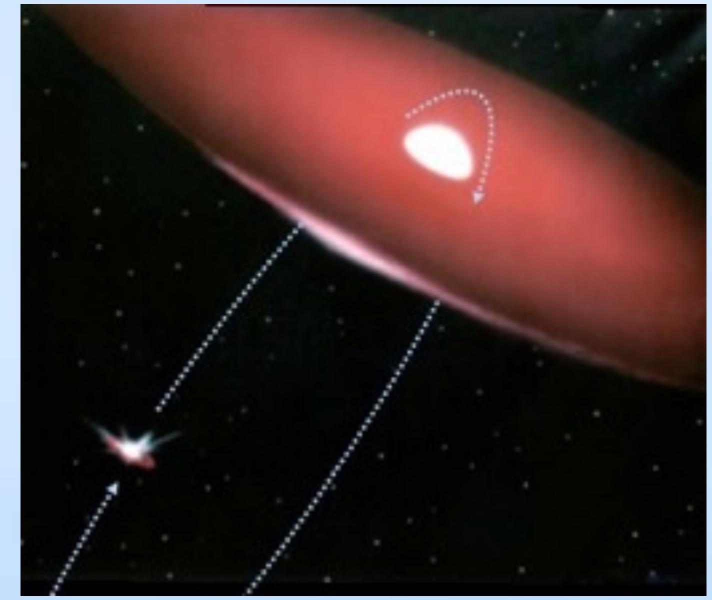
Multiwavelength Observations of 1FGL J1018.6-5856, and Hunting for More Binaries

Robin H.D. Corbet[1], **Joel B. Coley**[1], M. Alexander[2], C.C. Cheung[3], G. Dubus[4], P. Edwards[5], V. McBride[6], M.V. McSwain[2], J. Stevens[5]

1: University of Maryland, Baltimore County/NASA Goddard Space Flight Center
2: Lehigh University
3: Naval Research Laboratory
4: IPAG Grenoble
5: CSIRO Astronomy and Space Science
6: University of Cape Town

How to Make a Gamma-ray Binary?



- Two ingredients needed:
  - Power source.
  - Non-thermal mechanism. e.g. Fermi acceleration at shocks + inverse Compton scattering.
- The "conventional" mechanisms are:
  - Accreting microquasar (stellar mass black hole) with relativistic jets.
  - Pulsar <u>interacting</u> with the wind of a hot (O or B type) companion. Pulsar and stellar winds collide and form shocks.

High-Mass X-ray Binary/Gamma-ray Binary Connection?

- X-ray binaries may go through a gamma-ray binary phase early in their lives.
- A newly born neutron star is expected to be rapidly rotating and highly magnetized.
- Relativistic pulsar wind interacts with companion's wind and produces gamma rays until neutron star has spun down (e.g. Dubus 2006).
- Meurs & van den Heuvel (1989) predicted ~30 such systems in the Galaxy in this brief phase.

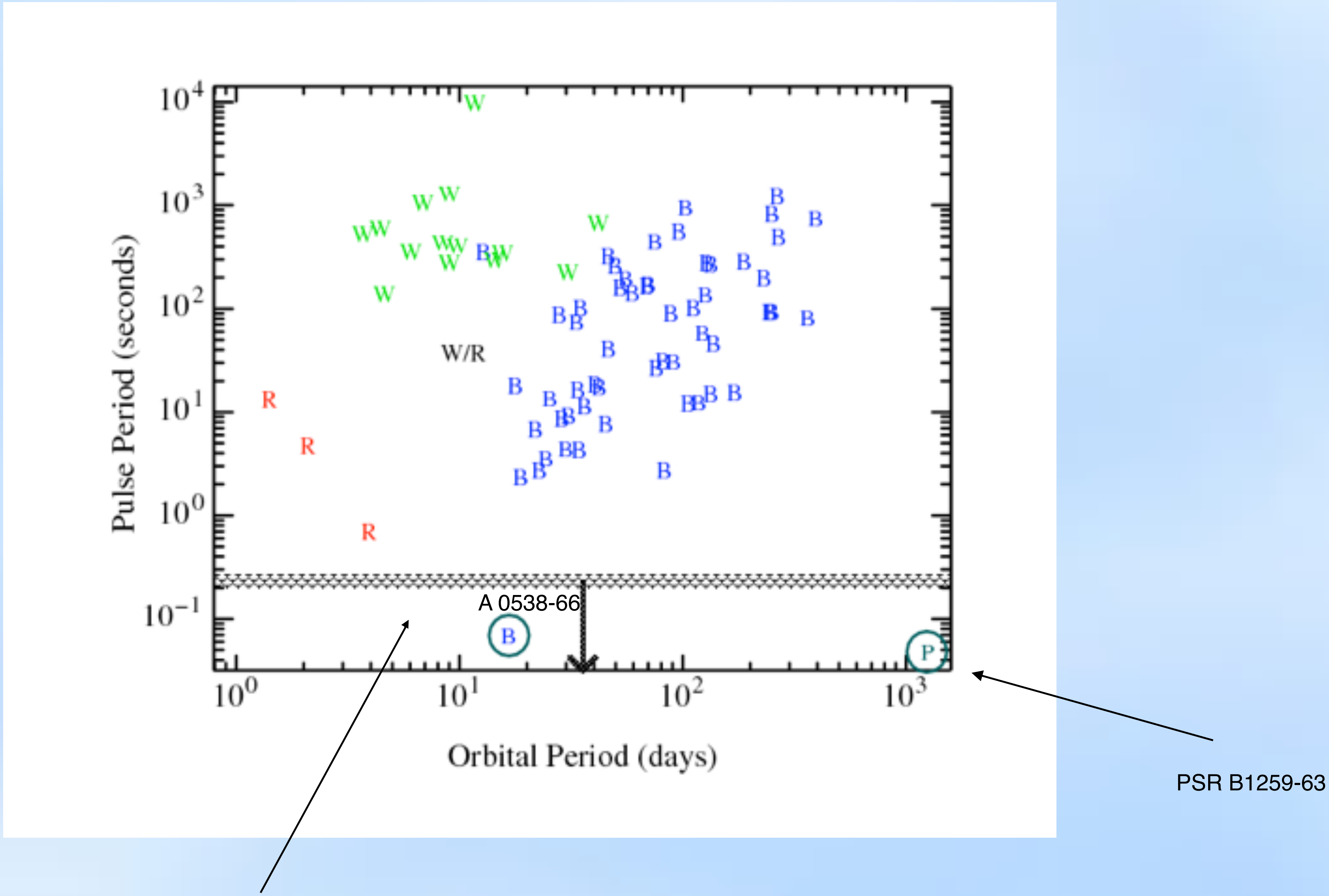
Pulsar wind pressure dominates for:

$$P_{spin} < 230\, B_{12}^{1/2}\, M_{15}^{-1/4}\, ms$$

B_{12} = magnetic field in units of 10^{12} G

M_{15} = mass transfer rate in units of 10^{15} $g\ s^{-1}$

HMXBs Born as Gamma-ray Binaries?



HMXBs containing neutron stars may begin as gamma-ray binaries with rapidly rotating neutron stars before spinning down.

The Fermi LAT

- Fermi was launched on June 11, 2008.
- The primary instrument is the LAT: 100 MeV (or lower) to 300 GeV (and higher).

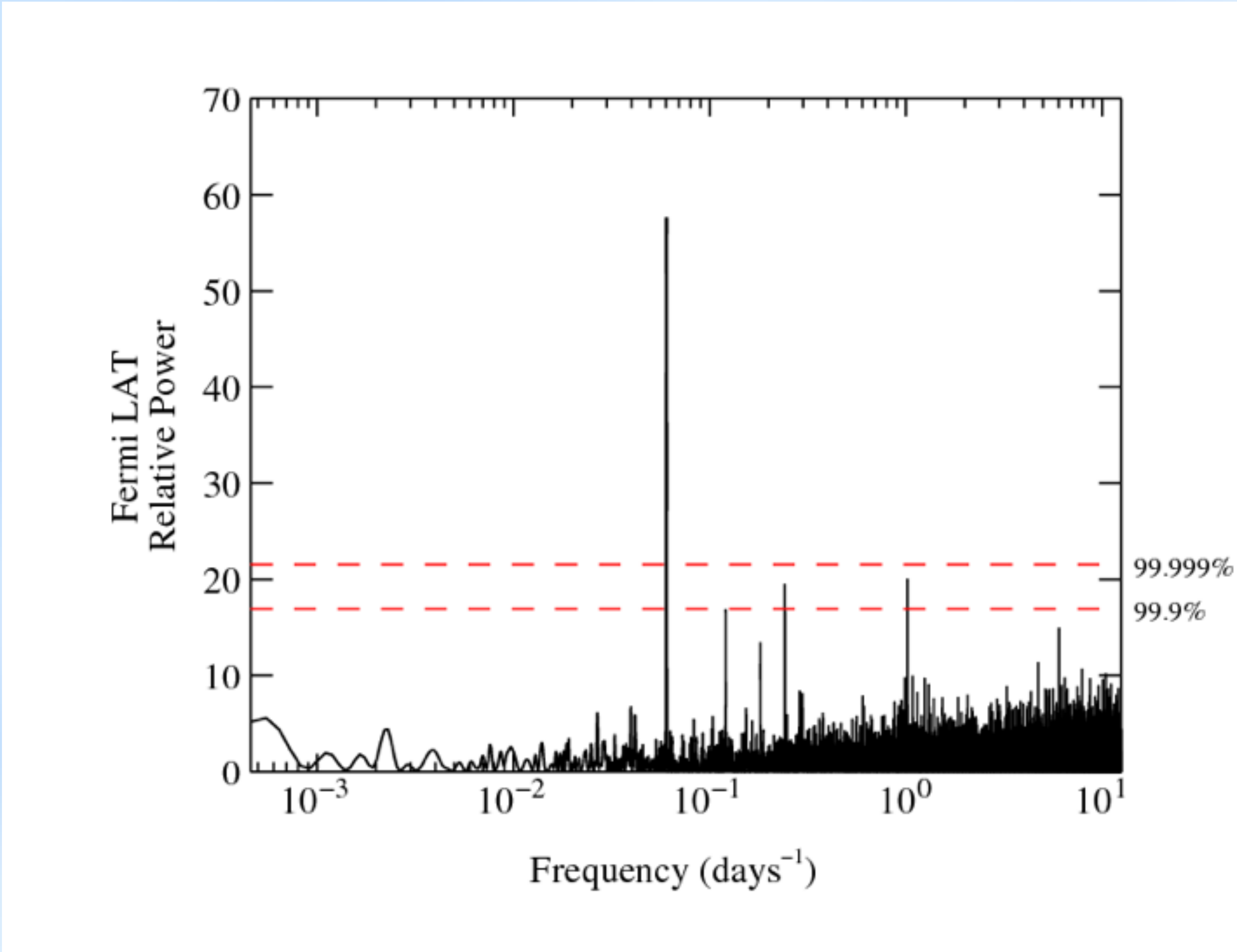
The LAT has several advantages over previous detectors:

