Discovering and Characterizing γ-ray Binaries: Timing and Multiwavelength Analyses

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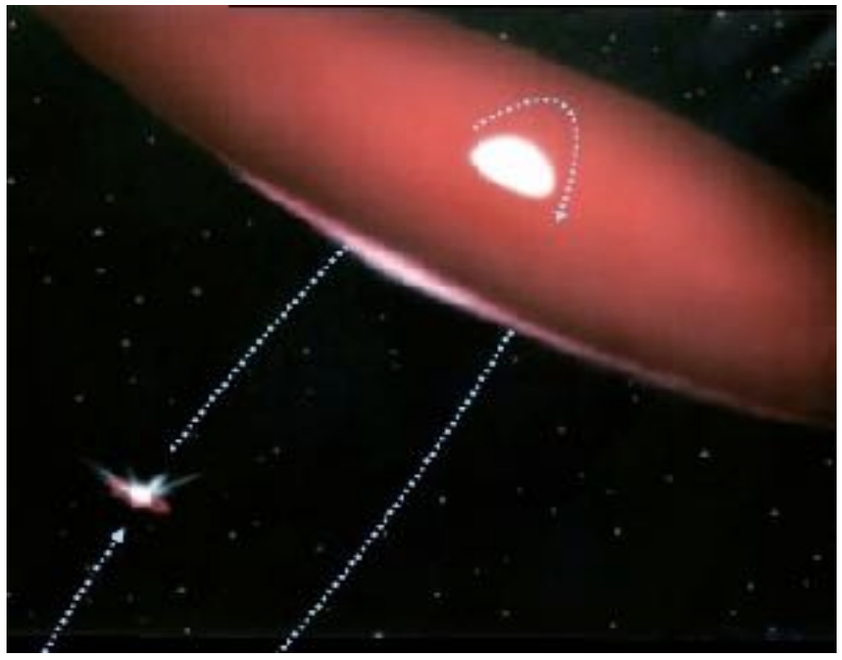
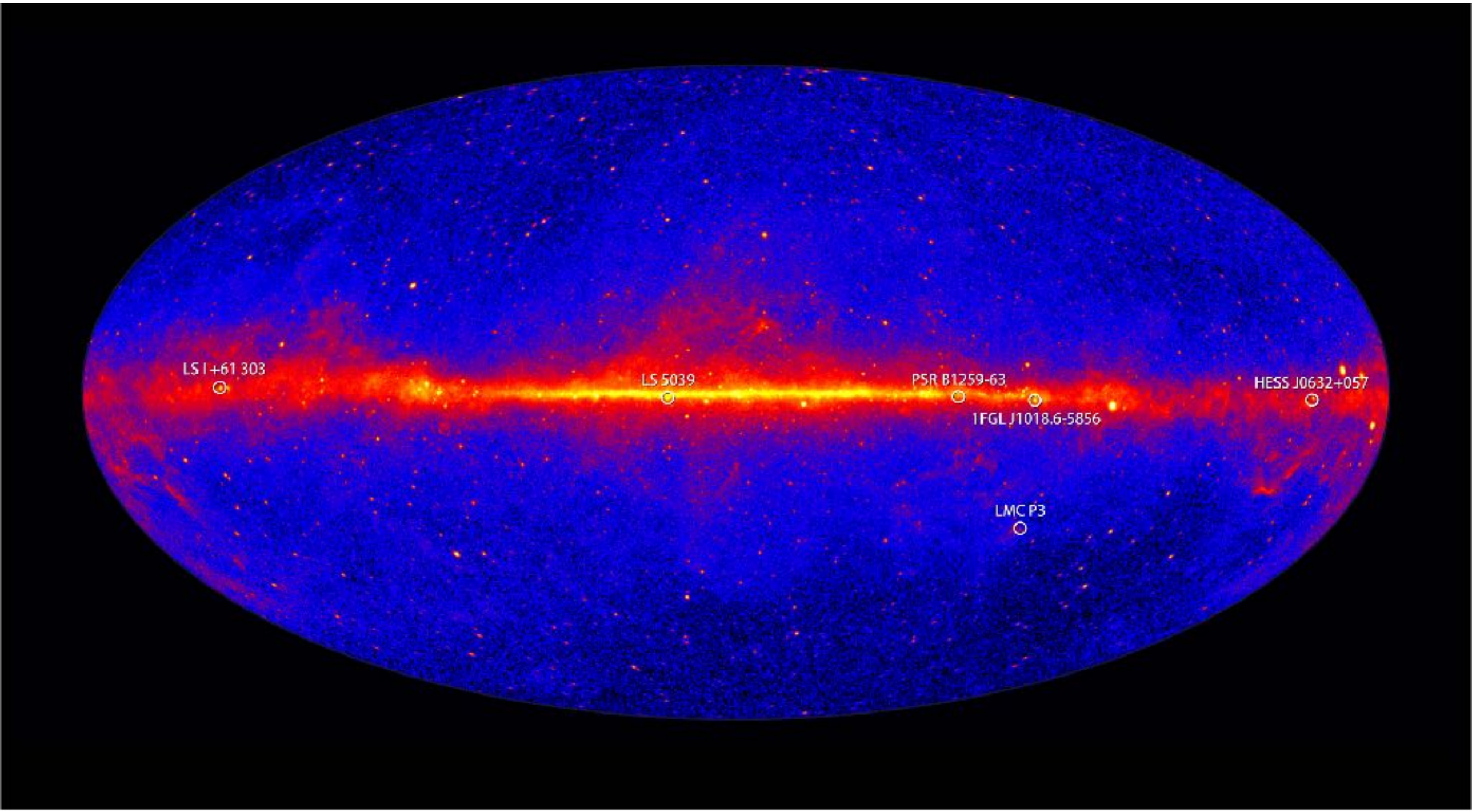
What is a Gamma-ray Binary?



- Binary with SED peak > 1MeV, contains compact object and OB star.
- Emission driven by interaction between binary components.
- Need:
    - Power source.
    - Non-thermal mechanism. e.g. Fermi acceleration at shocks + inverse Compton scattering.

- Pulsar orbiting a hot (O or B type) companion.
- Pulsar and stellar winds or Be disks collide and form shocks

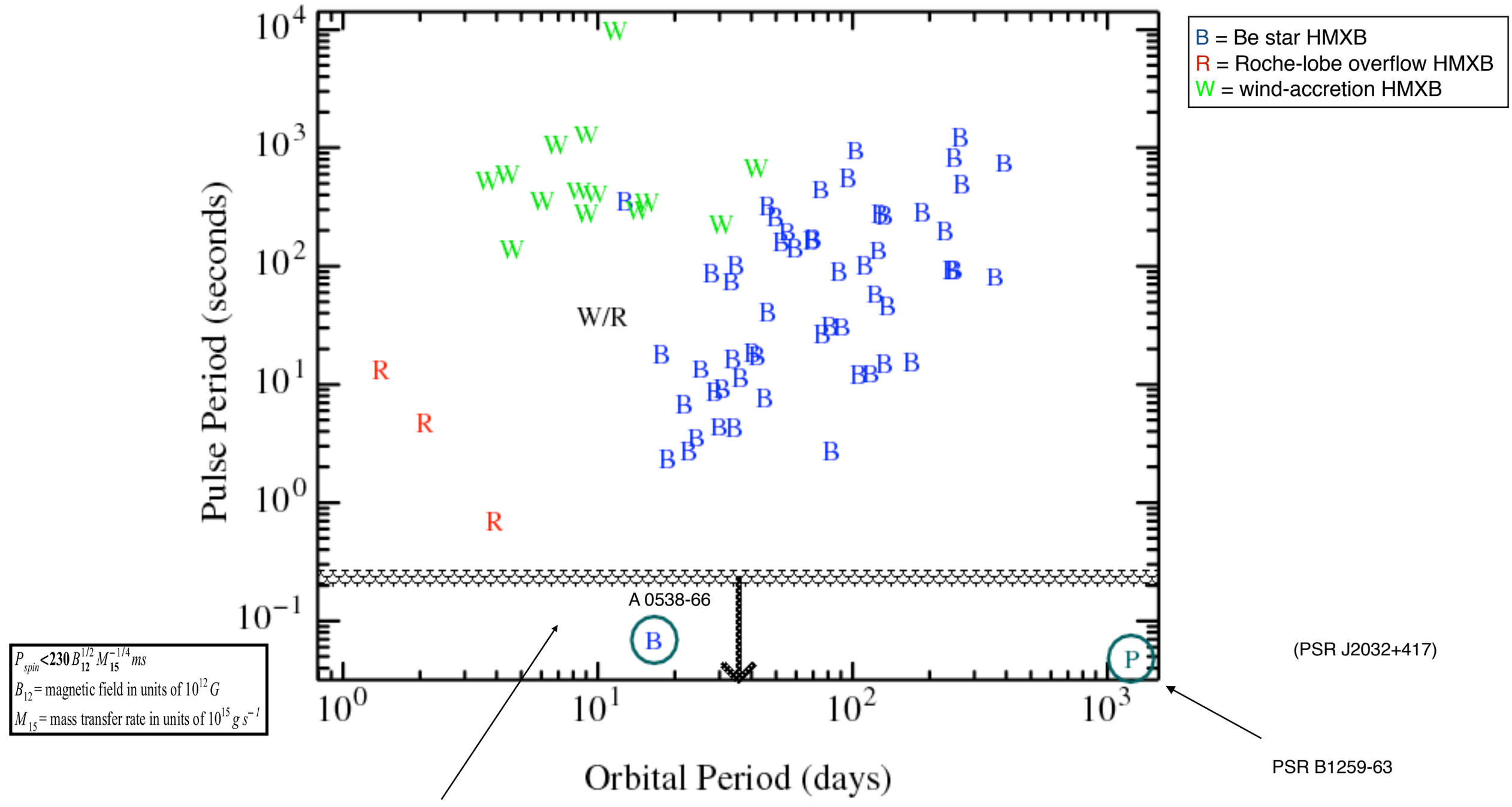
Very Few Gamma-ray Binaries are Known



J1018.6-5856 and LMC P3 were found from our searches.

(PSR J2032+4127 not plotted here.)

X-ray Binaries Born as Gamma-ray Binaries



HMXBs containing neutron stars may begin as gamma-ray binaries with rapidly rotating neutron stars before spinning down. (Later become neutron star/neutron star binaries.)

The Hunt for New Gamma-ray Binaries

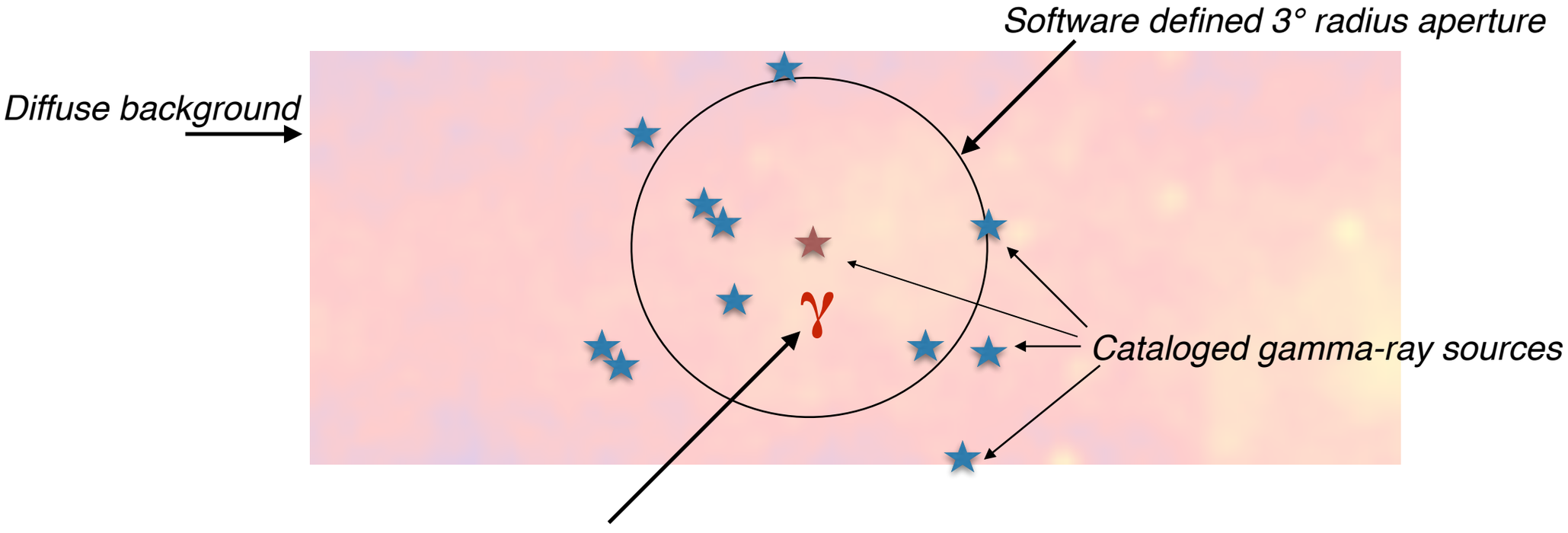
- ~30 binaries were predicted in the Milky Way as early phase of HMXB evolution.
- Dubus+ 2017 estimate 101^{+89}_{-52}
- Our program searches for gamma-ray binaries from detection of periodic variability.
- Use Fermi LAT (E > 100 MeV).
- Great for variability studies because it monitors entire sky with rapid cadence.
- We create light curves, and power spectra of these, for all sources in Fermi catalogs.

