UNIVERSITY OF DELAWARE

DEPARTMENT OF Physics and Astronomy

UNIVERSITY OF DELAWARE BARTOL RESEARCH INSTITUTE

VERITAS

VERITAS Observations of Gamma-ray Binary Systems

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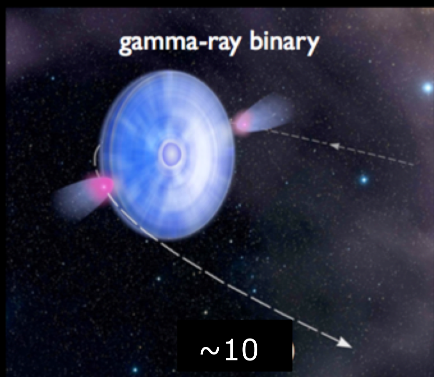
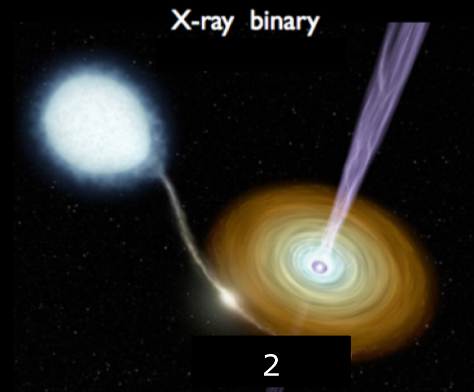
Department of Physics and Astronomy and the Bartol Research Institute

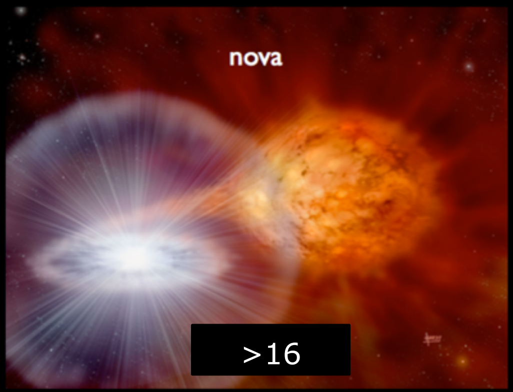
University of Delaware

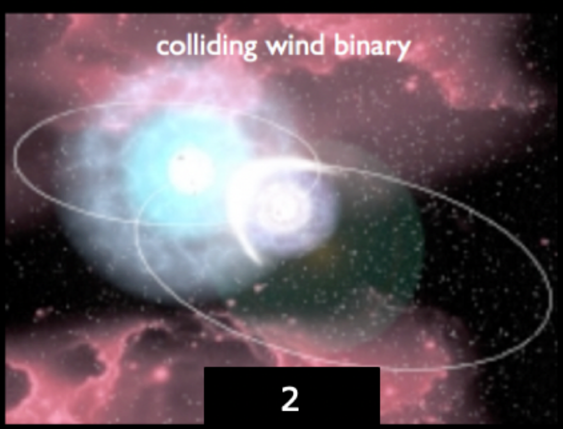
TeVPA 2022, Queen's University, Kingston

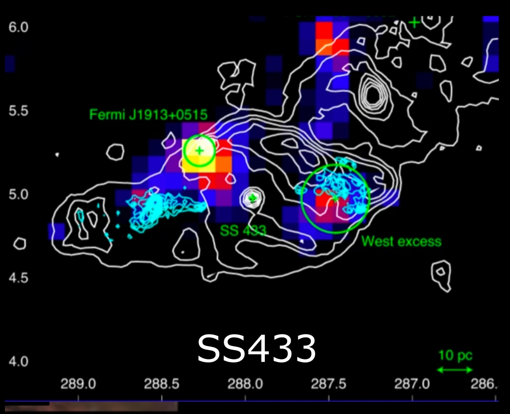
Systems with 2 objects that emit gamma-rays:







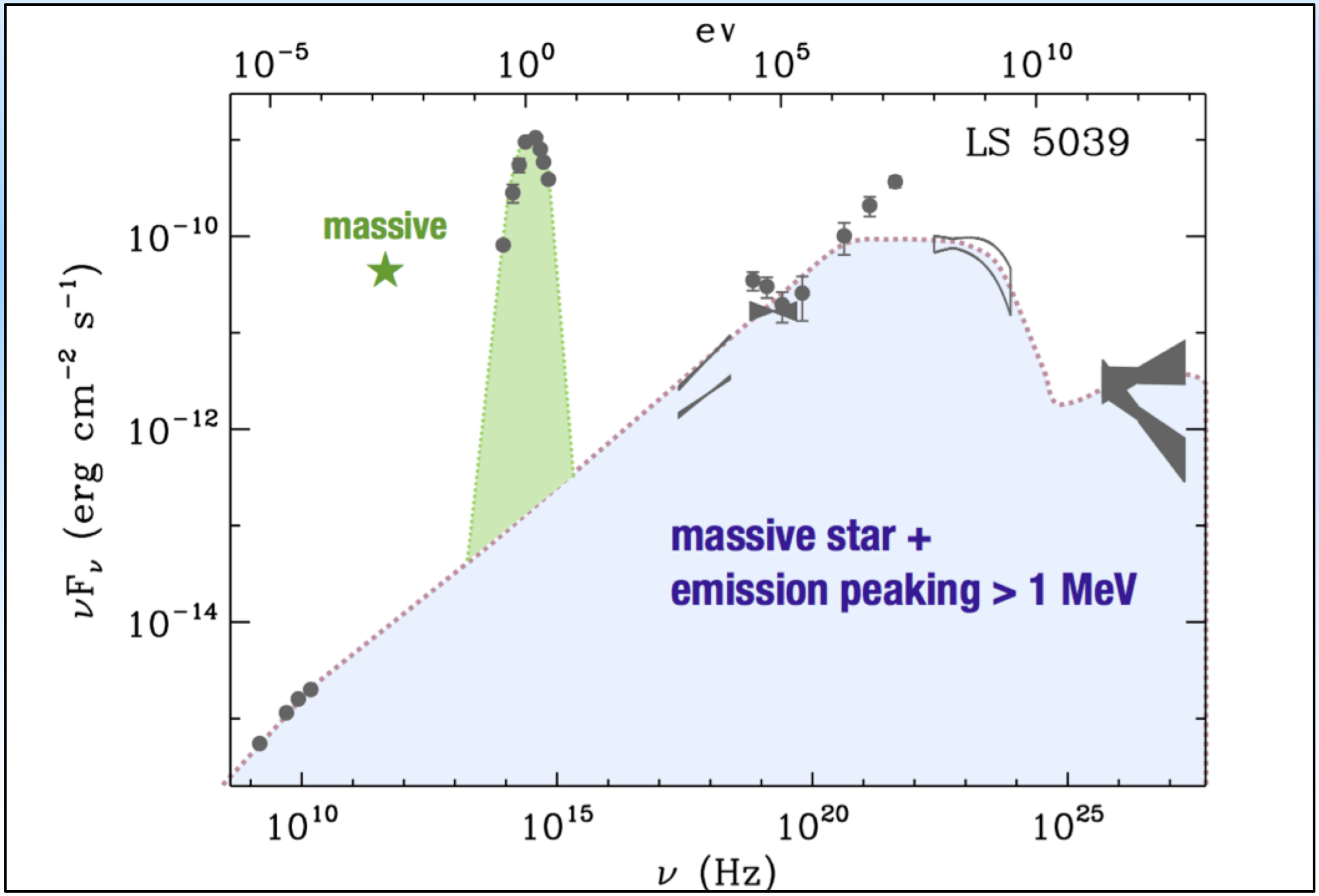




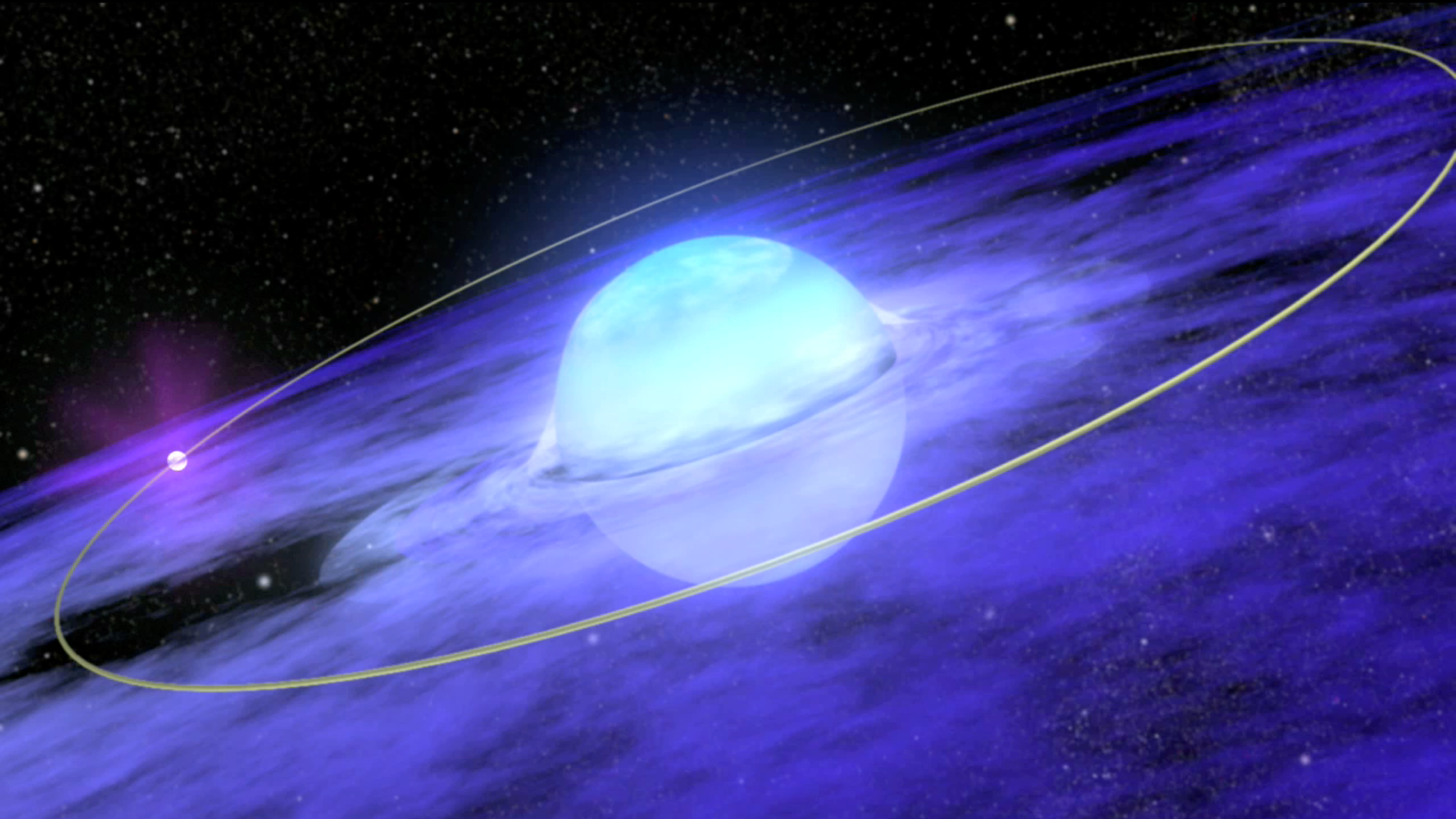
And now V4641 Sgr. (Huentemeyer for the HAWC Collaboration, this conference)

Gamma-ray binaries

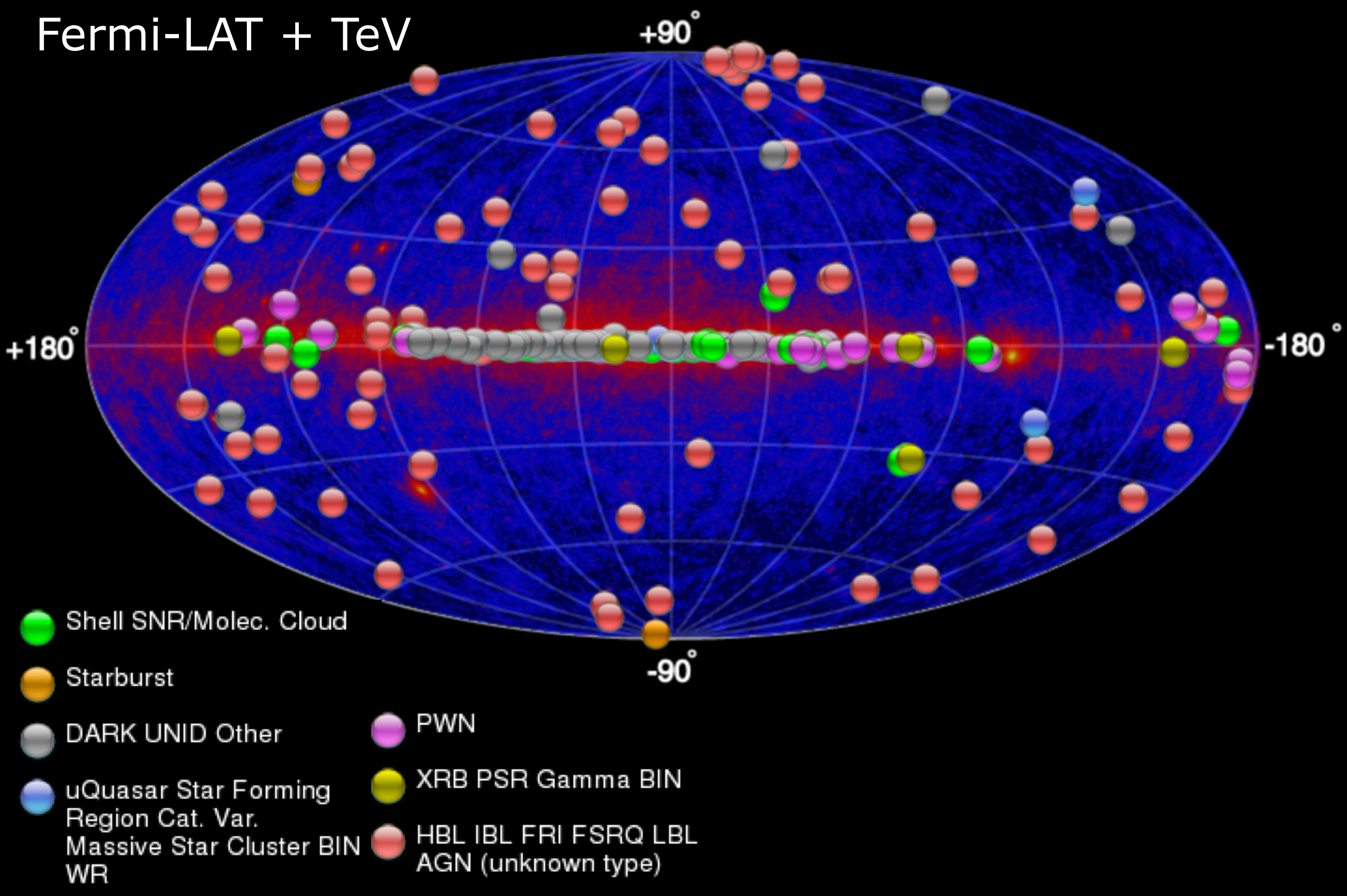
- Systems comprised of a massive star and a compact object (black hole or neutron star), **with periodic emission that peaks at energies > 1MeV.**



