Strong gravity with IXO:

Mariano Méndez

Kapteyn Astronomical Institute, University of Groningen, The Netherlands

with contributions from:

Dimitrios Psaltis
Didier Barret
Sudip Bhattacharyya

Strong gravitational fields

Equivalence principle: Relation between gravitational acceleration and space-time geometry.

Equivalence principle has been confirmed to an accuracy of about one part in 10^{12}.

(Notice, by the way, that the equivalence principle has only been tested in the weak-field limit.)

Strong gravitational fields

Einstein equations are not the only ones that satisfy the equivalence principle. They are the ones that follow from the simplest action (the Einstein-Hilbert action) consistent with the equivalence principle.

Equations derived from more complicated actions are still possible, and would not violate the Eq. principle.

Strong gravitational fields

So, what is a strong field?

From Schwarzschild space-time, the natural scale to measure the gravitational potential is:

$$\epsilon = \frac{GM}{c^2 r}$$

which is also related to the gravitational redshift.

Strong gravitational fields

Einstein equations are written in terms of quantities (e.g., the Ricci tensor) that measure the curvature of space-time. One measure of curvature (derived from the Ricci scalar) is:

$$\xi = \frac{GM}{c^2 r^3}$$

Strong gravitational fields

Deviations of GR in the Solar-System ≈ 10^{-5}. But:

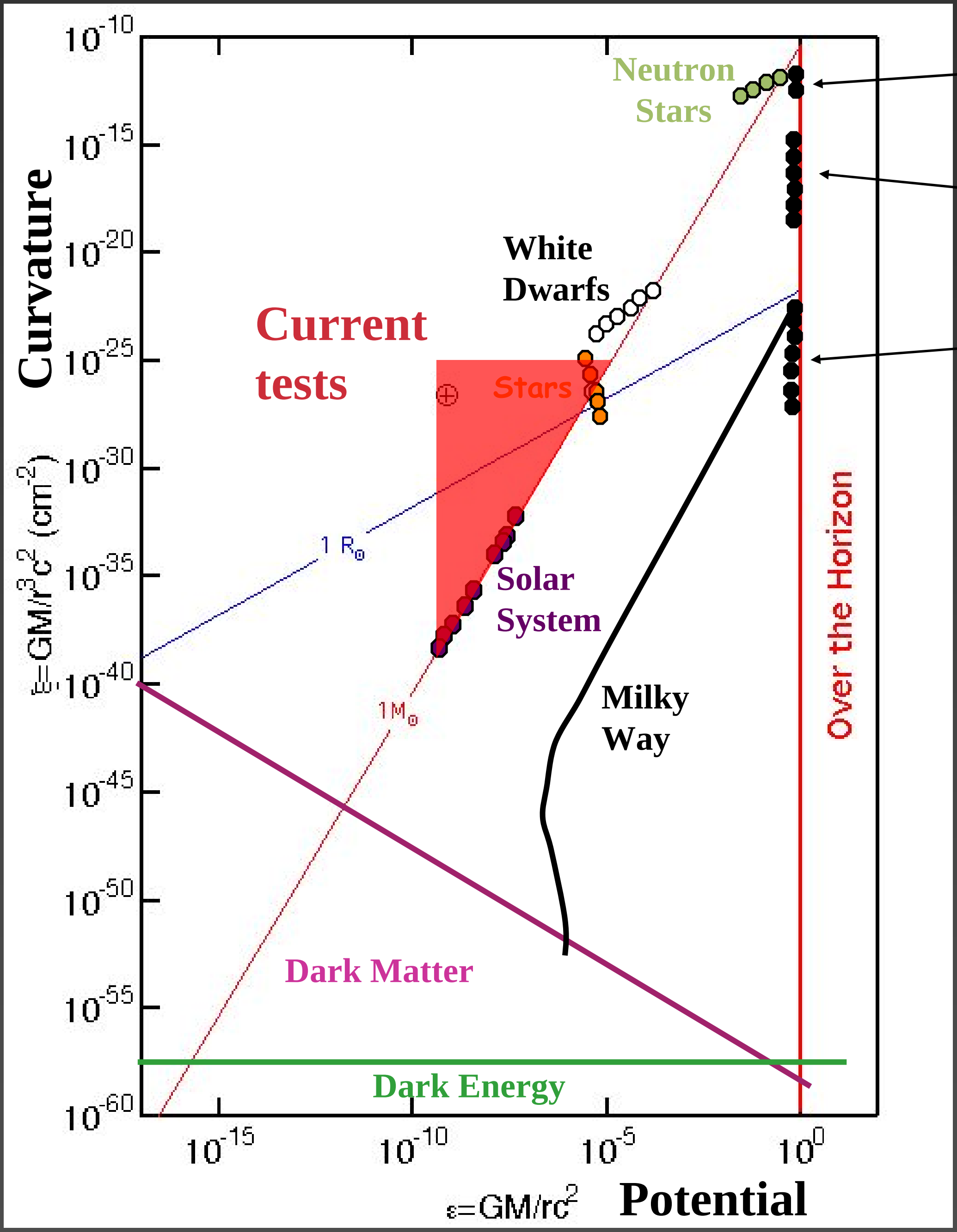
$$\epsilon = \frac{GM_\odot}{c^2 R_\odot} \approx 2 \times 10^{-6}$$

$$\xi = \frac{GM_\odot}{c^2 R_\odot^3} \approx 4 \times 10^{-28} \ \ \mathrm{cm}^{-2}$$

