Studying High-Mass Microquasars with HAWC

Chang Dong Rho (U. of Seoul), Ke Fang (U. of Wisconsin-Madison), Se Yeon Hwang (U. of Seoul), and Youngwan Son (U. of Seoul)

for the HAWC Collaboration, ***Astrophys.J.Lett.*** **912 (2021) 1, L4 (arXiv:2101.08945)**

ICRC 2021

16/07/21

HMMQ List and Basic Properties

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

Table 1. List of HMXB Microquasars in HAWC's FOV

Name	RA	DEC	T_*	R_*	d_*	Jet kinetic power L_{jet}	Distance D
			$[10^4$ K$]$	$[R_\odot]$	[AU]	$[\mathrm{erg\,s^{-1}}]$	[kpc]
LS 5039[a]	18:26:15.1	-14°50'54"	3.9	9.3	0.1	10^{36} [e]	2.9
CYG X-1[b]	19:58:21.7	+35°12'06"	3.1	20	0.2	$(4-14)\times 10^{36}$	2.2
CYG X-3[c]	20:32:26.5	+40°57'09"	4-5	<2	0.02	10^{38}	7.0
SS 433[d]	19:11:49.6	+04°58'58"	3.25	5.5[f]	0.5	10^{39}	5.5

- HMMQs may have common multi-wavelength emission mechanism
- Study HMMQs as one type of species by applying stacked analysis
- Study each HMMQ individually (gamma-ray flux upper limits)

High Altitude Water Cherenkov 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

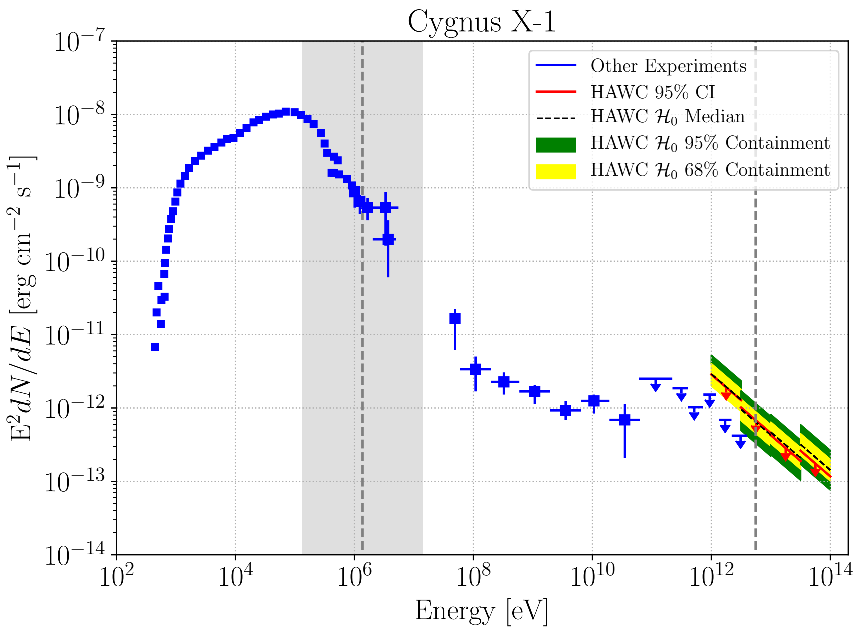
Dataset and Analysis Technique

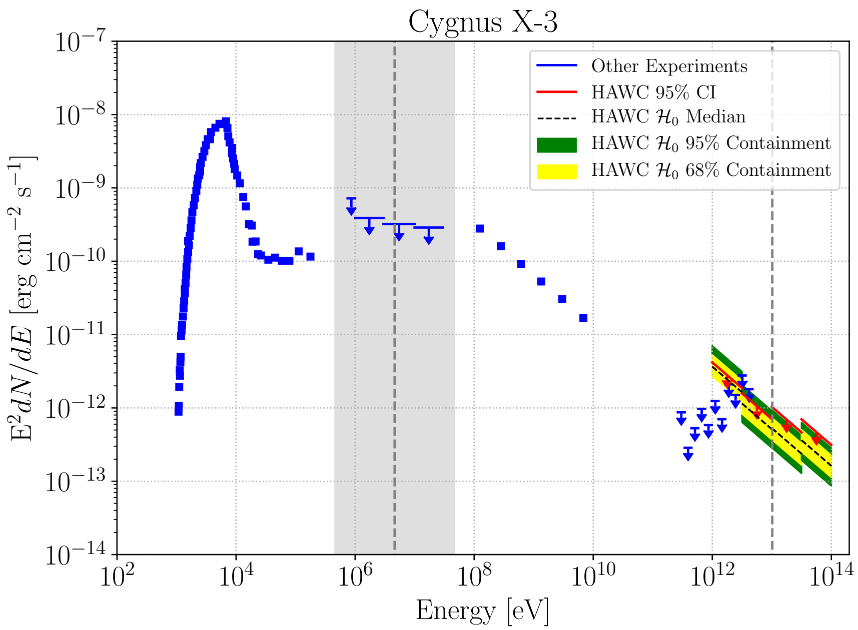
- Used **1,523 days** of HAWC data:
  - Fitting for the flux norm (point source; simple power law)

