X-ray diagnostics of extreme gravity in the vicinity of neutron stars and black holes

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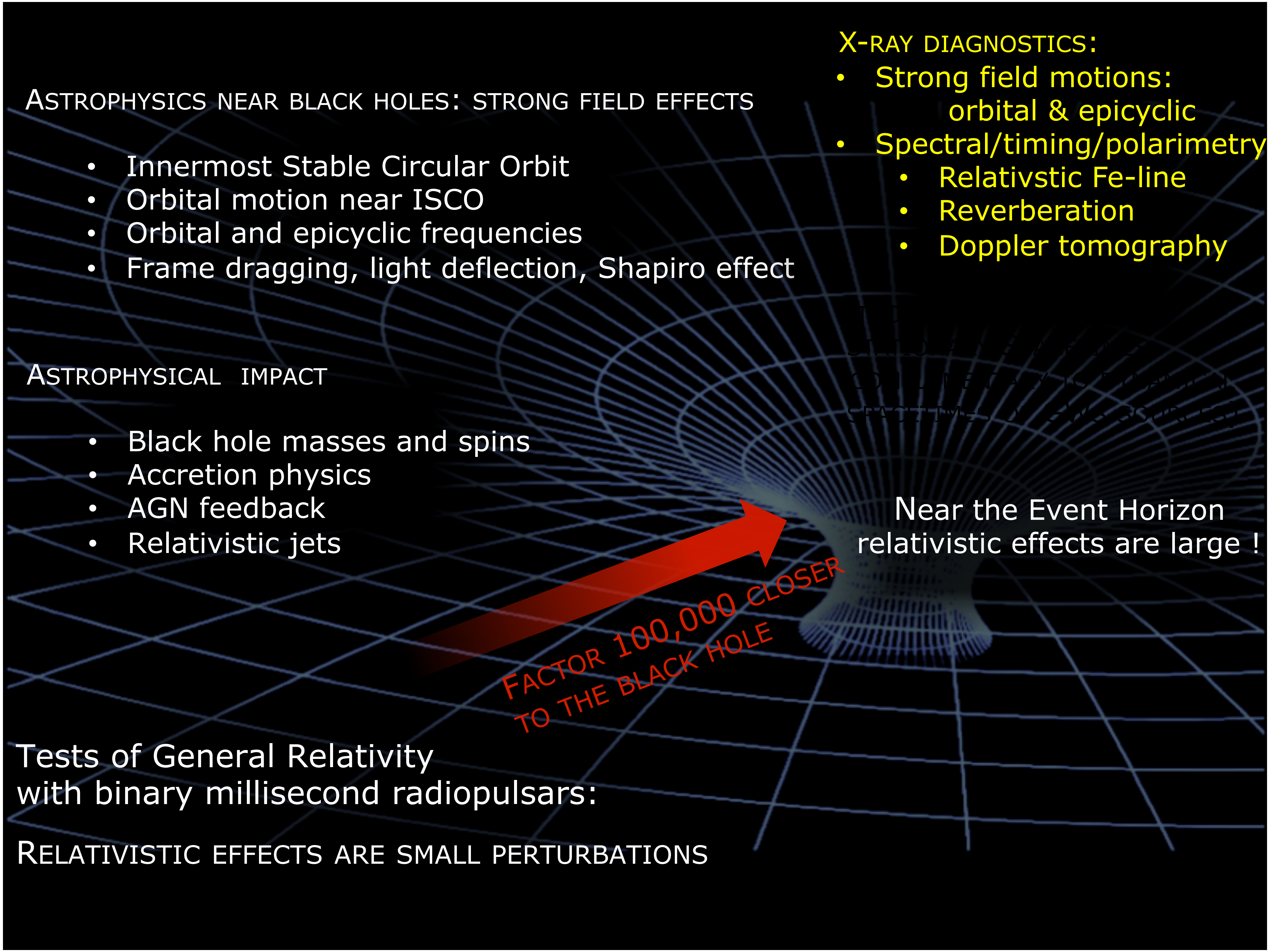
Relativistic Binary pulsars

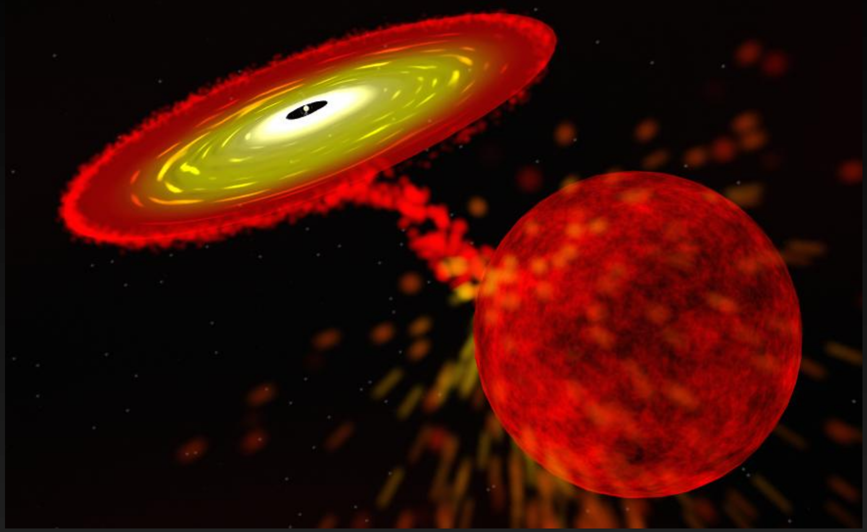
* Accurate test of gravity; several GR effects confirmed with very good accuracy

- periastron advance,
- orbital decay,
- time-dilation and gravitational red-shift parameter,
- sin of the inclination of the orbit
- mass of the companion
- relativistic precession

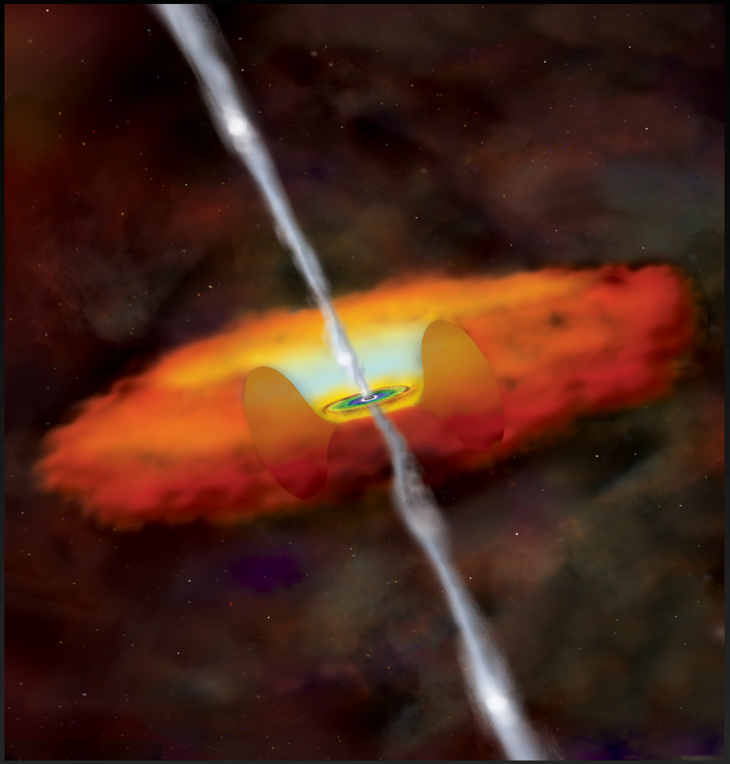
* BUT: direct measurements only at large radii ($R \sim 10^6$ Schwarzschild radii)


ASTROPHYSICS NEAR BLACK HOLES: STRONG FIELD EFFECTS
• Innermost Stable Circular Orbit
• Orbital motion near ISCO
• Orbital and epicyclic frequencies
• Frame dragging, light deflection, Shapiro effect
X-RAY DIAGNOSTICS:
• Strong field motions: orbital & epicyclic
• Spectral/timing/polarimetry
• Relativstic Fe-line
• Reverberation
• Doppler tomography
ASTROPHYSICAL IMPACT
• Black hole masses and spins
• Accretion physics
• AGN feedback
• Relativistic jets
Near the Event Horizon relativistic effects are large !
FACTOR 100,000 CLOSER TO THE BLACK HOLE
Tests of General Relativity with binary millisecond radiopulsars:
RELATIVISTIC EFFECTS ARE SMALL PERTURBATIONS

Accreting Black Holes



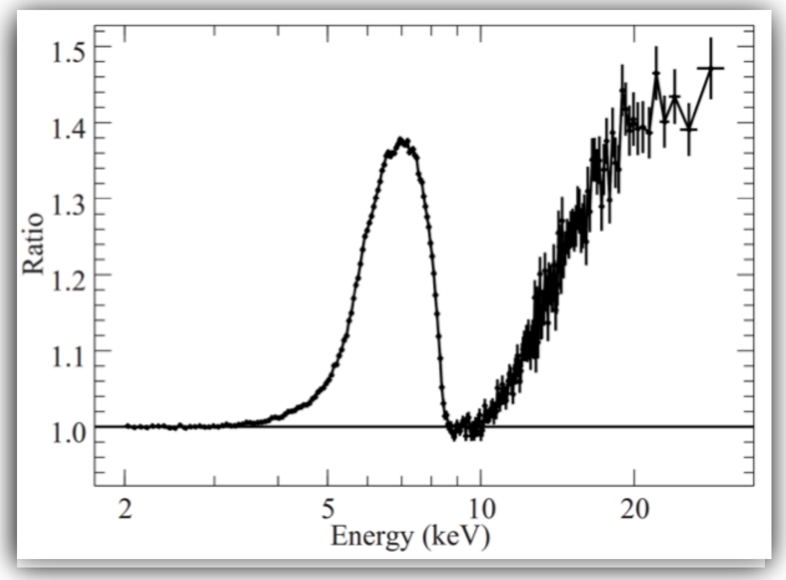
Stellar mass Black Holes in X-ray binaries



