Confronting the models of 3:2 QPOs with the rapid spin of the microquasar GRS 1915+105

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Aims and scope

Spectral fitting of the spin $a \equiv cJ/GM^2$ in the microquasar GRS 1915+105 estimate values higher than $a = 0.98$. However, there are certain doubts about this (nearly) extremal number. Confirming a high value of $a > 0.9$ would have significant consequences for the theory of high-frequency quasiperiodic oscillations (HF QPOs). Here we discuss its possible implications assuming several commonly used orbital models of 3:2 HF QPOs. We show that the estimate of $a > 0.9$ is almost inconsistent with two hot-spot, **relativistic precession (RP)** [1] and **tidal disruption (TD)** [2], models and the **warped disc (WD)** [3] resonance model. In contrast, we demonstrate that the **epicyclic resonance (Ep)** [4] and **discoseismic models** [5] assuming the c- and g- modes are favoured. We extend our discussion to another two microquasars that display the 3:2 HF QPOs. The frequencies of these QPOs scale roughly inversely to the microquasar masses, and the differences in the individual spins, such as $a = 0.9$ compared to $a = 0.7$, represent a generic problem for most of the discussed geodesic 3:2 QPO models. To explain the observations of all the three microquasars by one unique mechanism, the models would have to accommodate very large non-geodesic corrections.

Results

Assuming a Kerr geometry, the orbital frequencies (i.e., the three frequencies of the perturbed circular orbital motion: the azimuthal "Keplerian" frequency ν_{K}, the radial epicyclic frequency ν_{r}, and the vertical epicyclic frequency ν_θ) for a given radius depend only on mass and spin of the black hole. It is therefore possible to infer the black hole spin or mass from the observed 3:2 frequencies and concrete orbital models. The 3:2 QPO frequencies in GRS 1915+105 has been determined as $\nu_{\mathrm{U}} = (168 \pm 3)\,\mathrm{Hz}$, $\nu_{\mathrm{L}} = (113 \pm 5)\,\mathrm{Hz}$ [6]. Behaviour of the orbital frequencies in Kerr geometry has been extensively discussed in several studies [7, 8]. Using their formulae, we calculate the implied mass-spin functions for the models associating the 3:2 QPOs with a common radii by means of the definition relations given in Table 1. Following [9] and [4] and taking into account the estimated range of the mass of GRS 1915+105, $10.0\,\mathrm{M}_\odot < M < 18.0\,\mathrm{M}_\odot$ [6], we infer the expected ranges of the spin (see Table 1 and Figure 2).

Table 1: Frequency relations corresponding to individual QPO models and the spins implied by the 3:2 QPOs in GRS 1915+105 and the mass-range $10 - 18M_\odot$. The middle column indicates the ratio of the epicyclic frequencies determining the radii corresponding to the observed 3:2 ratio. The indicated ranges of spin also represent total spin ranges for the whole group of the three microquasars (see Figure 2).

Model	Relations		$\nu_{\mathrm{K}}/\nu_{\mathrm{r}}$ or $^*\nu_\theta/\nu_{\mathrm{r}}$	a ∼
RP	$\nu_{\mathrm{L}} = \nu_{\mathrm{K}} - \nu_{\mathrm{r}}$	$\nu_{\mathrm{U}} = \nu_{\mathrm{K}}$	$3/1^*$	< 0.55
TD	$\nu_{\mathrm{L}} = \nu_{\mathrm{K}}$	$\nu_{\mathrm{U}} = \nu_{\mathrm{K}} + \nu_{\mathrm{r}}$	$2/1$	< 0.45
WD	$\nu_{\mathrm{L}} = 2(\nu_{\mathrm{K}} - \nu_{\mathrm{r}})$	$\nu_{\mathrm{U}} = 2\nu_{\mathrm{K}} - \nu_{\mathrm{r}}$	$2/1$	< 0.45
Ep	$\nu_{\mathrm{L}} = \nu_{\mathrm{r}}$	$\nu_{\mathrm{U}} = \nu_\theta$	$3/2^*$	$0.65 - 1$
Kep	$\nu_{\mathrm{L}} = \nu_{\mathrm{r}}$	$\nu_{\mathrm{U}} = \nu_{\mathrm{K}}$	$3/2^*$	$0.70 - 1$
RP1	$\nu_{\mathrm{L}} = \nu_{\mathrm{K}} - \nu_{\mathrm{r}}$	$\nu_{\mathrm{U}} = \nu_\theta$	–	< 0.80
RP2	$\nu_{\mathrm{L}} = \nu_{\mathrm{K}} - \nu_{\mathrm{r}}$	$\nu_{\mathrm{U}} = 2\nu_{\mathrm{K}} - \nu_\theta$	–	< 0.45

