Testing the Lense–Thirring interpretation of LF QPOs in neutron stars

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Abstract

Low-frequency quasi-periodic oscillations (LF QPOs) in neutron star (NS) X-ray binaries are commonly interpreted as manifestations of Lense–Thirring (LT) precession of the inner accretion flow. We test this hypothesis using models of geometrically thick accretion tori in the Hartle–Thorne spacetime, focusing on the source 4U 1608–52, for which both LF QPO frequencies and the NS spin are observationally constrained. By comparing predicted LT precession frequencies with those allowed by realistic NS models, we find that parameter combinations capable of reproducing the observed LF QPOs are not compatible with realistic NS configurations. In particular, such configurations imply stellar radii exceeding the innermost stable circular orbit, thereby limiting the maximum achievable precession frequency. We therefore conclude that a direct identification of LF QPOs with the fundamental LT precession frequency is not viable for this source. Instead, our results suggest that the observed variability may be associated with harmonics of the LT precession frequency, consistent with some earlier suggestions in the literature.

Motivation

Quasi-periodic oscillations (QPOs) are among the most prominent variability features observed in the X-ray emission of accreting neutron stars (NSs), yet their physical origin remains poorly understood. They are generally believed to originate in the innermost regions of the accretion flow, where matter dynamics are strongly affected by the gravitational field of the compact object. QPOs therefore provide a unique opportunity to probe the physics of strong gravity as well as fundamental properties of neutron stars, such as their mass, radius, and spin. One important class of these phenomena are low-frequency QPOs (LF QPOs), typically observed at frequencies of a few to several tens of hertz.

A promising explanation for LF QPOs is Lense–Thirring (LT) precession — a general relativistic effect in which a spinning compact object drags the surrounding spacetime, causing the inner accretion flow to precess. This idea, originally proposed by Stella & Vietri (1998) and further developed in later works (e.g. Ingram et al. 2009), has attracted considerable attention and has been applied to a wide range of accreting systems. In NSs, however, the spacetime geometry is additionally affected by the stellar quadrupole moment, which may significantly modify the predicted precession frequencies. We therefore investigate whether LT precession in the Hartle–Thorne spacetime can reproduce the observed LF QPOs of the source 4U 1608–52 within realistic NS models.

Neutron star spacetime geometry

The spacetime around a slowly rotating NS is described by the Hartle–Thorne metric (Hartle & Thorne 1968). The metric is characterized by three parameters: the gravitational mass of the star M, its angular momentum $\mathcal{J}$, and its quadrupole moment Q. In Schwarzschild coordinates (t, r, θ, φ), using the $(-+++)$ signature and geometrized units $c = G = 1$, the metric coefficients are

$$g_{tt} = -\left(1-\frac{2M}{r}\right)\left[1+j^2F_1(r)+qF_2(r)\right], \quad g_{rr} = \left(1-\frac{2M}{r}\right)^{-1}\left[1+j^2G_1(r)-qF_2(r)\right],$$

$$g_{\theta\theta} = r^2\left[1+j^2H_1(r)+qH_2(r)\right], \quad g_{\varphi\varphi} = r^2\sin^2\theta\left[1+j^2H_1(r)+qH_2(r)\right], \quad g_{t\varphi} = -\frac{2M^2}{r}j\sin^2\theta, \tag{1}$$

where the dimensionless forms of the angular momentum $j = \mathcal{J}/M^2$ and the quadrupole moment $q = Q/M^3$ are used. The functions $F_1, \dots, H_2$ are given in Abramowicz et al. 2003. The maximum dimensionless angular momentum of an NS is approximately $j_{max} \sim 0.7$ (Lo & Lin 2011). The quadrupole parameter defined as q/j^2 takes values from $q/j^2 \sim 1.5$ for massive, compact NS to $q/j^2 \sim 10$ for less massive, highly oblate NS (Urbanec et al. 2013, Urbancová et al. 2019). A cautious NS mass estimation is in the range of $1.3 - 2.3M_\odot$ (e.g. Lattimer 2012, Özel & Freire 2016).

