The Equation of State of Neutron Stars:
Neutron-star masses, radii and internal composition.

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… and many others …

Neutron-star structure

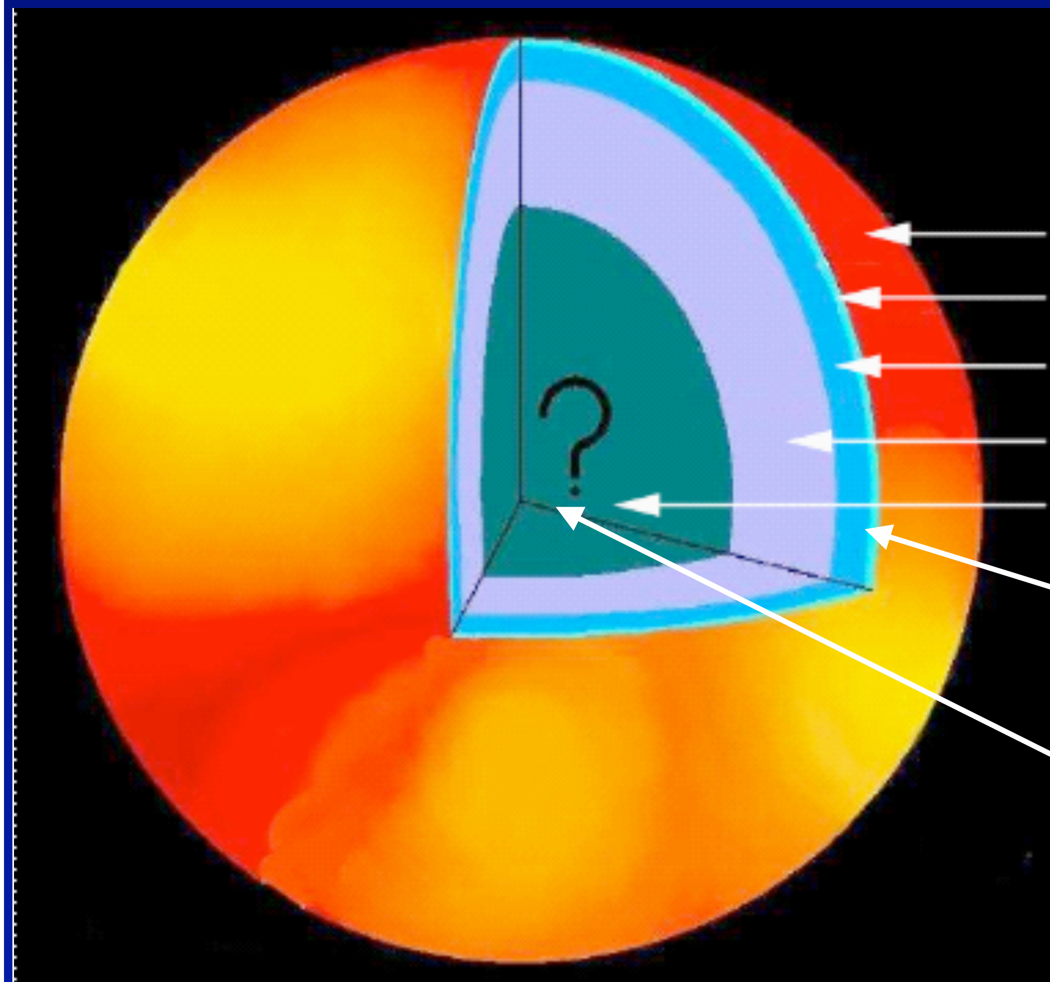

Figure courtesy of D. Page

Equation of State of nuclear matter

The interactions between the particles that constitute stars determines the equation of state (EOS), a relation between pressure and density, $P = P(\rho)$, that can be translated into a mass-radius relation, $M = M(R)$. For neutron stars (NS):

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

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

plus a prescription for $P = P(\rho)$

e.g., Shapiro & Teukolsky

Equation of State of nuclear matter

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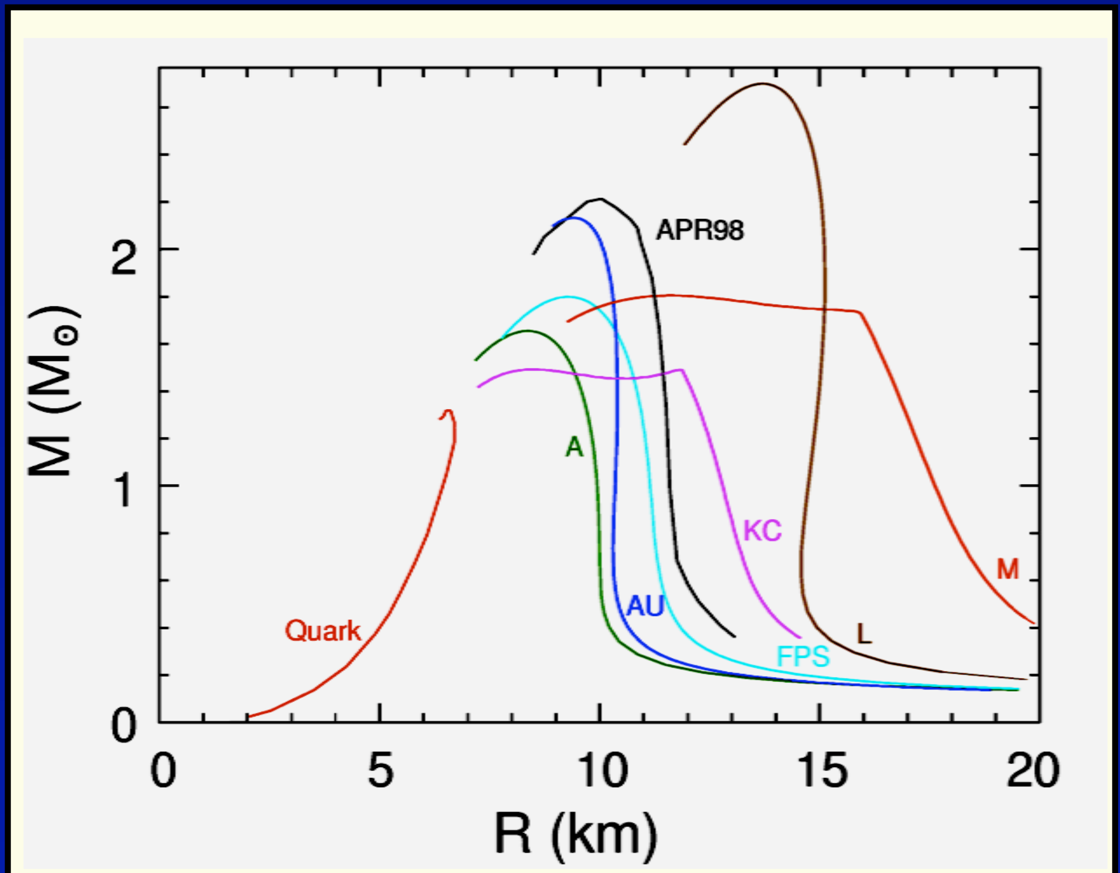
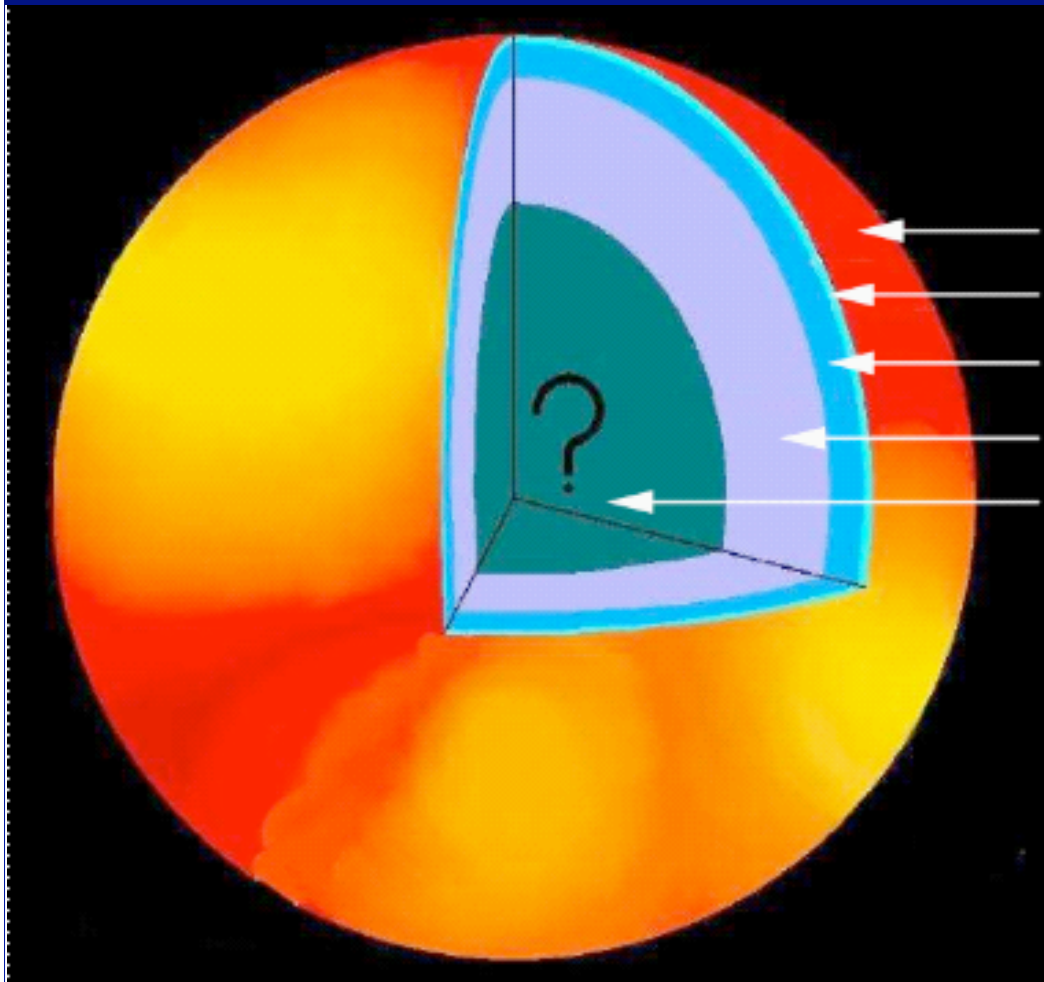


