Finding and Understanding Gamma-ray Binaries from Their Multi-wavelength Variability

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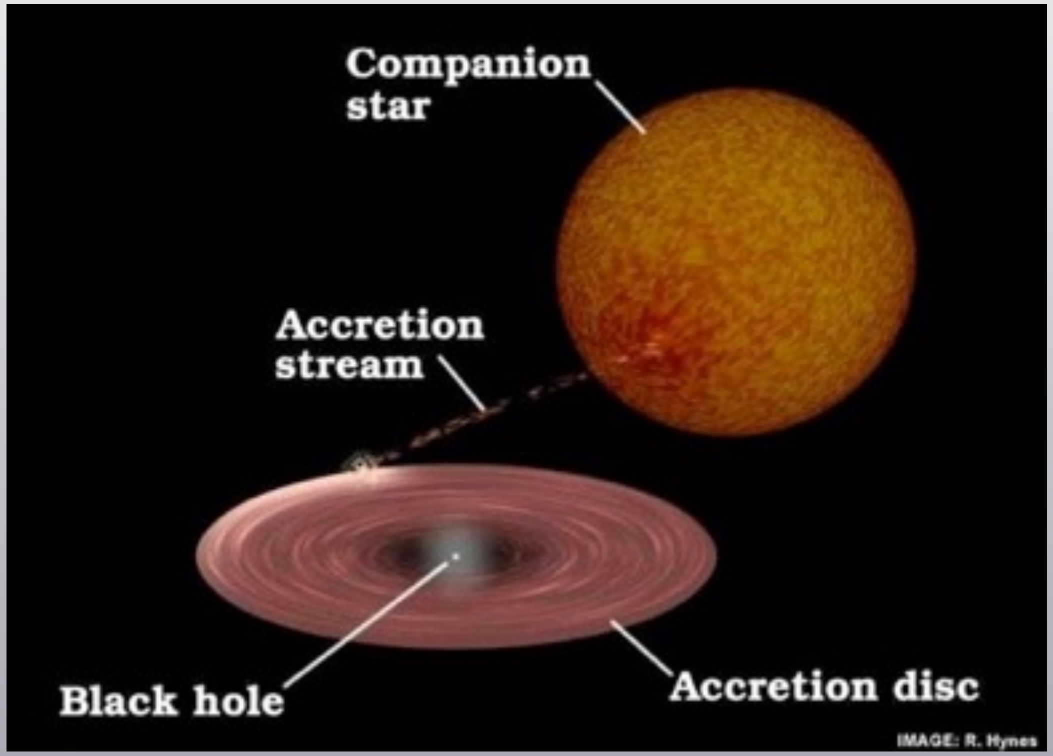
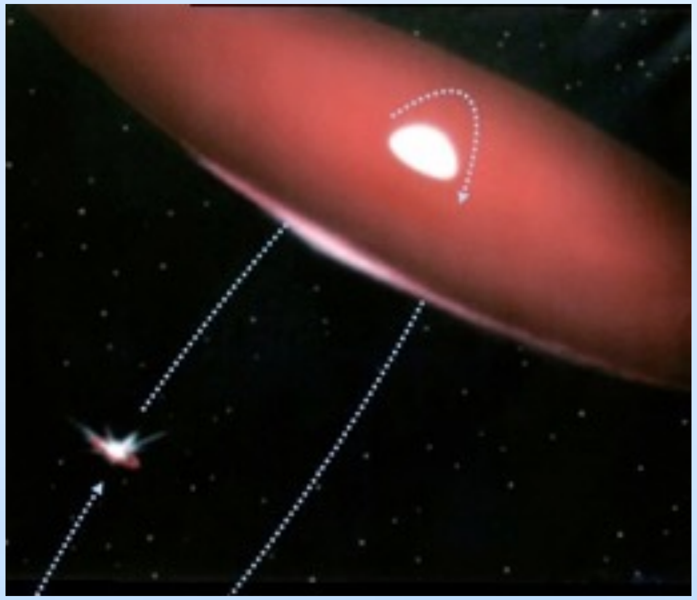
X-ray Binaries and Gamma-ray Binaries

- X-ray binaries and gamma-ray binaries (GRBis) both consist of a neutron star or black hole in orbit with a “normal” star.
- In both cases the energy comes from an interaction between the two components.



- X-ray binaries much more common than gamma-ray binaries. (Hundreds vs. handful.)
- For X-ray binaries energy source is gravitational potential energy. Situation is more complex for GRBis.

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.

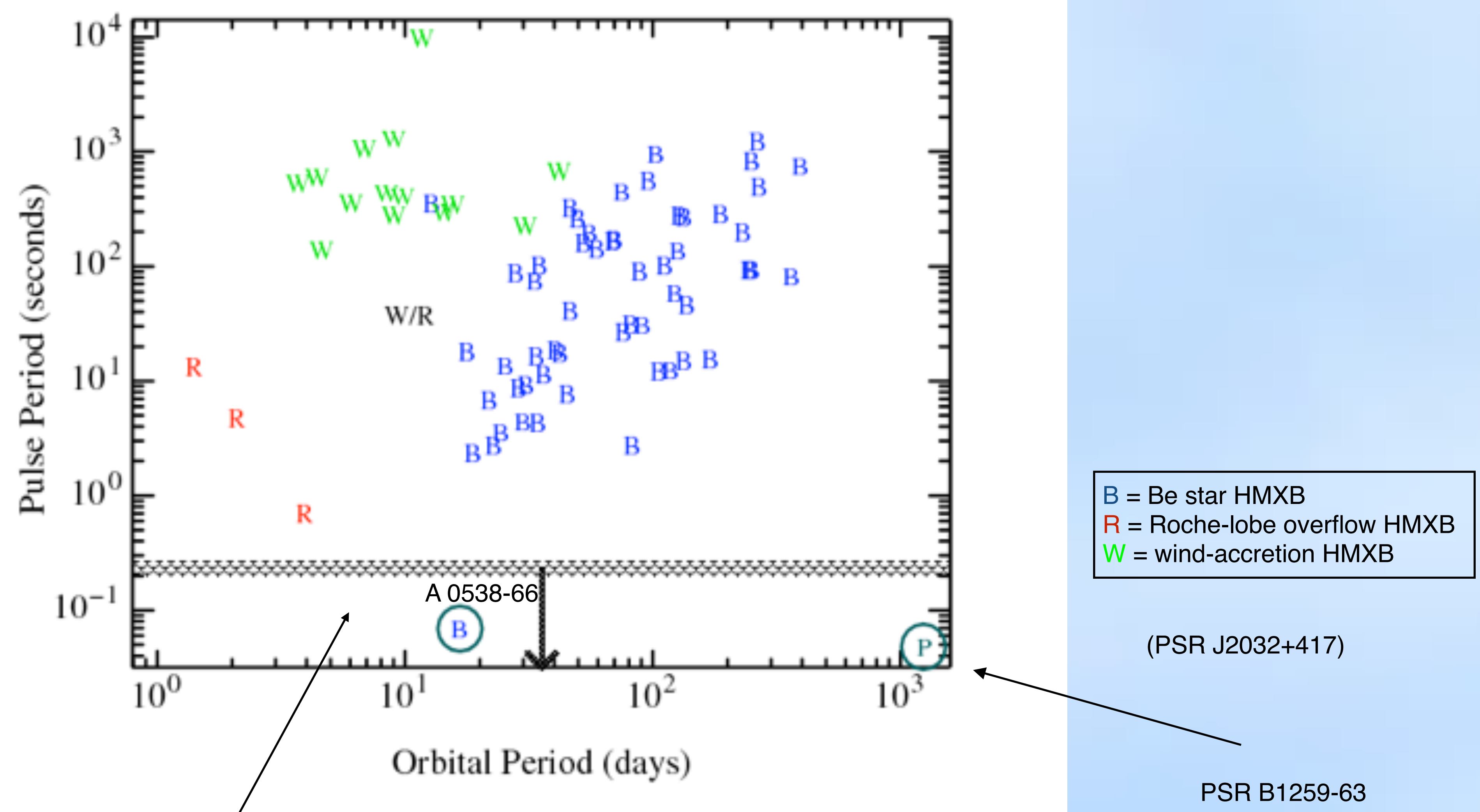
Pulsar wind pressure dominates for:

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

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 in June 2008.
- The primary instrument is the LAT: 100 MeV (or lower) to 300 GeV (and higher).

Several advantages over previous detectors:
- Instrument performance: Improved effective area, field of view, angular resolution.
- Observation mode: LAT mainly operates in sky survey mode. ***Entire sky is observed every ~3 hours***. Can study binaries on a wide range of timescales.

The Hunt for New Binaries

- Only a handful of gamma-ray binaries are known.

- But ~30 had been predicted in the Milky Way as early phase of HMXB evolution.
    1. Only one "new" source had previously been found with Fermi: 1FGL J1018.6-5856 with two years of data.
    2. Known gamma-ray binaries show modulation on their orbital periods.

- Hope to find new gamma-ray binaries from the detection of periodic variability.

