Fermi LAT Observations of Gamma-ray Binaries

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Overview

- Introduction to X-ray and Gamma-ray binaries.
- LS I +61° 303 and LS 5039 (with R. Dubois, G. Dubus, A. Hill, M. Kerr, T. Tanaka, D. Torres et al.; ApJ, ’09, 701, L123; Ap J, ’09, 706, L56).
- Cygnus X-3 (with S. Corbel, G. Dubus, M. Kerr, E. Koerding et al.; Science, ’09, 10.1126).
- Optimizing searches for new binaries (with M. Kerr et al.).

(Some material “borrowed” from Stephane Corbel and Richard Dubois.)

What is an X-ray binary?

- An X-ray binary is a stellar system with two components.
  - One is a "normal" star and the other is a black hole or neutron star.
  - Material is accreted from the normal star onto the compact object.
  - This releases large amounts of gravitational energy. This energy can result in heating and the production of X-rays.

Types of X-ray binary

- X-ray binaries are divided into two basic types:
  - High-mass X-ray binaries (HMXBs). The normal star is of spectral type O or B.
  - Low-mass X-ray binaries (LMXBs). The normal star is of spectral type G or later.
- Mass transfer occurs in a variety of ways.
  - Roche-lobe overflow. The normal star fill the gravitational equipotential surface that includes both stars.
  - Wind accretion. If the normal star has a strong wind (mainly OB stars), can accrete from this.

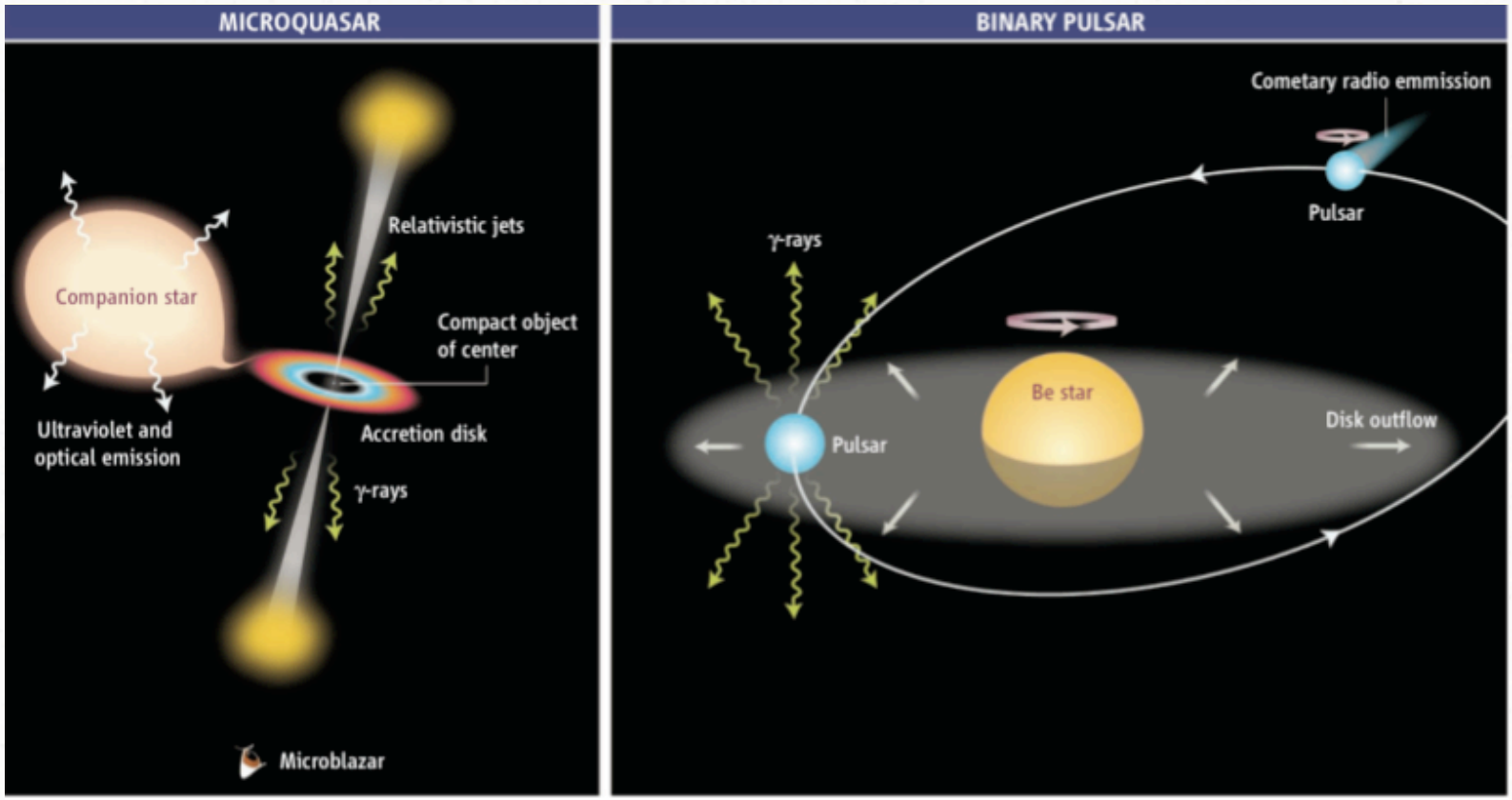
What is a gamma-ray binary?

- Related to X-ray binaries. I will use gamma-ray binary to mean:
  - a binary system including a compact object (black hole or neutron star) with detectable gamma-ray flux.
  - gamma-ray emission caused by interaction between the two binary components.
- Excludes radio pulsars in binaries.
- Excludes binaries without compact component (e.g. colliding wind system like eta Car).

Gamma-ray binaries compared to X-ray binaries

- The extra-solar X-ray sky is dominated by the emission from bright X-ray binaries.
- However, most types of X-ray binary do not appear to emit substantial gamma-radiation.
- In order for a binary to be a gamma-ray source need two things:
  - Power source.
  - Non-thermal processes. (e.g. relativistic electrons that generate gamma-rays via inverse Compton scattering.)

Making gamma-rays



from: Mirabel (Science 309, 714, 2006)

Microquasars.
- Analog of quasar.
- Accretion onto black hole (or neutron star?)
- High velocity jets are formed.

Interacting Pulsar/Early type star
- Powered by loss of rotational energy of neutron star.
- Involves interaction with companion. Not just emission from pulsar.

Why study gamma-ray binaries?

- Although gamma-ray binaries are rare, they offer excellent laboratories to study varying interaction between:
  - Pulsar wind and companion star.
  - Formation and properties of jets.
  - As the two stars orbit each other:
    - Variation in viewing angle.
    - Variation in stellar separation for eccentric orbits.
    - Conditions repeat each orbital cycle.

(Stolen from Jamie Holder!)

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...

"Historical" gamma-ray binaries

- Before Fermi, three confirmed gamma-ray binaries from TeV data:
  - LS I +61° 303. Pulsar/binary or microquasar?
  - LS 5039. Pulsar/binary or microquasar?
  - PSR B1259-53. Pulsar/binary system.
- Other gamma-ray binaries had been proposed but the evidence was much weaker:
  - Cyg X-3, Cyg X-1, Cen X-3, Her X-1, SS 433, A 0535+26, HESS J0632+057

The LAT's advantages for gamma-ray binaries

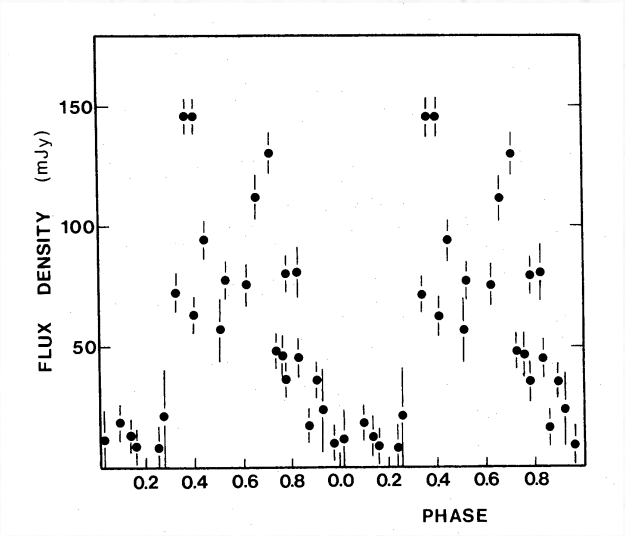
- Instrument performance. Greatly improved effective area, field of view, angular resolution compared to EGRET on CGRO (etc.).
- Observation mode: the LAT operates almost exclusively in sky survey mode. The entire sky is observed every two orbits (~3 hours).
  - binaries can be studied on a wide range of timescales (potentially from milliseconds or shorter to years).

Data analysis: Maximum likelihood and aperture photometry

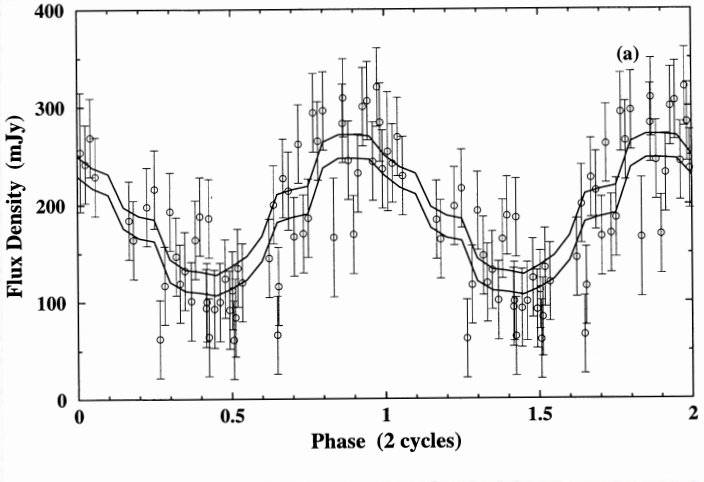
- Analysis of Fermi data can have some challenging aspects. e.g.
    - Small number of counts. Energy dependent point spread function. Significant Galactic background. Complex fields.
- Often need to do maximum likelihood fitting - model many sources and background.
- But, for variability studies simple aperture photometry can work well:
    - model independent, fast, no problems with few/ zero photons in time bin

LS I +61° 303

- Unusual low L_X high-mass X-ray binary.
- Radio outbursts with 26.496 day period, possible 4.4 yr super-orbital radio period.



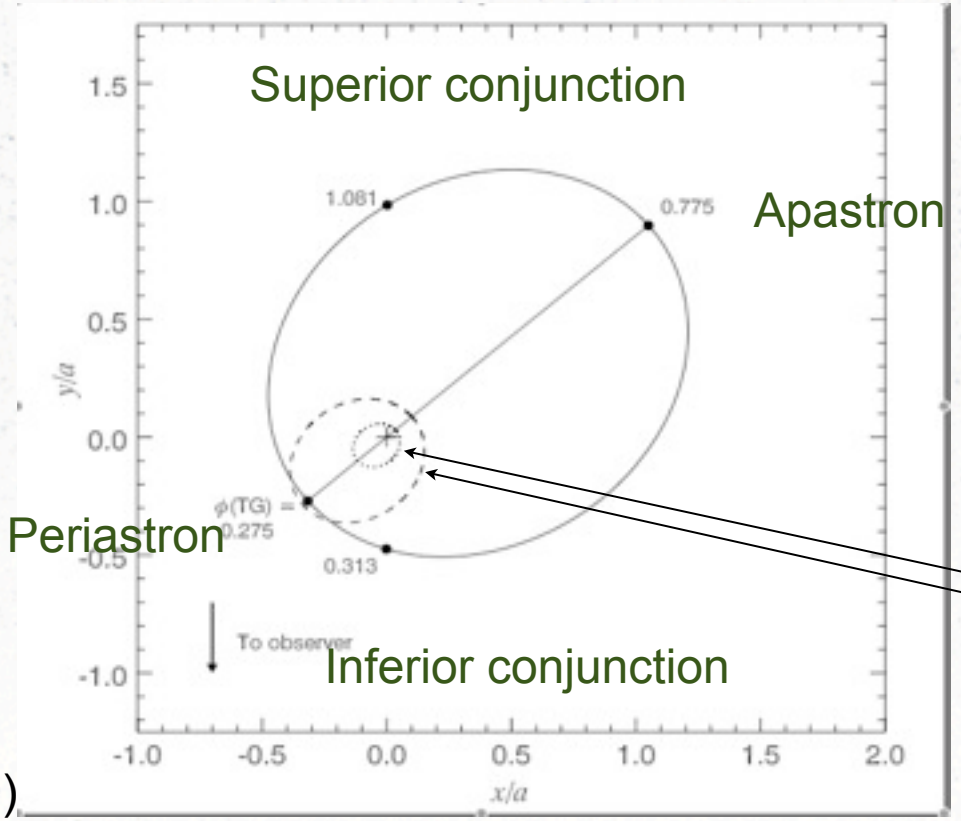
Orbital (radio): Taylor & Gregory 1982



Superorbital? Gregory 1999

LS I +61° 303

- B0Ve star counterpart in 26.5 day eccentric orbit.
- Radial velocity consistent with either neutron star or black hole.



