The Equation of State of Neutron Stars:

Neutron-star masses, radii and internal composition.

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Didier Barret (CESR), Frits Paerels (Columbia), Tod Strohmayer (NASA/GSFC), Phil Uttley (Southampton), Jon Miller (Michigan), Joern Wilms (Bamberg) …

… and many others …

IXO meeting – Paris – April 2010

Neutron-star structure

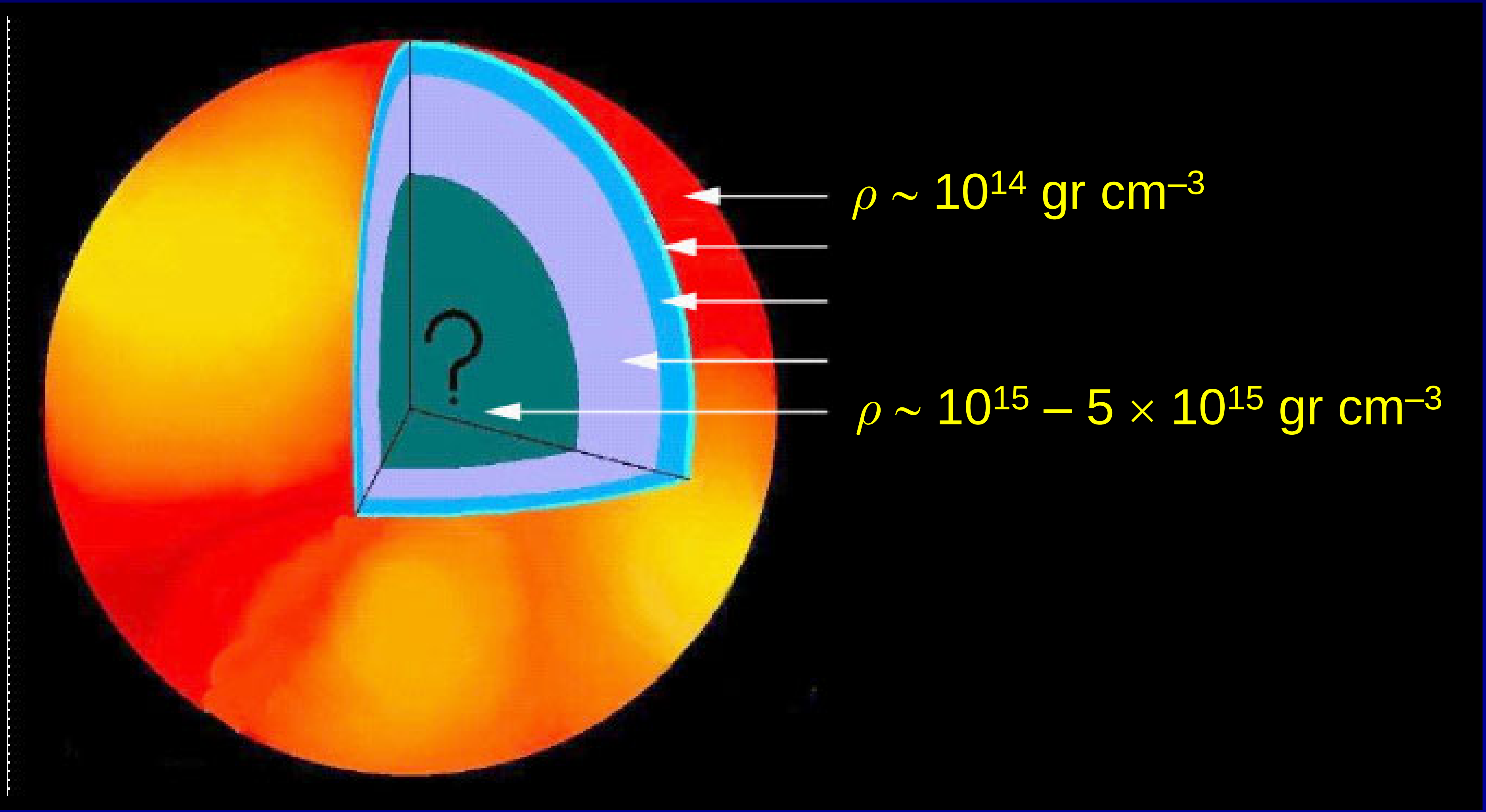


Figure courtesy of D. Page

Equation of State of nuclear matter

1. Use hydrostatic equilibrium and mass conservation in GR:

$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{c^2 r}\right)^{-1}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

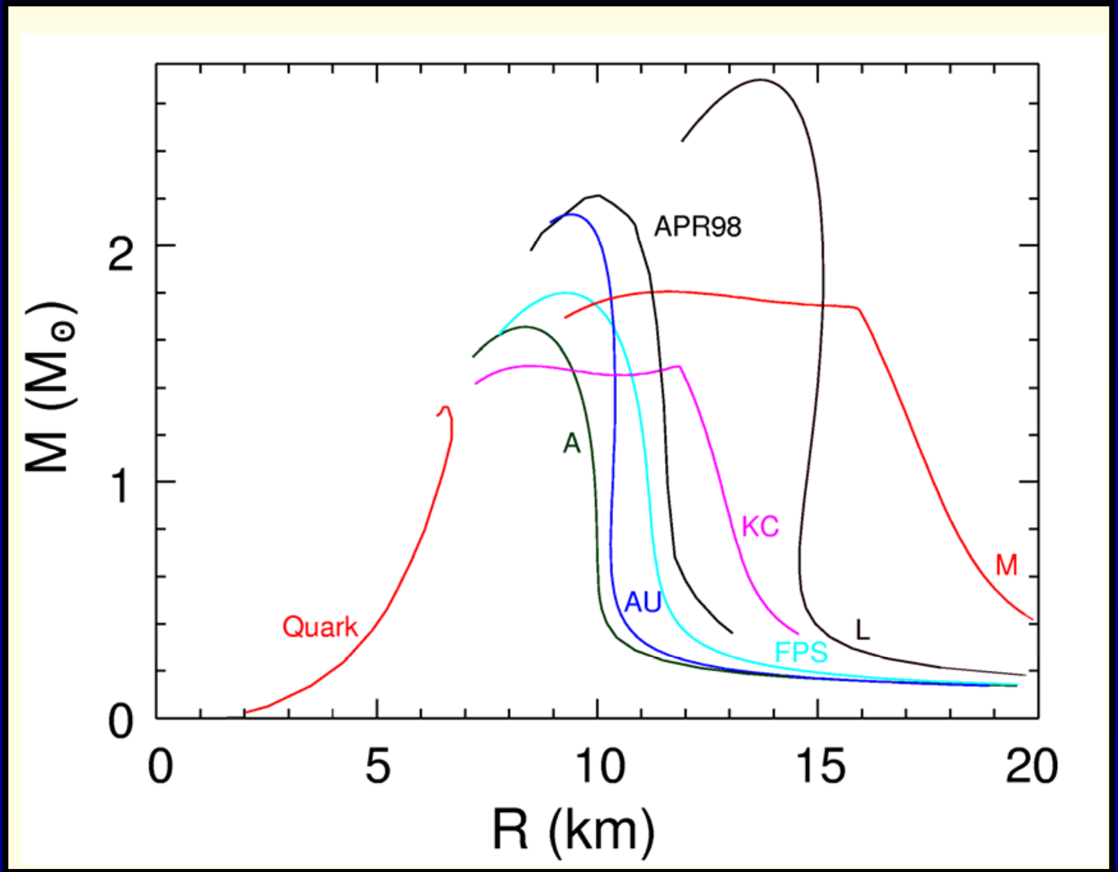
2. Add a prescription for the relation between pressure and density, $P = P(\rho)$.

3. Integrate from $P(r=0) = P_c$ to $P = 0$, which defines M and R.

For each prescription $P = P(\rho)$, this yields a family of solutions as a function of the initial condition, $P = P_c$.

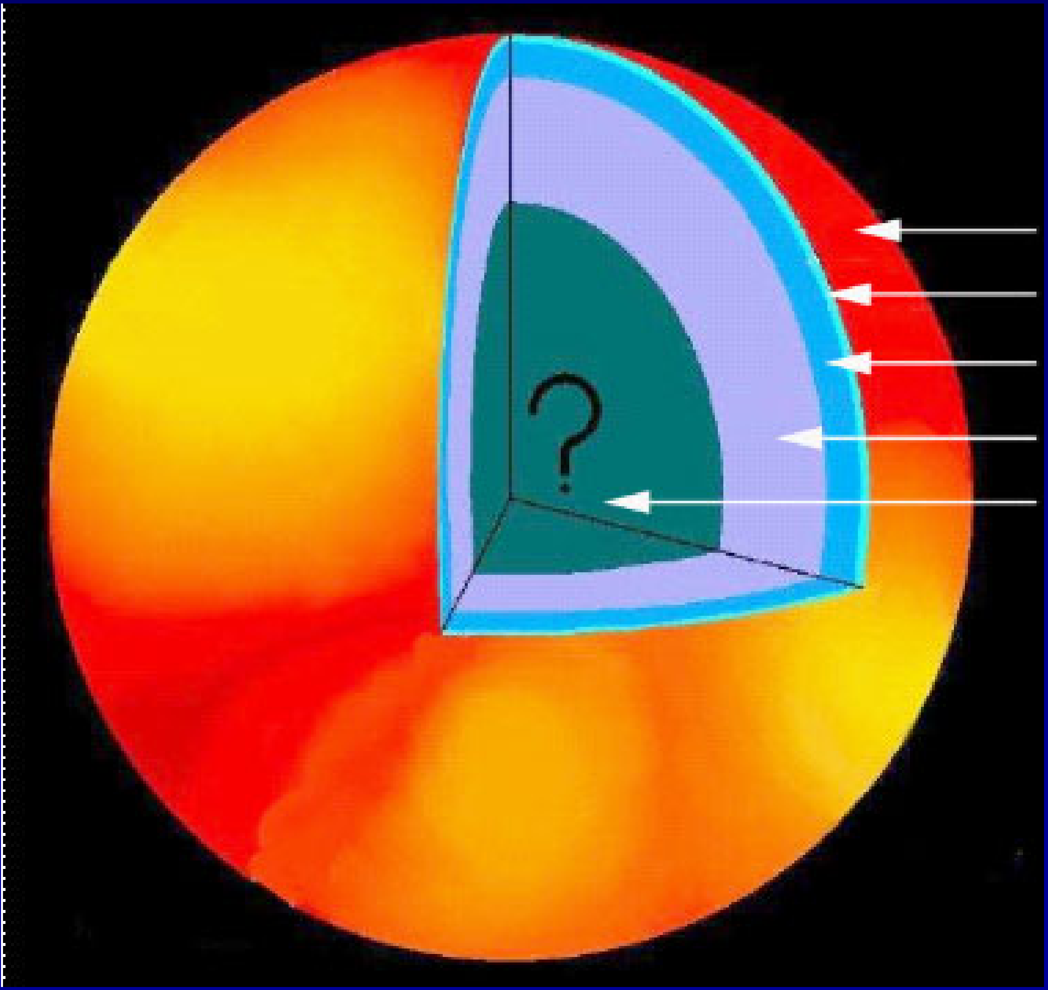
Equation of State of nuclear matter

The relation between $P = P(\rho)$, the so-called equation of state (EOS), is set by the interactions between the particles that constitute the star, and can therefore be mapped into a mass-radius relation, $M = M(R)$.



