A Non-radial Oscillation Mode in an Accreting Millisecond Pulsar?

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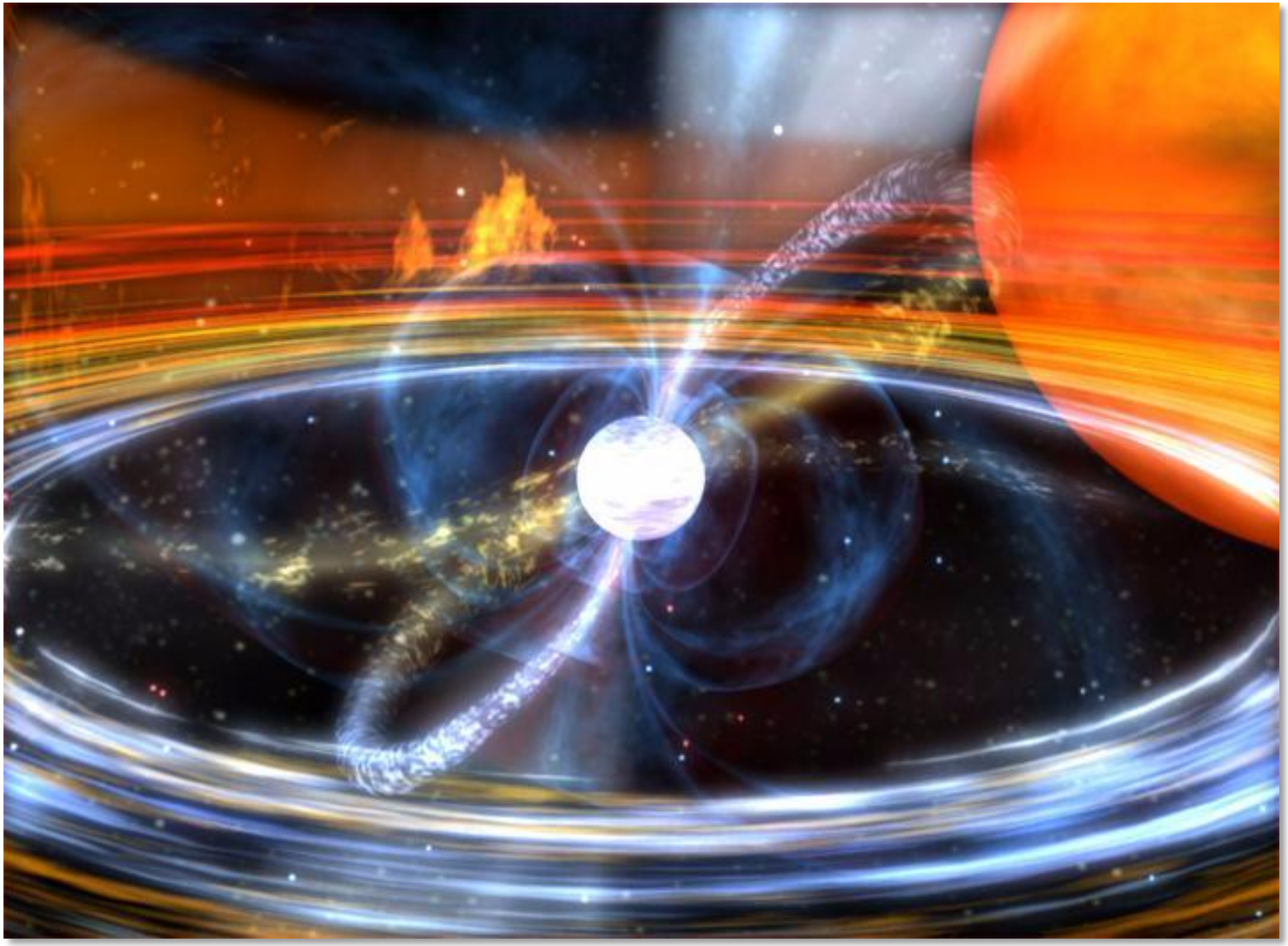
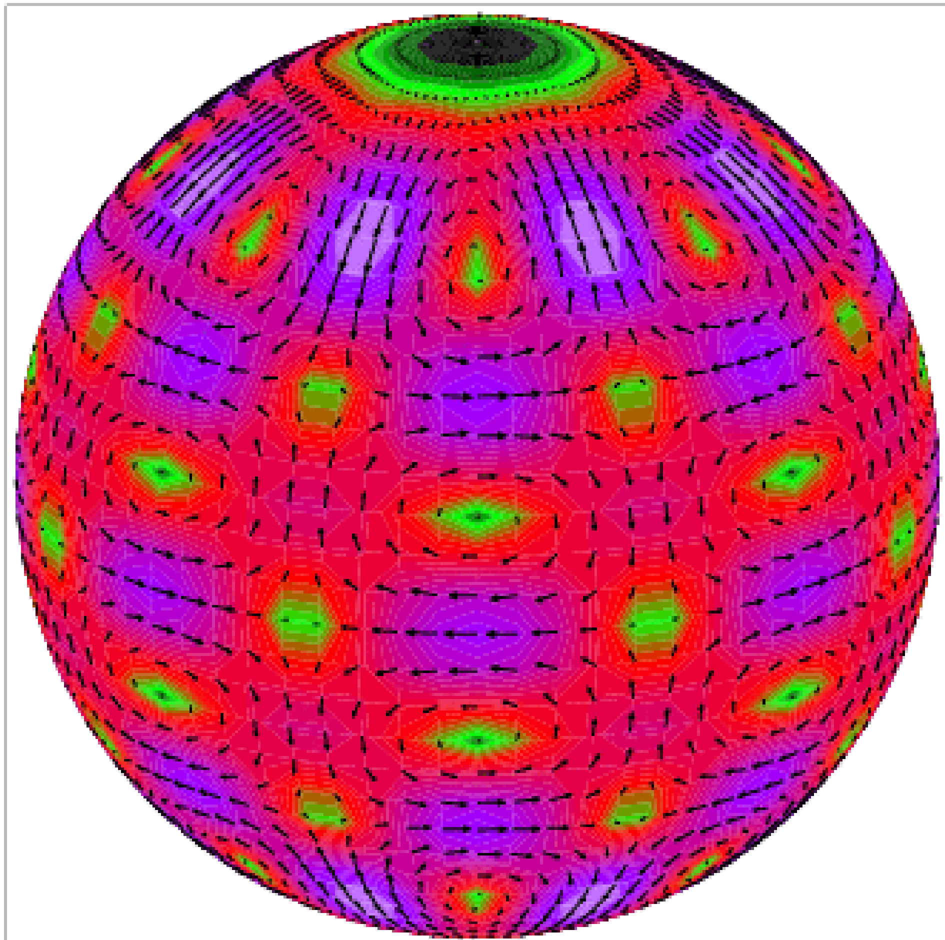


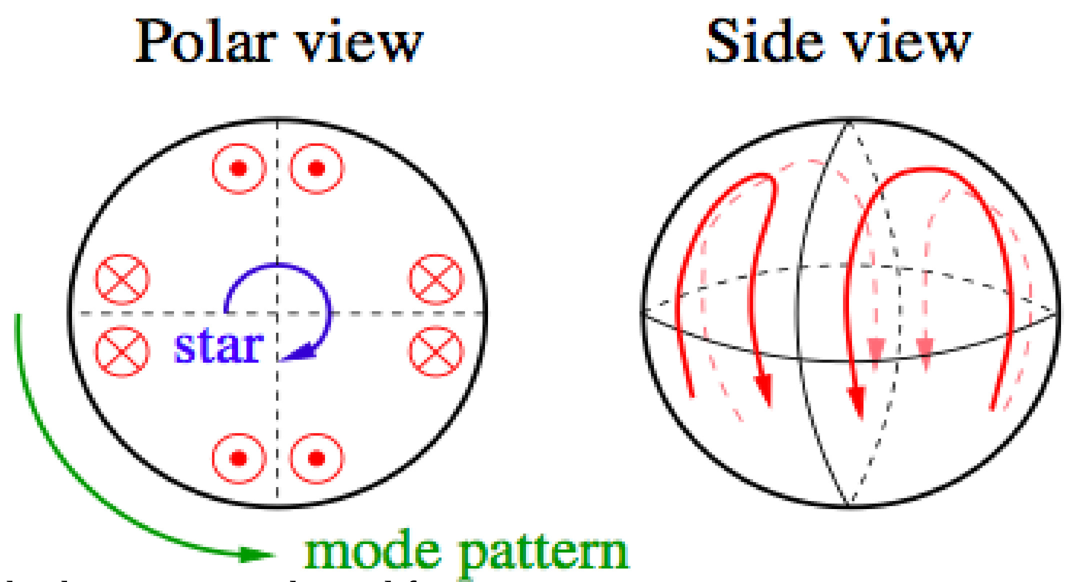
Neutron Star Seismology



Displacement field for an *l*=7, *m*=4 toroidal mode.

