Sonic-Point Spin-Resonance Model of Kilohertz QPOs

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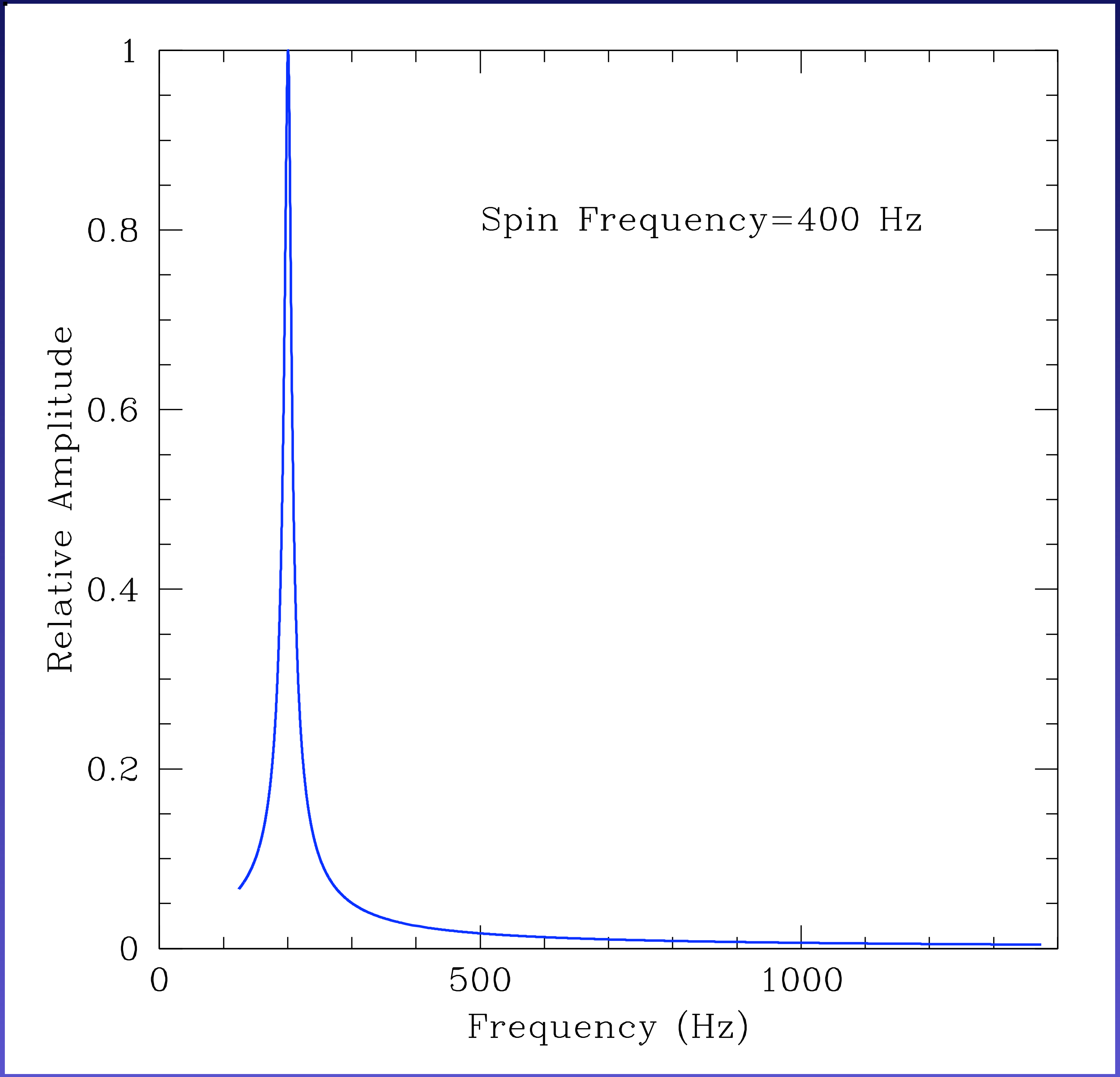
What We Think We Know About the Kilohertz QPO Sources