Cook, Shapiro & Teukolsky; Akmal, Pandharipande, Ravenhall; Heiselberg

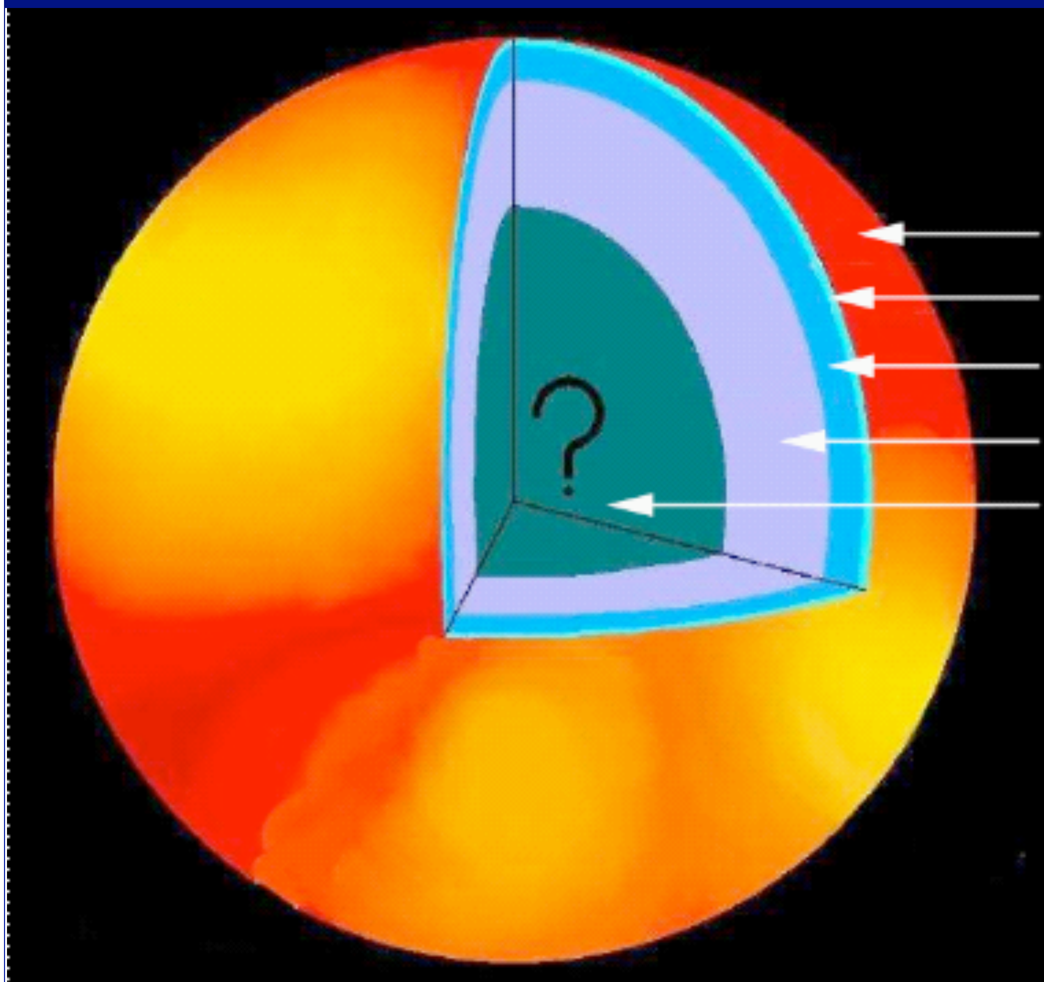
Equation of State of nuclear matter



EOS is reasonably well-known for the outer parts of the NS, but is 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.

Equation of State of nuclear matter



EOS models depend upon assumptions made about the phase of matter in the core: (e.g., hadrons, Bose-Einstein condensates, quark matter).

Each new phase increases the compressibility of the star, allowing for a smaller NS.

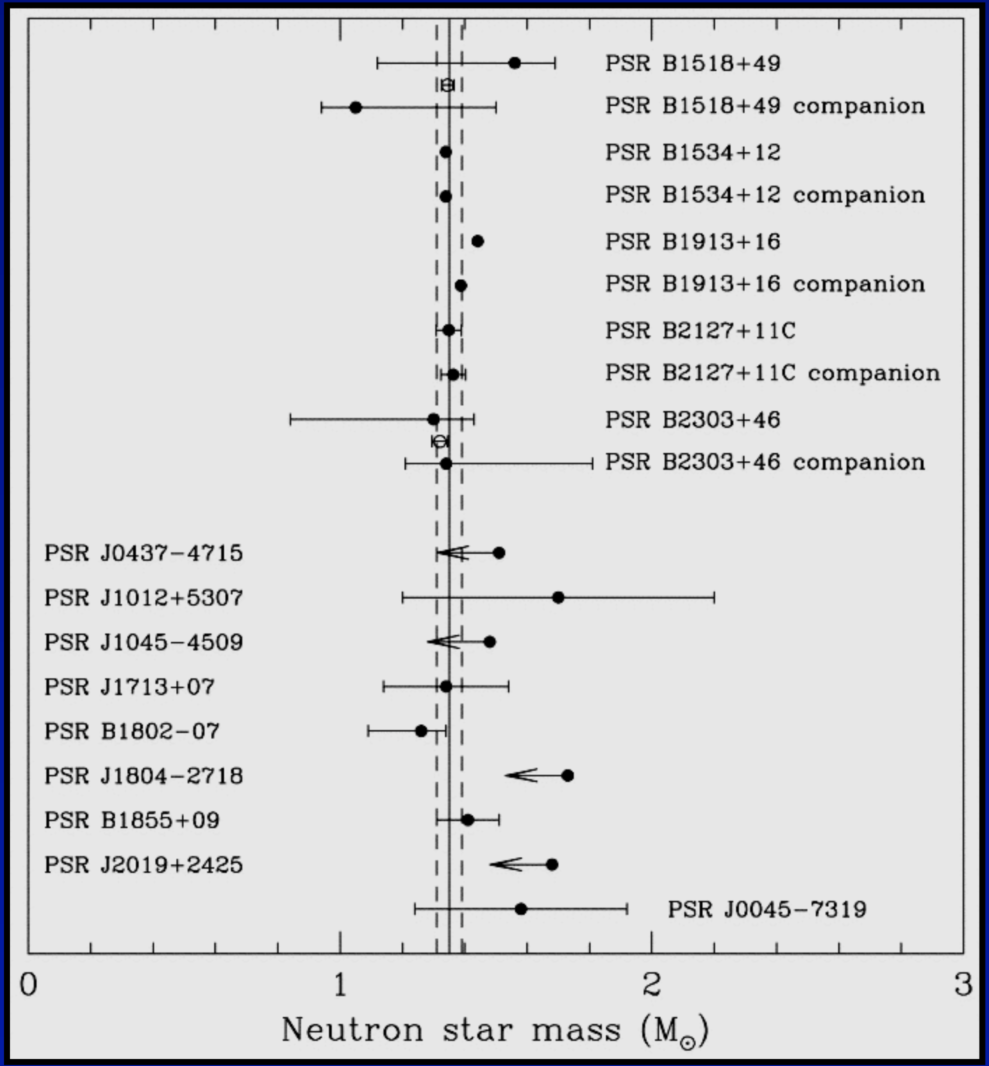
Neutron-star EOS: Why?

- 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.

Dynamical mass constraints

Masses of NS obtained from pulsars in binary systems.

$$\langle M \rangle = 1.35 \pm 0.04 M_{\odot}$$



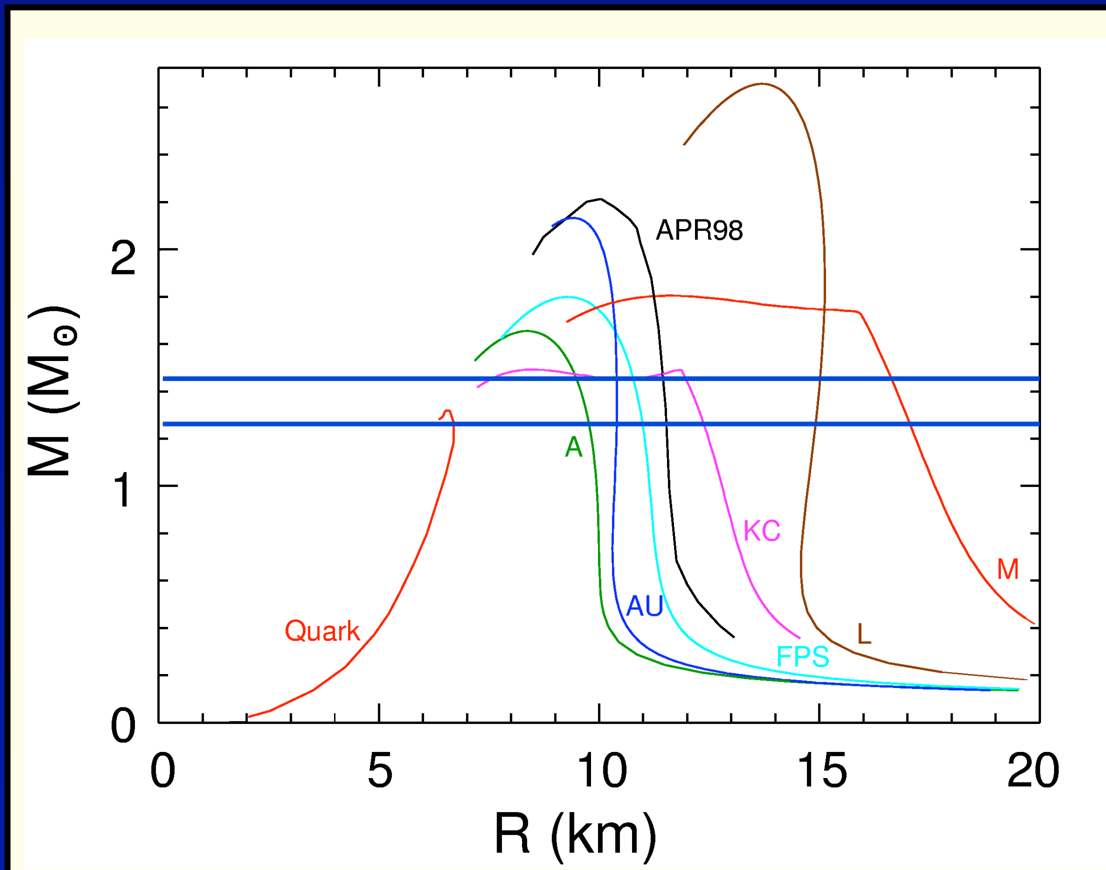
Thorsett & Chakrabarty

Equation of State of nuclear matter.

