Neutron Star Seismology with Accreting Millisecond Pulsars

Simin Mahmoodifar

NASA/GSFC

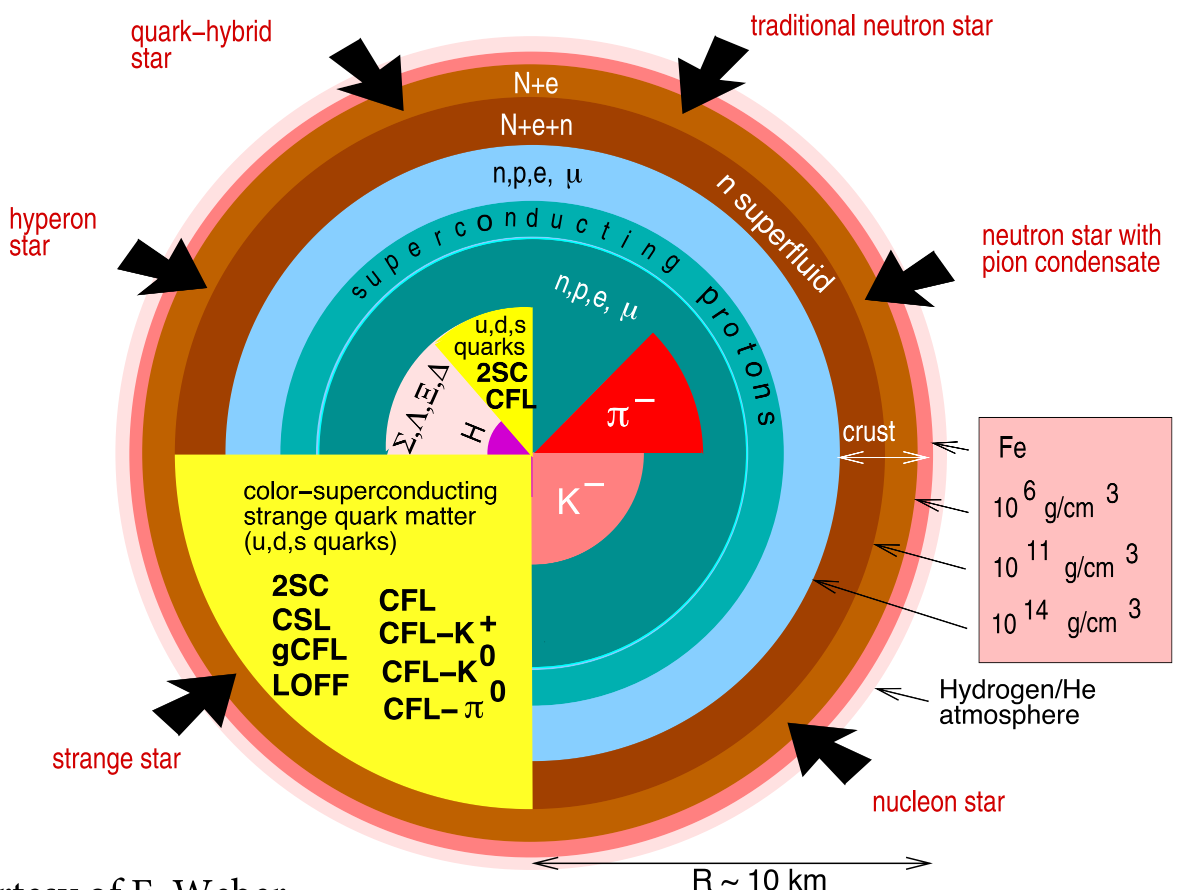
June 26, 2015

with Tod Strohmayer (NASA/GSFC).

NASA POSTDOCTORAL PROGRAM

Administered by Oak Ridge Associated Universities

Compact Stars: The only "laboratory" for the study of cold ultra-dense matter



Courtesy of F. Weber

They may contain exotic forms of matter that are predicted to exist at supranuclear densities.

Dynamic properties of NSs, such as their spin and temperature evolution as well as stellar oscillations can be powerful probes of NS interiors.

- Mass-Radius depends on the EoS
- **Transport properties** (e.g. emissivity, viscosity (shear, bulk), conductivity (electrical, thermal), . . .) depend on the **low energy degrees of freedom**

Non-radial oscillations of neutron stars

Pressure modes (p-modes and **f-modes)**: frequencies in the **1000-10000 Hz** range. Powered by internal pressure fluctuations.

Shear-dominated modes (**t-modes** and **s-modes**): frequencies **larger than ~30 Hz**. The overtones in the **kHz range**.

Gravity modes (g-modes): frequencies in the **1-100 Hz** range (in the slow rotation limit), buoyancy as their restoring force.

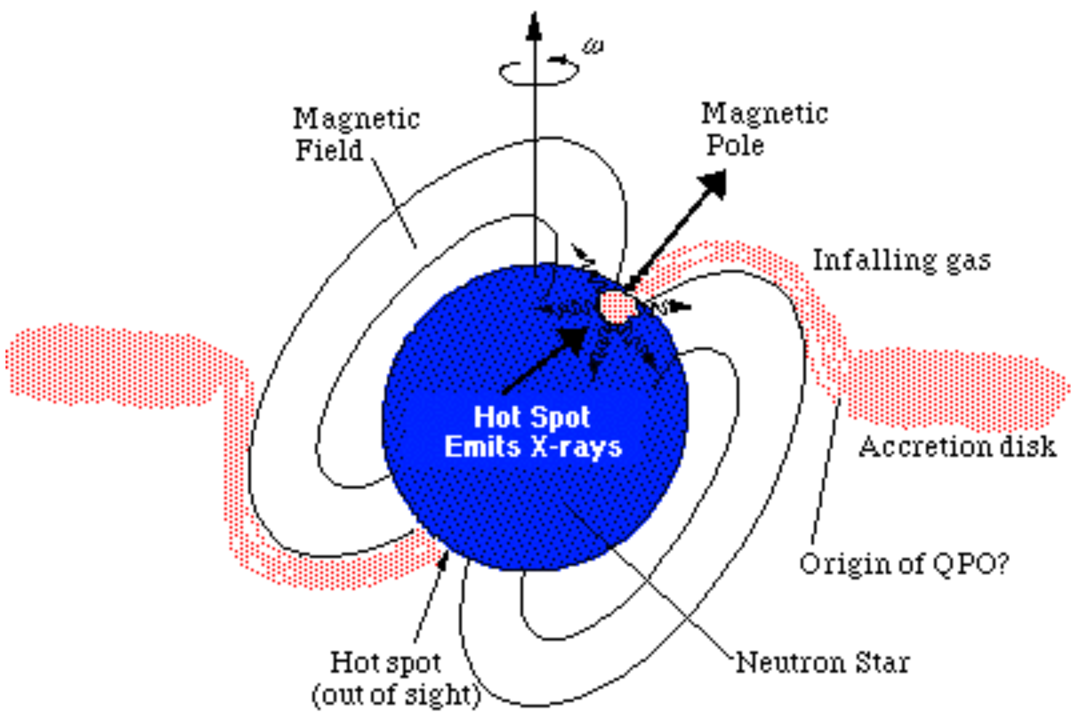
Inertial modes: Appear in a rotating star. The restoring force of the pulsations is provided by the Coriolis force. They have both significant toroidal (axial) and spheroidal (polar) angular displacements.

