Transport:

2 shuttles on Friday:

Early – Dana (3 max): 6:30am
Megan Longo
Sarah Story (11:00am)
Parisa Roustazadeh

Late – Jamie (6 max): 12:00pm
Giulia Migliori
Daniel Castro (4:20pm)
Noe Suarez
Jon Harris
David Staszak
Nissim Fraija

Receipts available

Andrea Albert
Daniel Castro
Jamie Cohen
Amanda Dotson
Nissim Fraija
David Green
Peter Jenke
Mehgan Longo
Giulia Migliori
Katey Mulrey
Tommy Nelson
Rebecca Reesman
Parisa Roustazadeh
Gunes Senturk
Dana Saxon
David Staszak
Sarah Story
Josh D. Wood
Josh Wood

Still tracking them down…

Eduardo de la Fuente
Joe Eggen
Jon Harris
Jedidah Isler
Jeremy Maune
Noe Suarez

Gamma-ray Binary Systems

Jamie Holder

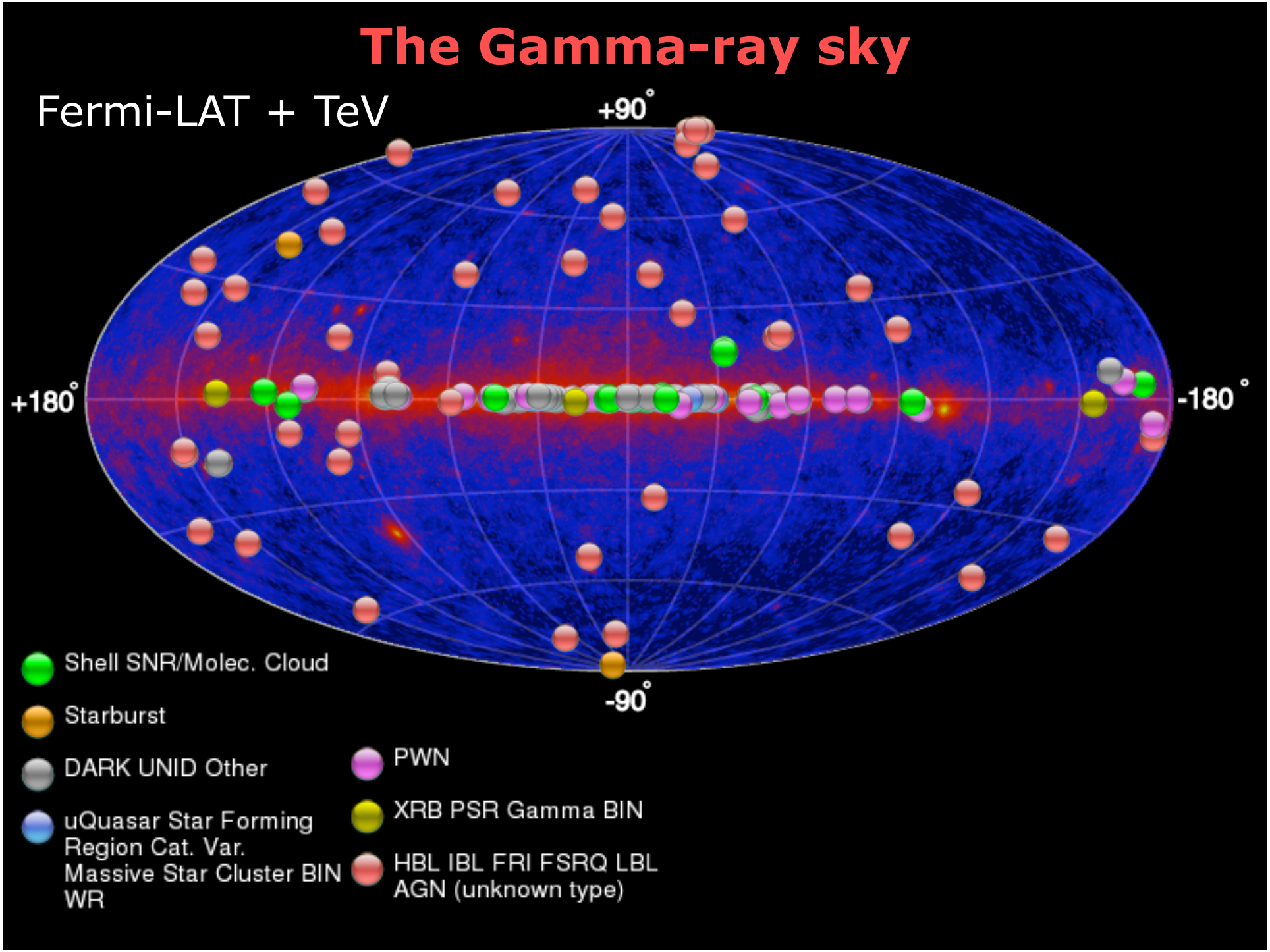
Bartol Research Institute/ University of Delaware

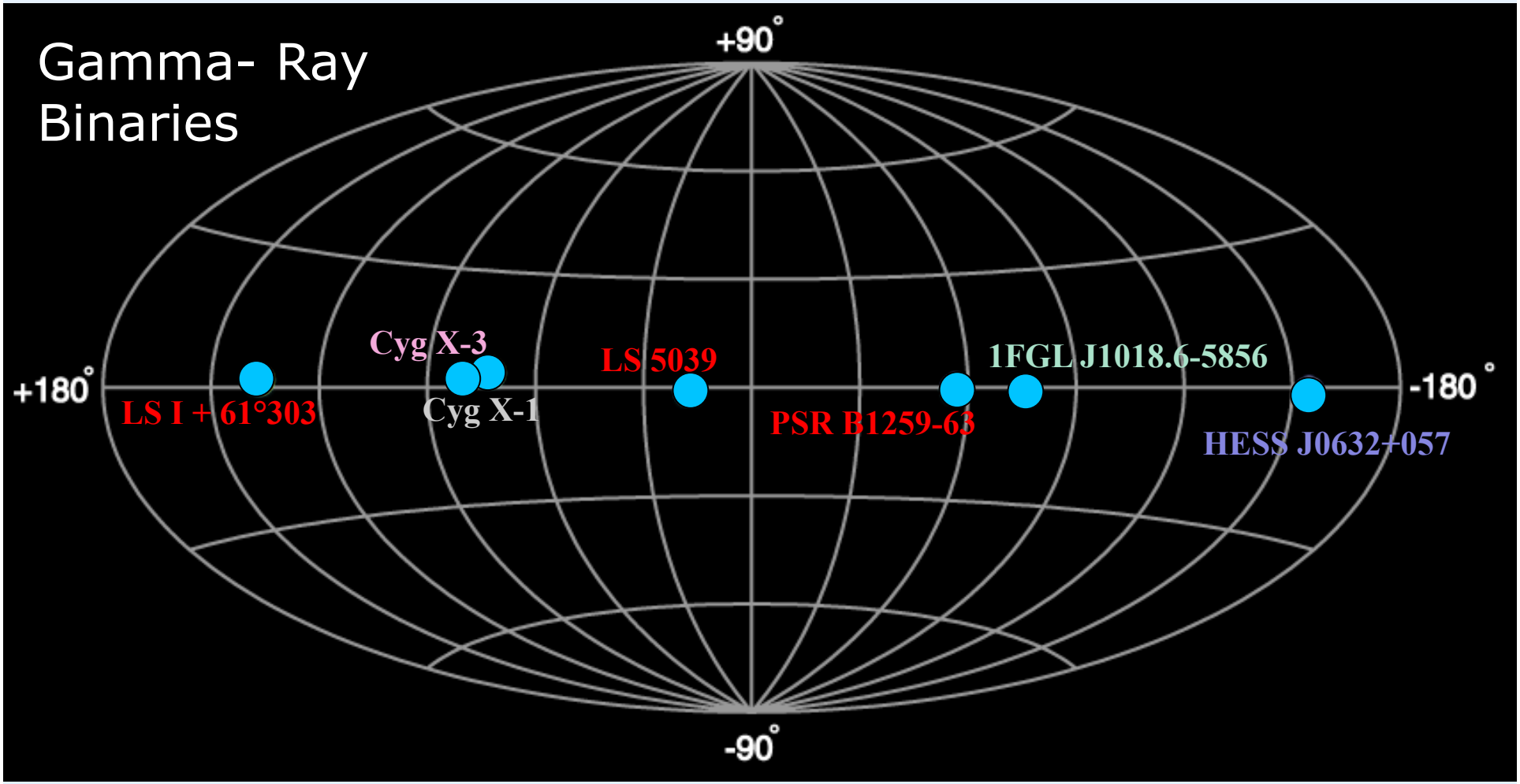
2011 Fermi School Lewes, Delaware

Overview

- Why are they interesting?
- Some history
- What drives them?
- Observational status
- Interpretation
- What next?

The Gamma-ray sky

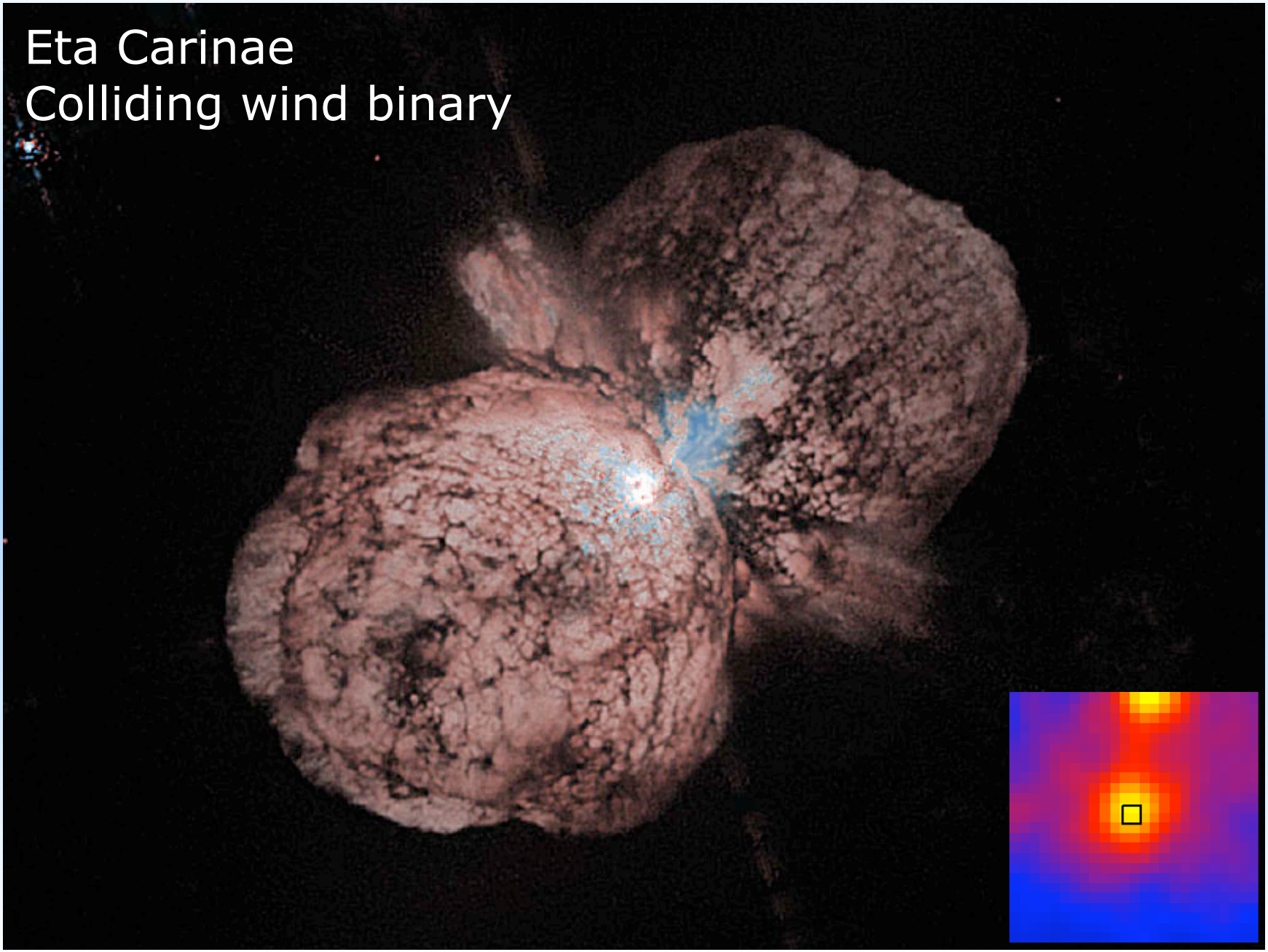



Gamma- Ray Binaries
+90°
+180°
-180°
-90°
Cyg X-3
Cyg X-1
LS 5039
1FGL J1018.6-5856
LS I +61°303
PSR B1259-63
HESS J0632+057

Why are these few so interesting?

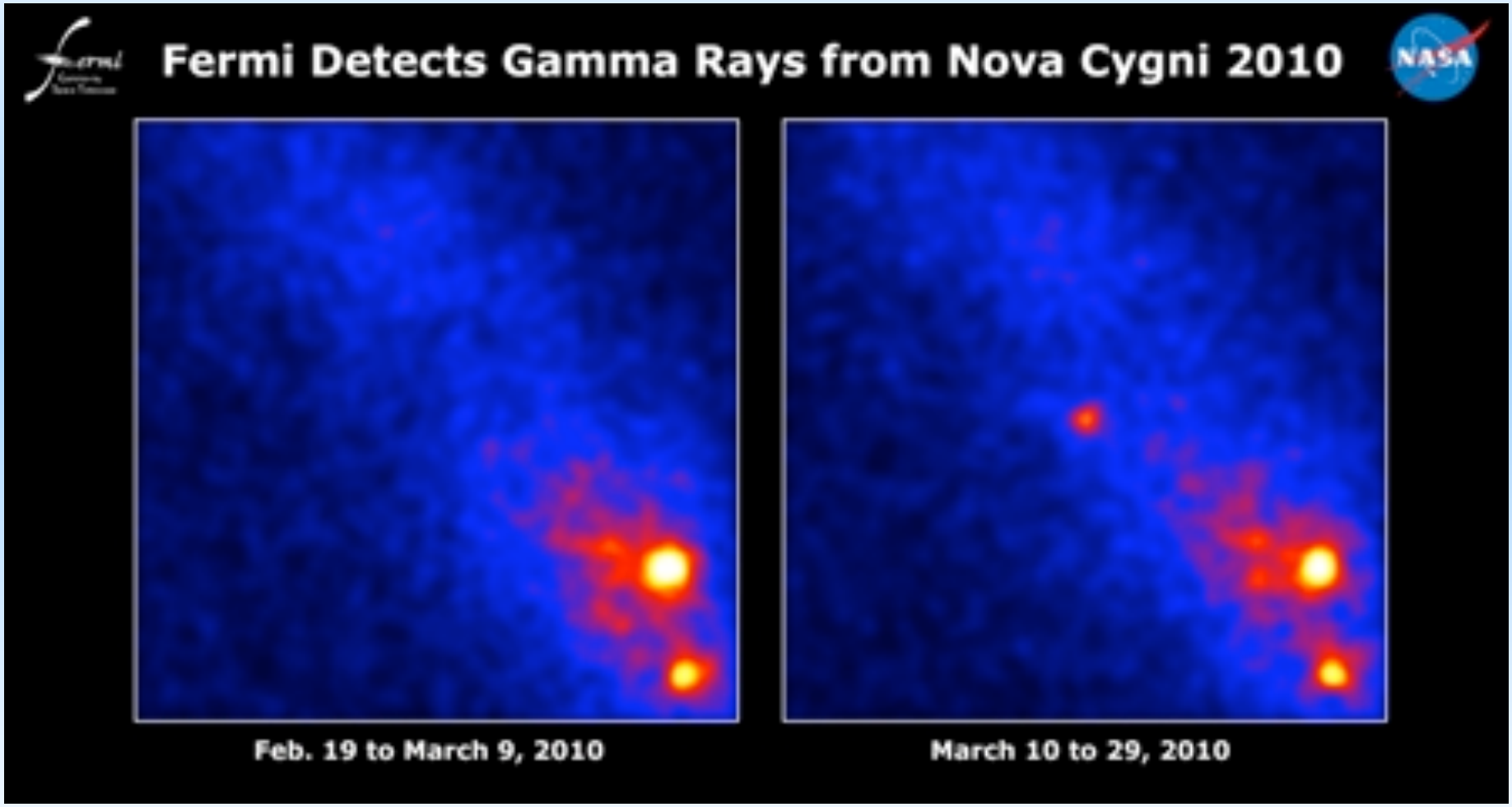
- Binaries are the *only* variable galactic TeV sources
- They are natural particle accelerators operating under varying, but ***regularly repeating***, environmental conditions
- Provide a constraining laboratory for models of particle acceleration, and gamma-ray production, emission and absorption processes.
- May provide the keys to an understanding of astrophysical jets
- 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, nature of the binary components and the conditions in the circumstellar environment are not well known.

Two Gamma-ray binaries I won't discuss!



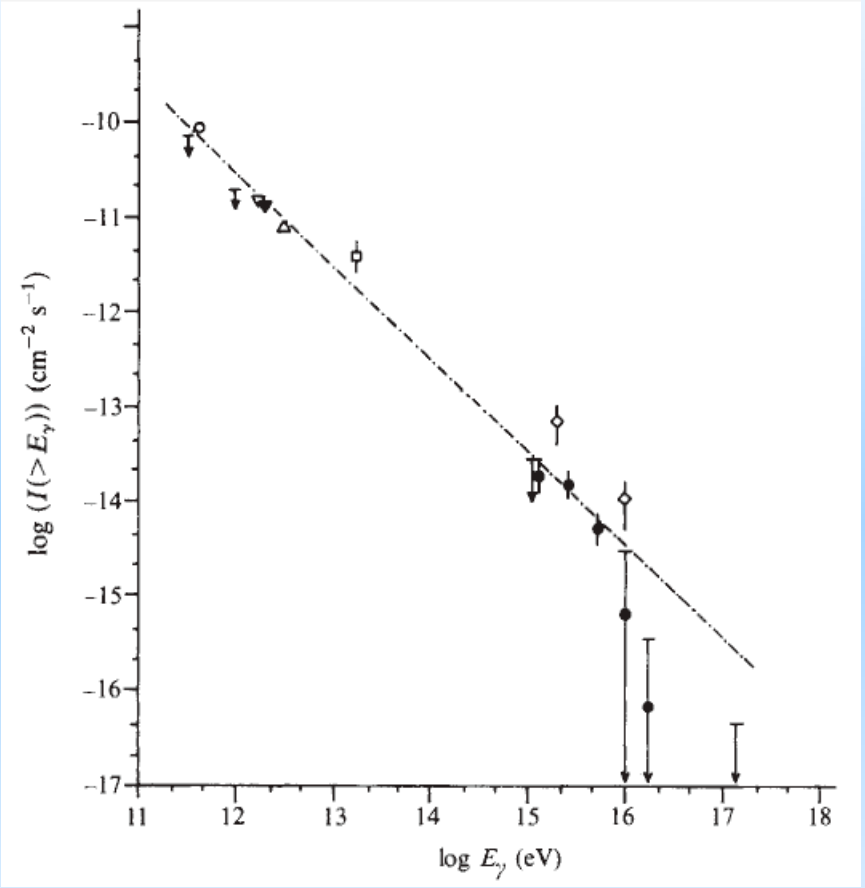
Two Gamma-ray binaries I won't discuss!