- The frequency $\nu_{\rm QPO2}$ and frequency behavior of the upper kilohertz QPO is consistent with the frequency of gas orbiting at the sonic point in the accretion disk produced by radiation drag forces (see Miller, Lamb & Psaltis 1998; Lamb & Miller 2001)
- Both the "fast" (~ 400–600 Hz) and "slow" (~ 200–400 Hz) burst oscillations are close to the spin frequency of the neutron star (see Cumming & Bildsten 2000; Strohmayer & Markwardt 2002; Chakrabarty et al. 2003; Strohmayer & Bildsten 2003)
- The kilohertz QPO frequency difference $\Delta\nu_{\rm QPO}$ is close to the spin frequency $\nu_{\rm spin}$ in the slow oscillators but close to half the stellar spin frequency in the fast oscillators (Wijnands et al. 2003), which suggests that the frequency $\nu_{\rm QPO1}$ of the lower kilohertz QPO is produced by a beat phenomena involving the orbital motion at the sonic radius
- How can the frequency $\nu_{\rm spin}/2$ be generated?

Resonance of the Star's Spin with Vertical Epicyclic Motion in the Disk

- The force of the X-ray beam or magnetic field rotating with the star excites vertical motion of clumps in the disk
- This effect peaks at the radius where the pattern frequency is equal to the vertical epicyclic frequency, i.e., where
- $$\nu_{\rm spin} - \nu_{\rm orb}(\rm resonance) = \nu_\psi$$
- At this "resonance radius," the beam or magnetic field of the star sweeps over the clump when it rises above the plane
- At the resonance radius $\nu_\psi(\rm resonance) \approx \nu_{\rm orb}(\rm resonance)$ and hence *individual clumps* oscillate vertically with the frequency $\nu_\psi(\rm resonance) \approx \nu_{\rm orb}(\rm resonance) \approx \nu_{\rm spin}/2$
- The clumps move in phase with the driving force and hence the *clump pattern* rotates with frequency $\nu_{\rm spin}$