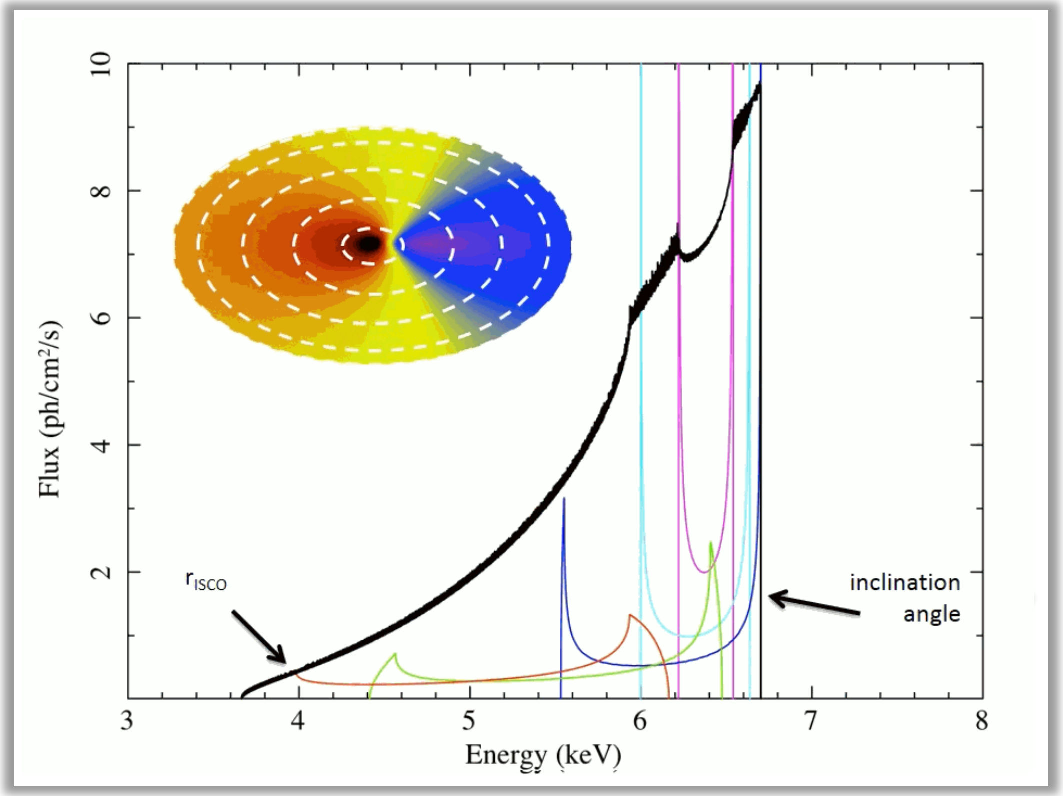
Supermassive Black Holes in nuclei of active Galaxies (AGN)

- Accretion-released energy leads to powerful X ray emission from the innermost disk regions
- X-ray flux is often very variable and spectra are complex

Fe-line diagnostics



eXTP-LAD simulation of
black hole X-ray binary
1ks integration
a* = 0.967±0.003

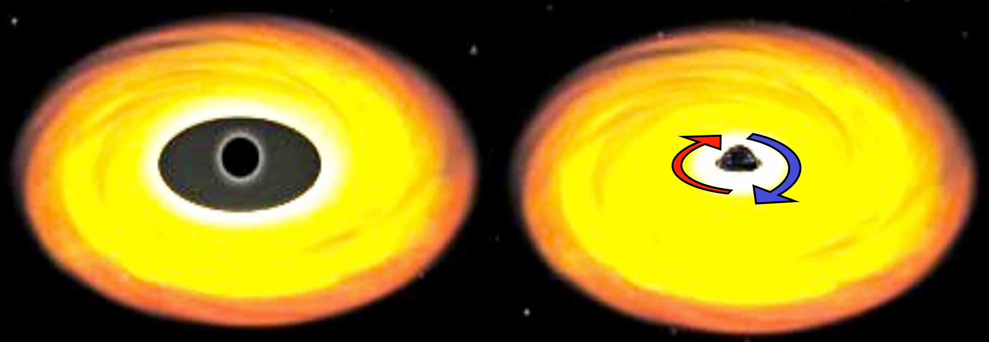


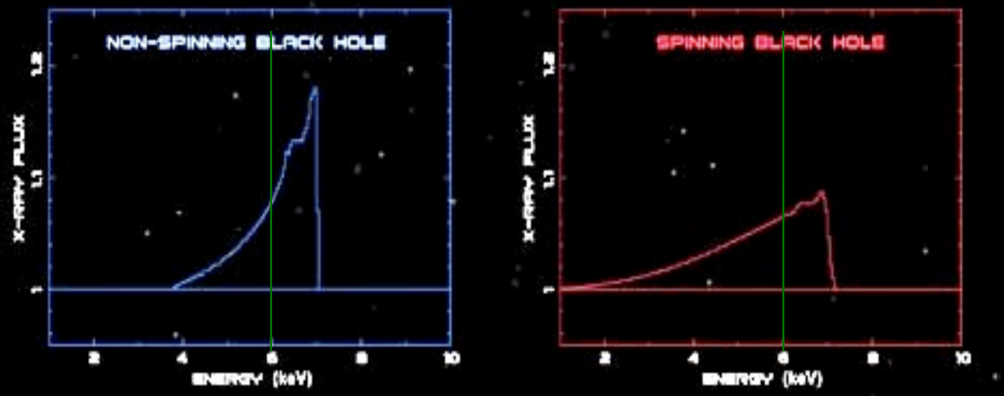
General relativity predicted velocity and redshift map of the accretion disk

Line profile integrated over entire flow encodes:

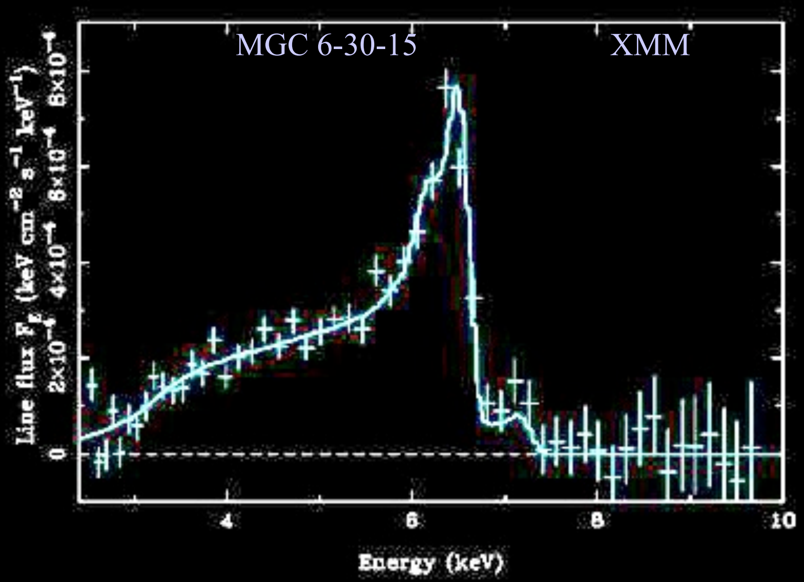
- Strong field relativistic effect: Doppler shifts and boosting, gravitational redshift, strong field lensing, black hole spin
- Observed in both Active Galactic Nuclei and X-ray binaries