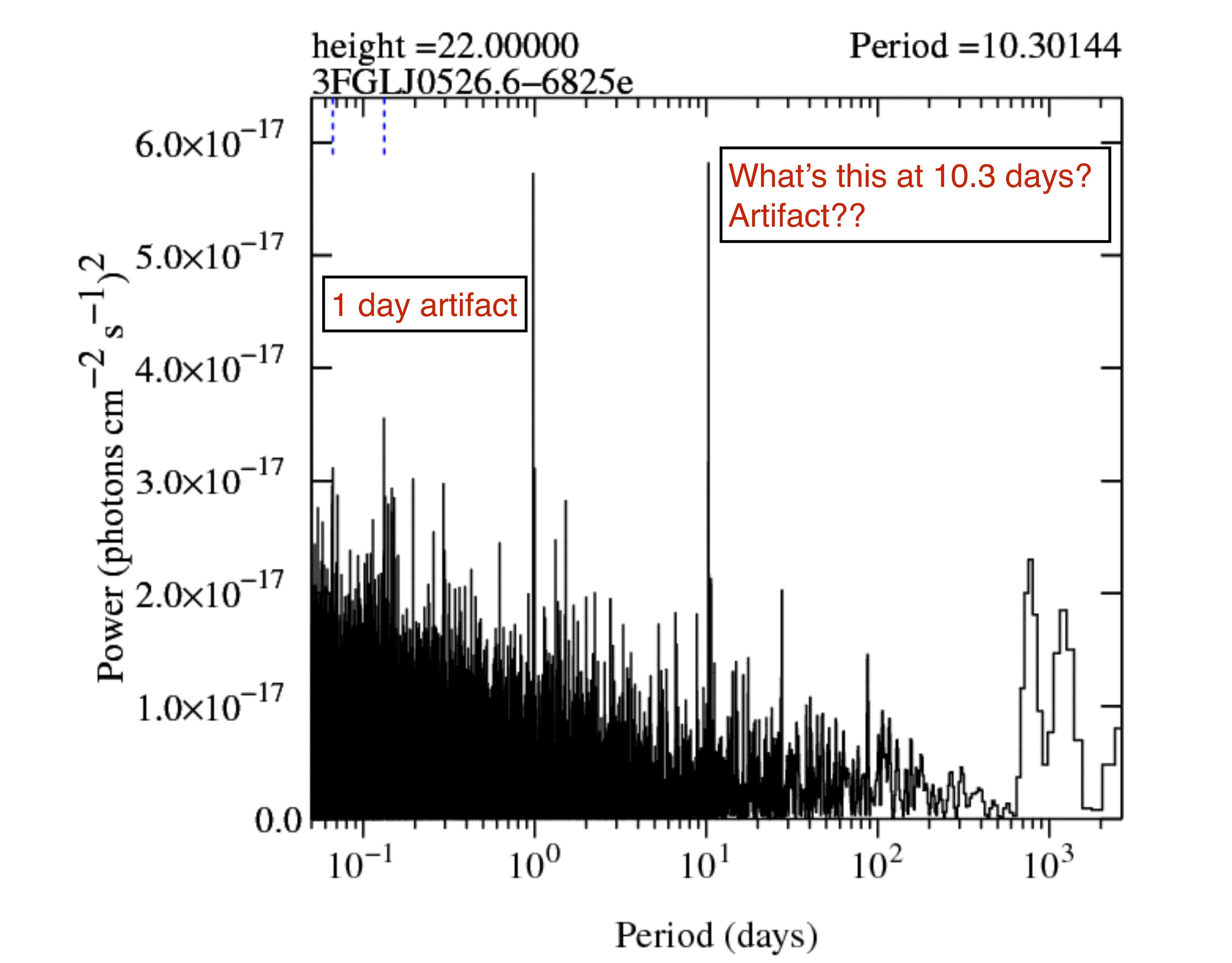
Difficulties in Hunting Gamma-ray Binaries

- Binary signals are rare.
- Artifact signals are common in LAT data!
    - 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.
- When a periodic signal is found, it can be hard to localize the source and find the counterpart.
- Fermi error circles large (many arc minutes) with systematics in crowded regions.
- Multi-wavelength observations vital to determine counterpart.
    - e.g. find X-ray sources in gamma-ray error region, then do radio and optical observations of those.

The Hunt for New Binaries

- There are 3033 unique sources in 3FGL catalog.
- Many sources are “unassociated” without counterparts.
- Produced light curves and power spectra for all sources. With a few “tricks” to increase signal-to-noise:
    - Probability-weighted aperture photometry.
    - Exposure-weighted power spectra.
- Known persistent binaries were easily detected.
    - *Pass 8 data increased binary signals in power spectra of known binaries by factor of 1.5.*
- Also saw curious signal from J0526.6-6825e - LMC treated as single source…

Power Spectrum of LMC as Single Source



Modulation Is Localized: Not an Artifact

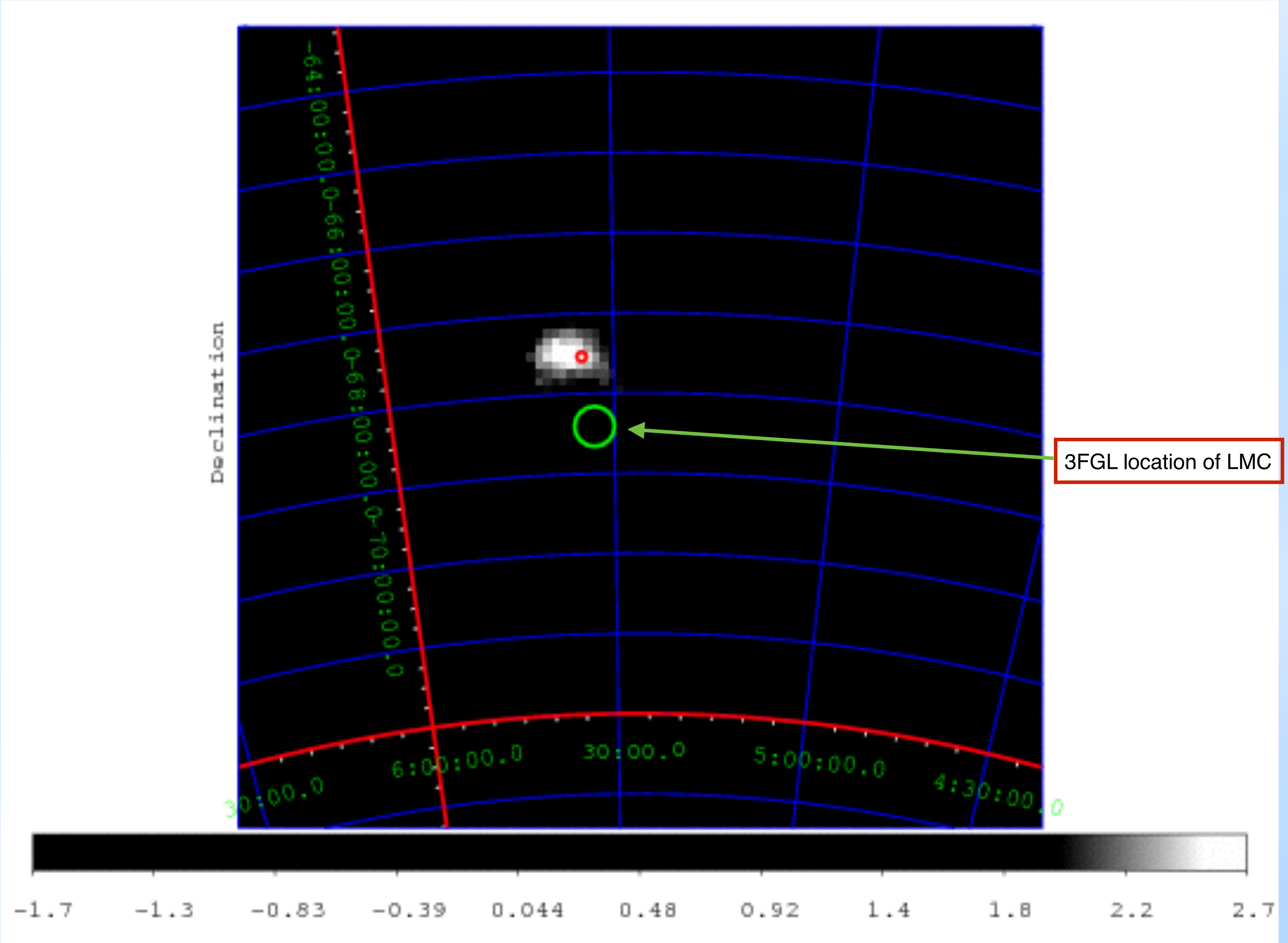
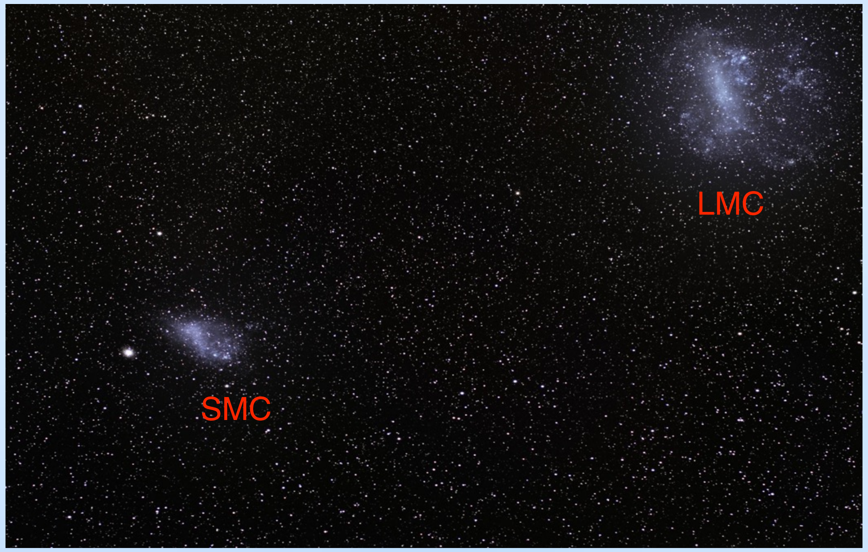


Image is difference of images at maximum phase and minimum phase for 10.3 day modulation.