- Instrument performance: Improved effective area, field of view, angular resolution compared to EGRET.
- Observation mode: the LAT has operated in sky survey mode most of the time. The ***entire sky is observed every ~3 hours***. Can study binaries on a wide range of timescales.

Multiwavelength Observations of 1FGL J1018.6-5856 (Coley et al., in prep)

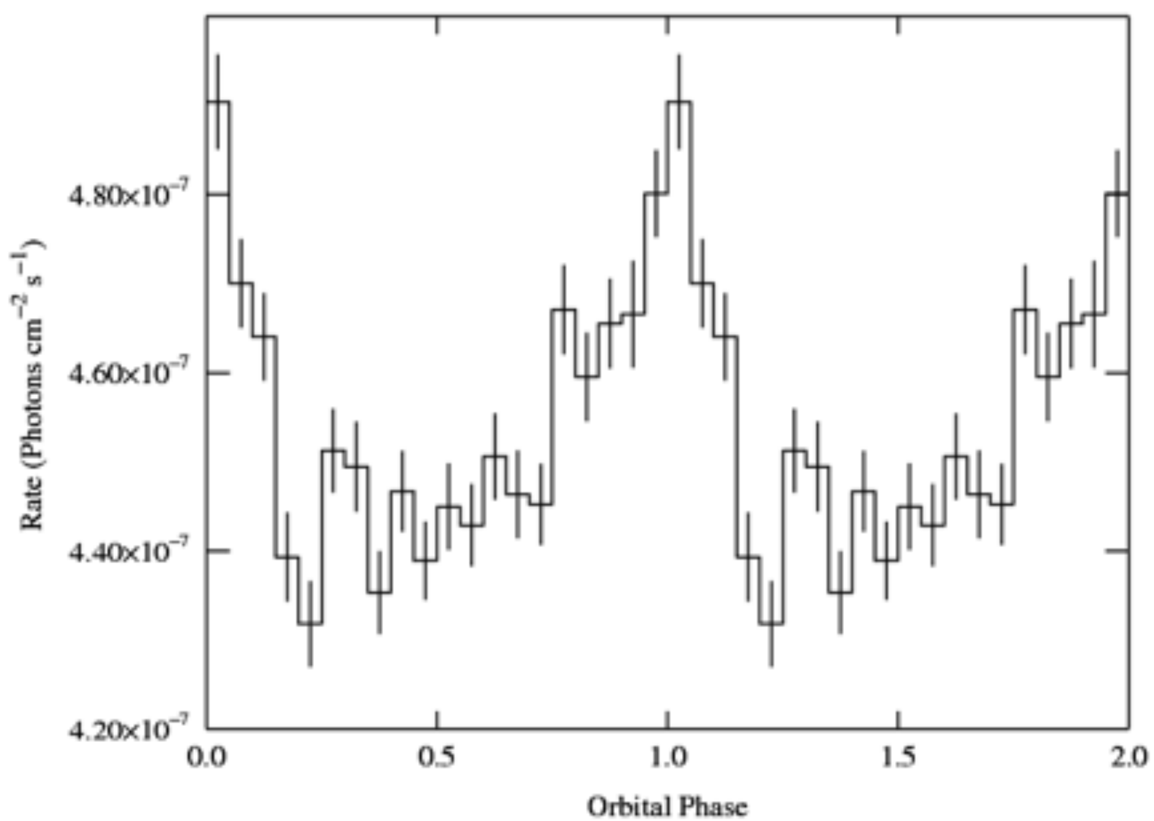
- 1FGL J1018.6-5856 was the first new gamma-ray binary found with Fermi.
- X-ray, optical, and radio counterparts were identified.
- We don't definitely know what is driving the gamma-ray emission.
    - J1018.6 may contain a rapidly rotating pulsar interacting with the wind of an O star.
    - But other explanations might be possible. e.g. magnetar model proposed for LS I + 61 303 (Torres+ 2012).
- The multi-wavelength observations were key to demonstrating that this is a gamma-ray binary.
- We now have much more extensive Fermi LAT observations (~3x), together with extended Swift X-ray data and ATCA radio observations.
- LAT analysis is also improved by use of 3FGL catalog for making models of region, and better calibrated LAT data (Pass 7 reprocessed).

Updated J1018.6 LAT Power Spectrum

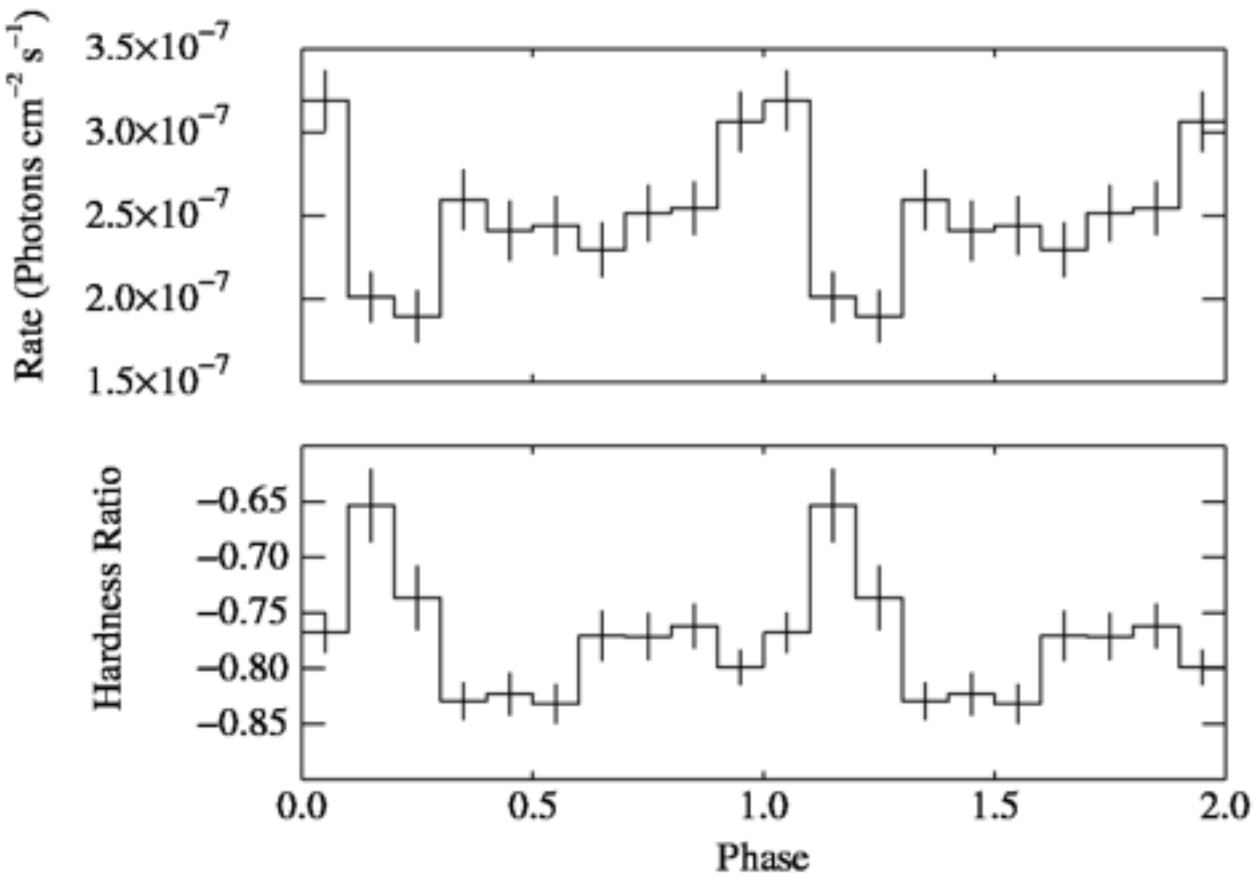


Orbital period refined to 16.531±0.006 day.
(cf. 16.58 ± 0.02 day in our discovery paper)

