Quasi-Periodic Oscillations from Relativistic Hydrodynamical Slender Tori

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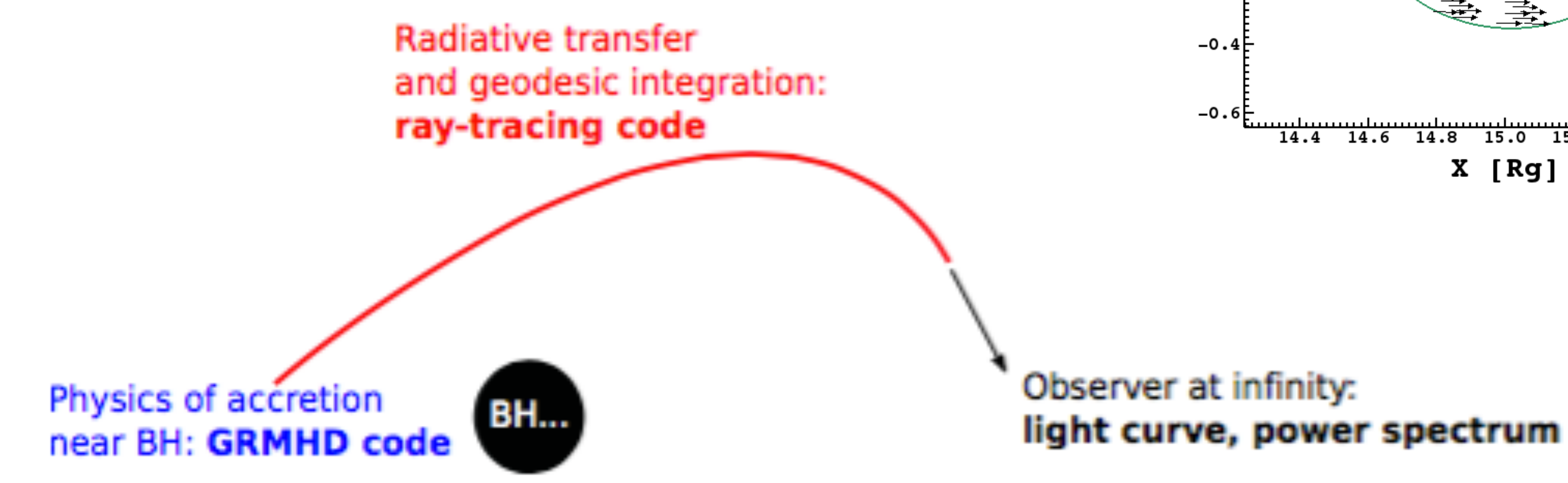
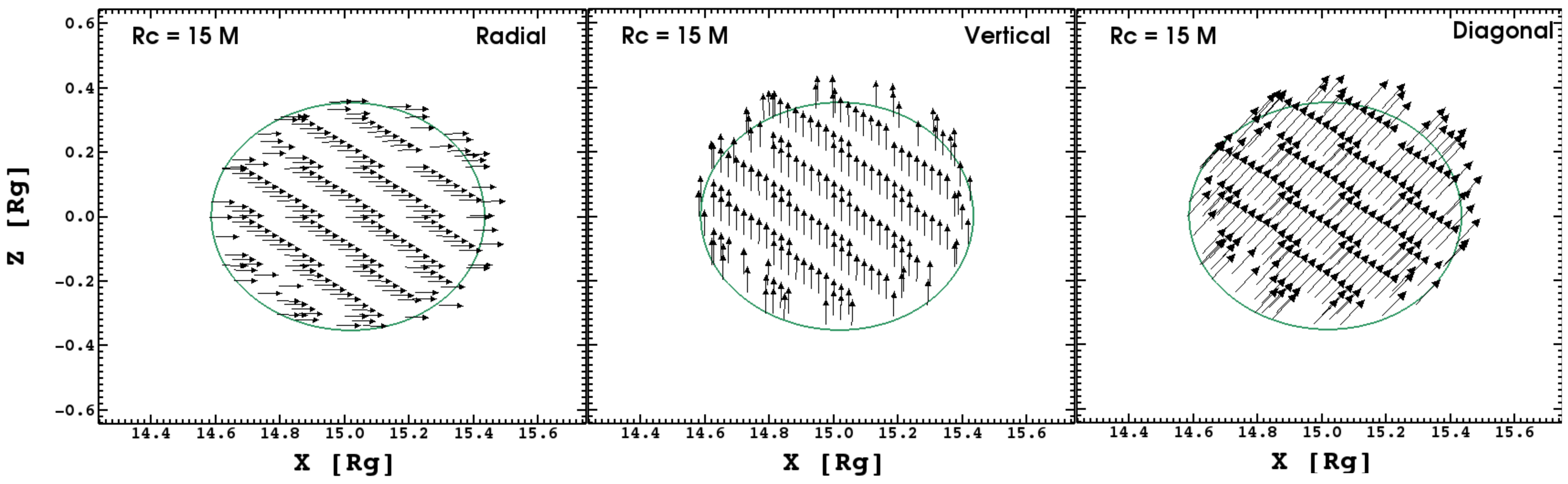
We simulate an oscillating purely hydrodynamical torus with constant specific angular momentum around a Schwarzschild black hole. The goal is to search for quasi-periodic oscillations (QPOs) in the light curve of the torus. The initial torus setup is subjected to radial, vertical and diagonal (combination of radial and vertical) velocity perturbations. The hydrodynamical simulations are performed using the general relativistic magnetohydrodynamics code *Cosmos++* and ray-traced using the *GYOTO* code. We found that a horizontal velocity perturbation triggers the radial and plus modes, while a vertical velocity perturbation triggers the vertical and X modes. The diagonal perturbation gives a combination of the modes triggered in the radial and vertical perturbations.

