

# VERITAS Binary Program

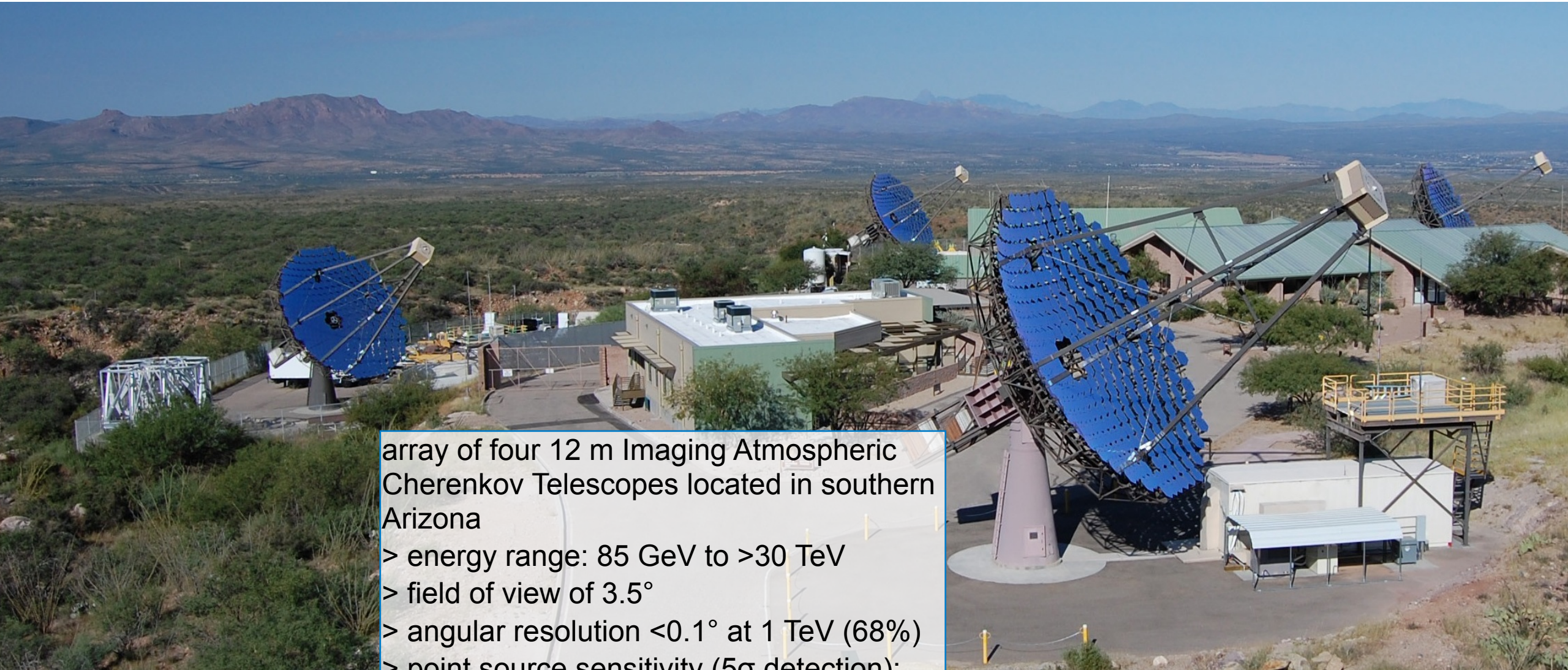


Tobias Kleiner for the VERITAS Collaboration

HELMHOLTZ

Variable Galactic Gamma Ray Sources VI, Innsbruck 2023





array of four 12 m Imaging Atmospheric Cherenkov Telescopes located in southern Arizona

- > energy range: 85 GeV to >30 TeV
- > field of view of  $3.5^\circ$
- > angular resolution  $<0.1^\circ$  at 1 TeV (68%)
- > point source sensitivity ( $5\sigma$  detection): 1% Crab in  $< 25$  h (10% in 25 min)

# VERITAS Binary Program HMXB

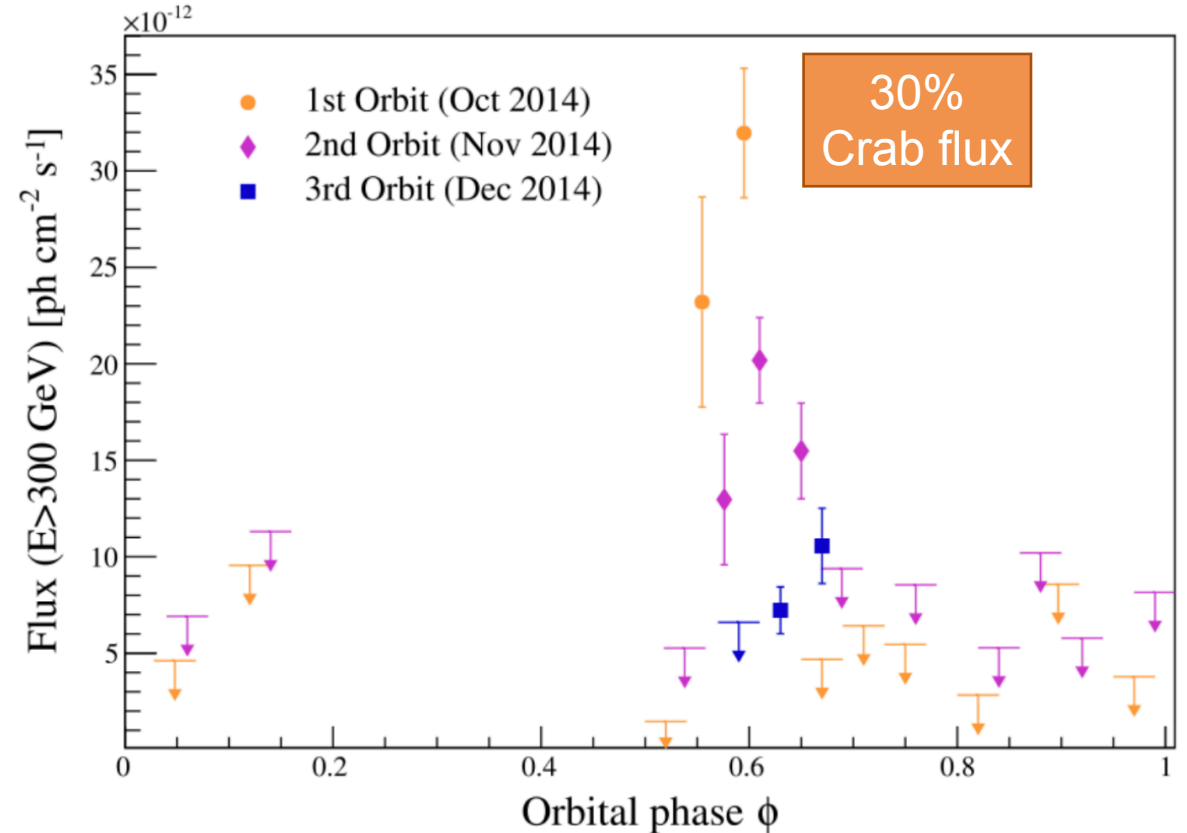
	type	orbital period	type of observation	exposure	reference
<b>1A 0535+262</b>	O+NS	111 d	during giant outburst	24 h	ApJ 2011
<b>4U 0115+634</b>	B0.2Ve+NS	24.3 d	during giant outburst	5.5 h	ApJ 2016
<b>Be/X-ray Binary discover program</b>	Be+NS/HB	-	filler program	(~130 h)	in preparation
<b>Cygnus X-1</b>	O9.7Iab + BH	5.6 d	Cygnus survey	15 h	ApJ 2018, ICRC 2009
<b>Cygnus X-3</b>	Wolf Rayet + BH?	4.8 h	FoV of TeV 2032+4130	44 h	ApJ 2013, ApJ 2018
<b>HESS J0632+057</b>	B0pe+NS/BH	315 d	regular since 2006 (10-30 h/season)	330 h	ApJ 2009, 2014, 2021 ICRC 2019
<b>LS 5039</b>	O6.5V+NS/BH	3.9 d		8h	AP 2020
<b>LS I +61 303</b>	Be+NS/BH	26.5 d	regular since 2006 (10-30 h/season)	330 h	ApJ 2008, 2009, 2011, 2013, 2016, 2021 ICRC 2021
<b>LS V +44 17</b>	B0.2Ve+NS	150 d	outburst + 2011-LTP	24 h	AT 2023
<b>PSR J2032+4127/ MT91 213</b>	Be+NS/BH	~50 y	archival; around periastron	180 h	ApJ 2018
<b>SS 433</b>	A+BH	13 d	unregular, 30h 2023	~(60-90)h	