For the **discoseismic modes** the individual observed QPOs correspond to different modes located at different radii [5]. The frequencies of these modes depend on the black hole spin and the speed of sound in the accreted gas, and scale roughly as $1/M$, whereas their dependence on the other parameters of the accreting system is supposed to be very weak [5]. Figure 1 illustrates the behaviour of three such modes: the **g-modes** (inertial-gravity waves that occur at the radius where ν_{r} reaches its maximum value), **c-modes** (corrugation vertically incompressible waves near the inner edge of the disk), and **p-modes** (inertial-pressure oscillations that occur near the edge of the disc).

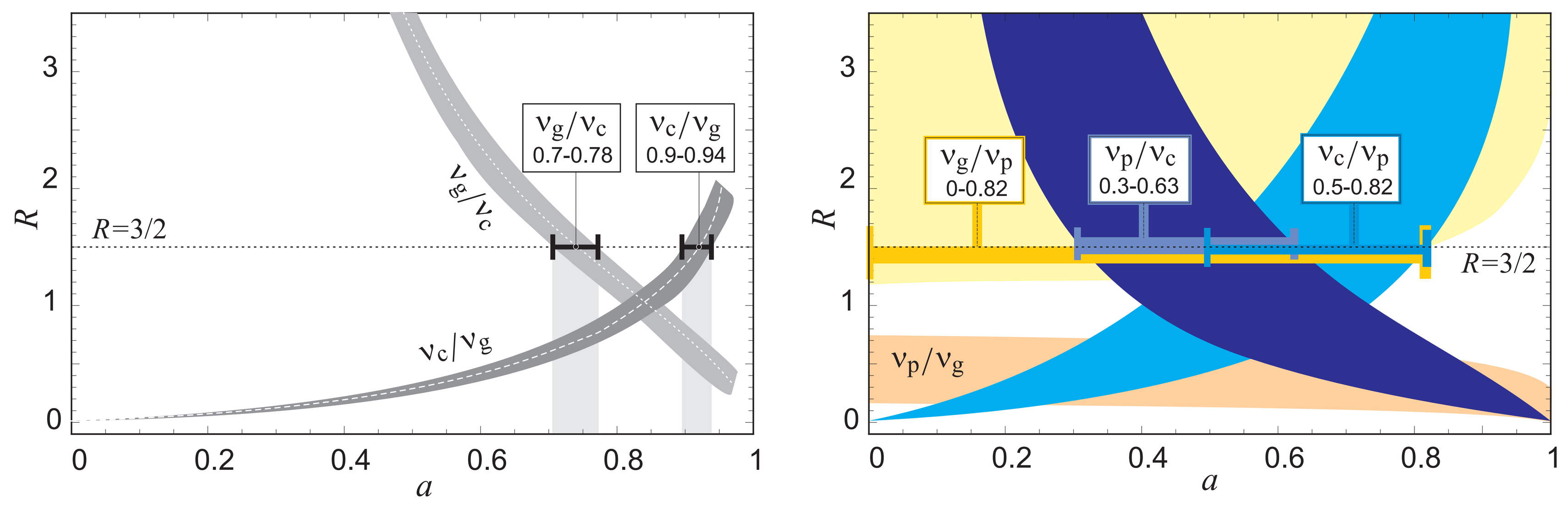

Fig. 1: Ratio R of the frequencies of the fundamental discoseismic modes (based on Wagoner et al., 2001). **Left:** Ratio of ν_{c} to ν_{g}. The spread of two functions corresponds to the uncertainty in the speed of sound. The horizontal dotted line denotes the 3:2 frequency ratio. Values in the boxes evaluate the spin ranges required by this ratio. **Right:** The same consideration, but including the p-modes.

Table 2: Ranges of a and M implied by the discoseismic models of the 3:2 QPOs. The values in the brackets indicate the referential interval of M for each microquasar. The shadows emphasize the ranges of M having some overlap with the referential values.