- V407 Cyg; Nova in a symbiotic binary (white dwarf + red giant)



A history of High Energy binary results

- Cygnus X-3 caused a lot of excitement in the 70's/ early 80's
- Numerous gamma-ray and cosmic ray air shower detectors claimed evidence for a modulated signal up to >10^{15}eV
- Even led to the prediction of a new particle ("the Cygnet")
- A cautionary tale… these results (and many subsequent ground-based gamma-ray binary detections in the 80's, up until the advent of Whipple/ HEGRA/CAT) are now widely discounted.

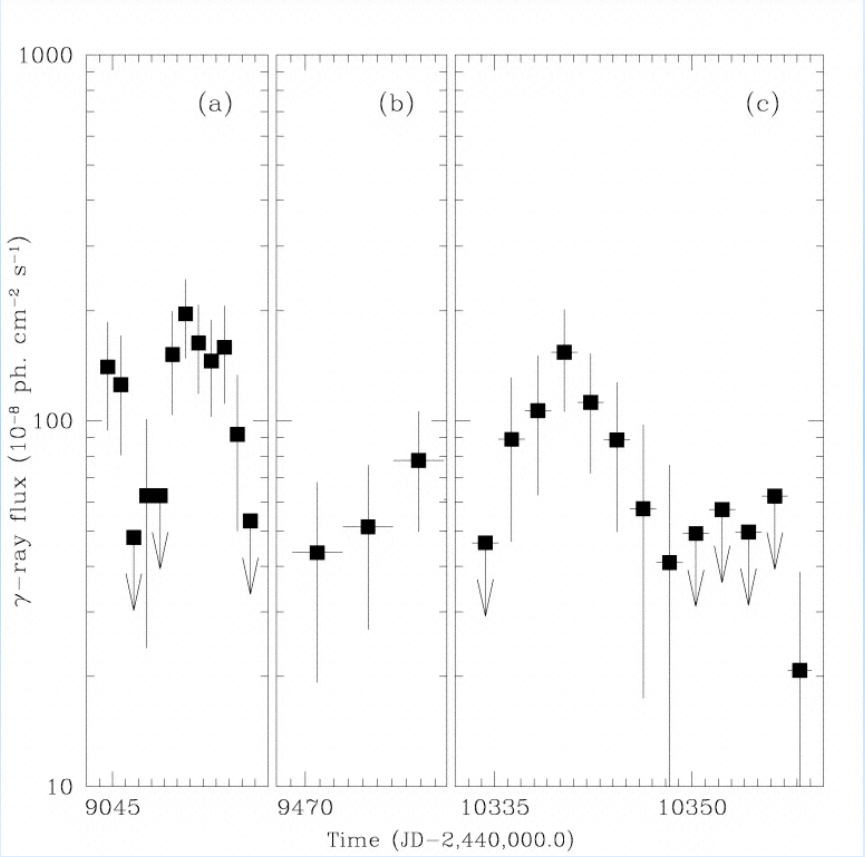


"Those who cannot remember the past are condemned to repeat it…"

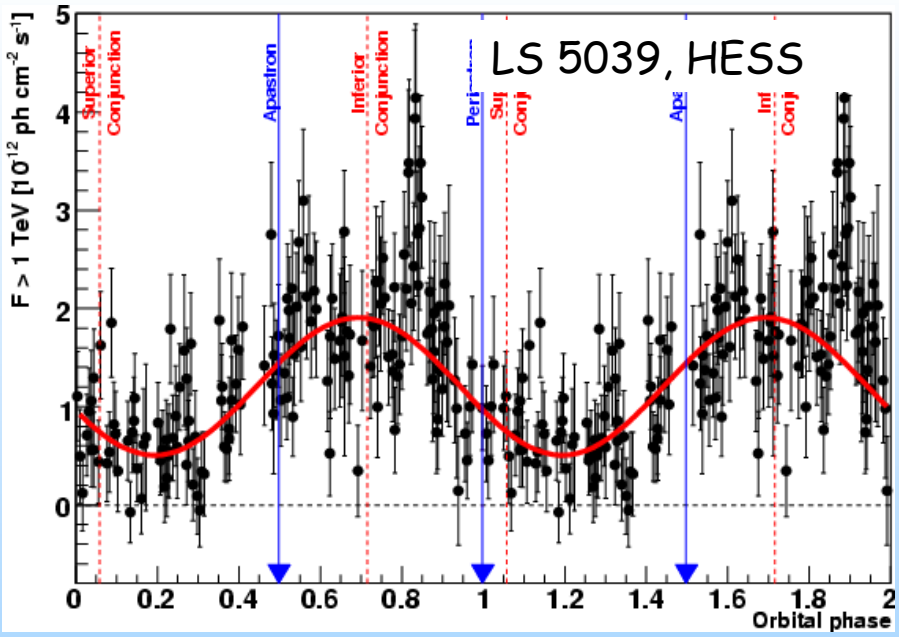
A history of High Energy binary results

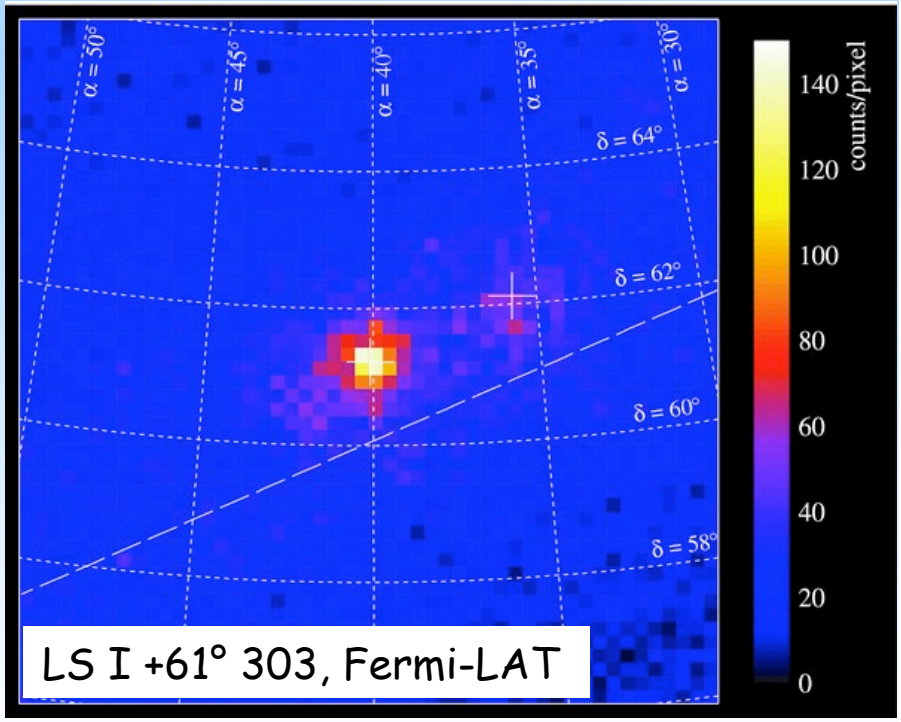
- Among 13 gamma-ray sources, COS-B detected 2CG 135+01; the error box contained a periodic radio and X-ray source (LS I +61° 303).
- Various EGRET sources were associated with binaries
  - 3EG J0241+6103 (LS I +61° 303), Tavani et al., ApJ 1998
  - 3EG J1824-1514 (LS 5039), Paredes et al., Science, 2000
  - 2EG J2033+4112 (Cyg X-3) Mori et al., ApJ, 1997
- But weak or no variability, no periodicity, and limited positional accuracy

3EG J0241+6103, Tavani et al.,1998

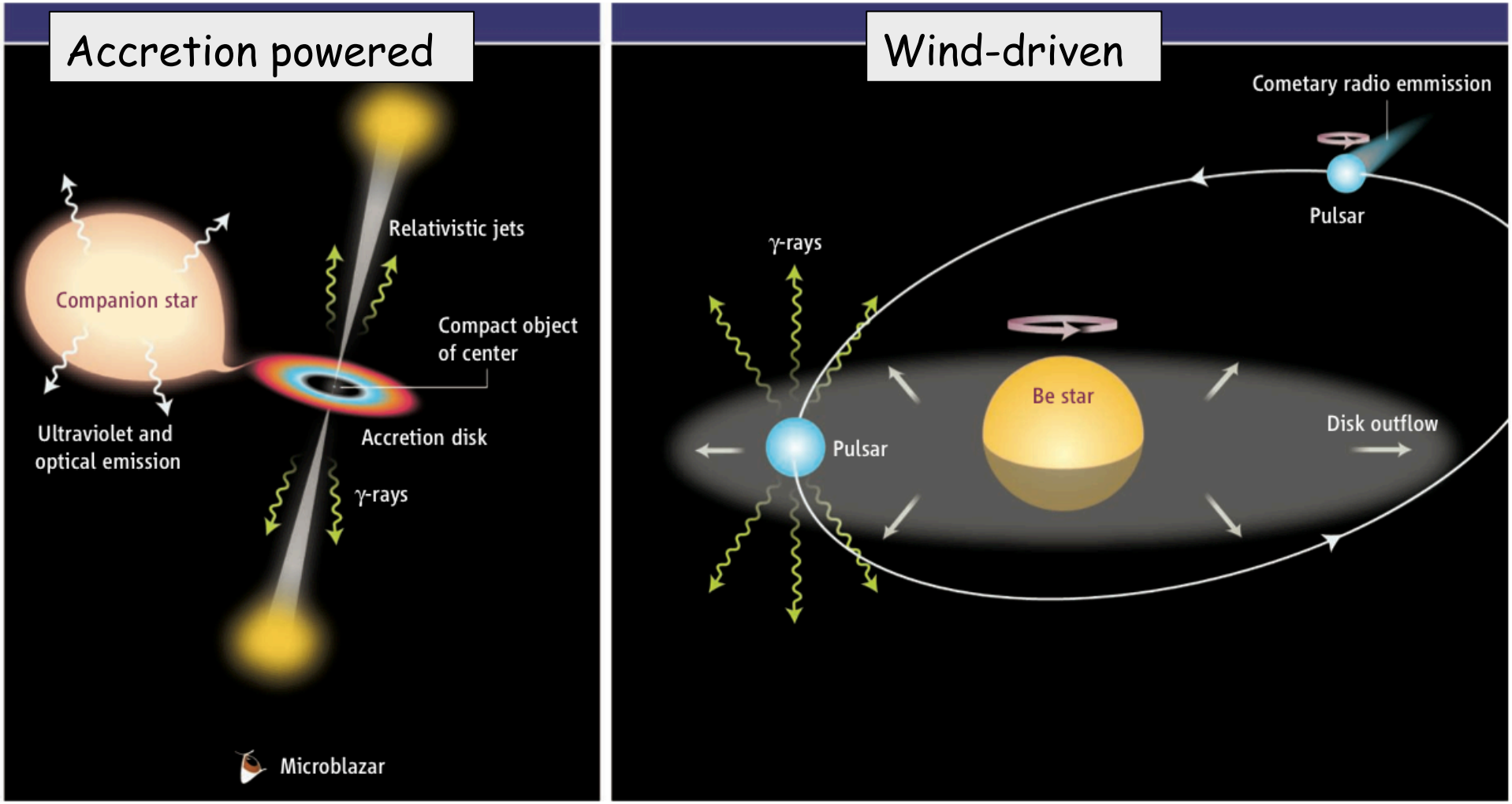


- 2004 – 2006: a few TeV sources strongly detected >100 GeV
  - PSR B1259-63 (H.E.S.S.)
  - LS 5039 (H.E.S.S.)
  - LS I +61° 303 (MAGIC)
- With good positions and clear, orbitally modulated variability, the associations are definitive.
- Fermi-LAT provided the next leap
  - Good sensitivity
  - Source localization
  - Near continuous monitoring
  - Firm ID of LS I +61° 303, LS 5039
- and… finally…. in 2009 both AGILE and LAT detect gamma-rays from Cygnus X-3

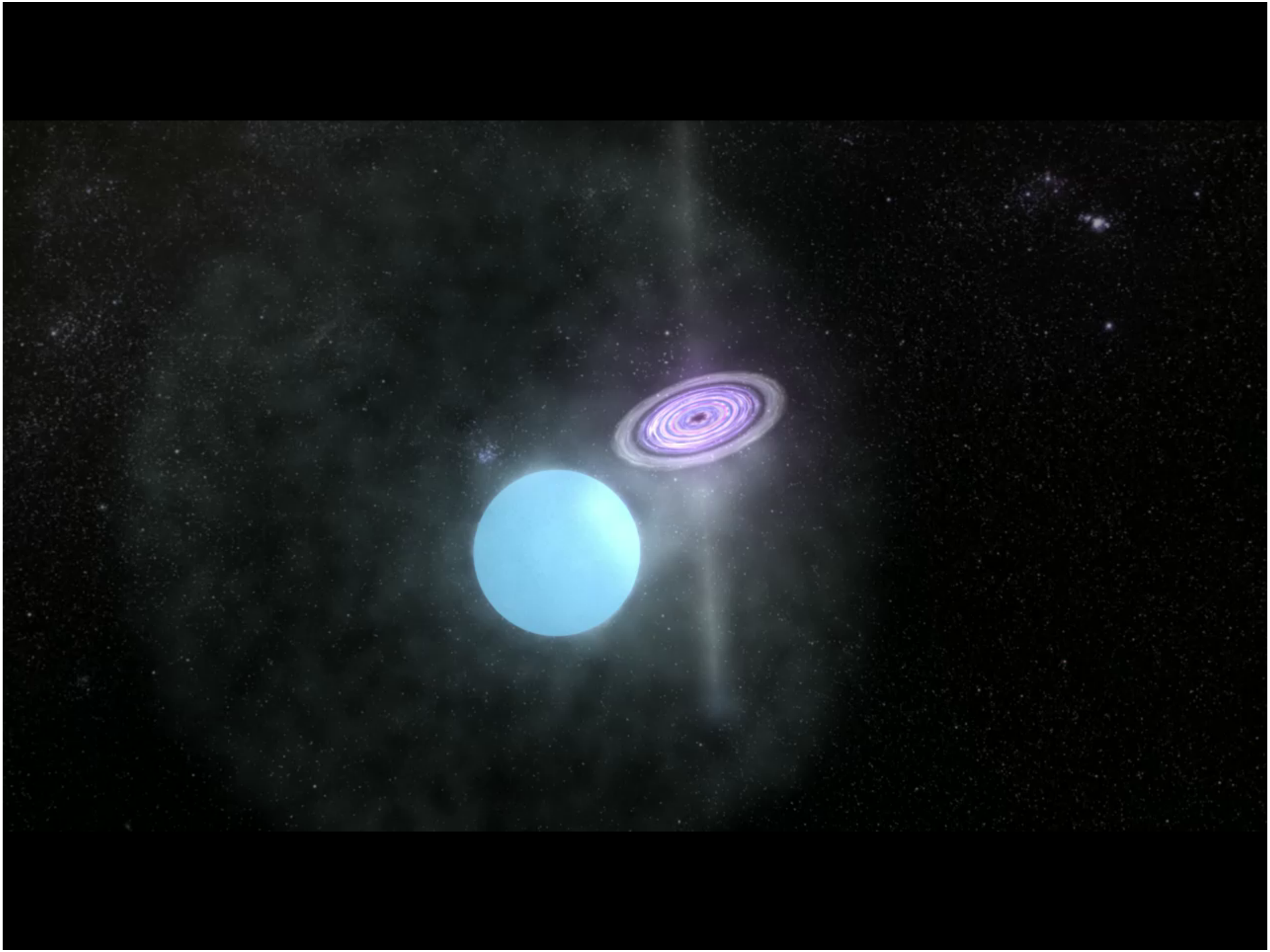


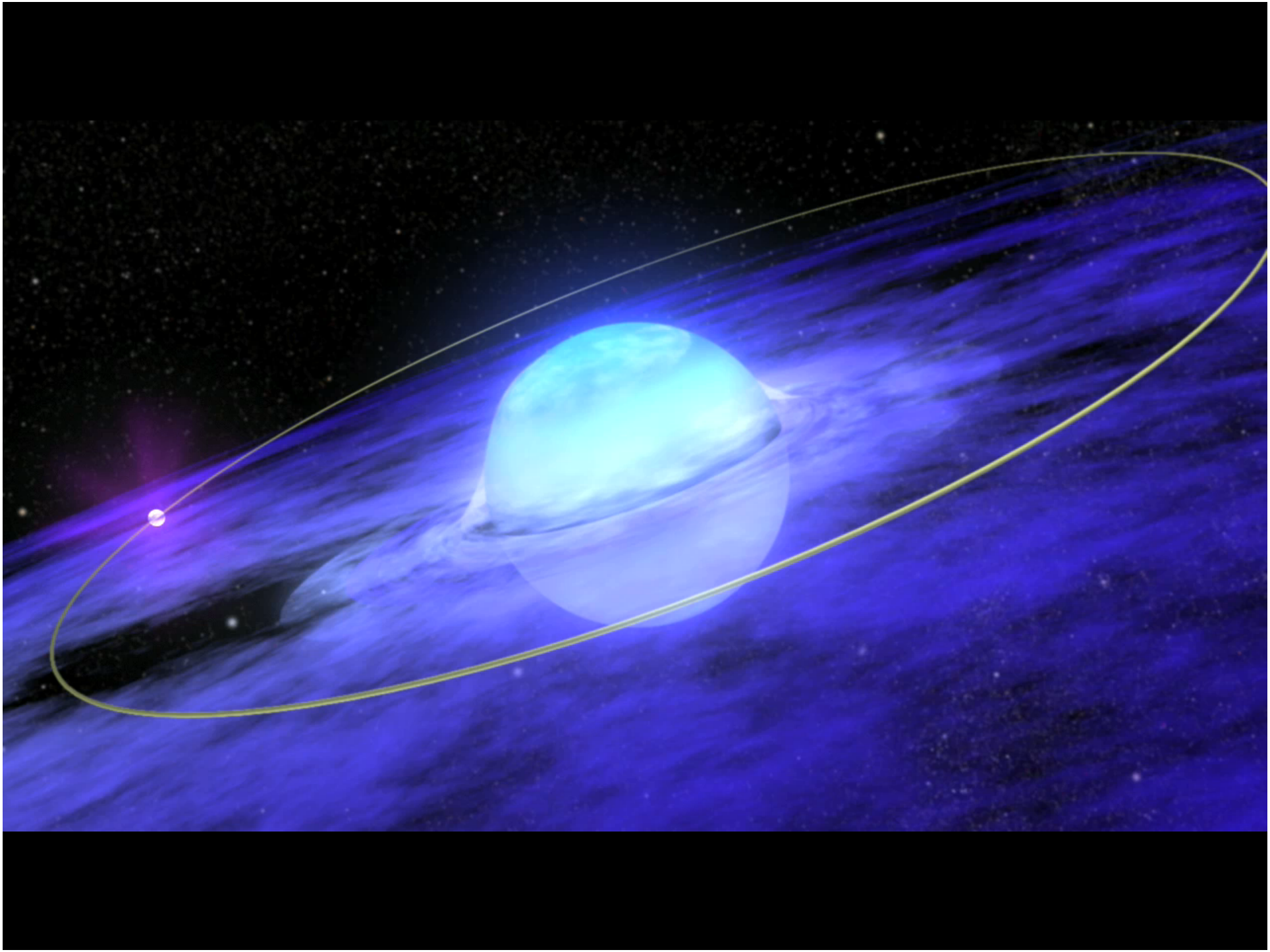


What drives them?