The interactions between the particles that constitute stars determines the equation of state (EOS), a relation between pressure and density, $P = P(\rho)$, that can be translated into a mass-radius relation, $M = M(R)$.

Note that some NS masses are very accurately known (in some cases down to 0.1%!!), but measuring the mass alone does not help.

Requires measurements of (a combination of) NS ***mass and radius.***



Neutron star EOS measurements and constraints

Time-resolved spectroscopy and photometry:

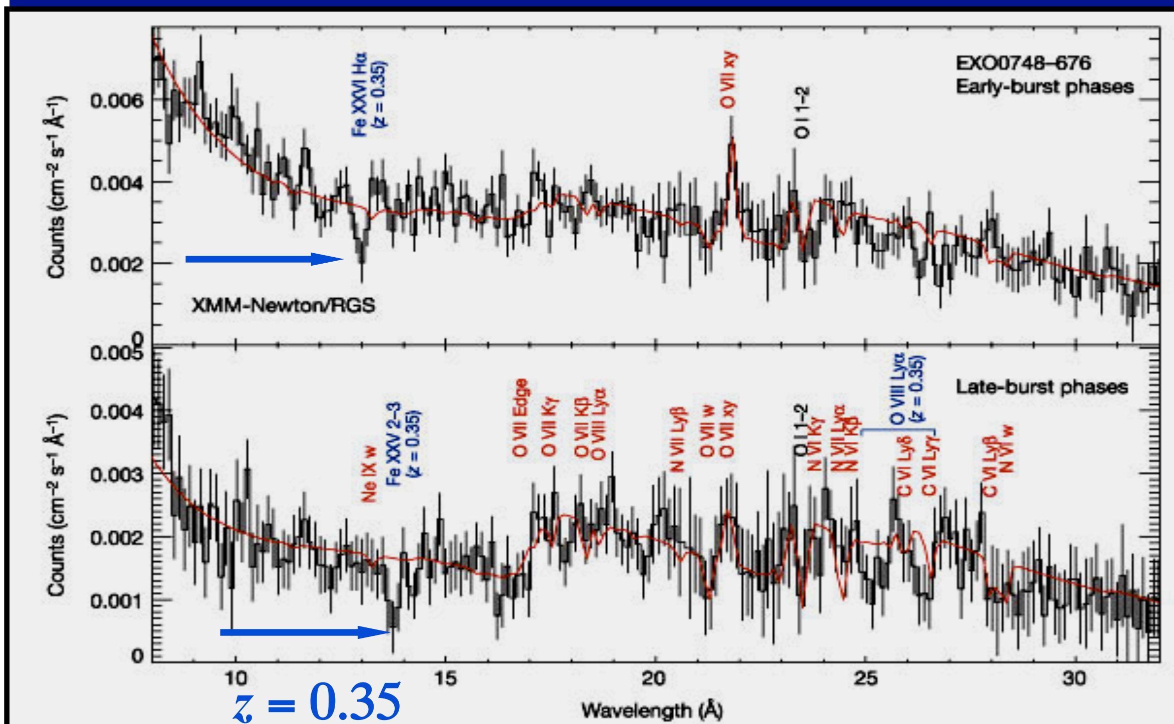
- Redshifted photospheric lines → M/R (potentially M/R^2).
- Profile of photospheric lines → $M\!-\!R$.
- Pulse waveform → $M\!-\!R$.
- Quasi-periodic oscillations → $M\!-\!R$.
- Fe emission (disc) lines → M/R (from disc)
- Frequency-resolved time-delay spectrum → R (from disc)

Photospheric absorption during X-ray bursts

EXO 0748−676, a known X-ray burster

XMM-Newton observed it as a calibration target:

∼ 335 ks with RGS cameras; spectra of 28 X-ray bursts co-added.



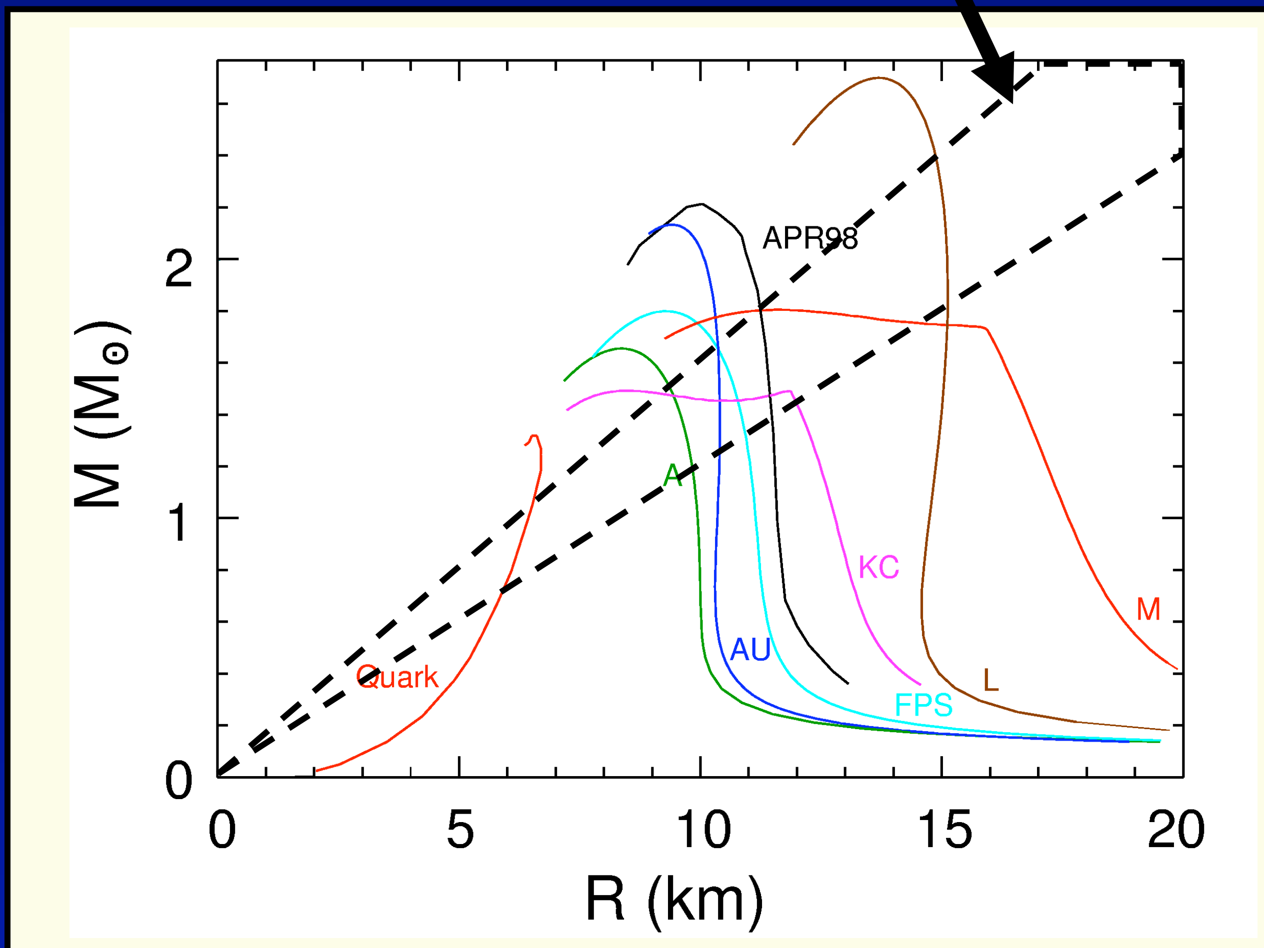
Absorption lines at λ 13.0Å and λ13.7Å in the combined early- and late-burst spectra, respectively.

Fe XXVI (n = 2-3) and Fe XXV (n = 2-3), respectively, at the same redshift $z = 0.35 \pm 0.01$.