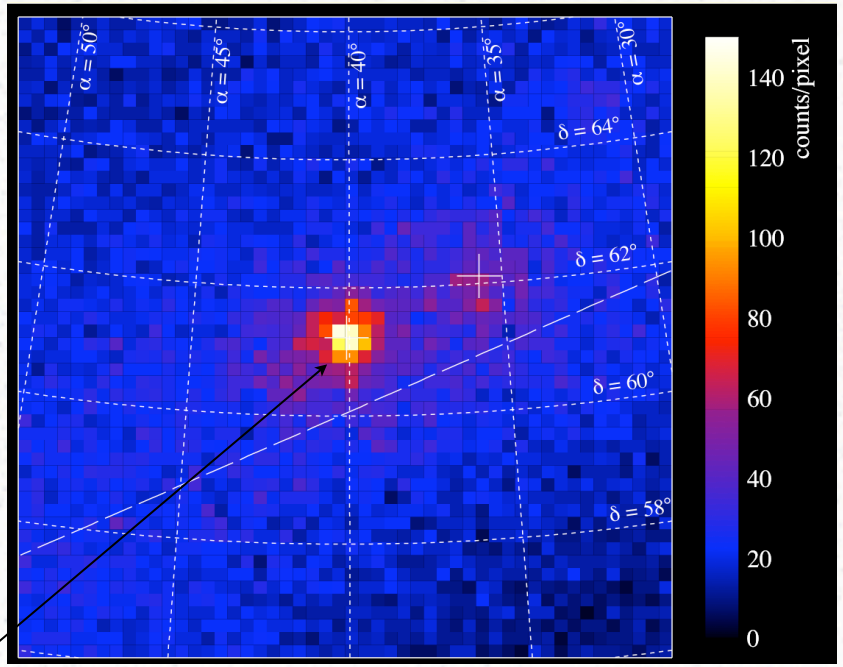
Orbit of Be star for 1.4M_o neutron star and 4 M_o black hole assumptions.

(Aragona et al. '09)

LS I +61° 303 continued

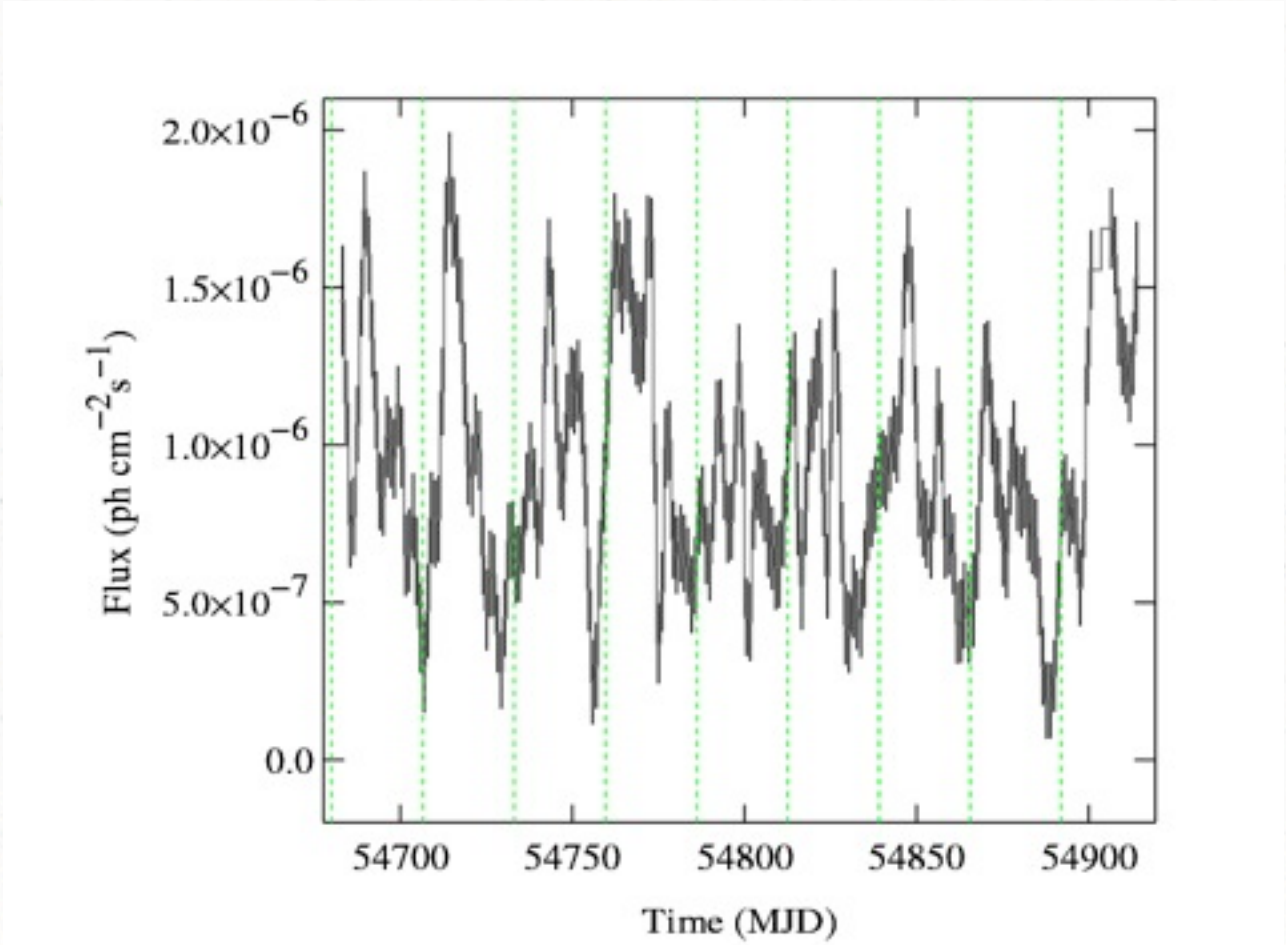
- Previously thought, but not proved, to be associated with Cos B/EGRET gamma-ray source.
- MAGIC/VERITAS observations show VHE (> 100 GeV) source modulated at 26 day period.
  - VHE maximum at apastron.
- SGR type burst seen once from vicinity – but it was not definitely shown to be associated with LS I +61° 303.

LAT image of LS I +61° 303



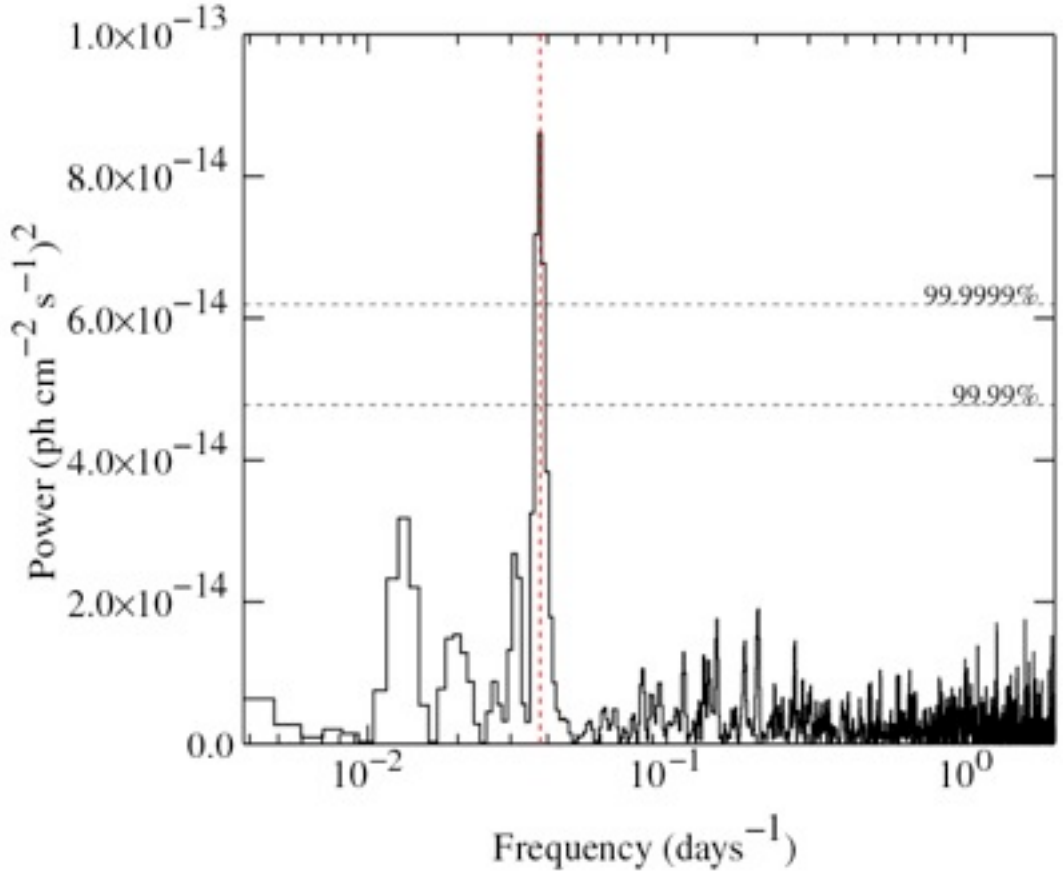
Strong source seen consistent with location of LS I +61° 303

LS I +61° 303 aperture photometry



Green lines show phase 0.
Source is highly variable.

LS I +61° 303 power spectrum

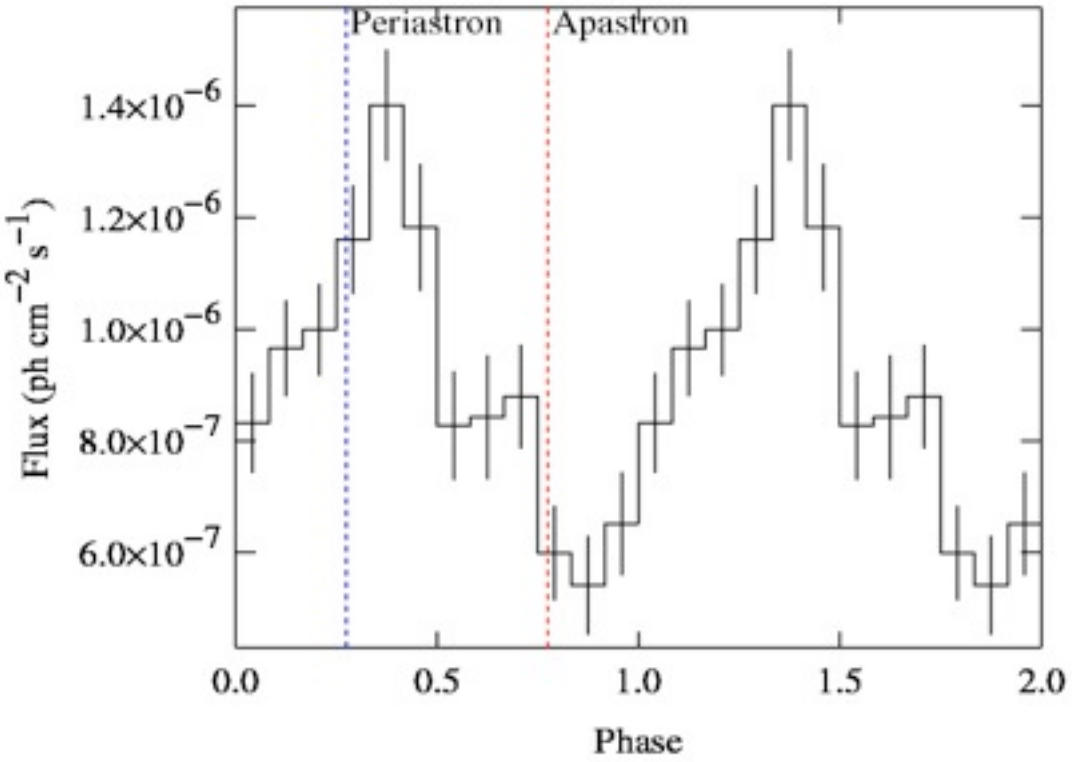


"Blind" search confidence levels.

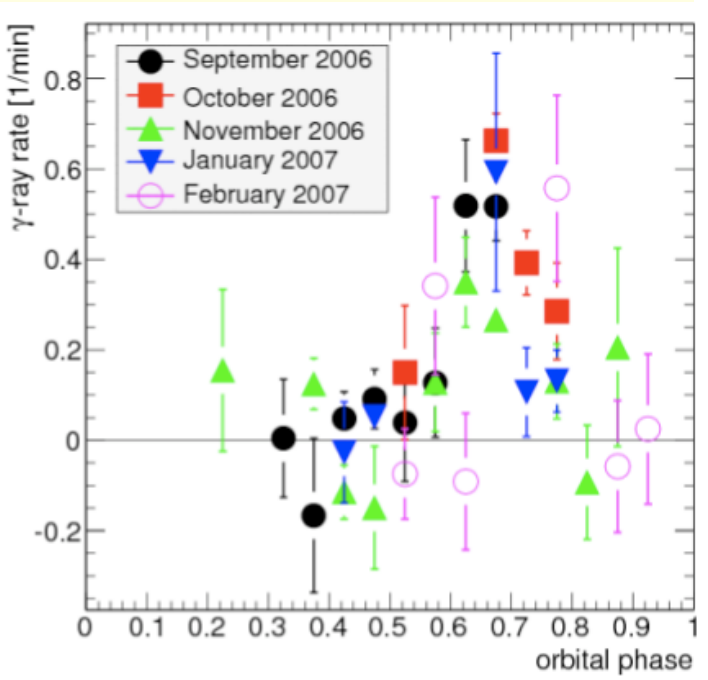
Red line shows known 26.5 day orbital period.