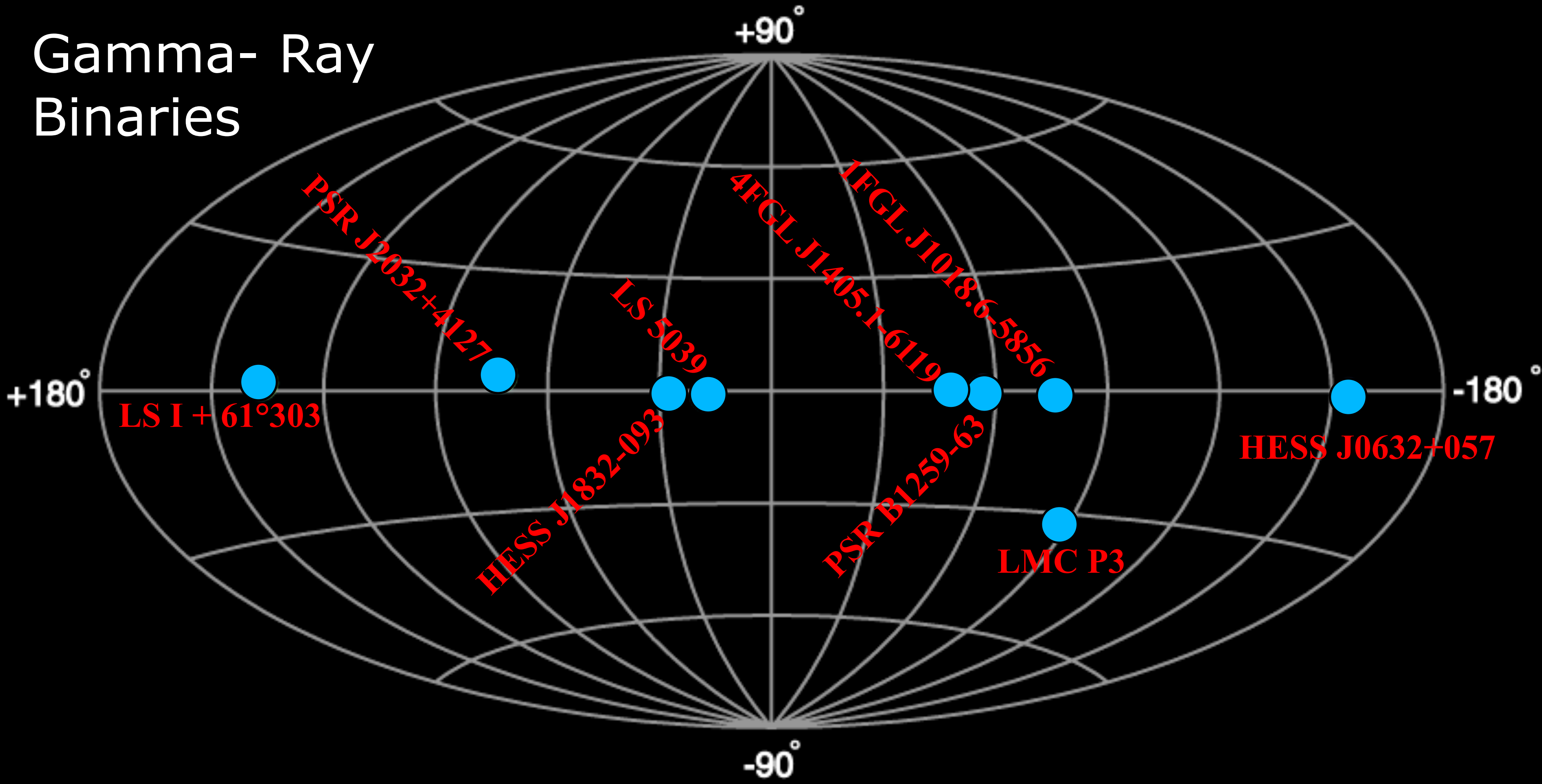
Credit G. Dubus



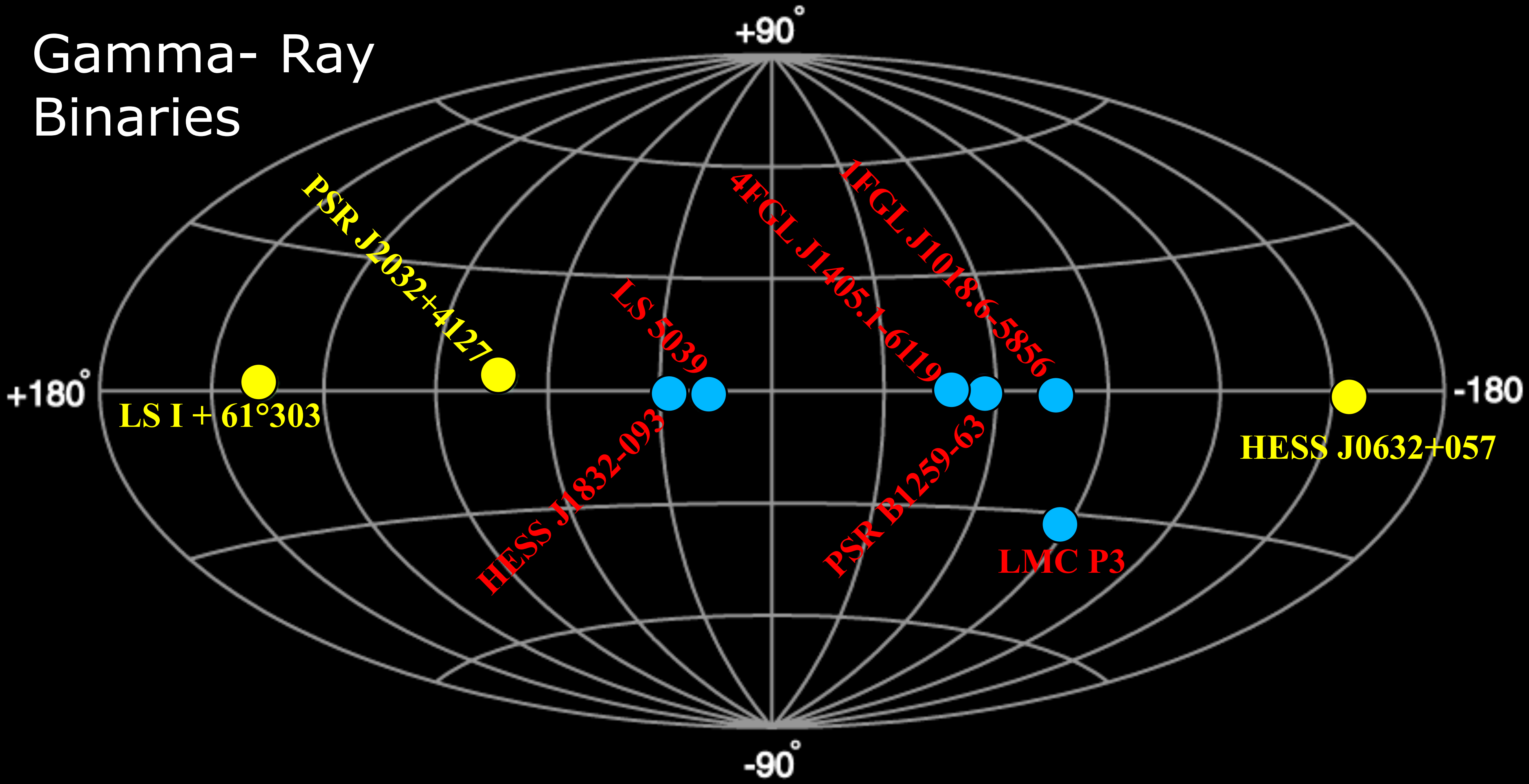
The Gamma-ray sky



Gamma- Ray Binaries



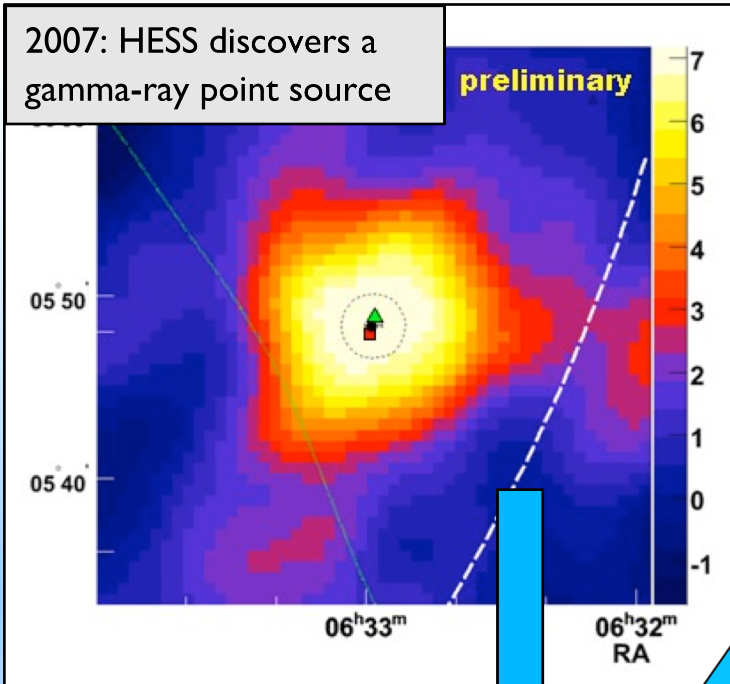
Gamma- Ray Binaries

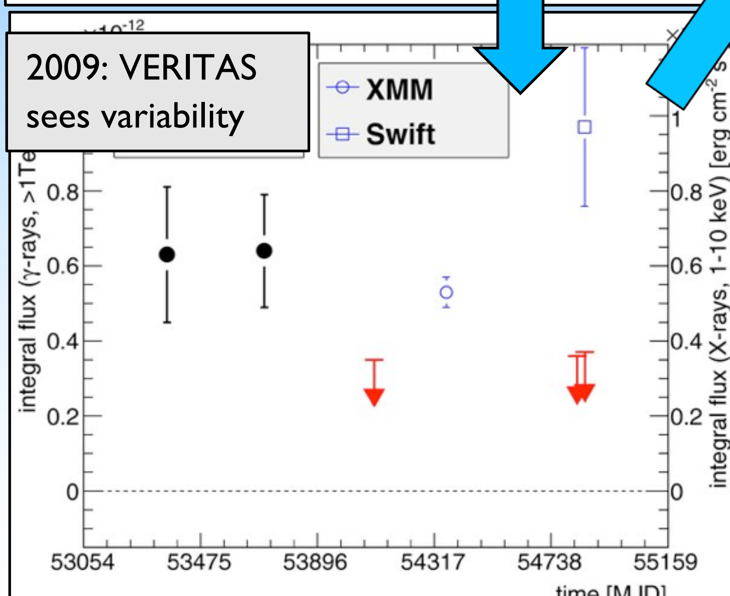


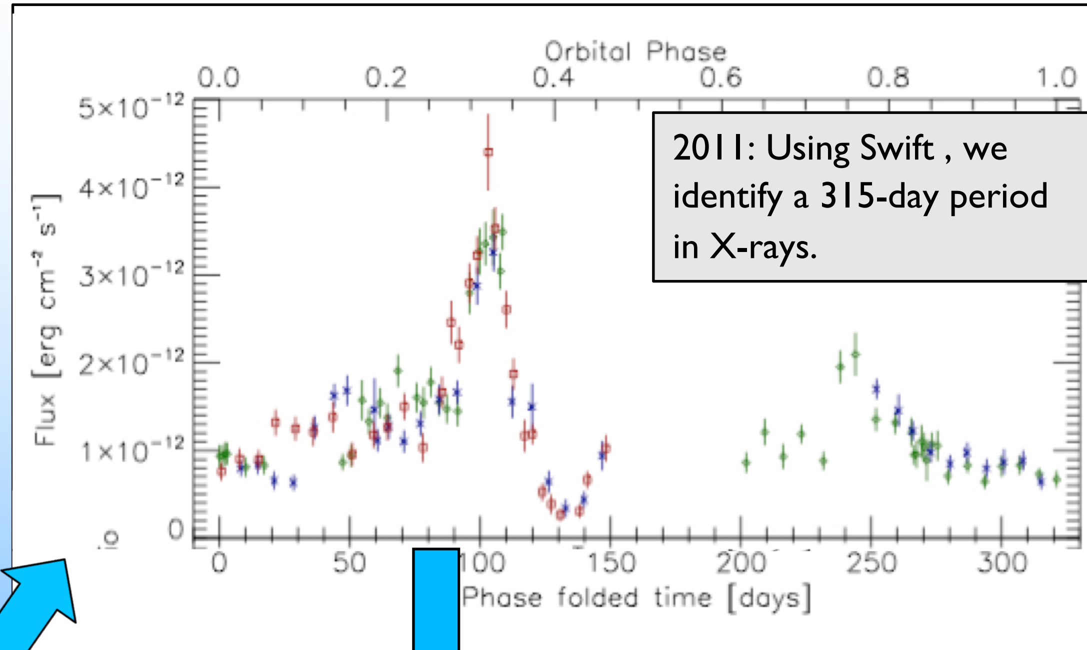
Why are these few so interesting?

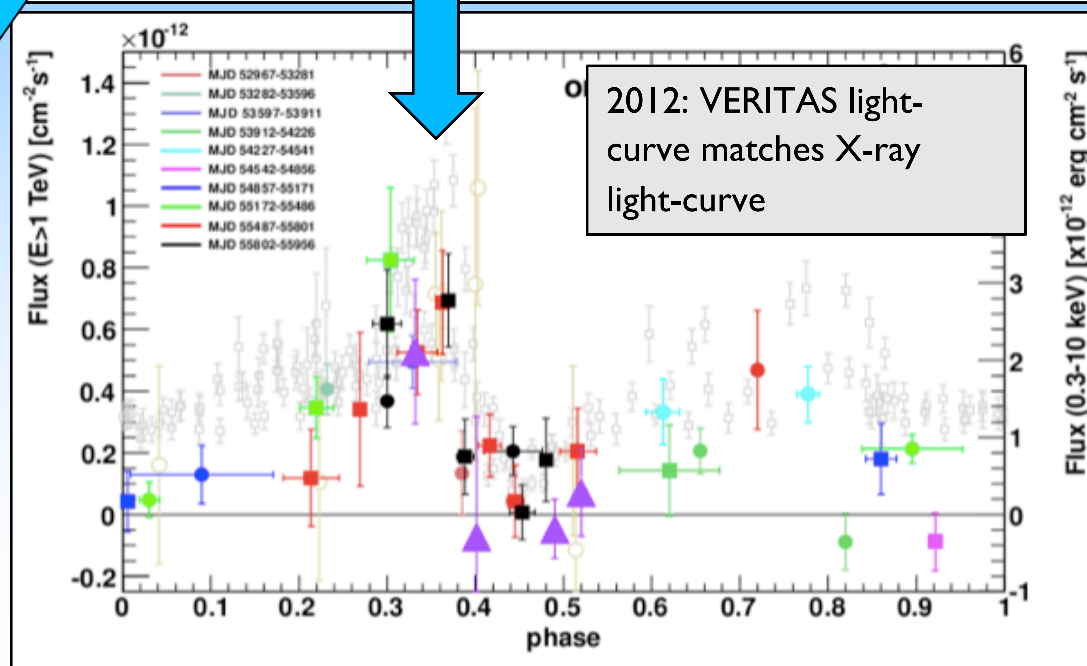
- Binaries ~~are~~ were(!) the only variable Galactic TeV sources.
- They are natural particle accelerators operating under varying, but ***regularly repeating***, environmental conditions.
- Provide a constraining *laboratory* for models of particle acceleration, and gamma-ray production, emission and absorption processes.
- Each system is unique – and the population, as well as the data quality, is increasing.
- *Caveat*: The systems are complex, with many competing processes, and the orbital parameters, the nature of the binary components and the conditions in the circumstellar environment are generally not well known.

A detective story: HESS J0632+057



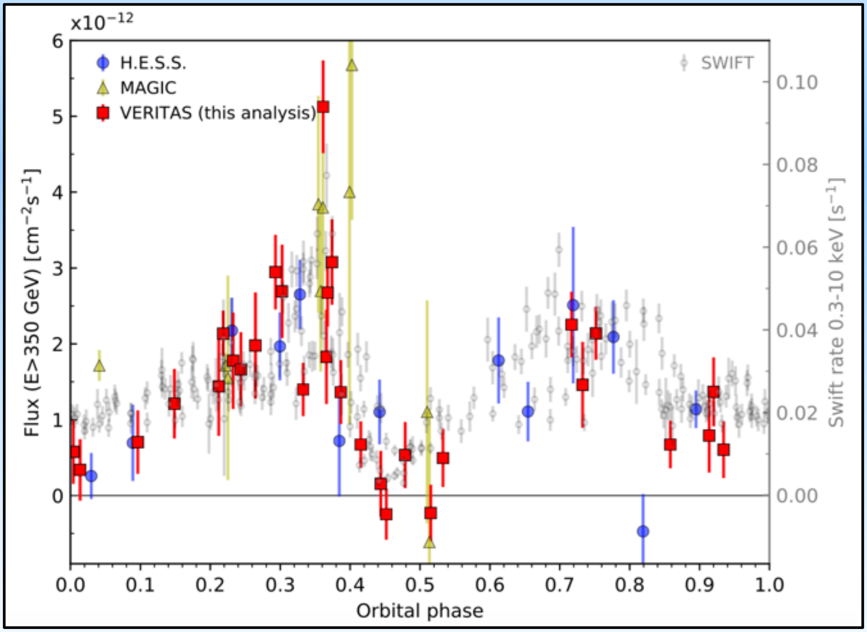


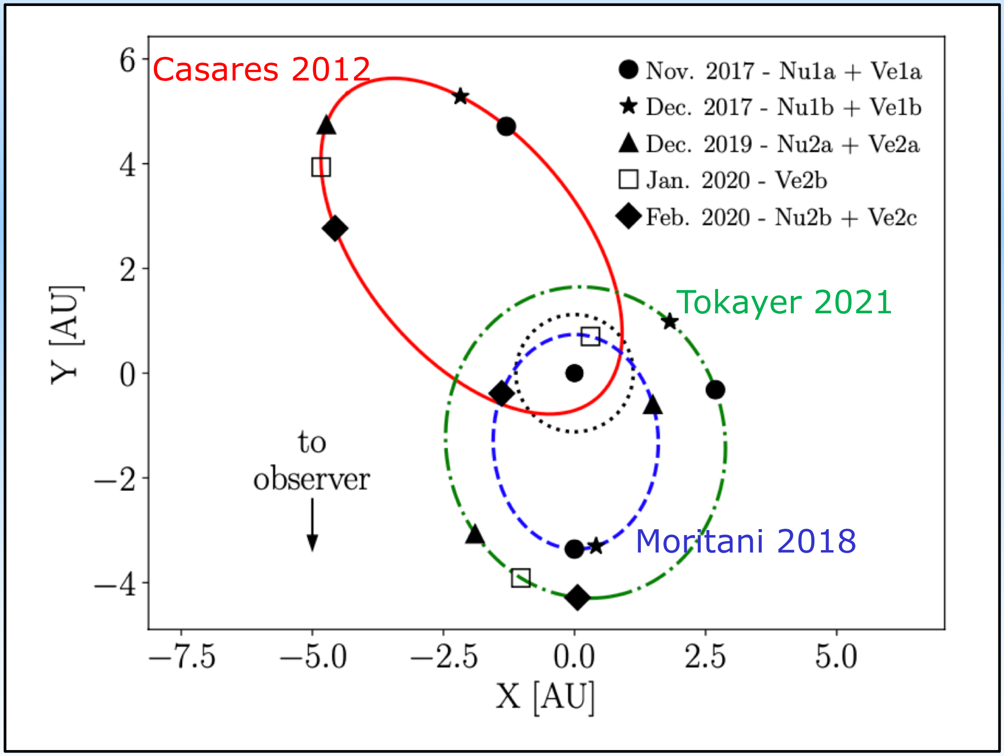




HESS J0632+057

- VERITAS has now covered all of the orbit, over a decade of observations.
- Orbital parameters from optical radial velocity measurements are improving.
- Periodic GeV emission has now been detected – but very faint.



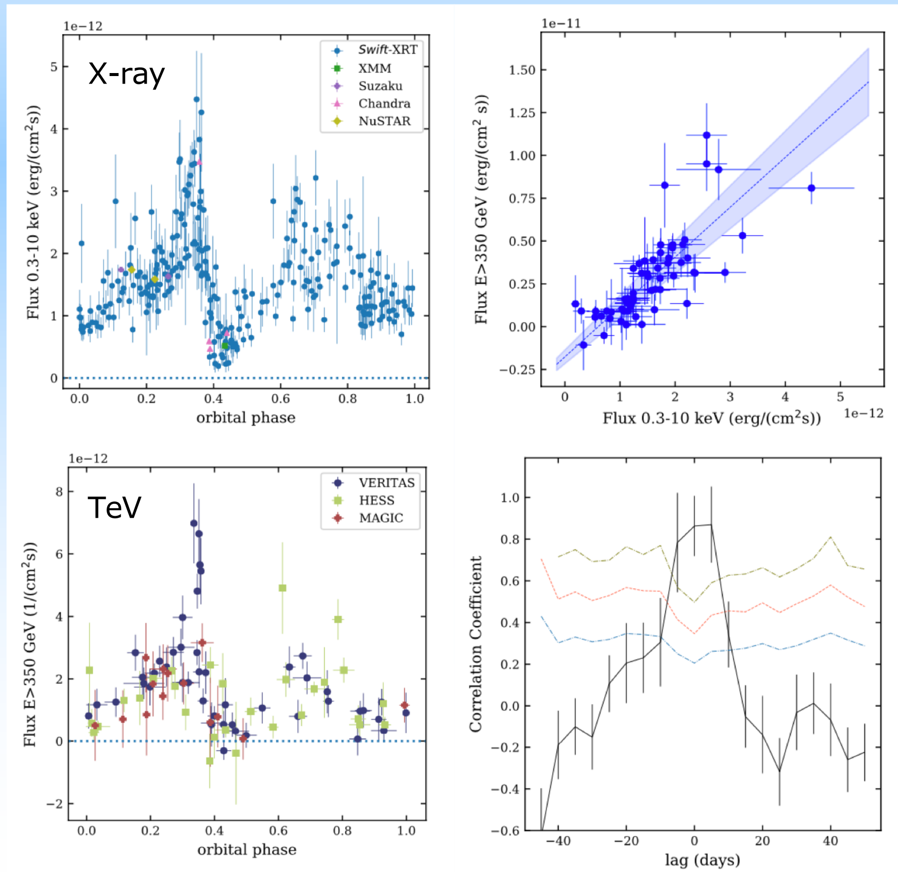


Tokayer, Y.M. et al., ApJ, 923, 17, 2021

HESS J0632+057: Latest results

- 450 hours of H.E.S.S., MAGIC, & VERITAS data collected over 15 years. (Adams, C.B. et al., ApJ, 923, 241, 2021.)
- Orbital period measured in TeV gamma-rays alone:
  - 316.7 ± 4.4 days, consistent with updated X-ray period (317.3 ± 0.7 days).
- X-ray and TeV fluxes are highly correlated, with zero time lag. Gamma-ray energy flux dominates.
- Rapid gamma-ray variability (flux decay times of 20 days), and orbit-to orbit variability.
- Modelling challenged by unknown orbital geometry, disk properties and unknown compact object (but see e.g. Kim et al: https://arxiv.org/abs/2208.01189).

