VERITAS observations of gamma-ray binaries.

Barcelona - May 2025

Gernot Maier for the VERITAS Collaboration

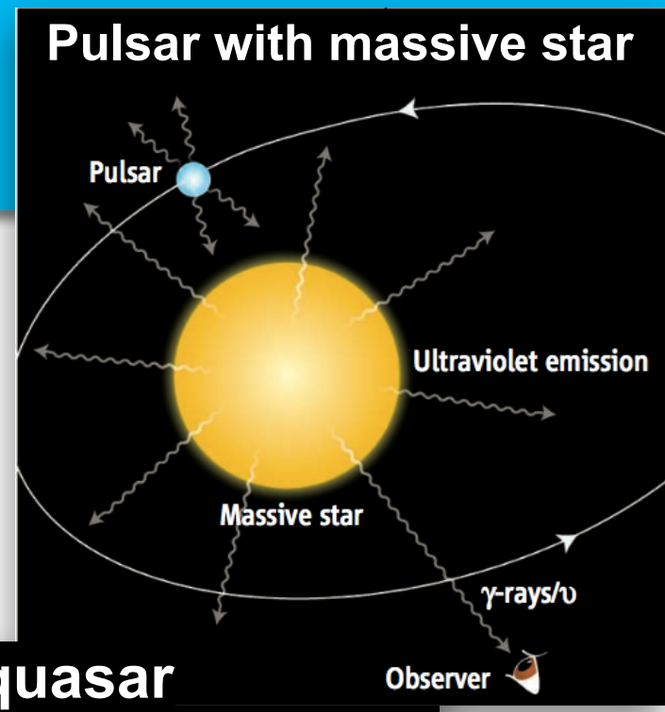
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

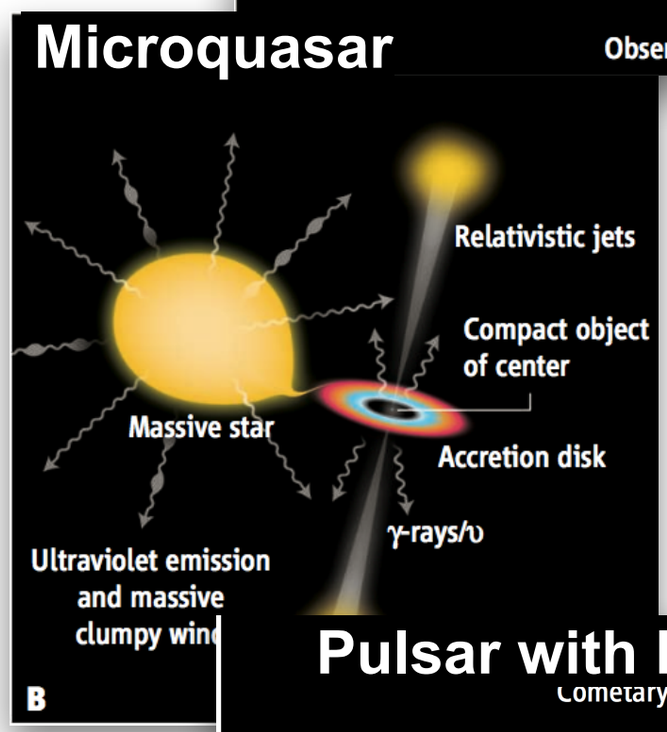
DESY.

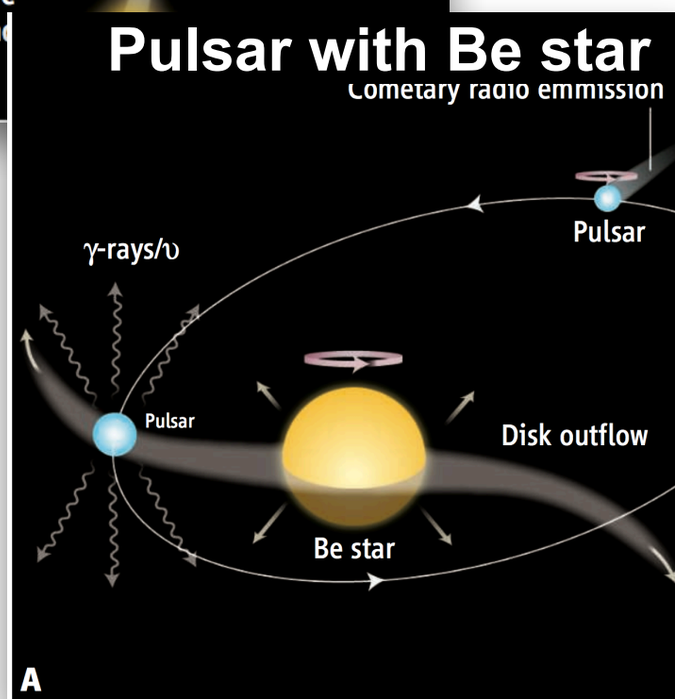
Gamma-ray binaries: key questions

Old slide from 2017...

- **Why do some binary systems emit gamma-rays?**
  - Only ~~5~~ >5 out of >150 known HMXBs are known to emit gamma rays above 100 GeV
- **Are binaries pulsar-wind or accretion powered?**
  - Are microquasars gamma-ray emitters? Yes
- **What modulates the variability?**
  - More and different variability detected than originally expected (on all time scales: flares, orbit, multi-year cycle, etc.)
- **What is the role of stellar winds / disks?**
- **How many gamma-ray binaries are out there?**
  - HESS J0632+057 was not even known to be a binary system (and is not yet detected at MeV-GeV energies)







Mirabel 2006

VERITAS

VERITAS Binary Program (1)

	type	orbital period	type of observation	exposure	reference
LS I +61 303	Be+NS	26.5 d	regular since 2006 (10-30 h/season)	>370 h	ApJ 2008, 2009, 2011, 2013, 2016, (2025)
HESS J0632+057	B0pe+NS	315 d	regular since 2006 (10-30 h/season)	>360 h	ApJ 2009, 2014, 2020, 2021, 2021, (2025)
PSR J2032+4127/ MT91 213	Be+NS	~50 y	archival; around periastron	180 h	ApJ 2018
LS 5039	06.5V+NS	3.9 d		8 h	APh 2020
SS 433	A+BH	13d		40-100 h	In preparation
1A 0535+262	O+NS	111 d	during giant outburst	24 h	ApJ 2011
4U 0115+634	B0.2Ve+NS	24.3 d	during giant outburst	5.5 h	ApJ 2016
Be/X-ray Binary discover program	Be+NS/HB	-	filler program	(~180 h)	In preparation

VERITAS Binary Program (2)

	type	orbital period	type of observation	exposure	reference
Cygnus X-1	O9.7Iab + BH	5.6 d	Cygnus survey	15 h	ApJ 2018, ICRC 2009
Cygnus X-3	Wolf Rayet + BH?	4.8 h	FoV of TeV 2032+4130	44 h	ApJ 2013, ApJ 2018
V 404 Cyg	K+BH	6.47 d	during giant outburst	4 h	ApJ 2016
MAXI J1820+070	$10M_\Theta$ star+NS/ BH	?	during hard X-ray outburst	12.2 h	MNRAS 2022
HMXBs & LMXBs in Cygnus region	-	-	survey of Cygnus region	2-6 h	ApJ 2018
V407 Cygni	Nova in a symbiotic binary		outburst (LAT)	5 h	ApJ 2012
Magnetars	SGRs+AXPs	-	ToO (GRB pipeline)		ICRC 2009
PSR J1023+0038	G+MSP	4.8 h	ToO (radio quiet/HE flare)	25 h	ApJ 2016

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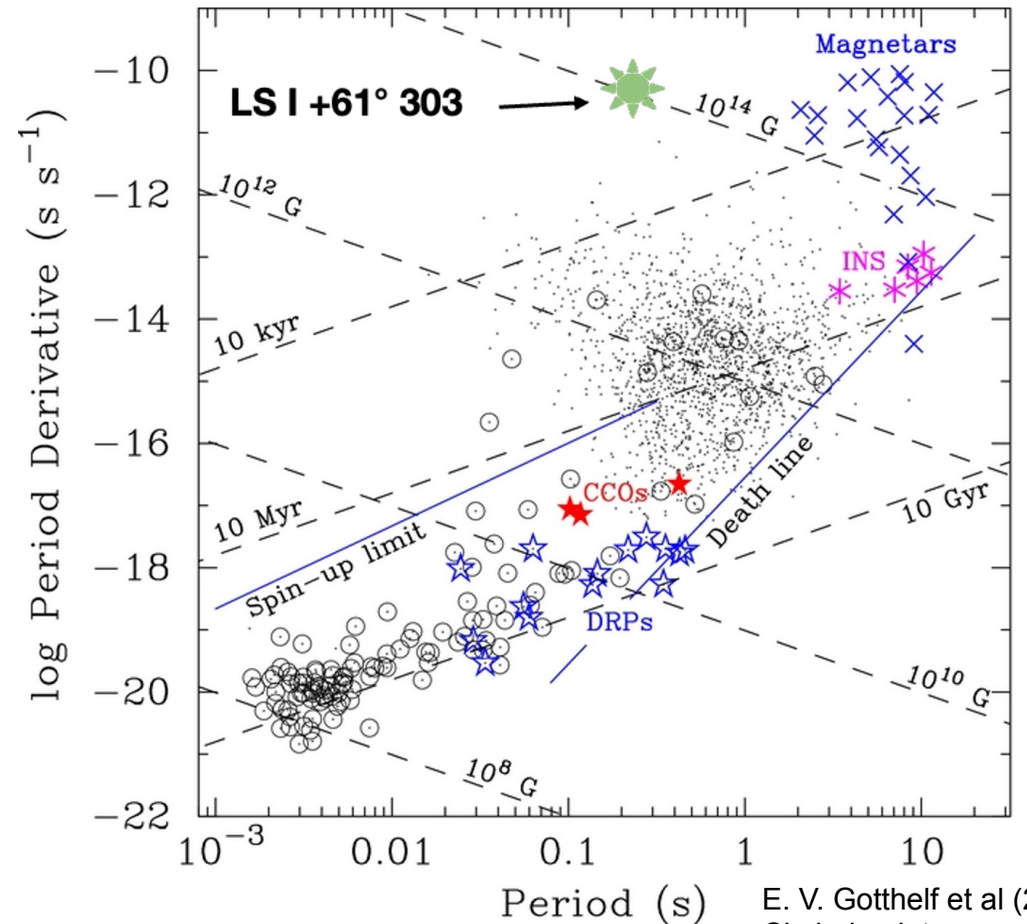
“Data-focused presentation on:”

- **LS I +61 303**
- **HESS J0632+57**

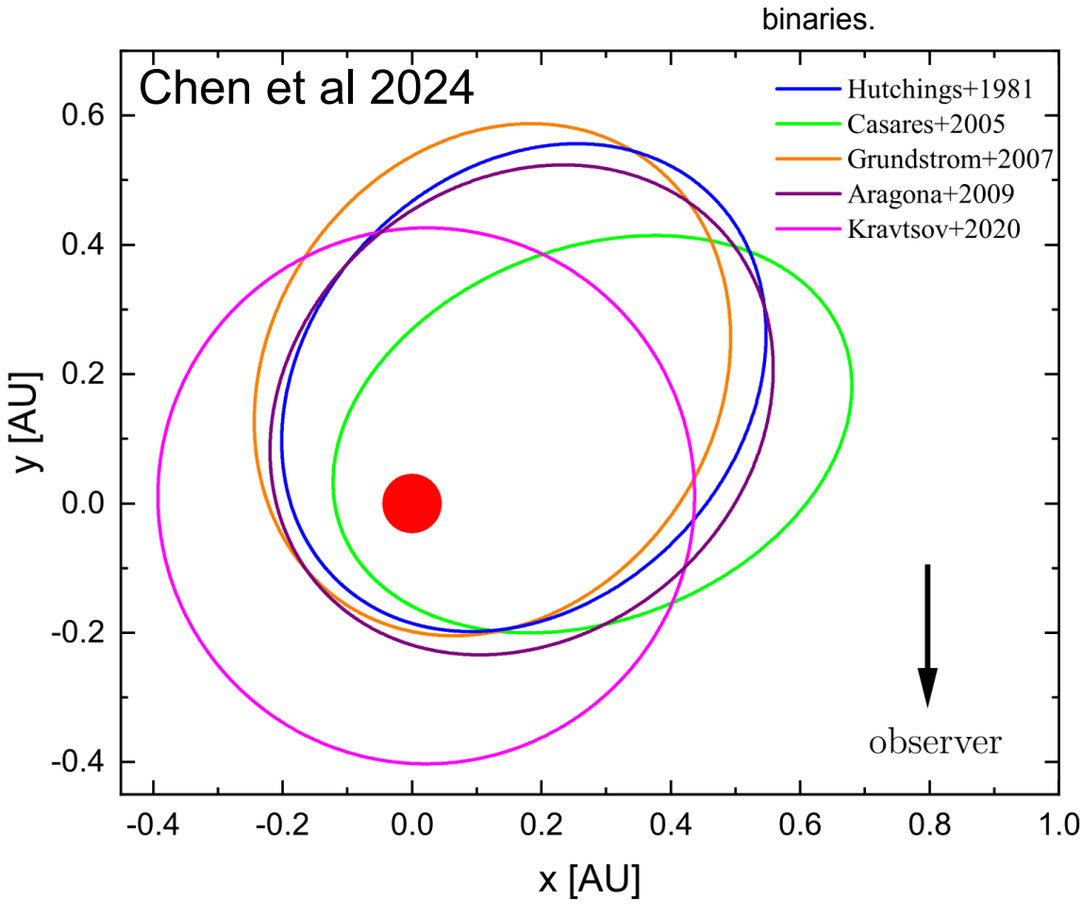
LS I +61 303

LS I +61 303

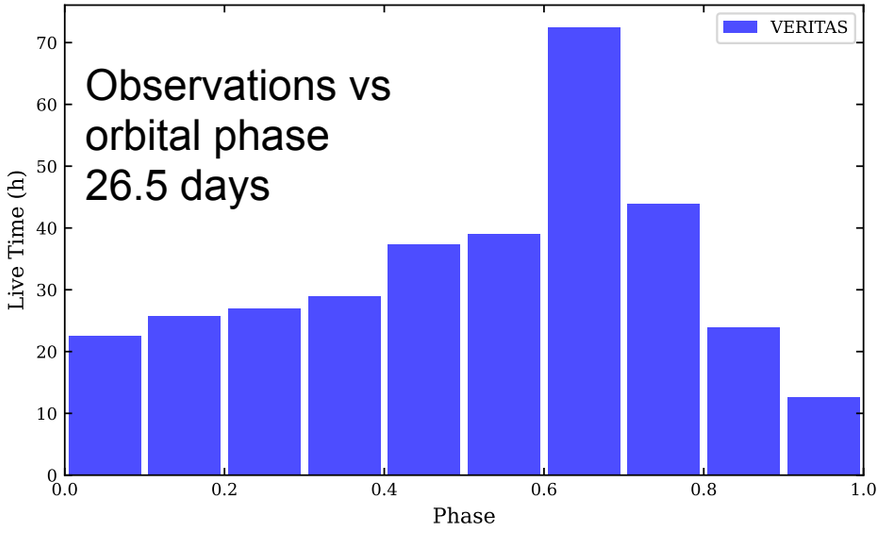
- Be + Neutron Star
- ~ 26.5 days orbital period
  (modulation across entire electromagnetic spectrum)
- 1667 day super-orbital modulation
- 269 ms (transient) pulsed emission (Weng et al 2022)
- Rapid (100s) variability / outbursts
  (e.g., Smith et al 2009)
- Radio structure
  (Massi et al 2004, Wu et al 2018)