# VERITAS Binary Program LMXB, other

	type	orbital period	type of observation	exposure	reference
<b>HMXBs &amp; LMXBs in Cygnus region</b>	-	-	survey of Cygnus region	2-6 h	ApJ 2018
<b>Magnetars</b>	SGRs+AXPs	-	ToO (GRB pipeline)		ICRC 2009
<b>MAXI J1820+070</b>	10M $\odot$ star+NS/ BH ?	?	during hard X-ray outburst	13 h	ICRC 2019, MNRAS 2022
<b>PSR J1023+0038</b>	G+MSP	4.8 h	TO (radio quiet/HE flare)	32 h	ApJ 2016
<b>V 404 Cyg</b>	K+BH	6.47 d	during giant outburst	4h	ApJ 2016
<b>V407 Cygni</b>	Nova in a symbiotic binary		outburst (LAT)	5h	ApJ 2012

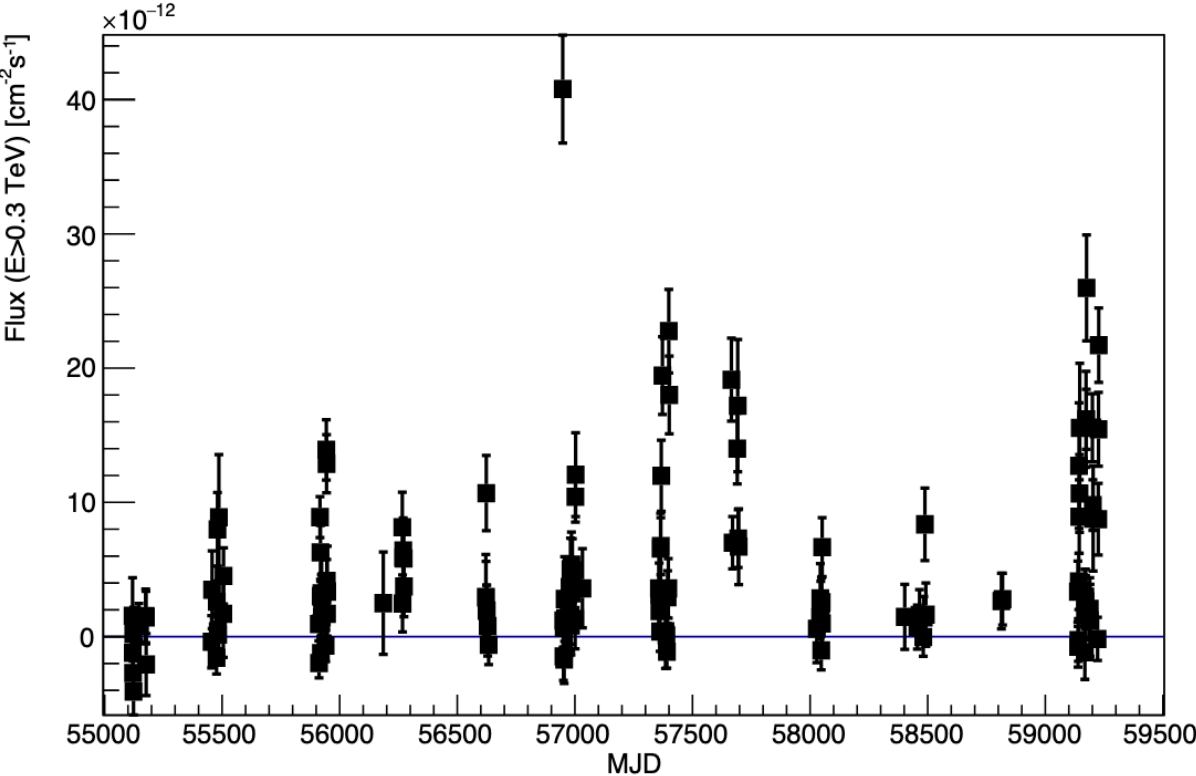
# LS I +61 303

- Galactic HMXB: Be star ( $10-15M_{\odot}$ ) with circumstellar disk + compact object ( $2-3 M_{\odot}$ , NS or BH) at 2 kpc
- Short term modulation with orbital period of  $26.496 \pm 0.0028$  day across electromagnetic spectrum
- Super-orbital modulation with 1667 days in radio, X-ray, GeV/TeV