- Two main analysis techniques used:
  - Individual HMMQ fits uses four quasi-differential energy bins with spectral index fixed at -2.7.

  - For stacking analysis, fits at $E_{\mathrm{piv}} = 7$ TeV, scanning through spectral index between -2.0 and -3.0 (interval of 0.1)

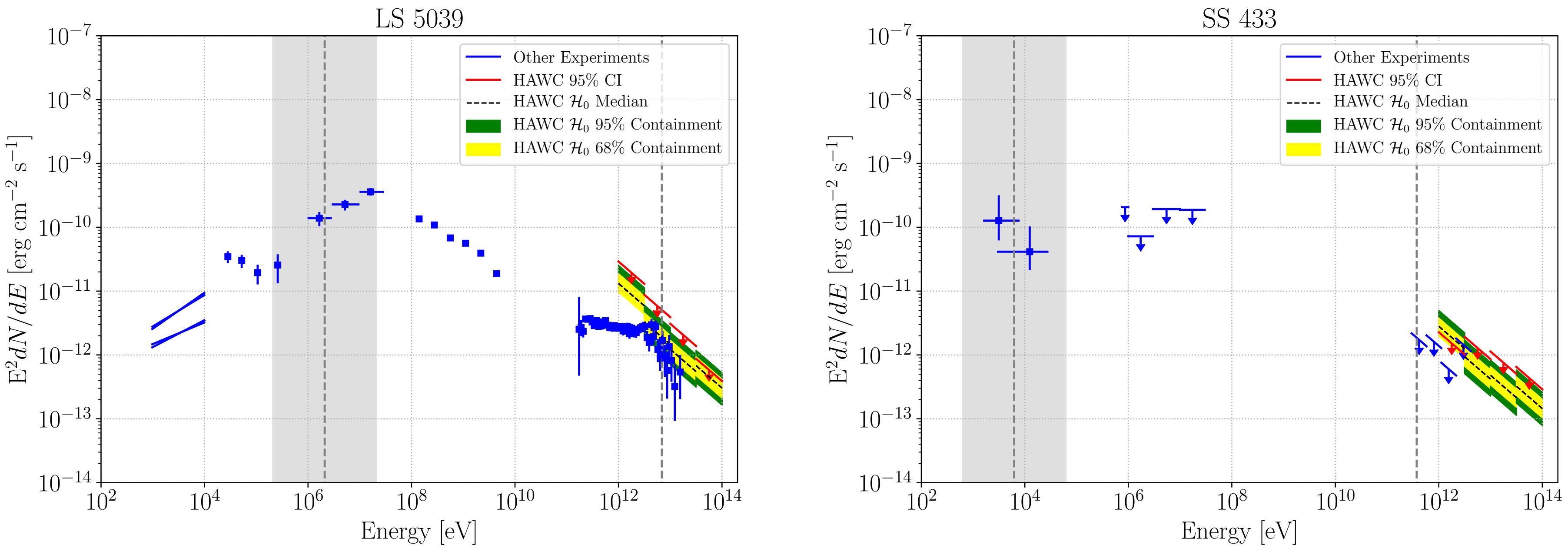
SED for HMMQs with 95% C.I. from HAWC





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

SED for HMMQs with 95% C.I. from HAWC



Our upper credible intervals < 2σ above expected HAWC limits -> no clear detection

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

Two Scenarios for Stacked Analysis

- This analysis relies on stacked likelihood of many independent fits of numerous sources, comparing the same physics model to the data of multiple sources
- The contribution factor decides how the fit to each source contributes to the total likelihood (model dependent)
- **Scenario I:** γ-ray luminosity is proportional to the kinetic power of the jets
- **Scenario II:** γ-rays are produced when relativistic electrons accelerated by the jets upscatter optical photons from the donor star

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

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

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.