LS I +61° 303: Folded light curve

LAT



Veritas



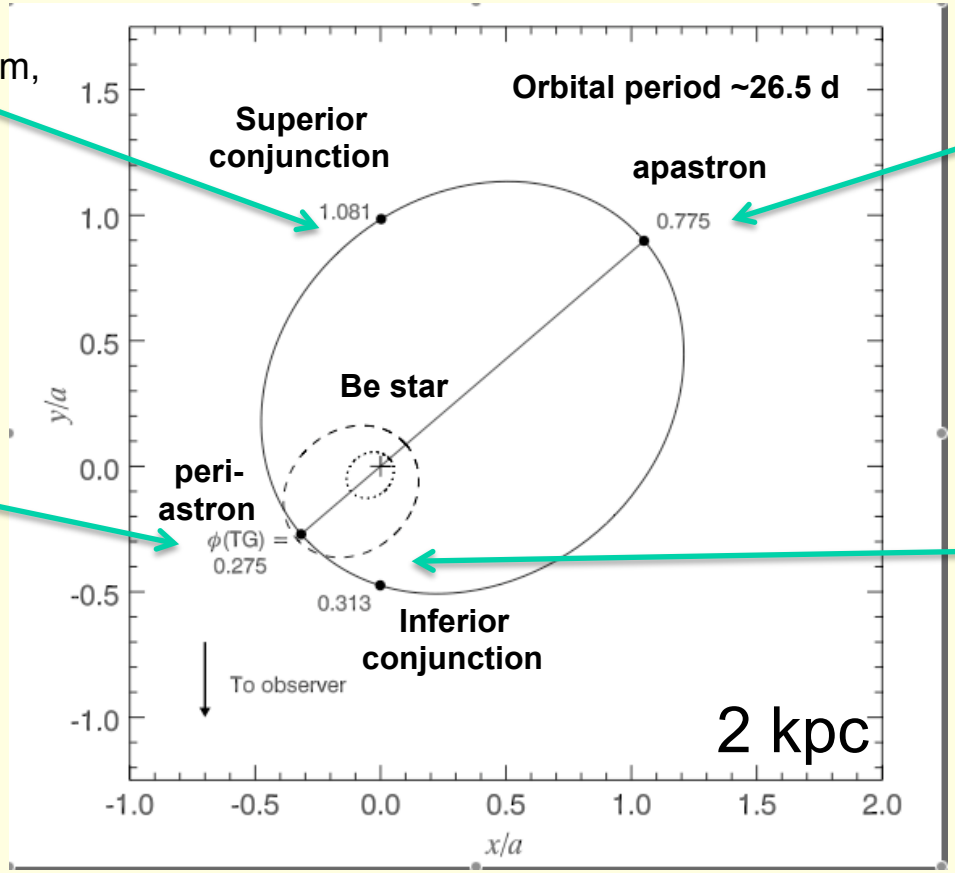
LAT emission peaks near periastron.
Different from modulation in TeV range.

Expected phase dependence of physical effects

Backscatter to observer: softer spectrum, higher flux

Brightest scattering target:

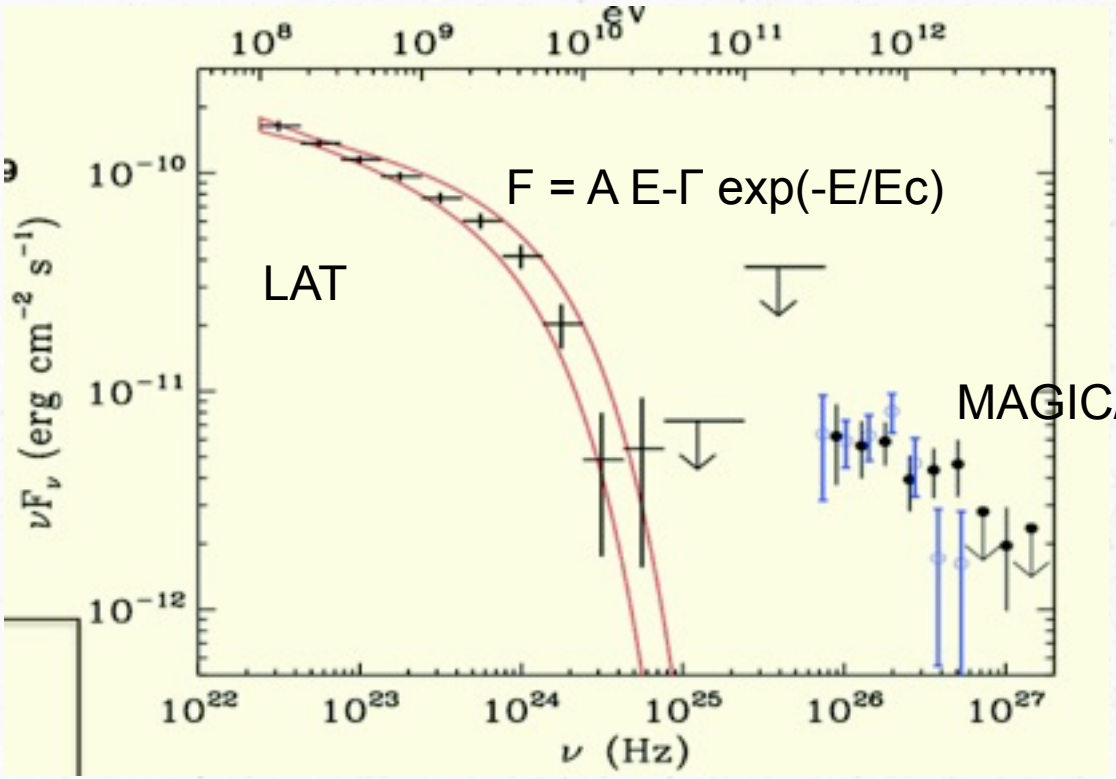
bright @ GeV
$\gamma\gamma$ annihilation @ TeV



Dimmest scattering target

Forward scatter to observer: harder spectrum, lower flux

LS I +61° 303 spectrum

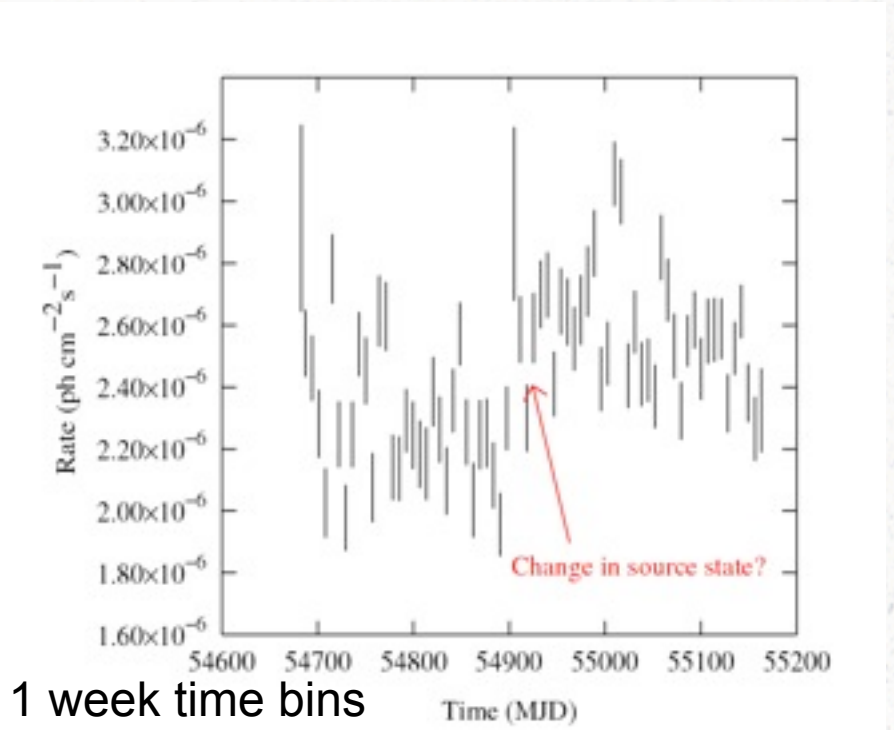


Note: no evidence for spectral variability over orbit.

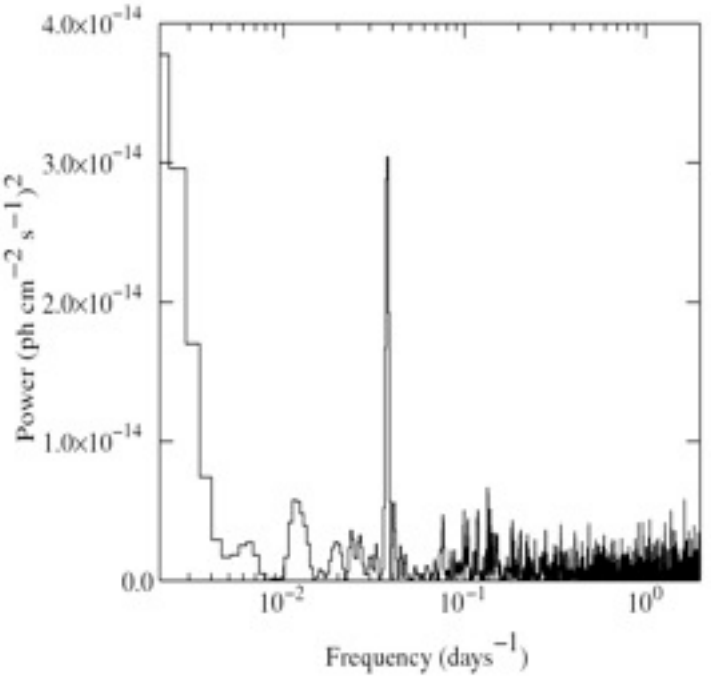
Cutoff power law fit to LAT.
Cutoff at 6.3 GeV with photon index = 2.21
Blue lines from VERITAS. Black circles from MAGIC
MAGIC/VERITAS not contemporaneous with LAT.

(November '09) Update on long-term changes in LS I +61° 303

Preliminary

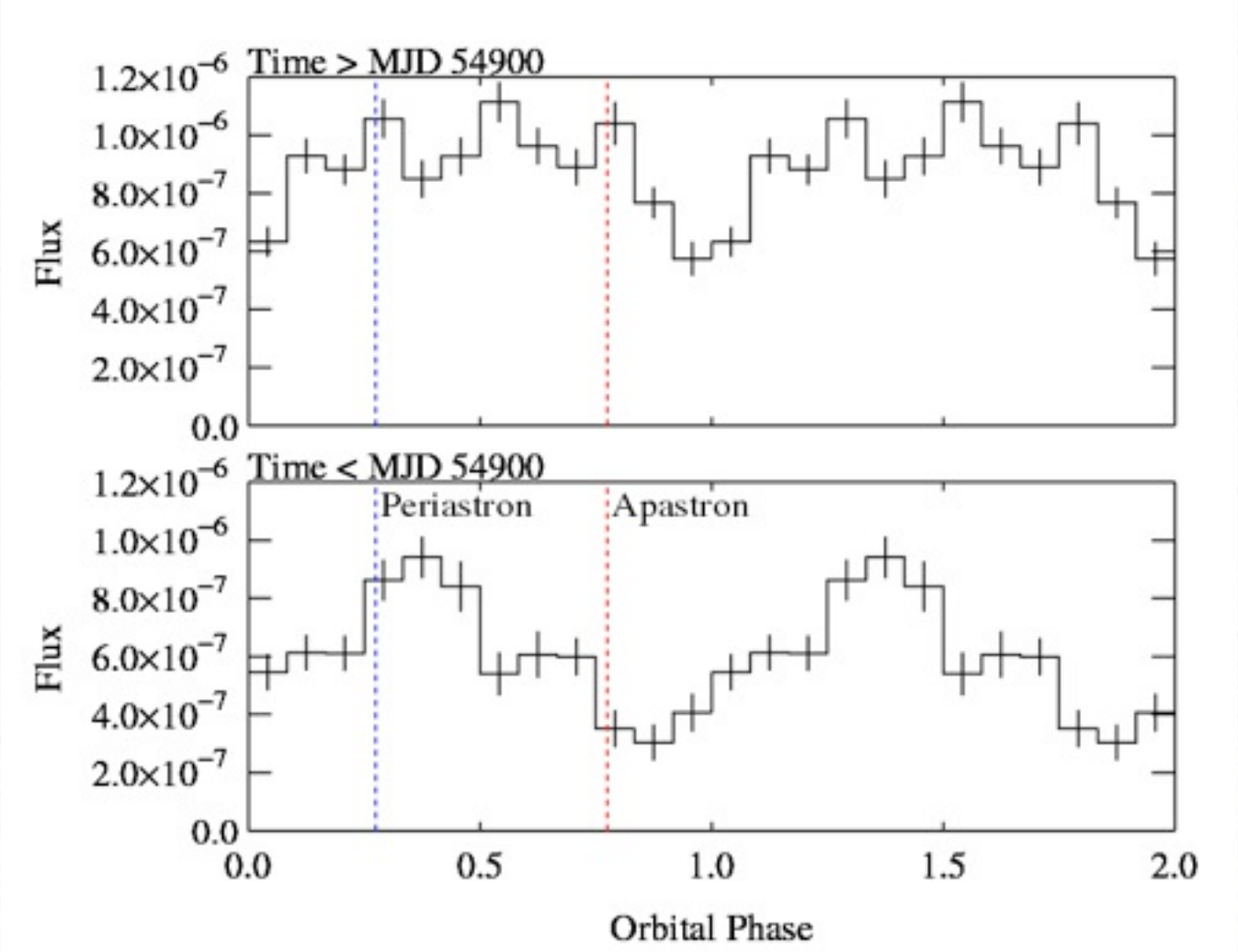


1 week time bins



Compared to the power spectrum in the ApJ paper, low frequency noise is now very strong.
Could this be connected to the "super-orbital" radio modulation?