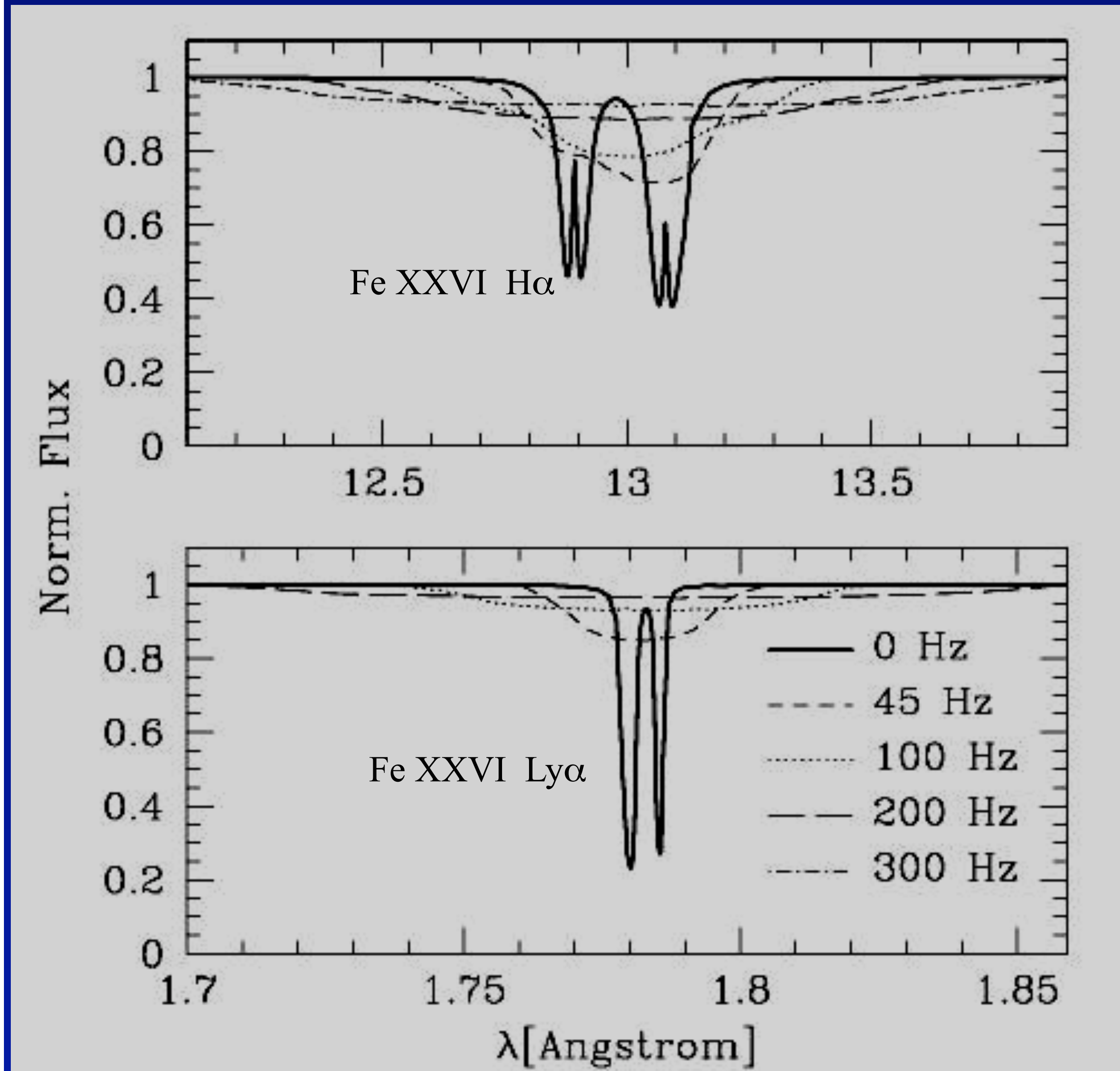
Cottam, Paerels & Méndez

EOS – Constraining mass and radius

$$M/R = 0.15 \pm 0.01 M_{\odot}/\text{km}$$



Rotational broadening of "structured" lines



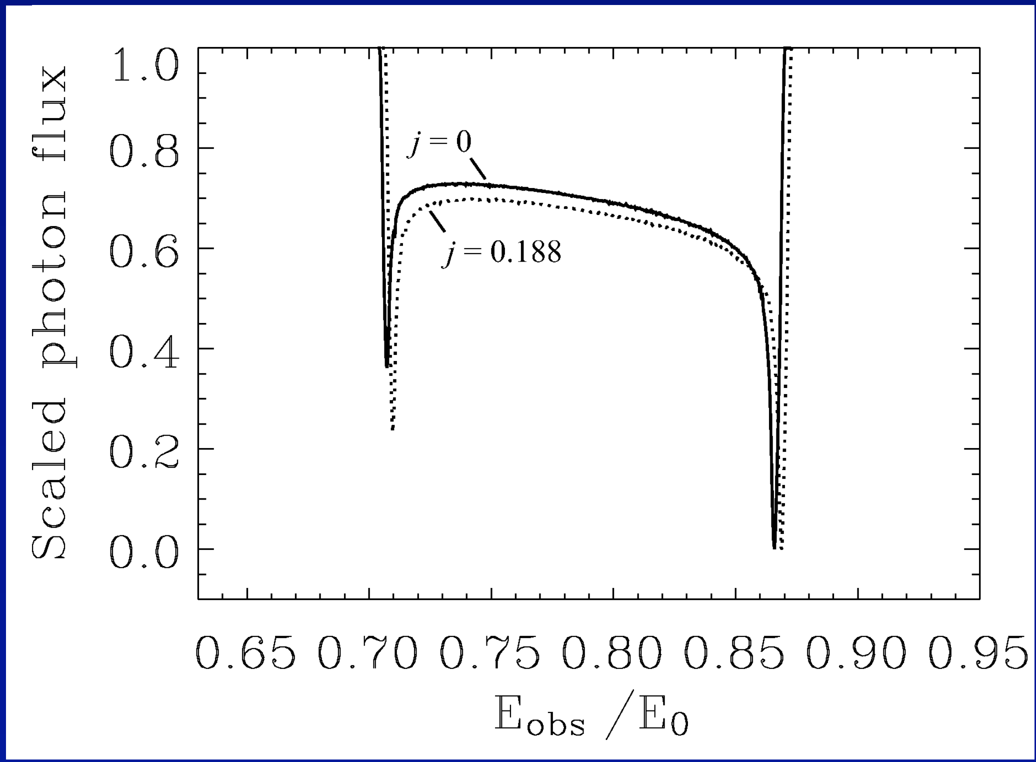
Rotational broadening may be significant, depending on spin frequency and viewing angle.

Chang et al.

Spectral line profile

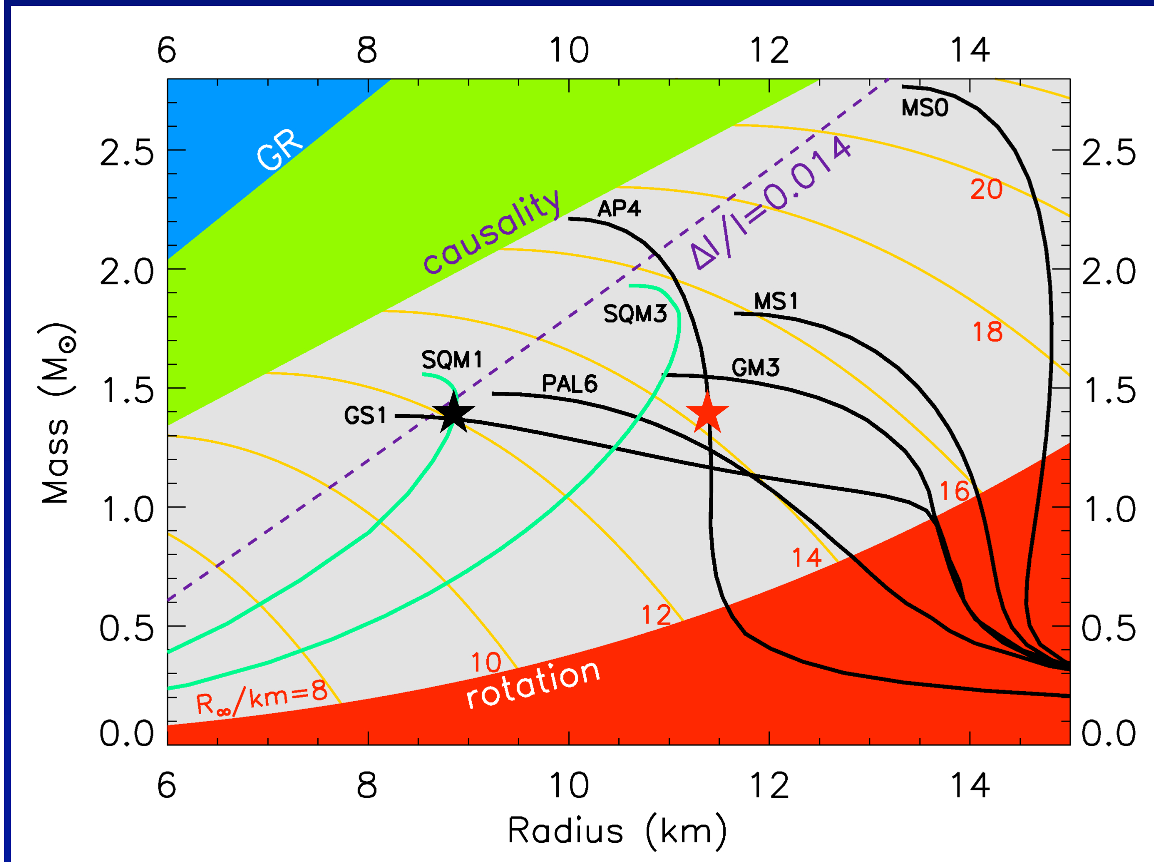
Mechanisms that affect the shape of spectral lines:

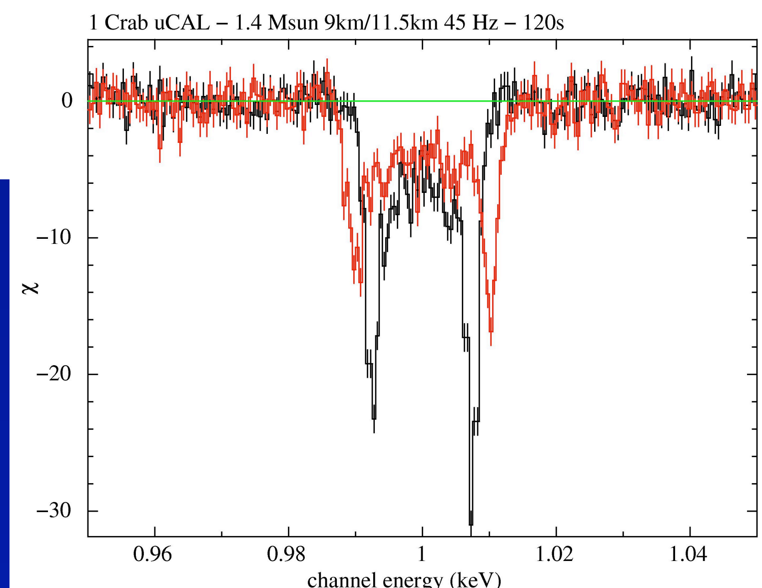
- longitudinal and transverse Doppler shifts,
- special relativistic beaming,
- gravitational redshifts,
- light-bending,
- frame-dragging.



Bhattacharyya et al.