The Magellanic Clouds

The Magellanic Clouds



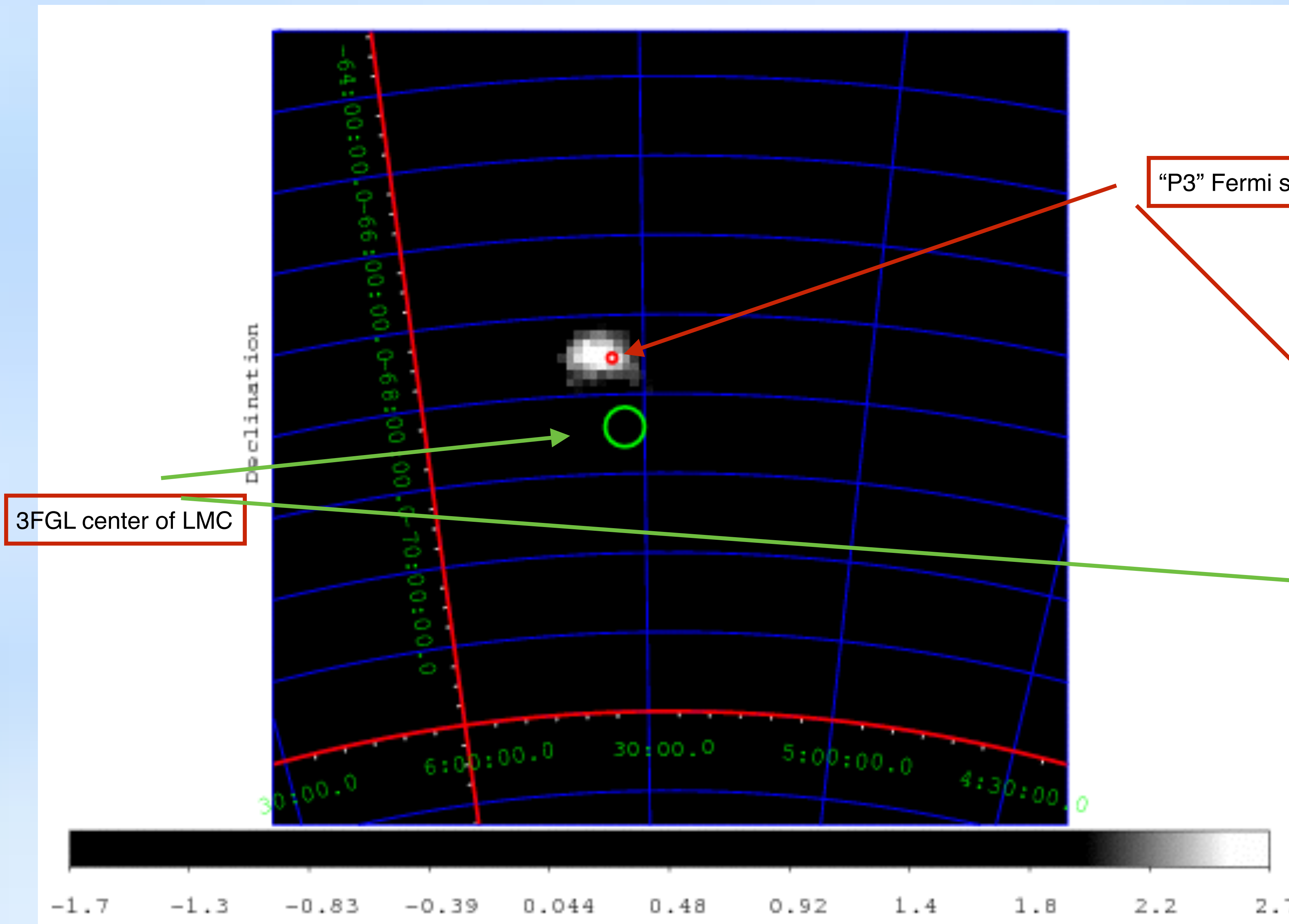
- The LMC is at a distance of ~50 kpc
- About 1% the mass of the Milky Way.
- However, star formation rate/unit mass is several times Galactic.
- The expected number of high-mass X-ray binaries depends on star formation rate, not mass. (Because lifetimes are short).

  - If gamma-ray binaries are early HMXBs, the relative population of GRBis should be similar.

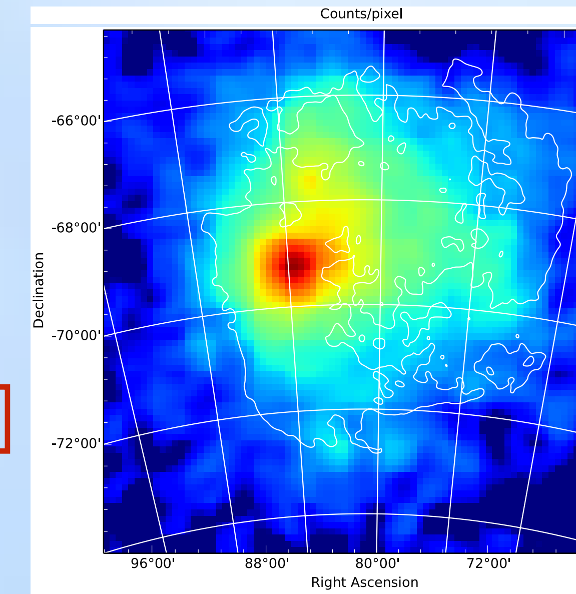
Recent Fermi Survey of LMC

- From 6 years of Fermi observations LAT team identified diffuse emission and four point-like objects in LMC (Ackermann+ 2016):
  - P1 = pulsar, PSR J0540-6919 (most luminous pulsar)
  - P2 = pulsar, PSR J0537-6910
  - P3 = ? several candidates suggested, but no good evidence
  - P4 = supernova remnant, N132D
- Our modulation map suggested we might be seeing periodic signal from "P3"…

Modulation Center
Near “P3” from New Fermi Survey



Ackermann+ 2016



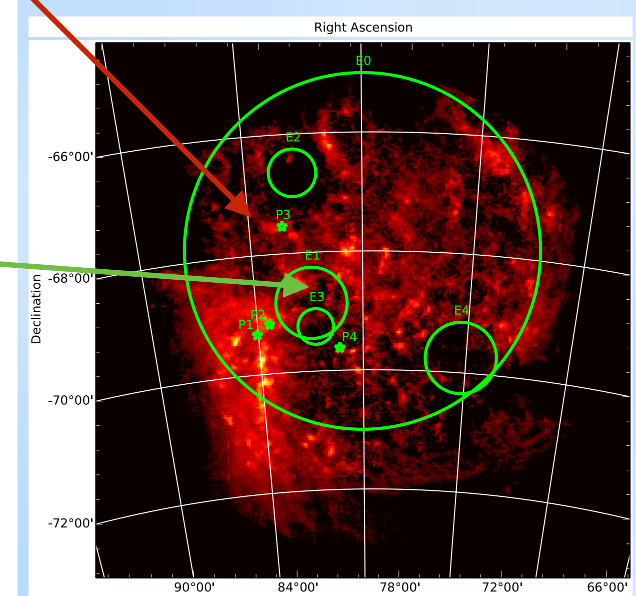
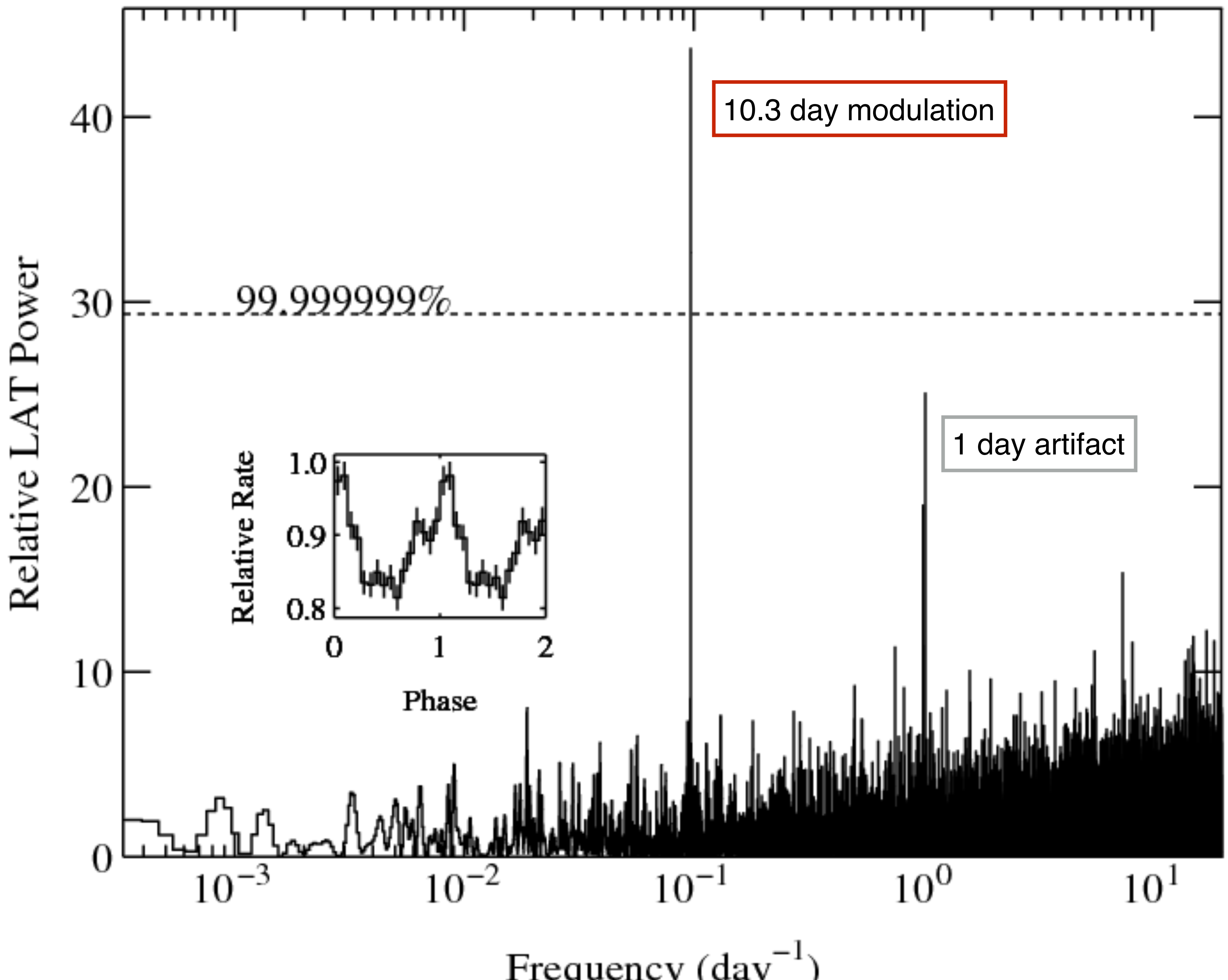


Image is difference of images at maximum phase and minimum phase for 10.3 day modulation.

