Modulation Mechanisms of High-Frequency QPOs

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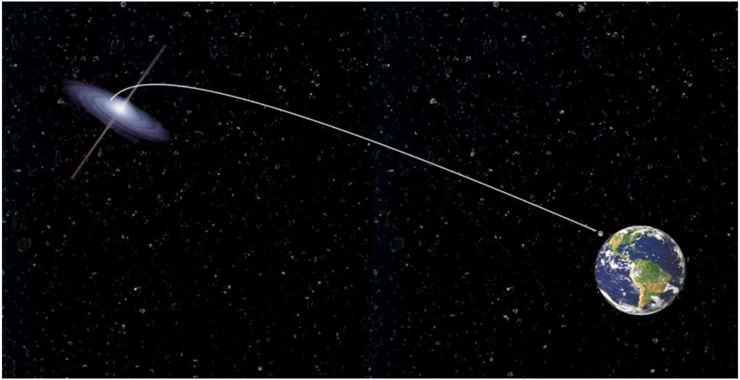
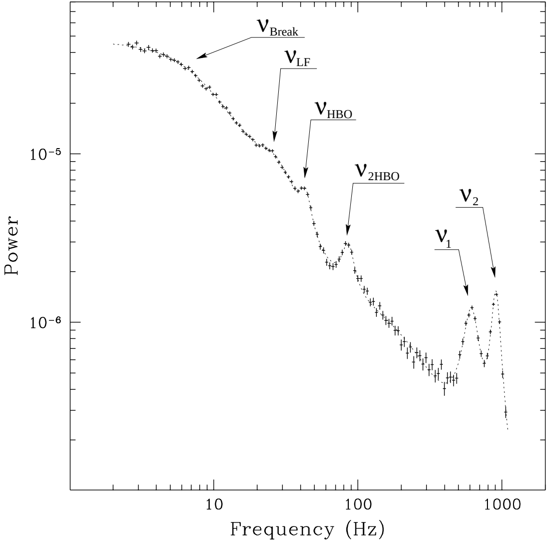
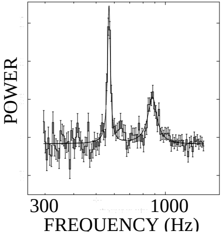


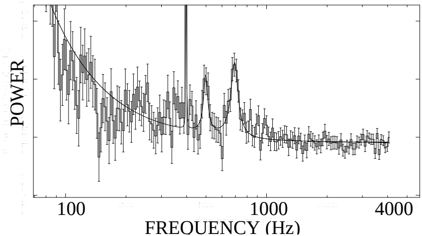
QPOs – Power spectra



QPOs in Neutron-Star Sources

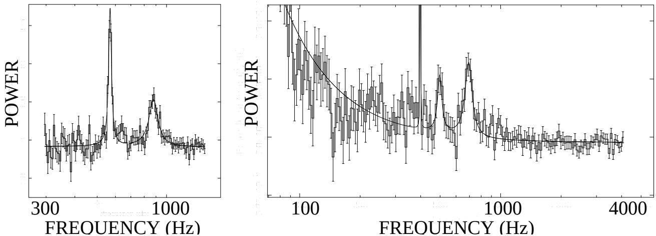
- by up to 30 sources
- peaks are sometimes paired, sometimes single
  (depends on source and conditions)
- strong and dominant feature
  amplitudes $1 - 15\,\%$ rms
- not fixed in position – frequencies change with count rate
  ν_U : $300 - 1300\,\mathrm{Hz}$
  ν_L : $150 - 1000\,\mathrm{Hz}$
  parallel tracks





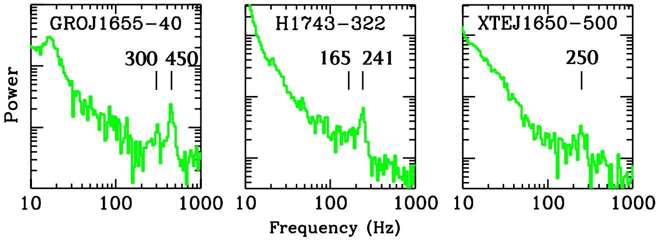
QPOs in Neutron-Star Sources

- peak separation ($\Delta\nu = \nu_U - \nu_L$) is not constant
  changes with frequency
  commensurate with spin frequency of NS or its half
- hard/soft photons time lags
  coronal model: hard lag soft (ex: Cyg X−1)
  QPOs: soft lag hard, emission form the surface/boundary layer



