UNIVERSITY OF DELAWARE

DEPARTMENT OF Physics and Astronomy

The Bartol Research Institute at the University of Delaware

VERITAS

cta

Gamma-ray Binary Systems

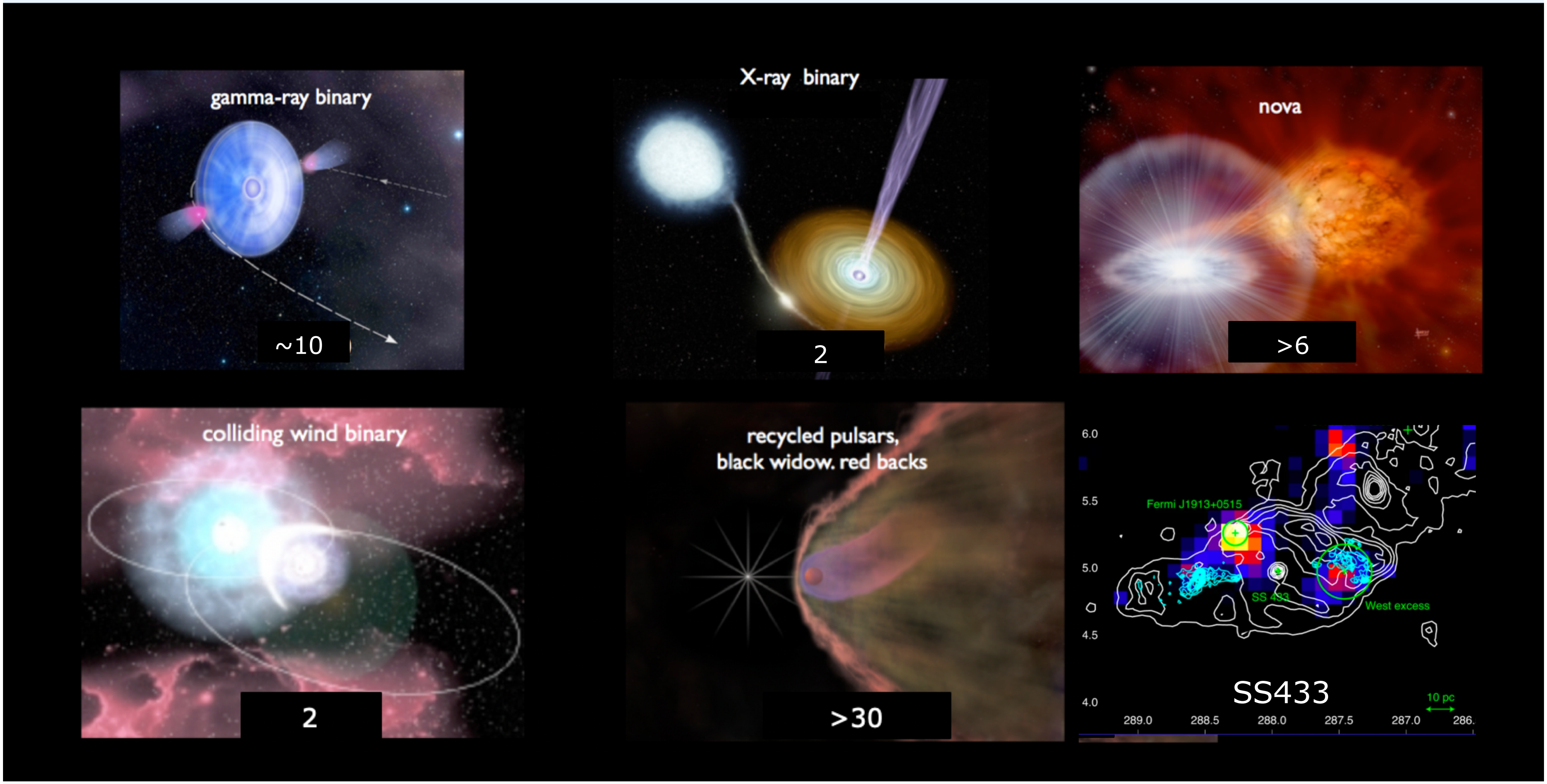
Jamie Holder

Bartol Research Institute/ University of Delaware

2021 APS April Meeting My spare room.

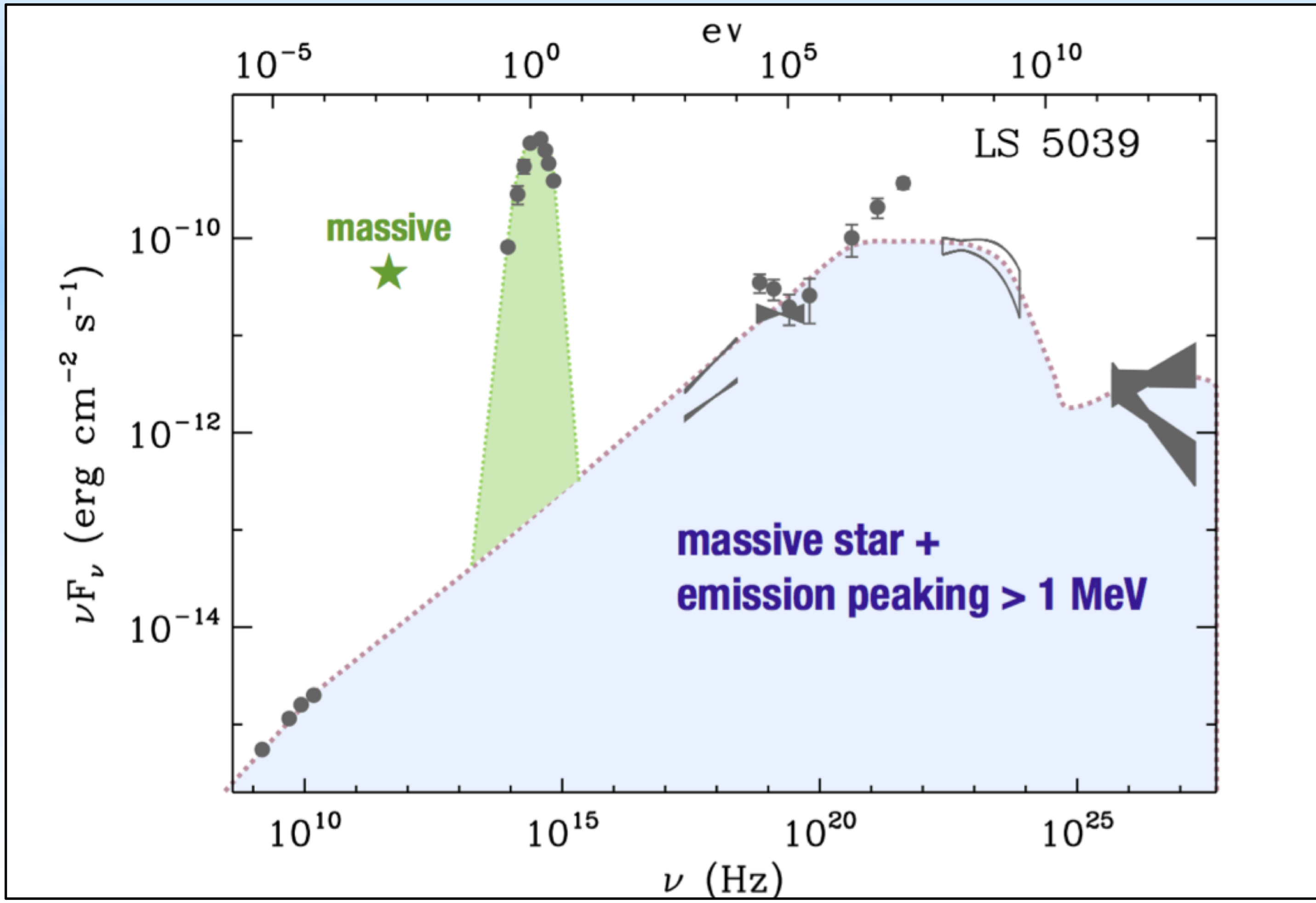
With thanks to Guillaume Dubus, Fermi Summer School 2014

Systems with 2 objects that emit gamma-rays:

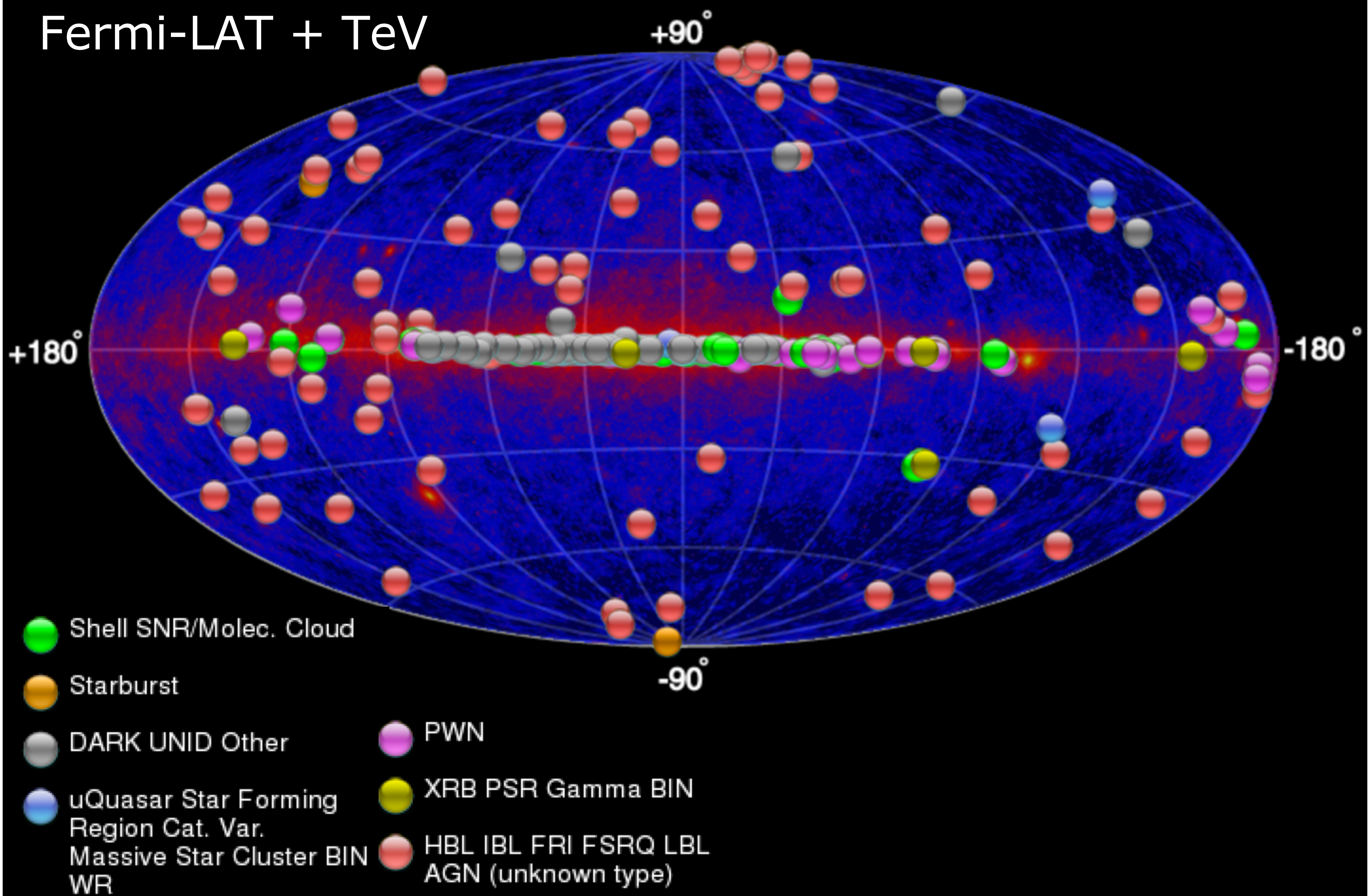


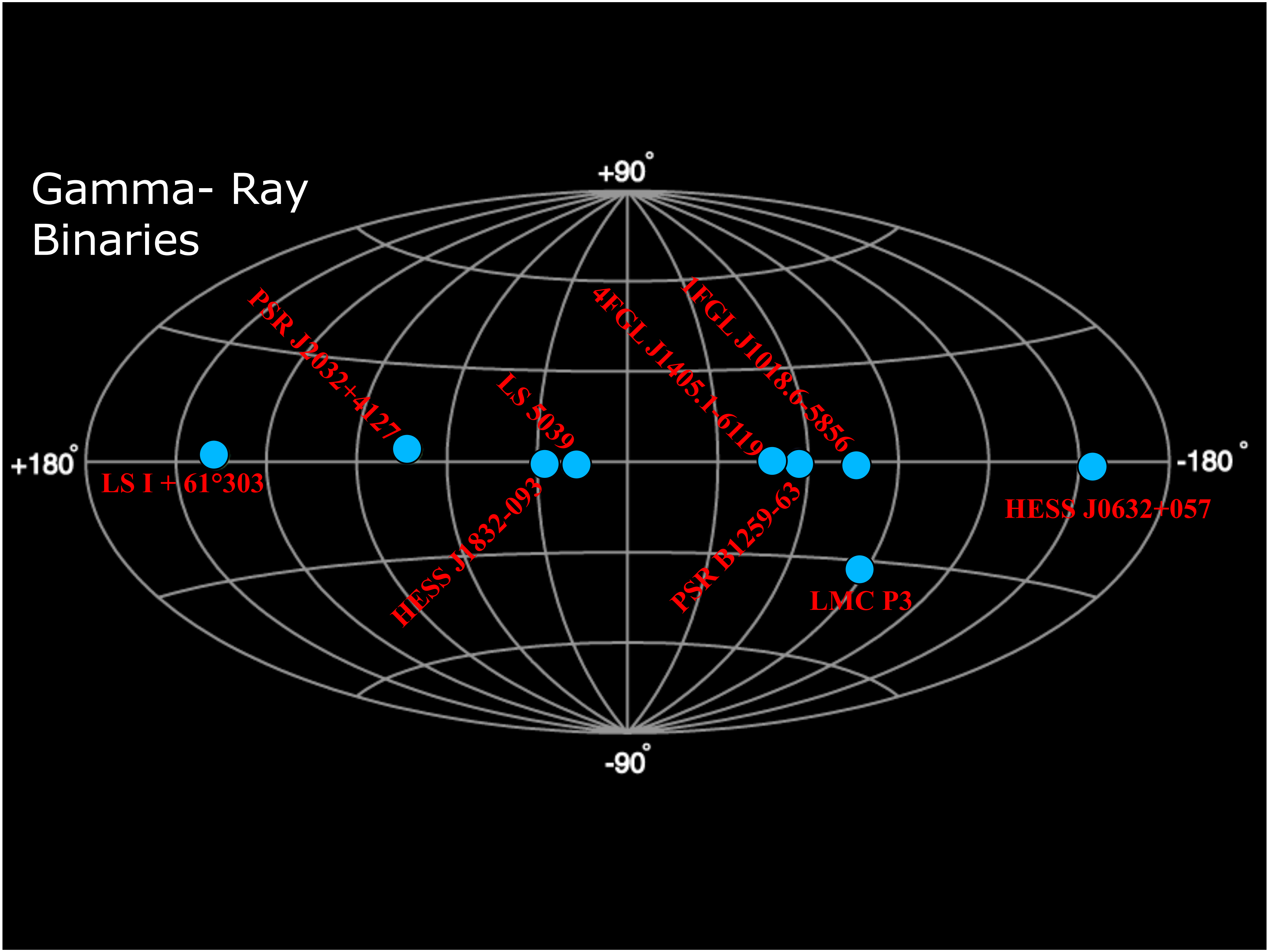
Gamma-ray binaries

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



The Gamma-ray sky




Gamma- Ray Binaries
+90°
-90°
+180°
-180°
PSR J2032+4127
LS 5039
4FGL J1405.1-6119
1FGL J1018.6-5856
LS I + 61°303
HESS J1832-093
PSR B1259-63
HESS J0632+057
LMC P3

Why are these few so interesting?