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

- γ-ray flux for scenario II is given by

Contribution Factor

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

Scenario II – powered by magnetic field

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

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

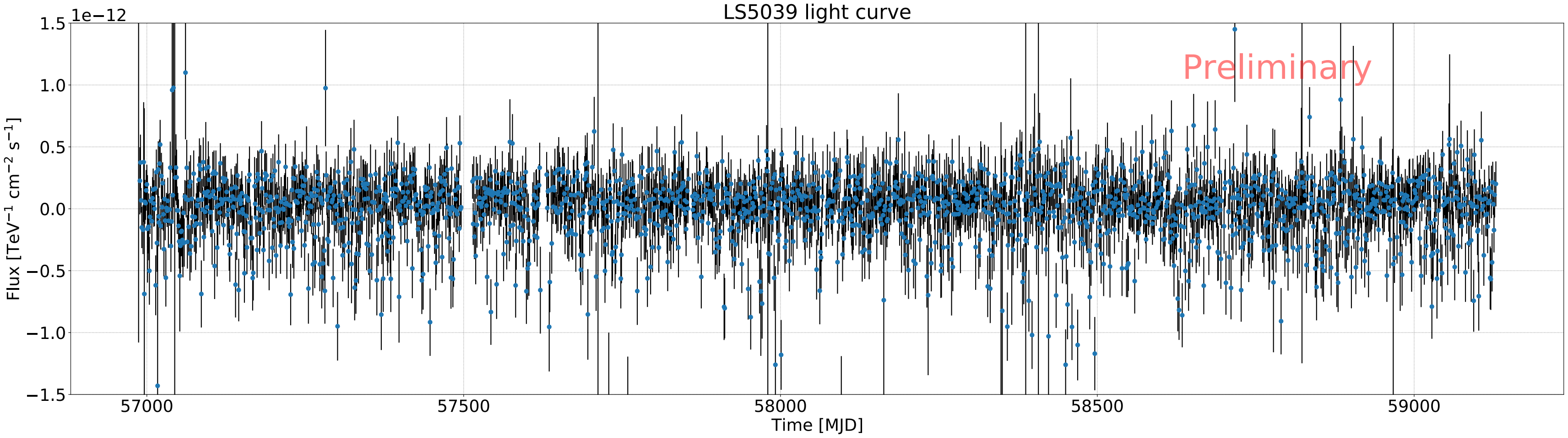
ϵ_{syn} = fraction of observed X-ray and MeV gamma-ray flux due to synchrotron emission

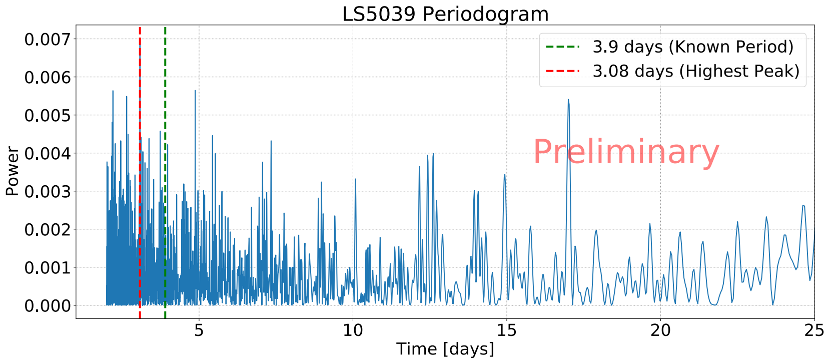
- Strong *B* field found by our stacking analysis suggests that the X-ray to MeV gamma-ray flux is not dominated by synchrotron radiation of VHE electrons.