Updated Folded LAT Light Curve



(Aperture photometry)

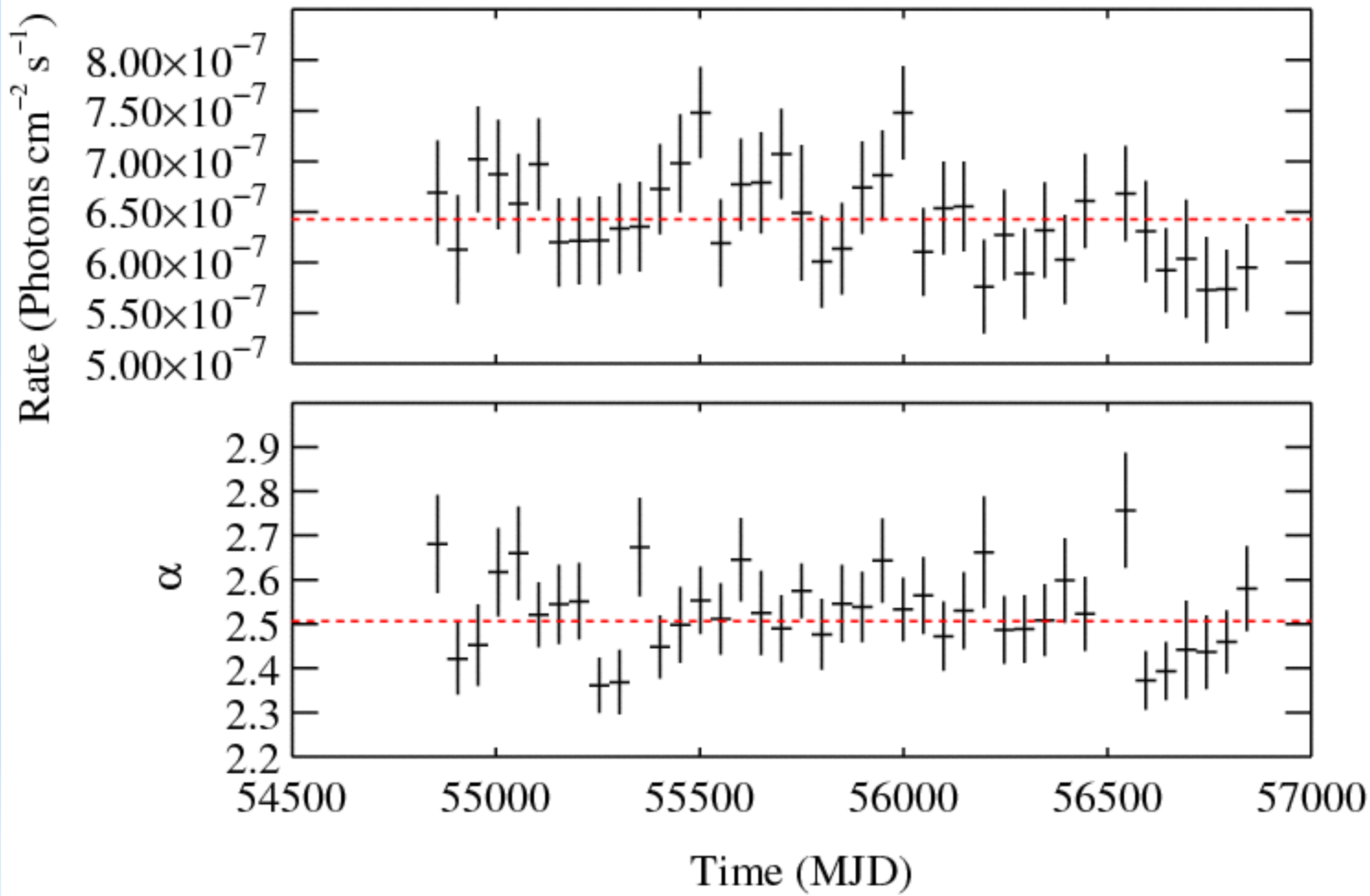


Likelihood analysis.
Soft and hard energy bands are 0.1–1 GeV, and 1– 300 GeV

Phase 0 defined as peak of folded LAT light curve.

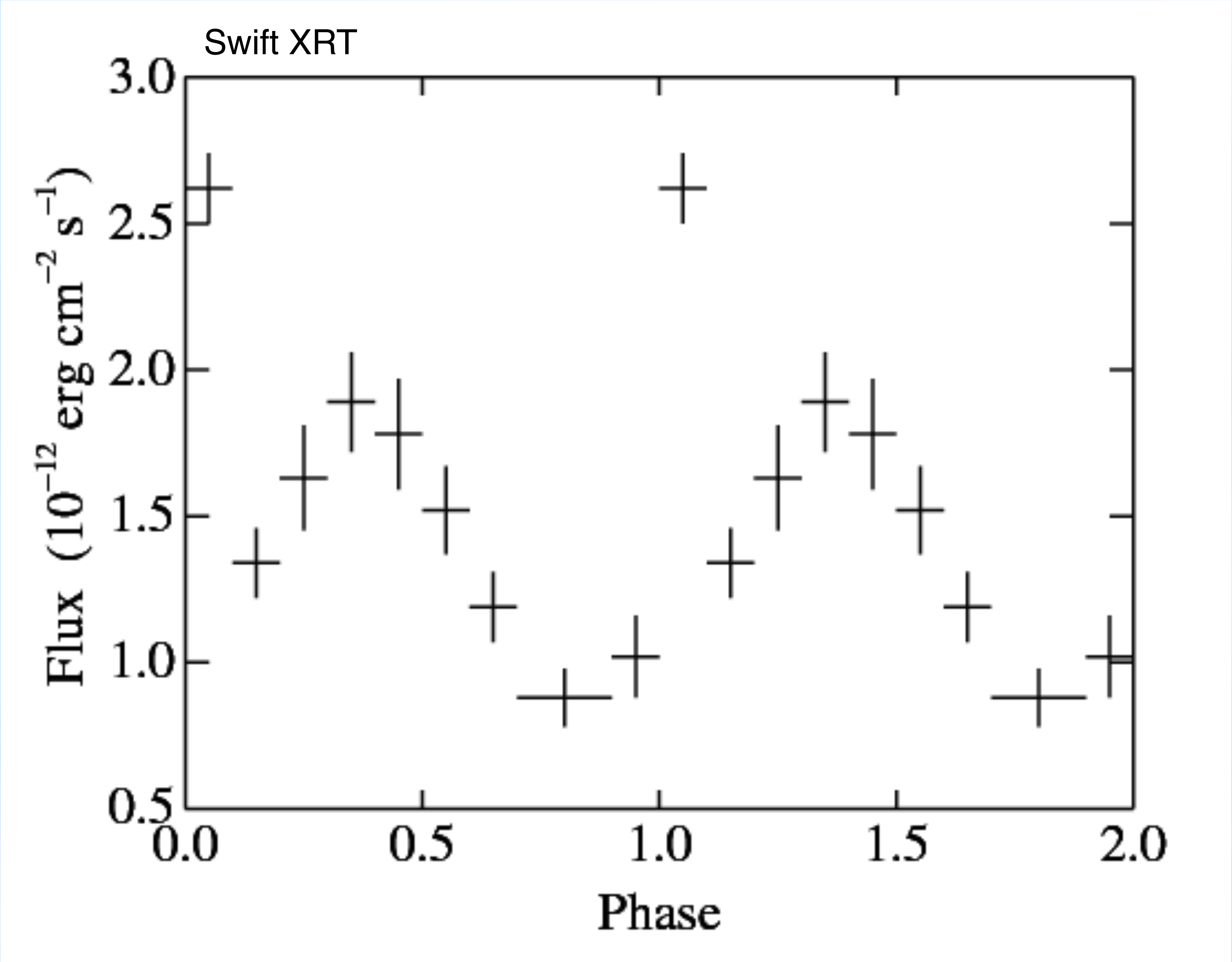
Flux changes are accompanied by spectral changes, but hardness peaks slightly after flux peak.