Phase-folded lightcurves

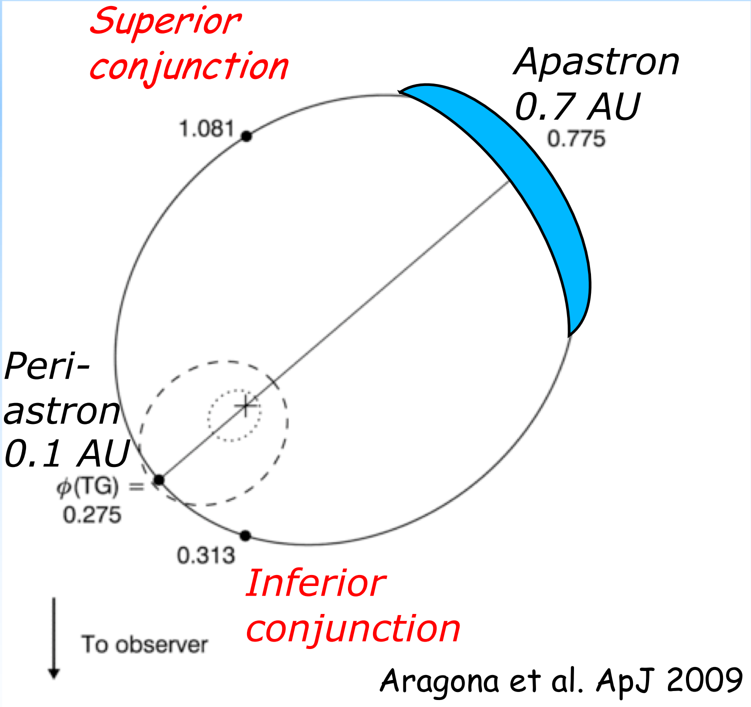


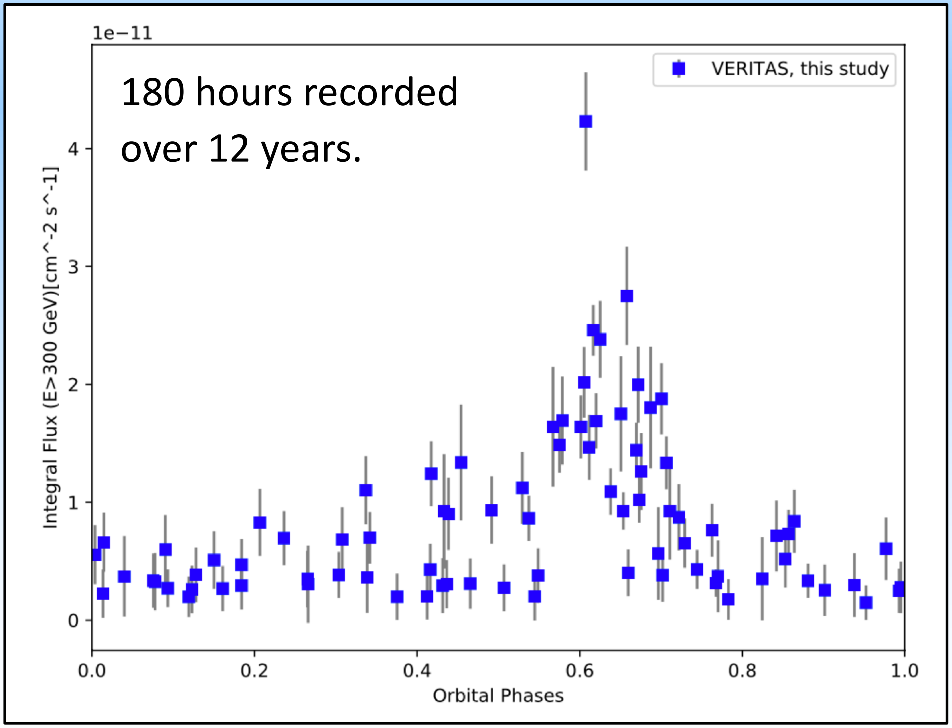
X-ray – TeV correlation

X-ray - TeV time lag

LS I +61° 303

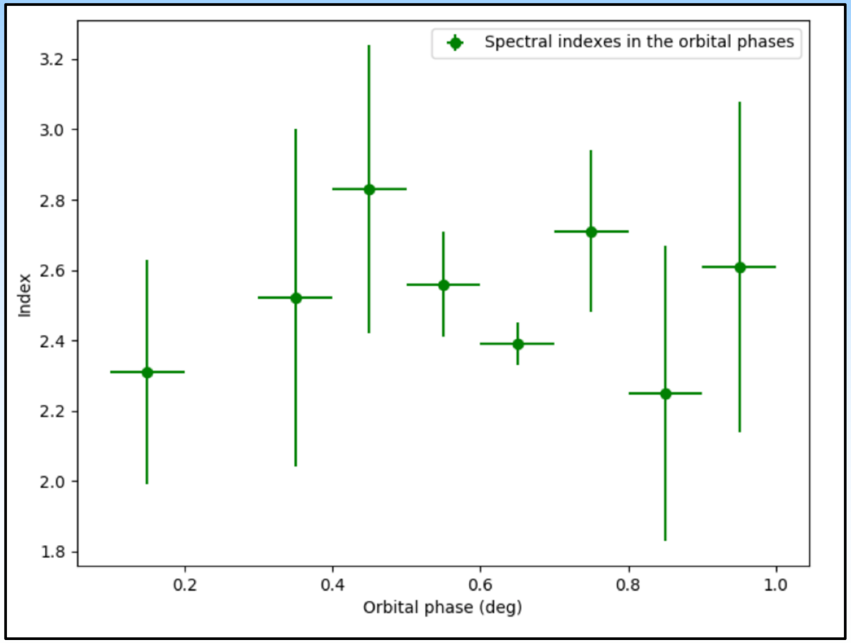
- Compact object orbiting an B0Ve companion ($12M_{sol}$)
- 26.5 day orbital period.
- Extended radio structures, modulated by orbital phase.
- Detected in TeV by MAGIC, then VERITAS. Brightest near assumed apastron (φ=0.5-0.8).
- Also bright in Fermi-LAT, but peak emission is at periastron, and spectrum cuts off at 6 GeV.

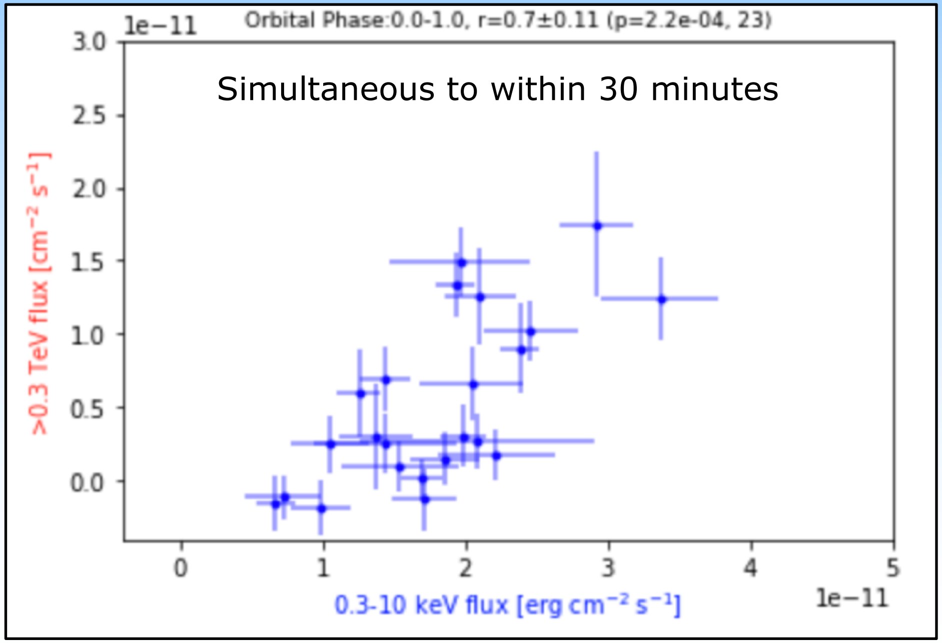




LS I +61° 303: Latest VERITAS Results

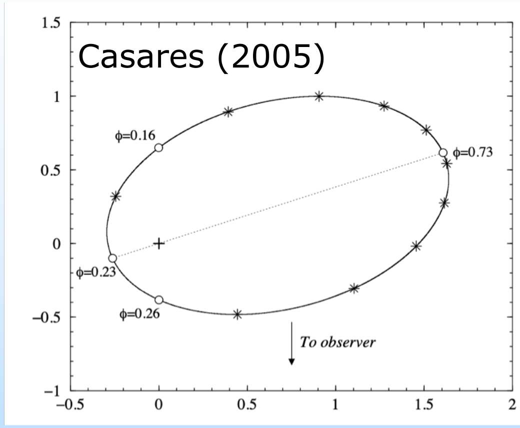
- 180 hours recorded over 12 years. Rapid variability on <1 day timescales
- Detected at all orbital phases. No evidence for spectral variability.
- Long dataset also allows search for super-orbital modulation
  - Super-orbital period = 4.6 years, seen at longer wavelengths and in TeV by MAGIC.
  - No evidence for super-orbital variability in VERITAS data alone. Joint study with MAGIC underway.
- TeV-ray and X-ray emission is well-correlated on short timescales.



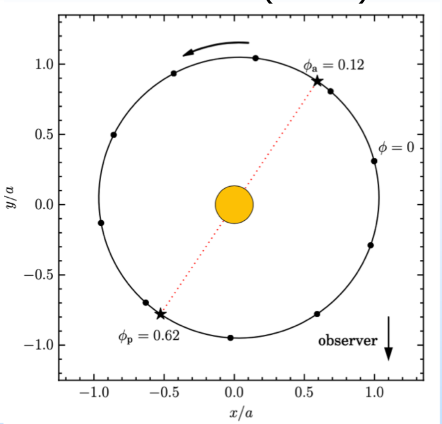


LS I +61°303: Recent updates

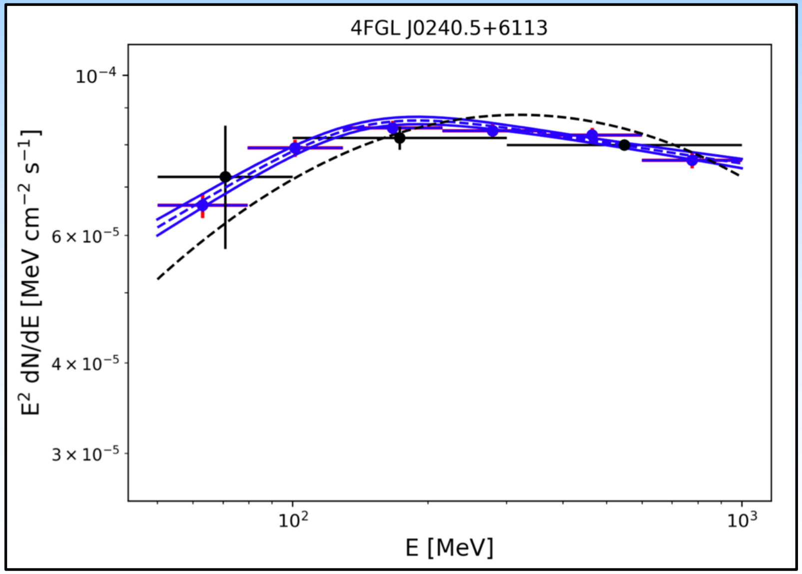
- New orbital solution suggests rather different geometry:
  - No eccentricity
  - Phase of periastron = 0.6



Kravtsov (2020)

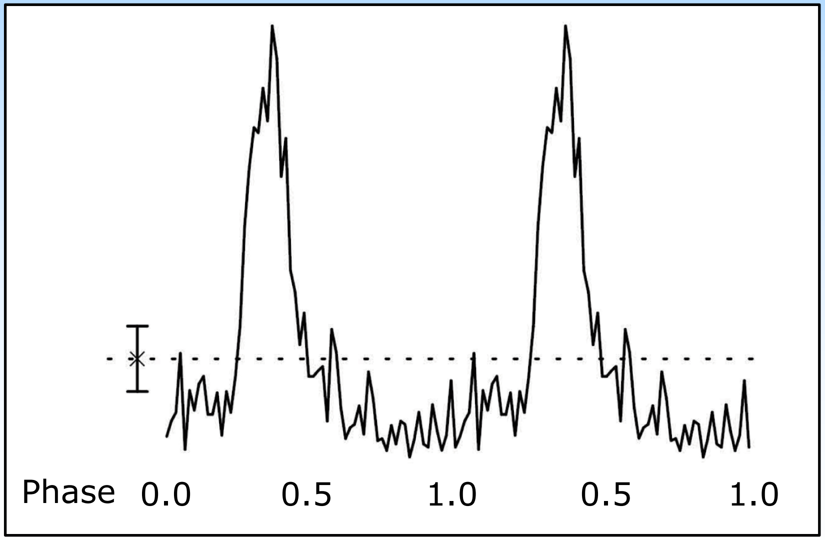


- Low energy spectral break suggests pion "bump".
- Are gamma-ray binaries important cosmic ray acceleration sites?



Fermi-LAT Collaboration arXiv:2205.03111

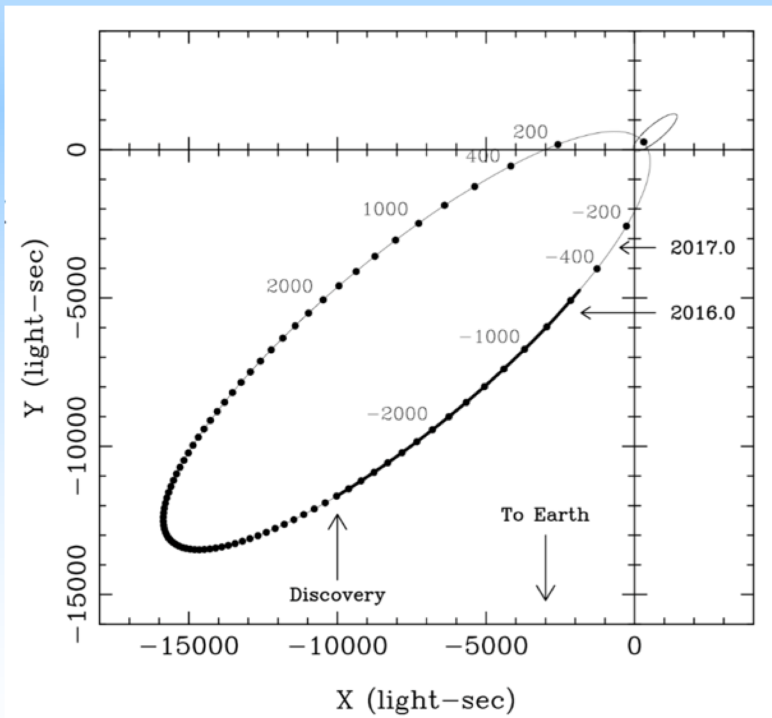
- FAST radio telescope detects pulsations with 269 ms period on one night (out of four).
- "strongly argues for the existence of a rotating neutron star within LS I +61° 303".