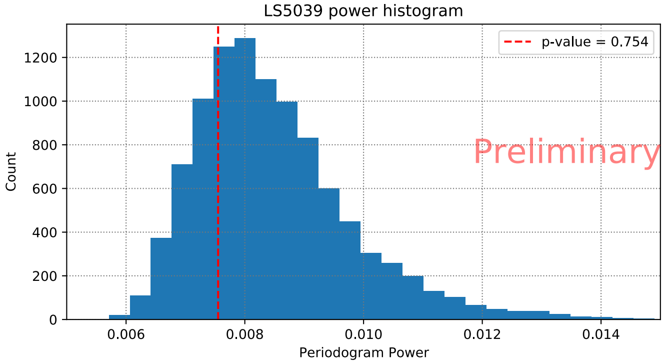
Astrophys.J.Lett. 912 (2021) 1, L4

Time Dependent Analysis

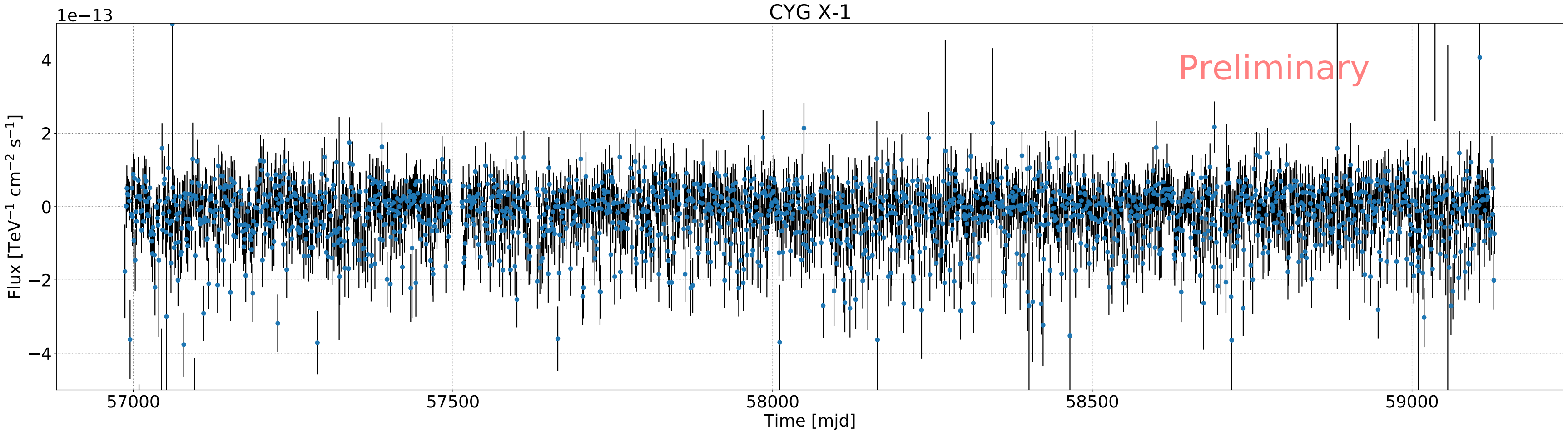
LS 5039 – 3.9 days

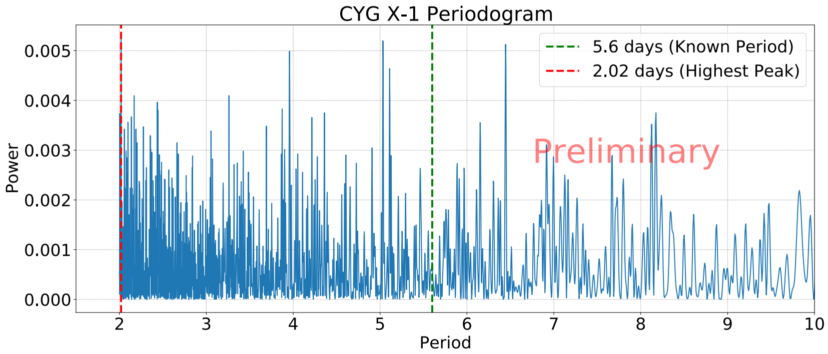


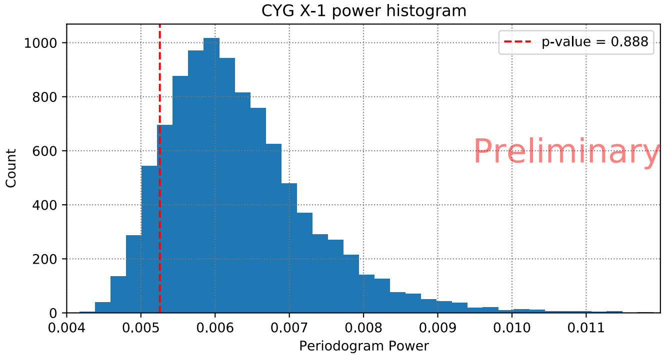




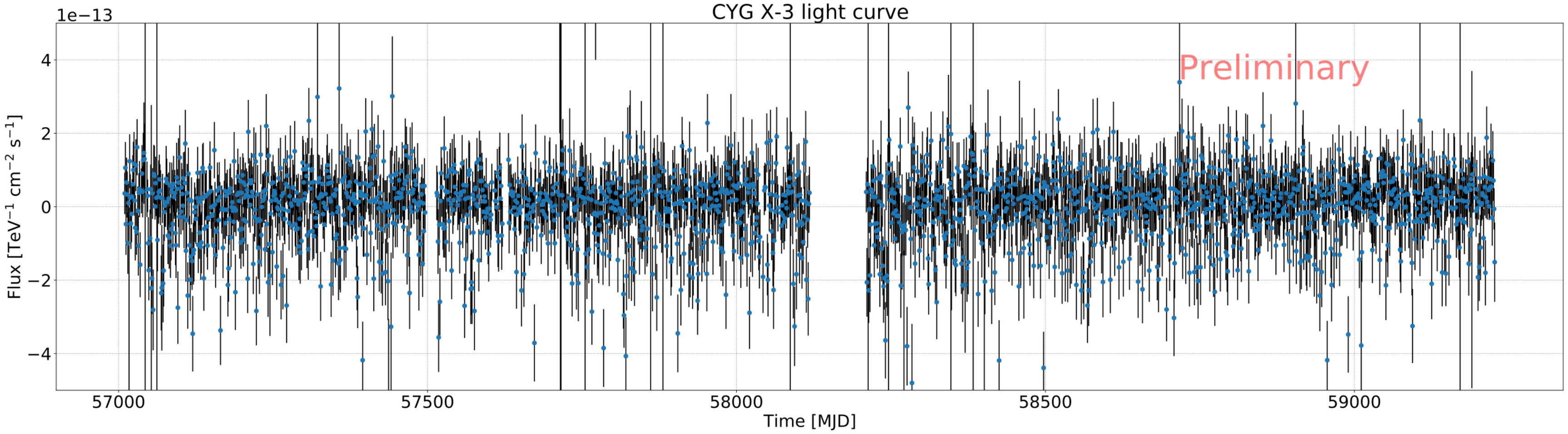
