Imprints of Strong Gravity in X-ray Variability of Neutron Star Boundary Layer

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Abstract

We analyze the impact of individual relativistic effects on the X-ray flux from a boundary layer obscured by a torus fragment. To this end, we developed a "Newtonian" limit of the fully relativistic ray-tracing code LSD and compared the resulting light curves.

Motivation

Our group often models the radiation of low-mass X-ray binaries (see, e. g., Török 2025). We use a complex relativistic code, LSD, developed by Pavel Bakala (see, e. g., Bakala et. al 2015). We now address the question: How weak must gravity be for the simplified Newtonian approach to be applicable in our analysis?

Outline

First, we summarize three geometries of light propagation that we will work with. Then we briefly describe a representative model of an orbiting torus fragment that will produce a variable light curve for comparison purposes. Next, we discuss the influence of gravitational redshift. Finally, we examine the impact of individual relativistic effects on the resulting variable light curves.

Conclusions

It is well known that gravitational redshift significantly affects photon energies even in moderately compact geometries (see Fig. 4). However, as shown in Fig. 6, the variable component of the flux in our test system is much less affected by relativistic effects.

In extreme compactness regimes, such as those typically considered in our analysis, a fully relativistic treatment is, of course, required. Nevertheless, already for a neutron star with a mass of 2 $M_\odot$ and a radius of 16 km, relativistic corrections have only a negligible impact on the fraction of obscured radiation in our example system.

The present results are for a single inclination; however, we plan to extend our analysis to other relevant physical scenarios in future work.

References

Bakala P., Goluchová (Klimovičovaá) K., Török G. et al. 2015, A&A, 581, 12

Török G., Klimovičová K., Lančová D. et al. 2025, APJ, 989, 10

Propagation of the light

We compare three approaches to the propagation of radiation in spacetime:

1) "**Relativistic**" – a fully relativistic ray-tracing approach that includes all relativistic effects.
2) "**No Doppler**" – light follows the same trajectories as in the "Relativistic" case, but photon energy remains unchanged.
3) "**Newton**" – light travels along straight lines, photon energy remains unchanged, the speed of light is effectively treated as infinite.

Comparing the results obtained with these three approaches allows us to understand the influence of individual relativistic effects. The methods are illustrated in Figure 1.