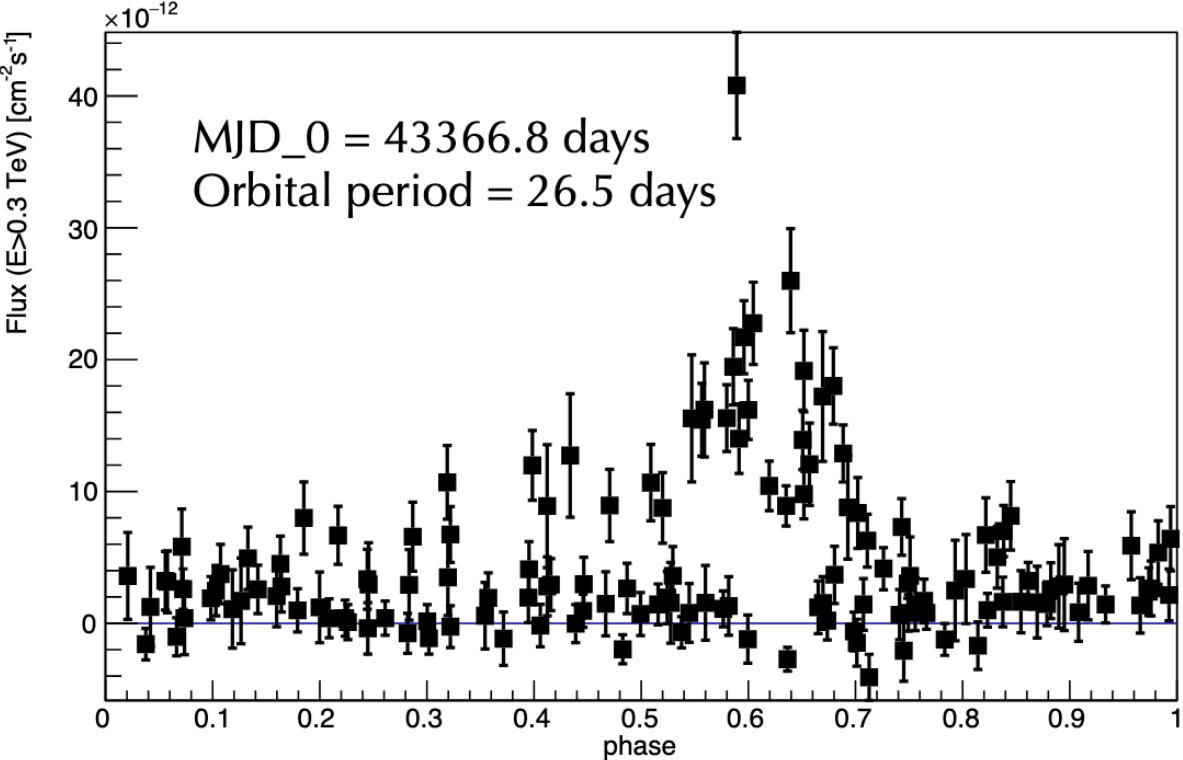


doi:10.3847/2041-8205/817/1/L7

# LS I +61 303 daily and orbital binned light curve



VERITAS nightly light curve 2009-2021



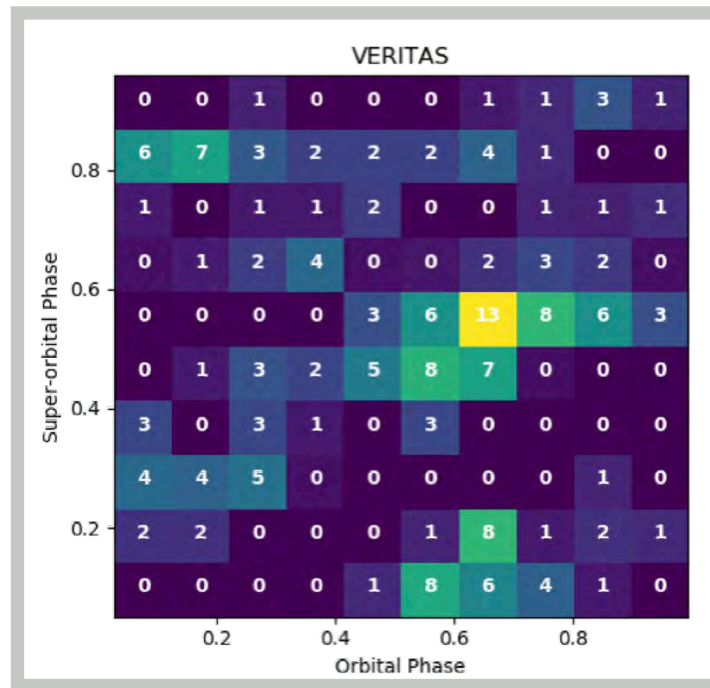
VERITAS orbital phase binned light curve 2009-2021

# LS I +61 303 orbital and super orbital

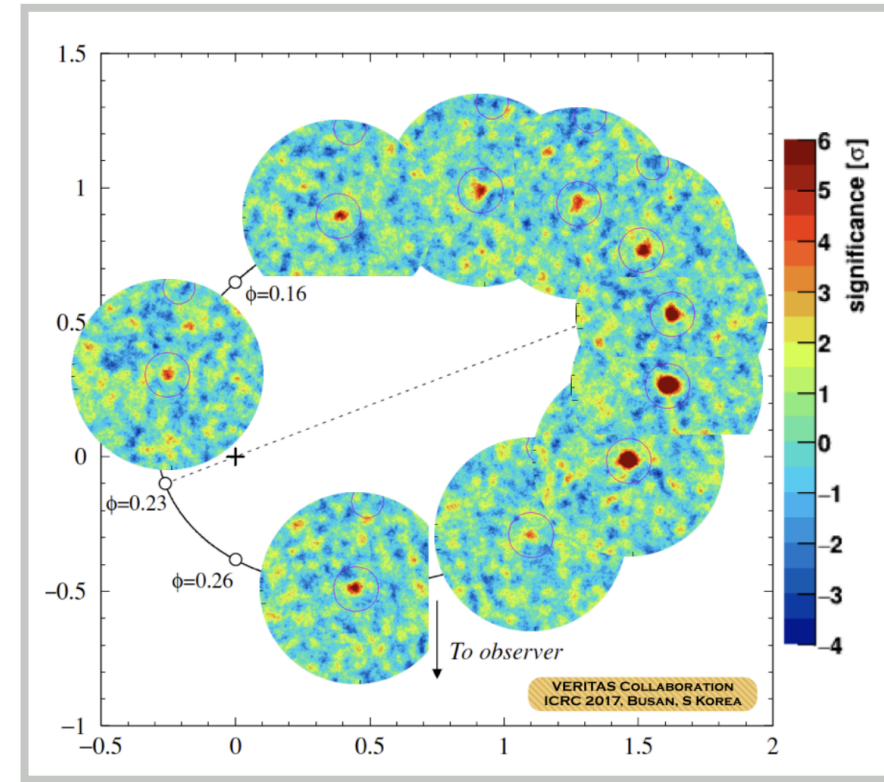
- Good orbital coverage, detection in all orbital phases
- Study of super orbital phases

Superorbital Phase	Live time (min)	Significance ( $\sigma$ )
0 - 0.1	1316.18	1.4
0.1 - 0.2	1240.15	13.1
0.2 - 0.3	1004.62	4.3
0.3 - 0.4	494.73	6.7
0.4 - 0.5	1934.35	23.3
0.5 - 0.6	2406.18	23
0.6 - 0.7	20.03	0.7
0.7 - 0.8	364.03	6
0.8 - 0.9	650.35	3.6
0.9 - 1	370.88	4.4

