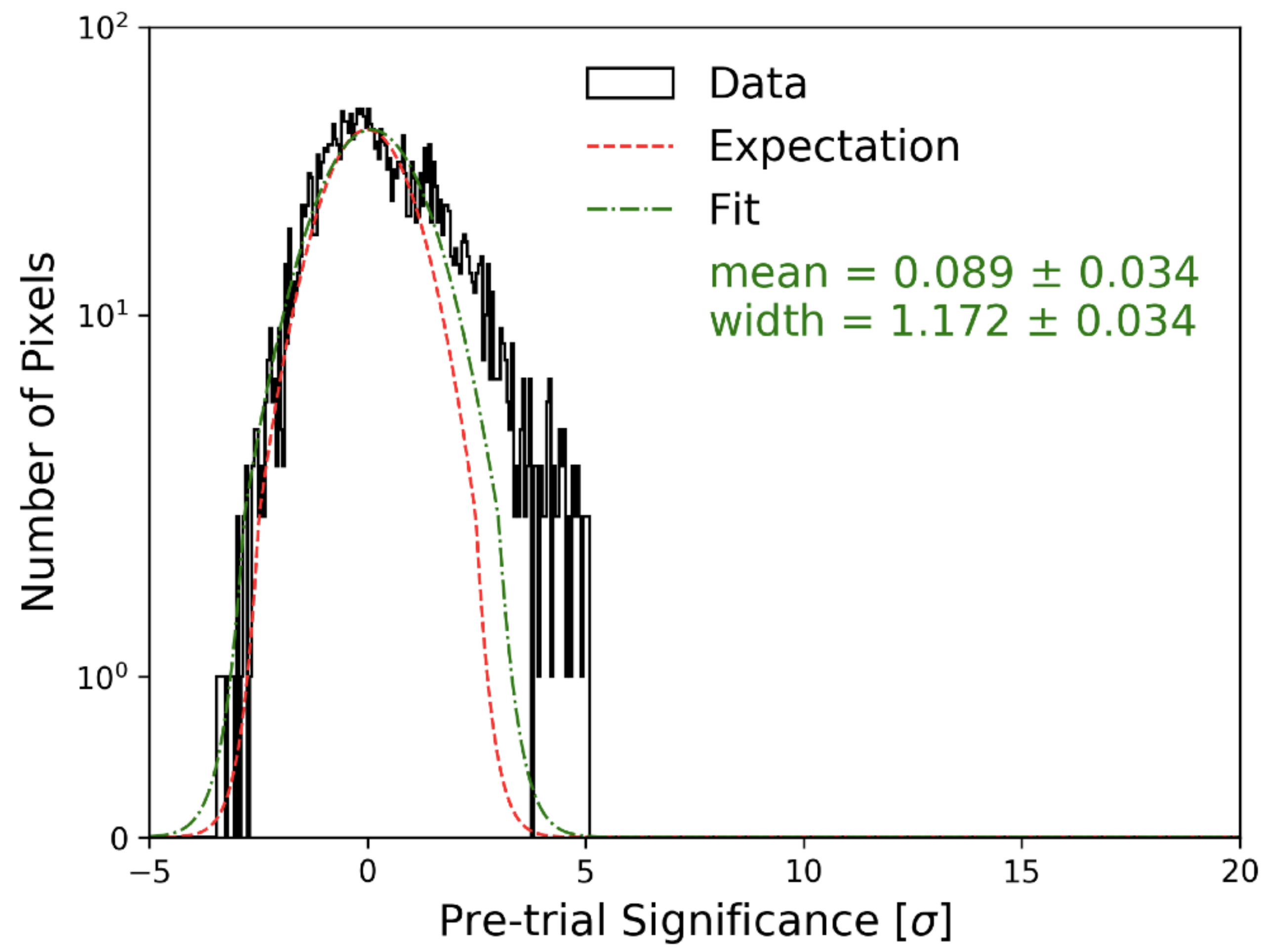


- Two SS 433 lobes and J1908 fitted simultaneously (normalisation, spectrum, size for MGRO J1908+06 and normalisation for each SS433 lobe)
- SS433 lobes spectral index assumed -2
- Semi-circular RoI to reduce GDE contamination