Cyg X-1 – 5.6 days





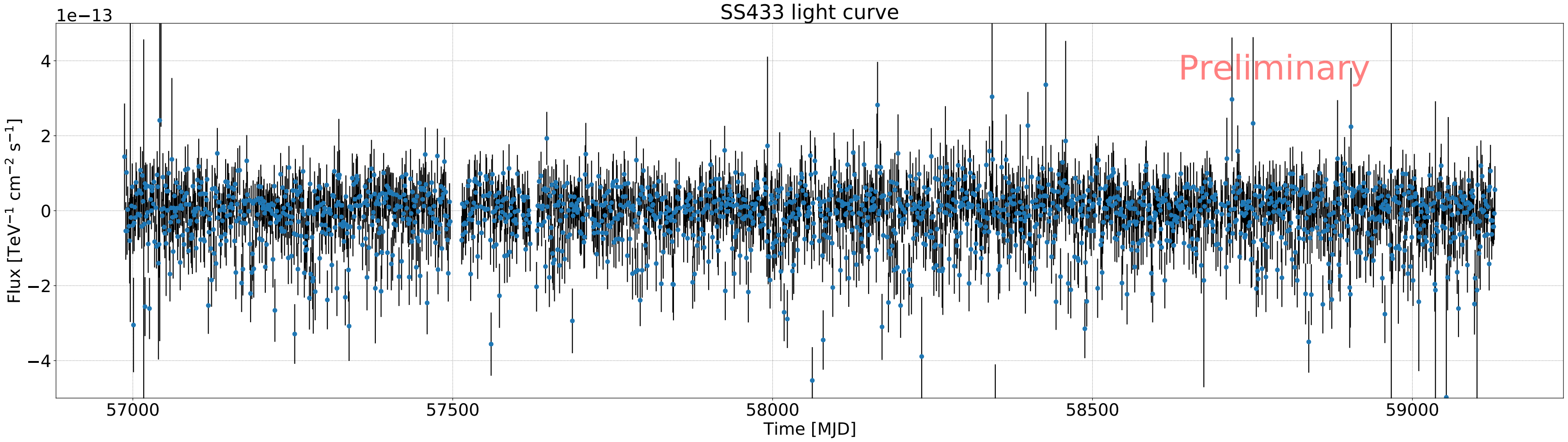


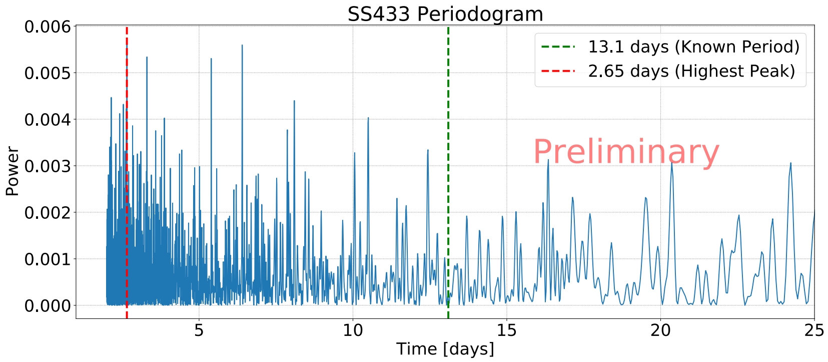
Cyg X-3 – 0.2 days

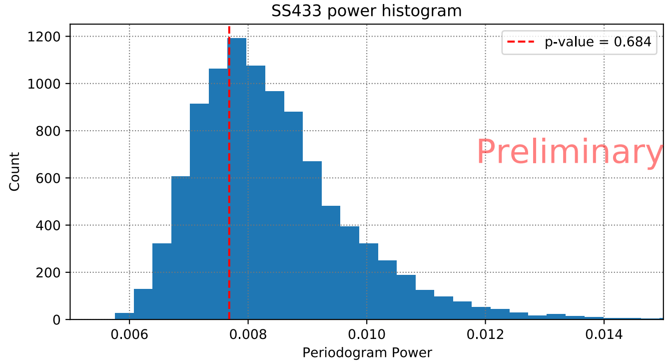


Periodogram not useful since period < 1 day

SS 433 – 13.1 days







Summary

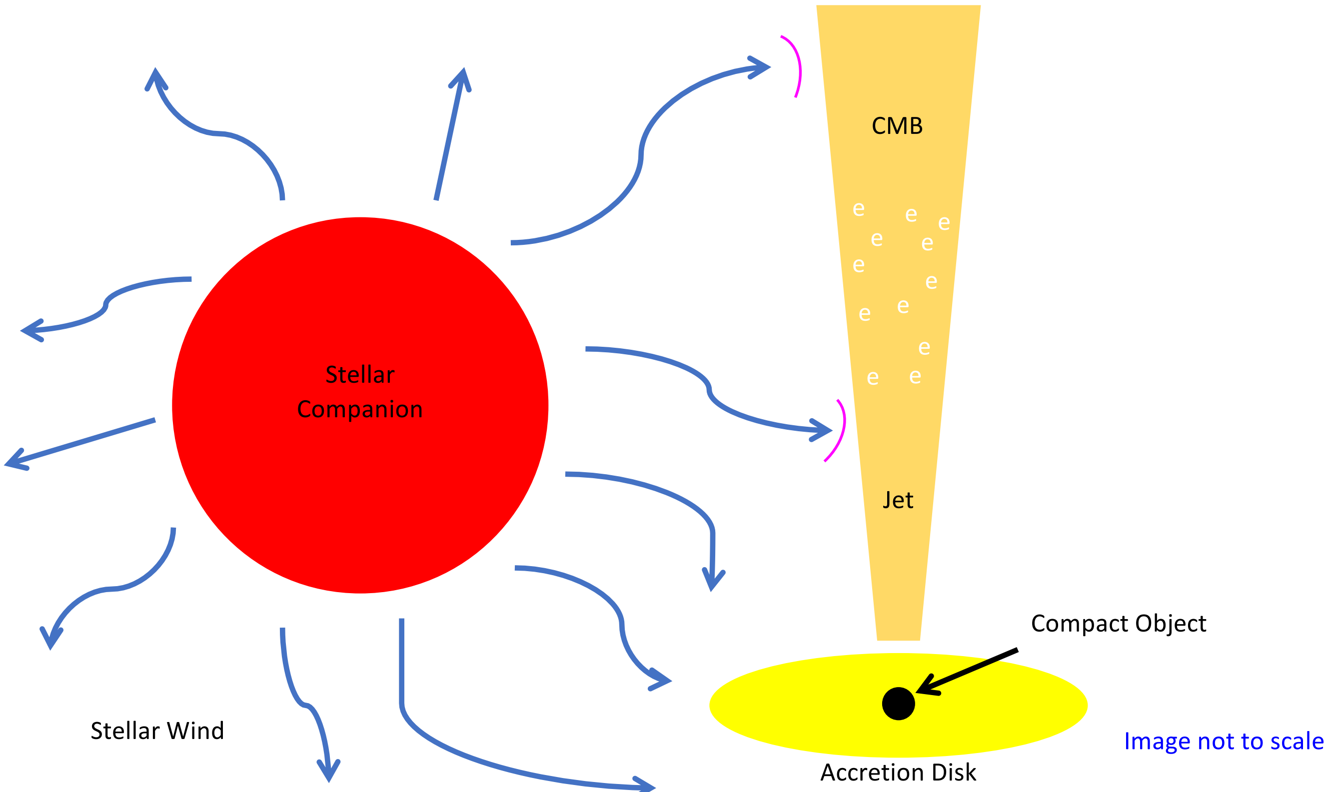
- No significant TeV γ-ray emission detected from the known HMMQs but most stringent limits are provided for > 10 TeV
- Derived upper limit on the γ-ray emission efficiency above 1 TeV, which also constrains the HE neutrino emission efficiency; implies that neutrino detection challenging for current neutrino detectors

