Burst Oscillations and Nonradial Modes of Neutron Stars

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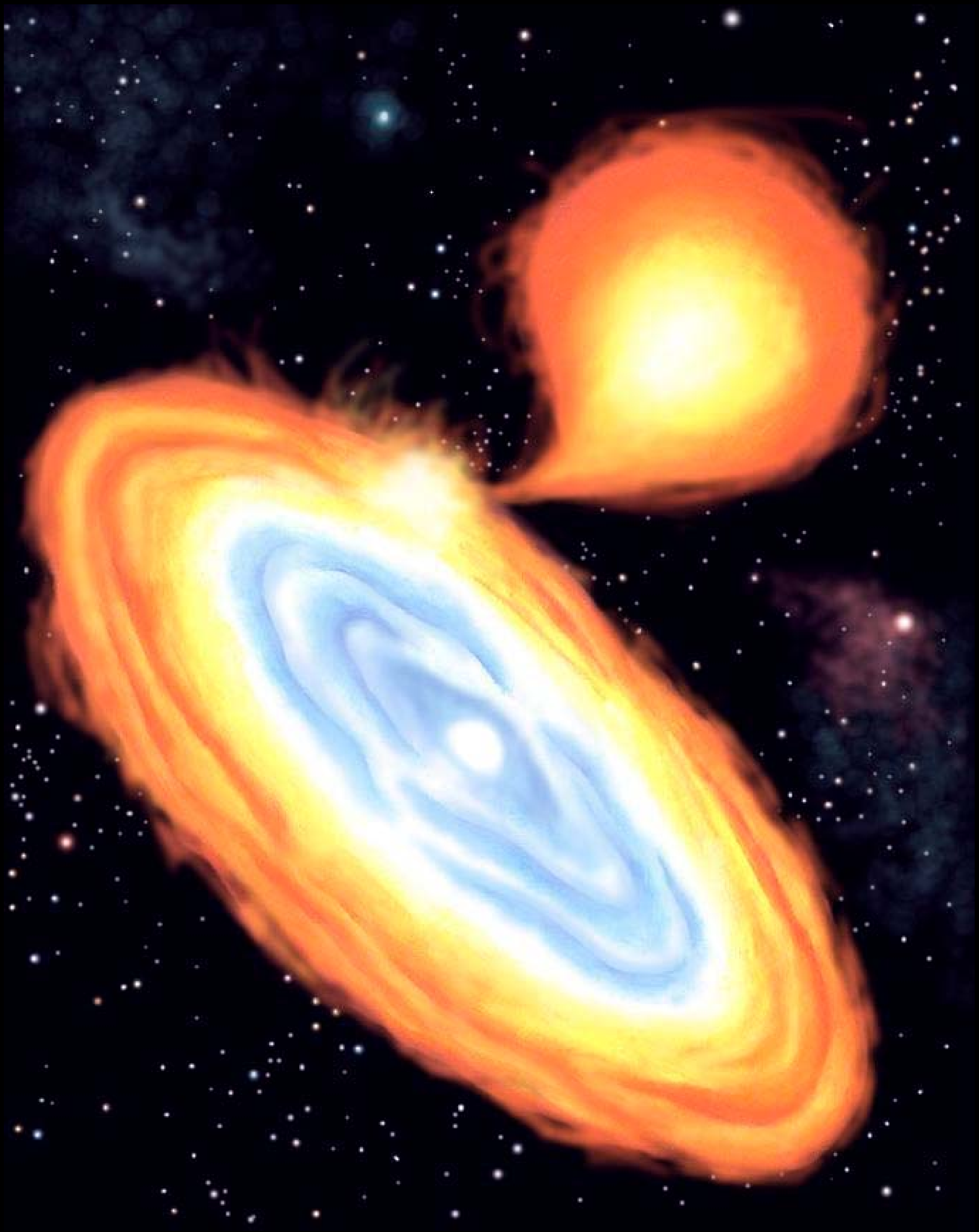
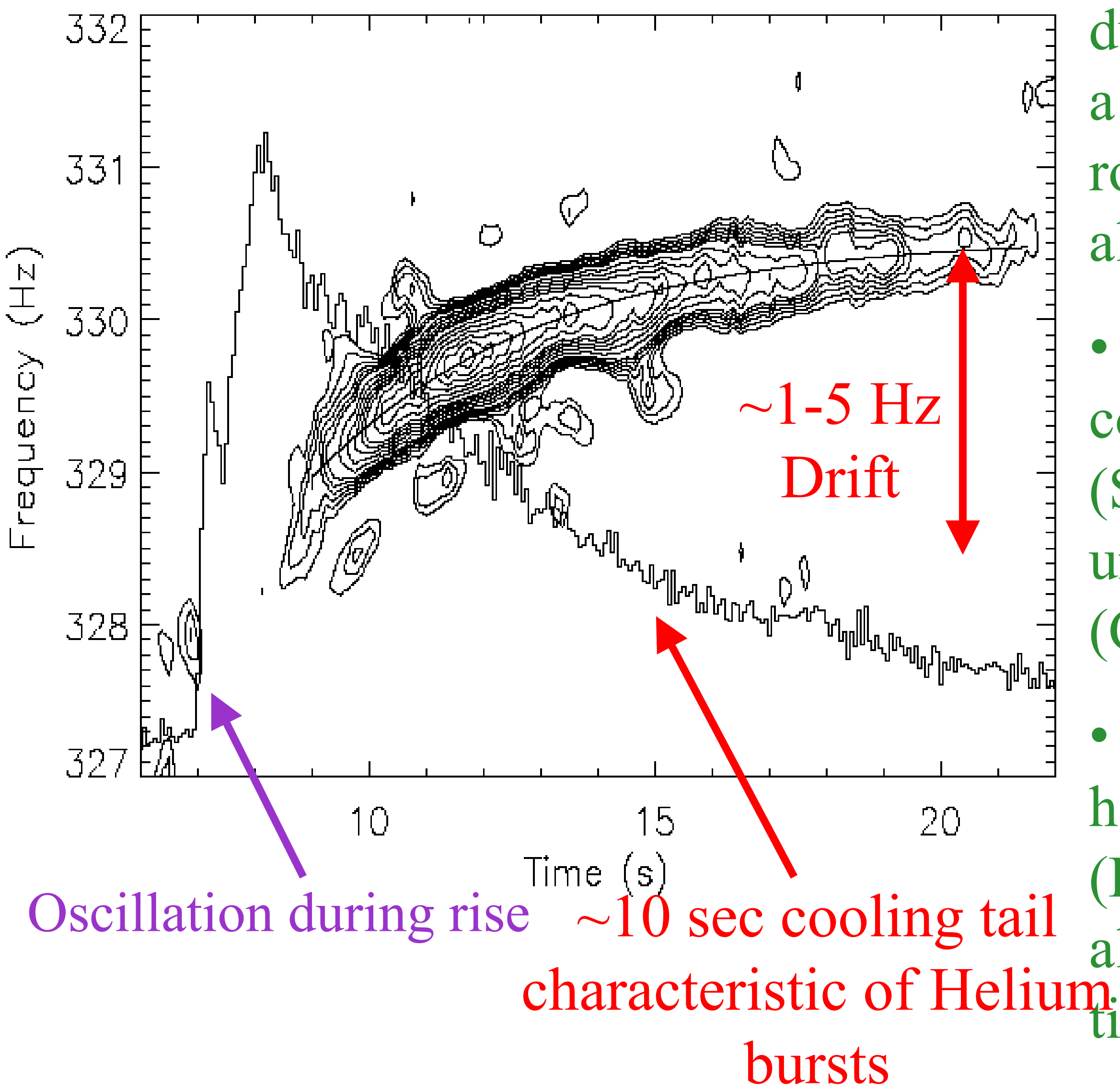
Piro & Bildsten 2004, 2005a, 2005b, 2005c (submitted)