Thick accretion flow

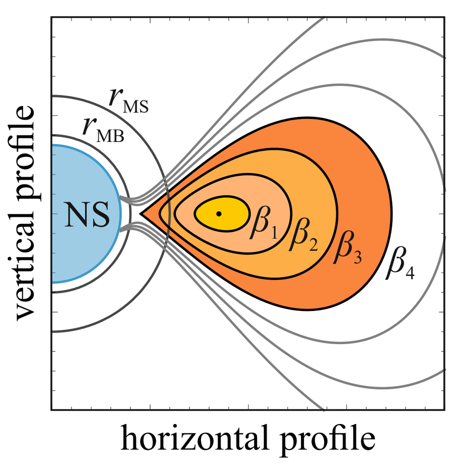

Figure 1: Shapes of tori with the same centre radius and different values of the thickness parameter β. Gray lines indicate open equipotential surfaces.

We consider a geometrically thick inner accretion flow orbiting a NS and adopt the Polish doughnut approach (Kozlowski et al. 1978, Abramowicz et al. 1978, Paczyński & Abramowicz 1982). In this framework, the torus is modelled as a stationary, axisymmetric perfect fluid with constant specific angular momentum throughout the flow. The specific angular momentum is chosen to correspond to the Keplerian value at the torus centre, where the pressure reaches its maximum. The fluid is further described by a polytropic equation of state.

The properties and structure of such tori in the Hartle–Thorne spacetime were analysed in detail by Matuszková et al. 2024a. Depending on the adopted value of the specific angular momentum, the torus centre may be located at the marginally stable orbit r_{MS} or farther out. The inner edge of the torus is determined by the equipotential structure and may extend down to the marginally bound orbit r_{MB}, which corresponds to a limiting configuration with the outer radius formally located at infinity. The geometrical thickness of the torus is characterized by the dimensionless parameter β. Figure 1 illustrates several representative torus configurations together with the locations of the marginally stable and marginally bound orbits.

Lense-Thirring precession

The LT precession frequency of a free test particle is defined as the difference between the orbital and vertical epicyclic frequencies, $\omega_{\mathrm{LT}}^{(0)} = \omega_{\mathrm{K}} - \omega_\theta$. In the Hartle–Thorne metric, these frequencies are given by

$$\omega_{\mathrm{K}} = \sqrt{\frac{M}{r^3}}\left[1 - j\frac{M^{3/2}}{r^{3/2}} + j^2\alpha_1(r) + q\alpha_2(r)\right], \quad \omega_\theta^2 = \frac{M}{r^3}\left[1 - j\beta_1(r) + j^2\beta_2(r) + q\beta_3(r)\right], \tag{2}$$

where the functions $\alpha_1, \dots, \beta_3$ are defined in Abramowicz et al. 2003.

For geometrically thick accretion flows, pressure effects modify the oscillation frequencies and the corresponding LT precession frequency differs from the test-particle case. To describe these corrections, we adopt the perturbative approach originally introduced by Papaloizou & Pringle (1984) and further developed in several later studies (Blaes 1987, Abramowicz et al. 2006, Blaes et al. 2006, Šrámková et al. 2007, and Straub & Šrámková 2009). Within this framework, the LT precession frequency of the torus can be written as

$$\omega_{\mathrm{LT}} = \omega_{\mathrm{LT}}^{(0)} + \beta^2\omega_{\mathrm{LT}}^{(2)}, \tag{3}$$

where $\omega_{\mathrm{LT}}^{(2)}$ represents the pressure correction term and β characterizes the geometrical thickness of the torus. The LT frequency in hertz is given by the equation $\nu_{\mathrm{LT}} = \frac{\omega_{\mathrm{LT}}}{2\pi}$. Oscillation modes of thick tori in the Hartle–Thorne spacetime were analysed by Matuszková et al. (2024b). An example of the behaviour of the LT frequency is shown in Figure 2 and is discussed in more detail in Török et al. (2025).