Long-Term LAT Light Curve of J1018.6



The long-term LAT light curve does not show any evidence for significant changes in the flux or spectrum.
Constancy is more like LS 5039 than LS I +61° 303

Updated Folded/Binned X-ray Light Curve



Confirms two component behavior - sharp peak at phase 0, together with sinusoidal component.
However, X-ray flare at phase zero does not always occur.
(See also An+ 2013, HESS collaboration 2015)

J1018.6 - Optical Monitoring

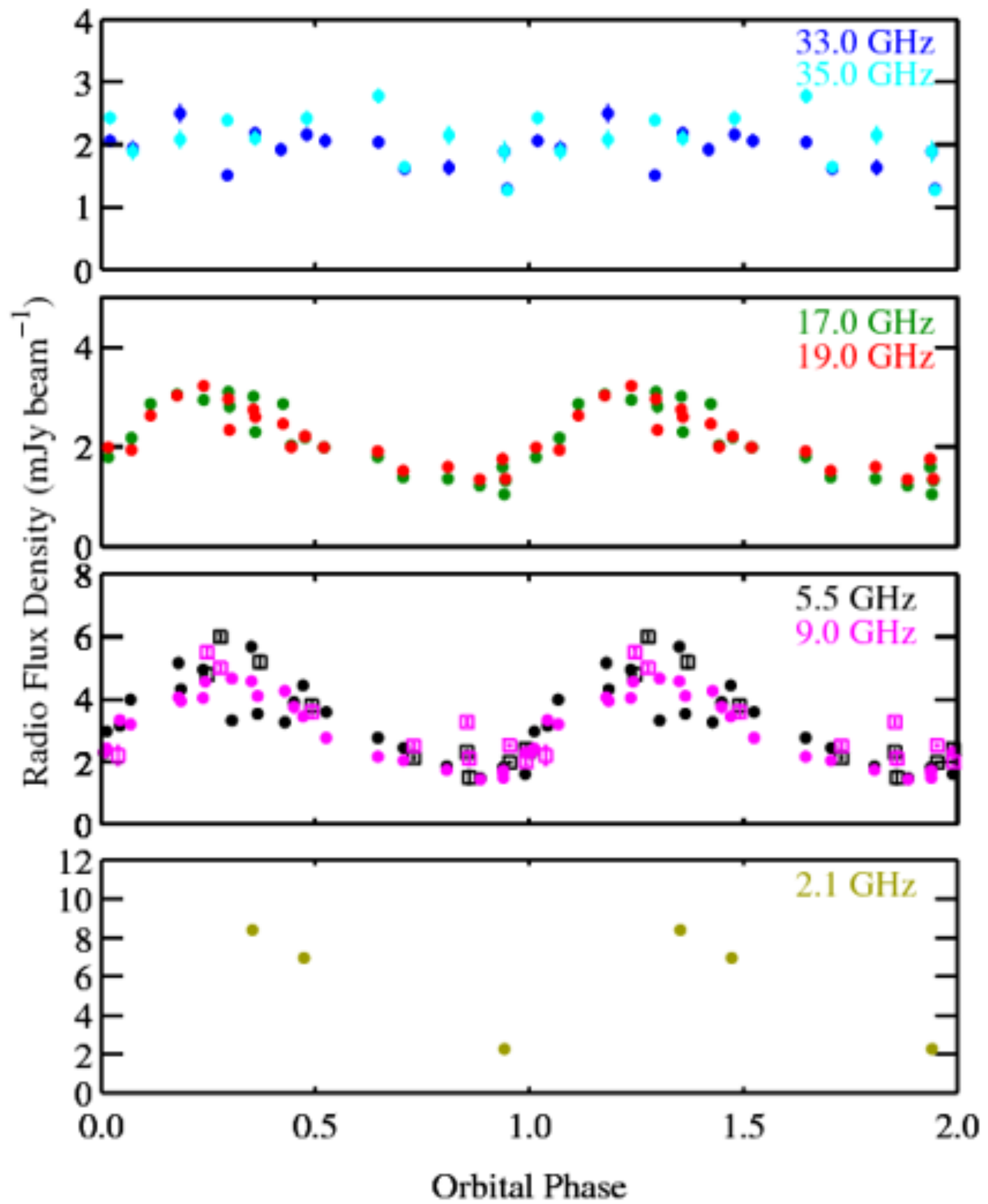
- Optical observations recently published by Waisberg & Romani (2015).
- Variable line equivalent widths implied wind contamination.
- Gave some constraints on mass of compact object and suggested not a black hole ($M < 2.2\ M_\odot$).
- We (Alexander & McSwain) are also monitoring in optical using Gemini.
- 8 spectra currently obtained, analysis in progress.

Multifrequency Folded Radio

Confirms radio flux is modulated on orbital period.

Radio amplitude dramatically decreases with increasing frequency.

Differs from LS 5039 (Marcote et al. 2015 - presentation later today).



Summary of J1018.6

- J1018.6 is similar to, but different from LS 5039.
- Similarities:
  - The primary stars are almost identical spectral type.
  - No obvious long term modulation in either source.
  - Modulation of gamma-ray spectrum on orbital period in both sources. But different behavior.
    - J1018.6 initially appeared to be harder when brightest, but with additional data possible phase lag seen.
- Differences
  - More complicated X-ray behavior in J1018.6
  - Radio modulation on orbital period in J1018.6

The Hunt for New Binaries

•Known gamma-ray binaries show modulation on their orbital periods.

•Hope to find new binaries from the detection of periodic variability. (J1018.6 was found from LAT power spectrum.)

•Even with the improved sensitivity of the LAT, count rates are still low.

- A “bright” source may only give ~20 photons/day.

•Need to have highest possible signal-to-noise light curves and to make sensitive period searches.

Optimizing Light Curves

- There are two basic ways to make LAT light curves:
  - Maximum likelihood fitting.
  - Aperture photometry.
- Likelihood fitting is slow, and is difficult/impossible if few/zero photons are present in a time bin.
- Aperture photometry is not optimal. Ignores source photons outside the aperture, includes background inside the aperture.
  - Problem compounded by strong LAT PSF energy dependence.
- Instead, use a "weighted photon/infinite aperture" technique. Sum the probabilities that each photon came from source of interest.
  - Can give a significant increase of Signal/Noise.

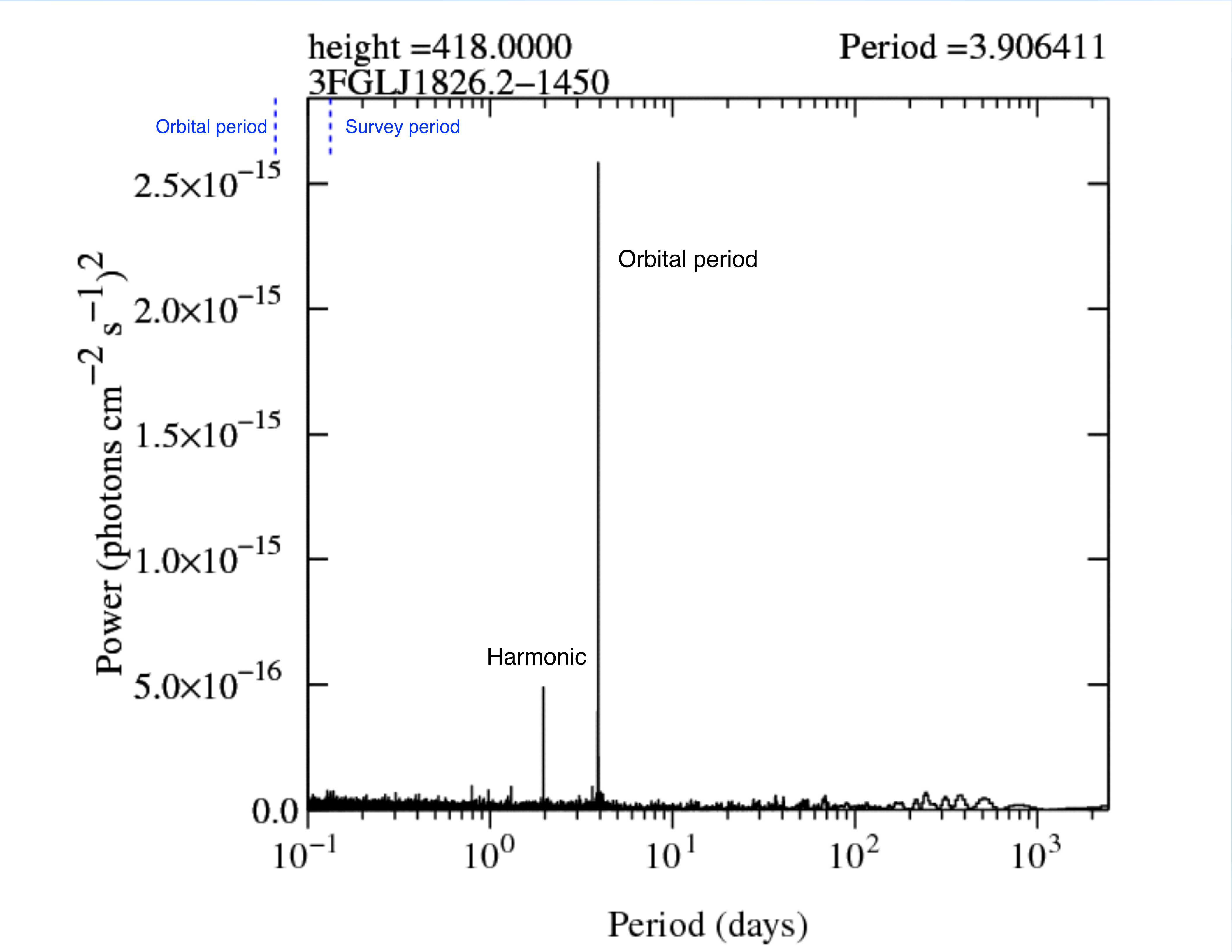
Optimizing Power Spectra

- To search for periodic modulation, use power spectra.
- We want ability to search for short orbital periods, like Cyg X-3's 4.8 hour period.
    - Short time bins are needed (e.g. < 1ks). Shorter than the LAT sky survey period of ~3 hours.
    - This gives big variations in exposure.
    - Use "exposure weighting" of each data point's contribution to the power spectrum.