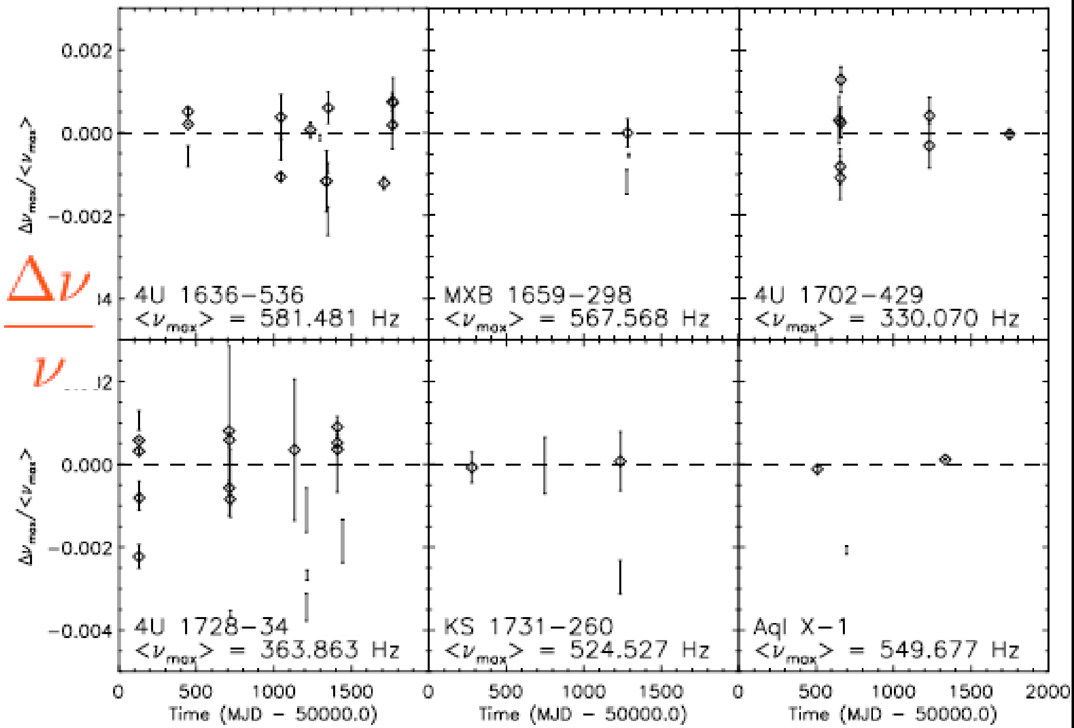
Burst Oscillations from LMXBs

4U 1702-429; Strohmayer & Markwardt '99



- Frequency and amplitude during rise are consistent with a hot spot spreading on a rotating star (Strohmayer et al. '97)
- Angular momentum conservation of surface layers (Strohmayer et al. '97) underpredicts late time drift (Cumming et al. '02)
- Ignition hot spot should have already spread over star (Bildsten '95; Spitkovsky et al. '02), so what creates late time asymmetry?!

The asymptotic frequency is characteristic to each object



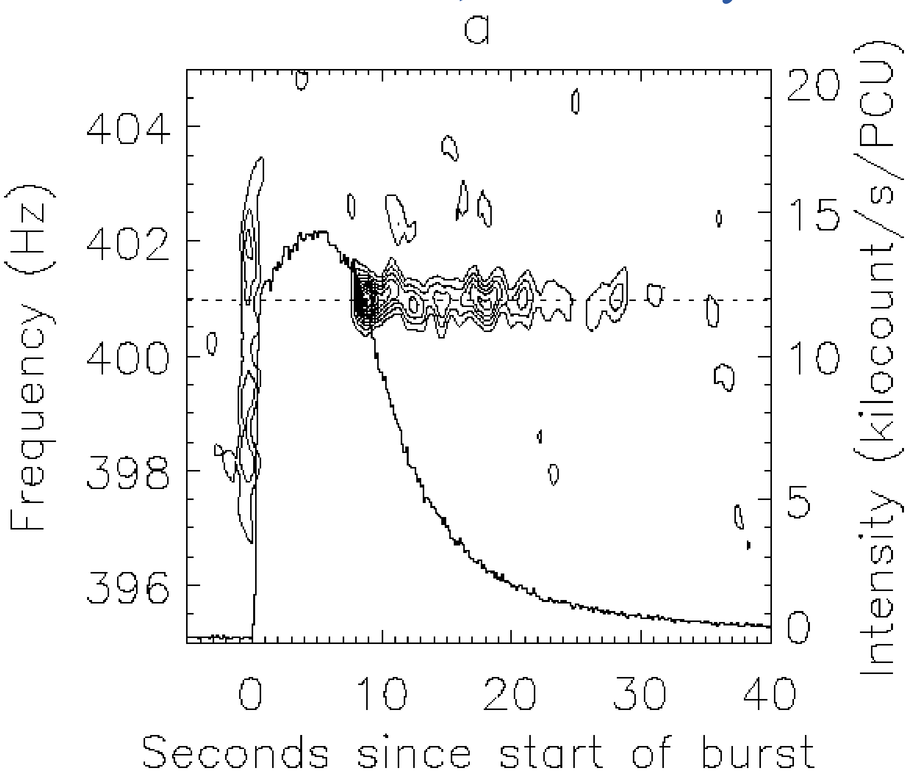
- Frequency stable over many observations (within 1 part in 1000 over years; Muno et al. '02)

It must be the spin…right?

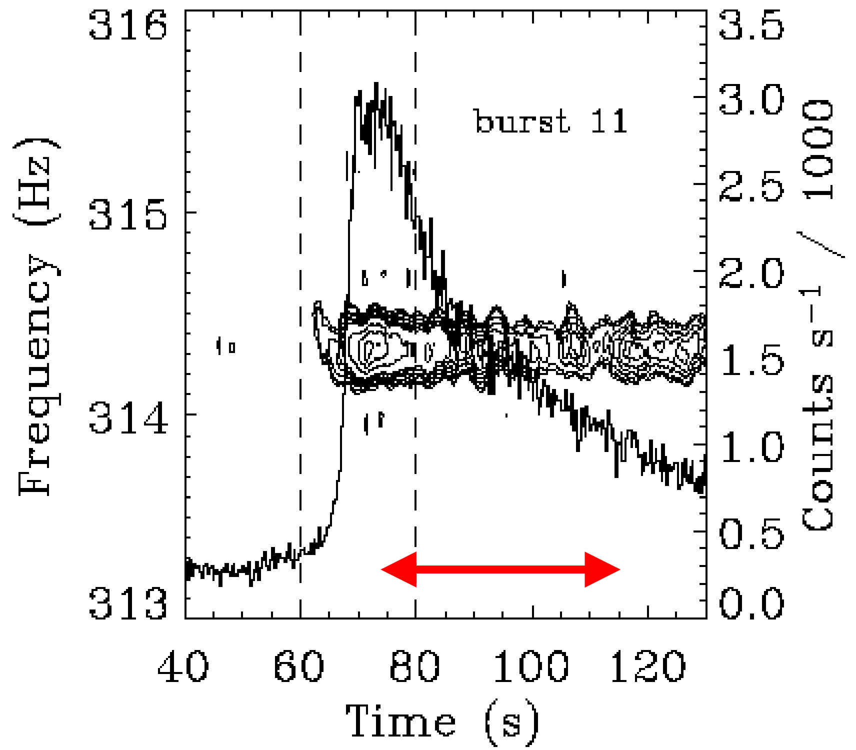
Source	Asymptotic Freq. (Hz)
4U 1608-522	620
SAX J1750-2900	600
MXB 1743-29	589
4U 1636-536	581
MXB 1659-298	567
Aql X-1	549
KS 1731-260	524
SAX J1748.9-2901	410
SAX J1808.4-3658	401
4U 1728-34	363
4U 1702-429	329
XTE J1814-338	314
4U 1926-053	270
EXO 0748-676	45

Burst Oscillations from Pulsars

SAX J1808.4-3658; Chakrabarty et al. '03



XTE J1814-338; Strohmayer et al. '03
Also see recent work by Watts et al. '05



~ 100 sec decay like H/He burst!

- Burst oscillation frequency = spin!
- No frequency drift, likely due to large B-field (Cumming et al. 2001)

What Creates Burst Oscillations in the Non-pulsar Neutron Stars?

Important differences:

- Non-pulsars only show oscillations in short (~ 2-10 s) bursts, while pulsars have shown oscillations in longer bursts (~ 100 s)

- Non-pulsars show frequency drifts often late into cooling tail, while pulsars show no frequency evolution after burst peak

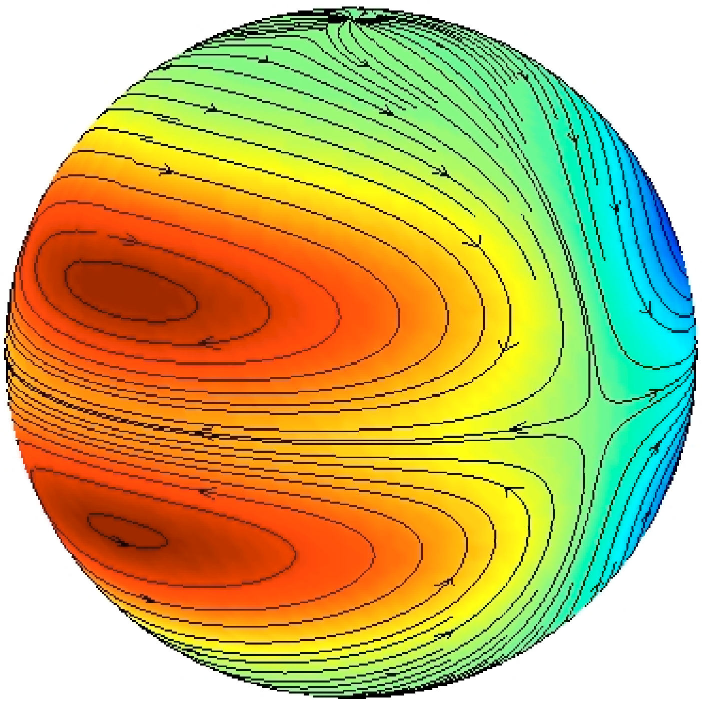
- Non-pulsars have highly sinusoidal oscillations (Muno et al. '02), while pulsars show harmonic content (Strohmayer et al. '03)

- The pulsed amplitude as a function of energy may be different between the two types of objects (unfortunately, pulsars only measured in persistent emission) (Muno et al. '03; Cui et al. '98)

These differences support the hypothesis that a different mechanism may be acting in the case of the non-pulsars.

