Twin peak kHz QPOs from black holes and neutron stars

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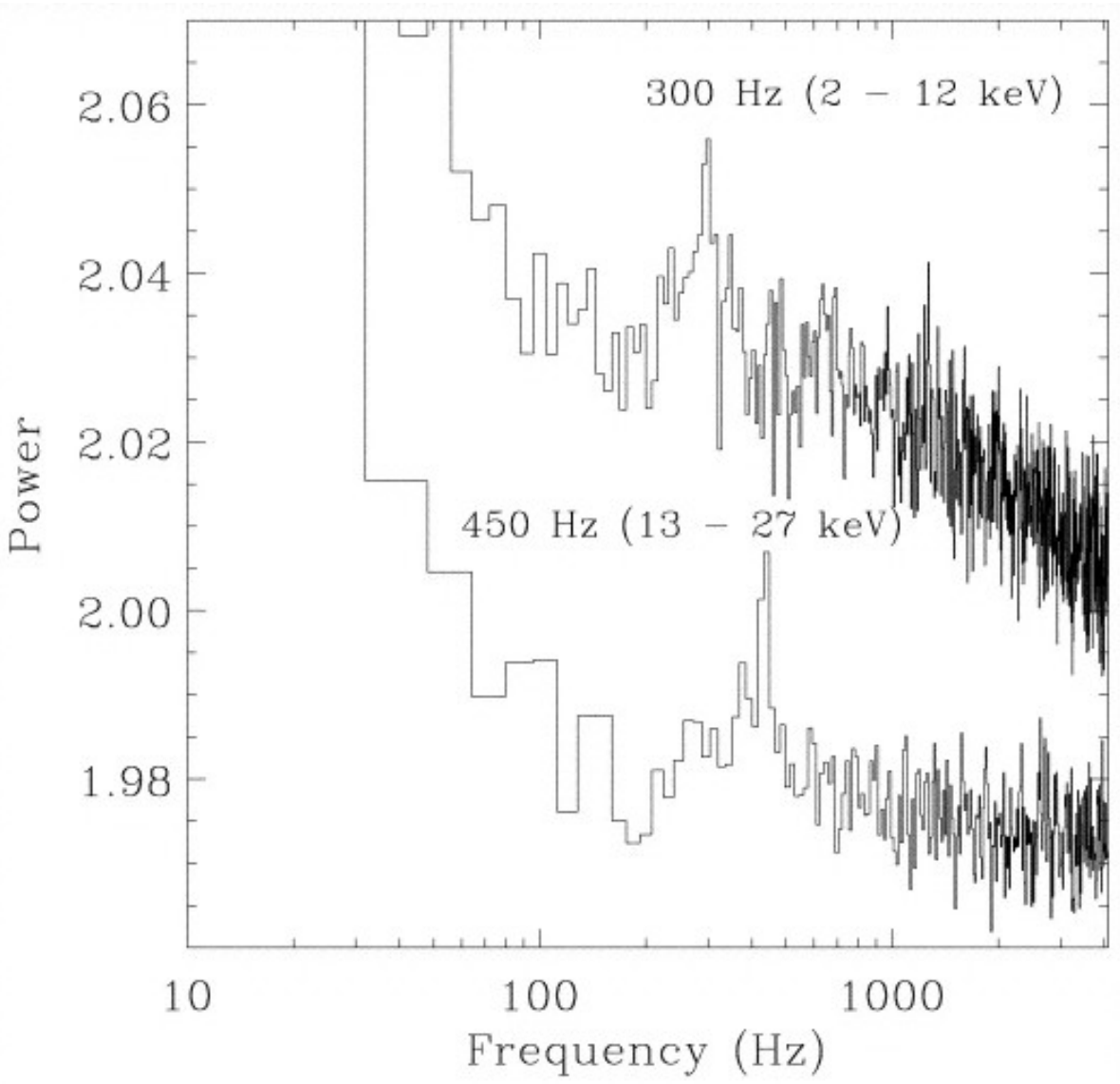
Rossi-XTE discovered kHz QPOs

The black hole GRO J1655-40



- Twin peak QPOs at a ratio of 3:2 (Strohmayer 2001).
- The QPO frequencies are stable over time.