Region of SS 433 after subtracting MGRO J1908+06

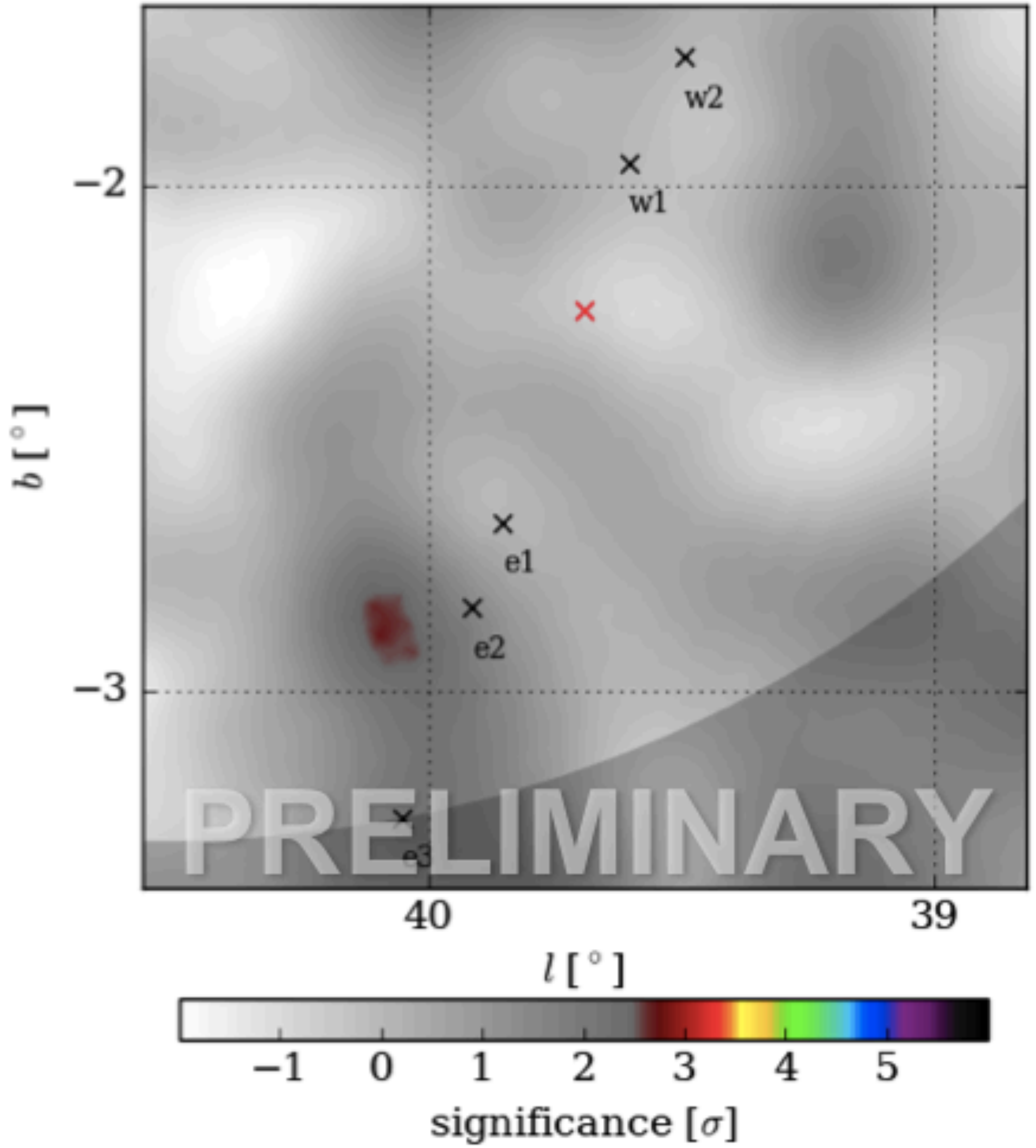


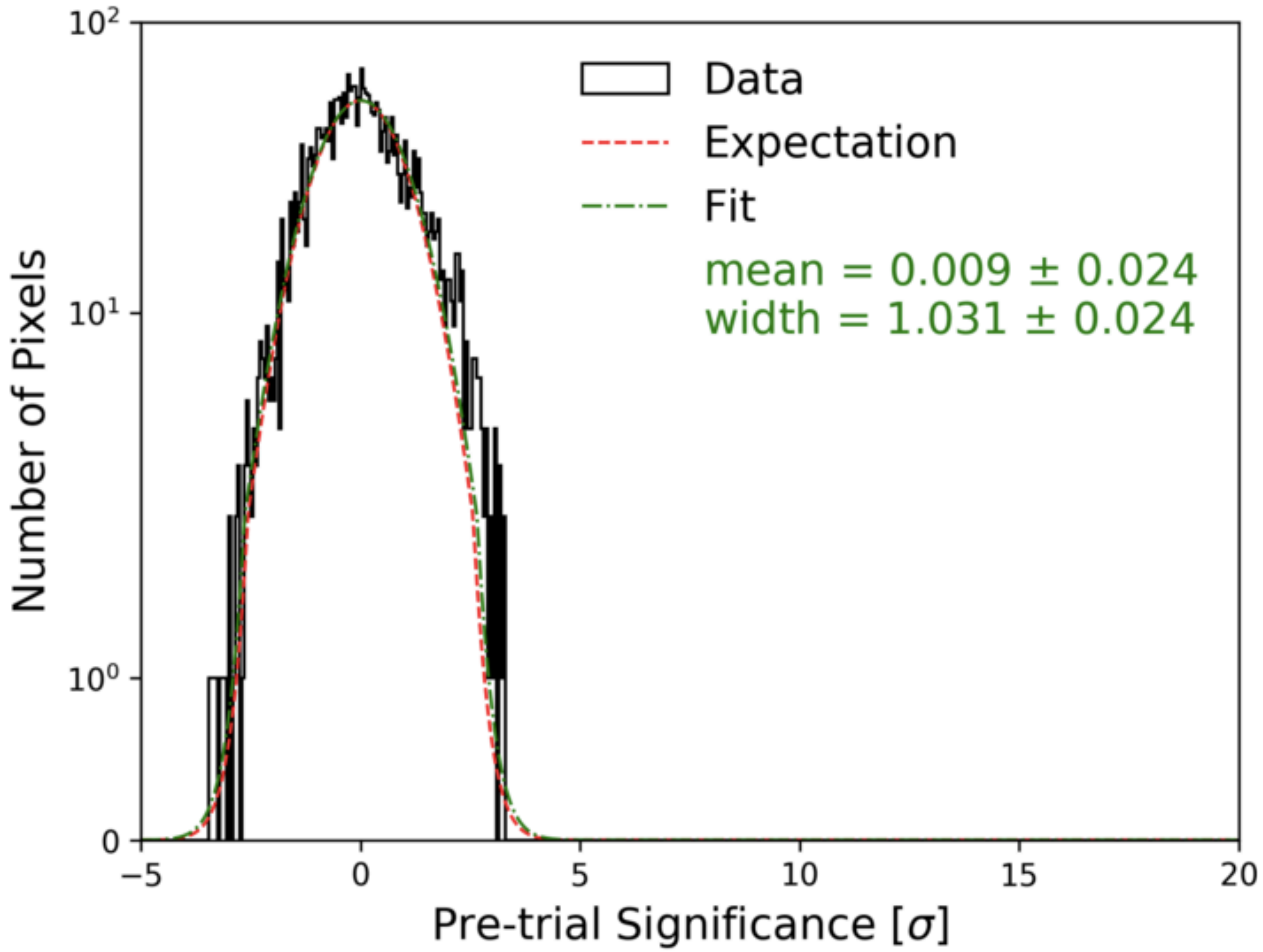




- PL of spectral index -2.0 has been assumed for both lobes.
- The pre-trial significance distribution shows improvement by removing J1908 but high significance tail still exists.