Difficulties in Hunting Gamma-ray Binaries

- Binary signals are rare.
- Artifact signals are common!
    - e.g. 53 day satellite precession period, 1 day modulation (background variation), 3 hour survey period, 1.5 hour orbital period, 1/4 year period near bright sources, the Moon 27.3 day period.
- Gamma-ray error boxes are large - can be hard to find counterparts.
- Fermi LAT point-spread function large, and energy dependent.

Optimizing Signal/Noise: Probability Photometry

- Aperture photometry with 3° radius..
- Don't sum *photons* in aperture, instead sum their **probability** of coming from source of interest.
- Construct model for 10° region from LAT catalog, including diffuse background.



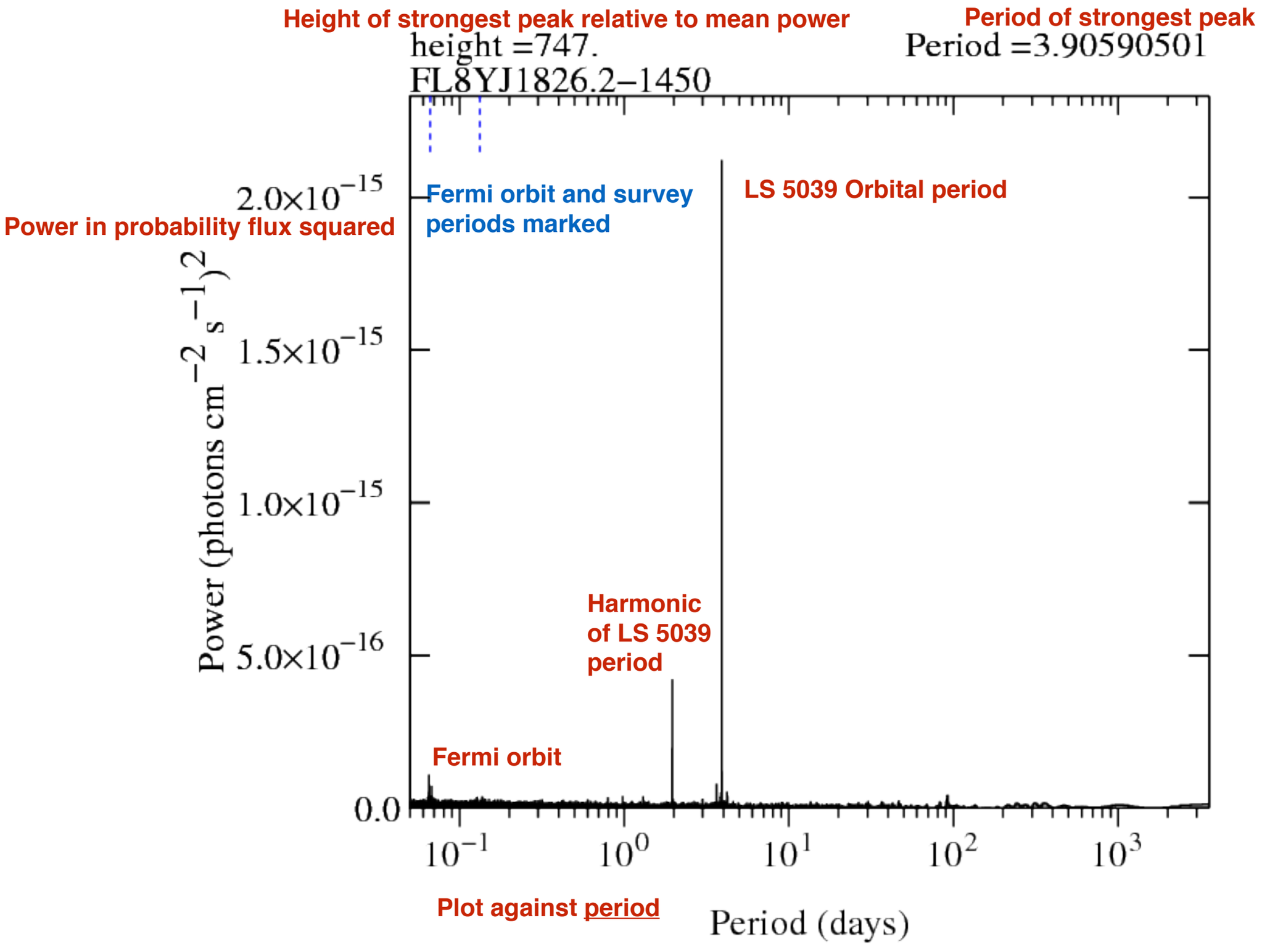
Photon in aperture - calculate probability it came from source of interest.

Optimizing S/N: Exposure-Weighted Power Spectra

- Light curves have 500s time resolution.
- As LAT moves across sky, the exposure from time bin to time bin changes drastically.
- Weight each data point's contribution to the power spectrum by relative exposure.
- Analogous to weighted-mean in time domain.

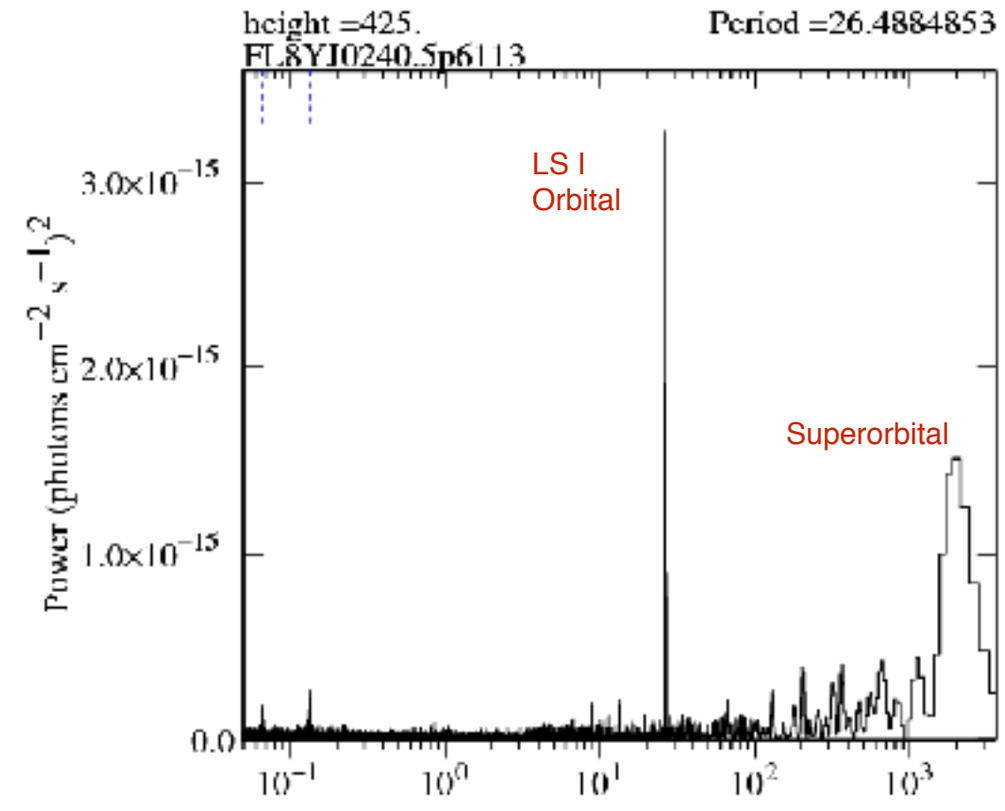
Example Output: LS 5039

- For every source we produce a plot of the power spectrum.
- This is LS 5039, strongest orbital peak of all sources.
  - Primary is *O5V star*.

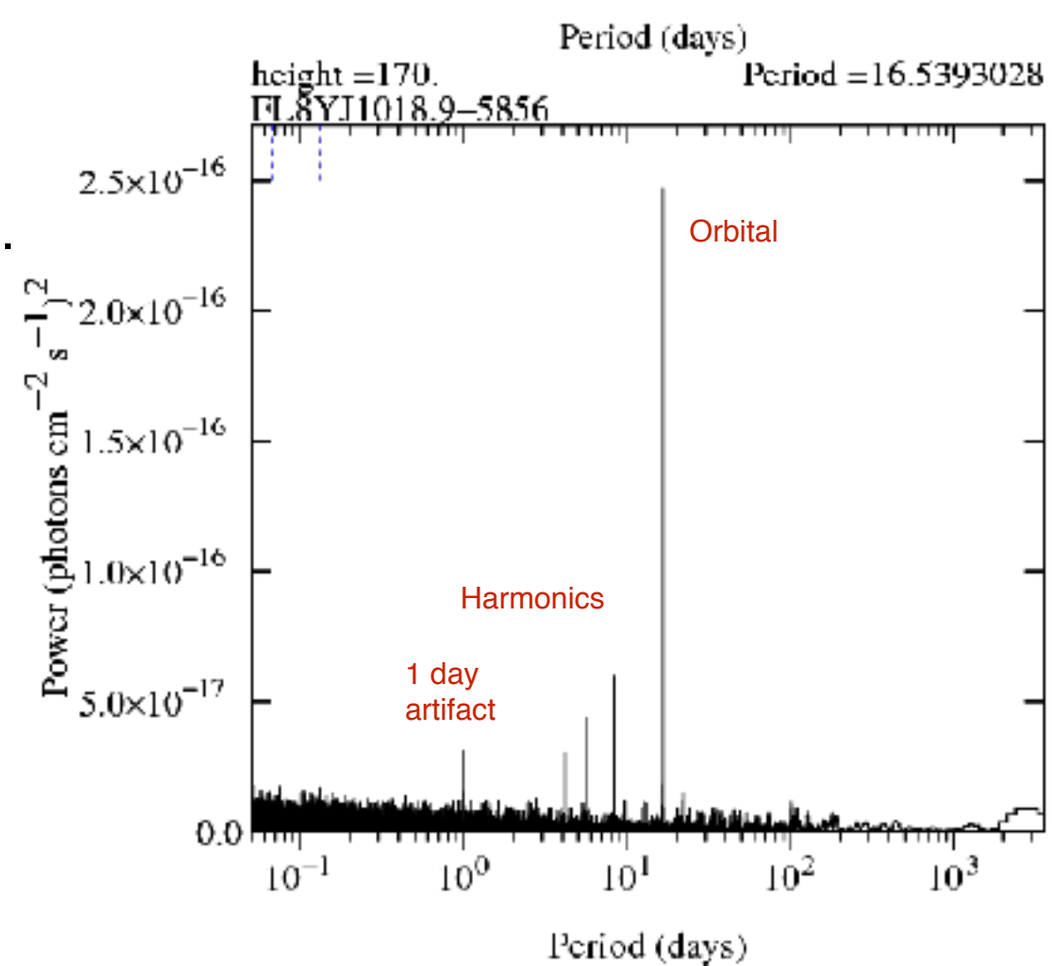


Results: The Other "Classical" Binaries

LS I +61° 303
26.5 day orbital period
1667 day superorbital period
Primary is *Be star*