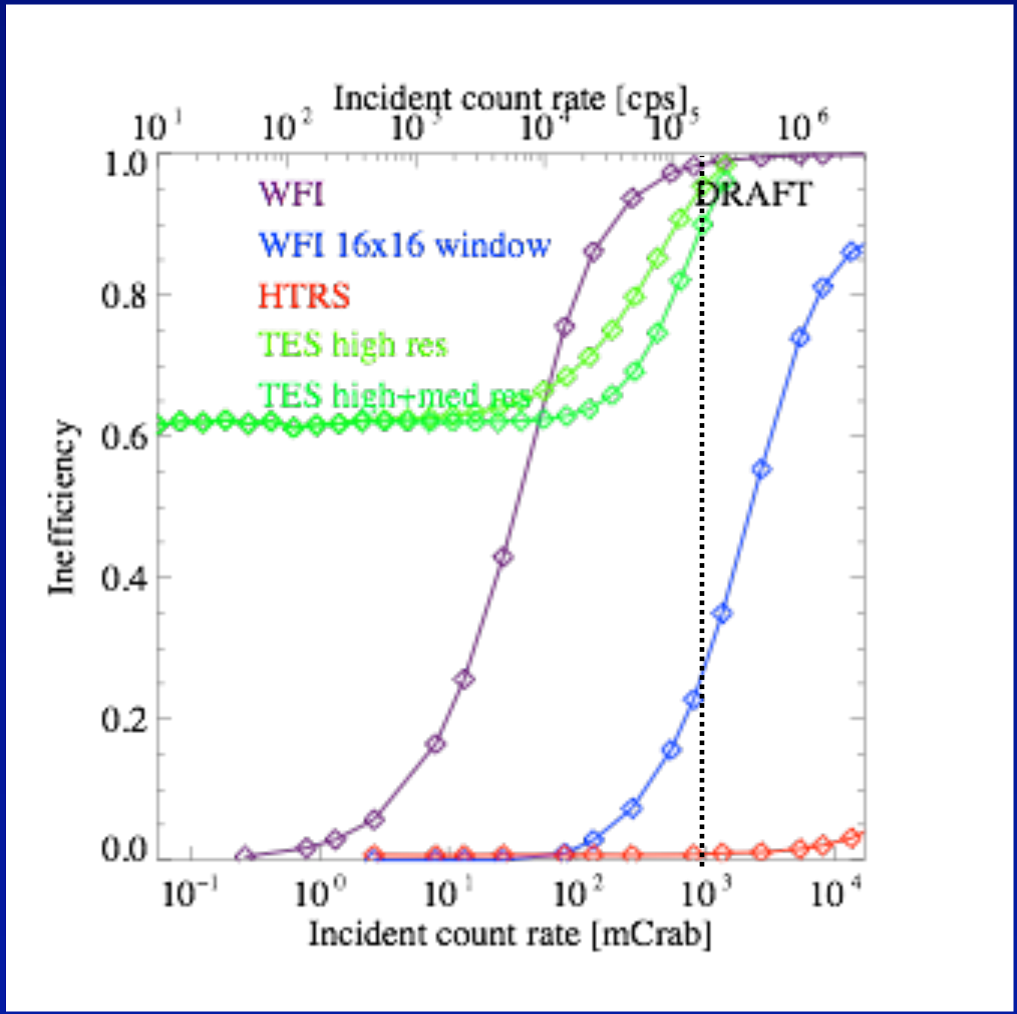
Simulated spectral line profile





Line profile calculations courtesy of S. Bhattacharyya

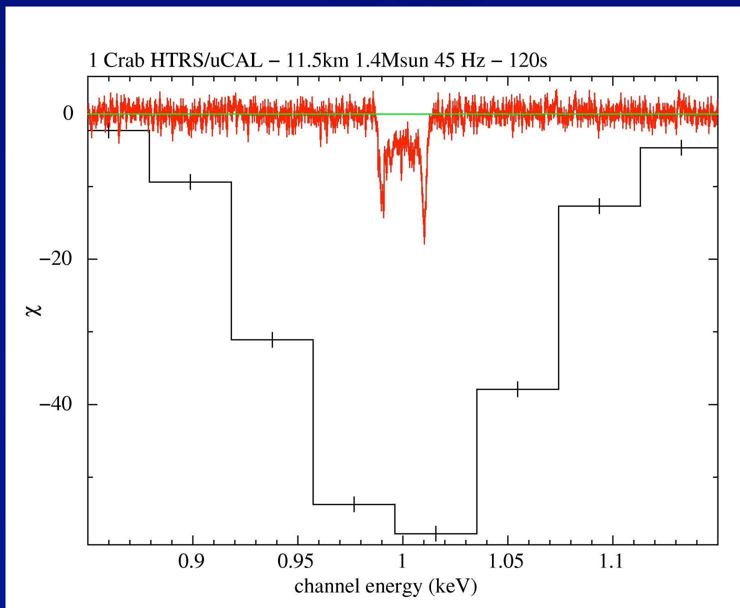
HTRS and Calorimeter

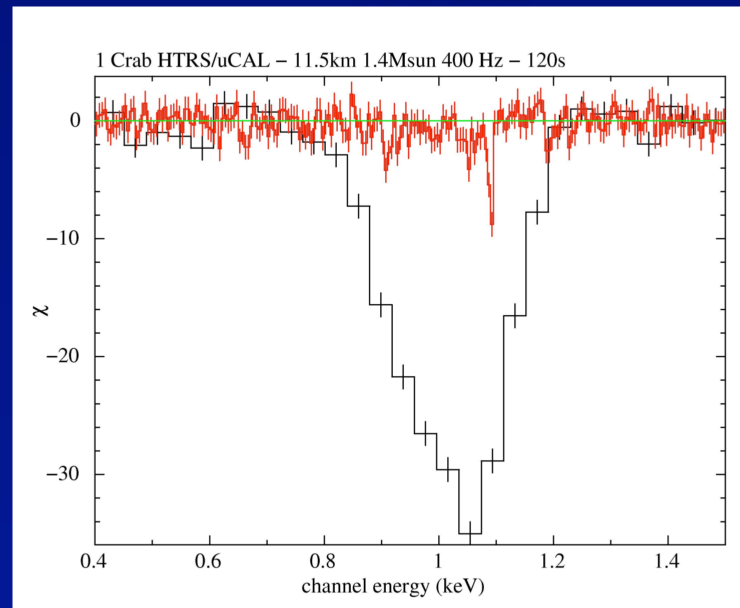


Simulations by J. Wilms et al.