Cook, Shapiro & Teukolsky; Akmal,Pandharipande, Ravenhall; Heiselberg

Equation of State of nuclear matter



EOS reasonably well-known for the outer parts, but unconstrained for the high-density core.

Uncertainty due to inability to extrapolate our knowledge of normal nuclei (with 50% proton fraction) to the high-density regime of nearly 0% proton fraction.

Neutron-star EOS: Why?

- QCD (e.g., existence of Bose-Einstein condensates or free quarks at low temperatures); relevant to high-energy and particle physics.

- Dynamics of supernovae explosions.

- NS–NS mergers, which are likely progenitors of short GRBs and sources of strong gravitational waves.

- Stability of neutron stars.

- NS cooling which, compared to observed NS temperatures, provides NS ages.

Equation of State of nuclear matter.

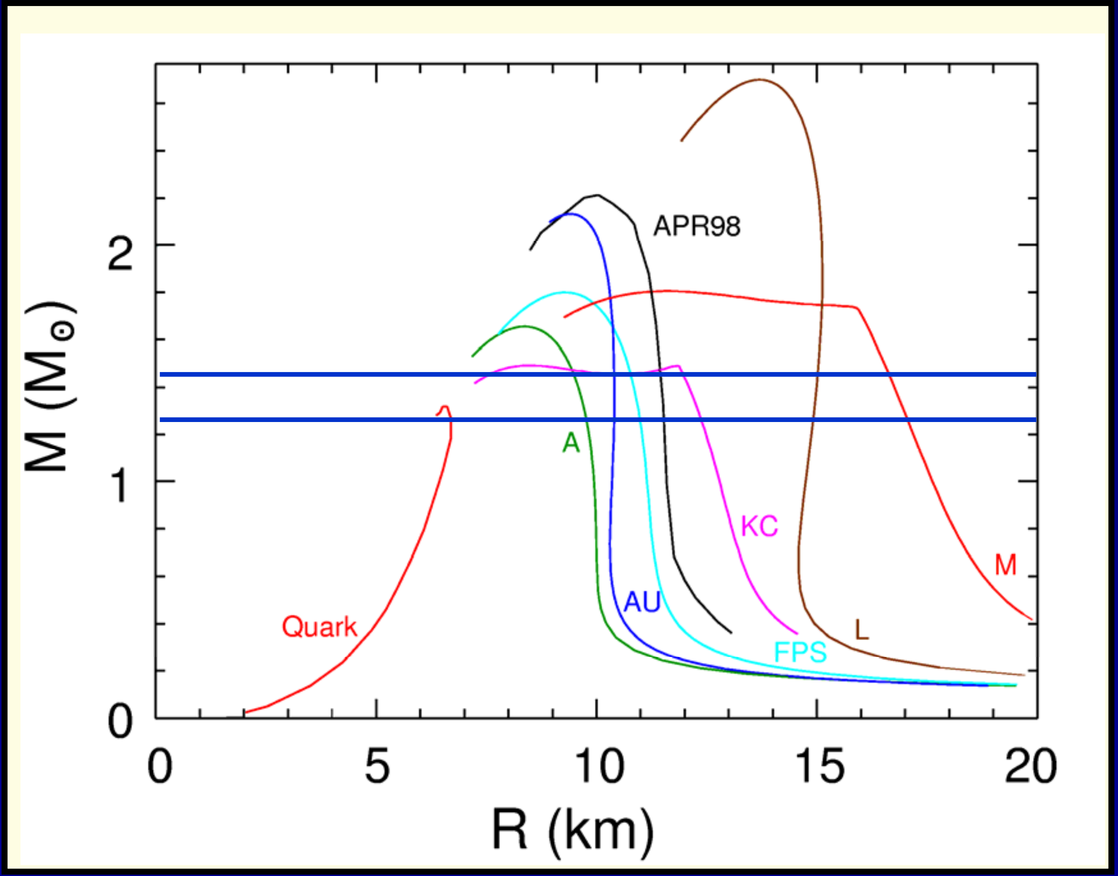
From pulsars in binaries
$\langle M \rangle = 1.35 \pm 0.04\ M_{sun}$

Some masses accurate down to 0.1% (!)

Mass alone not enough to exclude any EOS.

A combination of mass *and* radius required.

… or a massive NS.



Neutron star EOS measurements and constraints

Time-resolved spectroscopy and photometry:

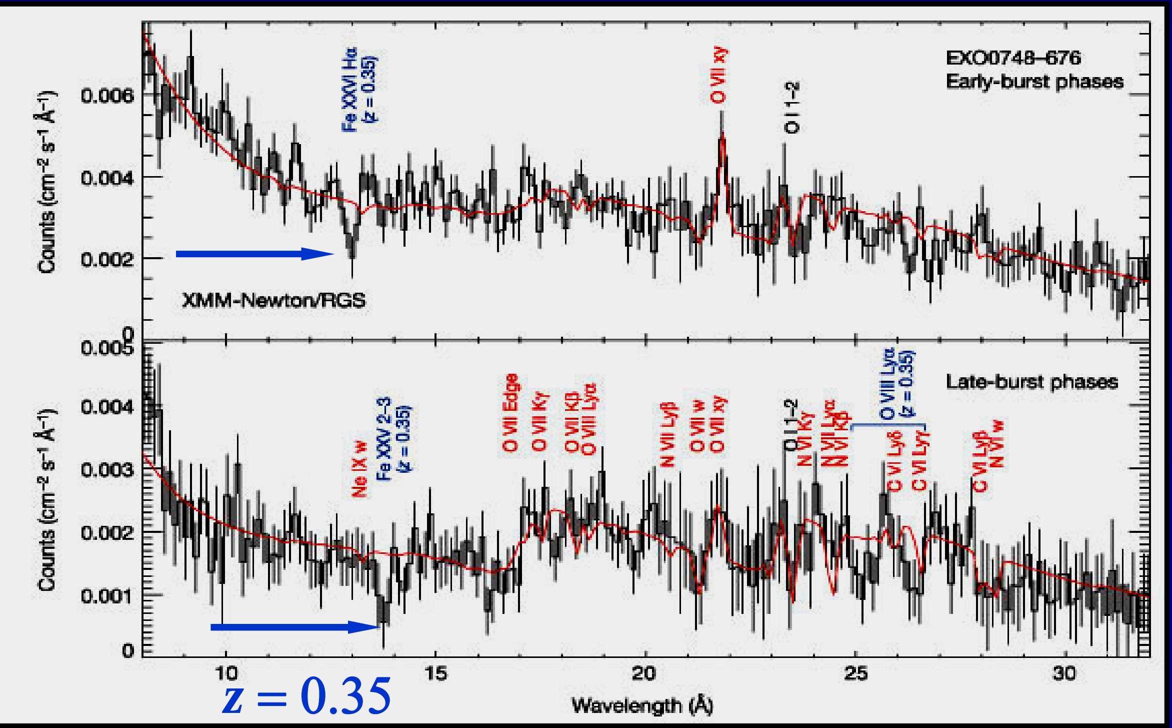
- Redshifted photospheric lines → M/R (potentially M/R^2)
- Profile of photospheric lines → M/R
- Pulsations waveform → M/R
- Quasi-periodic oscillations → $R\ (M)$ (from disc)
- Fe emission (disc) lines → $R\ (M)$ (from disc)
- Frequency-resolved time-delay spectrum → R (from disc)