- Stellar oscillations probe internal structure and conditions (e.g. helioseismology)
- For example, p-modes sense the sound speed. Mode frequencies scale as $< \rho >^{1/2}$ (thus M and R).
- Solid crust supports torsional shear modes, ${}_{l}t_{n}$ for n = 0 modes, effective wavelength is R, for n > 0 it is ΔR, if V_s = constant, then $f_{n=0} / f_{n>0} \sim \Delta R/R$, constrain crust thickness (magnetar QPOs).
- g-modes supported by buoyancy (thermal and density gradients), can probe R, and envelope structure.

r-modes: Spin and Thermal Evolution



Thanks to Simin Mahmoodifar

The amplitude of the r-mode evolves as $e^{i\omega t - \frac{t}{\tau}}$

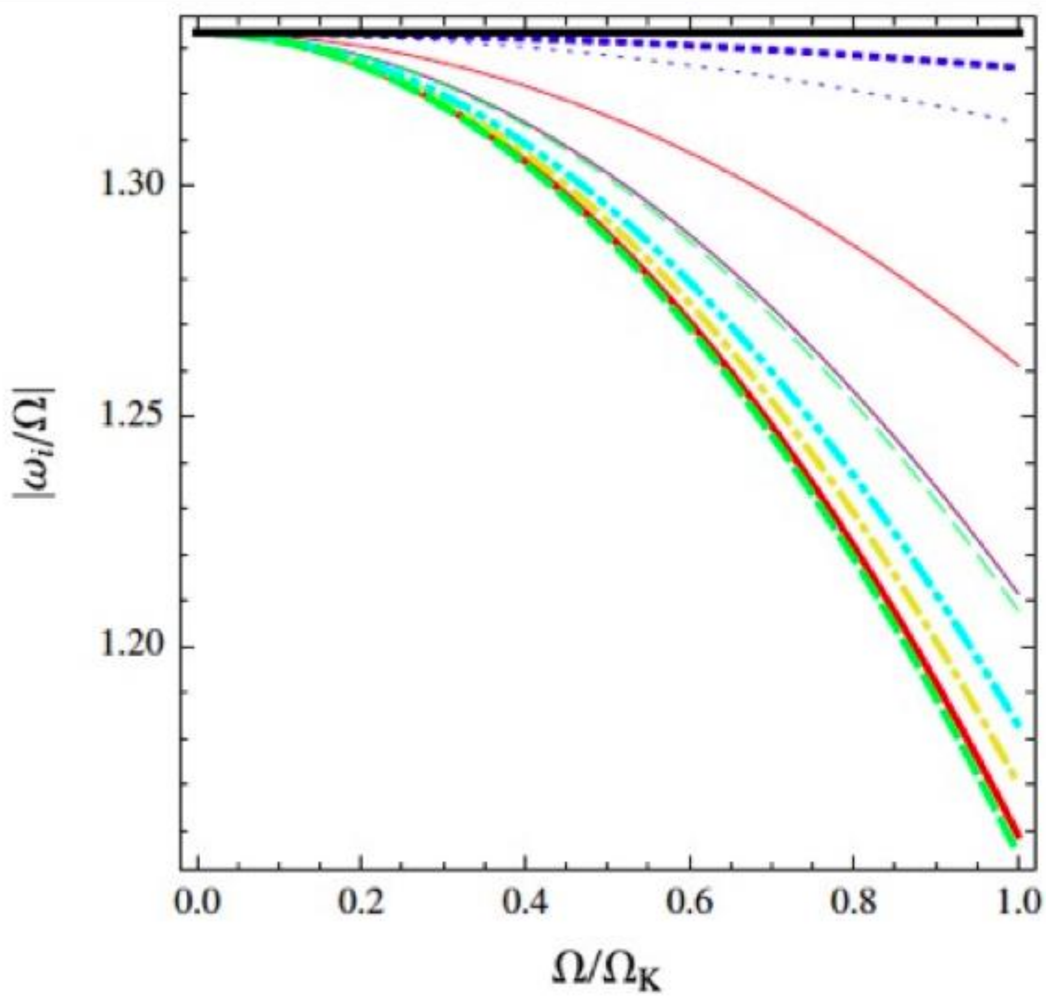
$$\frac{1}{\tau} = \frac{-1}{|\tau_{GR}|} + \frac{1}{\tau_S} + \frac{1}{\tau_B}$$

The fastest process dominates!

τ_{GR} :Gravitational radiation timescale
τ_S :Shear viscosity timescale
τ_B : Bulk viscosity timescale

- r-modes are global circulations on a rotating star (analogous to Rossby waves on Earth).
- Retrograde in frame rotating with the star, prograde in inertial frame, thus unstable to CFS gravitational radiation instability.
- Modes damped by viscous processes (shear, bulk), depends on phases of dense matter.
- Spin-down torque on the star, viscous damping heats the star.

r-modes: Potential Probe of Dense Neutron Star Matter



Alford, Mahmoodifar, Schwenzer, Phys.Rev.D 85, 024007

- As spin rate increases r-mode frequencies diverge from slow spin limit of $2\Omega/3$ (in rotating frame).
- Spin dependence of frequency is sensitive to EOS and phase of dense matter.

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

$$\omega_r \equiv \omega = \kappa(\Omega)\Omega$$

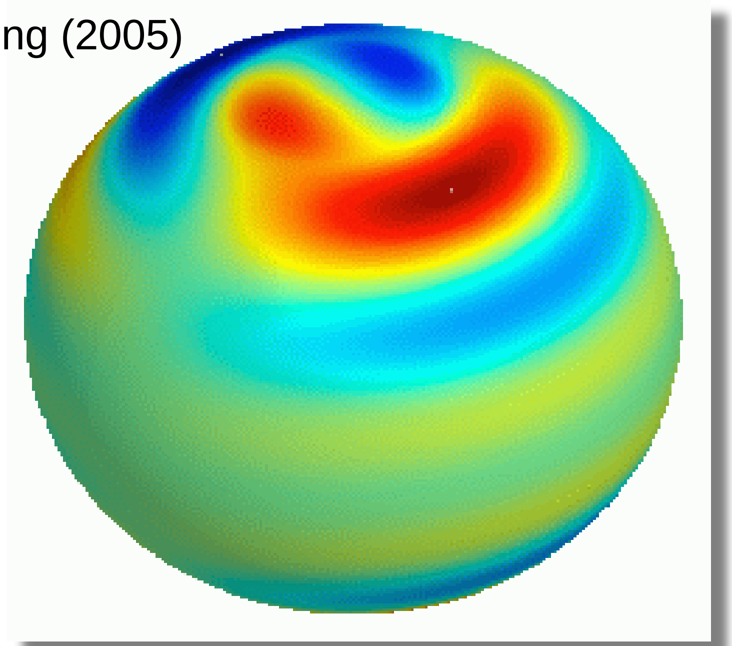
$$\kappa = \kappa_0 + \kappa_2 \frac{\Omega^2}{\pi G \bar{\rho}_0} + \cdots$$

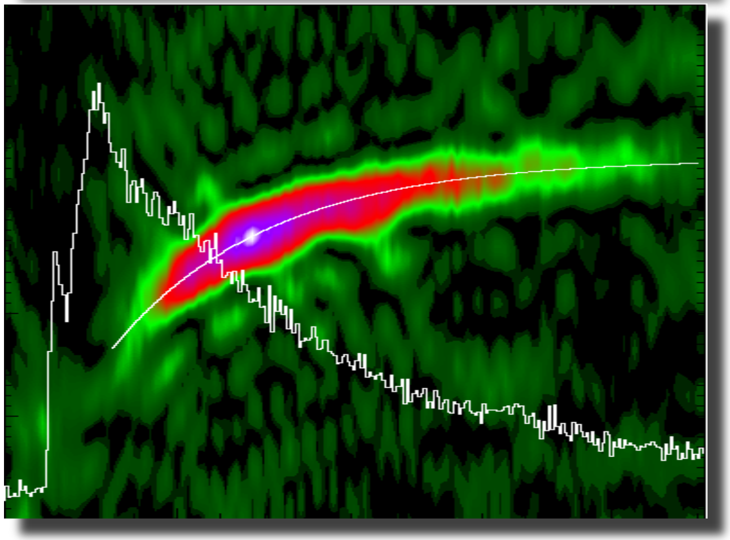
$$\kappa_0 = 2/\left(m+1\right)$$

How Might non-radial Oscillations be Observed?

- Pulsation modes can modulate the temperature across the neutron star's surface – coupled with spin can produce flux modulation at mode's **inertial frame** frequency.
- 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 modes include surface g-modes, and r-modes.
- Since hot-spot rotates with the star, the modulation frequency seen by a distant observer is the **co-rotating frame** frequency.

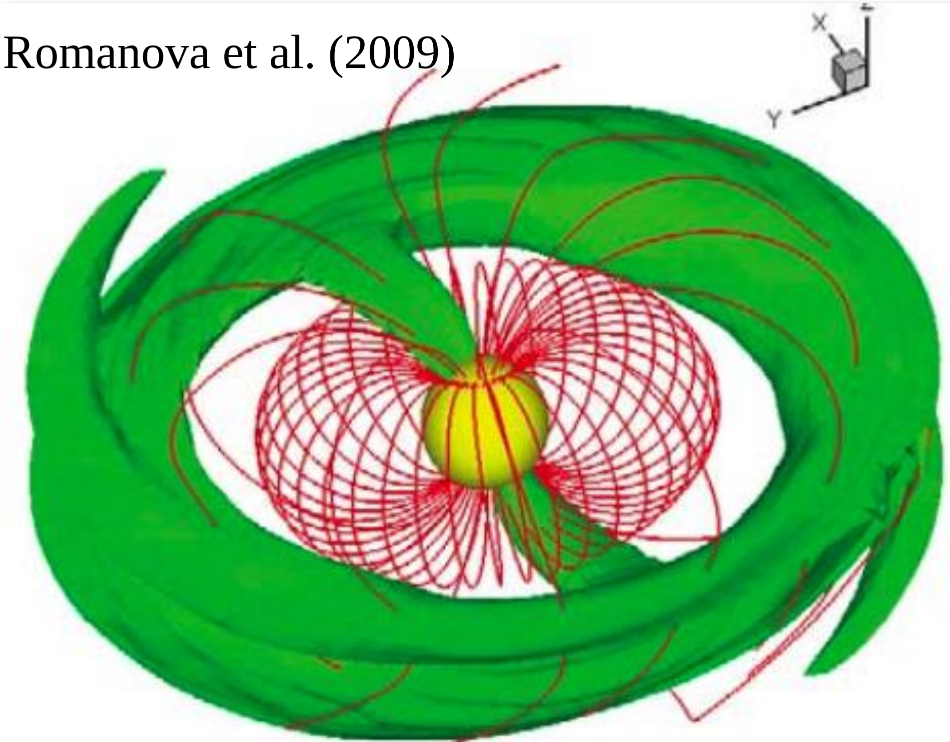
Cumming (2005)