Simulations

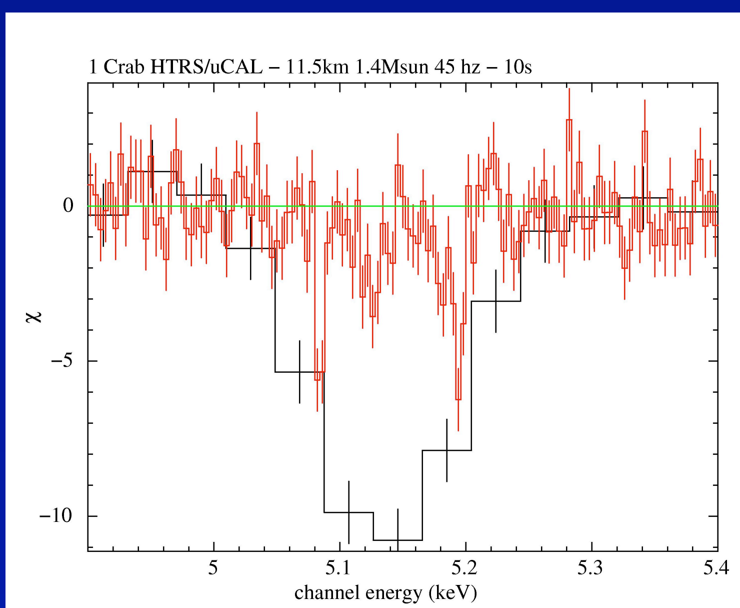
45 Hz | 400 Hz

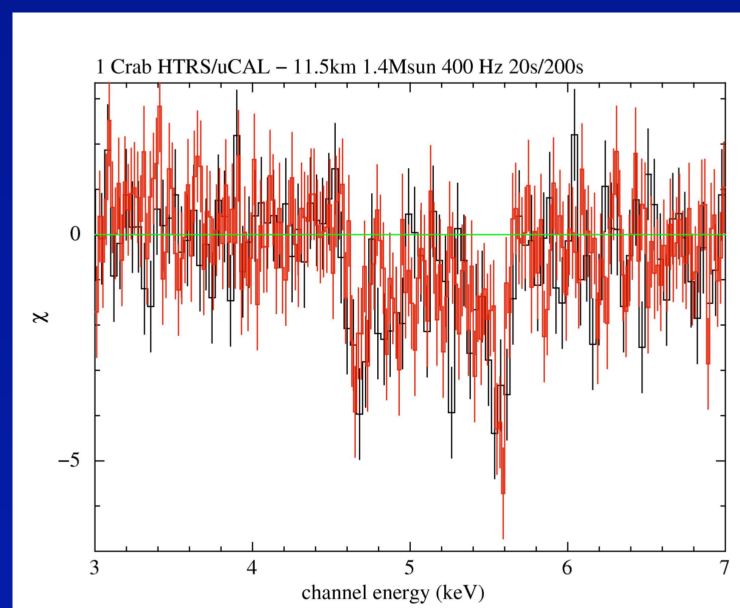




Fe XXVI
z **= 0.35**

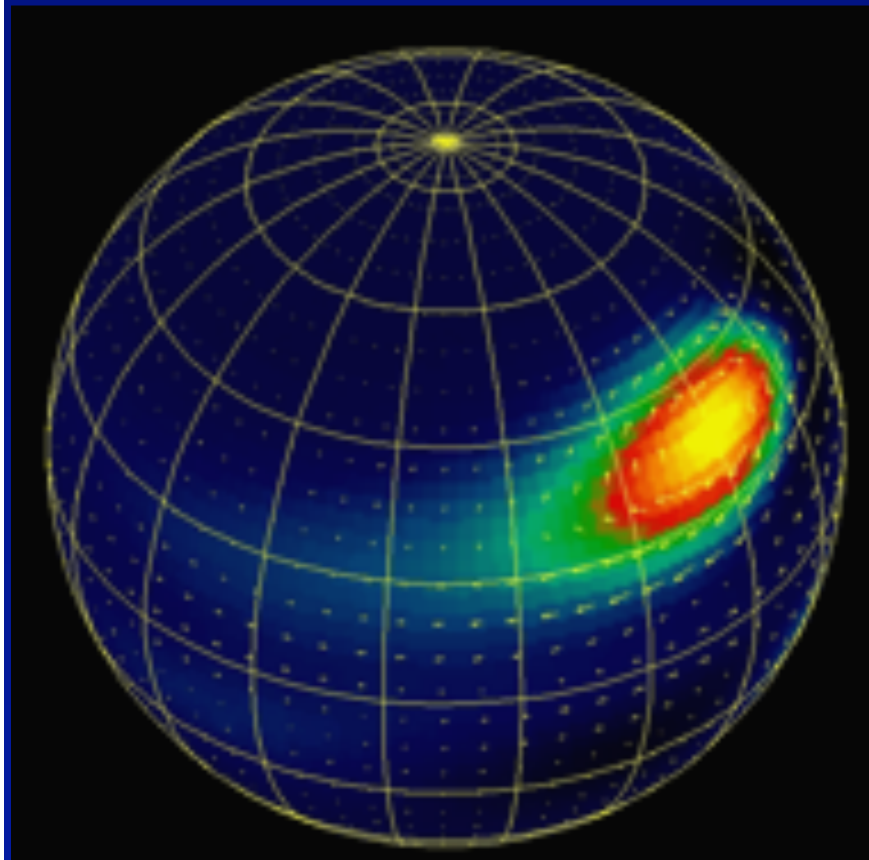
n **= 2 – 3**
Balmer α

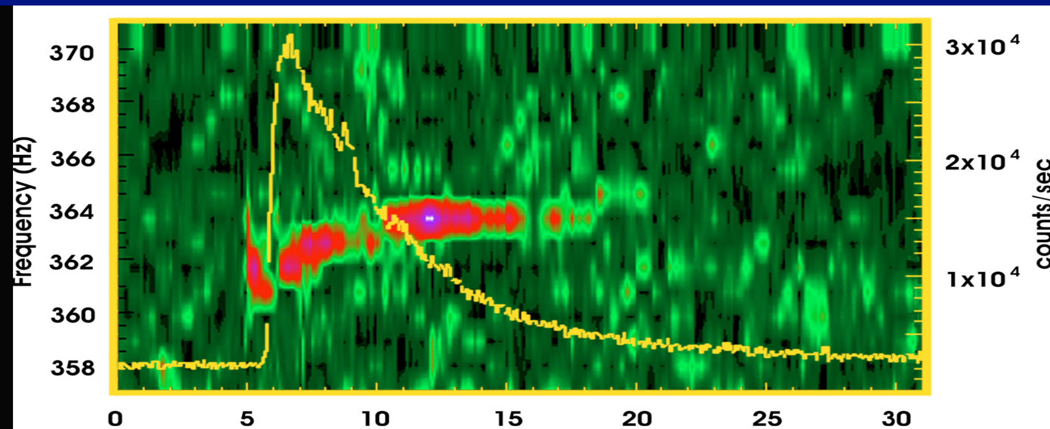




n **= 1 – 2**
Lyman α

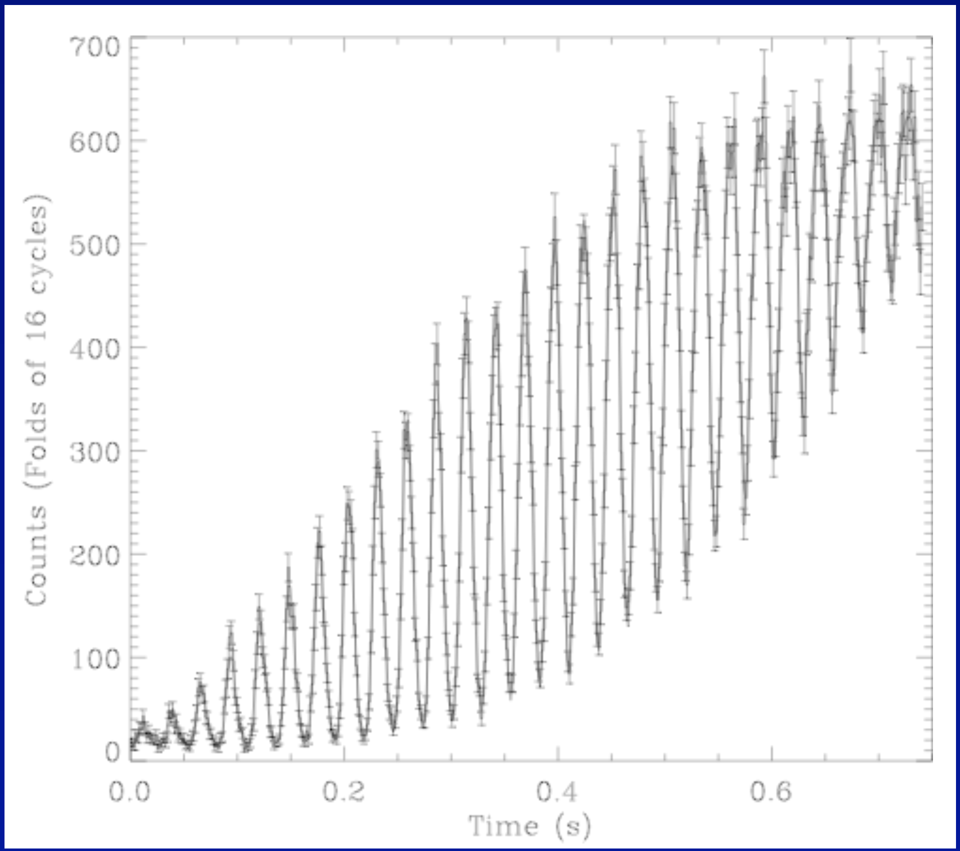
Pulsations during X-ray bursts

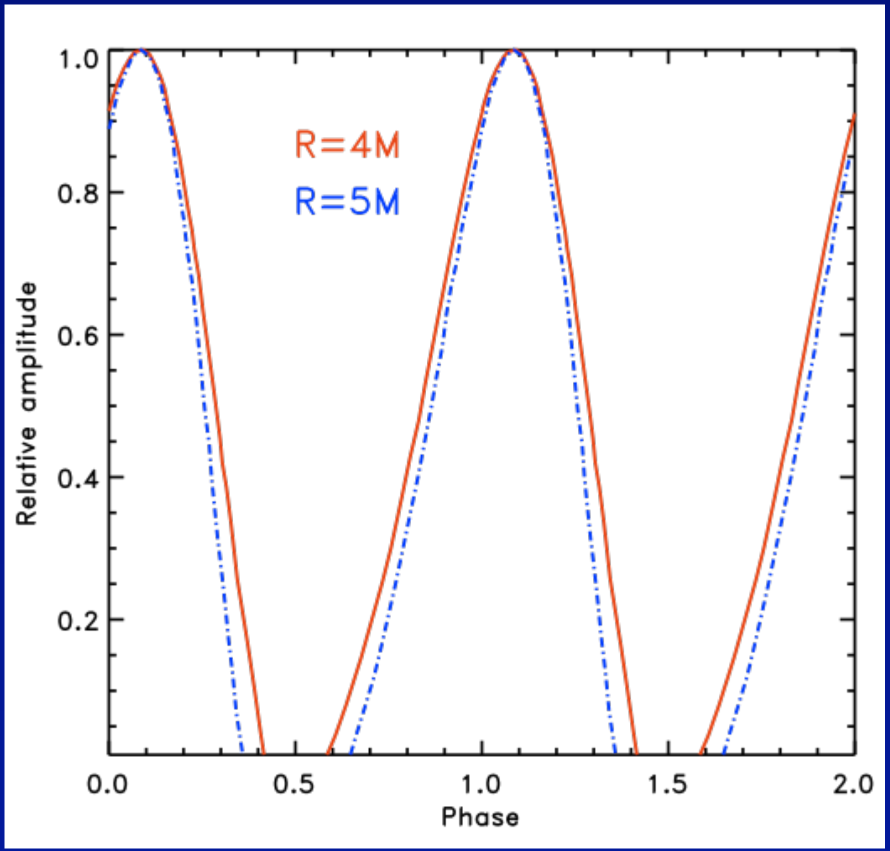




Strohmayer et al.; Spitkovsky et al.