Photospheric absorption during X-ray bursts

EXO 0748–676

335 ks with RGS cameras

Spectra of 28 X-ray bursts co-added



Fe 26 $n = 2 \rightarrow 3$

Fe 25 $n = 2 \rightarrow 3$

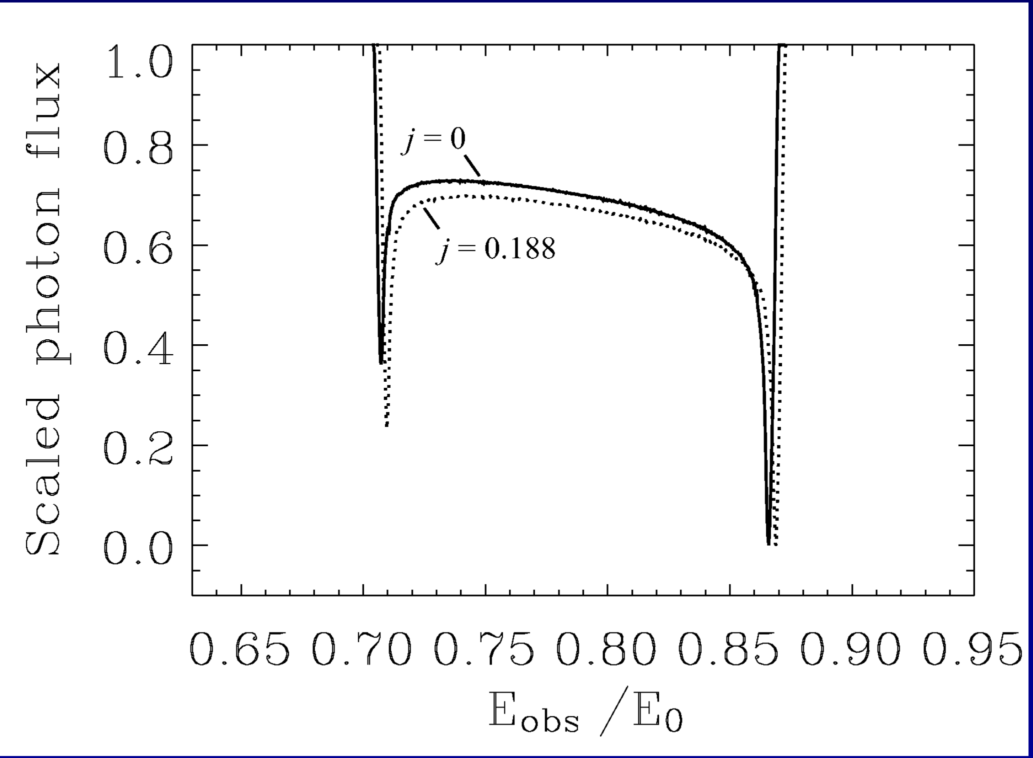
redshift $z = 0.35 \pm 0.01$

Cottam, Paerels & Méndez

Spectral line profile

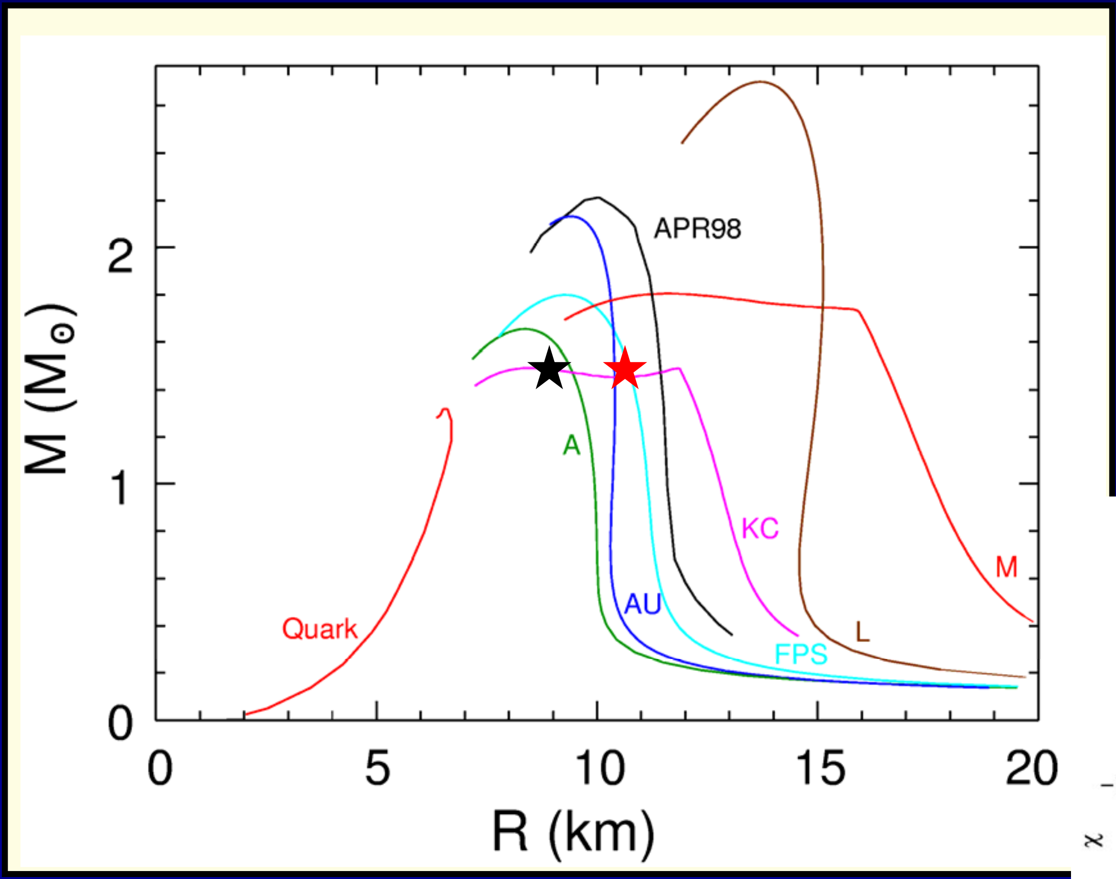
Line profile set by:

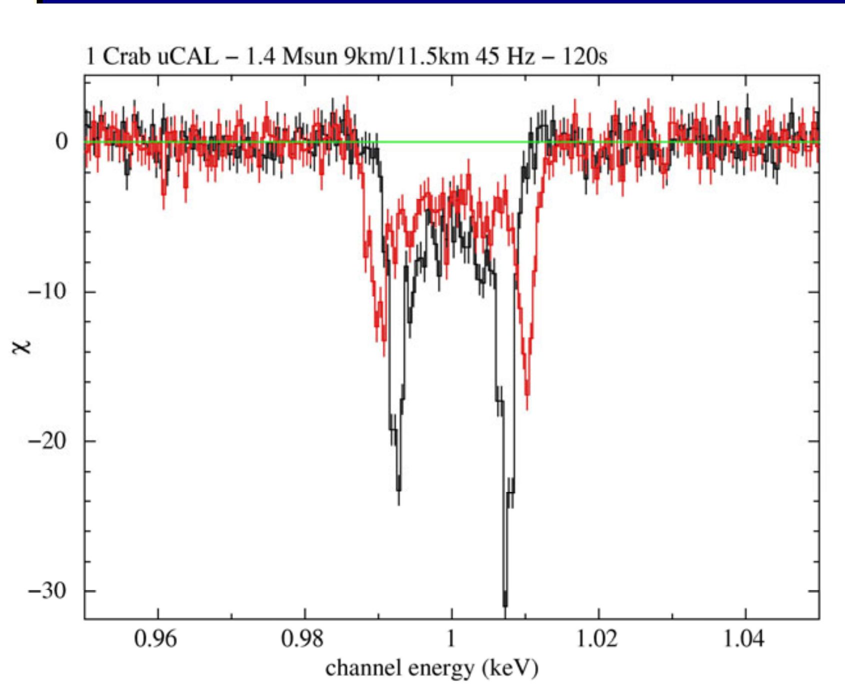
- longitudinal and transverse Doppler shifts
- special relativistic beaming
- gravitational redshift,
- light-bending
- frame-dragging



Bhattacharyya et al.