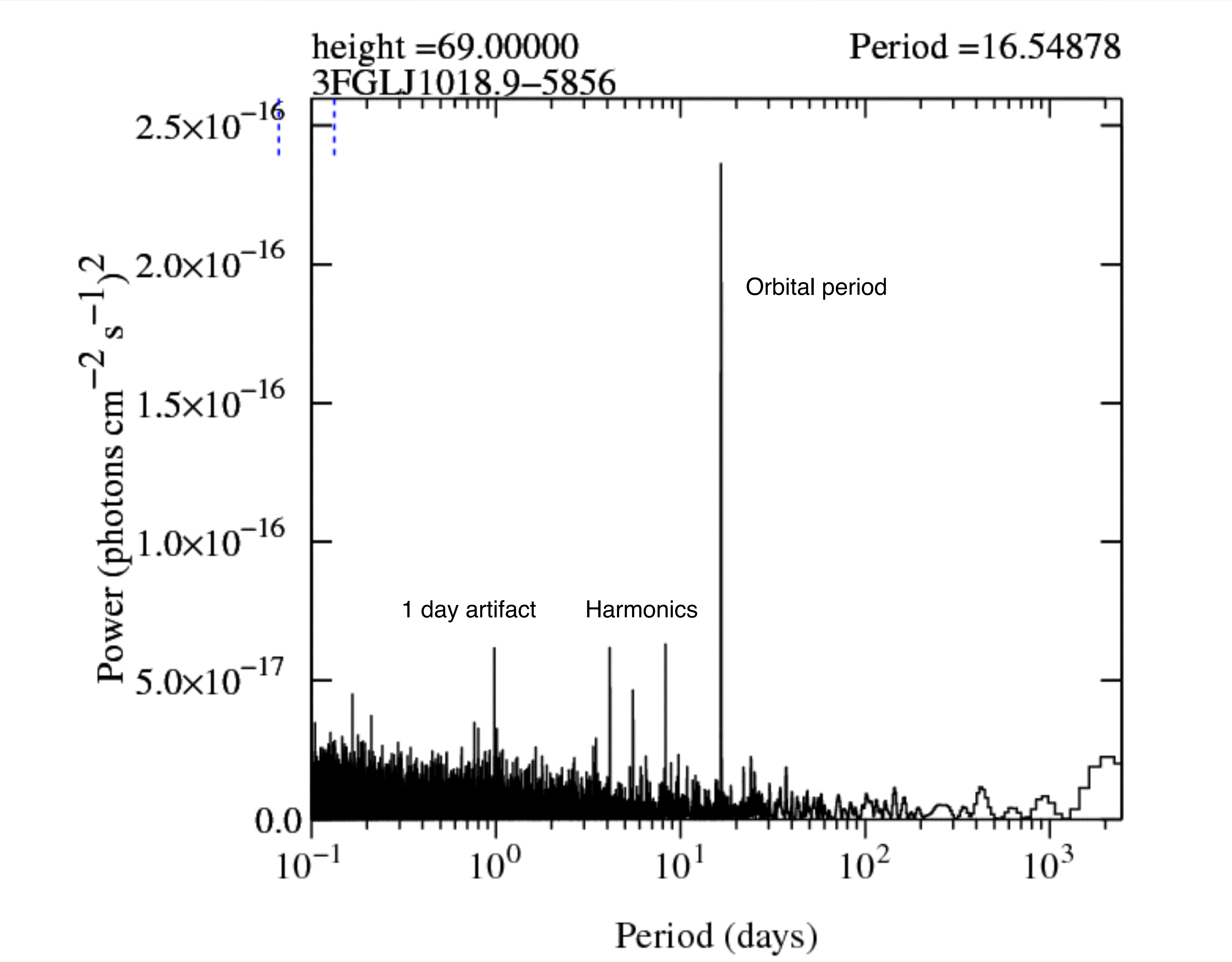
Searching for Binaries in the 3FGL Catalog

- The LAT team released the third LAT catalog in January 2015.
- Contains 3033 sources, many are still unidentified.
- We have made light curves and power spectra for all sources:
    - Use "probability" photometry - sum probability that photon came from source of interest. (Use 3FGL to create models to calculate this.)
    - 200s time bins. Allows search for short orbital periods (< 1 hour).
    - 100 MeV - 300 GeV with loose data selection criteria to maximize photons.
    - Calculate exposure-weighted power spectra for all sources.
    - Search period range from 0.1 days to length of light curve (2450 days here) and update weekly (shown here).
    - Less frequently do analyses for periods down to 0.025 days (0.6 hours).