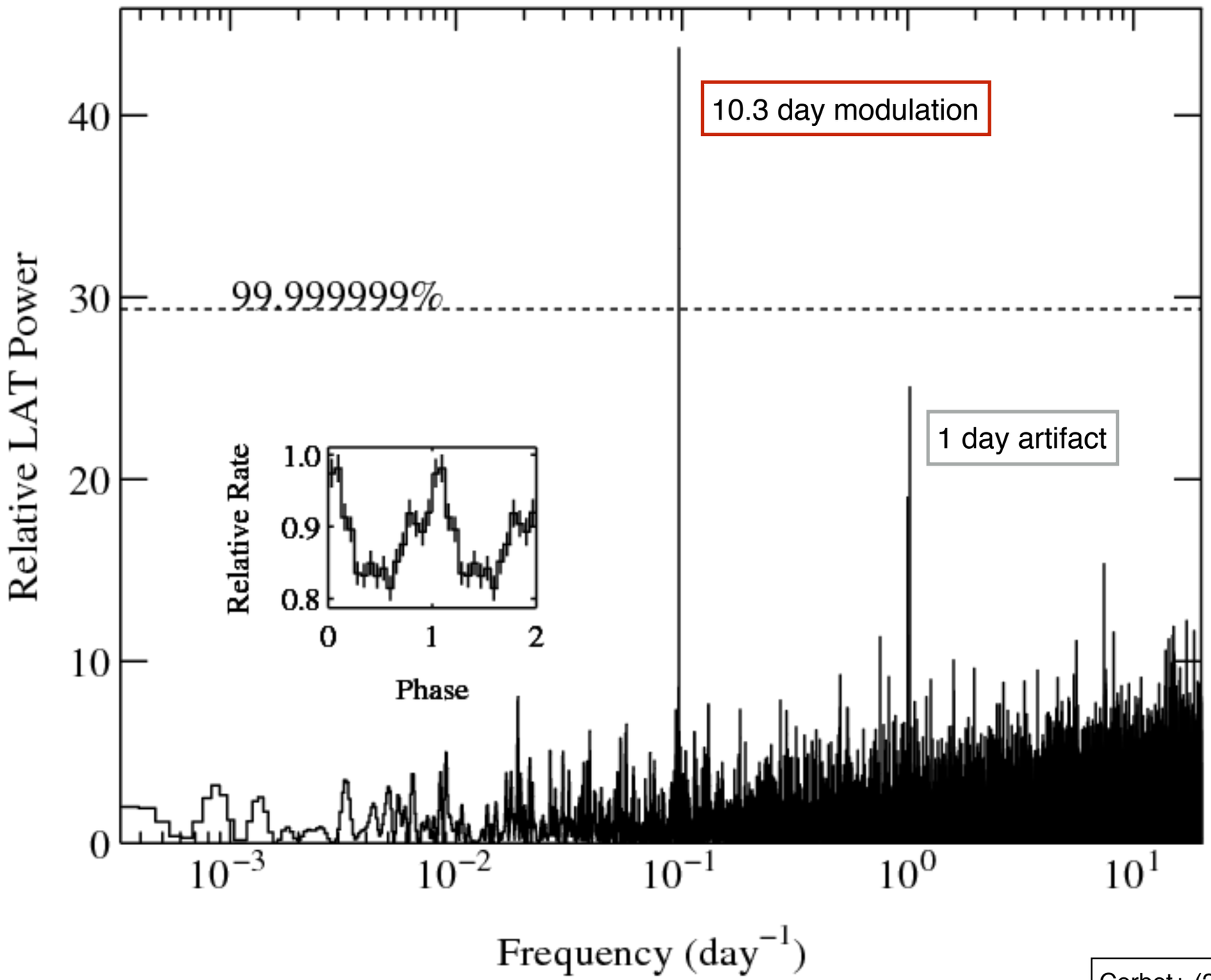


1FGL J1018.6-5856
Was our first "new" binary (2012).
Primary is *O6V*



Discovery of First γ-ray Binary Beyond Milky Way

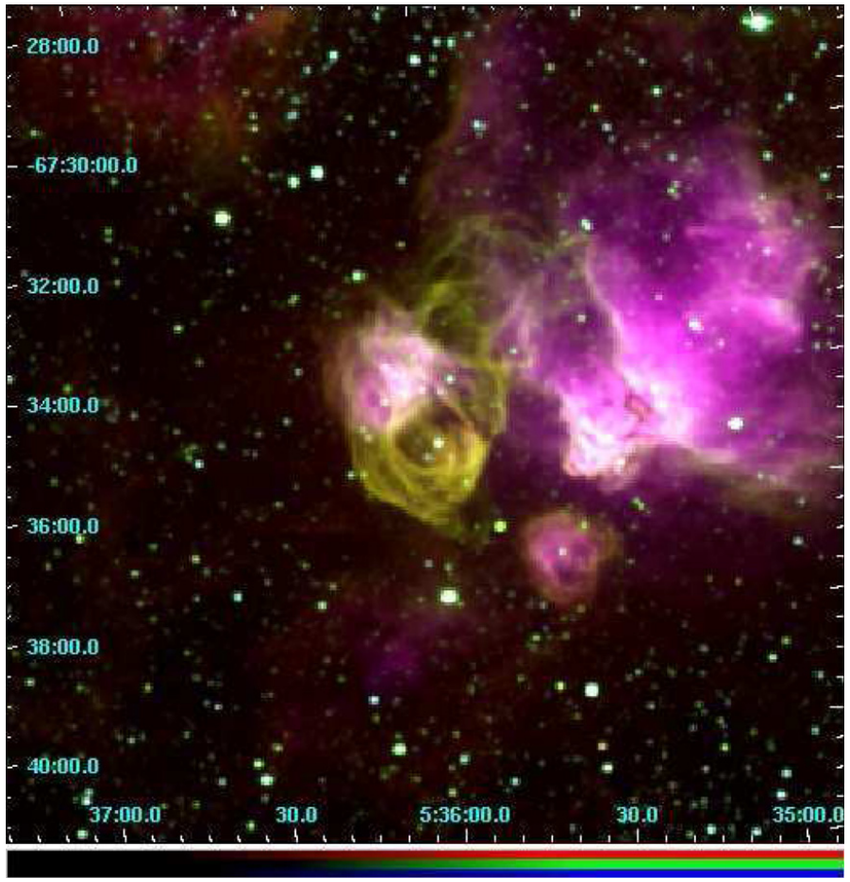
"LMC P3" was an unassociated source in the LAT LMC survey. (i.e., no definite counterpart)



Corbet+ (2016)

Counterpart? HMXB Candidate in an SNR

Chandra



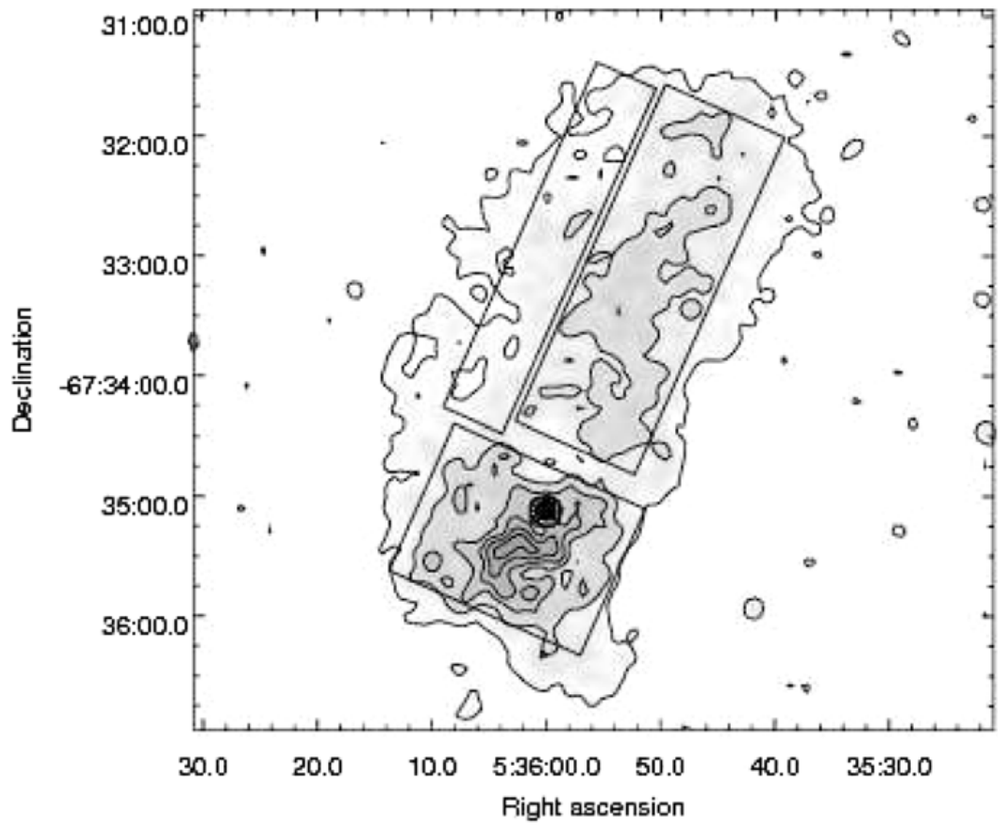


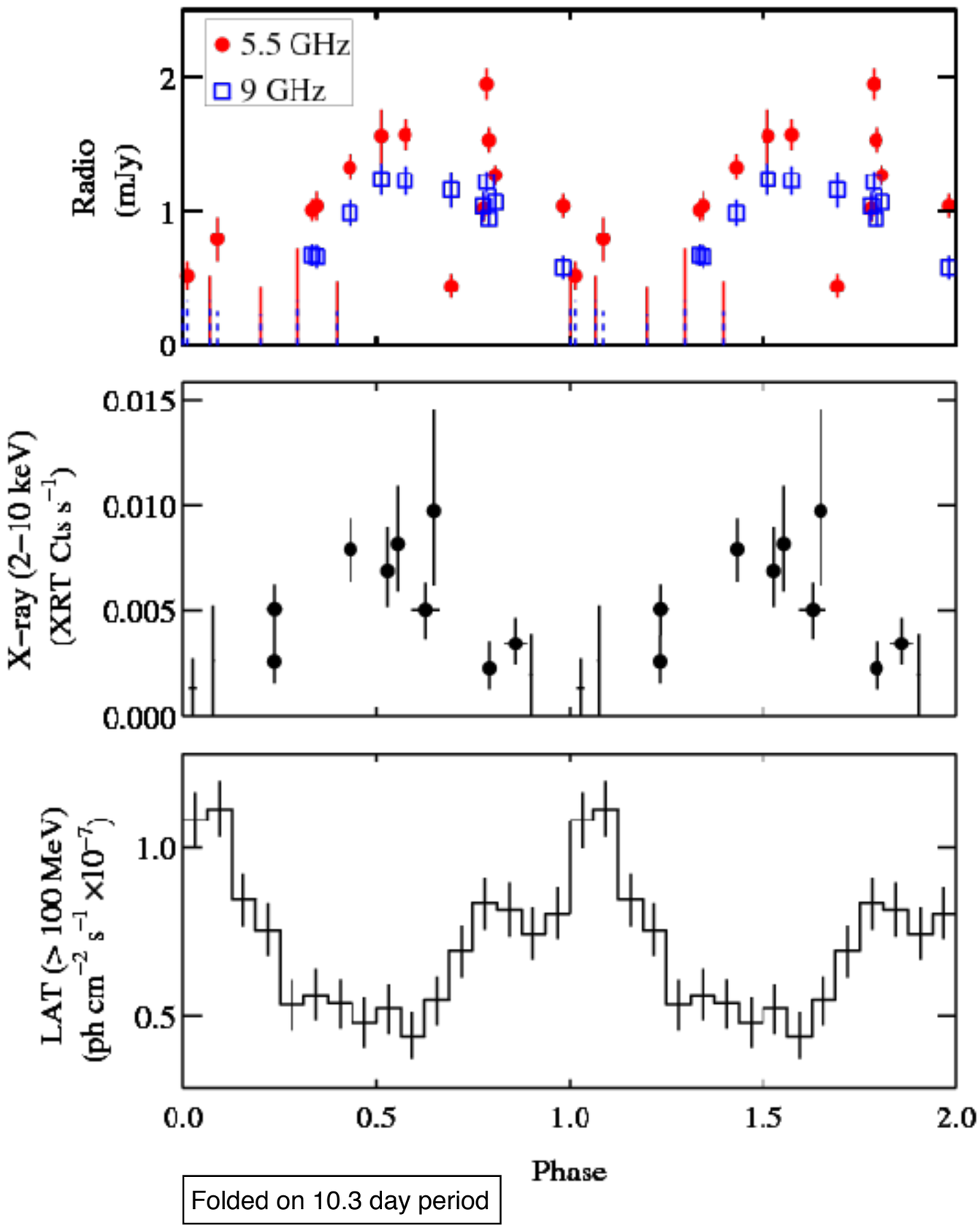
Figure 1. H II region DEM L241 showing H emission in red and [S II] emission in yellow. The [S II] emission defines the supernova remnant and correlates well with the X-rays. Figure from R. C. Smith & the MCELS Team (1999).

Seward+ (2012) had previously identified a candidate HMXB in the SNR DEM L241.
(L_x ~2x10^{35} ergs s^{-1}).
Optical counterpart is O5III star.

LAT team previously noted DEM L241 as a candidate for the counterpart of P3 (along with AGN, HII region etc.), although it was just outside LAT error ellipse.

We investigated this candidate HMXB with Swift TOO and ATCA…

Multiwavelength Properties of LMC P3



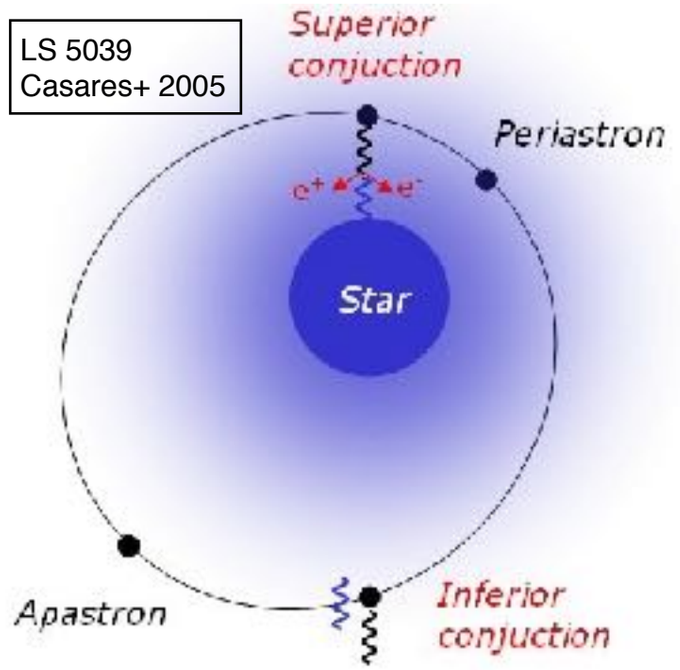
Radio

X-ray

Gamma-ray

Origin of Orbital Modulation

- There are two main effects that could modulate gamma-rays.
- Eccentric orbit with increased interactions near periastron.
- System geometry.
  - Gamma-rays arise from anisotropic inverse Compton scattering of seed photons from star on electrons in shock.
  - Strongest gamma-ray emission expected at superior conjunction.