Fe-lines from accretion disks around supermassive black holes in AGNs

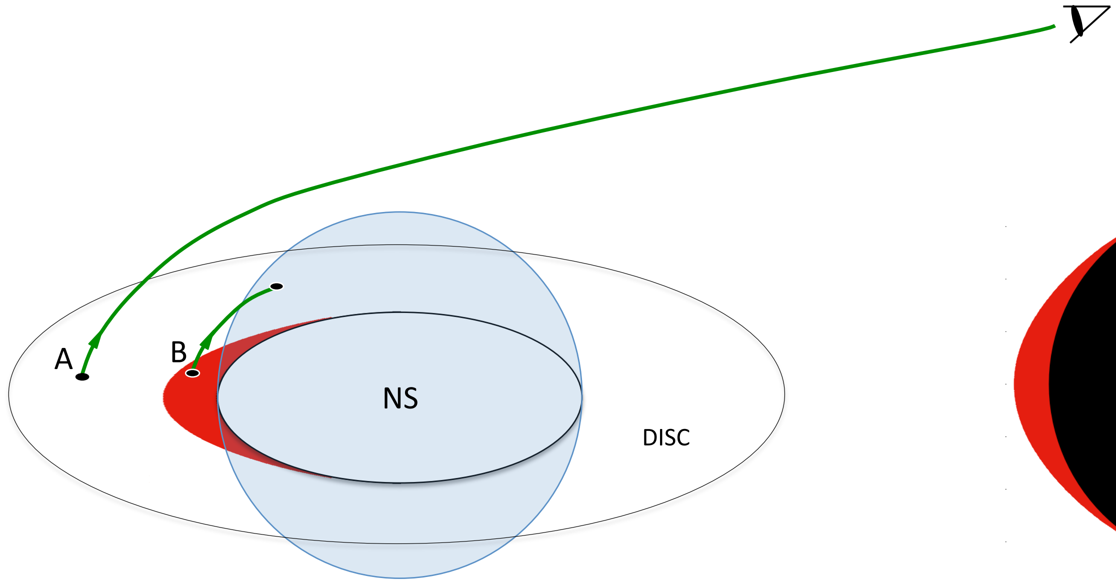


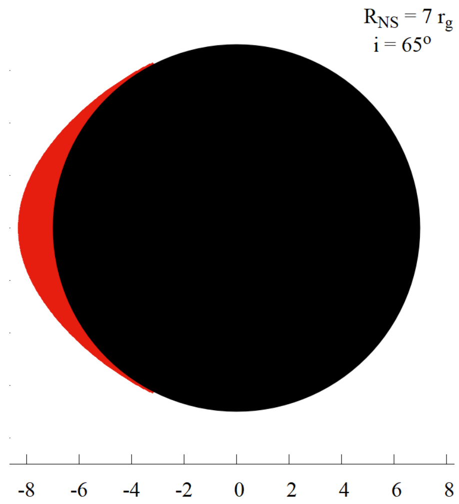


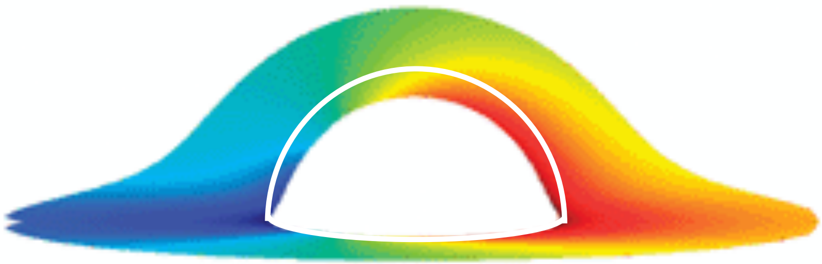
MCG 6-30-15:
- Kerr BH required to fit line profile



OBSCURATION BY THE NEUTRON STAR

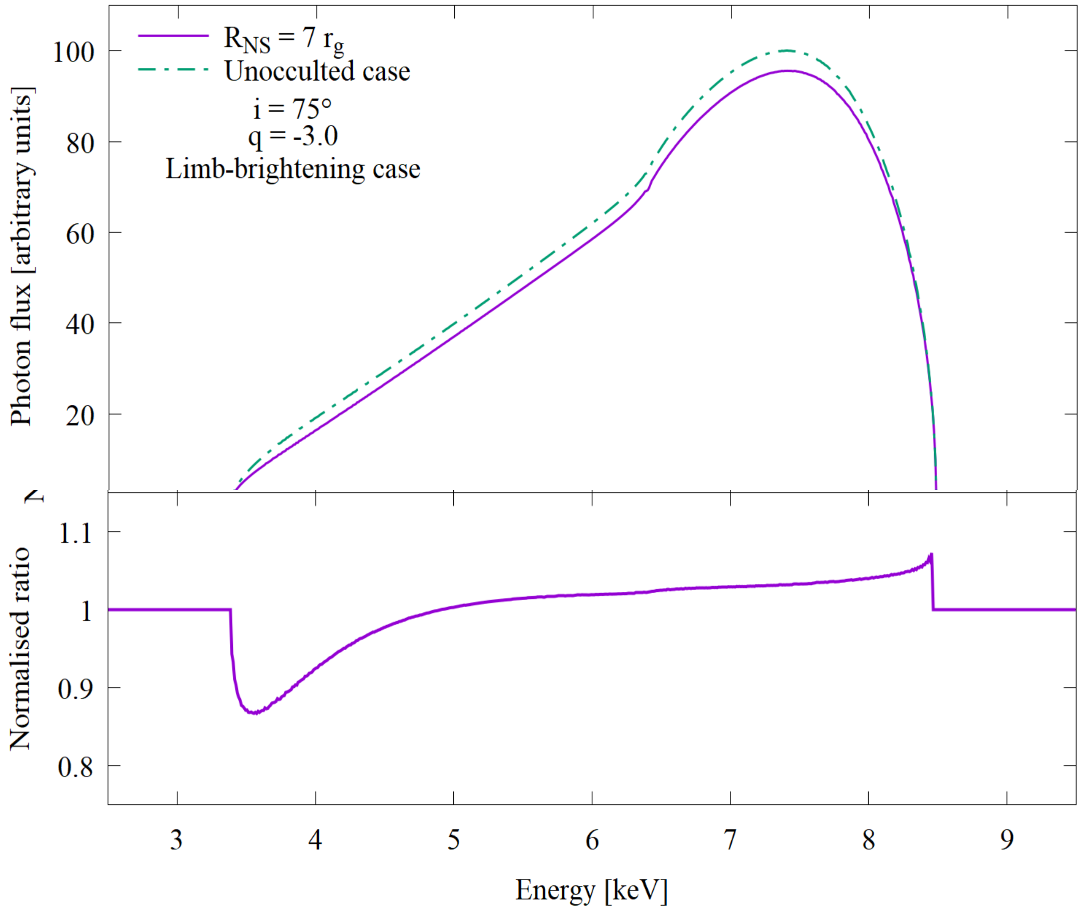






Occulted Fe-line profile:
→ Diagnostics of neutron star compactness R/M

FE-LINE PROFILE OBSCURED BY NEUTRON STAR

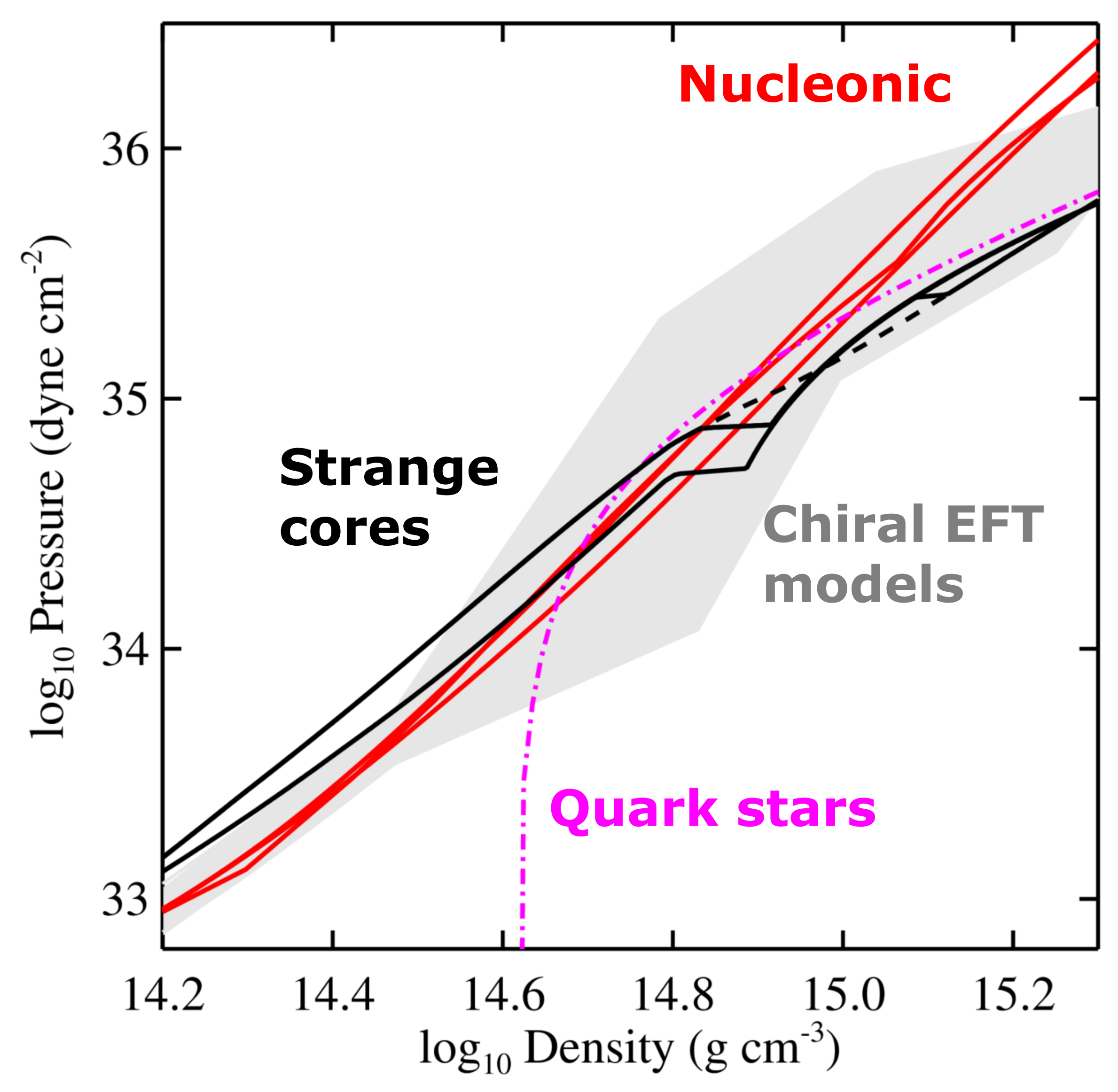


Distinct signature for:

- NS Radii > 6 R_g
- Inclinations > 60 deg

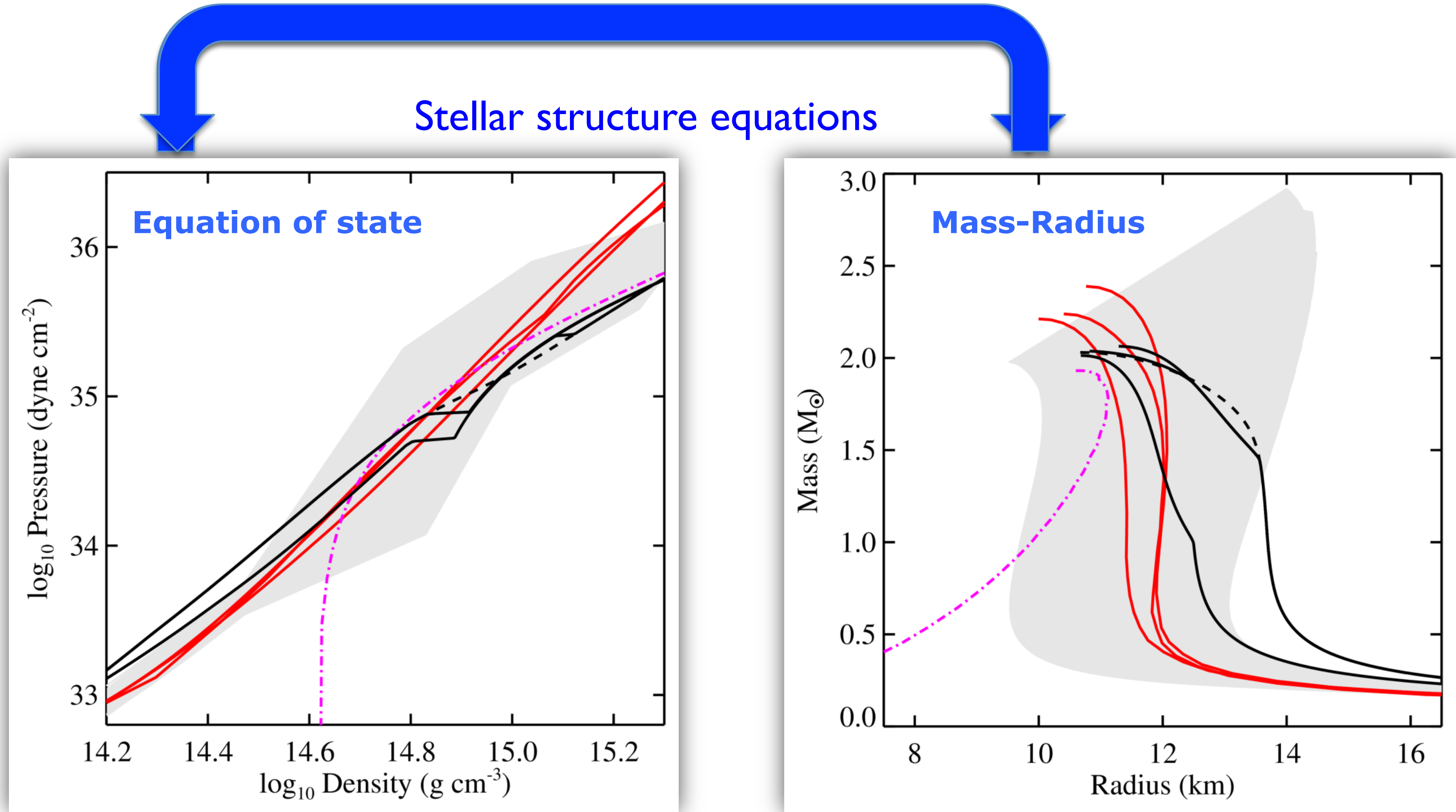
(La Placa, Bakala, Falanga et al.)

EOS: Equation of State of ultradense matter



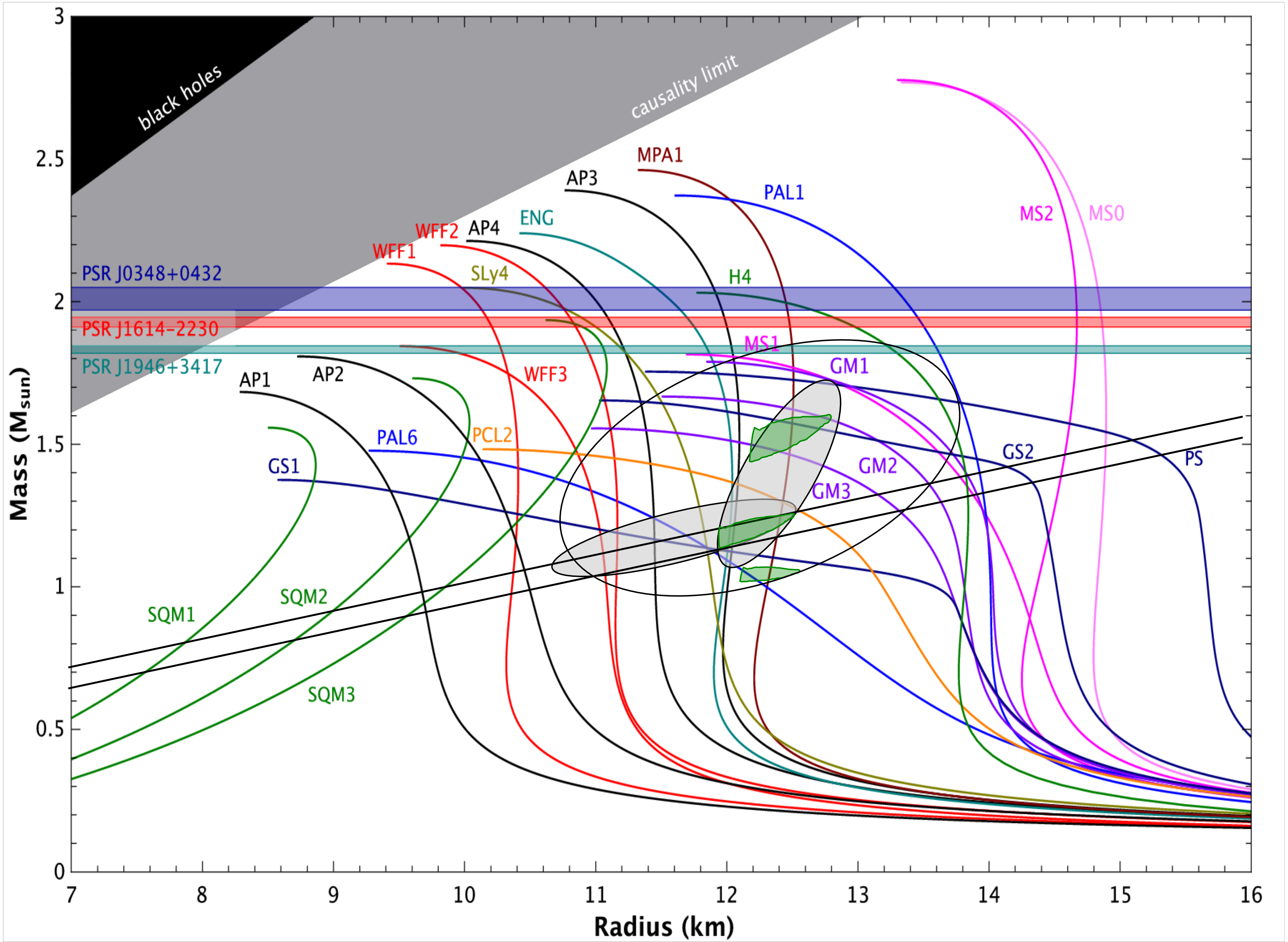
The strong force determines the 'stiffness' of neutron star matter.

This is encoded in the **Equation of State**.



MUST MEASURE **BOTH M AND R** TO **HIGH PRECISION**

NEUTRON STAR MASS-RADIUS RELATION



The corona contracts in a black-hole transient

E. Kara[1,2,3,4]*, J. F. Steiner[4], A. C. Fabian[5], E. M. Cackett[6], P. Uttley[7], R. A. Remillard[4], K. C. Gendreau[2], Z. Arzoumanian[2], D. Altamirano[8], S. Eikenberry[9,10], T. Enoto[11], J. Homan[12,13], J. Neilsen[14] & A. L. Stevens[15]

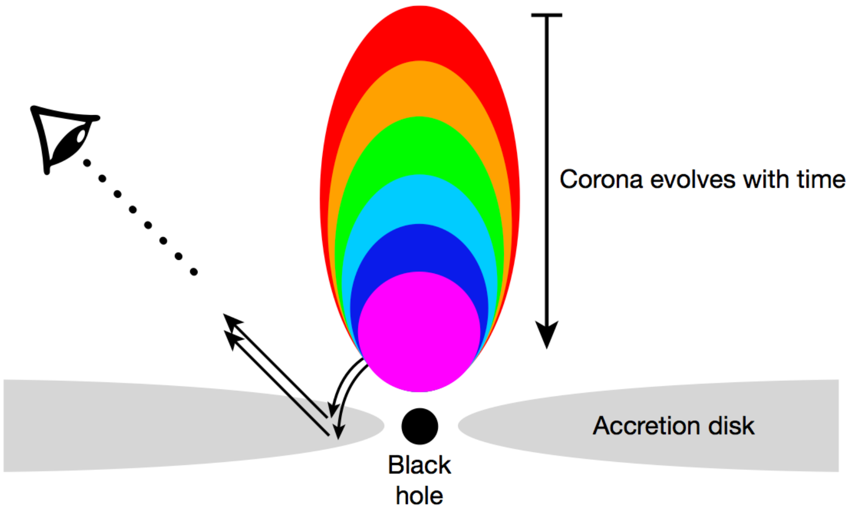


Fig. 4 | Schematic of the proposed geometry. Shown is a schematic of the proposed geometry, evolving from a vertically extended corona at early times to a more compact corona at late times. The corona has a static core at small radii that is responsible for most of the flux irradiating the disk, and the constant shape of the broad Fe line is due to this static core. As the corona decreases in vertical extent, the coronal variability timescale shortens, causing the shift in the thermal reverberation lag to higher frequencies. The decrease in vertical extent of the corona is also responsible for the decrease in the equivalent width of the narrow component of the Fe line at 6.4 keV.