Simulated spectral line profile





Line profile calculations courtesy of S. Bhattacharyya

XMS for bright sources

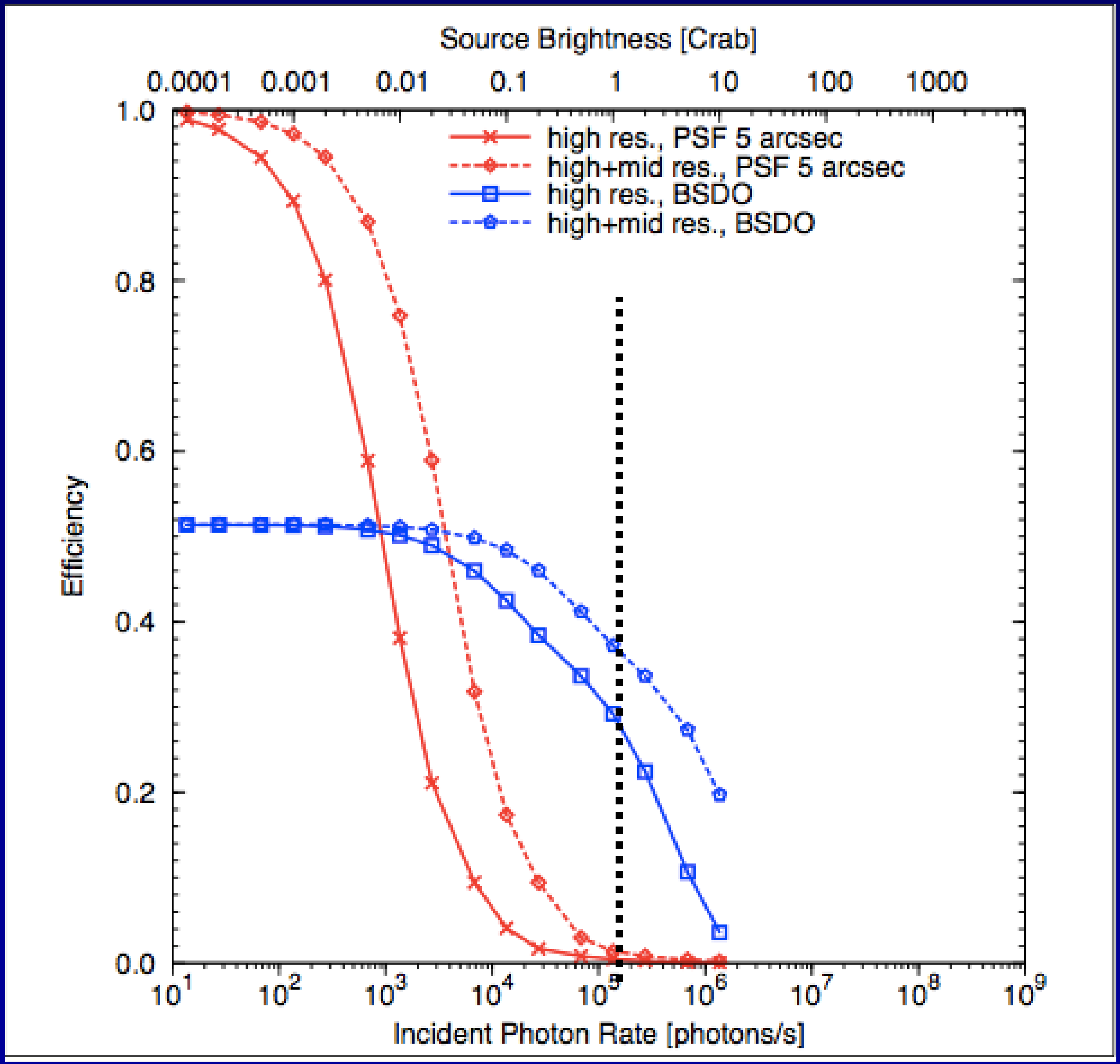
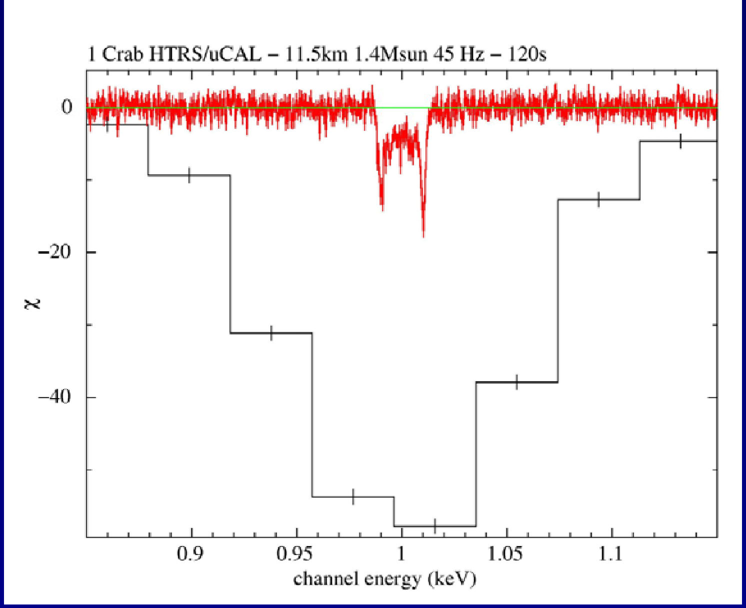
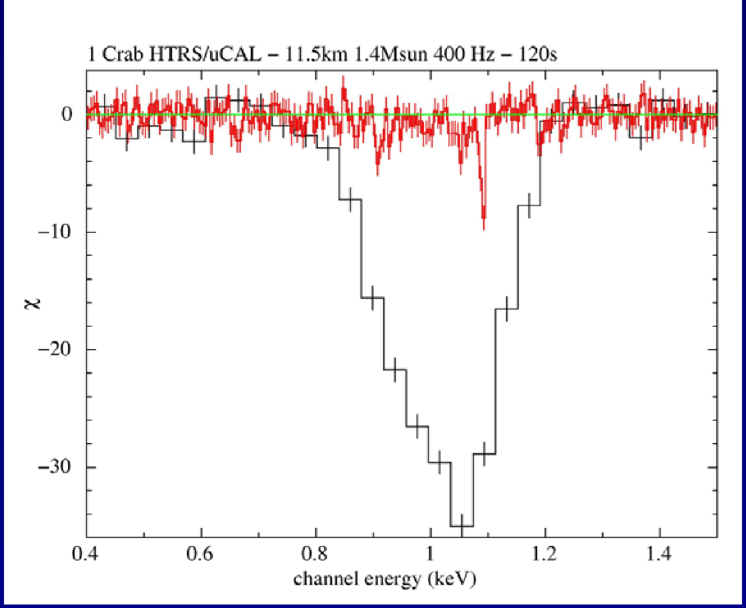


Figure from J. Wilms et al.