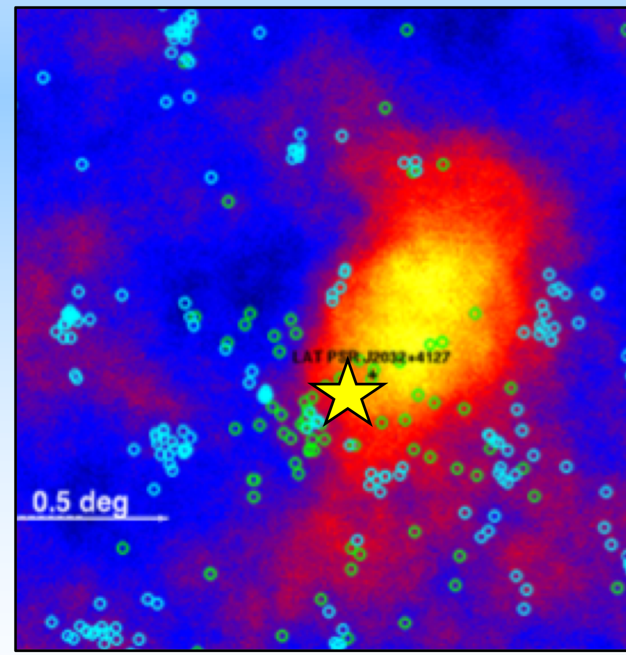


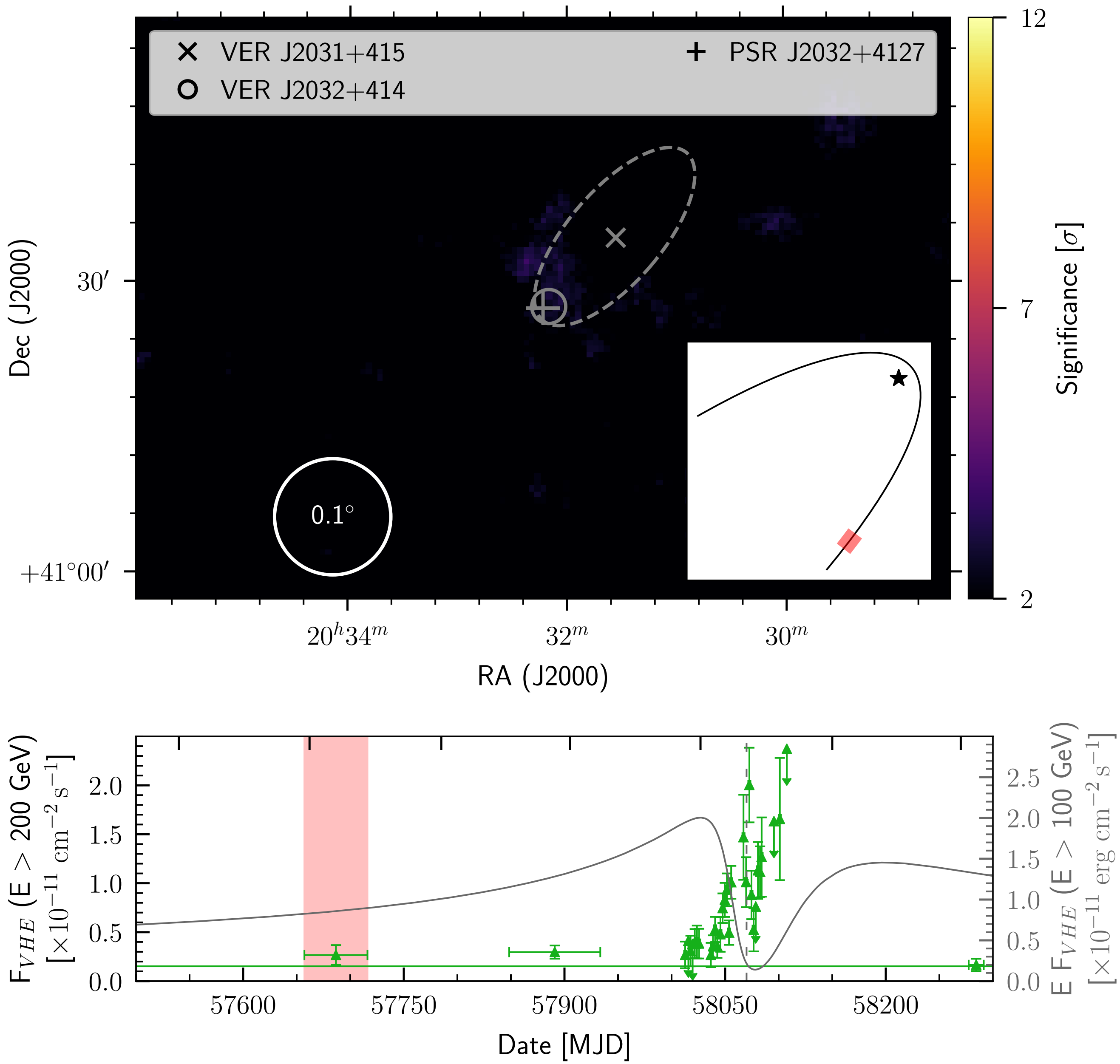
Weng. S. et al., Nature Astronomy, 6, 698

PSR J2032+4127 / MT91 213

- In 2014, Lyne et al. identified PSR J2032+4127 as the compact object in a binary system with a 15 M_{sol} Be star.
- The eccentricity is >0.97, and the orbital period 45 – 50 years!
- Pulsar timing defined periastron *very* precisely (Nov 13th 2017, 9pm)
- Intriguingly – the pulsar binary is located within a steady, extended TeV gamma-ray source.







VER J2031+415
VER J2032+414
PSR J2032+4127
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RA (J2000)
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20h34m
32m
30m
Significance [σ]
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F_VHE (E > 200 GeV) [×10^−11 cm^−2 s^−1]
E F_VHE (E > 100 GeV) [×10^−11 erg cm^−2 s^−1]
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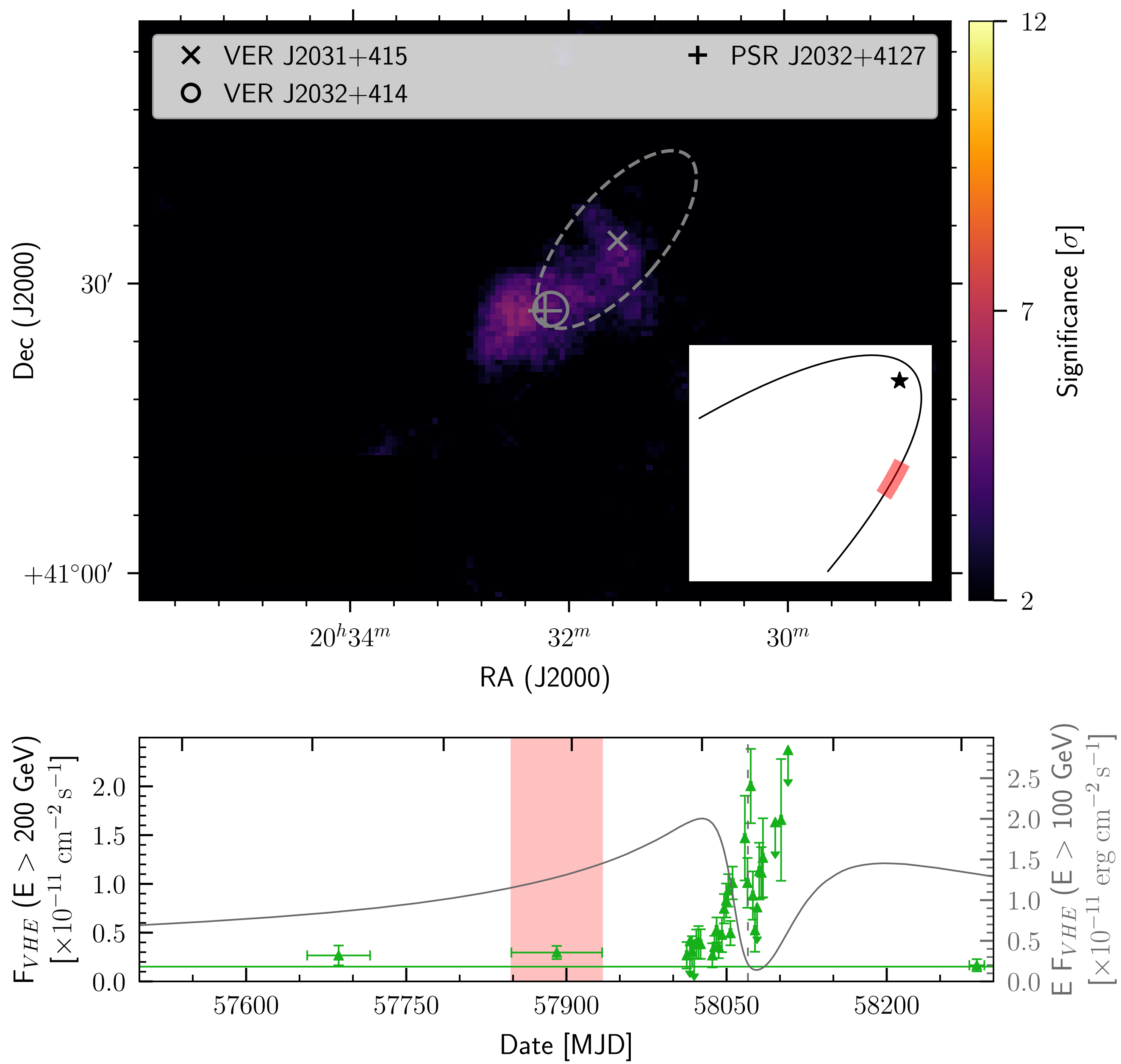

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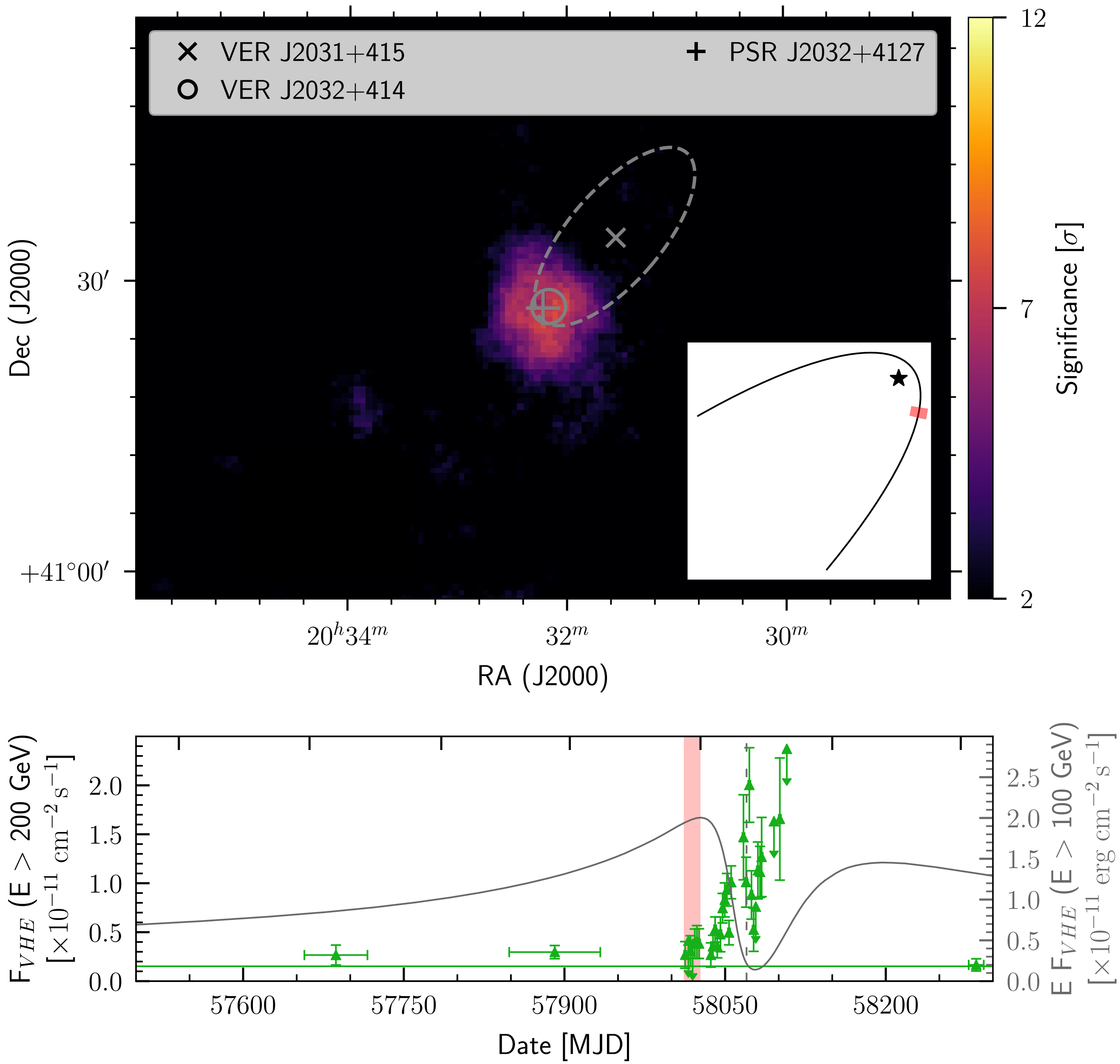

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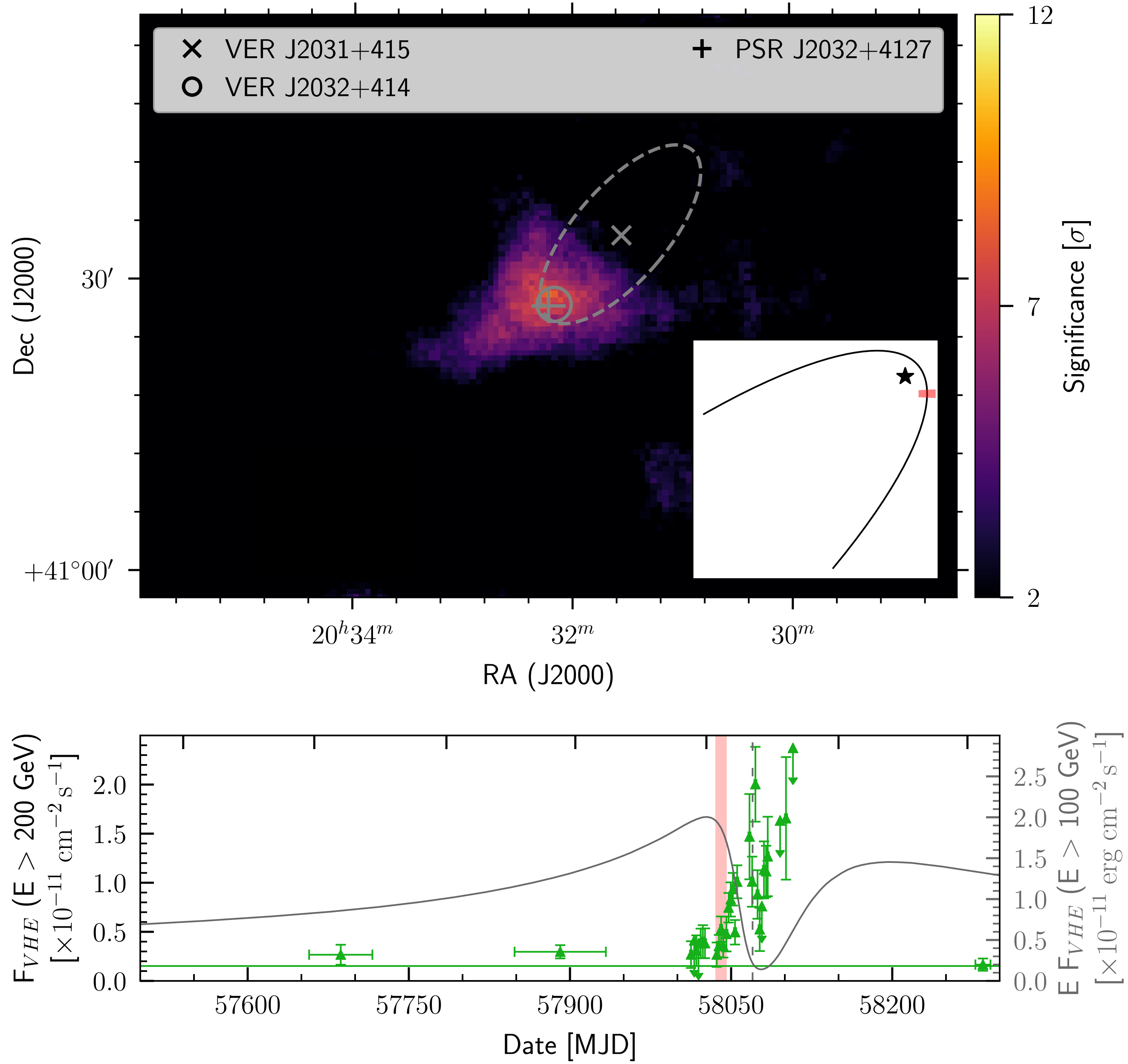

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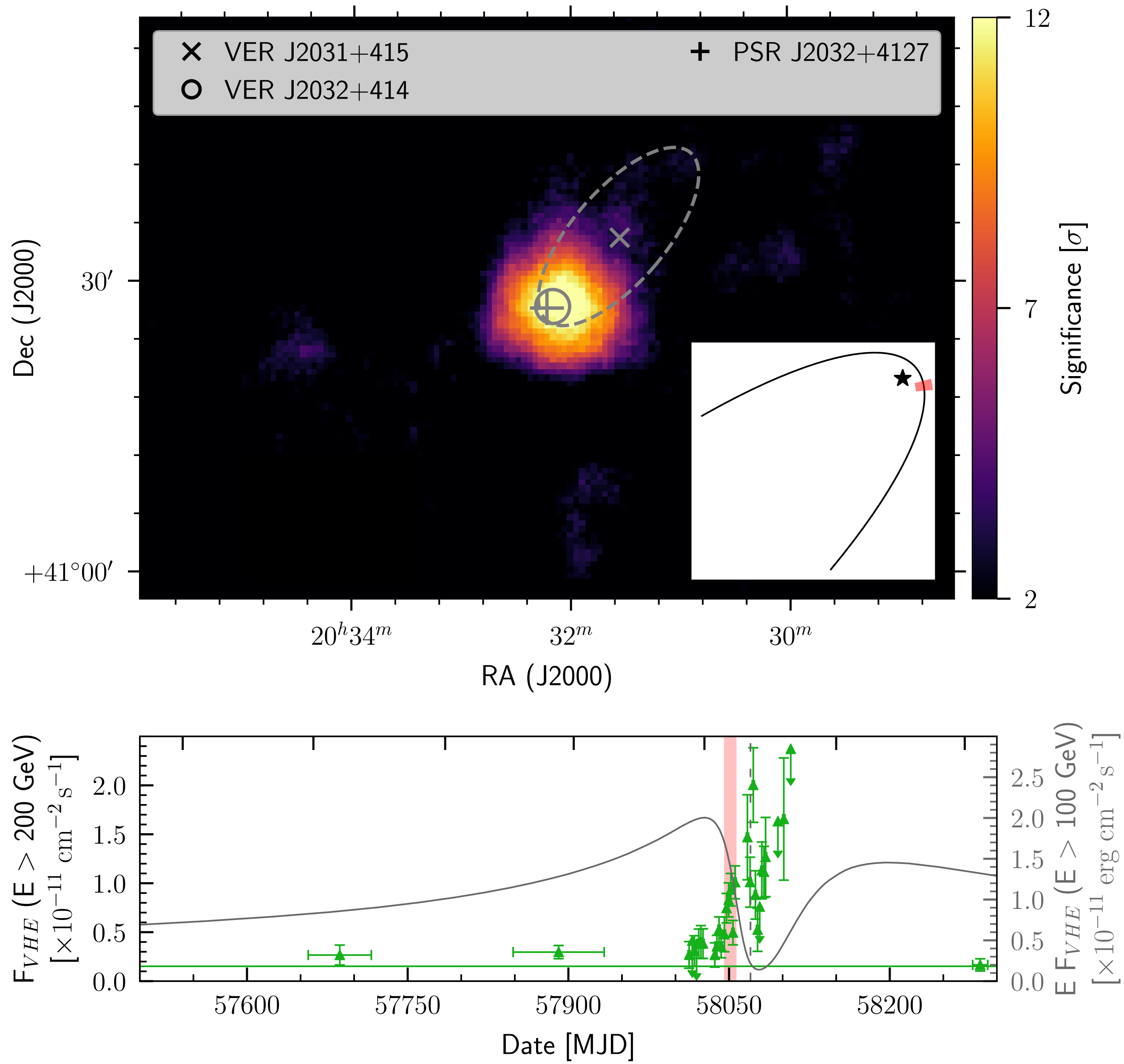