- Binaries are 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.

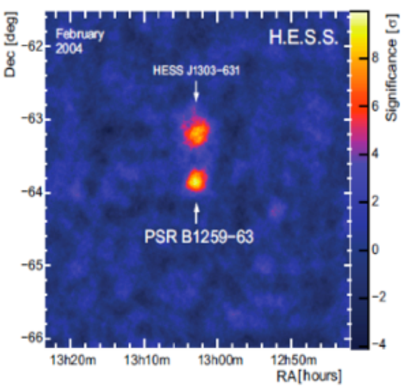
- *Caveat*: The systems are complex, with many competing processes, and the orbital parameters, the nature of the binary components and the conditions in the circumstellar environment are generally not well known.

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**

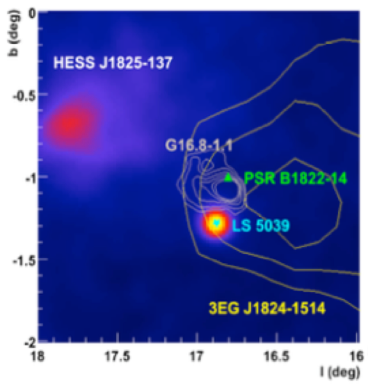
2004



PSR B1259-63

P=3.9 days

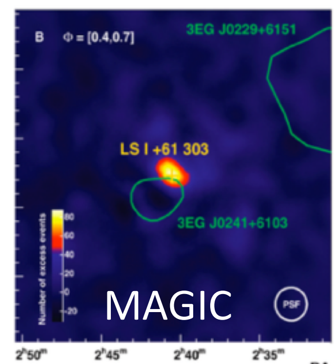
2005



LS 5039

P=26.5 days

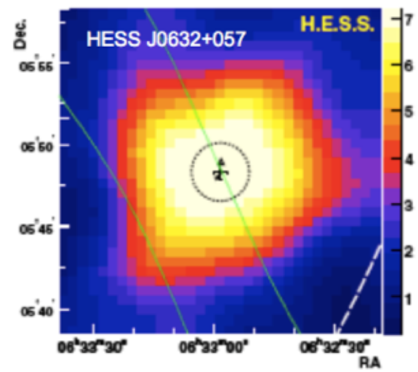
2006



LS I+61 303

P=315 days

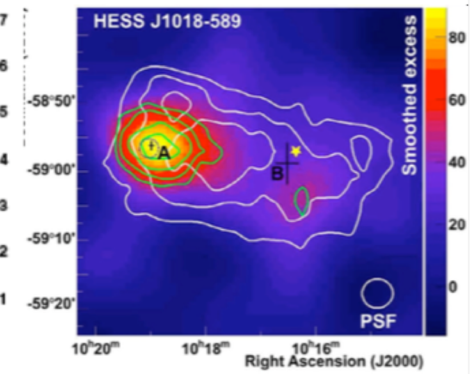
2008



HESS J0632+057

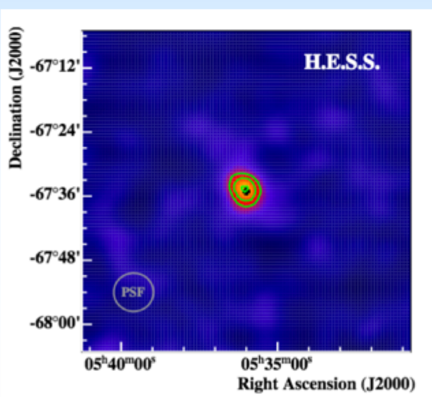
P= 16.6 days

2012



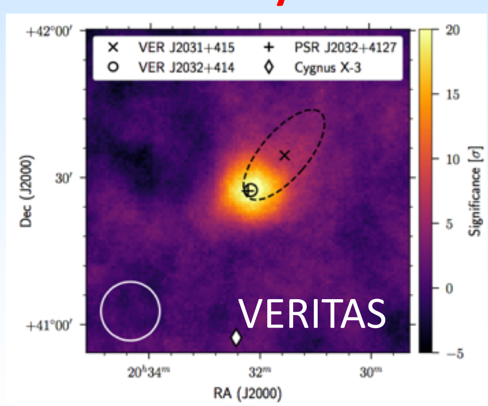
1FGL J1018.6-5856

P=10.3 days



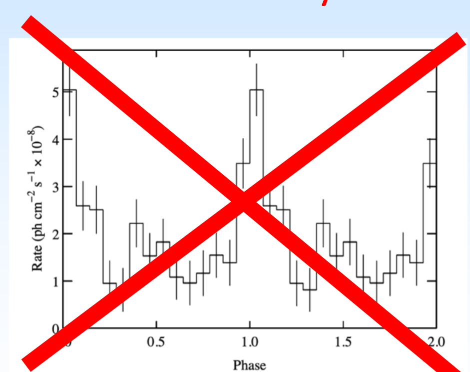
LMC P3

P=50 **years**



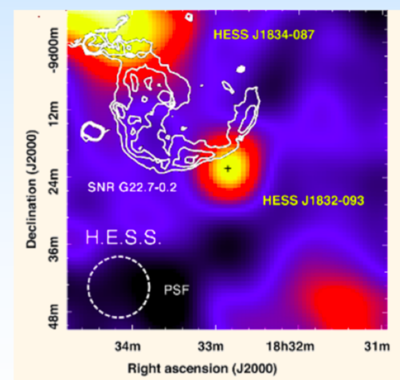
PSR J2032+4127

P=13.7 days



4 FGL J1405.1-6119

P=86 days

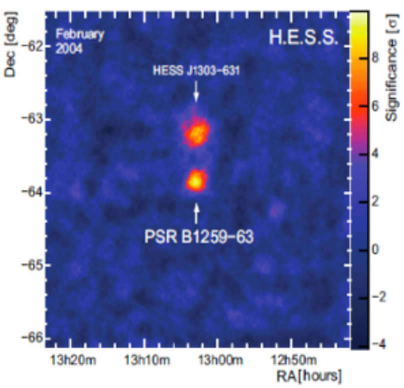


HESS J1832-093

GeV Gamma-ray binaries today

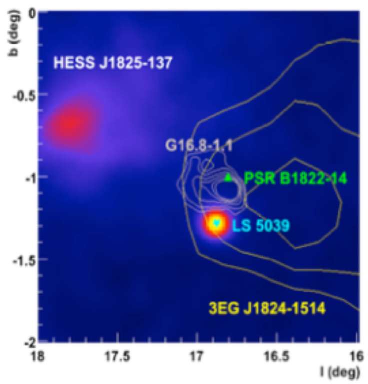
- GeV variability tied to the orbital period of the binary system

2004



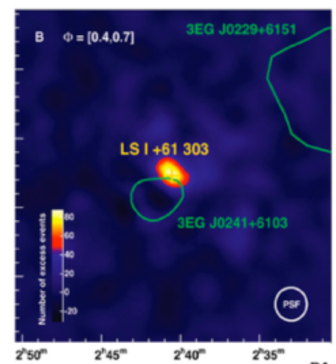
PSR B1259-63

2005



LS 5039

2006



LS I+61 303

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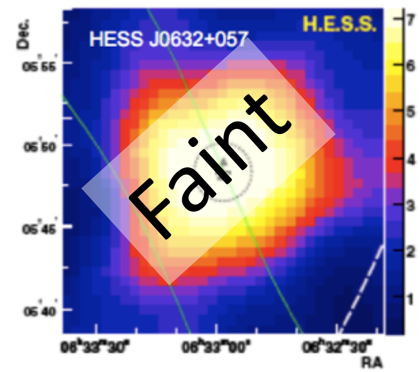
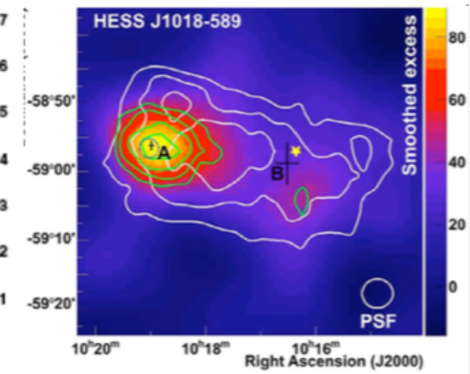