ICRC2019 (2020) 713



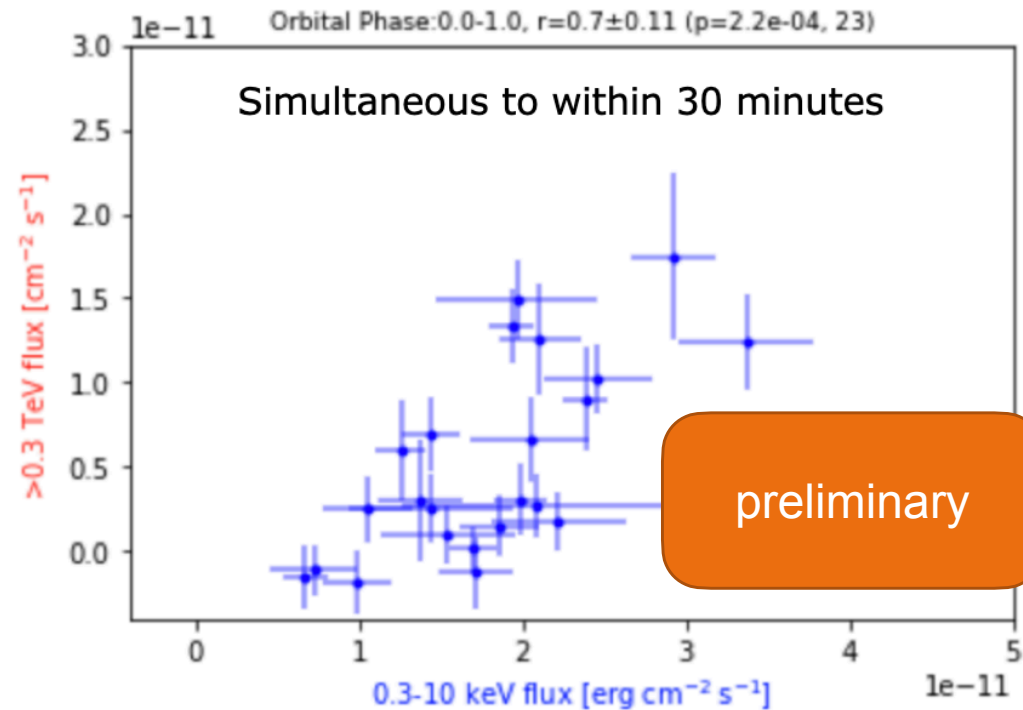
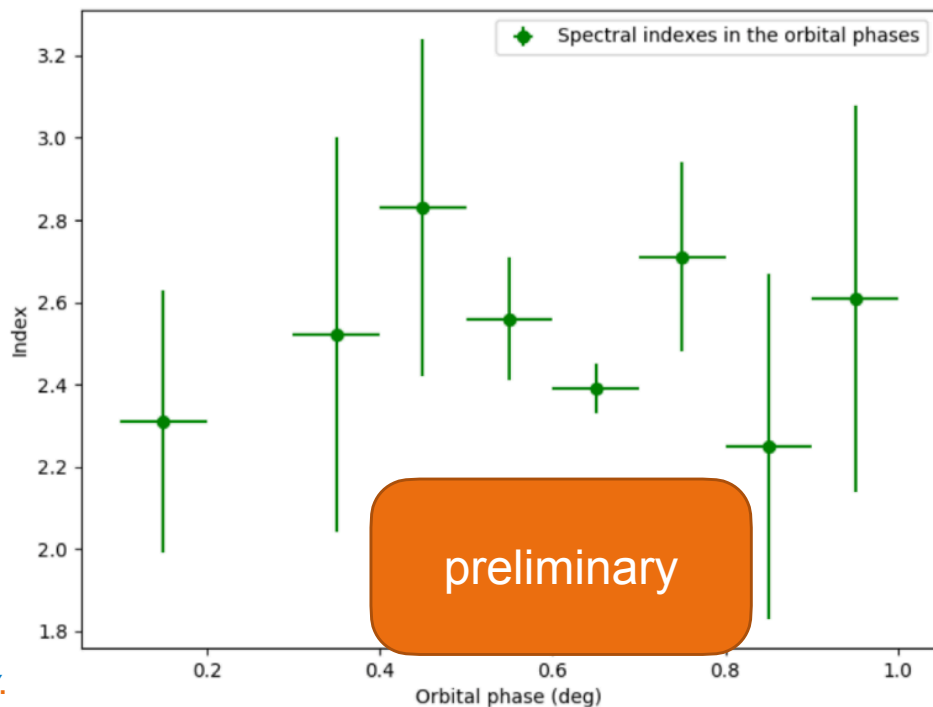
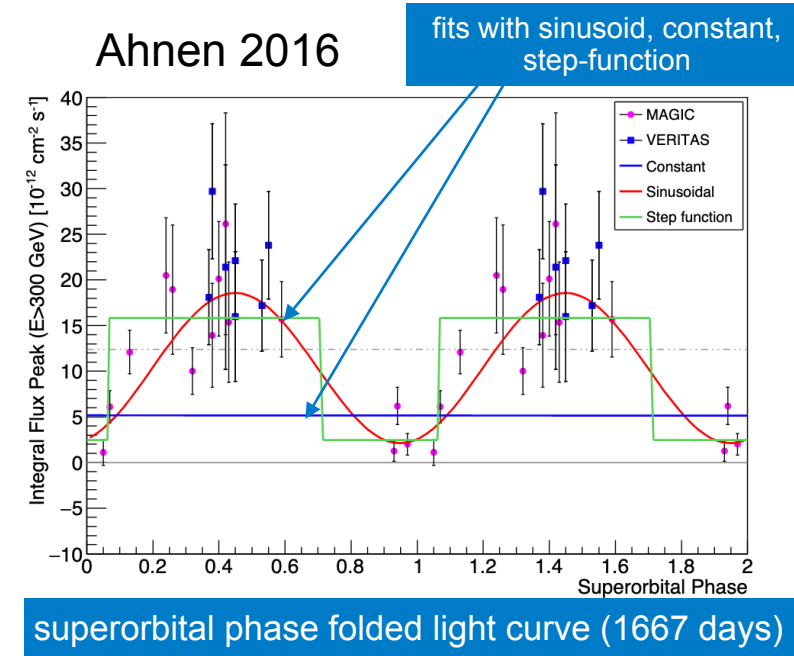
distribution of VERITAS observations (2008-2021, in hours)



VERITAS observations 2007-2016

# LS I +61 303 variability?

- Orbital phases: No evidence for spectral variability
- Super orbital phases: Combined analysis of MAGIC and VERITAS data in prep. for clearer measurement of super-orbital dependency
- Strong correlation between X-ray and VHE flux (Correlation coefficient =  $0.69 \pm 0.11$ )

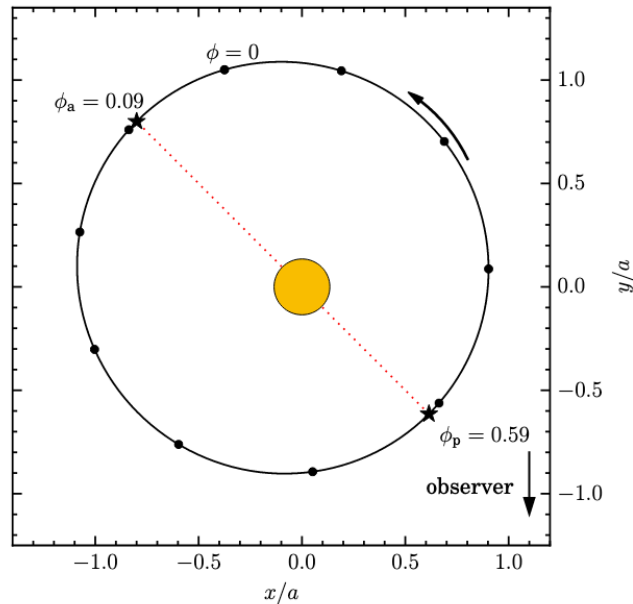




# LS I +61 303

- New orbital solution:
  - constrain eccentricity  $e < 0.15$ ,Phase of periastron = 0.6

Aragona ( $e=0.54$ ), Casares ( $e=0.72$ )

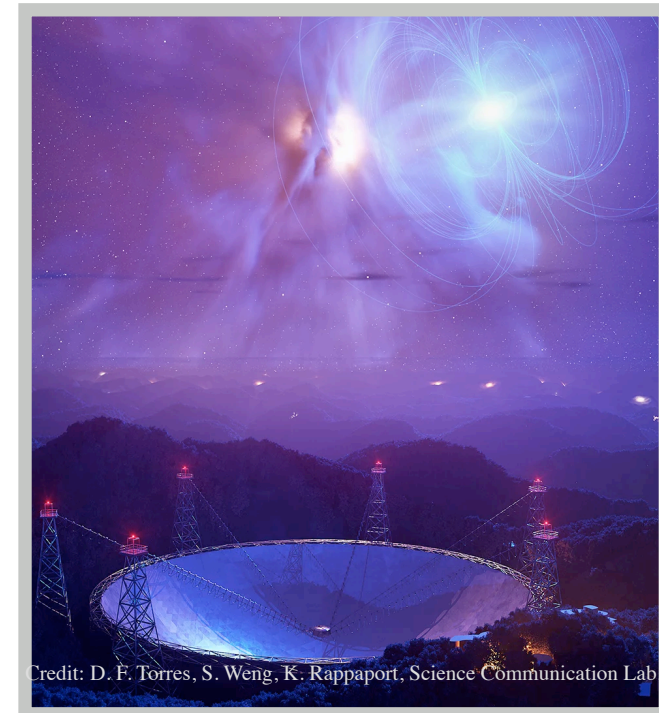


(Kravtsov, 2020)

FAST radio telescope: pulsations with 269 ms period

- “strongly argues for the existence of a rotating neutron star within LS I +61° 303”.