QPOs in Black-Hole Sources

- 7 known Galactic sources with HFQPO
  4 sources with double peaks observed occasionaly in outbursts exclusively in SPL state
- weak and transient
  amplitudes $0 - 5\,\%$ rms
  (sometimes observations must be grouped to get evidence)
- peaks are rarely paired, mostly single
  selection depends on TD/PL flux ratio



QPOs in Black-Hole Sources

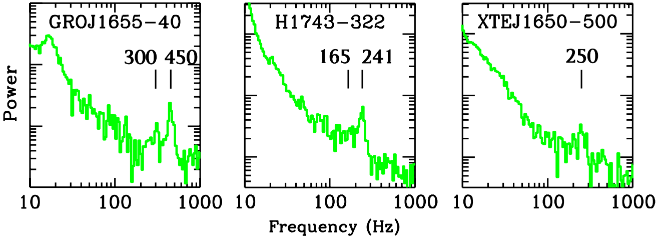
- fixed in position – frequencies do not change, $\Delta\nu = \text{const}$

  ν_U : $40 - 450\,\text{Hz}$

  ν_L : $30 - 300\,\text{Hz}$

- fixed frequency ratio (3 : 2)

XTE	1550−564	276/184 Hz	8.4−10.8 $M_\odot$
GRO	1655−40	450/300 Hz	6.0−6.6 $M_\odot$
GRS	1915+105	168/113 Hz	10.0−18.0 $M_\odot$
H	1743−322	240/160 Hz	—



QPOs – THE TWO QUESTIONS

- physical mechanism

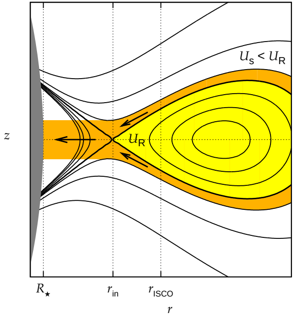
  Finding what and where oscilates?

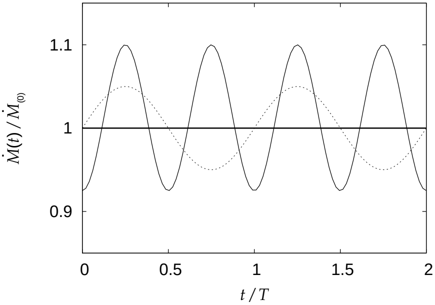
- modulation mechanism

  Finding how is the flux modulated?

Modulation mechanism – neutron stars

- Revnitsev & Gilfanov (2005): QPO modulation is in the boundary layer
- pressure supported disk around a neutron star
  if the inner part is perturbed by some oscillations, the accretion rate through the nozzle is strongly affected (and luminosity too); Horák (2005)





Modulation mechanism – black holes

- some mechanism has to modulate emergent flux at sufficient level
- in neutron stars this is done in boundary layer
- solely presence of disc is not sufficient
- more appropriate model:
  outer cool disc is transitioned into (or sandwiched by) a hot, thick and optically thin flow (torus)
- optically thin medium is transparent for photons
  relativistic light bending/lensing effects might be important (hot spots, arms, ...)

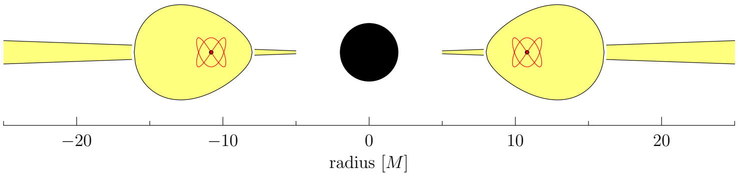
Torus model

- optically thin torus
- we impose two oscillation modes:

$$r(r) = r_0 + \delta r \sin(\omega_r t)$$

$$z(t) = \delta z \sin(\omega_z t)$$

- ω_r, ω_z are epicyclic frequencies

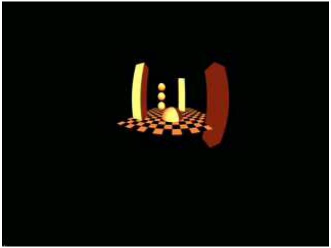


Effects: Aberration

Aberration arises because of the transformation between inertial frames

$$\tan\frac{\alpha'}{2} = \left(\frac{c-v}{c+v}\right)^{1/2}\tan\frac{\alpha}{2}$$

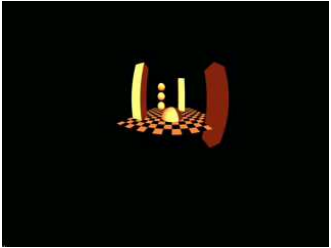
while $v < c$ it follows that $\alpha' < \alpha$ and thus all rays are rotated into the direction of motion (angular contraction)