LS I +61° 303: change in orbital modulation (Nov' '09)

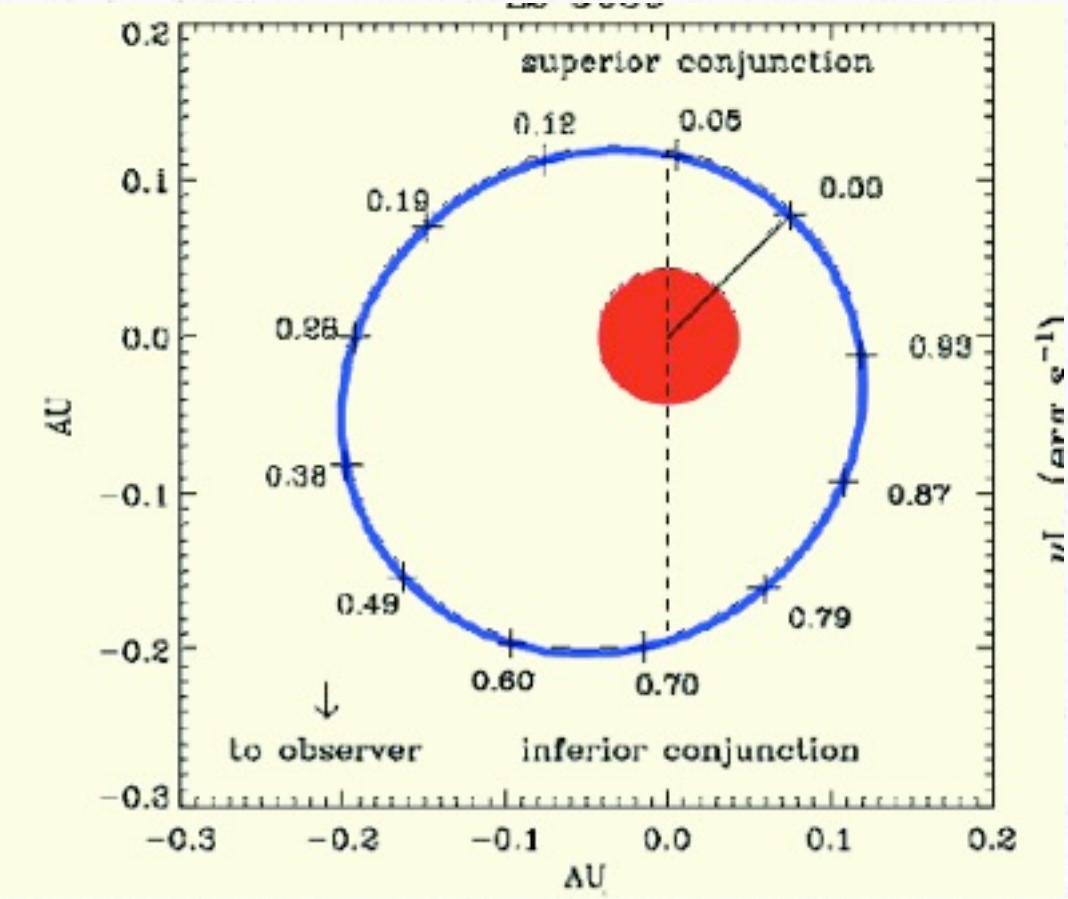


Preliminary

LS 5039

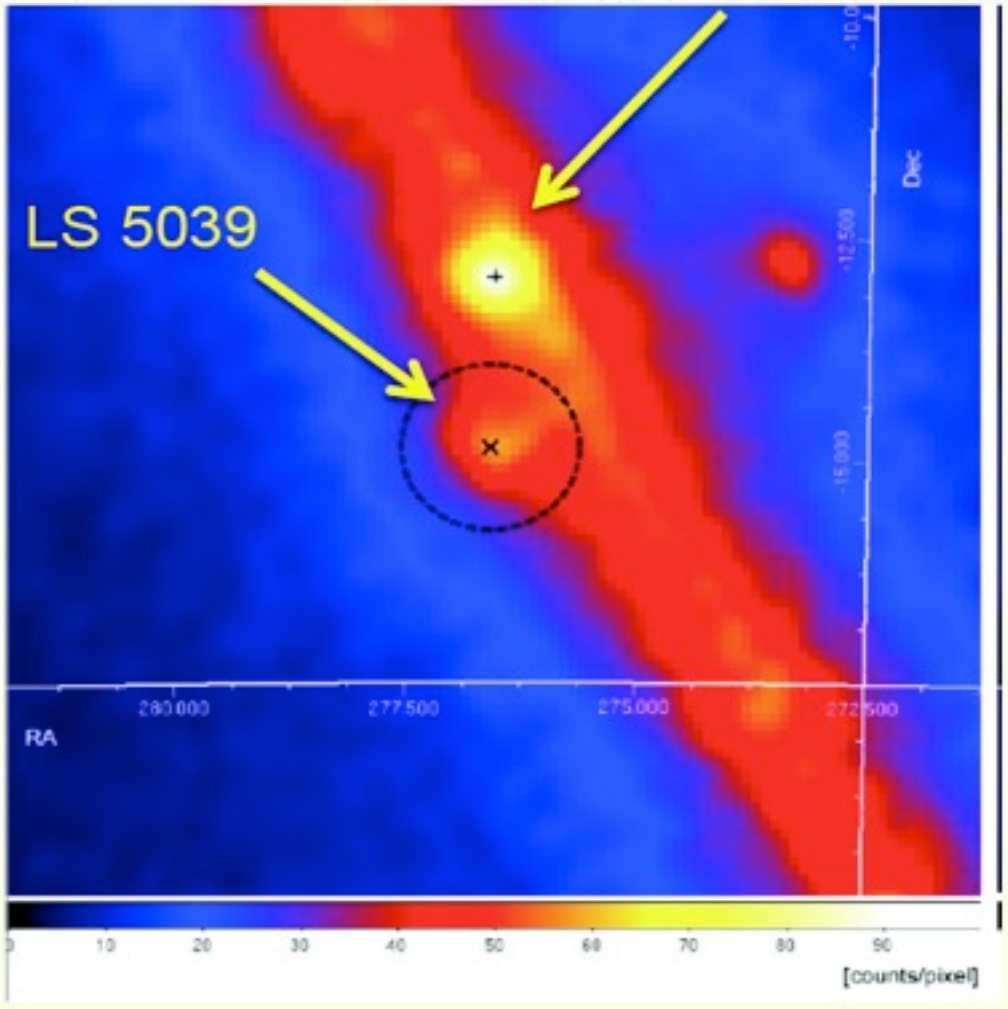
- High mass X-ray binary with 3.9 day orbital period and eccentric (e ~0.35) orbit. Primary is O6.5V star.
- Neutron star or black hole.
- Radio source with changing asymmetric morphology.
- Possible EGRET source (spatial coincidence, orbital).
- TeV emission modulated at orbital period seen with HESS.

Geometry of LS 5039



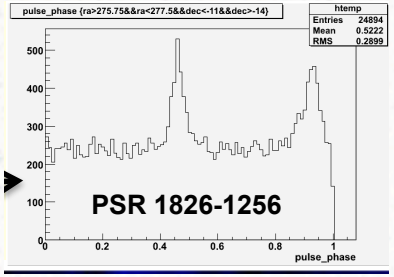
LS 5039's location

PSR 1826



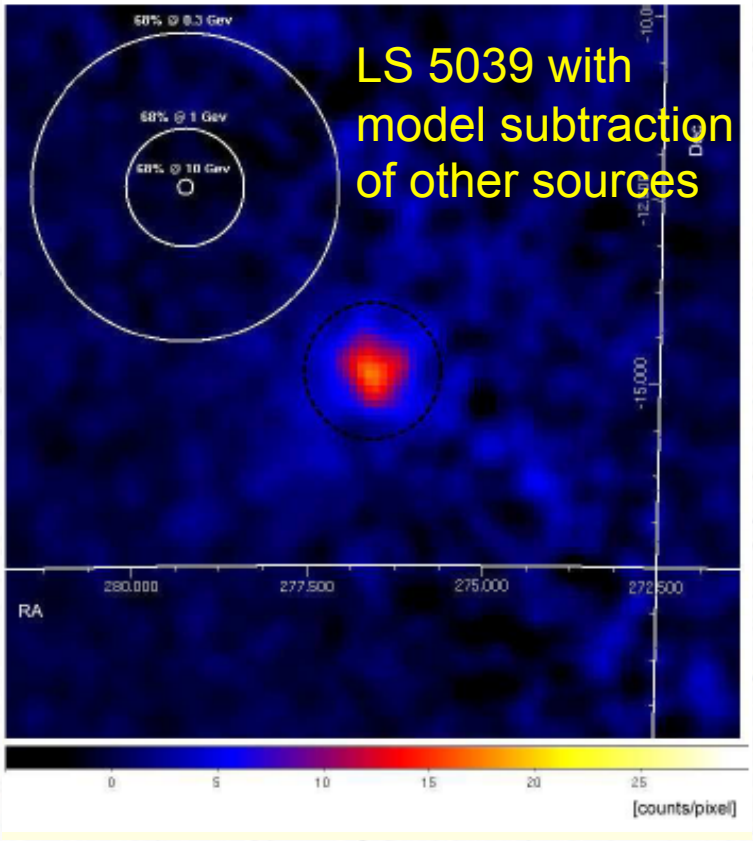
More complicated than LSI +61° 303.

LS 5039 is faint compared to the Galactic plane and there is also emission from the nearby pulsar PSR 1826-1256.



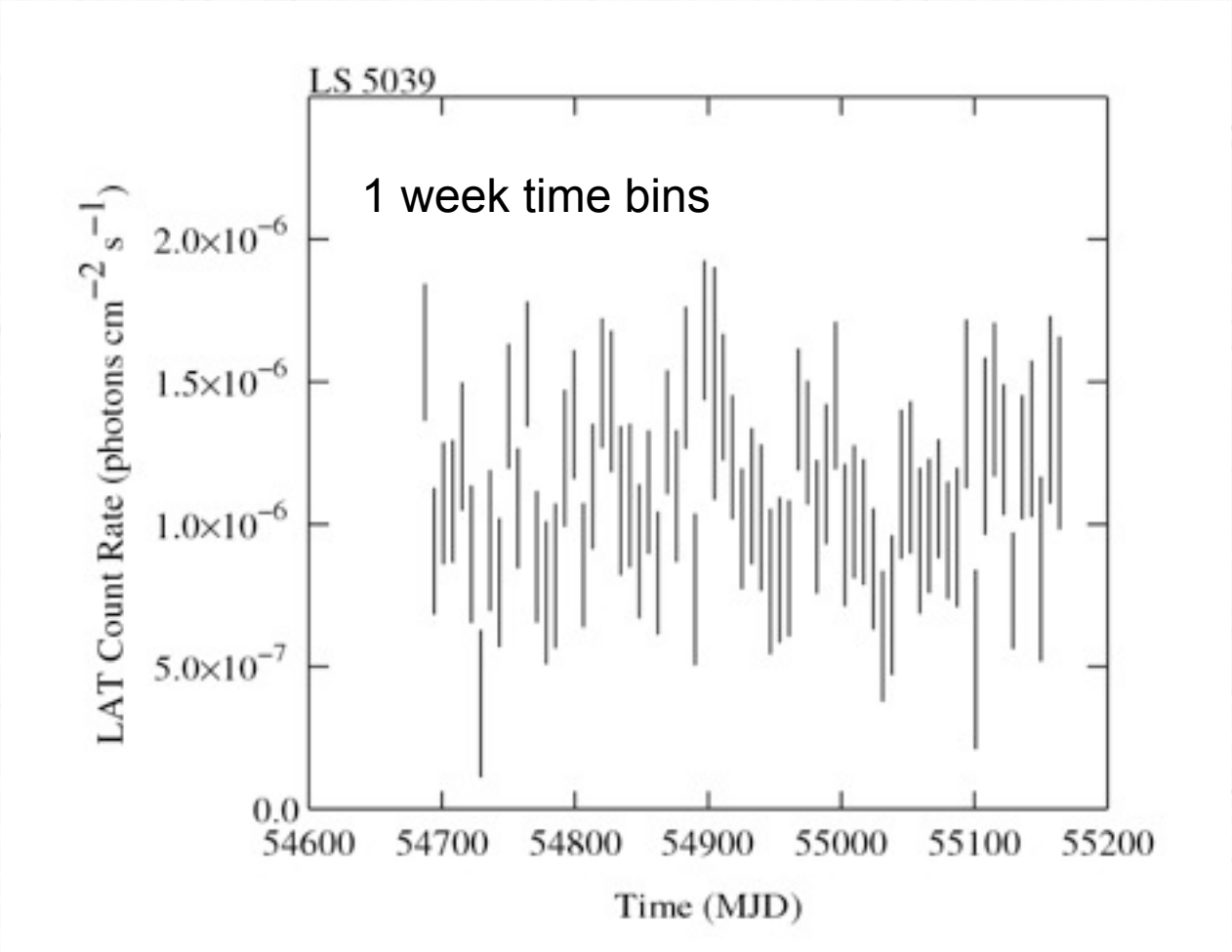
Phase select photons to remove pulsar, and model region including emission from the plane....

LS 5039 after cleaning...



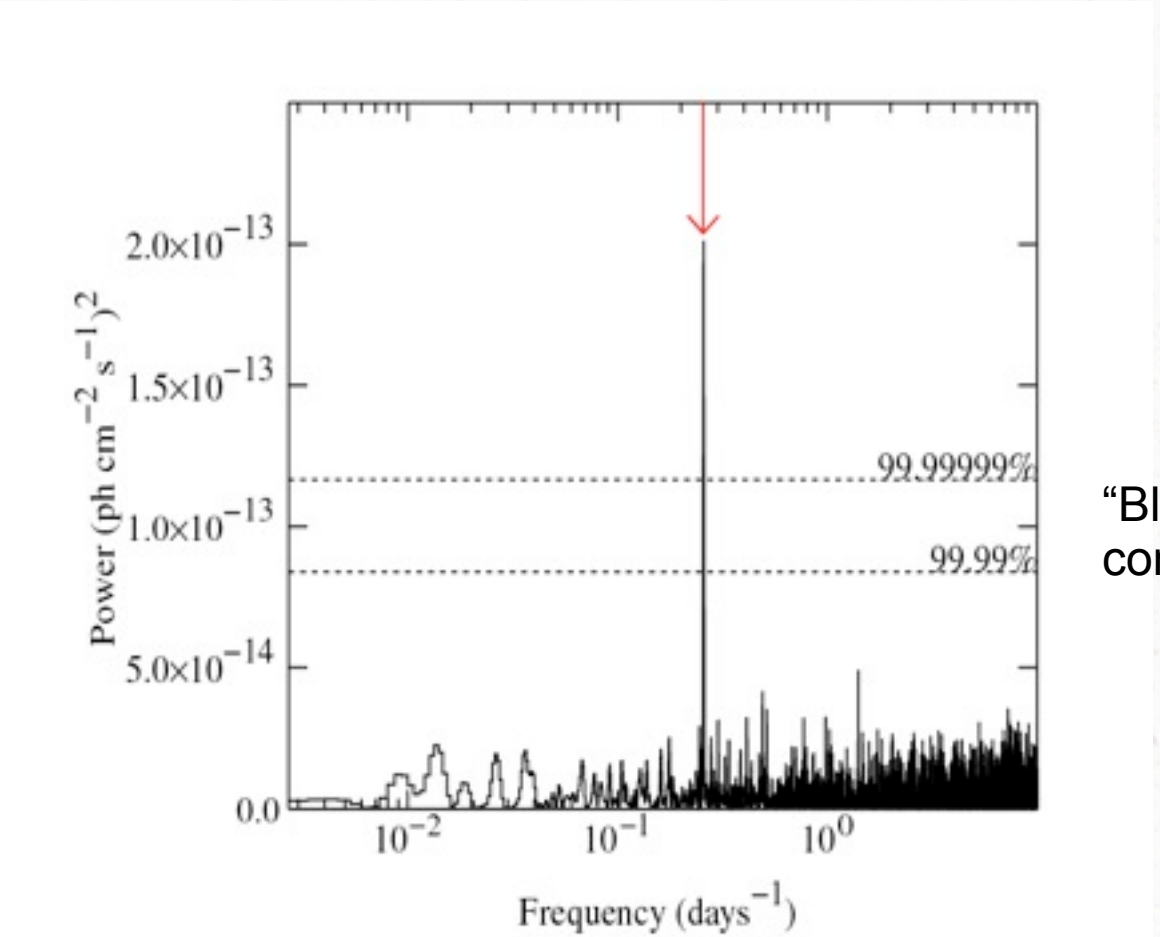
LS 5039 is detected at a significance of more than 25.5σ

Long-term light curve of LS 5039



No obvious signs of long-term variability.

