Twin-Peak QPOs from Oscillating Torus with Cusp

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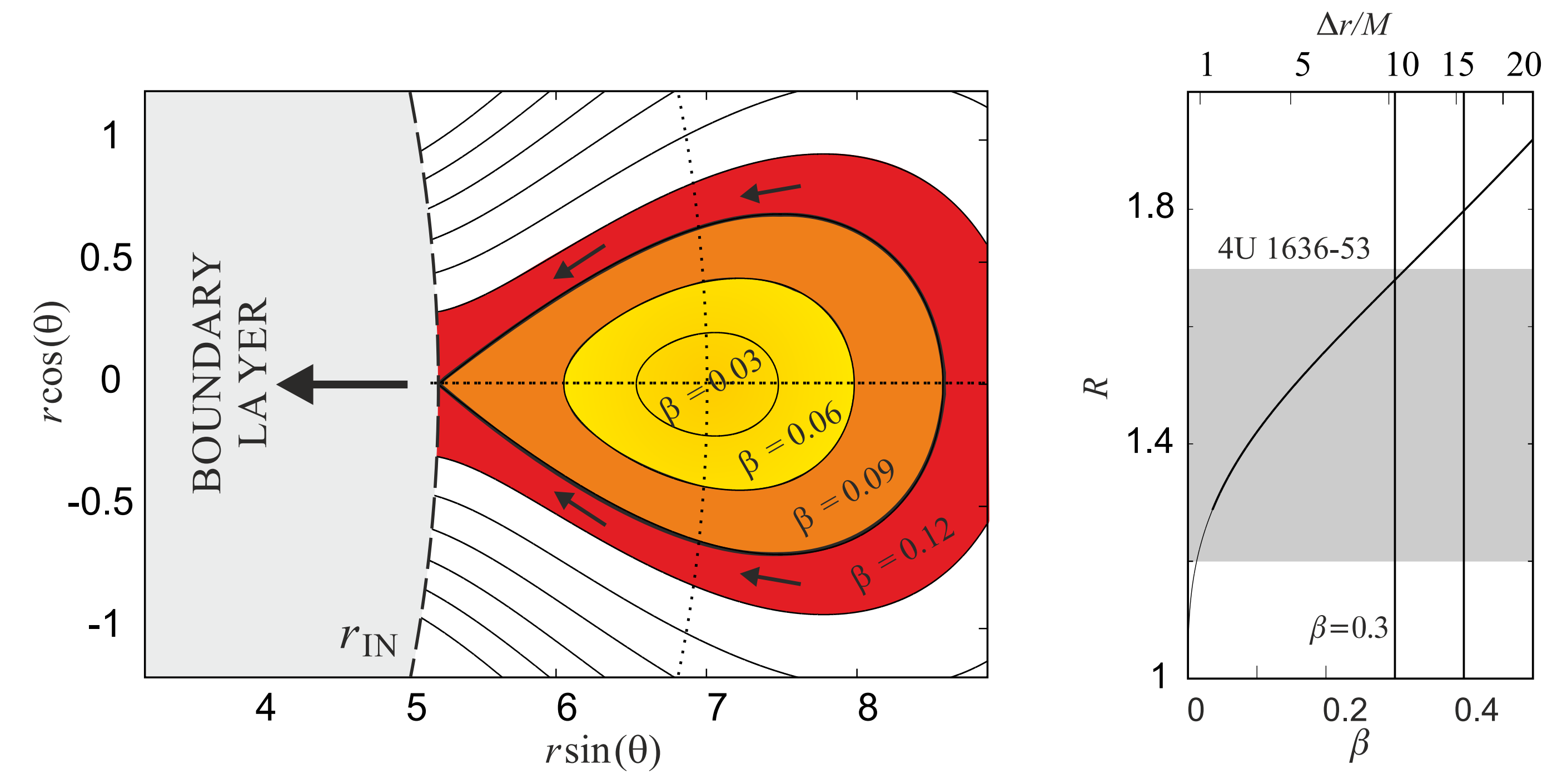
Summary

We consider a model of HF twin-peak quasi-periodic oscillations assuming an oscillating torus with cusp that changes location of its centre around radii very close to innermost stable circular orbit. The observed variability is assigned to global modes of accreted fluid motion that may give rise to strong modulation of both the accretion disc radiation and the accretion rate. We find that predictions of the model well match observational data for a dozen of sources.