Pulsations during X-ray bursts

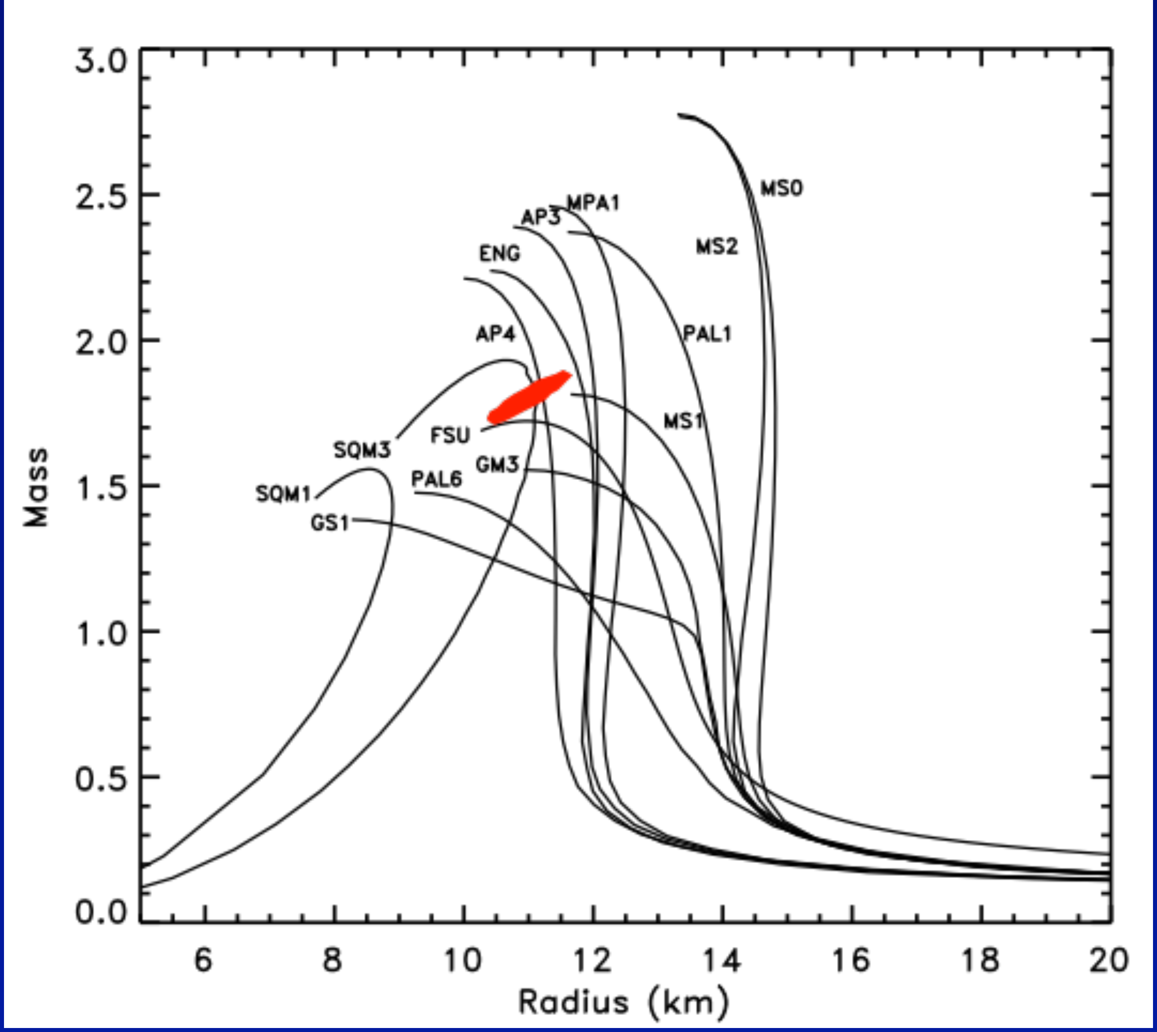




Simulated pulse profile for the rising phase of an X-ray burst (T. Strohmayer).

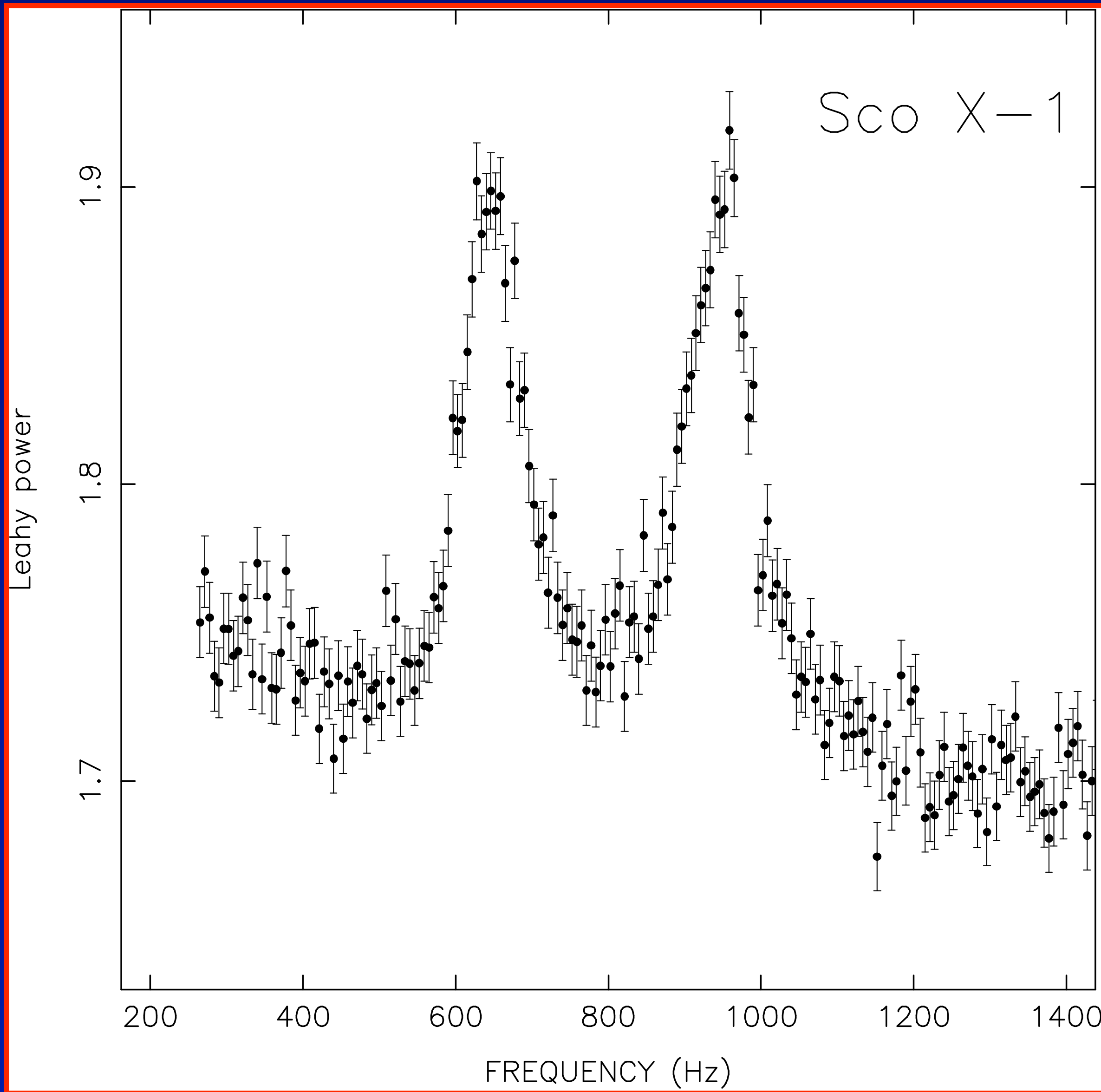
Simulated pulse profiles for a 1.8 solar mass NS with a spin frequency of 364 Hz. (C. Miller).

Pulsations during X-ray bursts

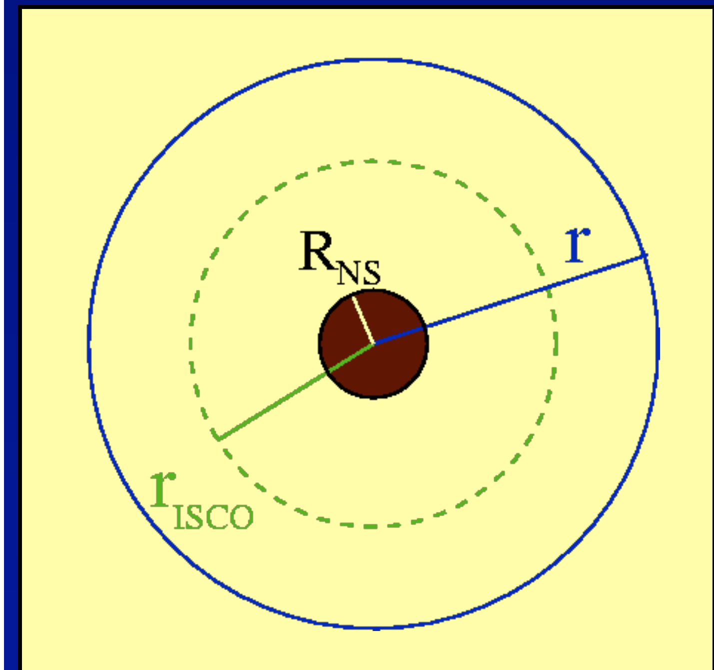


Mass and radius constraints from pulse-profile fitting. The red ellipse shows the 95% confidence regions from 5 typical bursts (C. Miller).

Quasi-periodic oscillations



Mass and radius constraints from timing



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

$$r_{\rm isco} \leq r$$

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

$$r_{\rm isco} = \frac{6GM_{\rm NS}}{c^2}$$

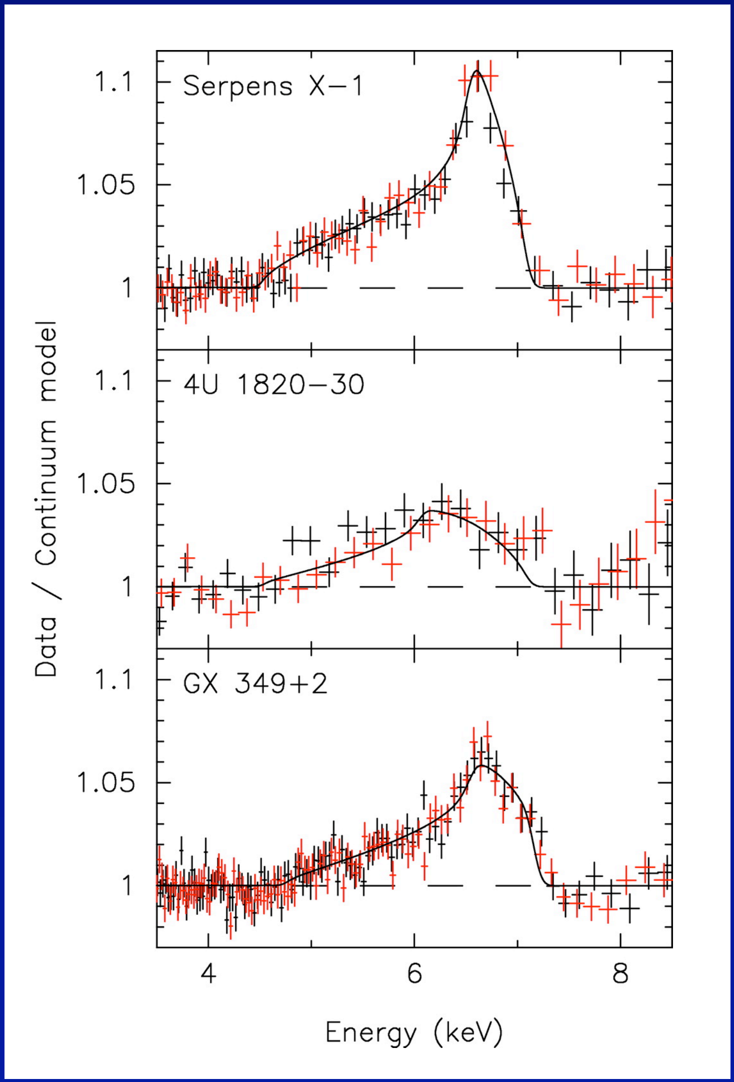
$$M_{\rm NS} \leq 2.2(\nu/1000{\rm Hz})^{-1} M_\odot$$