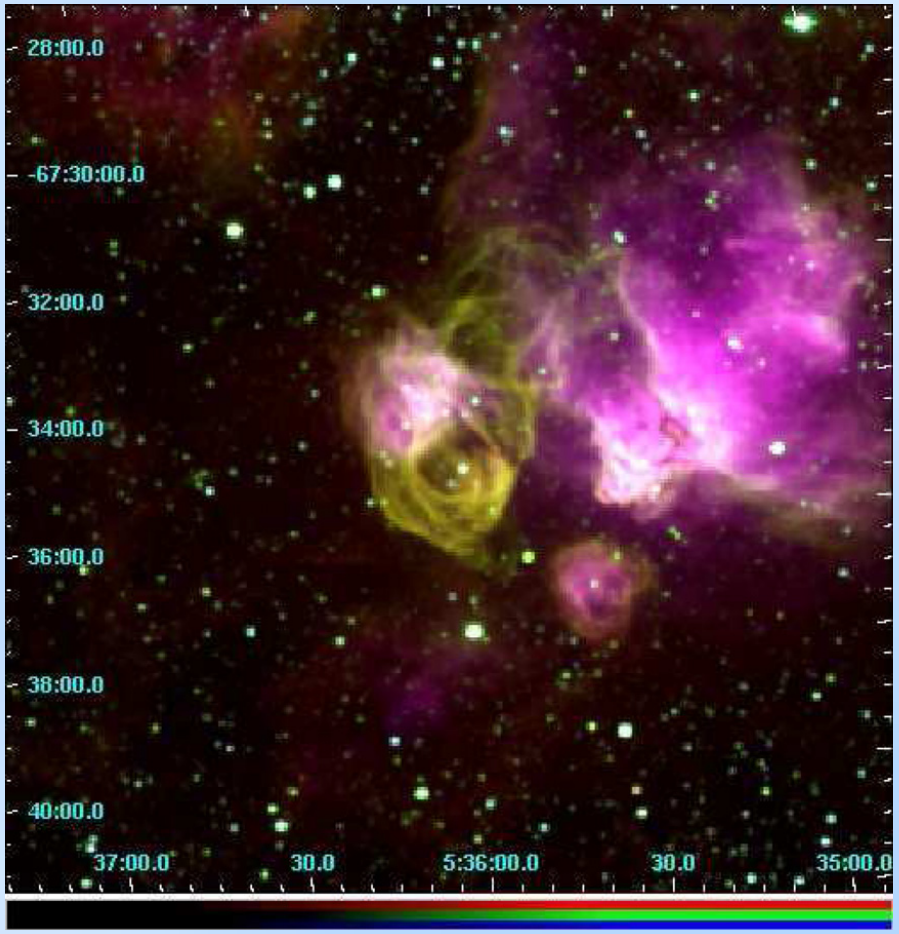
10.3 day Signal Boosted Using P3 Location



Implies the modulation as coming from “P3”. But what is P3?
This was an unassociated source in the LAT survey. (i.e., no definite counterpart)

Counterpart? HMXB Candidate in an SNR

Chandra



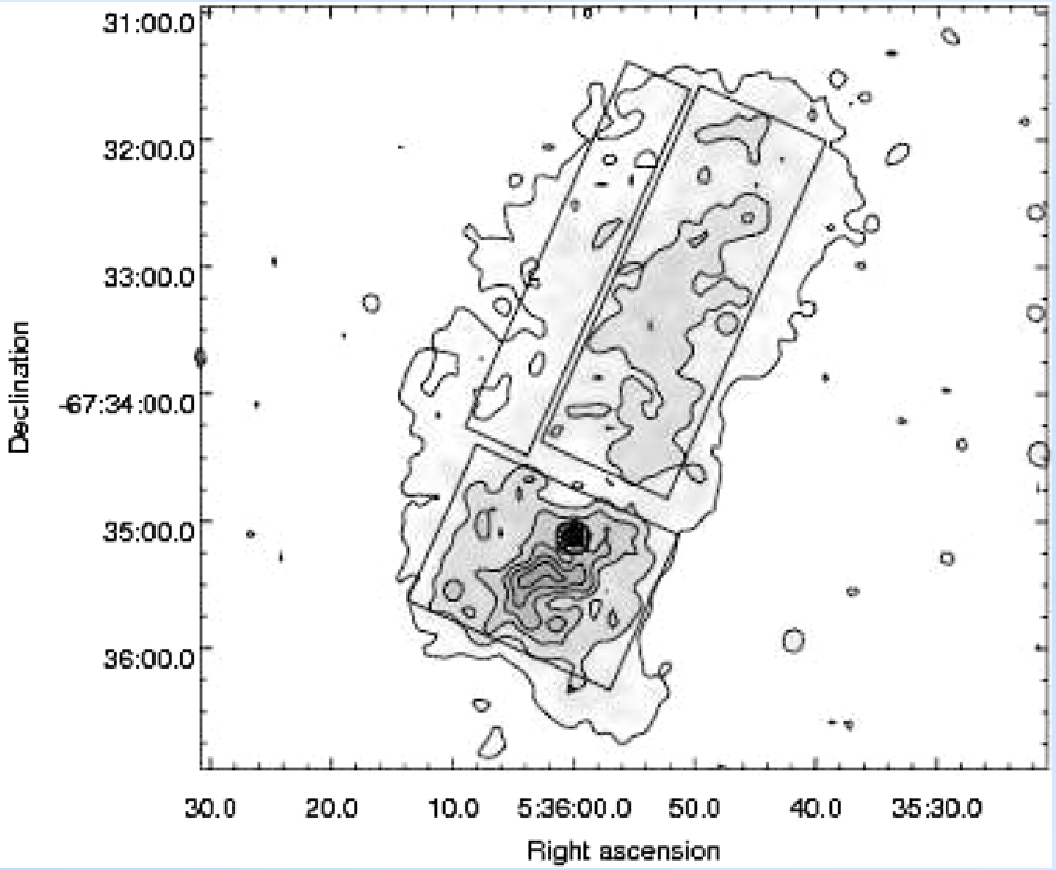


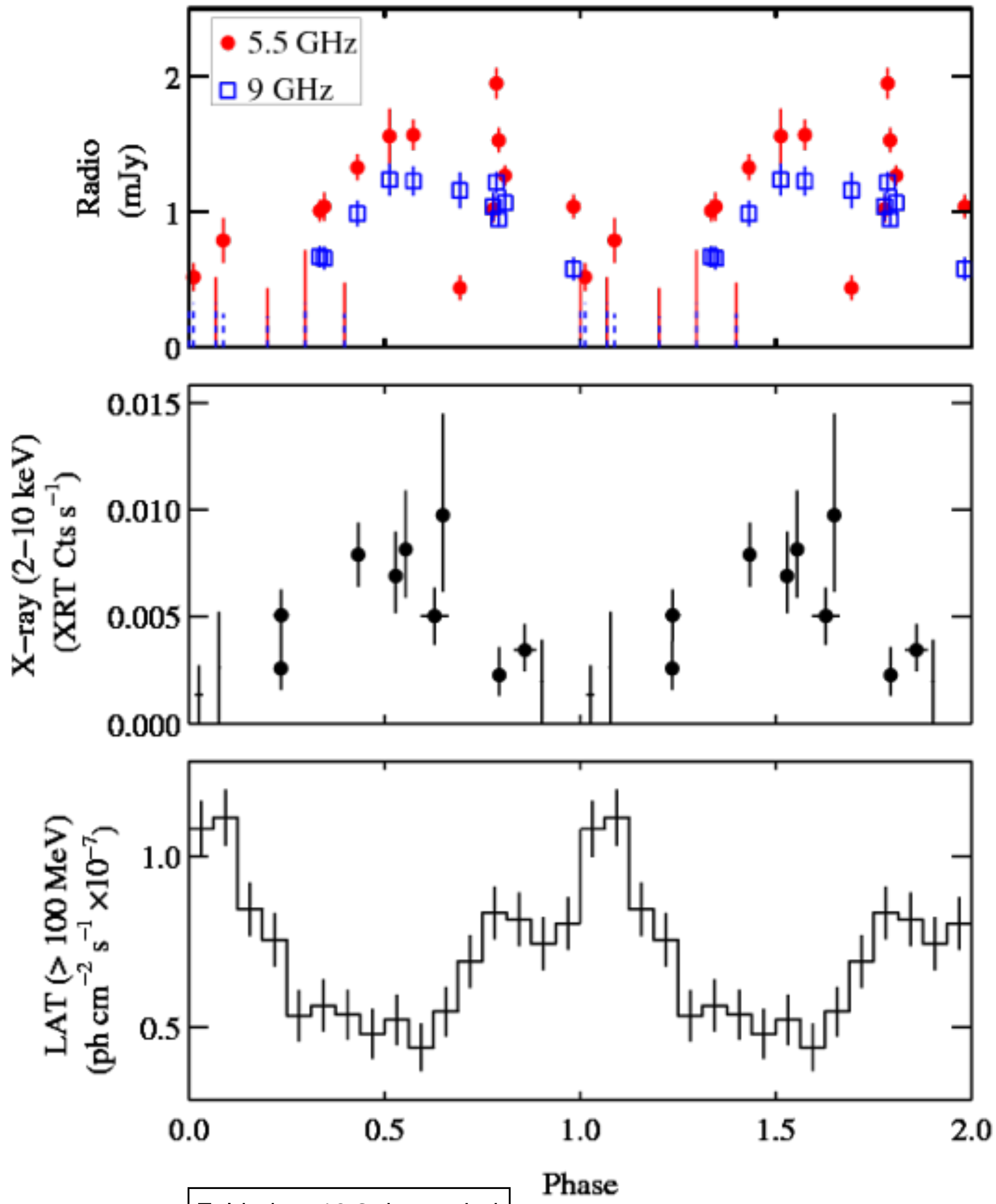
Figure 1. H II region DEM L241 showing H emission in red and [S II] emission in yellow. The [S II] emission defines the supernova remnant and correlates well with the X-rays. Figure from R. C. Smith & the MCELS Team (1999).

Seward, Charles+ (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…

Counterpart Confirmed!



Radio

X-ray

Gamma-ray

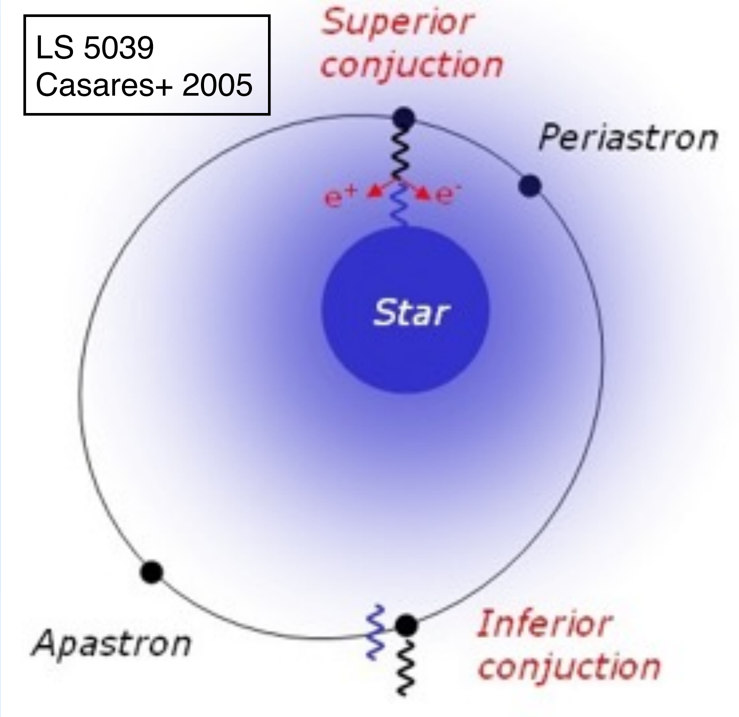
Folded on 10.3 day period

LMC P3 - A Luminous Source

- LMC P3 is at a distance of ~50 kpc.
- Compare to first binary 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 giant rather than main sequence (factor ~1.5).