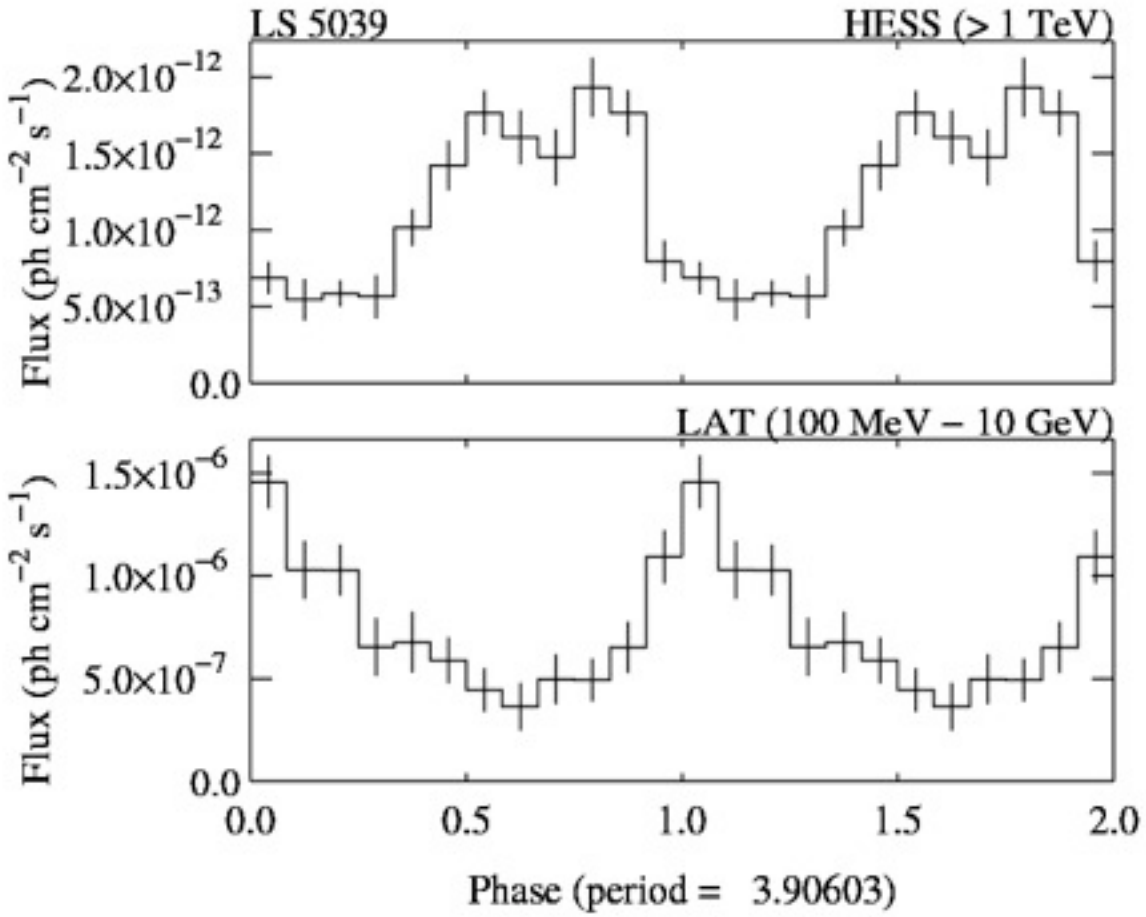
LS 5039: LAT power spectrum



"Blind" search confidence levels.

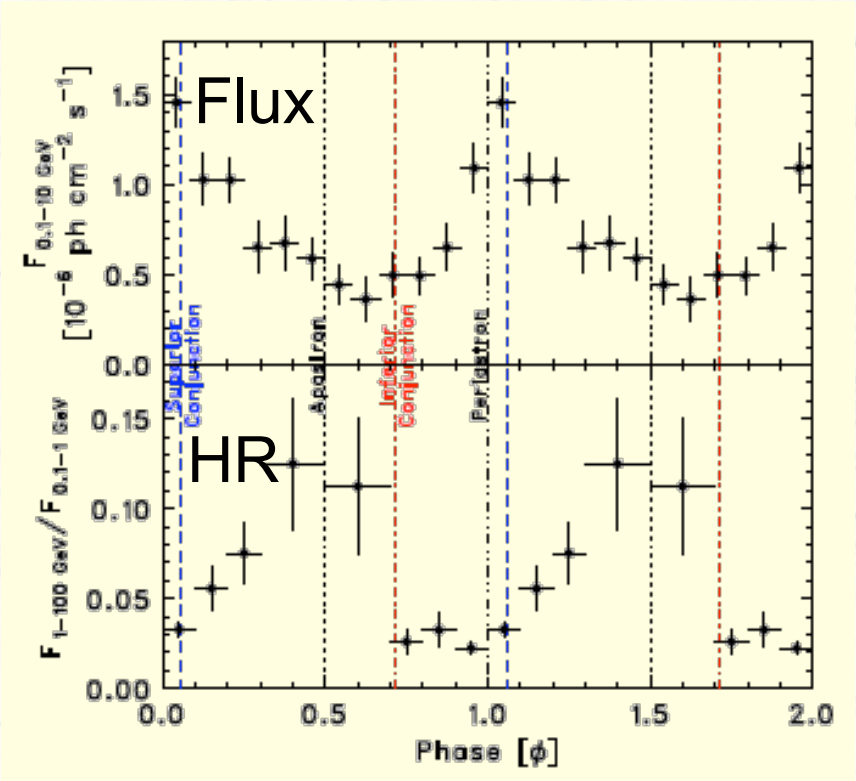
Red arrow shows known orbital period.
Very strongly detected in LAT light curve.

LS 5039: folded light curves



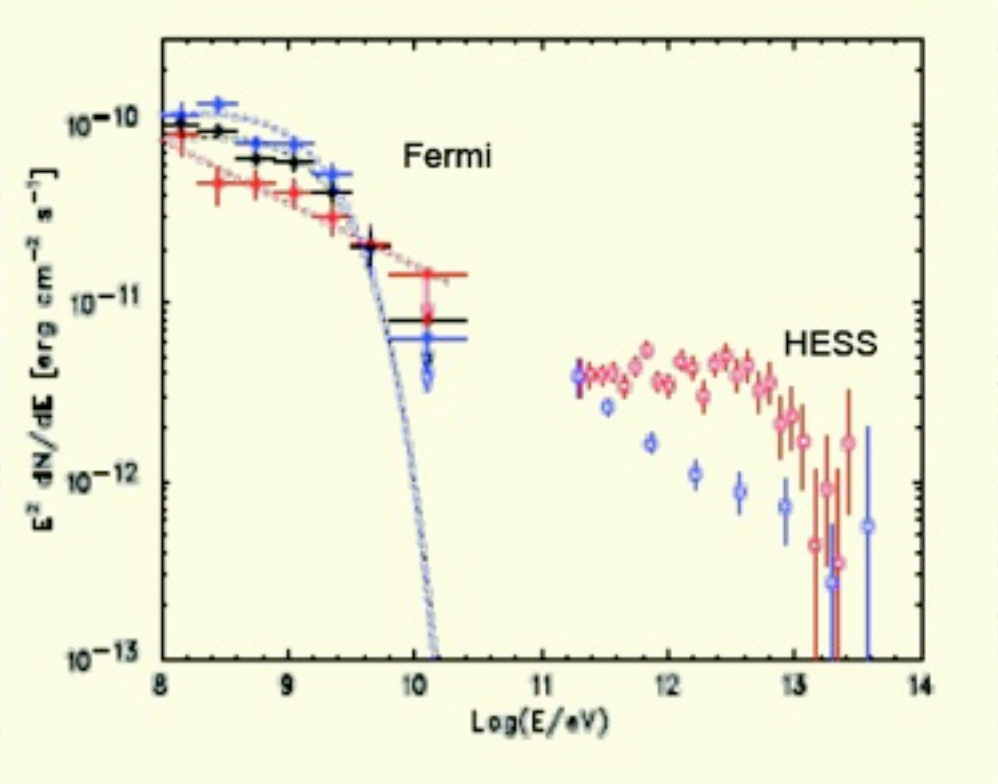
LAT flux peaks near periastron but is out of phase with TeV emission.

Energy dependence of LS 5039 modulation



Unlike LS I +61° 303, LS 5039 shows spectral variability over the orbit.

LS 5039 spectrum



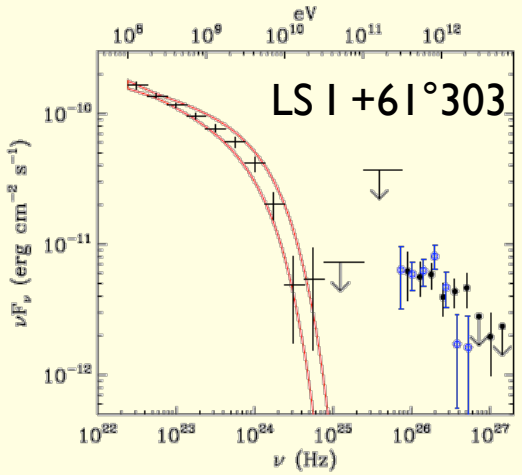
Blue = superior conjunction
Red = inferior conjunction

Similar to LS I +61° 303 the LAT spectrum shows an exponential cutoff at least at superior conjunction. (Too few counts at inferior conjunction.)

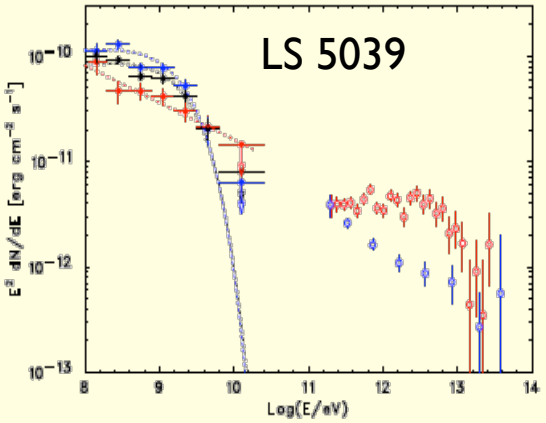
Similarities and differences of the "LS" sources

- Similarities:
  - Orbital modulation of LAT flux, not in phase with TeV emission.
  - Similar spectra.
- Differences:
  - LS I +61° 303 has long term variability not seen so far in LS 5039.
  - LS 5039 has orbital spectral variability not seen in LS I +61° 303.

What's going on in the "LS" sources?



Average spectrum:
Index: 2.21, Cutoff: 6.3 GeV



Average spectrum:
Index: 1.9, Cutoff: 2.1 GeV

- The gamma-ray spectra are reminiscent of Fermi spectra of pulsars.
- But pulsar emission alone can't explain the orbital variability.
- Further investigation required.