Whereas close to a neutron star or a black hole

$$\epsilon \approx 1$$

$$\xi \approx 2 \times 10^{-13} \ \ \mathrm{cm}^{-2}$$



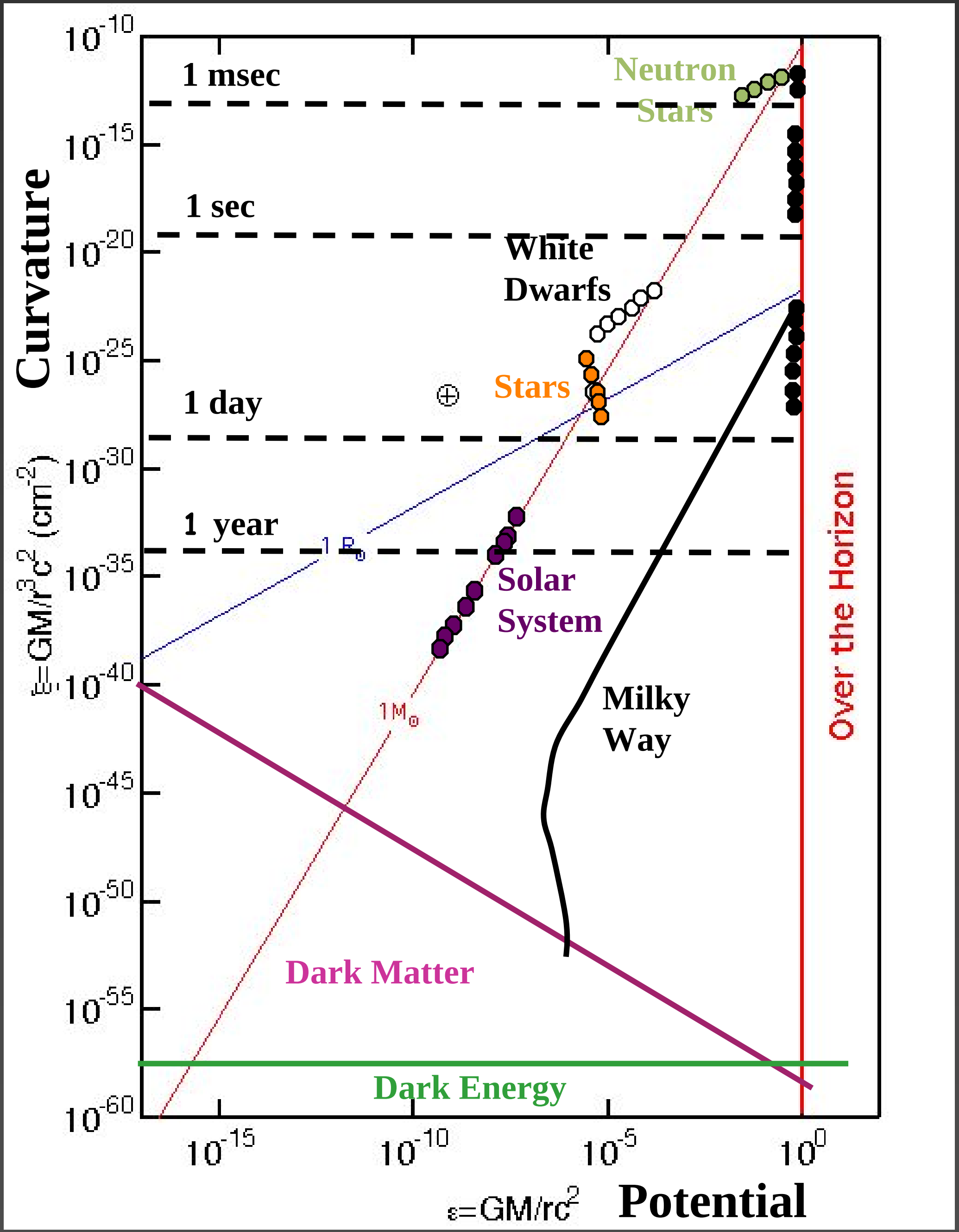
Black Holes in X-ray Binaries

Intermediate Mass Black-Holes

Active Galactic Nuclei

Gravitational Fields In Astrophysical Systems

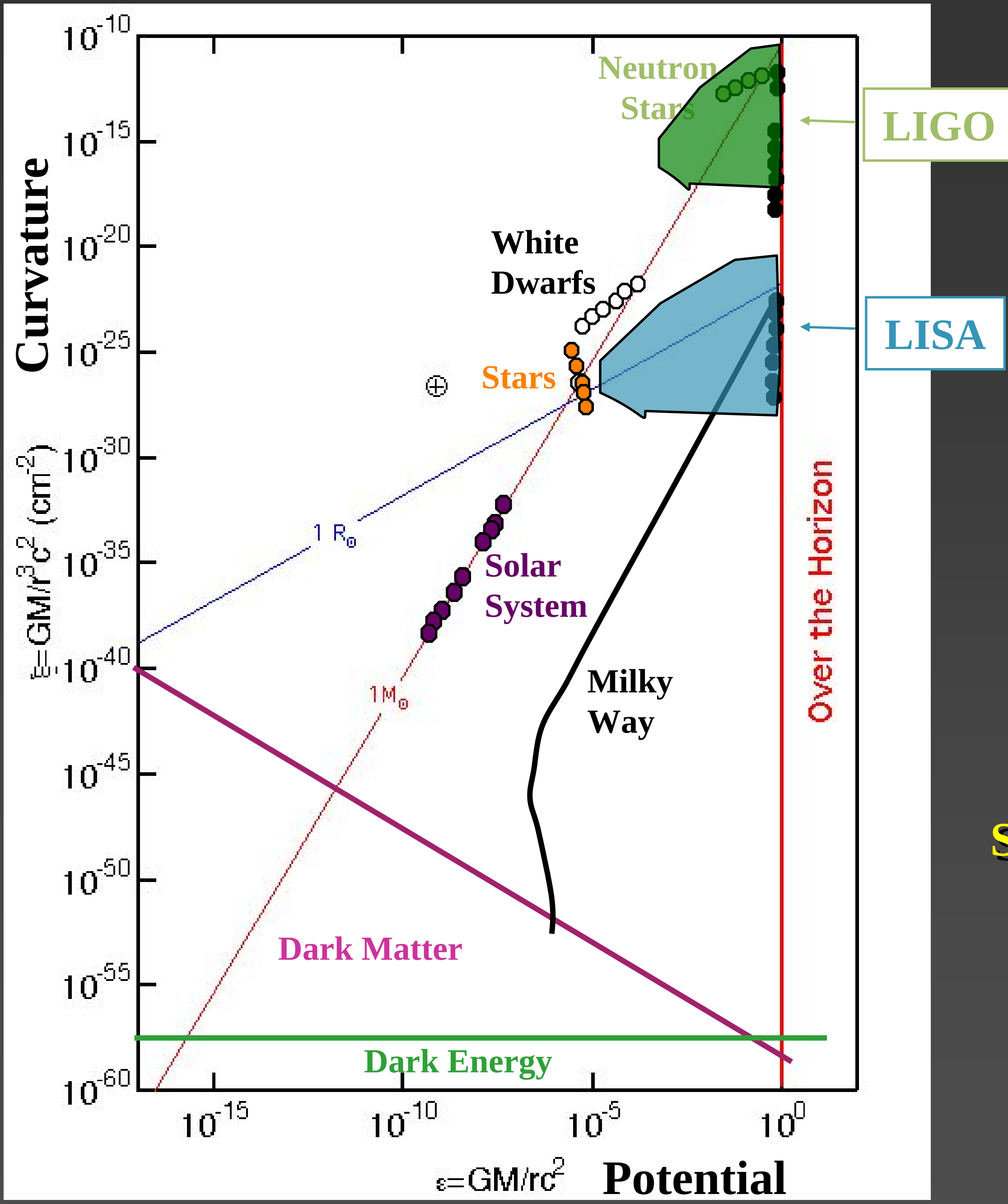
Psaltis (2008)



Fast X-ray timing!

How to Probe the Strong Gravitational Fields

Psaltis (2008)



Fast X-ray timing!

High-Frequency Gravity Waves (e.g., LIGO, GEO600)

How to Probe the Strong Gravitational Fields

Psaltis (2008)

NS and strong gravitational fields

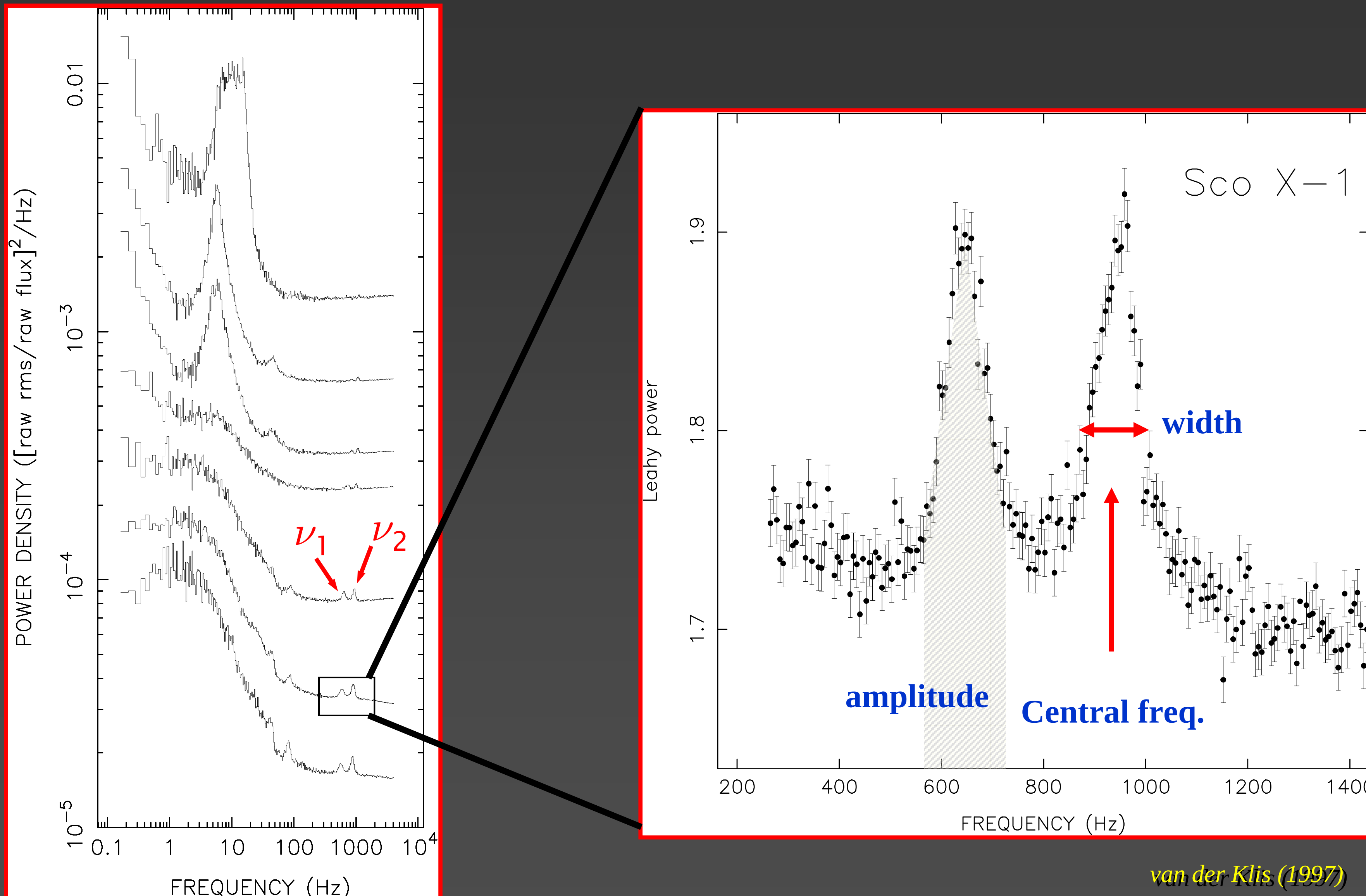
1. Kilohertz Quasi-Periodic Oscillations (kHz QPOs) as basic General Relativistic (GR) frequencies.

2. kHz QPOs and the Innermost Stable Circular Orbit (ISCO).