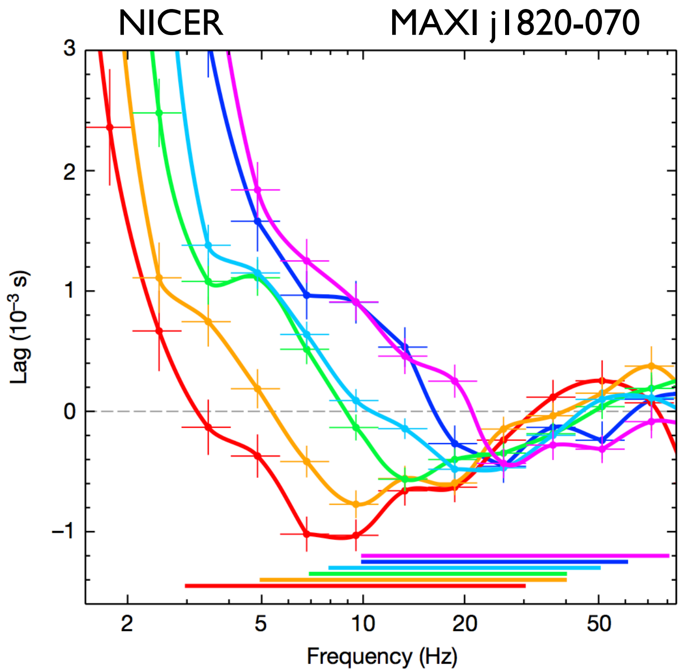
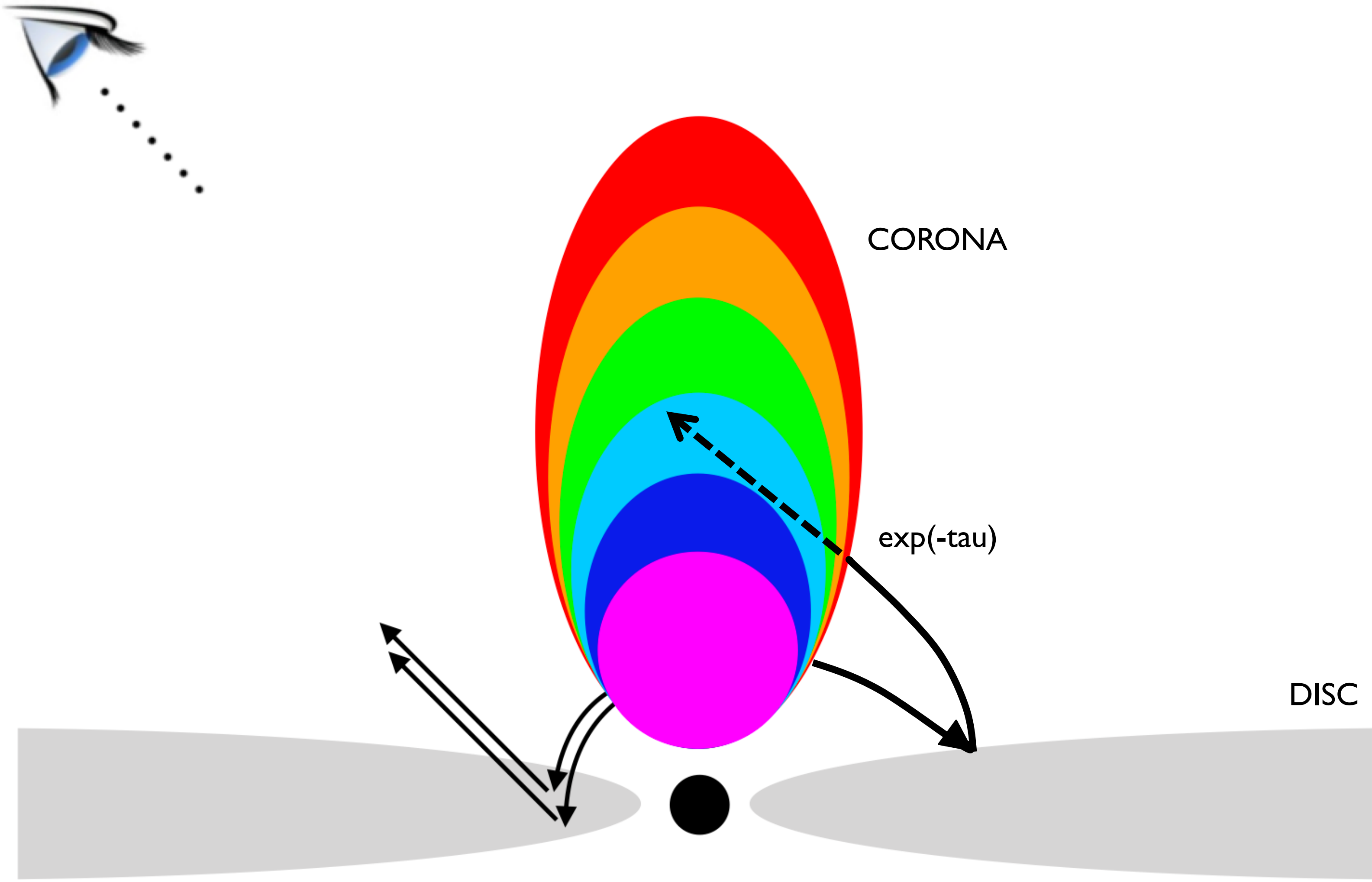


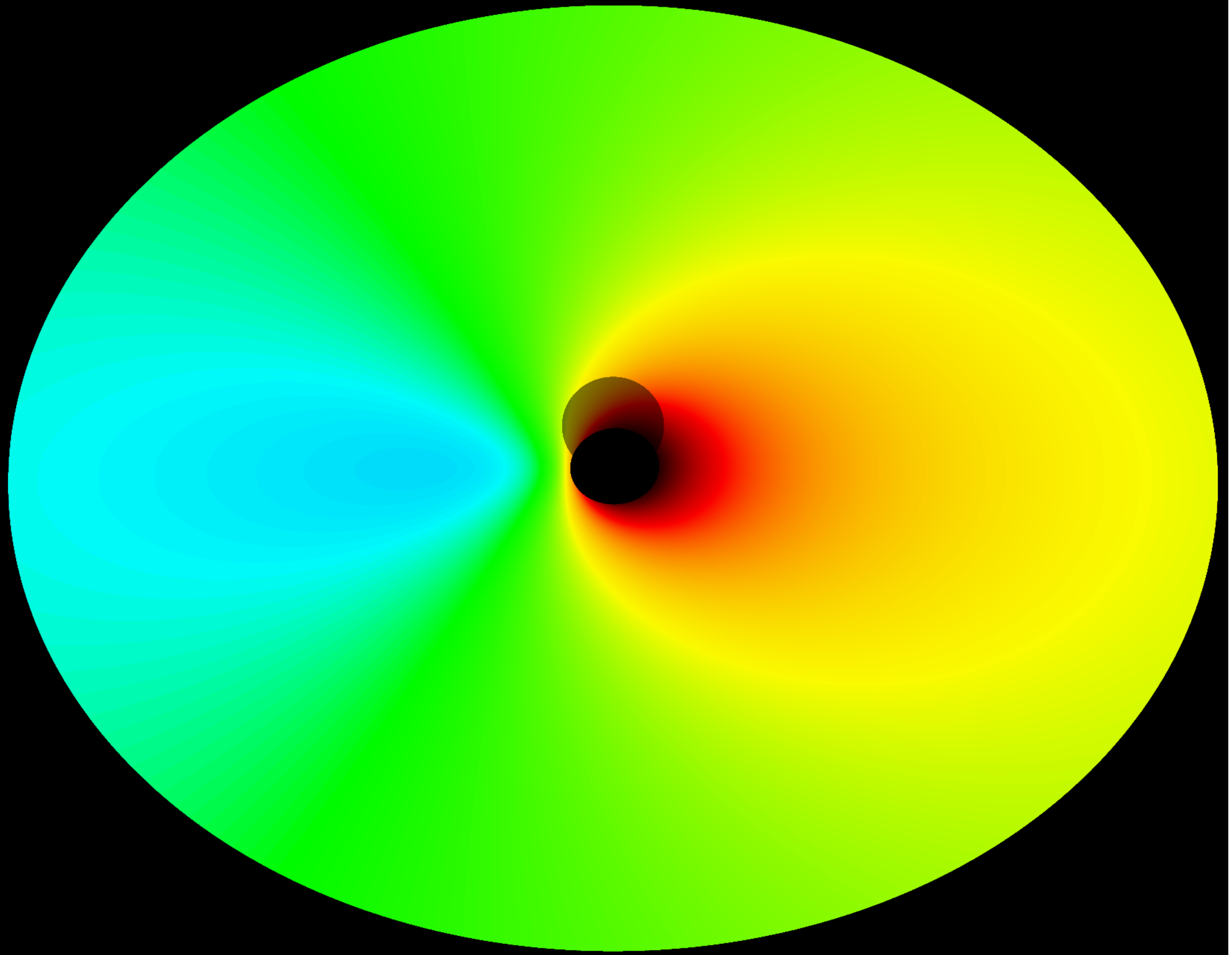
Fig. 2 | The evolution of the lag–frequency spectra. The evolution of the lag between 0.5–1 keV and 1–10 keV is shown as a function of temporal frequency for our six observation epochs. Colour-coding is as in Fig. 1. The points are connected with a Bezier join to guide the eye. A negative lag indicates that the soft band follows behind the hard band. The soft lag evolves to higher frequencies with time. The solid lines on the bottom portion of the figure indicate the frequencies used in the lag–energy analysis (Fig. 3). Vertical error bars indicate 1σ confidence intervals and horizontal error bars indicate the frequency binning.