Velocity perturbation to the stationary torus

$$\mathbf{u} = \begin{cases} (u_t, \eta, 0, u_\phi), & \text{Radial} \\ (u_t, 0, K\eta, u_\phi), & \text{Vertical} \\ (u_t, \eta, K\eta, u_\phi), & \text{Diagonal} \end{cases}$$



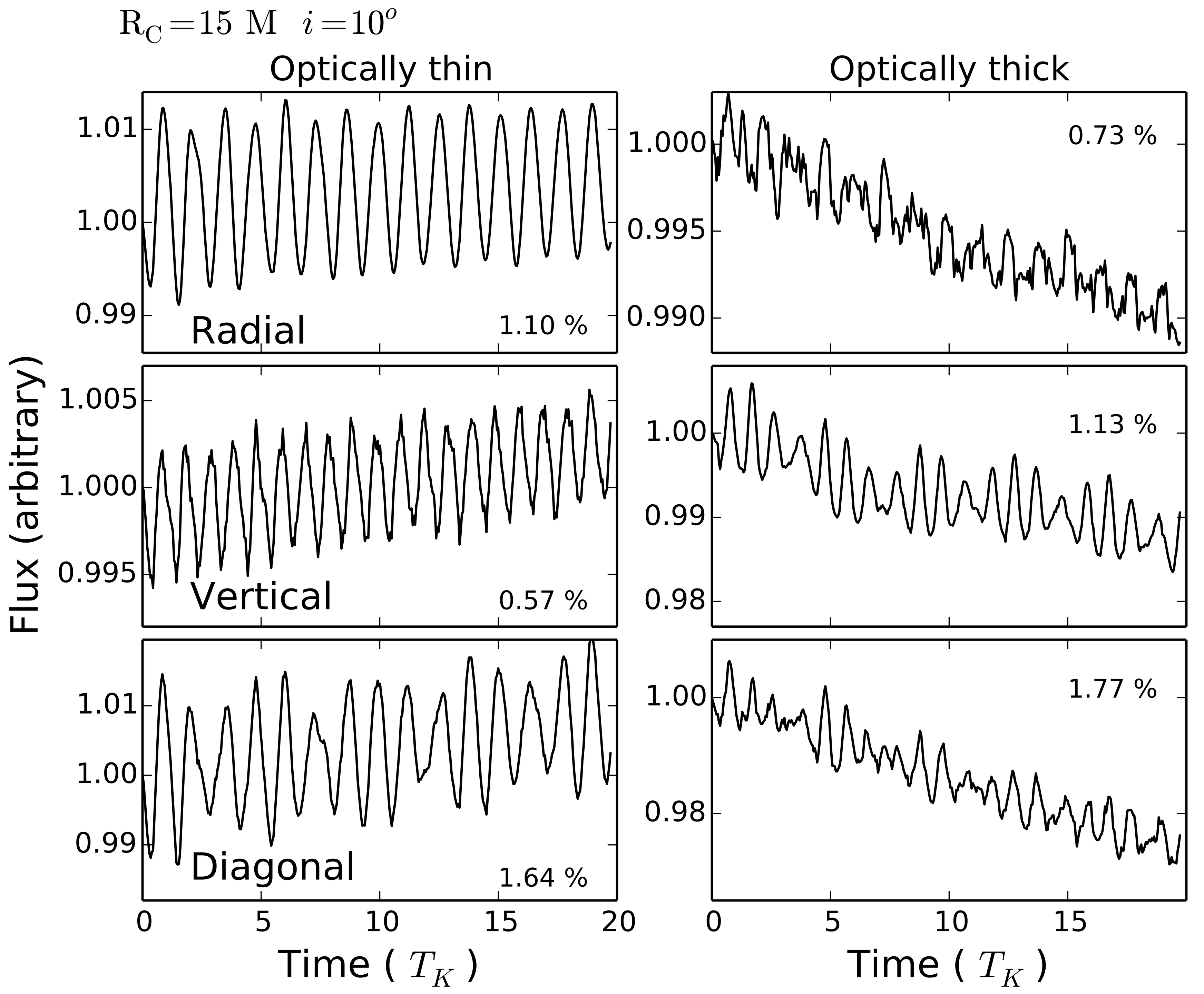
Cosmos++ (Anninos, Fragile, and Salmonson 2005)