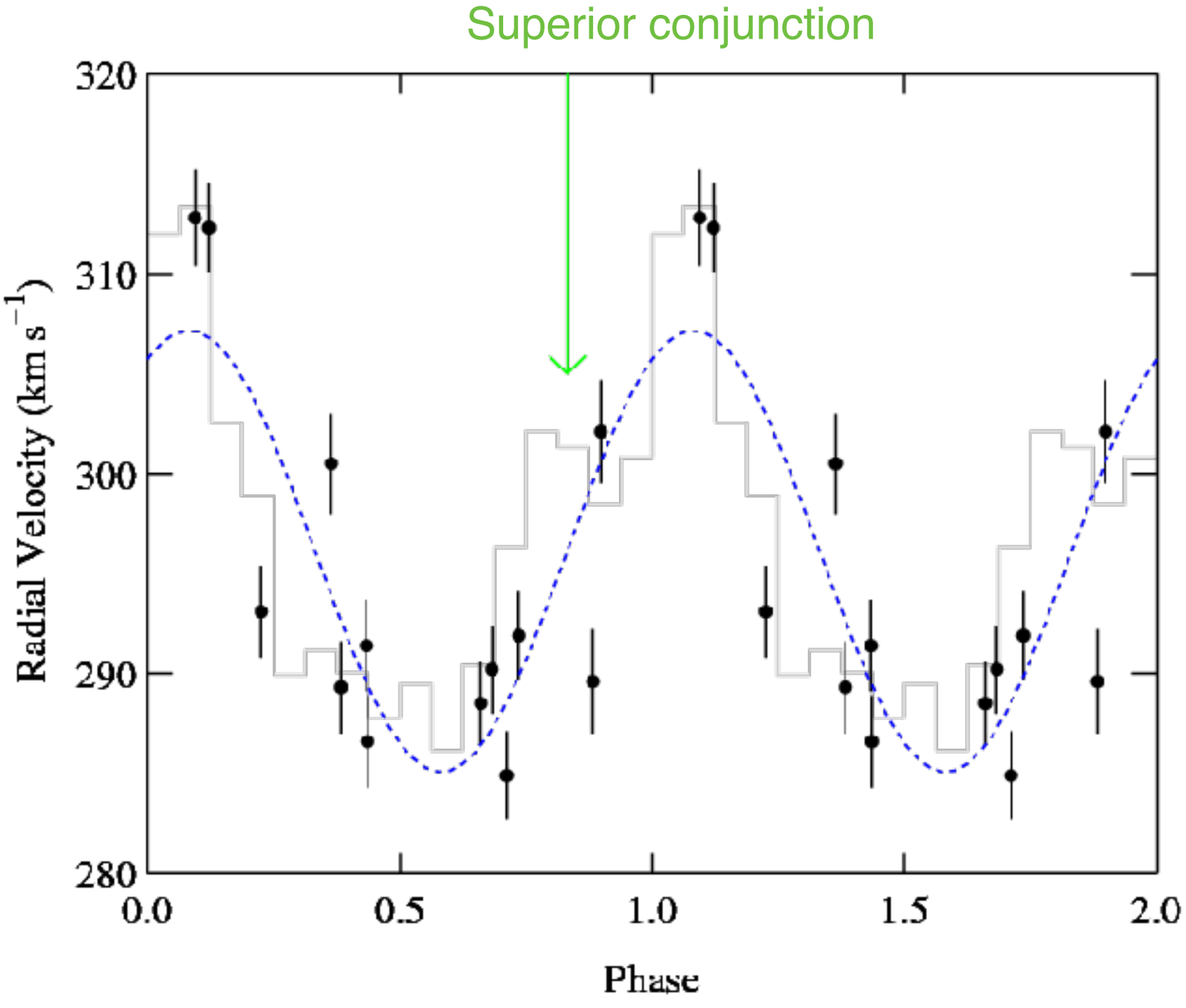


LMC P3: Optical Radial Velocity Measurements Favor Neutron Star

f(M) = (1.3 +1.1, -0.6) x $10^{-3} M_\odot$
For $1.4 M_\odot$ neutron star, i ~ 34-63°; for $10 M_\odot$ black hole, i =8±2°

Gamma-ray maximum after superior conjunction.

⇒ some eccentricity?



LMC P3 - A Luminous Source

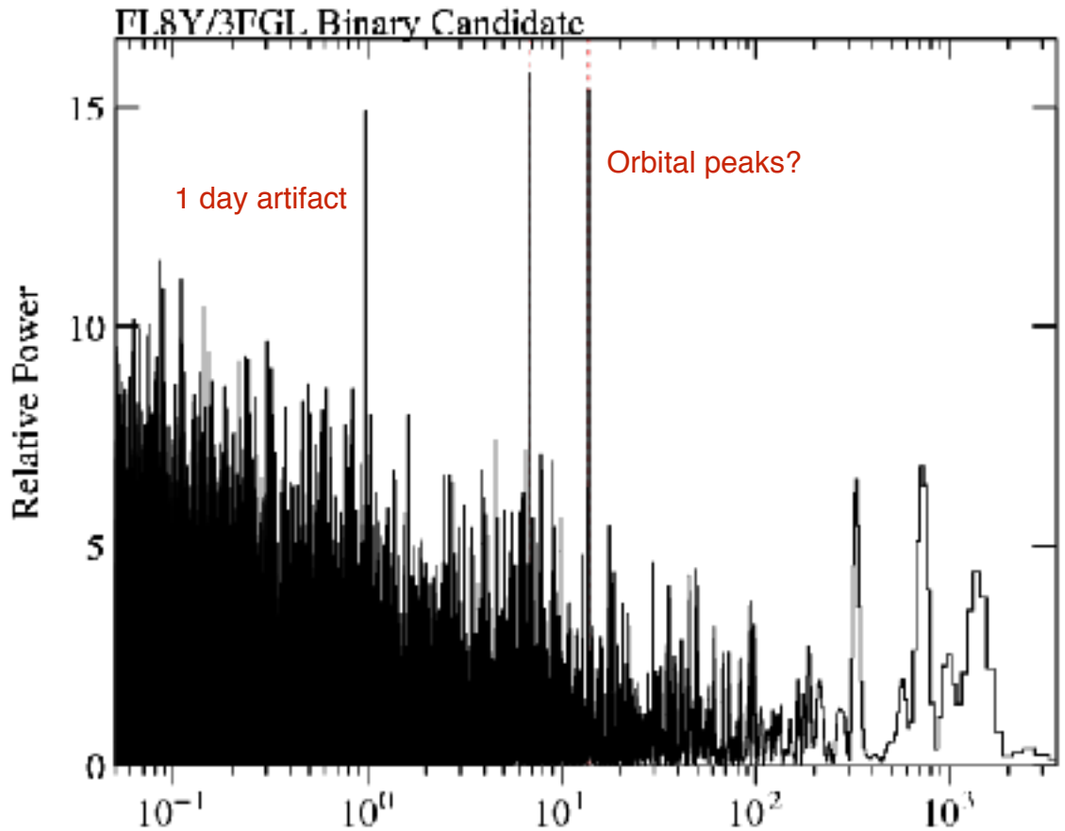
- LMC P3 is at a distance of ~50 kpc.
- Compare to first binary we found with Fermi, J1018.6 at a distance of ~5 kpc.
    - Gamma-ray luminosity ~4 × J1018.6 (~4×10^{36} erg s^{-1})
    - X-ray luminosity ~10 × J1018.6 (~10^{35} erg s^{-1})
    - Radio luminosity is ~10 × J1018.6
    - Optically brighter: companion is O5 giant rather than main sequence (as in LS 5039, J1018.6).
- Analysis is now in progress of XMM observations at X-ray maximum, minimum, and conjunction to better measure spectrum and changes, and search for pulsations (Coley+).

Searching the FL8Y Source List

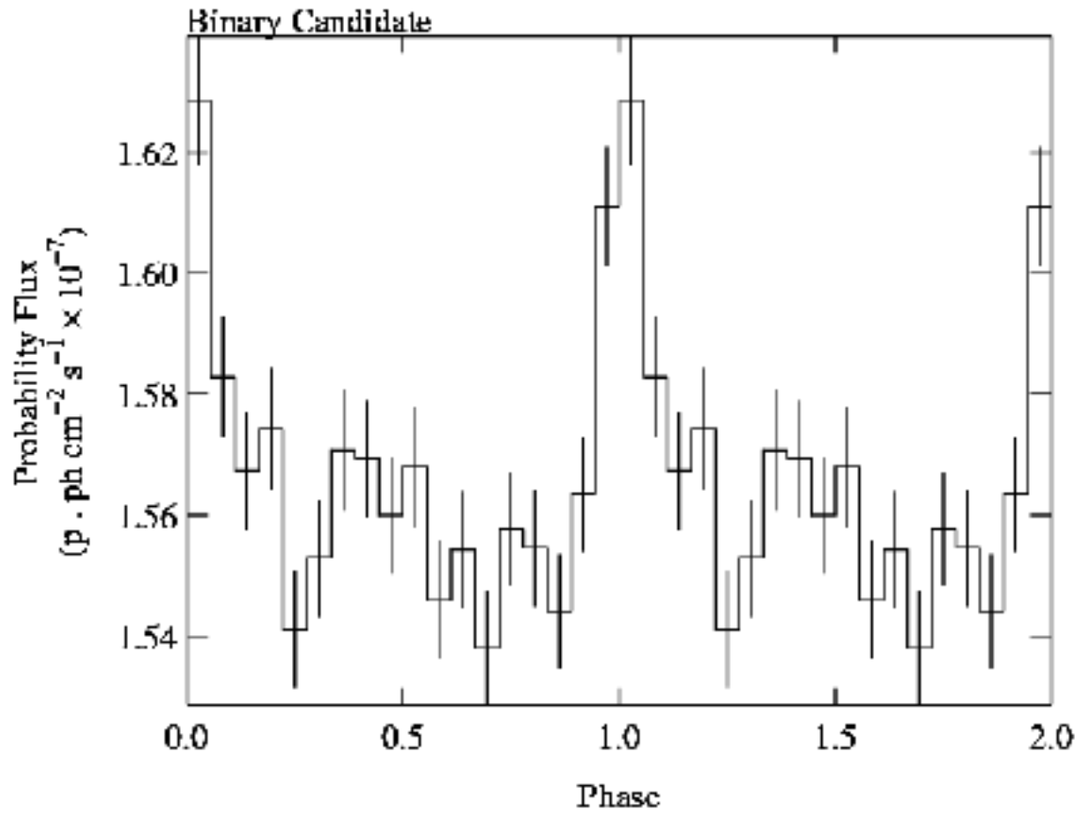
- Fermi FL8Y source list released in Jan 2018.
- Contains 5524 sources, compared to 3033 in 3FGL catalog.
- This is a precursor to 4FGL and not complete catalog (e.g. updated diffuse emission model not yet provided).
- Examine all sources, but concentrate on:
  - (i) sources close to the Galactic plane
  - (ii) candidate periods > 1 day. (high-mass systems, reduced search frequencies)
- In 3FGL we had ~4 candidate new binaries, with FL8Y all disappeared, apart from one…

A New Galactic Binary(?)