Accreting Millisecond X-ray Pulsars (AMXPs)

Romanova et al. (2009)

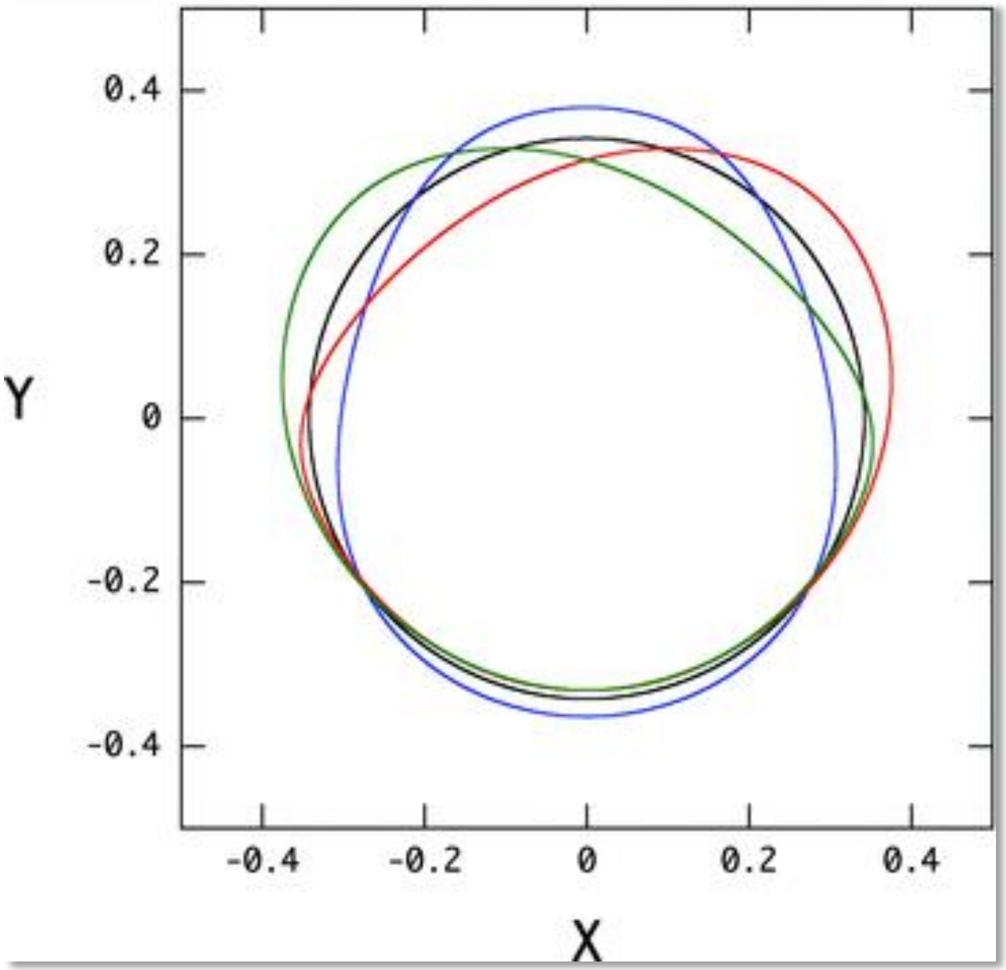


- Accretion stream close to spin axis produces X-ray hot-spot, spin modulation generates pulsations. (Lamb et al. 2009, Patruno & Watts 2011).

TABLE 7
ACCRETION AND NUCLEAR POWERED MILLISECOND PULSARS

Source Name	Spin Frequency [Hz]
Swift J1756-2508	182
XTE J0929-314	185
XTE J1807-294	190
NGC 6440	205
IGR J17511	245
IGR J17191-2821	294
MXB 1730-335	306
XTE J1814-338	314
4U 1728-34	363
HETE J1900.1-2455	377
SAX J1808.4-3658	401
4U 0614+09	415
XTE J1751-305	435
SAX J1748.9-2021	442
SAX J1749.4-2807	518
KS 1731-260	526
Aql X-1	550
EXO 0748-676	552
MXB 1659-298	556
4U 1636-536	581
IGR J00291-5934	599
SAX J1750.8-2900	601
4U 1608-52	620

Neutron Star Oscillations: perturbing the hot-spot



Numata & Lee (2010)

- 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 modes include surface g-modes, and r-modes.
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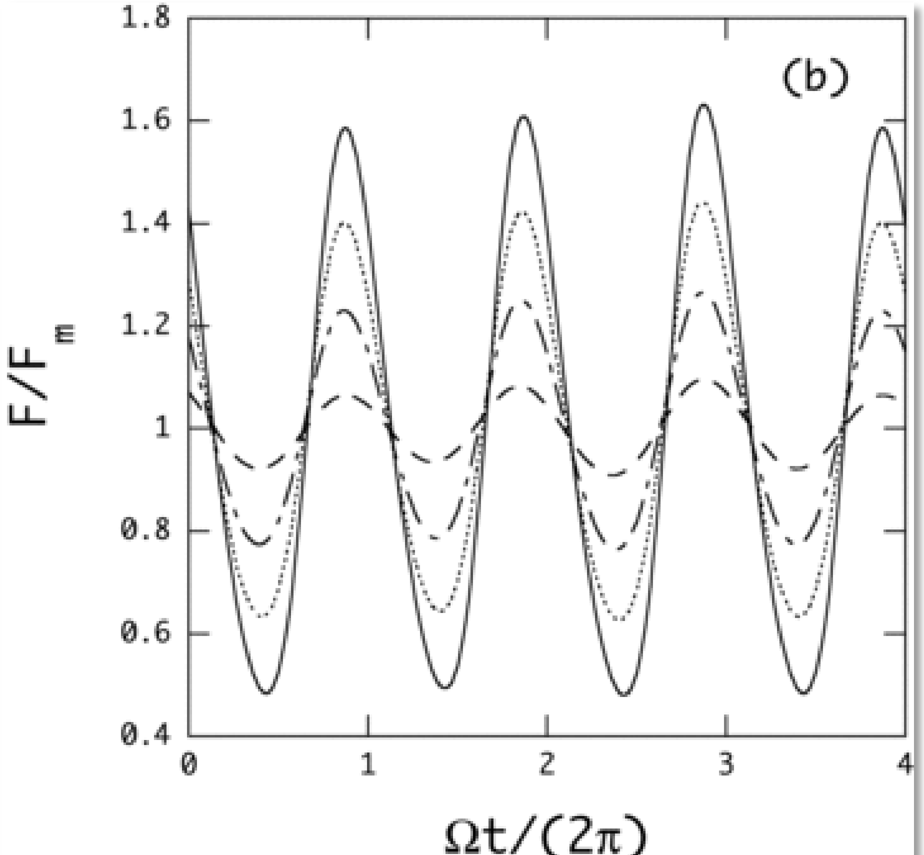
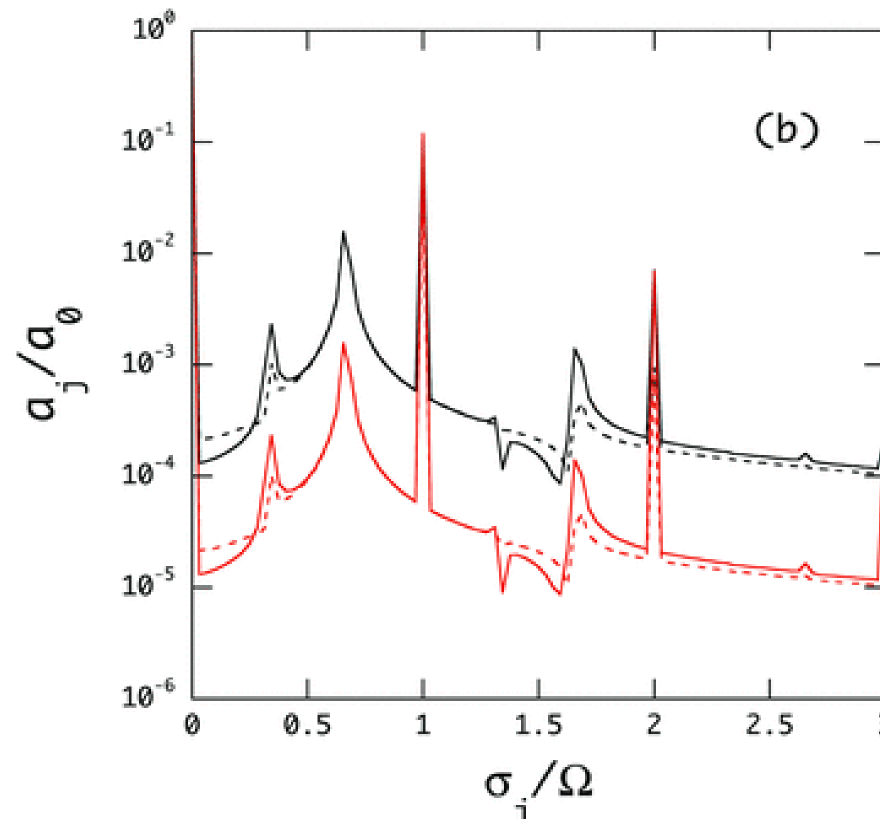
Pulsations: Light curves and Power Spectra