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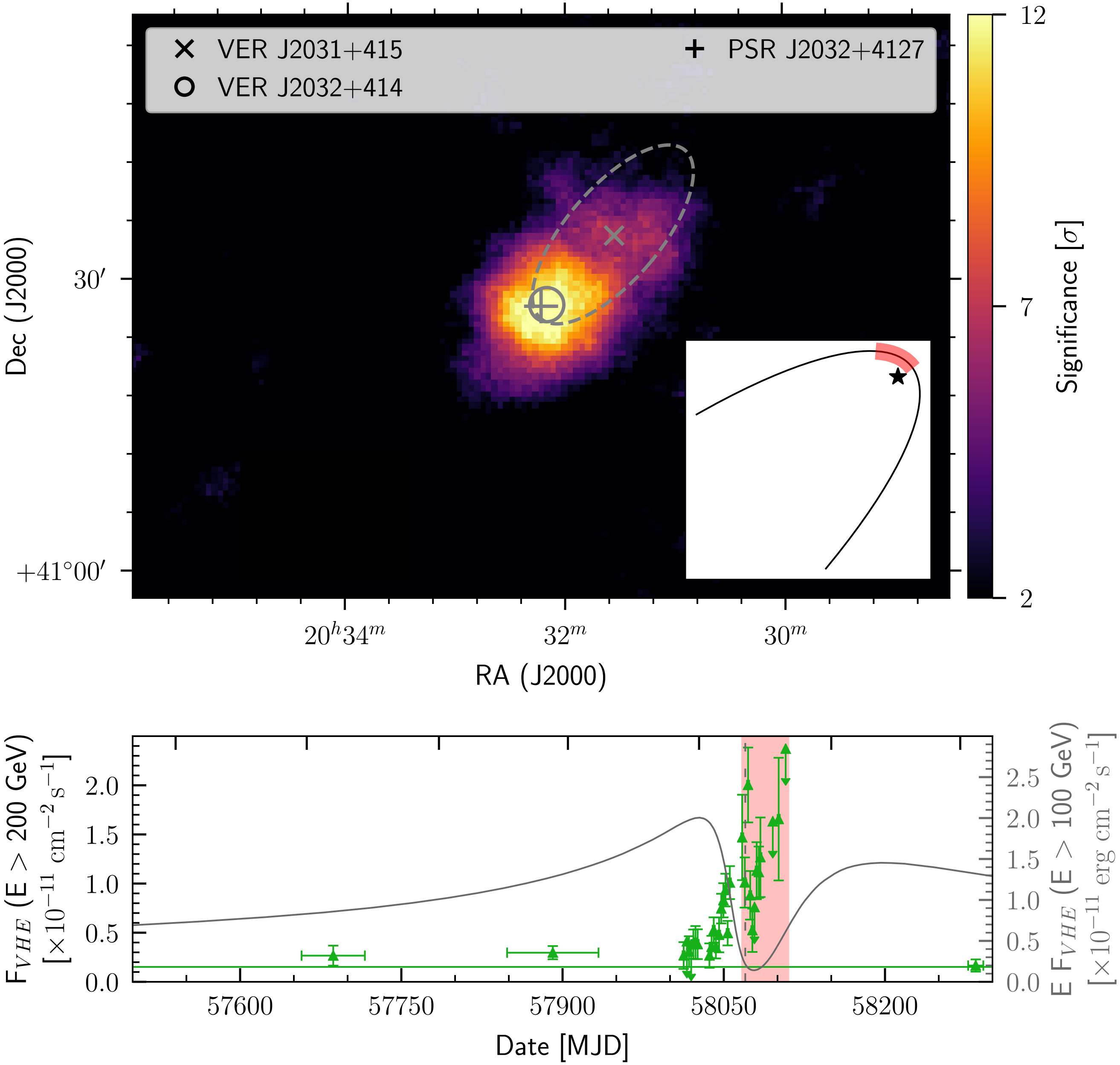
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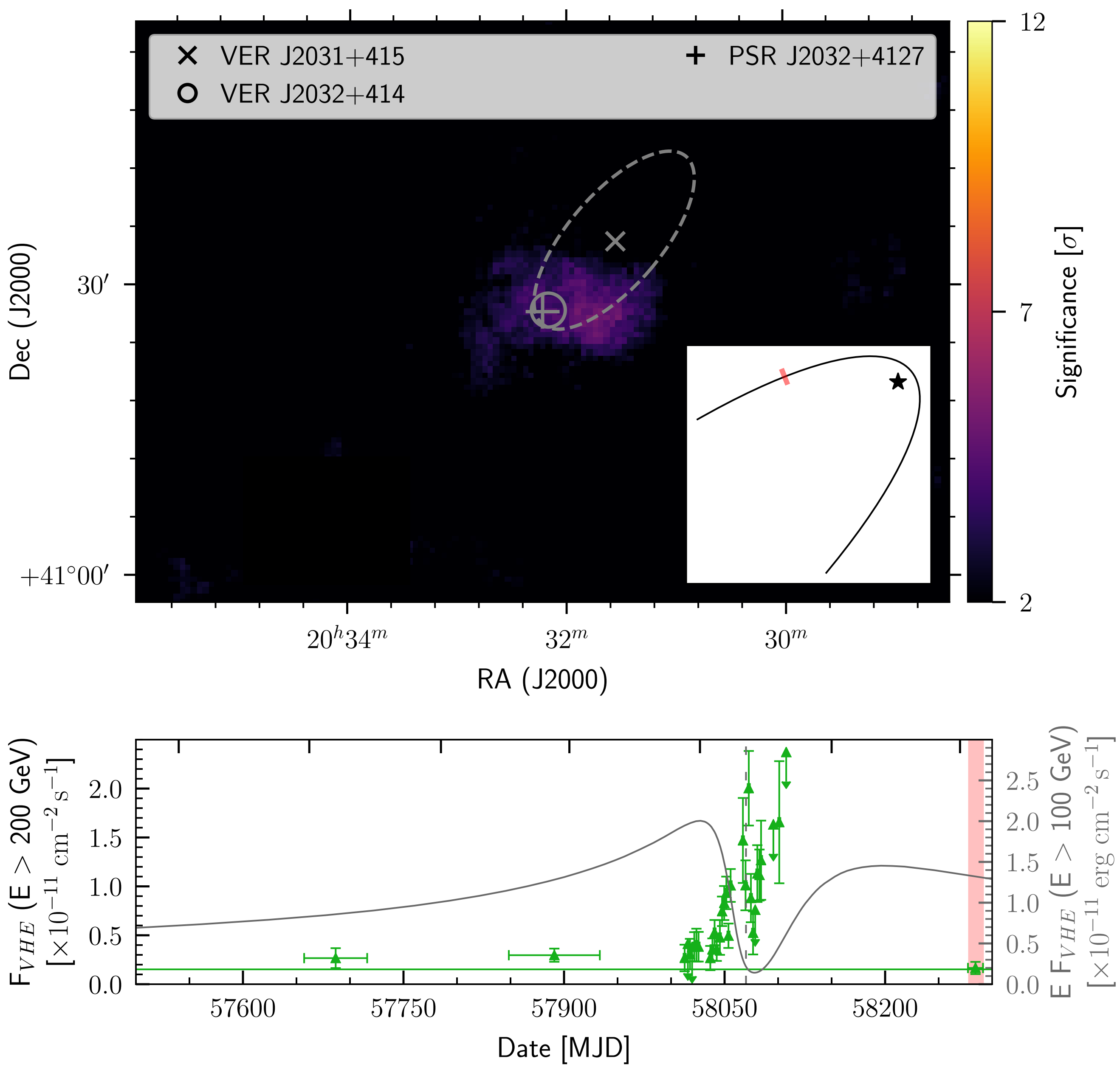
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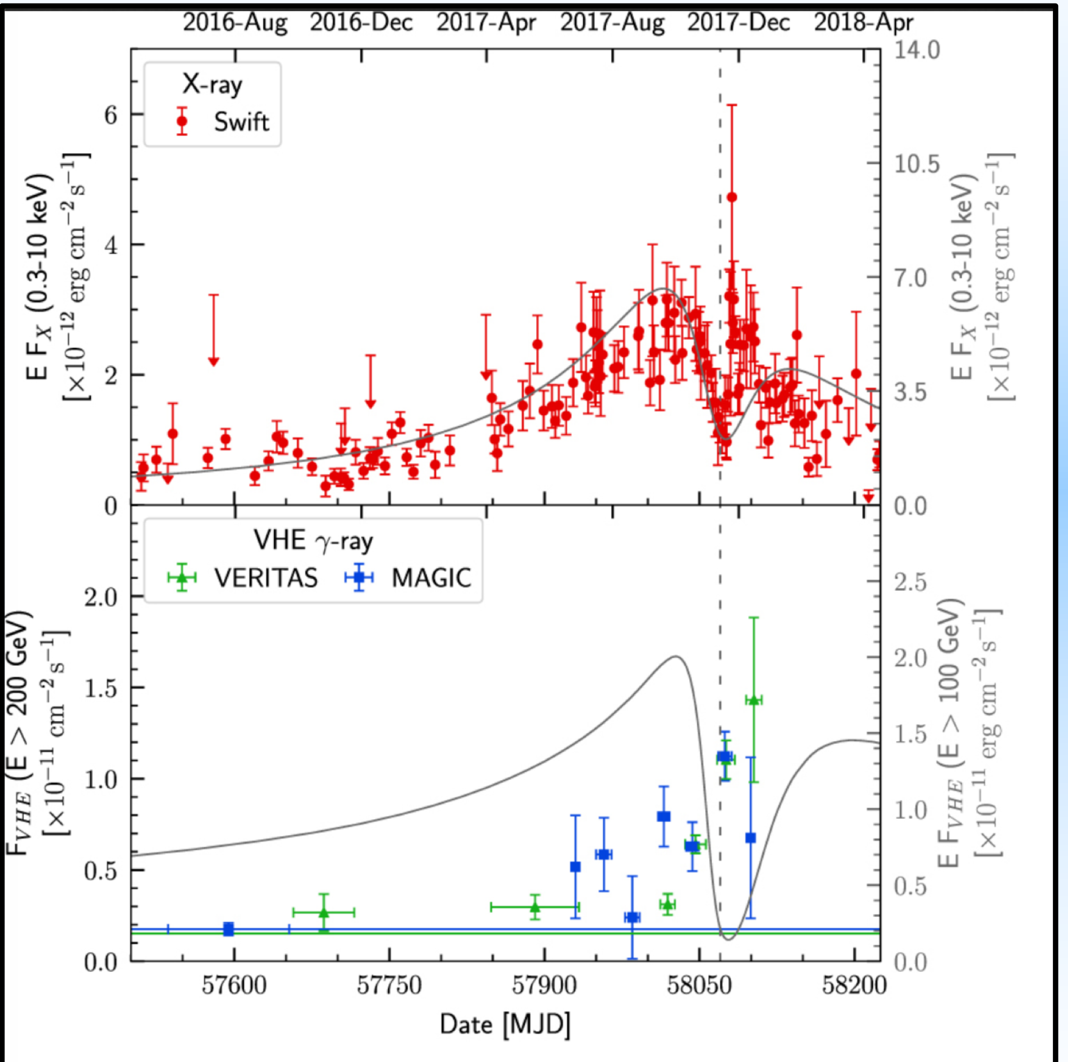
Lightcurve

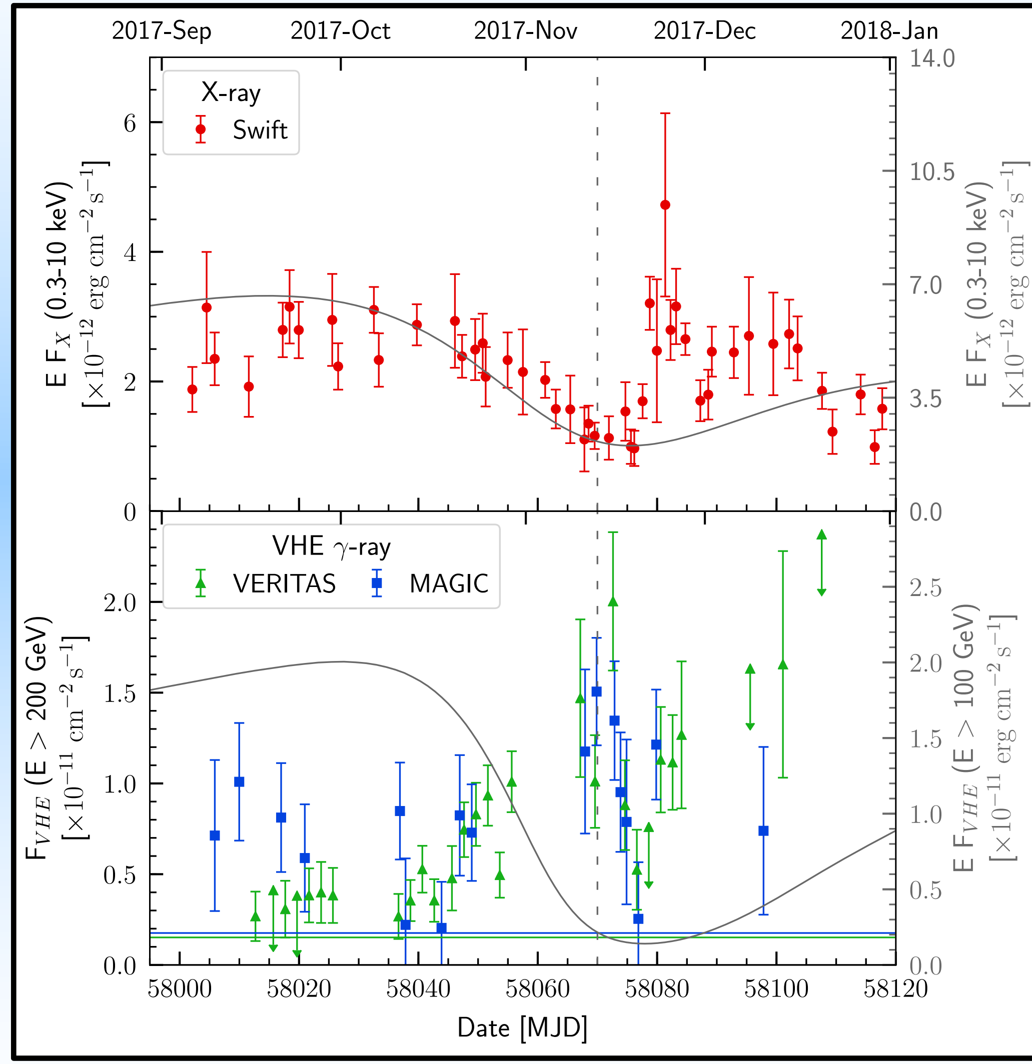


(a) Full Dataset

- Original TeV lightcurve **prediction** from Takata 2017 did not match the observations well.

Lightcurve

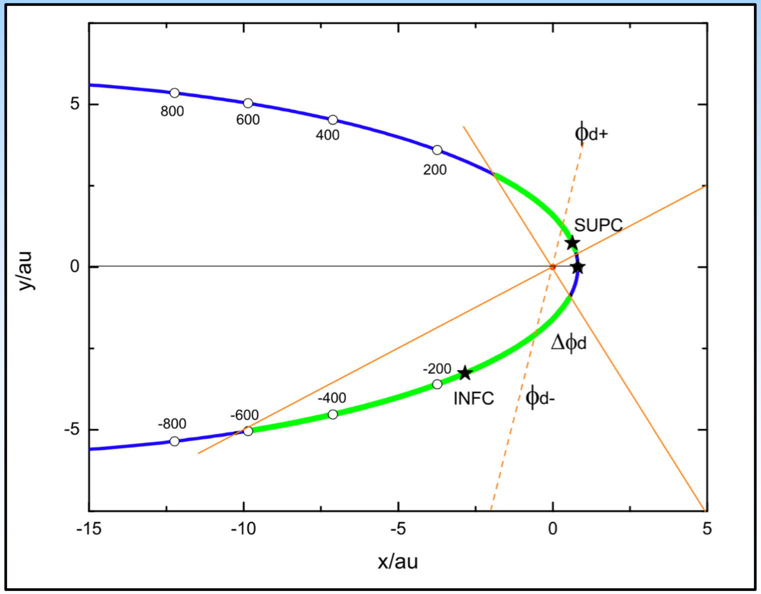
- Original TeV lightcurve **prediction** from Takata 2017 did not match the observations well.

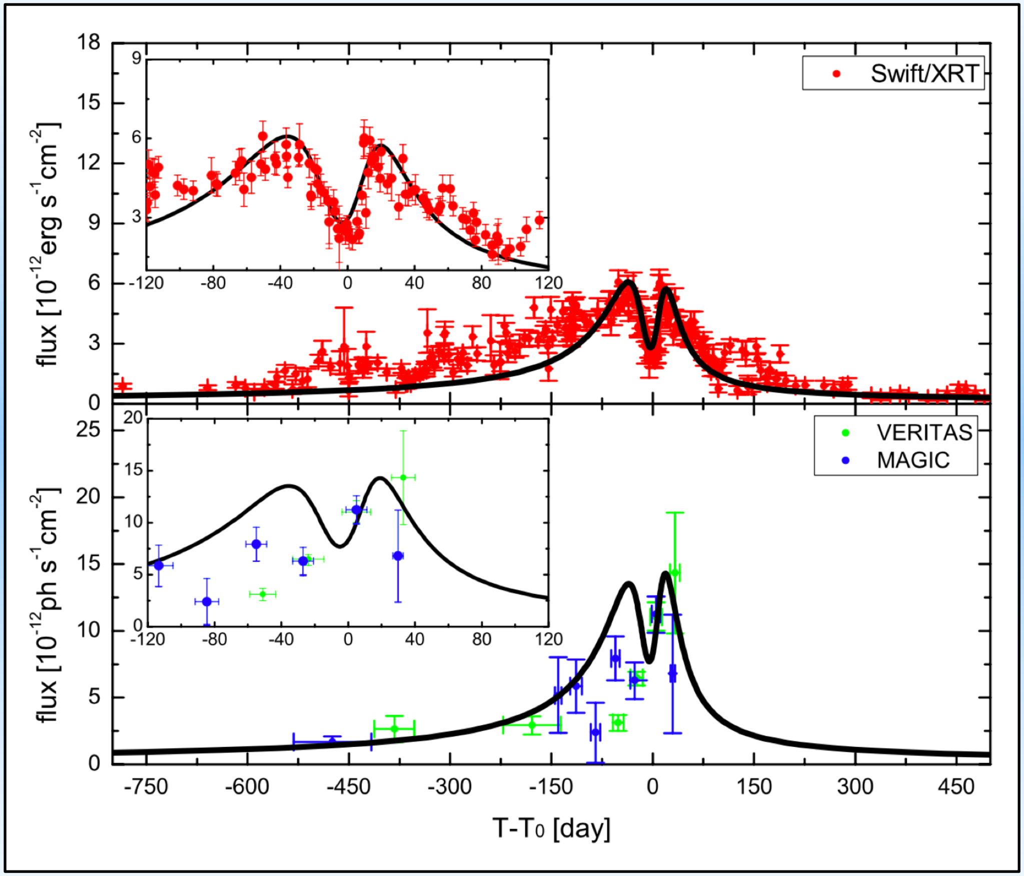


Periastron

Scientific method at work!
Updated model.