$$\epsilon_\nu \approx 3\epsilon_\gamma/2$$

- Constrained contribution of synchrotron emission by relativistic electrons between 10 keV and 10 MeV for the four HMMQs
- No orbital modulation in flux observed with HAWC daily maps

Back Up

High-Mass Microquasar (HMMQ)



Contribution Factor for Stacked Analysis

- This analysis relies on stacked likelihood of many independent fits of numerous sources.

$$\ln L\left(N_{obs}^{j,B}\middle|\Theta\right) = \sum_{B=1}^{9}\sum_{j=1}^{m}\ln P\left(N_{obs}^{j,B}\middle|\Theta\right)$$

- Flux norm (*A*) will be set as a free parameter. $\frac{dN}{dE} = A\left(\frac{E}{E_{piv}}\right)^{-\alpha}$

- Since all independent sources are stacked, we find and apply a suitable contribution factor based on a physics model.

- Spectrum: *power law* * *step function* * ***constant (contribution factor)***

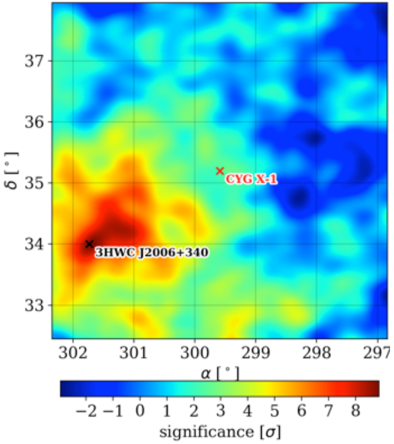
Quasi-differential Energy Bins

Table 2. Quasi-differential energy bins

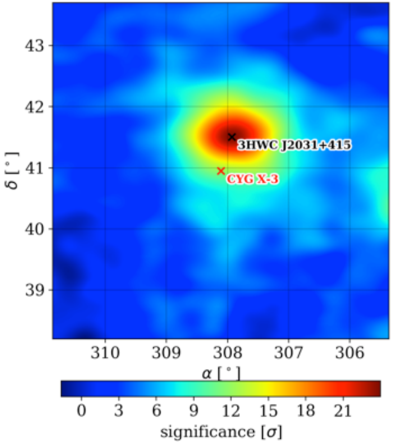
Energy Bin	Energy Range [TeV]	Pivot Energy [TeV]
1	1.0-3.2	1.8
2	3.2-10.0	5.6
3	10.0-31.6	17.8
4	31.6-100.0	56.2

