Multi-Wavelength Observations of Known, and Searches for New, Gamma-ray Binaries

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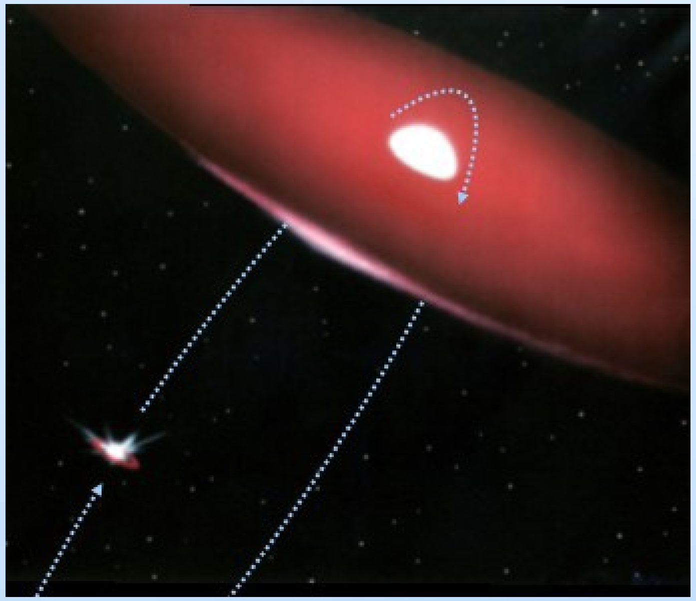
How to Make a Gamma-ray Binary?



- 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 interacting 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.

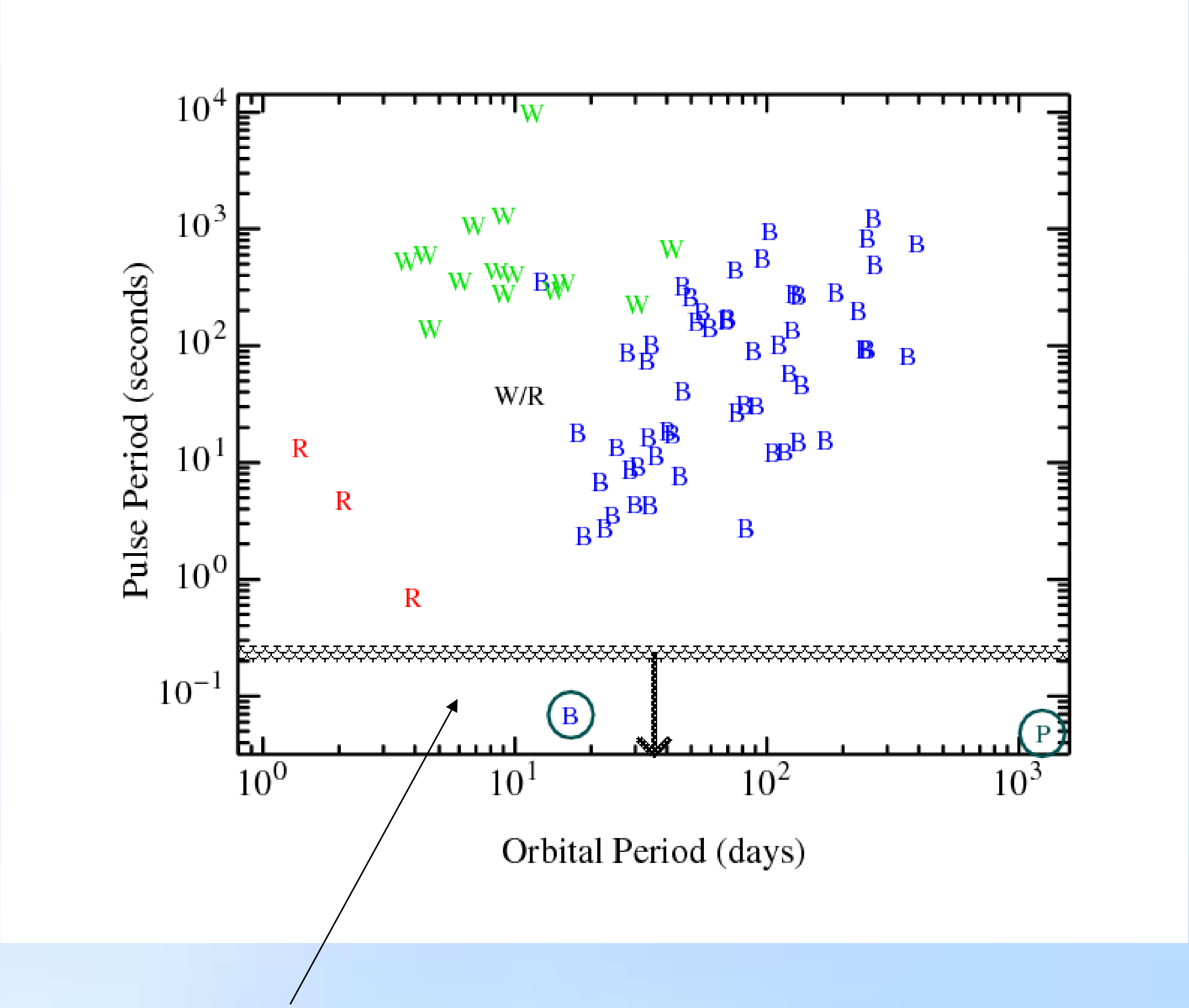
Pulsar wind pressure dominates for:

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

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

$\dot{M}_{15}$ = 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 furiously 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 operates in sky survey mode almost all the time. The ***entire sky is observed every ~3 hours***. Can study binaries on a wide range of timescales.

Few Gamma-ray Binaries are Known

- The Fermi LAT initially only detected:
  - Cygnus X-3: transient *microquasar*, Wolf-Rayet (+ black hole?). 4.8 hr orbital period.
  - LS I +61 303: Be star, *suspected pulsar companion*. 26.5 day orbital period.
  - PSR B1259-63: Be star, *definite 48ms pulsar companion*. 3.4 year orbital period.
  - LS 5039: O6.5V((f)) star, *suspected pulsar companion*. 3.9 day orbital period.
- These were all suspected, gamma-ray binaries - even before Fermi.
- (Cyg X-1 & HESS J0632+057 not detected with LAT, Cyg X-1 reportedly detected with AGILE)

Either the mechanisms that make gamma-ray binaries occur infrequently, or else more systems (as predicted) remain to be discovered!

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.
- 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.