Twin-peak QPOs

- QPO frequencies form a 3:2 ratio in black holes
- In neutron stars they follow the Bursa line

$$\nu_U = A\,\nu_L + B$$

(Abramowicz, Bulik, Bursa & Kluźniak 2003)

The mathematical model

- This behaviour can be interpreted as the dynamics of two coupled nonlinear oscillators.
- The 3:2 ratio in the black hole case is the result of a resonance between the two oscillators (Kluźniak & Abramowicz 2001).
- In neutron stars the oscillators are driven by the rotation of the neutron starm and the inner edge of the disc moves with the accretion rate.

What are the oscillators

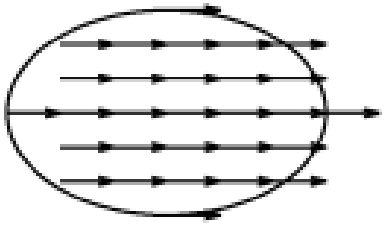
- The simplest modes are the horizontal and vertical epicyclic modes.
- In Newtonian gravity they oscillate at the Keplerian frequency.
- The frequency of the radial epicyclic motion is lower in strong gravity, and they form a 3:2 resonance at a radius that depends on the spin of the black hole (Kluźniak & Abramowicz 2002).

Other modes

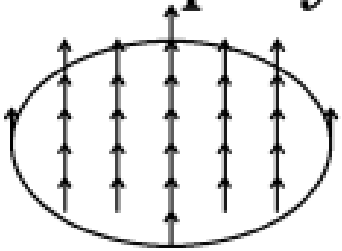
- An accretion torus can oscillate in many other modes too (Blaes et al. 2007).
- For instance X-modes and breathing modes.

Oscillatory modes in a torus (Blaes, Arras & Fragile 2006)

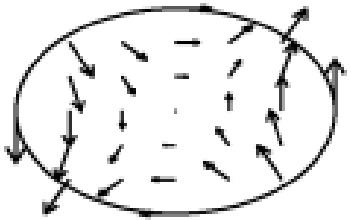
Radial Epicyclic (−+01)



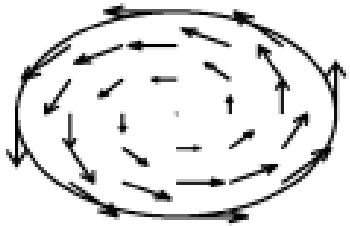
Vertical Epicyclic (+−01)



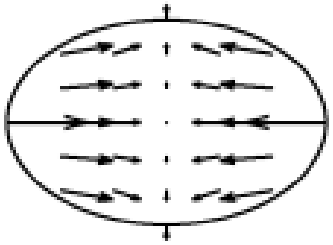
× Mode (−−02)



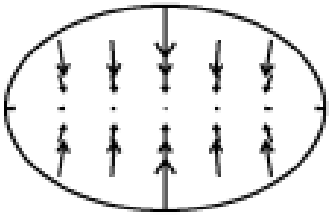
Inertial Mode (−−02)



+ Mode (++02)