- Updated model from Chen & Takata, 2020.
- Uses improved orbital solution and assumes an inclined disk



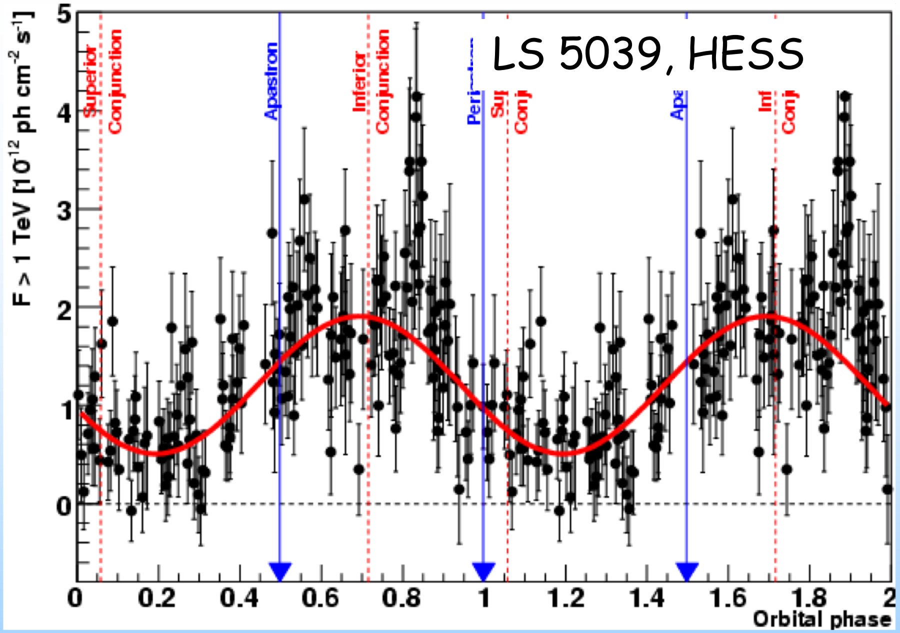


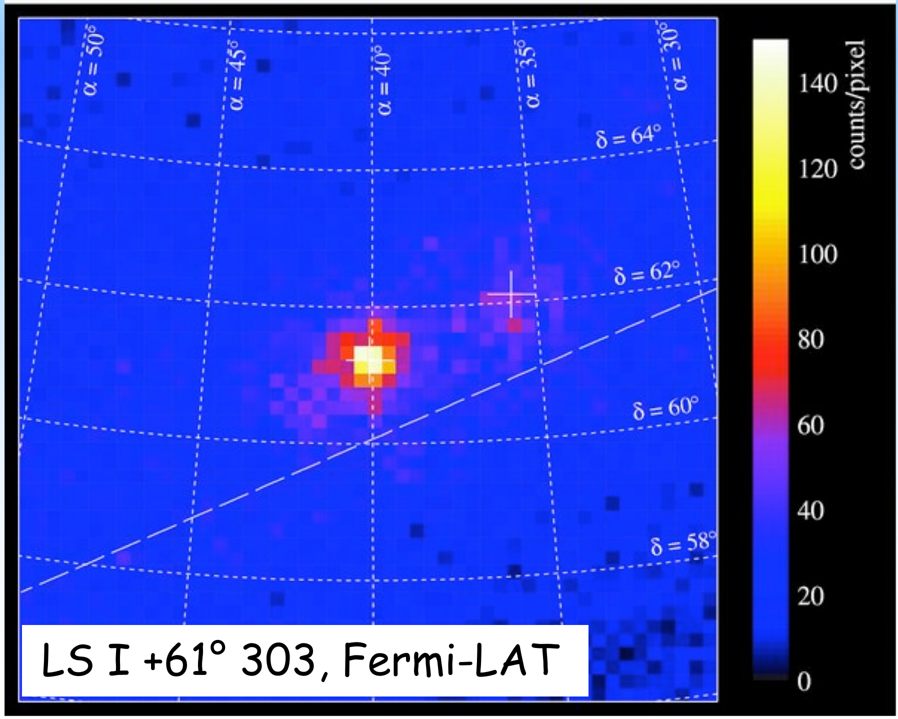
Summary

- Gamma-ray binaries are excellent laboratories for high energy particle astrophysics.
- VERITAS observations constitute a legacy archive, and continue to provide new insight.
- Multiwavelength observations are **critical** to discovery, and to understanding how these systems work. Progress sometimes requires patience…
- Fermi, and current generation TeV observatories including VERITAS continue to look – there may be more binaries hiding in the archives.
- CTA should see at least *some* more - one big observational question: How many GeV-faint gamma-ray binaries are there?

Backup

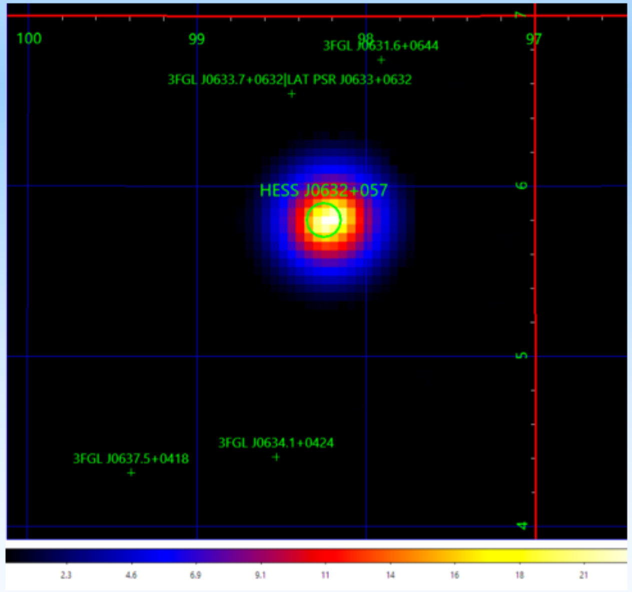
- 2004 – 2006: a few TeV sources strongly detected >100 GeV
  - PSR B1259-63 (H.E.S.S.)
  - LS 5039 (H.E.S.S.)
  - LS I +61° 303 (MAGIC)
- With good positions, high significance and repeatable detections, and clear, orbitally modulated variability, the associations are definitive.
- Fermi-LAT provided the next leap
  - Good sensitivity.
  - Good source localization.
  - Near continuous monitoring.
  - Firm ID of LS I +61° 303, LS 5039

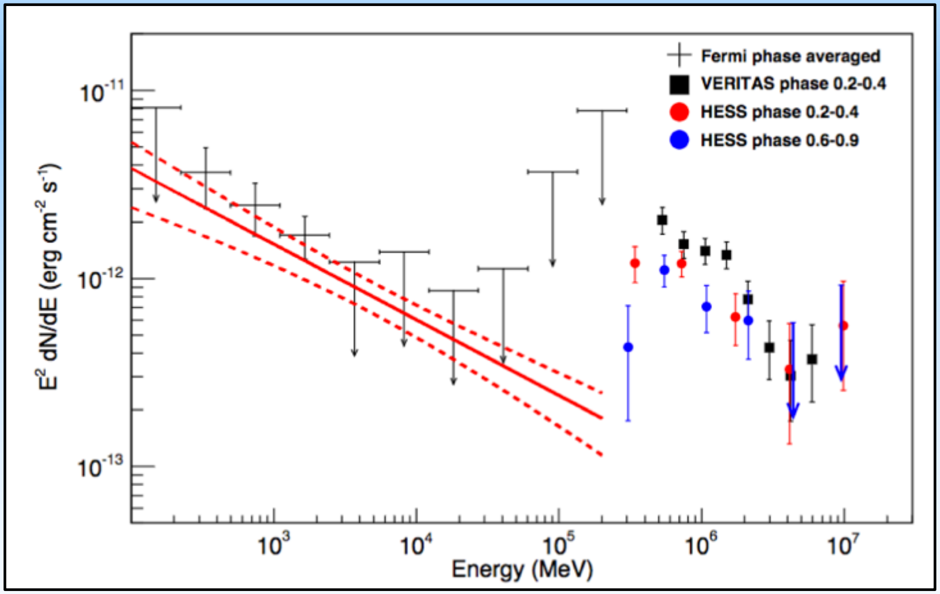




HESS J0632+057: GeV

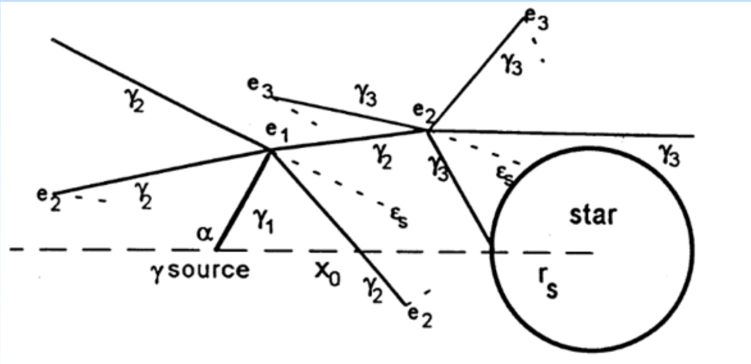
- First claimed at 3.6 σ based on two >200 GeV photons by Malyshev (2016)
- Careful pass 8 analysis by Li et al (2017) reveals faint modulated lower energy (<10 GeV) emission component.

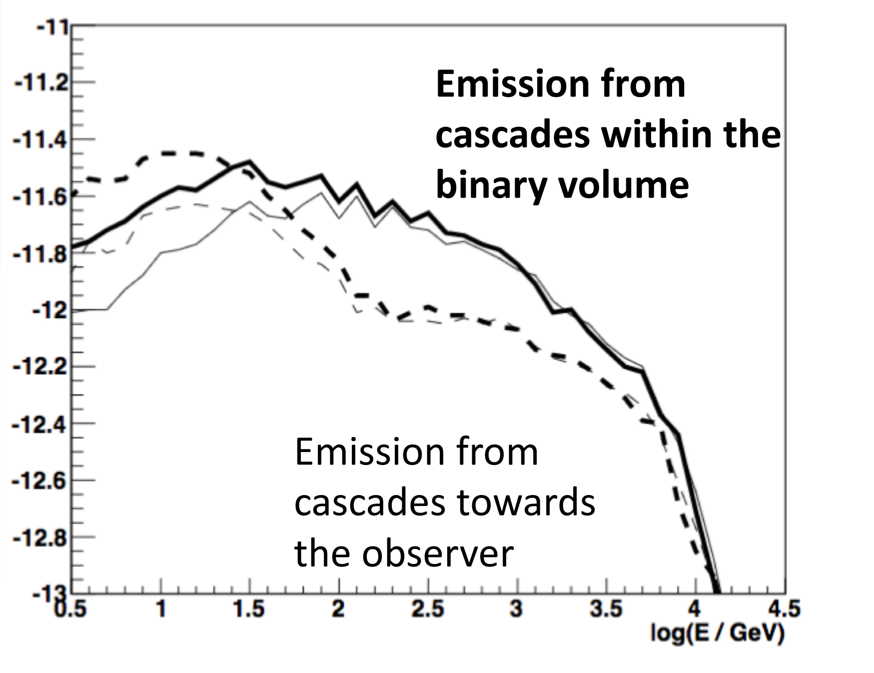




Pair cascades

- Very high energy gamma-ray photons may trigger electromagnetic cascades when they pair produce.
- These particles then produce inverse Compton gamma-ray emission in all directions, since the electrons/positrons are isotropized by strong magnetic fields (e.g. Bednarek 1997)
- The cascade development depends upon propagation through the anisotropic stellar photon fields.



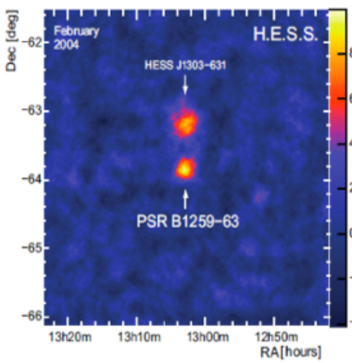


TeV Gamma-ray binaries today

- All show TeV variability tied to the orbital period of the binary system.
- Huge range of orbital parameters and stellar environments.

P=3.4 **years**

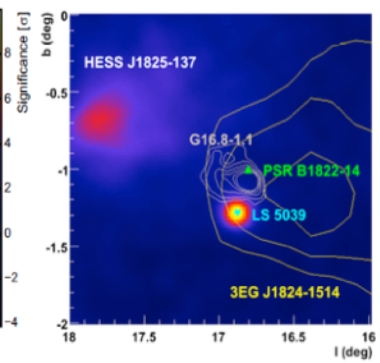
2004



PSR B1259-63

P=3.9 days

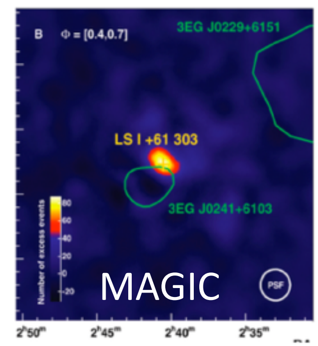
2005



LS 5039

P=26.5 days

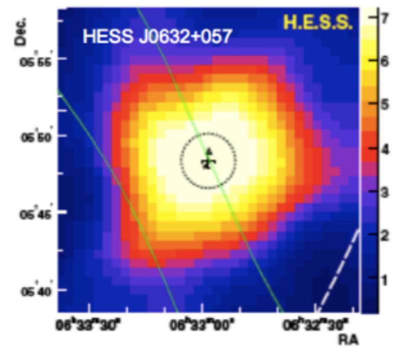
2006



LS I+61 303

P=315 days

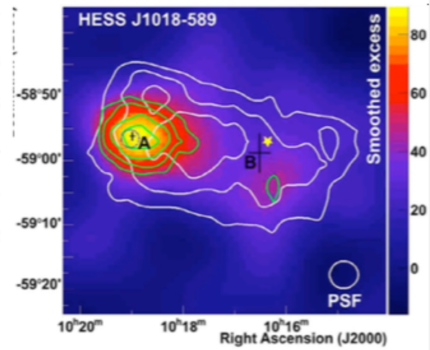
2008



HESS J0632+057

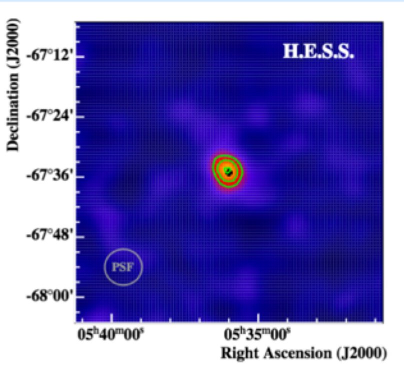
P= 16.6 days

2012



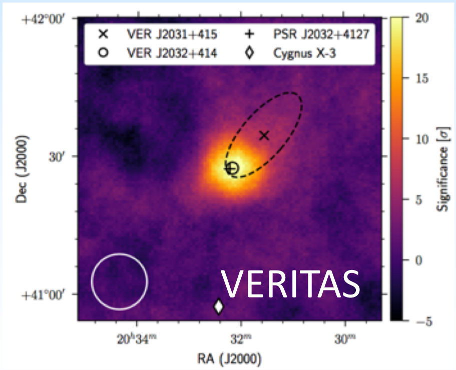
1FGL J1018.6-5856

P=10.3 days



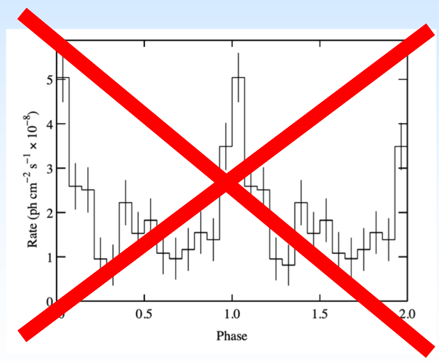
LMC P3

P=50 **years**



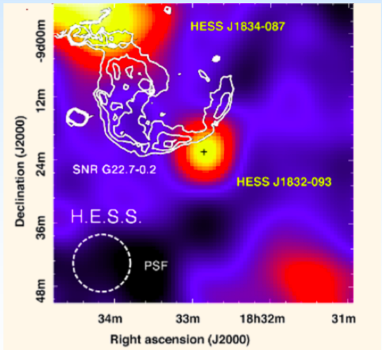
PSR J2032+4127

P=13.7 days



4 FGL J1405.1-6119

P=86 days

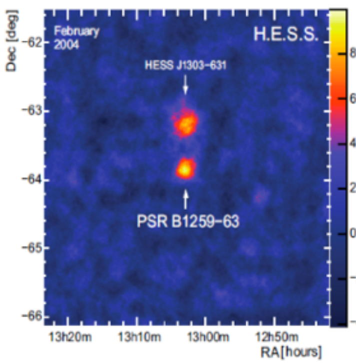


HESS J1832-093

GeV Gamma-ray binaries today

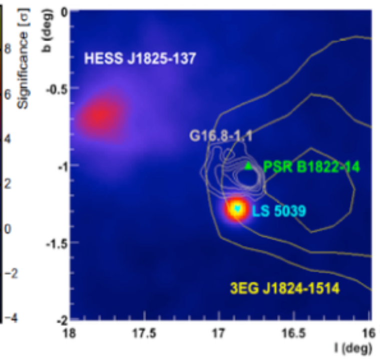
- GeV variability tied to the orbital period of the binary system