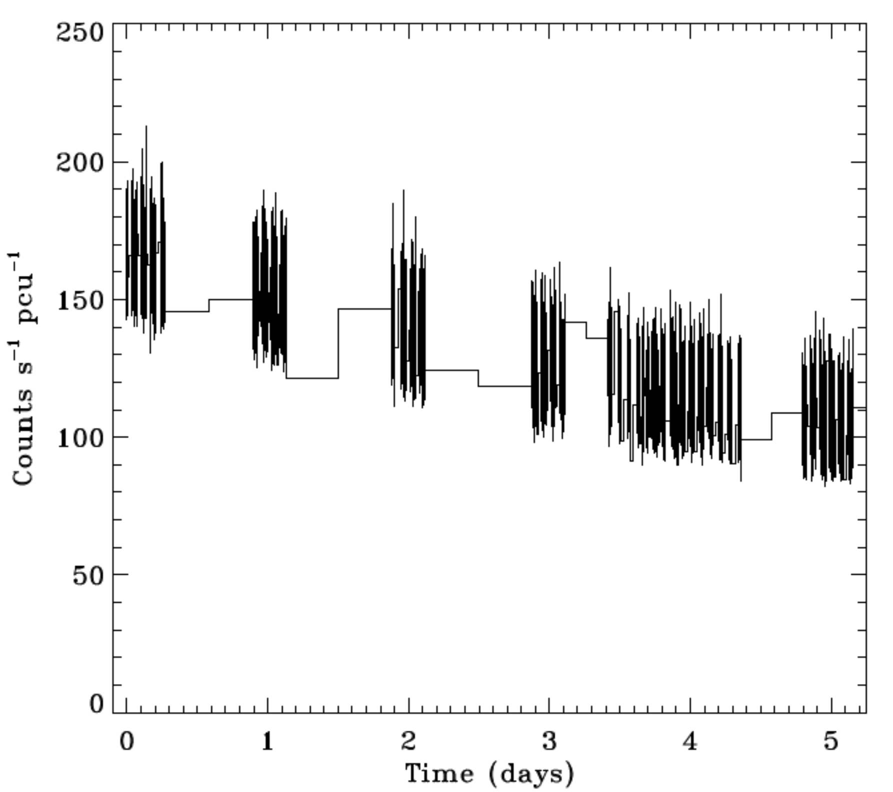


r-mode frequency encoded in the light curve at co-rotating frame frequency, 2Ω/3 (Numata & Lee 2010).



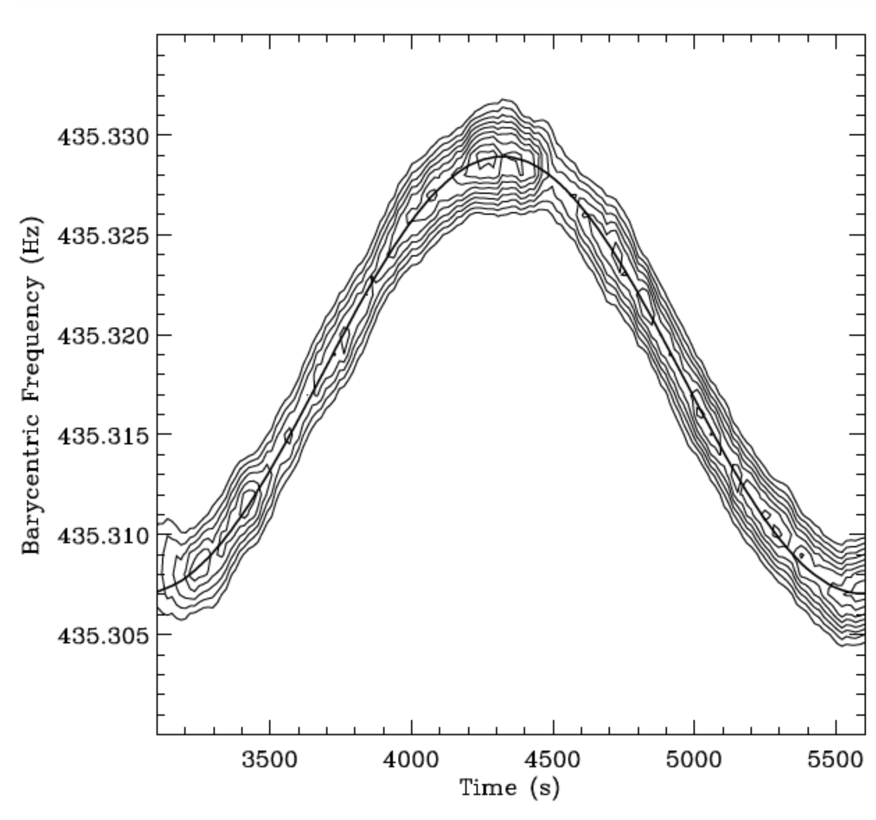
- Light curve modulation amplitude proportional to mode displacement amplitude $A = \max(|\xi_\theta|/R, |\xi_\phi|/R)$
- Observed modulation, a_j, can constrain *A*.

Pulsation Searches in AMXPs: XTE J1751−305



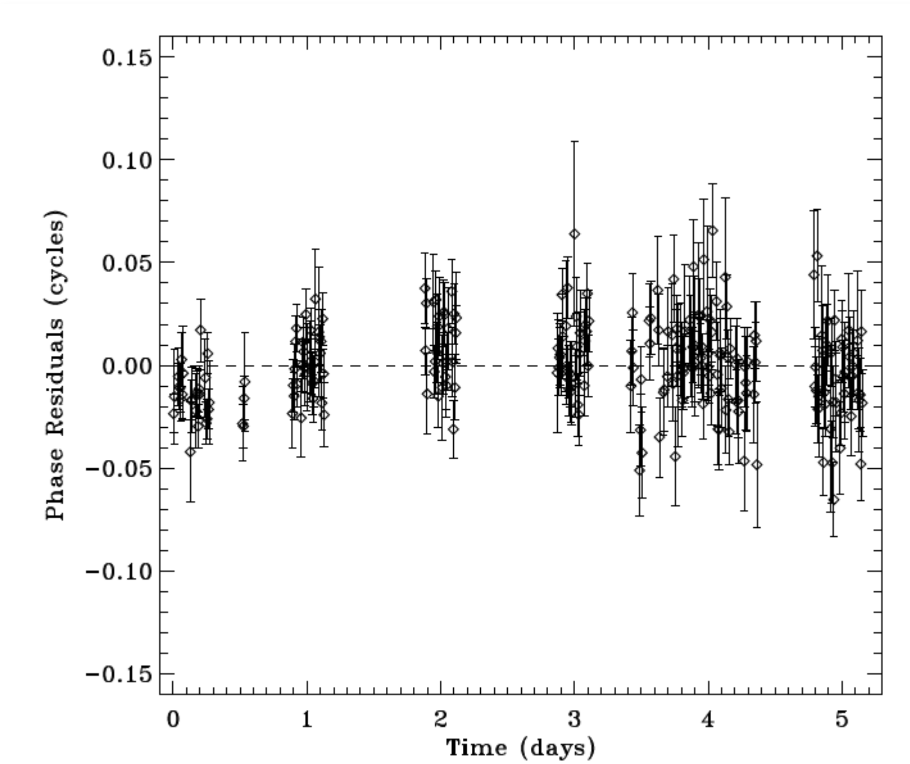
Strohmayer & Mahmoodifar arXiv:1310.5147

- Discovered in April 2002 with RXTE/PCA Galactic Bulge monitoring program (Markwardt et al. 2002), 435 Hz spin period.



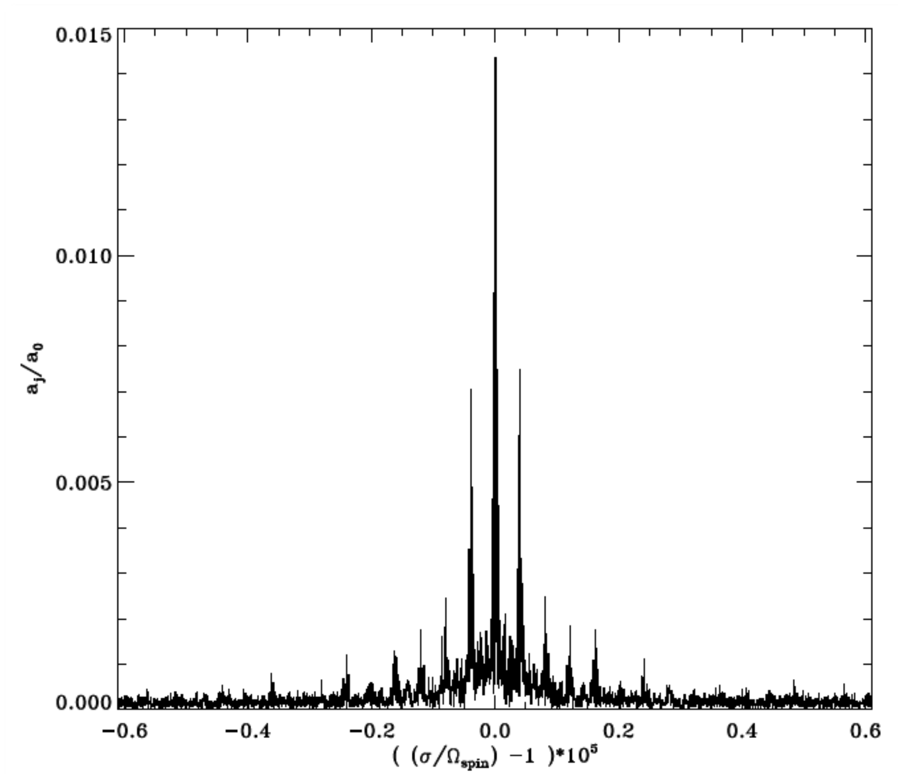
- Pulse timing revealed a 42.4 min orbital period, with a very low mass dwarf (likely He) companion.