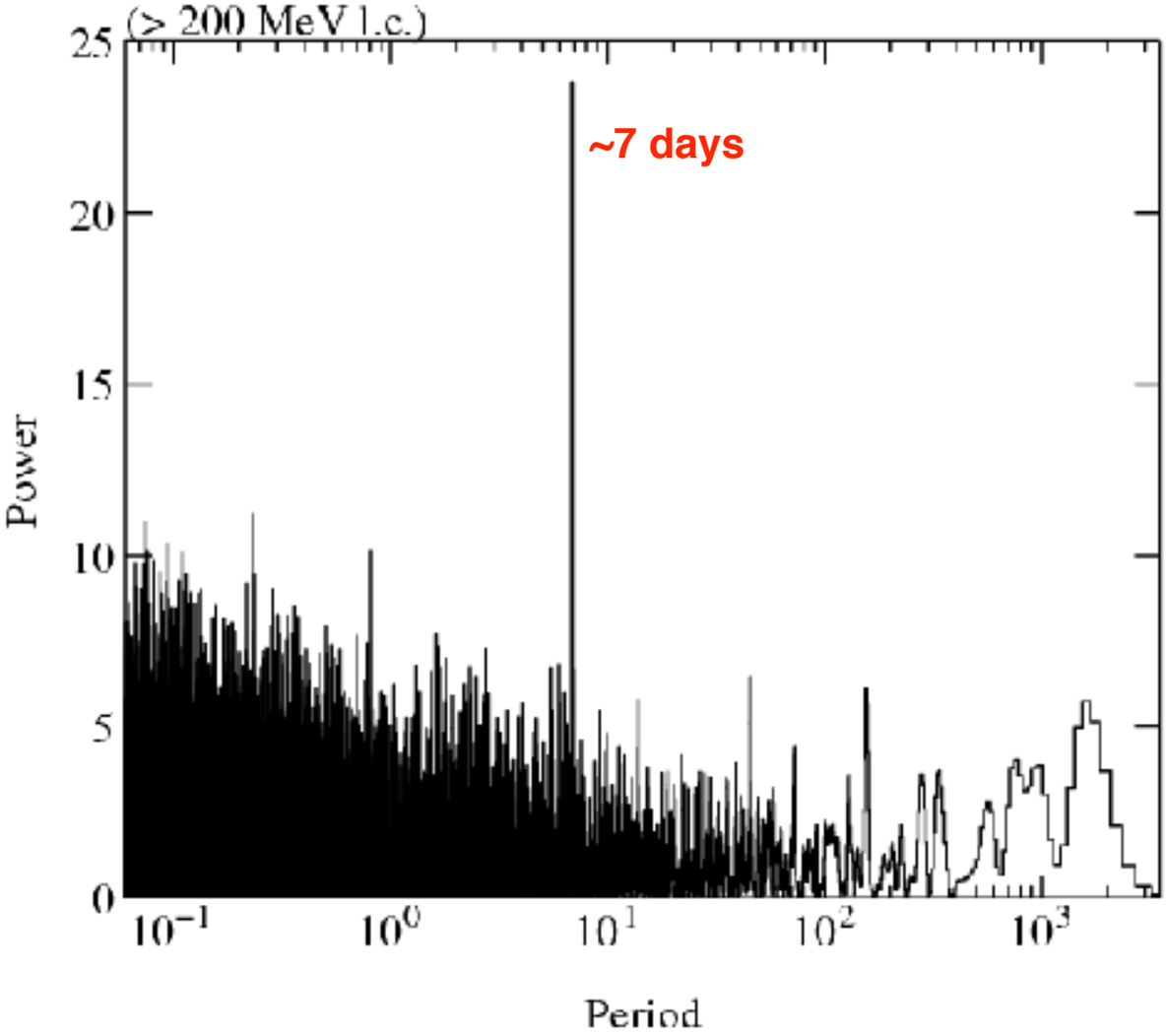
- Two harmonically related peaks at ~7 days and ~14 days.
- Each *individual* peak modest significance (0.005, 0.08)
- But probability of seeing *harmonic* of stronger peak by chance is 2×10^{-6}
- Source 0.3° from Galactic plane.



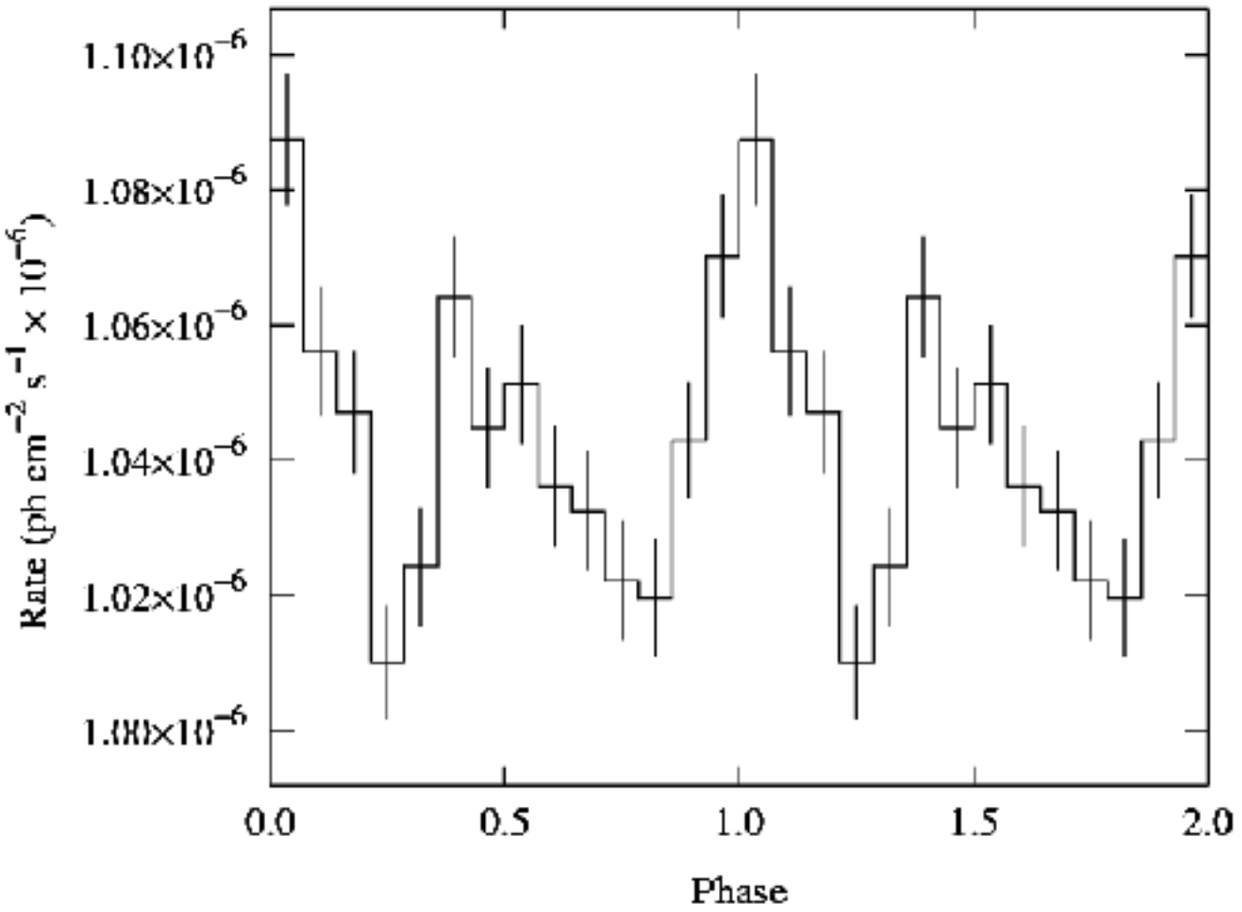
- Probability flux shows single sharp peak.
- But, photon weighting may affect photometric properties…



Power Spectrum of **Unweighted** Photons



Folded on 14 day period

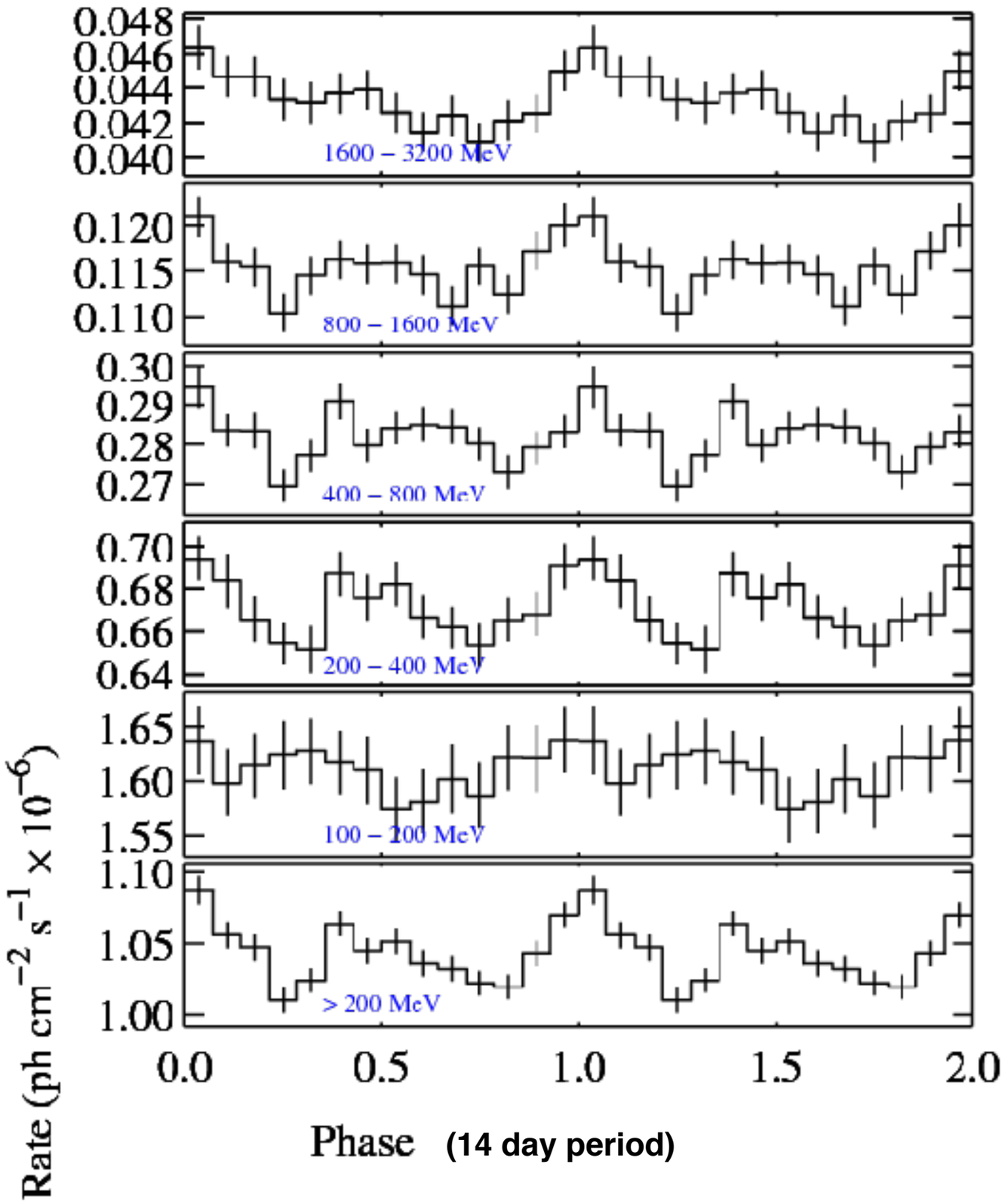


Without probability weighting

- Only strong *harmonic* at ~7 days is seen.
- Profile is double-peaked.

(For weighted analysis, higher-energy photons with smaller PSF are more heavily weighted.)