OBSCURATION BY CORONA

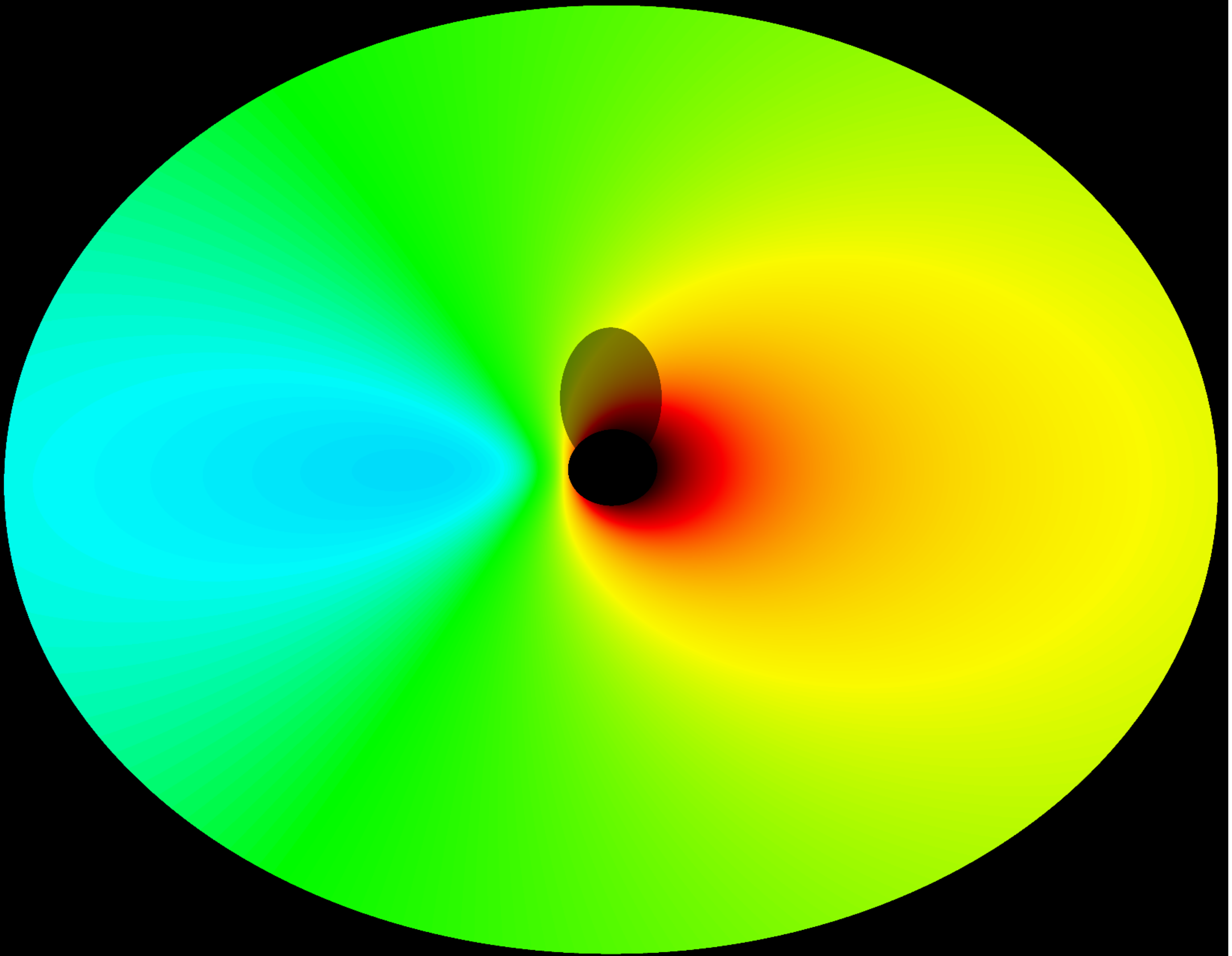


(adapted from Kara+18)