<u>Origin of Orbital Modulation</u>

- 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.
  - <u>Strongest</u> gamma-ray emission expected at <u>superior</u> conjunction.

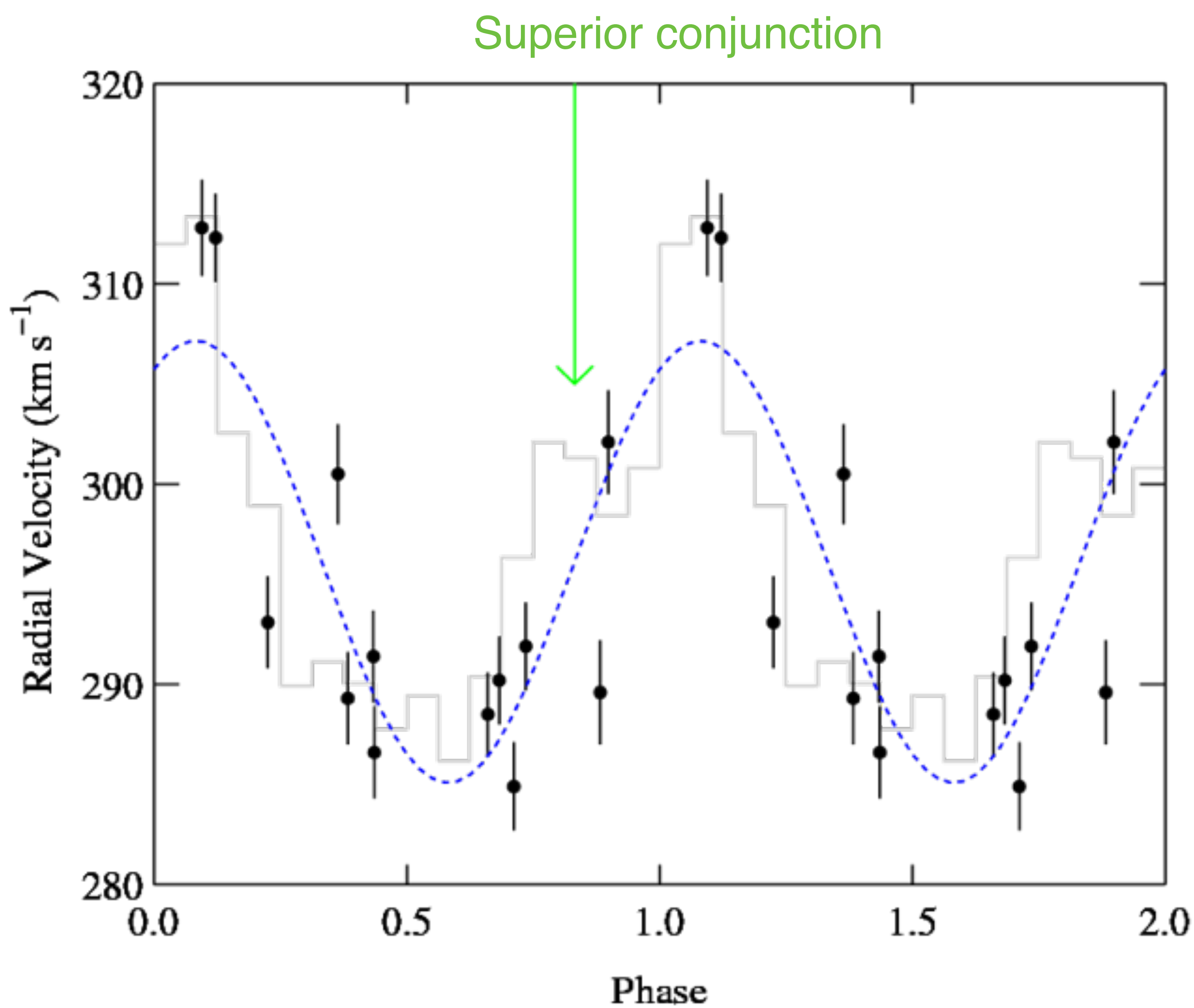


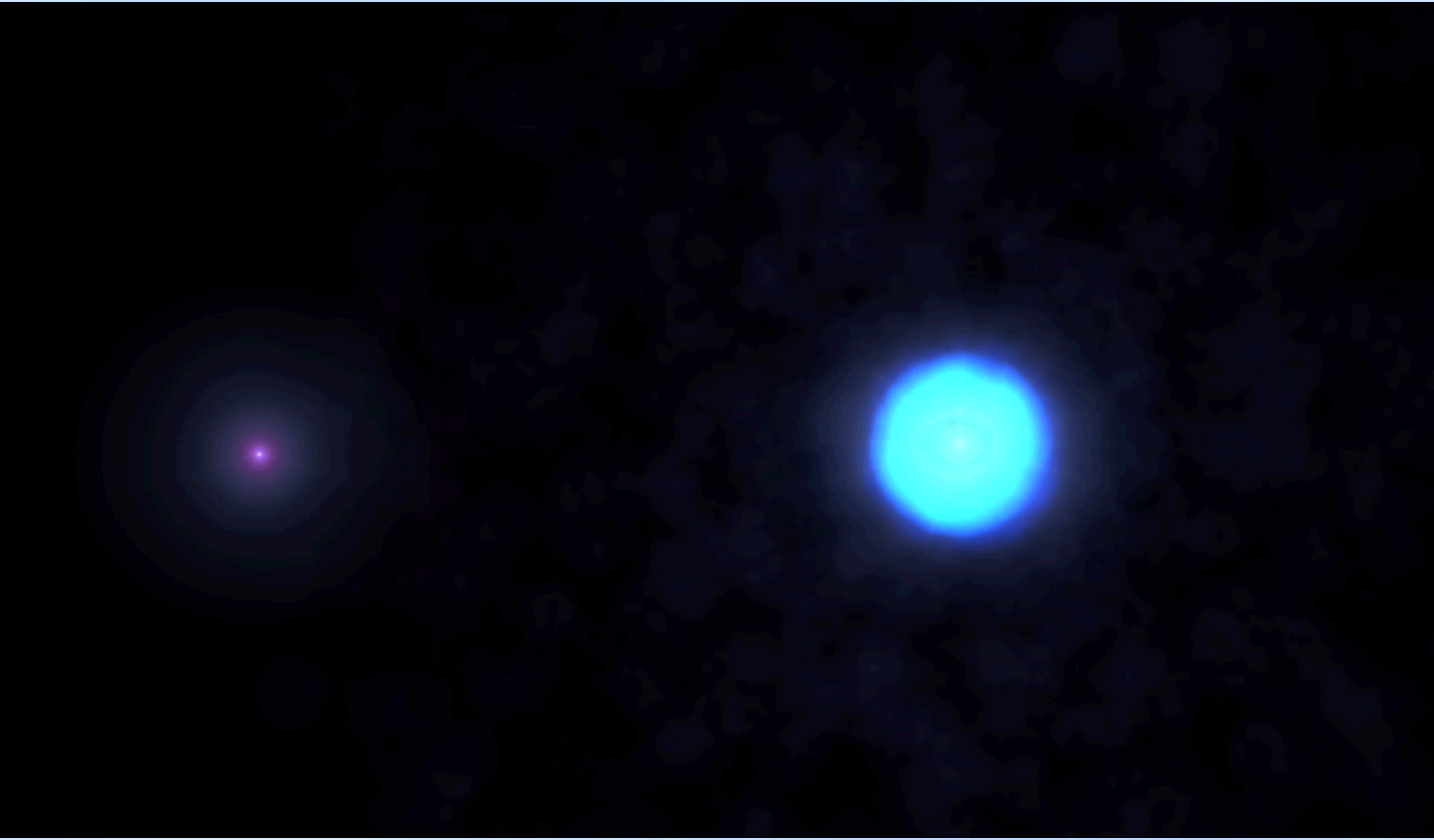
Optical Radial Velocity Measurements Favor Neutron Star

$f(M) = (1.3 +1.1, -0.6) \times 10^{-3} M_\odot$
For $1.4 M_\odot$ neutron star, $i \sim 34\text{-}63^\circ$; for $10 M_\odot$ black hole, $i = 8 \pm 2^\circ$

Gamma-ray maximum after superior conjunction.

⇒ some eccentricity?