		GRS 1915+105	XTE J1550-564	GRO J1655-40
Frequencies	a	$M/M_\odot$ [10.0 – 18.0]	$M/M_\odot$ [8.4 – 10.8]	$M/M_\odot$ [5.1 – 6.6]
$\nu_{\mathrm{U}} = \nu_{\mathrm{g}},\ \nu_{\mathrm{L}} = \nu_{\mathrm{c}}$	$0.70 - 0.78$	$6.4 - 9.0$	$3.9 - 5.5$	$2.4 - 3.3$
$\nu_{\mathrm{U}} = \nu_{\mathrm{c}},\ \nu_{\mathrm{L}} = \nu_{\mathrm{g}}$	**$0.90 - 0.94$**	$12.8 - 19.1$	$7.8 - 11.6$	$4.8 - 7.1$
$\nu_{\mathrm{U}} = \nu_{\mathrm{p}},\ \nu_{\mathrm{L}} = \nu_{\mathrm{c}}$	$0.30 - 0.63$	$1.1 - 5.0$	$0.7 - 3.0$	$0.4 - 1.8$
$\nu_{\mathrm{U}} = \nu_{\mathrm{c}},\ \nu_{\mathrm{L}} = \nu_{\mathrm{p}}$	$0.50 - 0.82$	$1.7 - 8.6$	$1.0 - 5.2$	$0.6 - 3.2$
$\nu_{\mathrm{U}} = \nu_{\mathrm{g}},\ \nu_{\mathrm{L}} = \nu_{\mathrm{p}}$	$0.00 - 0.82$	$3.9 - 9.7$	$2.4 - 5.8$	$1.5 - 3.6$
$\nu_{\mathrm{U}} = \nu_{\mathrm{p}},\ \nu_{\mathrm{L}} = \nu_{\mathrm{g}}$	—	—	—	—

Discussion and conclusions

We have found that the internal (epicyclic) resonance and the discoseismic model (dealing with c- and g- modes) are favoured in the case of GRS 1915+105 provided that $a > 0.9$. The TD, WD, RP, and RP2 models are then disfavoured. This statement was inferred assuming that ν_{K}, ν_{r}, and ν_θ are the exact geodesic frequencies. A similar analysis including the influence of non-geodesic effects would require very detailed study. Here we only roughly estimate the possible relevance of the non-geodesic effects. We define the relative non-geodesic correction $\Delta\nu \equiv (\nu_{\mathrm{observed}} - \nu_{\mathrm{predicted}})/\nu_{\mathrm{predicted}}$, which is needed to match the observations of GRS 1915+105 with a given model for a certain spin. From Figure 2, we can find that for $a \in (0.9, 1)$, the quantity $\Delta\nu^{\mathrm{RP}}$ changes from -40% to -60%. The same is roughly true for the TD and WD models, while for the RP2 model the required correction is even higher. Thus, our result is justified, except when considering of very large non-geodesic corrections.

Török et al. (2005) [4] pointed out that since the 3:2 QPO frequencies in microquasars scale roughly as $\nu_{\mathrm{U}} \doteq 2.8(M/M_\odot)^{-1}\,\mathrm{kHz}$ [6], their spins implied by the epicyclic resonance model should not vary much among them. It is apparent from Figure 2 that both different authors and different methods suggest (somewhat) different values of spin (and for one microquasar even different values of mass). The epicyclic resonance model favoured (along with the discoseismic model) in the GRS 1915+105 seems to match at least some of these estimates, but for the parameters of the XTE J1550-564 ($a \sim 0.7$, $M \sim 5 - 7M_\odot$) assumed in the figure it fails. If different spins ($a > 0.9$ in GRS 1915+105 and $a \sim 0.7$ in GRO J1655-40 and XTE J1550-564) were confirmed, the difficulty of matching the all observed 3:2 frequencies would clearly be rather generic for most of the orbital QPO models. Only the RP1 model [10] can survive with corrections of $|\Delta\nu|$ up to $\sim 20\%$ (see Figure 3), but the present physical interpretation of the RP1 model is unclear [10].