Cygnus X-3

- Cyg X-3 is a high-mass X-ray binary with a Wolf-Rayet star primary.
- Orbital period is exceptionally short for an HMXB at only 4.8 hours.
- The compact object is thought to be a black hole, but a neutron star can't be excluded.
- Radio outbursts are common and relativistic jets are produced.
- System is often classified as a “microquasar”

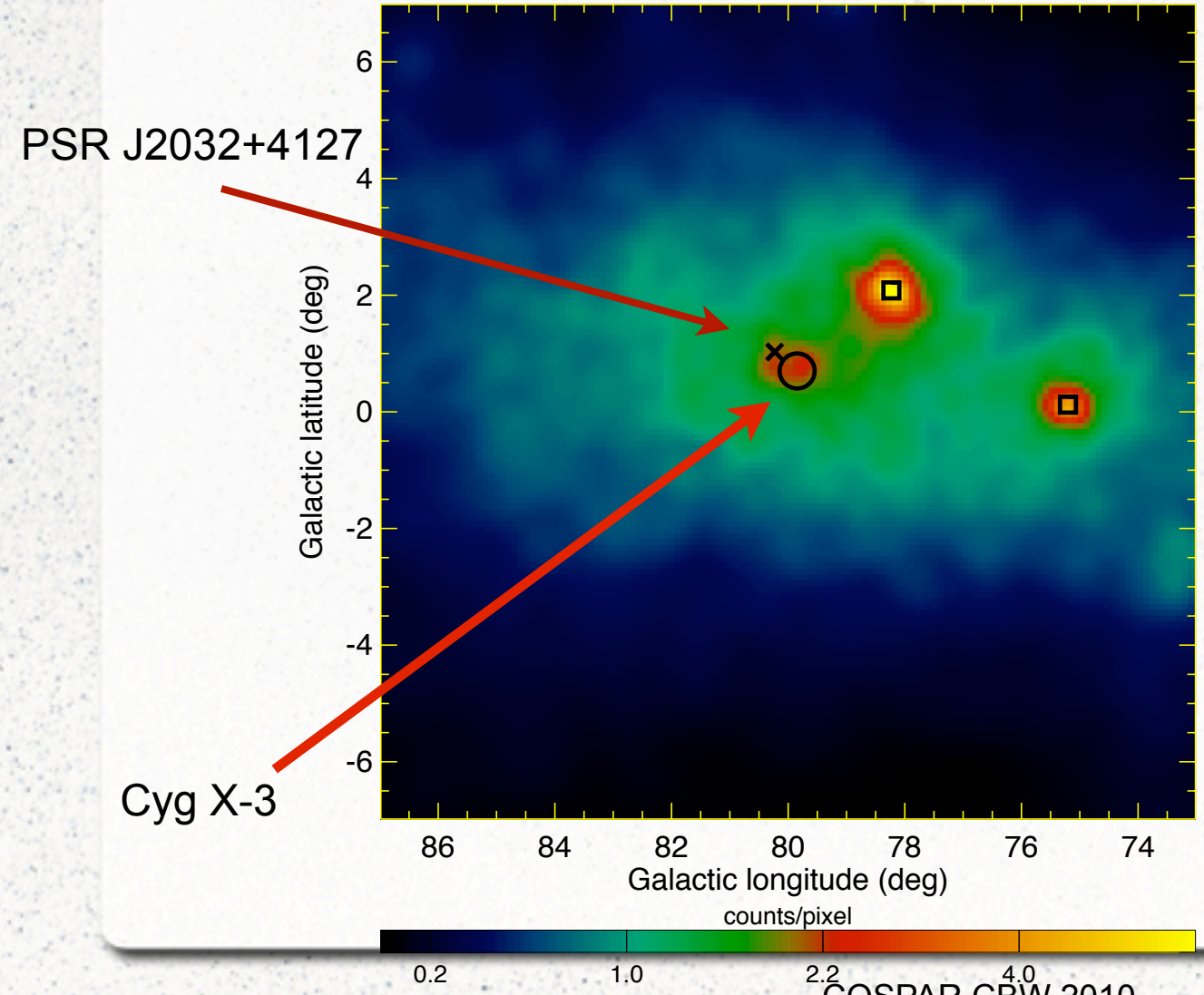
Cygnus X-3 in gamma-rays: Now you see it, now you don't...

- There have been various claims of detection of Cyg X-3 at high energies.
  - Lamb et al. ’77 reported detection with SAS-2 of source with orbital modulation.
  - Not seen with Cos B (Hermsen et al. ’87).
  - EGRET (Mori et al. ’97) saw a source consistent with the position of Cyg X-3, but didn’t see any orbital modulation.
  - Similar results at TeV energies. Early reports of detection, followed by non-detections with more sensitive instruments.

Cygnus X-3 and AGILE

- AGILE (Tavani et al. ’09) recently reported a detection of a source consistent with the location of Cyg X-3.
- AGILE didn’t see orbital modulation and so the identification of the AGILE source with Cyg X-3 was not 100% secure.

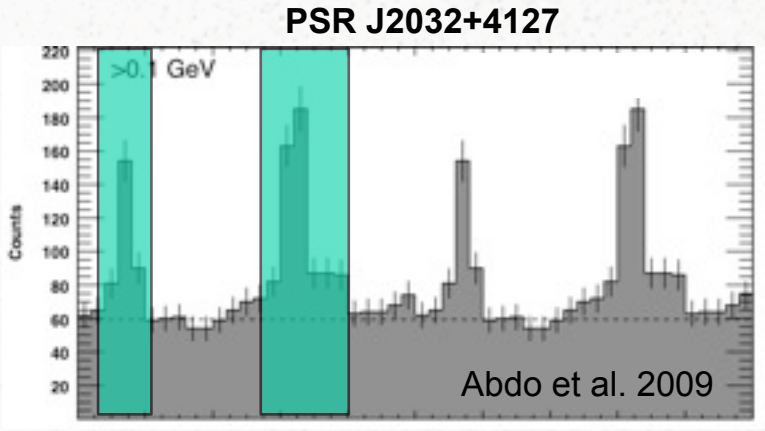
Cygnus Region



The Cygnus region is crowded and complex.

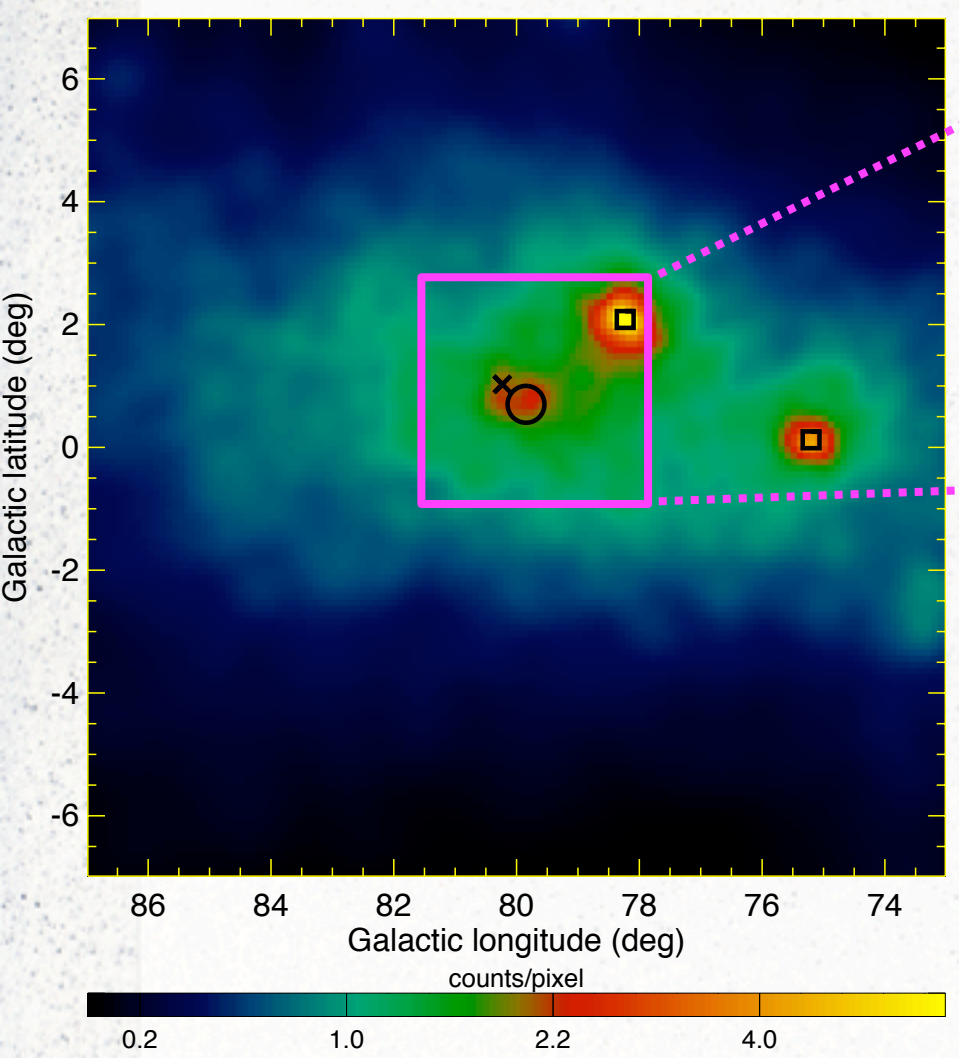
In addition to diffuse emission, there are 3 pulsars including PSR J2032+4127 only 30' from the location of Cyg X-3.

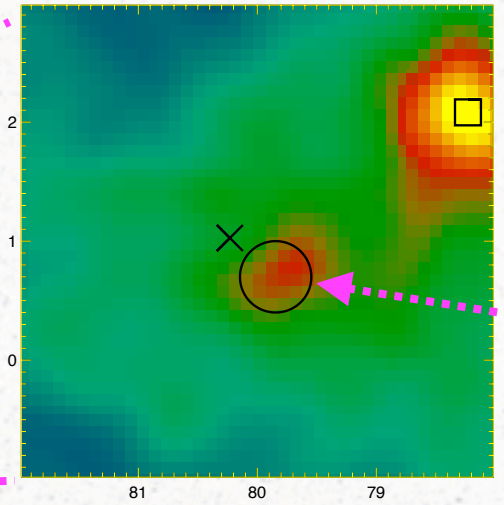
Removing the Pulsar Emission



Use the same “trick” as for LS 5039 to remove contaminating emission from nearby pulsar by selecting data from off-pulse emission only...

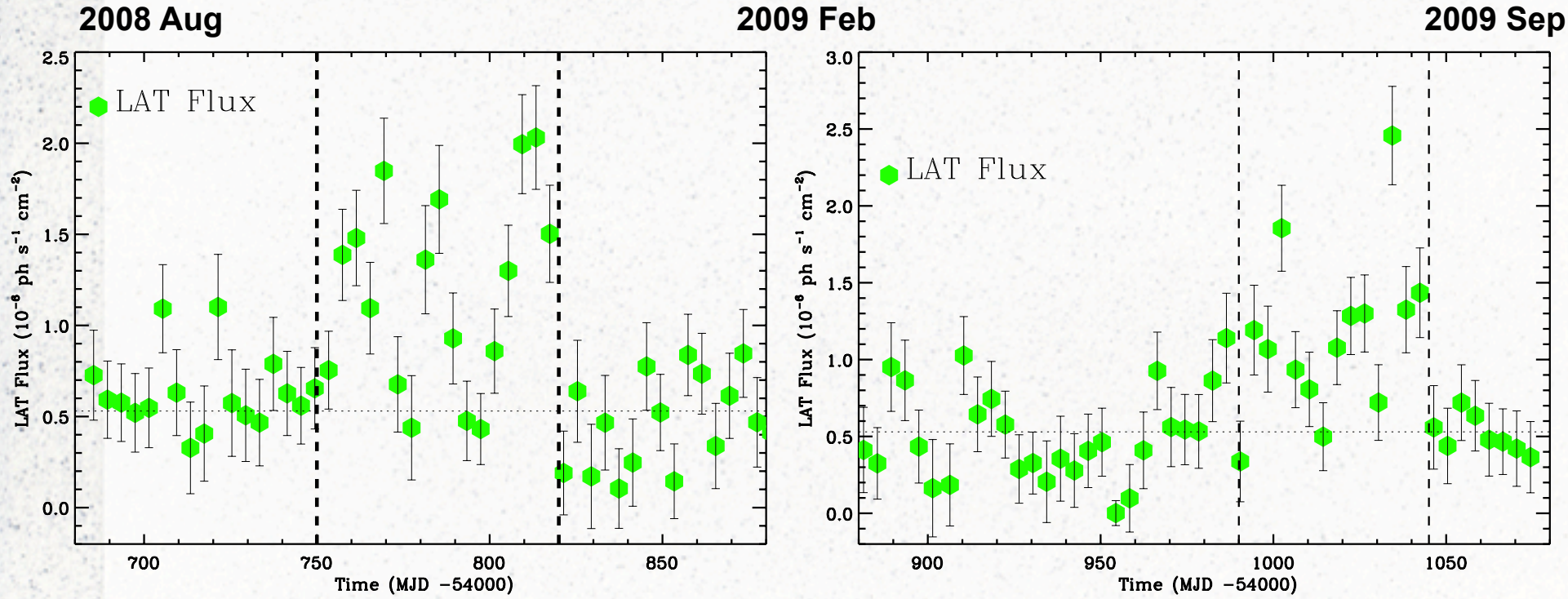
After phase selection





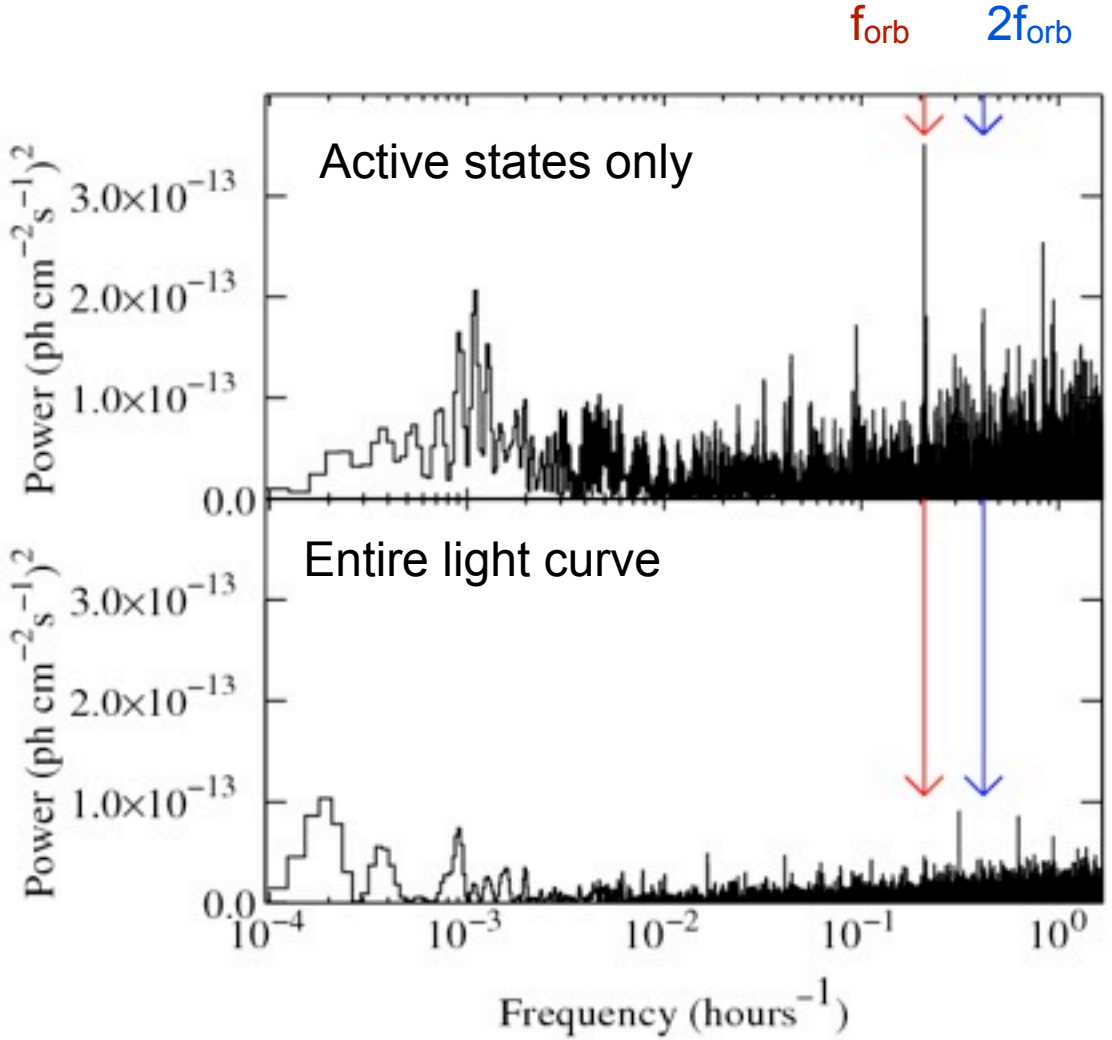
- No detection of PSRJ2032+4127
- Bright source at the location of Cyg X-3: ~ 29 s
- Average flux (>100 MeV): 1.19 +/- 0.06 (sta) +/- 0.37 (sys) 10^{-6} ph s^{-1} cm^{-2}
- Soft spectrum: PL index: 2.70 +/- 0.05 (stat) + 0.20 (syst)