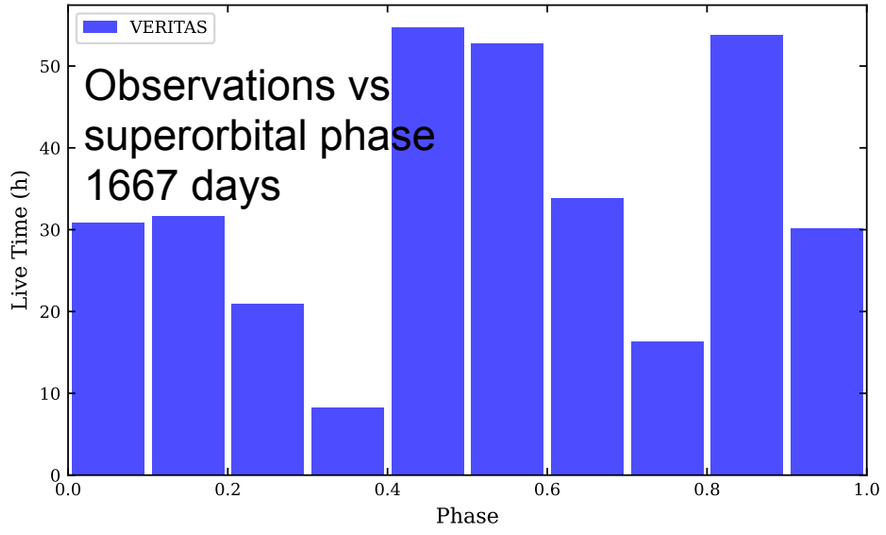


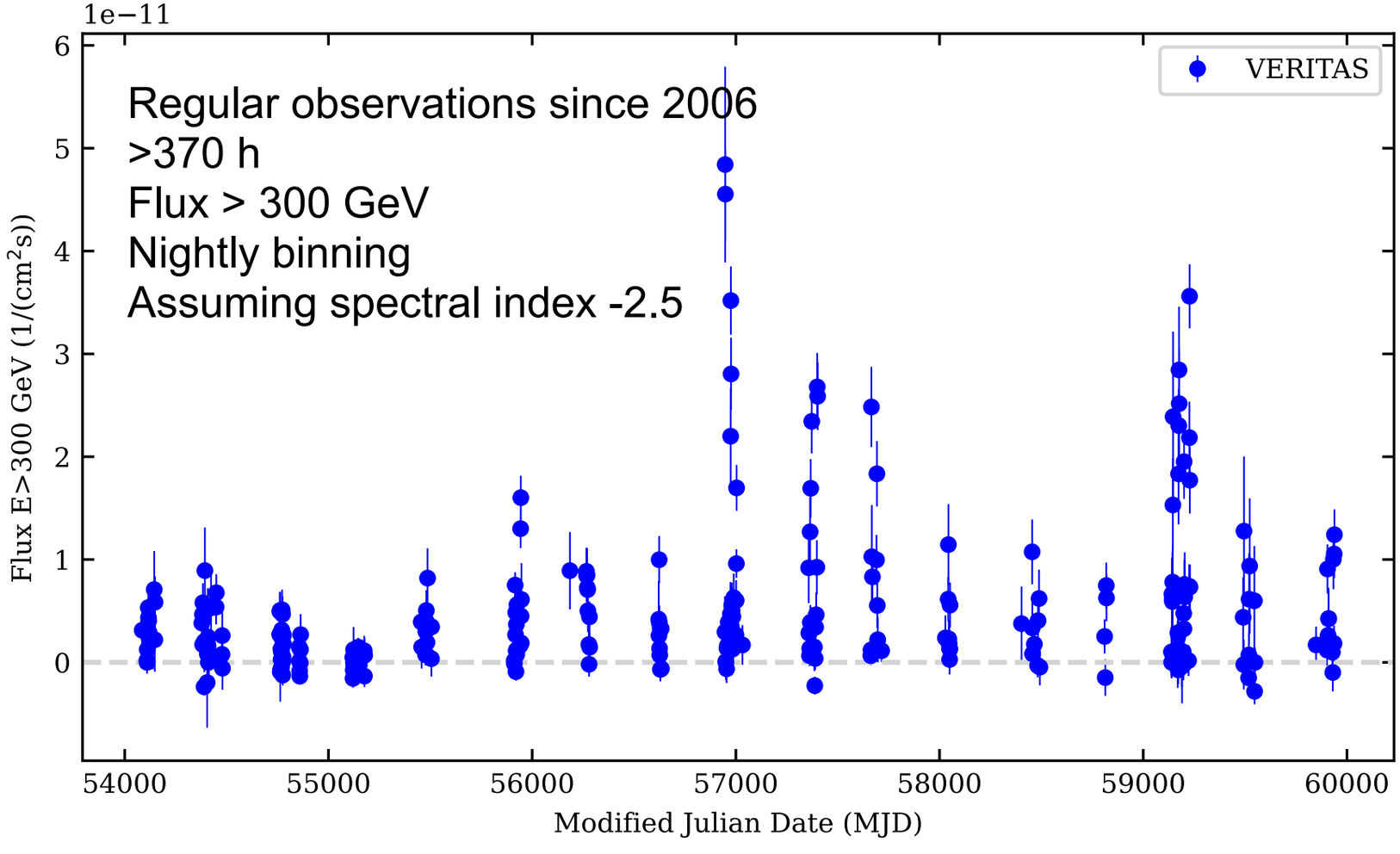
E. V. Gotthelf et al (2013). Circled points are pulsars in binaries.



VERITAS Observations of LS I +61 303

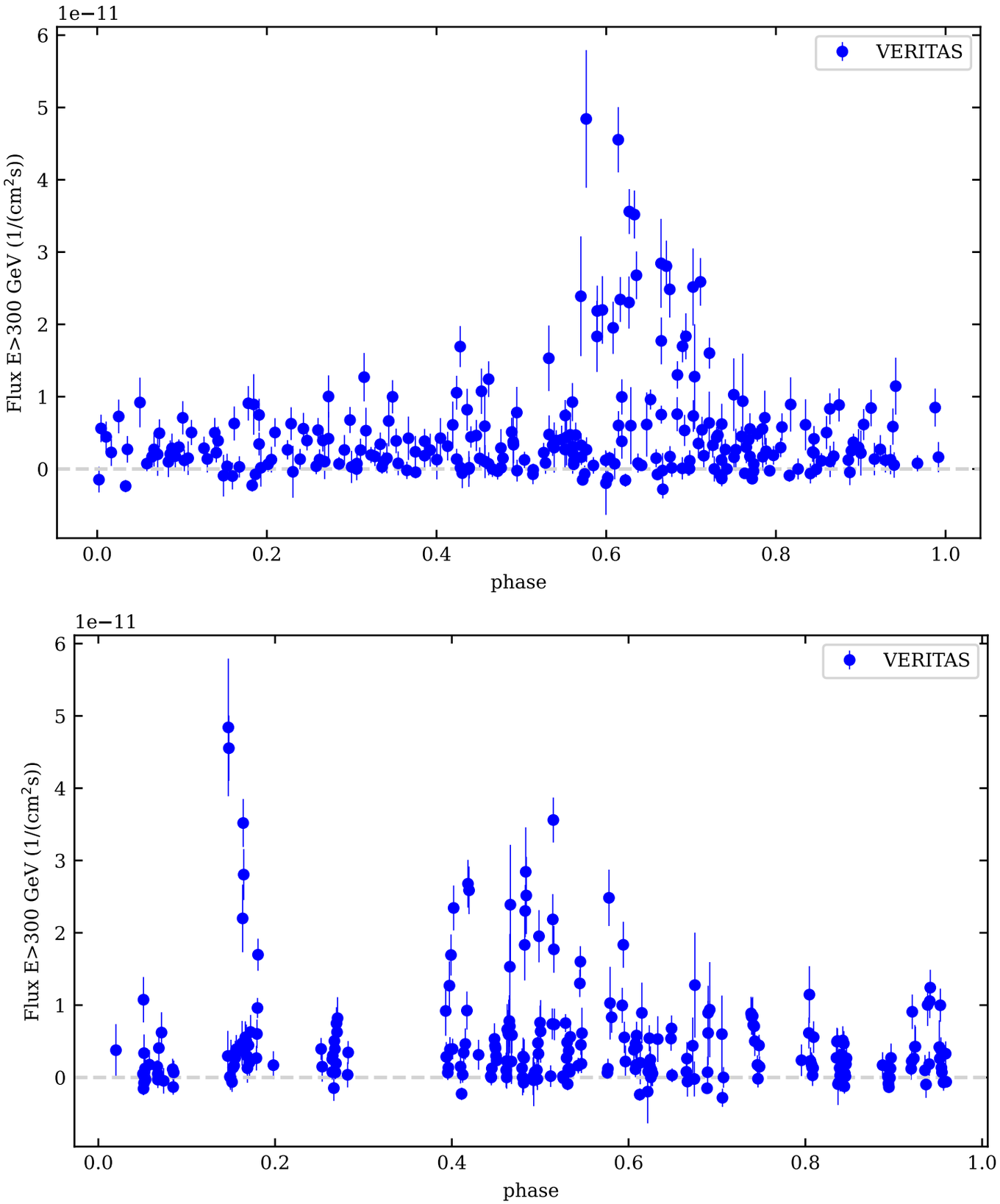






LS I +61 303 - phase binned

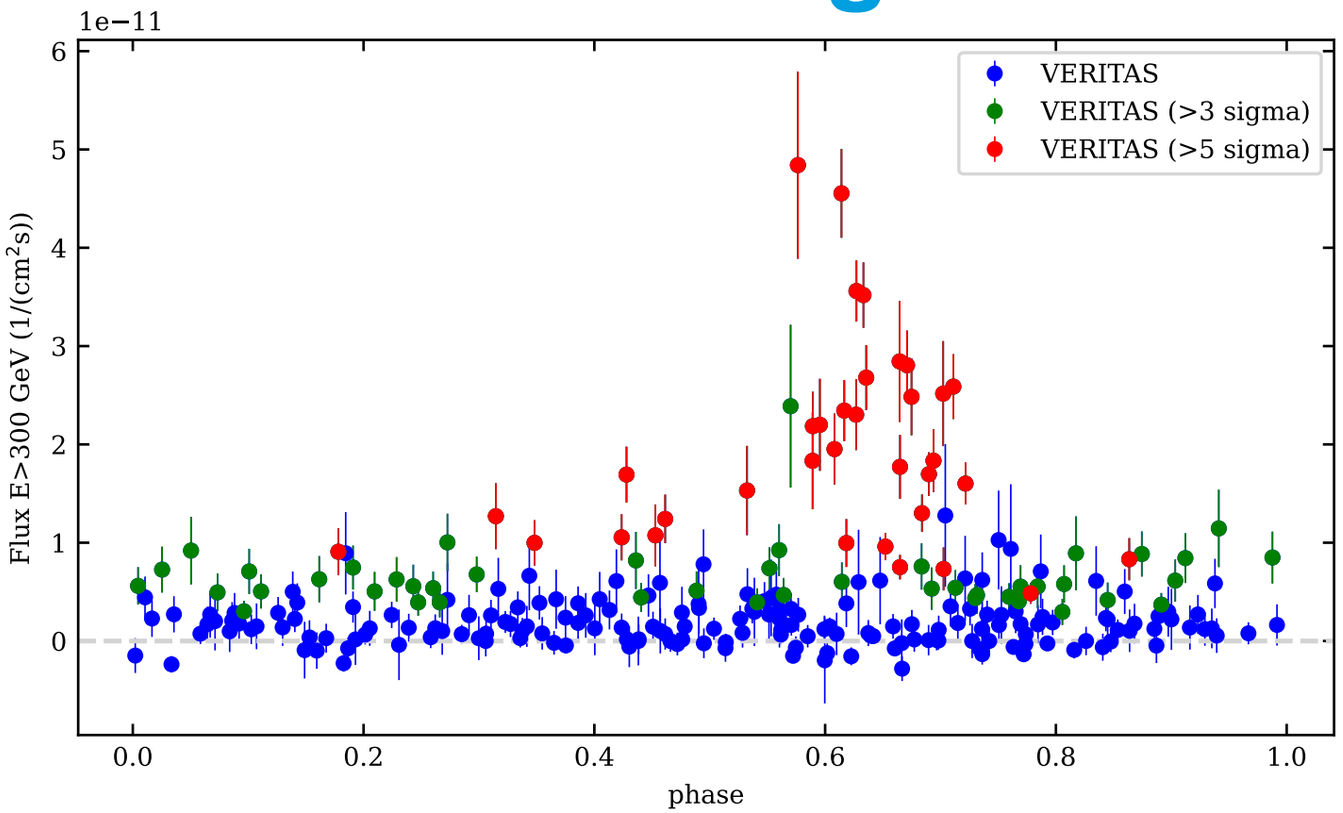
Orbital phase folded
26.496 days



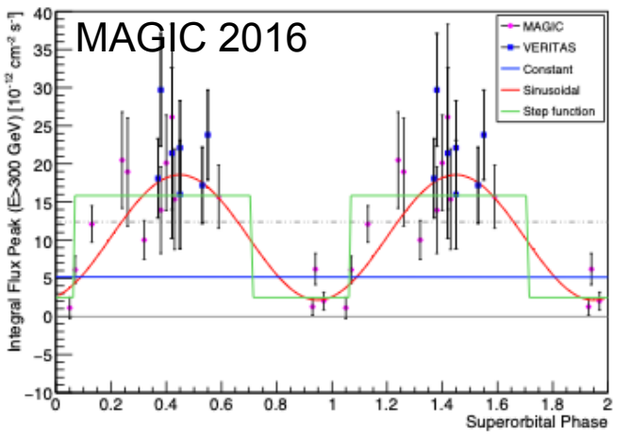
Superorbital phase folded
1667 days

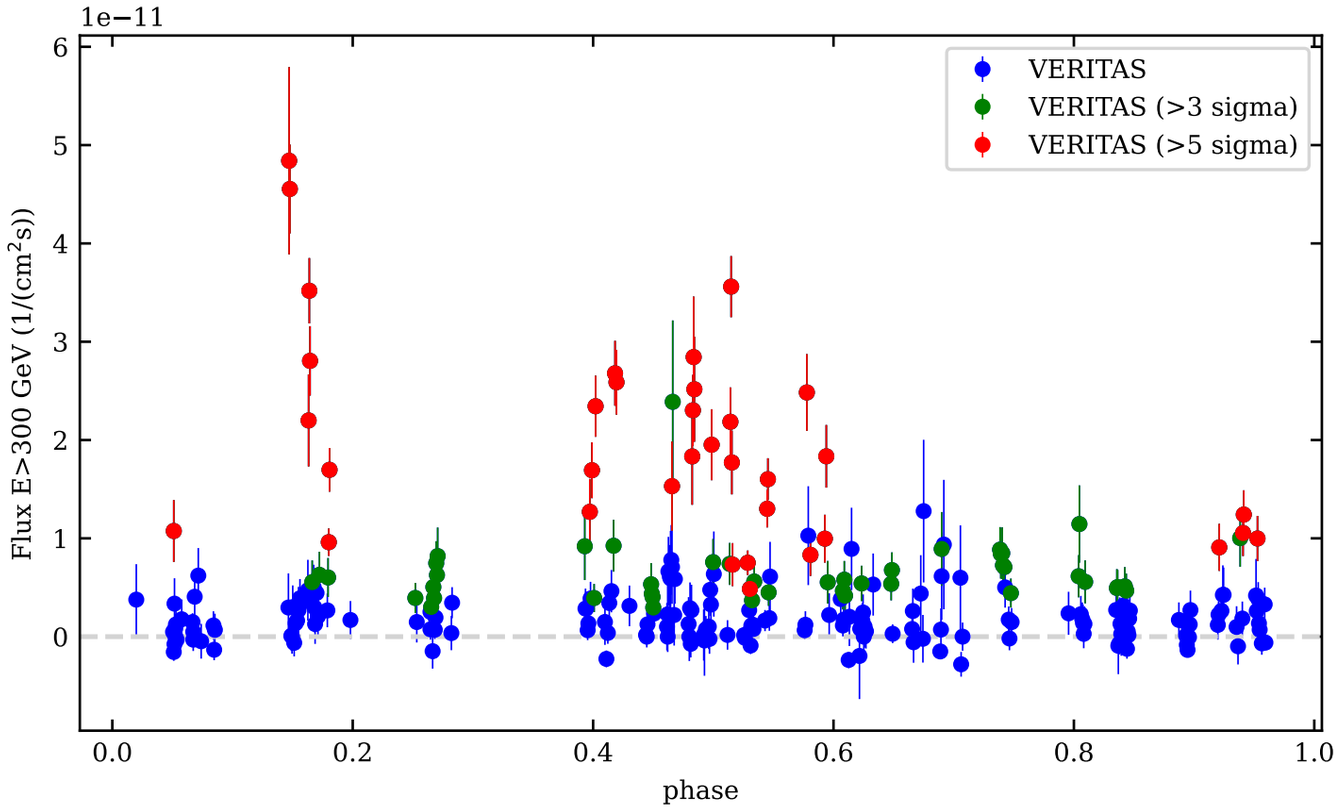
LS I +61 303 - phase binned - significance