XTE J1751–305 Search

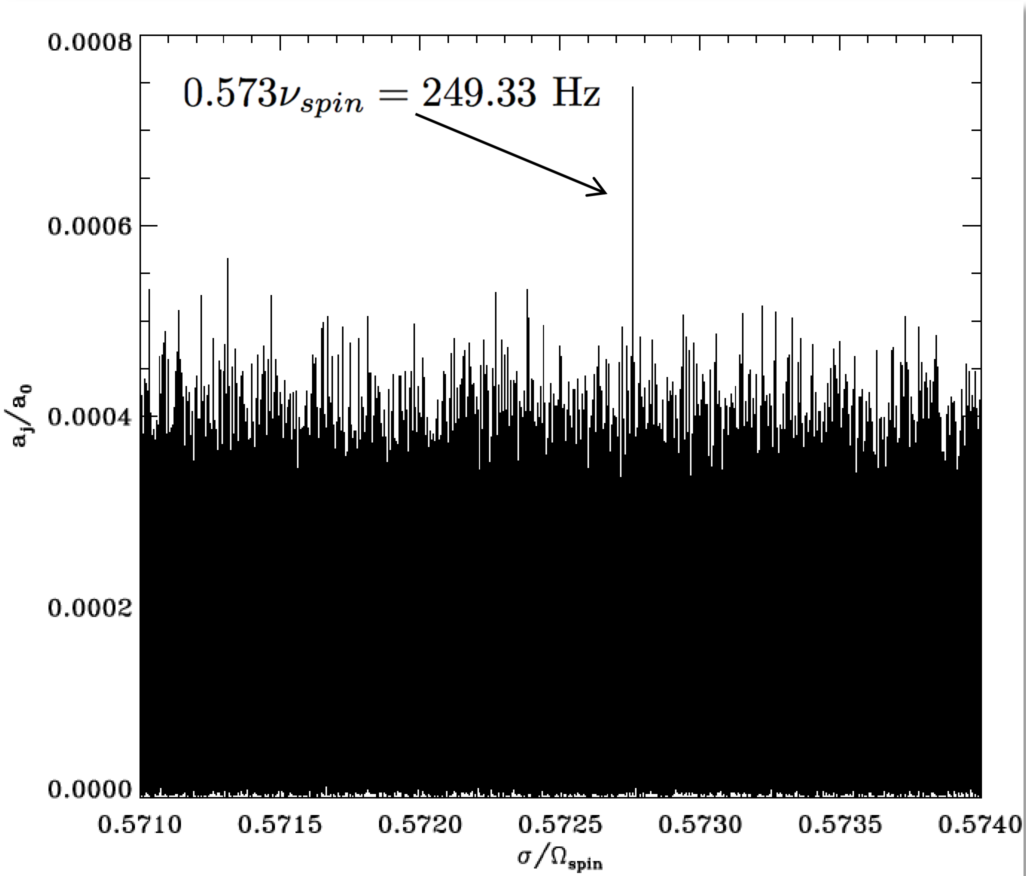


- Bin light curve using corrected times (2048 Hz sampling).
- Search for coherent signal, compute single FFT power spectrum, 2^{30} light curve bins.

- Use orbit model to remove time delays associated with neutron star's orbital motion.
- Observer is effectively at the binary's center of mass.



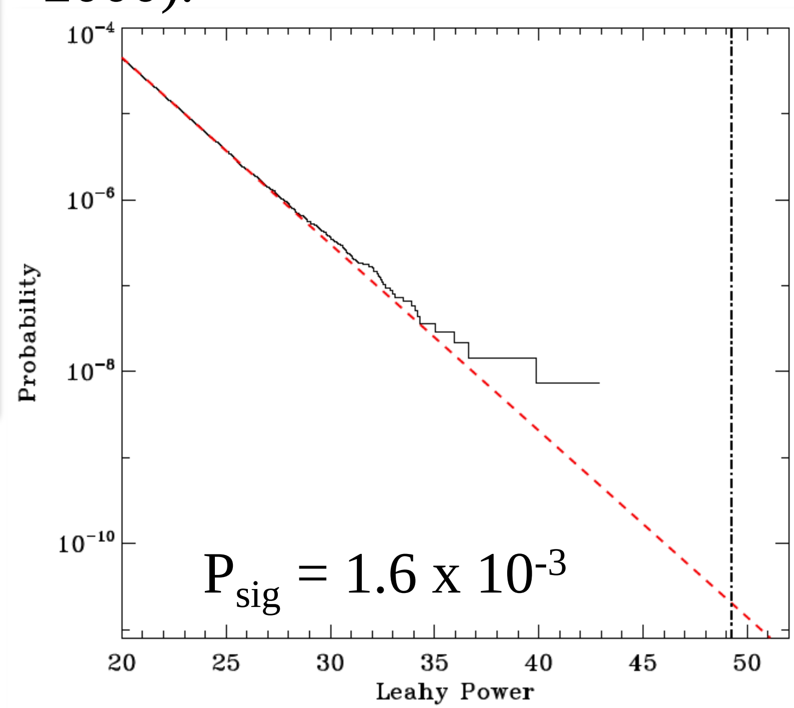
XTE J1751–305 Search con't



Can do targeted search in the frequency range where r-modes (and g-modes) are theoretically expected. Fast spin increases frequency (k_1), crust interactions decrease, k_2, (Yoshida & Lee 2000).

$$2/3 - k_1 \leq \omega/\Omega \leq (2/3 + k_2)$$

$$0.4166 \leq \omega/\Omega \leq 0.75667$$



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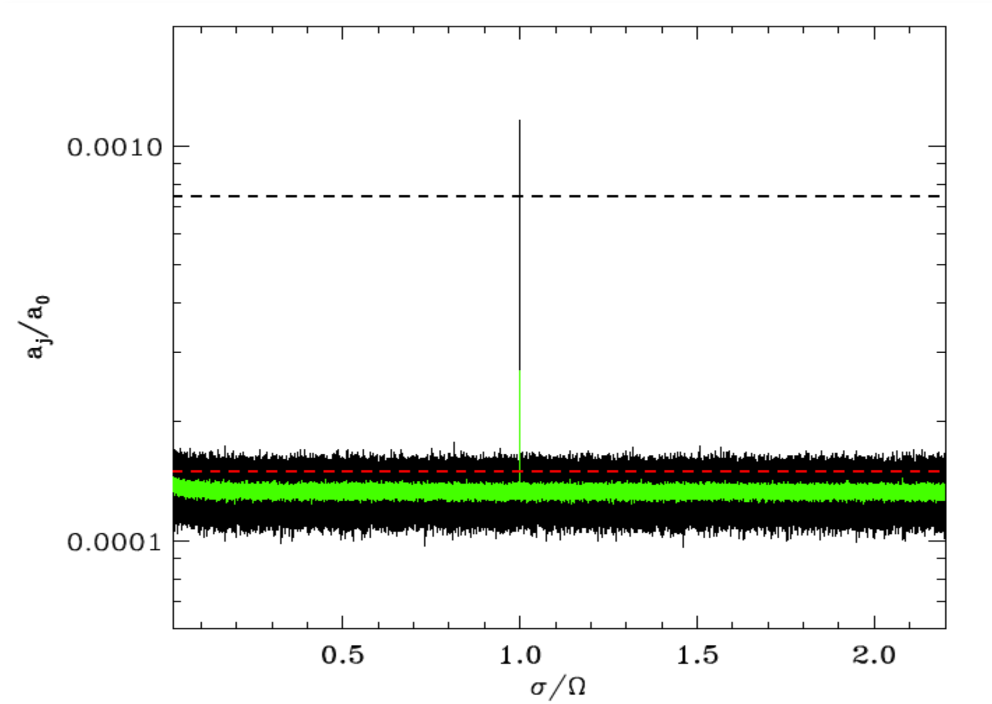
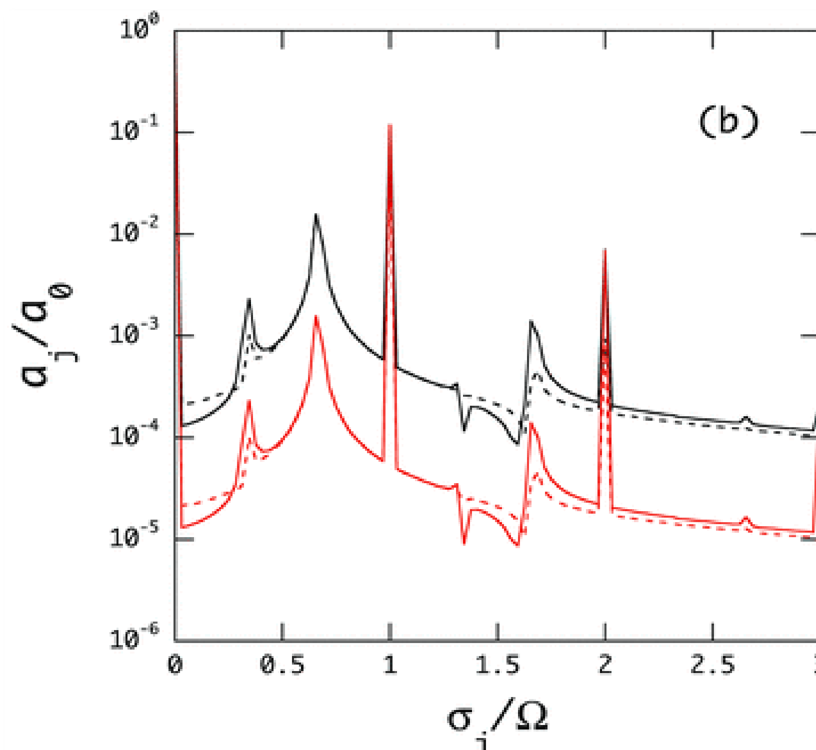
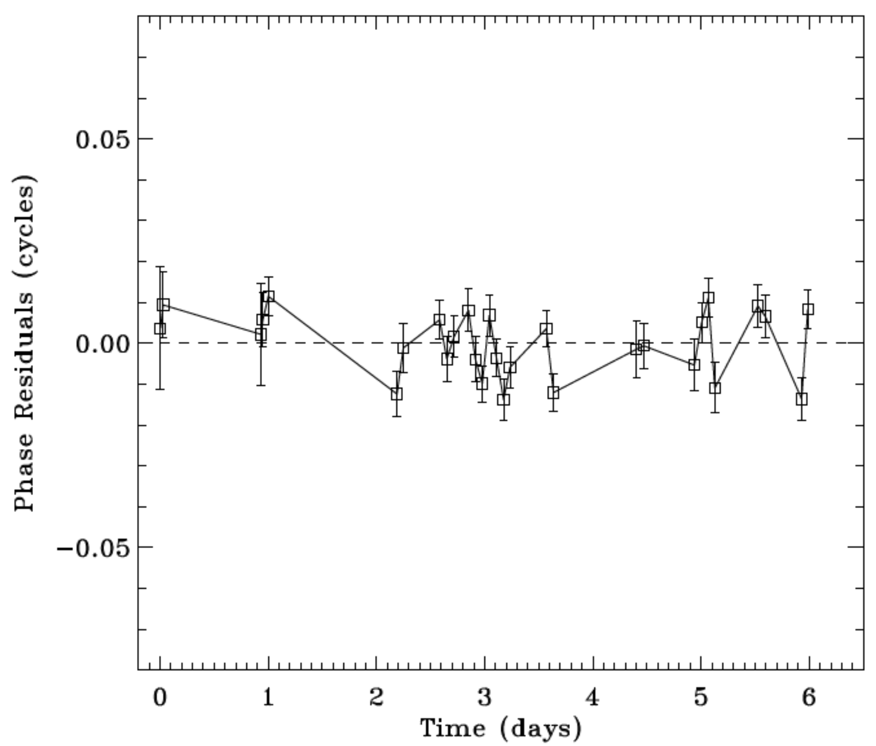