Perhaps Nonradial Oscillations?

Initially calculated by McDermott & Taam (1987) BEFORE burst oscillations were discovered (also see Bildsten & Cutler '95). Hypothesized by Heyl (2004).



Graphic courtesy of G. Ushomirsky

- Most obvious way to create a late time surface asymmetry in a non-magnetized fluid.
- Supported by the HIGHLY sinusoidal nature of oscillations
- The angular and radial eigenfunctions are severely restricted by the main characteristics of burst oscillations.

What angular and radial structure must such a mode have?…

What Angular Eigenfunction?

Heyl ('04) identified crucial properties:

- Highly sinusoidal nature (Muno et al. '02) implies m = 1 or m = -1

- The OBSERVED frequency is

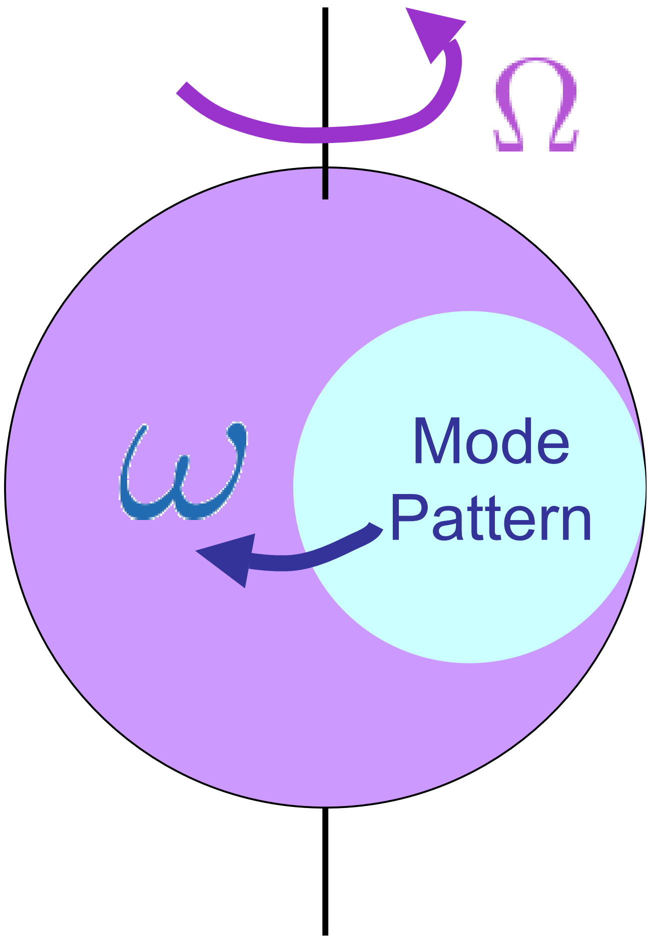
$$\omega_{\rm obs} = |m\Omega - \omega|$$

If the mode travels PROGRADE (m = -1) a DECREASING frequency is observed

$$\omega_{\rm obs} = \Omega + \omega$$

If the mode travels RETROGRADE (m = 1) an INCREASING frequency is observed

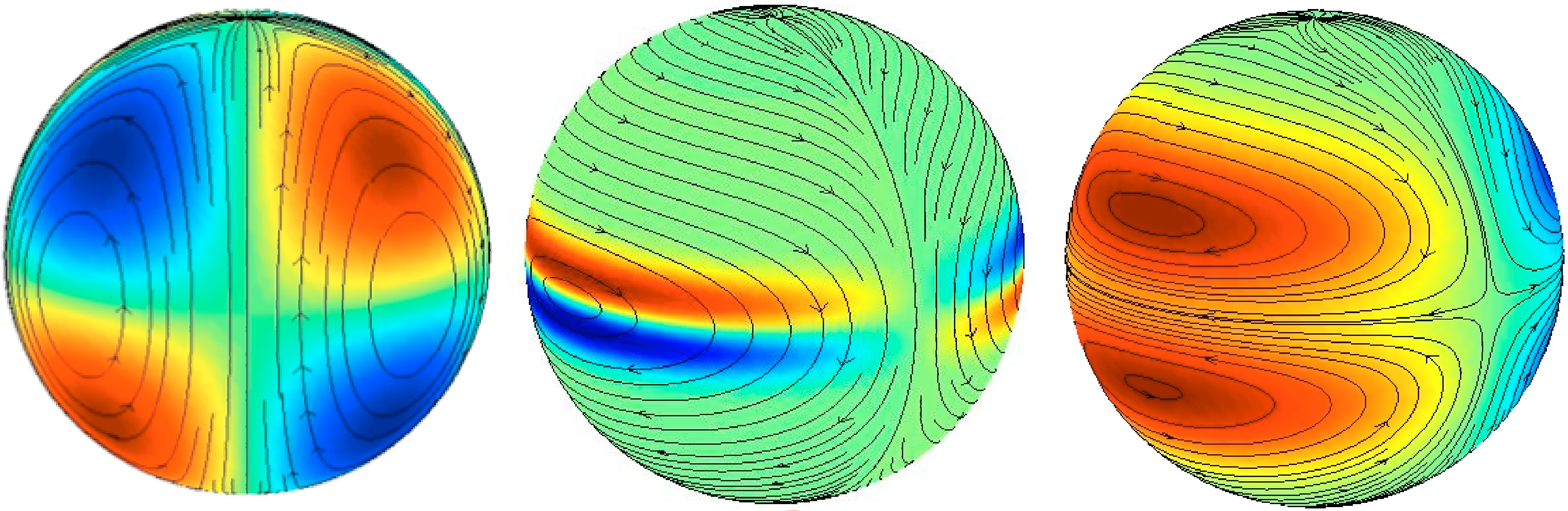
$$\omega_{\rm obs} = \Omega - \omega$$



Rotational Modifications

Since layer is thin and buoyancy is very strong, Coriolis effects ONLY alter ANGULAR mode patterns and latitudinal wavelength (through λ) and NOT radial eigenfunctions! (Bildsten et al. '96)

Inertial R-modes | $l = m$, Buoyant R-modes | $l = 2,\ m = 1$ Buoyant R-mode



$$\omega = \frac{2m\Omega}{l(l+1)}$$

Only at slow spin. Not applicable.

$$\lambda \sim \left(\frac{2\Omega}{\omega}\right)^2 \sim 10 - 10^3$$

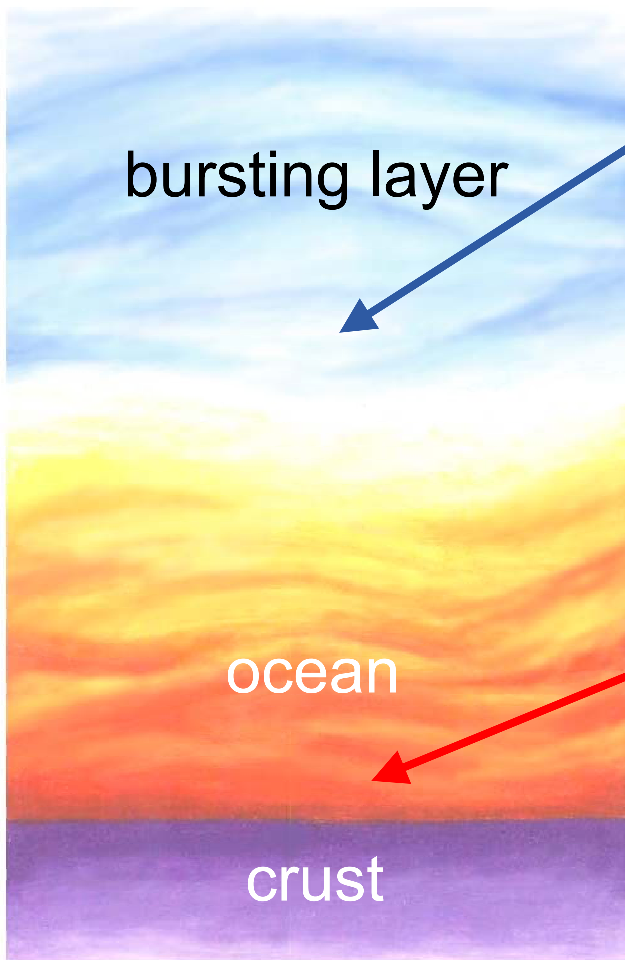
Too large of drifts and hard to see.