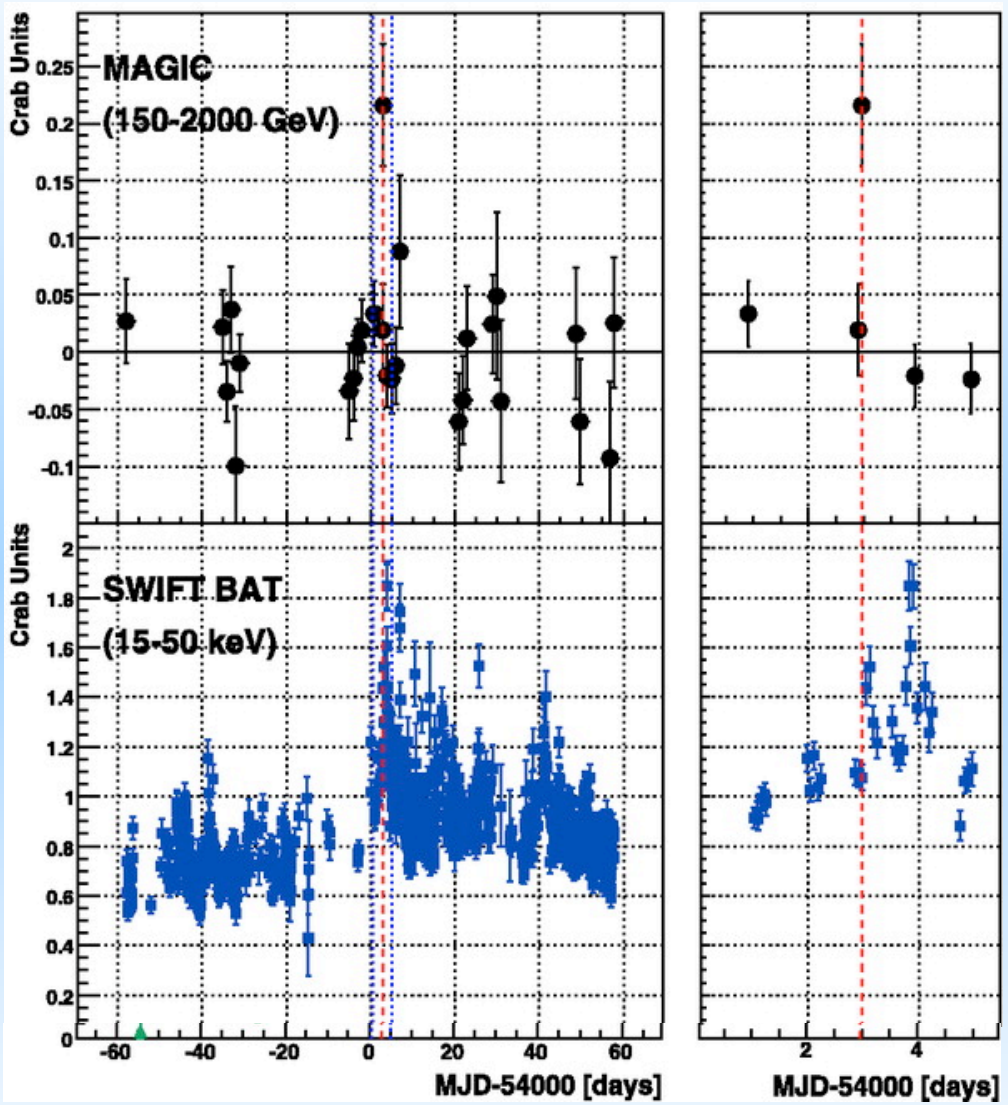
Mirabel (Science 309, 714, 2006)





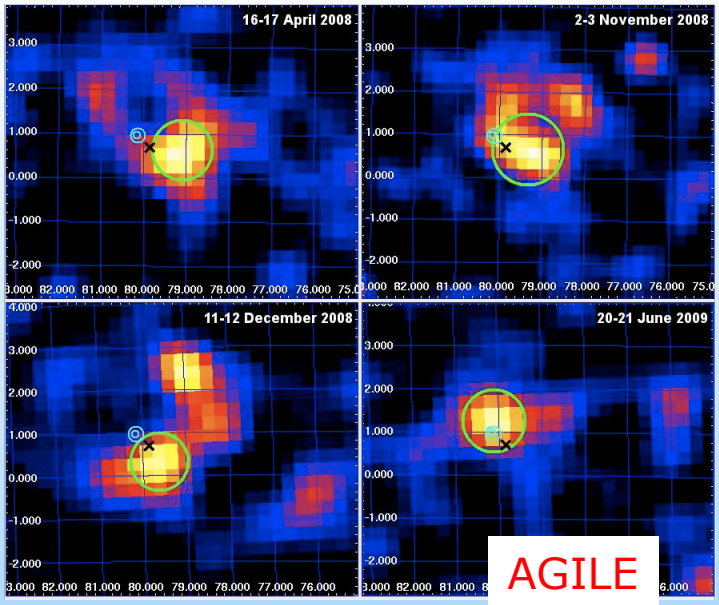
The black holes: Cygnus X-1

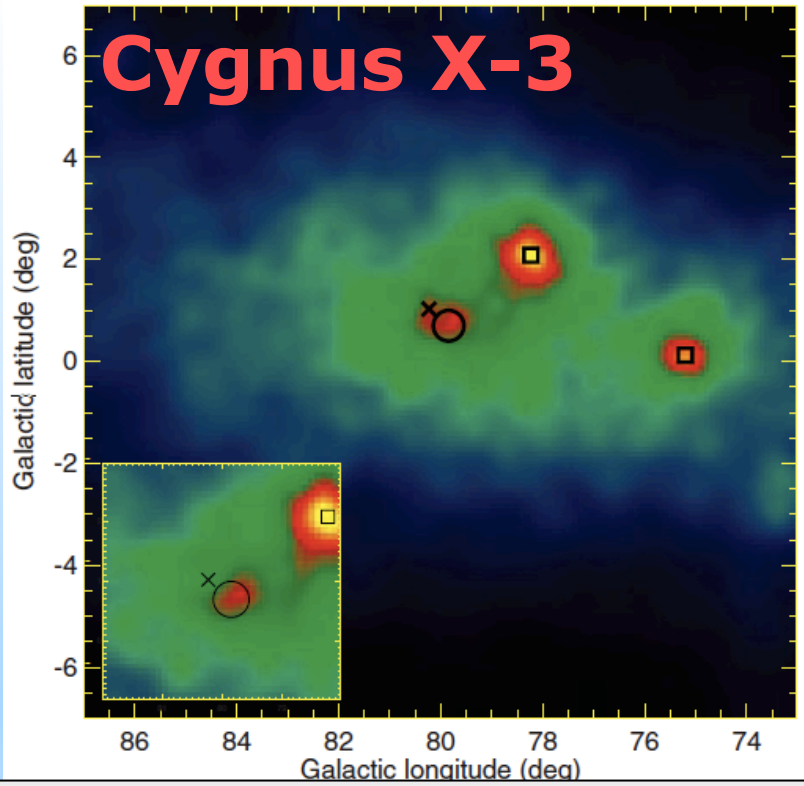
- Cygnus X-1
  - 21±8 $M_\odot$ compact object,
  - 40±10 $M_\odot$ O9.7Iab companion.
- 5.6 day circular orbit
- Accretion powered
- MAGIC observed 40 hours: no steady emission above ~100GeV
- See one episode at ~4σ, close to an X-ray flare
- AGILE also saw a ~4σ flare in 2009 above 100 MeV at a different orbital phase and spectral state.
- No Fermi-LAT detection (yet)



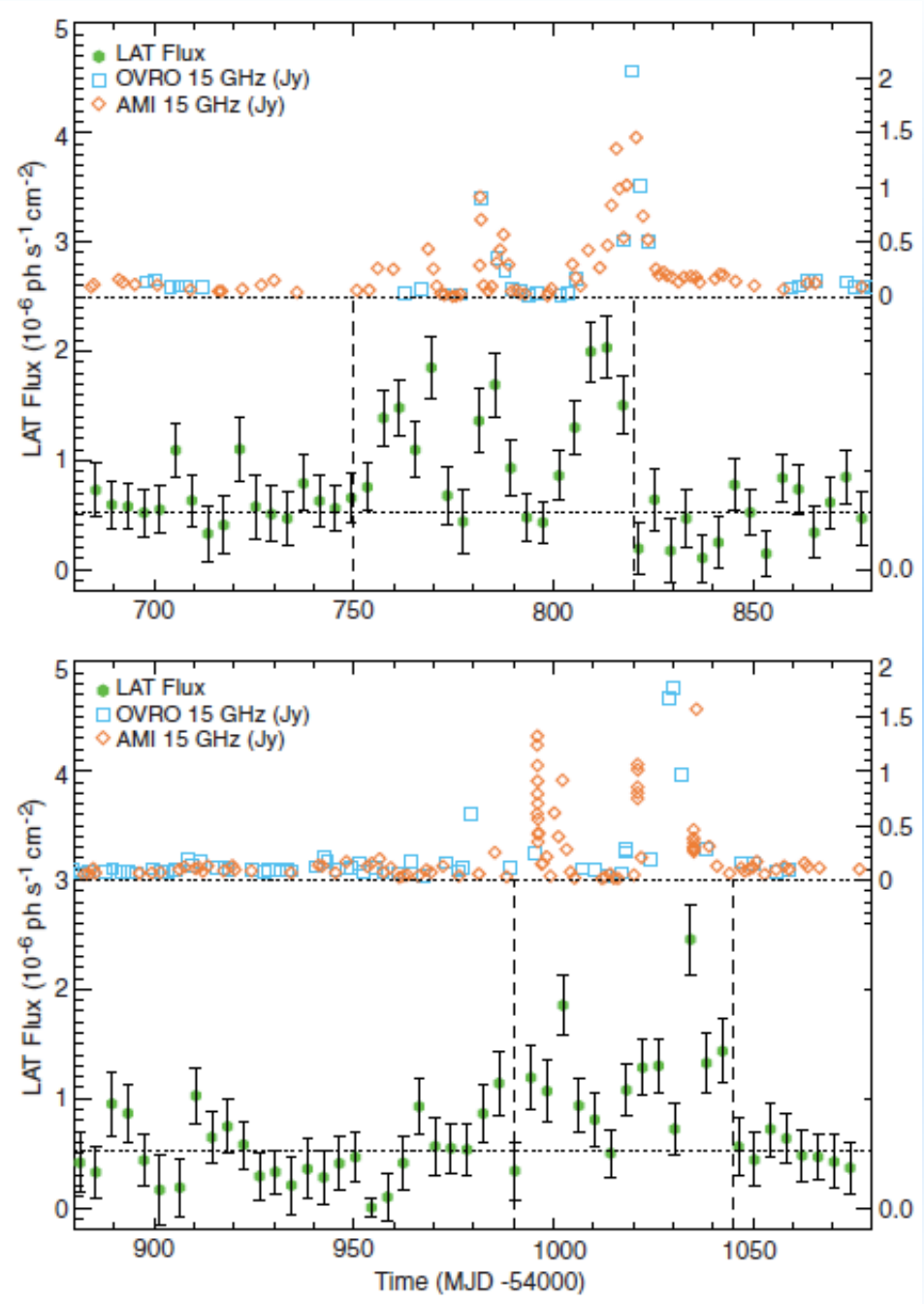
The microquasars: Cygnus X-3

- Cygnus X-3
  - 10-20 $M_{\odot}$ compact object,
  - Wolf-Rayet companion.
- 4.8 hour orbit
- Accretion powered
- AGILE detect 4 episodes of GeV emission during soft X-ray states
- New Fermi-LAT results presented yesterday (Stephane Corbel)
- Orbital modulation gives firm identification



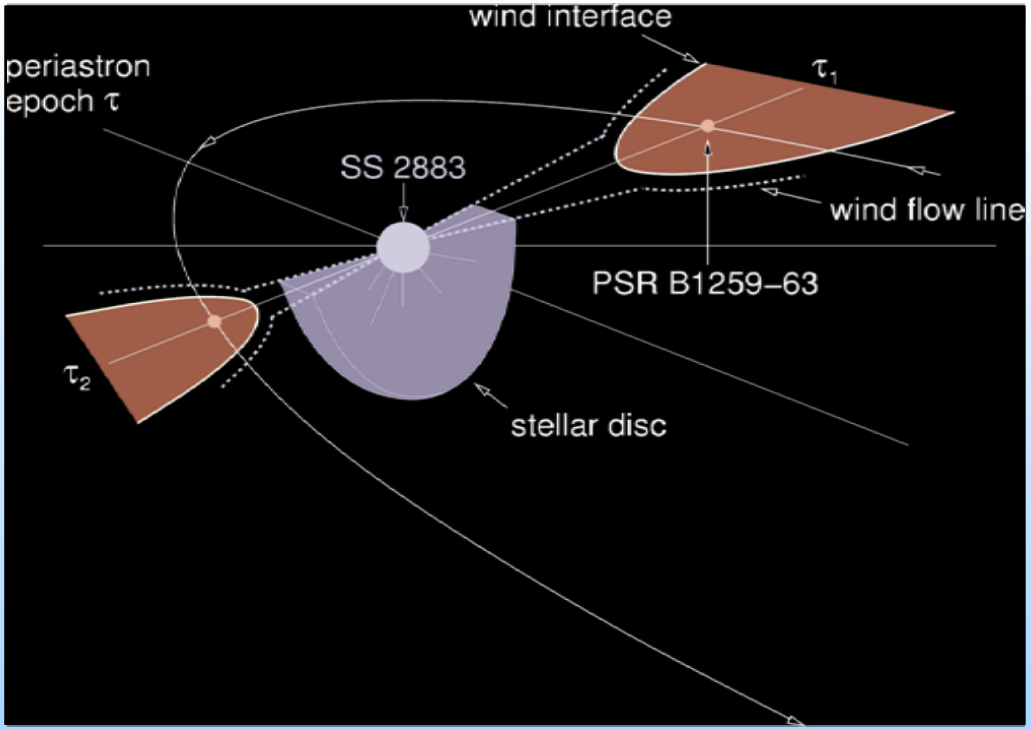


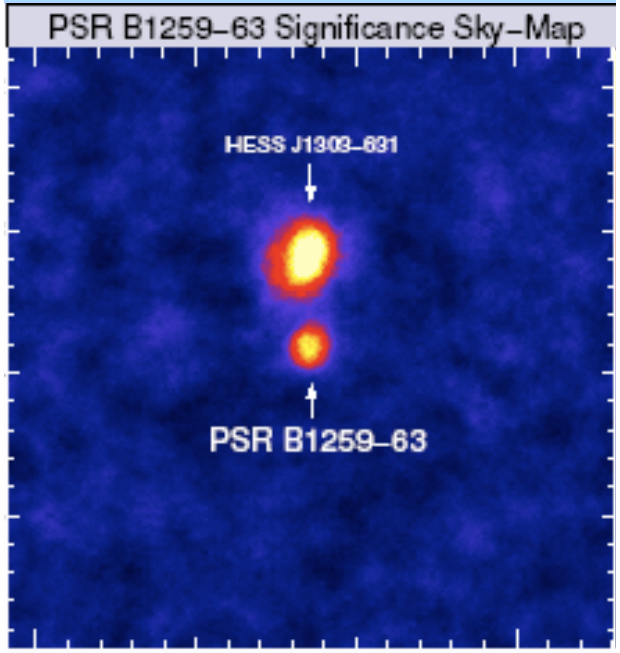
- Cygnus X-3
  - 10-20 $M_\odot$ compact object,
  - Wolf-Rayet companion.
- 4.8 hour orbit
- Accretion powered
- AGILE and Fermi-LAT detect it episodically
- Orbital modulation gives firm identification
- Emission peaks in the soft gamma-rays (upper end of a hard X-ray tail)

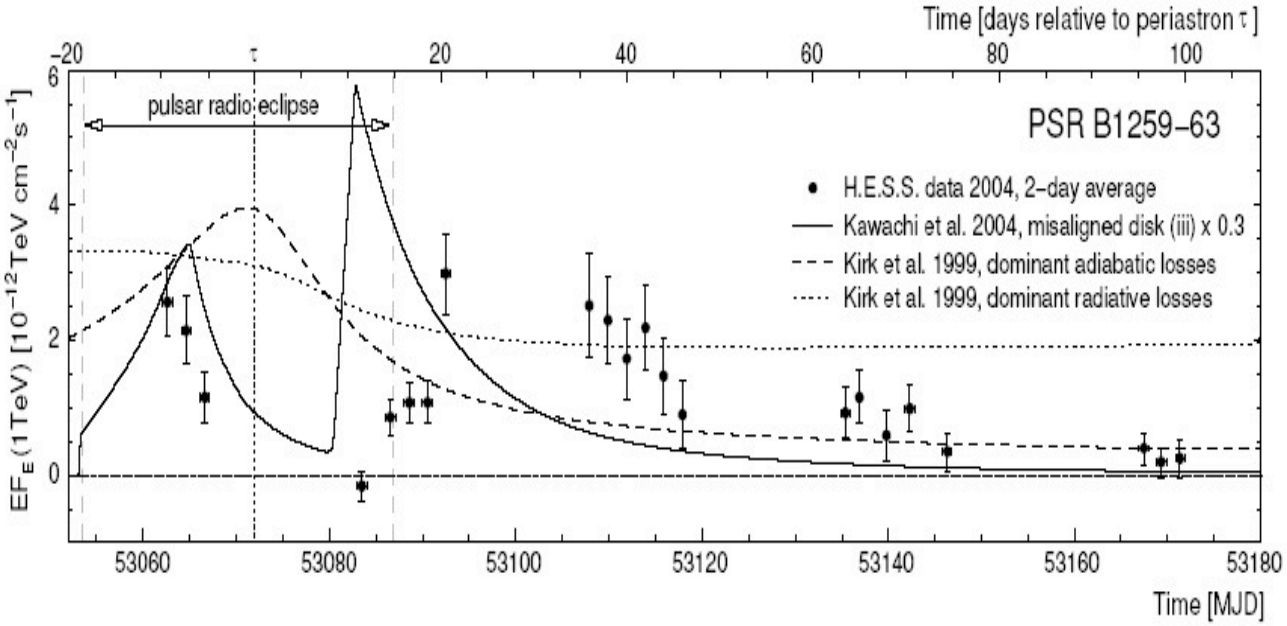


The Pulsar wind Binary: PSR B1259-63

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

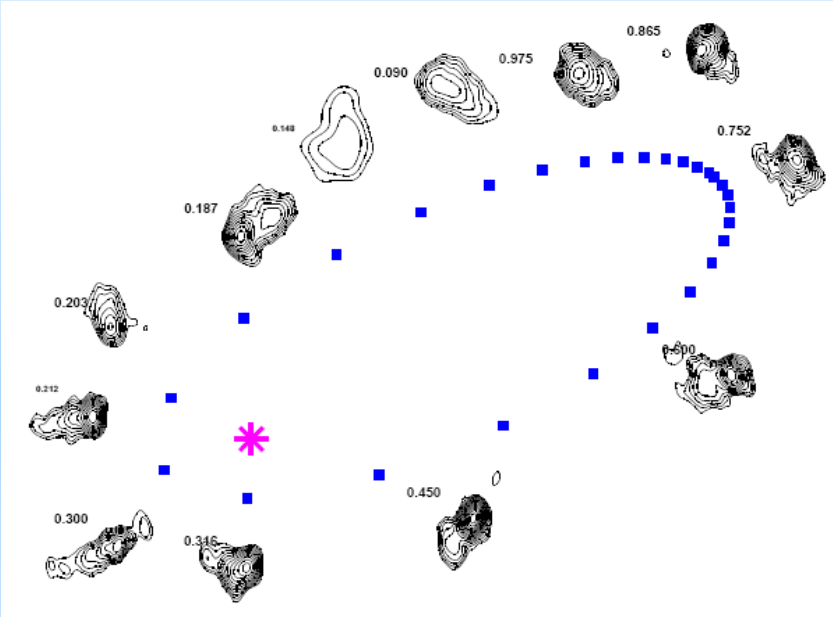






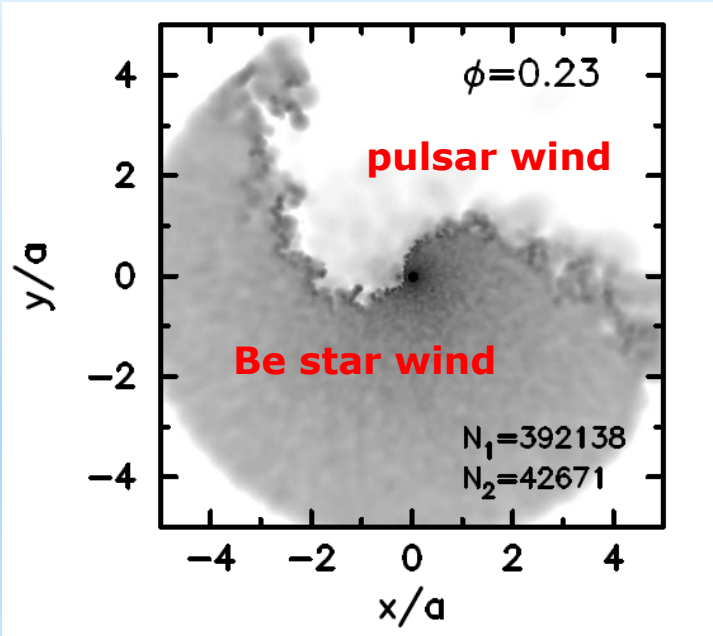
Pulsar wind binary or accreting black hole? It's not always so clear (e.g. LS I +61° 303)