r-modes: A well-known subset of the inertial modes. They are principally toroidal (axial). The pressure and energy density perturbations are small compared to the velocity perturbations.

$$\omega_r = 2m\Omega/(l(l+1))$$

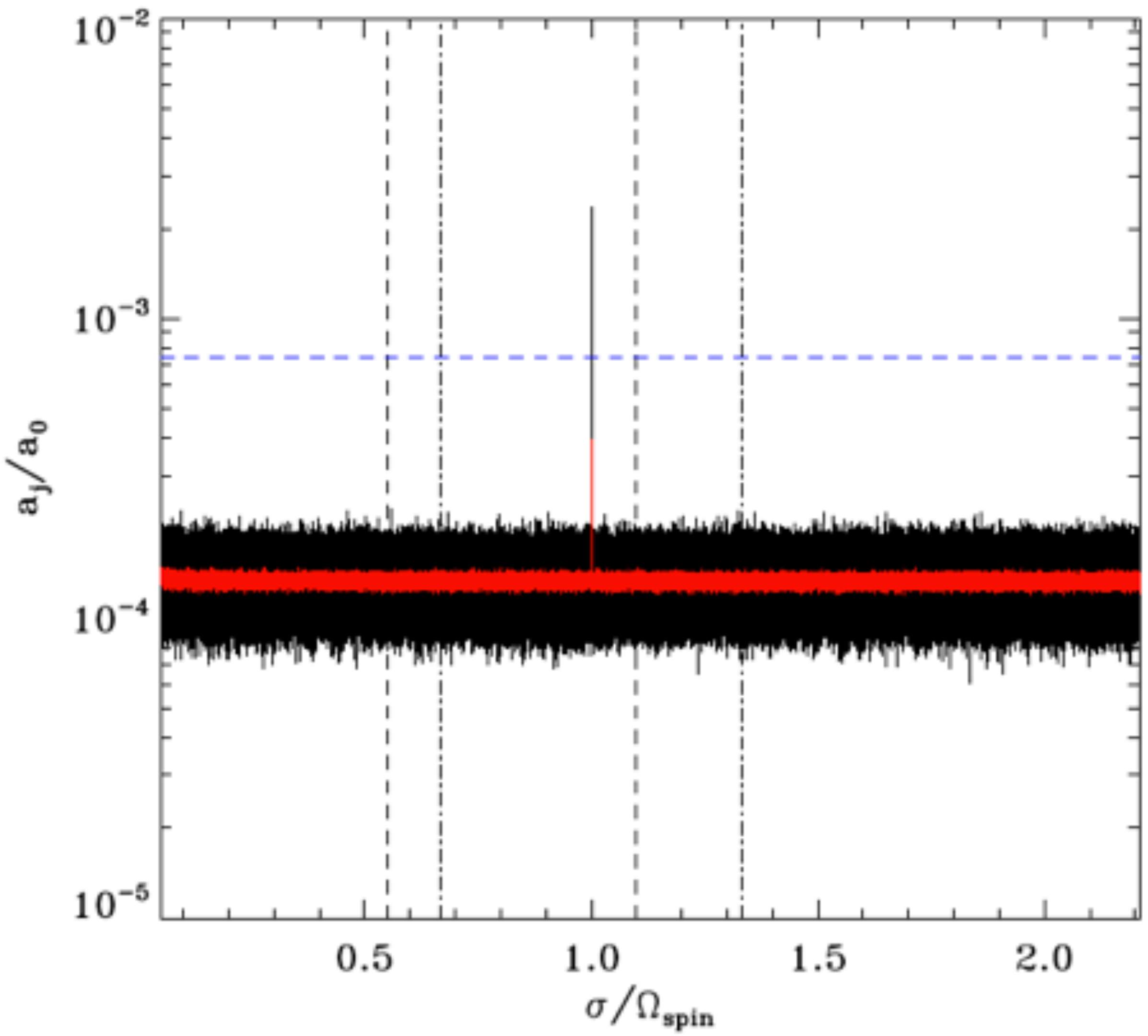
Accreting Millisecond X-ray Pulsars

Accretion stream close to spin axis –> X-ray hot-spot
Spin modulation –> pulsations
(Lamb et al. 2009, Patruno & Watts 2011)



http://imagine.gsfc.nasa.gov

Accretion-powered millisecond X-ray pulsars (AMXPs) show small-amplitude X-ray oscillations with periods equal to their spin periods.



How the presence of non-radial oscillations might be inferred from observations?

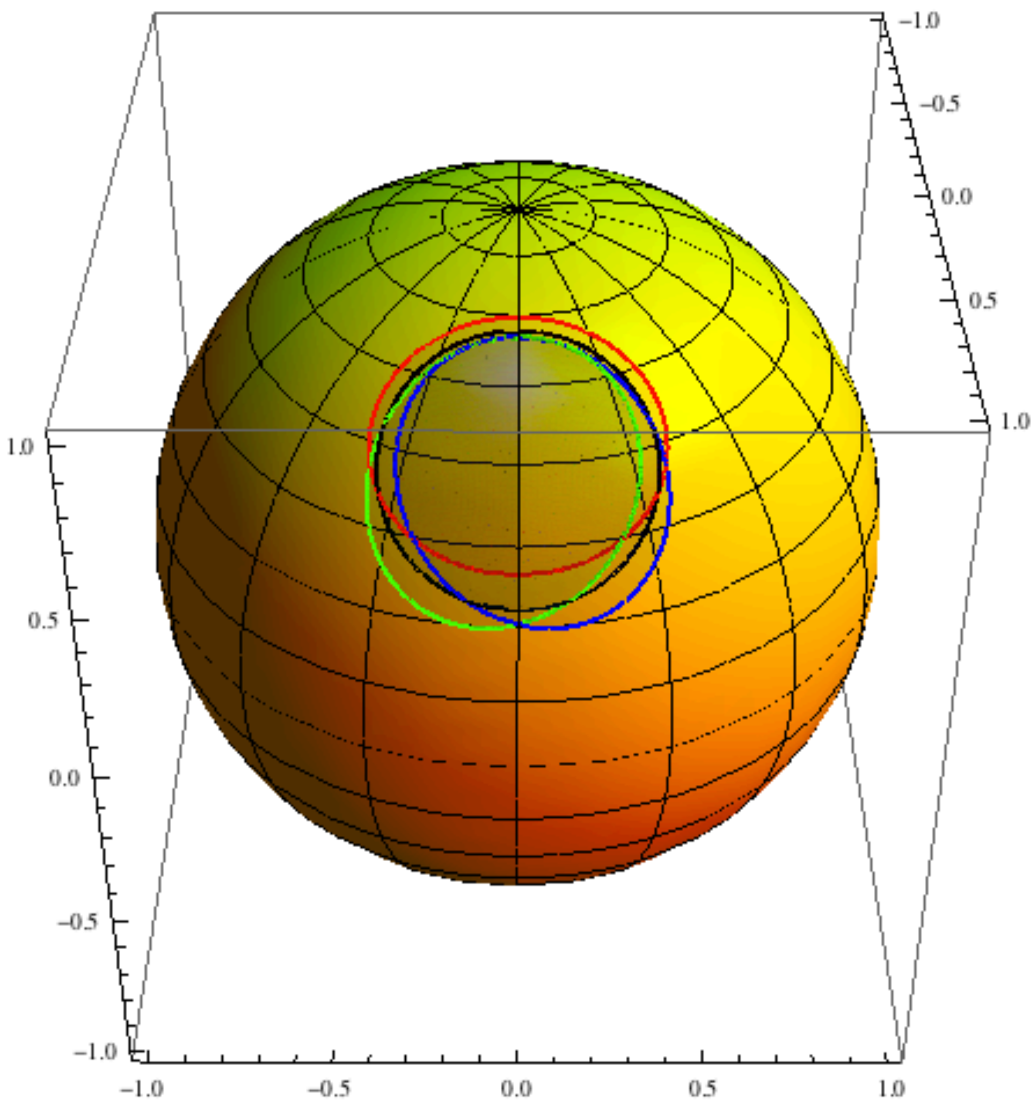
1) Pulsation modes can **modulate the temperature distribution** across the neutron star surface, coupled with spin can produce flux modulation at mode's **inertial frame** frequency.