$$\lambda = 0.11$$

Just right. Gives drifts as observed and nice wide eigenfunction

Modes On Neutron Star Surface

Depth	Density
$< 1\ \mathrm{m}$	$10^4\ \mathrm{g\ cm^{-3}}$
$H_b \approx 2\ \mathrm{m}$	$10^6\ \mathrm{g\ cm^{-3}}$
$H_c \approx 20\ \mathrm{m}$	$10^9\ \mathrm{g\ cm^{-3}}$



Shallow surface wave

$$\omega_s^2 = g H_b k^2 \frac{\Delta\rho}{\rho}$$

$$k^2 = \frac{\lambda}{R^2}$$

Crustal interface wave

$$\omega_c^2 = g H_c k^2 \frac{\mu}{P}$$

Piro & Bildsten 2005a

$$\frac{\mu}{P} \approx 10^{-2}$$

Strohmayer et al. ‘91

The First 3 Radial Modes

(using $\lambda = 0.11$)

- Mode energy is set to

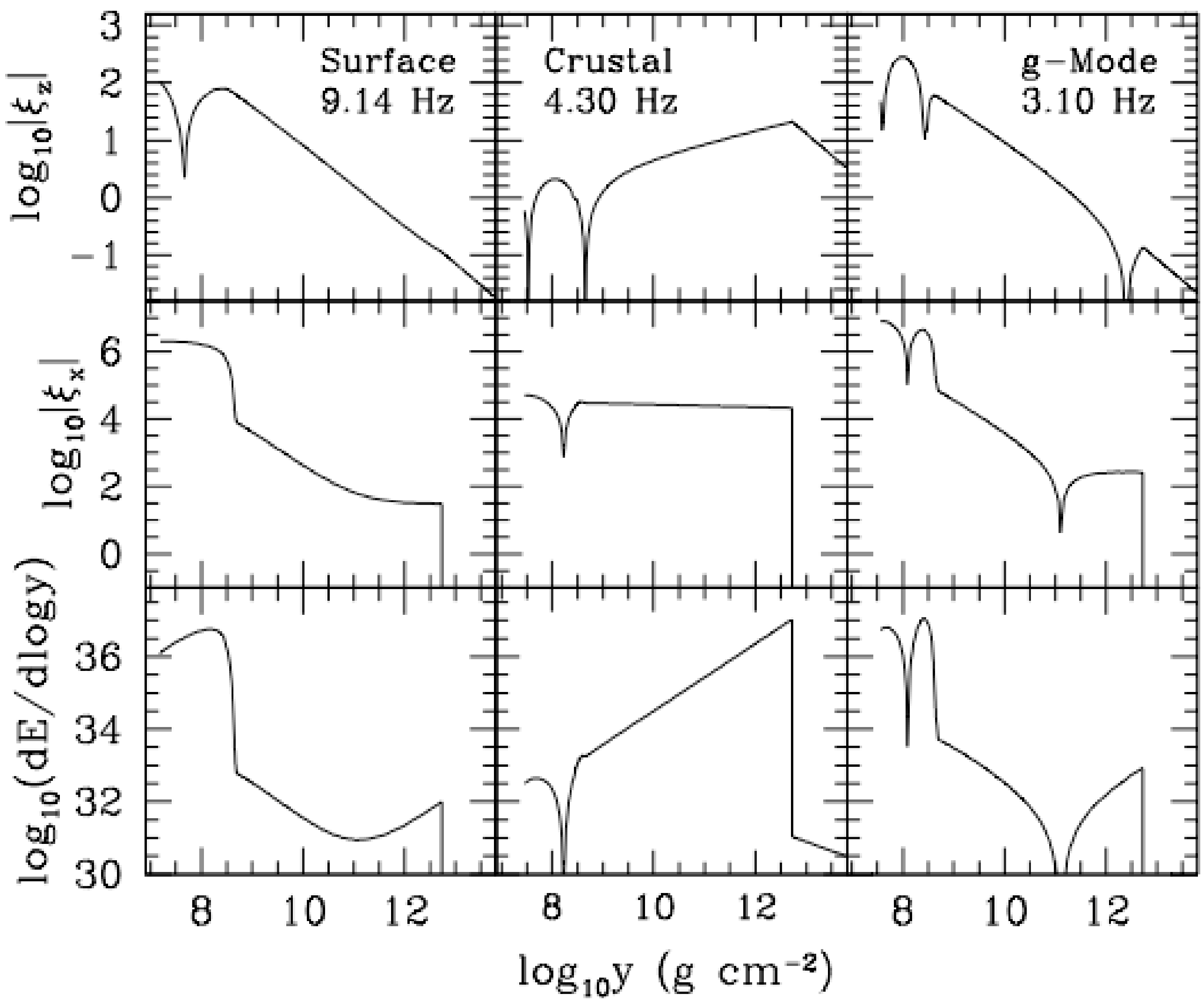
  5×10^{36} ergs

  10^{-3} of the energy in a burst (Bildsten '98)

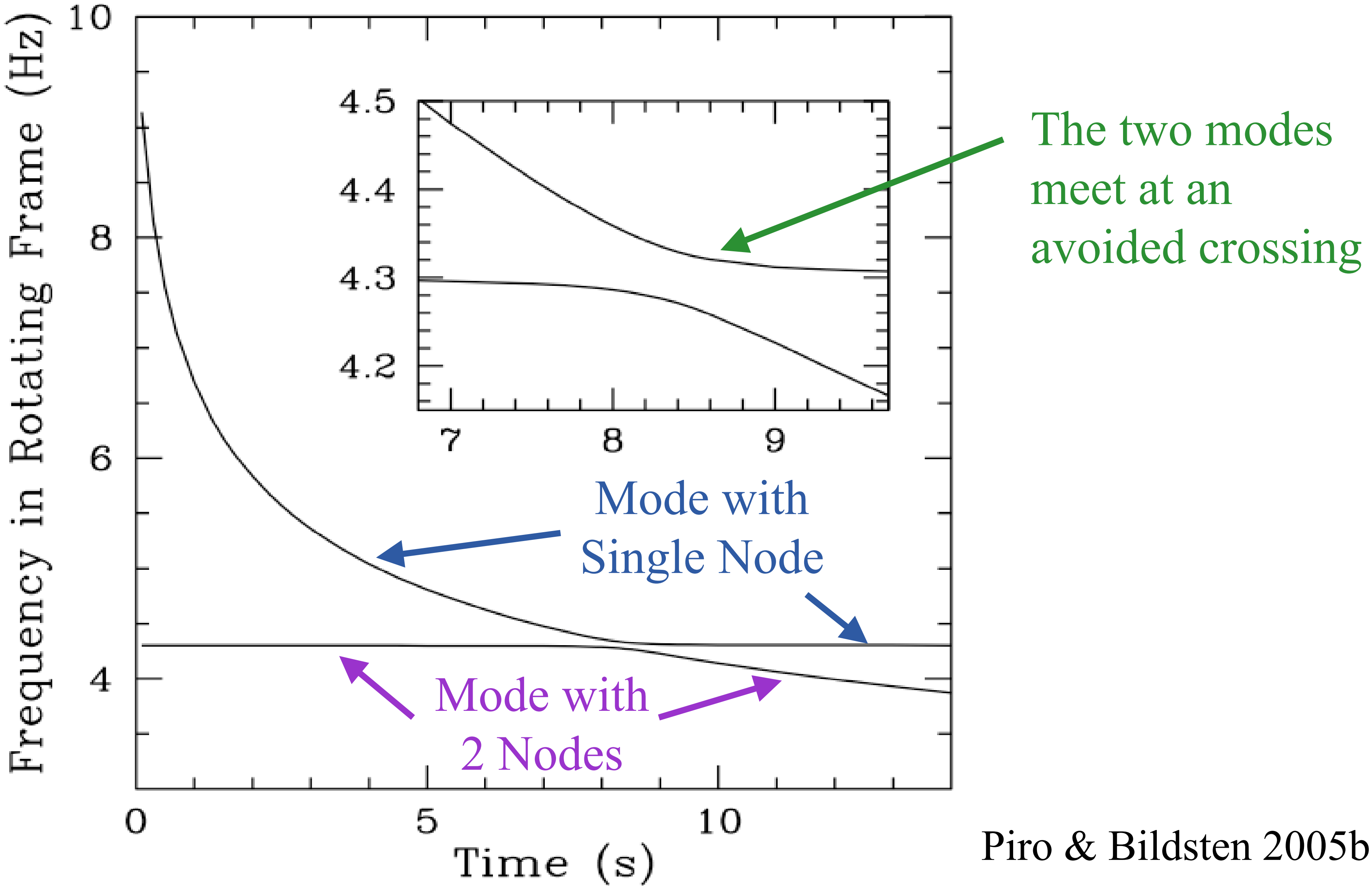
- Estimate radiative damping time using "work integral" (Unno et al. '89)