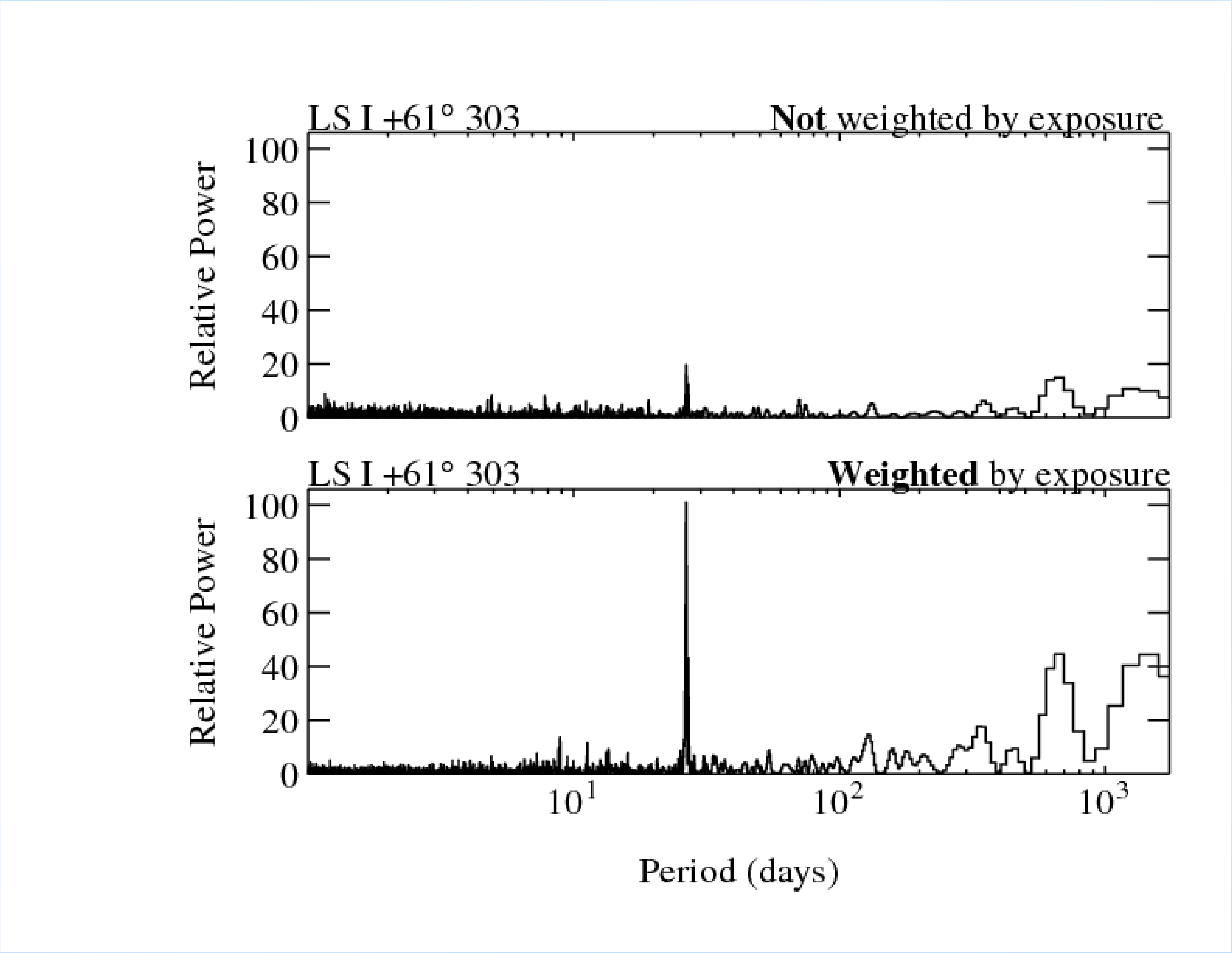
Optimizing Light Curves

- 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

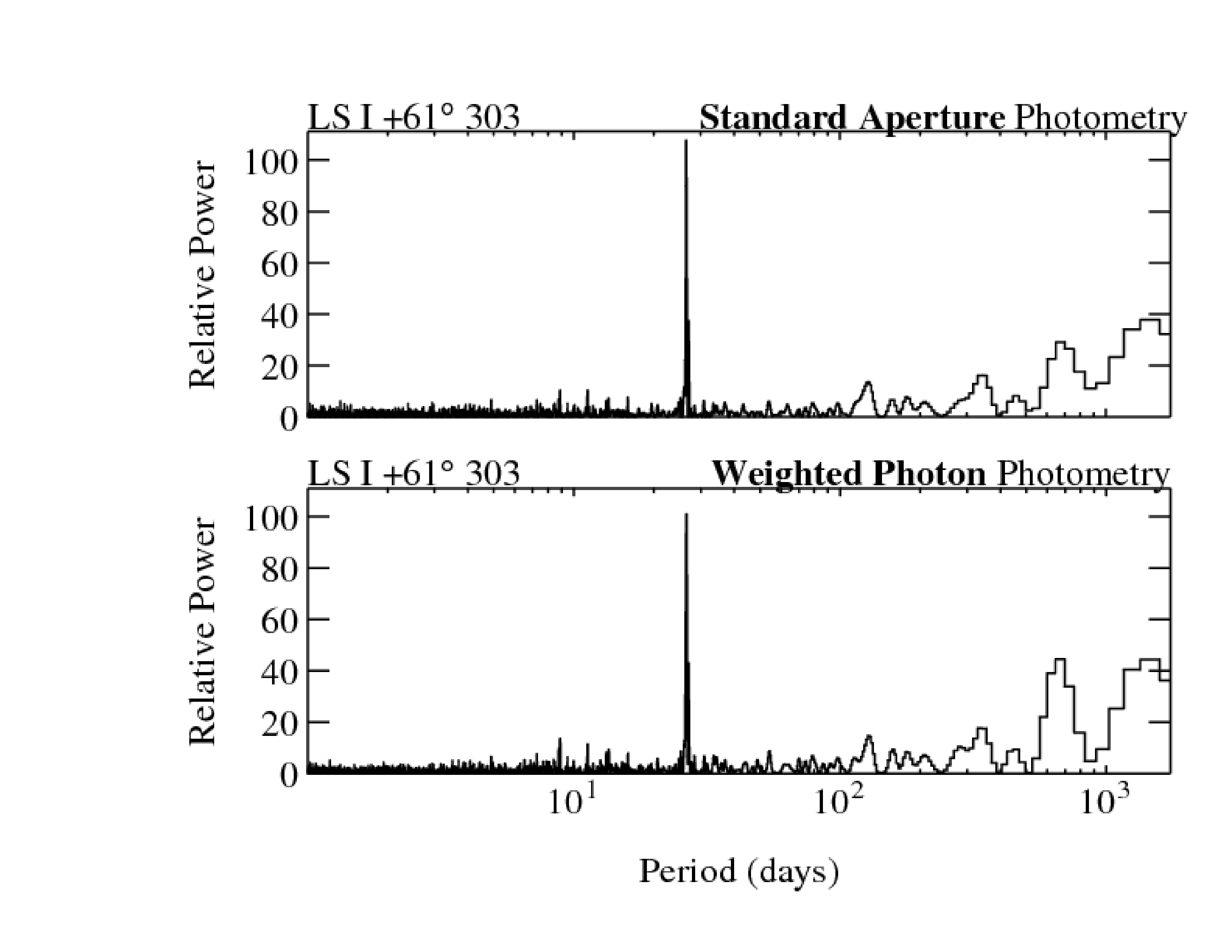
- To search for periodic modulation, use power spectra.
- We want ability to search for short orbital periods, like Cyg X-3's 4.8 hour period.
    - Short time bins are needed (e.g. < 1ks). Shorter than the LAT sky survey period of ~3 hours.
    - This gives big variations in exposure.
    - Use "exposure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

Weighting Power Spectrum Benefit



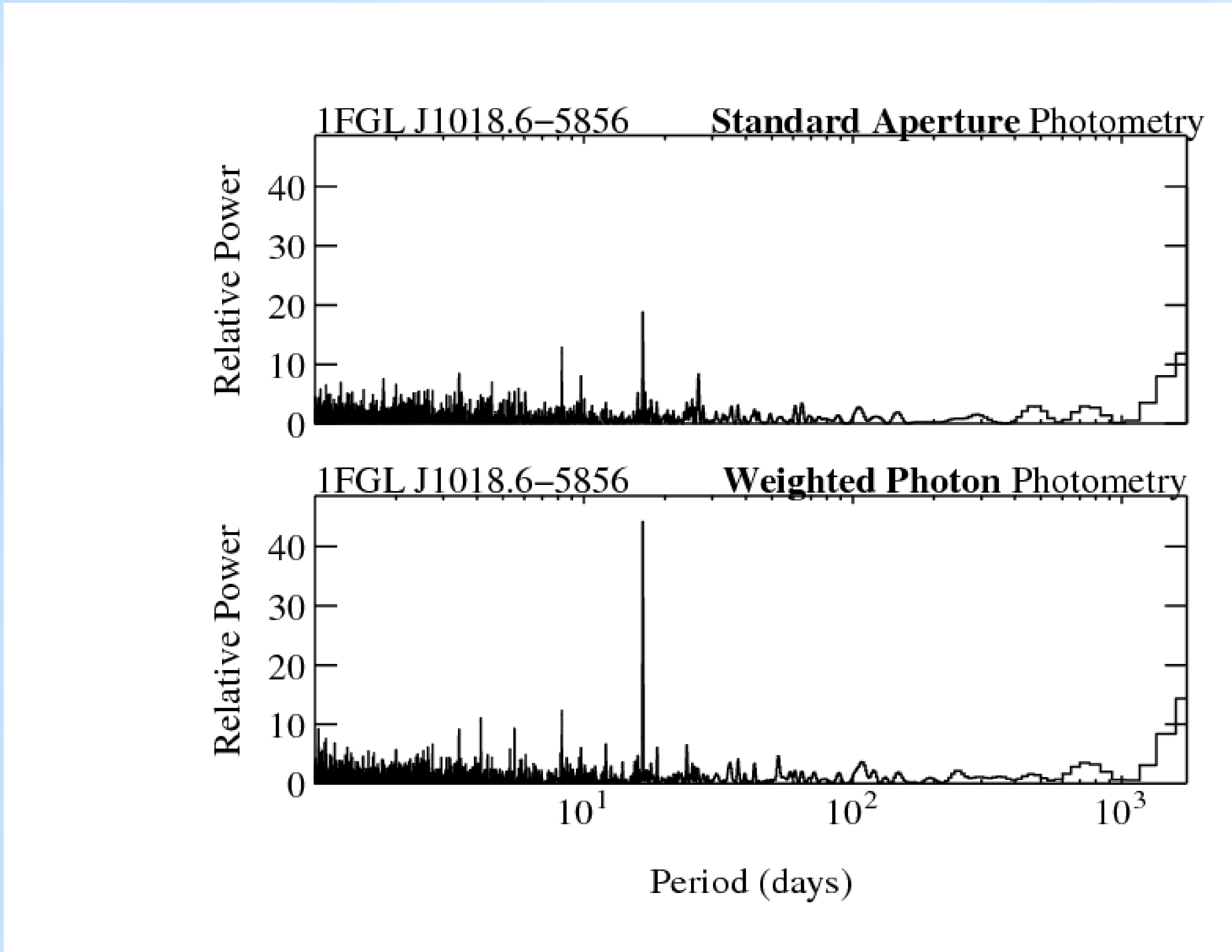
Exposure-weighting of power spectra is crucial for short (600s) time bins. Benefits reduced for longer time bins (e.g. 1 day) with less exposure variability.

Probability Weighted Photometry: Bright Source



For very bright sources there is not necessarily any benefit using probability weighted photometry rather than regular aperture photometry.

Probability Weighted Photometry: Fainter Source

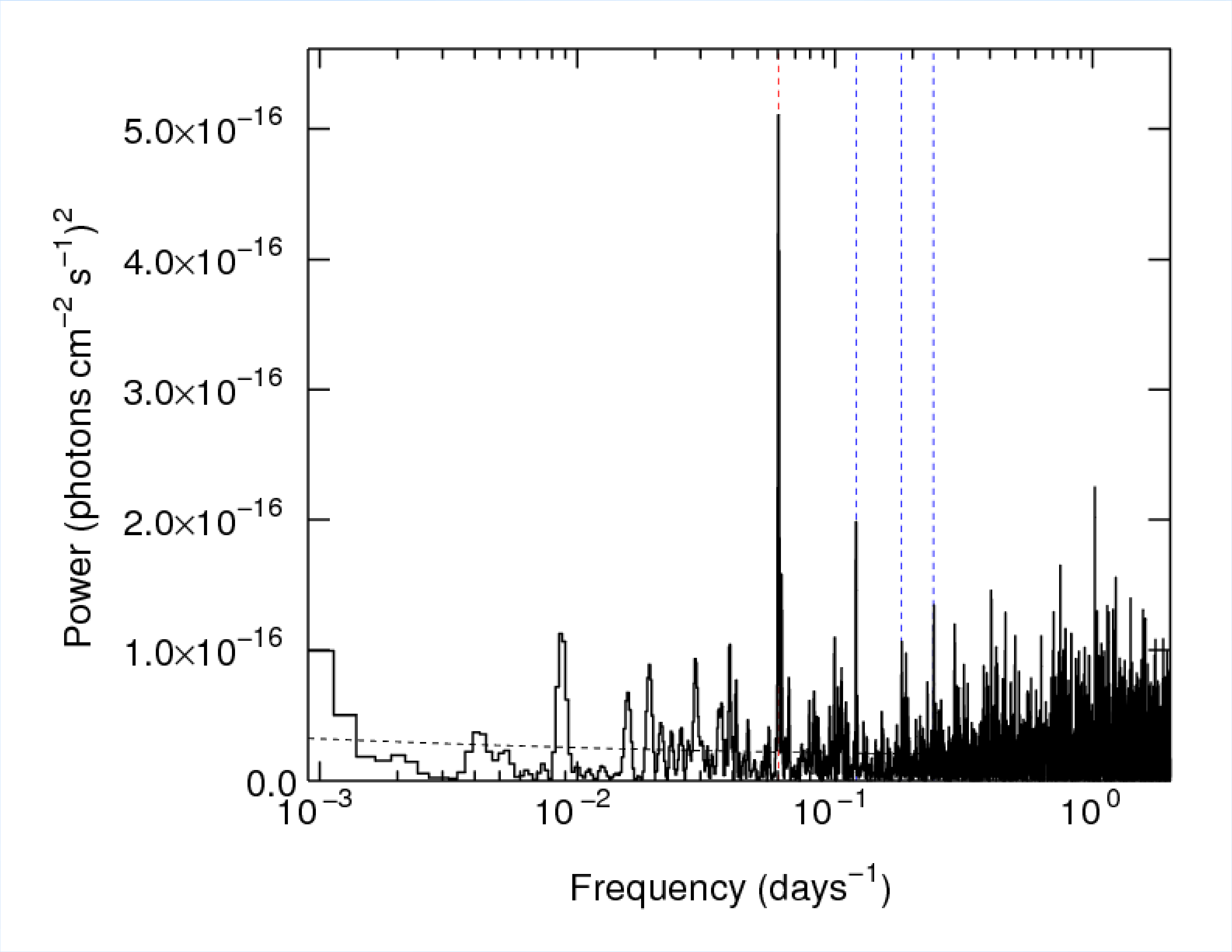


For fainter sources, probability weighted photon photometry can give large gain in signal-to-noise level.

History: First Large Search and Discovery of First New Source (Corbet, Cheung, Kerr+, 2012)

- The first Fermi LAT catalog (1FGL) contained 1,451 sources.
- Made light curves for all sources:
  - 3 degree radius aperture.
  - 600 s time bins (barycenter corrected).
  - 100 MeV to 200 GeV.
- Calculated exposure-weighted power spectra for all sources: 0.08 days to length of light curve (2 years at that time).
- Easily detected LS I +61 303 and LS 5039, but not Cyg X-3. (To detect Cyg X-3 must only use data from active states.)
- And a candidate for a new binary...