- Light curve calculations and modeling can connect observed amplitude, a_j, to mode amplitude (Numata & Lee 2010).

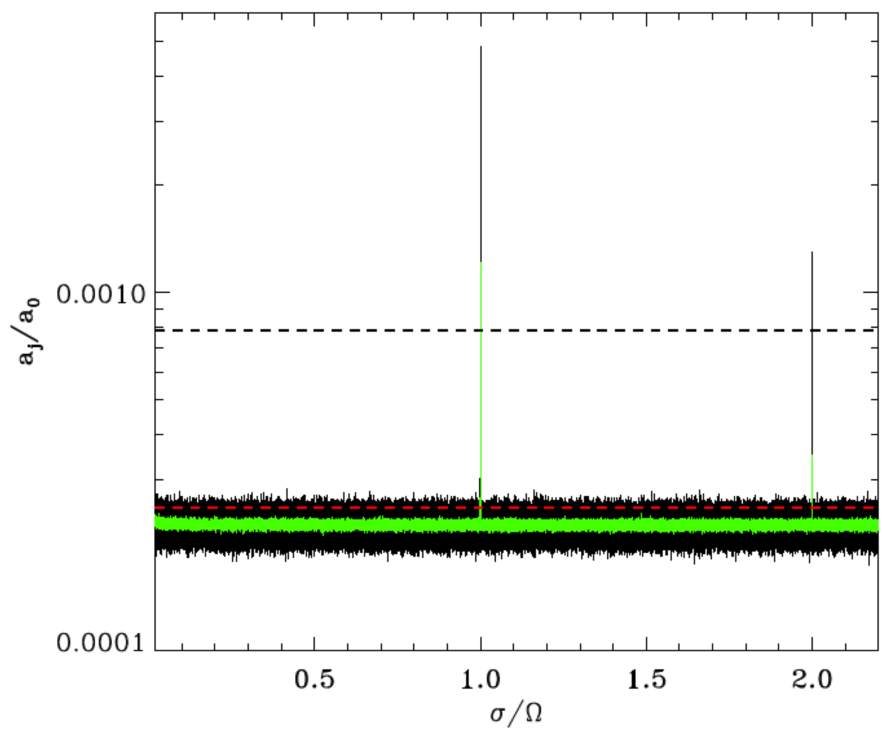


- Implied modulation amplitude of 7.5 x 10^{-4}, signal ~coherent over ~5 day light curve.
- No other broader bandwidth signals detected. Amplitude limit at ~2 x 10^{-4} .

Search in XTE J1814−338

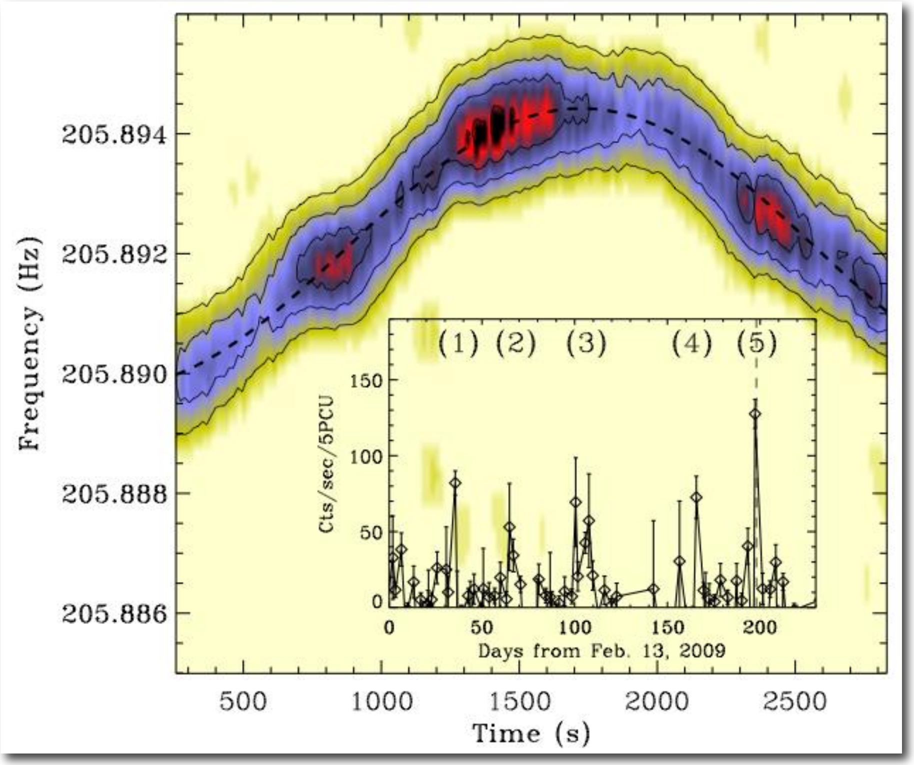


- Discovered in June 2003, 314.4 Hz spin frequency, 4.275 hr orbital period.
- Pulsar has strong first harmonic.

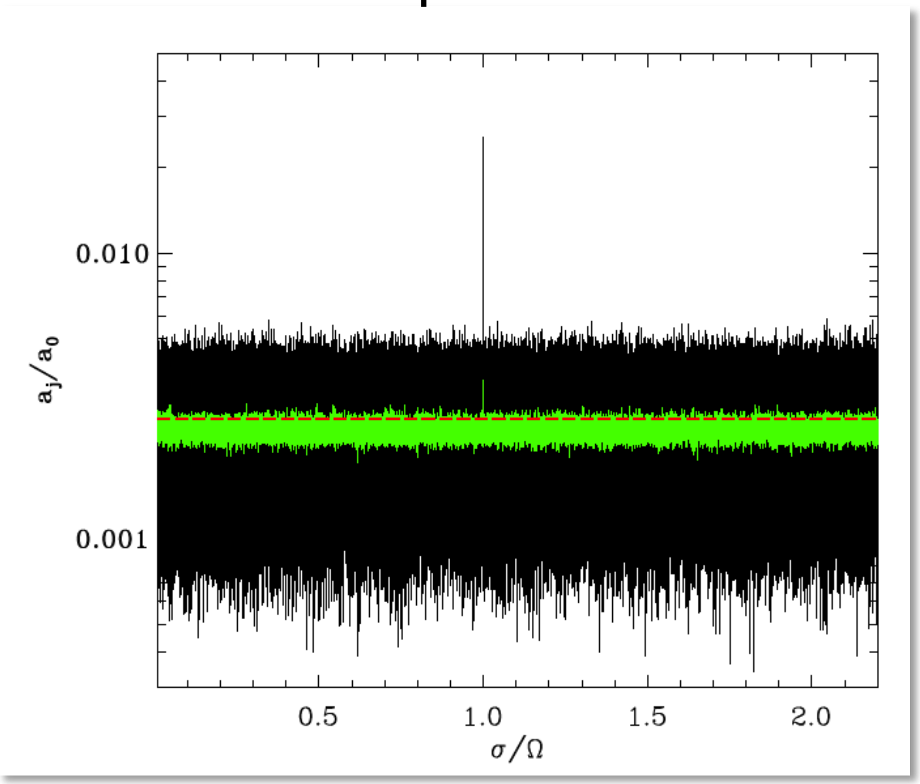


- Carried out similar search as for J1751. No candidate signals found. Set upper limit on amplitude of ~8 x 10^{-4} .