References

The poster is based on a present work in progress following the paper of **Török et al., 2016, Monthly Notices of the Royal Astronomical Society: Letters, Volume 457, Issue 1, p.L19-L23**.
This paper provides a discussion of the model for the 4U 1636-53 data. Here we extend our consideration to 11 other sources (see also the poster of Török et al., HEAD 2017).

Figure 1



LEFT: Illustration of the equipotential surfaces of an accretion torus. The yellow colour denotes a non-accreting equilibrium torus. The thick black curve which bounds the orange region signifies the critical equipotential surface. This situation corresponds to a torus with cusp and allows the Paczynski modulation of the boundary layer radiation. **RIGHT:** Relation between the thickness of the cusp torus and the observed frequency ratio R. The vertical shadow region indicates the interval of R corresponding to most of the available data of the atoll source 4U 1636-53.

Consideration of Neutron Star Rotation

In analogy to the results of Török et al. (2012, ApJ), we may expect that the mass M_0 belongs to a mass–angular-momentum relation implied by the cusp torus model. The result of two-dimensional fitting of the M and j parameters assuming 4U 1636-53 is shown in Figure 3. Indeed, the best fits are reached when M and j are related through a specific relation which can be approximated by the quadratic form as follows,

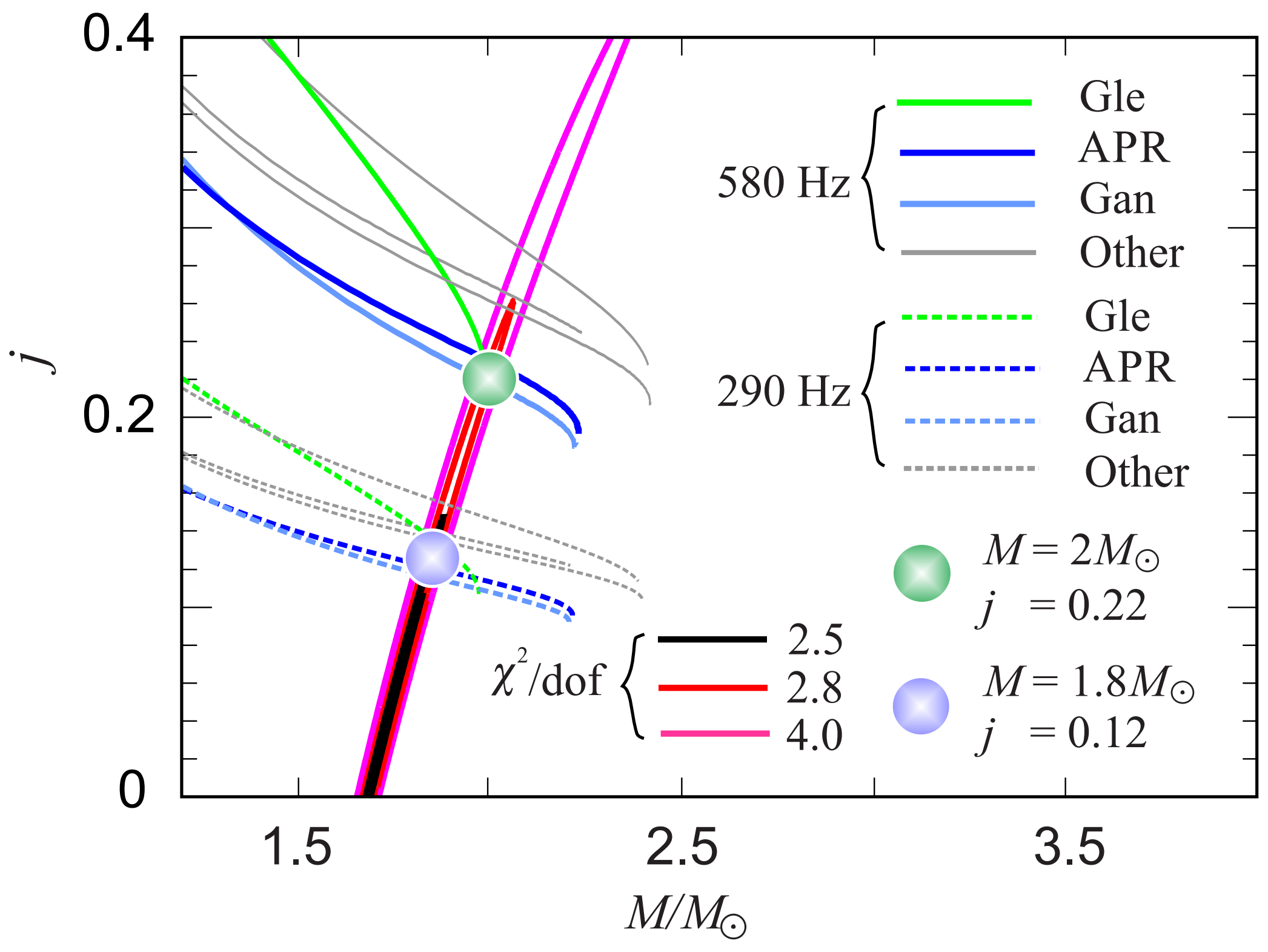
$$M = M_0[1 + 0.7(j + j^2)]. \tag{5}$$

Neutron Star Radius and Equation of State

There is a good evidence on the NS spin frequency of 4U 1636–53 based on the X-ray burst measurements. Depending on the hot-spot model consideration, the spin $\nu_\S$ reads either $\nu_\S \doteq 290\,$Hz or $\nu_\S \doteq 580\,$Hz. The value of 580Hz is usually preferred. One may therefore roughly compare the cusp torus model predictions to the predictions of models of rotating NS.