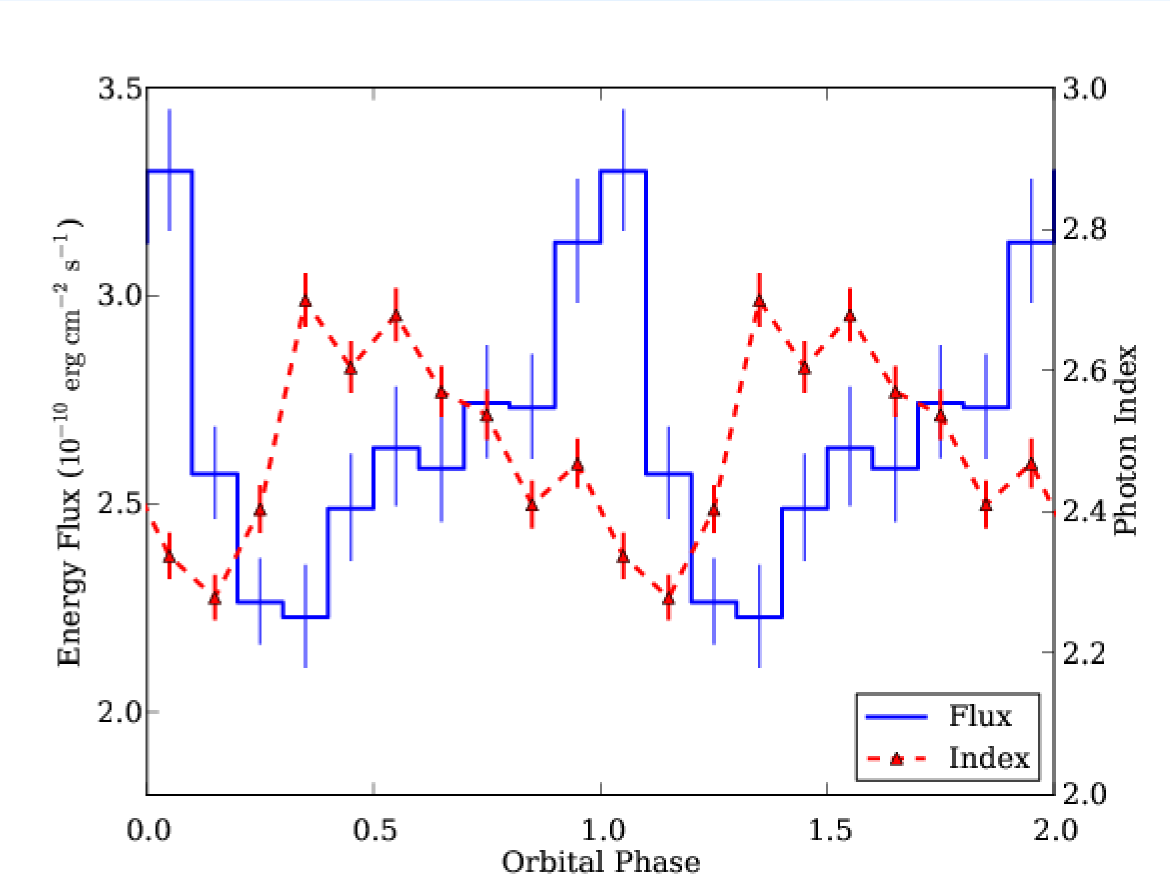
The Discovery of the Binary 1FGL J1018.6-5856



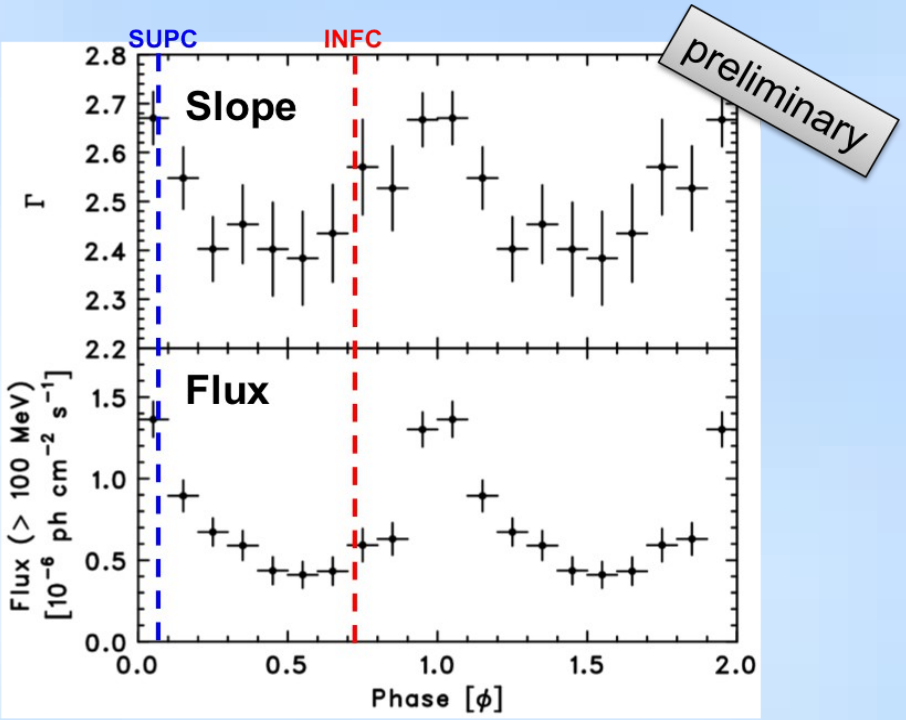
Probability of peak at 16.6 days arising by chance is < 10^{-7}.
Second (and possibly higher) harmonics of this period are also seen.

Flux/Spectral variability on 16.6 day period

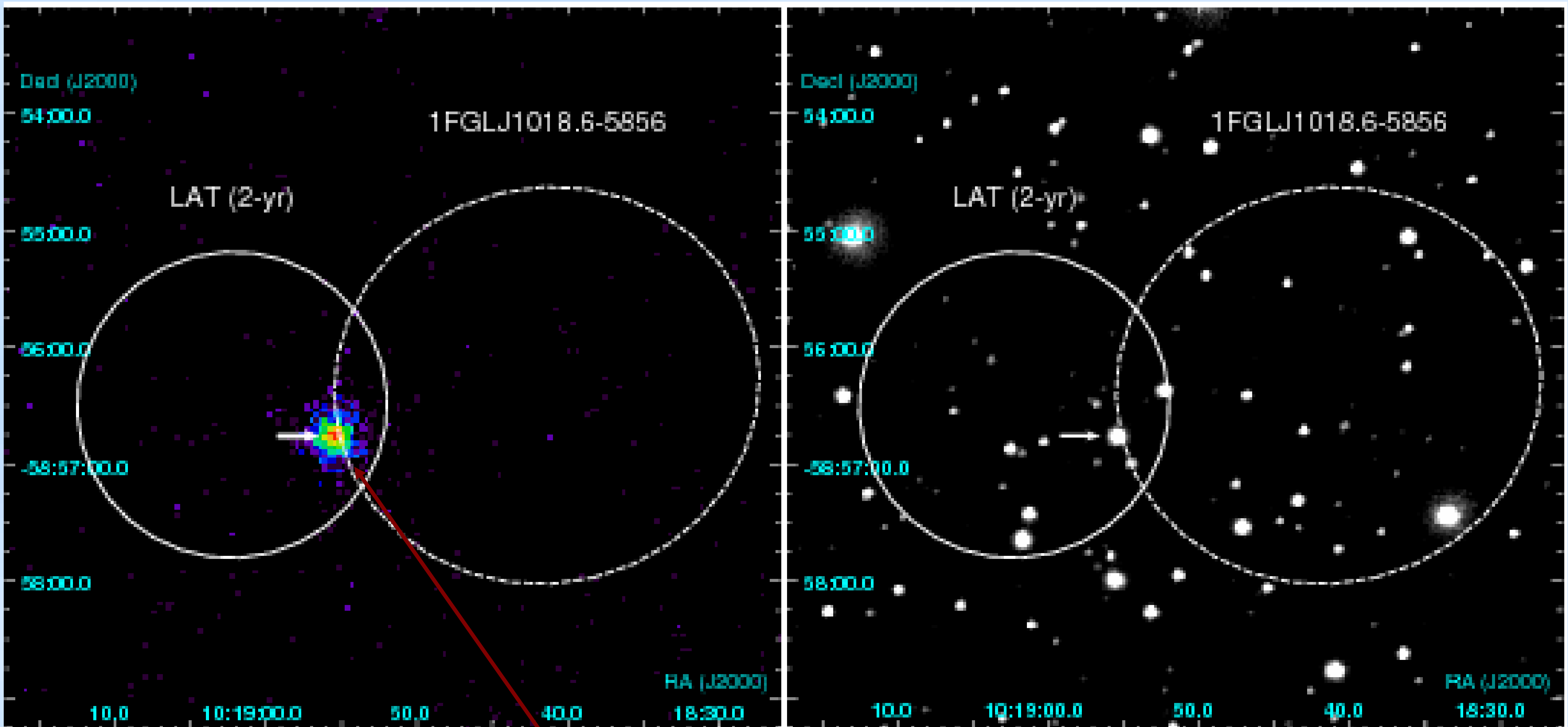
- Gamma-ray spectrum is also modulated on the 16.6 day period. (Harder when bright.)
- *Qualitatively* similar to LS 5039 (3.9 day period), but not LS I +61 303.
- Except... LS 5039 is softer when bright.



LS 5039
(Hadasch et al)



X-ray & Optical Counterparts

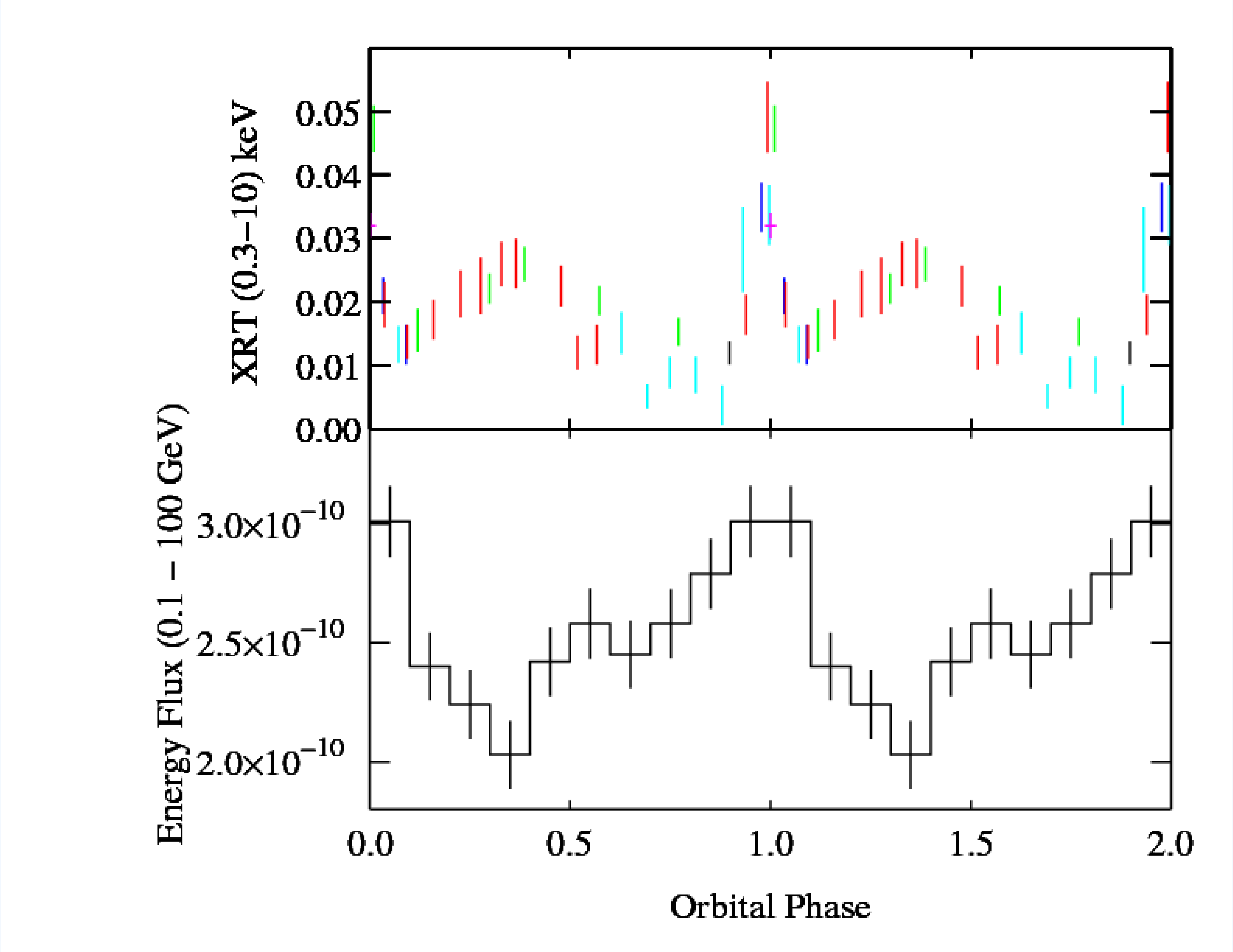


Swift XRT
(X-ray)

Swift UVOT
(UV/optical)

A prominent X-ray source is present at the edge of the LAT error circles. Optical source seen at X-ray position.