- Surface wave (single node) has best chance of being seen (long damping time + large surface amplitude)

$t_{\rm damp} \approx 20$ s $\quad t_{\rm damp} \approx 3000$ s $\quad t_{\rm damp} \approx 0.5$ s

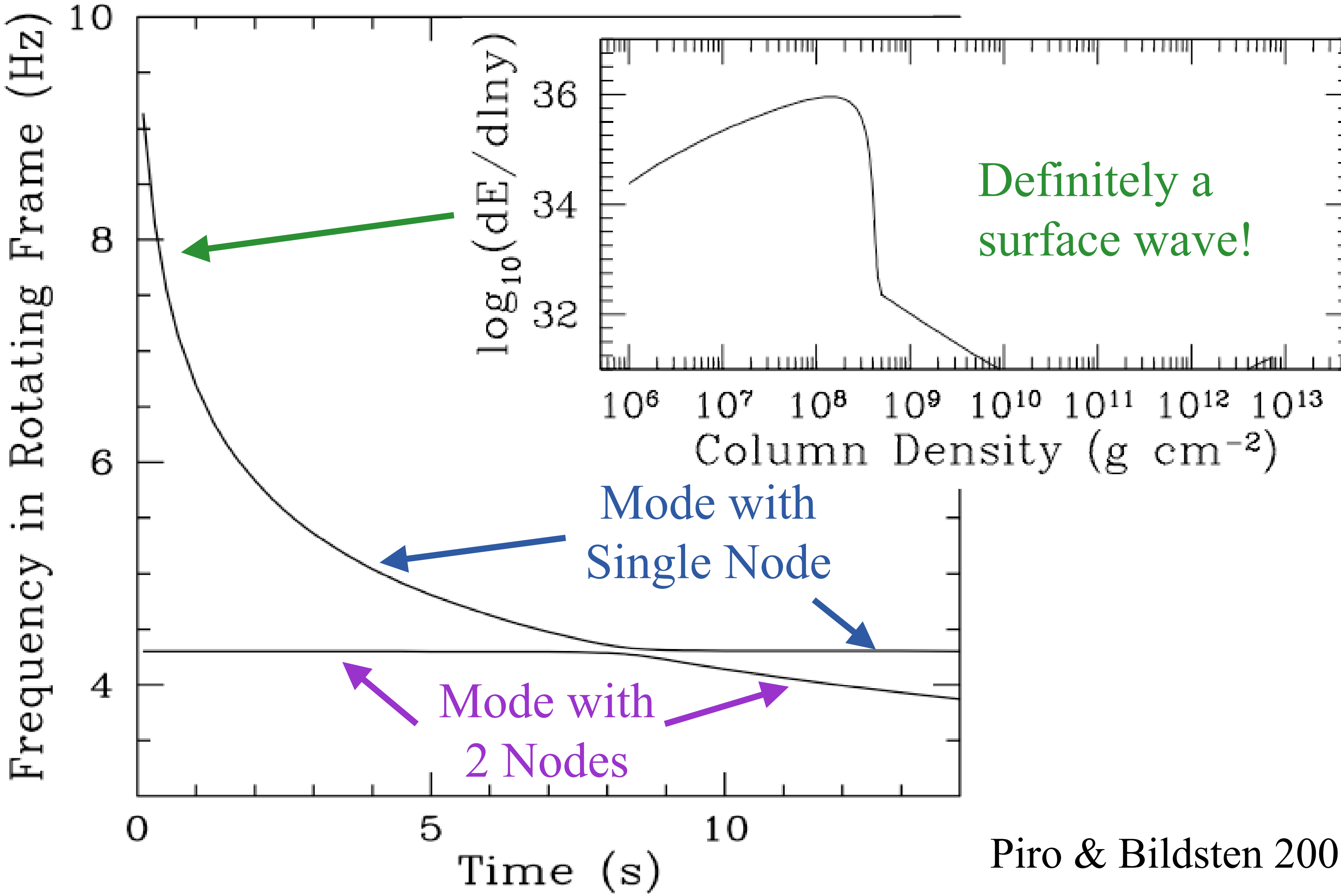


Avoided Mode Crossings



Piro & Bildsten 2005b

Avoided Mode Crossings



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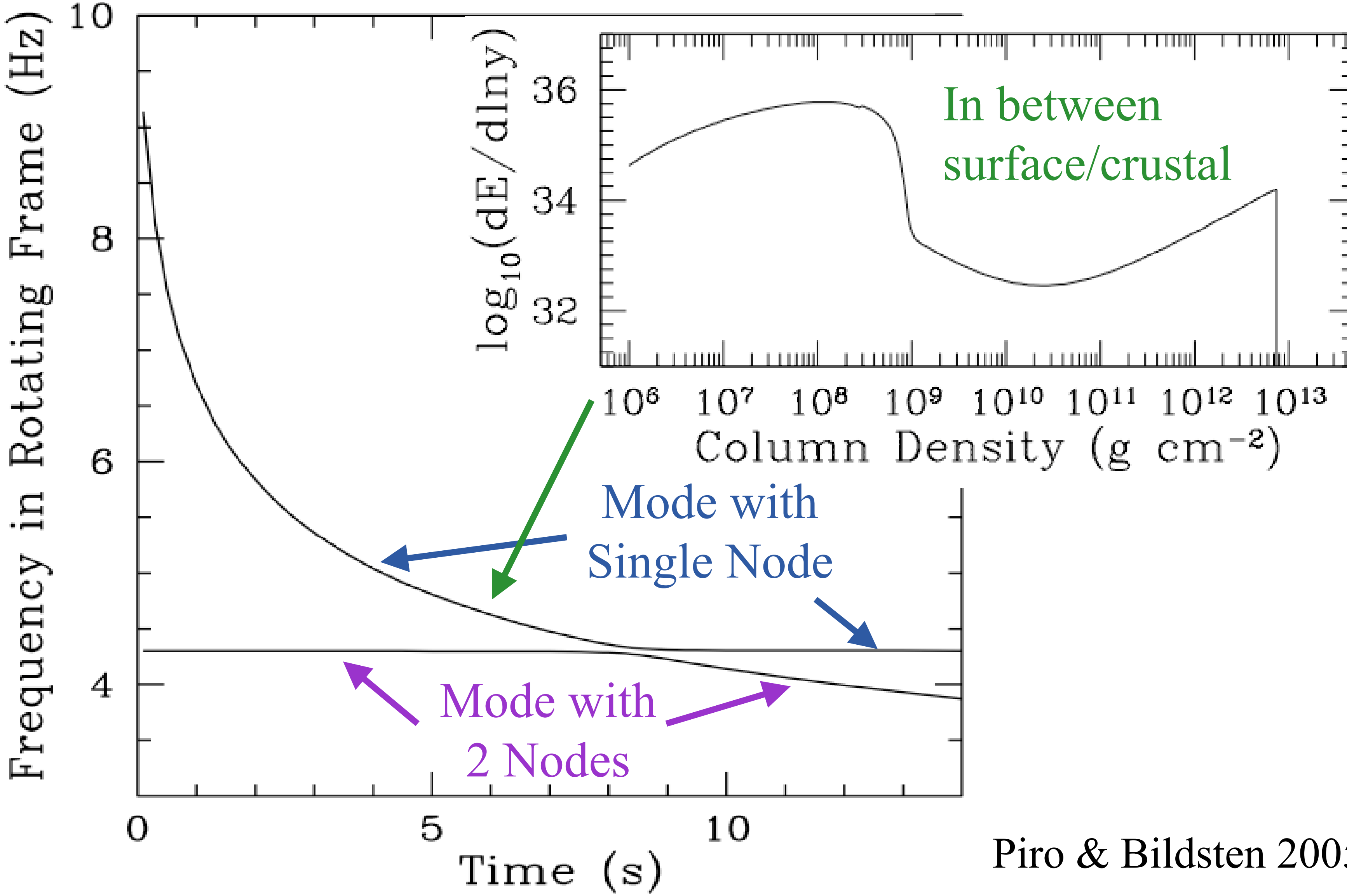