Because of the observational $1/M$ scaling, the above difficulty also arises for the discoseismic models. For these, we present in Table 2 the mass ranges implied by all combinations of the fundamental modes. These appear to overlap well with those observationally determined only for the model relating the upper and lower 3:2 QPO to the c- and g- mode provided that $a \in (0.90 - 0.94)$. For the other combinations related to different spins, the mass ranges differ from those in the observation. Clearly, there is the need for a substantial correction also for a unified 3:2 QPO model assuming fundamental discoseismic modes provided that microquasars had different spins of $a > 0.9$ compared to $a \sim 0.7$.

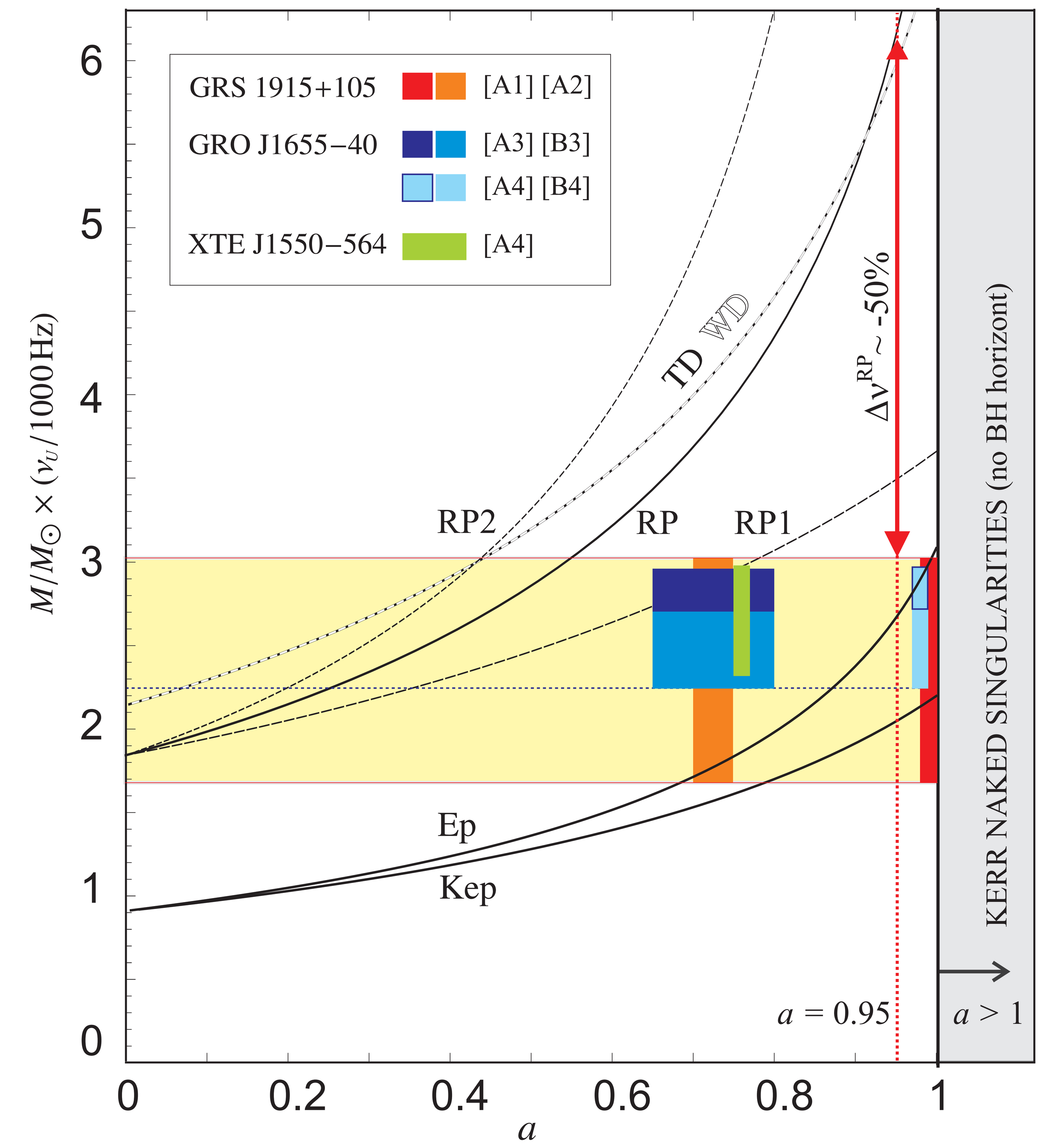

Fig. 2: Curves $\nu_{\mathrm{U}} \times M(a)$ implied by the individual geodesic models. The light yellow rectangle indicates the observationally determined interval of $\nu_{\mathrm{U}} \times M$ for GRS 1915+105. The red dotted vertical line denotes $a = 0.95$. The red vertical arrow indicates the correction needed to match the upper limit to $\nu_{\mathrm{U}} \times M$ with the RP model for this spin. The colour boxes are drawn for the mass and spectral spin estimates given by different authors for GRS 1915+105, GRO J1655-40 and XTE 1550-564. The dotted blue line indicates the lower observational limit to $M \times \nu_{\mathrm{U}}$ that is roughly common to GRO J1655-405 and XTE 1550-564. For the mass, Greene et al. (2001), Greiner et al. (2001), Orosz et al. (2002), Beer & Podsiadlowski (2002) [11], and McClintock & Remillard (2003) [6] provide commonly accepted mass estimates (denoted by letter A). Beer & Podsiadlowski (2002) present an alternative prediction (denoted by letter B) that moves the lower boundary of estimated mass of GRO J1655-40 from 6.0 to $5.1\ M_\odot$. For the spin, there were the following studies: 1 – McClintock et al. (2006) [12]; 2 – Middleton et al. (2006) [13]; 3 – McClintock et al. (2008) [14]; 4 – Miller et al. (2009) [15]. The spin estimates assume either the spectral continuum or the iron-line method.