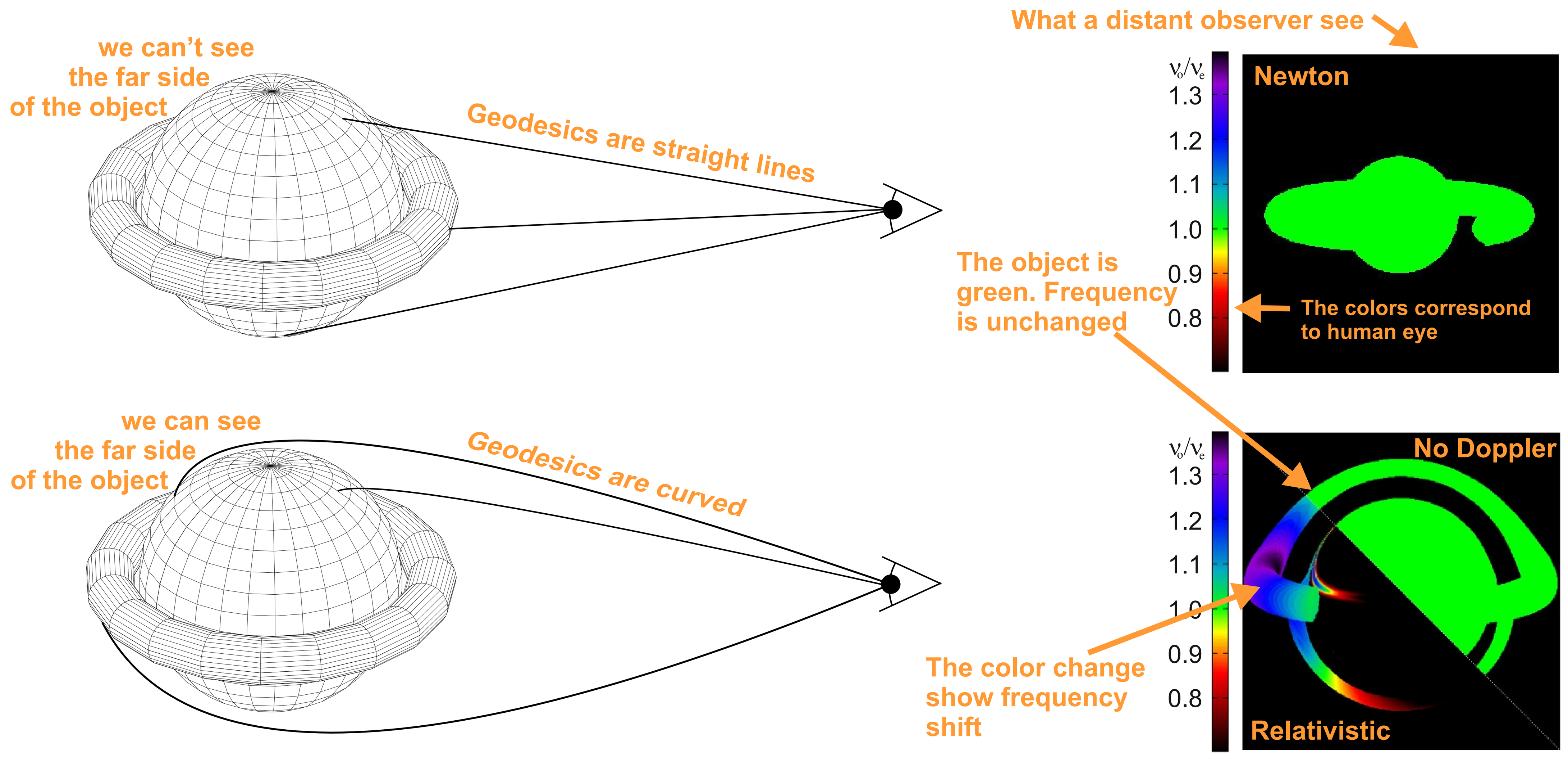

Figure 1: Illustration of the approaches to radiation propagation from the source to a distant observer. The upper panel shows the configuration referred to as "Newton," while the lower panel illustrates the remaining two models: "Relativistic" and "No Doppler".

Testing model

Components of the modeled system:

1) **Torus fragment** – an object formed by the disruption of an accretion torus.
2) **Star** with a bright boundary **layer** in the equatorial plane.

The boundary layer is partially obscured by the torus fragment, causing variability in the observed light curve. This configuration naturally enables the analysis of relativistic effects on the variability of accretion light curves. The same model is used in Török et al. (2025), and the configuration is illustrated in Fig. 2.

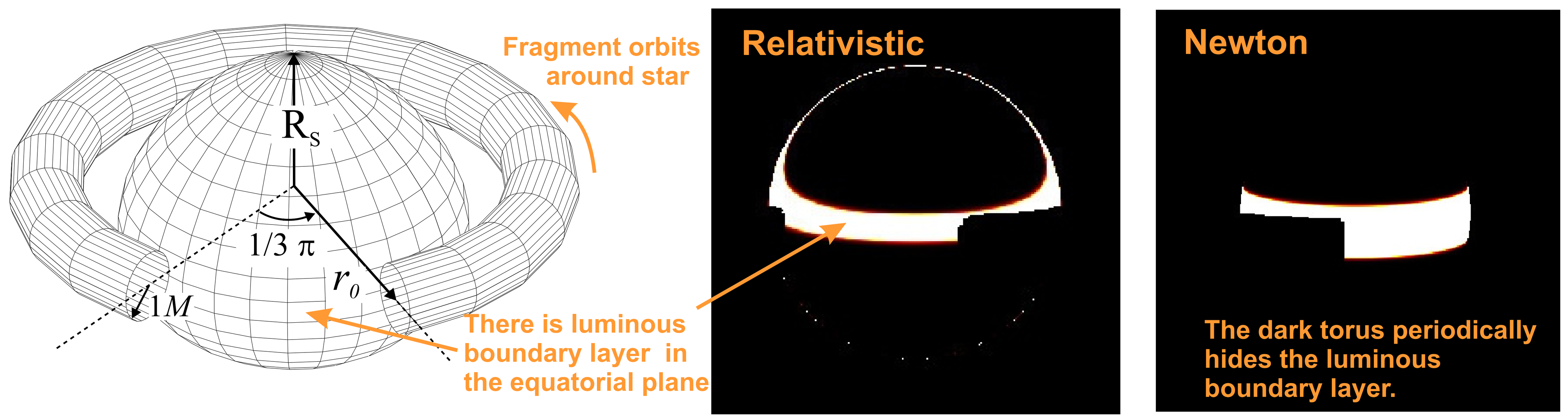

Figure 2: Illustration of the model used to test the influence of relativistic effects.