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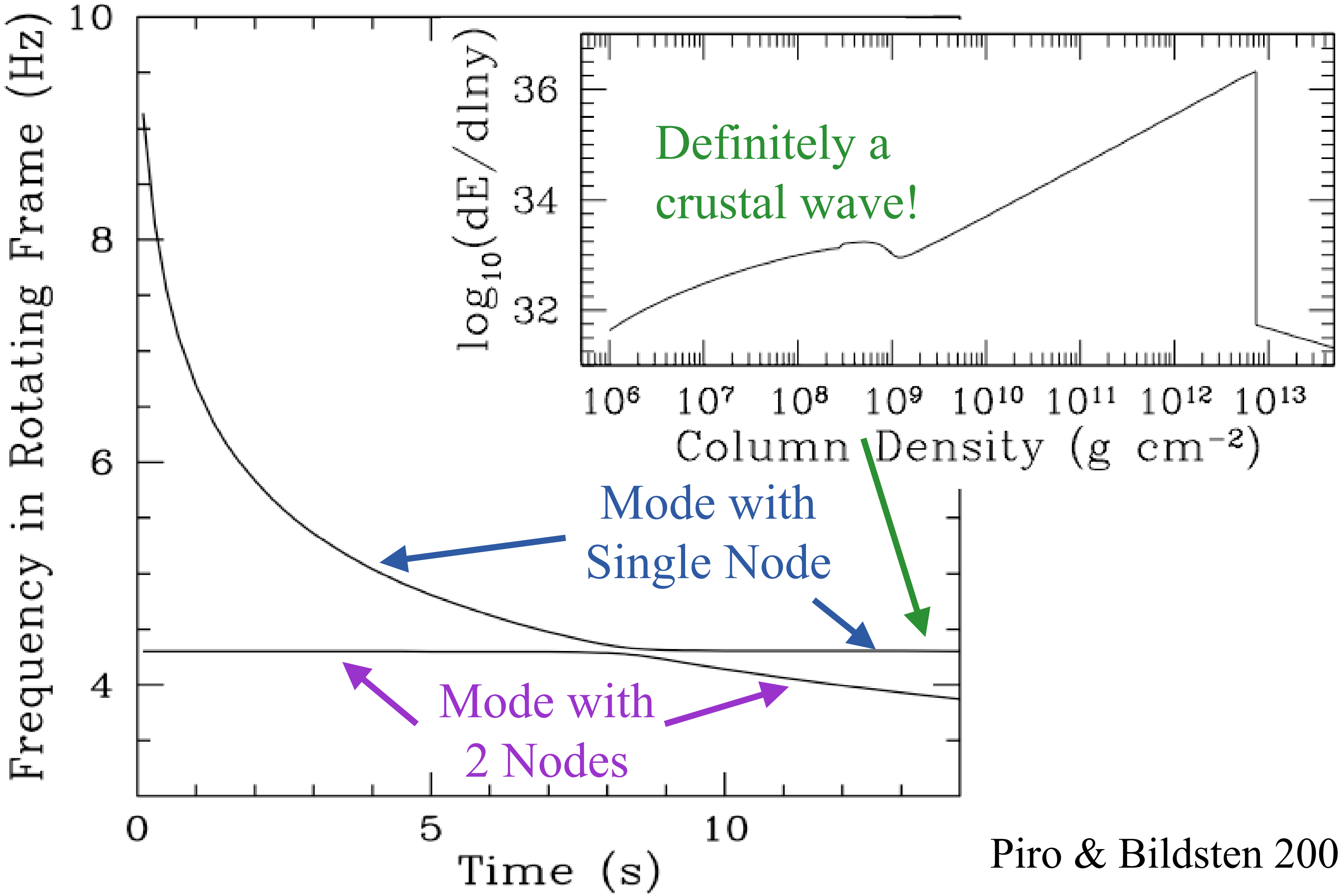
Avoided Mode Crossings



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Calculated Frequencies

400 Hz neutron star spin

$$\omega_{\rm obs} = |m\Omega - \omega|$$

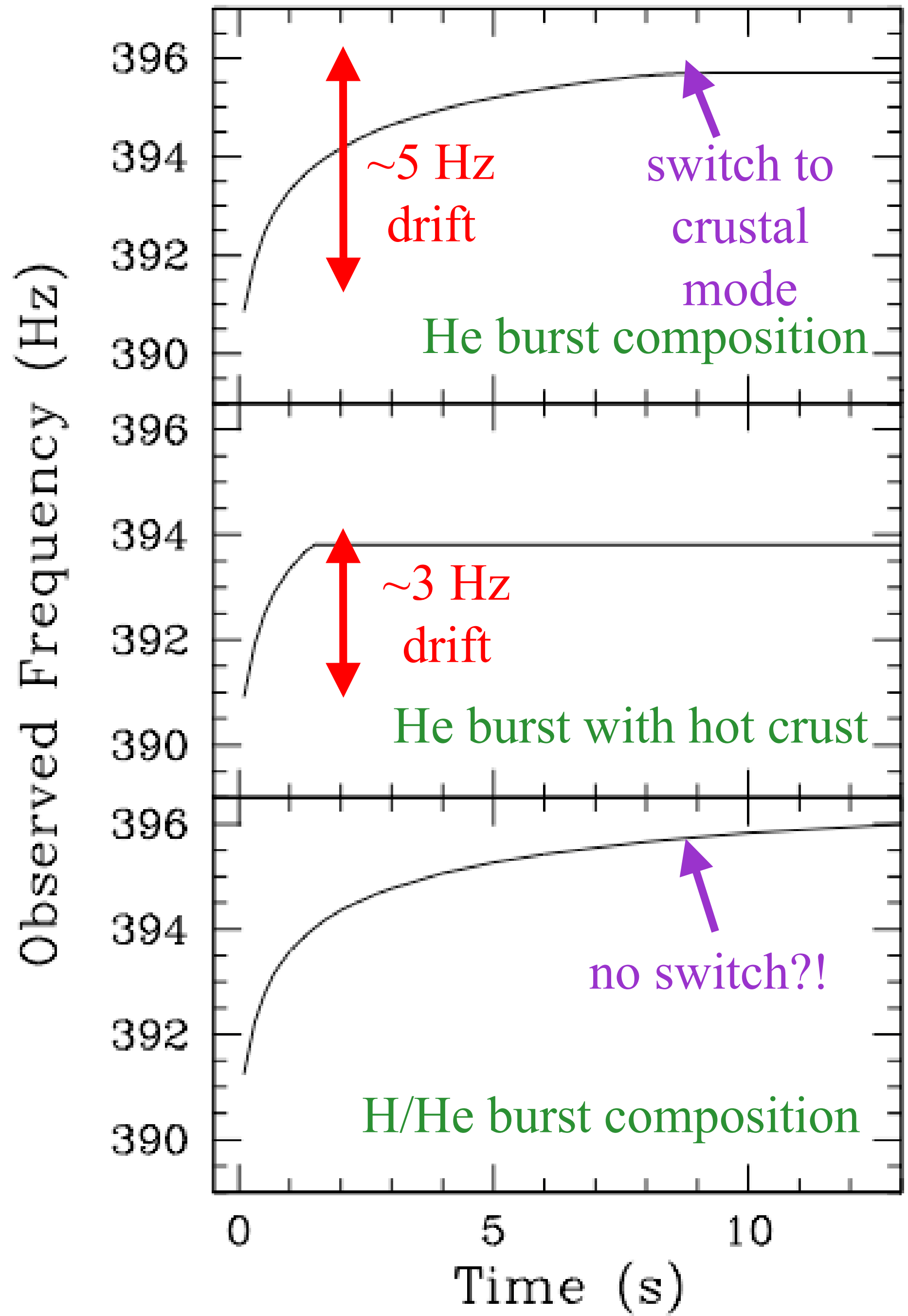
- Lowest order mode that matches burst oscillations is the $l = 2$, $m = 1$, r-mode

$$\lambda \approx 1/9 \approx 0.11$$

- Neutron star still spinning close to burst oscillation frequency (~ 4 Hz above)

All sounds nice…but can we make any predictions?