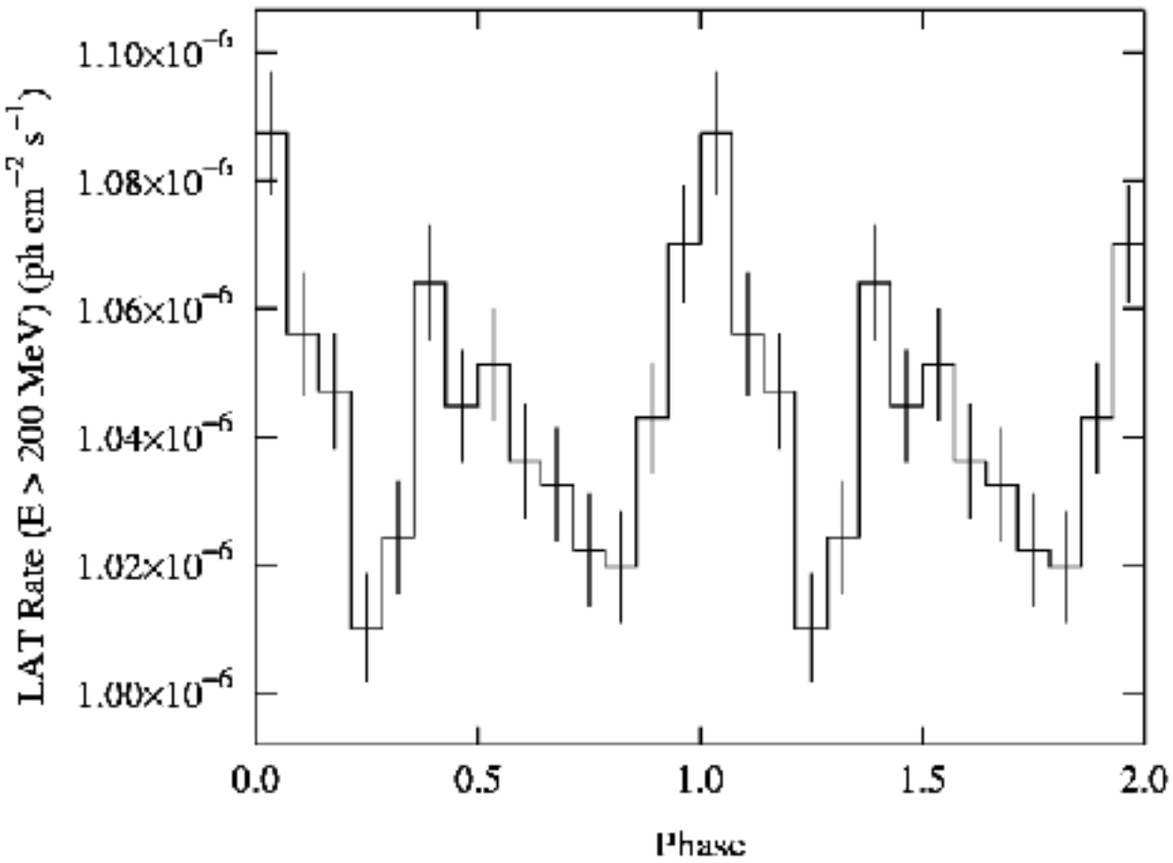
Energy Dependence of Modulation

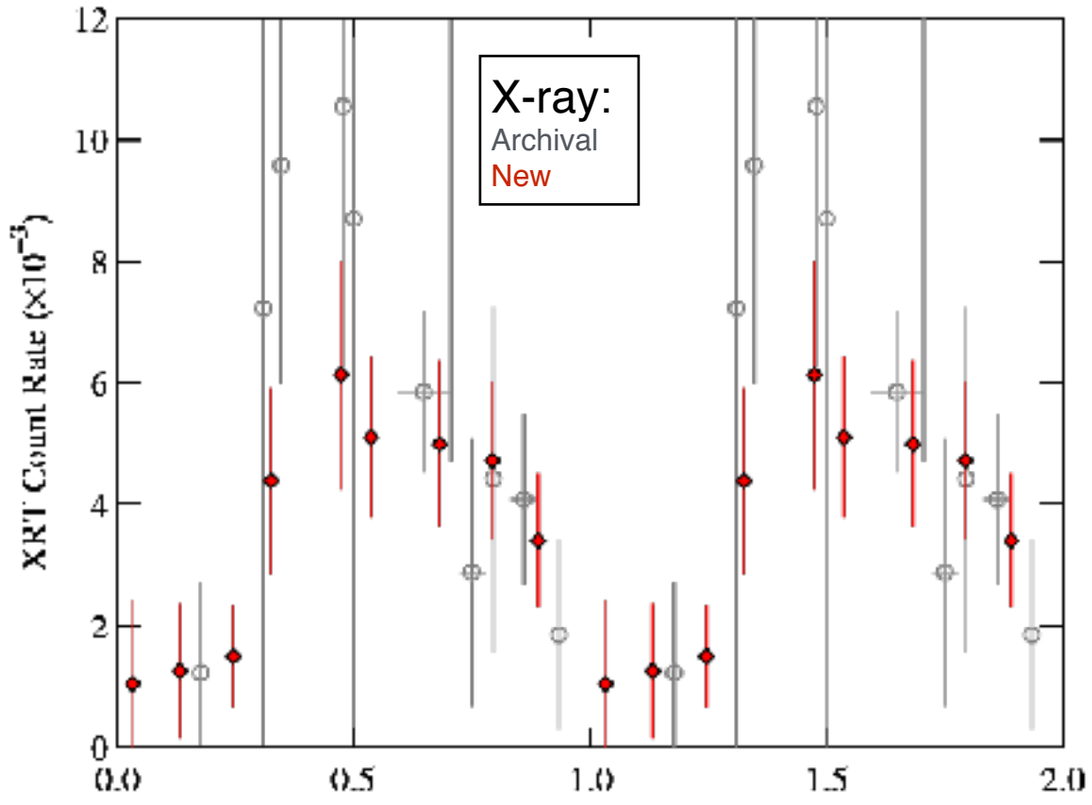


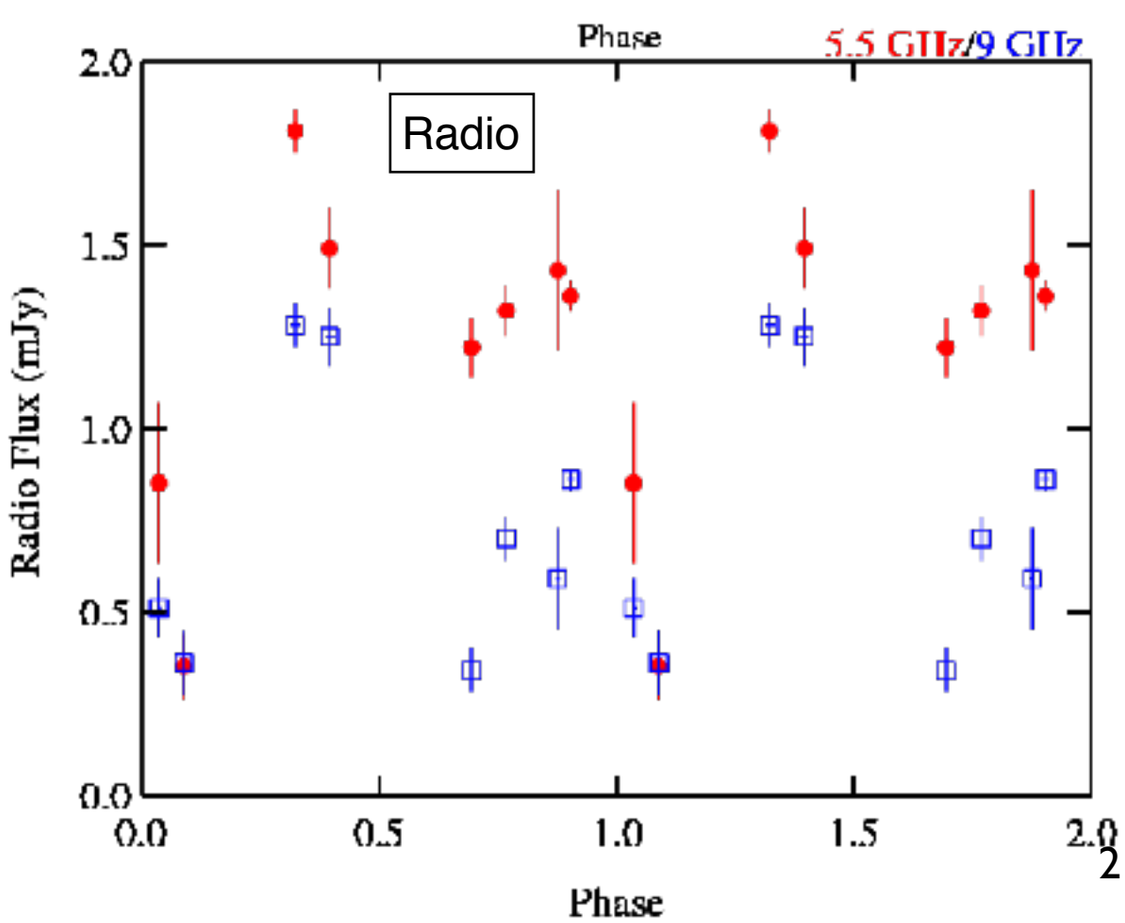
<u>Unweighted</u> photometry.

X-ray and Radio Support for New Source

LAT "unweighted" photometry







- "Conventional" LAT aperture photometry shows double-peaked profile on ~14 d period.

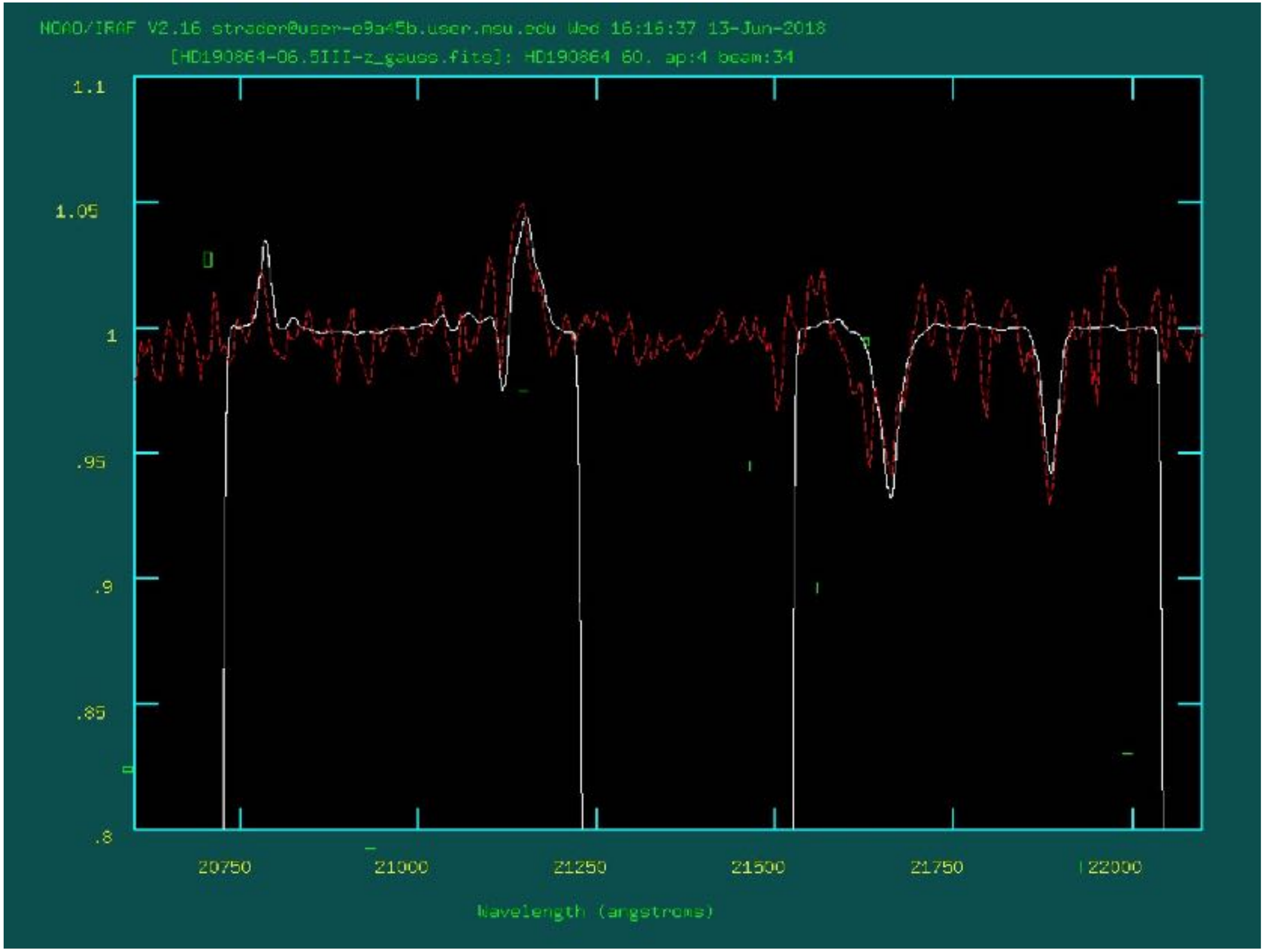
- *Secondary* γ-ray peak is *softer*.

- X-ray and radio appear modulated with *soft* peak.