In Figure 3 we include several mass-angular momentum relations expected from models of rotating NS. We assume the following set of EoS - SLy 4, APR, AU-WFF1, UU-WFF2 and WS-WFF3. Inspecting Figure 3 we can see that there are overlaps between the relations given by models of rotating stars and the relation inferred from the cusp torus model. In this figure we denote two particular values of angular momentum along with the corresponding masses that roughly represent these overlaps. Assuming the two chosen combinations of mass and angular momentum, we attempt in Figure 4 to fit the data by the torus frequencies considering *any* torus thickness, not only β_c. We then search for the combinations of β and r that exactly match each individual datapoint. Clearly, the obtained values are distributed very close to the cusp relation, $\beta = \beta_c(r)$, where we have $r > r_{\rm NS}$.

Figure 3



The mass-angular momentum contours obtained from the fitting of datapoints using the cusp torus model vs. mass-angular momentum relations predicted by models of rotating NS (4U 1636-53). These are drawn for several NS EoS and spin 290Hz or 580Hz inferred from the X-ray burst measurements. The two spots indicate the chosen combinations of angular momentum where the QPO model and EoS relations overlap.

Frequency Identification and Estimation of Neutron Star Mass

We identify the observed HF QPO frequencies with the frequencies of epicyclic modes of torus oscillations. The upper kilohertz QPO frequency is assumed to be the Keplerian orbital frequency of the fluid at the center of the torus where both pressure and density peak, and from which most of the torus radiation emerges. The lower kilohertz QPO corresponds to the frequency of the non-axisymmetric $m = -1$ radial epicyclic mode. Overall, we may write $\nu_U \equiv \nu_{\rm K}(r_0), \quad \nu_L \equiv \nu_{{\rm R},-1}(r_0, \beta)$. The QPO frequencies are thus strong functions of the position of the center of the torus r_0 and its thickness β.