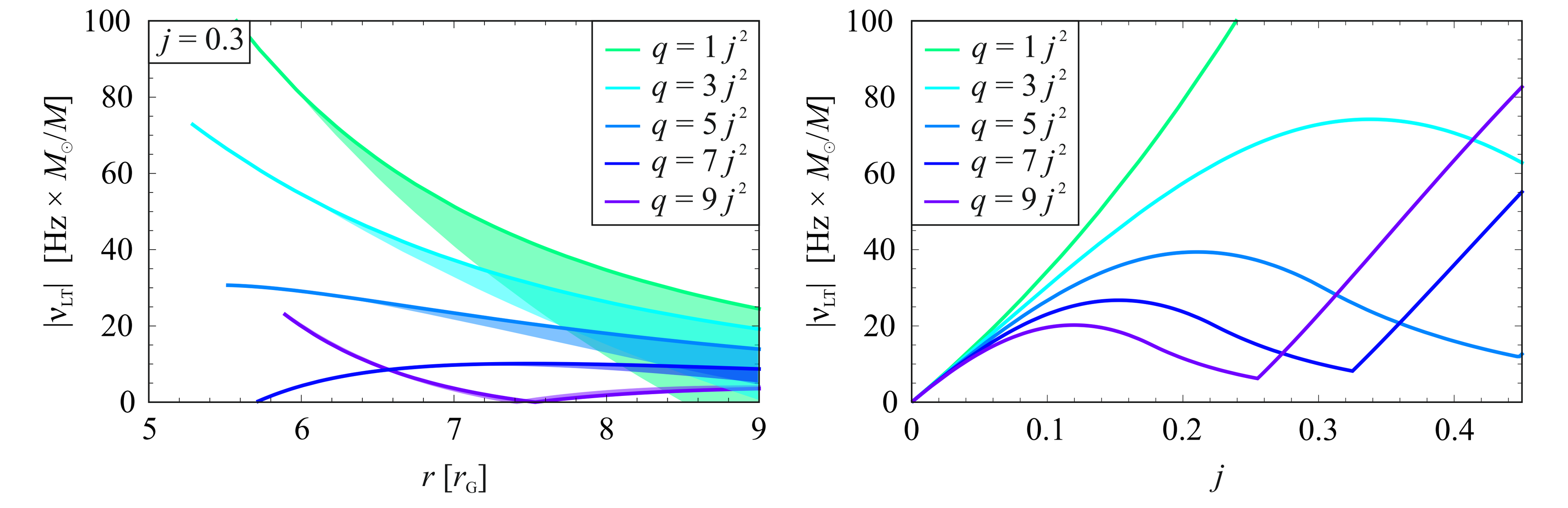

Figure 2: Behaviour of the LT frequency for various quadrupole parameters. *Left:* LT frequency as a function of radial coordinate. Solid lines correspond to test-particle (slender torus) frequencies, while shaded regions indicate frequencies modified by pressure effects in non-geodesic flows. *Right:* Maximum of the LT frequency as a function of the angular momentum of the star.