3. Surface (absorption) lines.

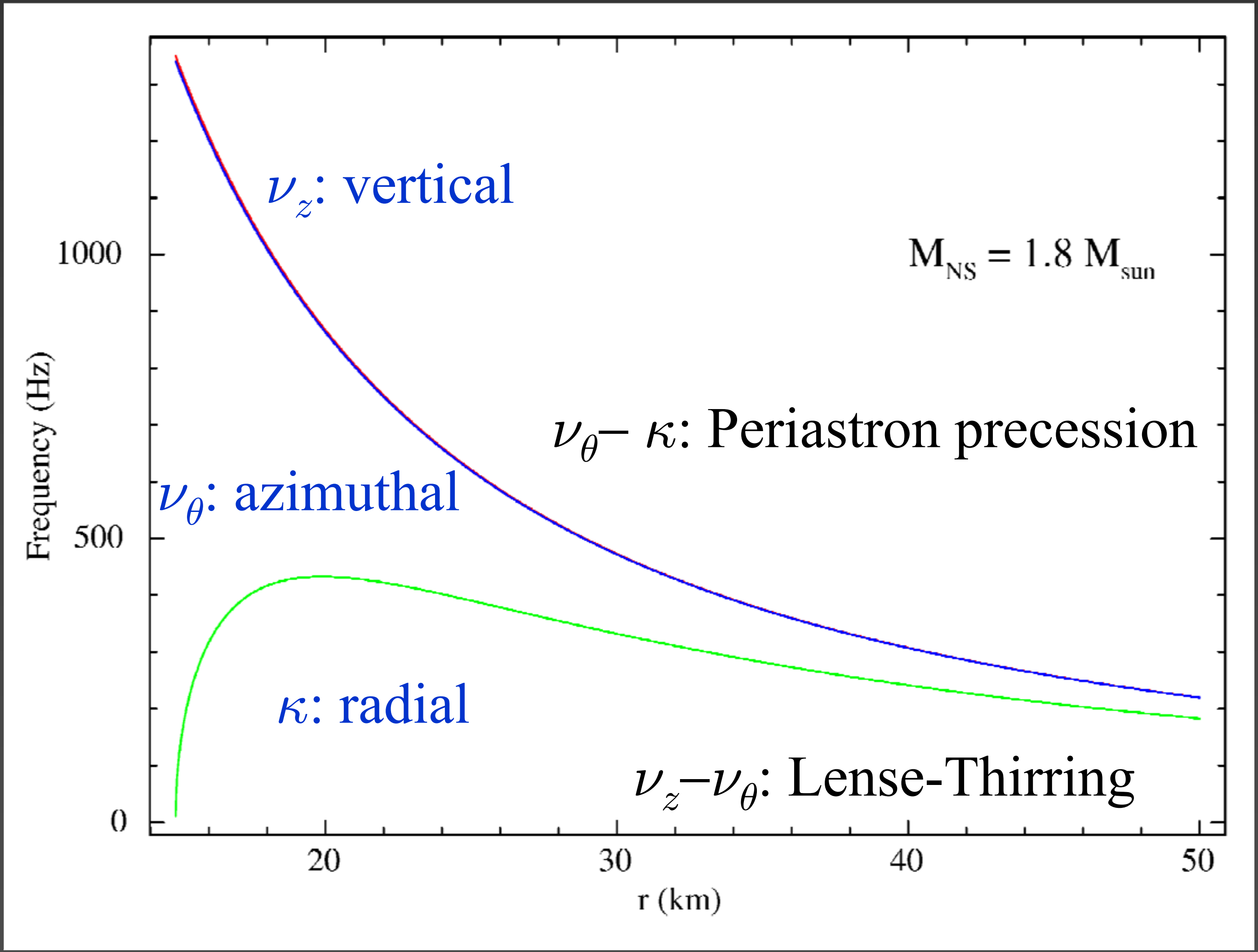
4. Emission lines from the inner accretion disc.

Strong gravitational field: kHz QPOs



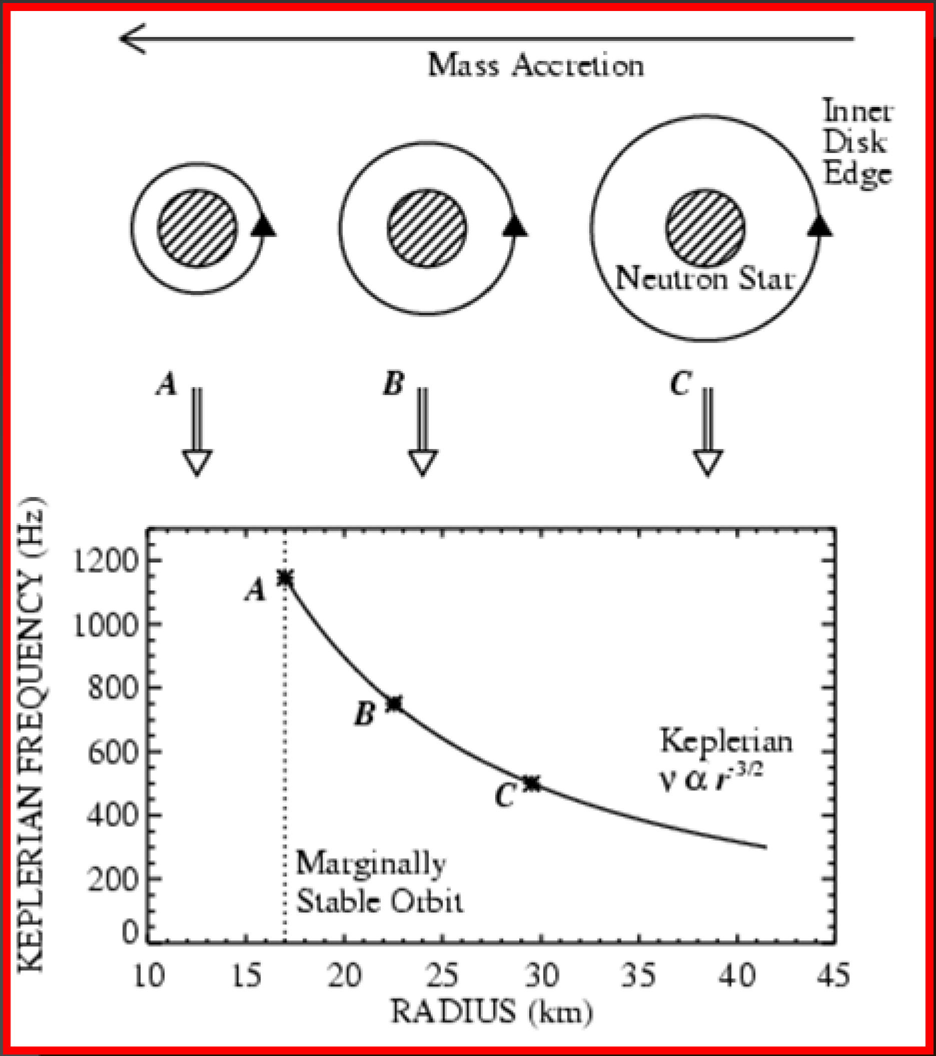
van der Klis (1997)

1. The 3 basic GR frequencies



Stella & Vietri (1999)

2. The ISCO

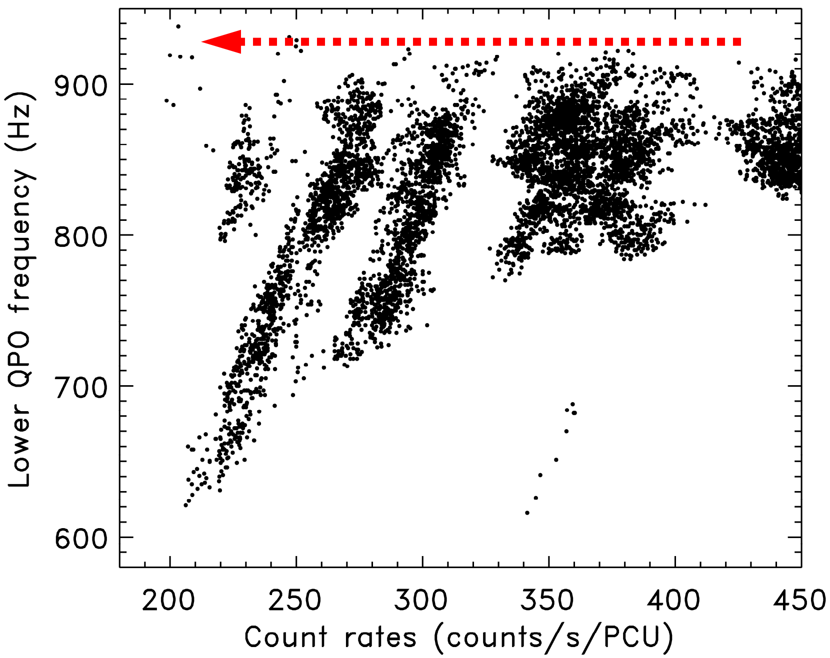


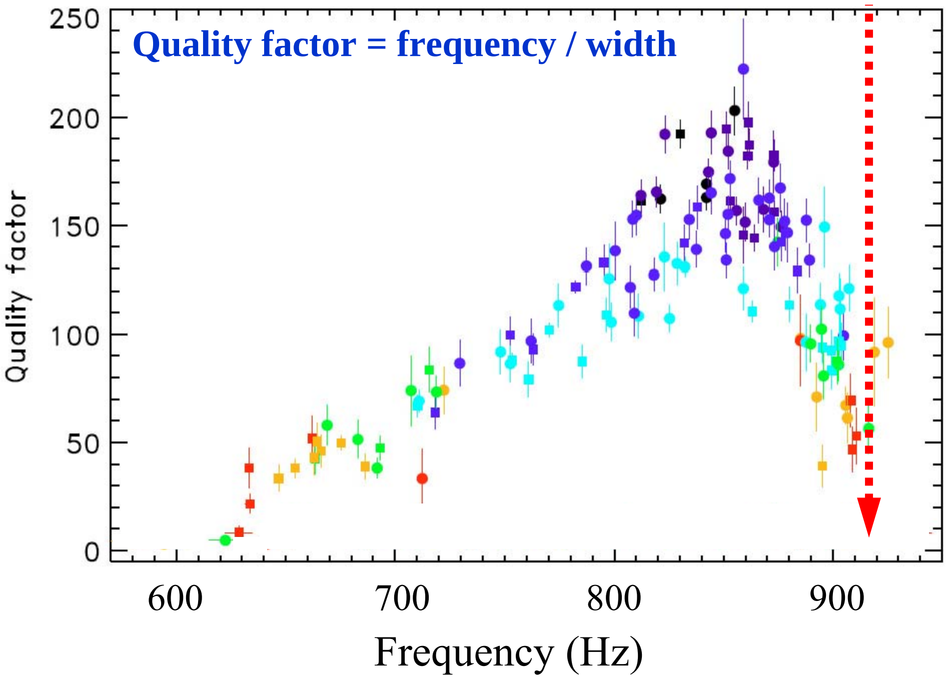
As the inner edge of the disc moves inwards, driven by mass accretion rate, the azimuthal frequency at that radial position in the disc increases.