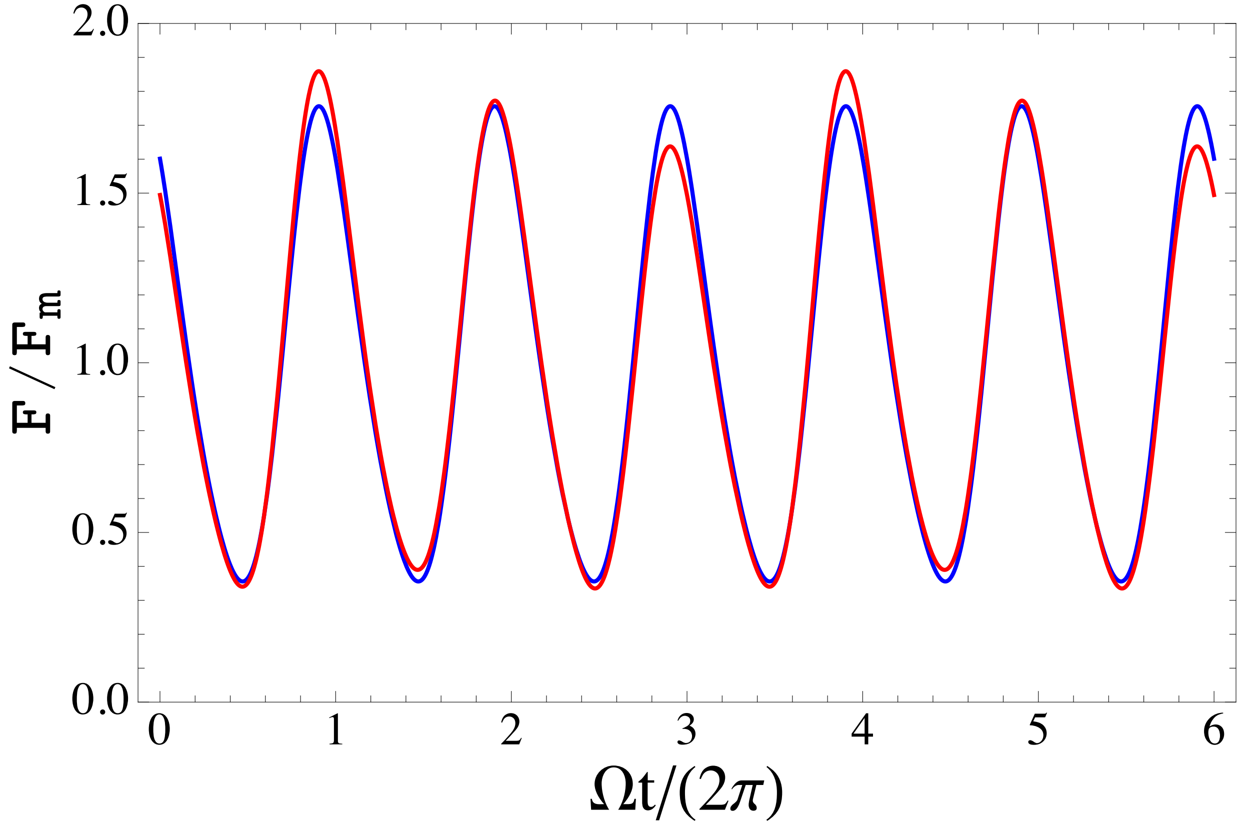
2) Surface motions induced by a particular oscillation mode can **perturb the X-ray emitting hot-spot**.

- Since hot-spot rotates with the star, the modulation frequency seen by a distant observer is the **co-rotating frame** frequency.

- **Most relevant for quasi-toroidal modes** (such as the r- and g-modes) in which the dominant motions are transverse.

Outer boundary of a deformed hot-spot





- Surface displacements generated by pulsation modes can periodically distort the X-ray emitting hot-spot (Numata & Lee 2010).

- Distortion is maximized for modes with dominant transverse (quasi-toroidal) displacements, such as g-modes and r-modes.

- Light curves produced by an unperturbed (circular) hot-spot (blue) and one perturbed by the l=m=2 r-mode (red).

- $\nu_{spin} = 435$ Hz, $M = 1.4 M_\odot$, R = 11 km, Observer's inclination angle= $\pi/3$.

Pulsation Searches using RXTE archival data:

XTE J1751-305

435 Hz spin frequency
42.4 min orbital period

XTE J1814-338

314.36 Hz spin frequency
4.275 hr orbital period

NGC 6440 X-2

205.89 Hz spin frequency
57 min orbital period

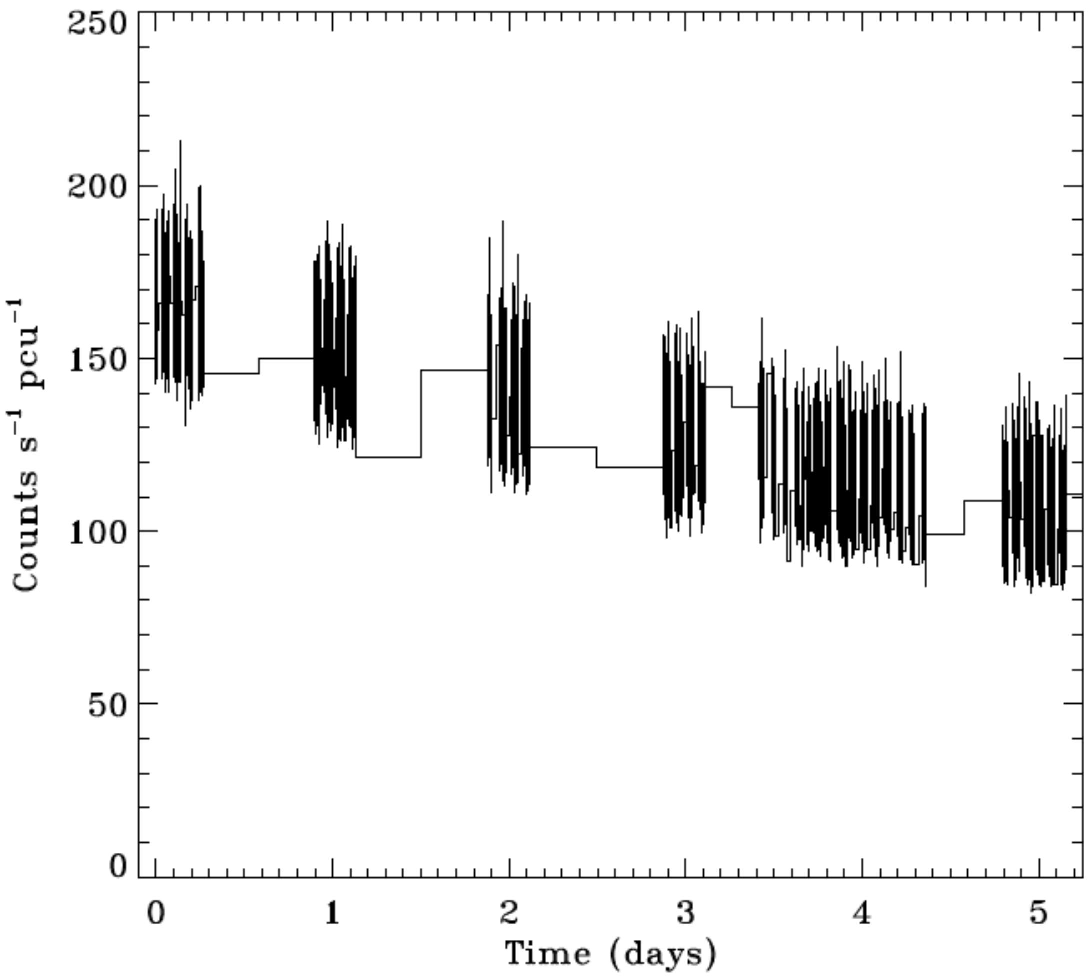
SAX J1808.4-3658

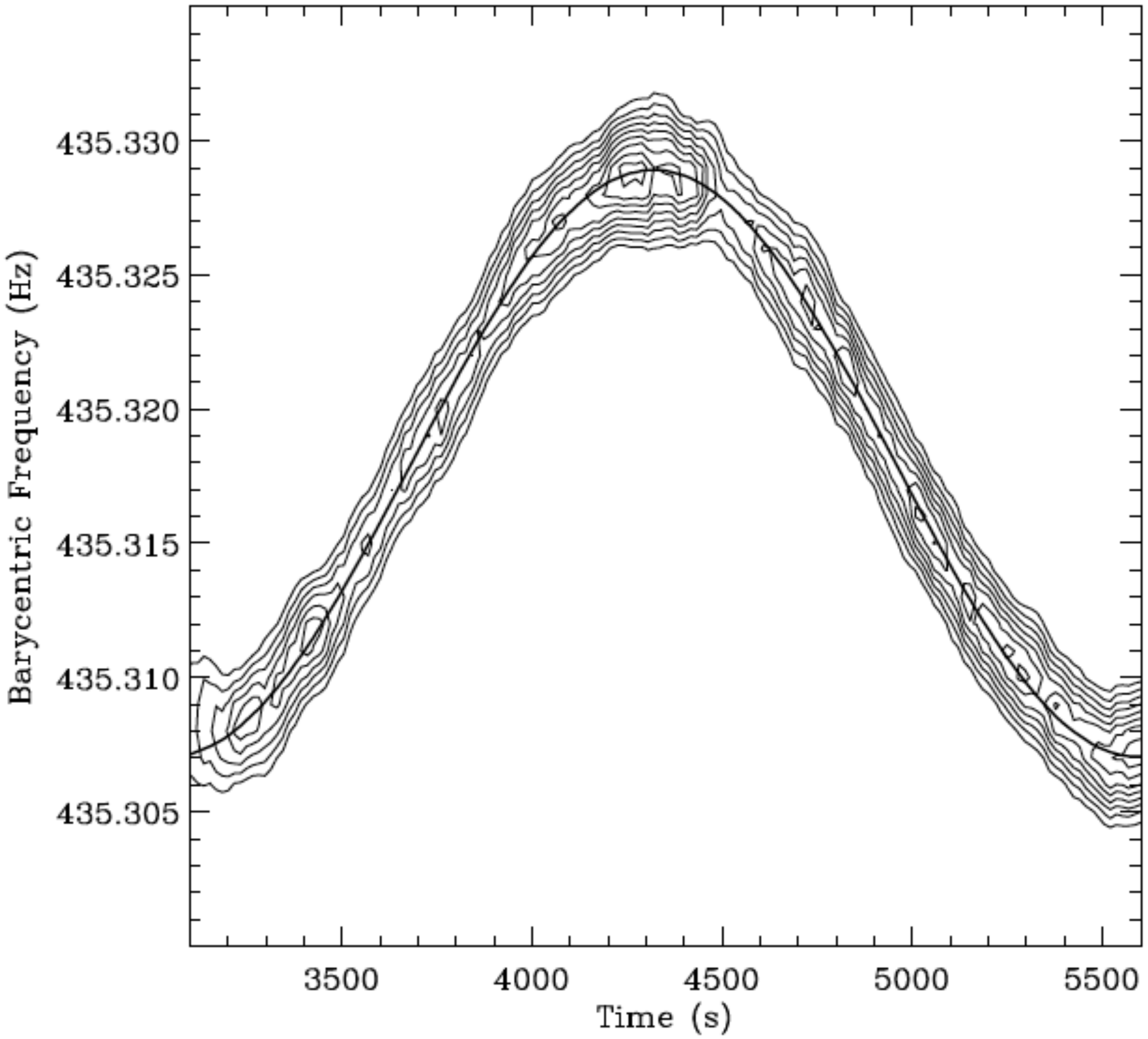
400.975 Hz spin frequency
2.014 hr orbital period

4U 1636-536

582 Hz spin frequency
3.8 hr orbital period

XTE J1751-305 (2002 outburst)





- Light curve in the 2 - 60 keV band from XTE J1751-305 used in our pulsation search.