Simulations

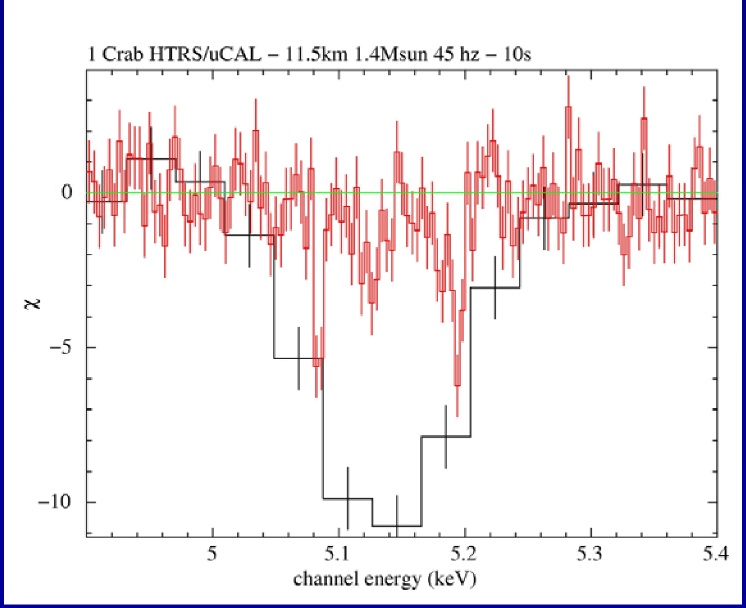
Spin = 45 Hz / Spin = 400 Hz

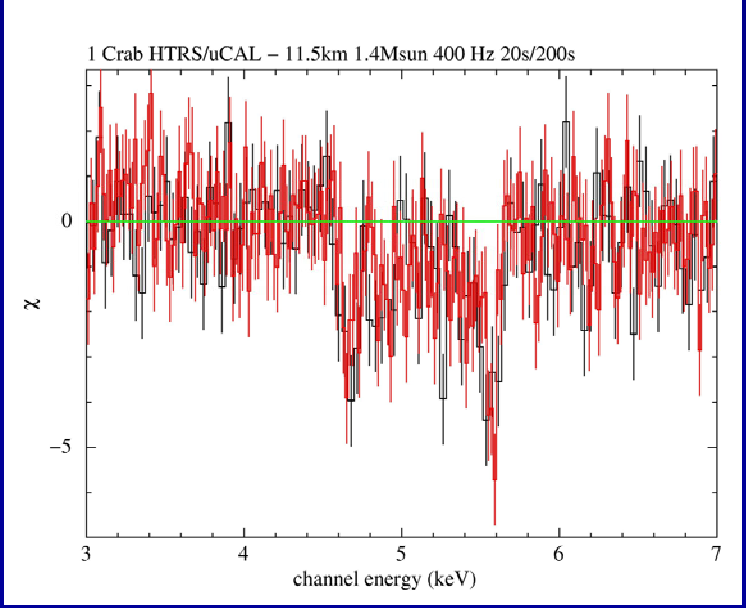




Fe XXVI
$z = 0.35$

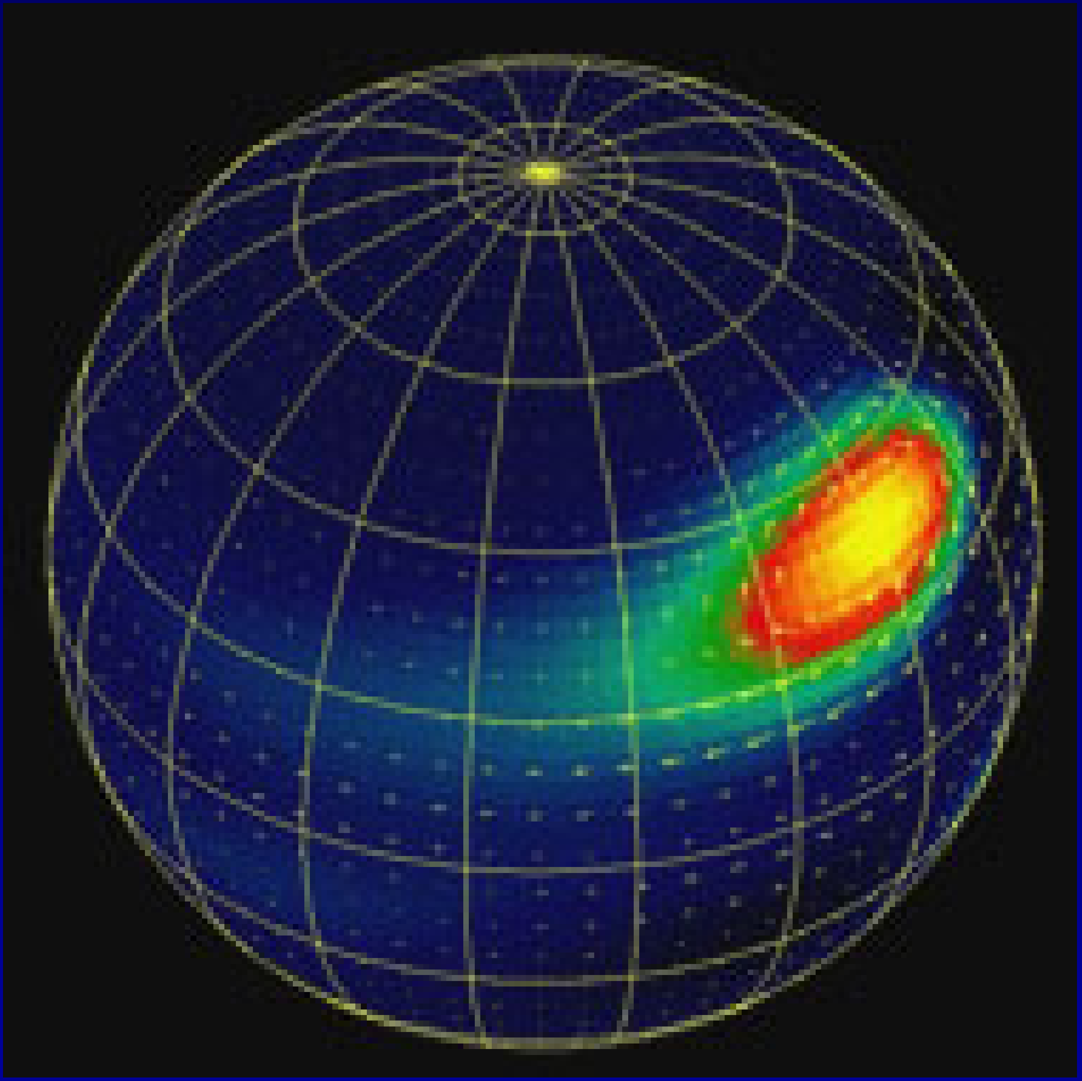
$n = 2 – 3$
Balmer α





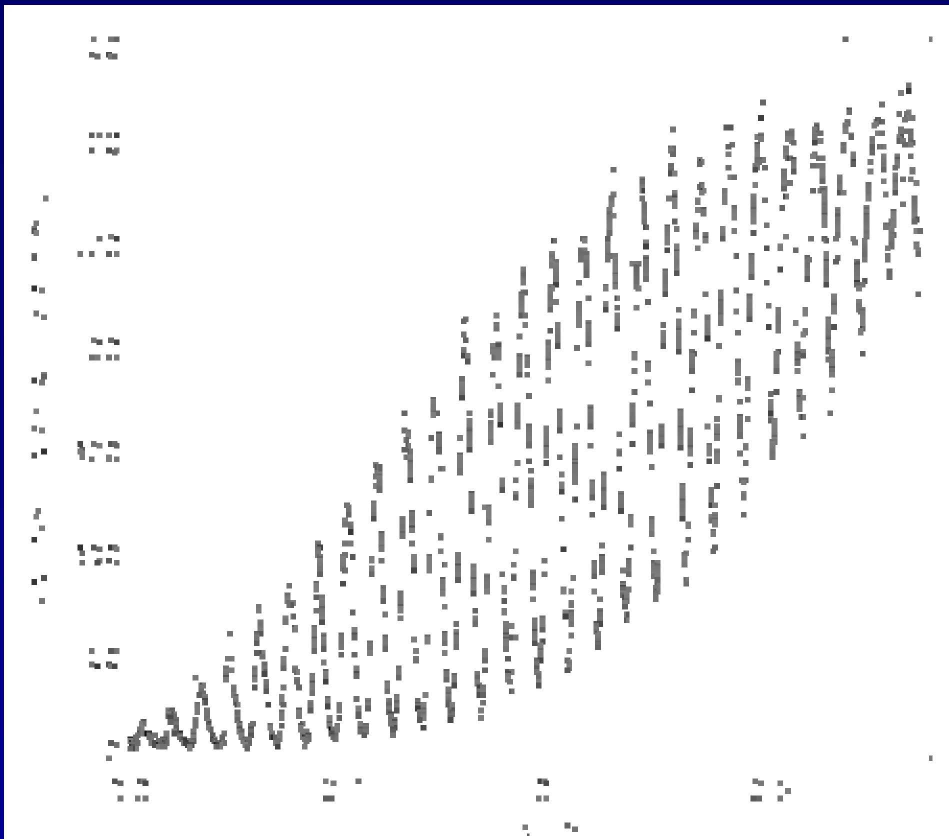
$n = 1 – 2$
Lyman α

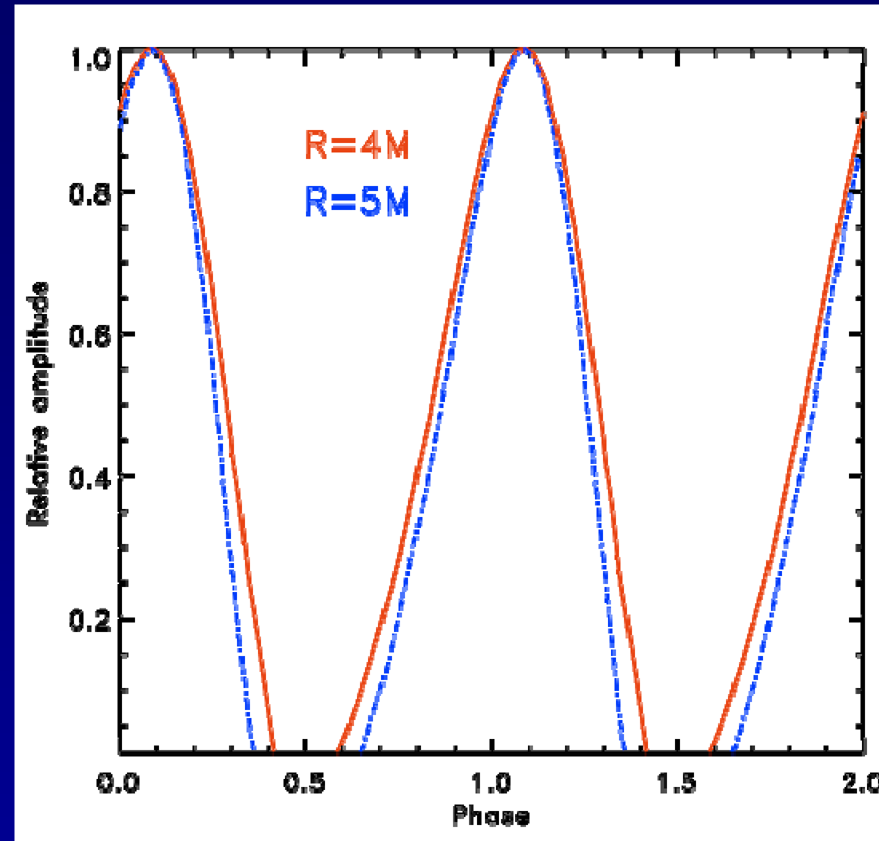
Pulsations during X-ray bursts



Strohmayer et al.; Spitkovsky et al.

Pulsations during X-ray bursts

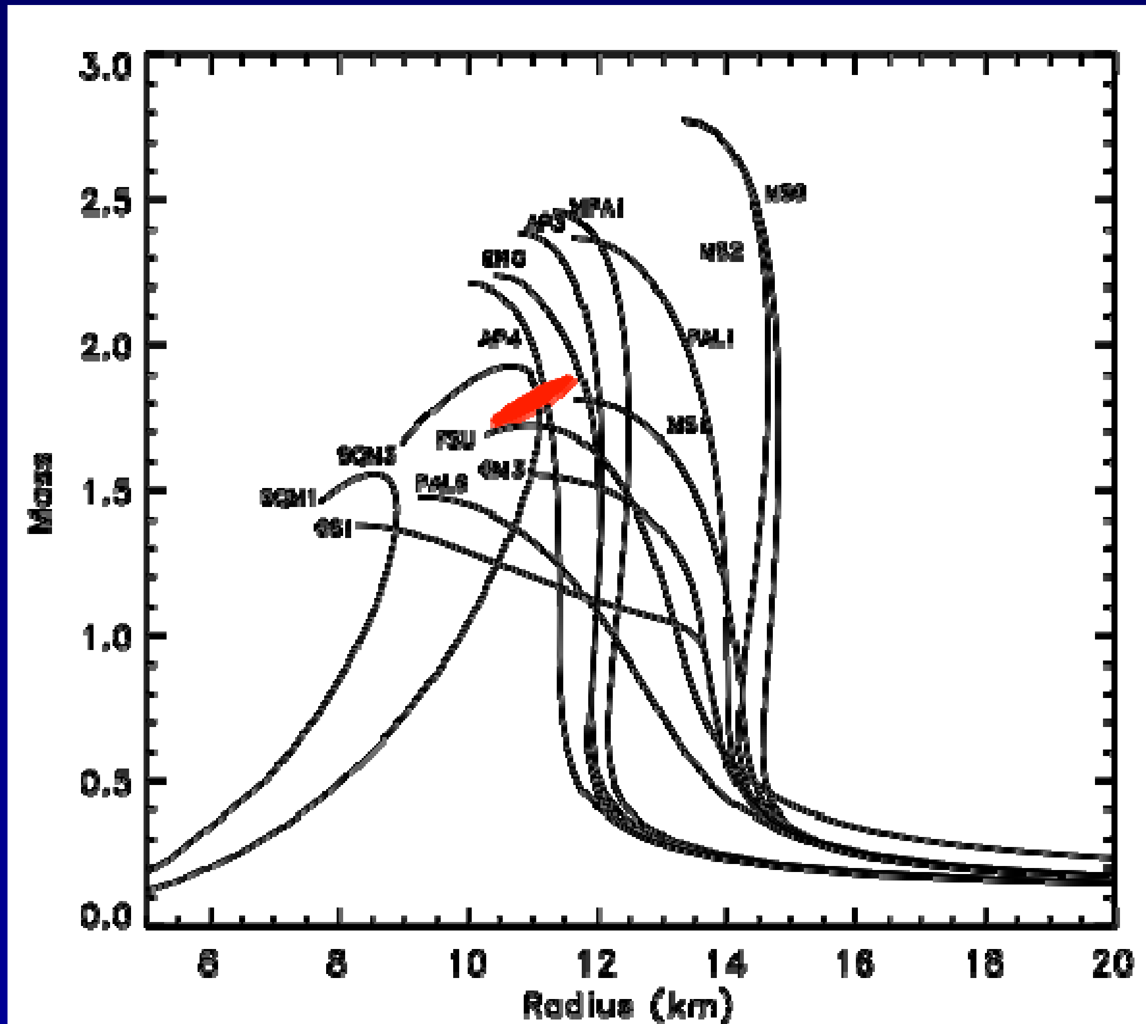




Simulated pulse profile for the rising phase of an X-ray burst (T. Strohmayer).