Residuals

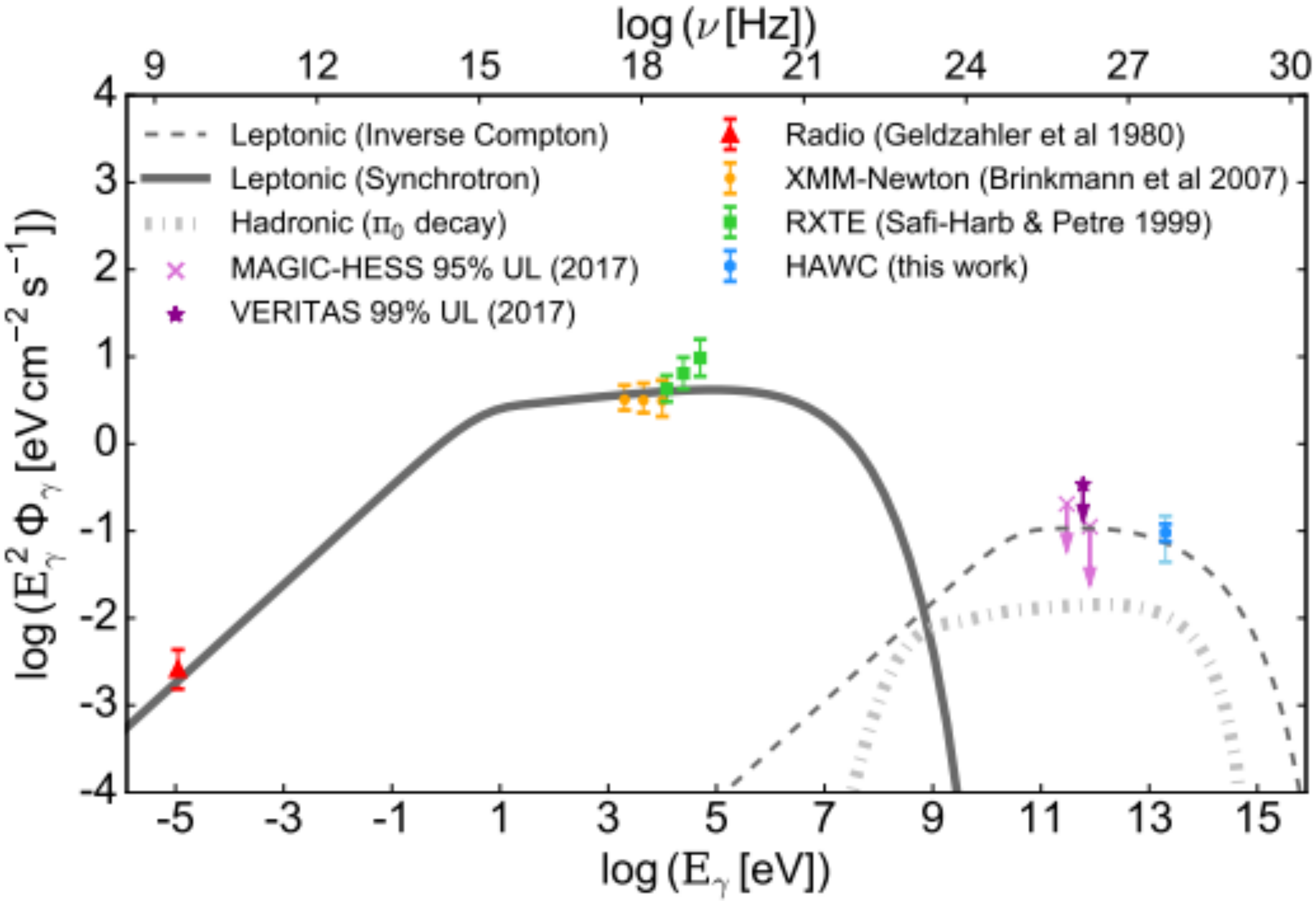




- Residual map with J1908 + lobes fitted and subtracted
- The residual significance distribution is zero-mean Gaussian, consistent with background only distribution.
- The two lobes of SS433 are detected after a joint fit at a significance of 5.4σ being spatially coincident with the jet termination regions, where x-ray lobes are detected.

Abeysekara et al. 2018

Multi-wavelength modeling (e1)



- Leptonic: radio + X-ray photons are produced via synchrotron emission in a magnetic field (16 microGauss) and TeV γ rays are produced via IC scattering of the same electron population with total kinetic energy equal to ~0.5% of the jet power.

Hadronic only model is disfavoured

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

- HAWC observation disfavours hadronic-only scenario, since observed gamma-ray emission requires ~100% (3 X 10^50 erg) of the jet energy necessary for accelerating protons. In addition, protons should have to spread to a few degrees before emitting gamma rays.