Results for NGC 6440 X-2



- Pulsar observed in only 4 RXTE orbits (not as much data as for J1751 and J1814).
- No candidate signals detected, with upper limits on the modulation amplitude of ~3 x 10^{-3}.



- *RXTE* Bulge scans caught glimpse of faint, recurrent transient in NGC 6440 (X-2) in August 2009. Pulsations seen at 205.9 Hz.

J1751: Possible Mode Identifications

- g-modes confined to envelope above the solid crust. Piro & Bildsten (2004) and Strohmayer & Lee (1996) computed modes in accreting helium burning envelopes (ε-mechanism). J1751 likely a helium-rich accretor. Non-rotating mode frequencies 20 – 30 Hz, but modes modified by fast rotation (Bildsten et al. 1996; Piro & Bildsten 2004).

$$\omega^2 = 2\Omega\omega_{l,0}\left[\frac{(2l_\mu - 1)^2}{l(l+1)}\right]^{1/2}$$

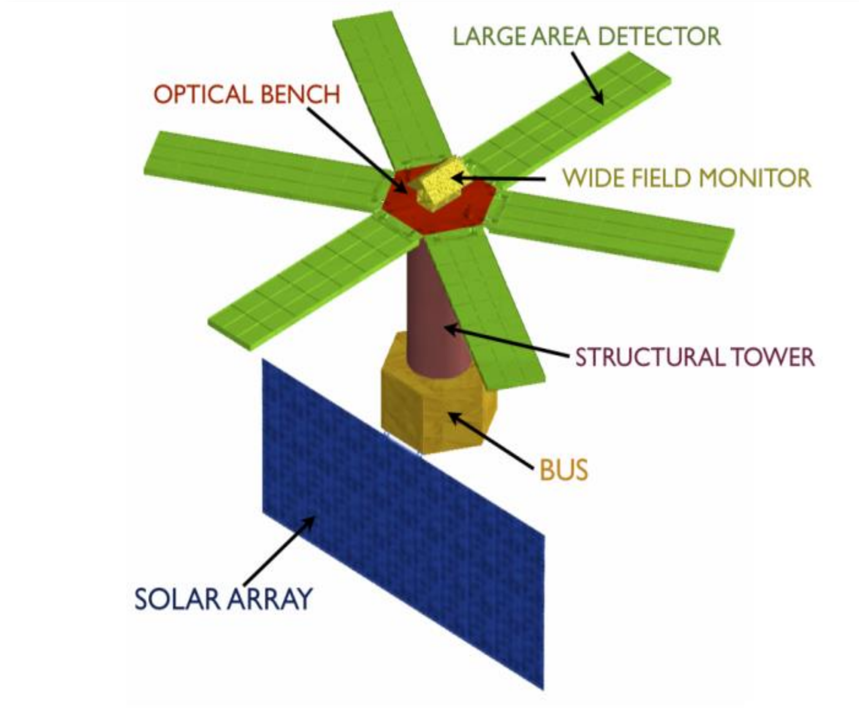
$l=2$, $m=1$, $l_\mu=3$ works

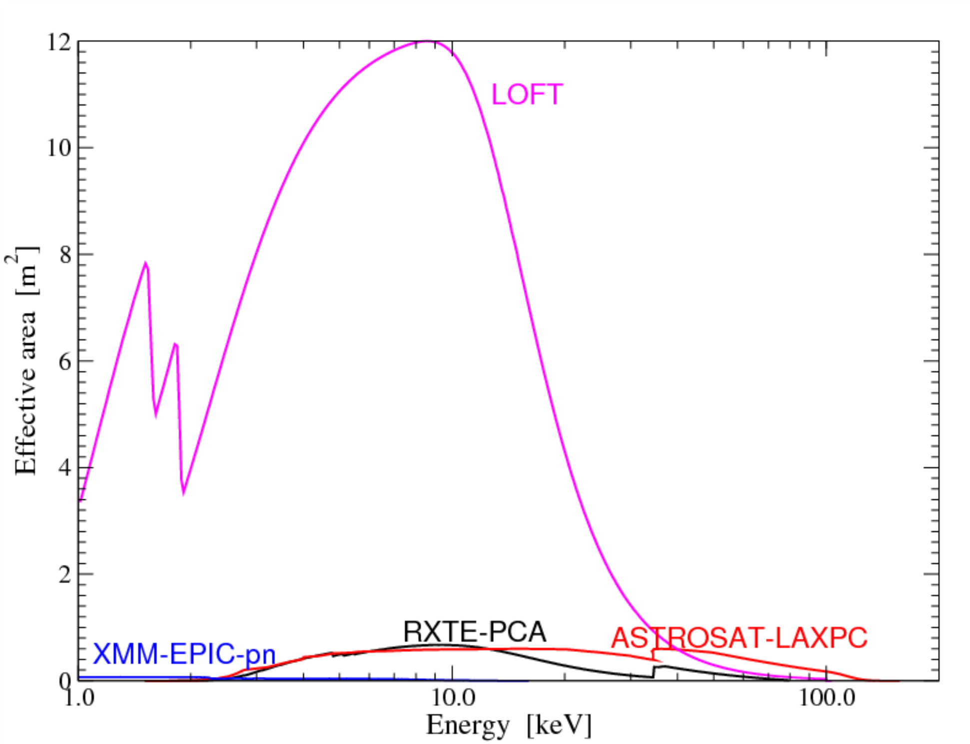
Issues: excitation for high accretion rates, but J1751 at ~ < 0.01 M_{edd} . Fast rotation "squeezes" displacements closer to equator, can mode modulate hot spot closer to pole?

- r-modes are influenced by the solid crust, avoided crossings with torsional modes can push frequency below 2Ω/3 (Yoshida & Lee 2001). Could perhaps account for frequency < 2/3. More detailed mode calculations needed for fast spin and realistic NS models.

Future Capabilities: LOFT

- Sensitivity for coherent search scales $\sim 1 / (N_{tot})^{1/2}$.
- LOFT/LAD 10-12 m^2 (3 – 15 keV)
- 20-30 x count rate of RXTE/PCA
- Likely can reach $a_{amp} \sim 1 - 2 \times 10^{-5}$



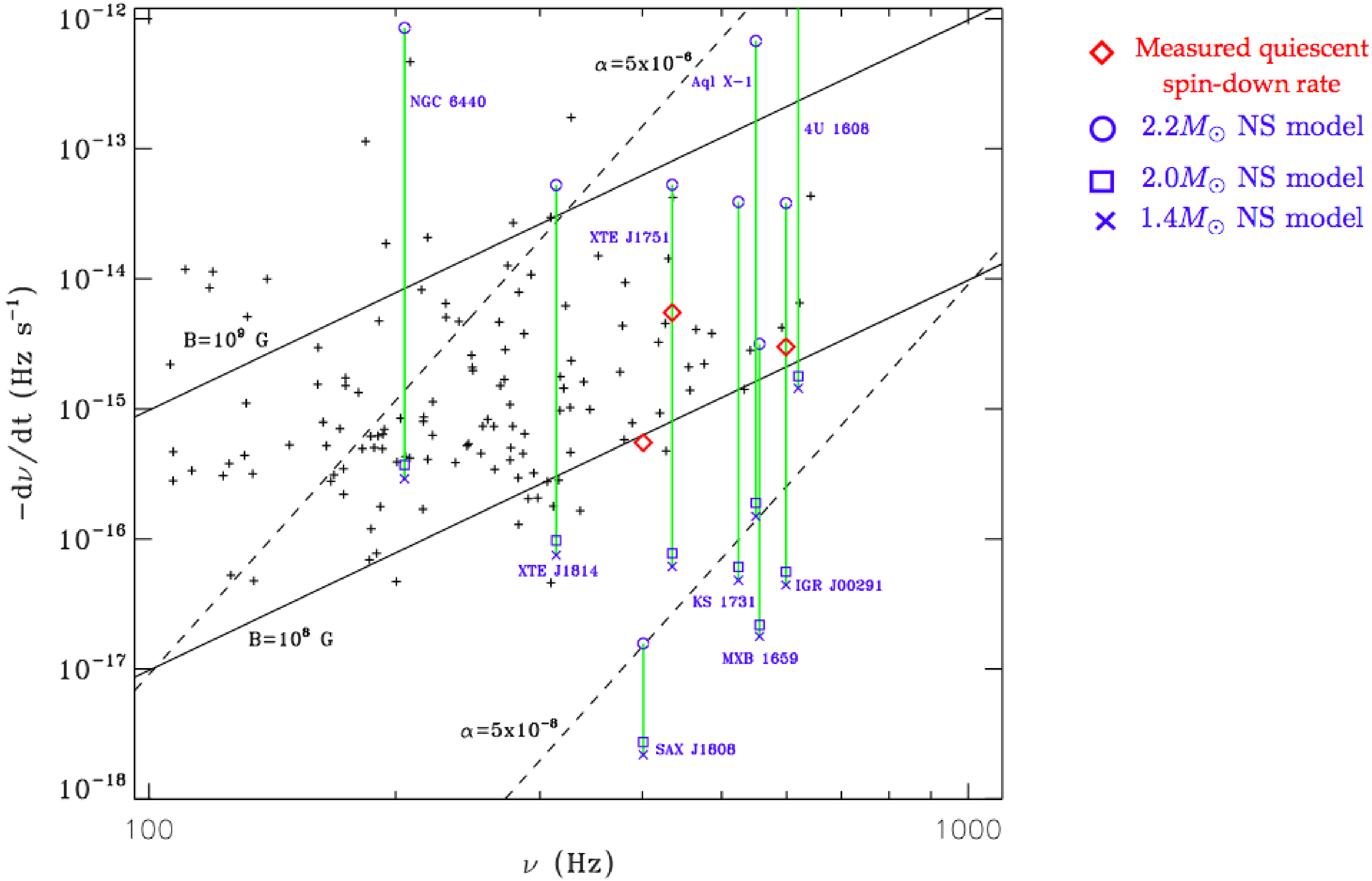


ESA M3 candidate mission, study report ("yellow book") recently submitted, down-select in early 2014. Potential launch 2022.