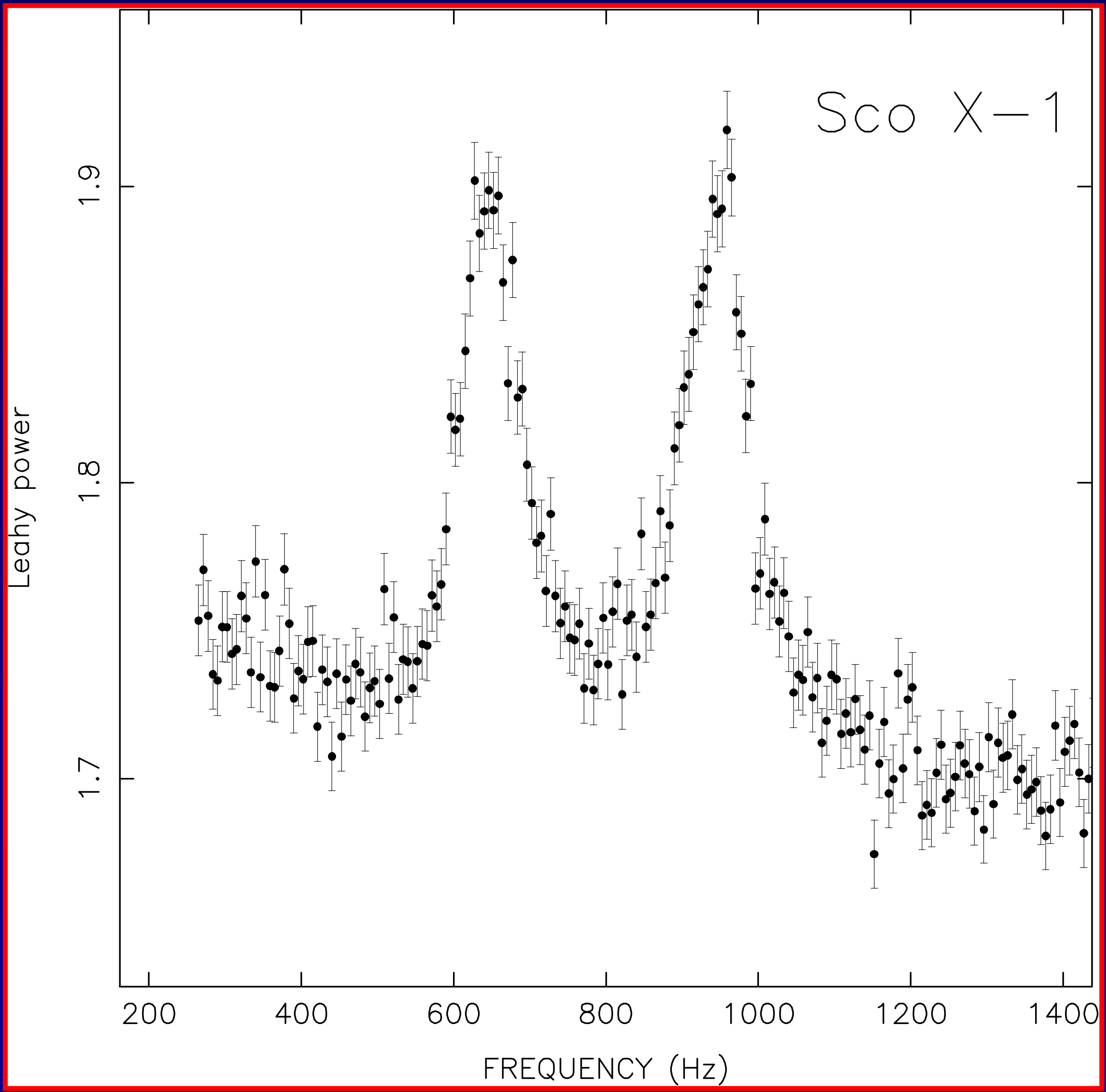
Pulse profiles for a 1.8 solar mass NS with a spin frequency of 364 Hz. (C. Miller).

Pulsations during X-ray bursts

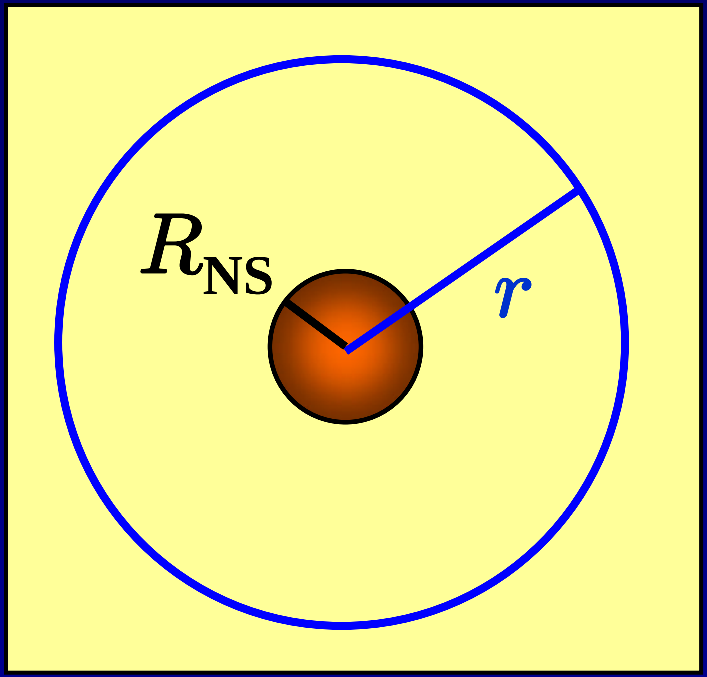


Mass and radius constraints from pulse-profile fitting. The red ellipse shows the 95% confidence regions from 5 typical bursts (C. Miller).

Quasi-periodic oscillations



Mass and radius constraints from timing



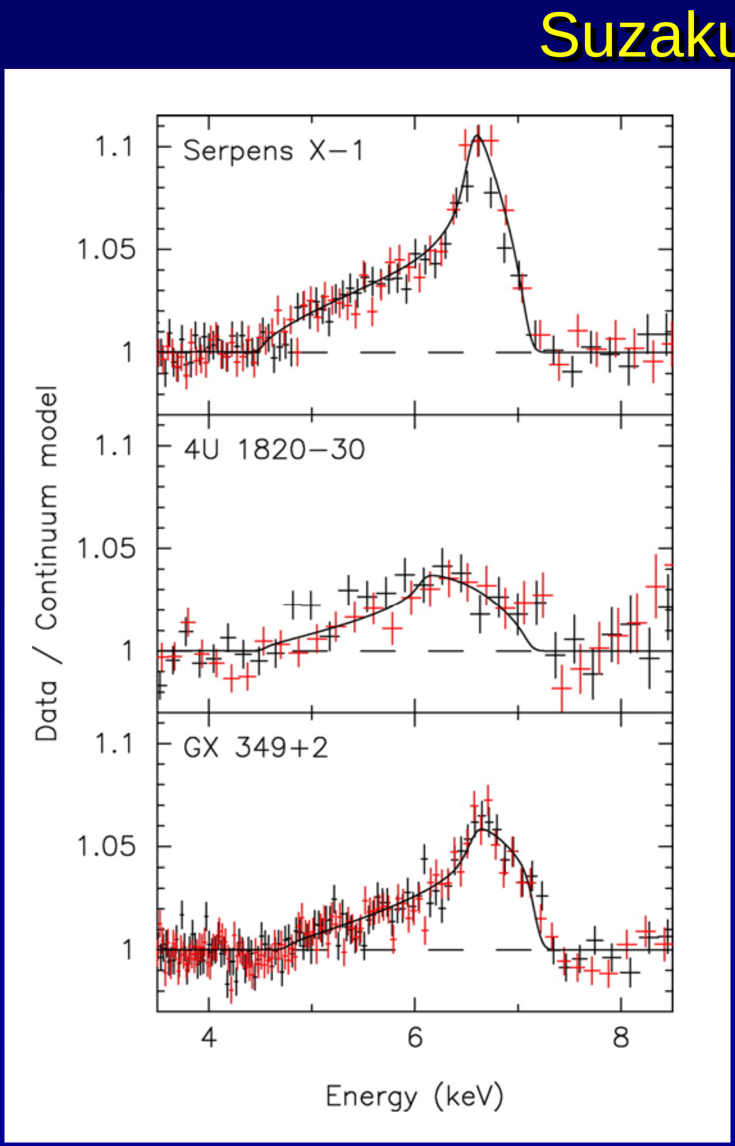
$$\nu = \frac{1}{2\pi}\sqrt{\frac{GM_{\rm NS}}{r^3}}$$

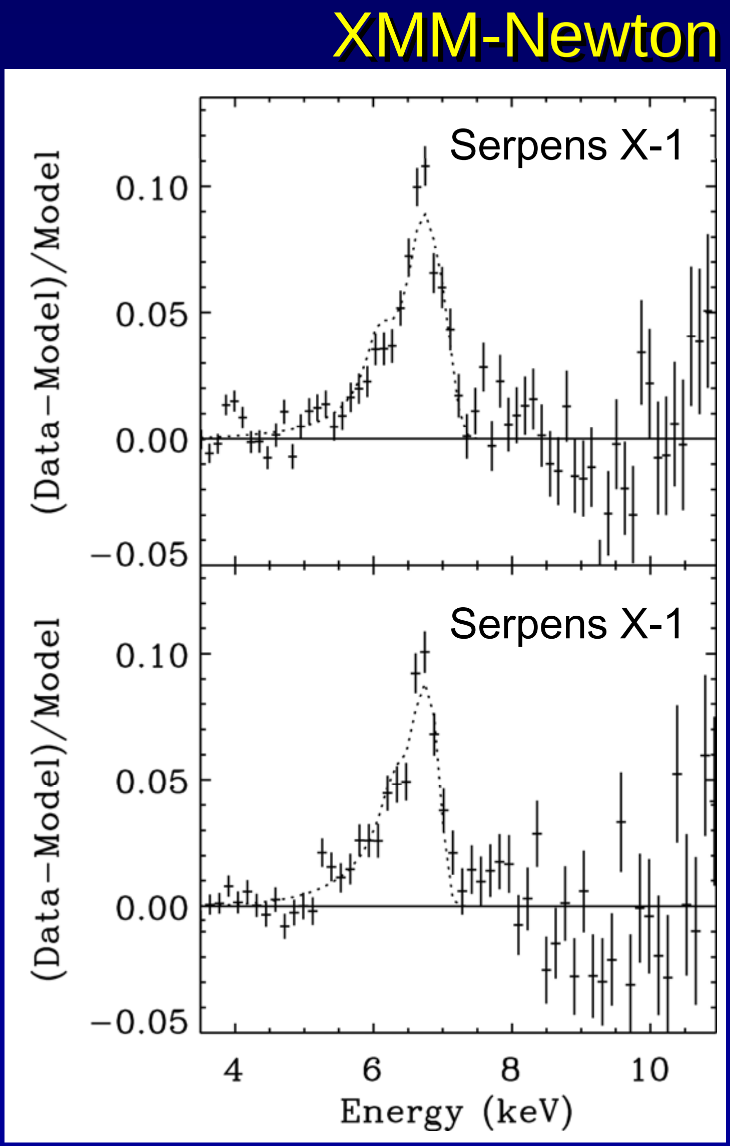
$$R_{\rm NS} \leq r$$

$$M_{\rm NS} \leq 2.2(\nu/1000\text{Hz})^{-1} M_\odot$$

$$R_{\rm NS} \leq 14.6(M_{\rm NS}/M_\odot)^{1/3}(\nu/1000\text{Hz})^{-2/3}\ \text{km}$$