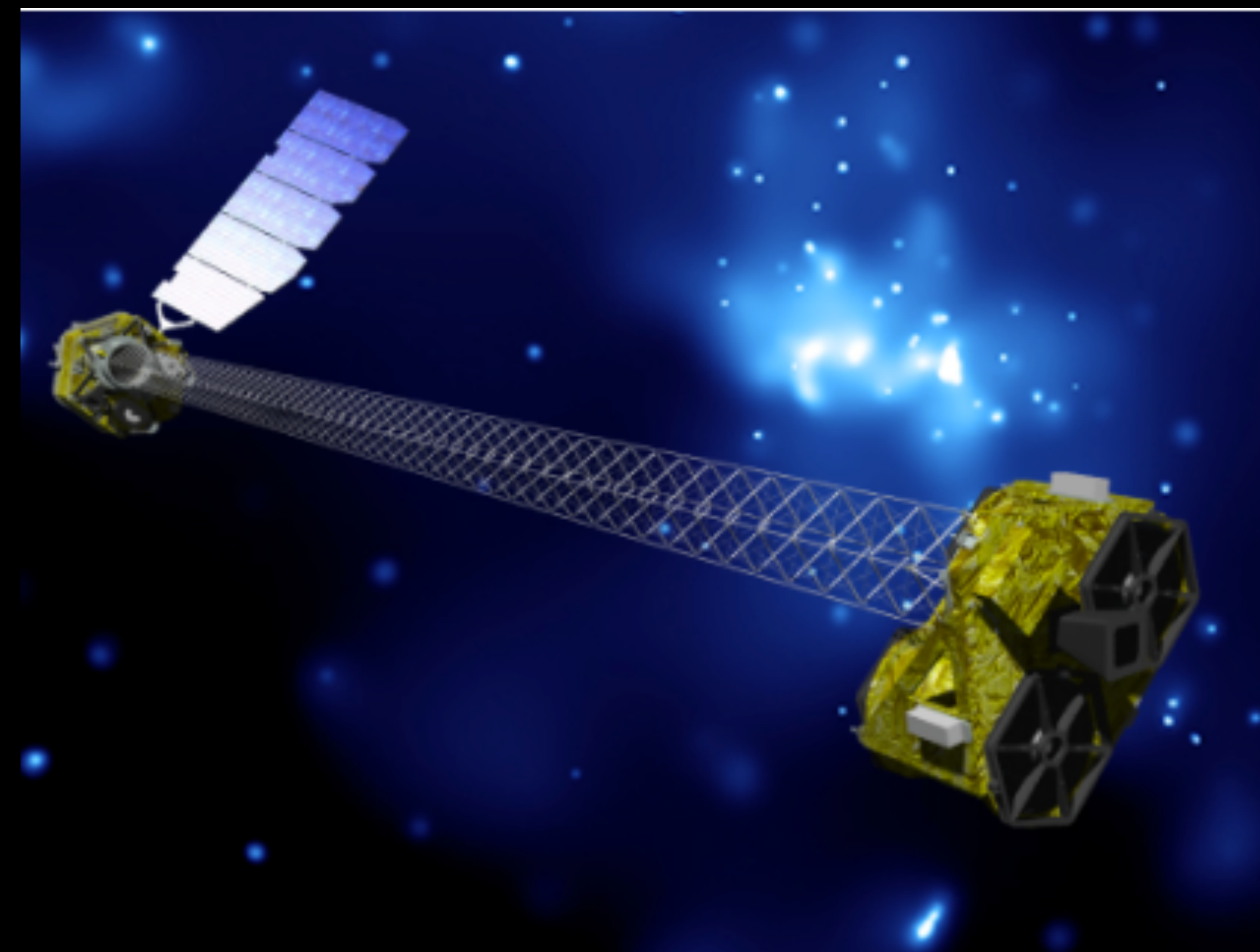
The new Gamma-Ray Binary LMC P3

- We finally have a new gamma-ray binary!
  - Second found with Fermi. First took 2 years. This took 5 more years, and improved "Pass 8" data.
- Surprisingly, it's in the LMC, not the Milky Way.
- Up to 10x more luminous than Galactic sources across a range of wavebands.
  - Neutron star is faster rotating? (P < 39 ms required).
  - Because primary is a giant, not main sequence?

Gamma-ray Binary Population

- Implications for lifetime of gamma-ray binaries? Number of gamma-ray binaries in the Milky Way?
  - Have we found all (or at least most) “classical” gamma-ray binaries in the Milky Way?
- Statistics of neutron star birth spin periods?
  - Faucher-Giguere & Kaspi derive 300 +/- 150 ms, resulting in little/no gamma-ray emission.
- Lifetimes of gamma-ray binaries?
  - Estimate of 10^5 years overestimate?
- Even this bright source would still not be visible at distance of Andromeda Galaxy. (How bright can gamma-ray binaries get?)

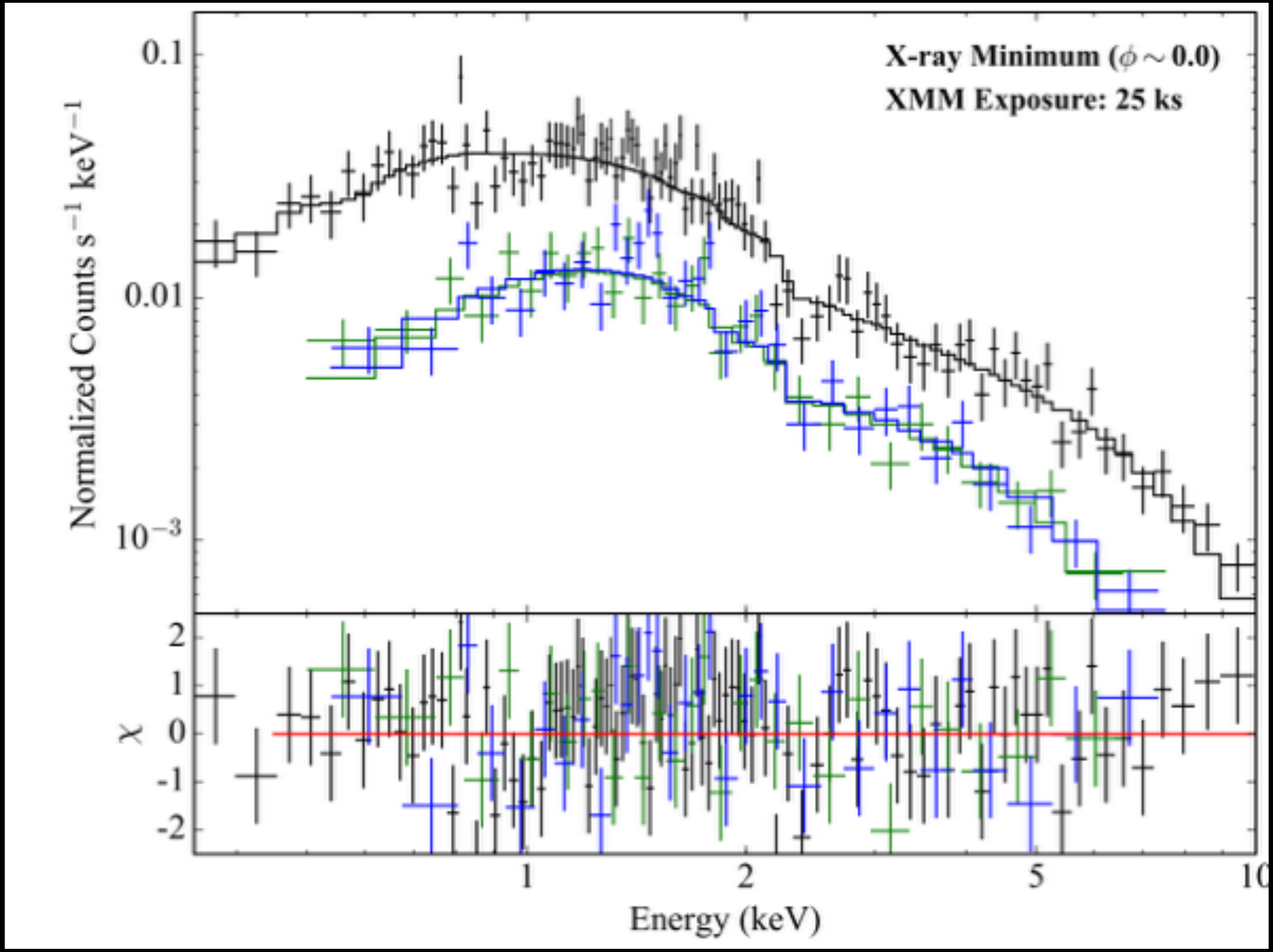
Approved AO-16 XMM and NuSTAR Observations of LMC P3 (Coley et al.)

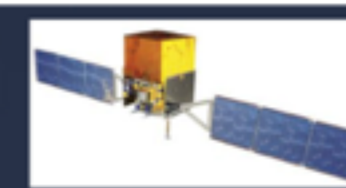
- Investigate phase dependence of N_H, Γ, and X-ray flux
- Search for possible neutron star rotation period with EPIC-pn
- Measure Γ and X-ray flux out to 40 keV (NuSTAR)

Image Courtesy: http://sci.esa.int/xmm-newton/18015-xmm-newton-spacecraft/

XMM-Newton Simulated Spectrum



- Three Observations: X-ray Max, X-ray Min, Inferior Conjunction
- Estimated Uncertainties on Γ and flux better than 5% and 8%
- Three Measurements of N_H



A Multi-Wavelength Study of the Gamma-Ray Binary 1FGL J1018.6-5856

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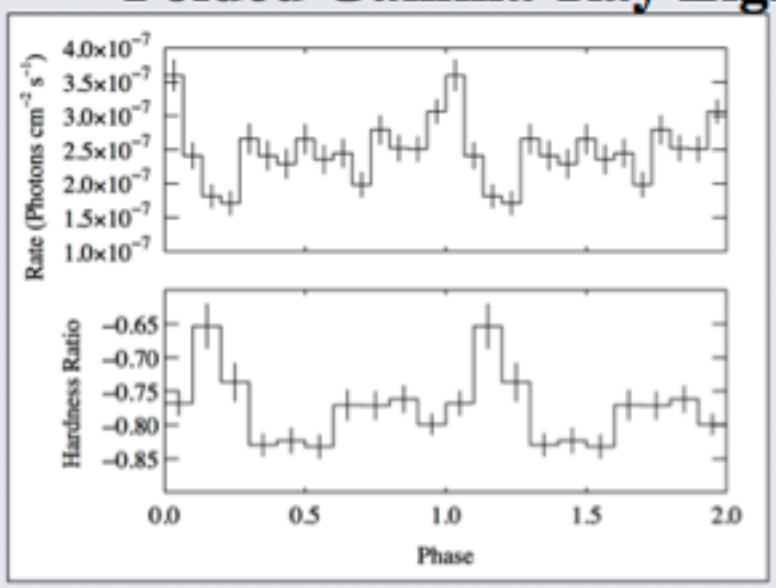
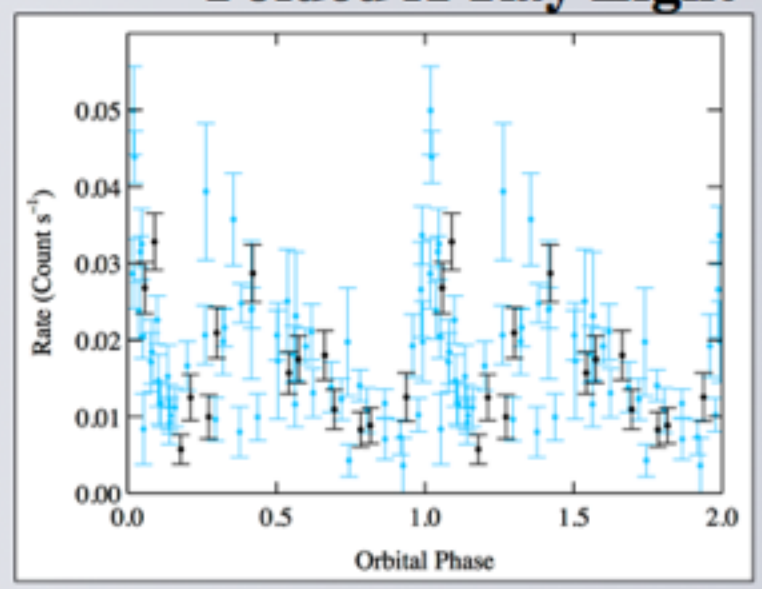
1FGL J1018.6-5856, the first gamma-ray binary discovered by the Fermi Large Area Telescope (LAT), consists of an O6 V(f) star and suspected rapidly spinning neutron star. While 1FGL J1018.6-5856 has been postulated to be powered by the interaction between a relativistic pulsar wind and the stellar wind of the companion, a microquasar scenario where the compact object is a black hole cannot be ruled out. We present the first extensive multi-wavelength analysis of 1FGL J1018.6-5856 with the Australia Telescope Compact Array (ATCA), Fermi LAT and the Swift X-ray Telescope to better study the emission properties over the 16.531±0.006 day orbital modulation. The radio amplitude modulation is found to decline with increasing frequency, which is a possible indication of free-free absorption. This is further supported by the absence of clear modulation in the highest-frequency, 33.0 and 35.0 GHz bands, which were not previously reported. The best-fit spectral model of the Swift XRT data consists of a single powerlaw with photon index 1.3—1.7 modified by an absorber that fully covers the source. This is possible evidence that 1FGL J1018.6-5856 is a non-accreting system.