Piro & Bildsten 2005b



Comparison with Drift Observations

- The observed drift is just the difference of

$$\frac{\omega_s}{2\pi} \approx 9.5 \text{ Hz}$$

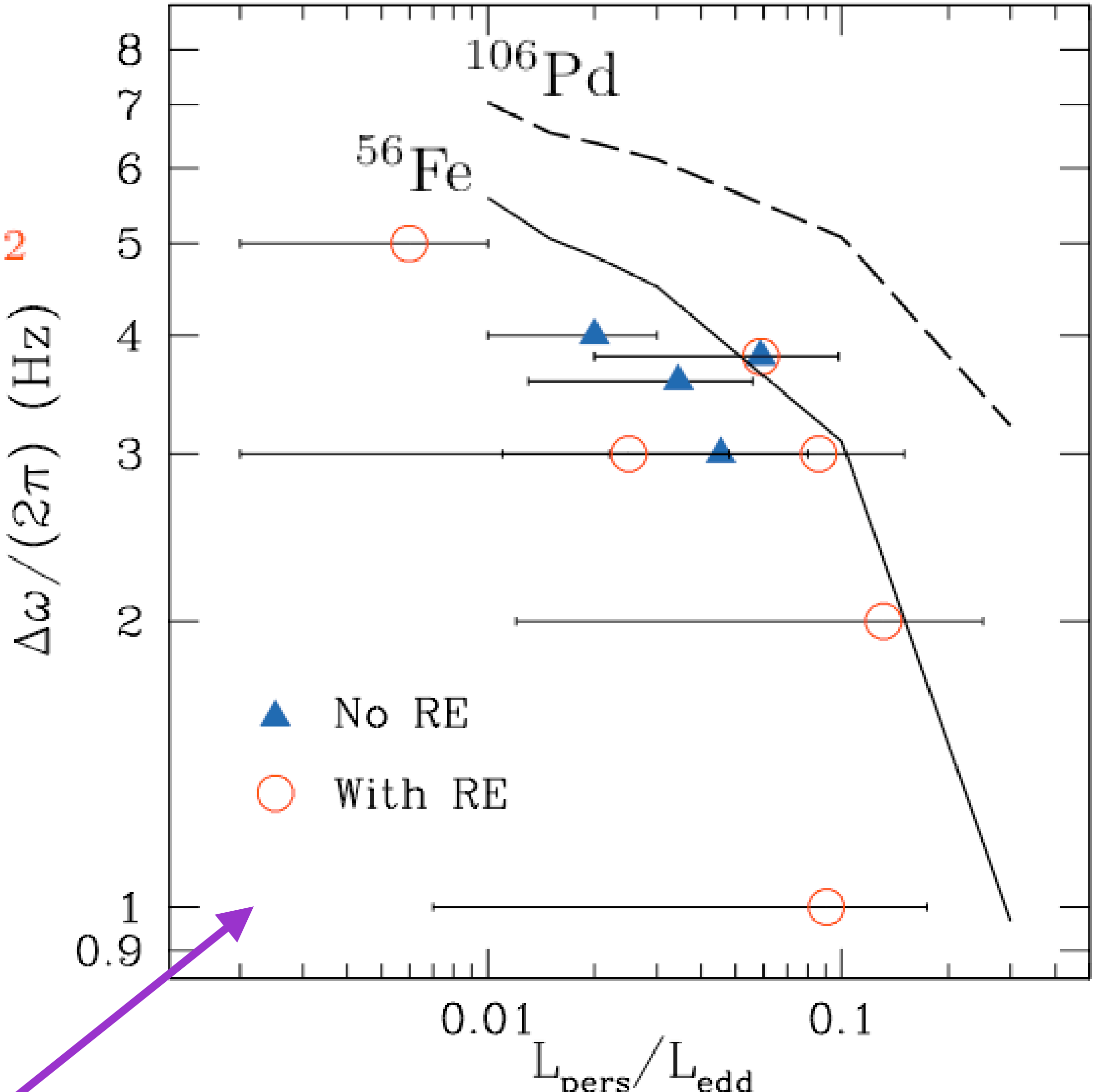
$$\frac{\omega_c}{2\pi} \approx 4.3 \text{ Hz} \left(\frac{64}{A_c} \frac{T_{c,8}}{3} \right)^{1/2}$$

- We calculated drifts using these analytic frequencies with crust models courtesy of E. Brown.

- We compared these with the observed drifts and persistent luminosity ranges.

- Comparison favors a lighter crust, consistent with the observed He-rich bursts.

Piro & Bildsten 2005b

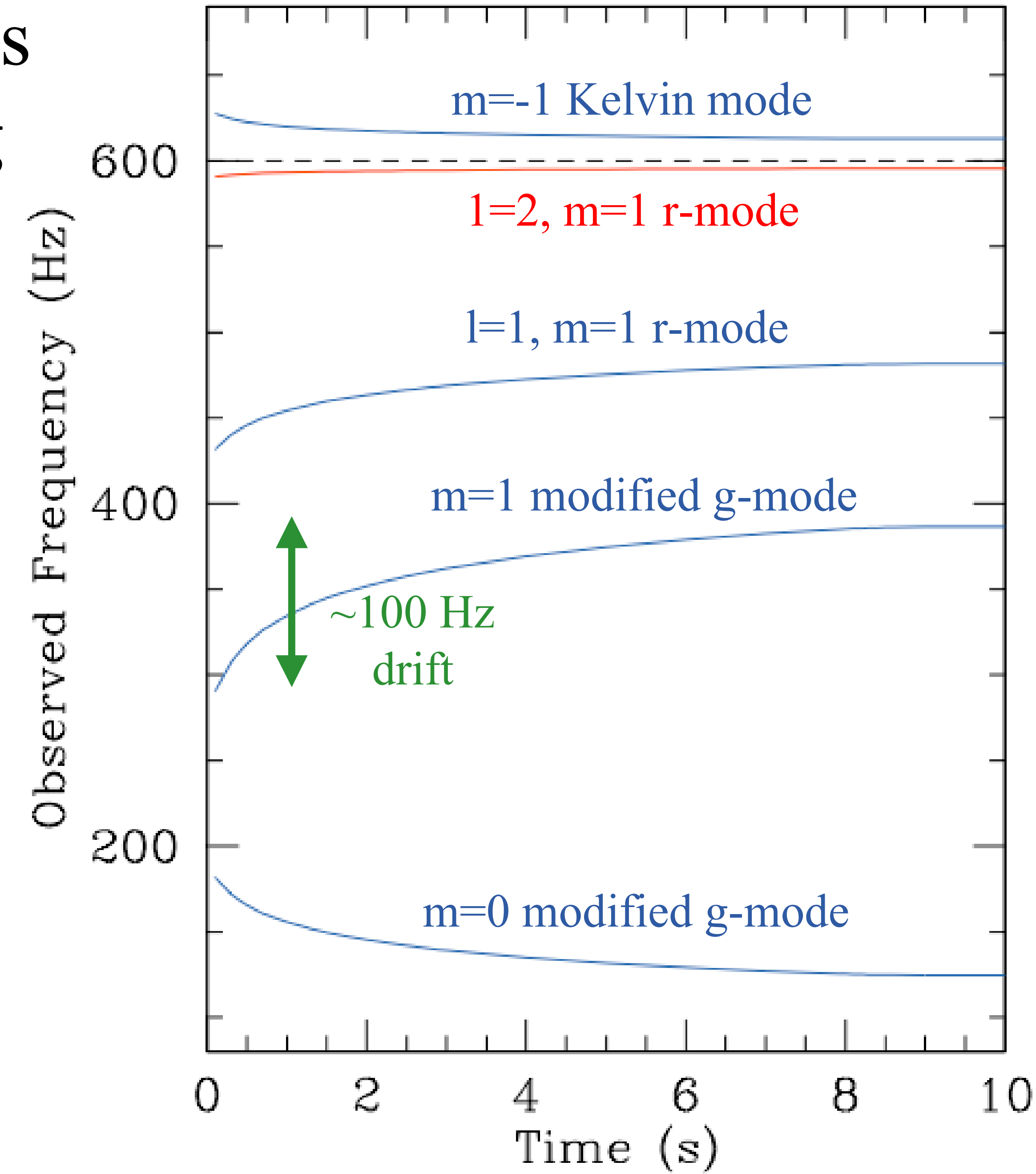


$$L_{\rm Edd} \approx 3 \times 10^{38} \text{erg s}^{-1}$$

Piro & Bildsten 2005b

Could other modes be present during X-ray bursts?

- Nothing precludes the other low-angular order modes from also being present.
- Such modes would show 15-100 Hz frequency drifts, so they may be hidden in current observations.