Orbital phase folded
26.5 days



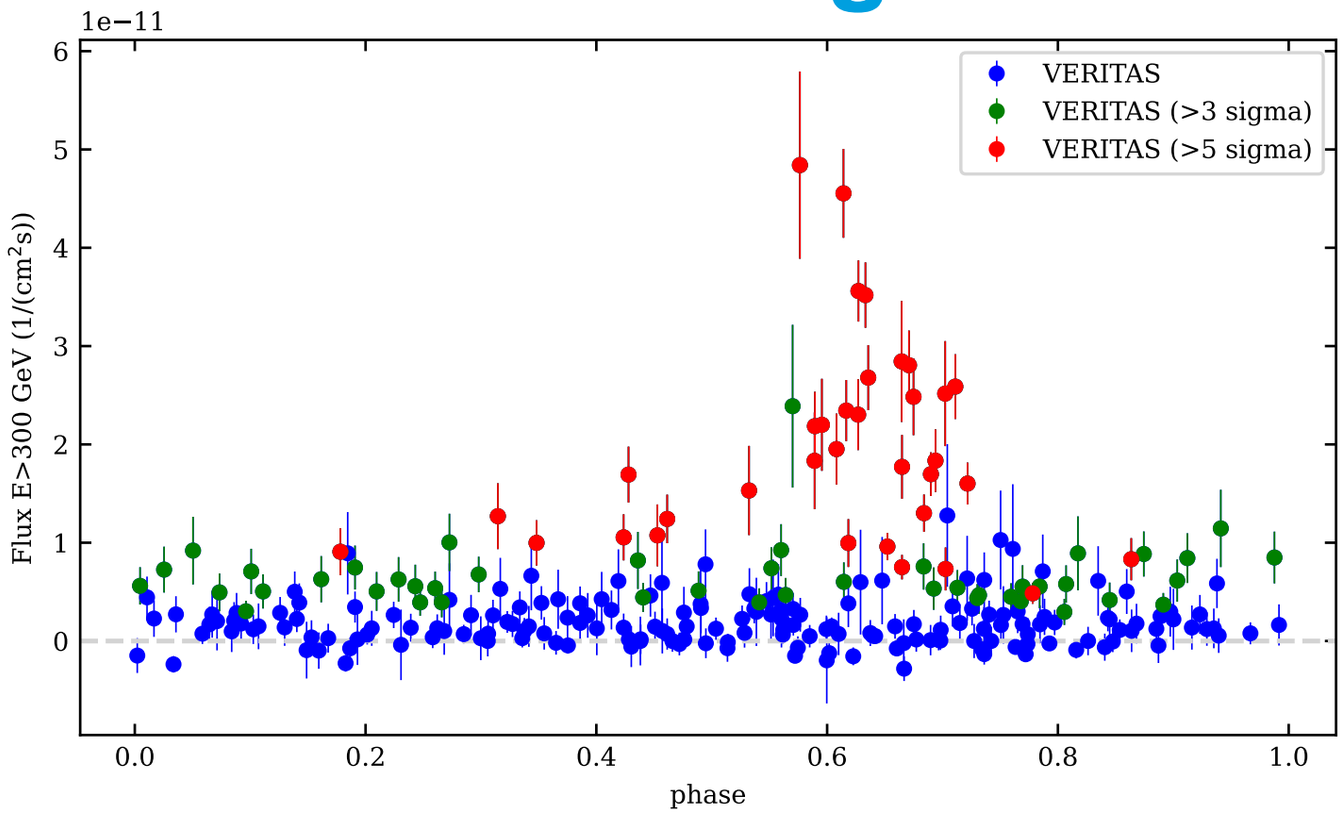
Super-orbital phase folded
1667 days





LS I +61 303 - phase binned - significance

Orbital phase folded
26.5 days



$$P_{beat} = P_{orb}P_{sorb}/(P_{sorb} - P_{orb}) \simeq 26.924 \text{ d})$$

Chernyakova et al 2023

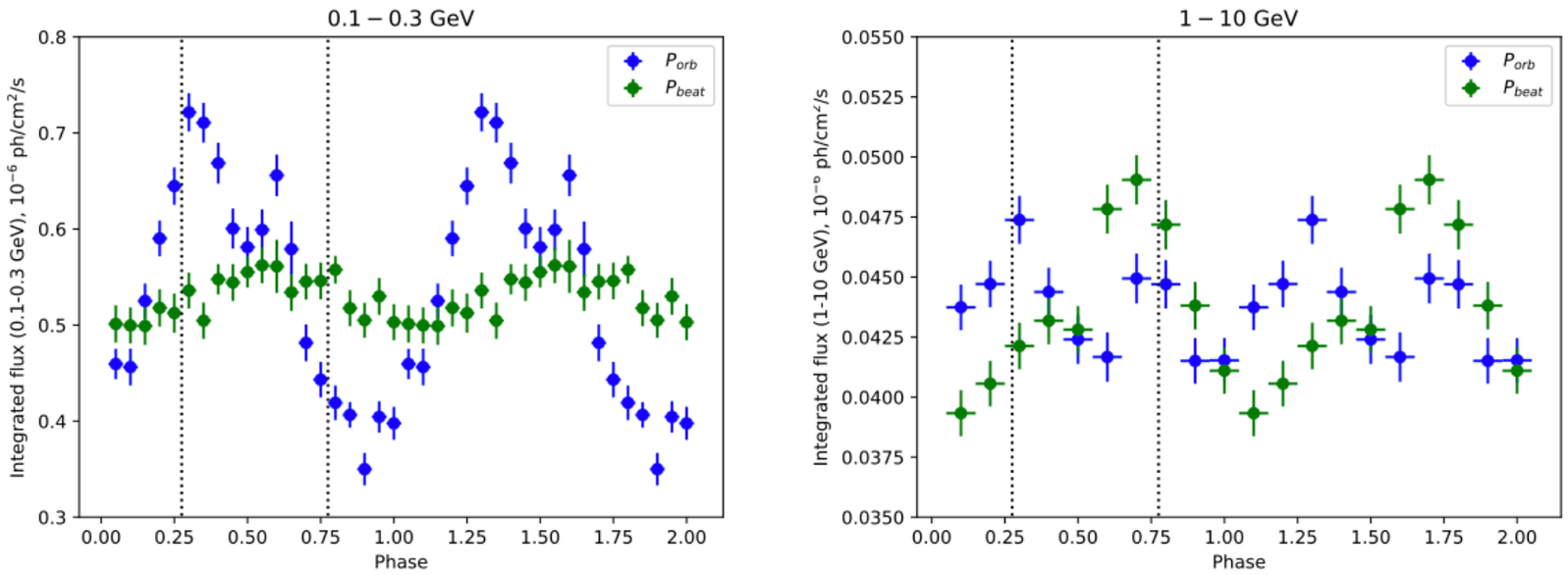
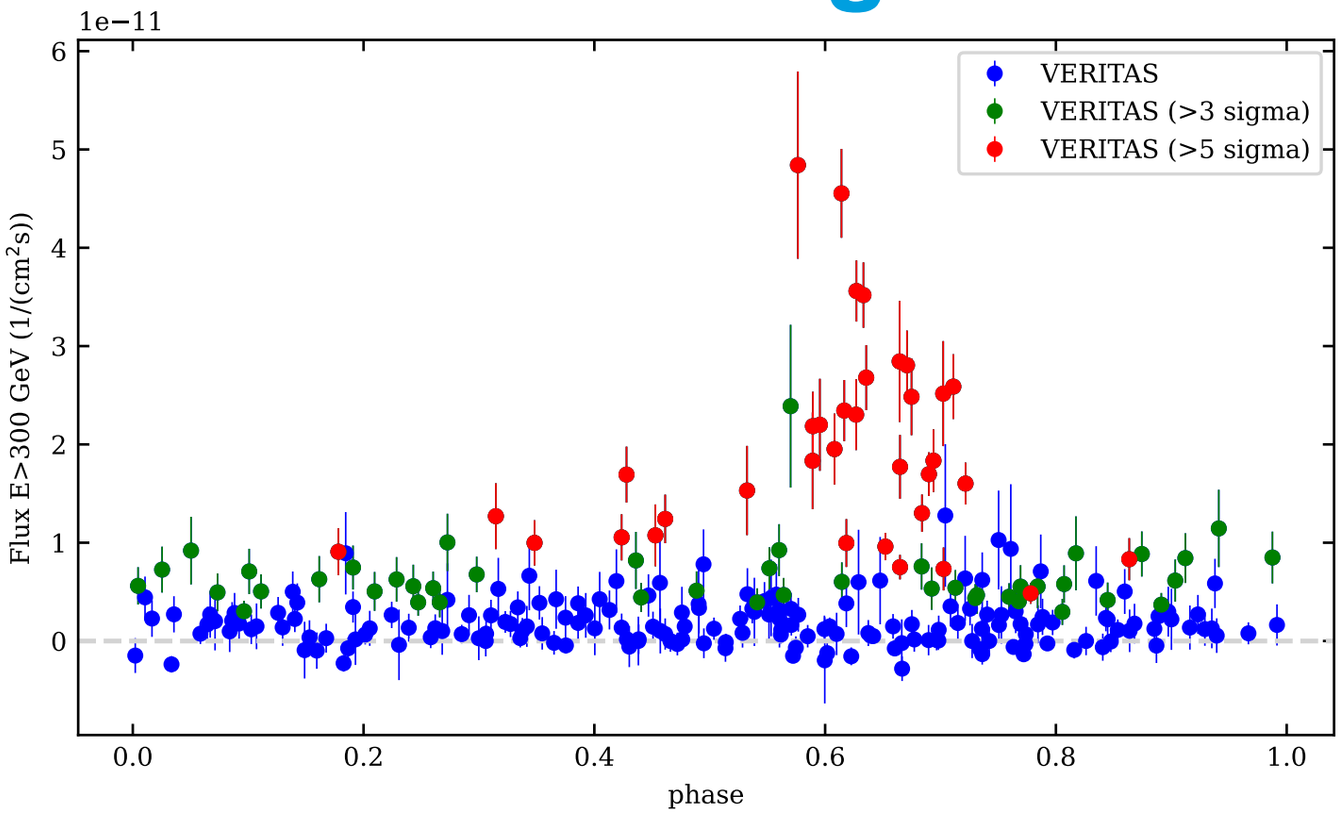
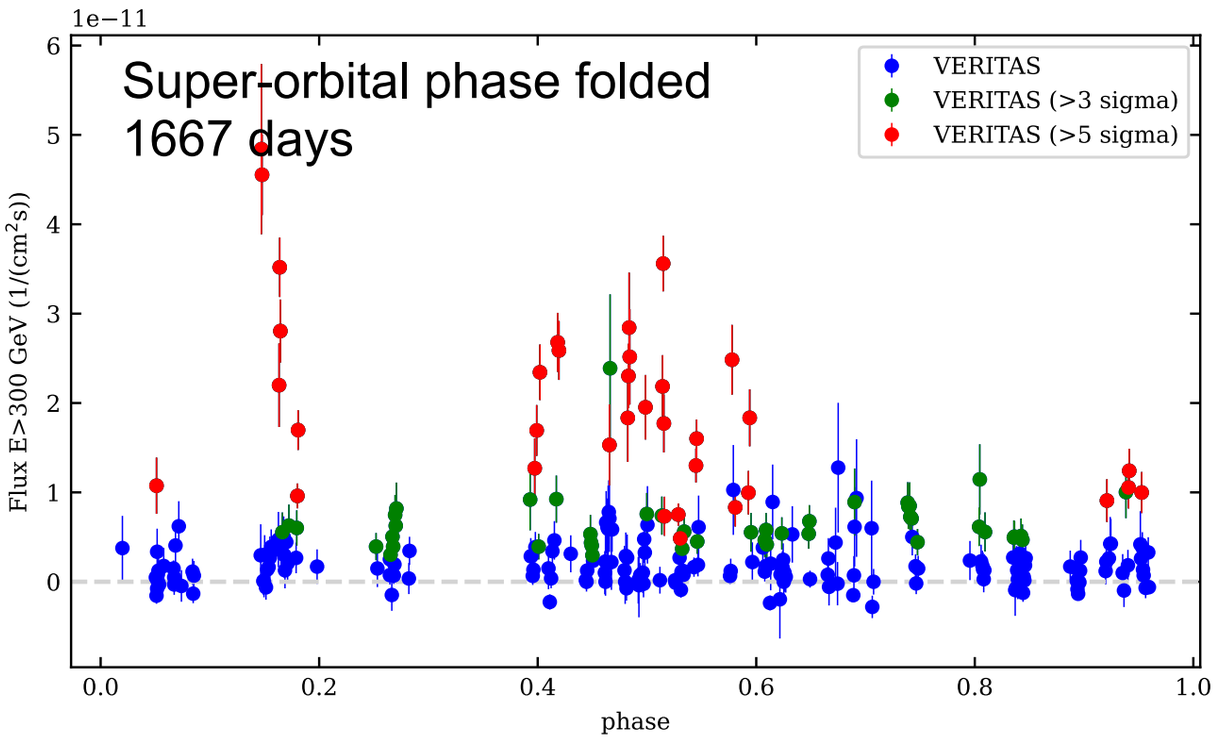


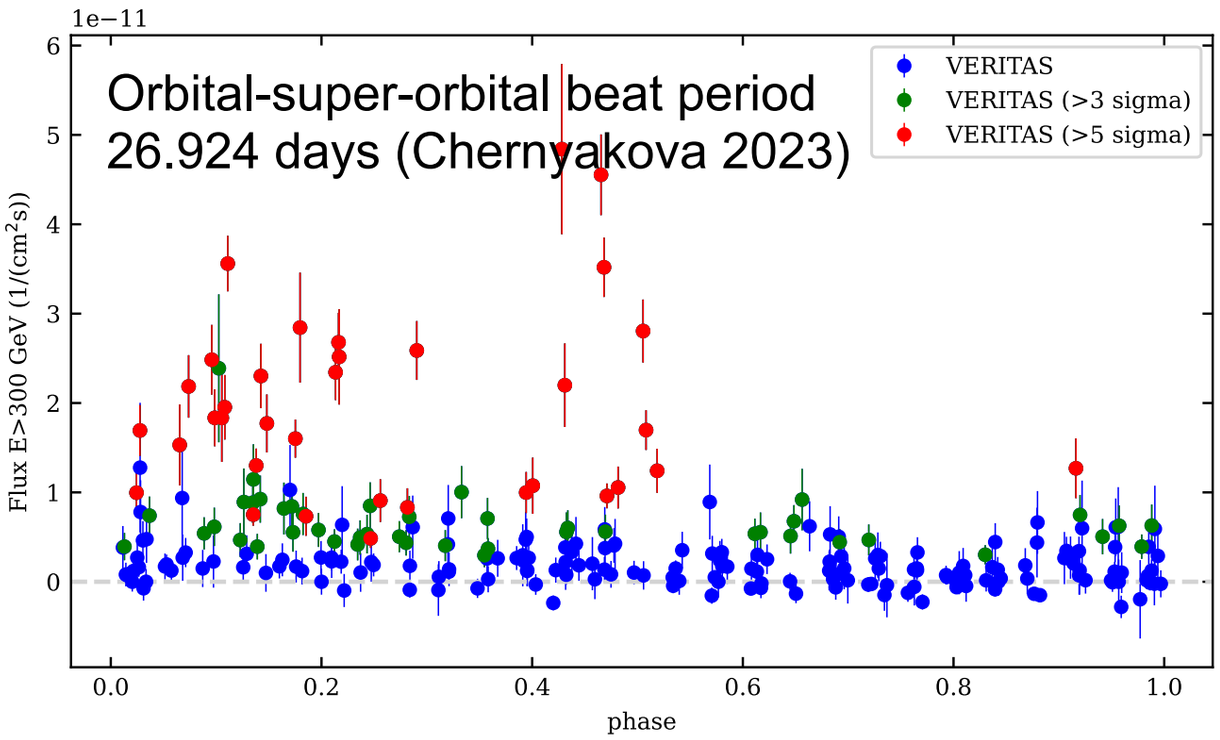
Figure 5. light curves of LS I +61°303 as seen by *Fermi/LAT* (binned likelihood analysis) convolved with orbital and beat-periods in different energy bands. Vertical lines show periastron (ϕ = 0.275) and apastron positions.