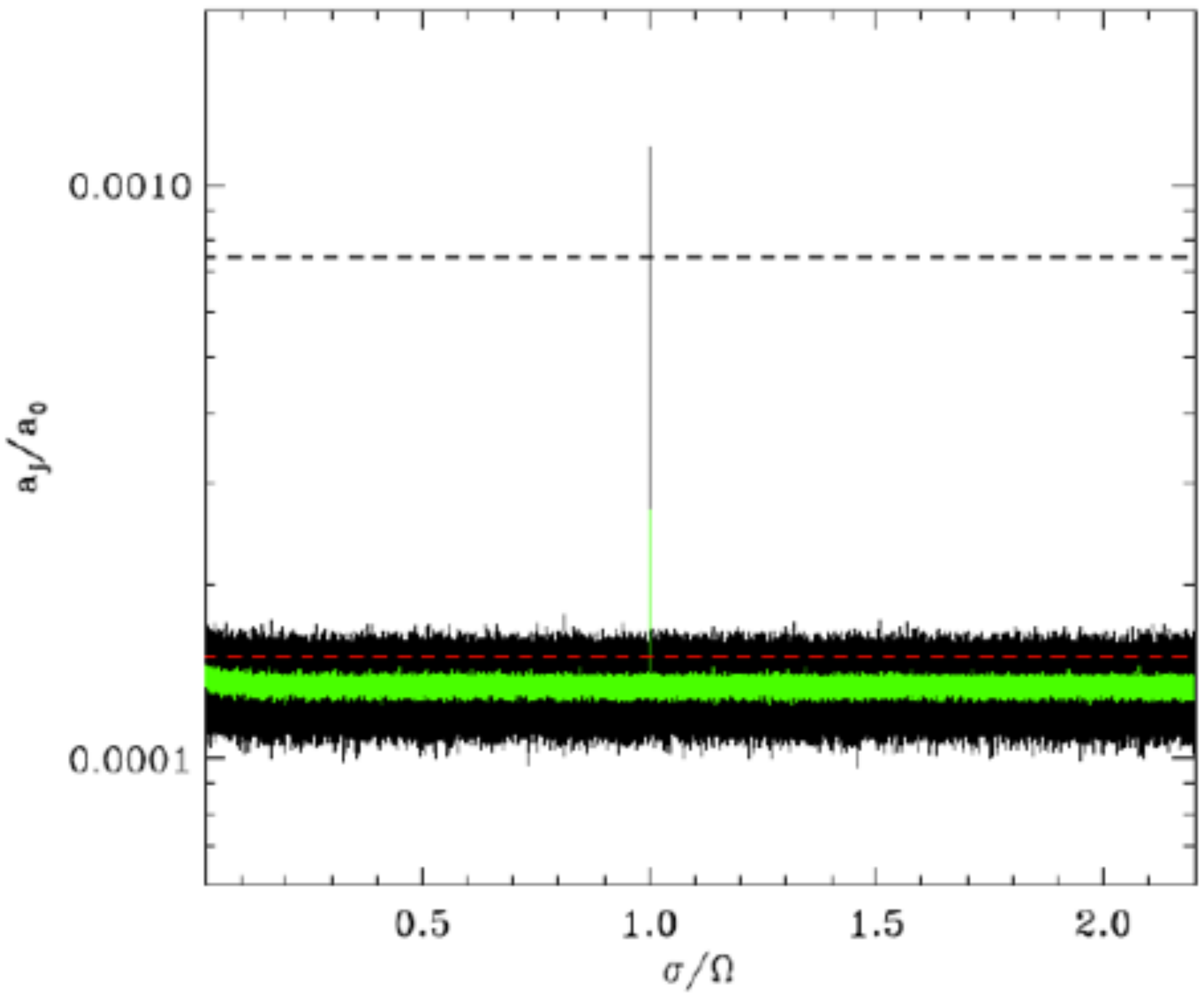
- These data span the brightest portion of the outburst onset.

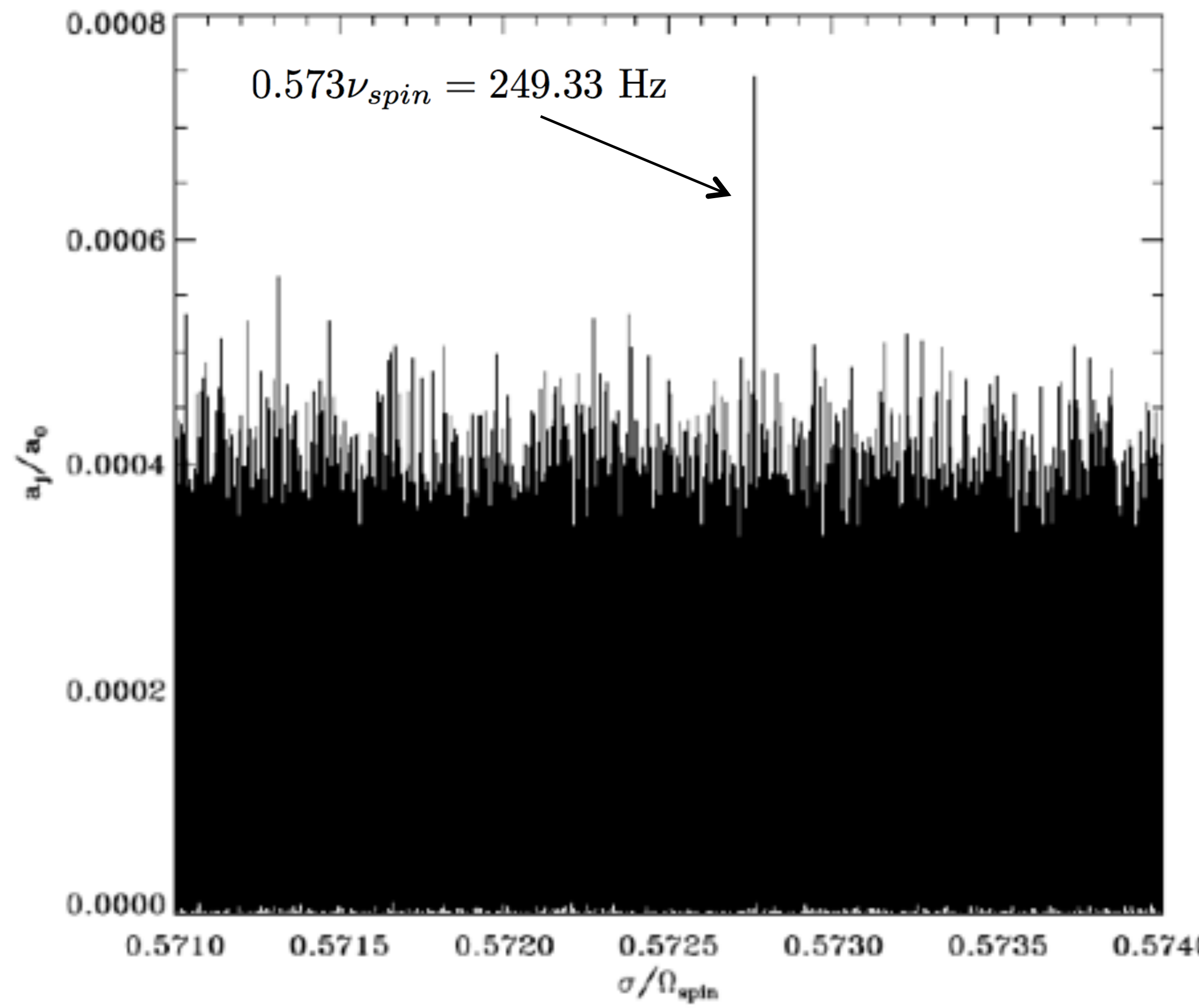
- Use orbit model to remove time delays associated with neutron star's orbital motion.

- Observer is effectively at the binary's center of mass.

Strohmayer & Mahmoodifar ApJ 784, 72 (2014)