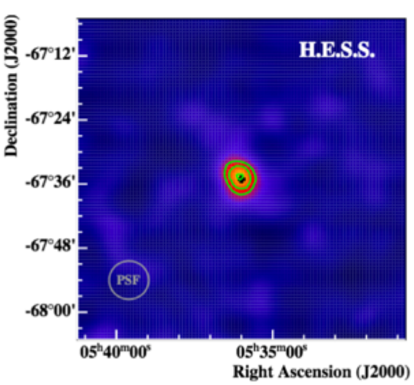
HESS J0632+057

2012



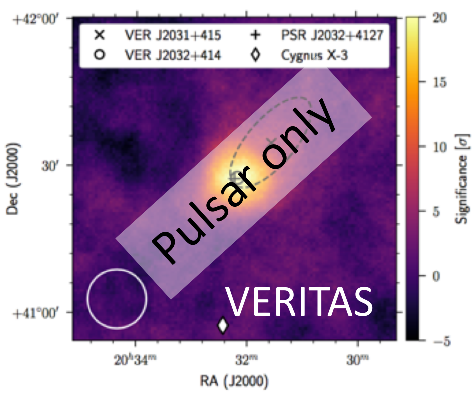
1FGL J1018.6-5856

2017



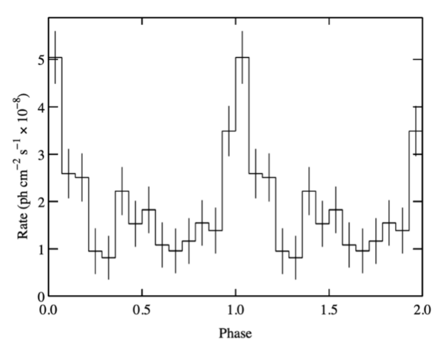
LMC P3

2017



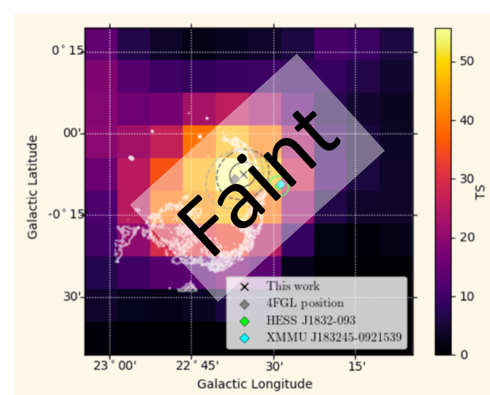
PSR J2032+4127

2019



4 FGL J1405.1-6119

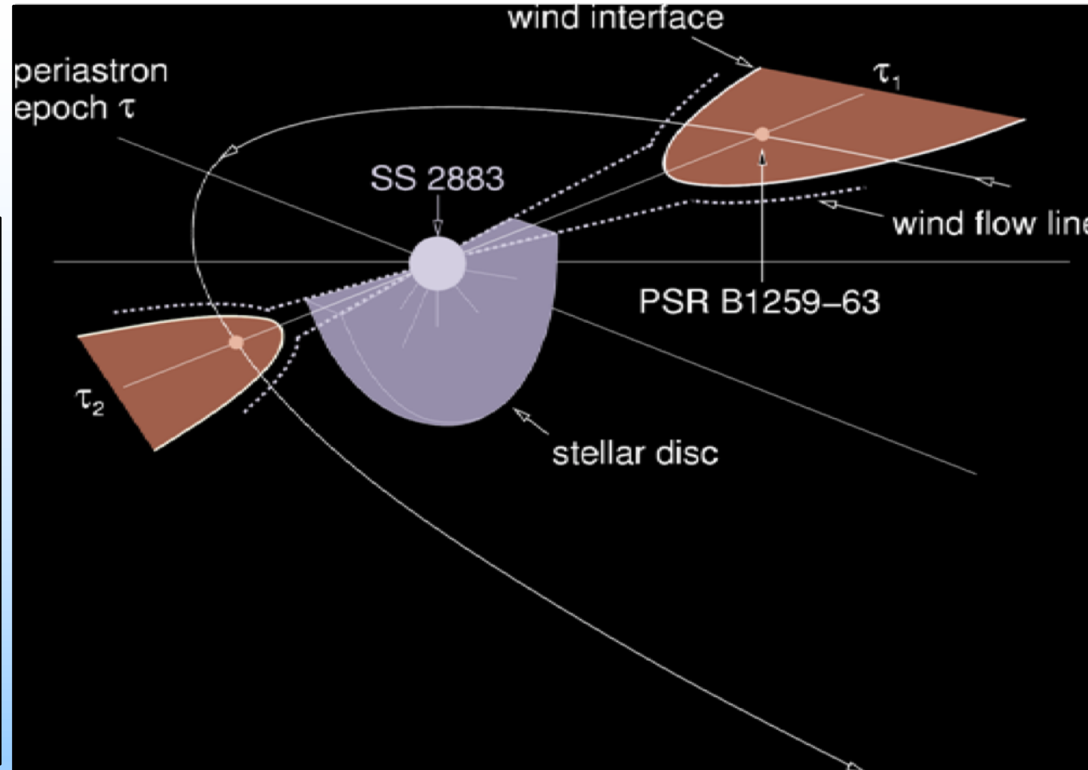
2020

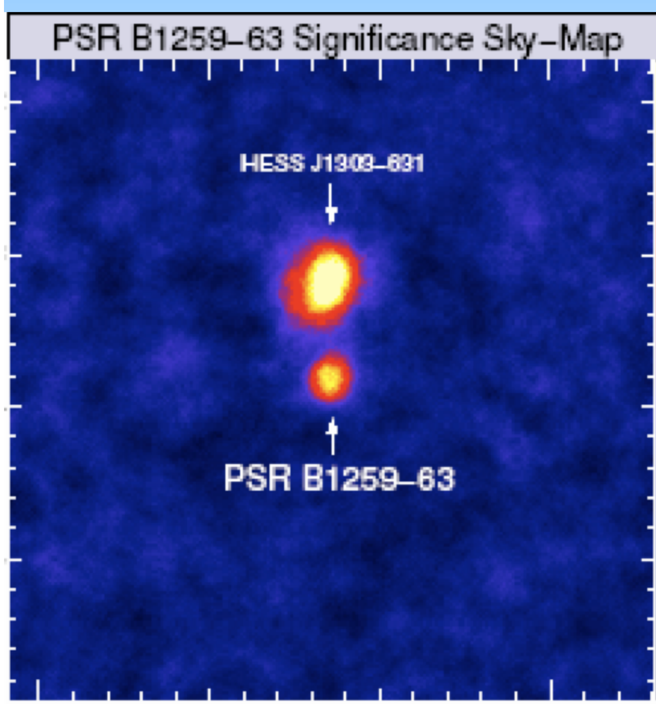


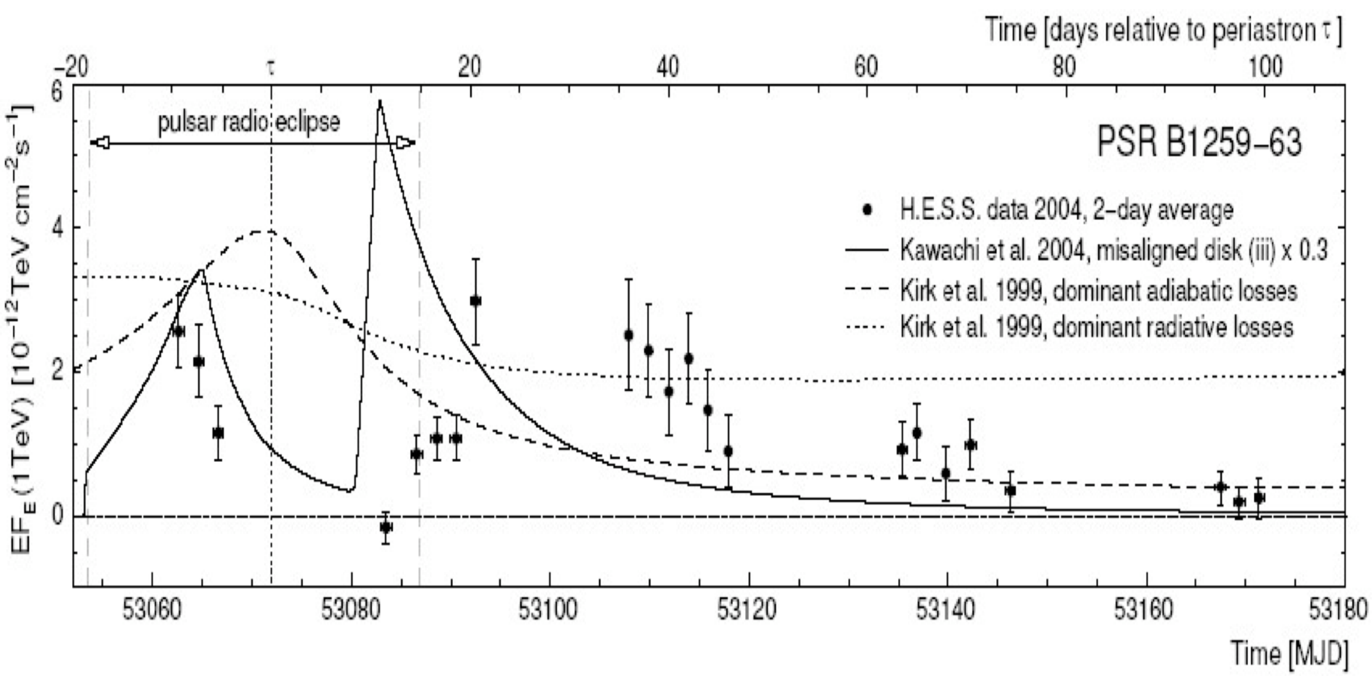
HESS J1832-093

The Pulsar wind Binary: PSR B1259-63

- 48 ms pulsar orbiting a B2e companion with inclined disk.
- 3.4 year, highly eccentric orbit.
- ~0.7 A.U separation at periastron (10 AU at apastron).
- First Detected by HESS over 2004 periastron.

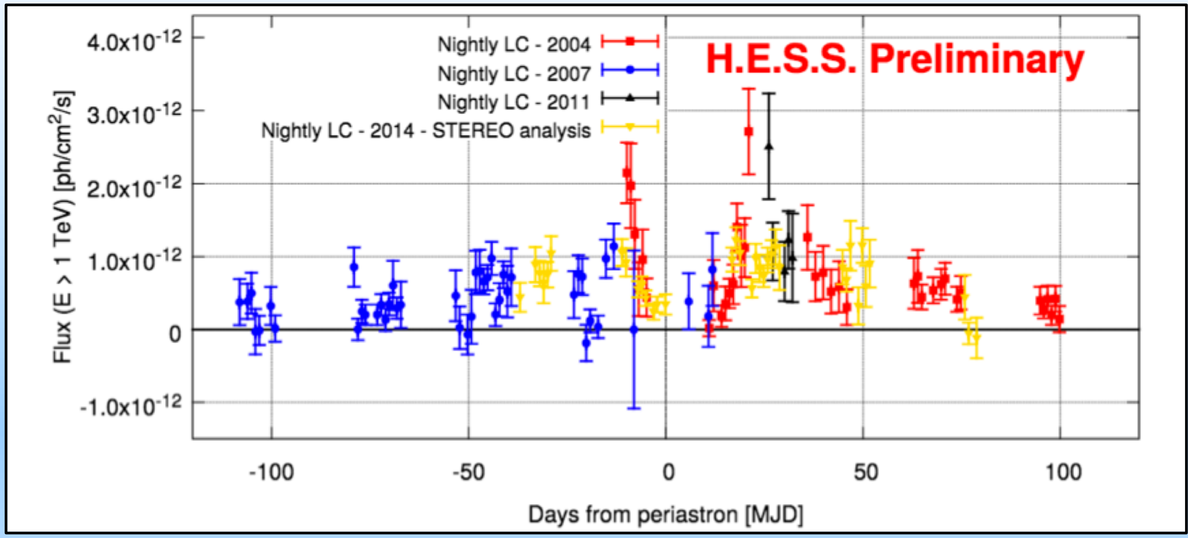




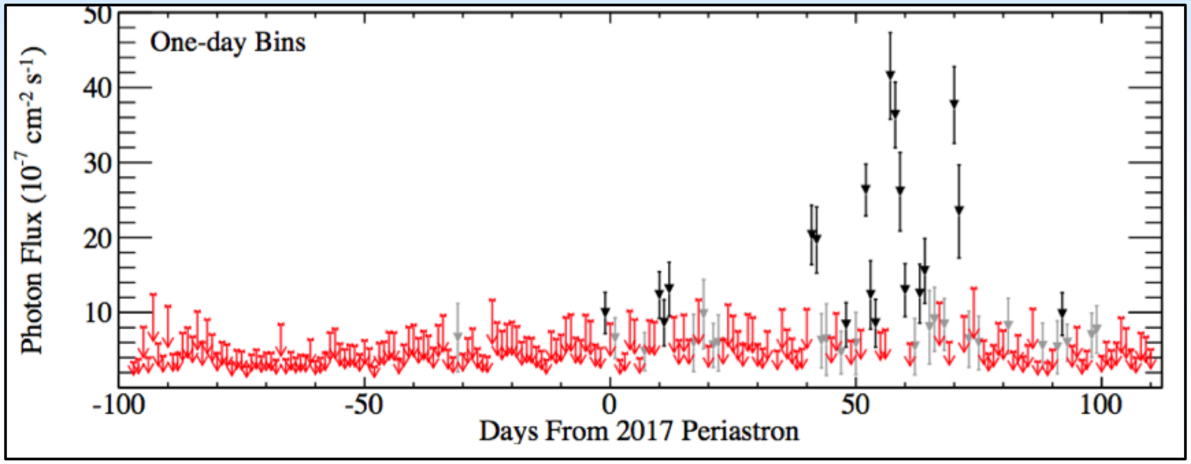


The Pulsar wind Binary: PSR B1259-63

- TeV: double-peaked lightcurve, with a sharp dip shortly after periastron.
- TeV emission corresponds to ~1% of the pulsar spin-down energy.

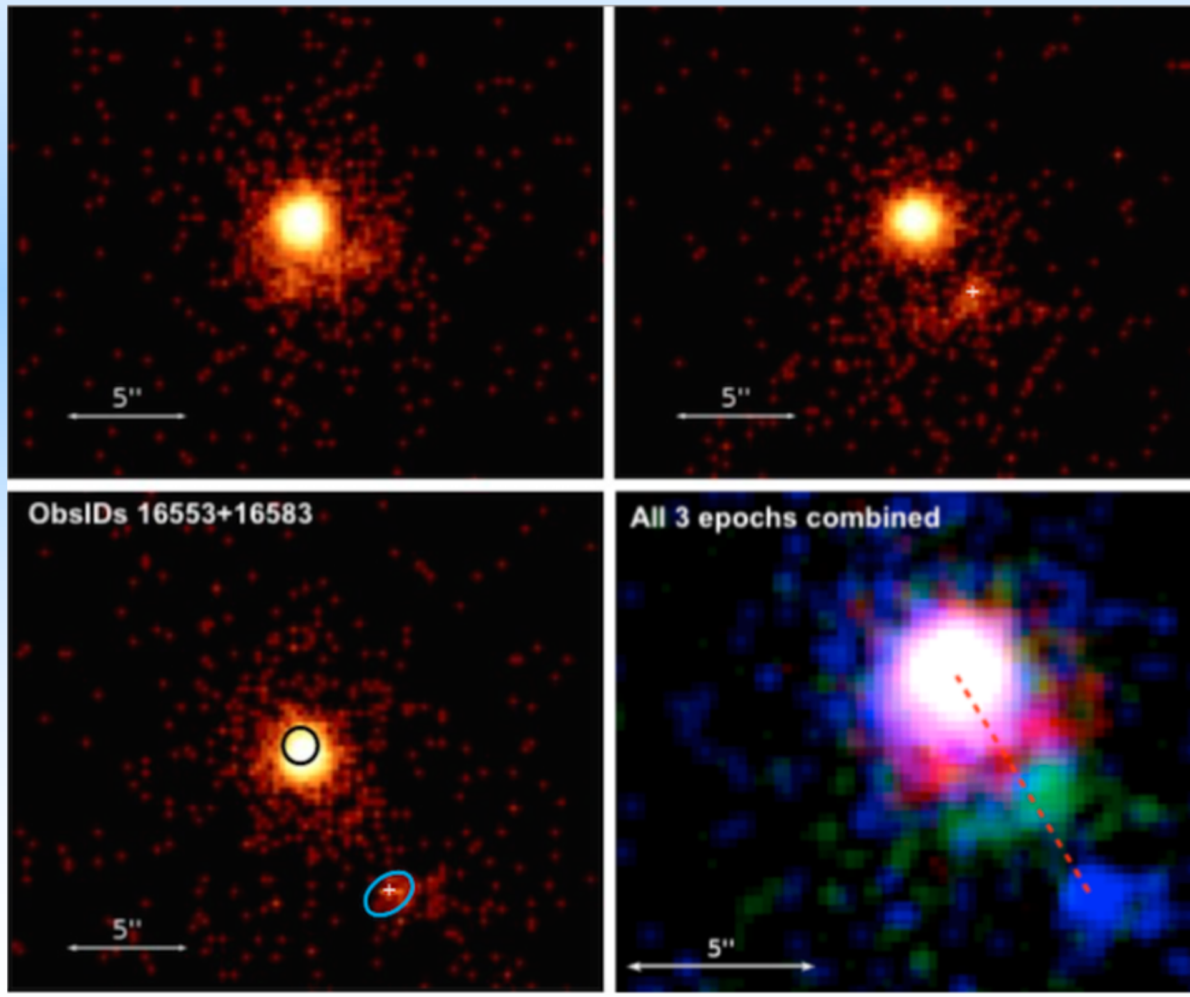


- GeV: bright flares, 30 – 70 days after periastron. Flares show rapid variability
- GeV emission > 100% of the pulsar spin-down energy.



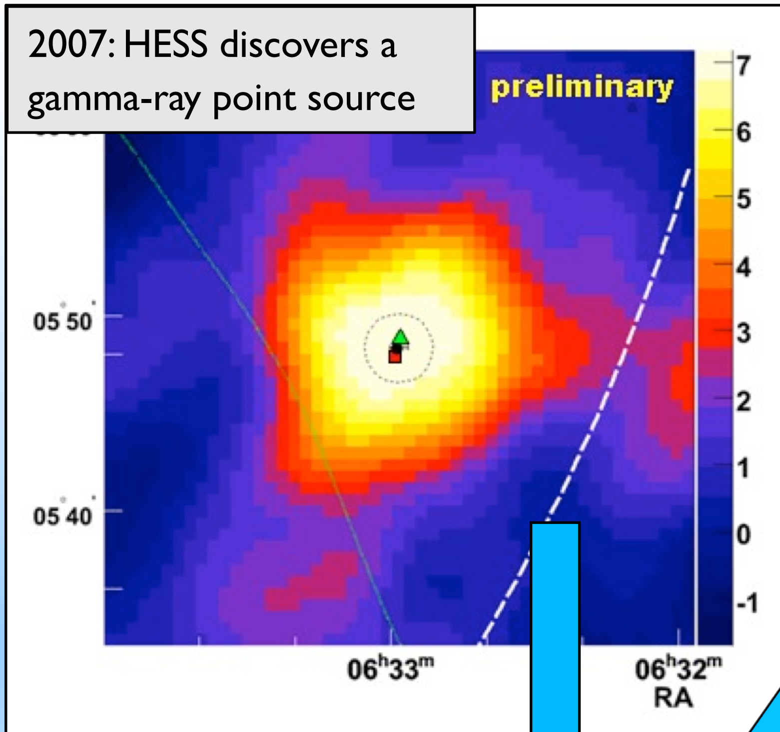
The Pulsar wind Binary: PSR B1259-63

- Chandra observations reveal an extended object moving away from the system with a projected velocity of 0.07c (Pavlov et al., 2015).
- May be a fragment of the decretion disk, ejected by interaction with the pulsar?