Dhawan et al.
Proceedings of the VI Microquasar Workshop



- Radio observations show rotating tail
- X-ray observations show no spectral features (e.g. no accretion disk bump)
- Supports pulsar wind model

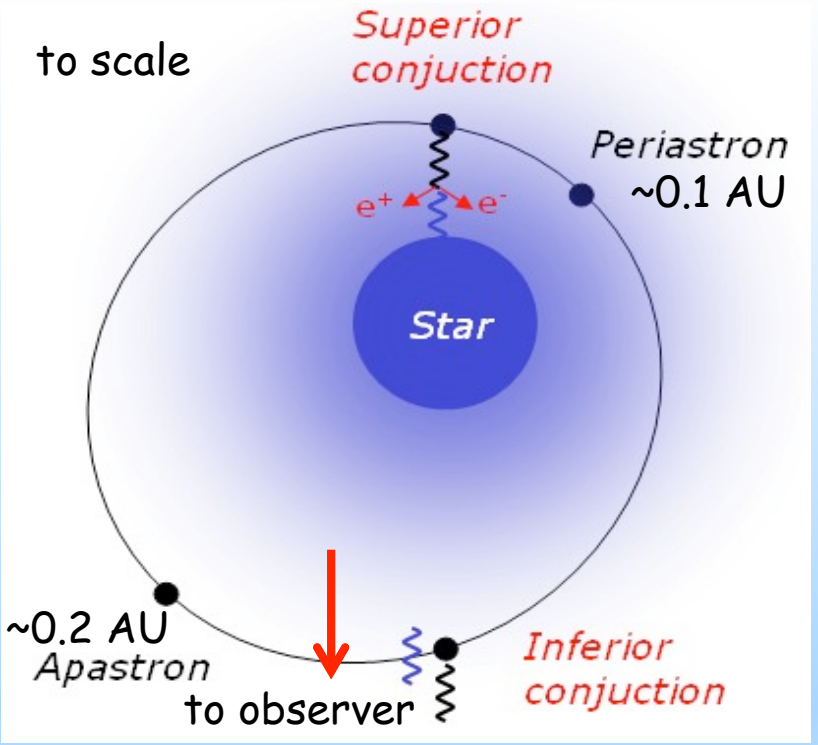
Romero et al. astro-ph/0706.1320

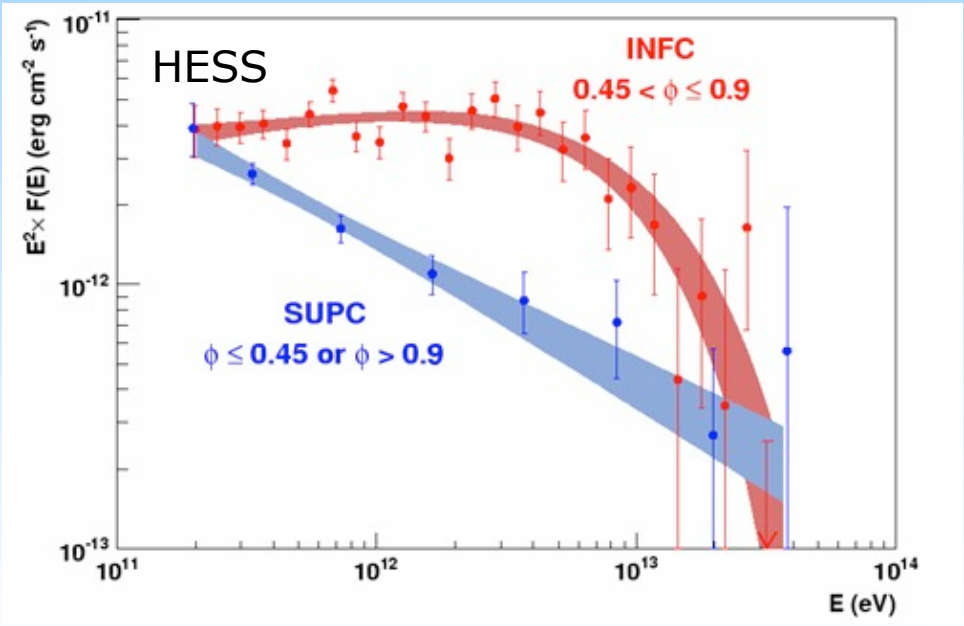


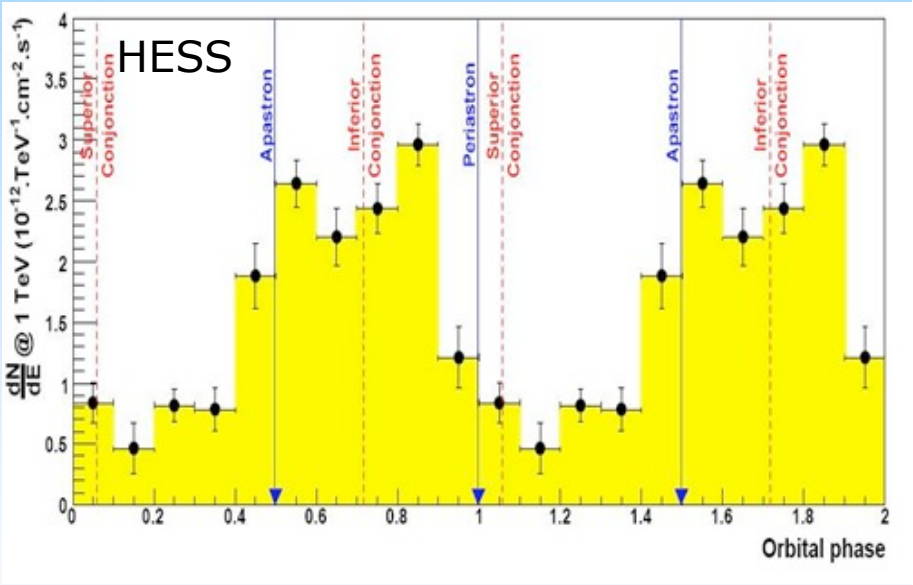
- Relative wind strengths are such that you cannot produce simple elongated shape seen in VLBI images.
- Gamma-ray lightcurve is more easily explained by variable accretion
- Prefer microquasar model

The "not sures": LS 5039

- Compact object orbiting an O6.5V companion ($23M_{\odot}$)
- 3.9 day, inclined orbit, e=0.35
- HESS measure clear periodicity >200GeV
- emission peaks at inferior conjuction
- spectrum varies





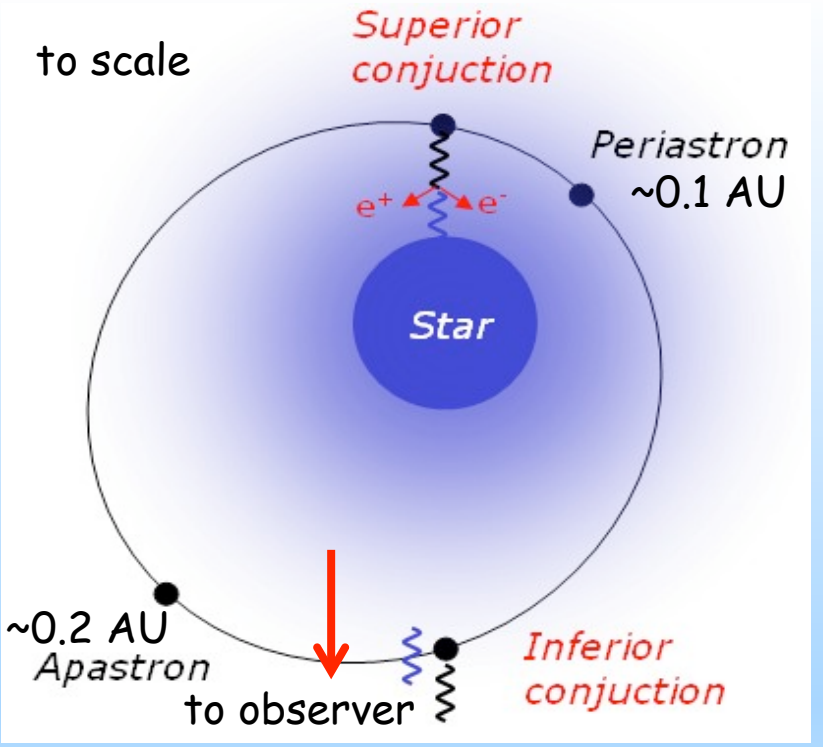


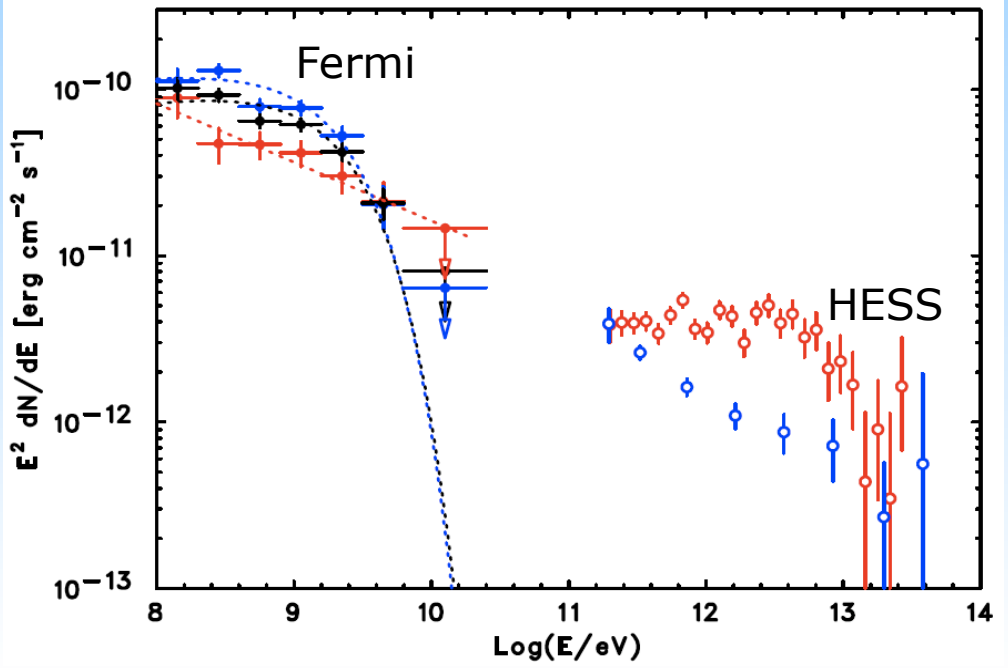
LS 5039

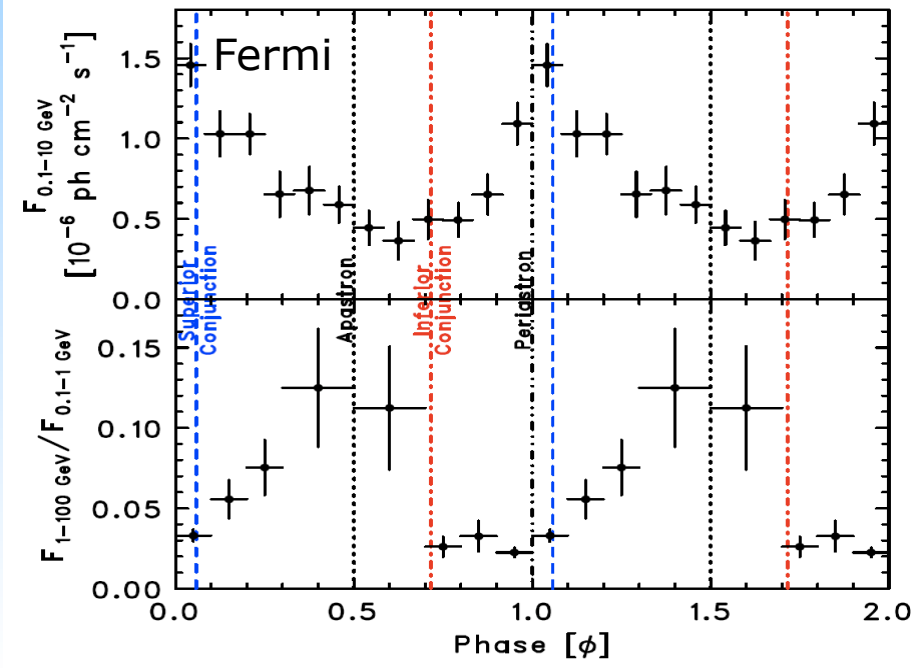
- Detected by Fermi-LAT (BSL)
- Orbital modulation now measured
- See Dubois, this Symposium

(and arXiv:0910.5520, ApJL 706, L56)

- Flux variability *anti-correlated* with HESS
- Spectral variability, and ~2 GeV cut-off observed

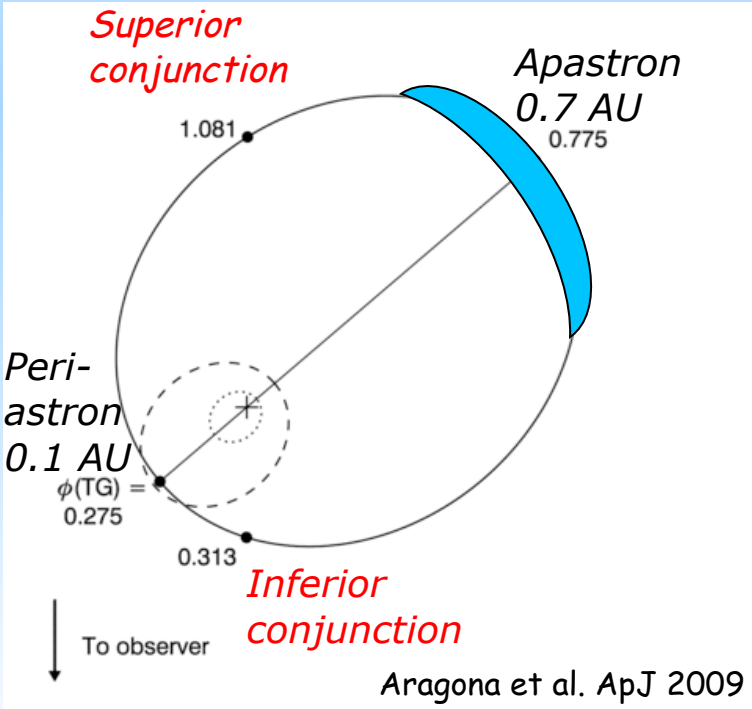




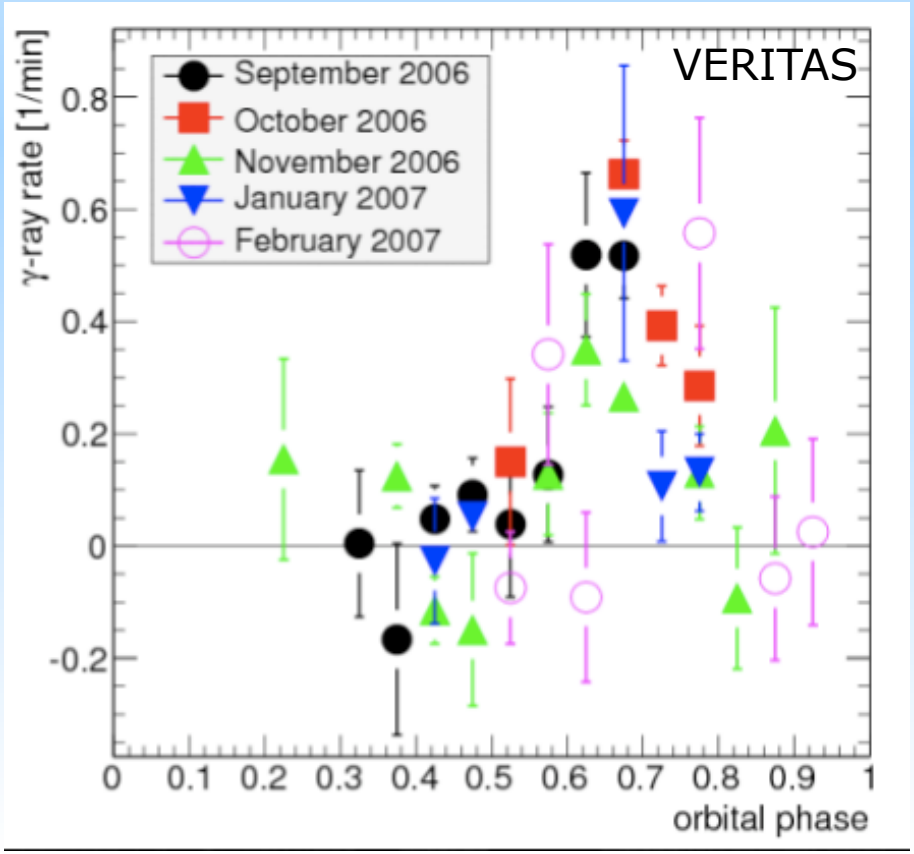


LS I +61° 303

- Compact object (Black hole or Neutron star) orbiting an BOVe companion ($12M_{\odot}$)
- 26.5 day, inclined orbit, e=0.54
- extended radio structures; microquasar? Probably not….
- Detected by MAGIC, then VERITAS
- Strong TeV emission initially only detected near apastron (ϕ=0.5-0.8)