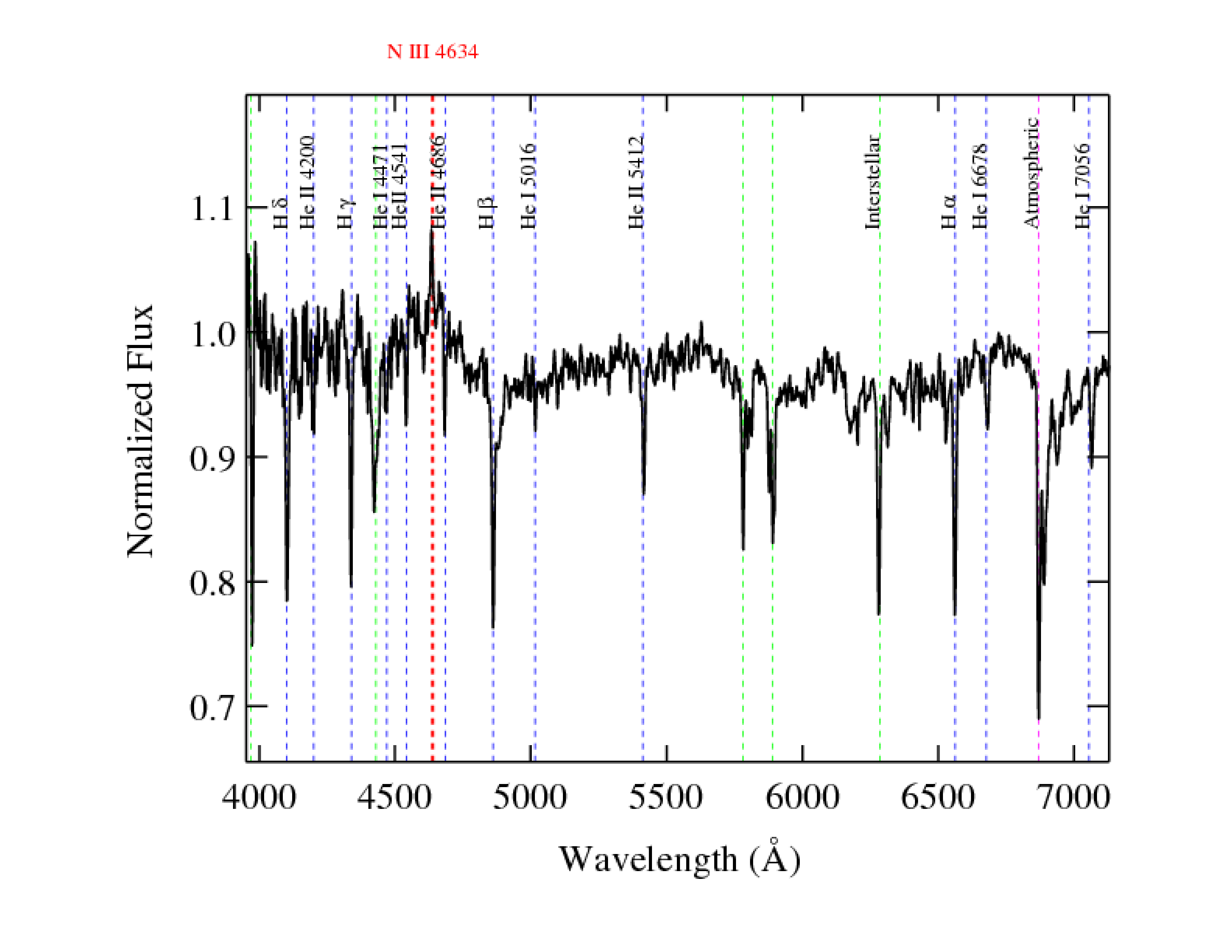
Large X-ray variability (Swift XRT)



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

Optical Spectrum of 1FGL J1018.6-5856

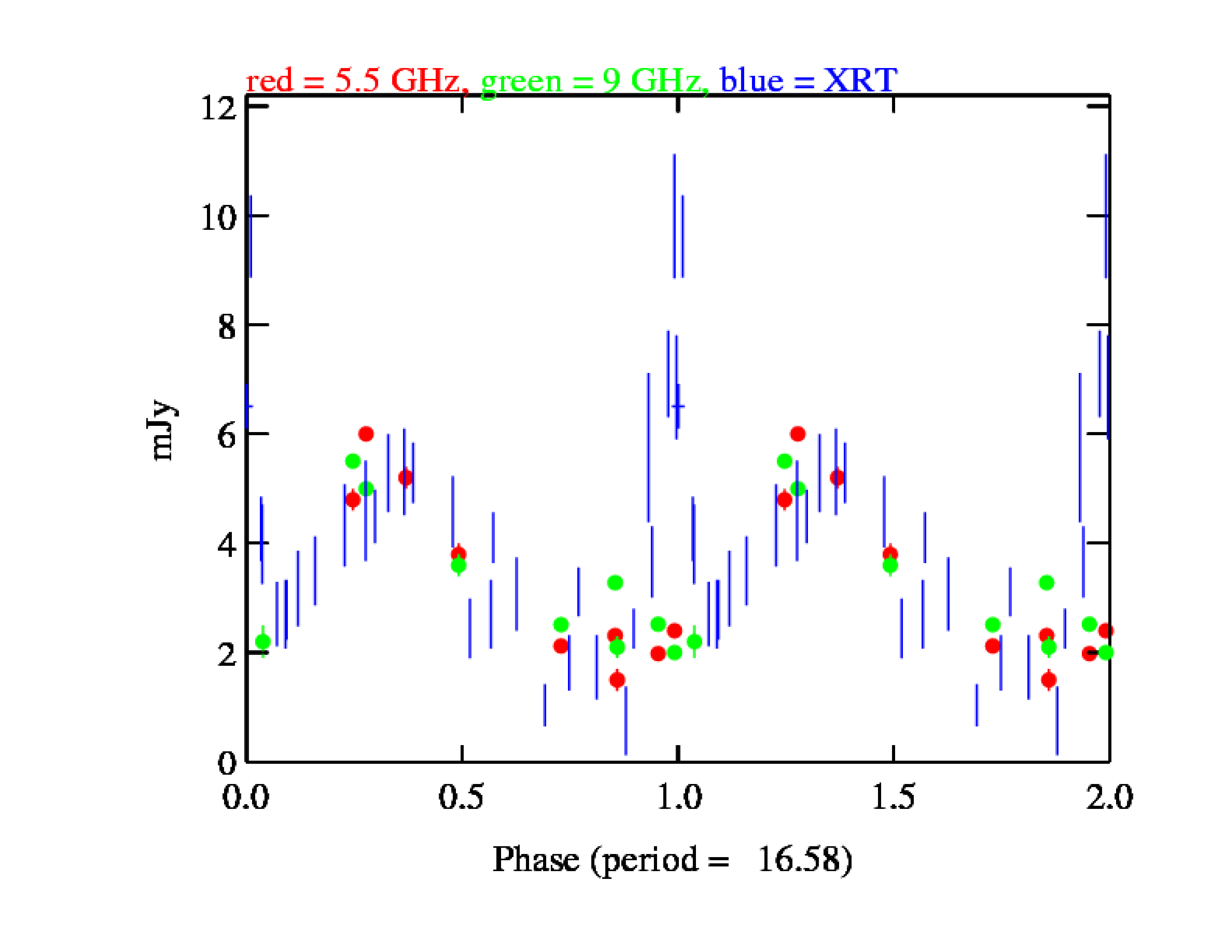
- H, He I/II lines indicate early spectral type.
- He II 4686Å absorption ⇒ main sequence.
- He II/I ratio ⇒ ~O6.
- NIII emission ⇒ O6V((f)).
- Spectral type is almost identical to LS 5039.



SAAO 1.9m telescope

Interstellar absorption lines ⇒ E(B-V) ~1.25.
V ~12.6 (ASAS Catalogue)
Distance ~5 kpc (± 2kpc)

Variable Radio Counterpart

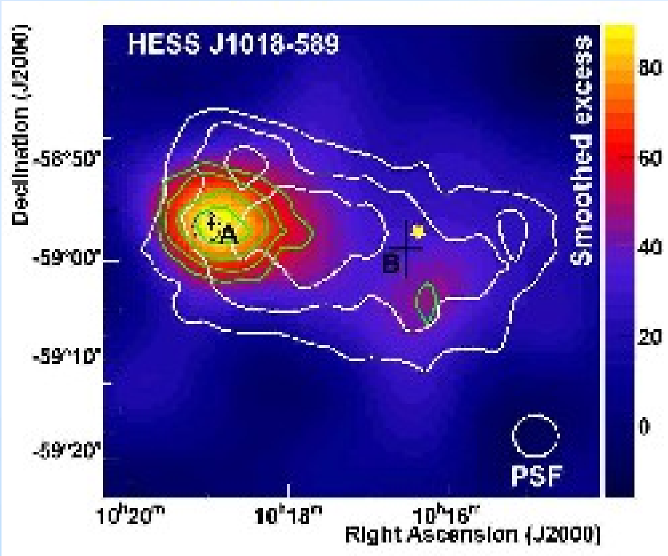


(ATCA Radio data)

The radio flux appears to be modulated on the orbital period.
But, no increase at phase 0.
Radio flux may be following sine wave component of X-ray flux.

TeV Counterpart to 1FGL J1018.6?

- The H.E.S.S. team (2012) reported discovery of HESS J1018-589.
- Positionally coincident with SNR G284.3–1.8 and 1FGL J1018.6– 5856 (diffuse extension towards PSR J1016–5857).
- TeV emission is seen (at least sometimes) from LS 5039 and LS I +61° 303.
- Is this the TeV counterpart of 1FGL J1018.6??
- Temporal variability in the TeV source would confirm association.



1FGL J1018.6-5856 Overview

•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).

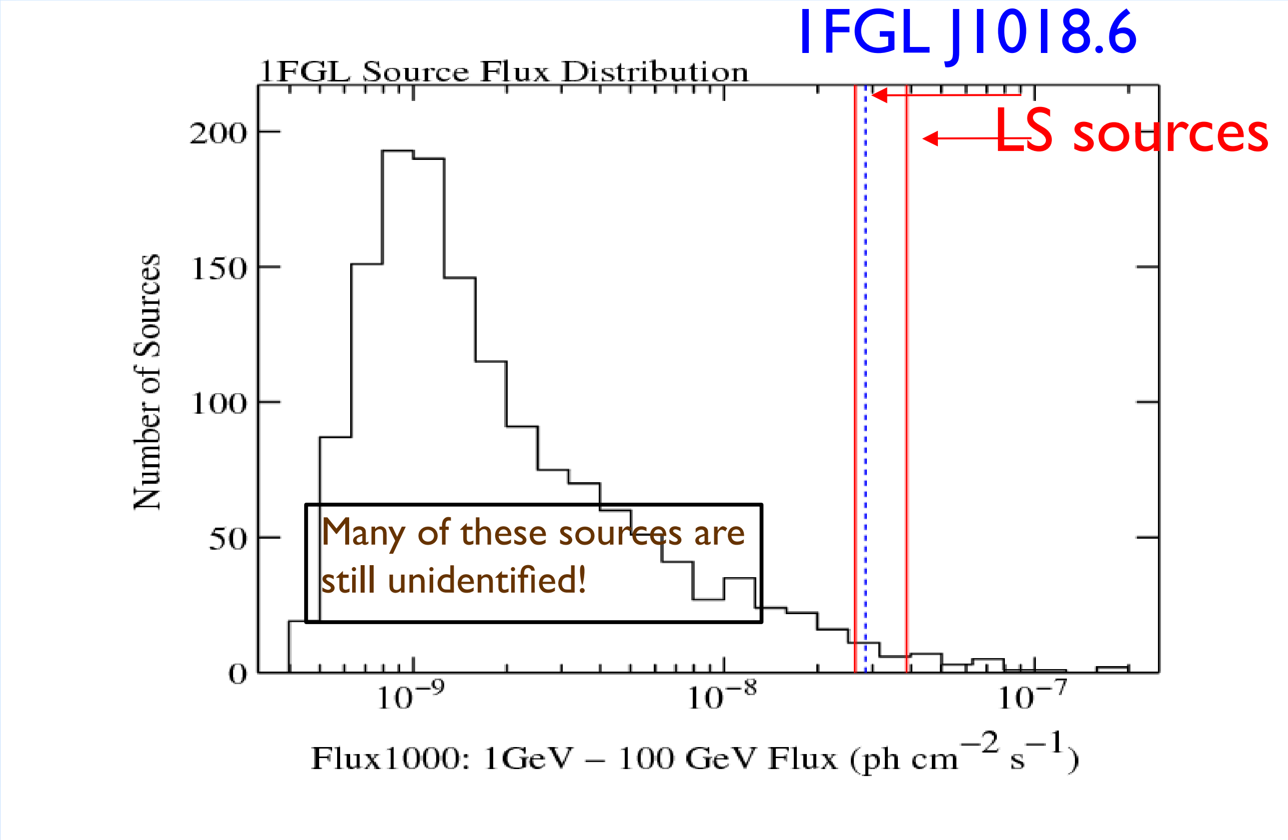
•The multi-wavelength observations were key to demonstrating that this is a gamma-ray binary.