Maximum orbital frequency is the Keplerian frequency at the ISCO.

Miller Lamb & Psaltis (1998)

2. The ISCO





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Barret et al. (2006)

kHz QPOs: Some details

1. No unique identification of QPOs with the basic GR (or other) frequencies → Possible solution: Simultaneous timing and spectroscopy (see below).

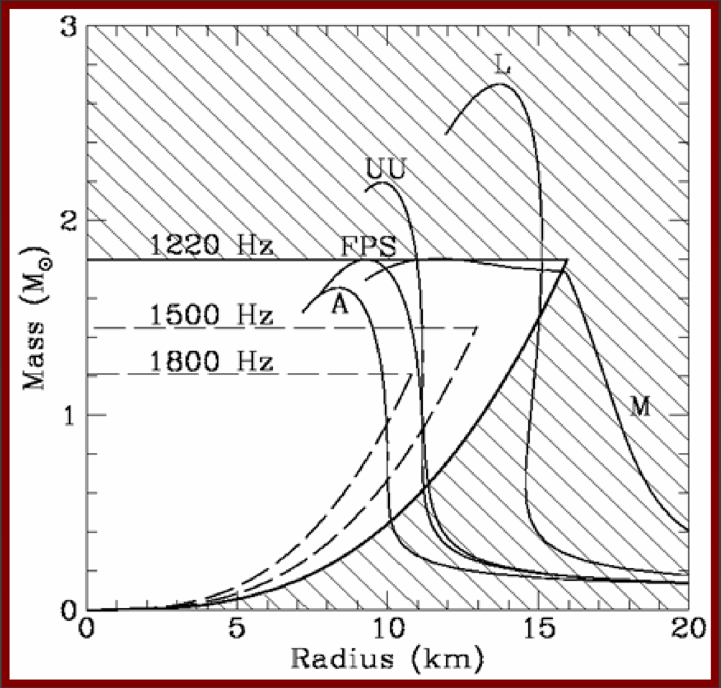
2. Identification of the ISCO requires that:

   - From pair of QPOs, the one at higher frequencies is the Keplerian (vertical) GR frequency (most, but not all, models propose this), and

   - Keplerian (vertical) frequency is the highest frequency in the disc. True for test particles; super-Keplerian frequencies may appear in real discs.

Disc orbital-frequency interpretation

- In most models, highest kHz QPO interpreted as orbital frequency at inner edge of the Keplerian disk
- If true, this immediately constrains neutron star mass and radius.



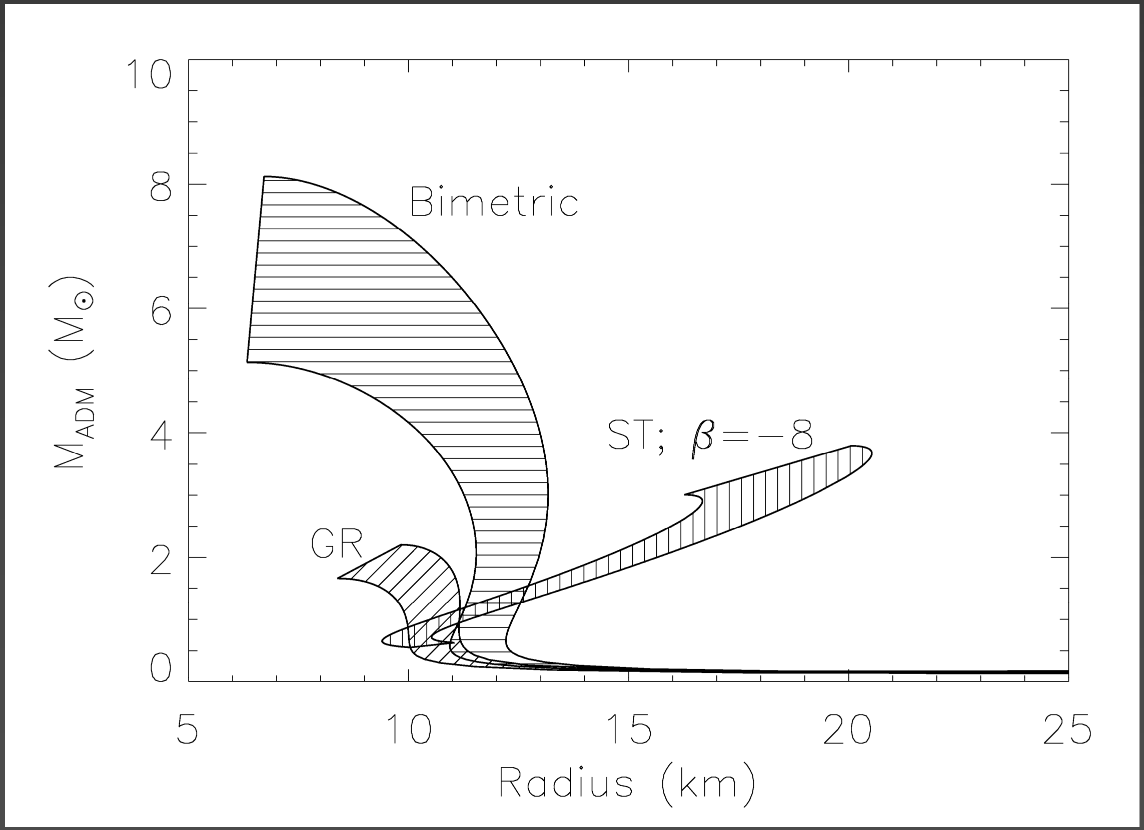
- QPOs vary in frequency, but remain always below ~1.3 kHz (not a matter of sensitivity).
- An ISCO frequency of 1.3 kHz corresponds to a ~2 M_{sun} neutron star.

Miller Lamb & Psaltis (1998)

3. Surface (absorption) lines

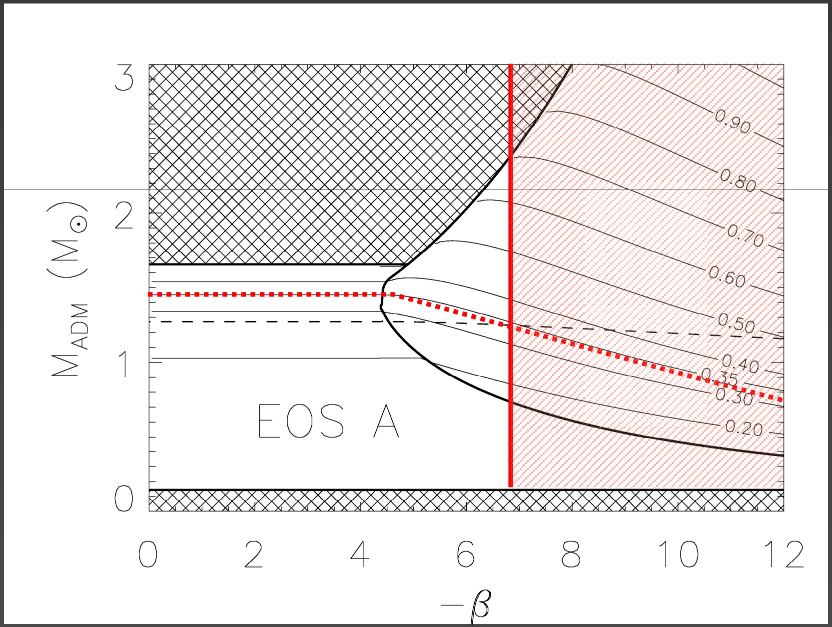
Scalar-Tensor extensions to Einstein's theory → Extra scalar field described in terms of the parameter β.

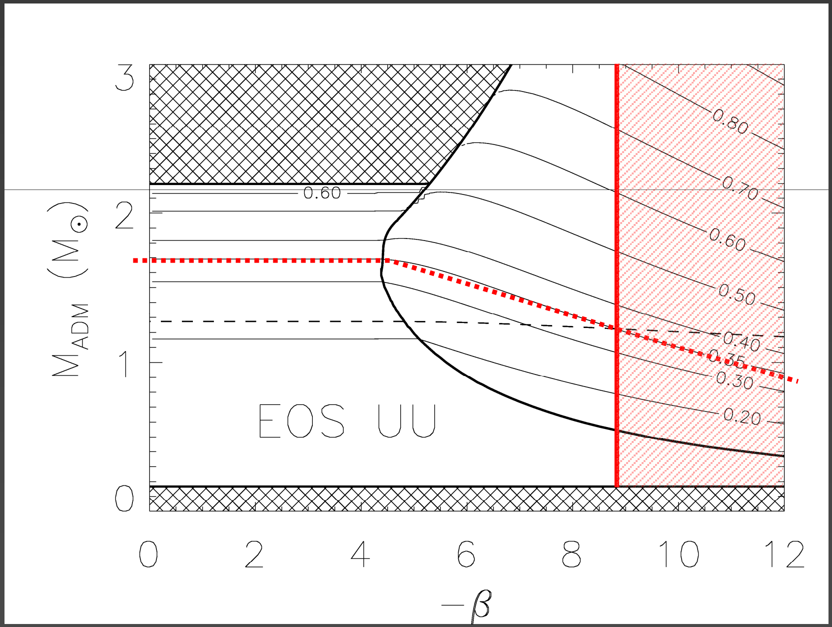
From binary-pulsar timing $\beta \geq -8$.