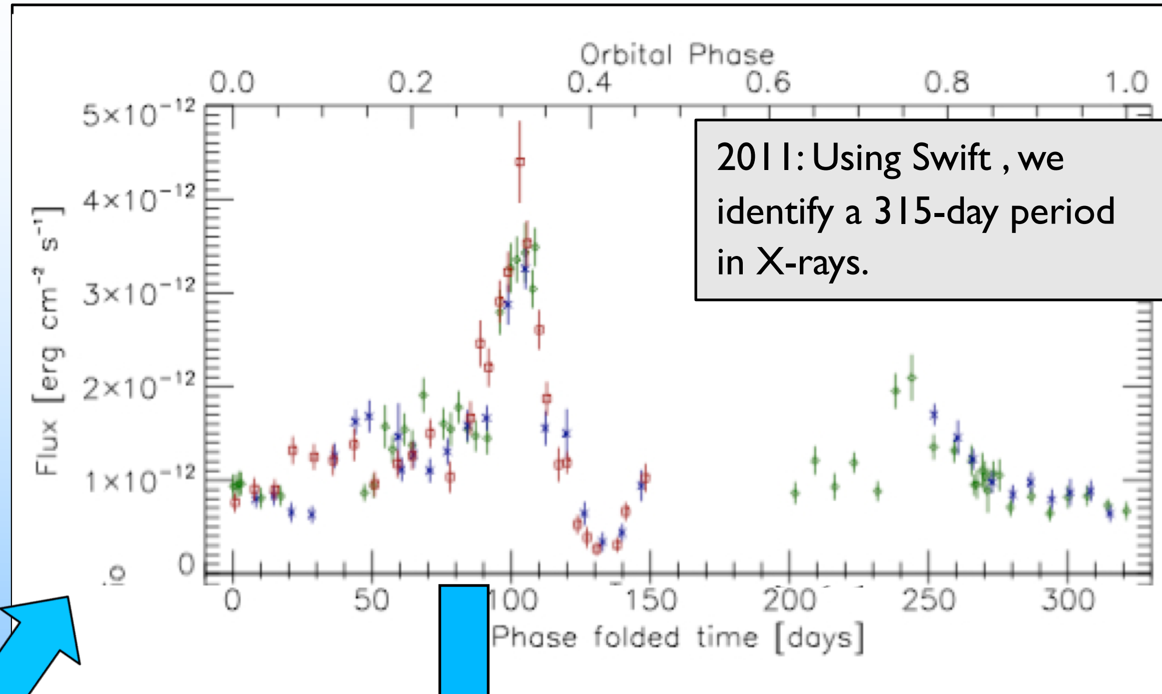


The detective story: HESS J0632+057

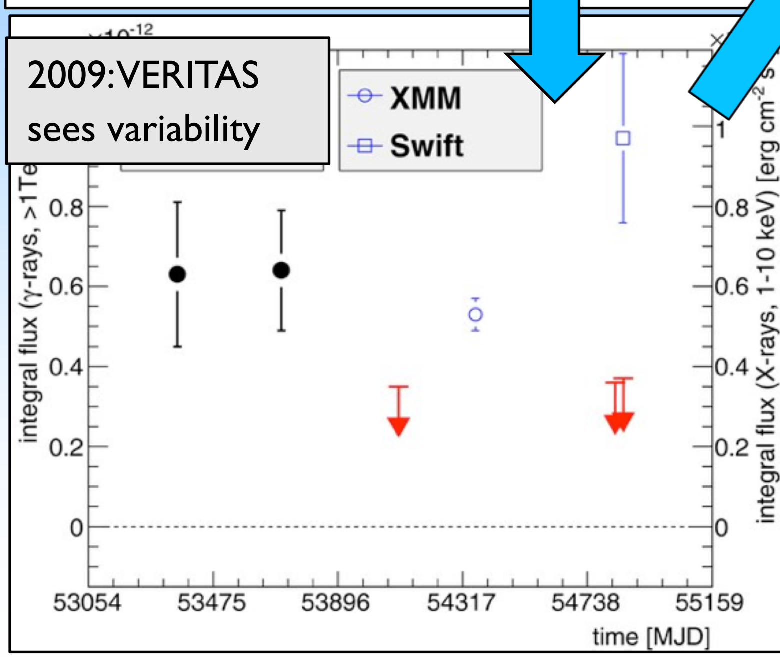
2007: HESS discovers a gamma-ray point source



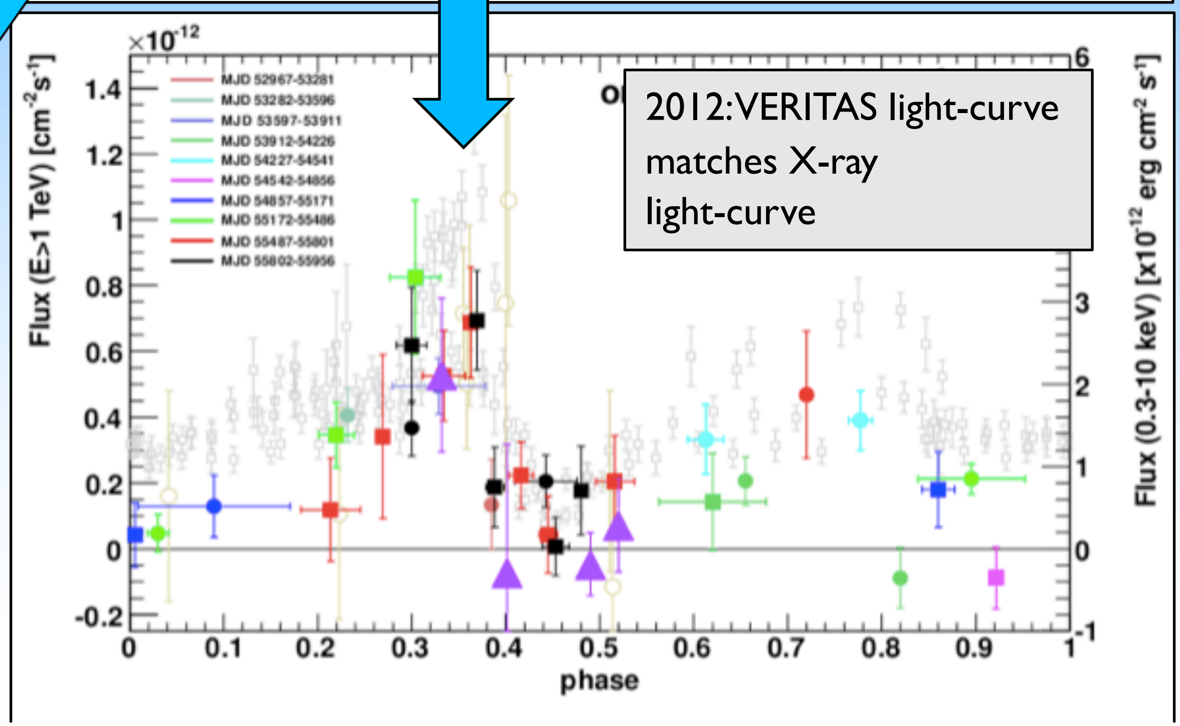
2011: Using Swift , we identify a 315-day period in X-rays.



2009: VERITAS sees variability

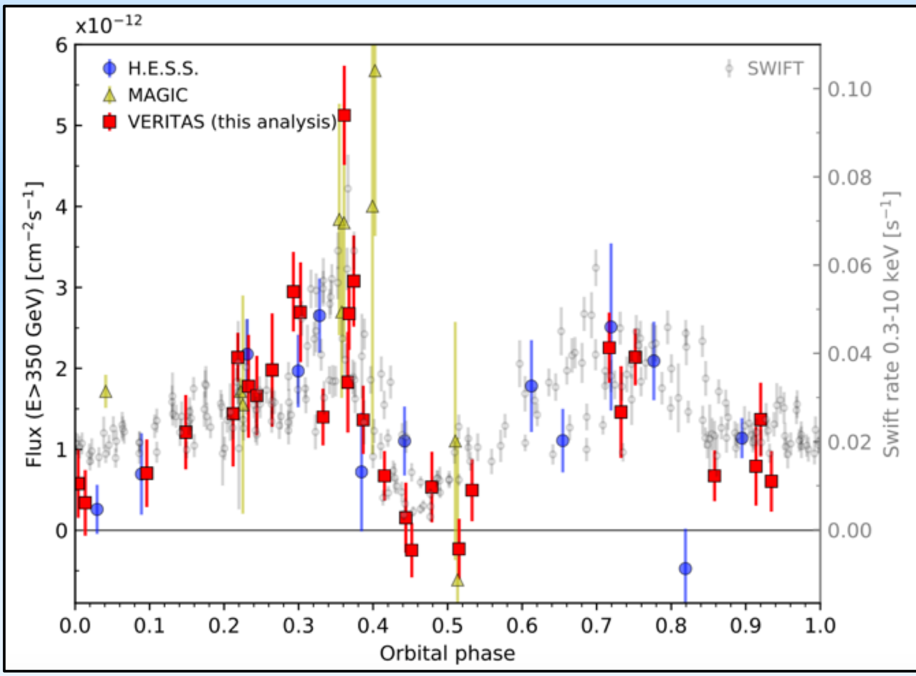


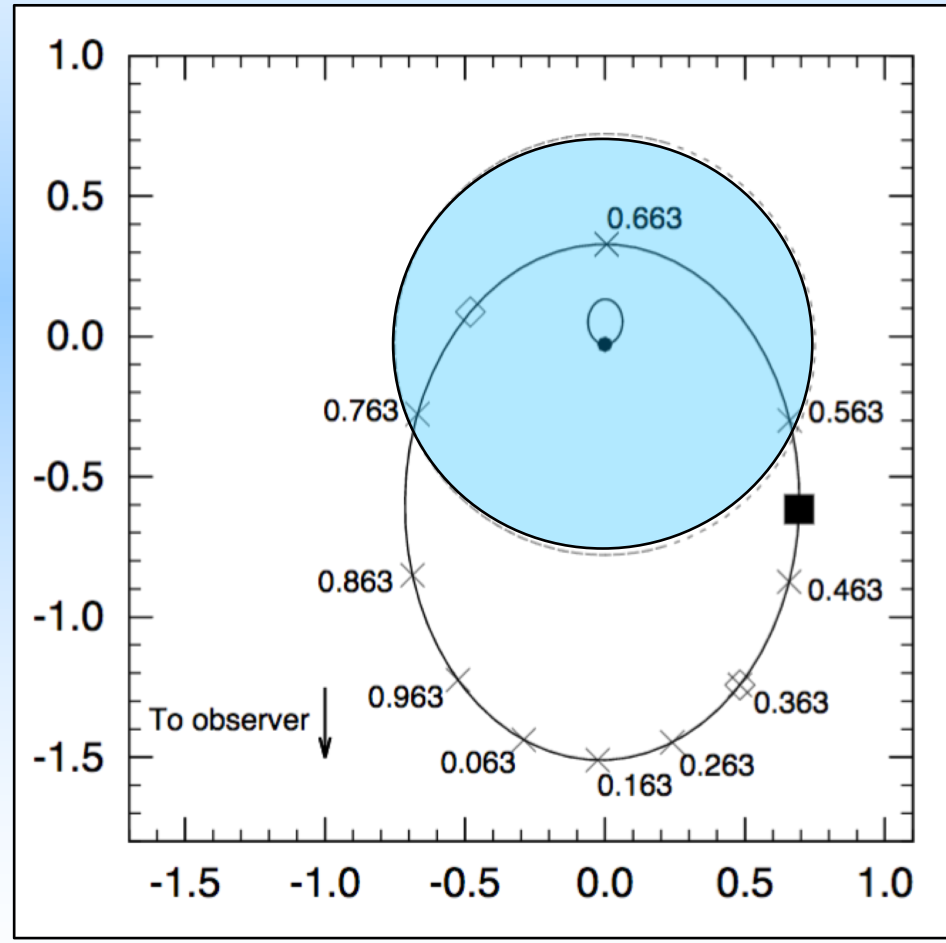
2012: VERITAS light-curve matches X-ray light-curve



HESS J0632+057

- VERITAS has now covered all of the orbit, over 11 years of observations.
- Estimates of the orbital parameters from optical radial velocity measurements are improving.
- Periodic GeV emission has recently been detected – but very faint.