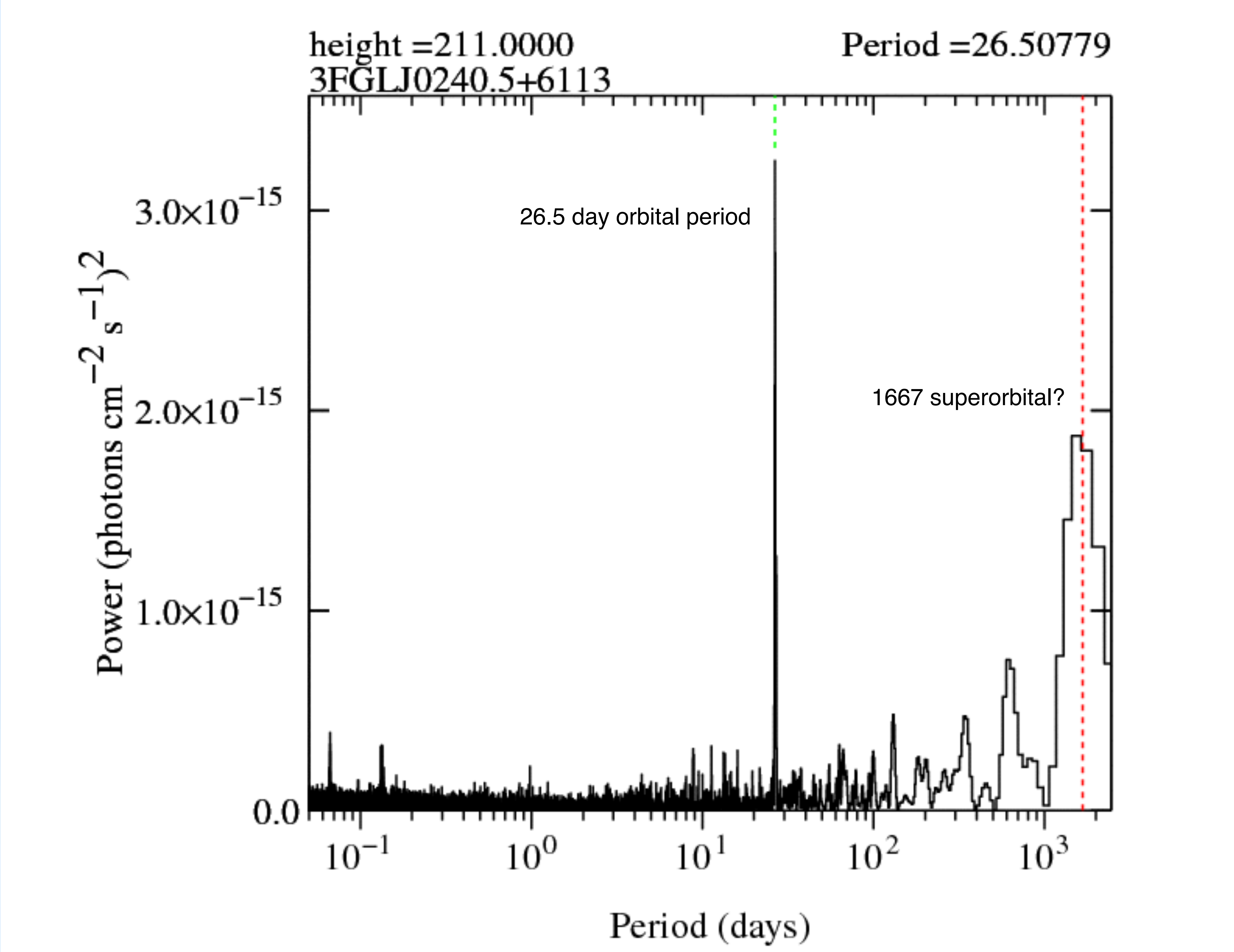
Examples of 3FGL Power Spectra
LS 5039



1FGL J1018.6-5856

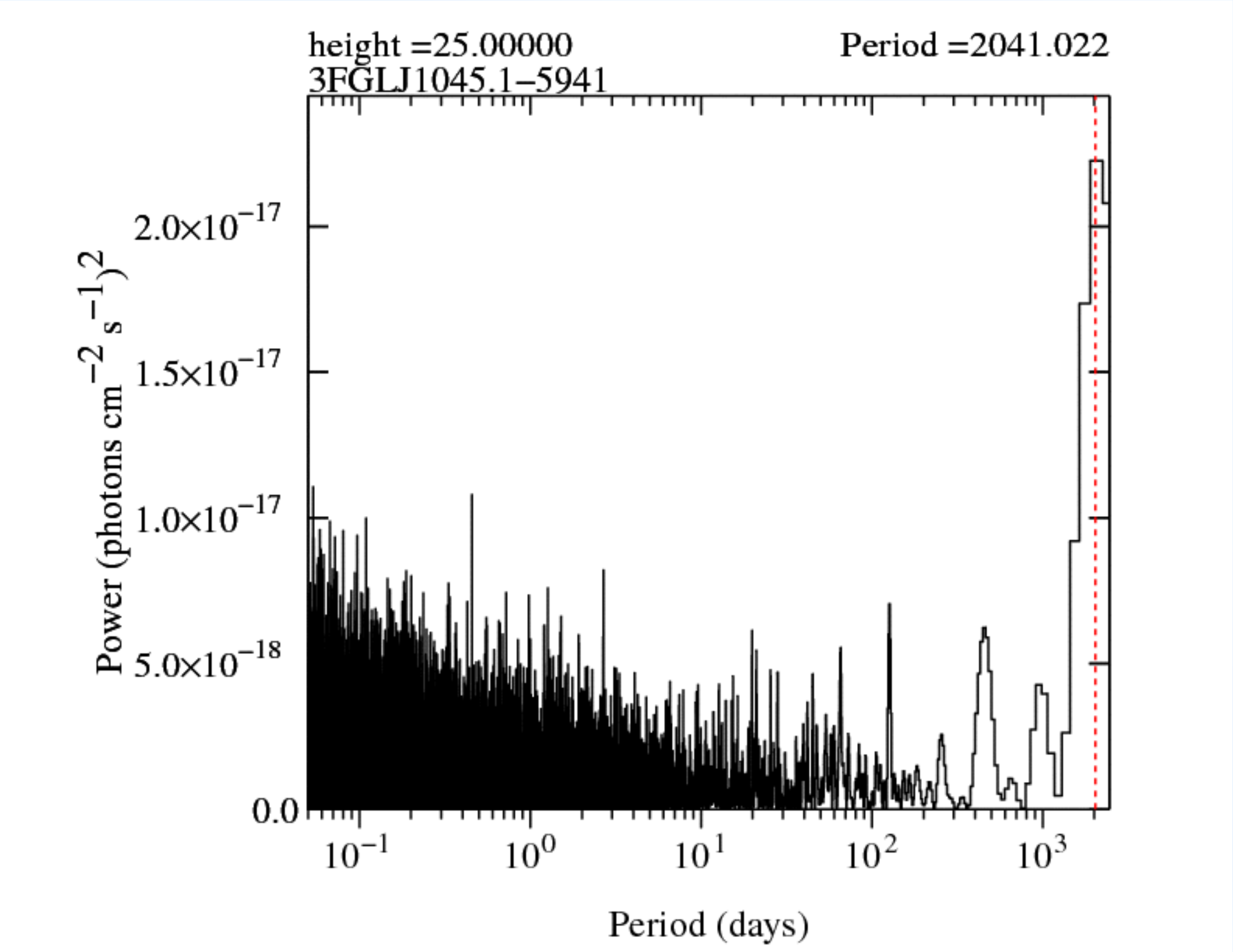


LS I +61° 303



~1.5 superorbital cycles now covered

3FGL J1045.1-5941 = eta Car??

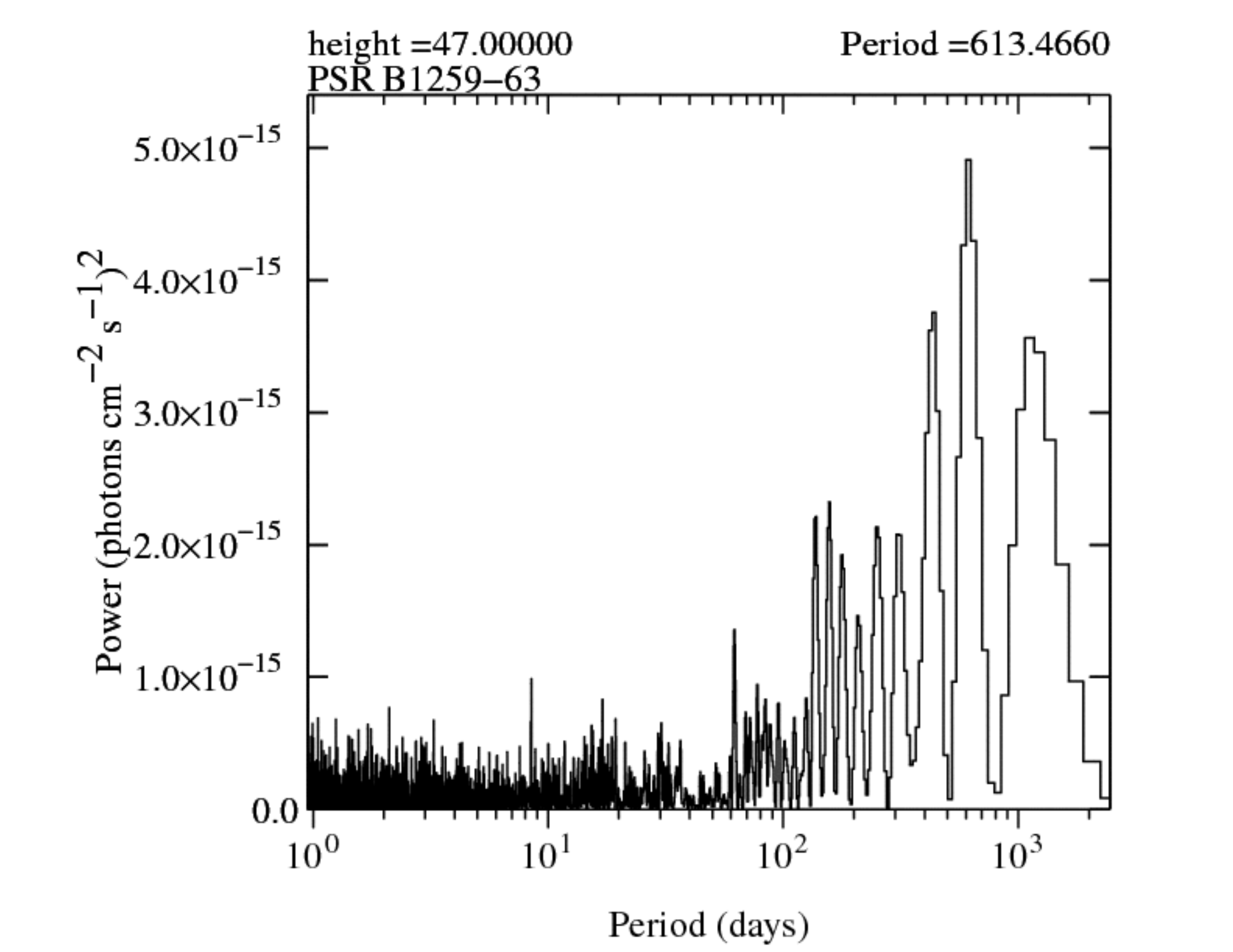


eta Car orbital period = 2023 days; length of light curve = 2450 days (1.2 cycles)

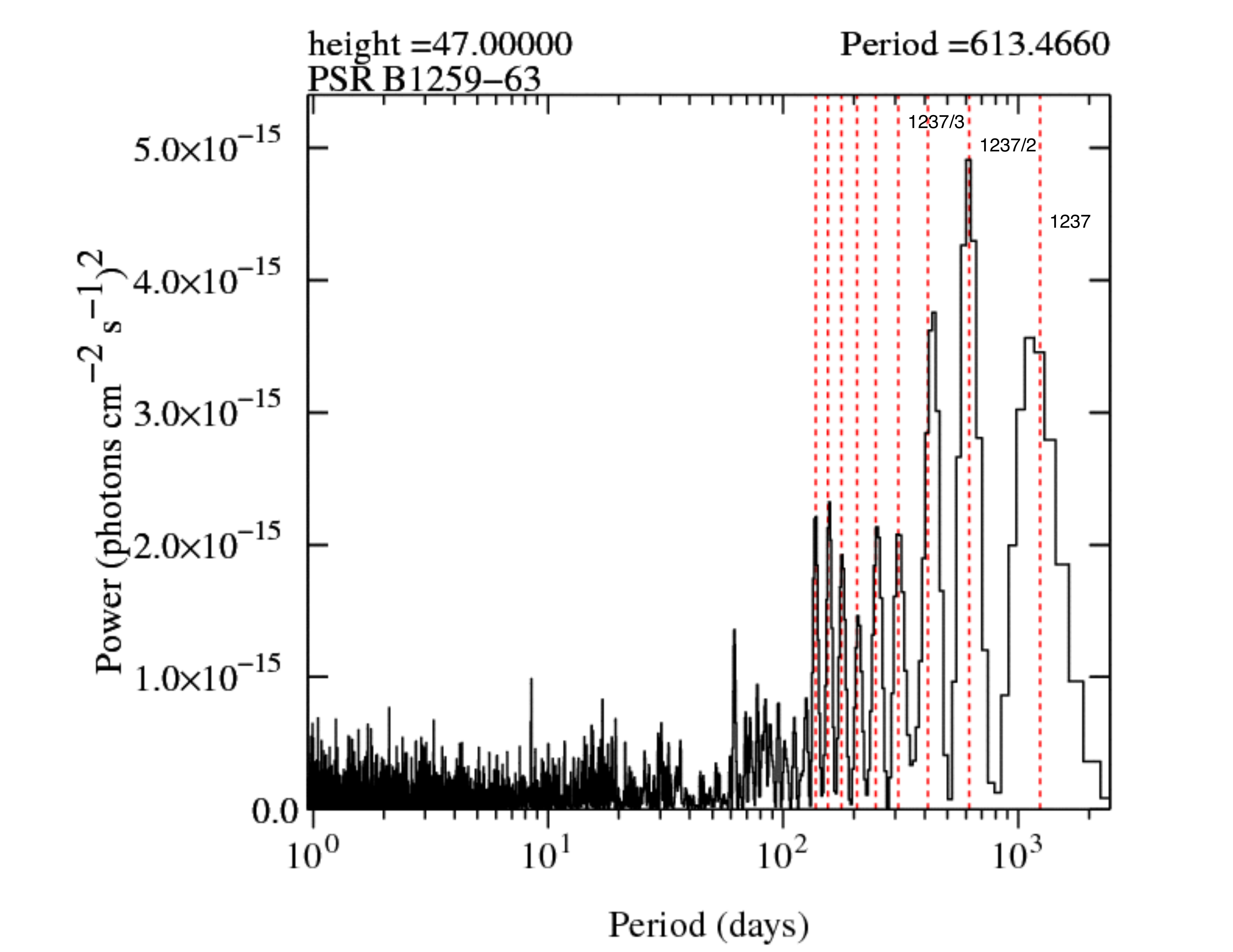
Known Binaries **not** in the 3FGL

- Because of the criteria used for LAT catalog source selection two important binaries are not included in the 3FGL:
  - Cygnus X-3
  - PSR B1259-63
- In both cases this is because gamma-ray emission is not persistent and average flux low.
- Cyg X-3 is only gamma-ray active during brief soft X-ray states. (It was in 2FGL catalog.)
- PSR B1259-63 is only detected in gamma-rays around periastron in its 1237 day orbit.