Dedeo & Psaltis (2003)

Gravitational redshift



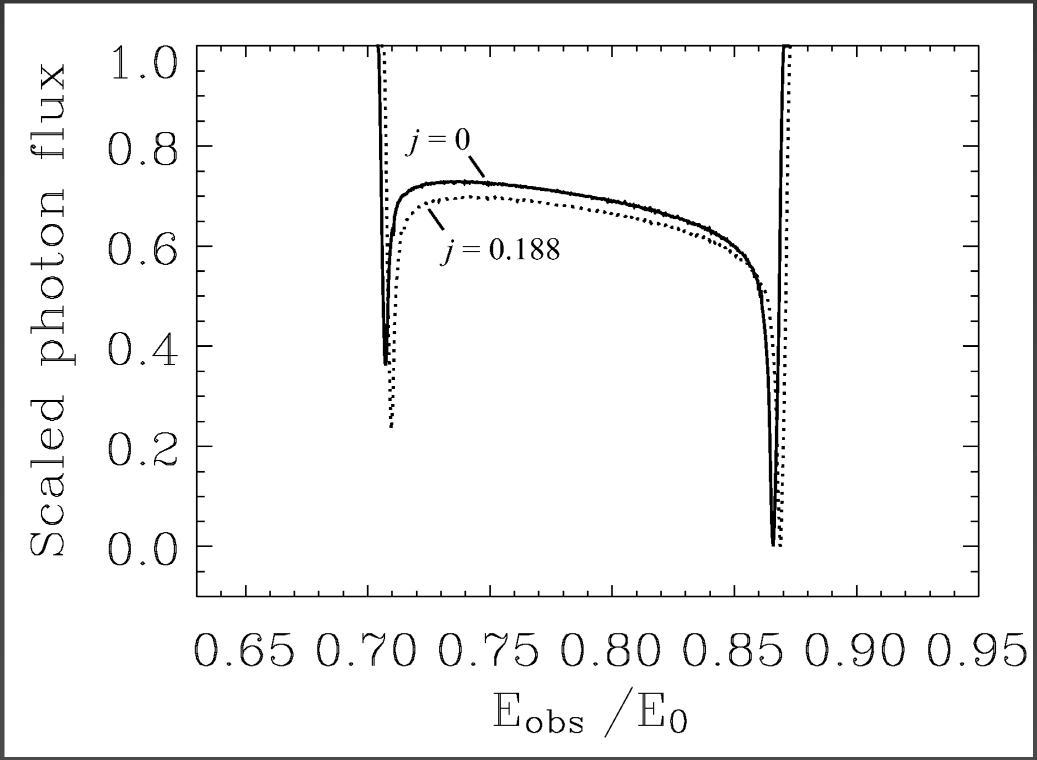


Dedeo & Psaltis (2003)

Line profiles

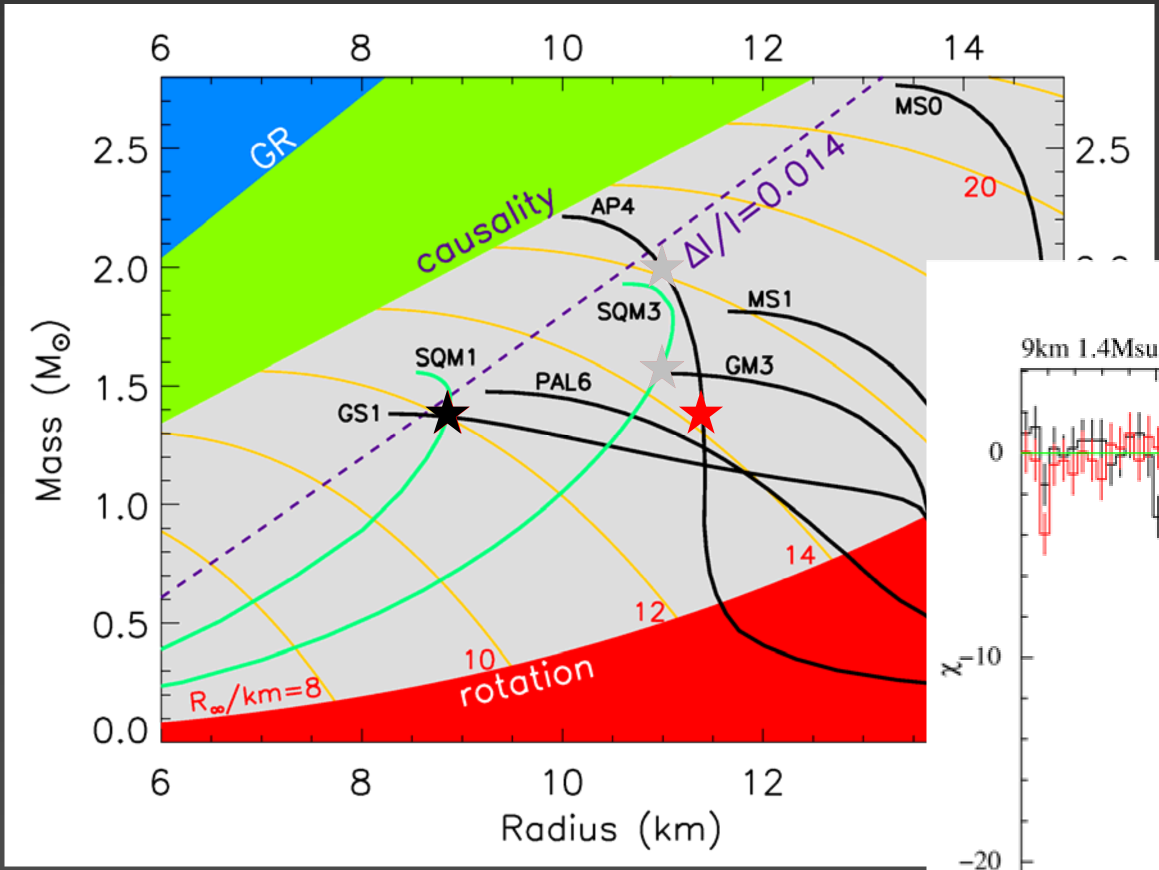
Surface absorption lines are broadened du to:

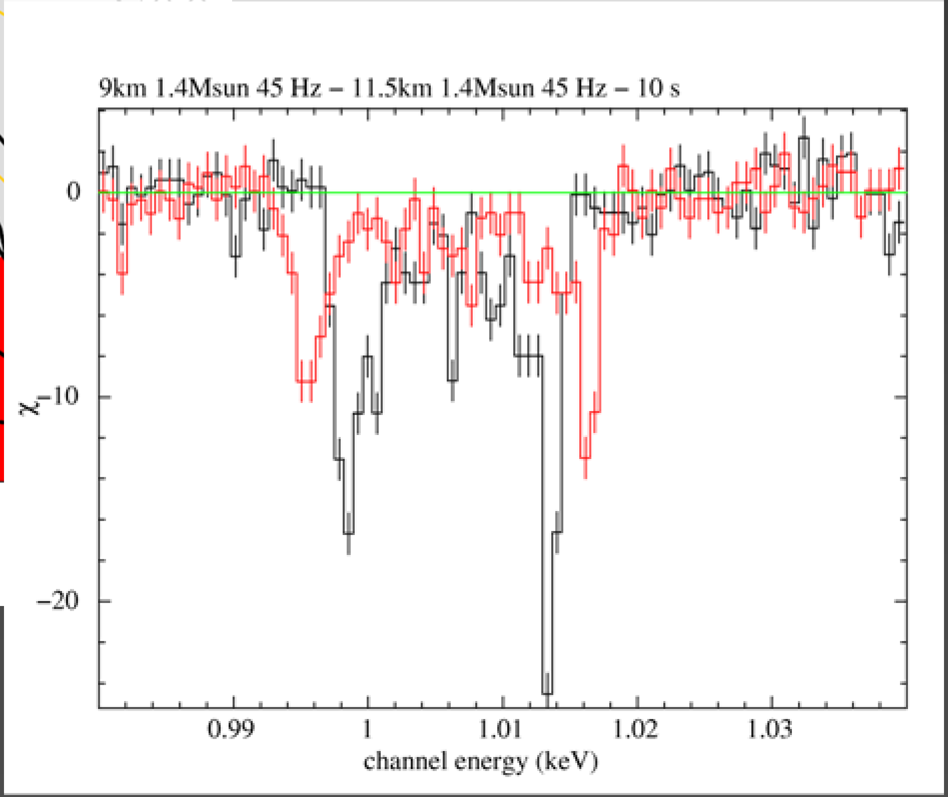
- longitudinal and transverse Doppler shifts,
- special relativistic beaming,
- gravitational redshifts,
- light-bending,
- ***frame-dragging (Lense-Thirring).***



Bhattacharyya et al. (2006)