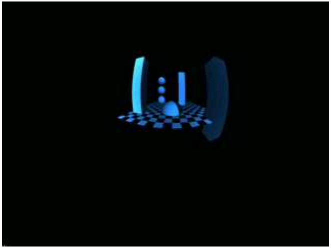


Effects: Doppler shift

Light from moving objects will appear to have different wavelengths depending on the relative motion of the source and the observer.

$$\frac{\nu'}{\nu} = \frac{1 + \dfrac{v}{c}\cos\alpha}{\left(1 - \dfrac{v^2}{c^2}\right)^{1/2}}$$

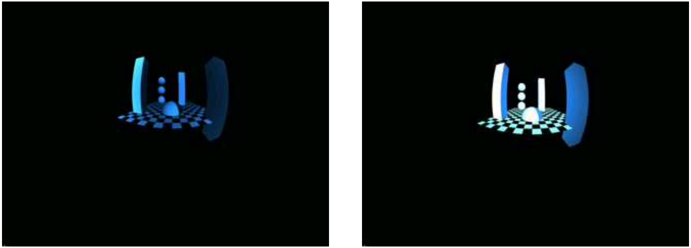




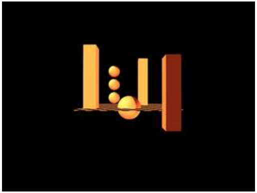
Effects: Headlight

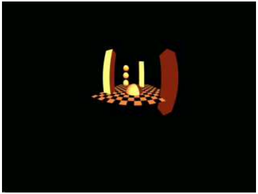
The angular contraction concentrates light in the direction of motion

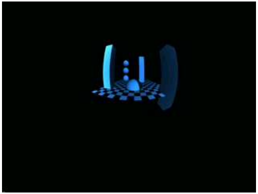
$$\frac{I'}{I} = \frac{\left(1 - \frac{v^2}{c^2}\right)^{1/2}}{\left(1 + \frac{v}{c}\cos\alpha\right)^2}$$

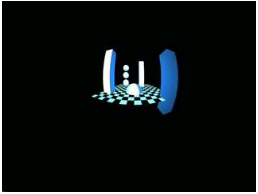


Effects: All special relativistic





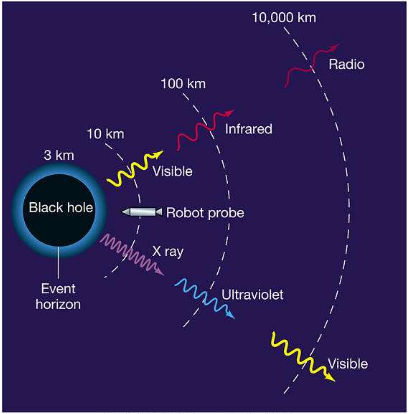




EFFECTS: GRAVITATIONAL REDSHIFT

Photon lose energy while climbing up the gravitational potential well

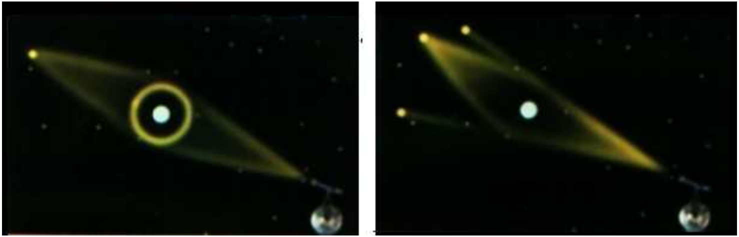
$$\frac{\nu'}{\nu} = \sqrt{1 - \frac{2GM}{r\,c^2}}$$



EFFECTS: GRAVITATIONAL LIGHT BENDING

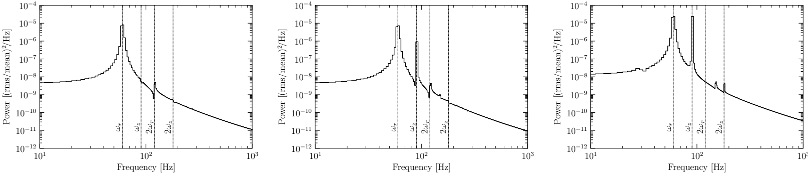
Photons trajectories get bendt round massive objects.

$$\left(\frac{1}{r^2}\frac{\mathrm{d}r}{\mathrm{d}\phi}\right)^2 + \frac{1-2M/r}{r^2} = \frac{1}{b^2}$$