LF QPOs corresponding to LT frequency

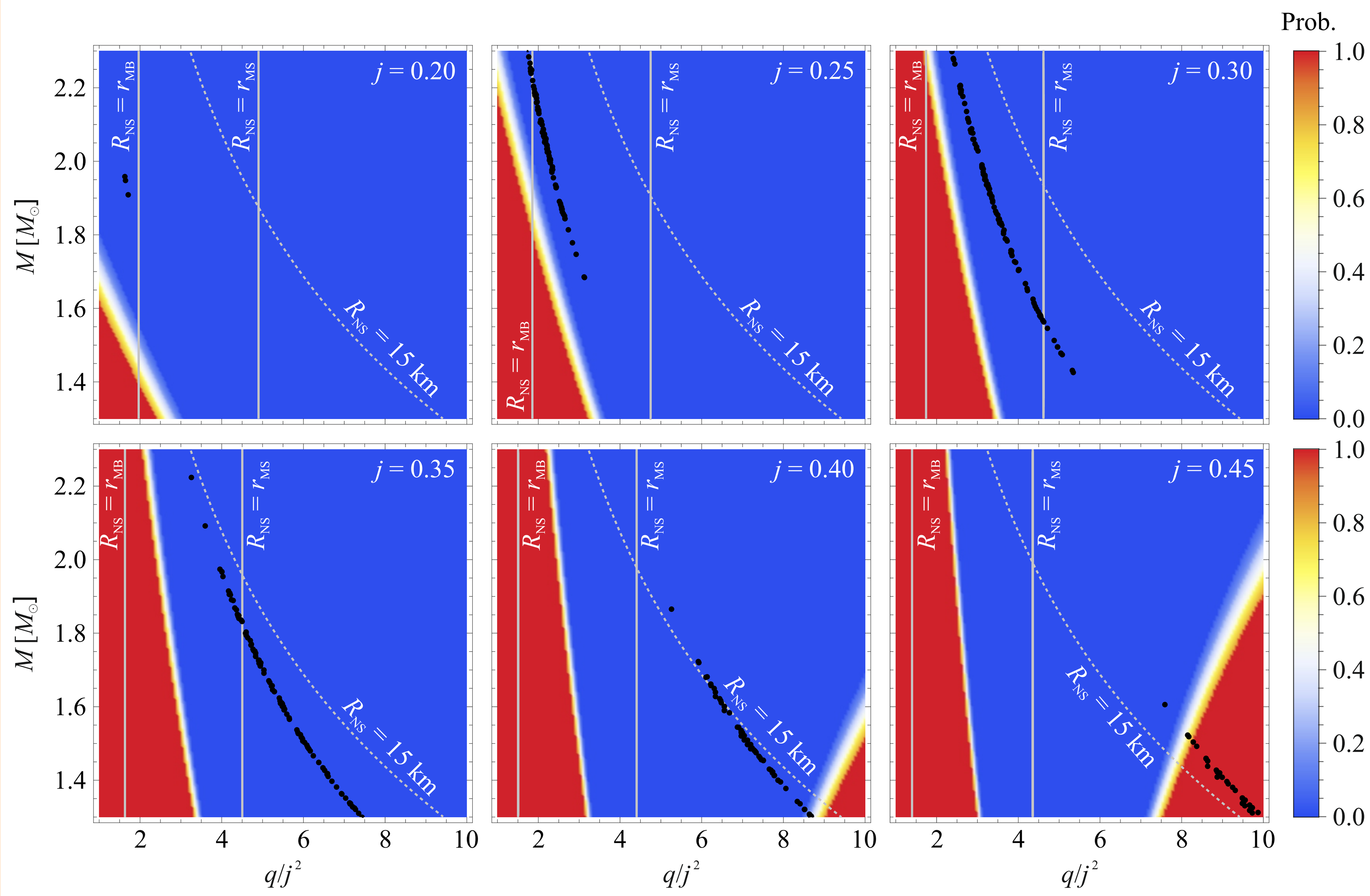

Figure 3: Probability map of reproducing the observed LF QPO frequencies in the (M, j, q) parameter space, assuming that the observed frequencies correspond to the fundamental LT precession frequency. The colour scale represents the likelihood that a given combination of parameters reproduces the observed frequencies. Overplotted points correspond to NS configurations obtained from selected EoS at a fixed rotational frequency.