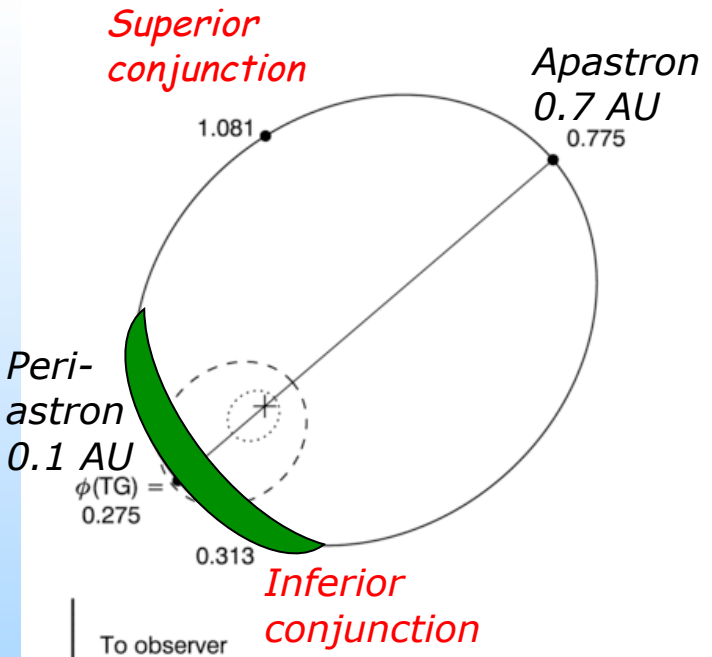


Aragona et al. ApJ 2009



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



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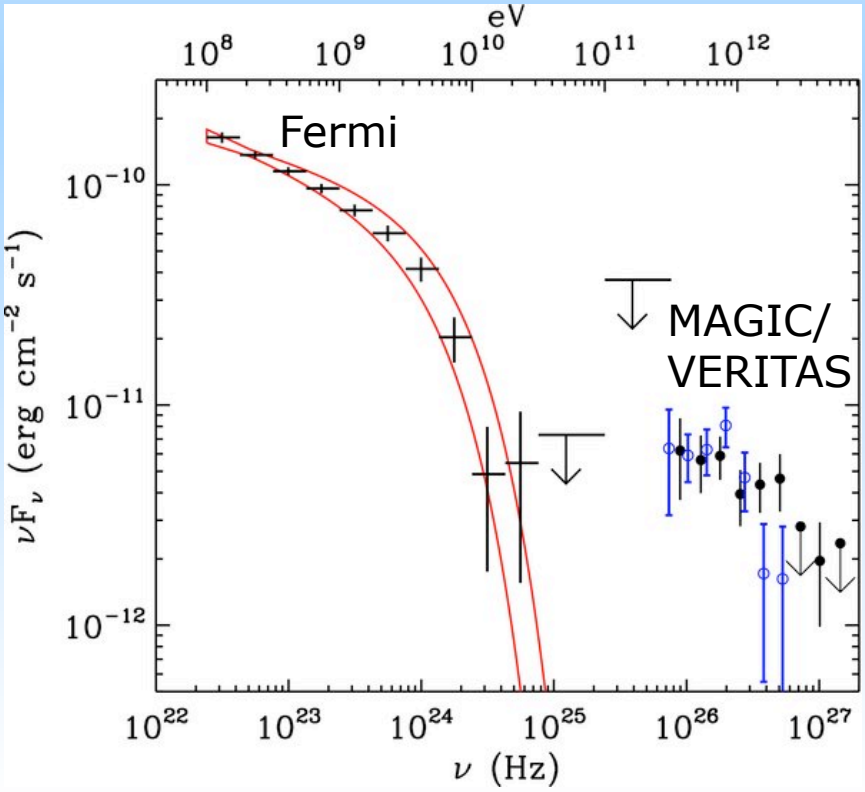
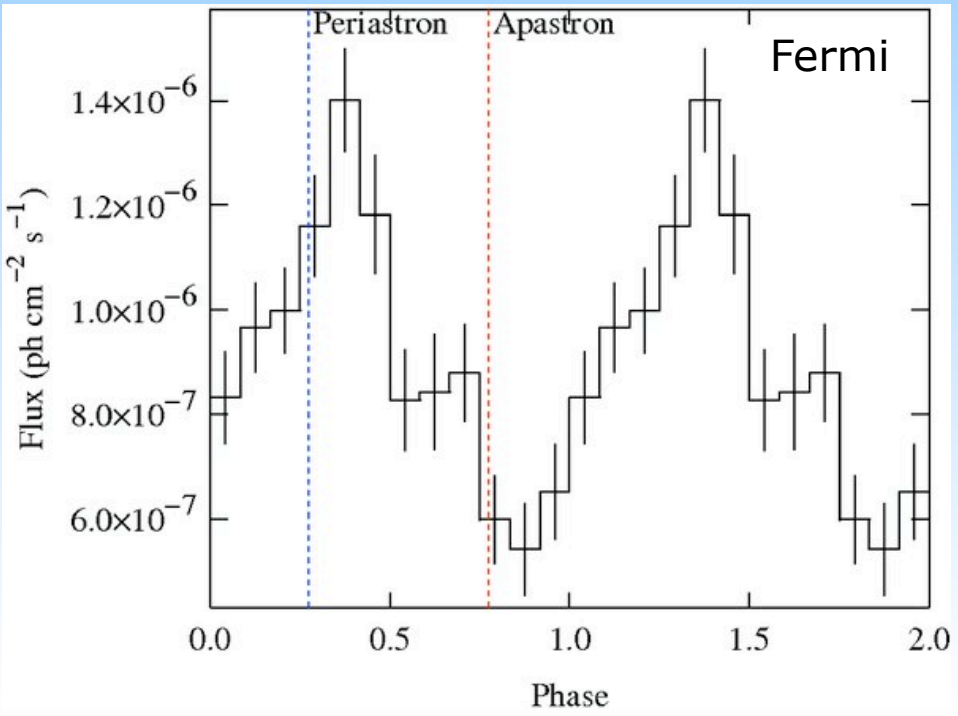
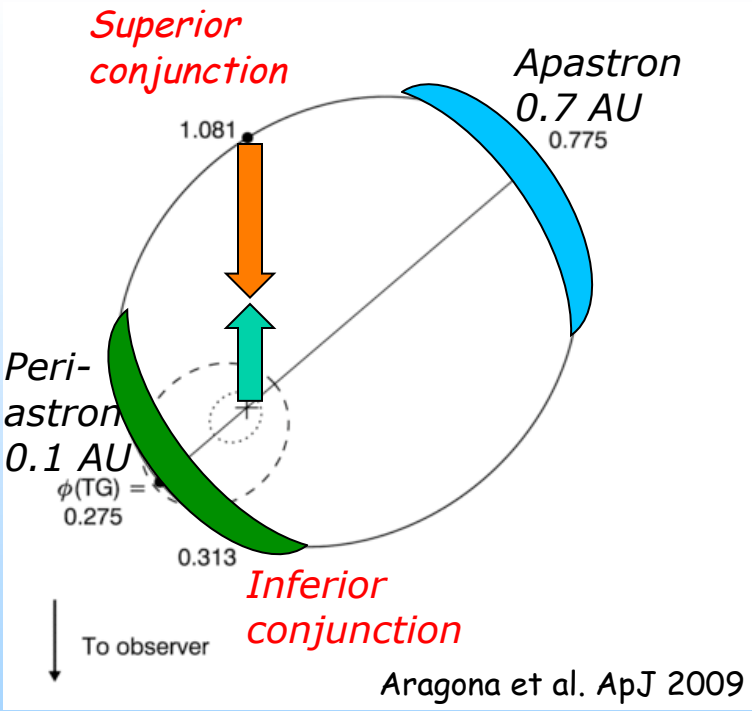


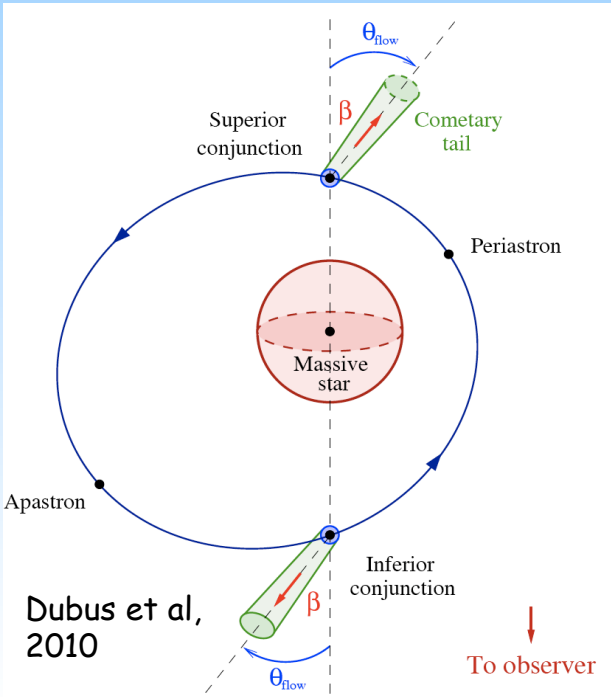


LS I +61° 303

- Competing processes
  - Assume Inverse Compton production -> high energy electrons boost stellar photons to gamma-ray energies
  - At superior conjunction, Inverse Compton production peaks over all energies
  - At superior conjunction, photons > 30 GeV are most heavily absorbed
- Doesn't fit the lightcurves very well
  - Moderate Doppler boosting helps
- Why is there a 6 GeV cut-off?
  - Different mechanism for GeV and TeV?
  - GeV emission spectrum appears magnetospheric – but then why is the GeV emission modulated at all? Where are the pulses?



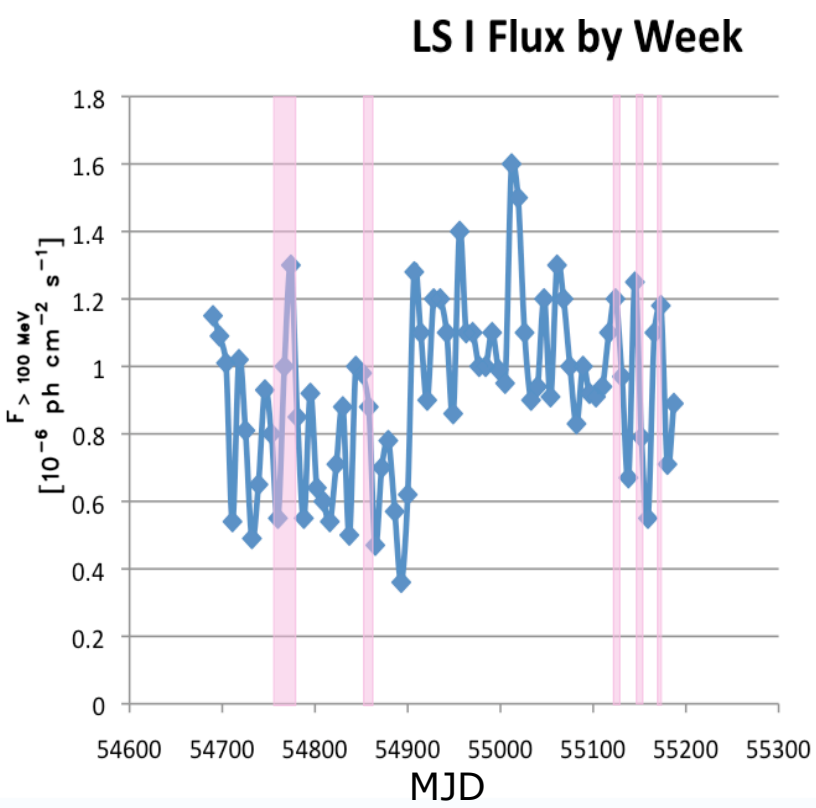
Aragona et al. ApJ 2009

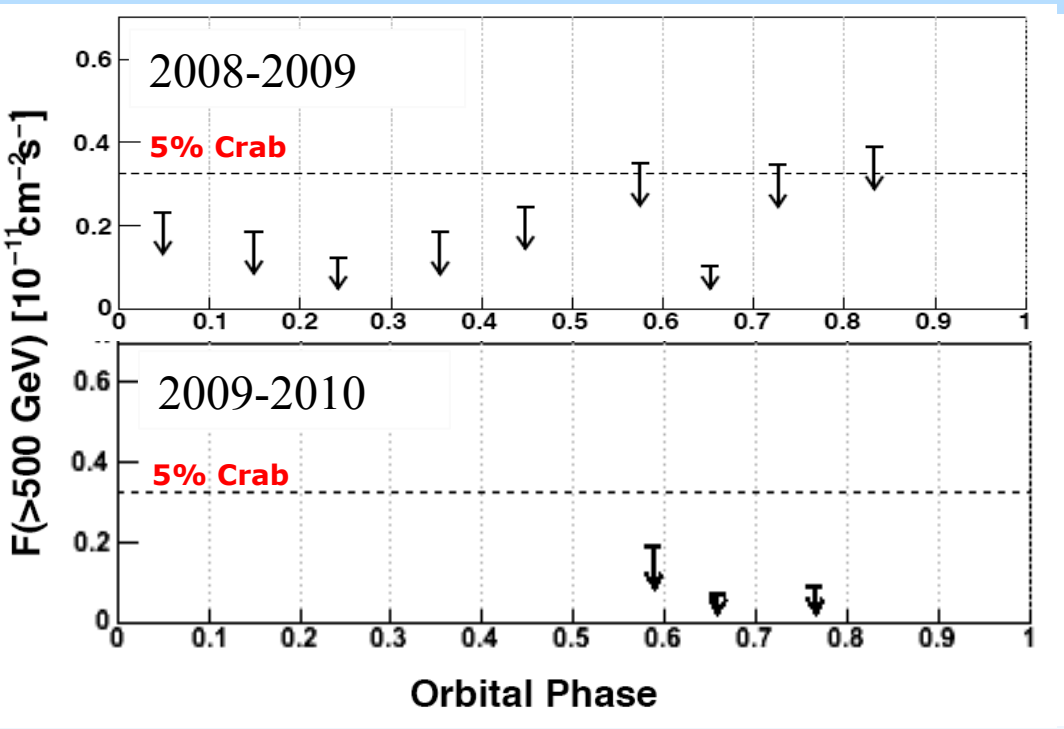


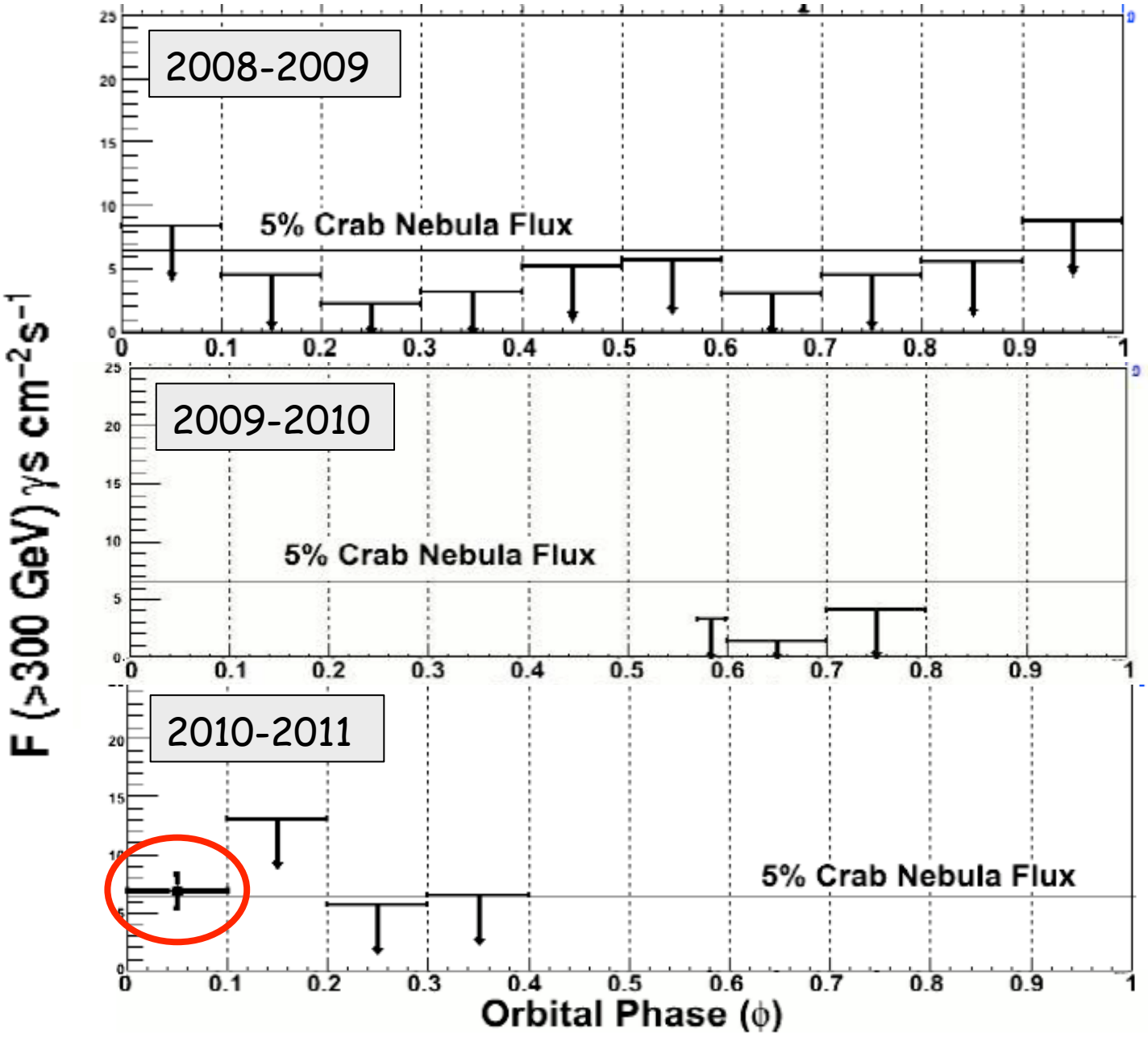
Dubus et al, 2010

Contemporaneous observations complicate things further

- No apastron detection by VERITAS since the launch of Fermi, despite good exposure.
- Fermi light curve shows variability not associated with the orbit – and the orbital modulation has faded
- Is it "weather"? Are there longer-term cycles? More data needed!!
- LSI +61 303 is interesting, but difficult…