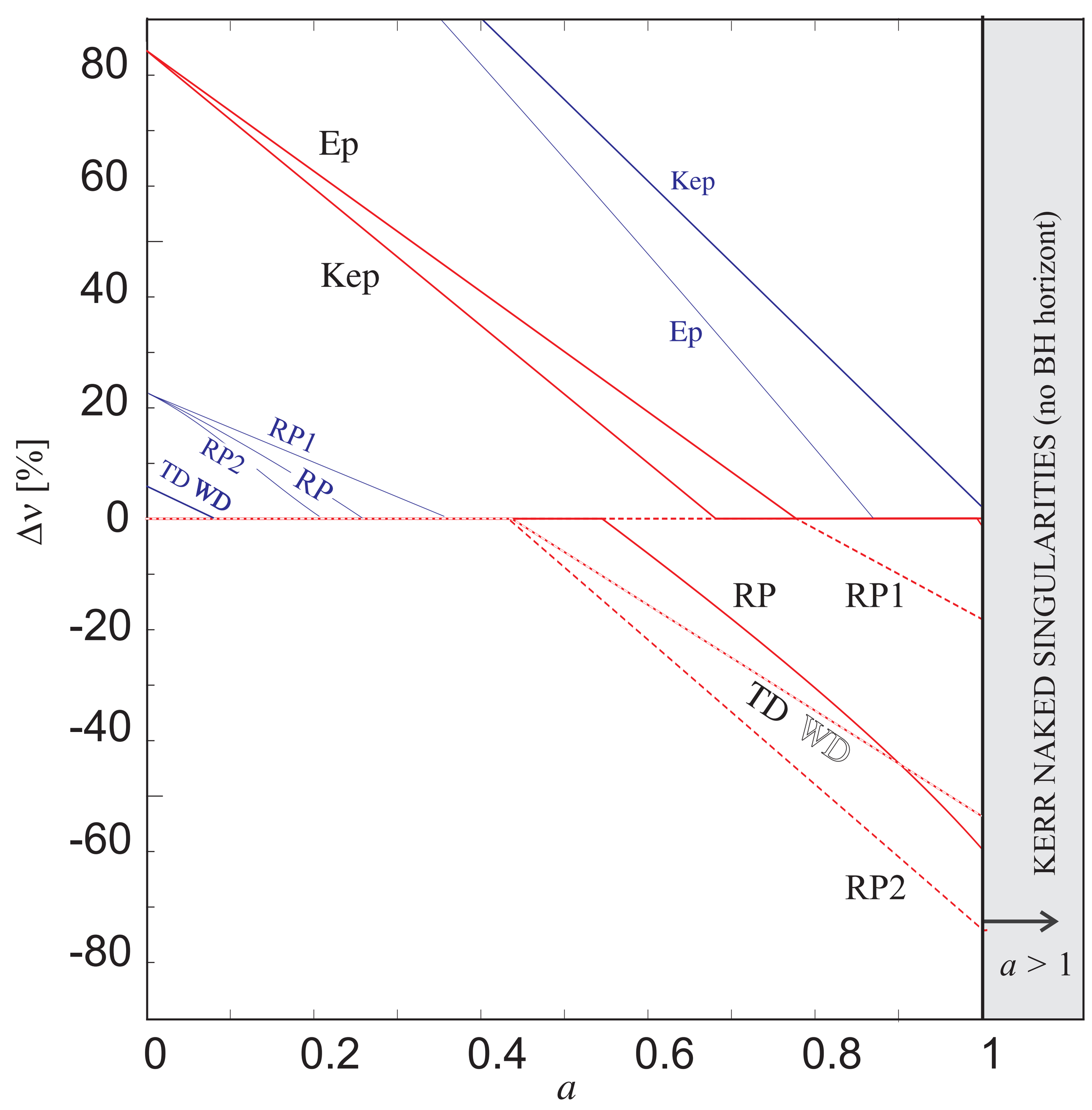

Fig. 3: Non-geodesic corrections required for a given model, spin and source. The red curves indicate the minimal corrections required in the case of GRS 1915+105. Parts of these curves with a negative sign also roughly indicate the corrections required for the other two microquasars. The blue curves indicate positive corrections for these microquasars determined by the lower limit to their $M \times \nu_{\mathrm{U}}$ indicated by the blue dotted horizontal line in Figure 2.

References

[1] Stella, L., Vietri, M., 1999, Phys. Rev. Lett., 82, 17

[2] Čadež, A., Calvani, M., Kostić, U., 2008, A&A, 487, 527; Kostić, U., Čadež, A., Calvani, M., Gomboc, A., 2009, A&A, 496, 307

[3] Kato, S., 2001, PASJ, 53, 1; Kato, S., 2004, PASJ, 56, 559; Kato, S., 2004, PASJ, 56, 905

[4] Török, G., Abramowicz, M. A., Kluźniak, W. & Stuchlík, Z., 2005, A&A, 436, 1

[5] Wagoner, R. V., 1999, Phys. Rev., 311, 259; Wagoner, R. V., Silbergleit, A. S. & Ortega-Rodríguez, M., 2001, ApJ, 559, L25; Wagoner, R. V., 2008, New Astronomy Reviews, 51, pp. 828–834

[6] McClintock, J. E & Remillard, R. A., 2003, astro-ph/0306213