LAT light curve of Cyg X-3



Two main active periods are seen. (i) October to December 2008 and (ii) June to August 2009.
There may be one or several flares occurring during each active state.
Peak flux corresponds to ~ 5 x 10^{36} $(d/7\ kpc)^2$ erg s^{-1}

Cyg X-3 orbital period search



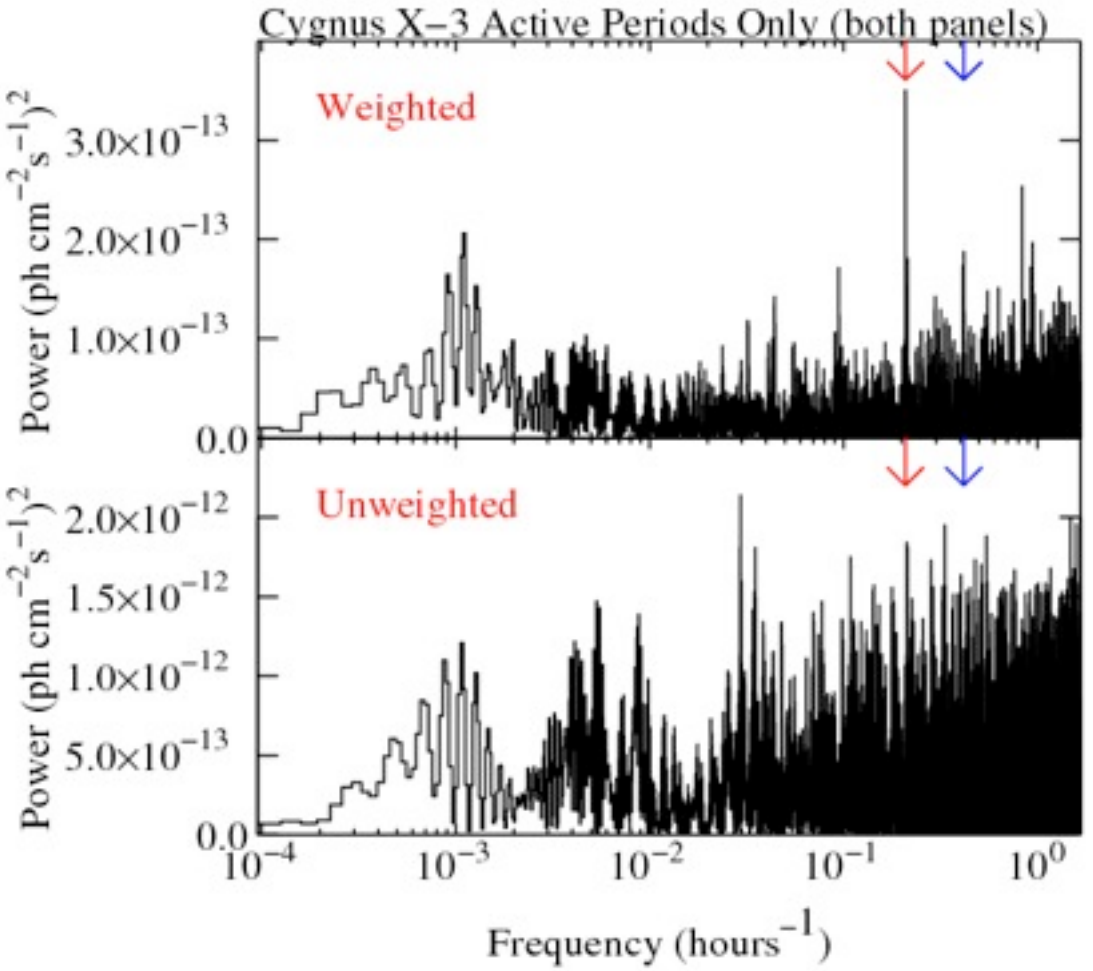
During the active states the orbital period is detected with a false alarm probability of 2×10^{-9}.

The period cannot be seen if the entire dataset is used.

This proves that the LAT source is Cyg X-3!

(Note, weighting of data points was required)

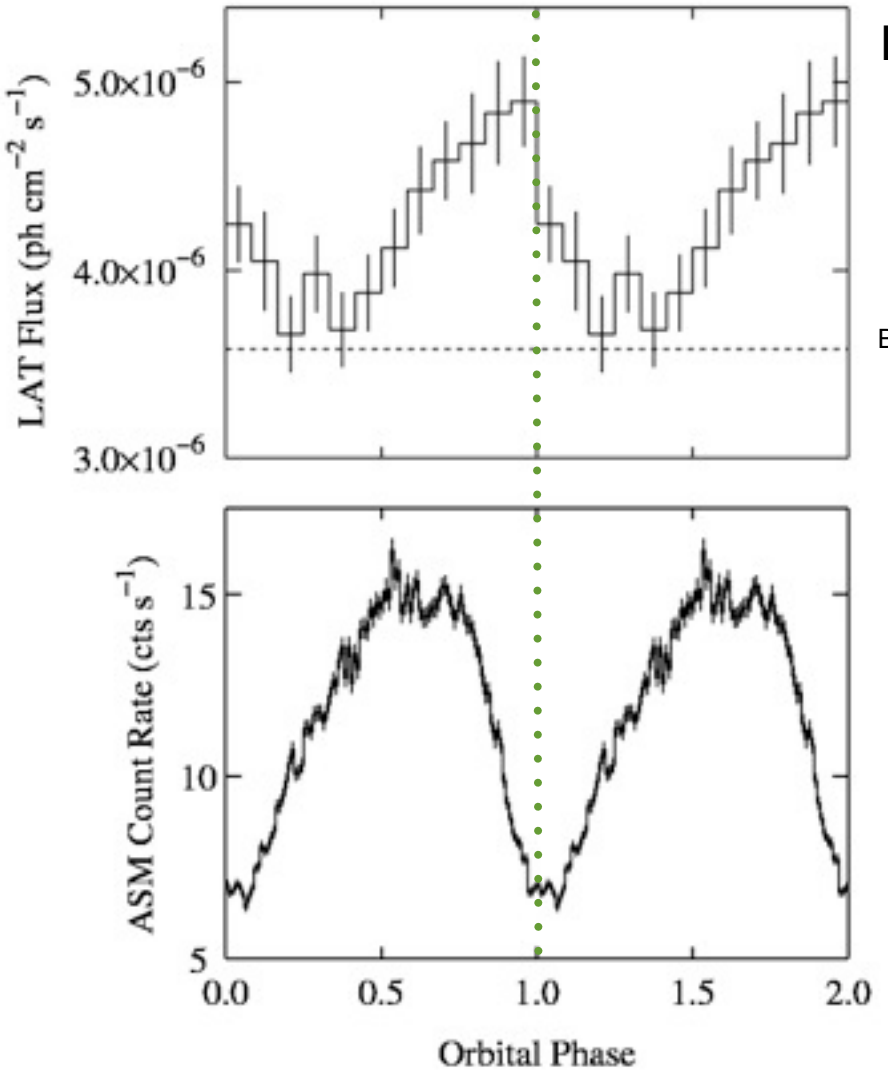
Effects of weighting for Cyg X-3



Exposure weighting was essential to detect the orbital period of Cyg X-3.

This is because short time bins had to be used.

Orbital modulation of Cyg X-3



LAT

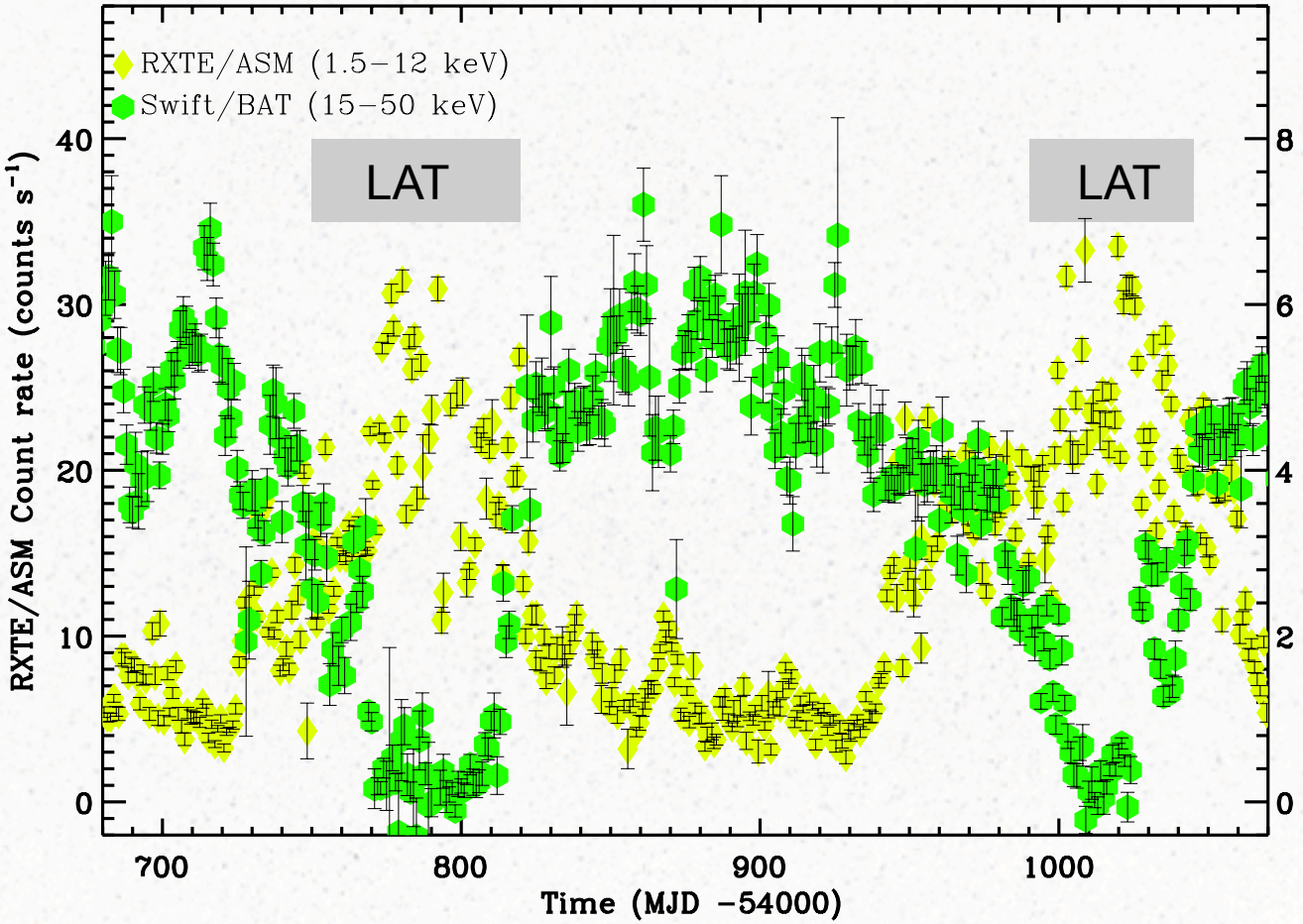
Background.

RXTE ASM
(2 - 12 keV)

LAT folded light curve shows ~100% modulation.

Shape is similar to RXTE ASM but 0.3 - 0.4 phase difference.