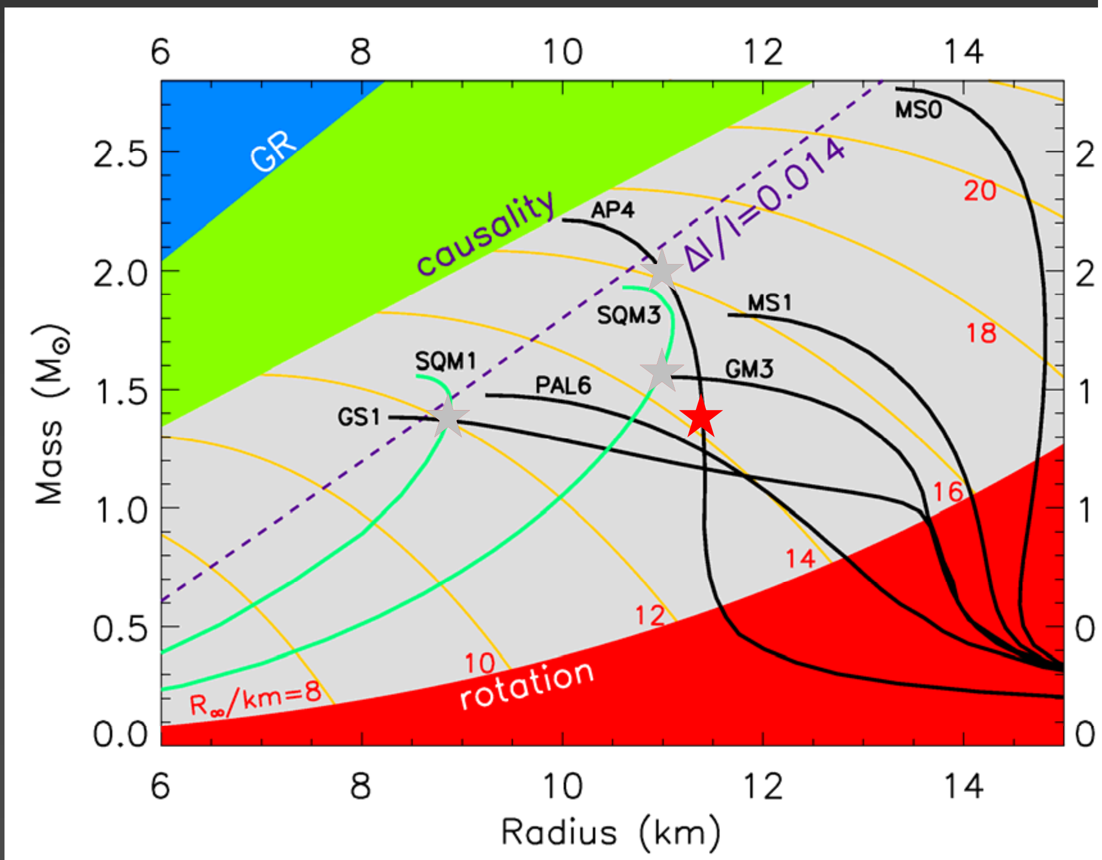
Spectral line profile: XEUS simulation

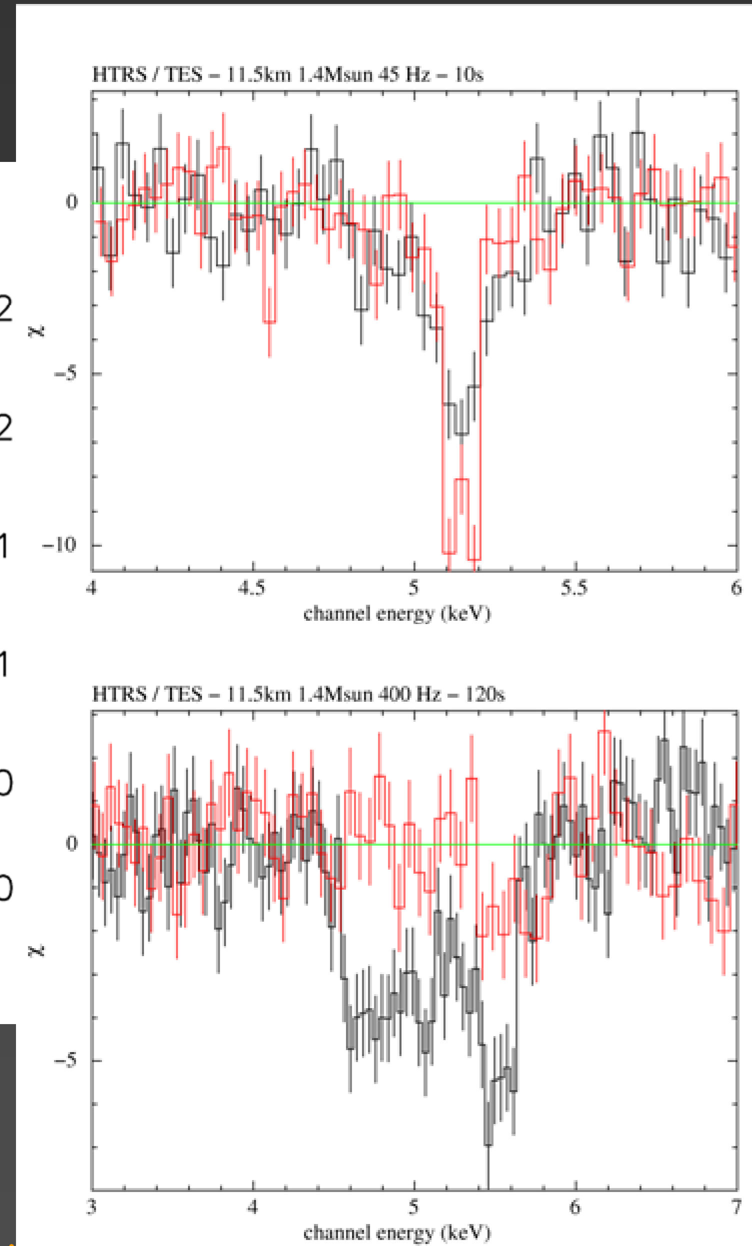




Line profile calculations courtesy of S. Bhattacharyya

Spectral line profile: XEUS simulation





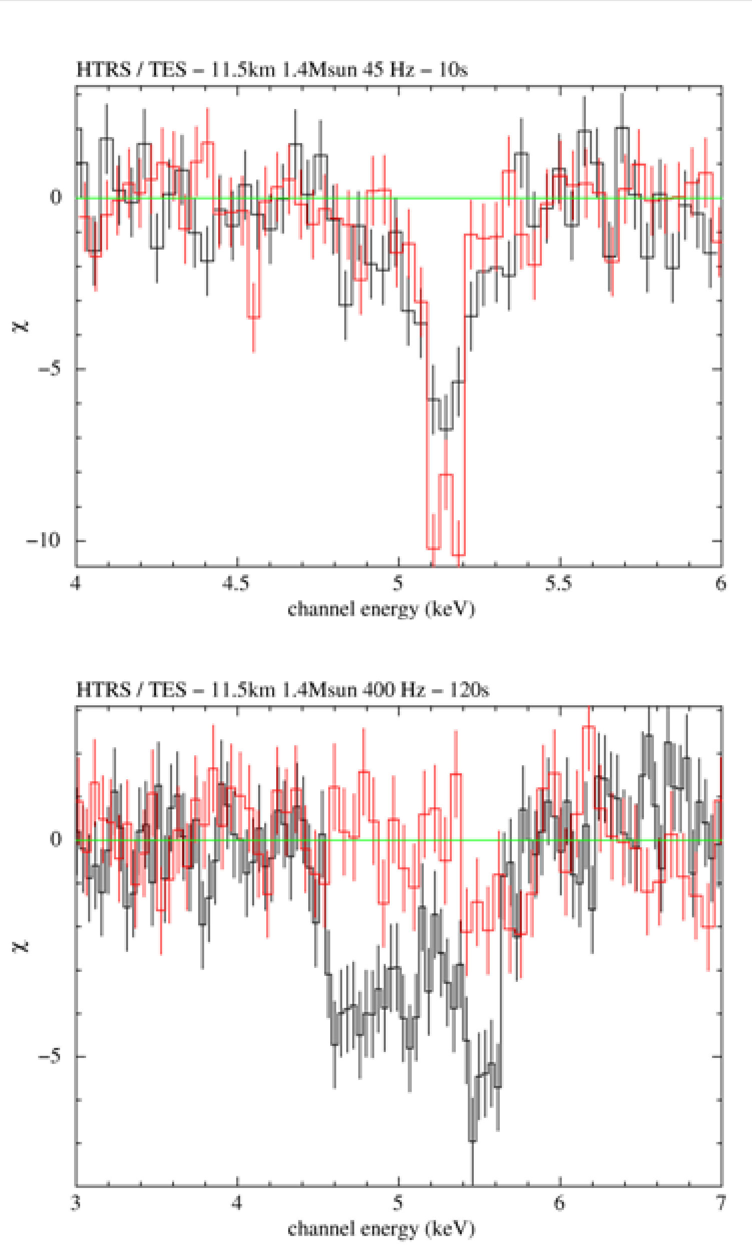
Spectral line profile: XEUS simulation

- Average count rate ~8000 c/s in 120 s

- A factor of 5 – 10 higher during the brightest parts of the burst