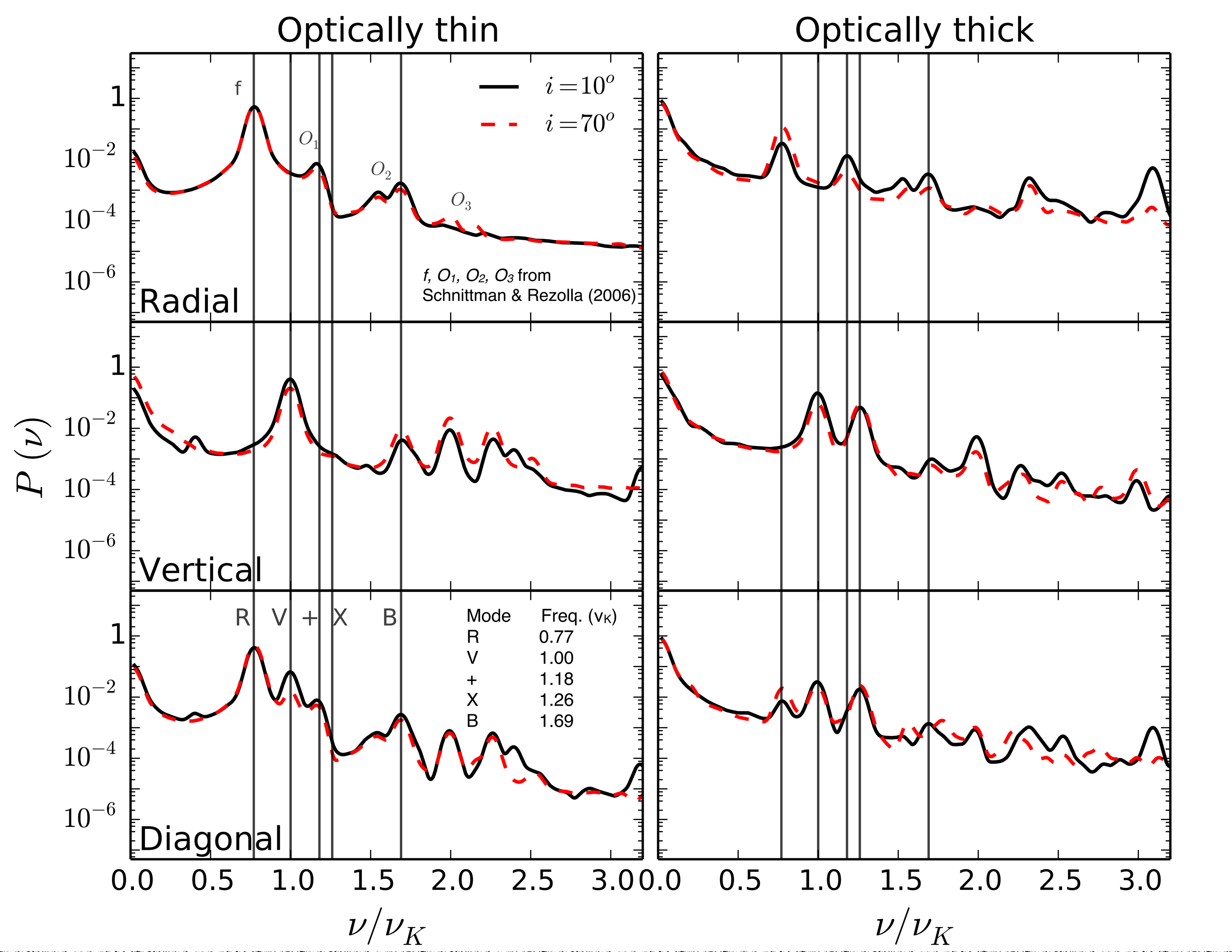


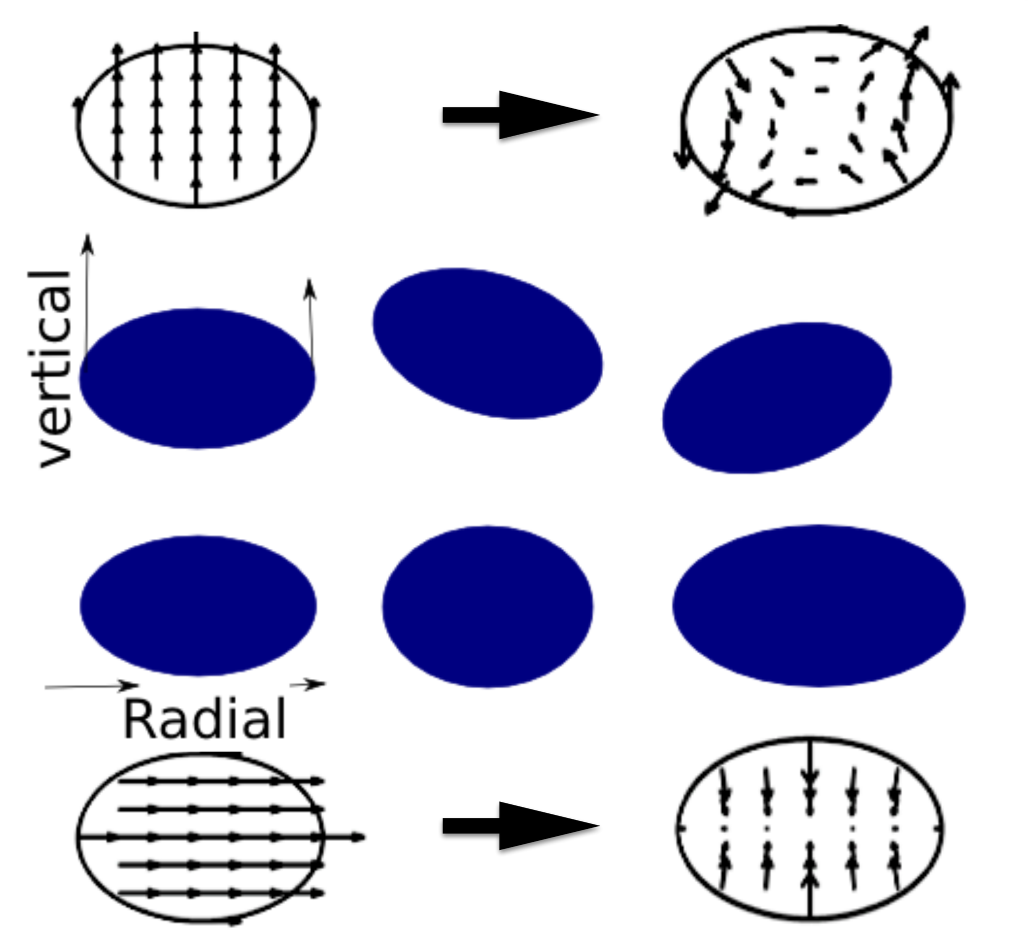
Ray tracing assumes two cases:

- ☑ Optically thin ➔ Bremsstrahlung radiation
- ☑ Optically thick ➔ Blackbody radiation

GYOTO (Vincent, Paumard, Gourgoulhon, and Perrin 2011)







Conclusions:

1. A uniform radial perturbation of the velocity field can trigger both the radial mode and the plus mode. Likewise, a uniform vertical perturbation of the velocity field can trigger the vertical mode and an X-mode. We also found that no matter where we place the center of the torus, we see a similar response. We argue that the presence of both the radial and plus mode or the vertical and X-mode is owing to non-uniform velocity vectors of the vertical and radial eigenmodes in an even slightly non-slender torus.

2. We did *not* find any clear dependence on inclination in our ray-traced light curves for optically thin case, whether the torus was nearly edge-on or nearly face-on. We suspect that this is due to the fact that our tori are very slender and compressible

3. We found that the two different radiative models we considered can give very different lightcurves and hence different PDS. In particular, the optically thin and thick cases give different powers in the plus- and X-modes.

4. A clear domination of peaks in a 3:2 ratio (X/vertical, plus/radial, or vertical/breathing) is not observed.

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Also available on ArXiV:1510.07414

Acknowledgments: This research was supported by Polish NCN grant UMO-34 2011/01/B/ST9/05439 and 2013/08/A/ST9/00795. Part of the work was supported by the Polish NCN grant 2013/09/B/ST9/00060