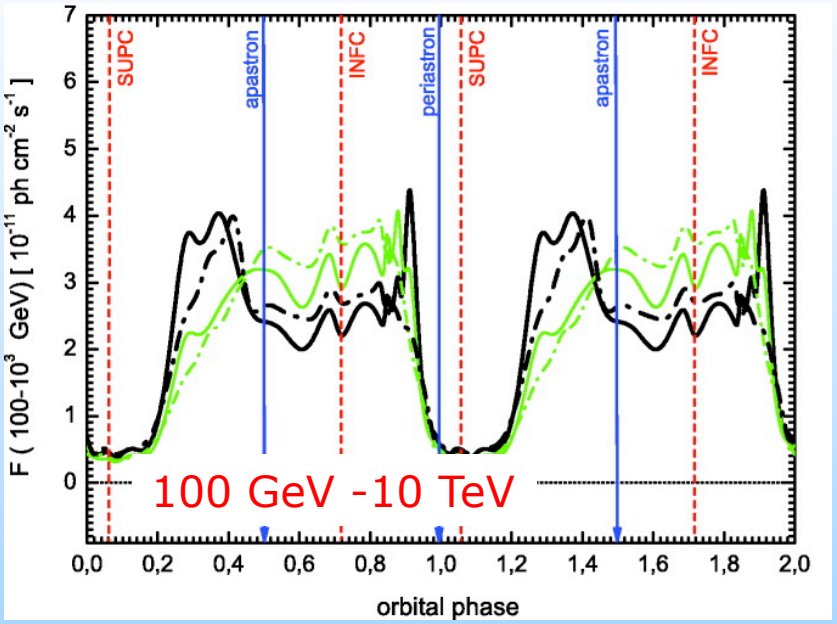
- LSI +61 303 is interesting, but difficult…

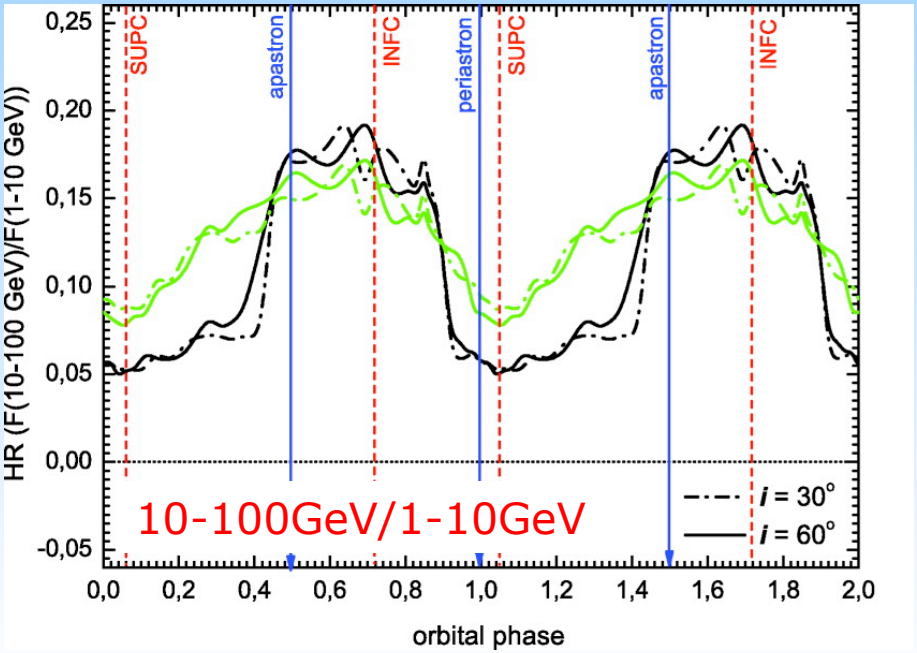
A few things to think about (not exhaustive)...

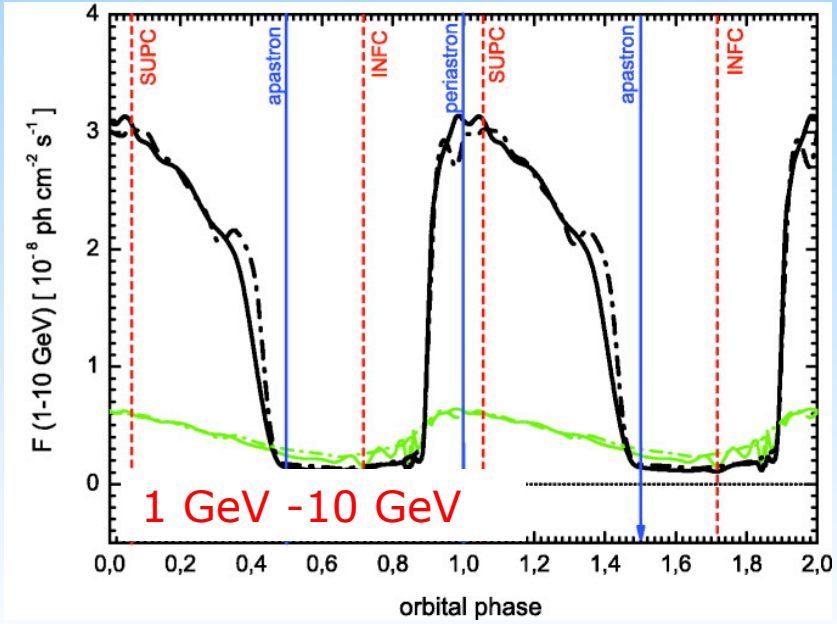
What is the power source?	Accretion-powered jet	Pulsar wind		
What is the particle acceleration mechanism?	Jet shocks	Magnetic reconnection	Wind shocks	
What are the dominant particles?	Hadronic	Leptonic		
How are the γ-rays produced?	Pion decay	Inverse Compton	Curvature Radiation	
Where are the γ-rays 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	Unknown geometries	

Many of these are not mutually exclusive...

- Difficult, but detailed predictions can be made, and are beginning to be strongly tested
- (e.g. Sierpowska-Bartosik & Torres, LS 5039)

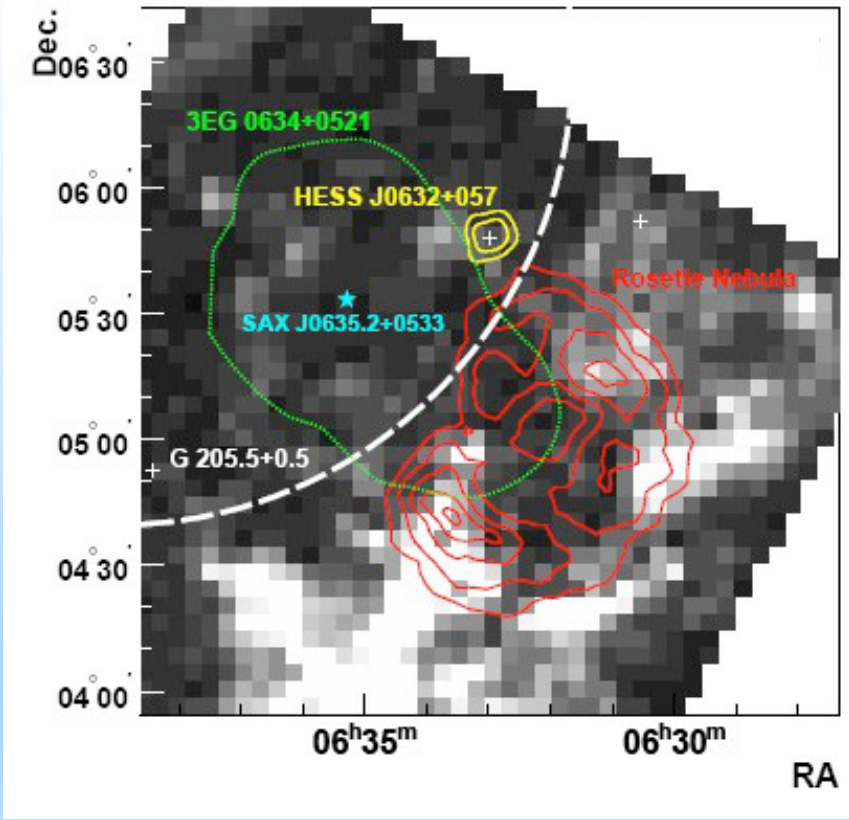




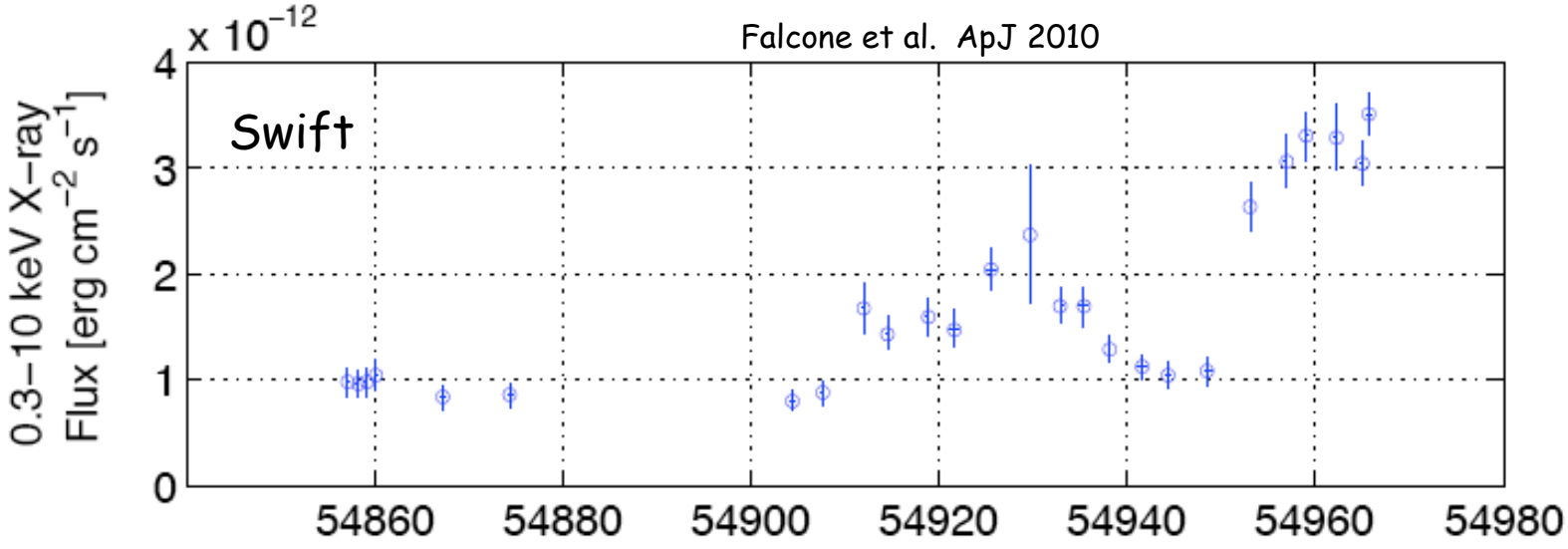


HESS J0632+057

- Unidentified TeV HESS source in the Galactic plane (Γ=2.53, Flux~3% Crab)
- A rare unresolved source (<2′)
- VERITAS detections and limits reveal gamma-ray variability
- MWL follow-up shows a hard spectrum X-ray source (Γ=1.2 – 1.9) & faint radio source coincident with a B0pe star (MWC148). Not a Fermi source.
- Swift measures long term variability



Falcone et al. ApJ 2010



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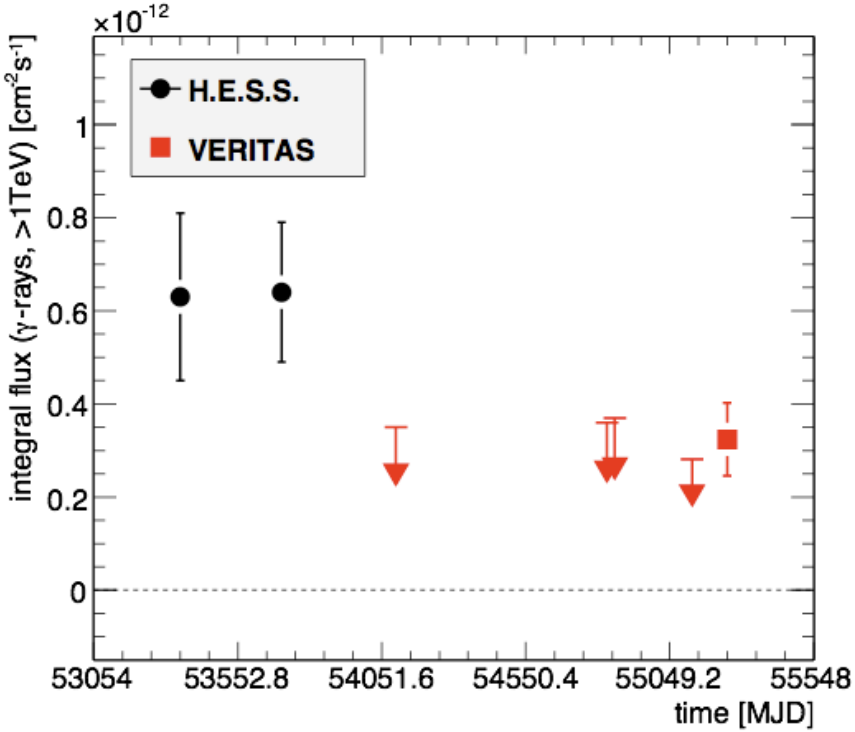
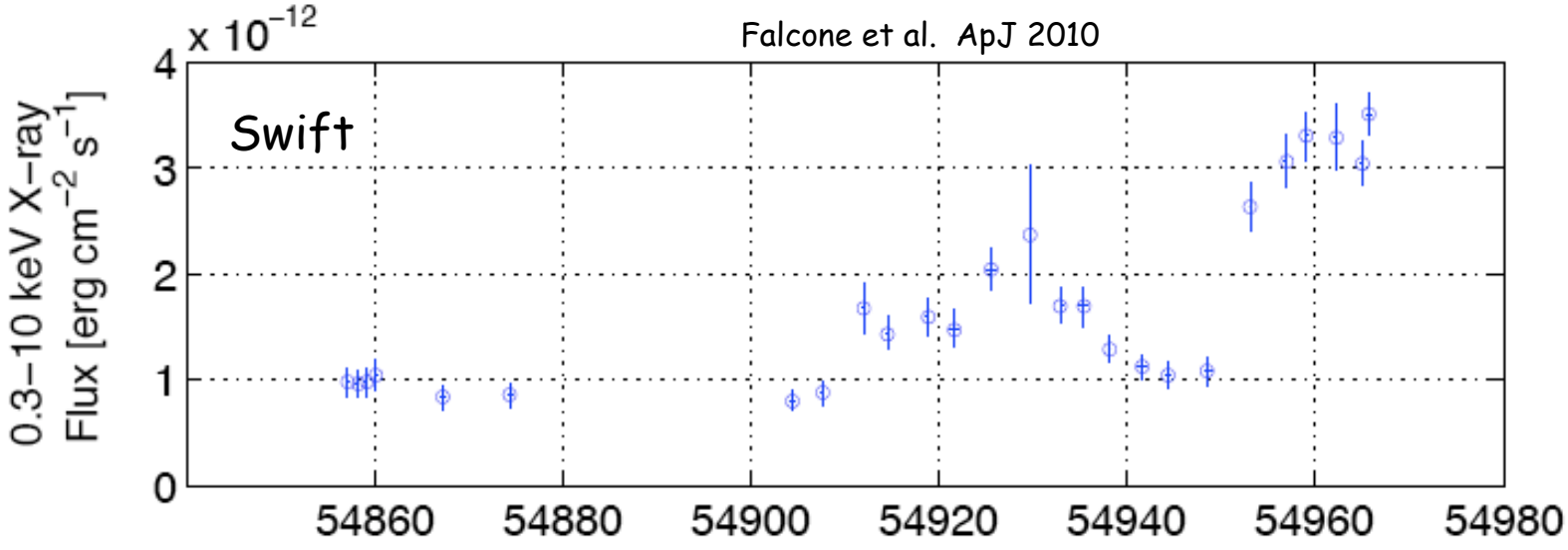
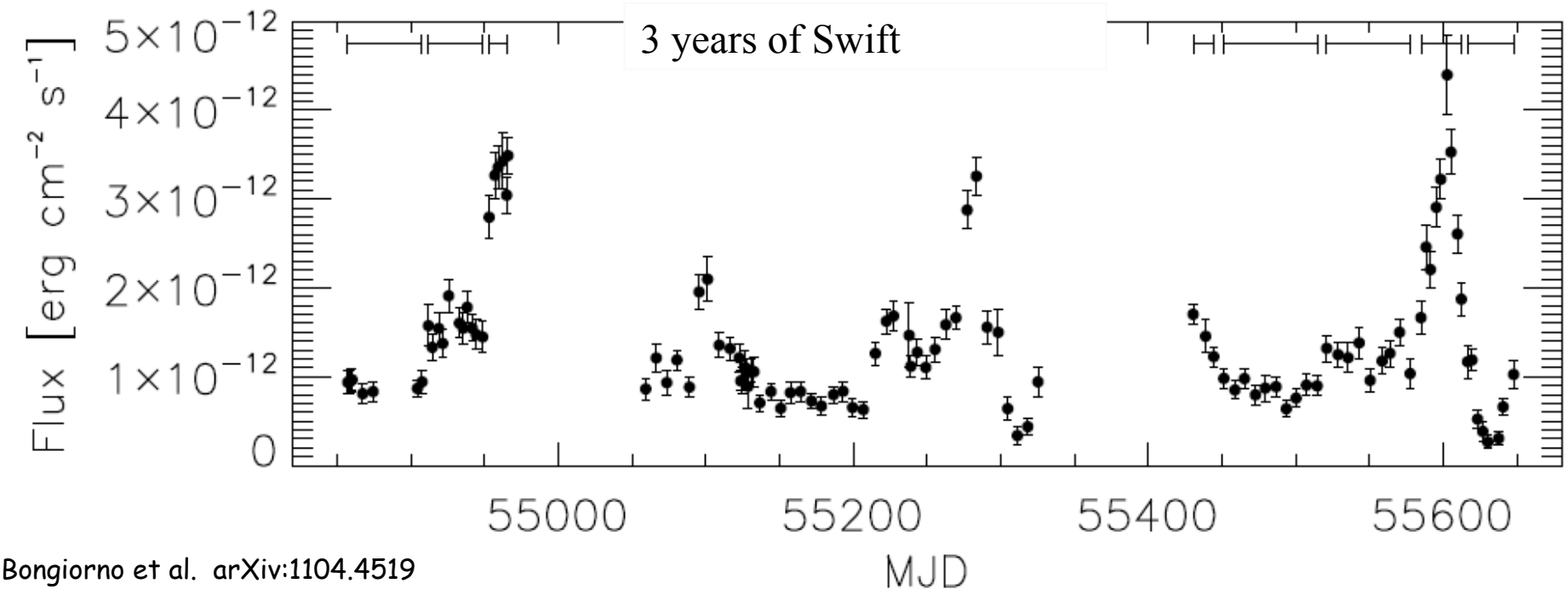