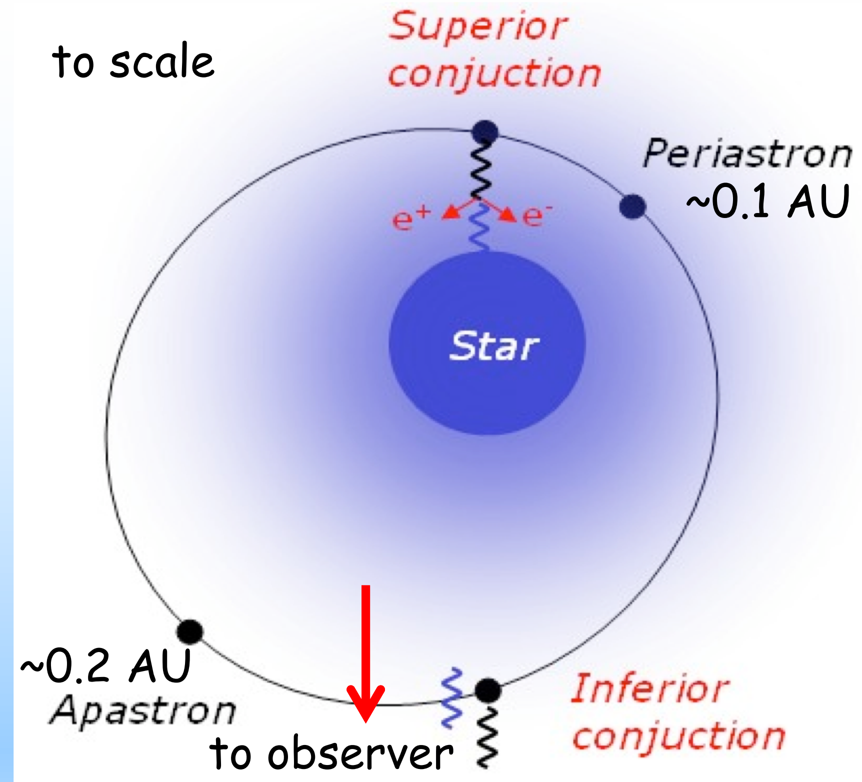


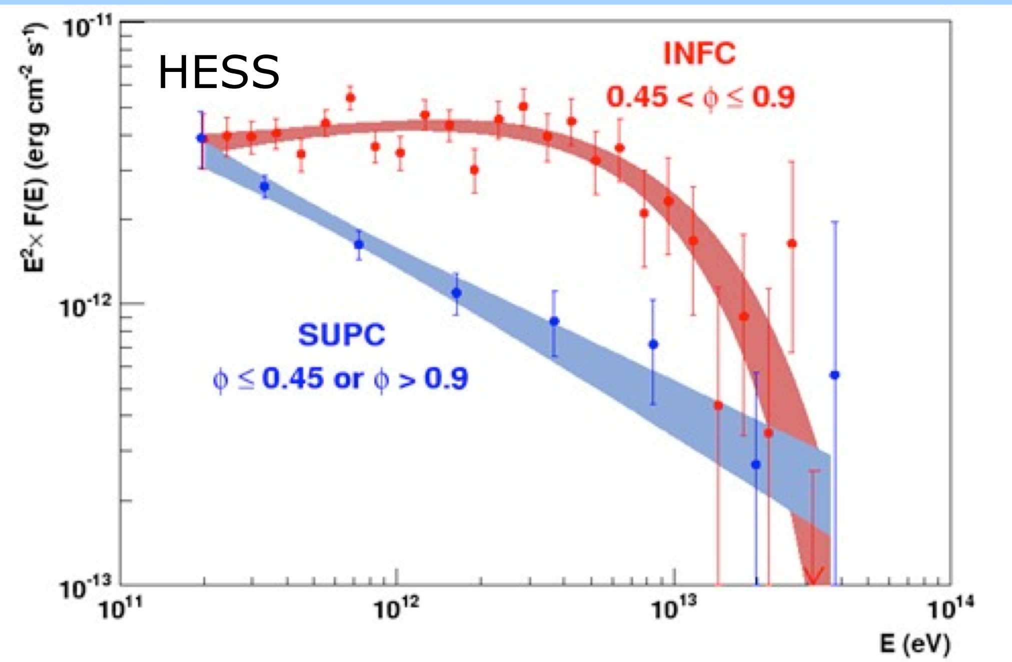


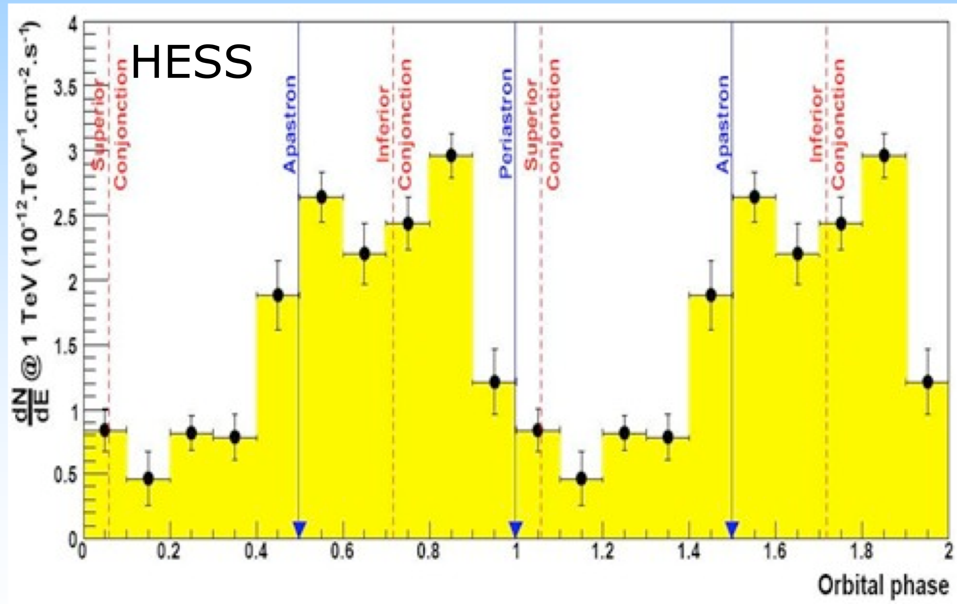
Moritani et al., 2018

The Timepiece: LS 5039

- Compact object orbiting an O6.5V companion ($23M_{sol}$)
- 3.9 day, inclined orbit, e=0.35
- HESS measure clear periodicity >200GeV
- Emission peaks at inferior conjunction.
- Spectrum varies.
- TeV period is now more accurate than optical!

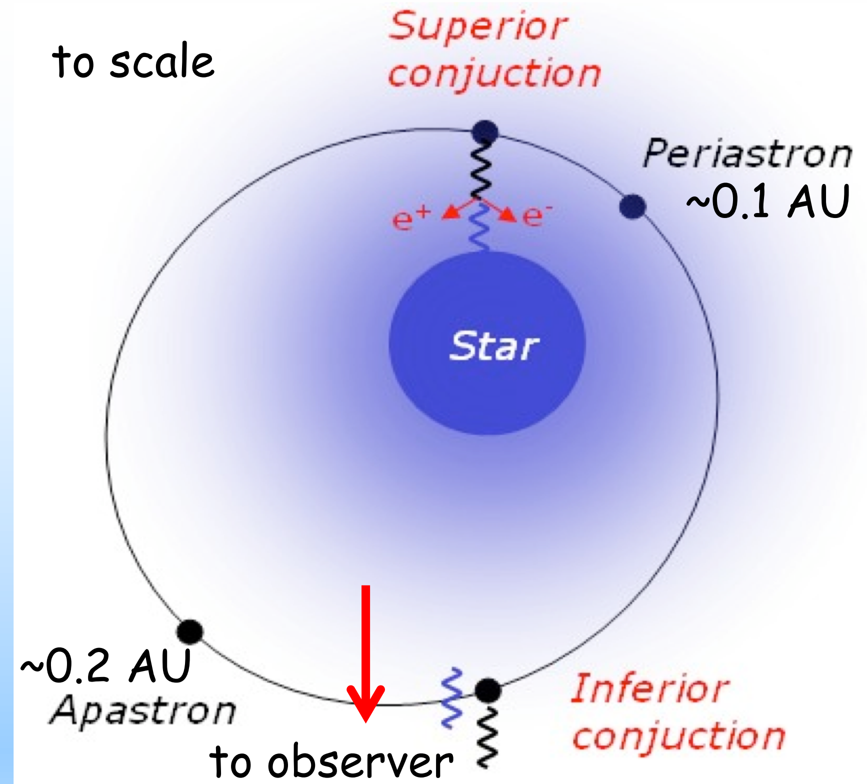


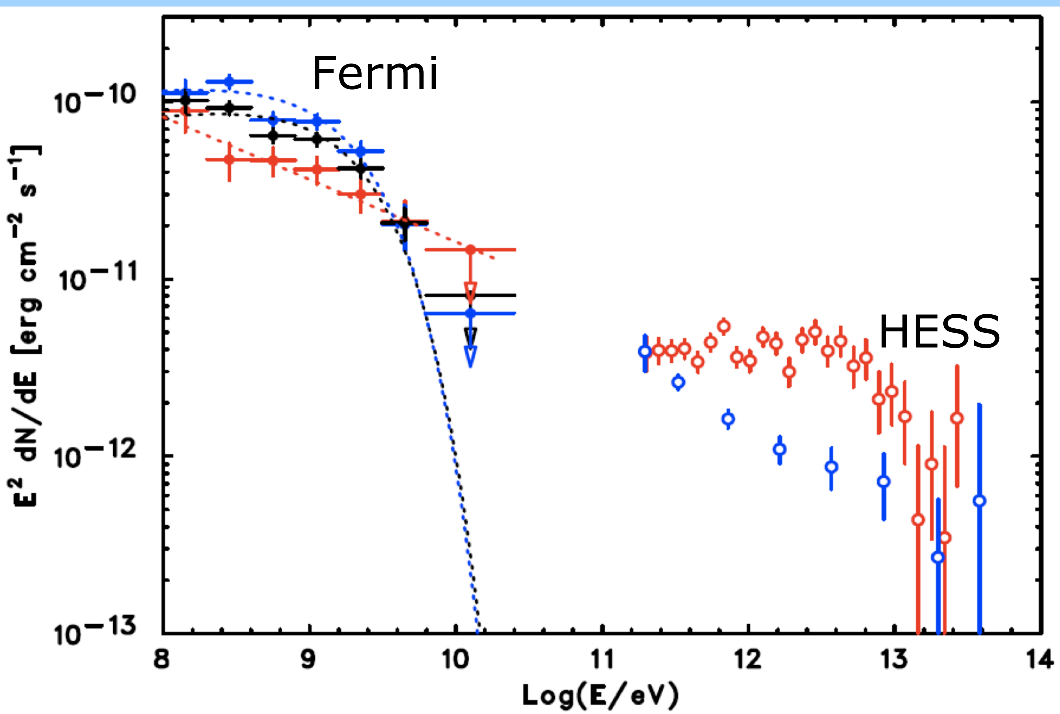


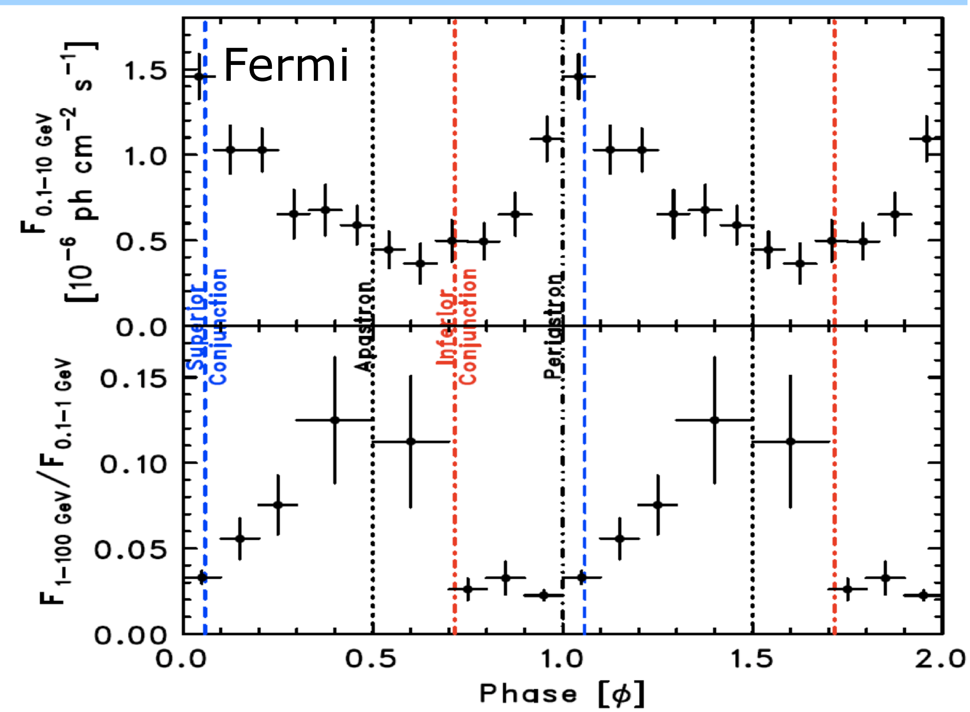


The Timepiece: LS 5039

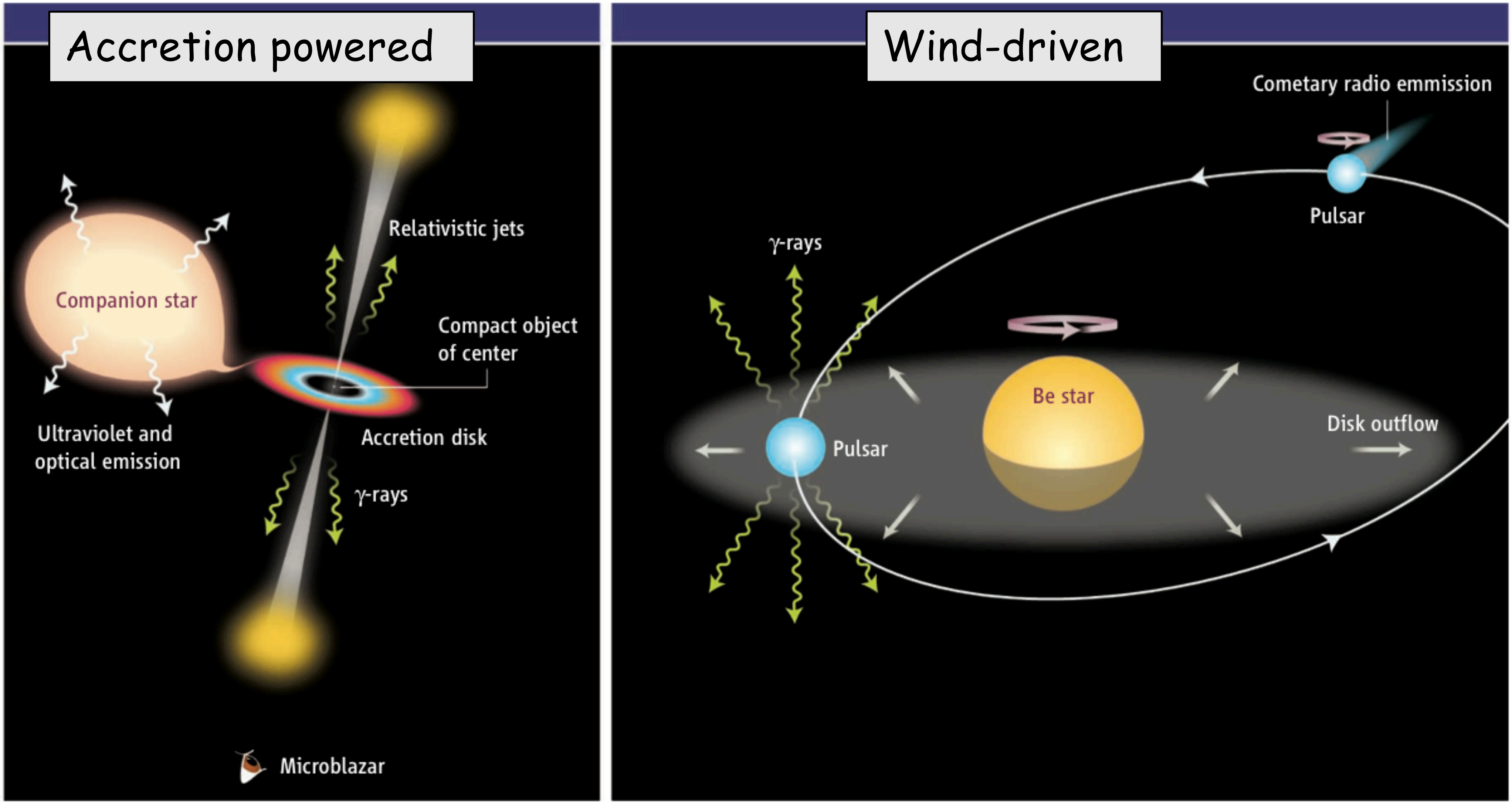
- Seen by Fermi-LAT (BSL)
- Orbital modulation
- Flux variability *anti-correlated* with HESS
- Spectral variability.
- 2 GeV cut-off observed.
  - The GeV and TeV spectra do not connect smoothly. Suggests different mechanisms.