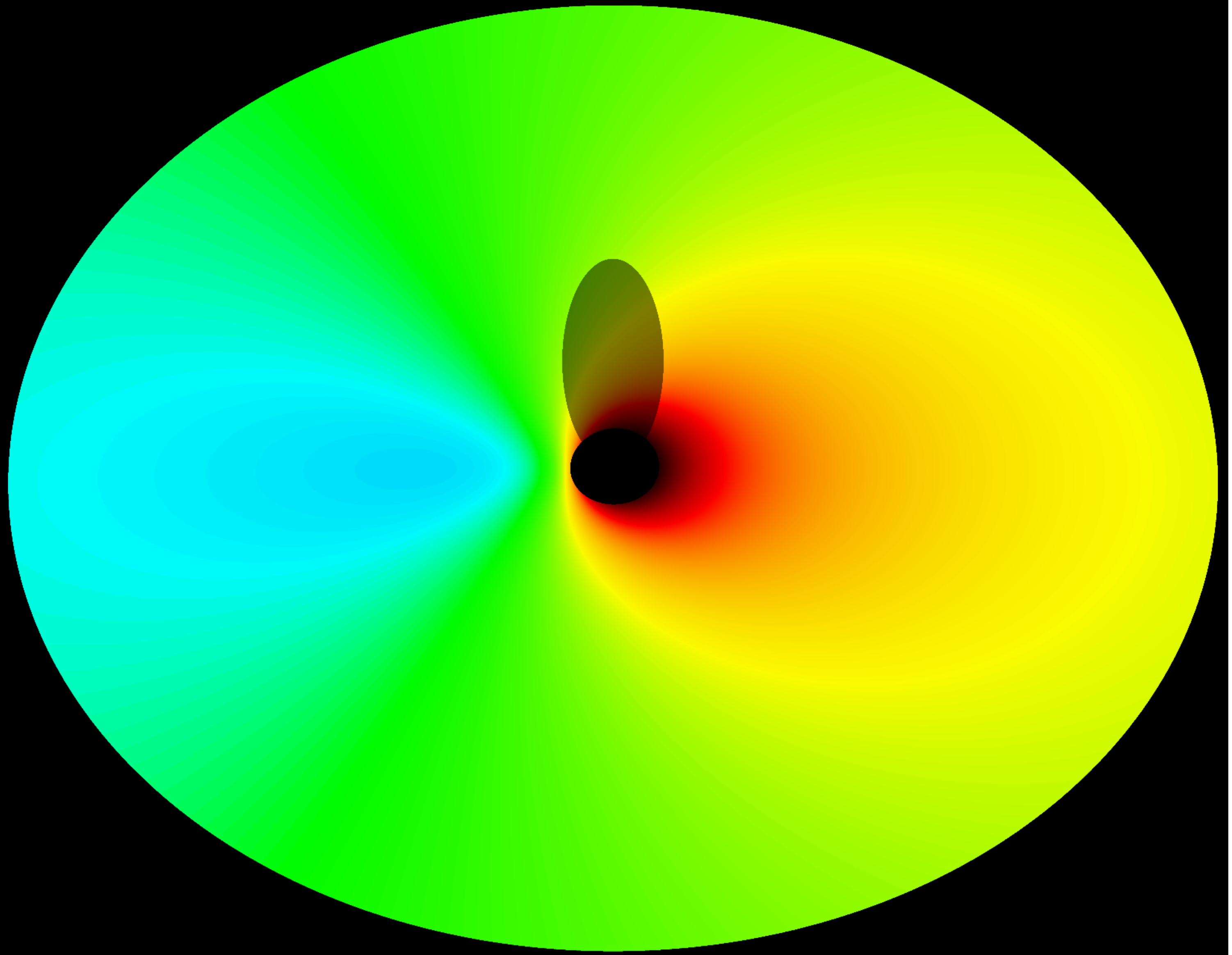
Ellipsoidal geometry



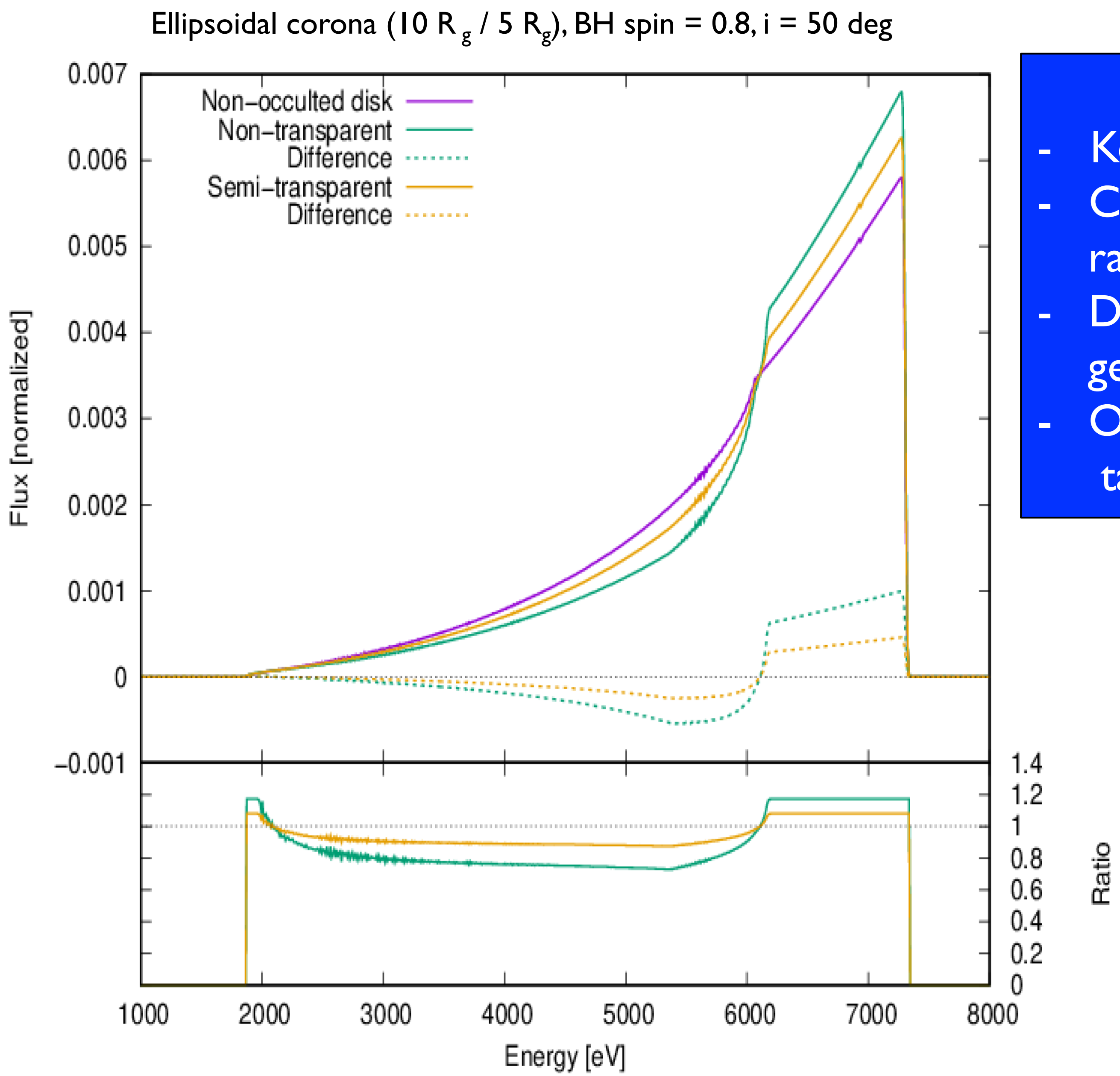
Ellipsoidal geometry



Ellipsoidal geometry



FE-LINE PROFILE OBSCURED BY CORONA



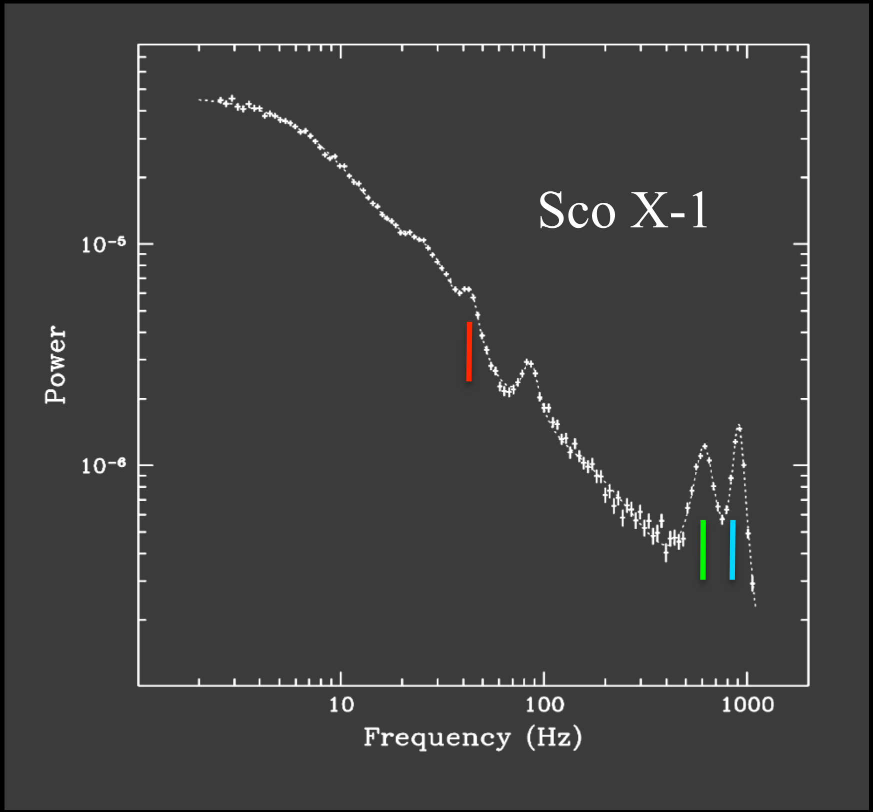
MODEL

- Kerr metric
- CPU intensive ray-tracing approach
- Different coronal geometries explored
- Optical depths: tau = 0.7 (50%

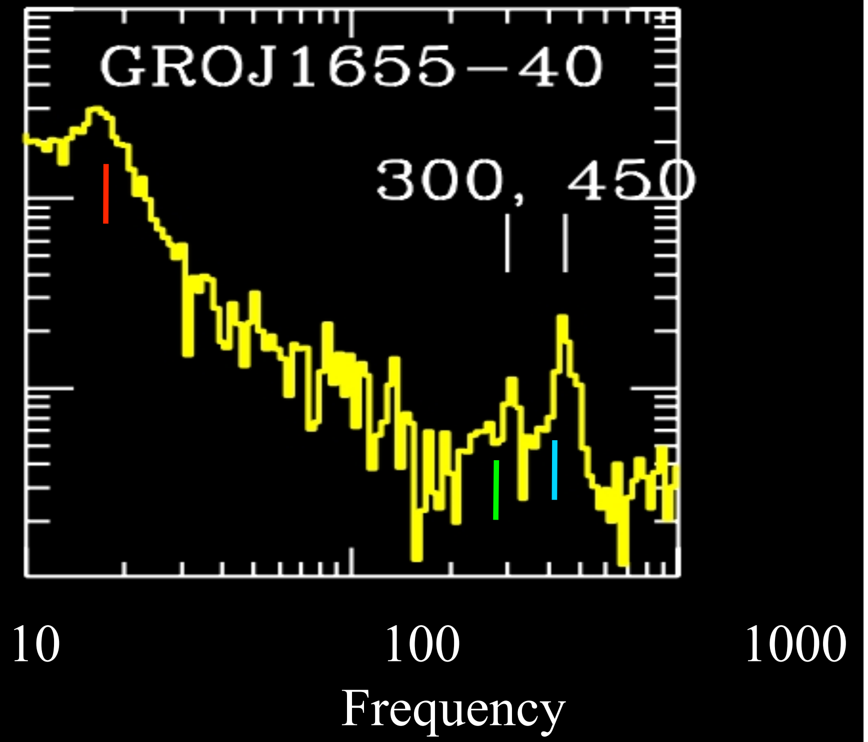
Bakala, La Placa et al.