LF QPOs corresponding to the first harmonic of LT frequency

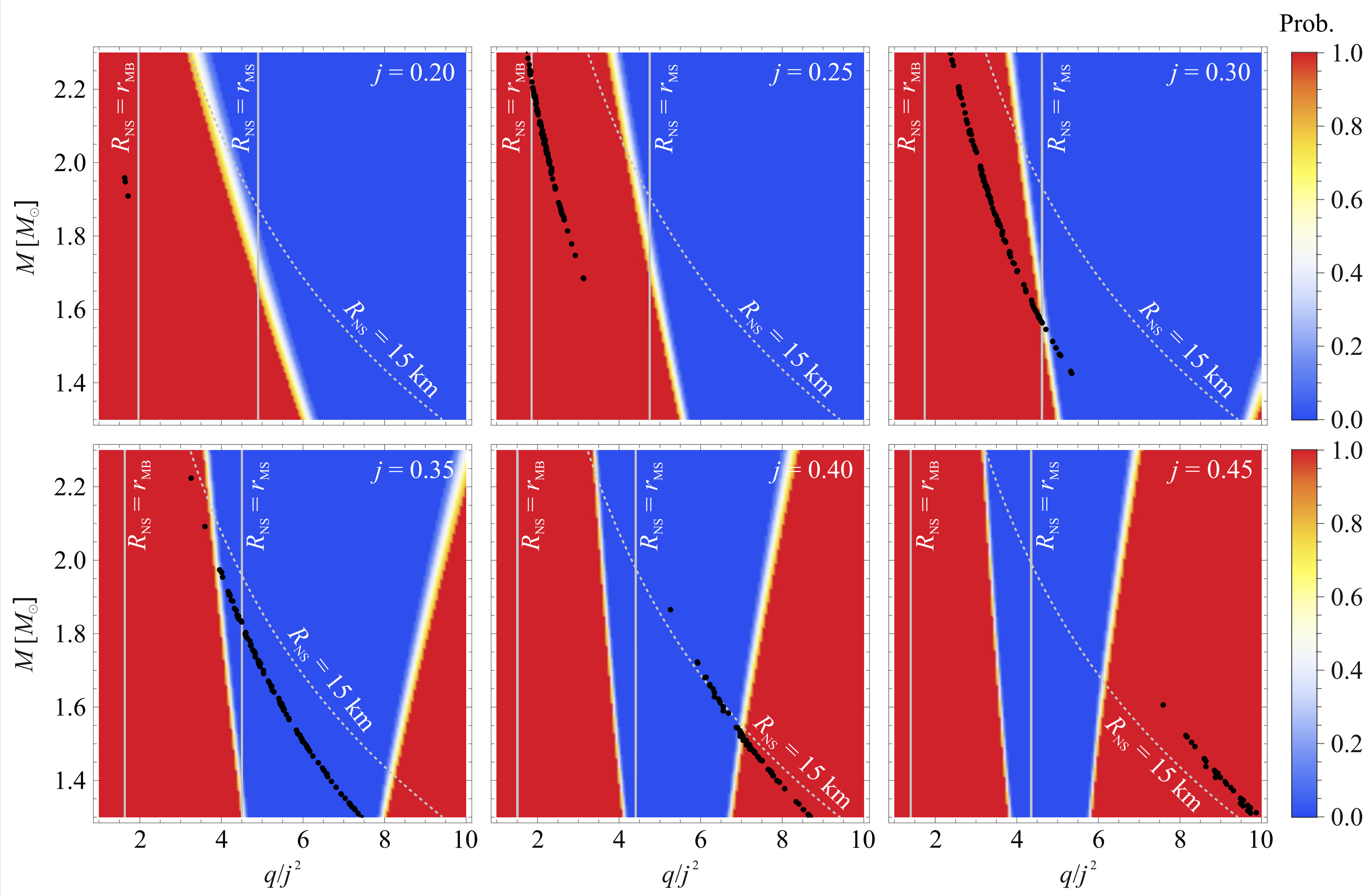

Figure 4: Same as Fig. 3, but assuming that the observed LF QPO frequencies correspond to the first harmonic of the LT precession frequency ($2\nu_{\mathrm{LT}}$) rather than the fundamental precession mode.

Conclusions

Using Hartle–Thorne models of precessing accretion tori, we tested whether the observed LF QPOs of 4U 1608–52 can be explained as fundamental Lense–Thirring (LT) precession frequencies. We find that realistic neutron star models do not allow sufficiently high LT frequencies, mainly because configurations with high precession frequencies imply stellar radii larger than the innermost stable circular orbit (see Figure 3). This limits the formation of tori capable of reproducing the observed variability. Our results therefore disfavour a direct identification of LF QPOs with the fundamental LT frequency and instead point toward a possible interpretation involving harmonics of LT precession (see Figure 4).

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