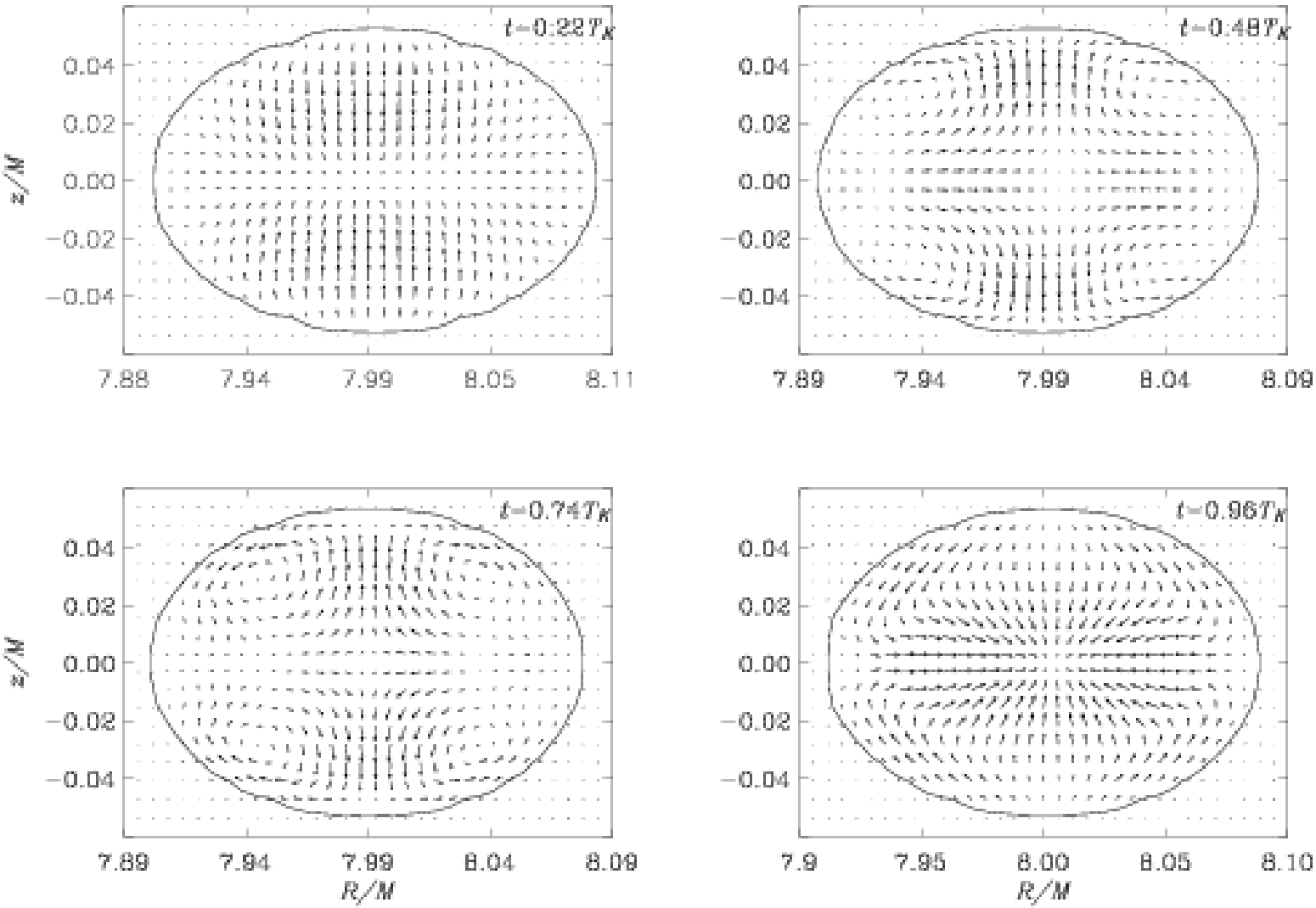
Breathing Mode (++10)



Nonlinear coupling of the epicyclic modes

- Sramkova, Torkelsson & Abramowicz (2007) have simulated epicyclic oscillations in a torus.
- Our simulations do not find a coupling between the epicyclic modes within the range of parameters that we tested.
- However there is an acoustic mode at 1.5 times the Keplerian frequency.