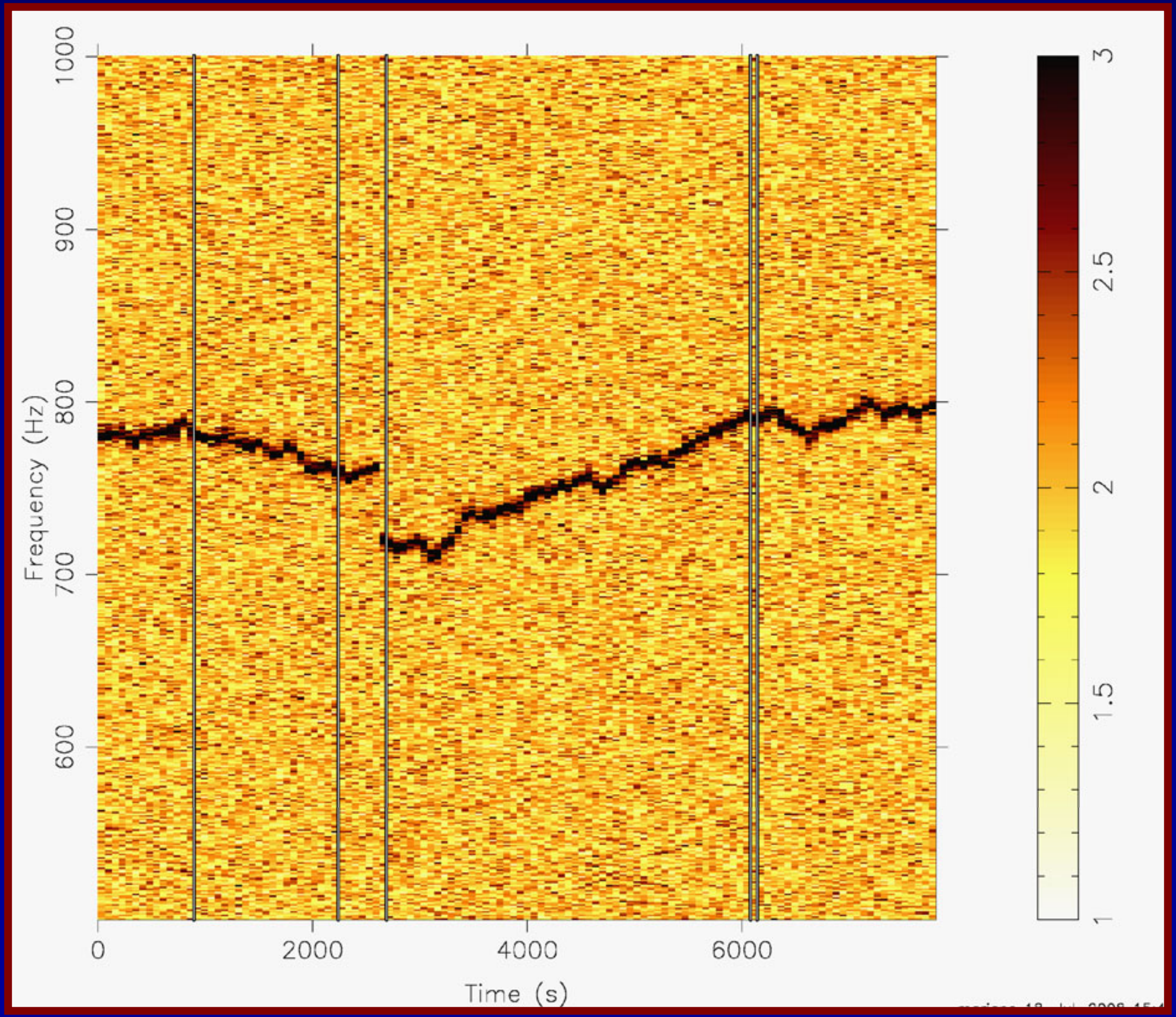
Emission lines from the inner disc





Cackett et al.; Bhattacharyya & Strohmayer

Inner disc radius

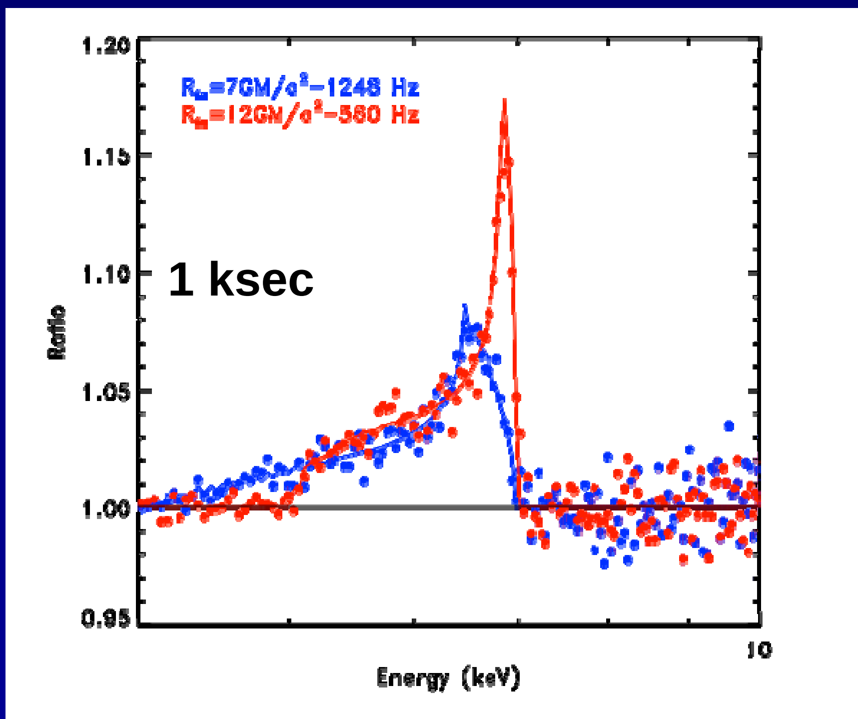


Mendez et al.