XTE J1751-305





$$0.573\nu_{spin} = 249.33 \text{ Hz}$$

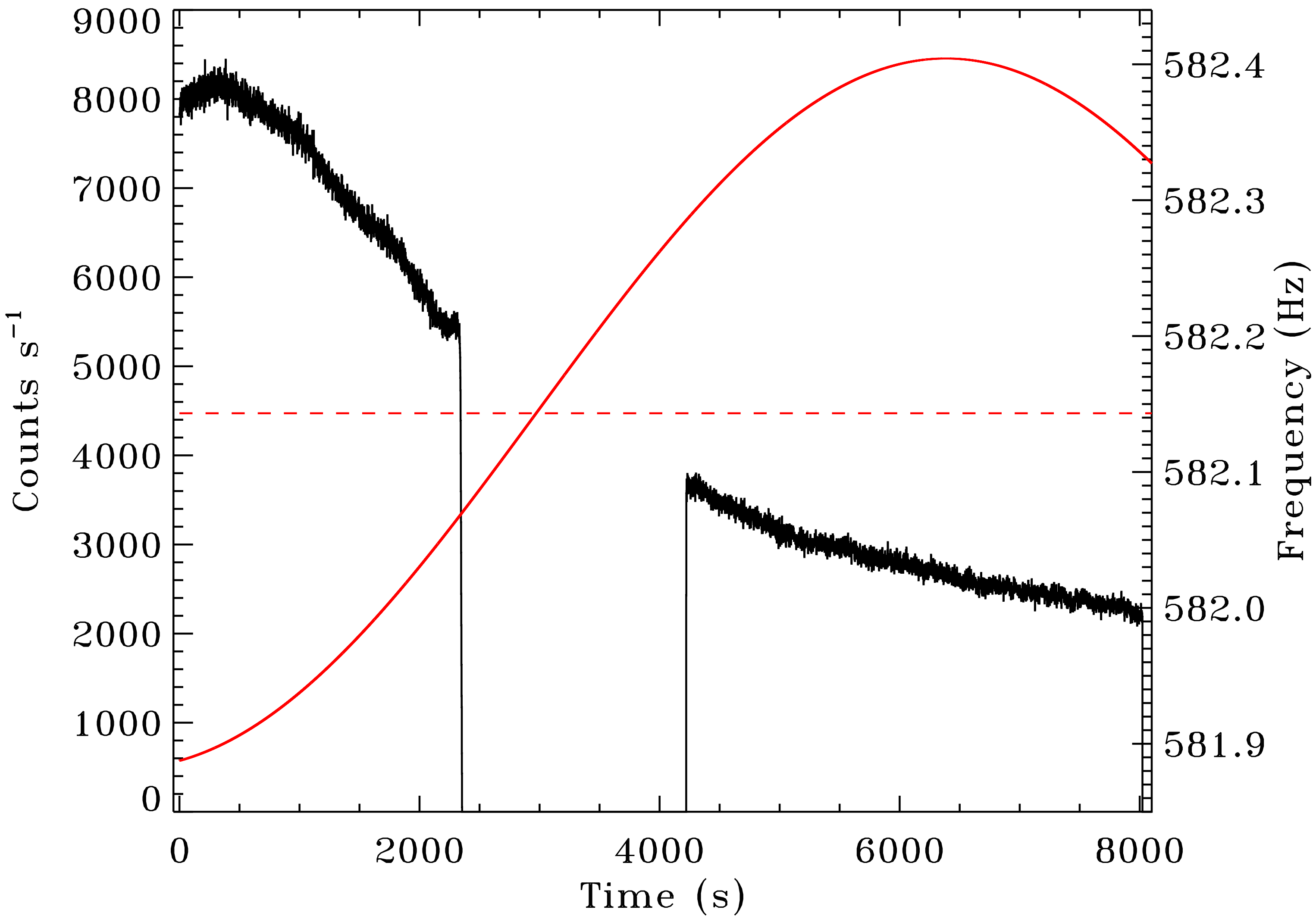
Search for coherent signal, compute single FFT power spectrum, 2^{30} light curve bins.

Estimated significance: 1.6×10^{-3}
Slightly better than a 3σ detection!

Targeted search in the frequency range where r-modes (and g-modes) are theoretically expected.

Implied modulation amplitude of 7.5 x 10^{-4}, signal coherent over ~ 5 day light curve.

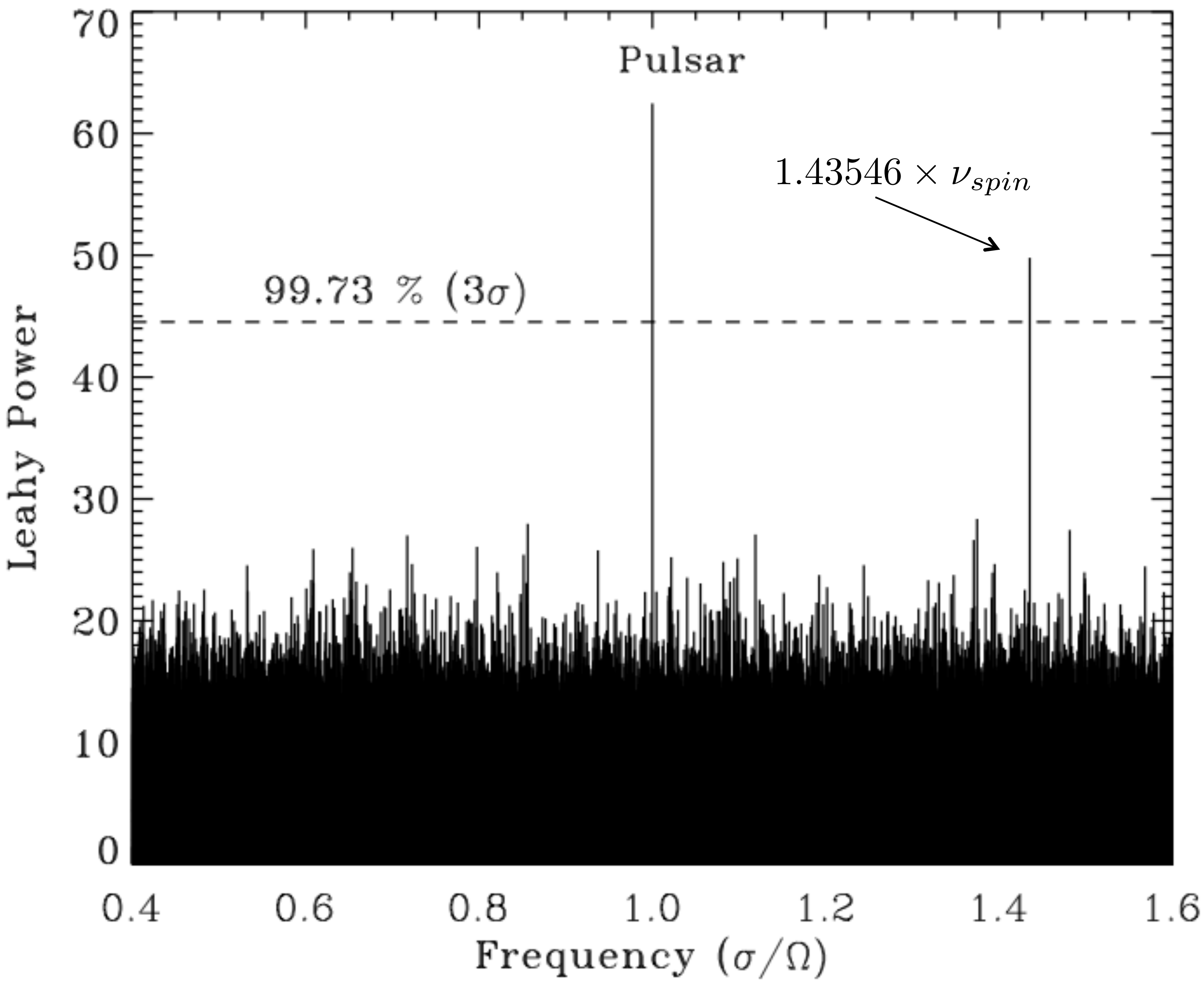
4U 1636-536 (2001 superburst)



Black curve (left axis): Light curve of the portion of February 22, 2001 thermonuclear superburst from 4U 1636-533 used in our pulsation search

Red curve (right axis): The orbital frequency model used to correct the event times

4U 1636-536



Estimated significance: 2.5×10^{-4}

$\exp(-49.3/2) \times N_{trials} = \exp(-49.3/2) \times (4 \times 3.17 \times 10^6)$

Comparing the frequencies identified in J1751-305 and 4U 1636-536

For the AMXP source the modulation mechanism is likely due to oscillation-induced perturbations to the hot-spot fixed in the rotating frame of the star ⟶ modulations at the co-rotating frame frequencies.