Amplitude-Energy Relation of Modes

Also see Heyl 2005 and Lee & Strohmayer 2005

Mode amplitude is unknown => we can ONLY fit for SHAPE of relation

- Linearly perturbed blackbody

$$\frac{\Delta I}{I} = \frac{E'}{kT}\frac{e^{E'/kT}}{e^{E'/kT}-1}\frac{\Delta T}{T}$$

- Low energy limit

$$E < kT\sqrt{1-r_g/R}$$

$$\Delta I/I \propto \text{constant}$$

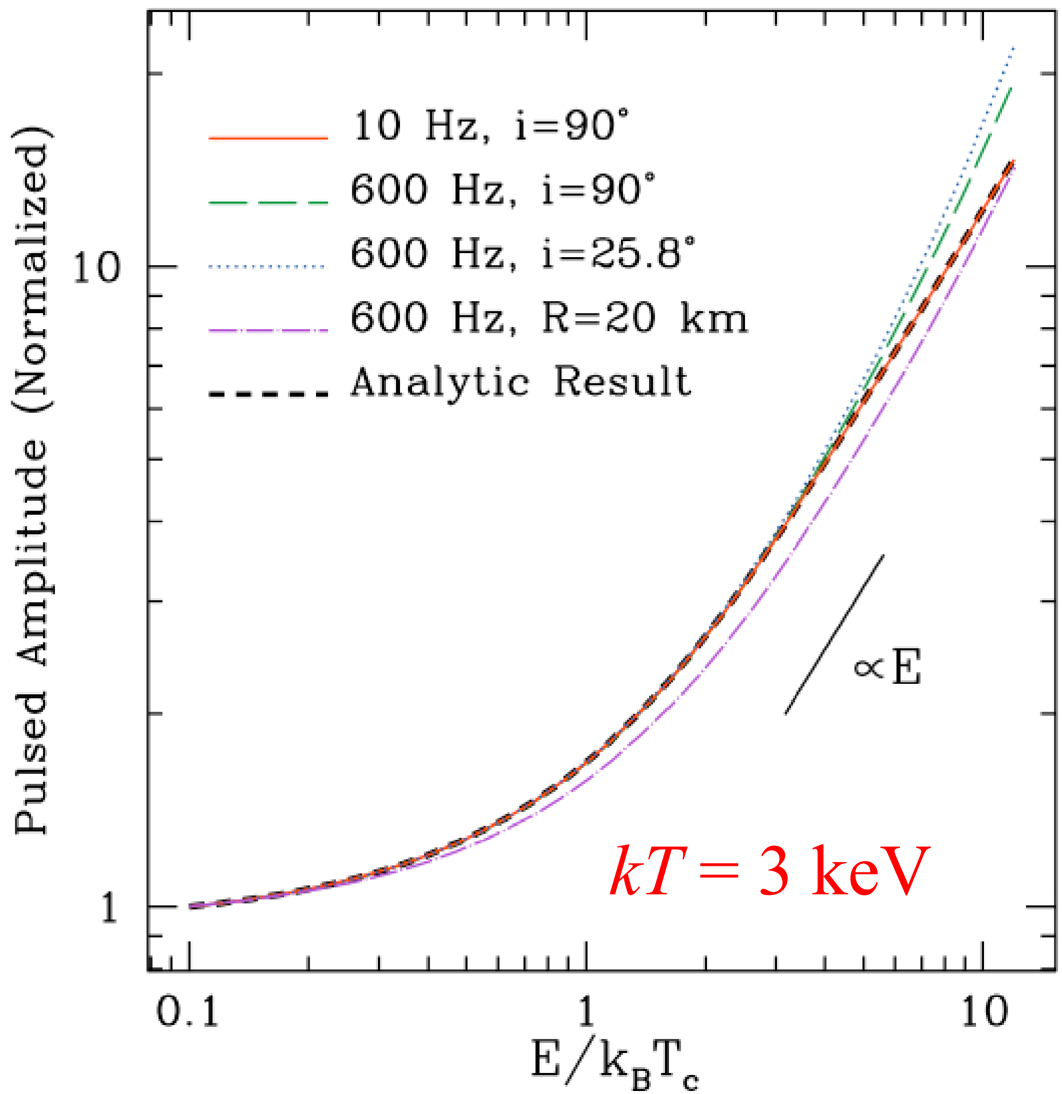
- High energy limit

$$E > kT\sqrt{1-r_g/R}$$

$$\Delta I/I \propto E/kT$$

Compares favorably with full integrations including GR! (when normalized the same)

Piro & Bildsten 2005c (submitted)



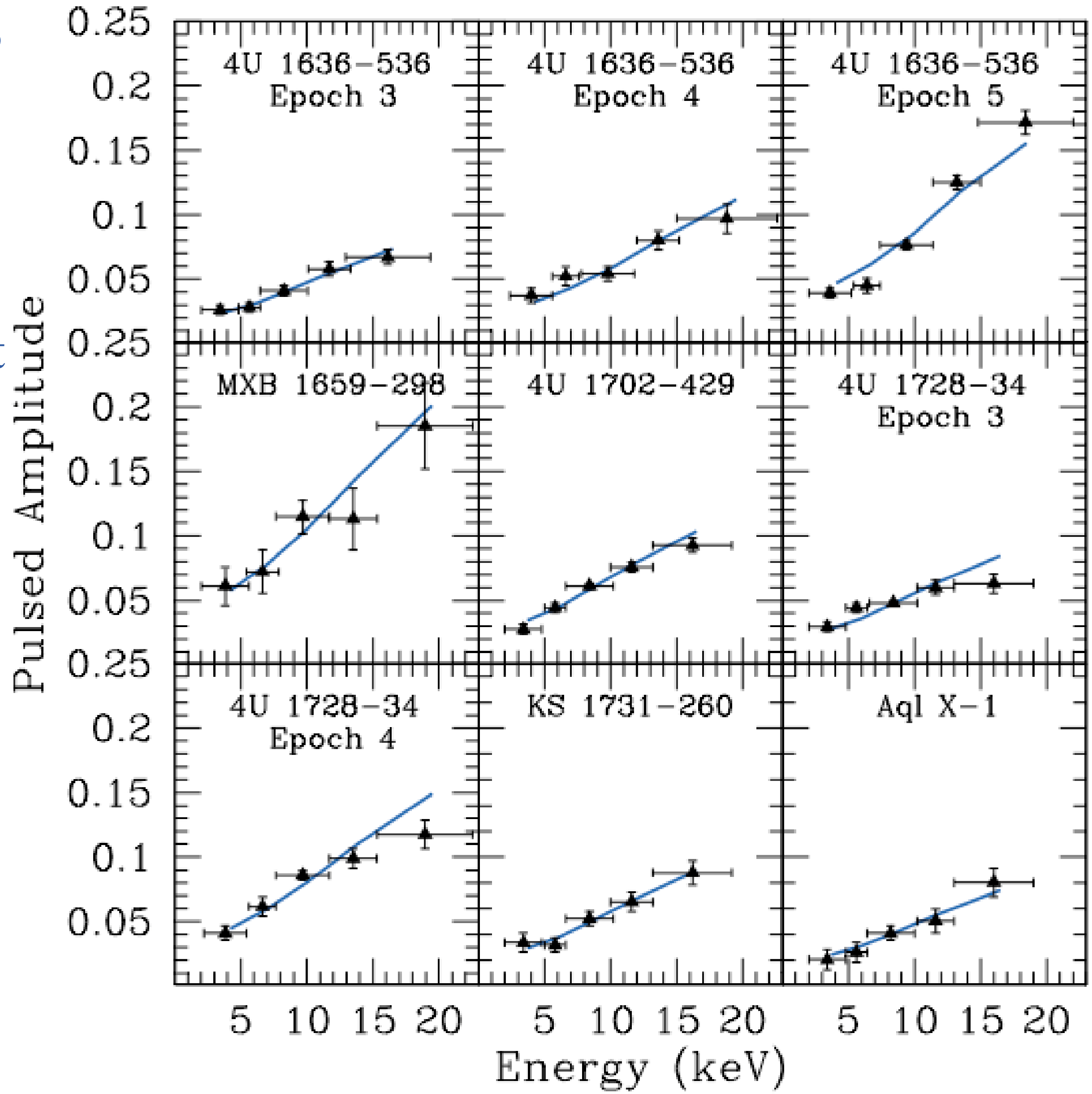
Comparison with Observations

Piro & Bildsten 2005c (submitted)

- Data from Muno et al. '03
- Demonstrates the difficulty of attempting to learn about NSs
- Low energy measurement would allow fitting for

$$kT\sqrt{1 - r_g/R}$$

- This begs the question: What is the energy dependence of burst oscillations from pulsars! (these differ in their persistent emission)



Conclusions

- A surface wave transitioning into a crustal interface wave can replicate the frequency evolution of burst oscillations. Only ONE combination of radial and angular eigenfunctions gives the correct properties!

- The energy-amplitude relation of burst oscillations is consistent with a surface mode, but this is not a strong constraint on models nor NS properties

Future work that needs to be done

- IMPORTANT QUESTION: What is amplitude-energy relation for pulsars DURING burst oscillations?

- Can burst oscillations be used to probe NS crusts?

- More theory! Why only 2-10 sec bursts? What is the excitation mechanism? (Cumming '05)