Response of the Accretion Disk at $\nu_{\text{spin}}/2$

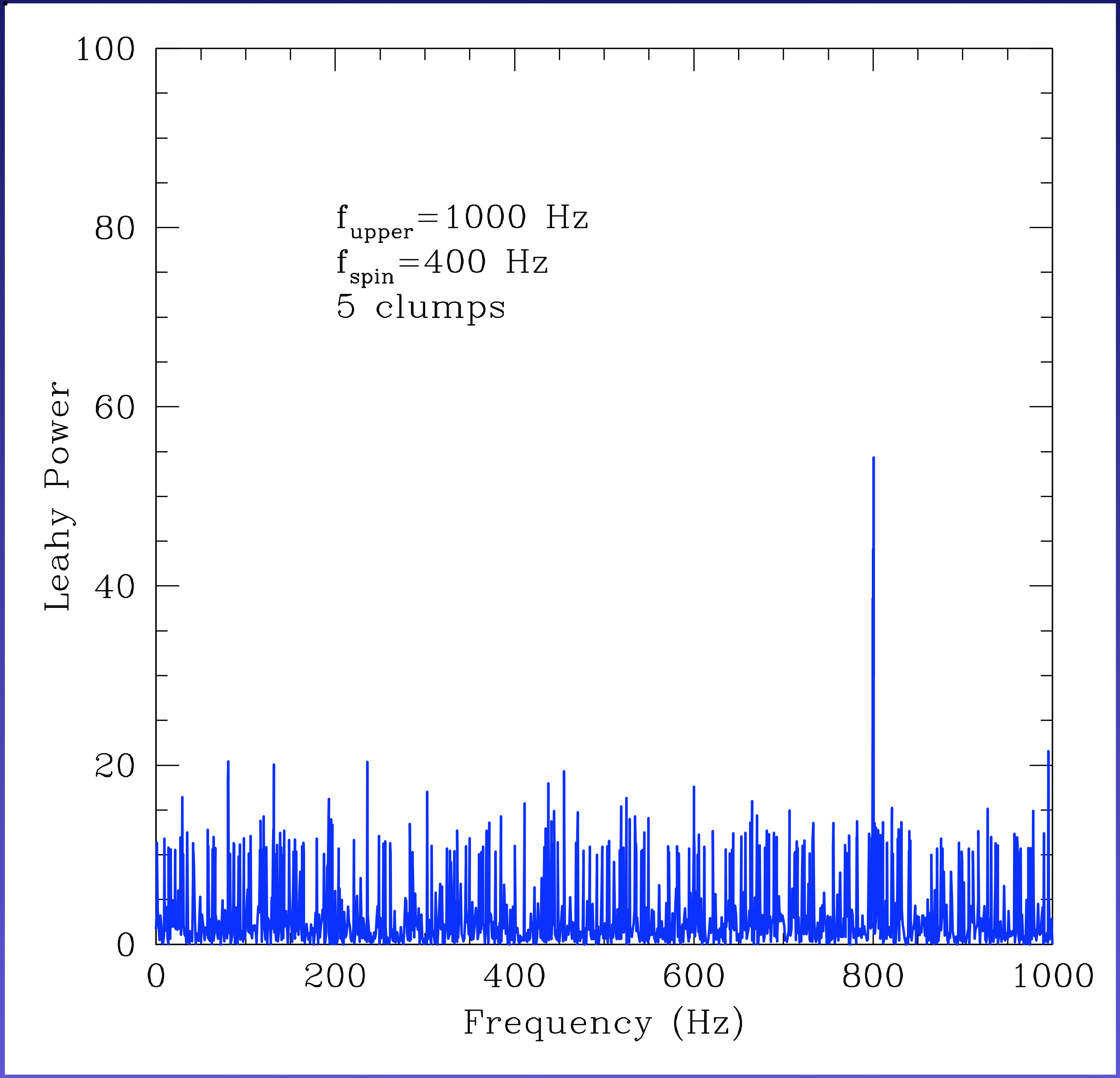


When the Star is Spinning Fairly Rapidly

The spin resonates with the vertical epicyclic frequency in the inner magnetosphere, where the disk flow is very clumpy —

- Scattering of radiation by *individual* clumps dominates
- A pattern of radiation from near the star rotates with the sonic point orbital frequency $\nu_{\mathrm{orb}}(\mathrm{sonic\ point})$
- This radiation pattern illuminates or shadows clumps at the resonance radius with frequency
- $$\nu_{\mathrm{beat1}} = \nu_{\mathrm{orb}}(\mathrm{sonic\ point}) - \nu_{\mathrm{spin}}/2$$
- Consequently the radiation from the accretion disk oscillates with this frequency
- This is the lower kilohertz QPO in fast rotators

Modulation of the Flux from the Accretion Disk at $\nu_{\rm beat1} = \nu_{\rm orb}(\text{sonic point}) - \nu_{\rm spin}/2$