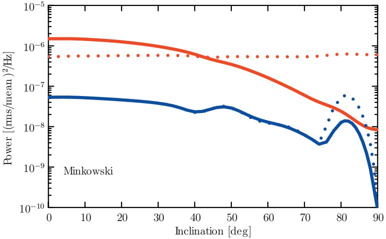
Effect of Geometry

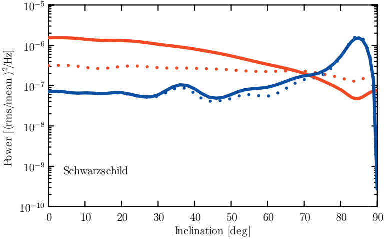
- Newton ($c \to \infty$): no time delays, rigid body, no ω_z power
- Minkowski: time delays, elastic body, ω_z power shows
- Schwarzschild: time delays + lensing, ω_z gains more power



Effect of Inclination

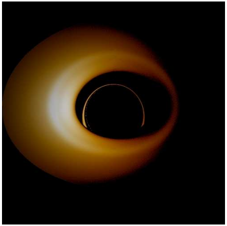
- most featured, but hard to be tested
- face-on: radial oscillation dominates (doppler)
- edge-on: vertical oscillation dominates (lensing)

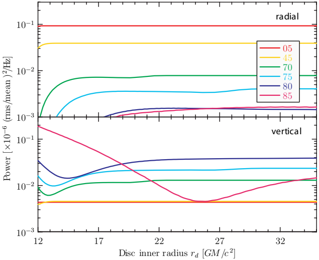


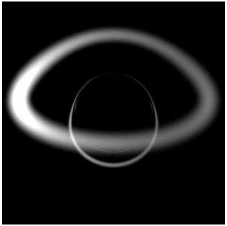


EFFECT OF DISC OBSCURATION

- surrounding cool disc obscures inner torus
- can be tested observationally
- blocking of higher-order photons changes ω_z power substantially

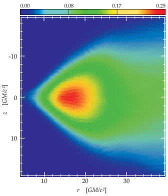


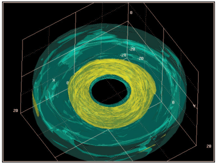




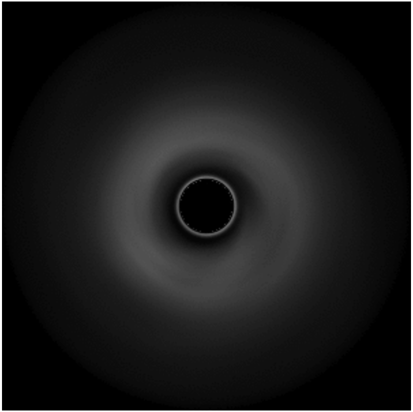
Ray-Tracing a 3D MHD Simulation

- usefull in connection with 3D MHD accretion flow simulations
- gives the real lightcurve & powerspectrum as detected by a distant observer (satellite)
- PDS may differ substantially from the one obtaind by a simple flow analysis
- strong geometrical effects



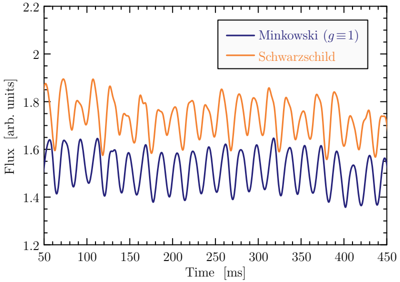


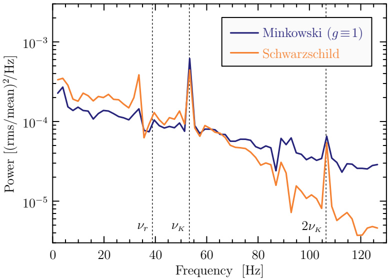
Ray-Tracing a 3D MHD Simulation



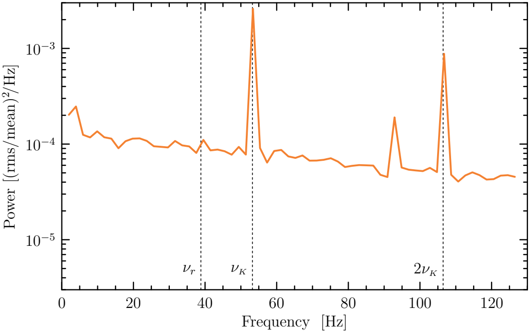
Ray-Tracing a 3D MHD Simulation

Lightcurves & power-spectra of a ray-traced MHD simulation:





Inclination dependence of ray-traced power-spectrum:



MHD SIMULLATIONS & TORUS MODEL