So what drives them?



Mirabel (Science 309, 714, 2006)

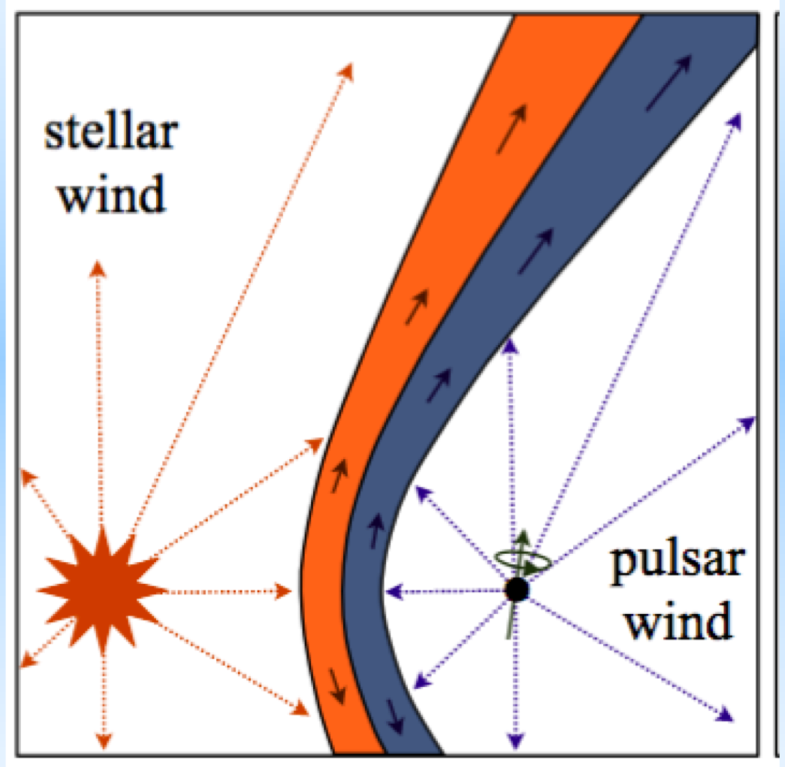
A few things to think about (far from exhaustive)...

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	Circumstellar environment	Wind collision region	Pulsar wind zone
	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...

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

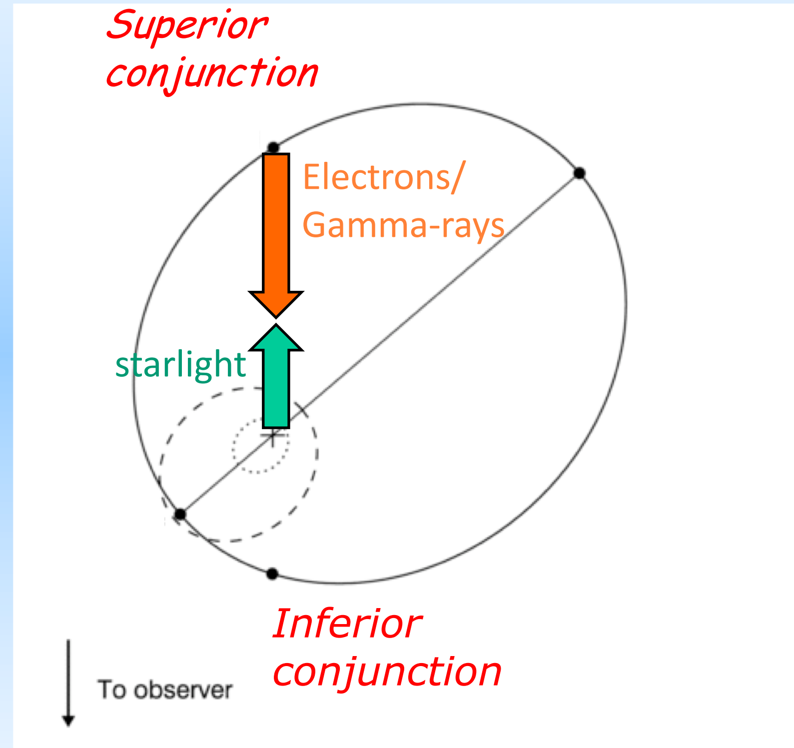
$$\frac{R}{d} \approx \frac{1}{1+\eta^{1/2}} \quad \text{with} \quad \eta = \frac{\dot{M}_{\rm w} v_{\rm w}}{\dot{E}/c}$$

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.

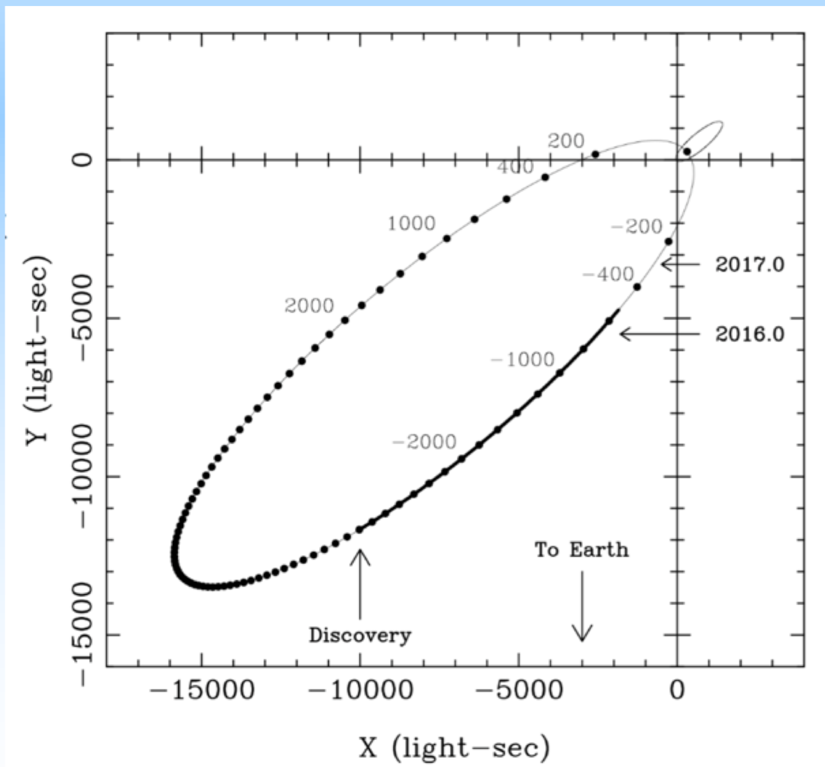
- However… gamma-rays with energies >30 GeV are absorbed by pair production with starlight!
- At superior conjunction, TeV photons are most heavily absorbed.

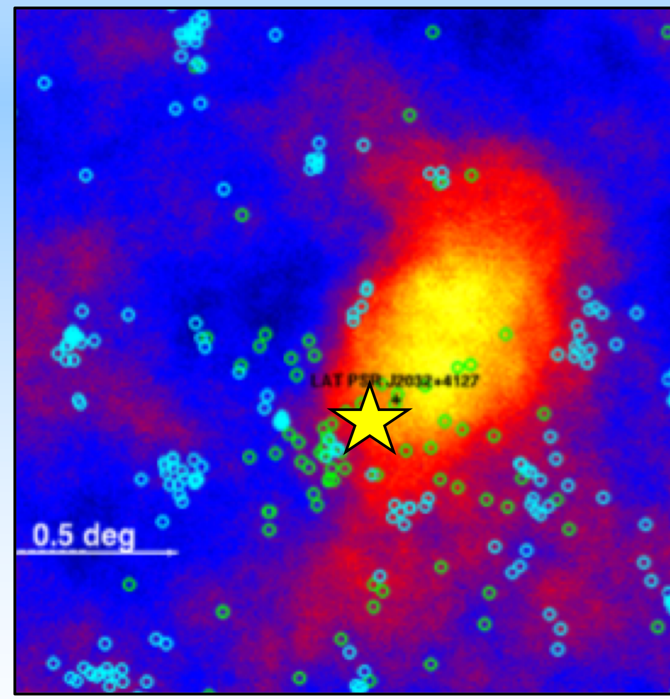
- Leads to a natural anti-correlation between GeV and TeV lightcurves

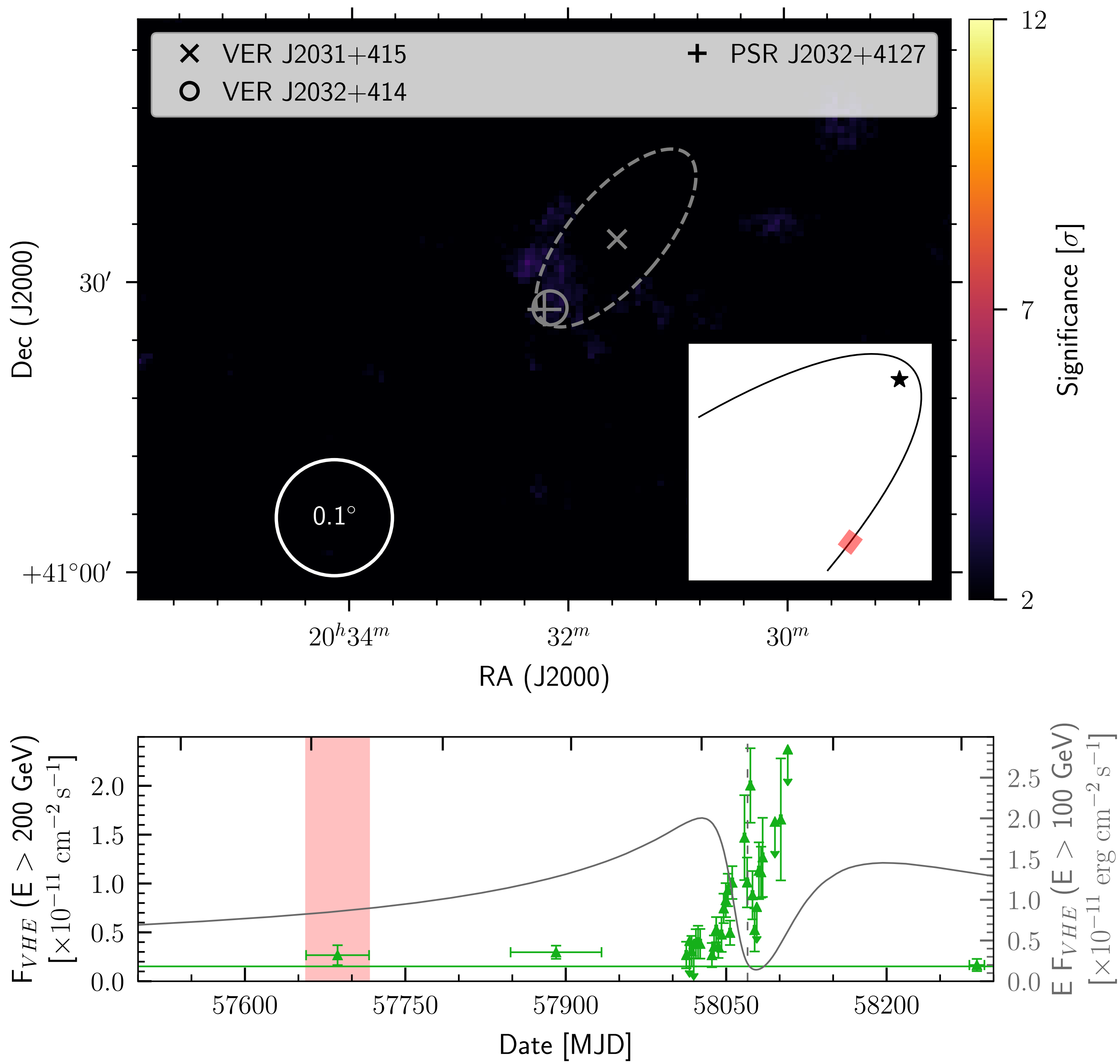


PSR J2032+4127 / MT91 213

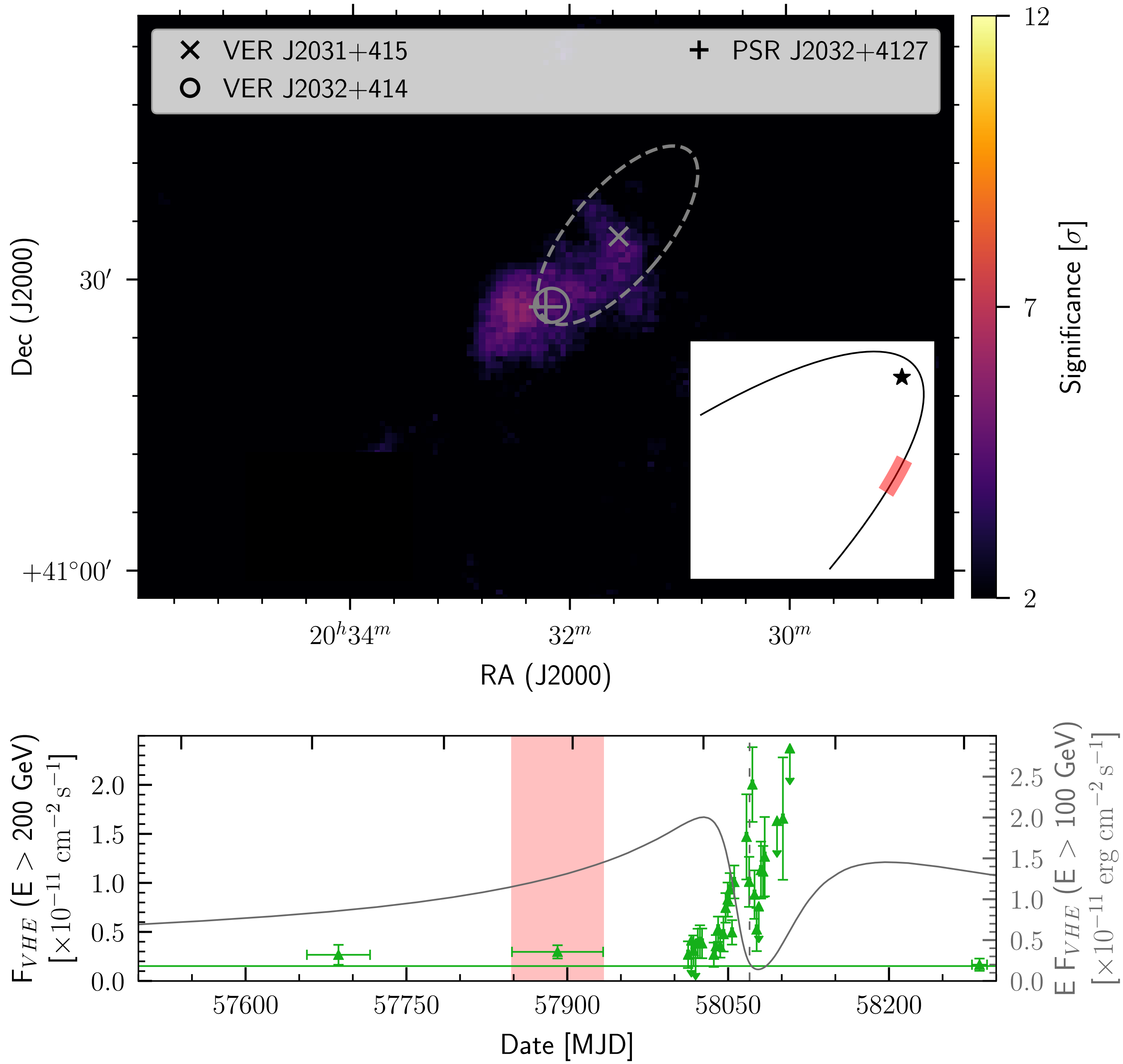
- In 2014, Lyne et al. identified PSR J2032+4127 as the compact object in a binary system with a 15 M_{sol} Be star.
- The eccentricity is >0.97, and the orbital period 45 – 50 years!
- Pulsar timing defined periastron *very* precisely (Nov 13th 2017, 9pm)
- Intriguingly – the pulsar binary is located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