Falcone et al. ApJ 2010



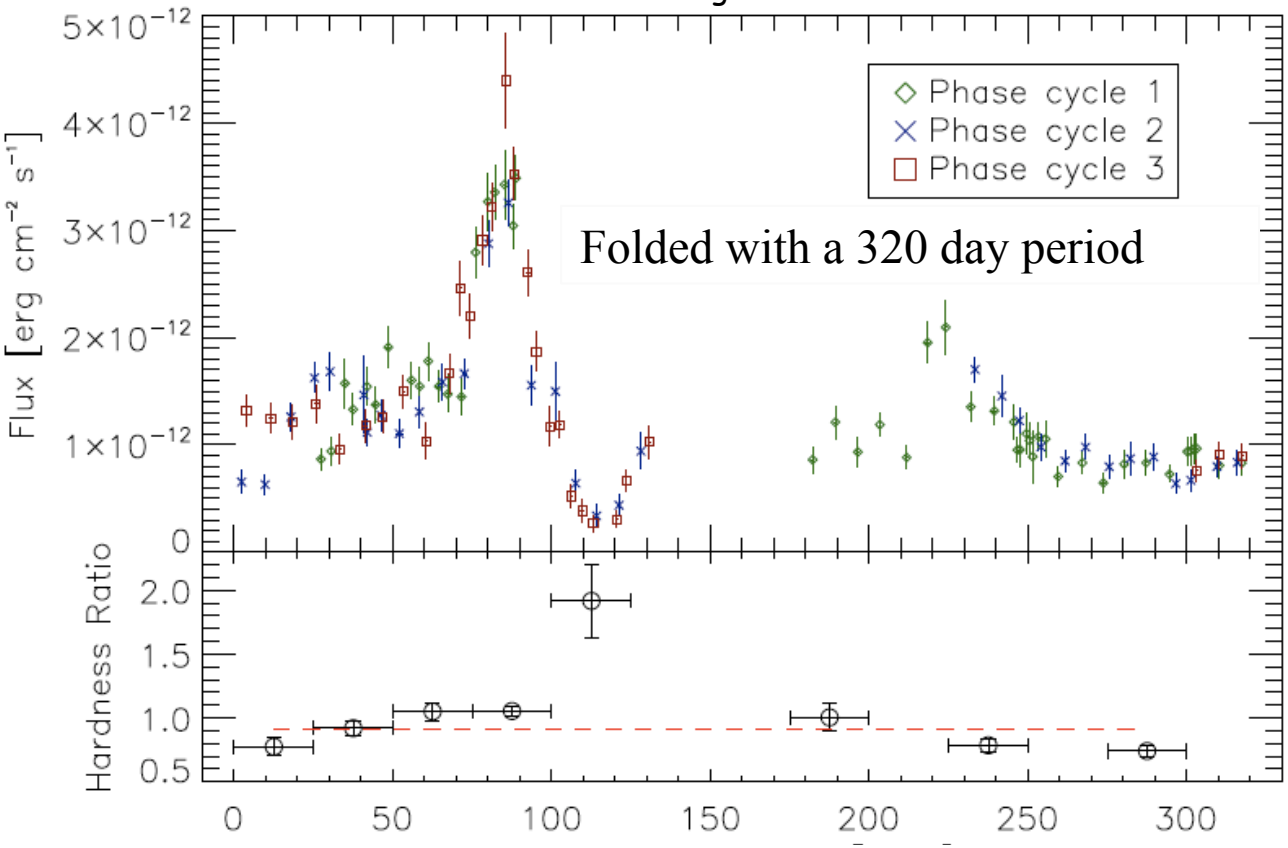
- Swift Observations have continued over the past 3 years



Bongiorno et al. arXiv:1104.4519

- Swift Observations have continued over the past 3 years
- Clear evidence recently found for a 320 day period
- VERITAS observations were pre-planned to cover X-ray high state
- Gamma-ray flaring detected (~4% Crab)

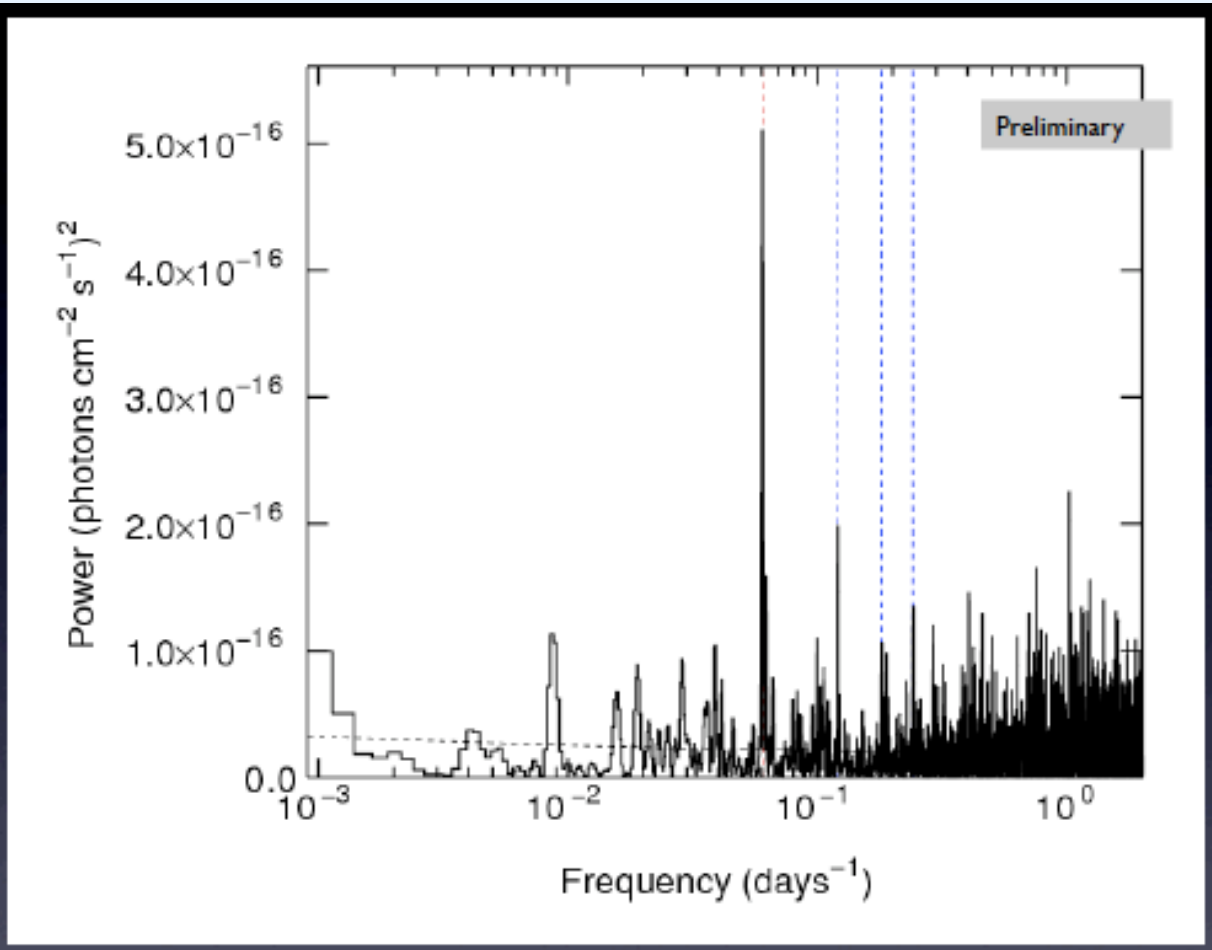
Bongiorno et al. arXiv:1104.4519



VERITAS Reports Increased Activity of HESS J0632+057 in Very High Energy Gamma Rays

ATel #3153; *Rene A. Ong, for the VERITAS Collaboration*
on 8 Feb 2011; 22:54 UT

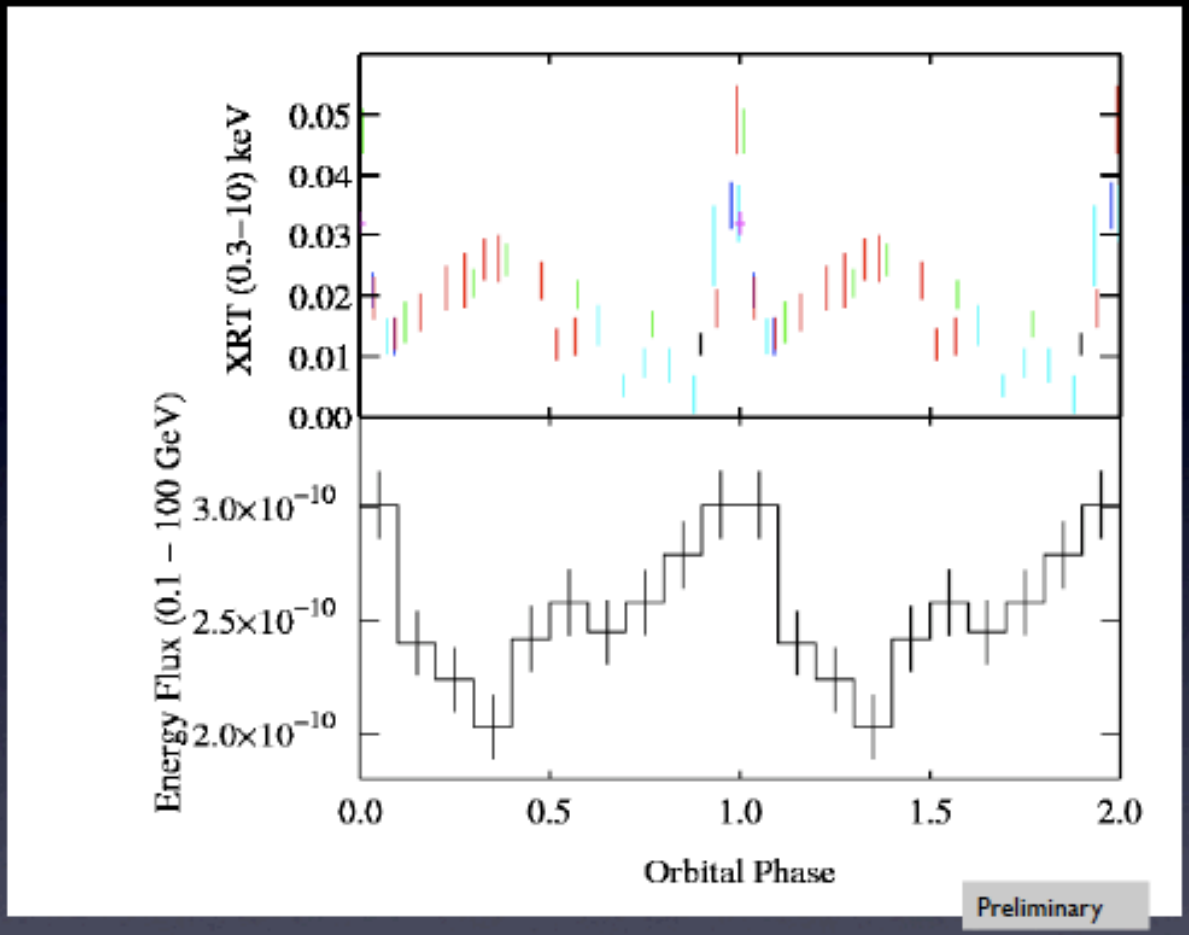
A New Gamma-ray Binary: 1FGL J1018.6-5856



Probability of peak at 16.6 days arising by chance is < 10^{-7}.

Slides shamelessly stolen from Robin Corbet's Fermi Symposium presentation

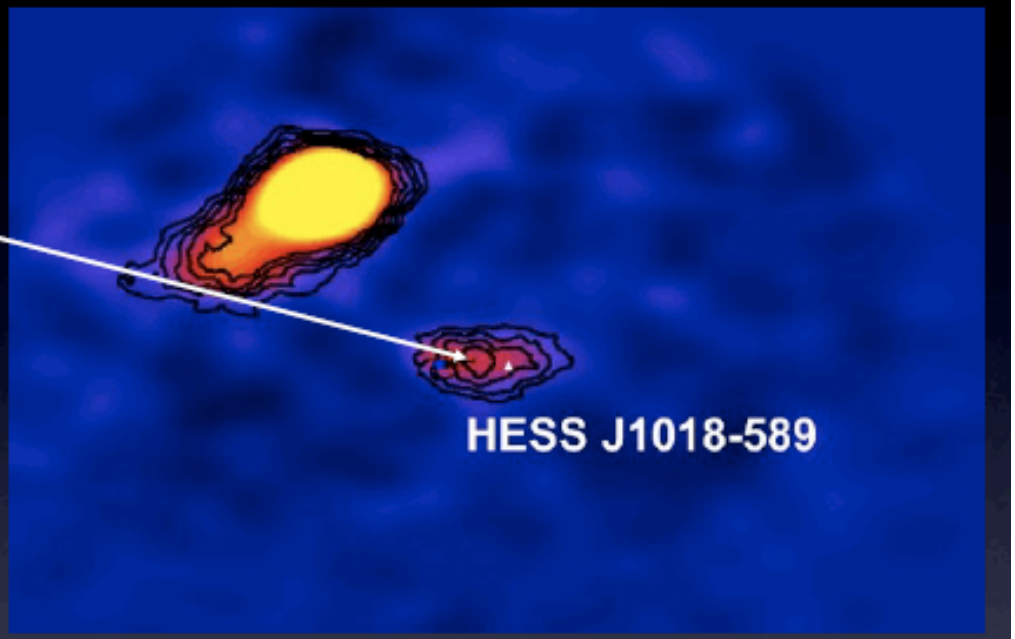
Large X-ray variability (Swift XRT)



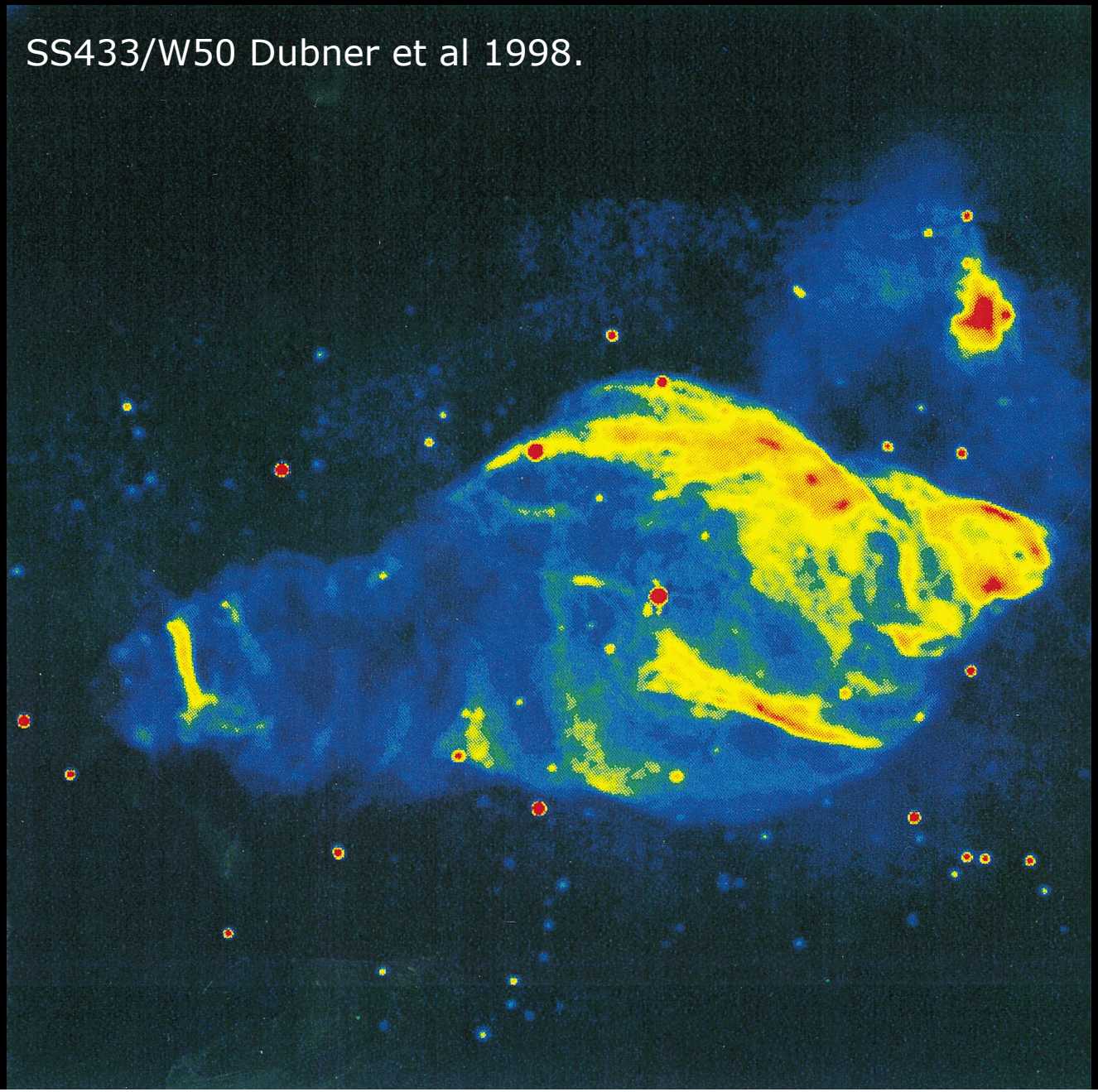
- Different colors (top panel) show X-ray data from different 16.6 day cycles.
- Flare-like behavior near phase 0, coinciding with gamma-ray maximum.
- X-ray modulation also has a quasi-sinusoidal component with peak at phase ~0.4

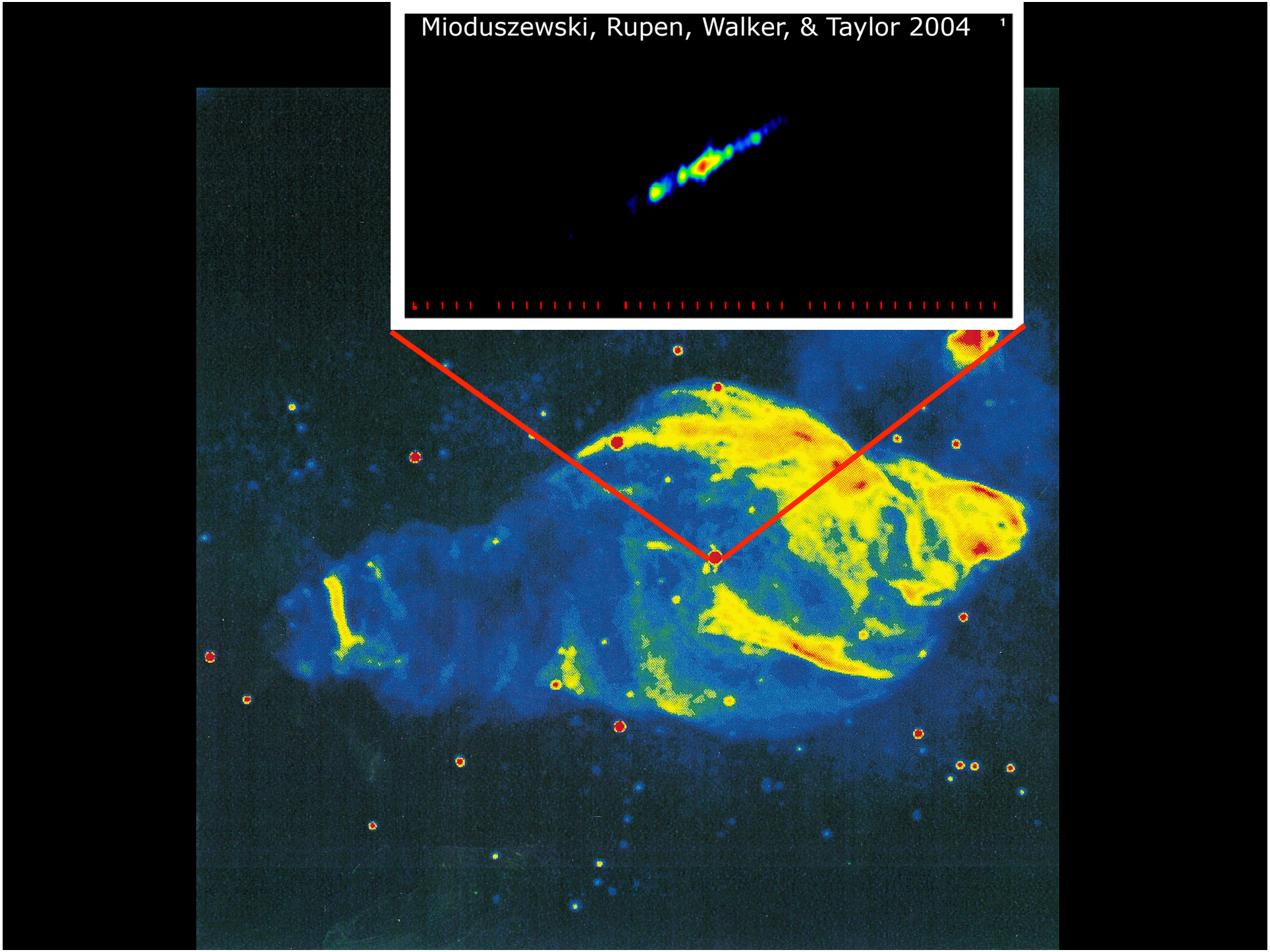
TeV Emission from the Vicinity of 1FGL J1018.6-5856

- H.E.S.S. (de Ona Wilhelmi et al., 2010) reported a TeV source in this region.
- The positions are consistent, but it's not certain the HESS source is associated with 1FGL J1018.6-5856.
- TeV emission is seen (at least sometimes) from LS 5039 and LS I +61 303,
- Is this the TeV counterpart of 1FGL J1018.6??