LS I +61 303 - phase binned - significance

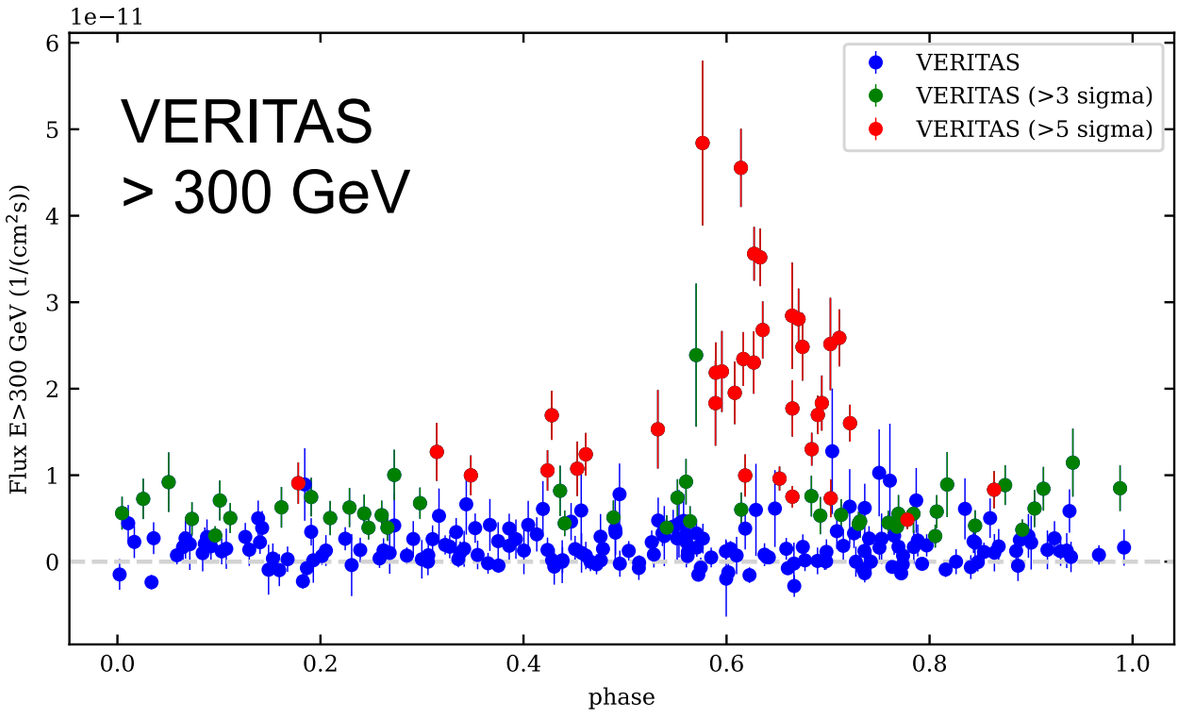
Orbital phase folded
26.5 days

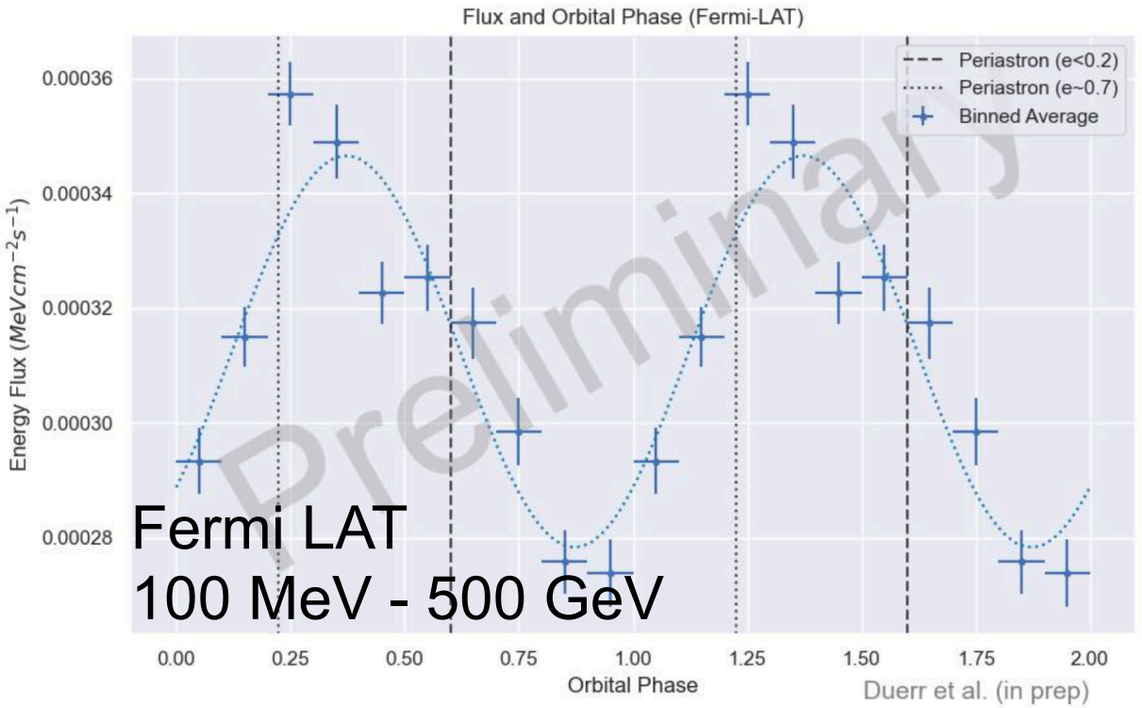


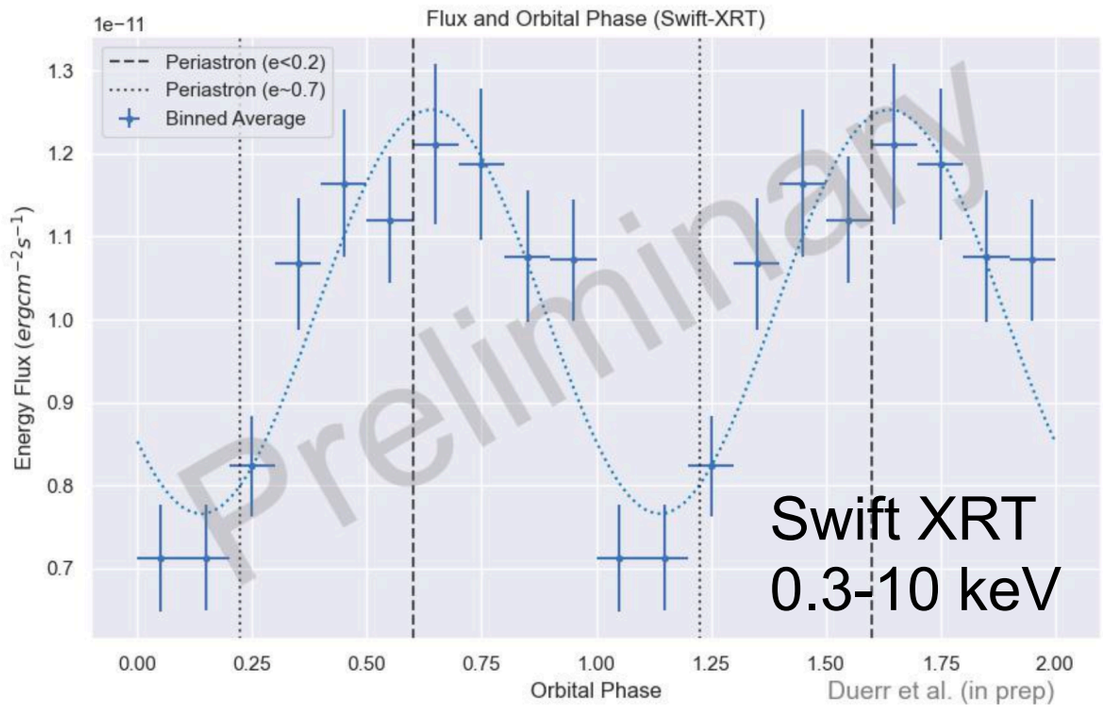




LS I +61 303 - TeV, GeV, X-ray

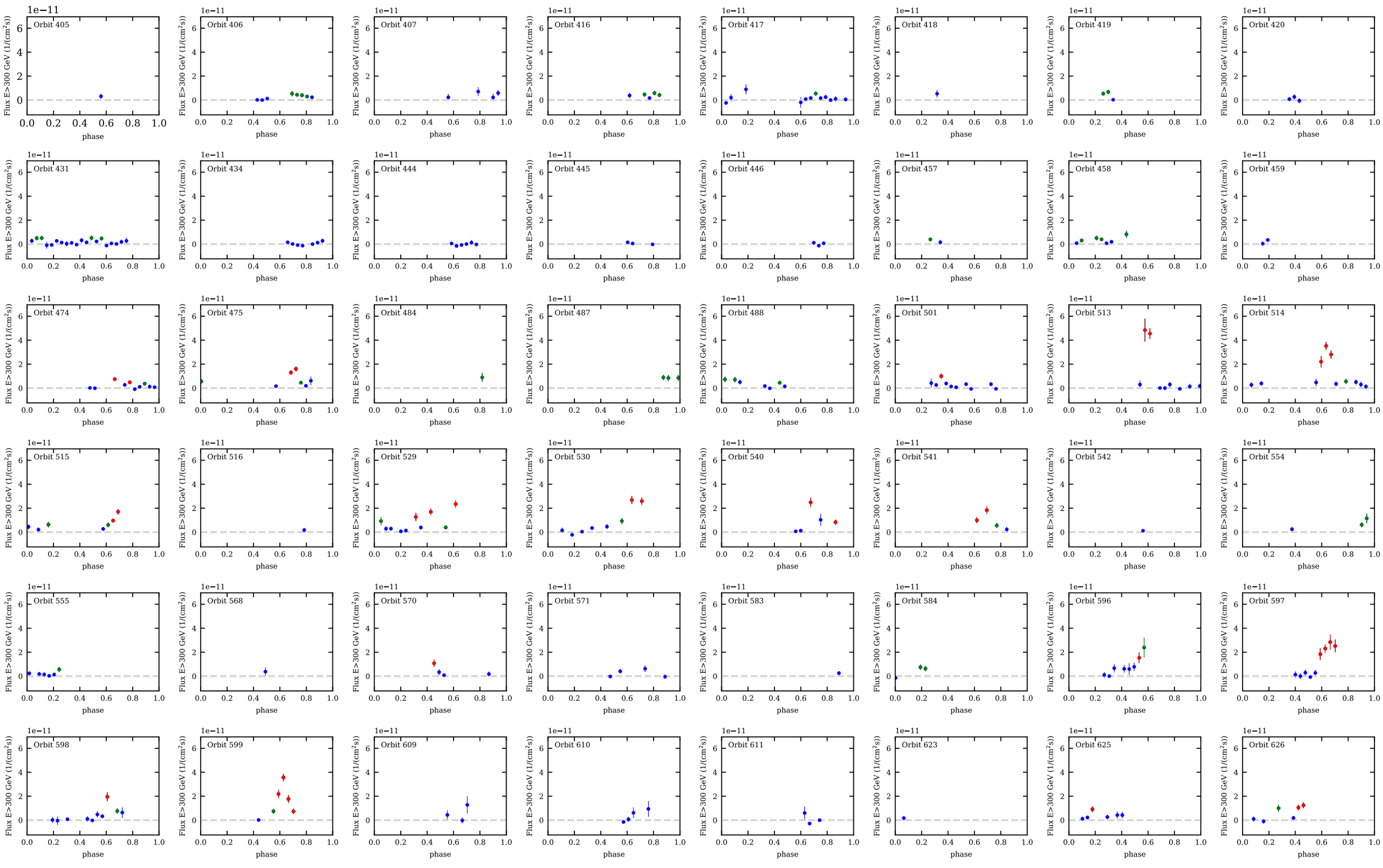




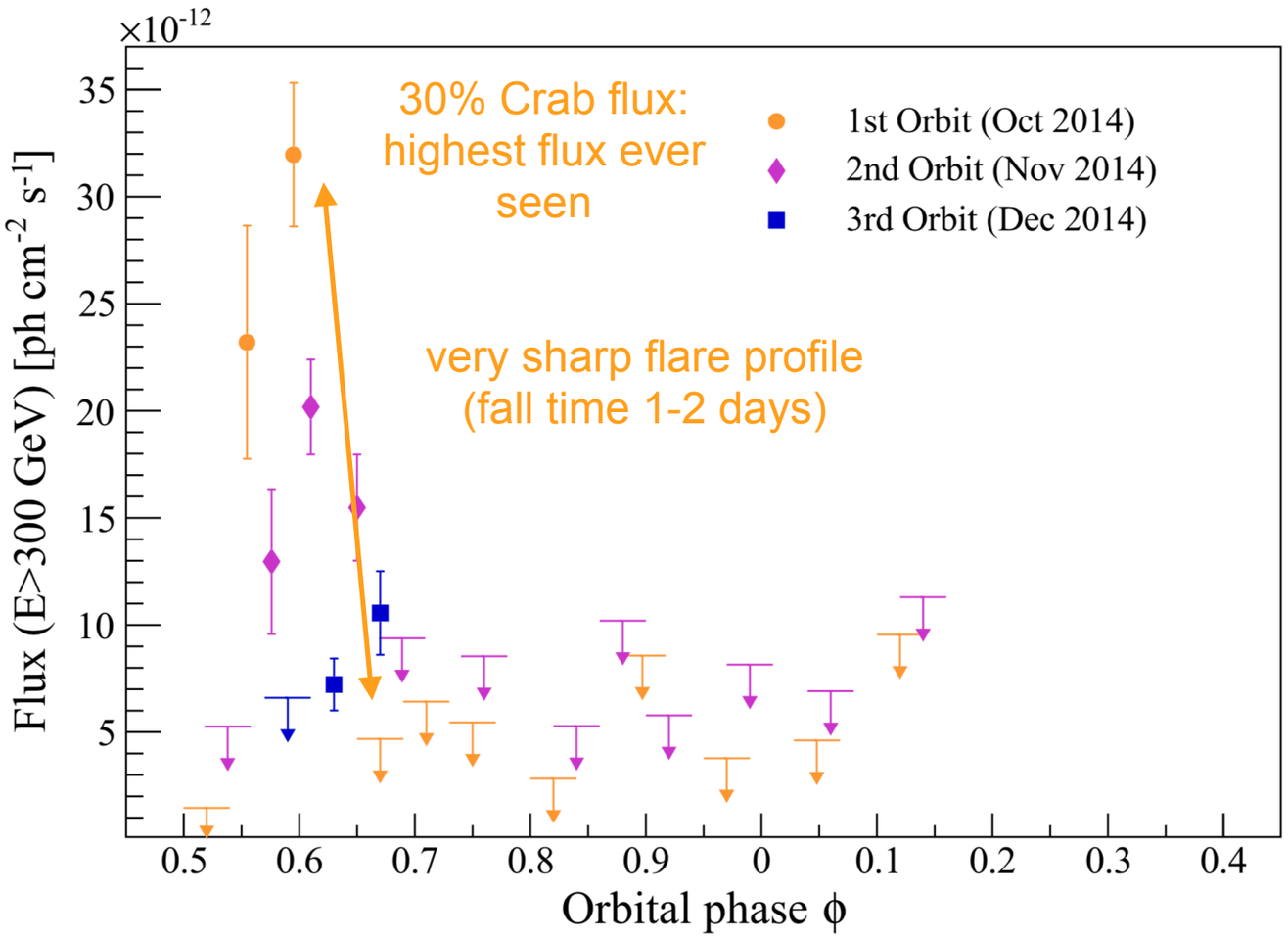


See Anne Duerr's talk at VGS Dublin 2024

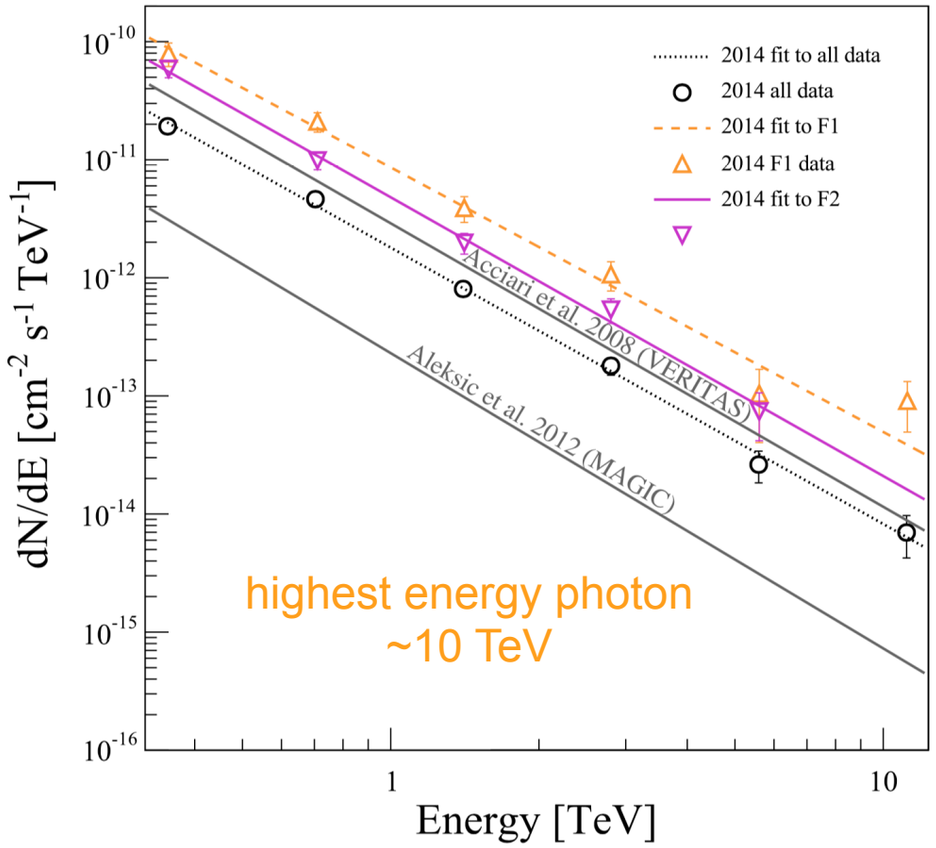
LS I +61 303 - per orbit



LS I +61 303 - 2014/2015 - bright state or flare?

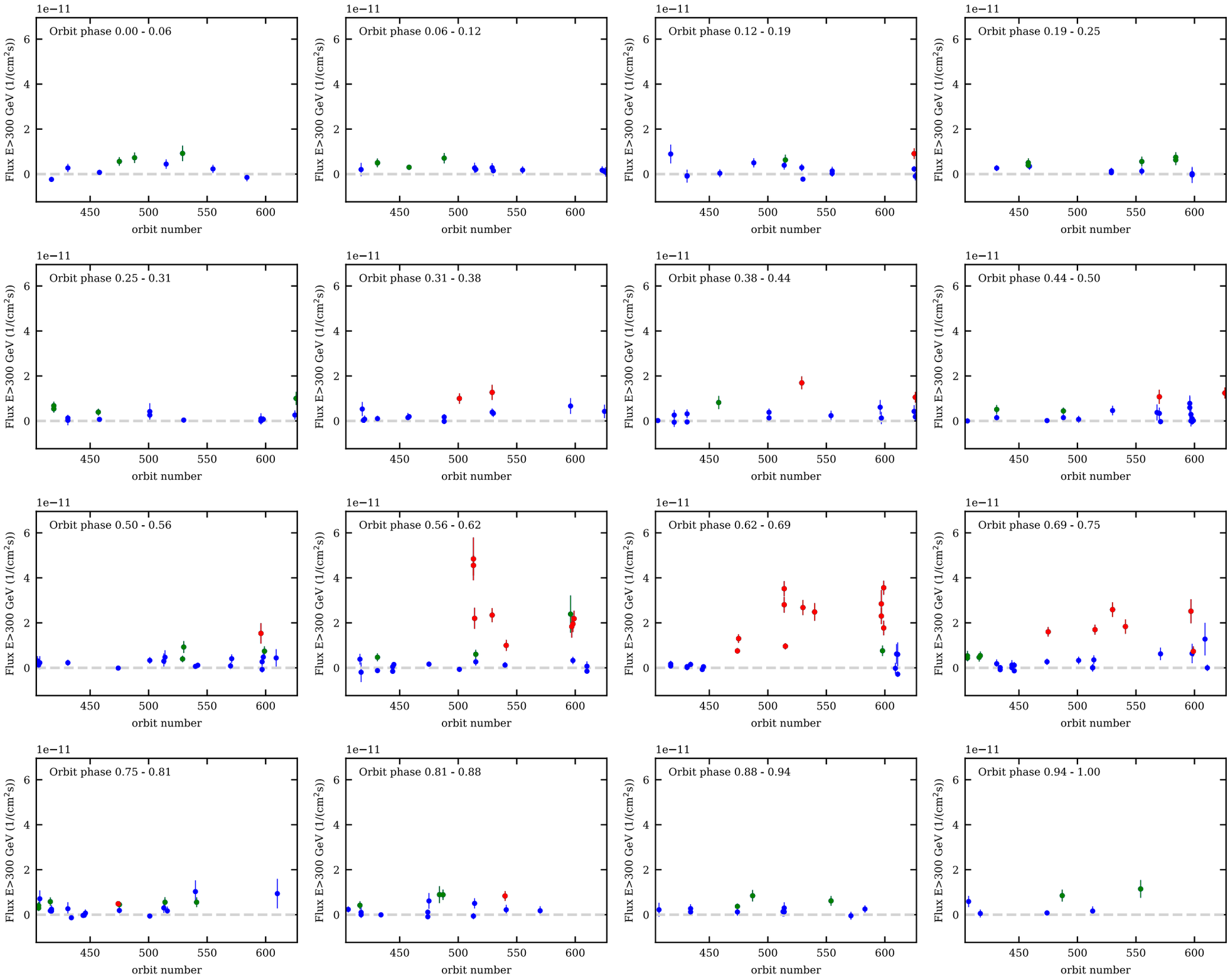


Archambault et al (VERITAS Collaboration) 2016



- exceptional or missed due to the low coverage in gamma-ray observations?