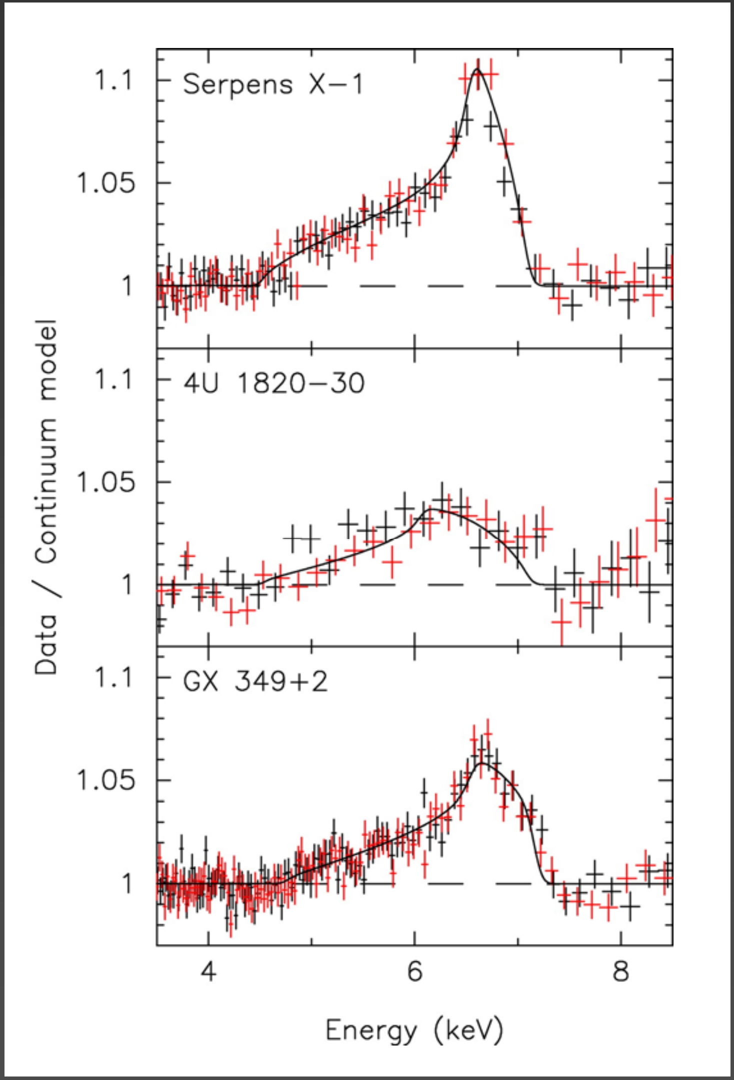
- The average flux is 30 mCrab

- Typical bursters ~1 Crab at the peak

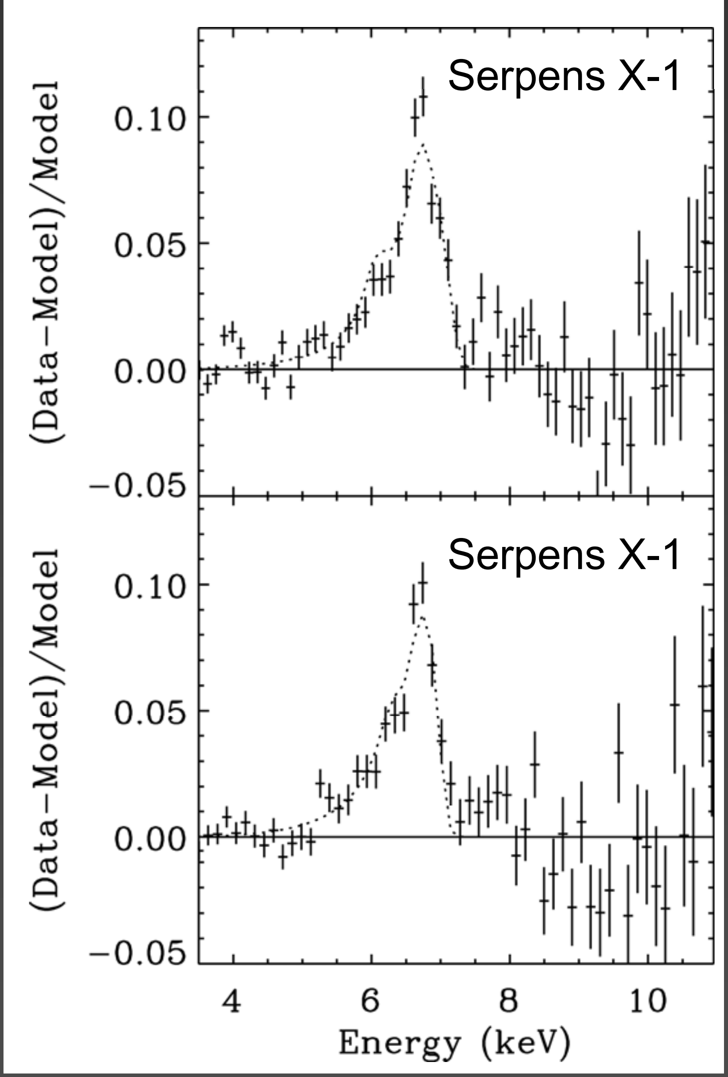


4. Emission lines from the inner disc

Suzaku

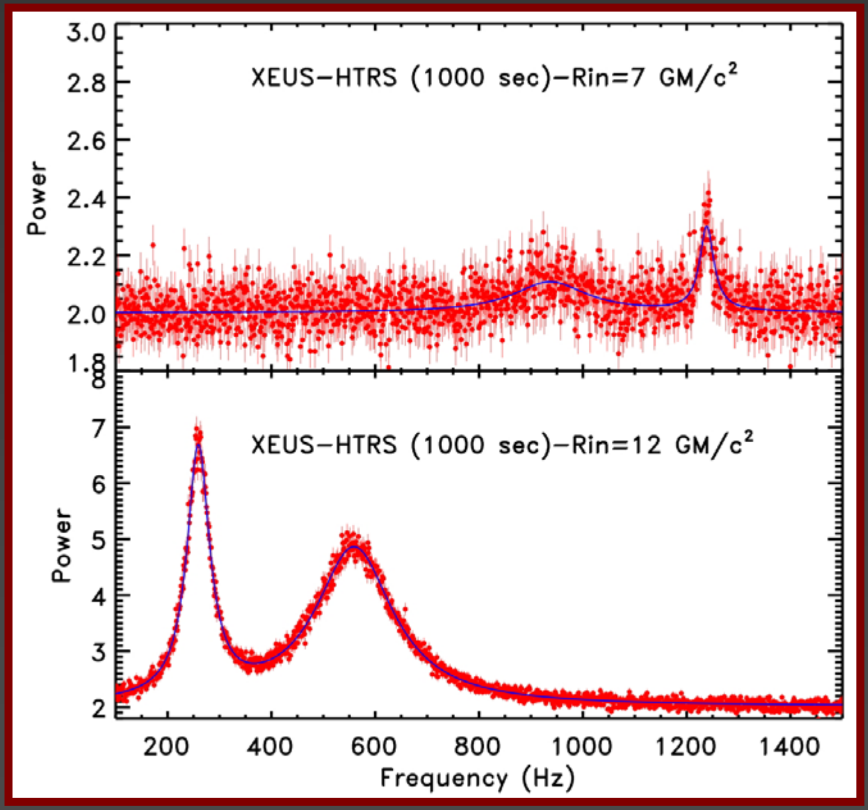


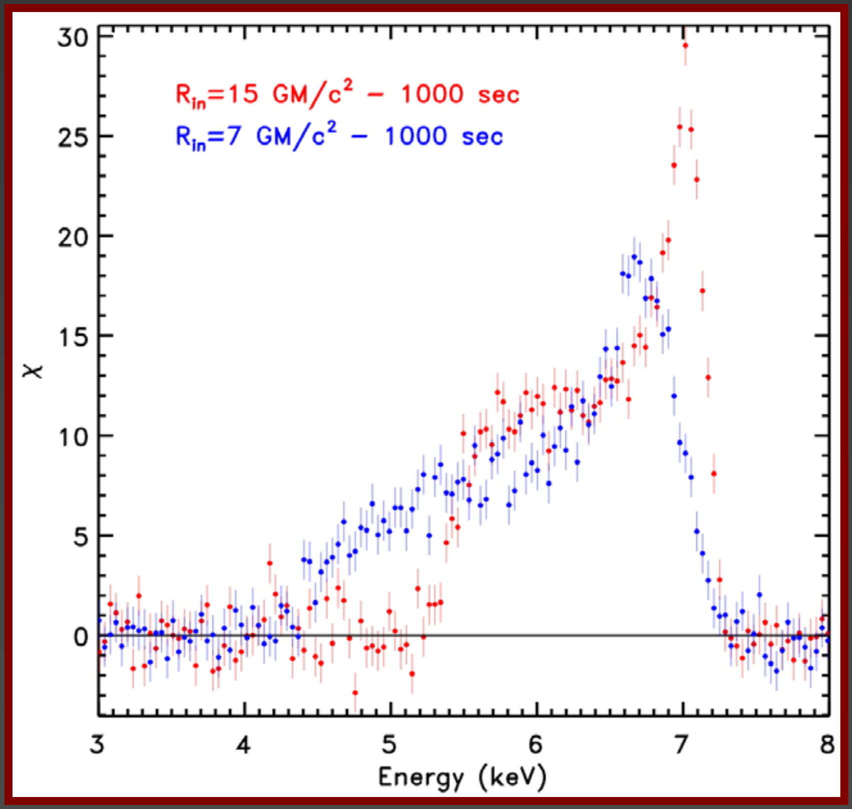
XMM-Newton



Cackett et al. (2008); Bhattacharyya & Strohmayer (2007)