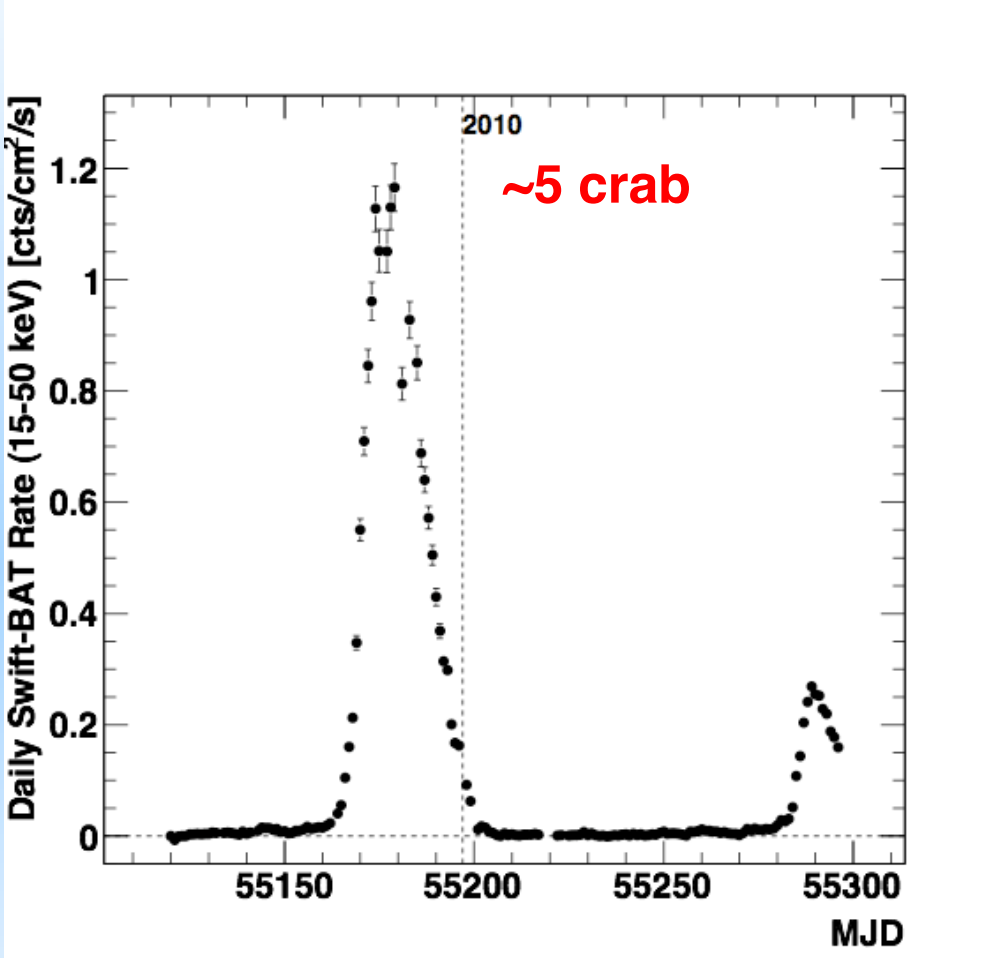
How else might gamma-rays be produced?




Mioduszewski, Rupen, Walker, & Taylor 2004
1

1A0535+262

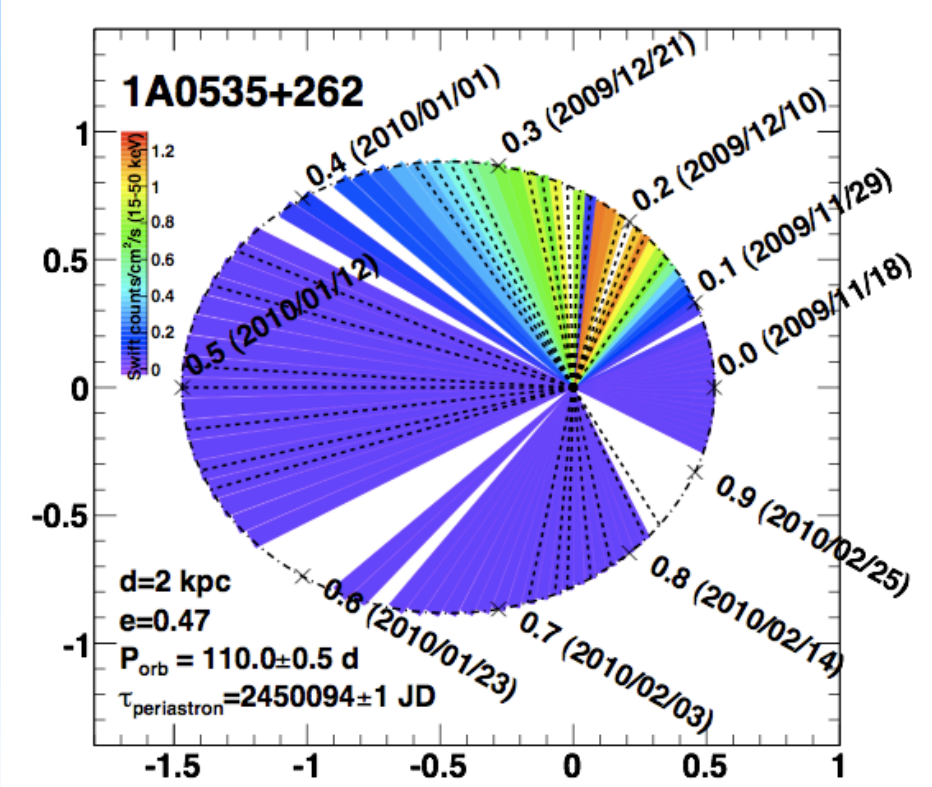
- HMXB, Be-star and X-ray pulsar (PSpin=104s)
- Orbital period 110 d, eccentric orbit (e= 0.47)
- Distance 2.4±0.4 kpc
- Hard X-ray spectra; non-thermal particle populations
- Giant outbursts every ~5 years since 1975
- VHE emission?: Cheng & Ruderman mechanism; VHE maximum expected about 10-20 days after X-ray flare (Orellana & Romero 2004)

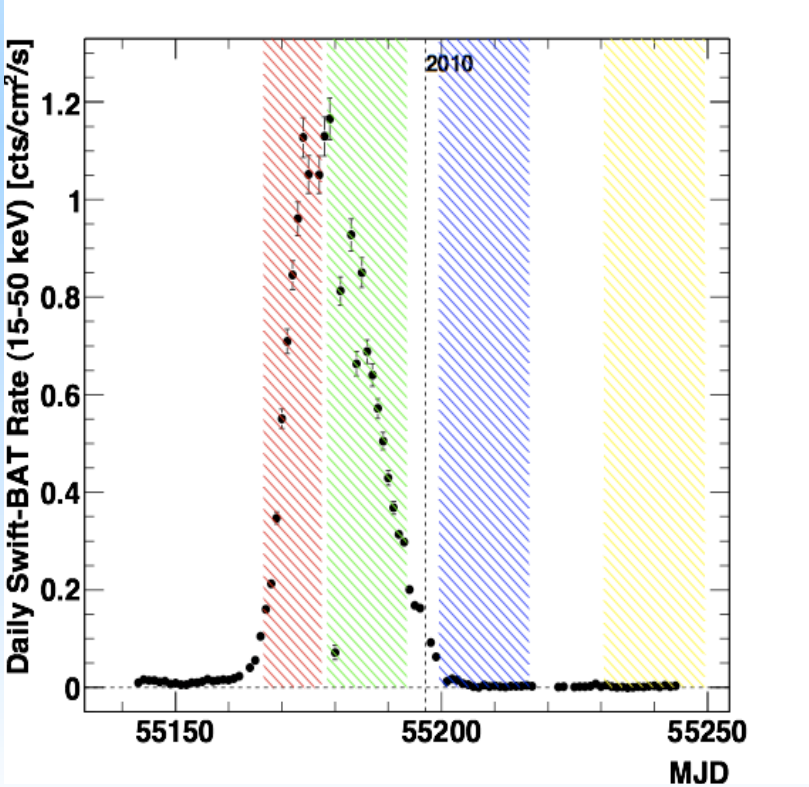


But: no detailed modeling for VHE emission, no flux prediction, SED, etc.

1A0535+262

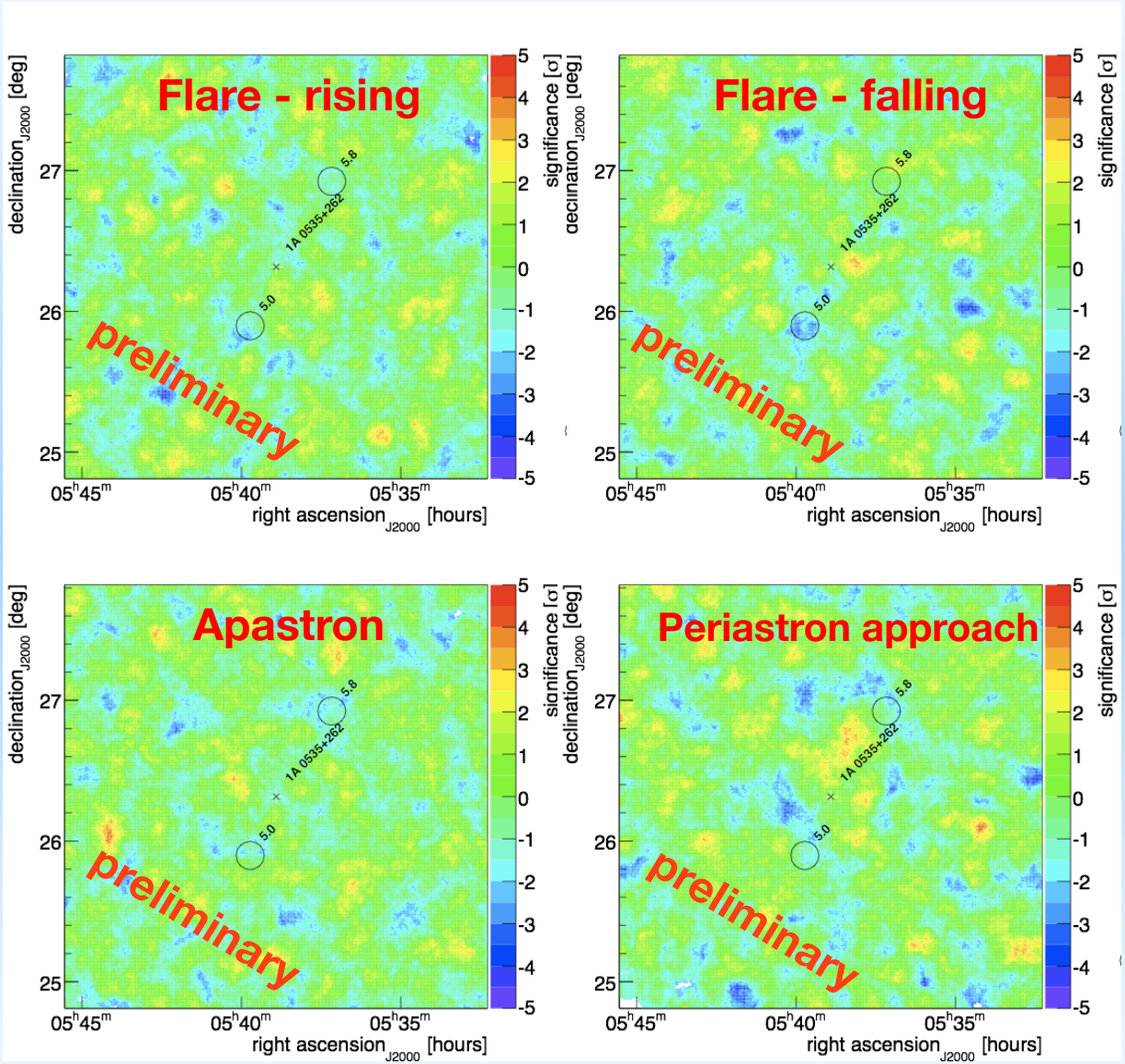
- Dec 2009: ToO triggered on flaring Be/X-ray binaries
- 23 hours of data with VERITAS, all high elevations: mean ~70°
- Good coverage of flare phase (rising/falling edge), apastron and periastron approach
- Flare occurred at best time for VERITAS





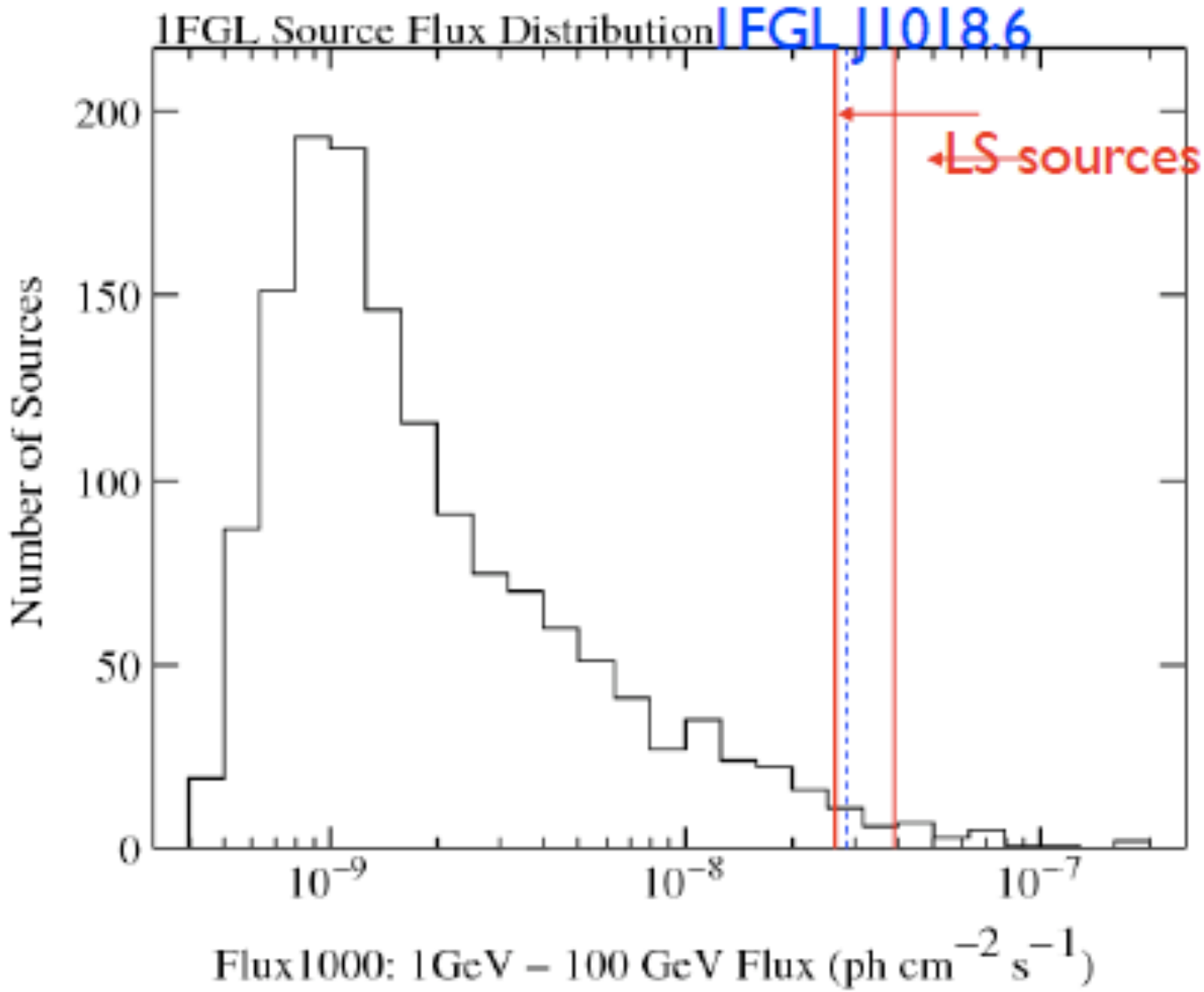
1A0535+262

- Results still in prep. (Gernot Maier, Angelo Varlotta)
- 5-8 hours of VERITAS observations in each bin
- No VHE emission detected
- 99% flux upper limits above 300 GeV: 0.5-2% Crab Nebula flux
- Lots of data at other wavelengths available
- Definitive results with this generation of IACTs



Summary

- Gamma-ray binaries constitute a small, but uniquely valuable, population of high energy sources.
- The field is extremely active: some key observational questions which may be resolved shortly
  - What is the cause of the Fermi-LAT GeV cutoffs?
  - What other binaries does the LAT see?
  - What did HESS & Fermi see from PSR B1259-63 in 2010/2011?
  - Does Cygnus X-3 produce TeV emission? When?
  - What is HESS J0632+057?
- Ongoing multiwavelength campaigns on most of these objects.


1FGL Source Flux Distribution
1FGL J1018.6
LS sources
Number of Sources
200
150
100
50
0
10^{-9}
10^{-8}
10^{-7}
Flux1000: 1GeV – 100 GeV Flux (ph cm^{-2} s^{-1})