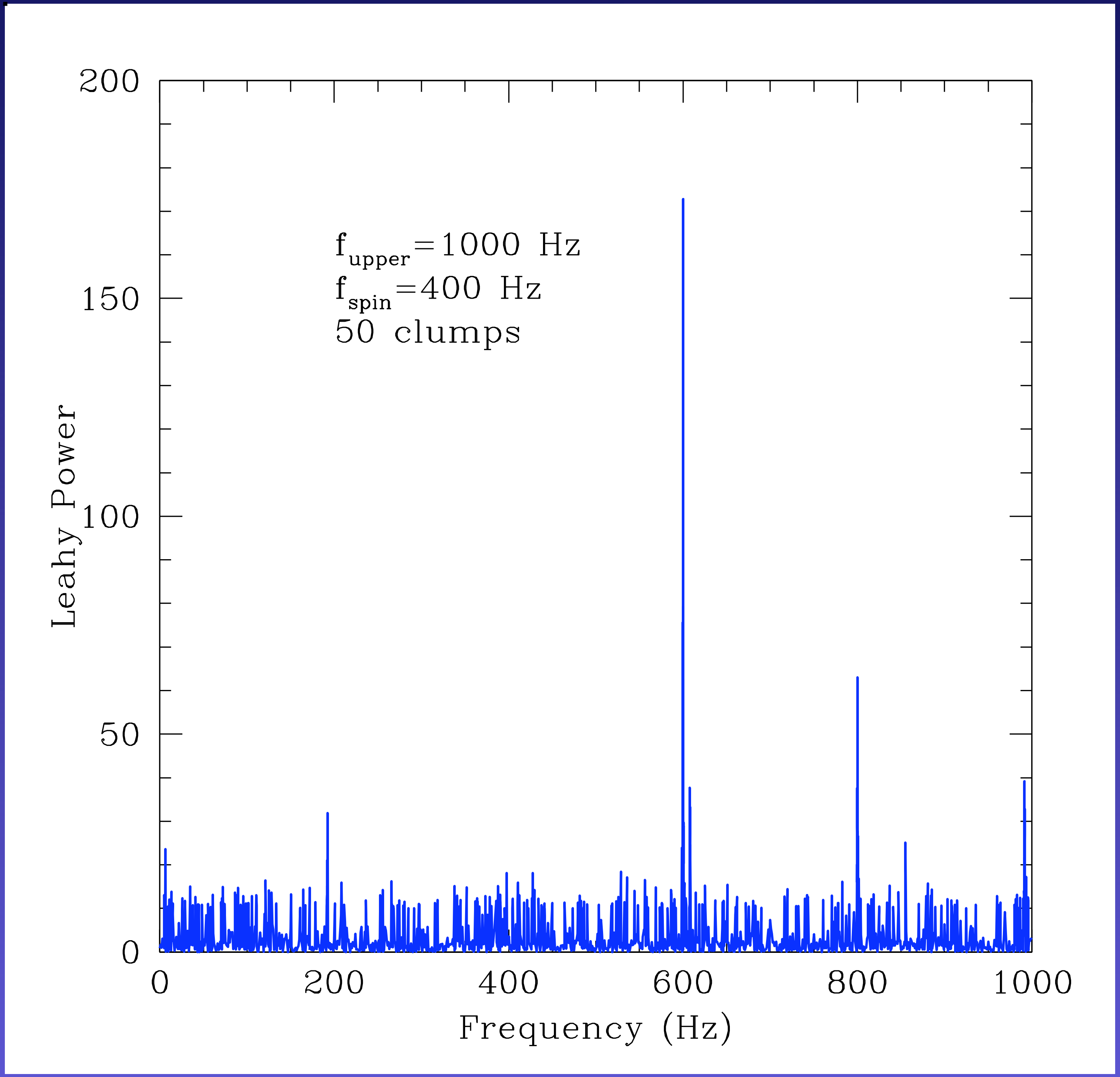


When the Star is Spinning Fairly Slowly

The spin resonates with the vertical epicyclic frequency in the outer magnetosphere, where the disk flow is fairly smooth —

- Scattering of radiation by *the pattern* of clumps dominates
- A pattern of radiation from near the star rotates with the sonic point orbital frequency $\nu_{\rm orb}(\text{sonic point})$
- This radiation pattern illuminates or shadows clumps at the resonance radius with frequency
- $$\nu_{\rm beat2} = \nu_{\rm orb}(\text{sonic point}) - \nu_{\rm spin}$$
- Consequently the radiation from the accretion disk oscillates with this frequency
- This is the lower kilohertz QPO in slow rotators

Modulation of the Flux from the Accretion Disk at $\nu_{\text{beat2}} = \nu_{\text{orb}}(\text{sonic point}) - \nu_{\text{spin}}$



Conclusions

- The Sonic-Point Spin-Resonance (SPSR) model generates the frequency $\nu_{\rm QPO1}$ of the lower kHz QPO in two different ways, depending on whether the star's spin resonates with the vertical epicyclic frequency in the disk close to the star or further away
- For faster spinning stars, the resonance occurs closer to the star, where the flow is very clumpy, so the lower kHz QPO frequency is $\nu_{\rm QPO1} = \nu_{\rm orb}(\text{sonic point}) - \nu_{\rm spin}/2$
- For slower spinning stars, the resonance occurs further from the star, where the flow is smoother, so the lower kHz QPO frequency is $\nu_{\rm QPO1} = \nu_{\rm orb}(\text{sonic point}) - \nu_{\rm spin}$
- The model appears able to explain the observed variation of the kHz QPO frequency difference $\Delta\nu_{\rm QPO} = \nu_{\rm QPO2} - \nu_{\rm QPO1}$