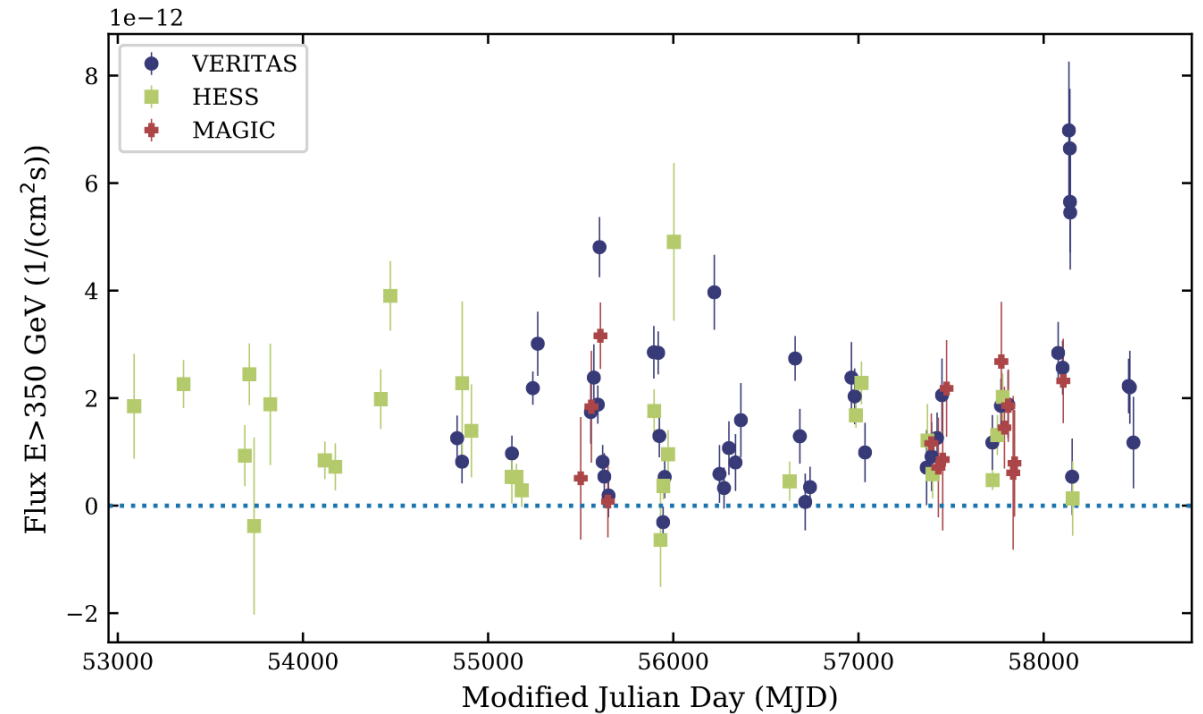
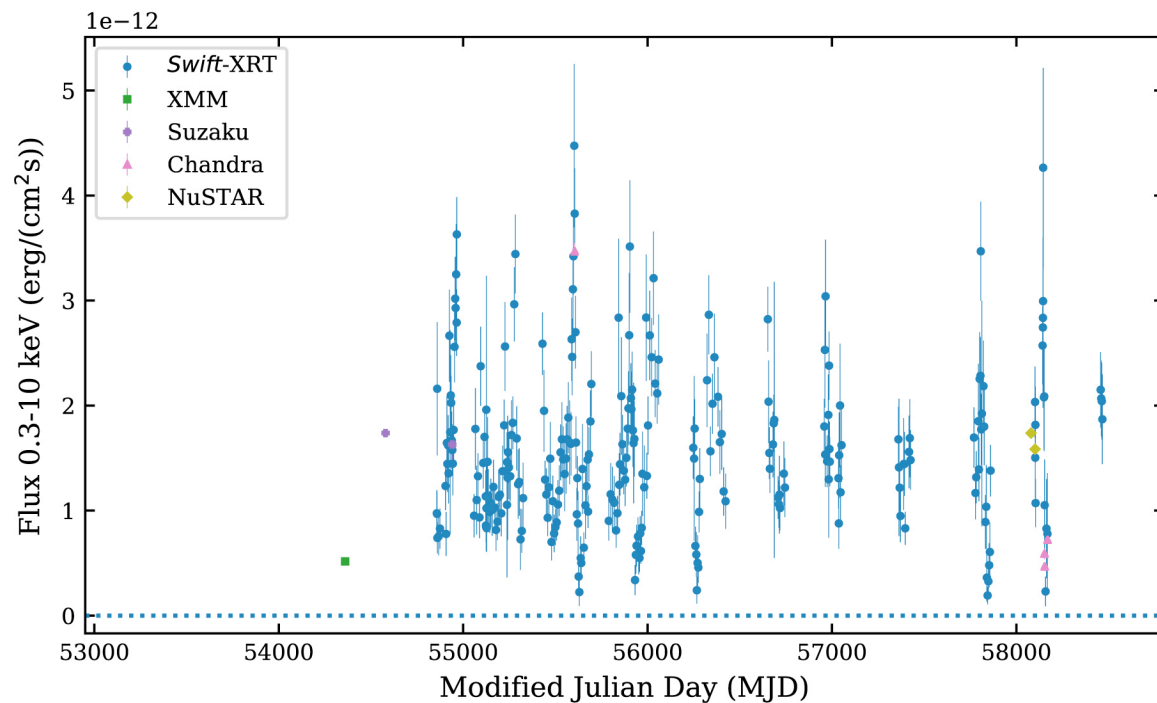
Weng, SS., Qian, L., Wang, BJ. *et al.* (2022)



Credit: D. F. Torres, S. Weng, K. Rappaport, Science Communication Lab

# HESS J0632+057

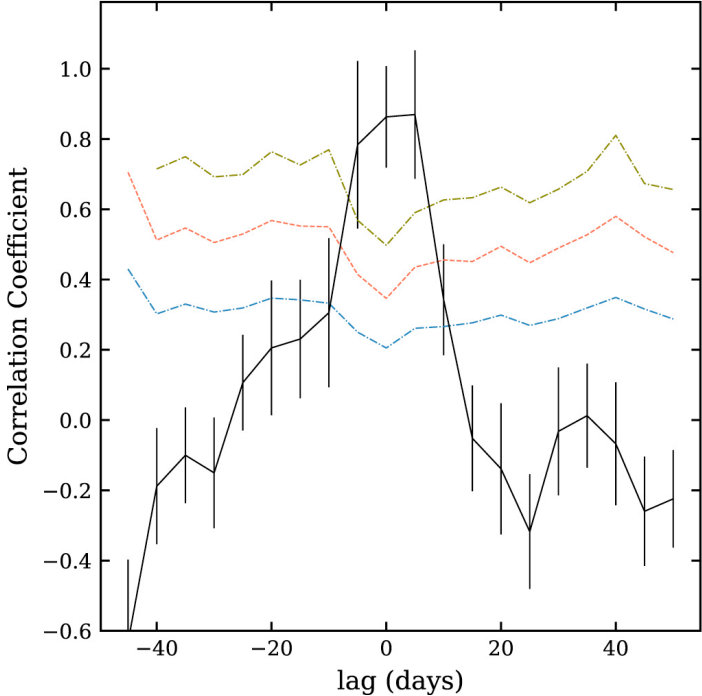
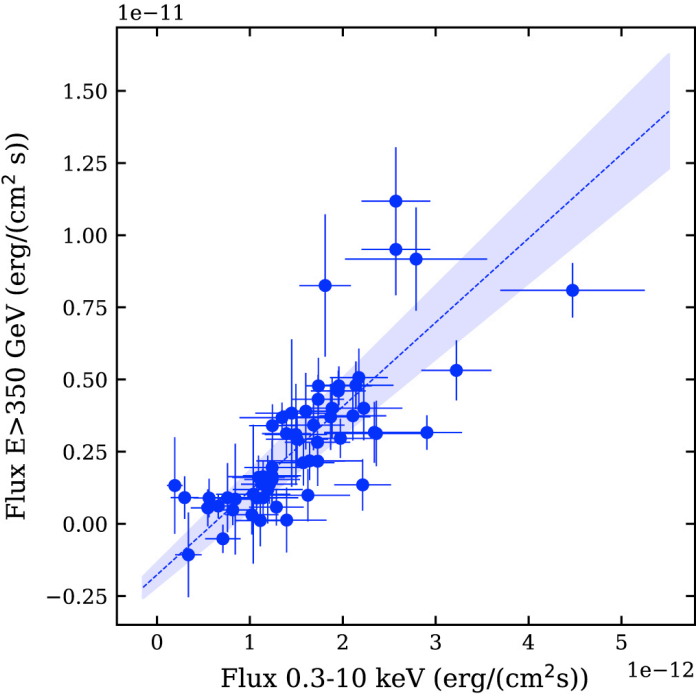
- 450 h H.E.S.S., MAGIC and VERITAS data collected over 15 years
- B0pe star ( $M = 16M_{\odot}$ ) + compact object ( $2-3 M_{\odot}$ ) at 1.1-1.7 kpc
- $(316.7 \pm 4.4)$  days orbital period,  $(317.3 \pm 0.7)$  days in x-ray