Strong Field Diagnostic: X-ray Fast variability and Quasi Periodic Oscillations

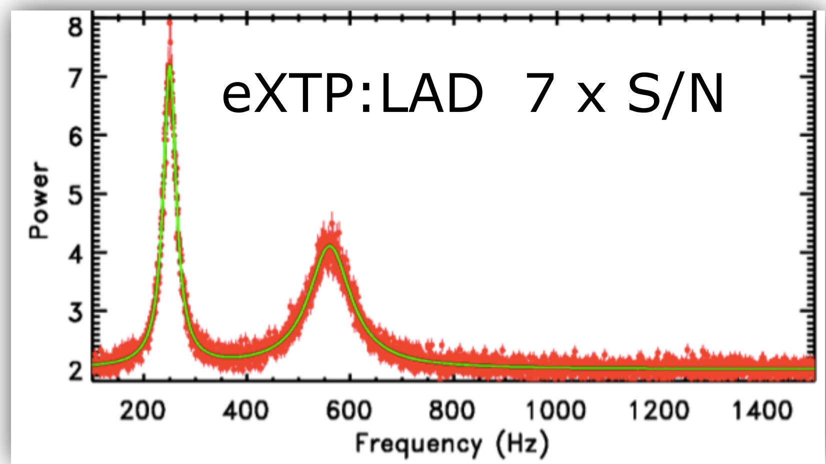
Accreting neutron stars



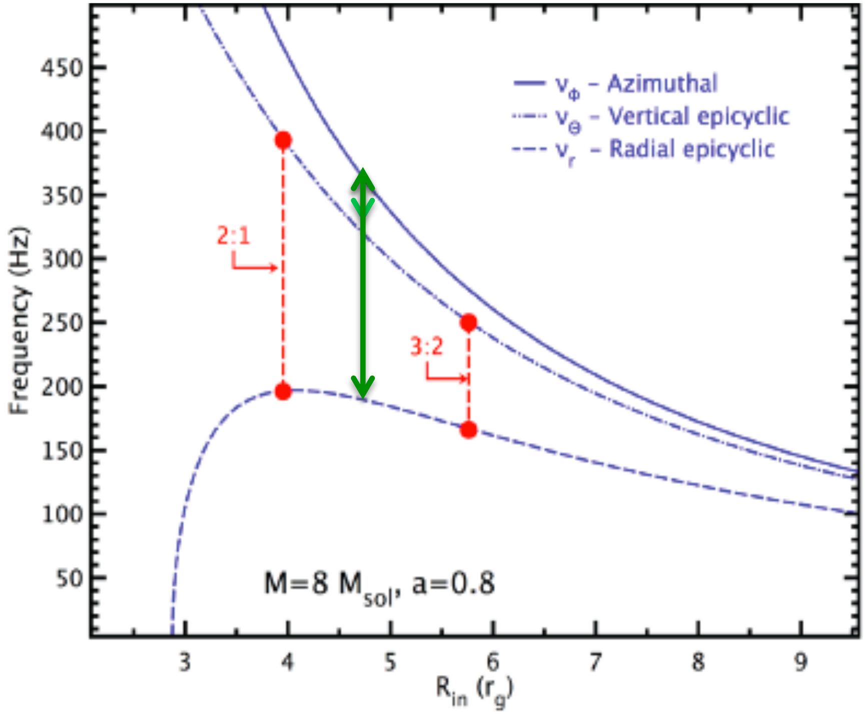
Accreting black hole candidates



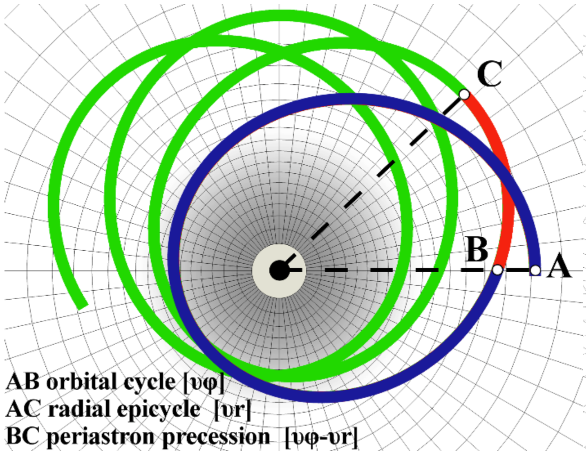
Frequencies of motion in strong gravity

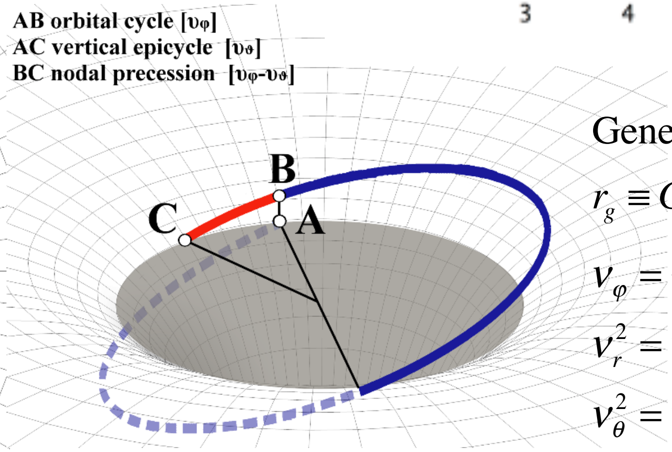


- Epicyclic Resonance (fixed r)
- Relativistic Precession: nodal and periastron



GR orbital, epicyclic and precessional frequ





General relativity:

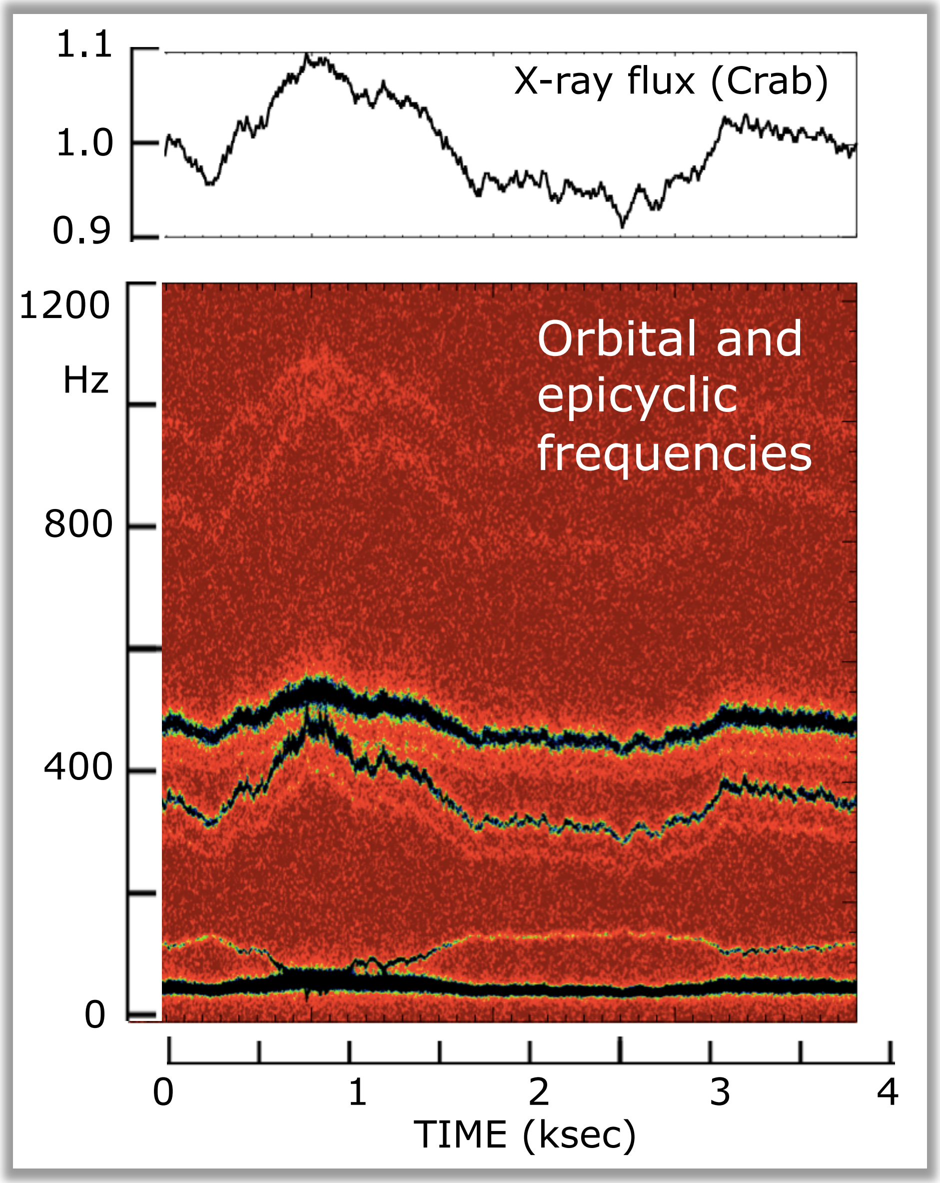
$$r_g \equiv GM/c^2 \qquad j \equiv Jc/GM^2$$

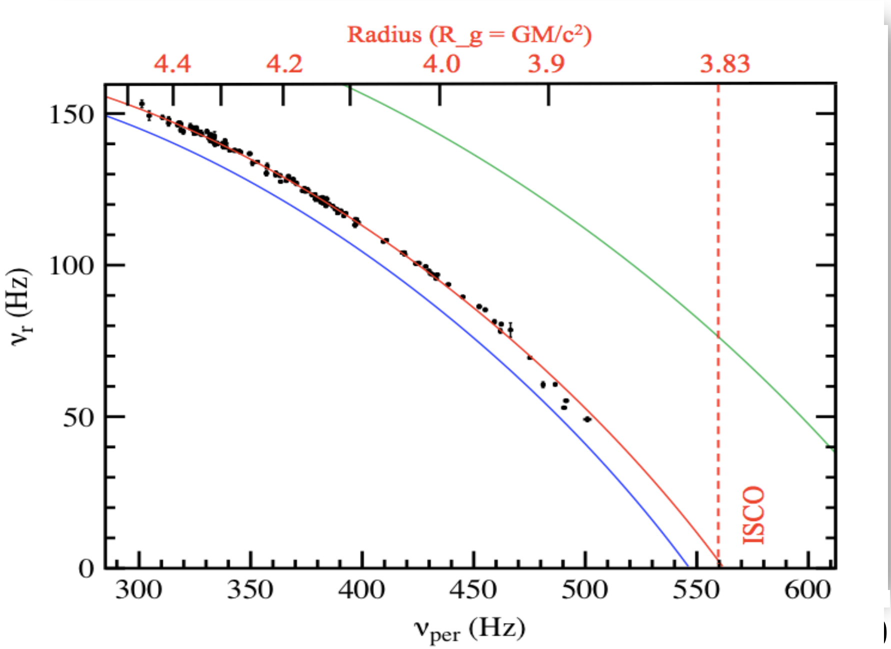
$$\nu_\varphi = \sqrt{GM/r^3}\,/\,2\pi(1 + j(r_g/r)^{3/2})$$

$$\nu_r^2 = \nu_\varphi^2(1 - 6(r_g/r) + 8j(r_g/r)^{3/2} - 3j^2(r_g/r)^2)$$

$$\nu_\theta^2 = \nu_\varphi^2(1 - 4j(r_g/r)^{3/2} + 3j^2(r_g/r)^2)$$

Timing diagnostics: relativistic epicyclic motion





- Precisely measure orbital and epicyclic frequencies at each radius
- Compare to GR predictions
- Measure black hole mass and spin to < 0.3 % precision

X-ray diagnostics of extreme gravity in the vicinity of neutron stars and black holes

- Relativistic Fe-lines
- Quasi-Periodic Oscillations

- Polarisation
- Multicolor blackbody disk emission
- Extreme gravitational lensing