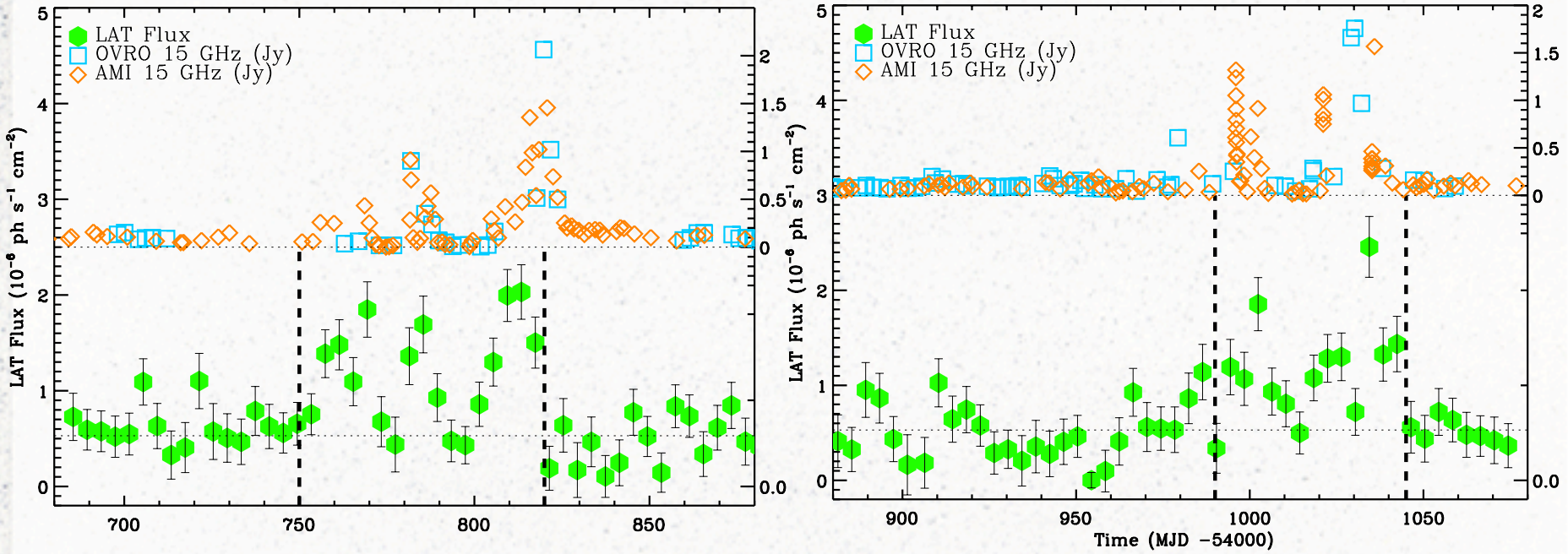
When is Cyg X-3 γ-ray active?



LAT detections correspond to soft X-ray states.

Connection to ultra-soft state associated with relativistic electrons.

Relativistic jets in Cyg X-3

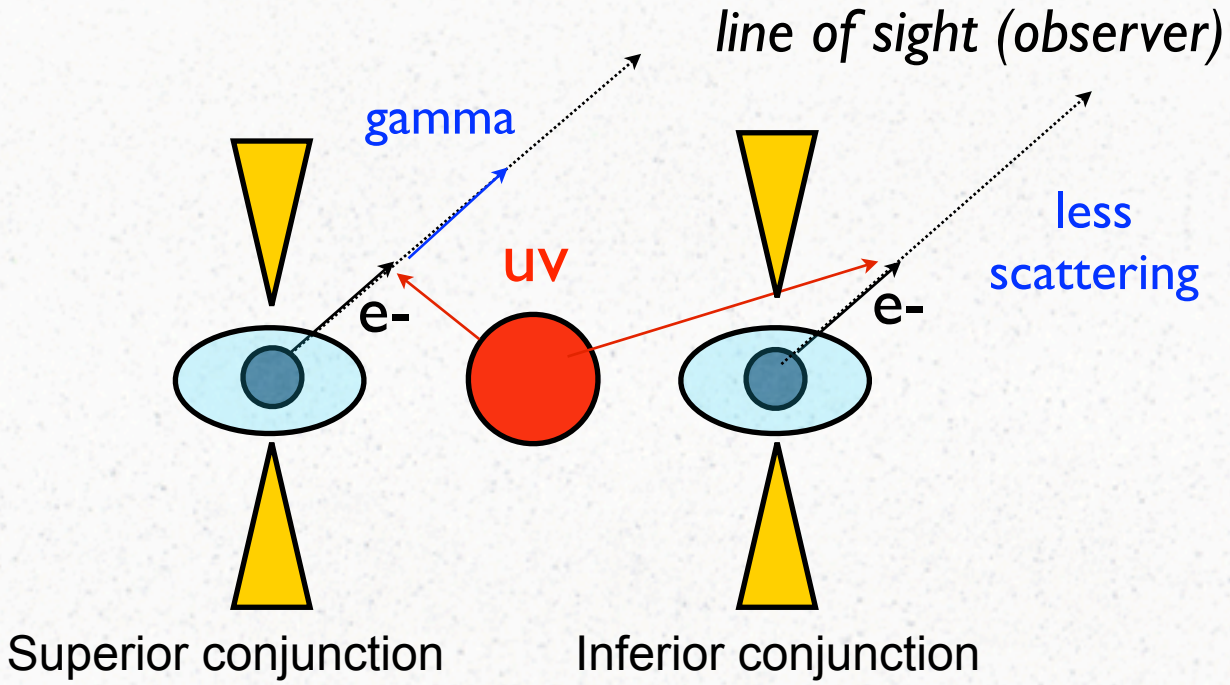


The two gamma-ray active periods of Cyg X-3 closely coincide with radio flaring intervals.

There is a hint that the gamma-ray emission precedes the radio emission, but a cross-correlation analysis does not strongly constrain this.

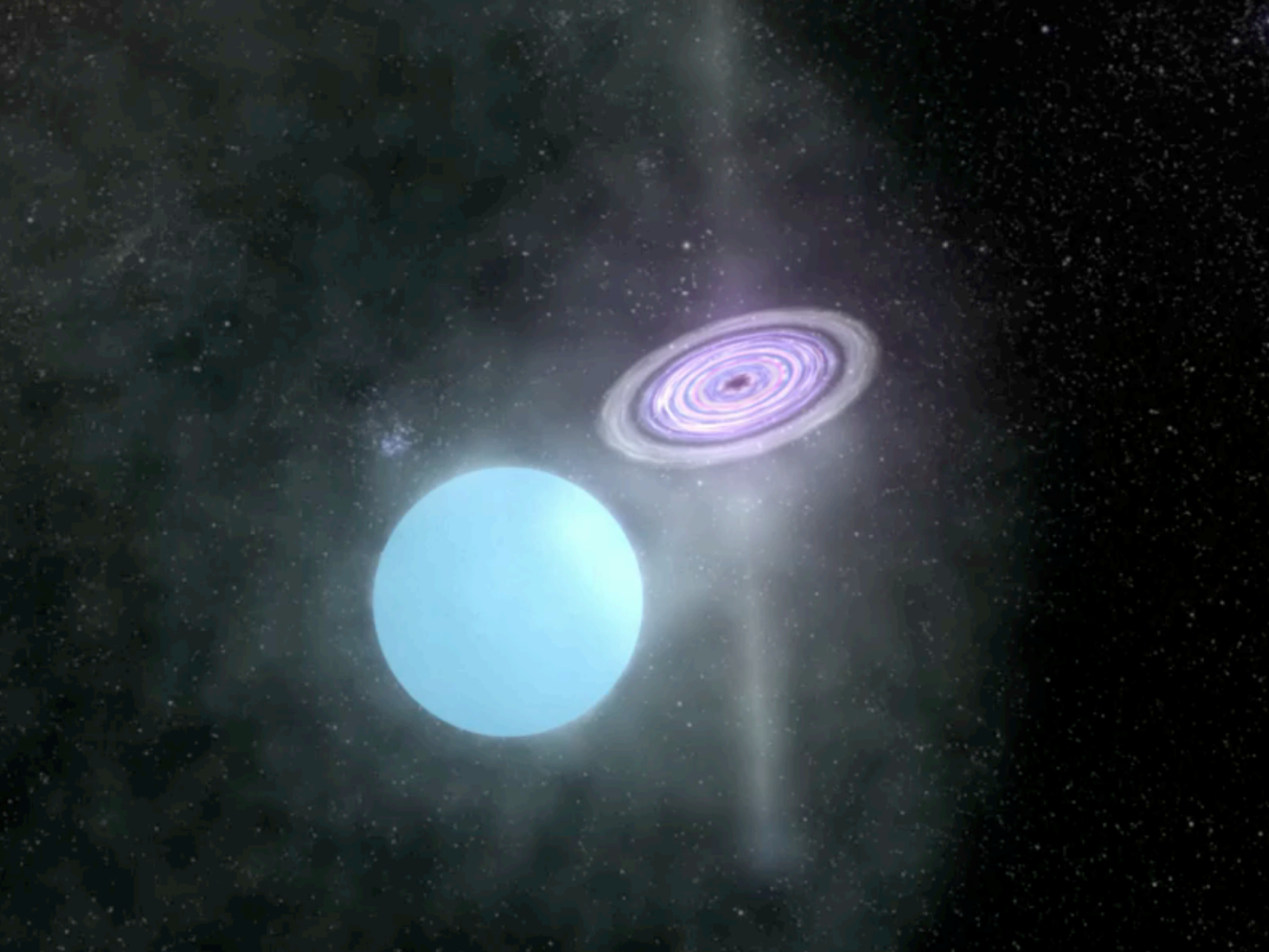
Radio lag is 5 ± 7 days.

Model for Cyg X-3



- γ-rays can not originate too close to accretion disk (pair production)
- Within system: Modulation due to inverse Compton (IC) scattering on UV photons. More IC at superior conjunction (head-on collisions)
- Consistent with X-ray minima and phasing of orbit (Hanson et al. '00)
- e^- in corona (= base of jets?). Extension of hard X-ray power-law to 100 MeV consistent with Fermi (but steepening).

Next slide shows artist's impression by Walt Feimer (+ input from Frank Reddy)



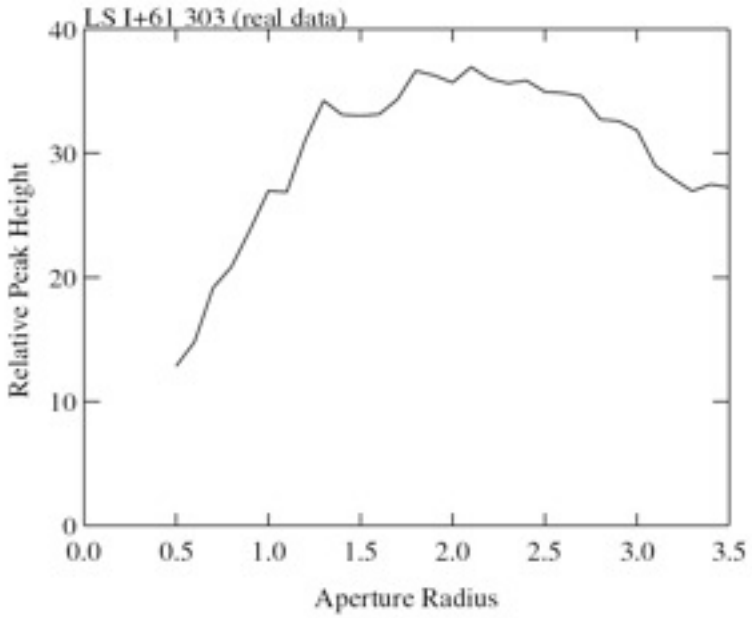
Hunting for More Gamma-ray Binaries: Optimizing Signal-to-Noise

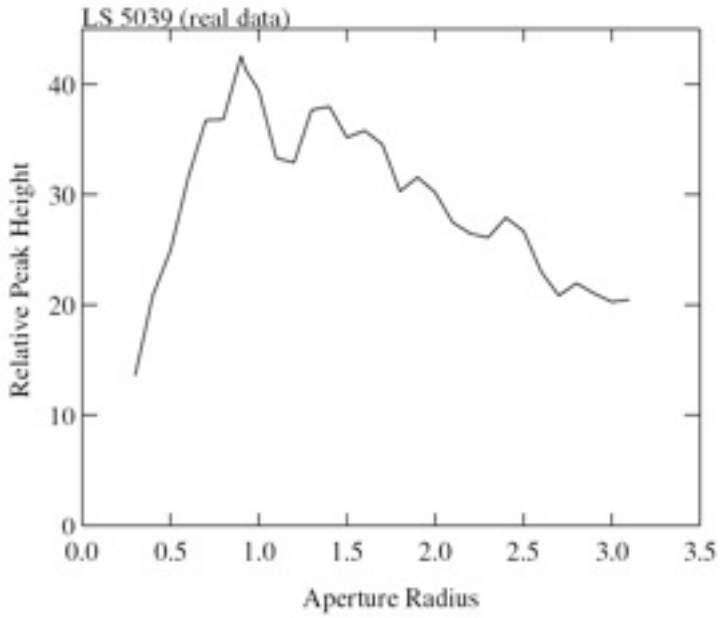
- Fermi has found very many gamma-ray sources, many still without identifications.
- However, the number of interacting binary sources is extremely low. So far, no completely unexpected binaries have been found.
- The most convincing way to show that a source is a binary would be the detection of periodic modulation in the light curve.
- What should be done to obtain the most sensitive searches for periodic modulation?

Power spectrum weighting

- As previously discussed, weighting gives great increase in sensitivity if there is large variation in error bar sizes.
- For the LAT we get a large variation in exposure times per time bin if we use short time bins.
- We want to look for systems with short orbital periods like Cyg X-3, so need to use short time bins and weighting.

LAT S/N aperture dependence





Look at the strength of orbital modulation in the two LS sources and see how this varies depending on the aperture used.

For LS I +61 303 optimum aperture radius is much larger than for LS 5039.

Status of gamma-ray binary hunt

- Extracted light curves for all 1451 "1FGL" sources using 1 degree aperture.
- Searched for modulation down to 1.2 hours with weighted power spectra.
- Also extracted light curves at locations of known X-ray binaries, even if there was no cataloged LAT source.
  - Galactic sources lie on the plane where it may be hard to identify them.
- No obvious new binaries have been found yet...

Next steps in the hunt...

- Update search as additional data are available.
- Determine optimum apertures and energy ranges to maximize S/N for each source (with Matthew Kerr).
- Just having longer light curves works wonders!
- "Infinite aperture" technique is also being developed by *Matthew Kerr*.
    - This assigns a probability that any photon came from the source.
    - Possibly ultimate S/N since all photons are used?

Conclusion

- Fermi LAT has detected periodic emission from 3 gamma-ray binaries (proves ID):
  - LS I +61° 303 and LS 5039 (neutron stars?)
  - Cyg X-3 (black hole?)
- Modulation at GeV energies compared to TeV and keV constrains emission mechanisms.
- Gamma-ray binaries are relatively rare but can teach us a lot.
- PSR B1259-63 will be at periastron in 2010.
- A search for more systems is underway...