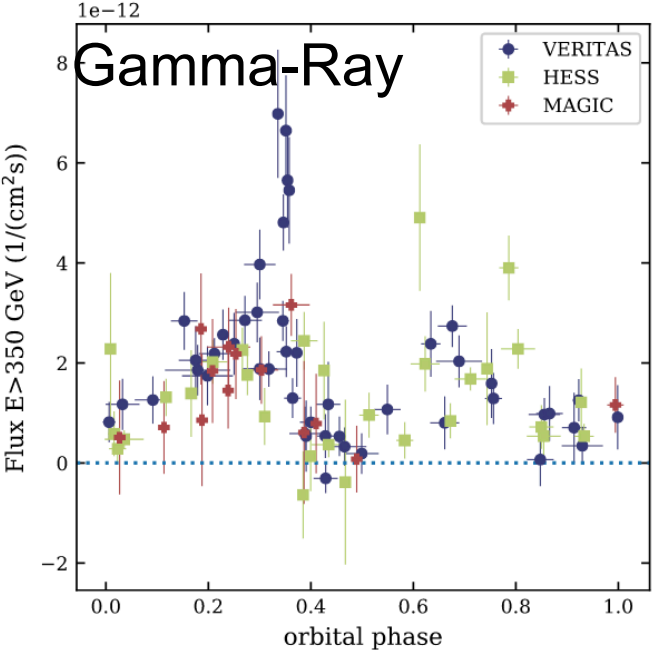
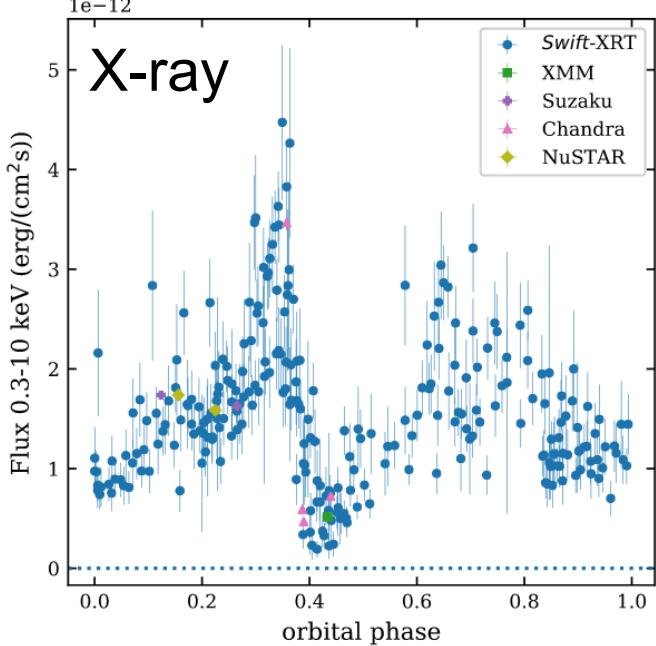
# HESS J0632+057 in X-ray and Gamma-ray

- X-ray and TeV flux highly correlated without significant time-lag

common origin of the radiation ?



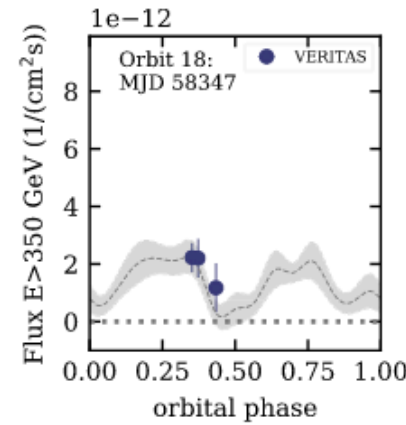
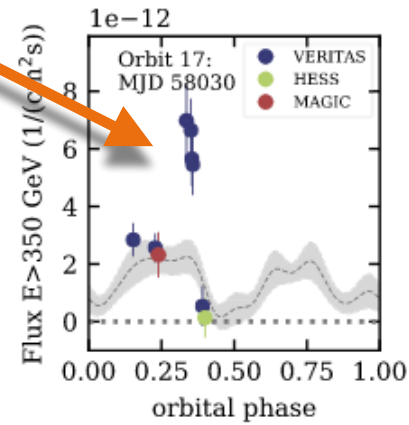
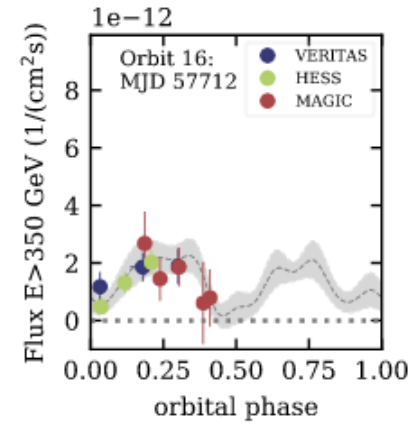
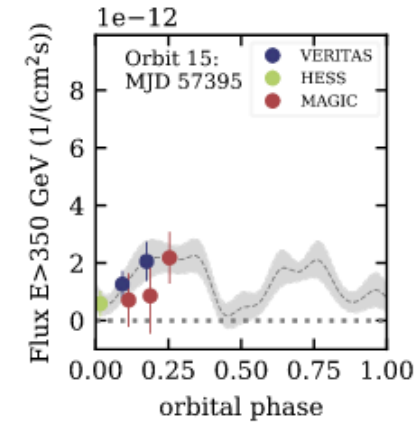
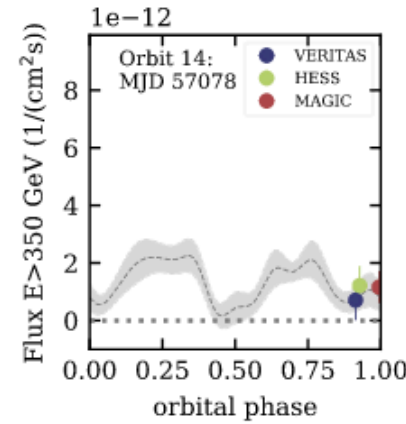
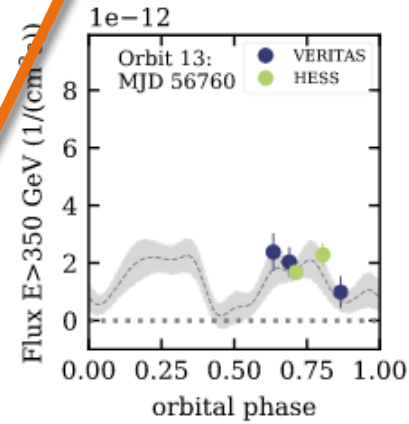
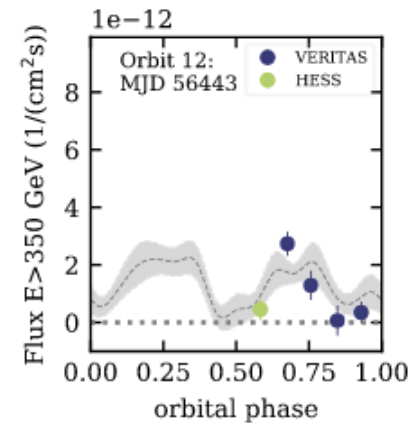
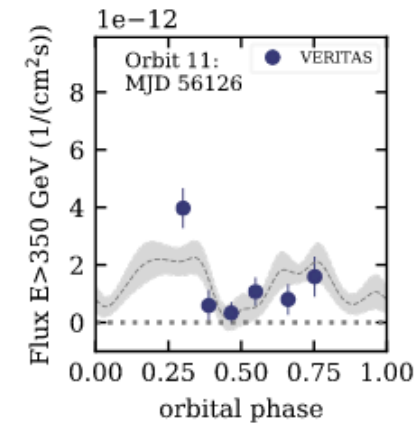
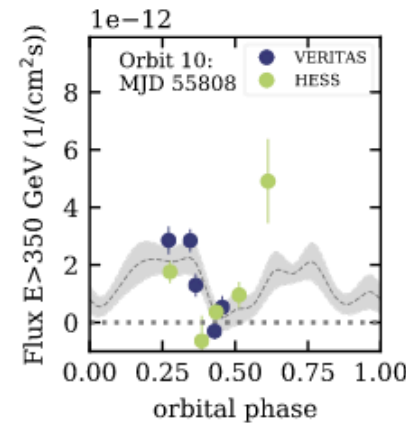
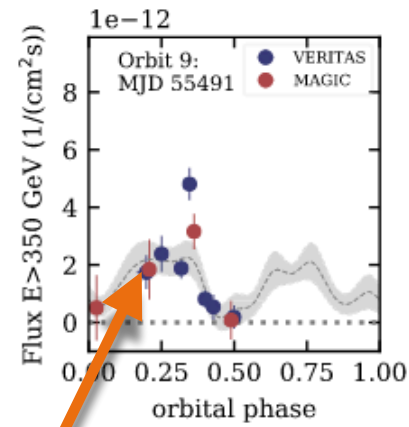
Phase-folded Light Curves