Gemini/Flamingos near-IR spectrum shows counterpart is O6.5 III

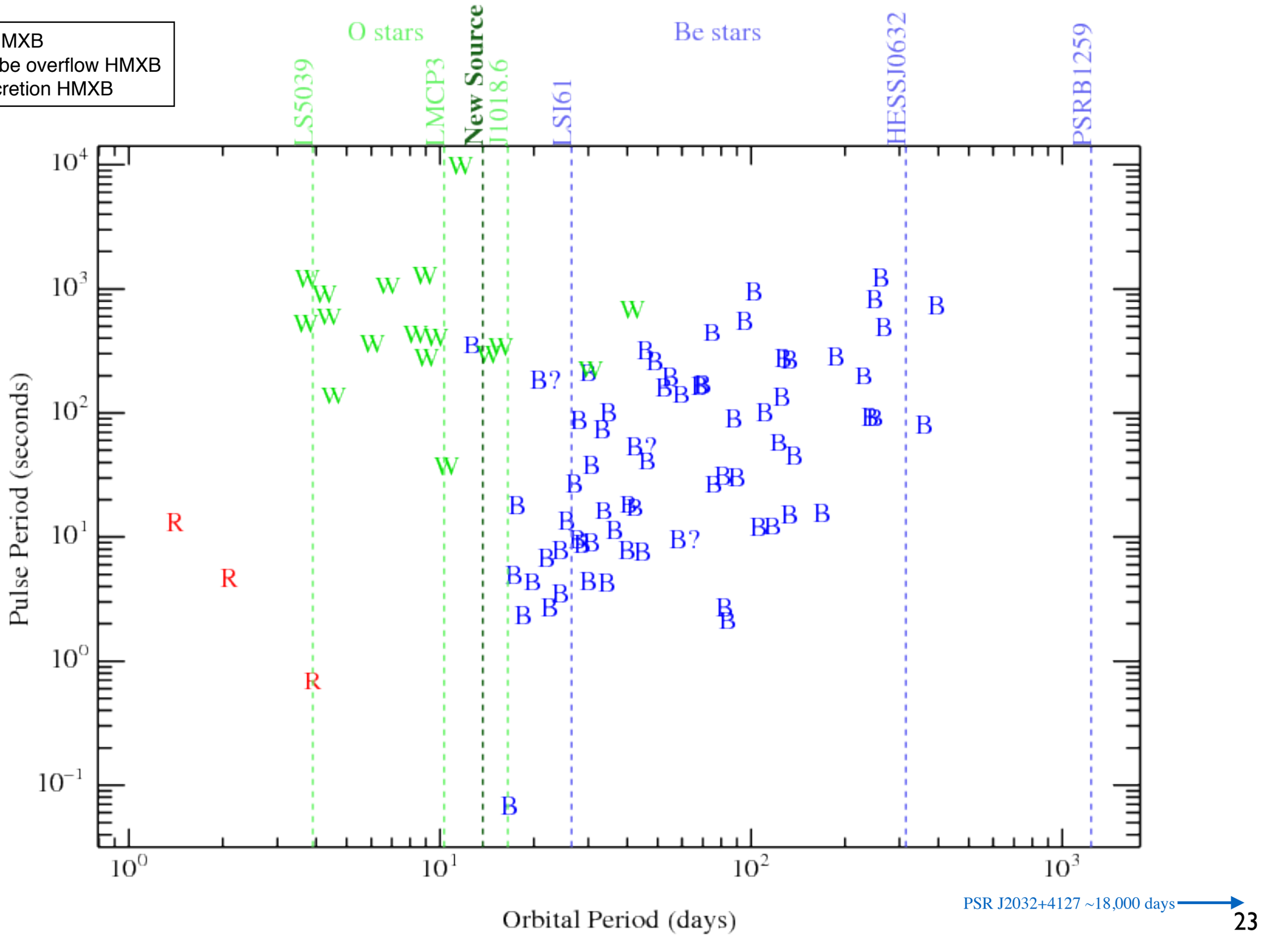
Confirms it's a binary!

(distance ~6 kpc)



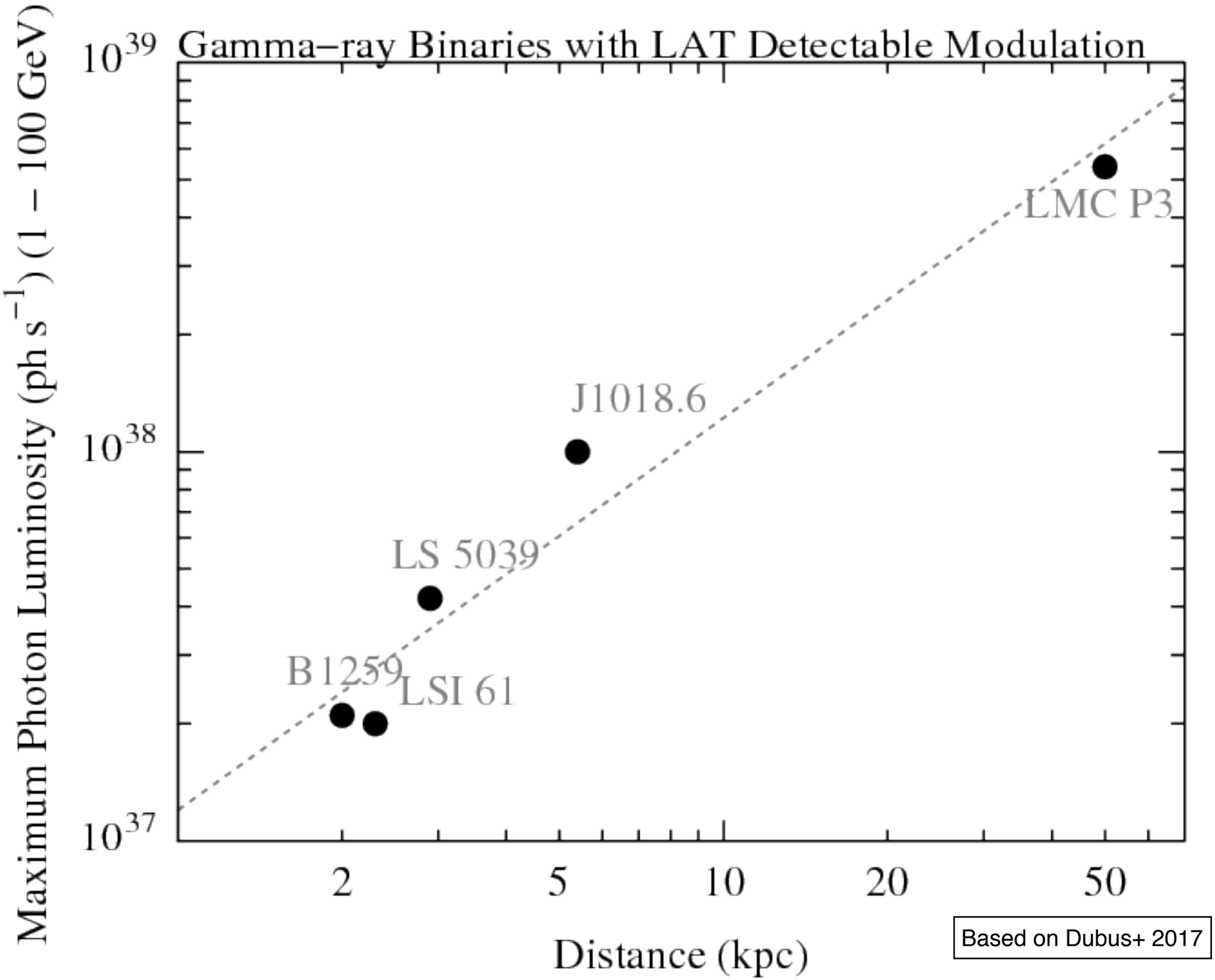
Orbital Periods: Gamma-ray & X-ray Binaries

B = Be star HMXB
R = Roche-lobe overflow HMXB
W = wind-accretion HMXB



PSR J2032+4127 ~18,000 days →

How Far Are We Detecting Gamma-ray Binaries?



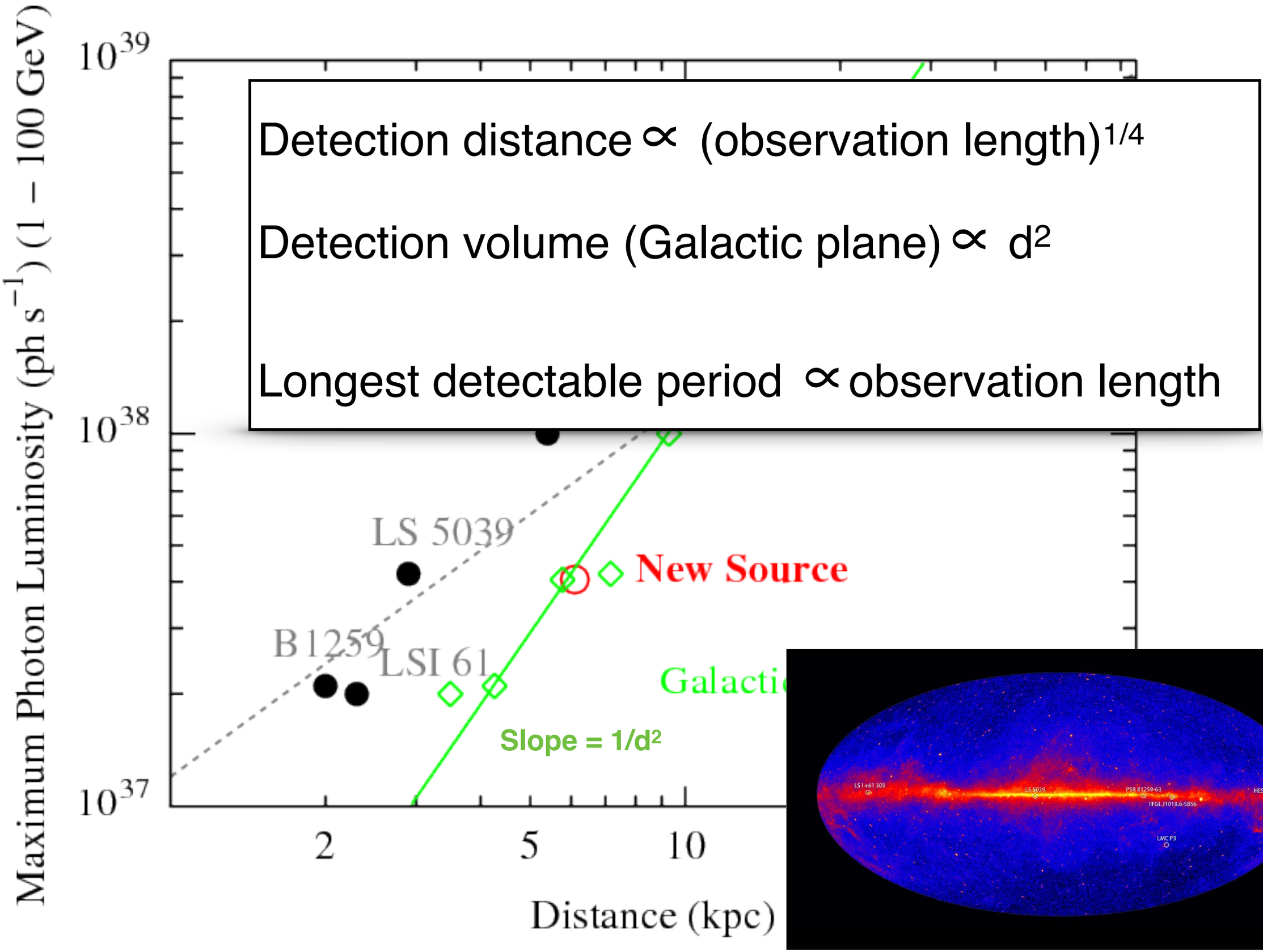
Based on Dubus+ 2017

How Far Could We Find Gamma-ray Binaries?

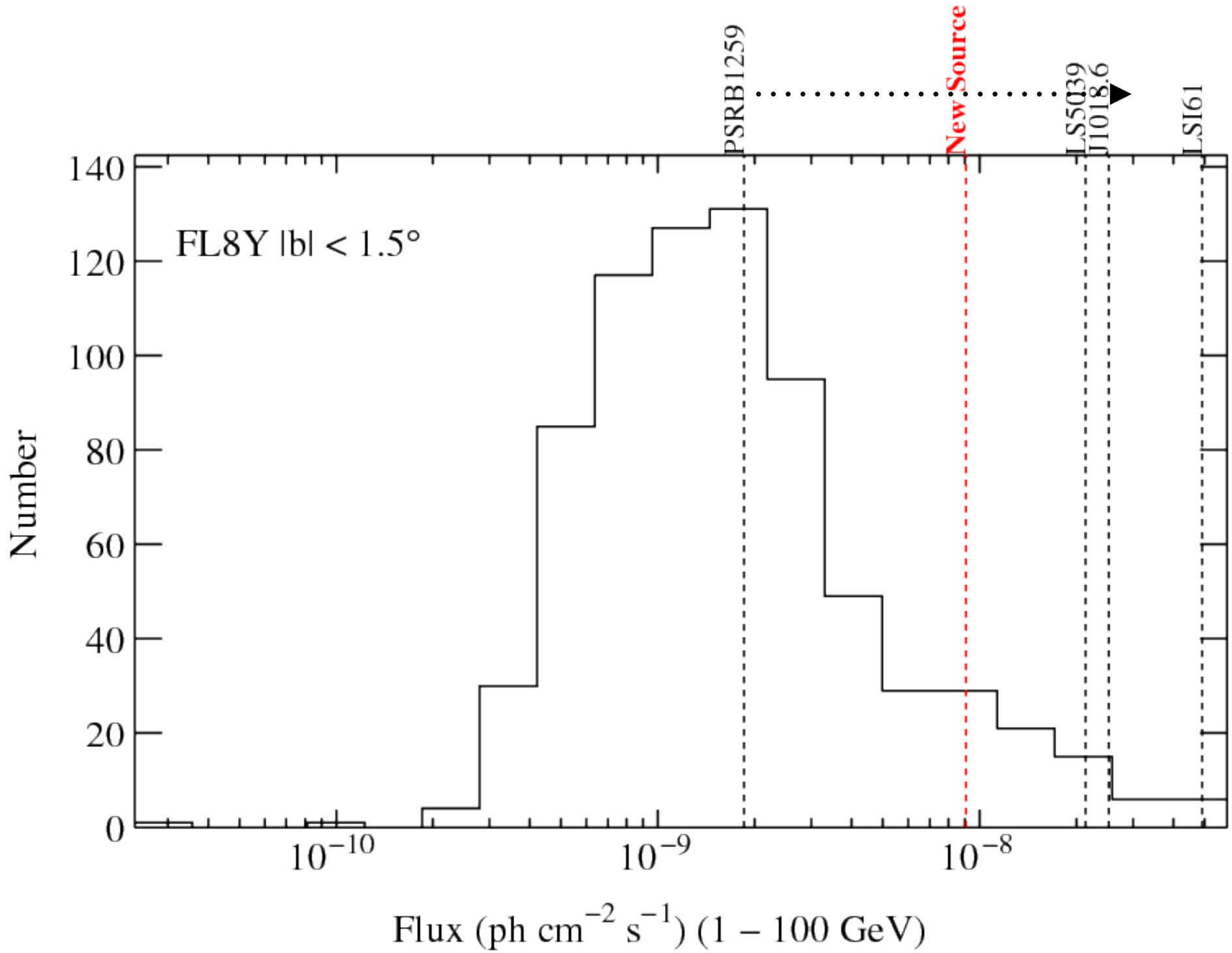
Detection distance ∝ (observation length)$^{1/4}$