Gravitational red-shift

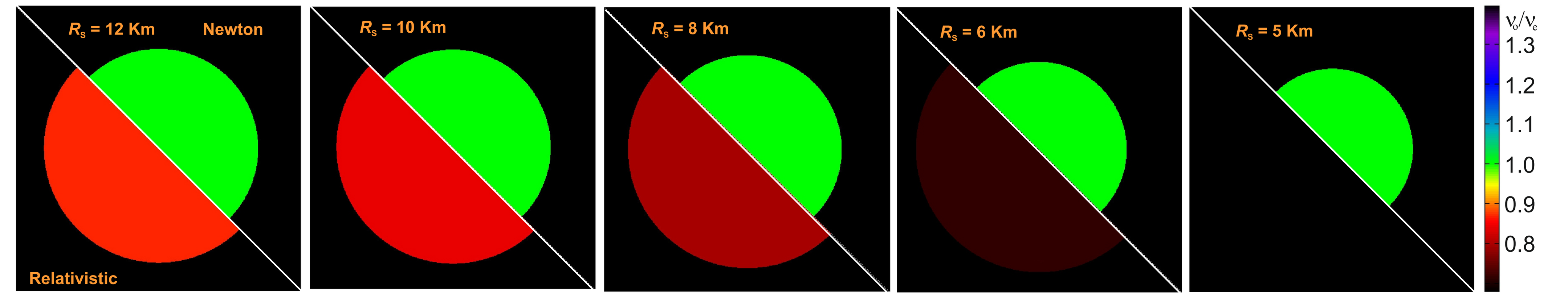

Figure 3: A star as seen by a distant observer when all relativistic effects are included, compared to the case where they are completely neglected.

Impact of gravitational redshift

Gravitational redshift can be computed analytically. Nevertheless, it is useful to visualize its influence, as this helps to better distinguish the impact of the individual relativistic effects discussed in the next section. For illustration, Fig. 3 shows a solar-mass neutron star with different radii (i.e. different strengths of the gravitational field) as seen by a distant observer, while Fig. 4 presents a direct comparison of the observed fluxes. It is clear from the figure — and can also be verified analytically — that gravitational redshift has a significant effect on the resulting light curves even for moderately strong gravitational fields. The parameters of the stars in Fig. 4 are intentionally the same as those in Fig. 6.

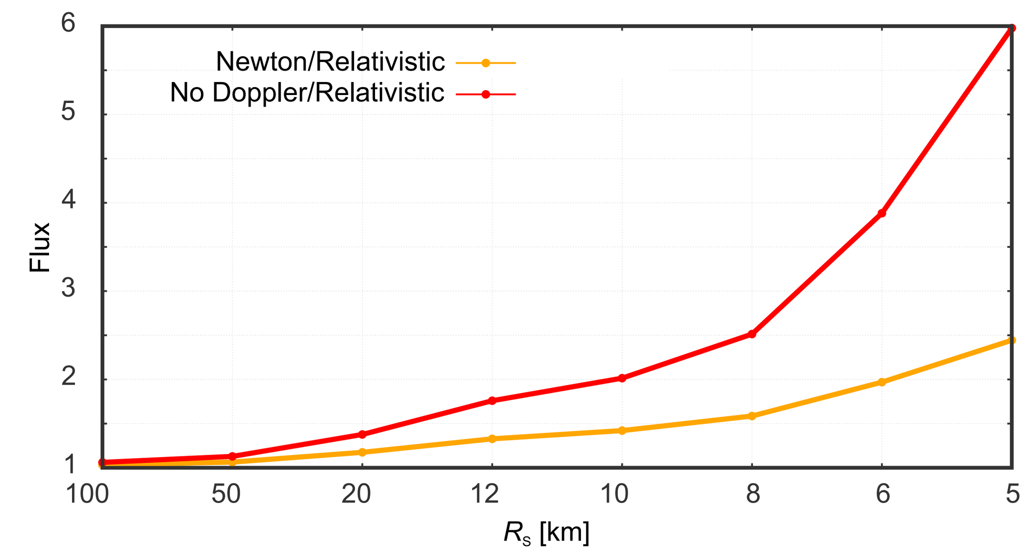

Figure 4: Radiation from a unit-mass star as a function of radius for "Newton" and "NO Doppler" configuration normalised by "Relativistic".