# HESS J0632+057

- Observations over 18 orbits
- strong Gamma ray variability, orbit to orbit
- Two outbursts during orbits 9 (2011 January) and 17 (2018 January)
- two orbits with flux decay time of  $\leq 20$  days

?decretion disk structural change?

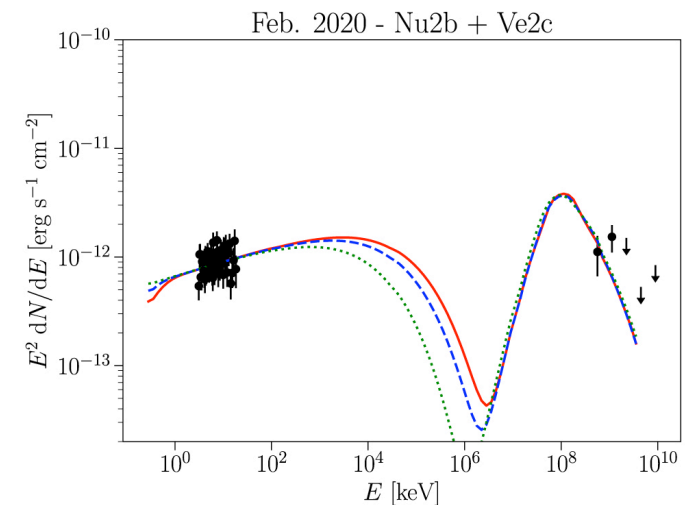
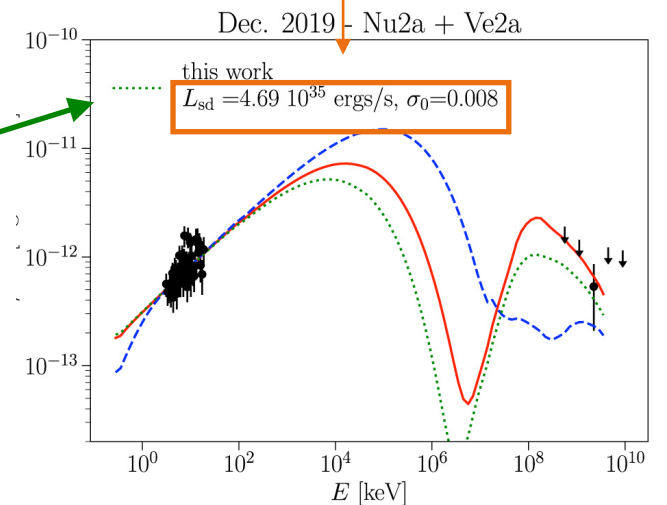
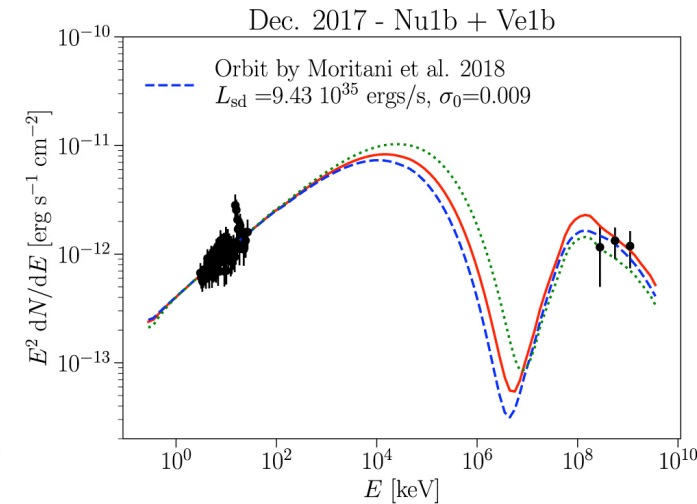
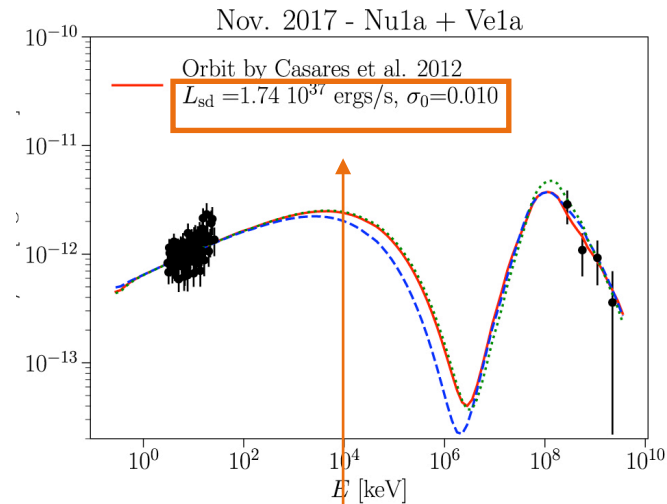
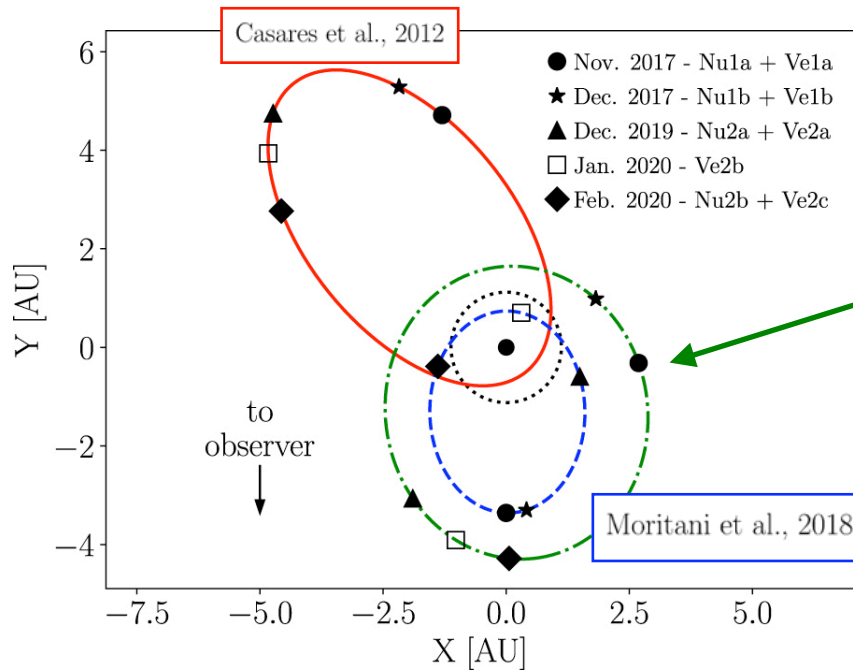