Continuing Monitoring 1FGL J1018.6-5856

- X-rays: Swift monitoring (Donato/Cheung)
    - Long term variability. Repeatability of orbital modulation.
- X-rays: Suzaku phase constrained (Tanaka et al.)
    - Emission mechanisms.
- Radio: ATCA (Edwards et al.)
    - Orbital modulation of radio flux. Long term variability.
- Optical: Radial velocity measurements (Romani et al.)
    - Determine system geometry, constraints on compact object (neutron star vs. black hole).
- Optical: photometry (McSwain et al.)
    - System geometry and constraints on compact object.

Where are the Rest of the Binaries?

-So far, we've only found binary periods in bright sources.



Evolutionary models predict we should see more binaries in the "iceberg" of the lower-flux Fermi sources.

Continued Search for More Binaries

- Continue to perform periodicity searches on all cataloged sources, hoping to find more binaries.

- Use 2nd Fermi catalog (2FGL) which contains 1,873 sources, and better source characterization than 1FGL catalog.
  – Accurate source parameters are required to calculate photon probabilities for source origin.

- Automatically update light curves and power spectra of all sources every week.

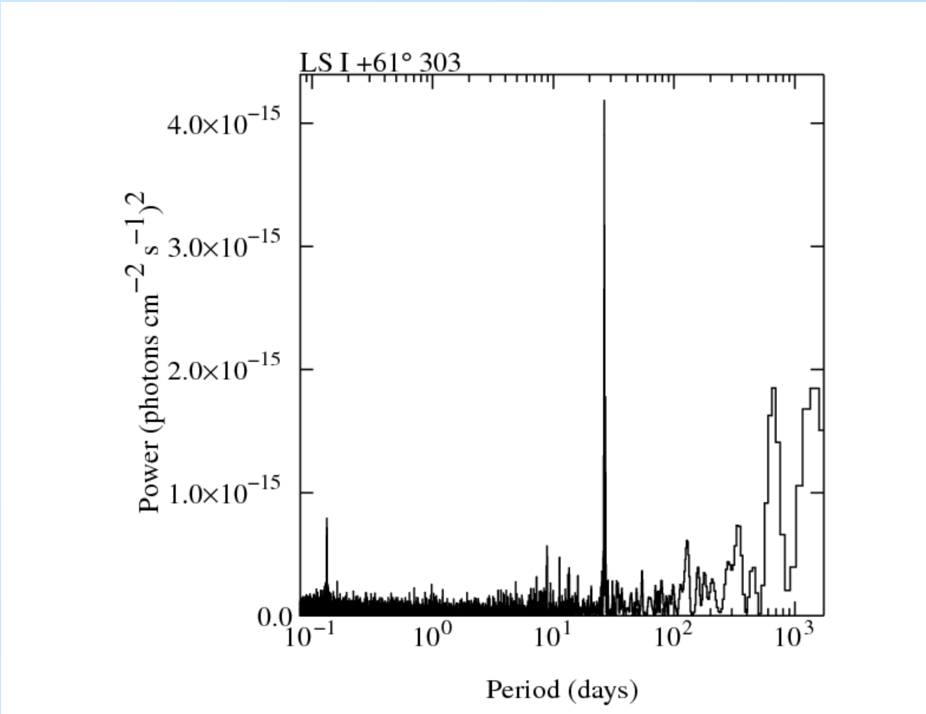
- LAT binary search sensitivity is continually improving as more data accumulate. (S/N ~Time). Now have ~4.8 years data.

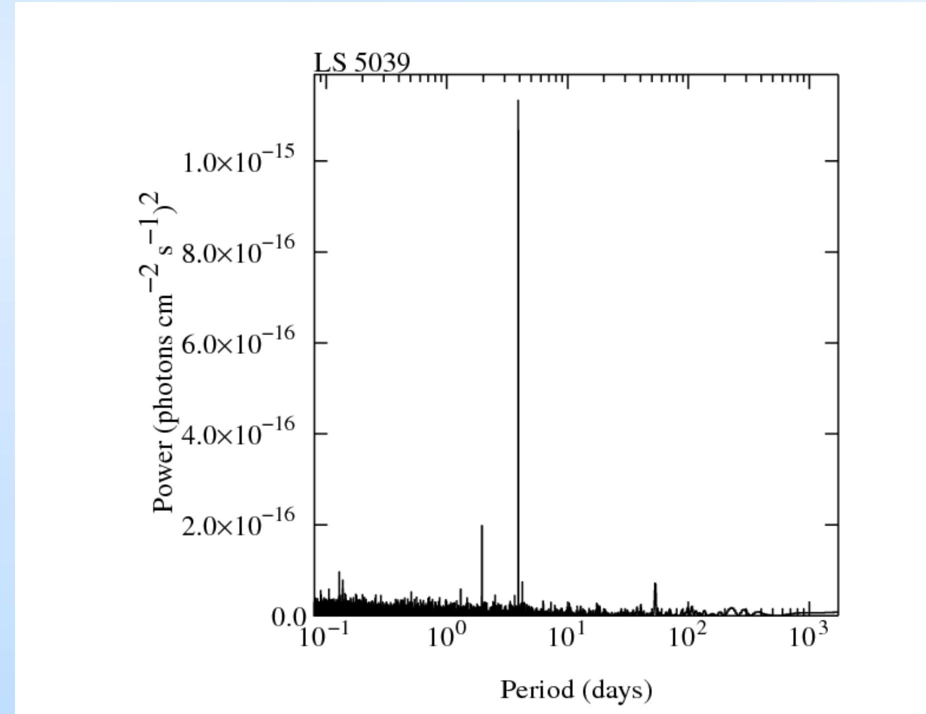
- Examples from current search results....

Differing Long-Term Variability of High-Mass Gamma-ray Binaries

- LS 5039 (similar optical counterpart to J1018.6) has constant gamma-ray modulation and no long-term modulation. (Hadasch+ 2012)
- LS I +61 303 has significant long-term variability.
  - Orbital modulation can disappear (Hadasch+ 2012).
- How does the long-term gamma-ray variability of J1018.6 compare?

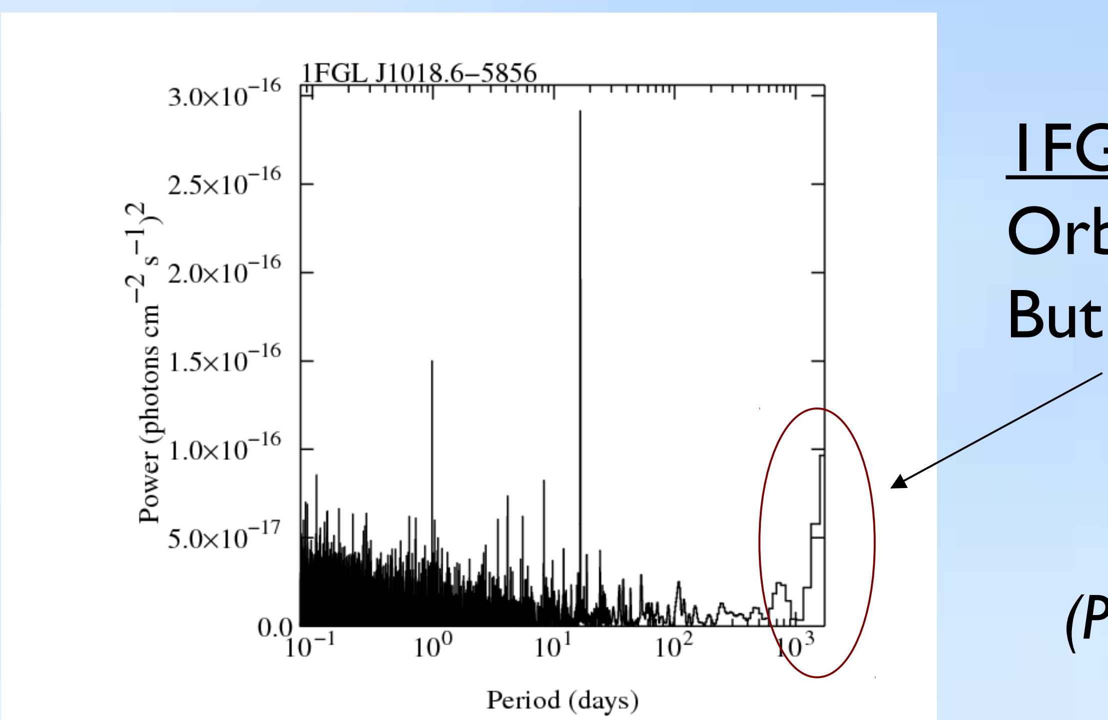
Different Variability in 3 High-Mass Binaries





LS I +61 303 has significant long-term variability, orbital modulation is intermittent.

LS 5039 has no long-term variability, orbital modulation is persistent.



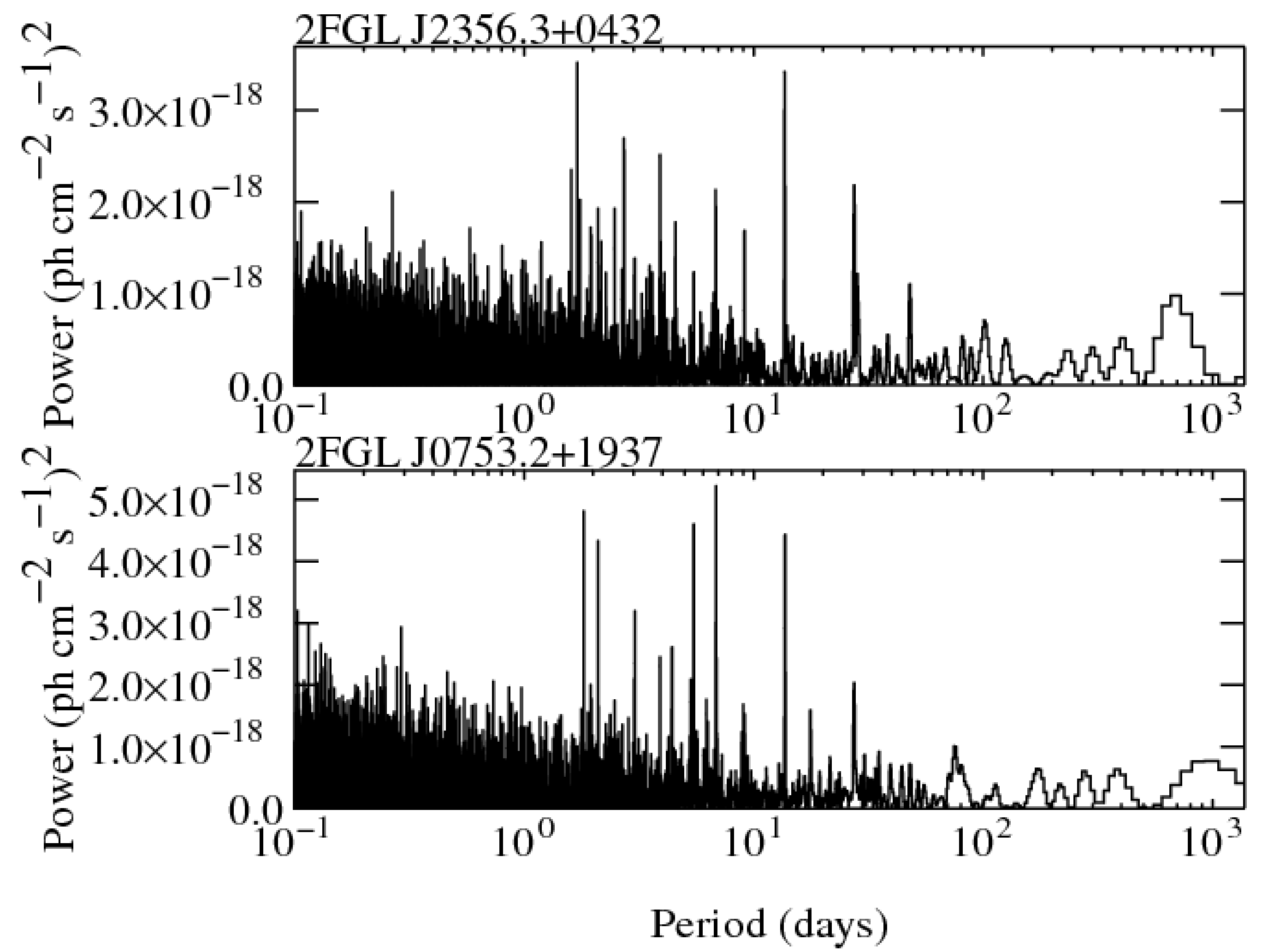
1FGL J1018.6-5856 is similar to LS 5039.
Orbital modulation persistent.
But also has some long-term variability.