  (VERITAS observed ~10% of the orbits of LS I +61 303 in the past 15 years)
- flares with time scales of a few hundred seconds are observed in X-rays
  (e.g. Smith et al 2009)

LS I +61 303 - per orbit number



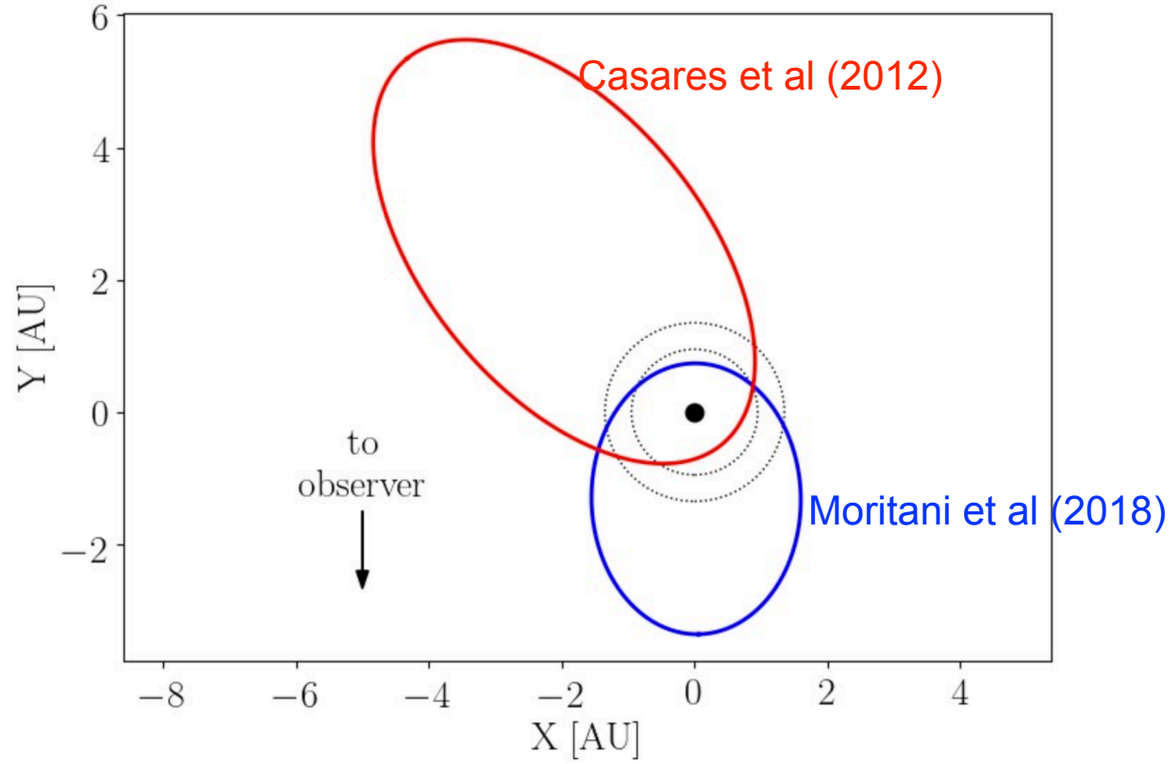
LS I +61 303 - spectral variability

Work in progress…

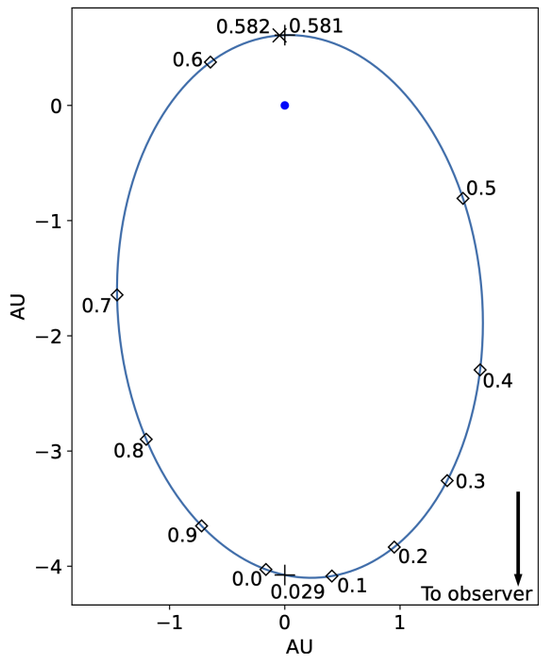
HESS J0632+057

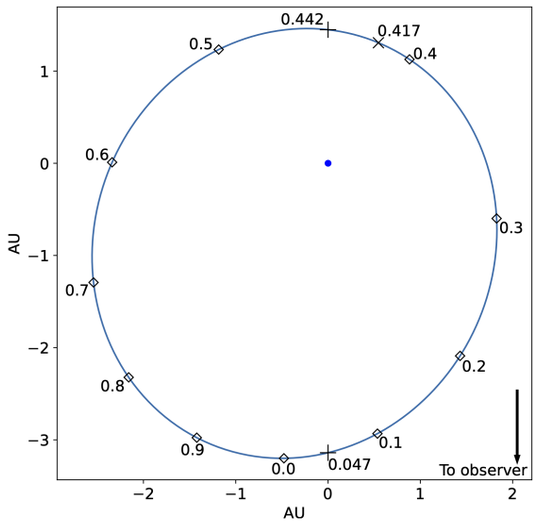
HESS J0632+057

- Be (MWC 148) + Neutron Star / black hole
- 315-320 days orbital period
- variable in X-rays and gamma rays
- weak at MeV-GeV
- Uper limits on pulsed emission (X-ray, Radio)
- Distance 1.1-1.7 kpc