kHz QPOs + Spectroscopy

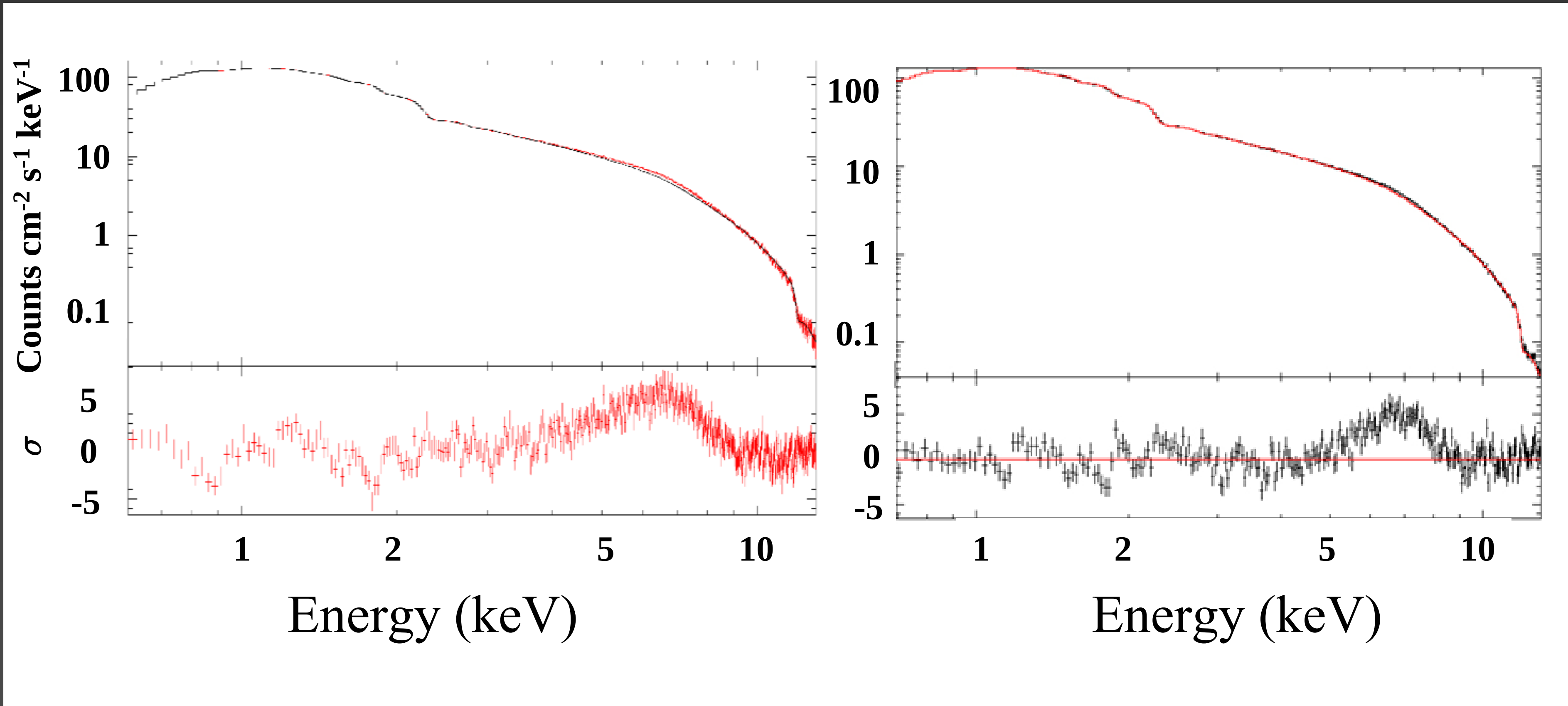




XEUS/HTRS simulations by Didier Barret

Emission lines and continuum

4U 1636–53 – XMM-Newton/Epic-PN



Left: Continuum emission + Line from 6 r_g

Right: Continuum emission + Line from 12 r_g

Timing

1. Kilohertz Quasi-Periodic Oscillations (kHz QPOs) as basic General Relativistic (GR) frequencies.

2. kHz QPOs and the Innermost Stable Circular Orbit (ISCO).

<u>HTRS:</u>

- Band pass: 1 – 25 keV Amplitude increases with energy
- Effective area: At least 4 × RXTE ($\gtrsim$4 m^2)
- Time resol.: $\tau \lesssim 10\ \mu s$
- Max. count rate: $\sim 10^6$ c/s Bright sources

Spectroscopy

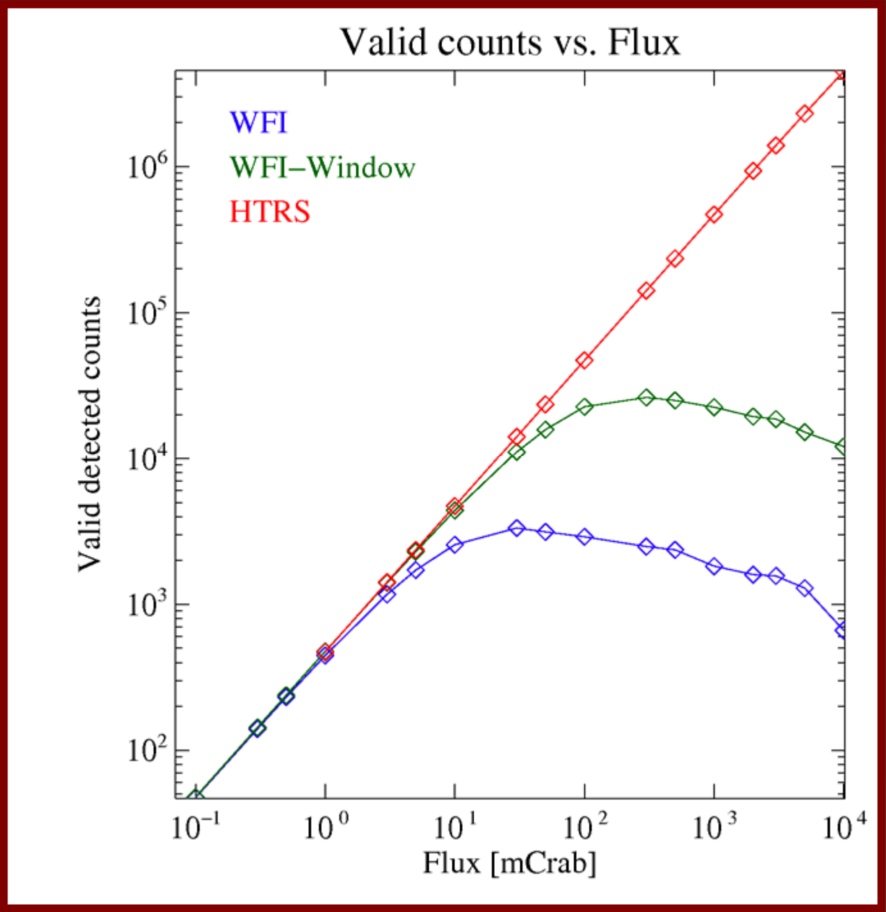
3. Surface (absorption) lines.

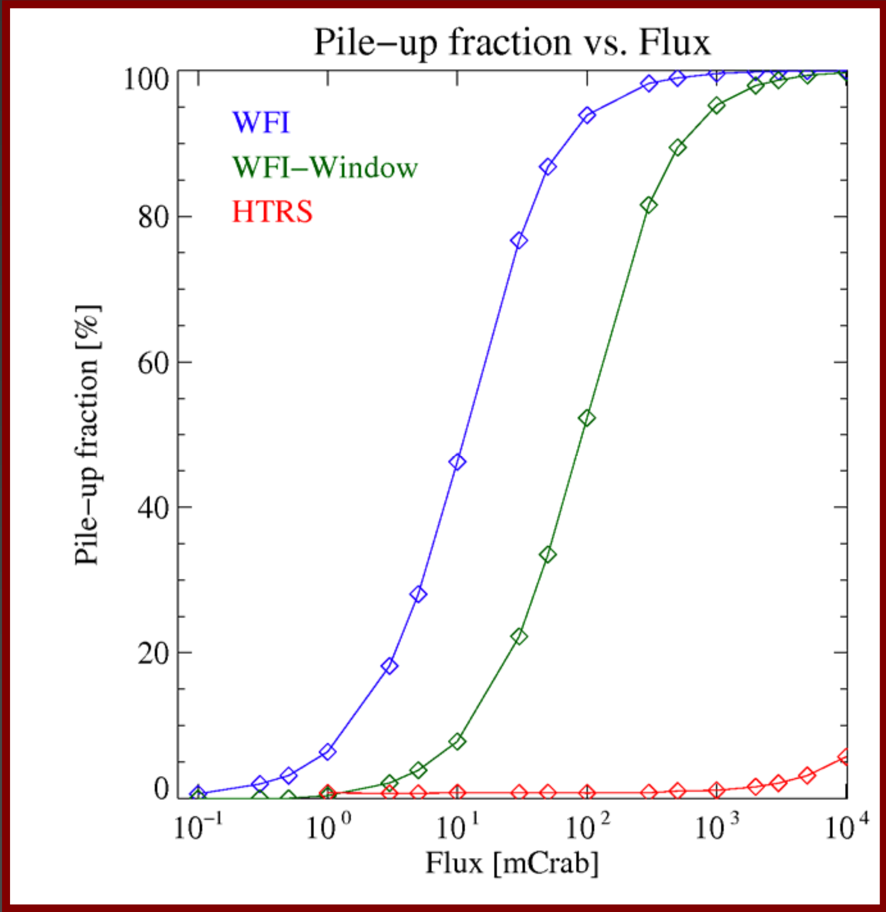
4. Emission lines from the inner accretion disc.

WFI + NFI:

- Band pass: 0.3 – 25 keV Redshifted Oxygen; continuum around Fe K
- Effective area: $\gtrsim 4\ m^2$ Absorption lines in individual X-ray bursts (~10 s)
- Max. count rate: ~few $\times 10^5$ counts/s during 1–5 s X-ray bursts

Count rate capabilities





Simulations of the WFI by Jörn Wilms and Michael Martin for 75μm pixels, 2μs read out, and 64x64 pixel read-out mode.