Folded Gamma-Ray Light Curve



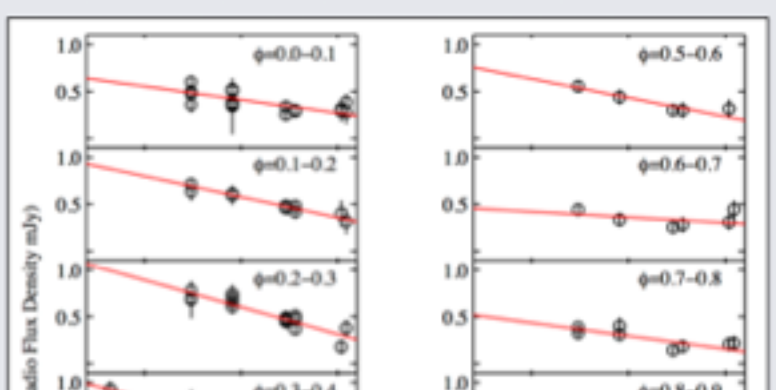
Fermi LAT light curve in the 0.1-300 GeV band (top) based on a likelihood analysis folded on the 16.5 day orbital period. The hardness ratio (bottom) is produced taking the results from the likelihood analyses of the soft and hard energy bands, 0.1-1 GeV and 1-300 GeV, respectively.

Folded X-Ray Light Curve



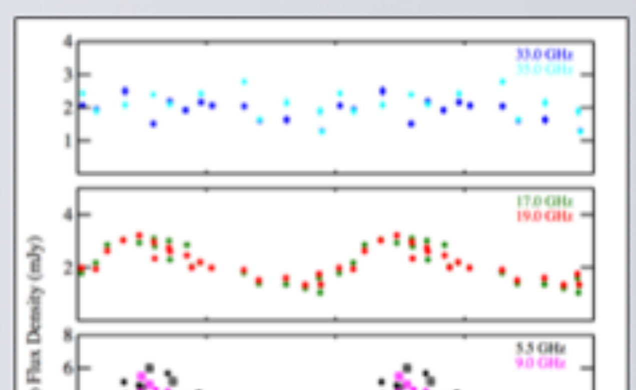
Swift XRT X-ray light curves folded on the orbital period. The light blue data is prior to MJD 55984[1,2]. The black data points after MJD 55984[2,3,4]. The modulation a sharp maximum at phase 0 and a broad maximum phase ~0.4. This is consistent with previous observations[1,2,5].

Phase-Resolved Radio Spectra



Orbital phase-resolved ATCA radio spectra covering frequencies in the 2.1-35.0 GHz band. The red lines indicate the best fit for a power-law model, which is a possible indication of free-free absorption.

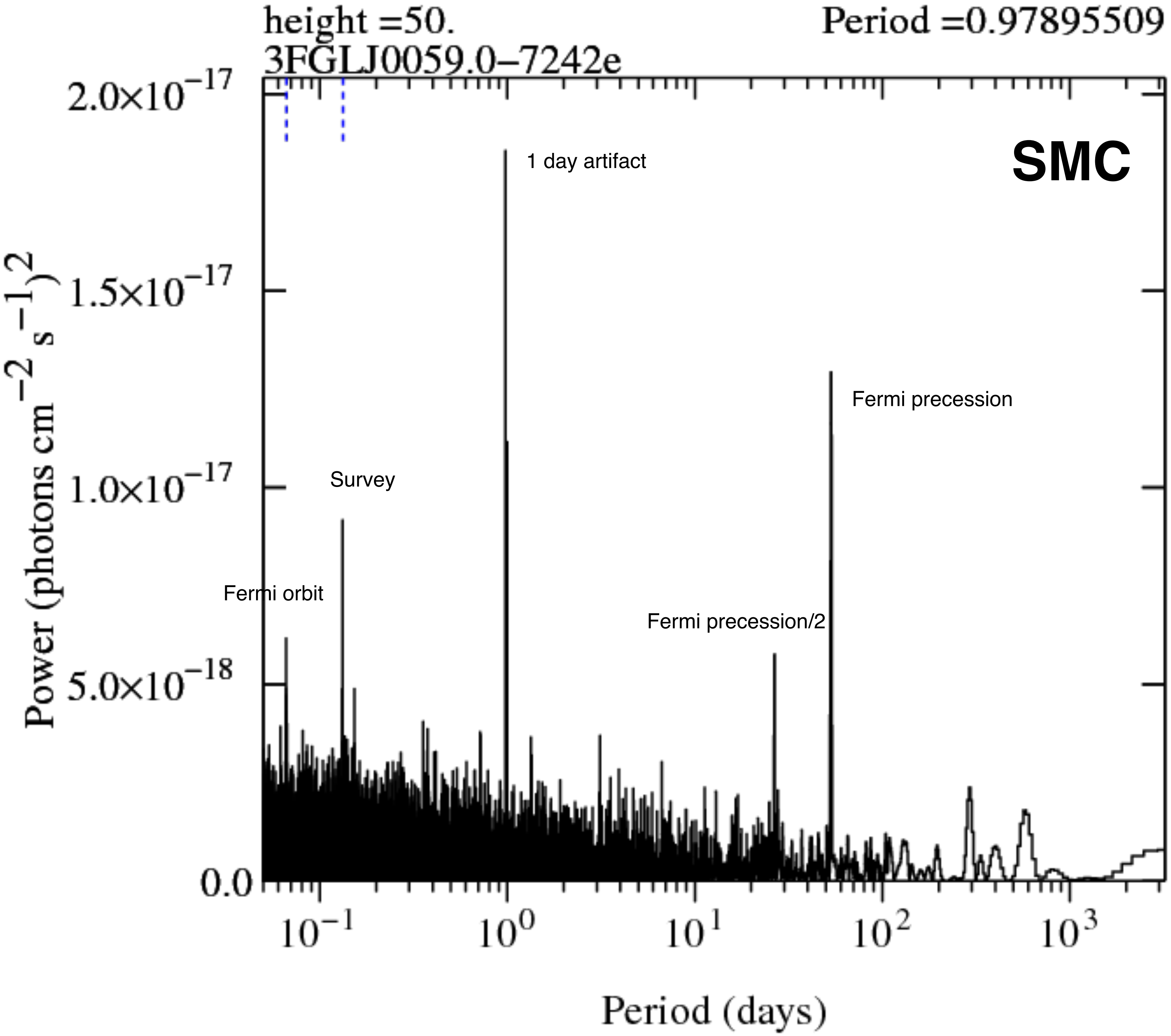
Folded Radio Light Curves



ATCA radio light curves folded on the orbital period. A broad maximum is found at phase 0.4. The amplitude modulation decreases with increasing frequency. Light curves at 33.0 and 35.0 GHz do not show clear modulation on the orbital period[4].