PSR B1259-63 (i)

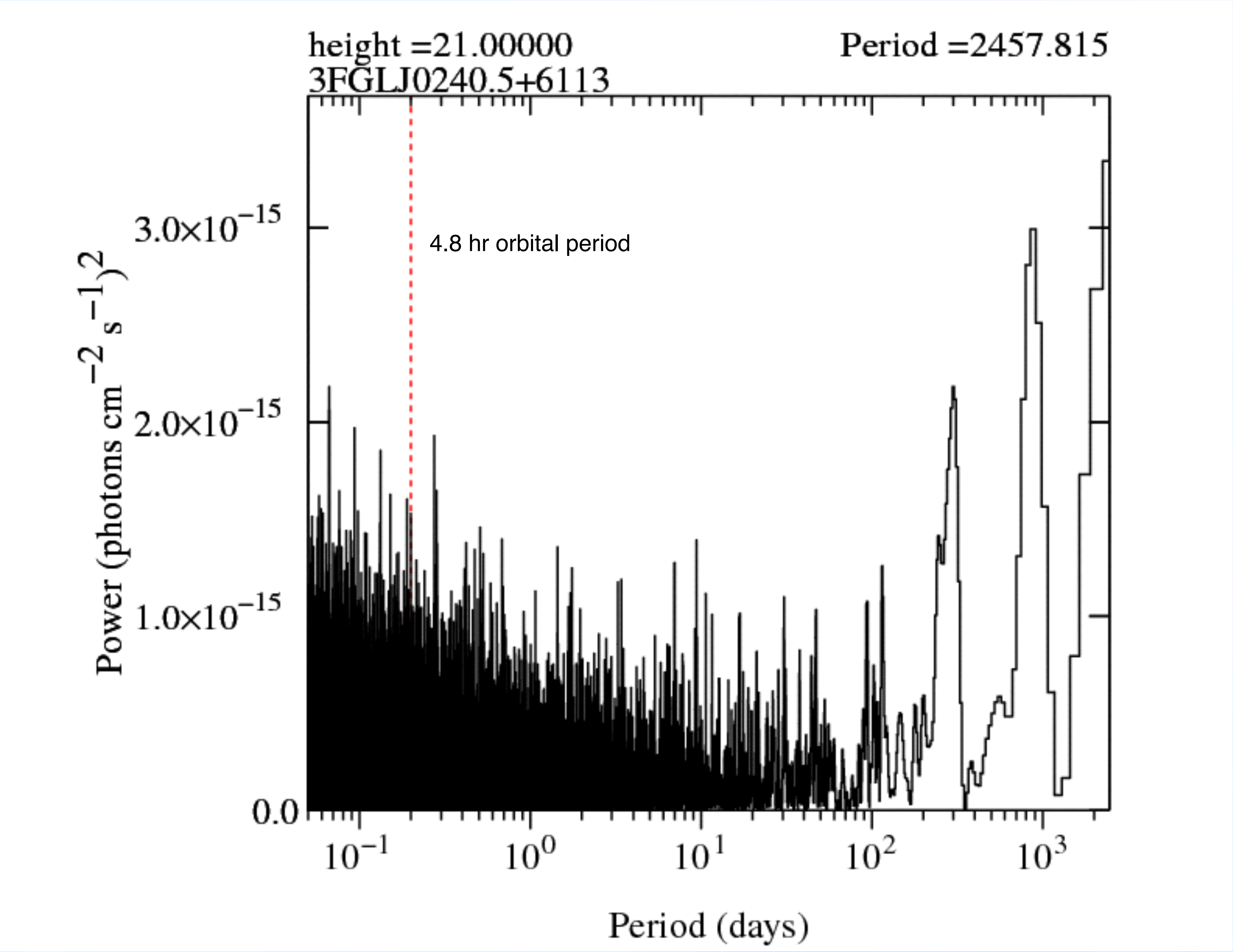


PSR B1259-63 (ii)



All low-frequency peaks in power spectrum are harmonics of 1237 day orbital period.
~2 binary cycles now covered.