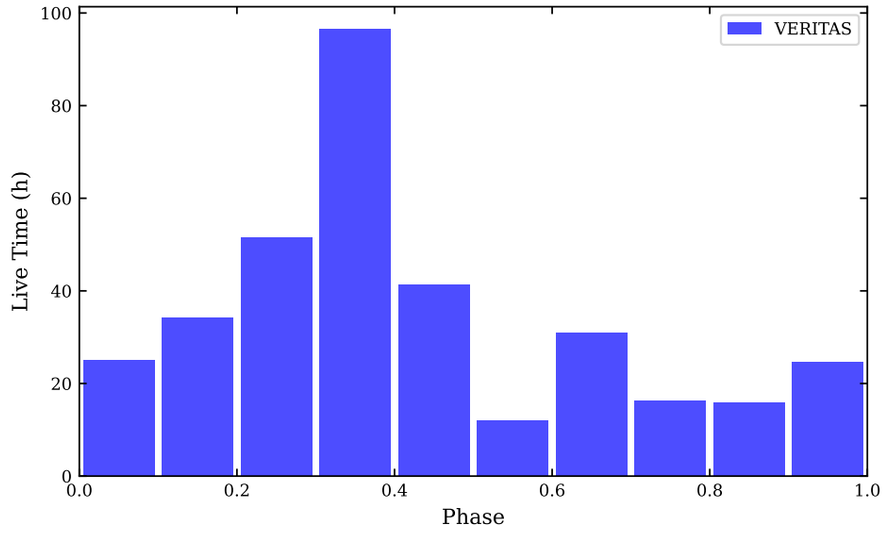


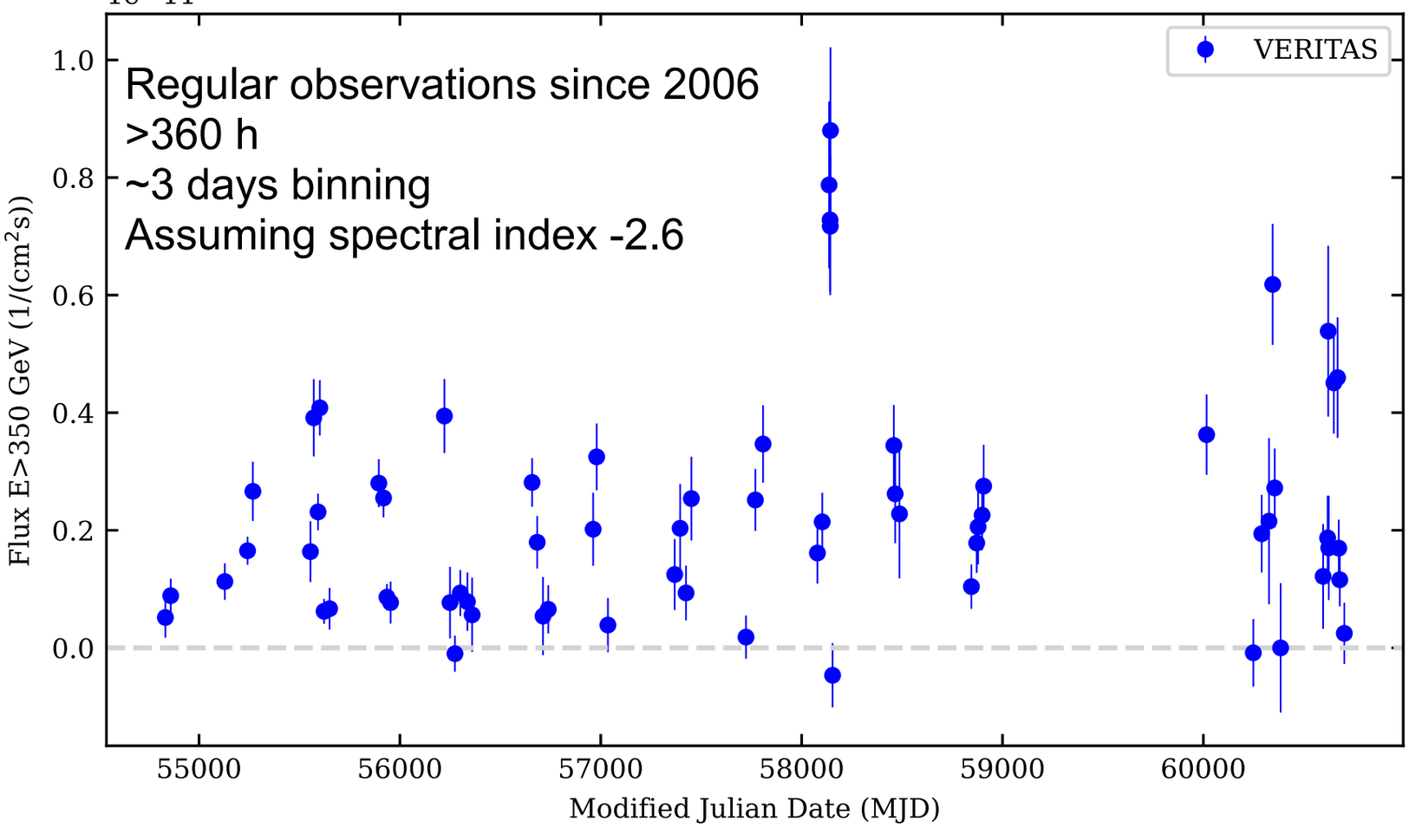
Matchett & van Soelen 2024





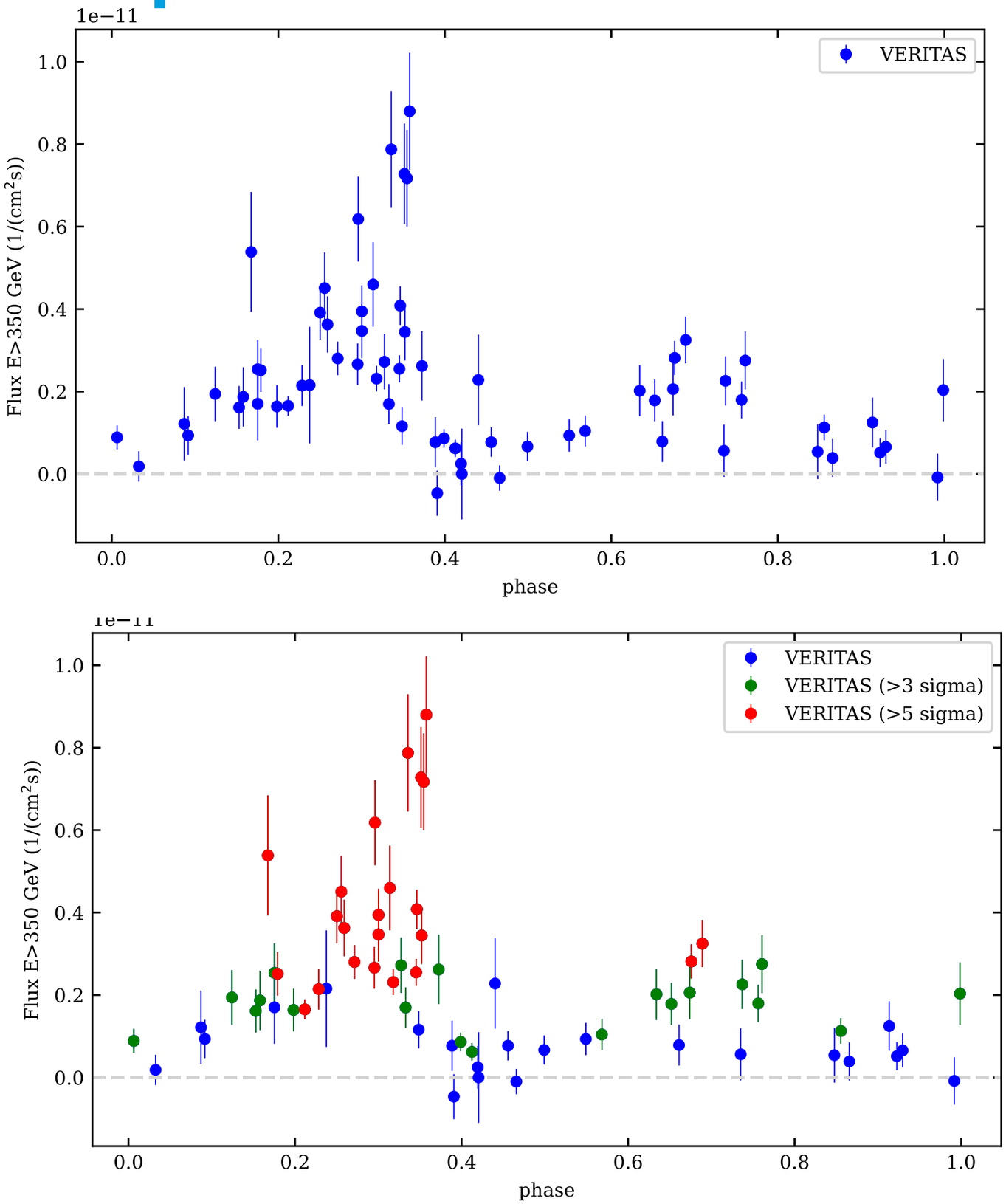
VERITAS Observations of HESS J0632+057



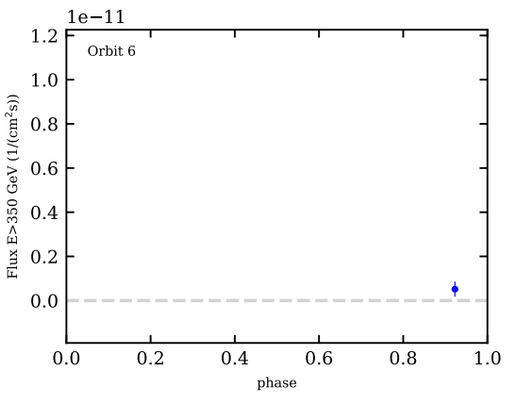


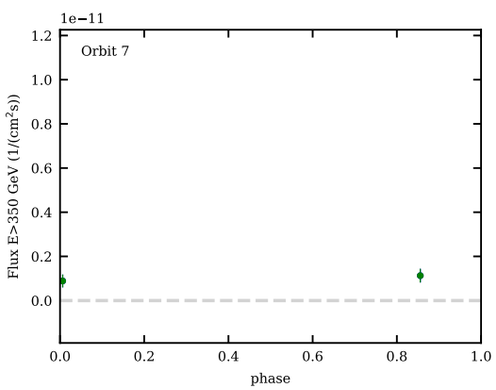
HESS J0632+057 - phase binned

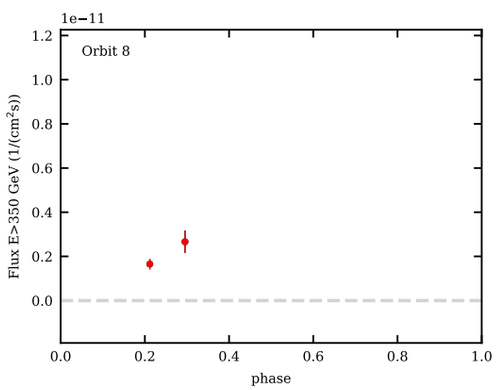
Orbital phase folded
317.3 days

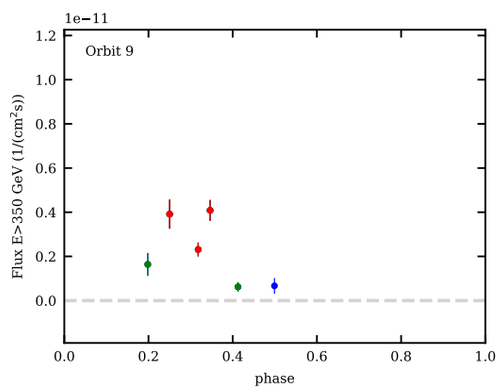


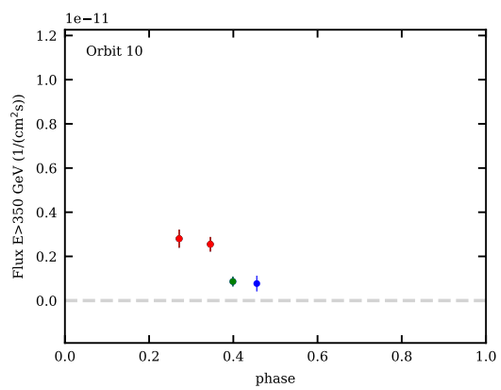
HESS J0632+057 - per orbit

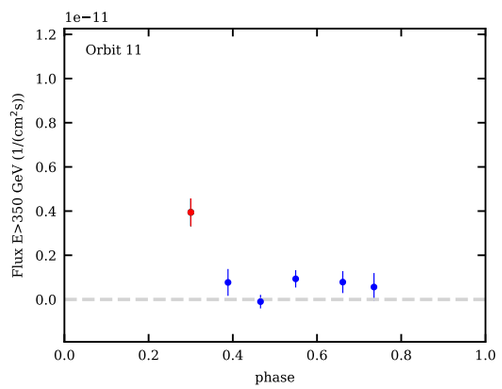


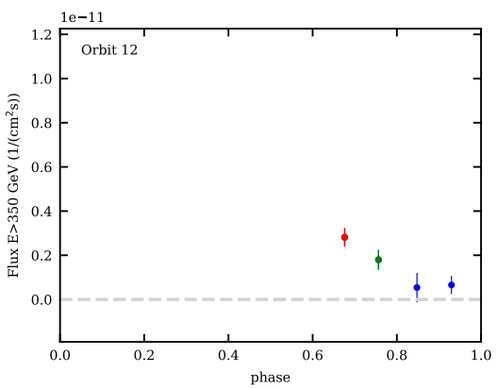


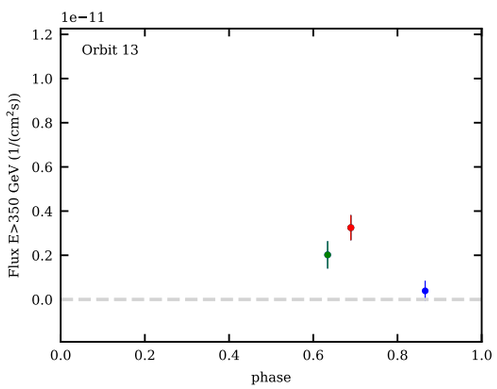


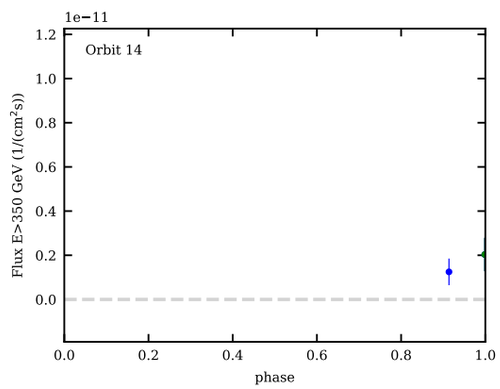


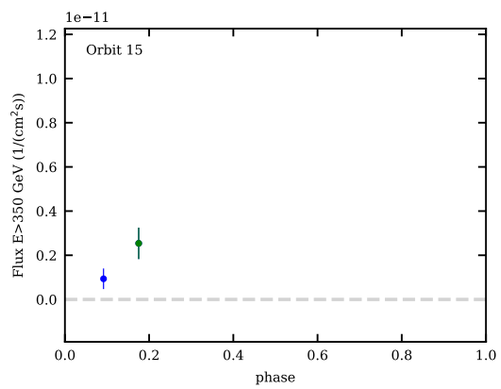


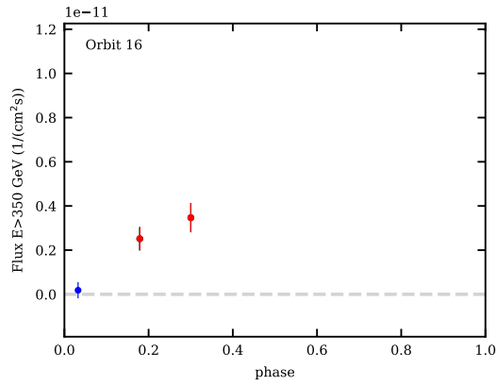


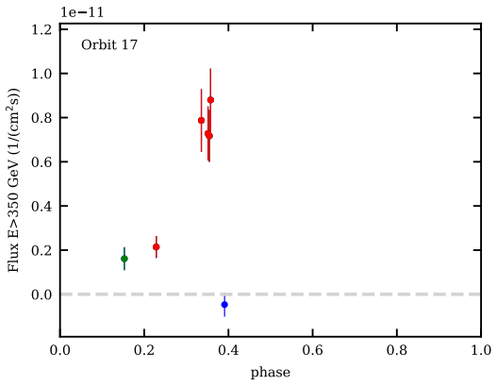


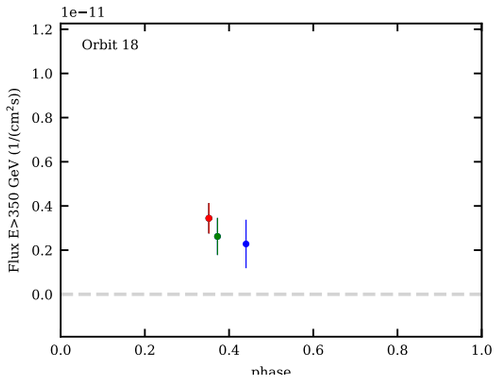


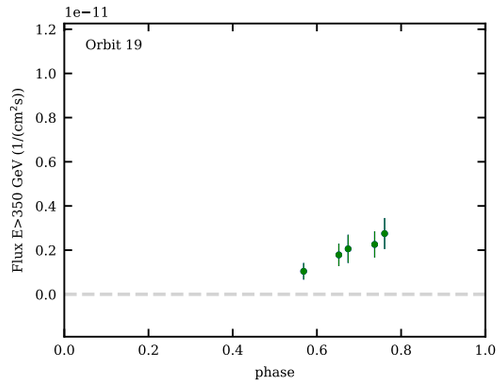


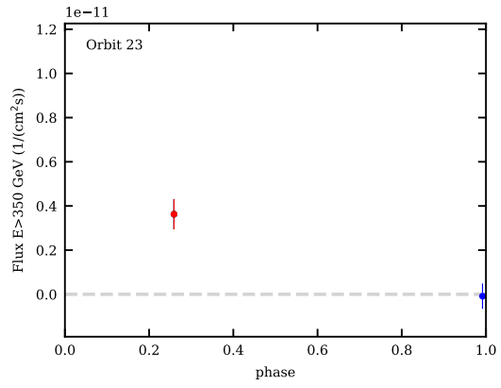


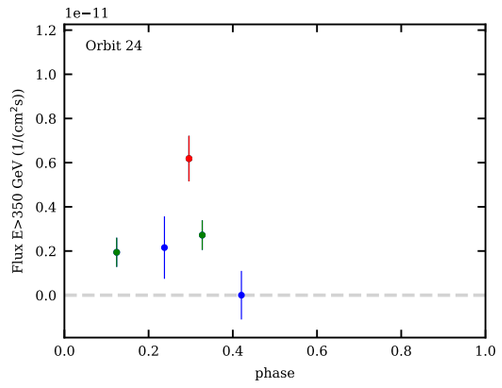


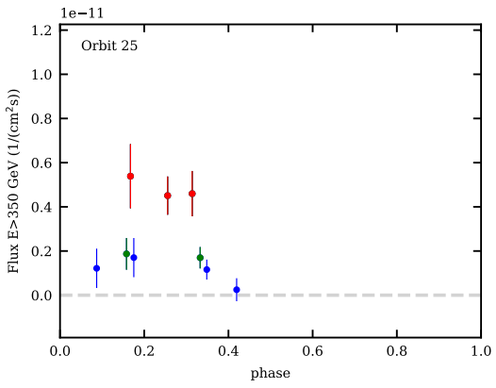




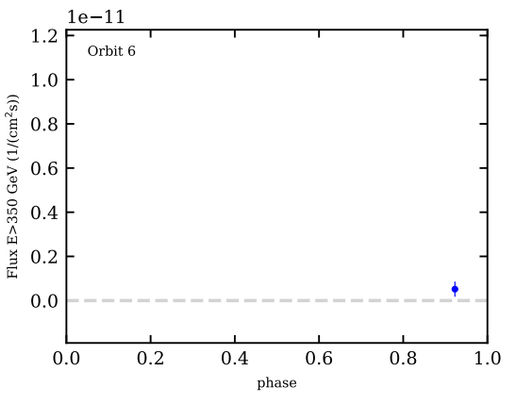