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

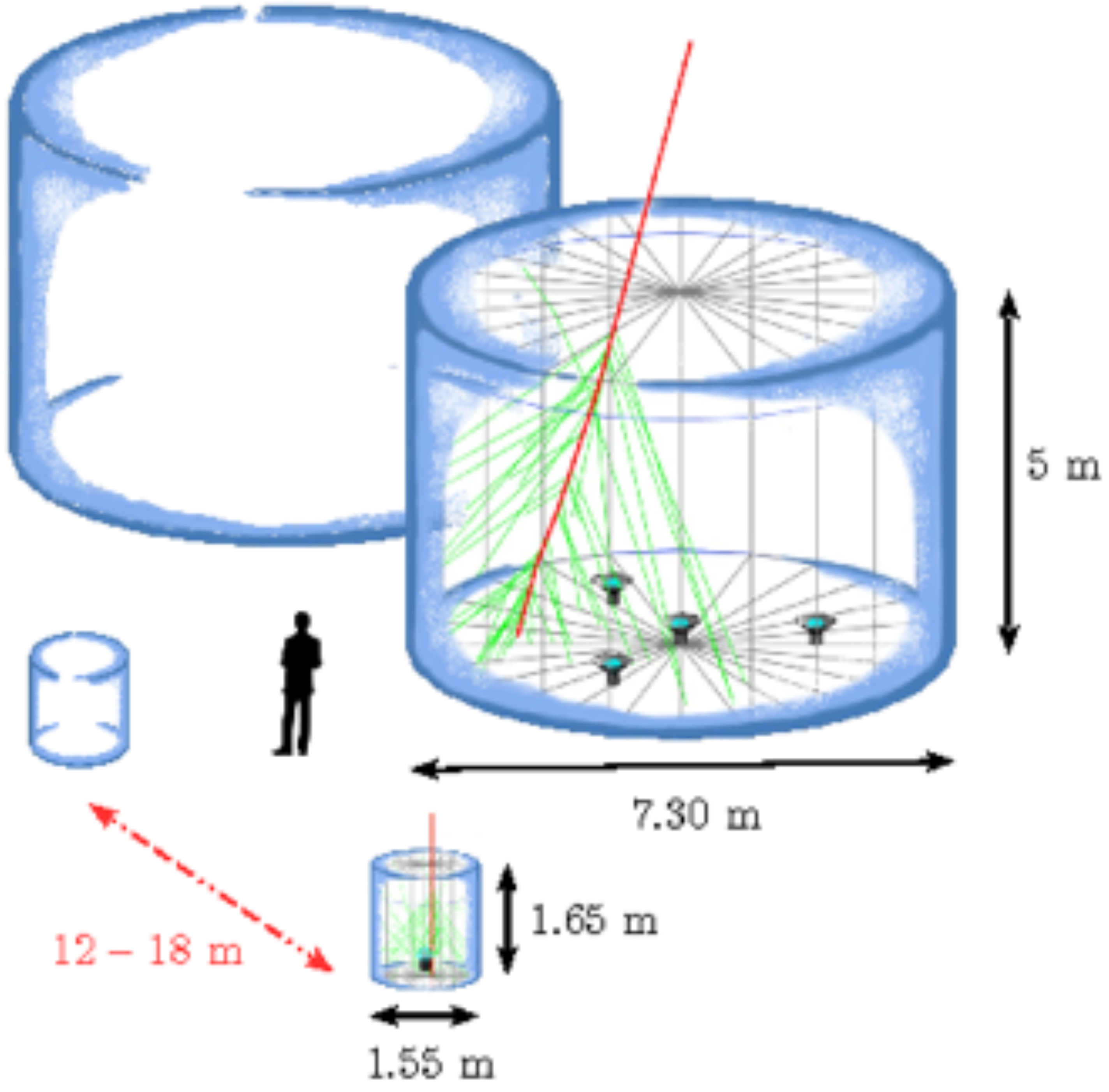
1. Emission region is ~40 pc from central binary.
2. Diffusion length scale is ~35 pc at these energies, assuming ISM.

Origin of the emission

SS 433 is an object which we expect particle acceleration: presence of jets and interaction regions make it a good candidate accelerator.

- Acceleration mechanism to produce ~1 PeV electrons.
- Acceleration in magnetic fields: possible up to a few hundred TeV. Above that, acceleration time exceeds cooling time for 16 μG fields.
- Acceleration in standing shocks (Fermi acceleration): can reach PeV energies, but at present no multi-wavelength evidence for large shocks in the interaction regions.
- The origin of the emission from SS 433 is however not clarified.

HAWC with Outriggers



- 345 water-Cherenkov detectors in a sparser array surrounding the main-array.
- Instrumented area increase by a factor of 4.
- Data recording started since 2018 August.
- Increase of well-reconstructed showers number above multi-TeV energies.

Summary and outlook

- Detection of multi TeV gamma-rays from SS 433/W50 regions, e1 and w1, with > 5σ post-trial significance (combined) in 1017 days of HAWC observations.
- Parental particle spectra and acceleration mechanism unclear.
- Spectra of SS433 jet lobes with future measurements from HAWC.
- Perspective for improving analysis of VHE gammas from SS 433 and other binary candidates with outriggers.