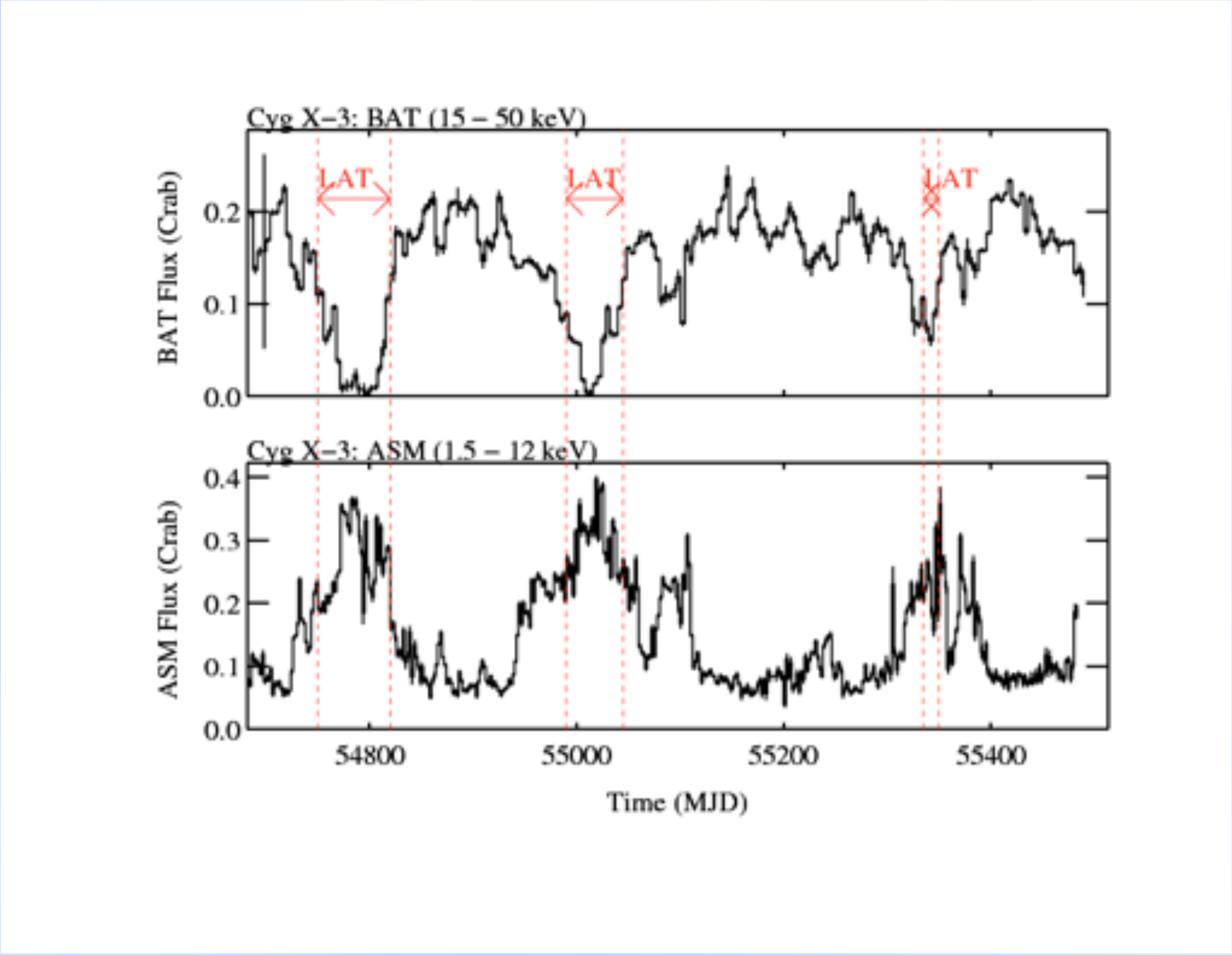
Cygnus X-3



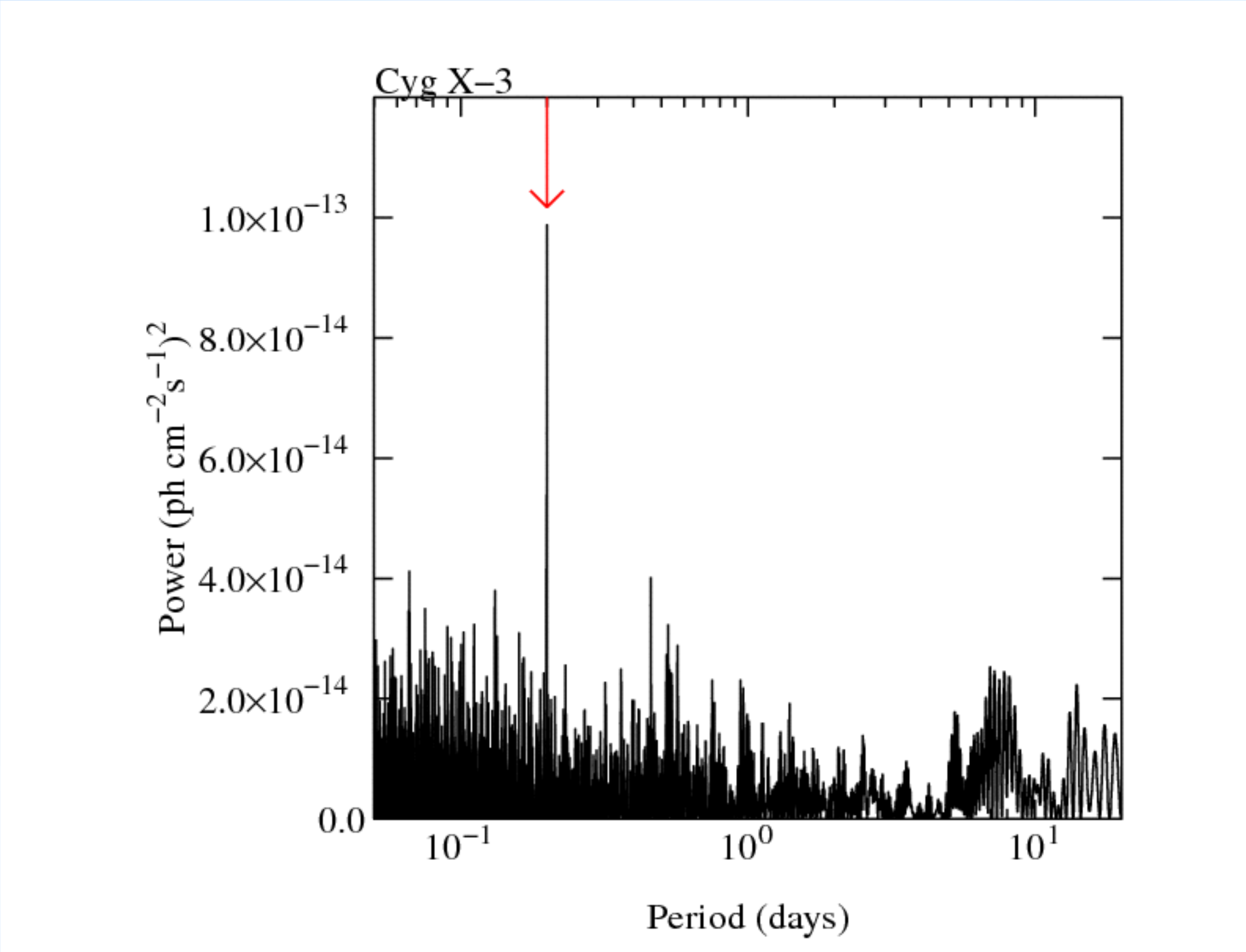
In power spectrum of total light curve only long period variability is seen.
To detect orbital modulation need to select active periods.

Cyg X-3 Intermittent Activity

- Cygnus X-3. Microquasar, Wolf-Rayet primary + black hole (??). 4.8 hr period.
- Transient: emits gamma-rays for brief periods of time during soft X-ray states.



Cyg X-3 LAT Power Spectrum of Active Time Ranges Only

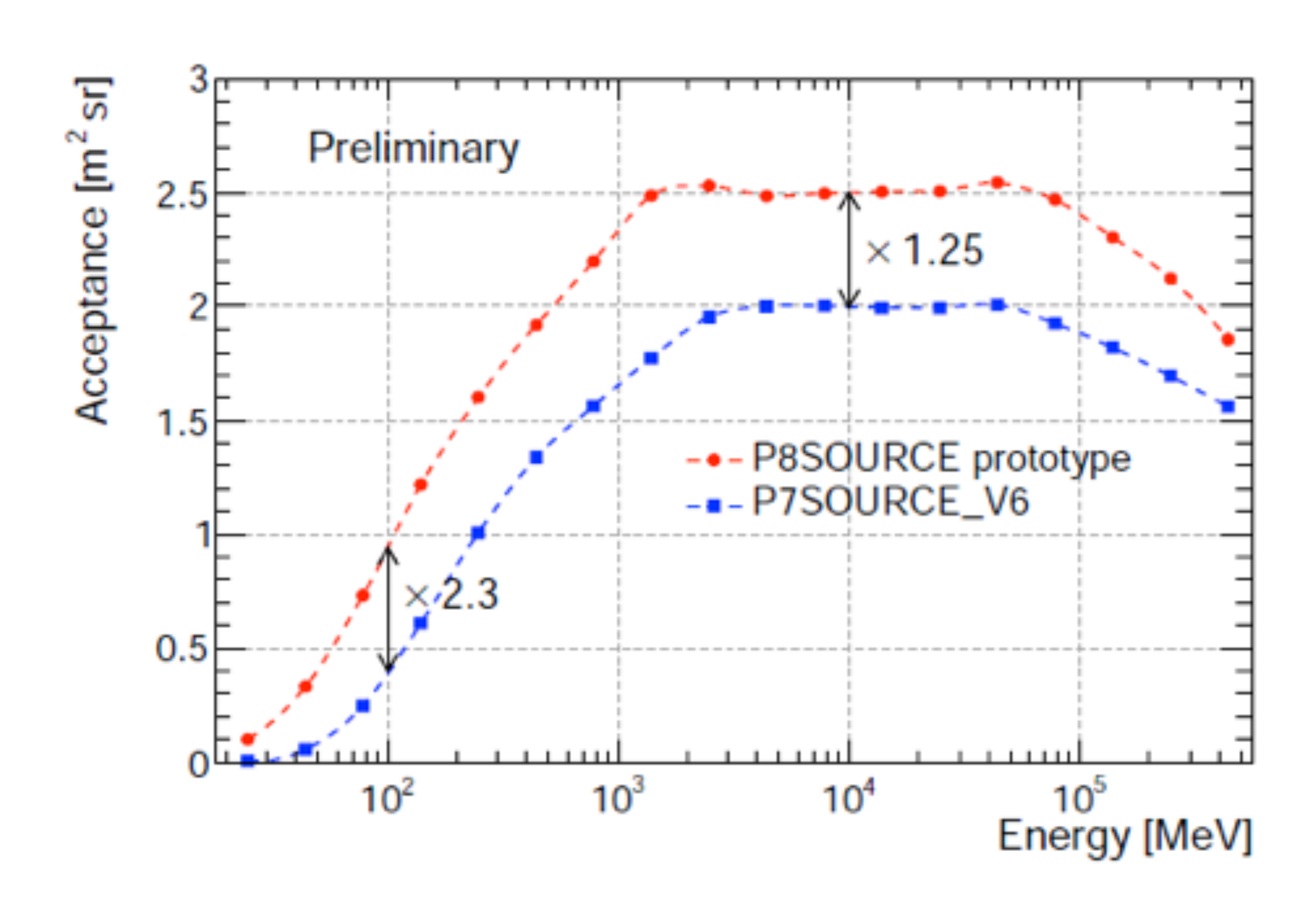


Fundamental Revisions to LAT Data Extraction

- Extraction of gamma-ray information from the LAT is complicated.
  - Gamma rays create electron-positron pairs in the LAT.
  - Electrons & positrons create tracks, and release their energy in the LAT tracker and calorimeter.
  - The tracker and calorimeter information must then be used to reconstruct the energy and direction of the gamma ray.
- Must distinguish between low gamma-ray rate, and higher rate charged particle background.
- The LAT team has made fundamental changes to processing with "Pass 8"...

The Promise of Fermi LAT Pass 8

- Pass 8 is radical revision. Improvements include:
  - Significant reduction in background contamination.
  - Increased effective area.
  - Improved point spread function.



Atwood et al. (2013)

4th Fermi Symposium : Monterey, CA : 28 Oct-2 Nov 2012

Pass 8 data and software are hoped to be released soon.

Fermi Science Support Center is supporting testing and updating of documentation for Pass 8.

Indications are that binary signals in power spectra ***do*** *significantly increase with Pass 8 as hoped.*

Summary

- Population of pre-HMXB GRBis predicted, but few known.
- Extensive multi-wavelength observations of 1FGL J1018.6-5856 permit detailed investigation of system parameters.
- We have made light curves and power spectra for all 3033 3FGL sources using techniques to boost signal-to-noise. (30 day resolution light curves available on FSSC web site.)
- Pass 8 LAT data and software available soon. Boosts sensitivity of period searches and studies of known systems.
- Gamma-ray binaries are not necessarily in catalogs, must consider X-ray binaries and other types of objects.
- Multiwavelength data important for known systems and confirming candidates.
- Long-term variability studies increasingly possible.