Impact of relativistic effects on X-ray flux

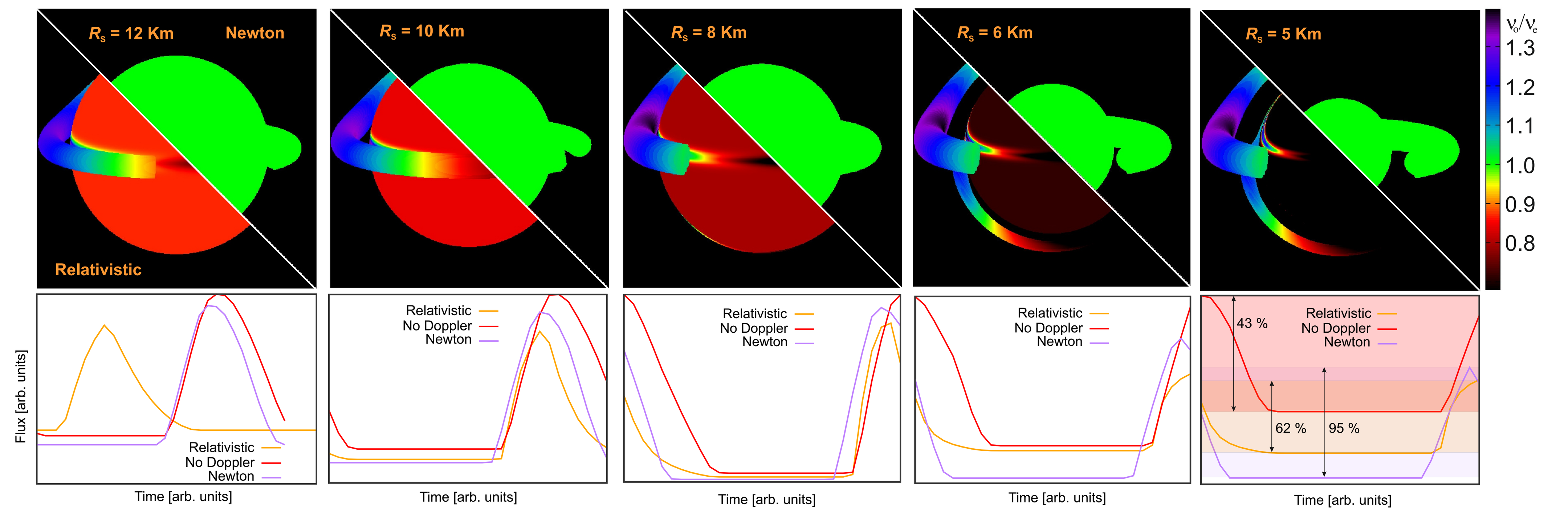

Figure 5: A star and torus fragment as seen by a distant observer when all relativistic effect are included and when relativistic effect are completely neglected.

The main results

The main results are presented in Fig. 6, which shows the dependence of the fraction of radiation affected by obscuration for all three considered cases. For illustration, we assume a star with one solar mass. It can be seen that when the stellar radius decreases below approximately 8 km, relativistic effects become strong. Moreover, this figure allows one to easily estimate the corresponding limit for stars of different masses using the approximate relation

$$R_b = 8\frac{M}{M_\odot}\mathrm{km} \qquad (1)$$

where M is the stellar mass and $M_\odot$.

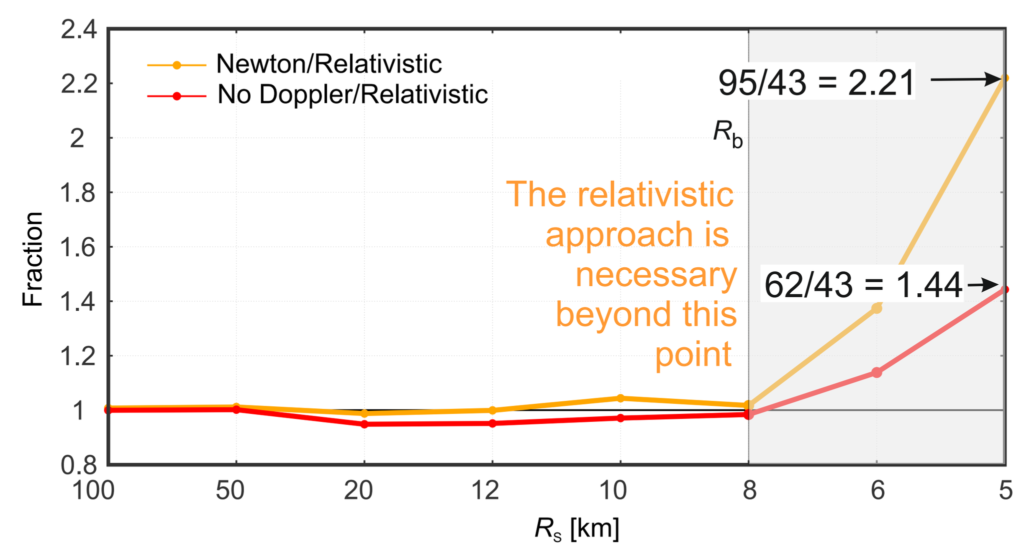

Figure 6: Fraction of the light curve which is influenced by osbscuration efect of a torus fragment for two configurations: "No Doppler" and "Newton". Fractions are normalized by fraction observed when all relativistic effect are included.