(Peaks at ~3hours, 1 day, & 53 days are artifacts.)

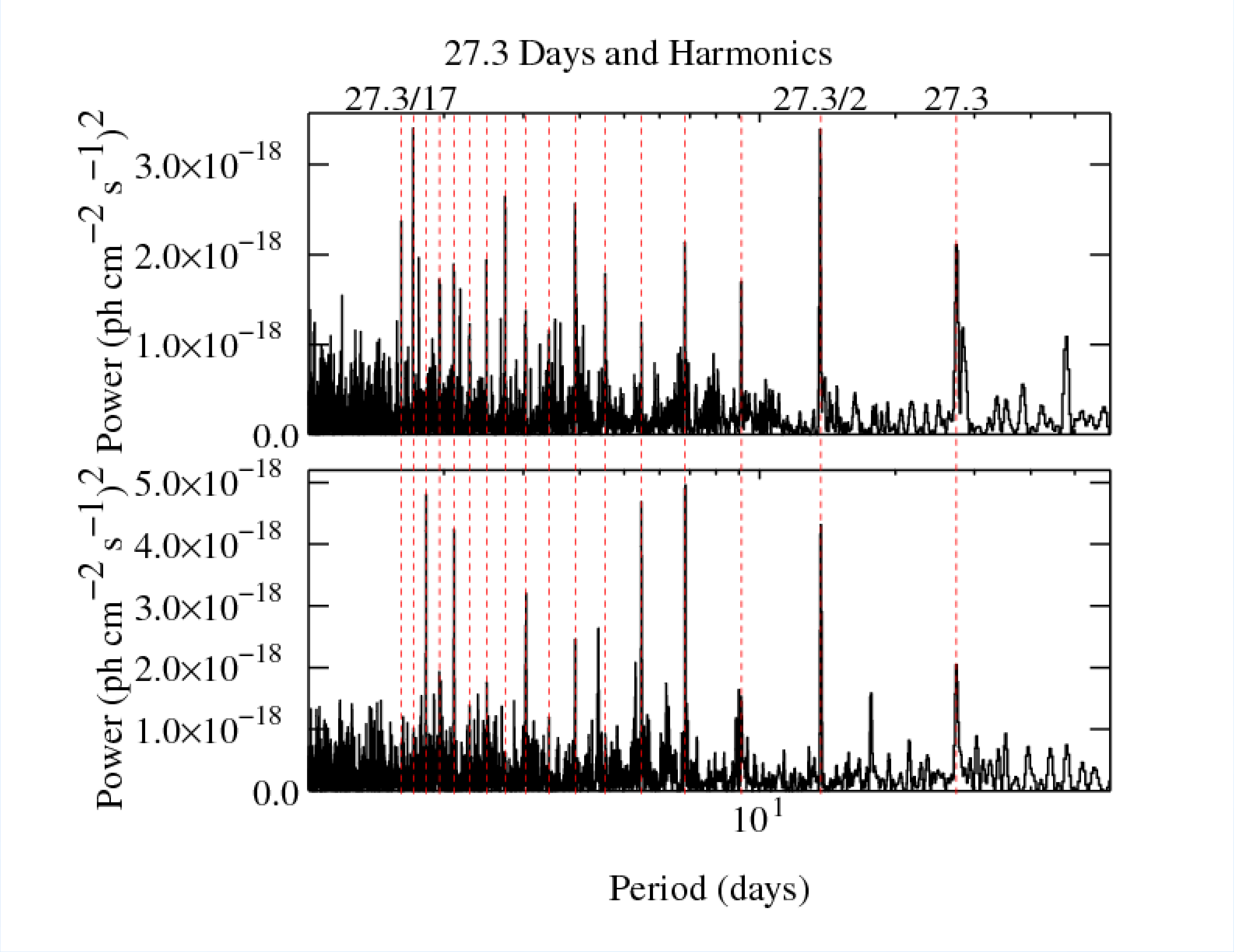
Looking for Stars and Finding the Moon

(Corbet, Cheung, Kerr, & Ray, 2013)

- Peculiar sets of power spectrum peaks noticed in two sources:

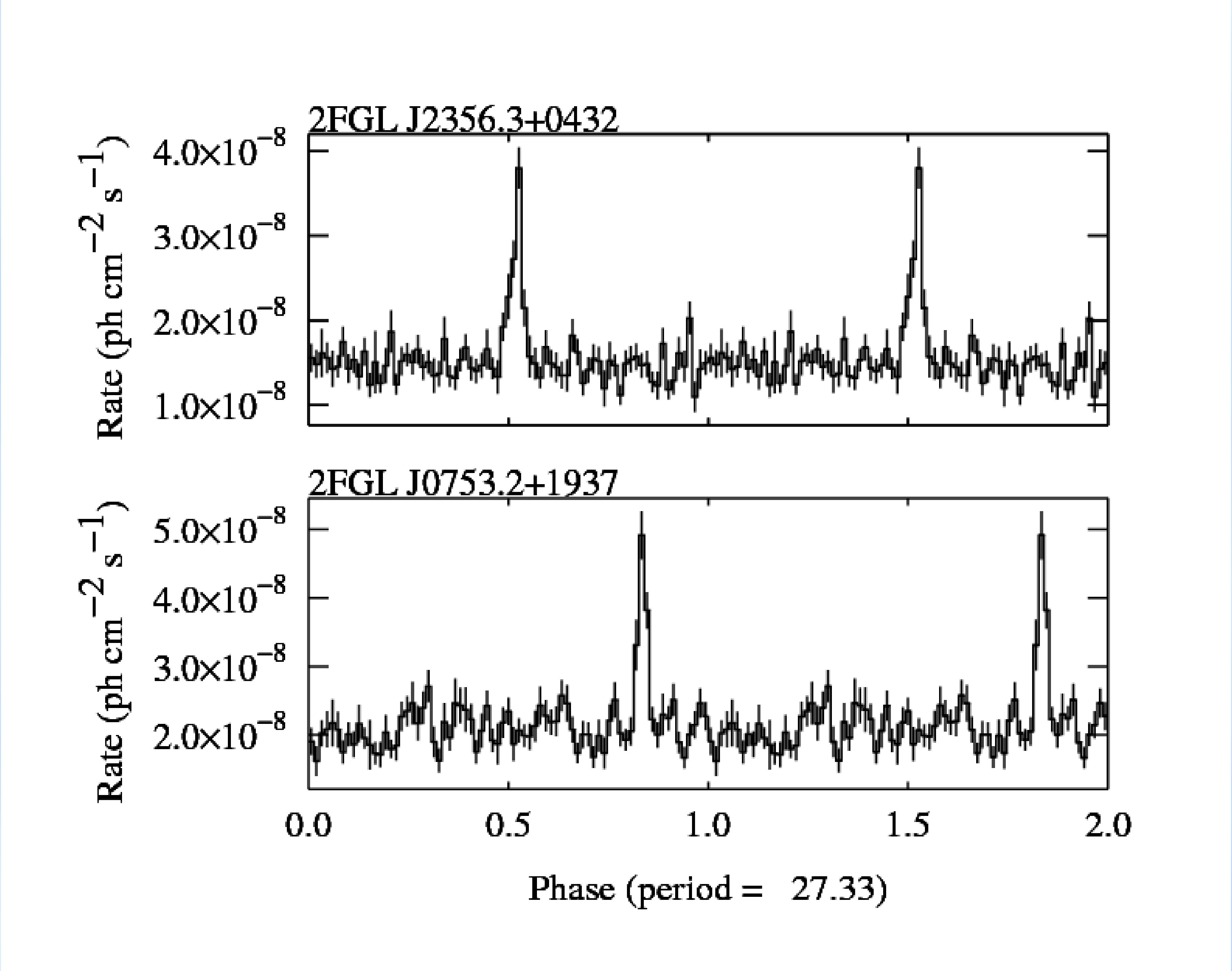


Harmonics, harmonics



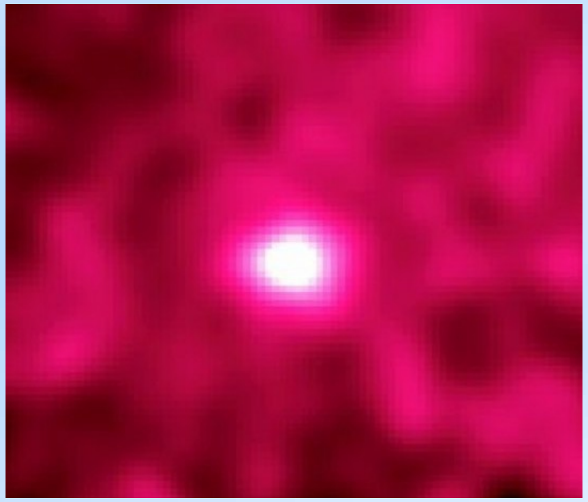
All peaks are 27.3 days and harmonics of this up to 17th