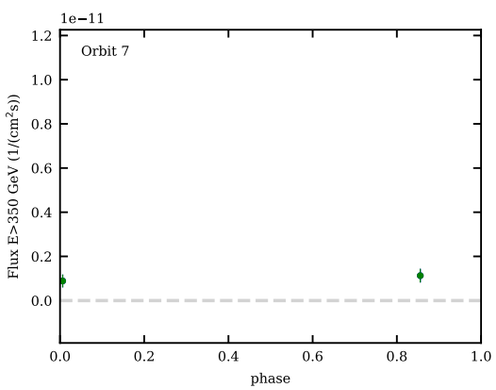


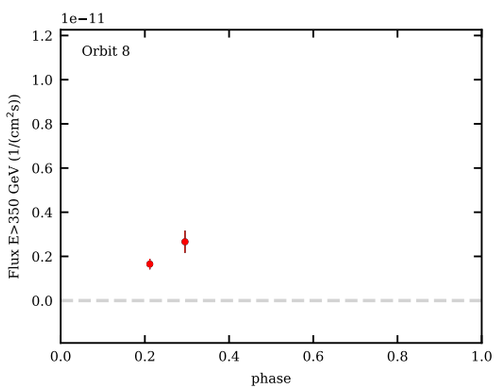


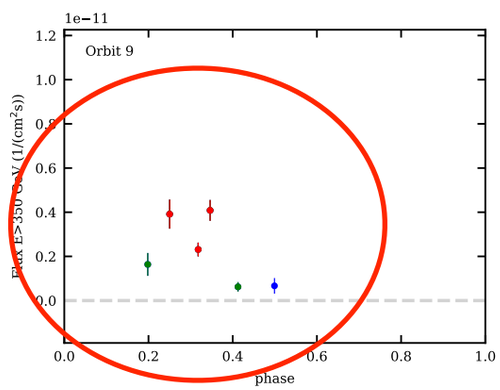


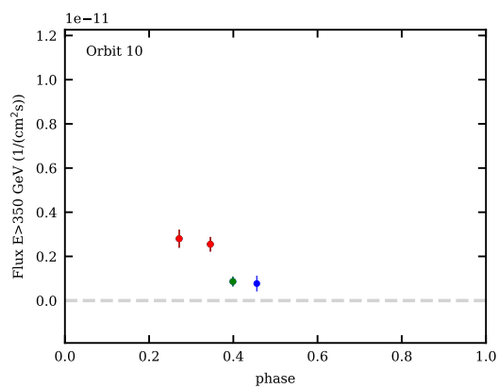
HESS J0632+057 - per orbit

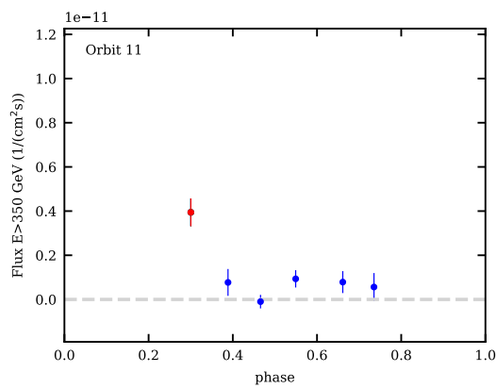


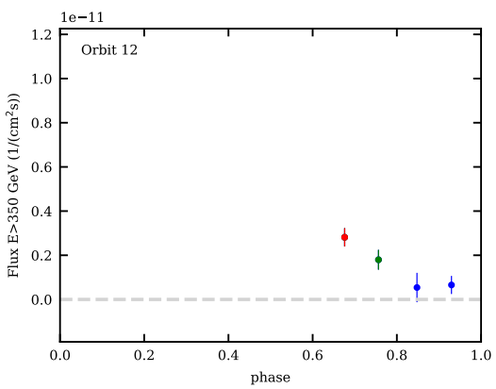


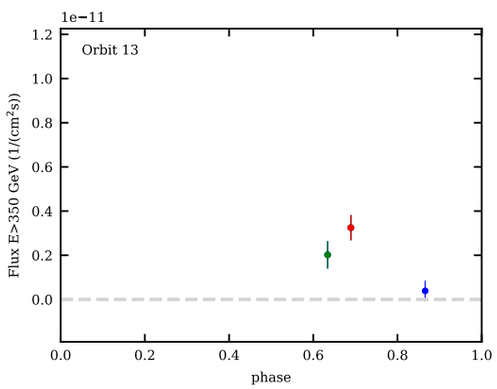


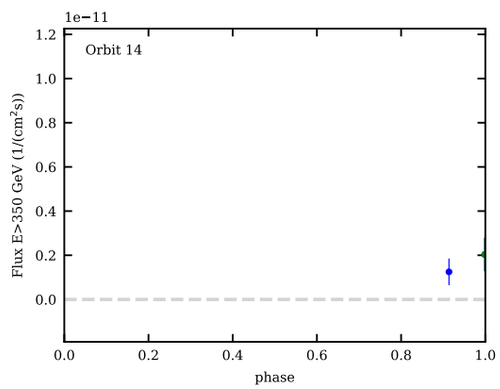


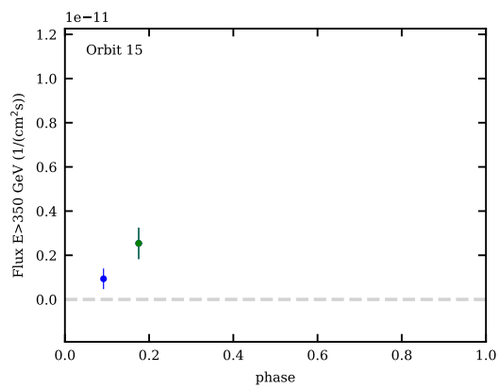


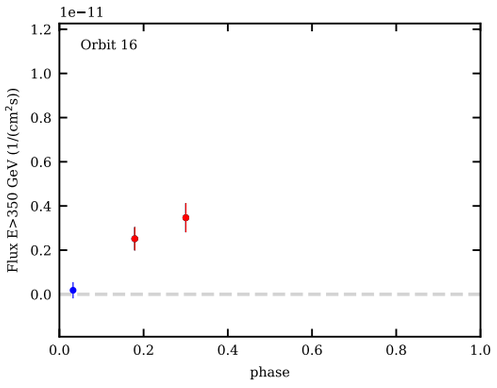


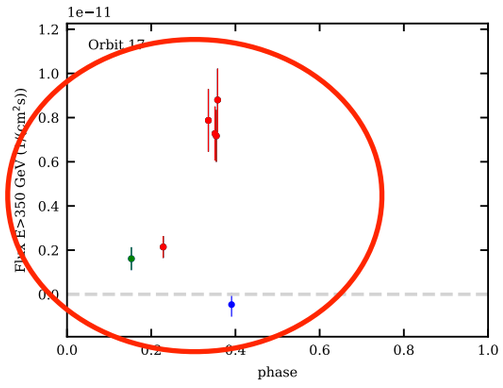


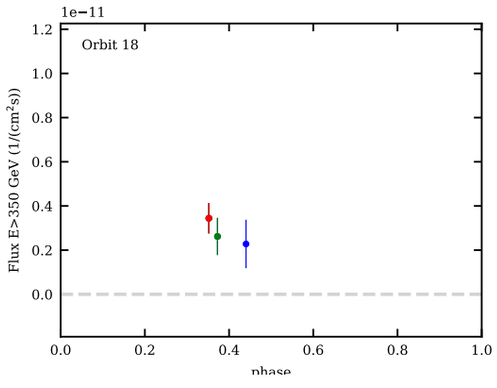


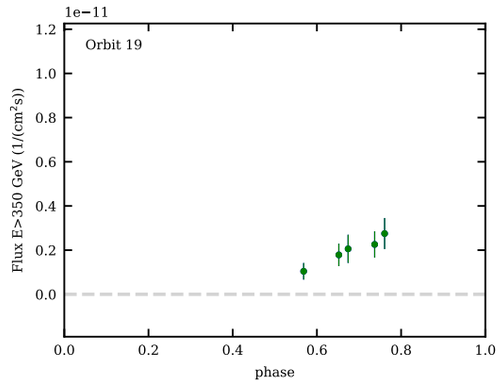


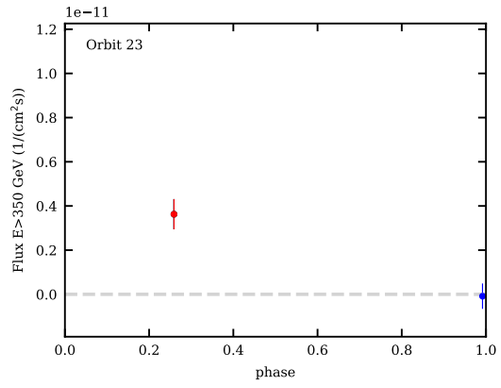


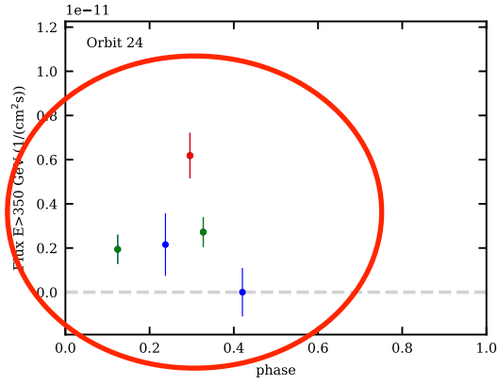


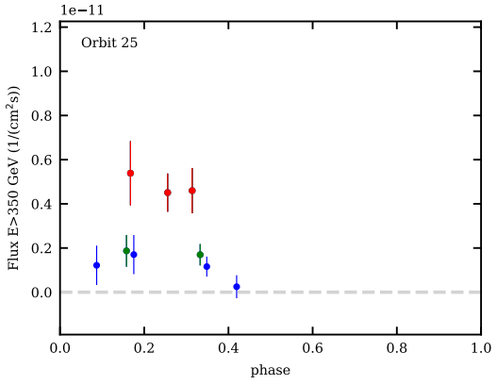












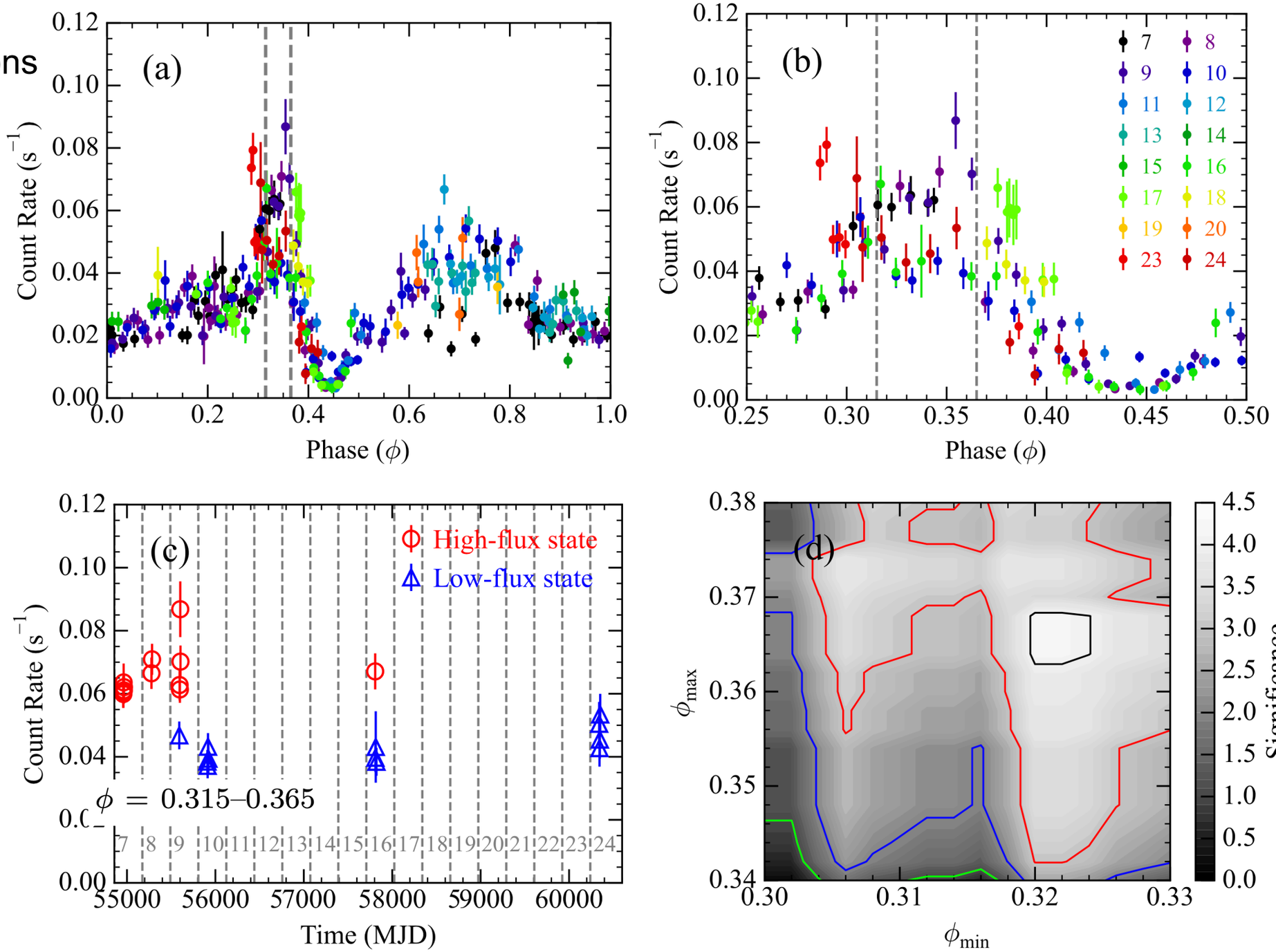
HESS J0632+057 - X-ray 0.15-10 keV

To be submitted

Multi-wavelength Study of HESS J0632+057: New Insights into Pulsar-Disk Interaction

Jaegeun Park,[1] Hongjun An,[1] Anne Duerr,[2] Chanho Kim,[1] Gernot Maier,[3] Natalie Matchett,[4] Kaya Mori,[5] Brian van Soelen,[4] and VERITAS Collaboration[6]