VER J2031+415
VER J2032+414
PSR J2032+4127
0.1°
Dec (J2000)
30′
+41°00′
20h34m
32m
30m
RA (J2000)
Significance [σ]
12
7
2
F_VHE (E > 200 GeV) [×10^−11 cm^−2 s^−1]
E F_VHE (E > 100 GeV) [×10^−11 erg cm^−2 s^−1]
0.0
0.5
1.0
1.5
2.0
2.5
57600
57750
57900
58050
58200
Date [MJD]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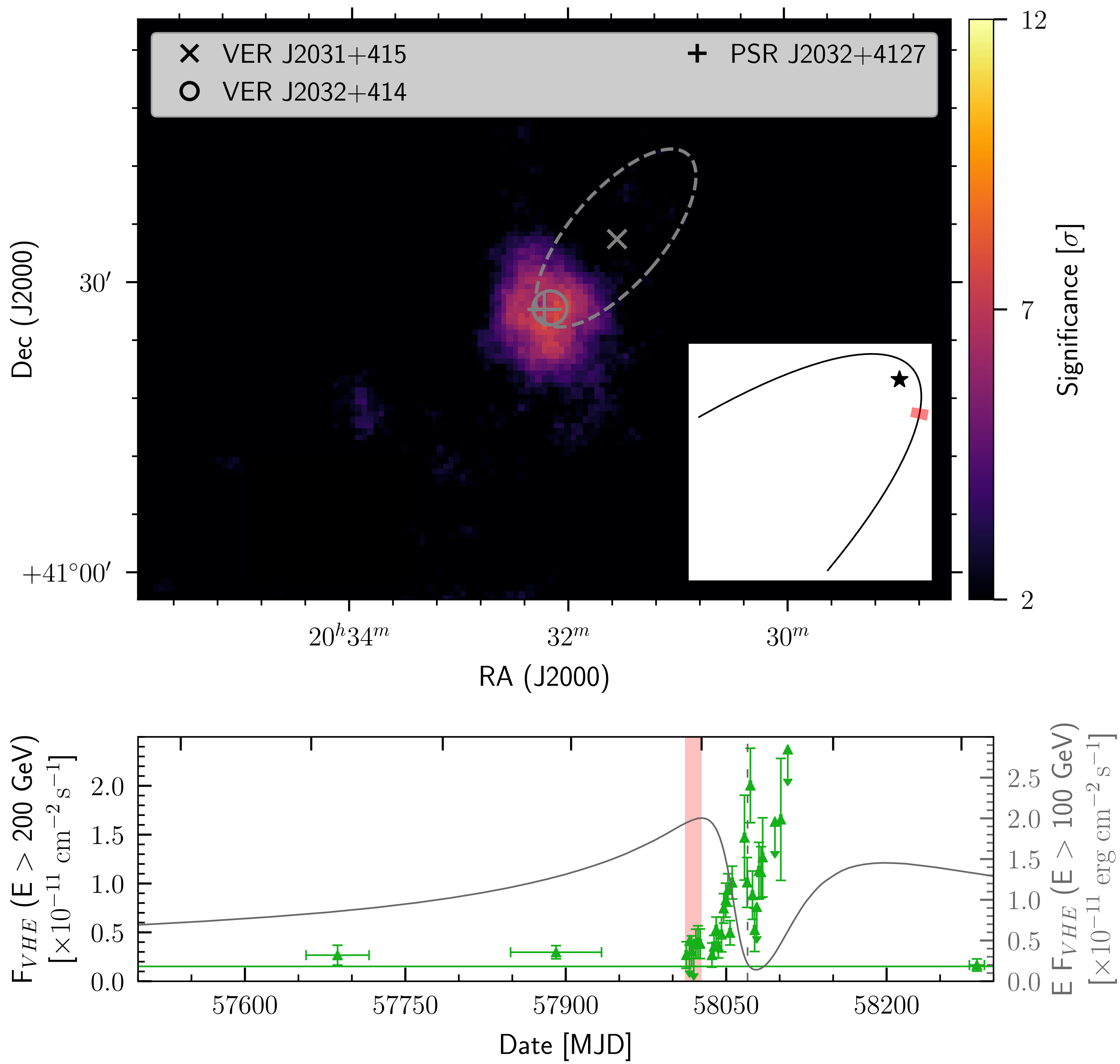

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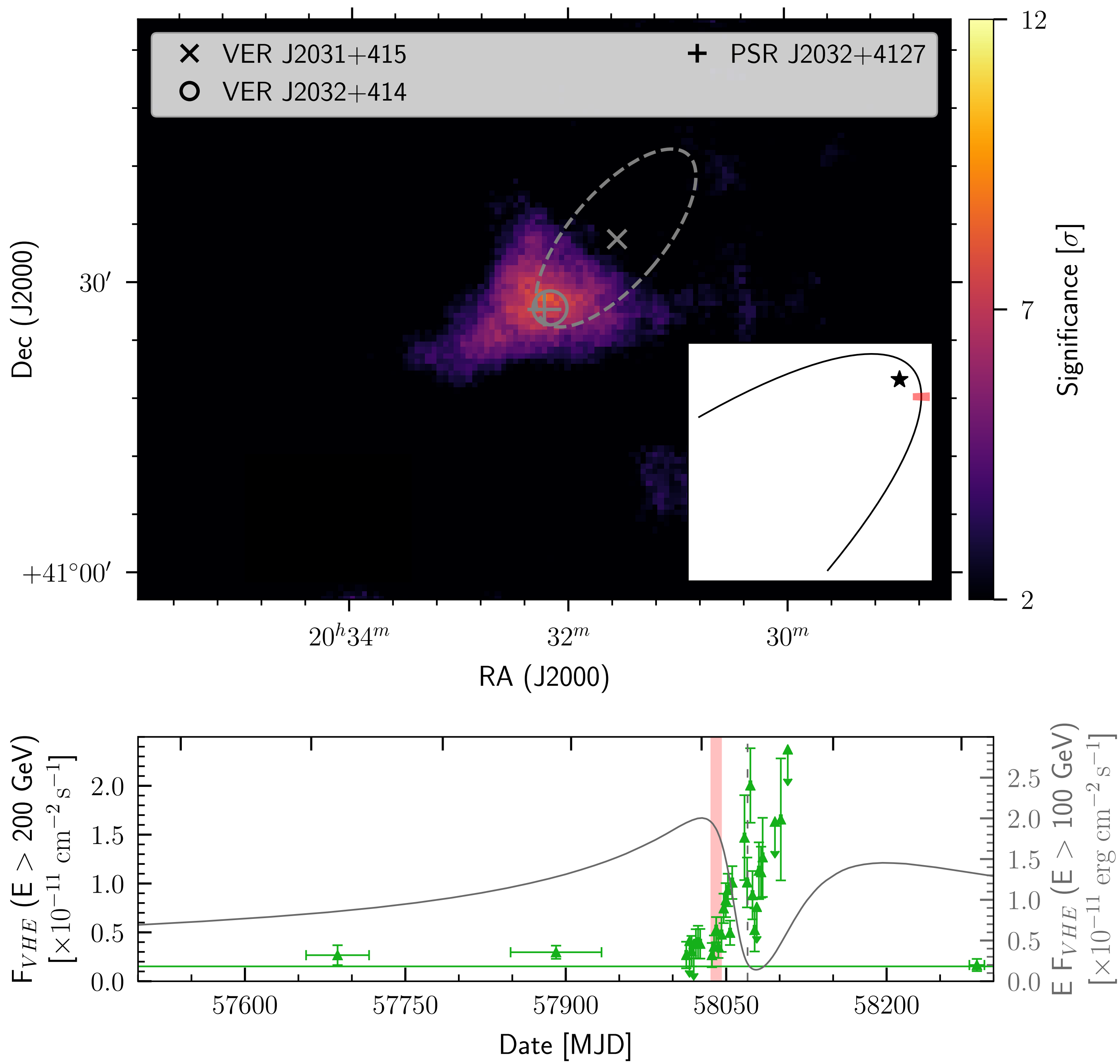

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Significance [σ]
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F_{VHE} (E > 200 GeV) [$\times10^{-11}$ cm^{-2} s^{-1}]
E F_{VHE} (E > 100 GeV) [$\times10^{-11}$ erg cm^{-2} s^{-1}]
Date [MJD]
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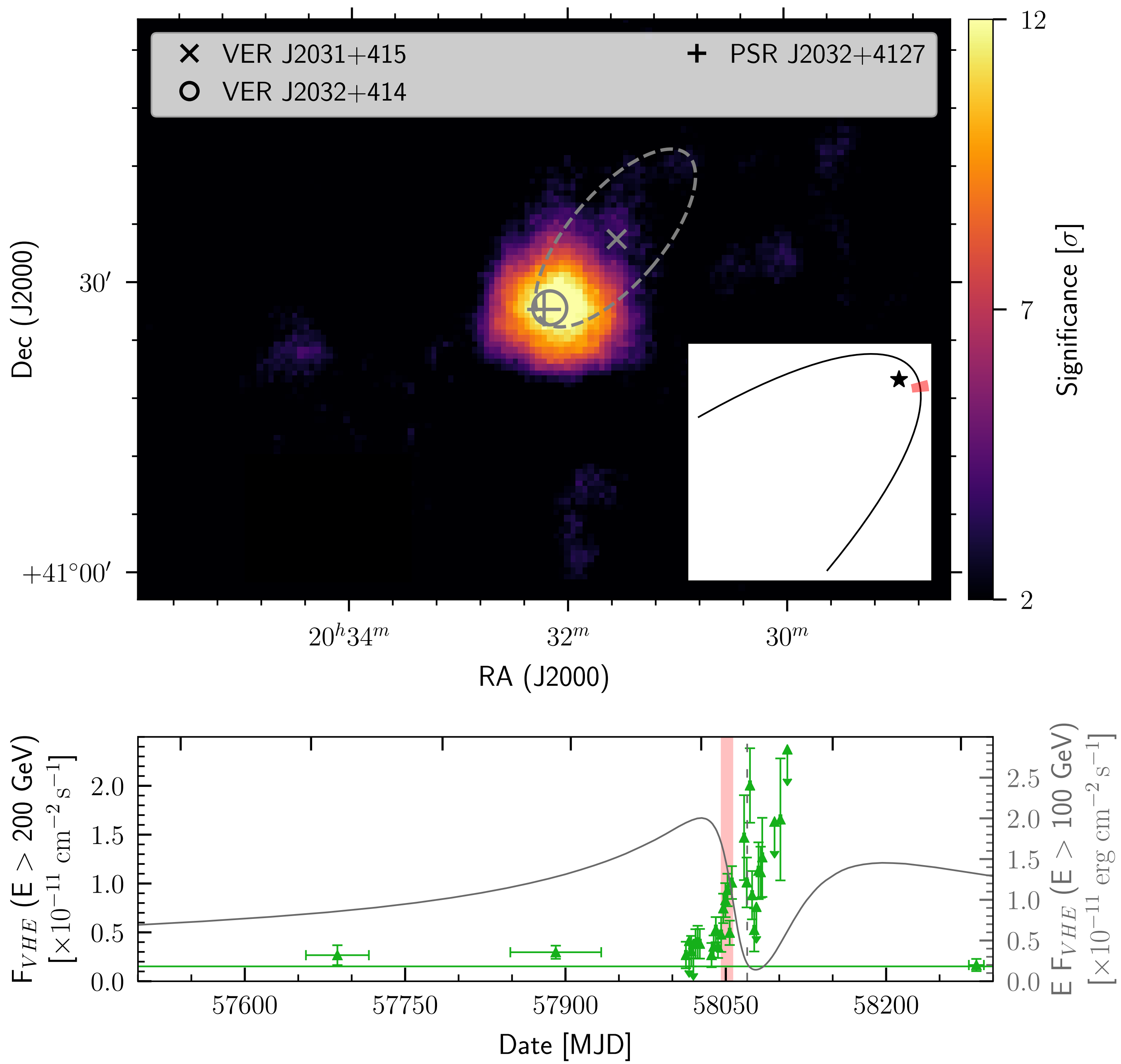