Light Curves Folded on 27.3 Days



Getting Mooned

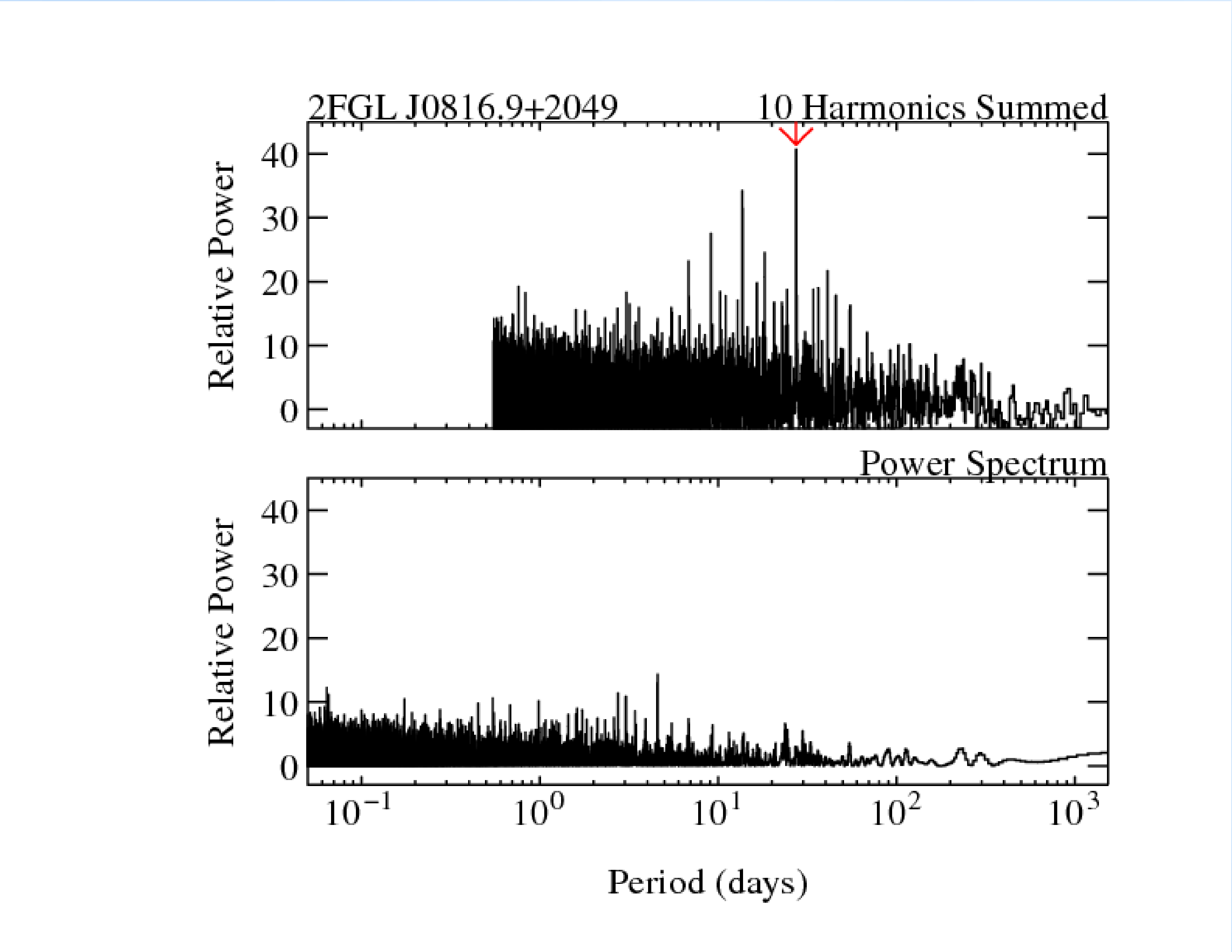
- 27.3 days is sidereal period of the Moon.
- Both sources are in the path of the Moon.
- Separation of peaks between two sources is consistent with lunar interpretation (based on RA).
- Interaction of cosmic rays with Moon's surface results in production of gamma rays.
    - Moon is fairly bright gamma-ray source: ~10^{-6} ph cm^{-2} s^{-1}, even detectable with EGRET.



Lunar Lessons

- Gamma-ray emission from the Moon can contaminate LAT light curves.
  - Software (P. Ray) now available at Fermi Science Support Center to exclude times when Moon too close to a source.
- Sources that periodically flare briefly are not well suited to detection in a power spectrum:
  - Investigated several other period search techniques.
  - Find summing harmonics in power spectrum (cf. Buccheri et al. 1983) works well...

Summing Harmonics to Detect Flares



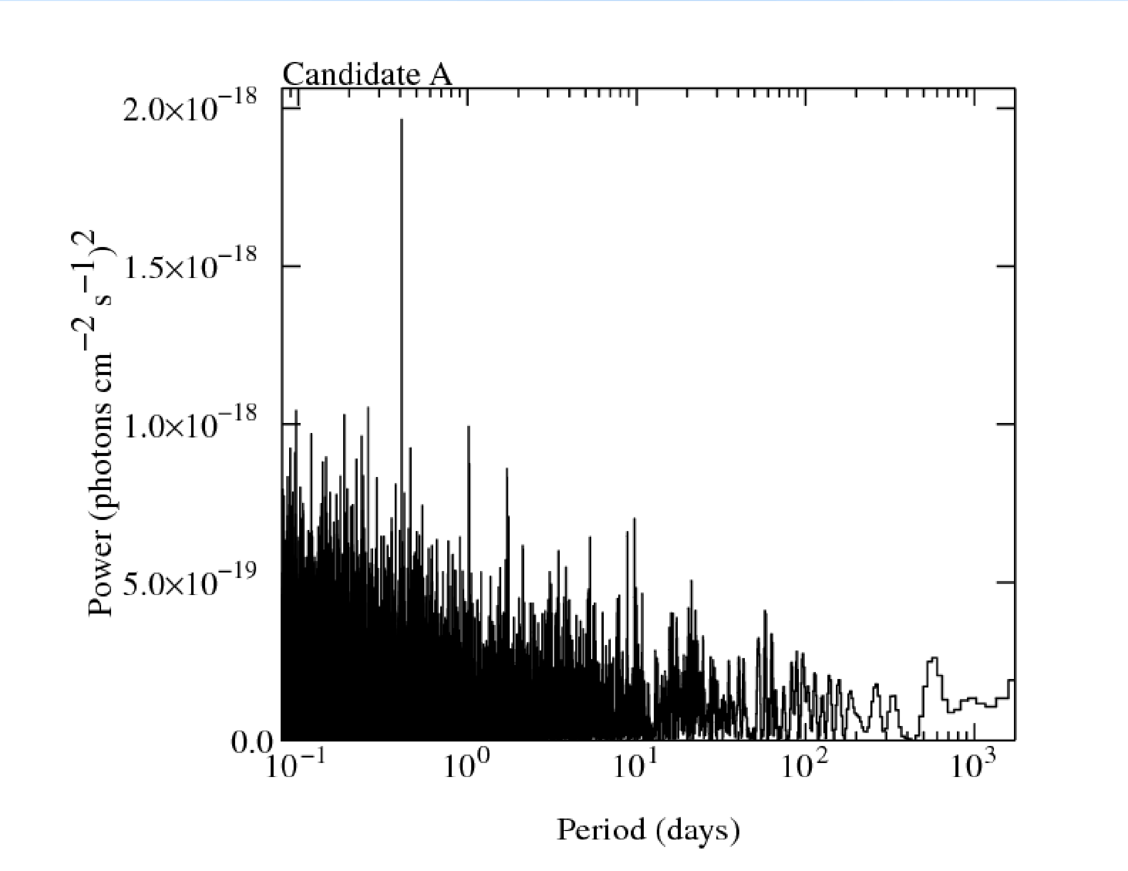
Harmonic summing detects periodic "flaring" caused by Moon's passage close to a source.
Reveals lunar contamination for ~40 sources in total.

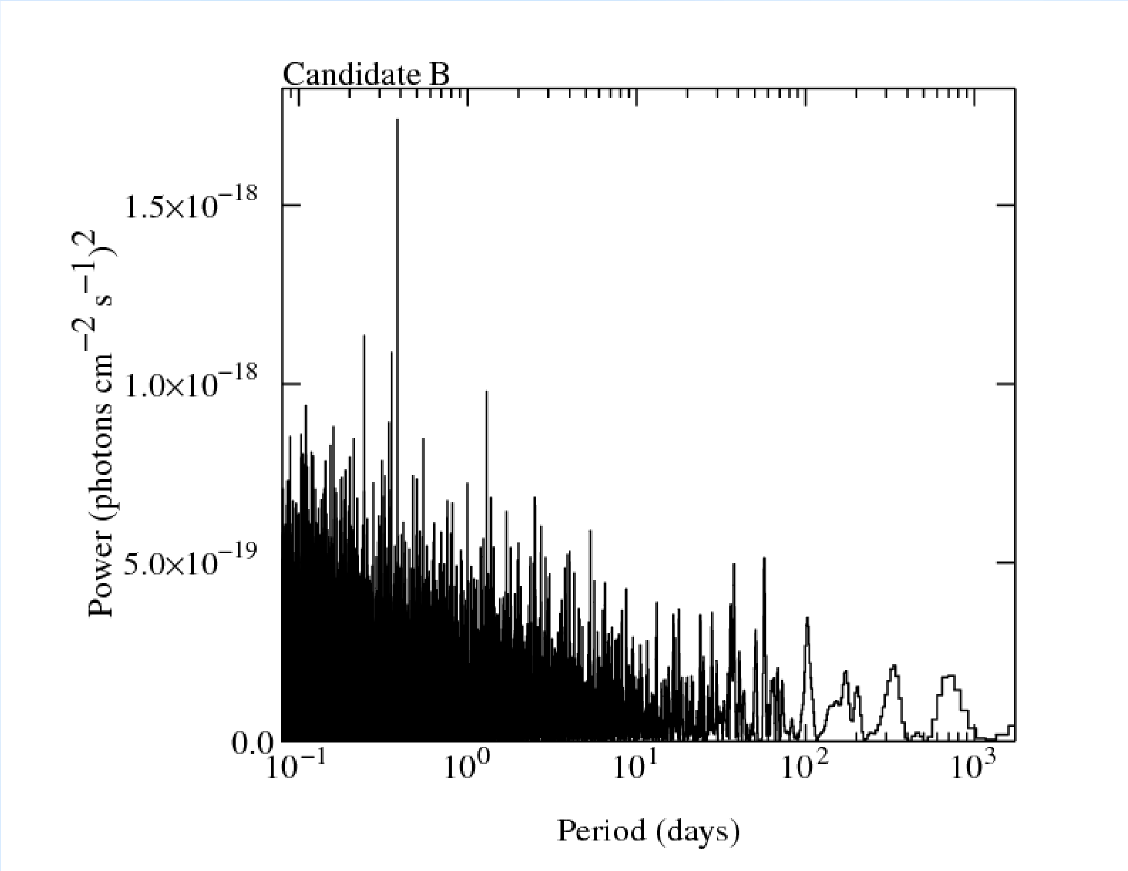
Harmonic summing can also detect periodic brief flares intrinsic to a source.
e.g. highly eccentric orbits such as PSR B1259-63.

Dealing with Binary Candidates

- The Fermi LAT has now been operating for nearly 5 years.
- The percentage increase in the amount of data now increases rather slowly.
- How can we determine if candidate binaries with modest significance modulation really are binaries?
    - Monitor power change at candidate frequency. Since a single frequency is monitored, statistical "penalty" of number of frequencies searched no longer applies.
    - Classify the gamma-ray source using multi-wavelength data.