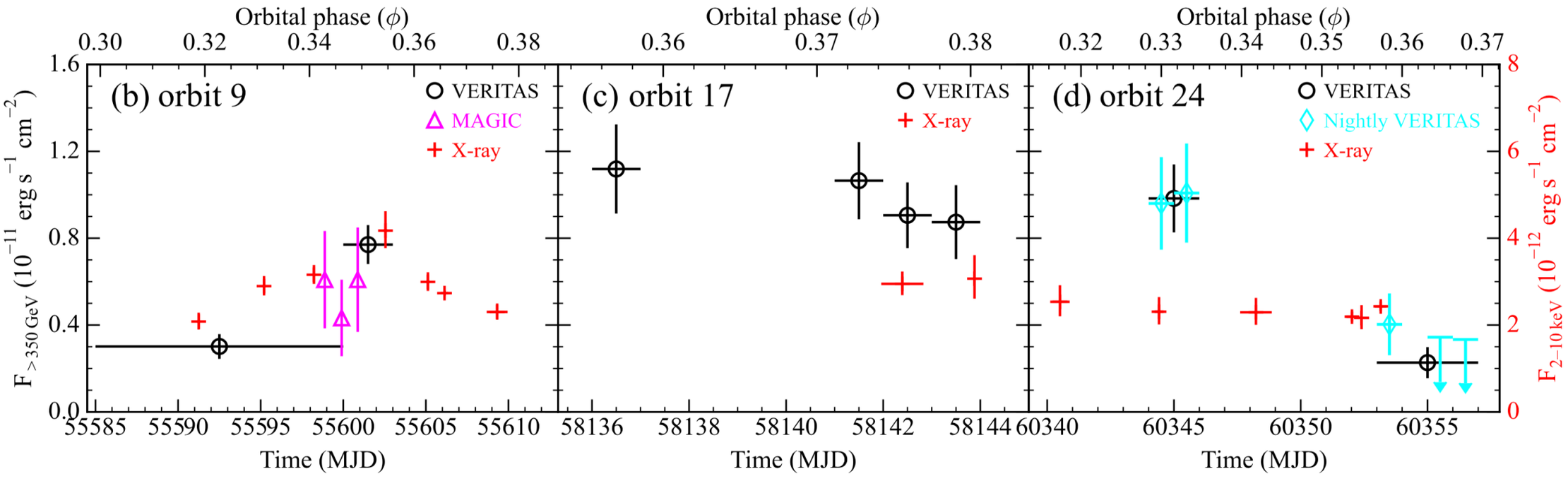
Swift XRT
289 Observations

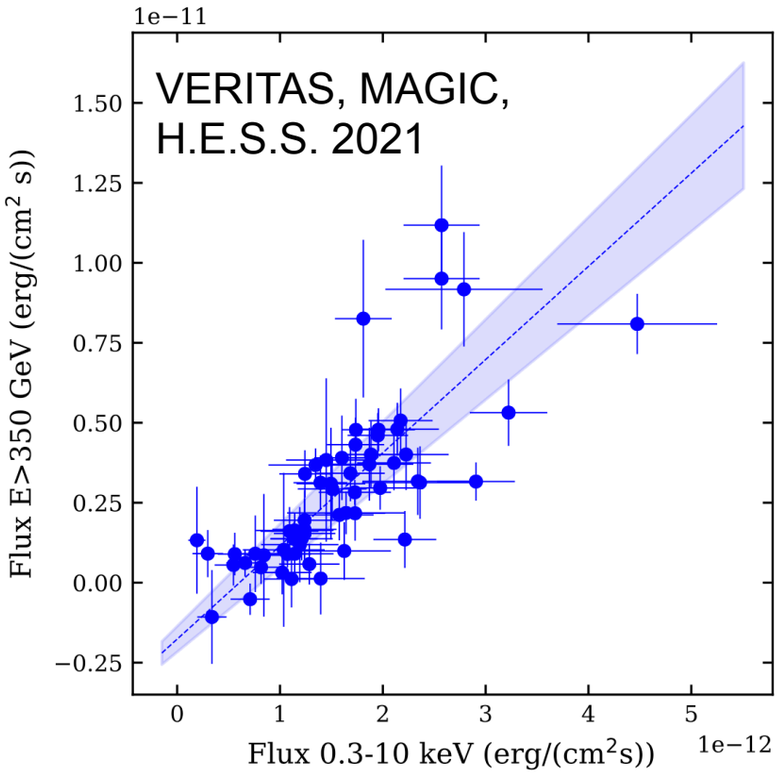


Good indication that this is long-term modulation

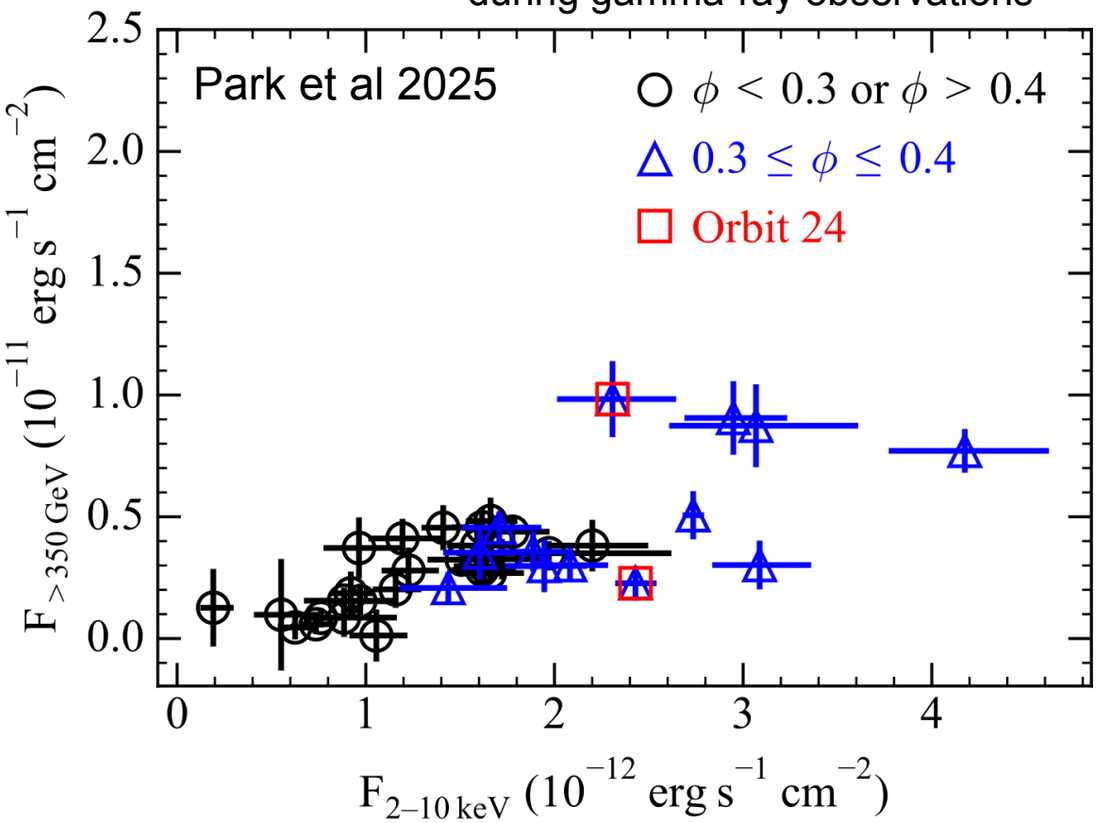
HESS J0632+057 - TeV / X-ray at 3 orbits

Park et al 2025





Contemporaneous: X-ray observations conducted during gamma-ray observations

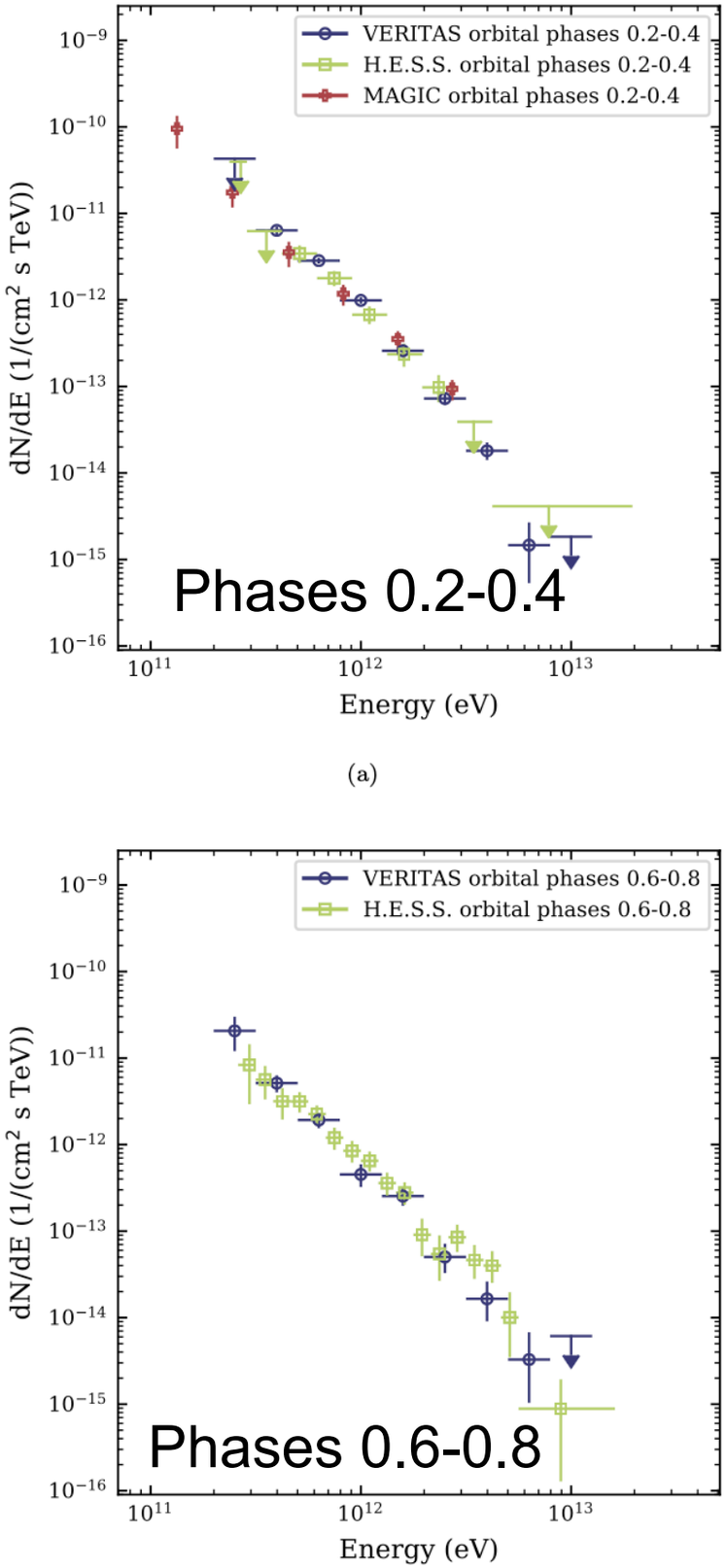


HESS J0632+057 - Spectral (Non-) Variability

VERITAS, MAGIC, H.E.S.S. 2021

VERITAS	2.67 ± 0.04
H.E.S.S.	2.45 ± 0.12
MAGIC	2.48 ± 0.11

VERITAS	2.52 ± 0.14
H.E.S.S.	2.34 ± 0.1



Conclusions

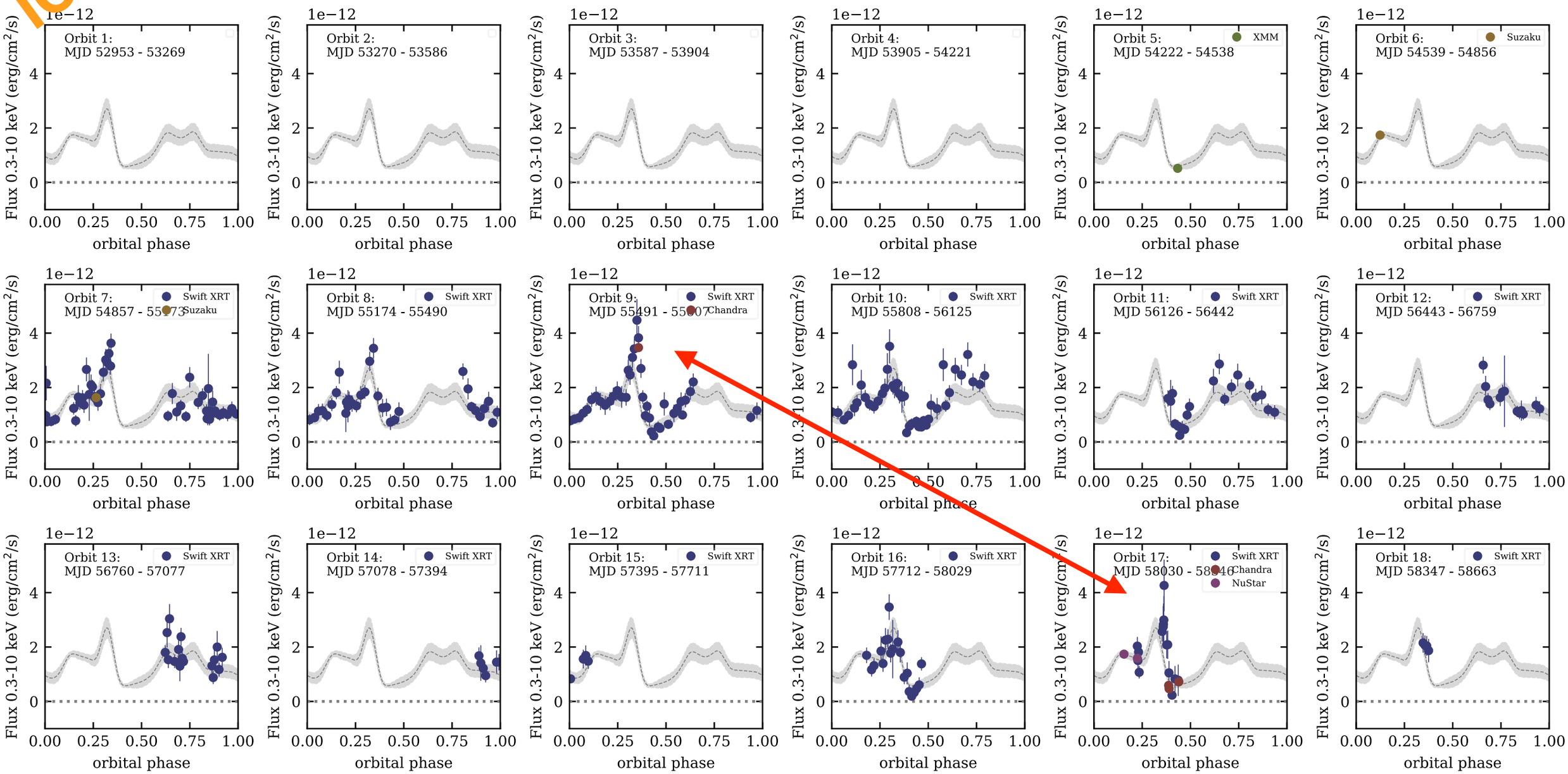
- **Large datasets obtained over >18 years with VERITAS**
  - 48 orbital periods and 4 super-orbital periods for LSI +61 303
  - 17 orbital periods for HESS J0632+057
- **Variability on different time scales for both systems**
  - Importance of short-term variability (~days) and orbit-to-orbit variability
  - Attention required due to incomplete coverage when comparing / averaging / correlating fluxes at different wavelengths
- **Rich multi-wavelength data set - ongoing deep analysis**

Backup

Bright states - X-rays

ICRC 2019

Large data set - but still limited coverage per orbit



Assuming an orbital period of 317.3 days
Grey band: average Swift XRT light curve
(68% uncertainty band)