For the superburst, where the whole surface is emitting, the stellar surface emission can be modulated by a mode, perhaps due to local variations in the temperature ⟶ modulations at the inertial frame frequencies.

$$\omega_i = m\Omega - \omega_r$$

For an m=2 mode: $\omega_r/\Omega = 2 - 1.43546 = 0.56454$

This is very close to the candidate frequency ratio of 0.57276 we identified in the AMXP XTE J1751-3052 , suggesting that the frequencies identified in the two sources could perhaps be associated with the same oscillation mode

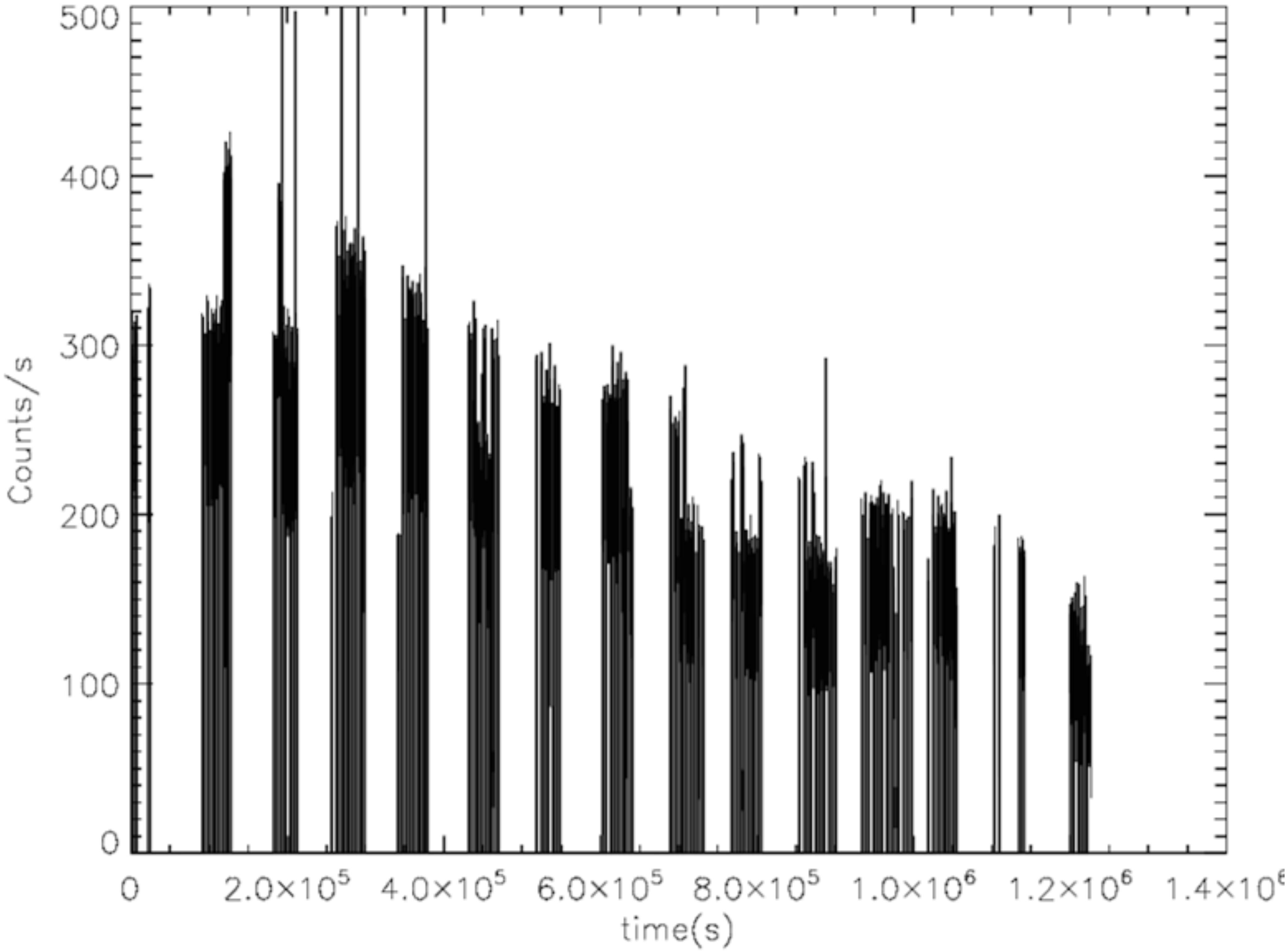
Possible mode identifications for J1751:

- Surface **g-modes**

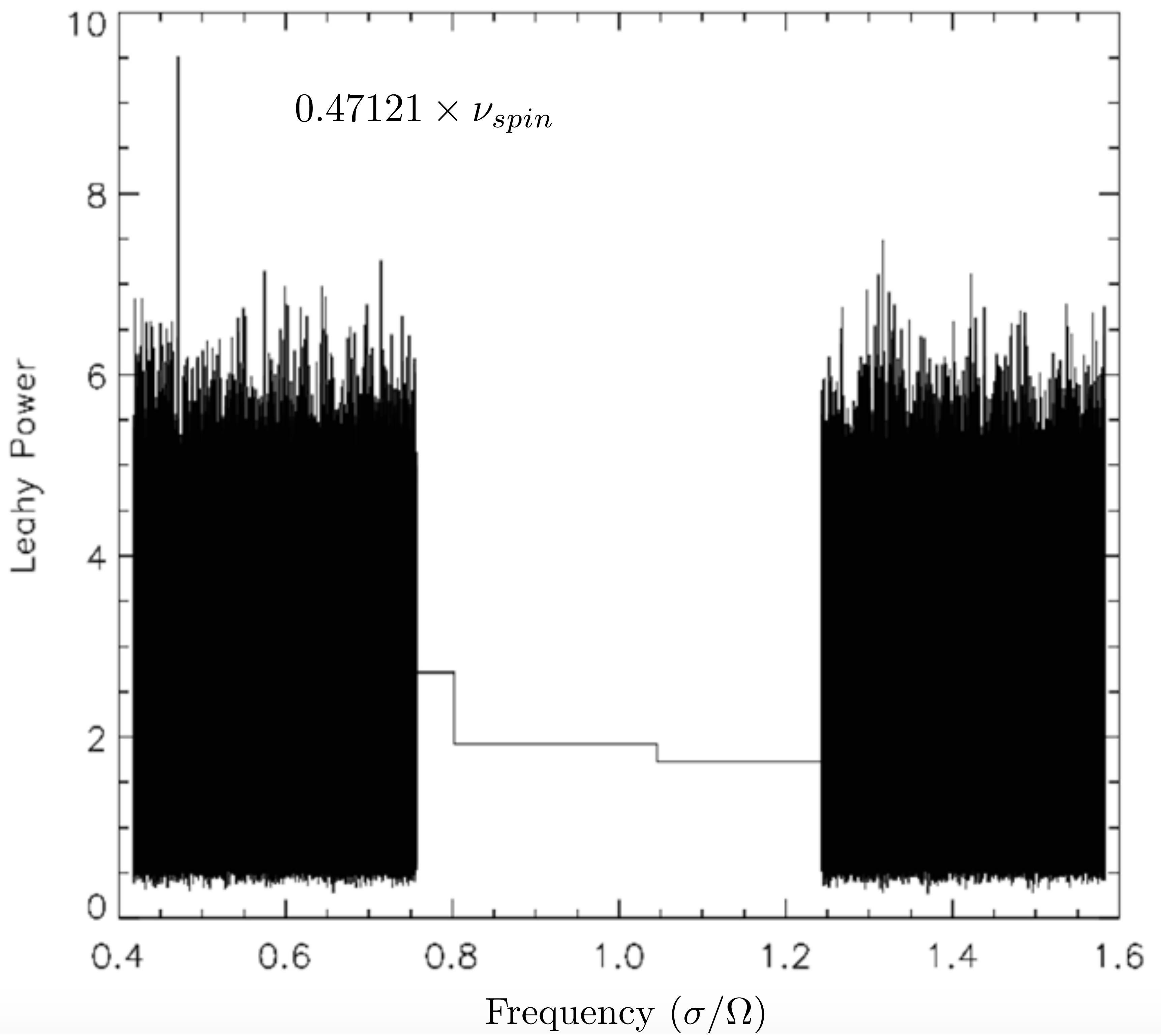
- Inertial modes

- **Core r-modes**?

SAX J1808.4-3658 (2002 outburst)

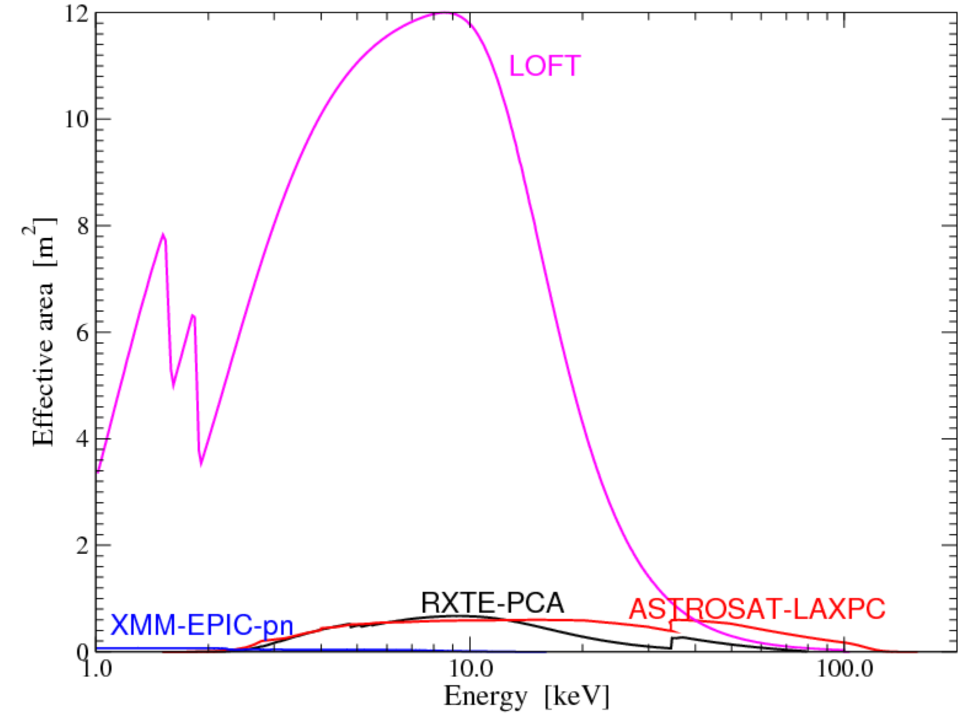


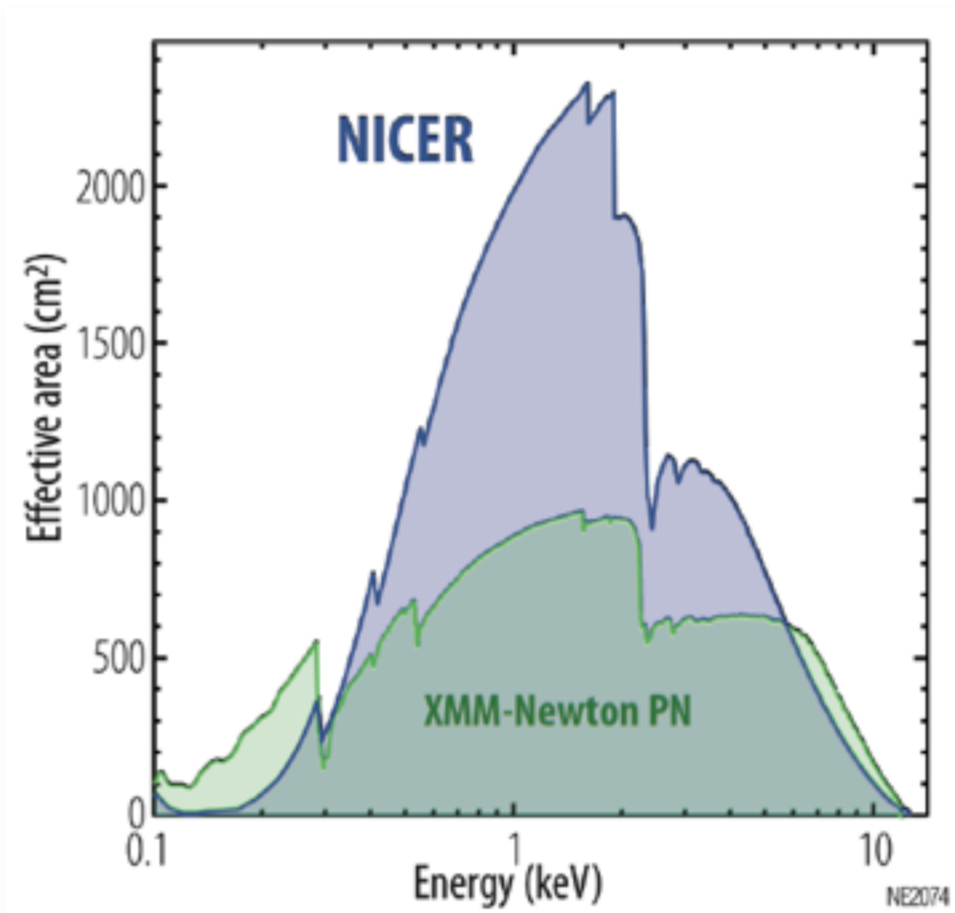
SAX J1808.4-3658 (2002 outburst)



Future capabilities: NICER and LOFT?

- Sensitivity for coherent search scales ~ $1 / (N_{tot})^{1/2}$.
- LOFT/LAD 8.5 m^2 (2 – 30 keV)
- 15-20 x count rate of RXTE/PCA
- Likely can reach $a_{amp} \sim 1 - 2 \times 10^{-5}$





- NICER has smaller effective area than RXTE, but it may detect a brighter source or a longer observation time
- NICER enables searches for oscillation modes in rotation-powered pulsars.

Conclusion and Outlook

- Detection of global neutron star oscillation modes would open a new window on neutron star interiors.
- Even small mode amplitudes may influence the X-ray flux at measurable levels.
- Confirmation of candidate in J1751, and other source detections would be important.
- Additional searches using the RXTE data in more AMXPs underway.
- Light curve calculations for g-modes, to explore "visibility" of modes squeezed closer to the equator.
- Larger collecting areas, more photons needed to improve sensitivities (LOFT could contribute).