Examples of Modest Significance Candidates





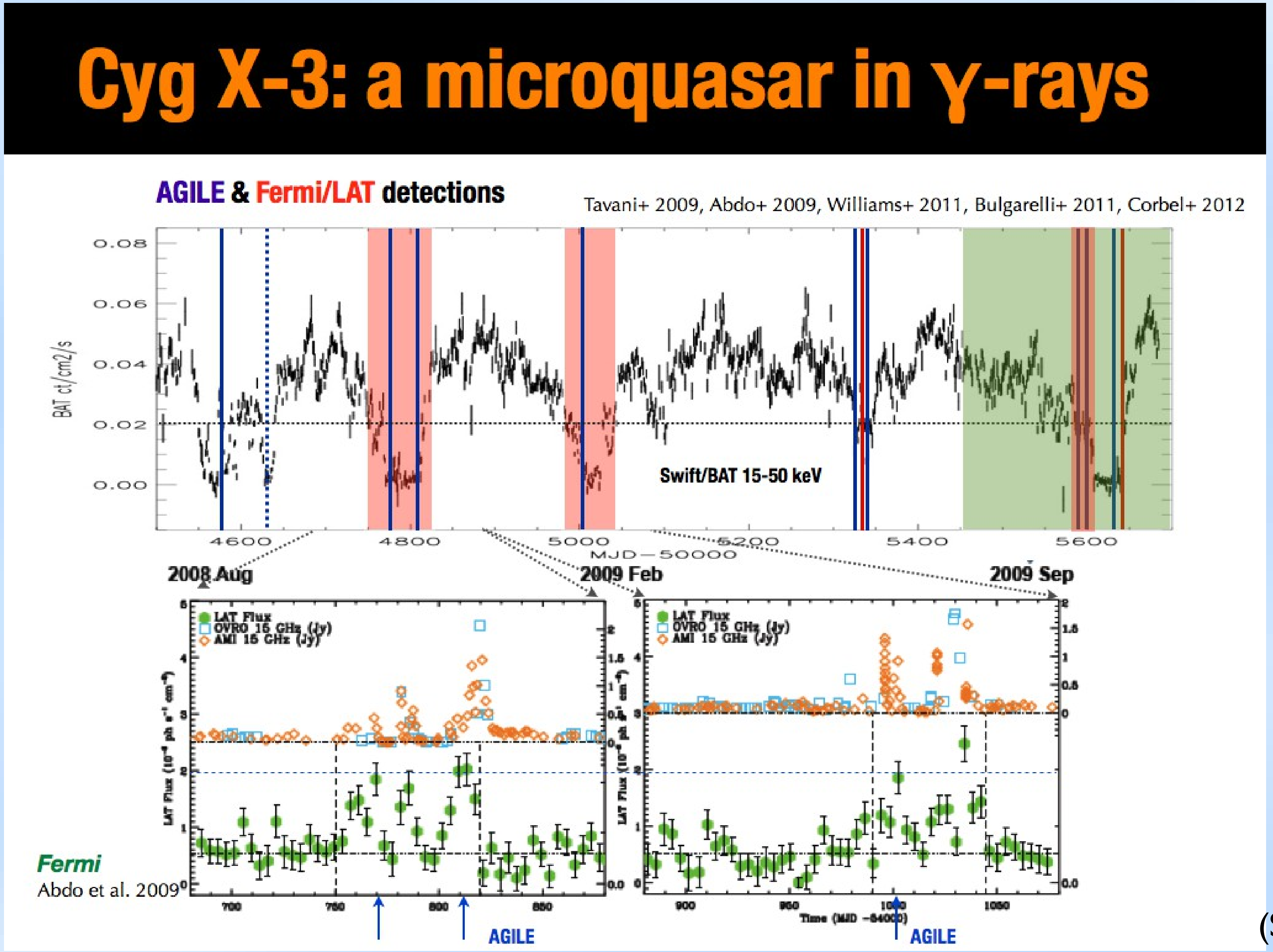
Period ~0.41 days
False alarm probability ~10^{-4}
Galactic latitude -4°

Period ~0.39 days
False alarm probability ~10^{-4}
Galactic latitude -4°

If signals are real, length of periods suggests low-mass sytems.
(Relationship to black widow/redback millisecond pulsars??)

Candidate A has remained at about same significance level for last ~1.5 years.
⇒ if real, modulation is intermittent.

Intermittency in Gamma-ray Emission



(Slide courtesy S. Corbel)

Cyg X-3 is a dramatic example of a system where gamma rays are only produced during particular states. (Soft X-ray states.)
Makes search for binaries more difficult...

Classification via Multi-Wavelength

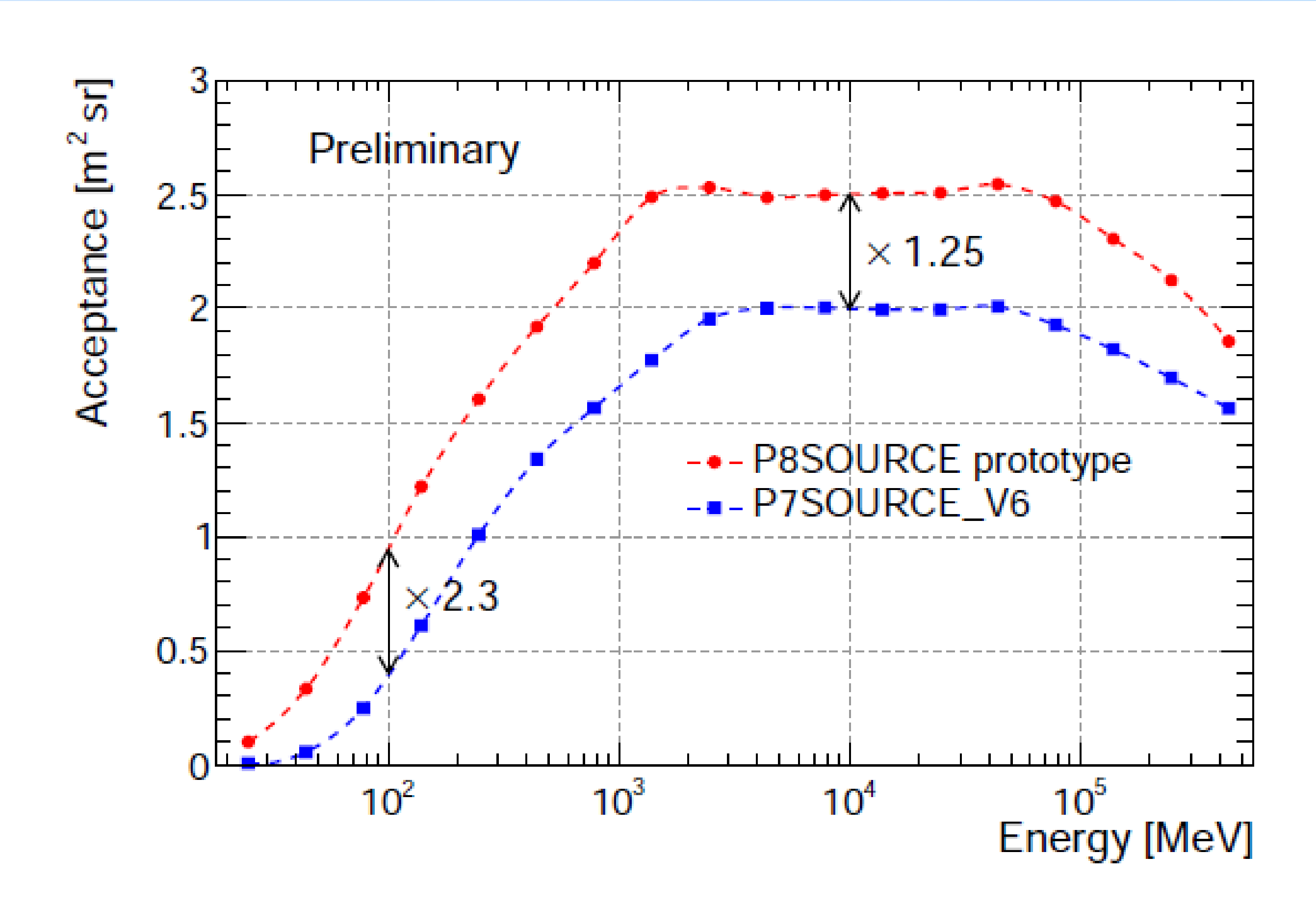
- Two facets of multi-wavelength approach:
  - If a gamma-ray source has a stellar counterpart, then it is extremely likely to be a gamma ray binary.
  - If modulation at same period as seen in the gamma-ray source is found at another wavelength, the identification is definite.
- Hierarchical approach:
  - Obtain X-ray image of Fermi error box:
    - Swift can reveal brightest sources, Chandra and XMM provide deeper images.
    - For all X-ray sources detected:
      - Obtain optical spectra, optical photometry, search for periodicity
      - Search for (variable) radio counterpart with ATCA etc.

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.
- Versions of algorithms/software are called "Passes".
  - Pass 6 was used at launch, Pass 7 is the current version.
  - The LAT team is now developing Pass 8....

The Promise of Pass 8

- Pass 8 is radical revision. Potential 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

If these improvements are realized, then it will provide an enormous boost for “photon-starved” binary searches!

Summary

•The Fermi LAT is the most sensitive high-energy gamma-ray detector ever flown.

•There are still very few gamma-ray binaries known, even though a population of pre-High-Mass X-ray Binaries is predicted.

•We have developed techniques to increase signal-to-noise of LAT light curves and power spectra, and to search for non-sinusoidal modulation.

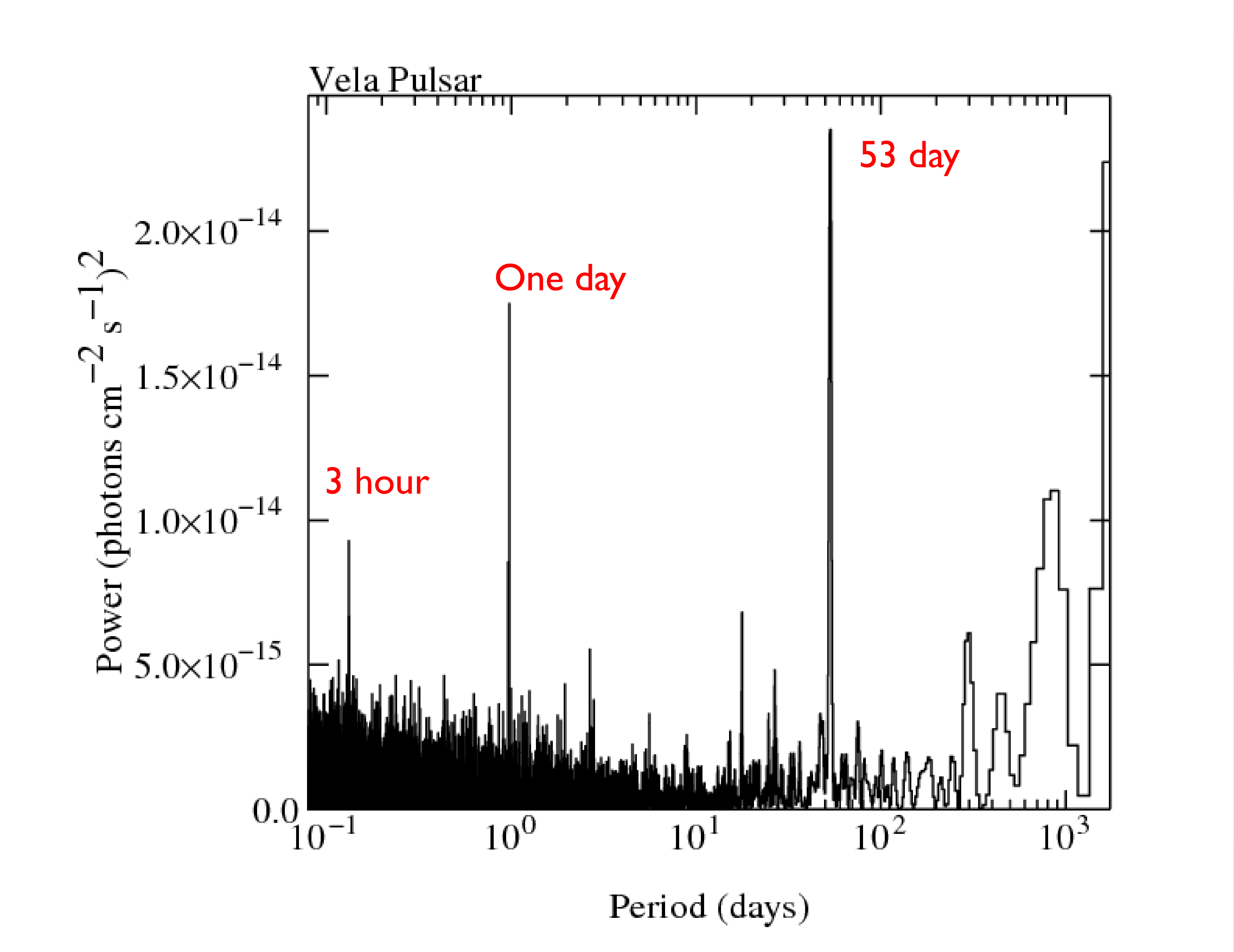
•One completely new system (1FGL J1018.6-5856) was found from 2 years' worth of data.

•There are hints of more systems, and we are using a multi-wavelength approach to classify these sources.

•Pass 8 LAT processing, and additional data, promise improved sensitivity.

Backup Slide

Non-Binary Signals in Power Spectra



The Vela pulsar is the brightest Fermi source and very constant. Its power spectrum shows artifacts that are also seen in other sources. These include the ~3 hour sky survey period, ~1day, and the 53 precession period of Fermi's orbit.