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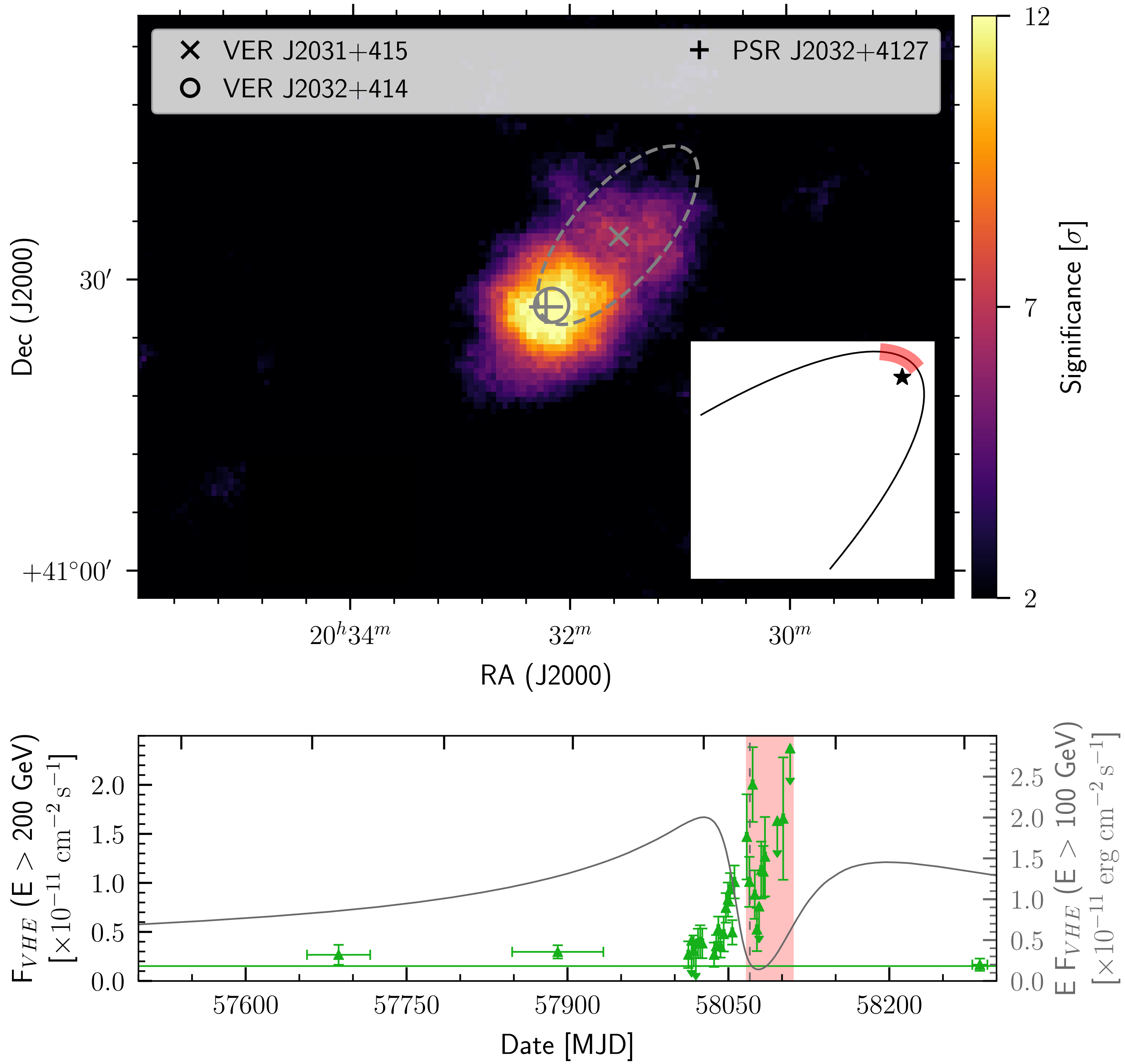
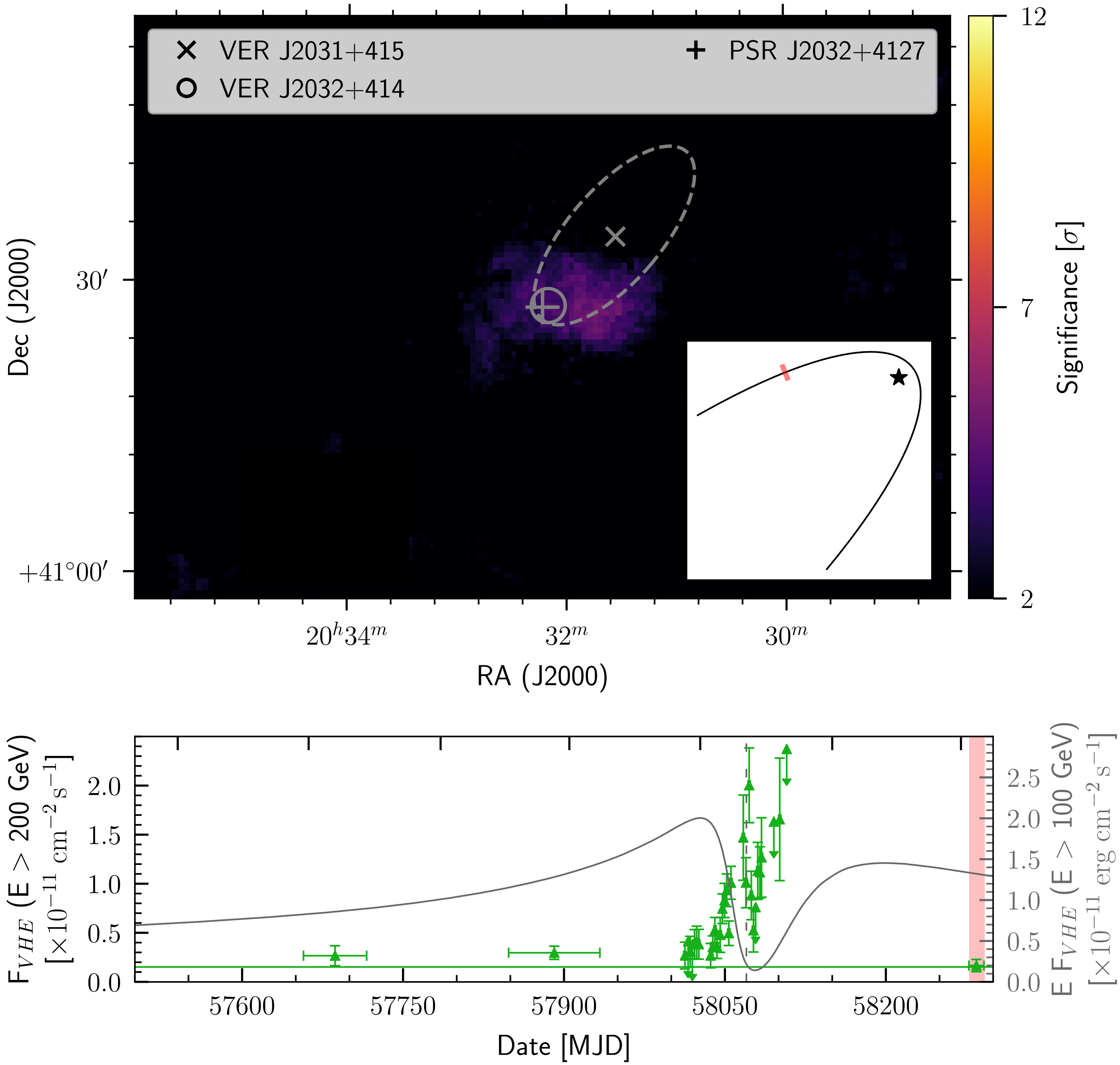
58200
Date [MJD]



VER J2031+415
VER J2032+414
PSR J2032+4127
Dec (J2000)
RA (J2000)
Significance [σ]
F$_{VHE}$ (E > 200 GeV) [$\times 10^{-11}$ cm^{-2} s^{-1}]
E F$_{VHE}$ (E > 100 GeV) [$\times 10^{-11}$ erg cm^{-2} s^{-1}]
Date [MJD]

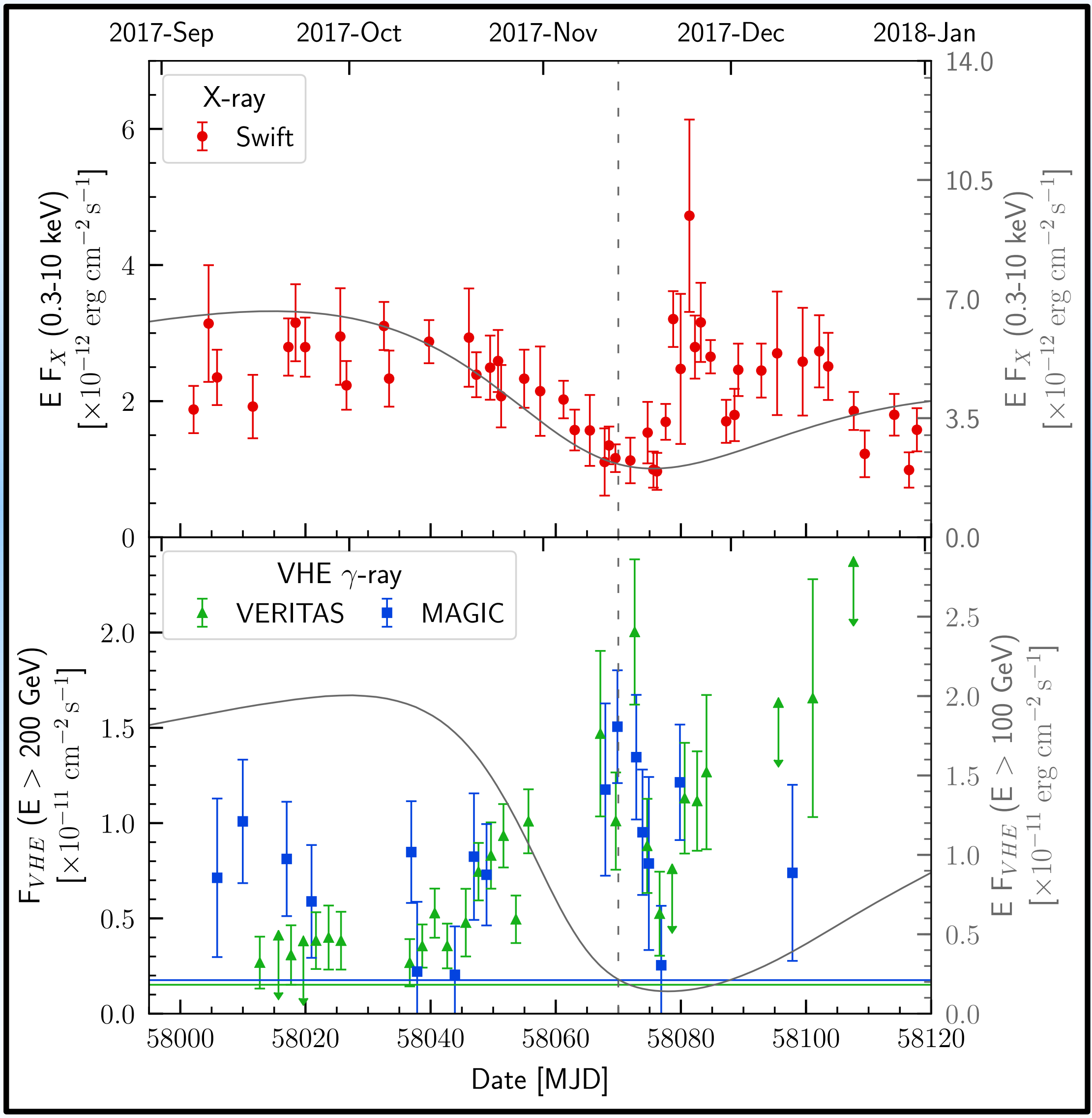


VER J2031+415
VER J2032+414
PSR J2032+4127
Significance [σ]
12
7
2
Dec (J2000)
30′
+41°00′
20h34m
32m
30m
RA (J2000)
F_VHE (E > 200 GeV) [×10^−11 cm^−2 s^−1]
2.0
1.5
1.0
0.5
0.0
E F_VHE (E > 100 GeV) [×10^−11 erg cm^−2 s^−1]
2.5
2.0
1.5
1.0
0.5
0.0
57600
57750
57900
58050
58200
Date [MJD]

Lightcurve

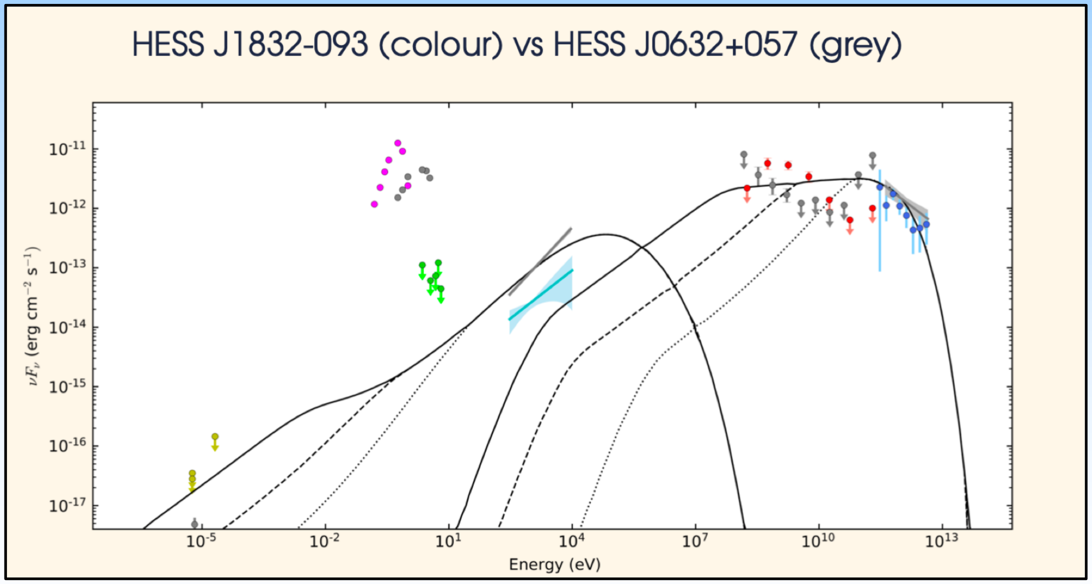
- Post-periastron X-ray flare may indicate disk crossing.
- TeV flux suppression after periastron (around superior conjunction) may be due to gamma-gamma absorption.

Model from Takata et al, 2017, with parameters from Li et al 2017.



Summary

- Gamma-ray binaries are excellent laboratories for high energy particle astrophysics.
- Multiwavelength observations are critical to discovery, and to understanding how they work.
- Fermi continues to look – there may be more binaries hiding in the archive.
- CTA should see at least *some* more – but it generally takes some multi-wavelength detective work to identify them, and a Galactic plane survey strategy is not optimal.
- Big observational question: How many GeV-faint gamma-ray binaries are there?



Martí-Devesa & Reimer 2020, A&A, 637, A23