Other Nearby Galaxies: SMC

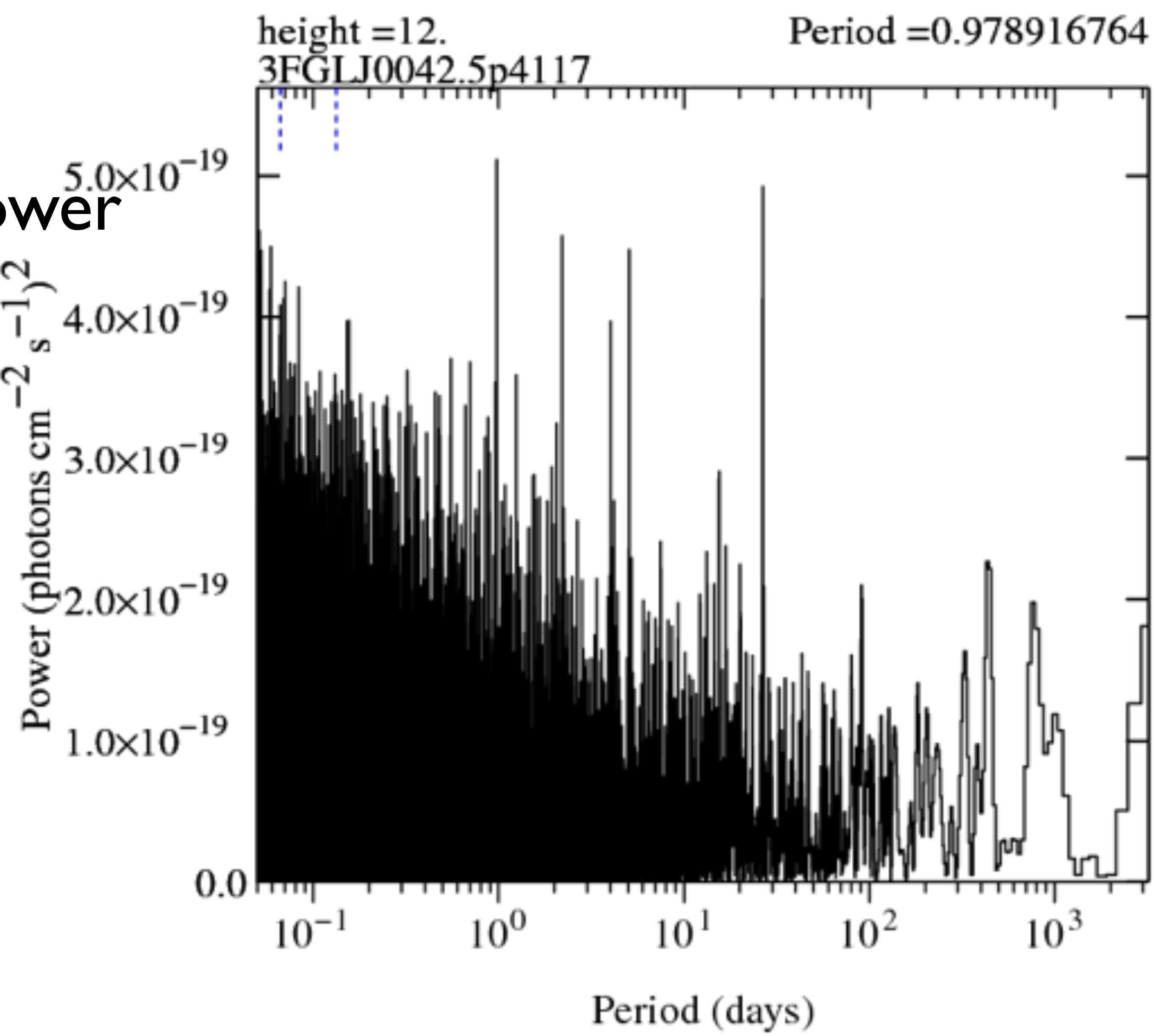
- We had a surprise with the LMC, what about our other neighbors?
- The SMC less massive than LMC, but has an overabundance of Be star high-mass X-ray binaries.
    - Suggests burst of star formation several million years ago.
    - Also one supergiant binary: SMC X-1
- In 3FGL the SMC is listed as a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



- Nothing in SMC power spectrum so far. (Only artifacts)
- But with better model of SMC with individual sources?
- As observation length increases, see long period systems?

Other Nearby Galaxies: Andromeda

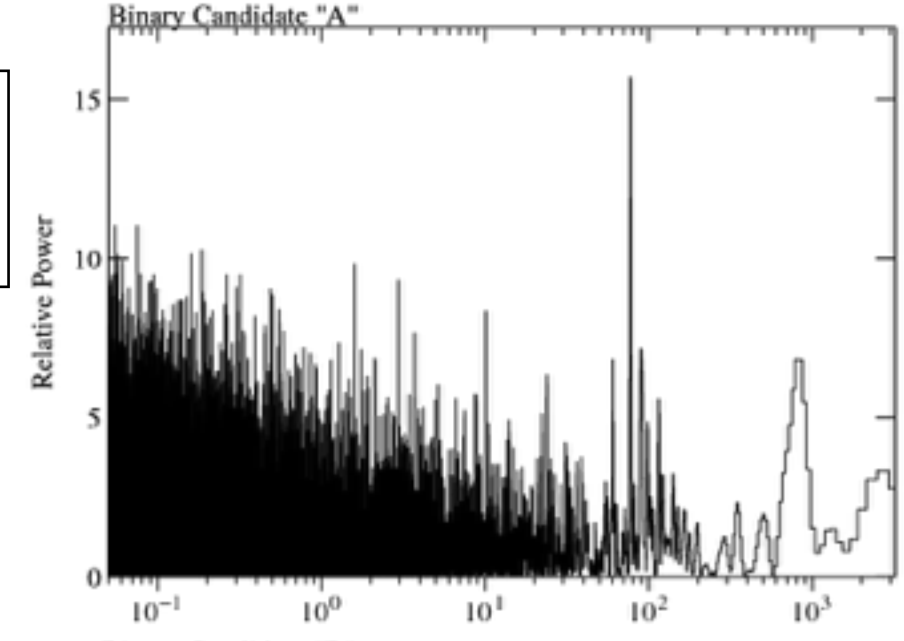
- The Andromeda galaxy (M31) is > 10x greater distance than the LMC (~780 kpc).
- So, don't expect binary systems to be detectable… But ought to look!
- Unsurprisingly, nothing seen.
- Will continue to monitor power spectrum.



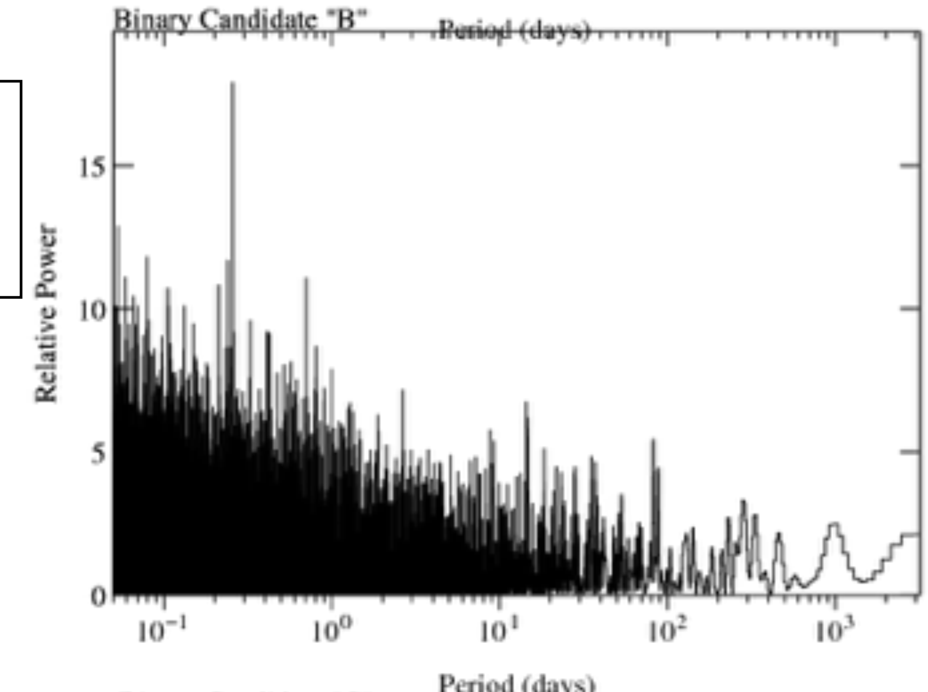
Work in Progress: Marginal Candidates

- From our 3033 power spectra we to search for signs of other binaries.
- Concentrate on sources:
  - (i) close to the Galactic plane
  - (ii) candidate periods > 1 day. (high-mass systems, reduced search frequencies)
- Three sources of potential interest.
- Statistical significance is modest.
- We are using multi-wavelength approach (that worked for J1018.6 and LMC P3) :
  - (i) find radio and X-ray counterparts
  - (ii) search for consistent modulation in multi-wavelength counterparts

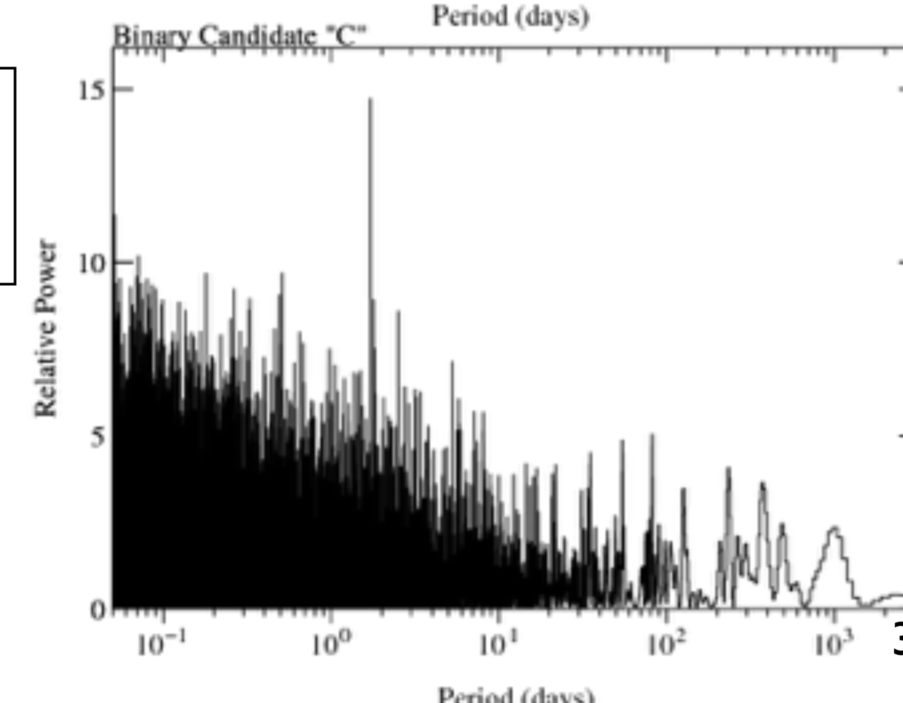
"A": P ~ 80 days (Be-like period)
Significance ~1%
b = -1.1 degrees



"B": P ~ 0.25 days (Cyg X-3 like period, lacks bright X-ray counterpart)
Significance ~0.1%
b = 0.8 degrees



"C": P ~ 1.7 days
Significance ~2%
b = 0.05 degrees, near Supernova Remnant



Note: significances **only** based on number of **frequencies** searched.
Does **not** take account of **number of sources**.

Future Prospects

- The "4FGL" LAT source catalog is anticipated for later this year.
- The LAT team is also updating the model for the diffuse emission from the Galactic plane.
- These will result in:
    - (i) Better models for existing sources.
    - (ii) An large number of new sources.
- We will have both higher signal-to-noise light curves of known sources, and many new sources to search for signs of binary modulation.
- Pass 8 gave us one more binary, will 4 FGL give us another one?!