Detection volume (Galactic plane) ∝ d^2

Longest detectable period ∝ observation length



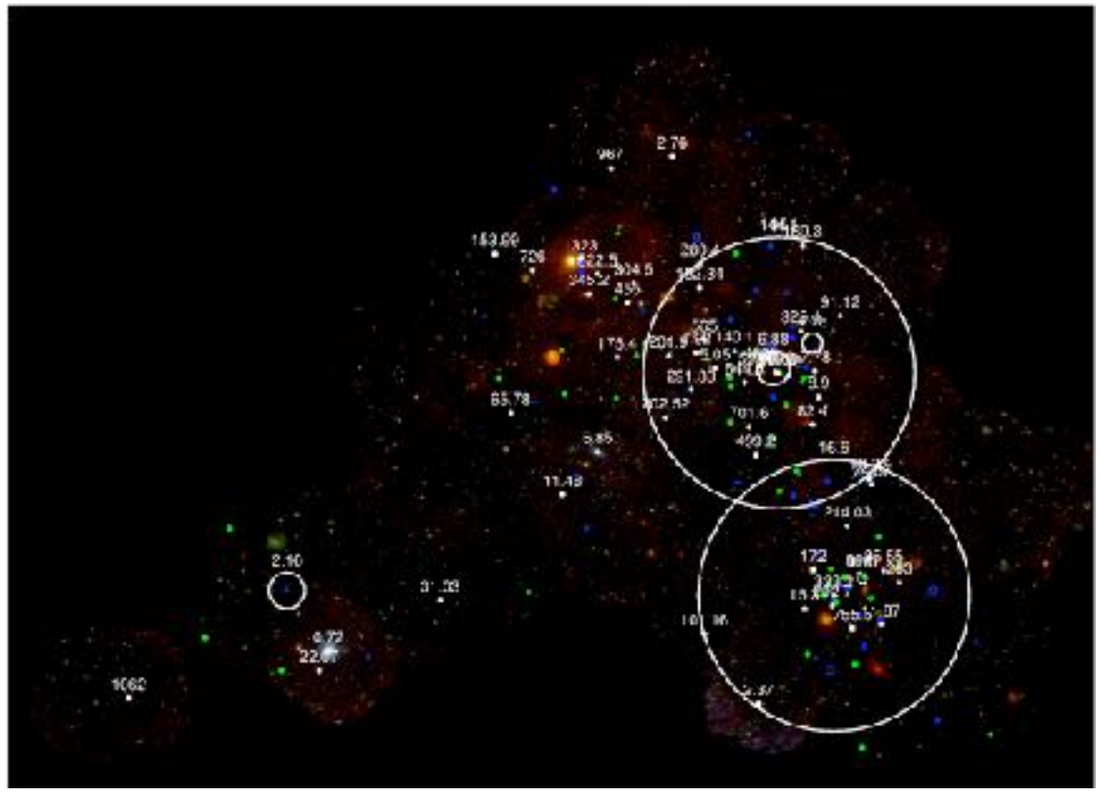
Still Only Seeing the Tip of the (Flux) Iceberg?



Although **mean** flux of B1259 is low, periodic flares are much *brighter* (Johnson, Tam).

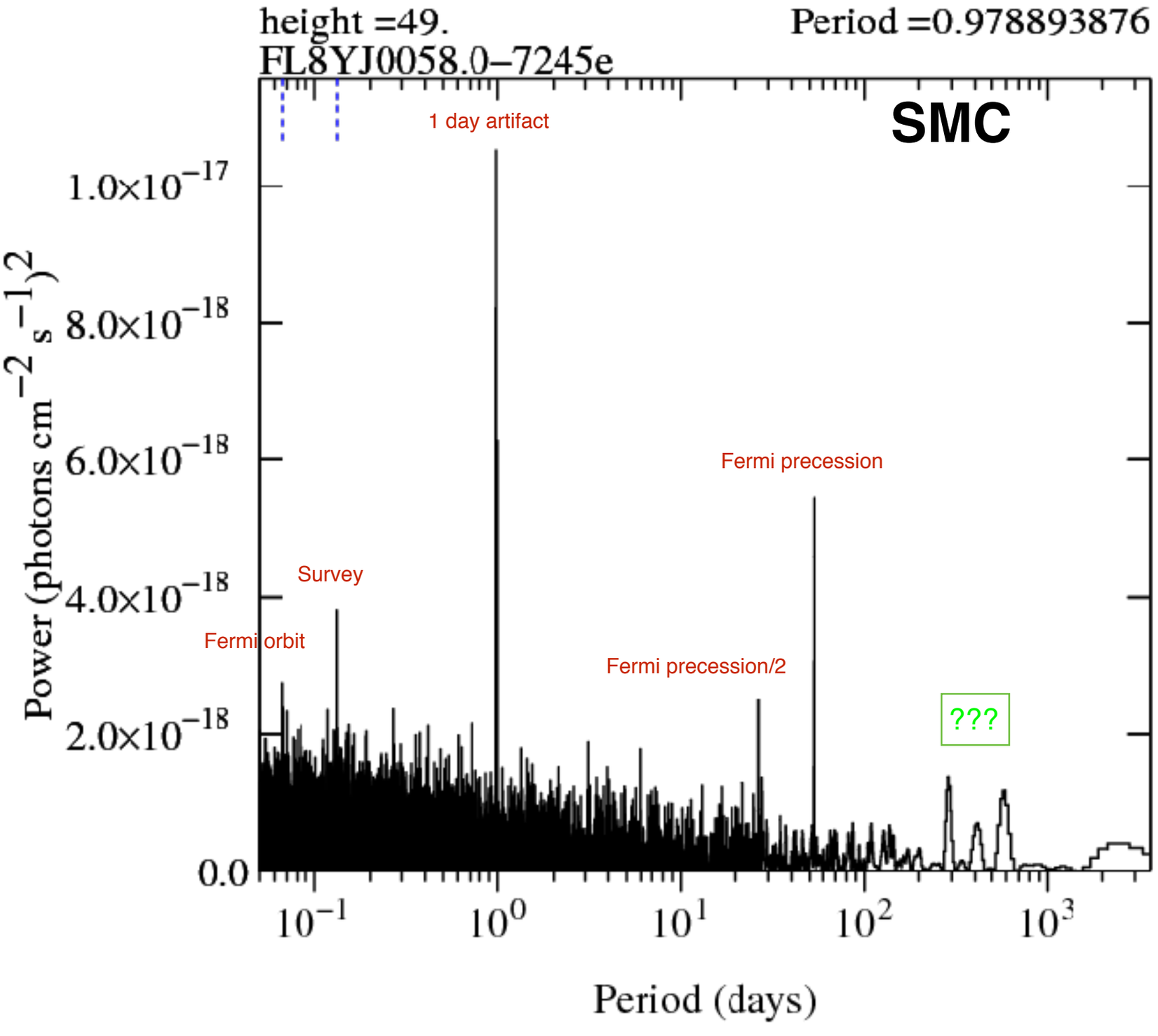
Other Nearby Galaxies: SMC

- We had a surprise with the LMC, what about our other neighbors?
- The SMC (~60 kpc) is less massive than LMC, but has overabundance of Be star high-mass X-ray binaries.
  - Suggests burst of star formation several million years ago.
  - Also one supergiant binary: SMC X-1
- In 3FGL/FL8Y the SMC is listed as a single source (like LMC was in 3FGL).
- Any sign of anything…?



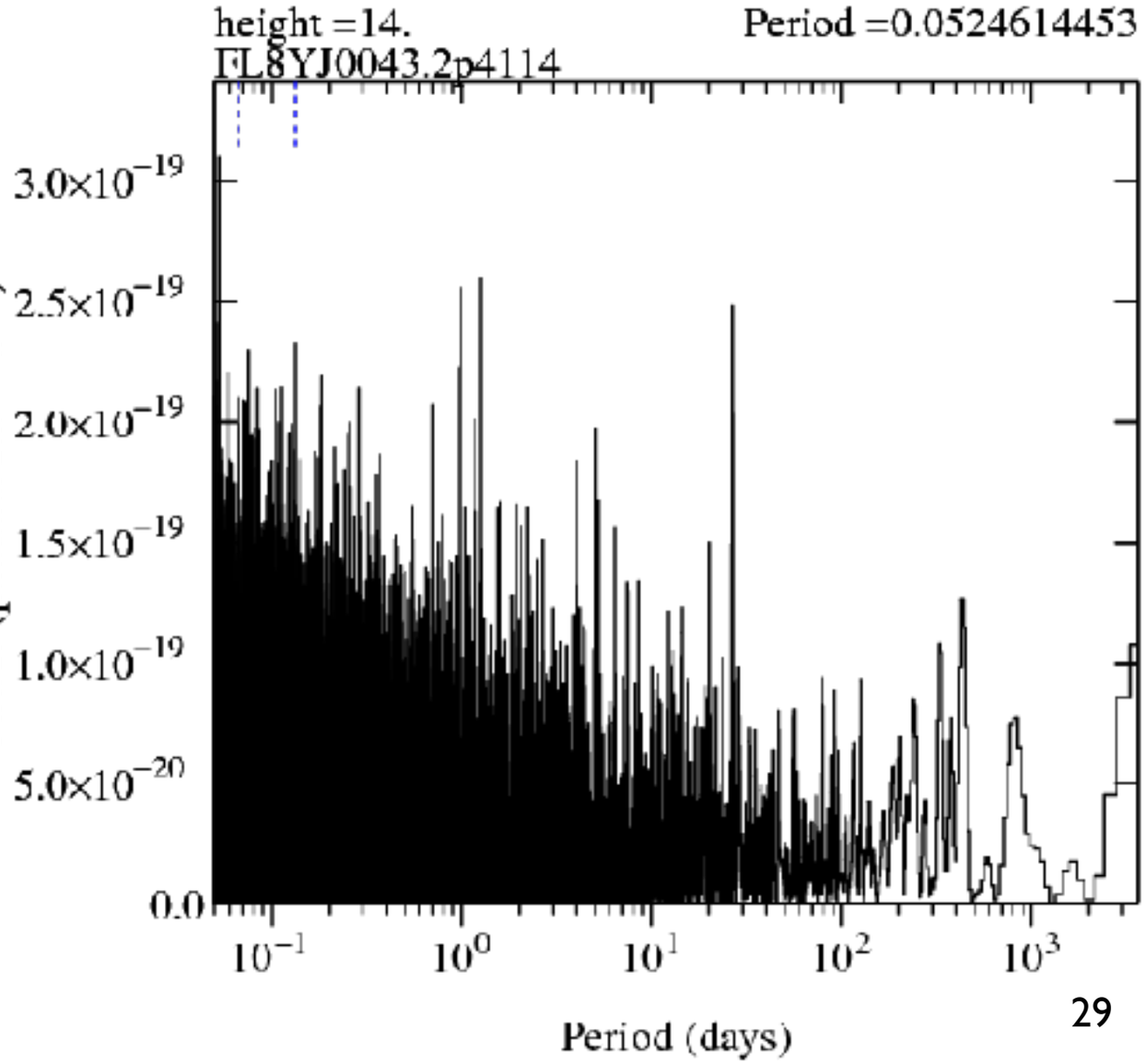
X-ray binaries in the SMC (Haberl, 2015)

- Nothing seen in SMC so far.
- As observation length increases, see long period systems? (And increase signal-to-noise.)
- Was star formation burst that made HMXBs too long ago?



Other Nearby Galaxies: Andromeda

- Andromeda galaxy (M31) is ~780 kpc. Over10x greater distance than the LMC.
- So, don't expect binary systems to be detectable…
- But ought to look, and it is in 3FGL/ FL8Y!
- Nothing seen.
- Continue to monitor power spectrum.



Galactic Binary Population & Future Prospects

- Power spectra are a powerful way to find binaries.
  - Need modulated GeV emission, with period ≪ light curve length.
- Multiwavelength observations crucial to confirm binaries, and understand astrophysics.
- We have one more binary with O star primary!
  - The third O star binary we found from LAT variability.
- Galactic population of γ-ray binaries is still unclear.
  - We are probably only scratching the top of the luminosity distribution. (Particularly Be star systems.)
- We continue to search for systems as Fermi acquires more data, and eagerly await the 4FGL catalog…