We consider here the configuration of a torus with cusp which is defined by

$$\beta(r_0) \doteq \beta_c(r_0). \tag{1}$$

In other words, we expect that for a given r_0 the torus is always close to its maximal possible size filling its ‘Roche-like’ lobe (see Figure 1 for illustration). Therefore, for a given accreting central compact object, our model predicts that the QPO frequencies are functions of a single parameter r_0,

$$\nu_{\rm u} \equiv \nu_{\rm K}(r_0), \quad \nu_{\rm l} \equiv \nu_{{\rm R},-1}\left[r_0, \beta_c(r_0)\right]. \tag{2}$$

Non-Rotating Approximation

Assuming non-rotating NS we plot In Figure 2 the sequence of equipotential contours of tori with cusp that provide the best match to the 4U 1636-53 data. The best fit is compared to the best fit obtained for the RP model. Clearly, the cusp torus model matches the observed trend better than the RP model. We may write $\chi^2/{\rm dof} = 2.3$ for the cusp torus model while for the RP model we have $\chi^2/{\rm dof} = 16.4$. The NS mass inferred from the cusp torus model, within 2σ confidence level, reads

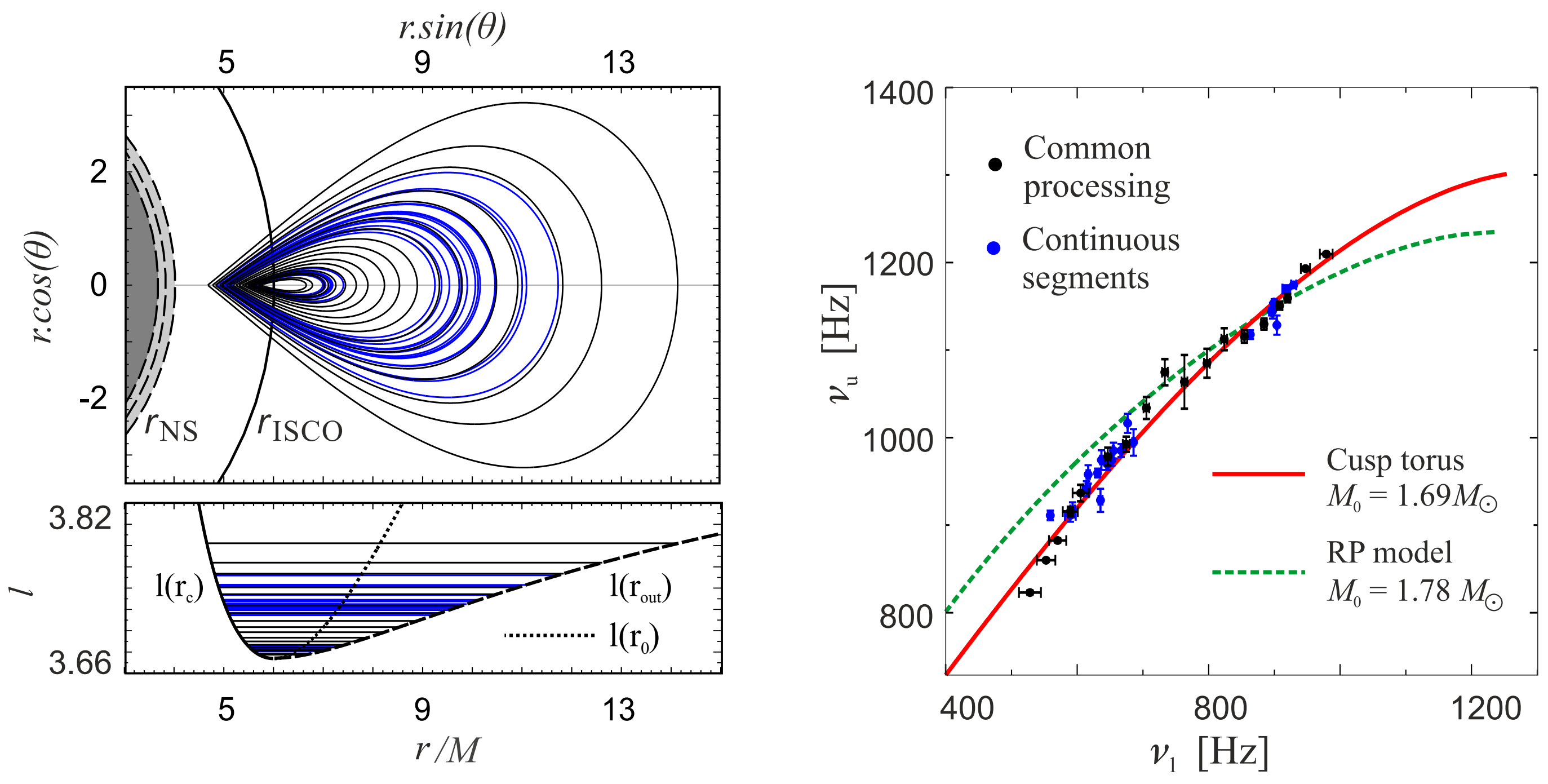
$$M_0 = 1.69[\pm 0.01]\,M_\odot. \tag{3}$$