2004



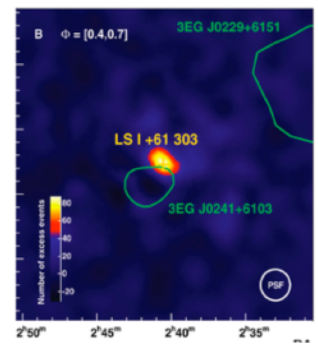
PSR B1259-63

2005



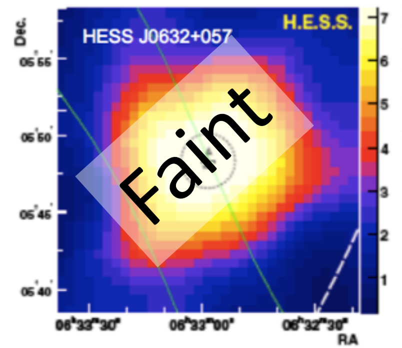
LS 5039

2006



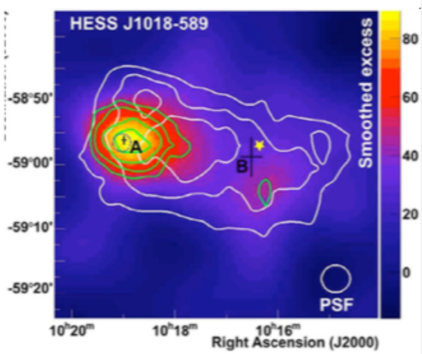
LS I+61 303

2008



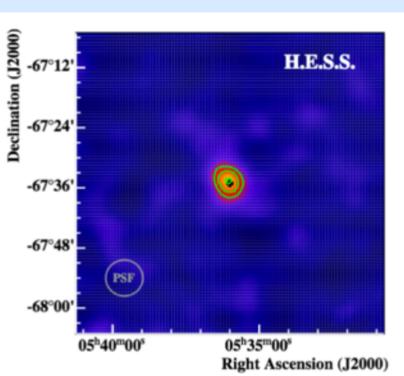
HESS J0632+057

2012



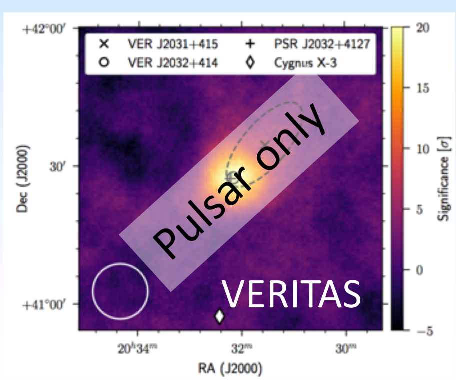
1FGL J1018.6-5856

2017



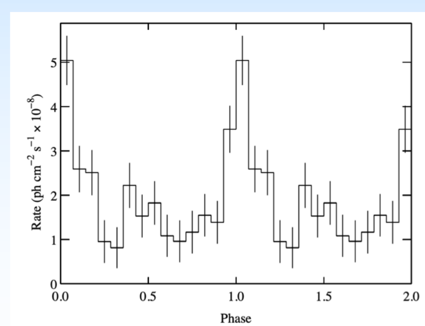
LMC P3

2017



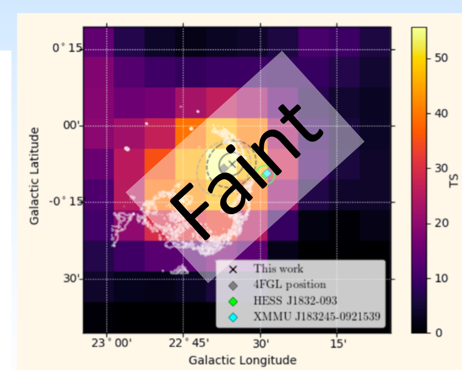
PSR J2032+4127

2019



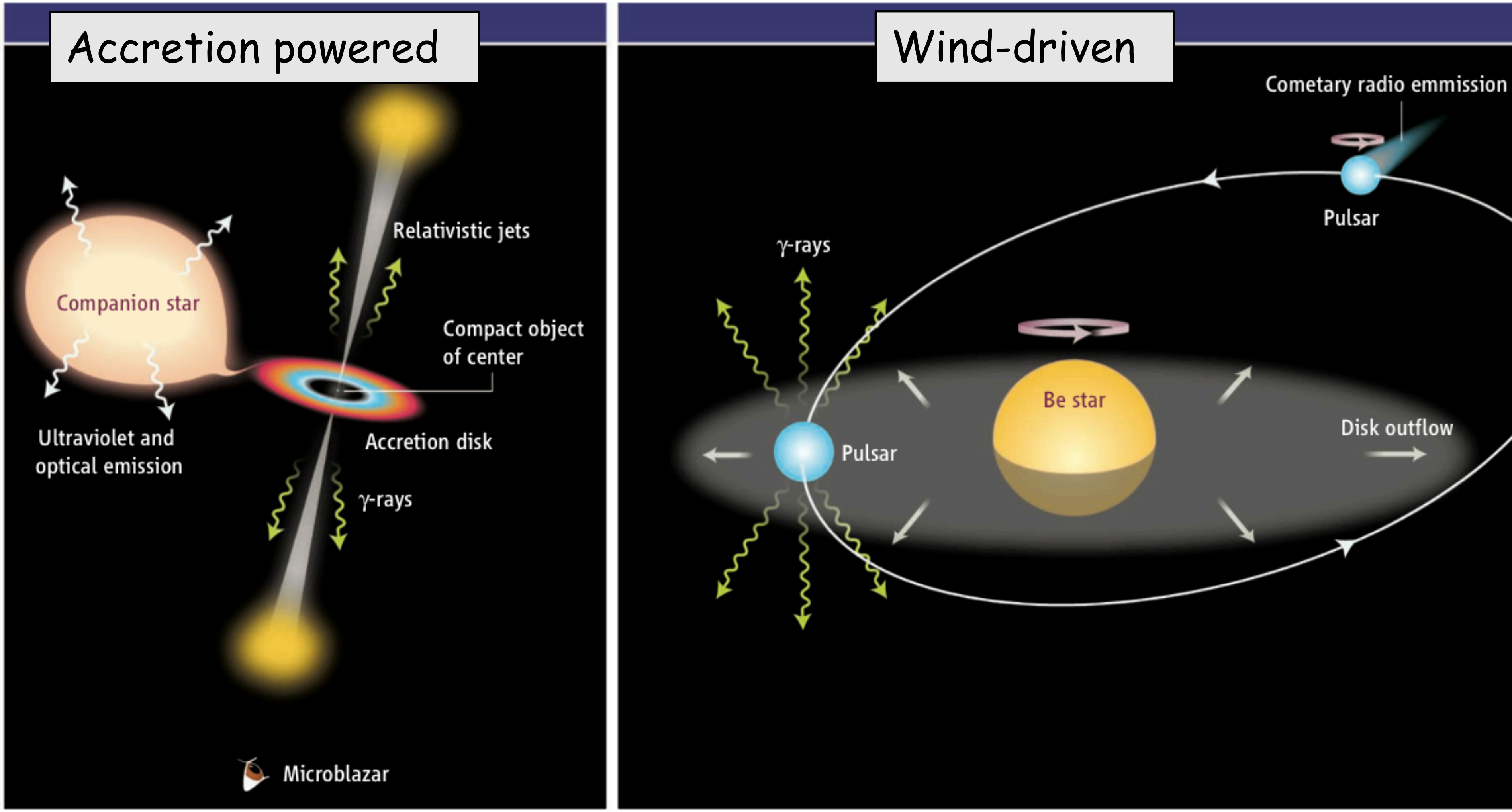
4 FGL J1405.1-6119

2020



HESS J1832-093

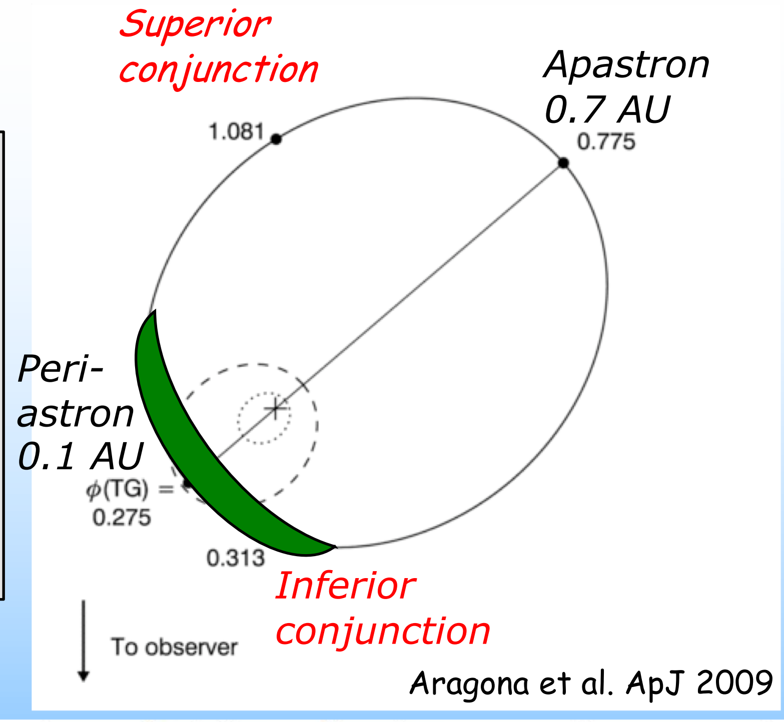
So what drives them?

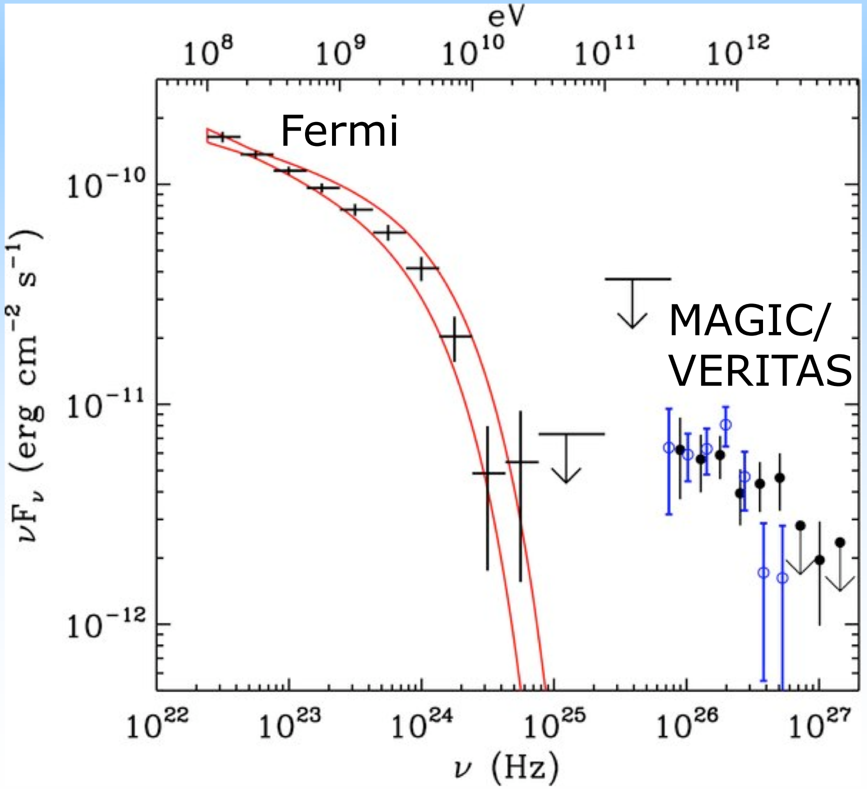


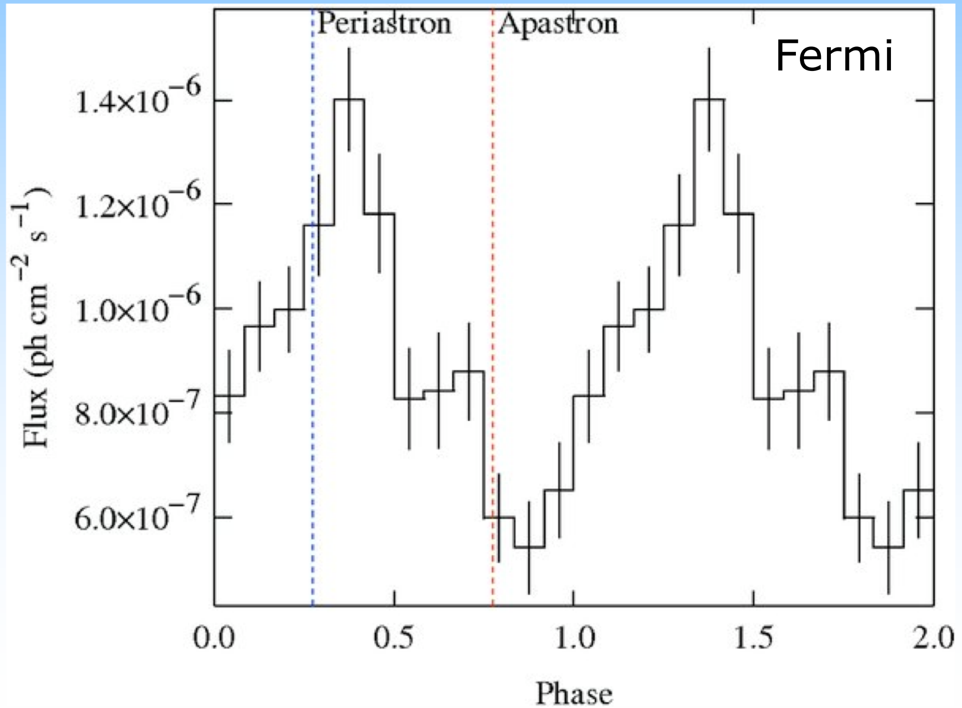
Mirabel (Science 309, 714, 2006)

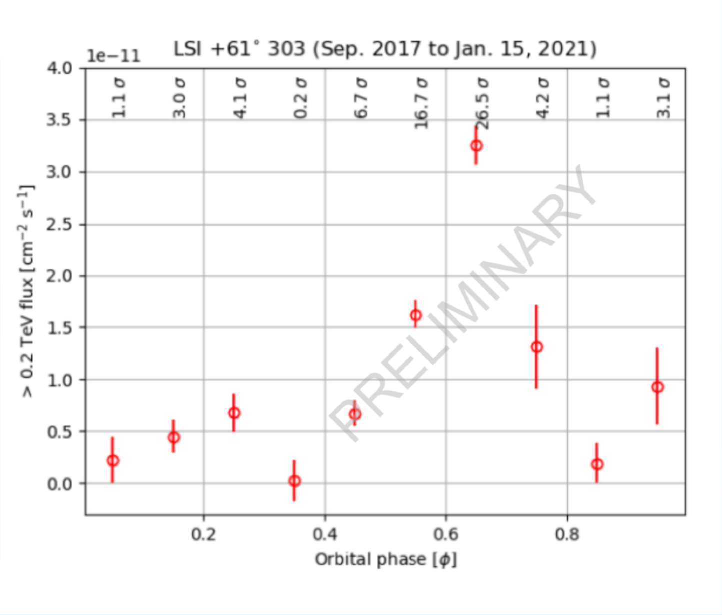
LS I +61° 303

- Detected by Fermi-LAT (BSL)
- Orbital modulation well measured
- Emission peaks near *periastron*
- Cut-off at 6 GeV observed between LAT and VERITAS
  - The GeV and TeV spectra do not connect smoothly. Suggests different mechanisms.









LSI +61° 303 (Sep. 2017 to Jan. 15, 2021)
1e−11
1.1 σ
3.0 σ
4.1 σ
0.2 σ
6.7 σ
16.7 σ
26.5 σ
4.2 σ
1.1 σ
3.1 σ
PRELIMINARY
> 0.2 TeV flux [cm⁻² s⁻¹]
Orbital phase [ϕ]

A few things to think about (far from exhaustive)…

What is the power source?
- Accretion-powered jet
- Pulsar wind

What is the particle acceleration mechanism?
- Jet shocks
- Magnetic reconnection
- Wind shocks

What are the dominant particles?
- Hadronic
- Leptonic

How are the γ-rays produced?
- Pion decay
- Inverse Compton
- Curvature Radiation

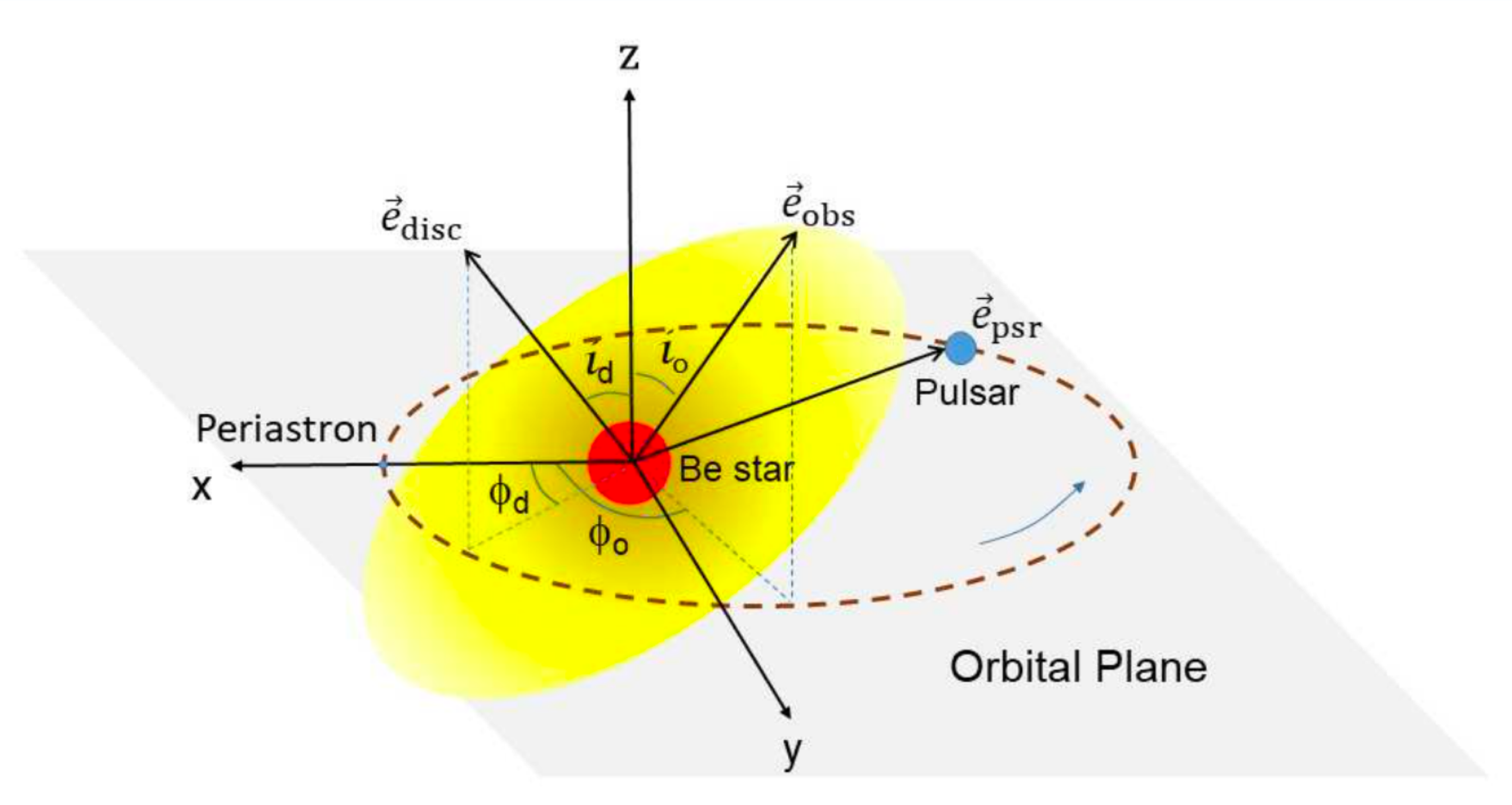
Where are the γ-rays produced?
- Near the jet
- Wind collision region
- Pulsar wind zone
- Circumstellar environment
- Pulsar magnetosphere