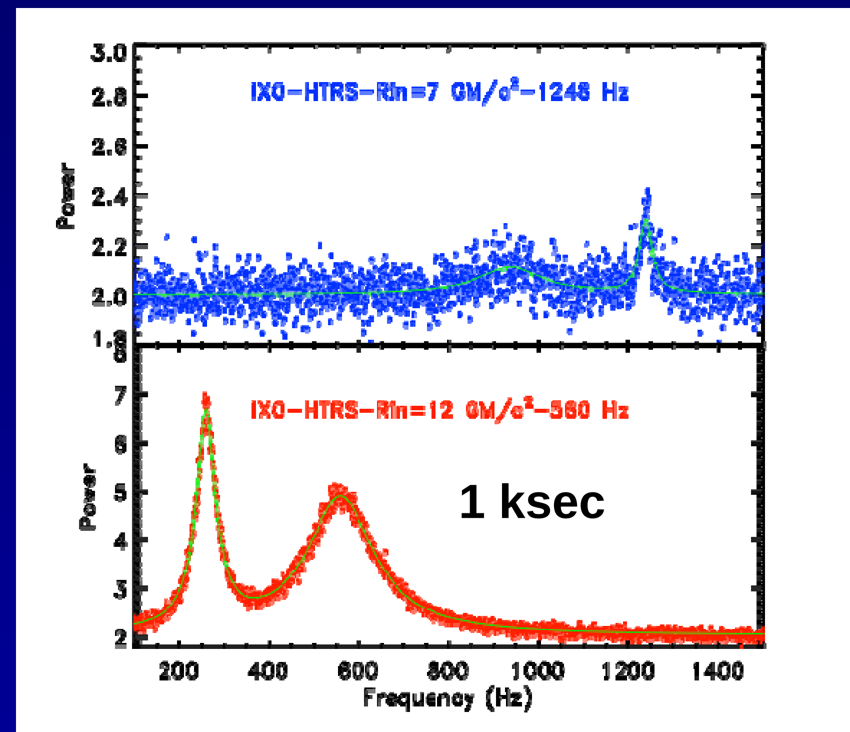
4U 1608–52

Tracking the inner disc radius

Data / continuum



Power



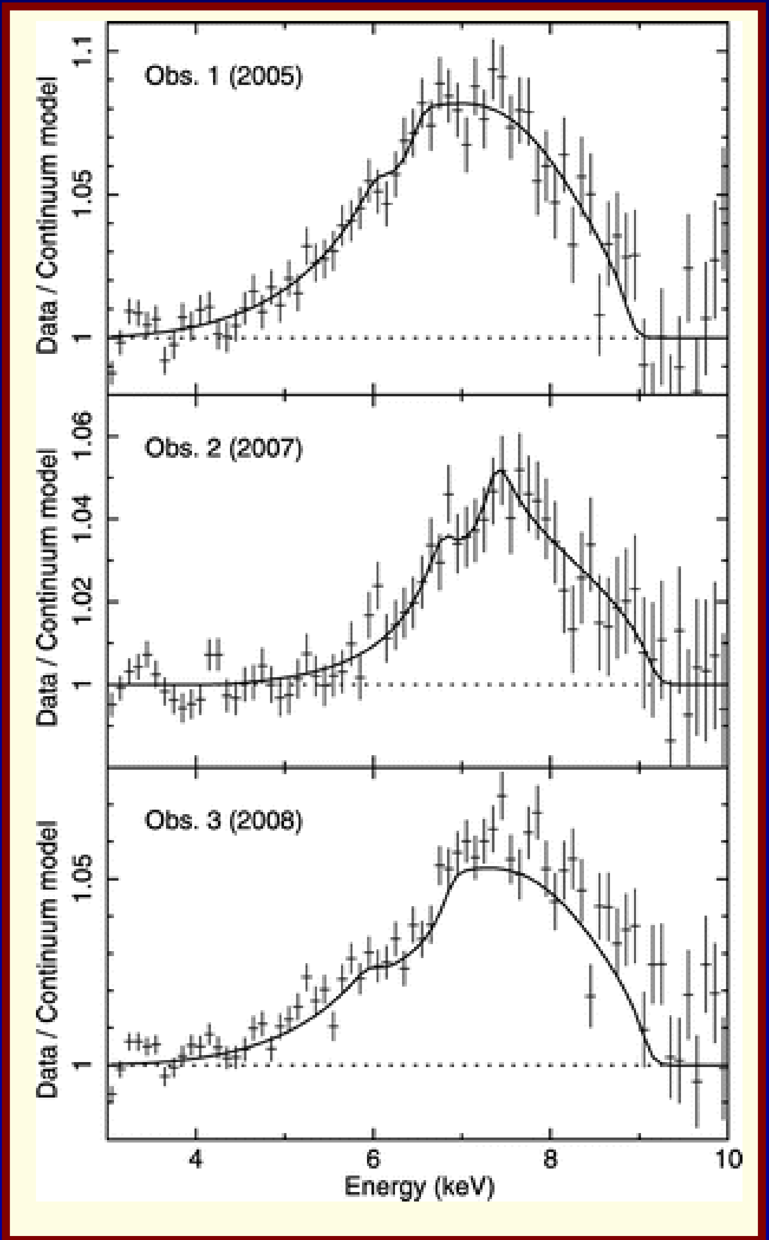
Energy (keV)

Frequency (Hz)

IXO/HTRS simulations by D. Barret

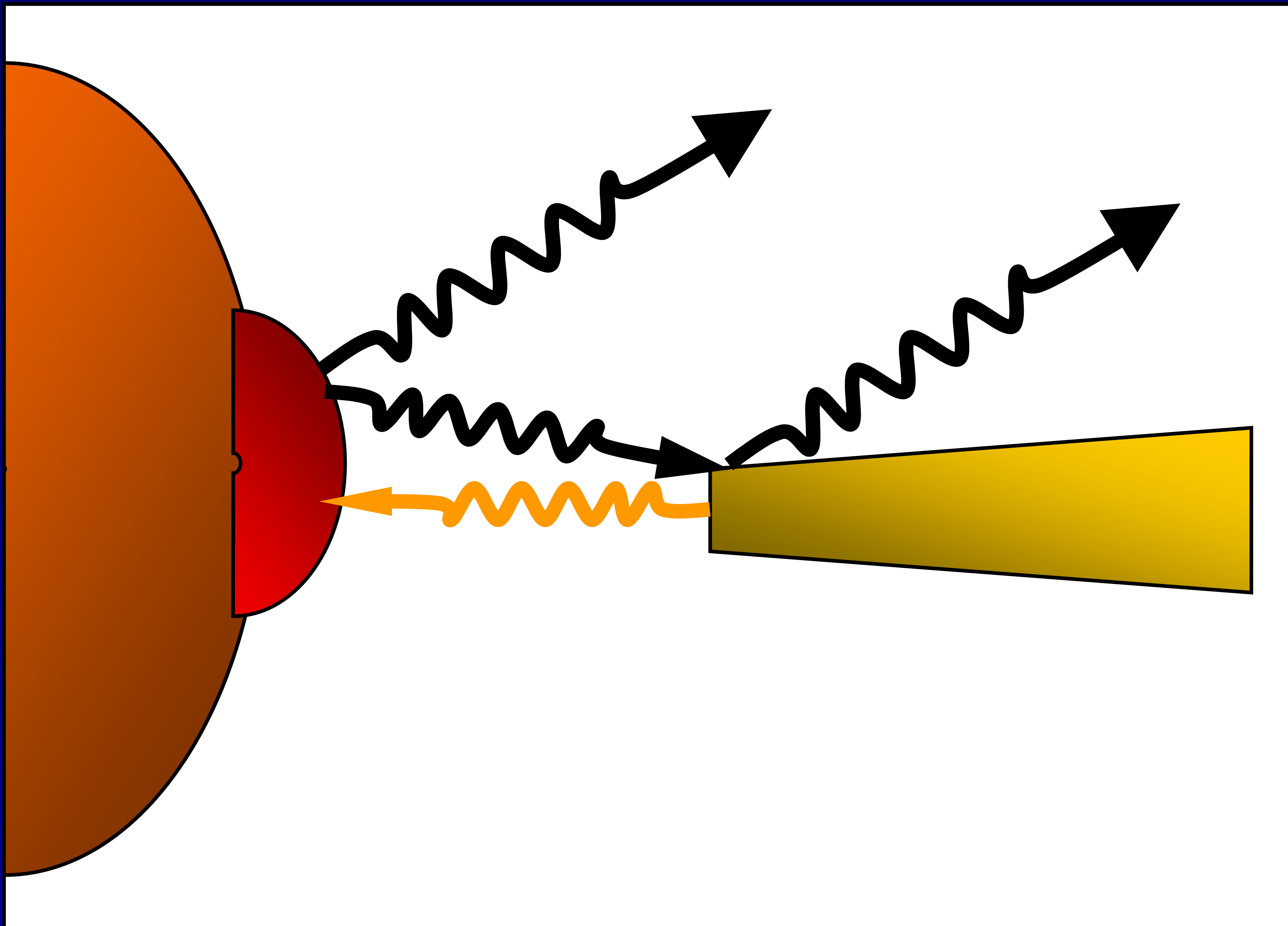
Iron line

4U 1636-53

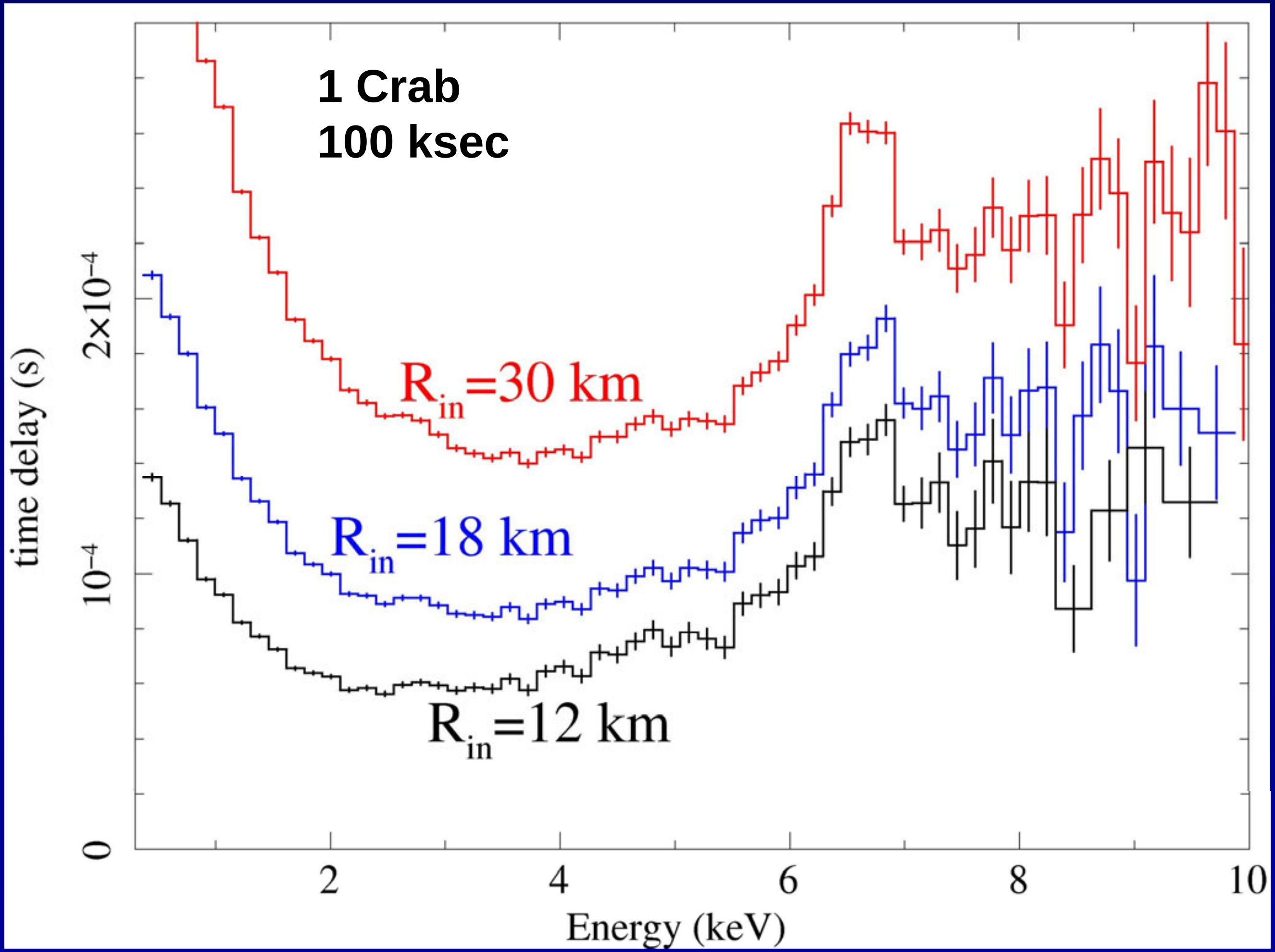


Pandel et al.; Altamirano et al.

Frequency-resolved time-delay spectrum



Frequency-resolved time-delay spectrum



IXO/HTRS simulations by P. Uttley

Neutron-star EOS: Summary

- Multiple complementary (redundant) constraints of M and R
- Requirements:

  - High time resolution (time scales ~ 1 ms)

  - High count-rate capability (count rates ~ 1 Crab or more)

  - Moderate spectral resolution (line broadening)
- HTRS is the primary instrument for this science
- Complementary information from XMS / WFI / XGS