We further compare the model to the data of 4U 0614+09, 4U 1608-52, 4U 1636-53, 4U 1728-34, 4U 1735-44, 4U 1820-30, 4U 1915-05, IGR J17191-2821, Sco X-1 and GX 17+2. For these sources we obtain fits comparable to the case of 4U 1636-53 and

$$M_0 \in (1.5\,M_\odot,\ 1.9\,M_\odot). \tag{4}$$

For two more sources, XTE J1807 and Circinus X-1, we obtain reasonable fits assuming an approximative frequency relation corresponding to the model. Nevertheless, there is no clear physical interpretation of these two matches (see the poster of Török et al., HEAD 2017).

Figure 2



LEFT: Sequence of cusp tori corresponding to the one-parametric fit ($j = 0$) of the 4U 1636-53 data. The neutron star radii $r_{\rm NS}$ are drawn for three particular NS EoS (Gle, APR, and GAN) that are further assumed within Figure 3. The bottom panel indicates the angular momentum behaviour along with the positions of the torus centre r_0 and both the inner and outer edge, r_c and $r_{\rm out}$. **RIGHT:** The corresponding frequency relation plotted together with the datapoints. For the sake of comparison we also present the best fit implied by the RP model ($j = 0$).

Model Perspectives

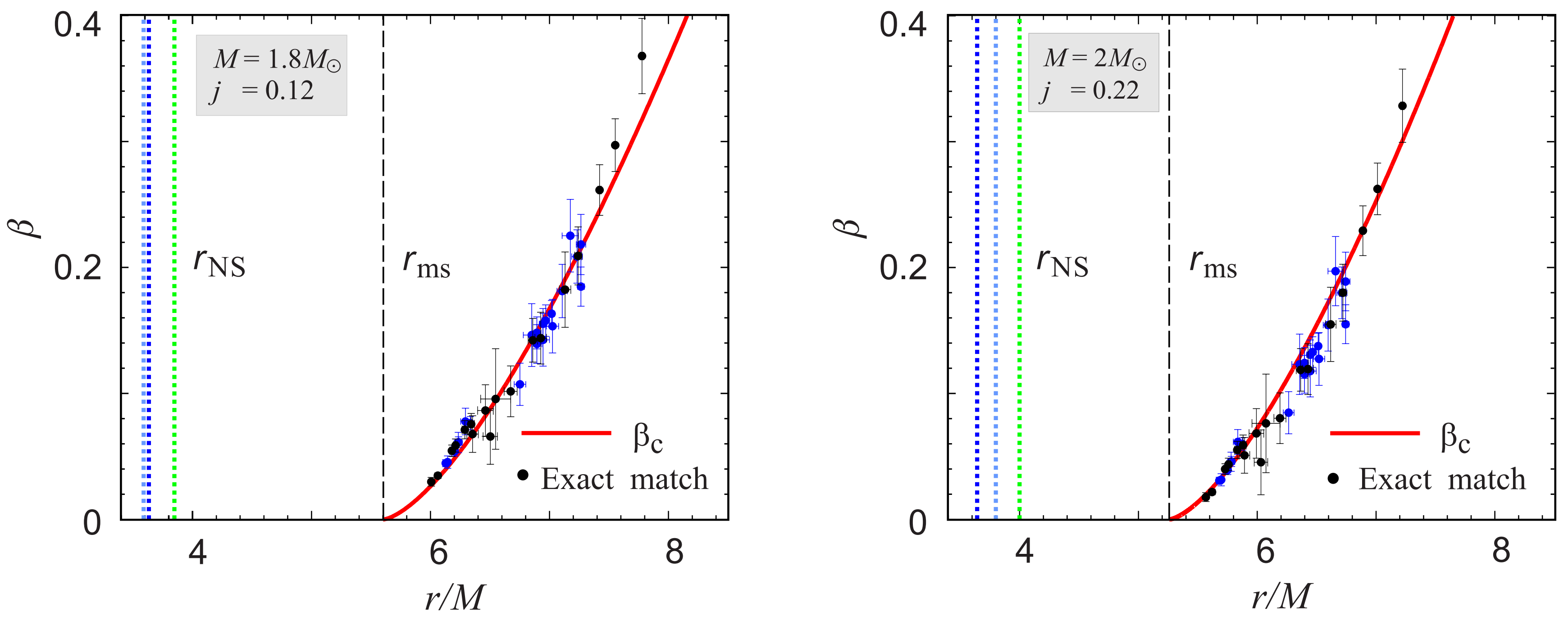
A more careful and computationally demanding investigation of the influence of spin should be applied in a consequent work. Nevertheless, we can conclude that there is a very strong indication that the twin-peak QPOs can be identified with a particular non-axisymmetric $m = -1$ radial epicyclic mode and Keplerian orbital motion associated to a torus with cusp.

These modes may naturally provide strong modulation of both the emerging radiation and the accretion rate, and their eigenfunctions change only weakly on the spatial scale of the turbulent motion. They are thus very good candidates for explaining the high amplitudes of HF QPOs.

Low Frequency QPOs

The presented concept also has the potential to explain the observed low frequency QPOs. The frequencies of vertical modes seem to be very sensitive to the NS quadrupole moment. Their consideration therefore may exceed the framework of the Kerr spacetime approximation adopted here. Having said that, we roughly investigate also the frequencies of the non-axisymmetric $m = 1$ vertical epicyclic mode for tori with cusp. This mode corresponds to the low-frequency global precession of an inclined torus, and is analogical to the “tilted hot flow precession”. Assuming the same mass, angular momentum and radii as those in the right panel of Figure 3, we obtain values of tens of Hertz that are of the same order as the observed frequencies. The $m = -1$ vertical epicyclic mode may therefore play the same role in the framework of the cusp torus model as the Lense-Thirring precession in the framework of the RP model.

Figure 4



The consideration of the β and r combinations that exactly match the individual datapoints for the two chosen combinations of mass and angular momentum. The color-coding is the same as in Figure 2. The red line denotes the numerically calculated cusp torus relation.

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