[7] Aliev, A. N. & Galtsov, D. V., 1981, GR&G, 13, 899

[8] Török, G. & Stuchlík, Z., 2005, A&A, 437, 775

[9] Abramowicz, M. A. & Kluźniak, W., 2001, A&A, 374, L19

[10] Horák, J., 2008, A&A, 486, 1; Bursa, M., 2005, In Proc. of RAGtime 6/7: Workshops on Black Holes and Neutron Stars, ed. S. Hledík and Z. Stuchlík (Opava: Silesian University in Opava), pp. 39–45

[11] Greene, J., Bailyn, Ch. D. & Orosz, J. A., 2001, ApJ, 554; Greiner, J., Cuby, J. G. & McCaughrean, M. J., 2001, Nature, 414, pp. 522–525; Orosz, J. A., Groot, P. J., van der Klis, M., McClintock, J. E., Garcia, M. R., Zhao, P., Jain, R. K., Bailyn, Ch. D. & Remillard, R. A., 2002, ApJ, 568, 845; Beer, M. E. & Podsiadlowski, P., 2002, MNRAS, 331, 351

[12] McClintock, J. E., Shafee, R., Narayan, R., Remillard, R. A., Shane D. W. & Li-Xin, L., 2006, ApJ, 652, 518

[13] Middleton, M., Done, Ch., Gierlinski, M. & Shane, D. W., 2006, MNRAS, 373, 1004

[14] McClintock, J. E., Narayan, R., Shafee, R., 2008, In Black Holes, ed. Livio, M. & Koekemoer, A., Cambridge University Press

[15] Miller, J. M., Reynolds, C. S., Fabian, A. C., Miniutti, G. & Gallo, L. C., 2009, ApJ, 697, 900

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