Significance Maps – RHMXBs

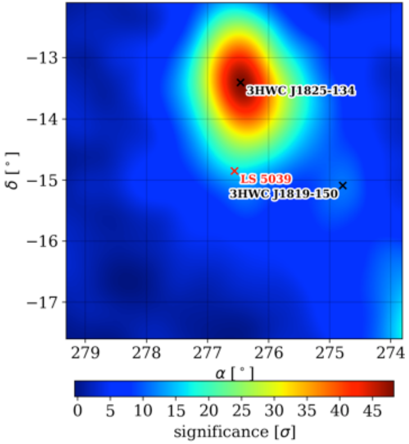
Cyg X-1



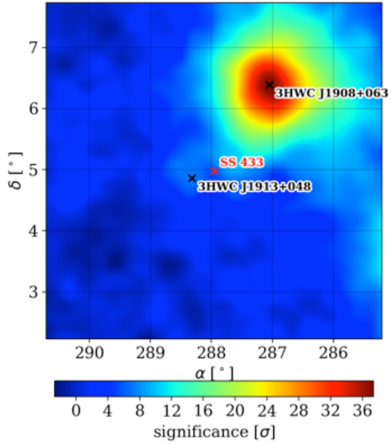
Cyg X-3



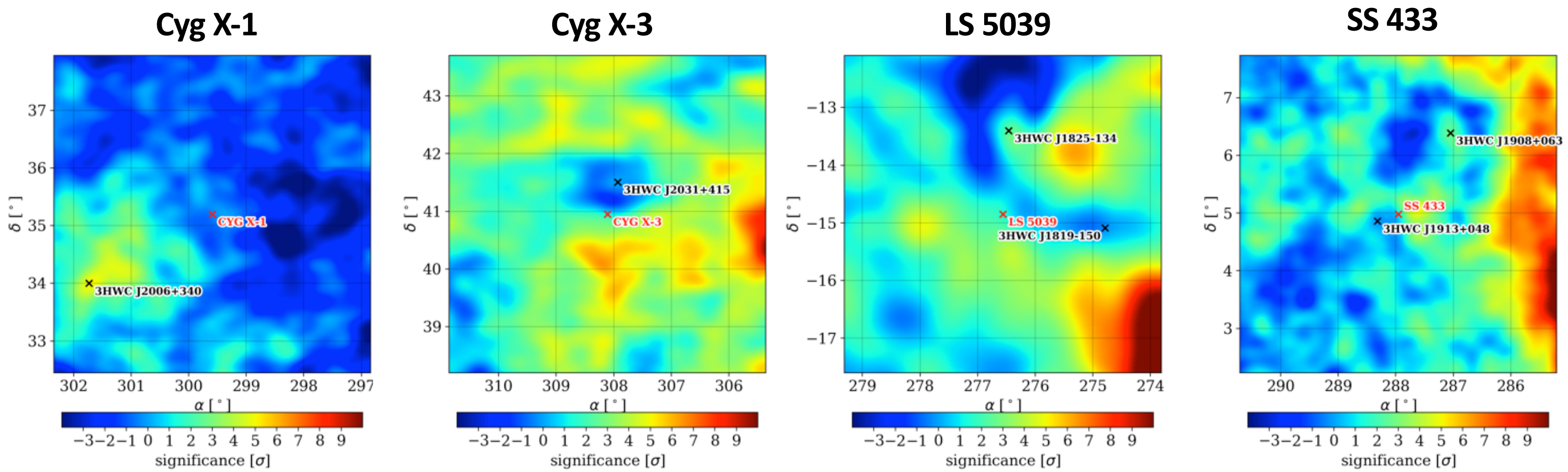
LS 5039



SS 433



Significance Maps (Residual) – RHMXBs



- No complex modelling. Used 3HWC catalog to fit and subtract sources

❖ Note: Gaussian morphology used to fit extended sources by default

Source Properties for Scenario II

Table 4. Derived Source Properties.

Name	u_0 $[\mathrm{erg\,cm^{-3}}]$	F_{KN} at $E_{e,\mathrm{bk}}$	$E_{\mathrm{syn,bk}}$ [keV]	$E_{e,\mathrm{bk}}$ [TeV]
LS 5039	820	4.9×10^{-5}	2100	6.9
CYG X-1	380	1.1×10^{-4}	1400	5.6
CYG X-3	2560	1.55×10^{-5}	4620	10.2
SS 433	5.5	7.2×10^{-3}	6.2	0.4

*Derived assuming *B* = 1 G

Other Studies

- Log parabola model used to test that γ-ray spectrum may not follow a power law

$$\Phi_\gamma = \frac{F_{\mathrm{syn}}\, u_0\, f_{\mathrm{KN}}}{u_B} K_l \left(\frac{E}{E_{\mathrm{piv}}}\right)^{-\alpha_l - \beta_l \log(E/E_{\mathrm{piv}})}$$

- $\gamma\gamma$ pair production absorption is negligible for tail-on interaction (at < 100 TeV) and we predict a factor of unity attenuation overall