# HESS J0632+057 orbital solutions

Obs.	MJD Range	Observation Time (hours)	Significance ( $\sigma$ )	Flux <sup>a</sup> ( $10^{-12}$ cm <sup>-2</sup> s <sup>-1</sup> )	Luminosity ( $10^{32}$ erg s <sup>-1</sup> )
Ve1a <sup>b</sup>	58073–58083	7.4	5.7	$2.8 \pm 0.6$	$6.6 \pm 1.4$
Ve1b <sup>b</sup>	58101–58103	6.0	6.4	$2.6 \pm 0.5$	$6.1 \pm 1.2$
Ve2a	58837–58851	6.9	1.3	$<1.7^c$	$<4.0^c$
Ve2b	58867–58878	7.8	4.5	$1.6 \pm 0.4$	$3.8 \pm 0.9$
Ve2c	58897–58906	8.3	4.6	$1.7 \pm 0.5$	$4.0 \pm 1.2$

Y. M. Tokayer *et al* 2021

- NuSTAR, VERITAS, MDM, Swift
- Orbital geometry, disk properties and nature of the compact object remain uncertain
- Orbital parameters need further constrains.

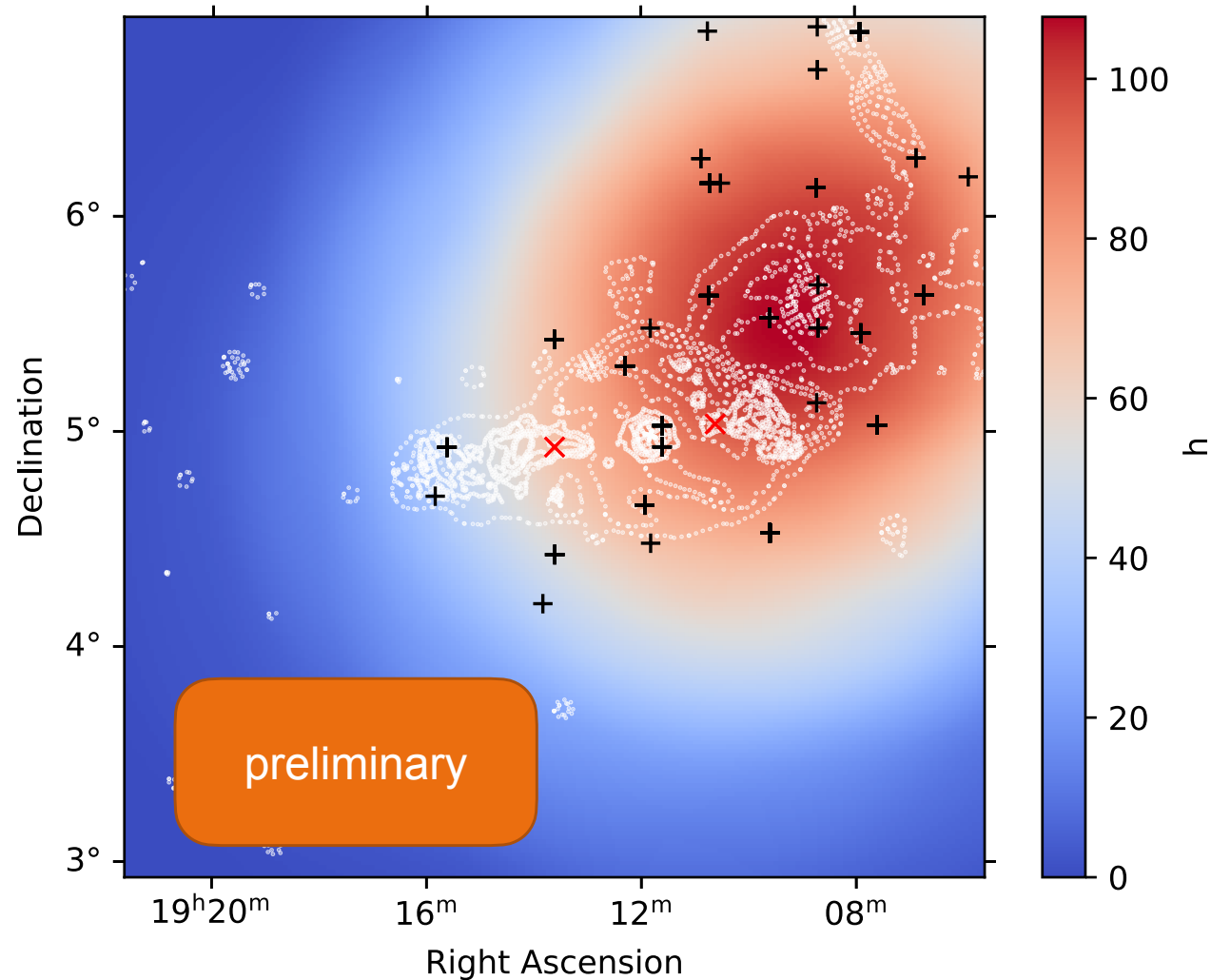


# Microquasar SS 433

- Analysis of SS 433 in progress and further observations (30h-40h) this season.

Stay tuned

preliminary



VERITAS Acceptance corrected exposure of SS 433

# VERITAS Nova Follow Up Program

- Continuing Nova Observation and Follow Up Program:
  - Nova Per 2020:
    - 1.0 sigma, 3.1 excess events, 10 hours of exposure time
  - Nova Her 2021: report 11-27-21, VERITAS observation 11-28-21,
    - -1.0 sigma, 100 minutes of exposure time AT2021afpi Astronomer's Telegram, No. 15078, 2021
- Triggering conditions:  $>30^\circ$ , 1h after Trigger
- Fast alert system crucial: NASA-GCN, (e.g. alerts from the Swift, Fermi and INTEGRAL satellites), GAIA photometric alerts, ASAS-SN and ALARRM

# Summary - VERITAS Binary Observations

- Large and extending VERITAS archive on LS I +61 303 and HESS J0632+57 >300h
- Binaries are ideal candidates for testing many questions of particle astrophysics
- Multi-wavelength observations important to constrain models further
- Variability in LS I +61 303 and HESS J0632+57