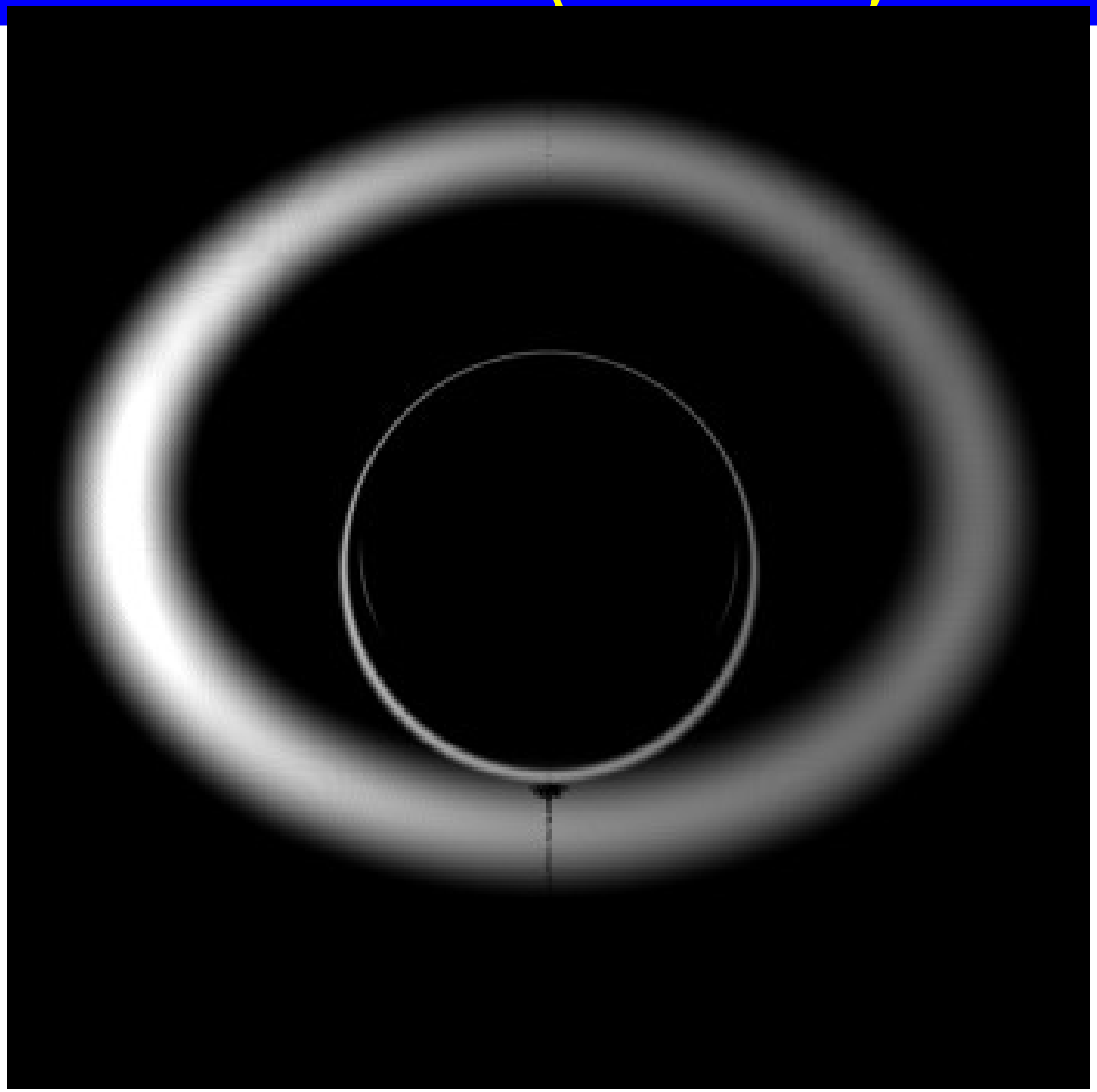
Slender torus around a black hole



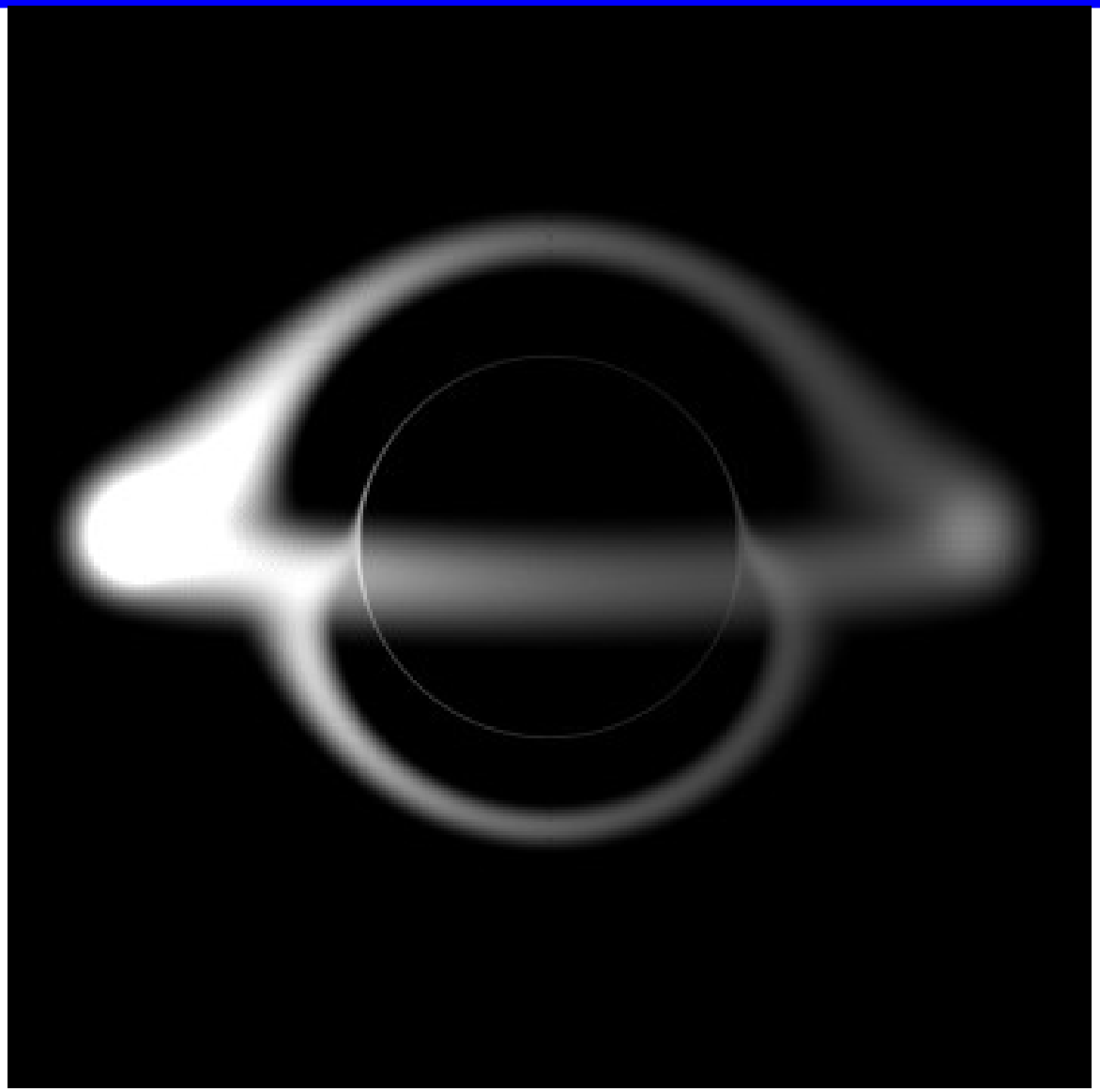
How is the X-ray emission modulated?

- Light bending and relativistic beaming can modulate the X-ray emission from an oscillating torus.

A torus viewed from 45 degrees latitude (Bursa)



A torus viewed from 5 degrees latitude (Bursa)



Conclusions

- Rossi-XTE has discovered kHz QPOs from accreting black holes and neutron stars.
- Twin peak QPOs can be interpreted as the nonlinear interaction between two oscillatory modes.
- Which modes?