Conclusions, Future Work

- Detection of global neutron star oscillation modes would open a new window on neutron star interiors. Confirmation of candidate in J1751, and other source detections would be important.
- Additional searches using the RXTE data in more AMXPs underway (including SAX J1808).
- Better r-mode computations for realistic NS models with fast rotation and solid crusts.
- Light curve calculations for g-modes, to explore "visibility" of modes squeezed closer to equator.
- Larger colleting areas, more photons needed to improve sensitivities, LOFT, and NASA's NICER can contribute.

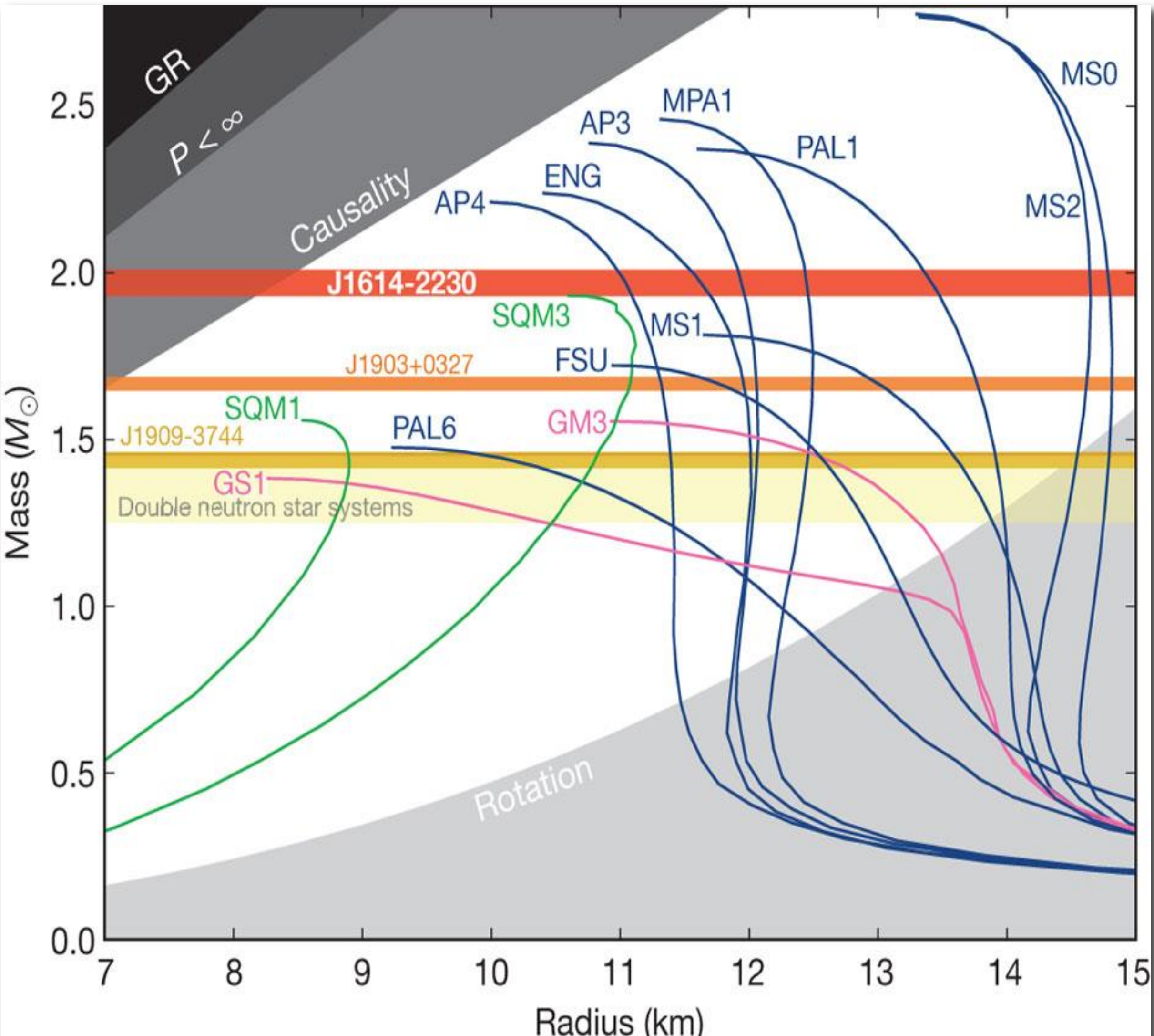
r-mode spin-down limits



Mahmoodifar & Strohmayer, ApJ **773**, 140 (2013)

The Neutron Star Equation of State

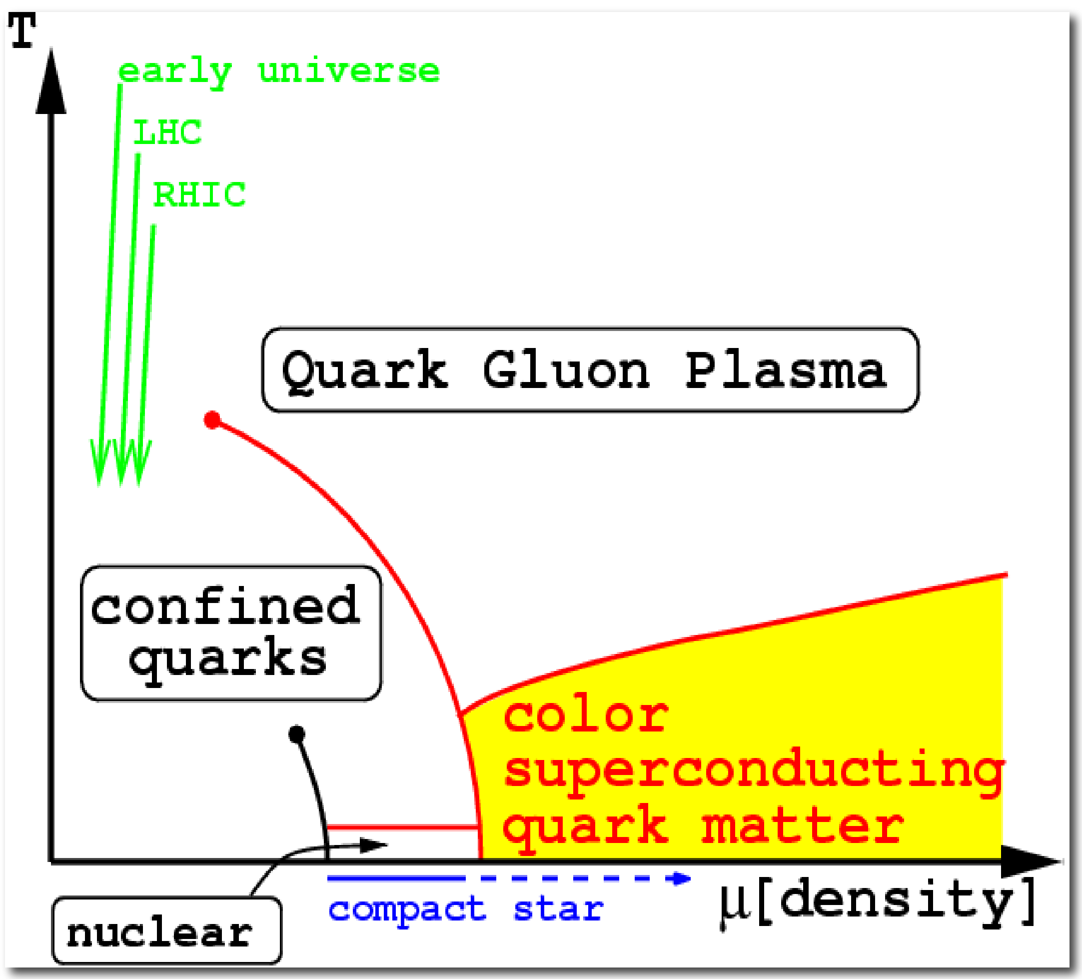
Demorest & Ransom 2011



- High mass measurements, limit softening of EOS from hyperons, quarks, other exotic stuff.
- Most good mass measurements at low end, and systems not conducive to radius estimates, EOS not constrained strongly.
- Need either masses for higher mass systems (accretors), and/or possibility to get R (AMPs).

QCD phase diagram: New states of matter

Rho 2000



- Aspects of QCD phase diagram still uncertain. Neutron stars may be only way to probe low T, high ρ.
- Recent theoretical work has explored QCD phase diagram (Alford, Wilczek, Reddy, Rajagopal, et al.)
- Exotic states of Quark matter postulated, CFL, color superconducting states.
- Neutron star interiors could contain such states. Can we infer its presence from observations?