What modulates the flux?
- Geometry
- Photon fields
- Matter density
- B-fields

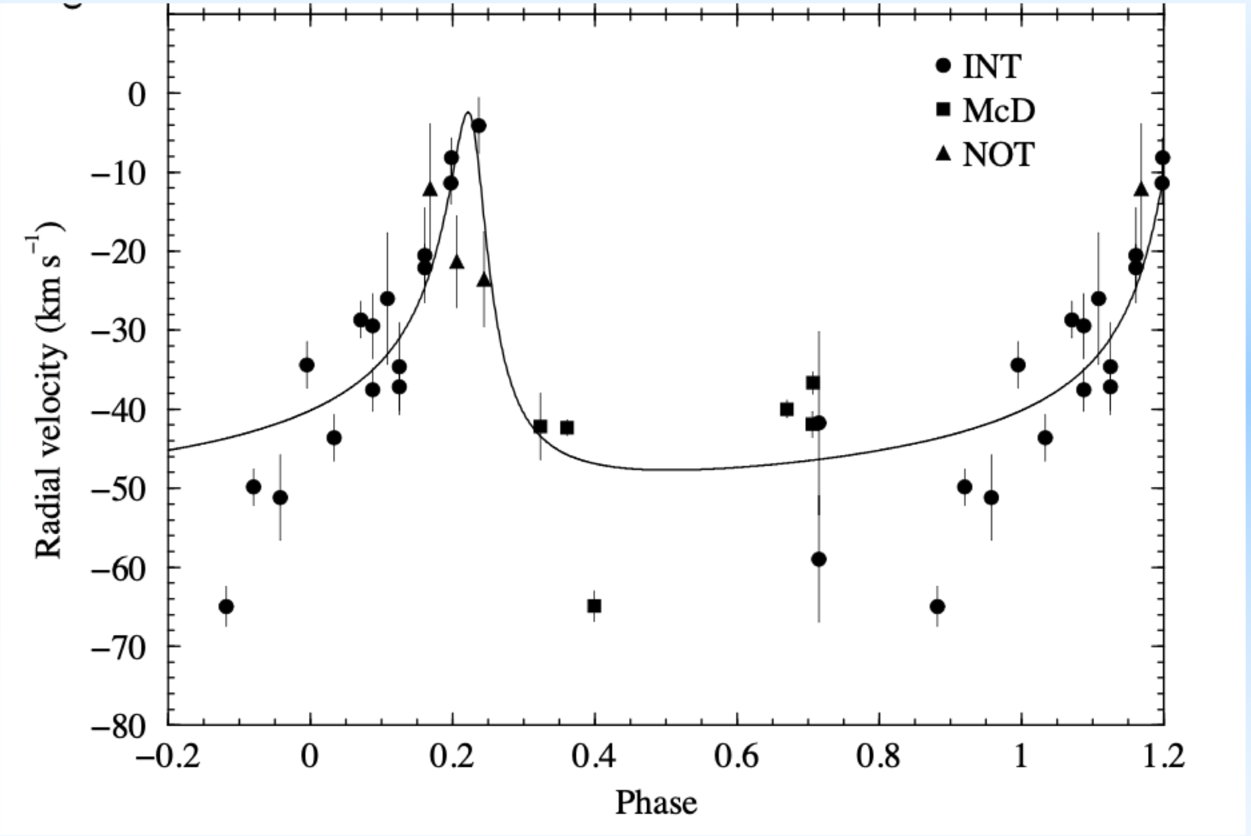
Other effects?
- Wind clumping
- Pair cascades
- Doppler boosting

Many of these are not mutually exclusive…

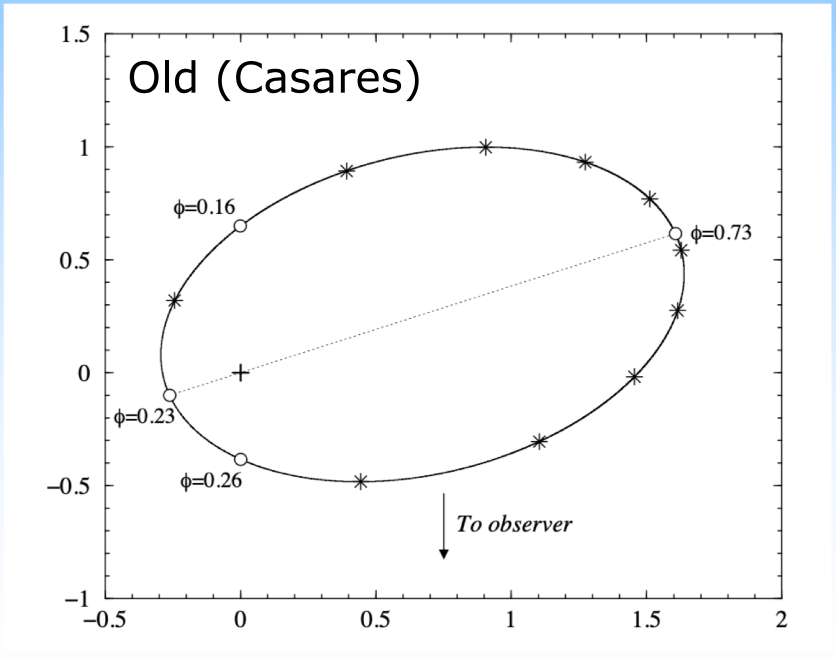
...And we rarely have complete information:

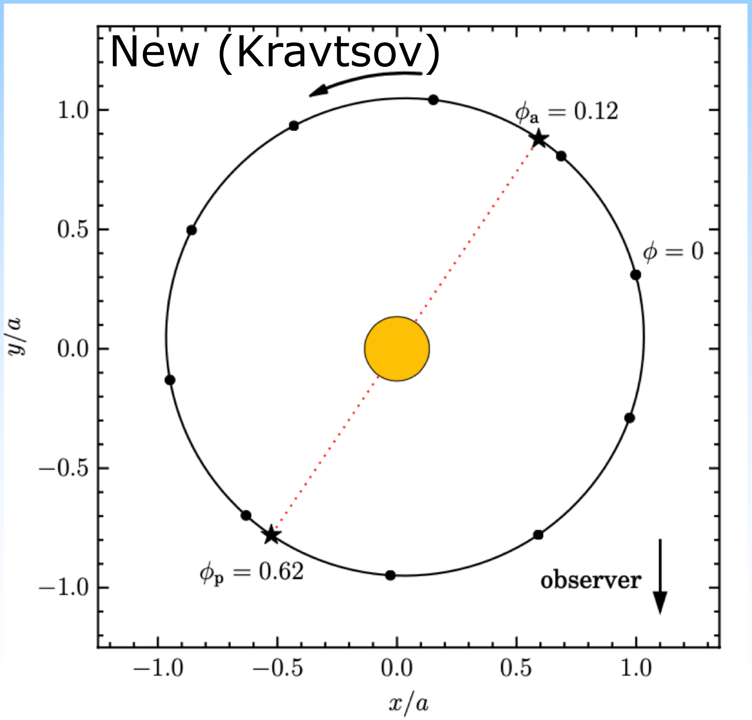


Radial velocity measured using spectral lines: LS I+61 303



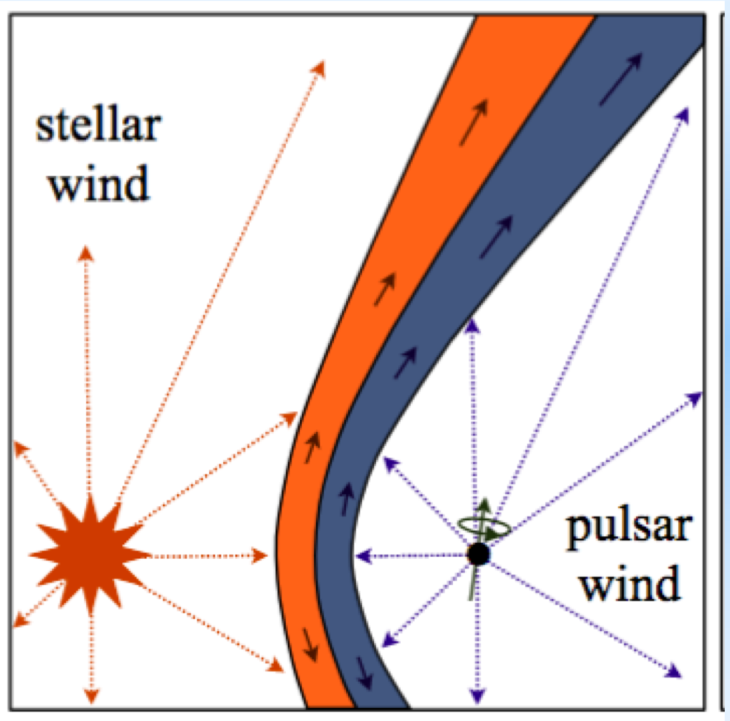
- The material producing the spectral lines is not the star!
  - It is in the circumstellar disk, or a gaseous shell *around* the star
- It may not correlate well with the orbital motion…
- Polarization measurements provide an alternative – and give a very different orbital solution for this object





The basic picture in the wind-driven scenario

- Pulsar wind and the stellar wind collide and form a shock.
- Location of the shock depends upon the relative wind momenta.
- Location of shock determines the magnetic field strength, and the photon and matter densities.
- Shock converts pulsar wind energy into accelerating particles (but how?),
- High energy particles produce gamma-rays.



Dubus et al, 2015

$$\frac{R}{d} \approx \frac{1}{1+\eta^{1/2}} \quad \text{with} \quad \eta = \frac{\dot{M}_{\rm w} v_{\rm w}}{\dot{E}/c}$$

Competing processes

- Inverse Compton gamma-ray production:
  - High energy electrons boost stellar photons to gamma-ray energies.
  - **Maximum energy** given by a **head-on collision** – natural asymmetry.
- At superior conjunction, Inverse Compton production peaks over **all** energies.
- However… gamma-rays with energies >30 GeV are absorbed by pair production with starlight!
- At superior conjunction, ***TeV*** photons are most heavily absorbed.
- Leads to a natural **anti-correlation** between GeV and TeV lightcurves

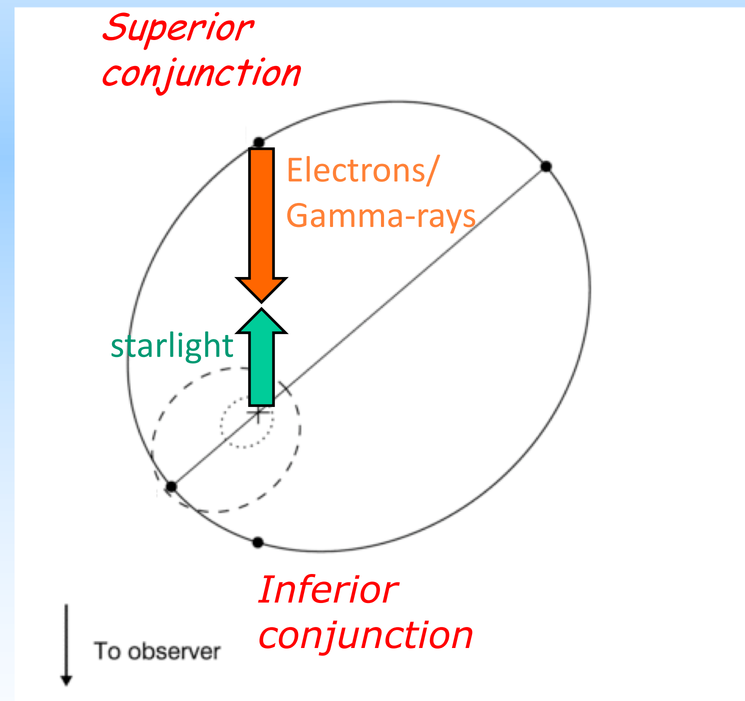
$$\hbar\omega_{out} = \gamma^2 \hbar\omega_{in} [1+\beta\cos\theta]^2$$

for a head-on collision $\theta = 0, \cos\theta = 1$

relativistic $\Rightarrow \beta \sim 1$

$$\hbar\omega_{max} = \gamma^2 \hbar\omega_{in} (1+1)^2$$

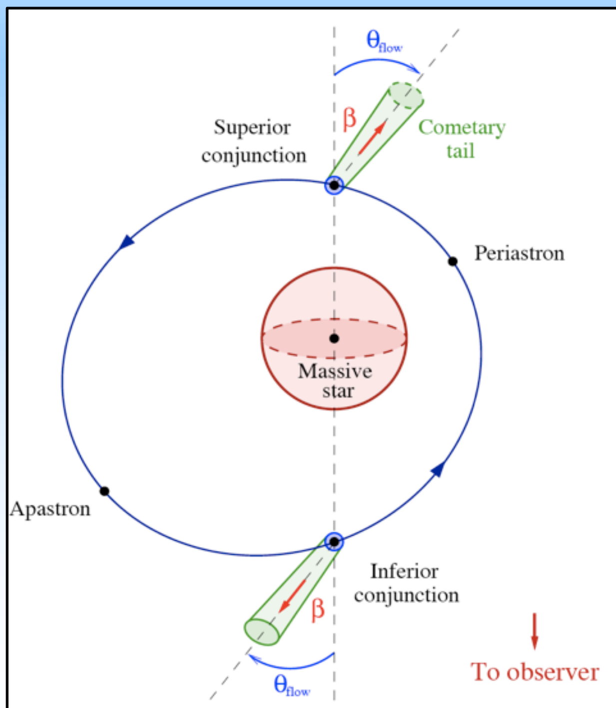
$$\hbar\omega_{max} = 4\gamma^2 \hbar\omega_{in}$$



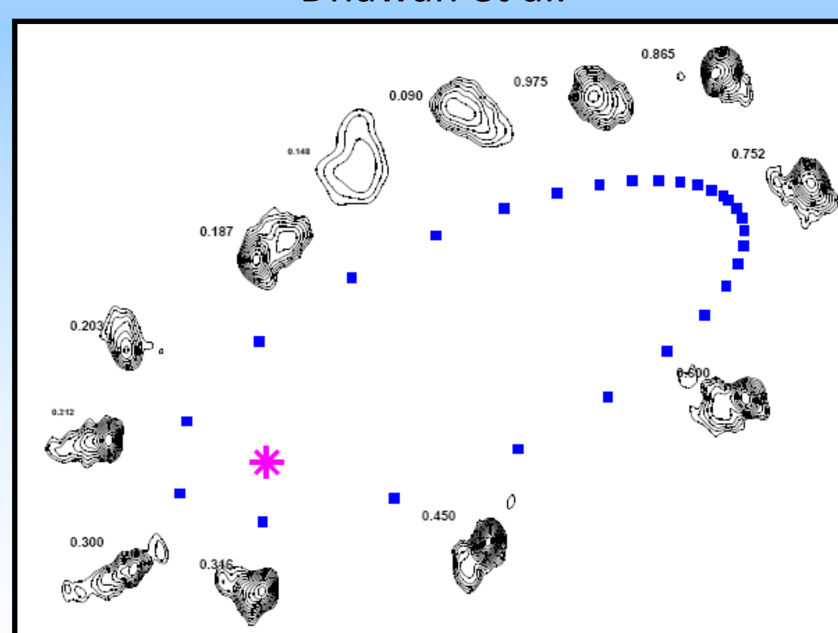
Doppler boosting

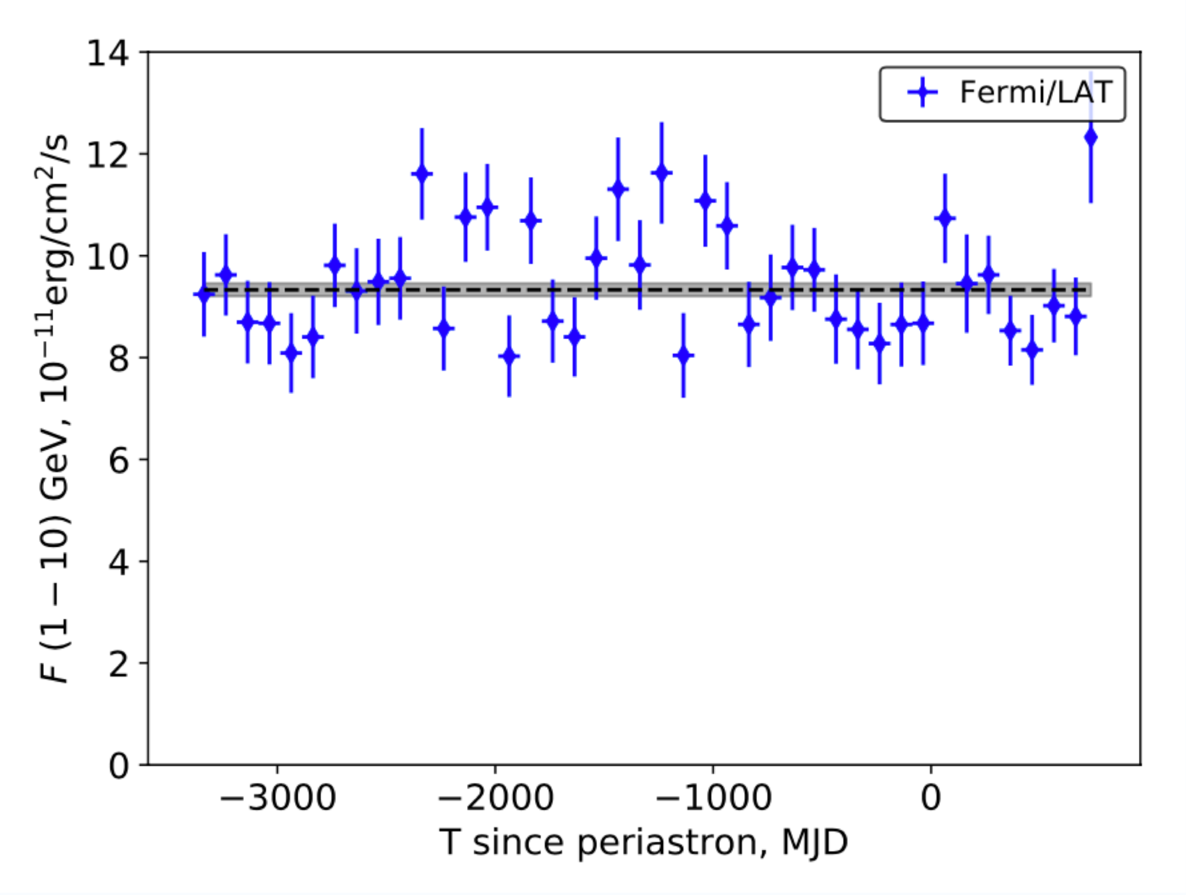
$$D = \frac{1}{\gamma(1 - \beta\cos\theta)}$$

- The shocked wind is mildly relativistic, and flows away from the shock apex asymmetrically
- Leads to **Doppler boosting**, which either enhances or suppresses gamma-ray emission
- Boost factor depends upon the angle at which the shocked wind is viewed
  - analogous to blazar jets.
- Orbitally modulated radio structures have been observed (e.g. LS I+61 303)



Dhawan et al.





Chernyakova et al arXiv:2004.11884