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

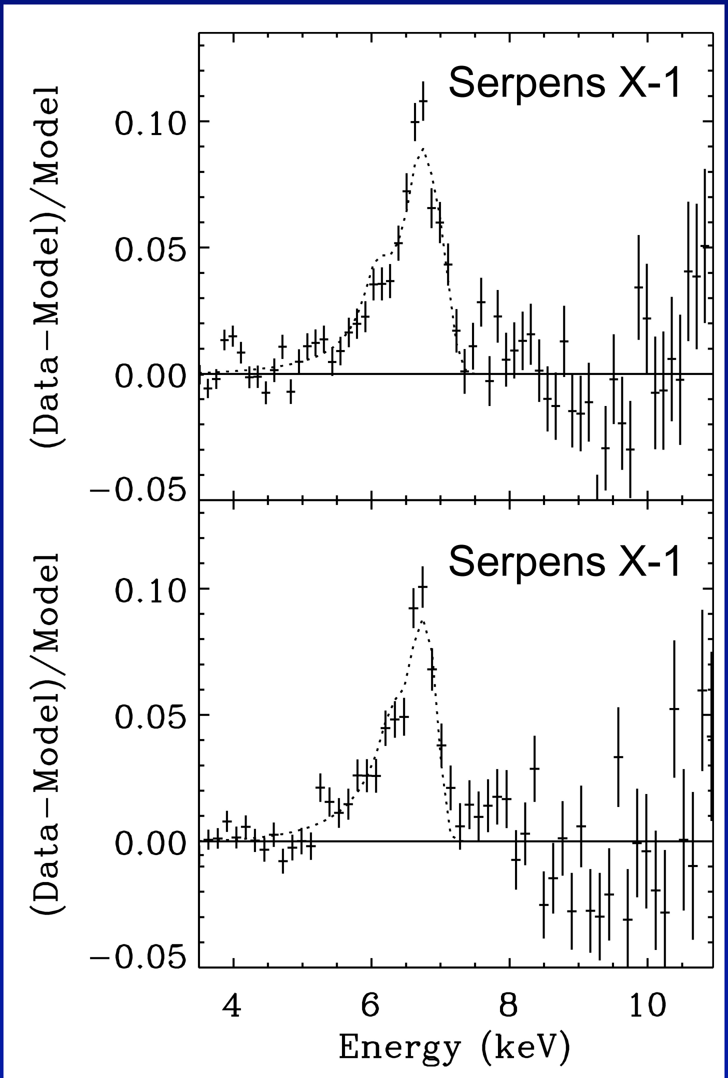
C. Miller et al.

Emission lines from the inner disc

Suzaku



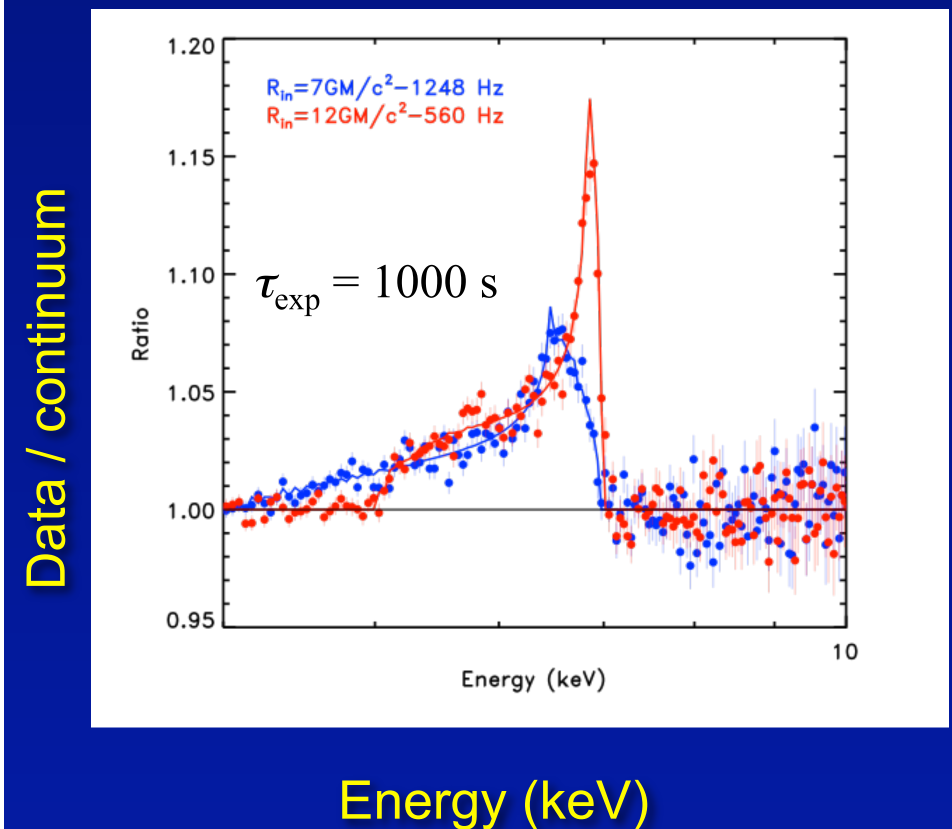
XMM-Newton

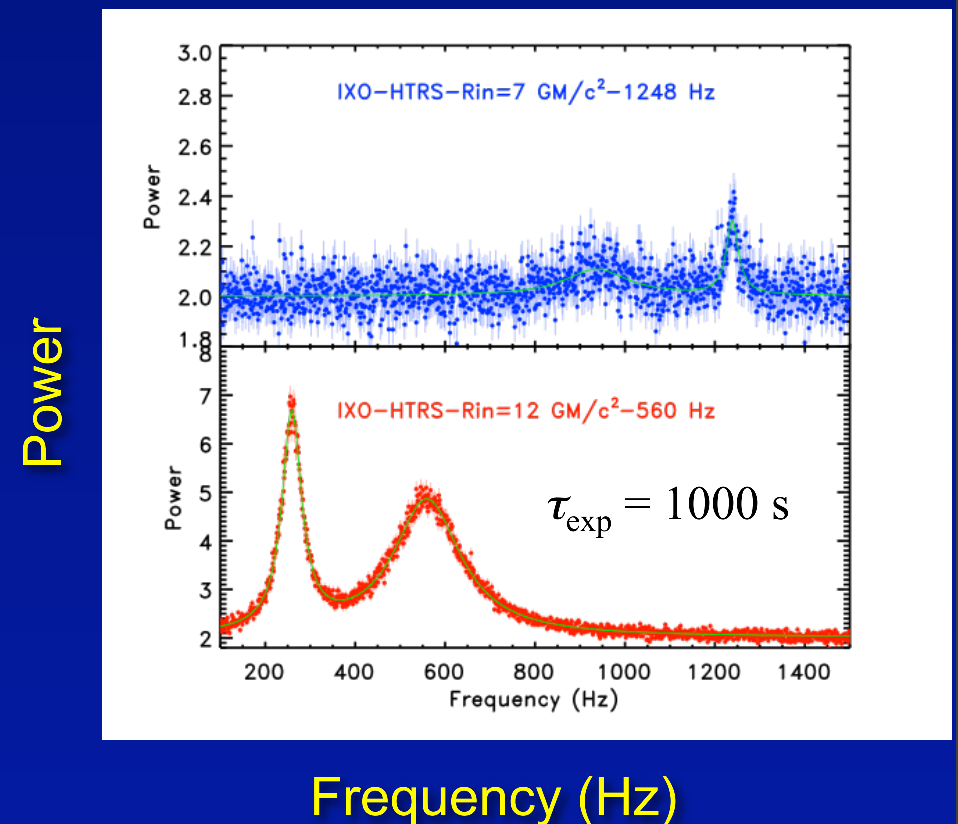


$M/R = 0.03 - 0.17 M_{\odot}/\mathrm{km}$

Cackett et al.; Bhattacharyya & Strohmayer

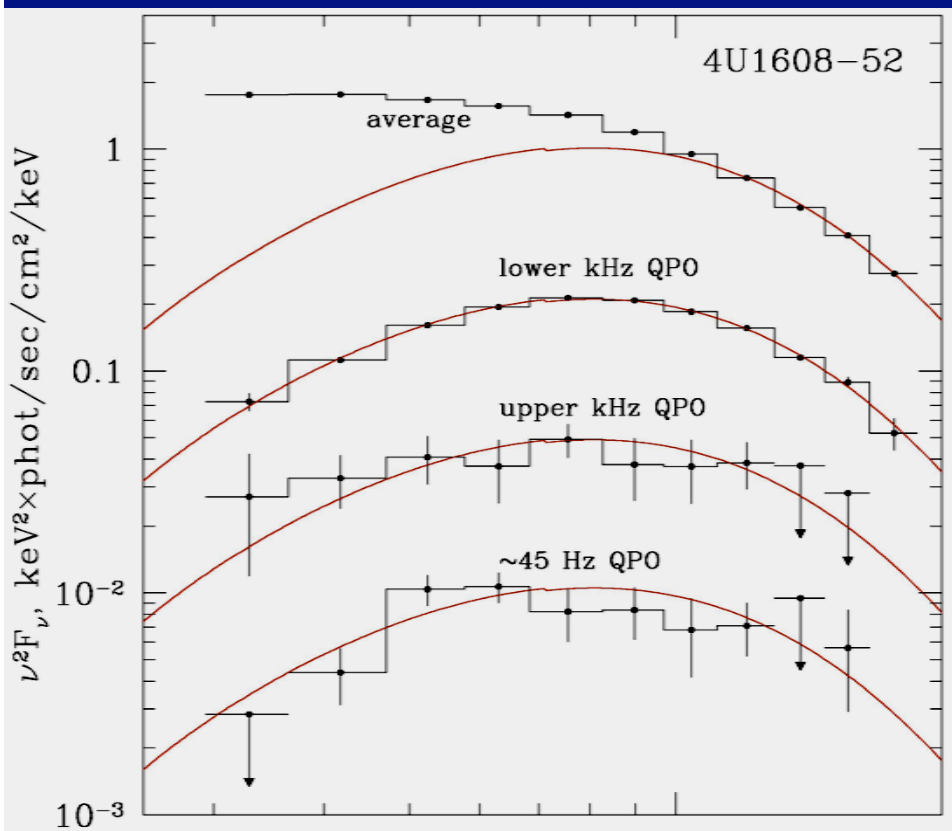
Tracking the inner disc radius

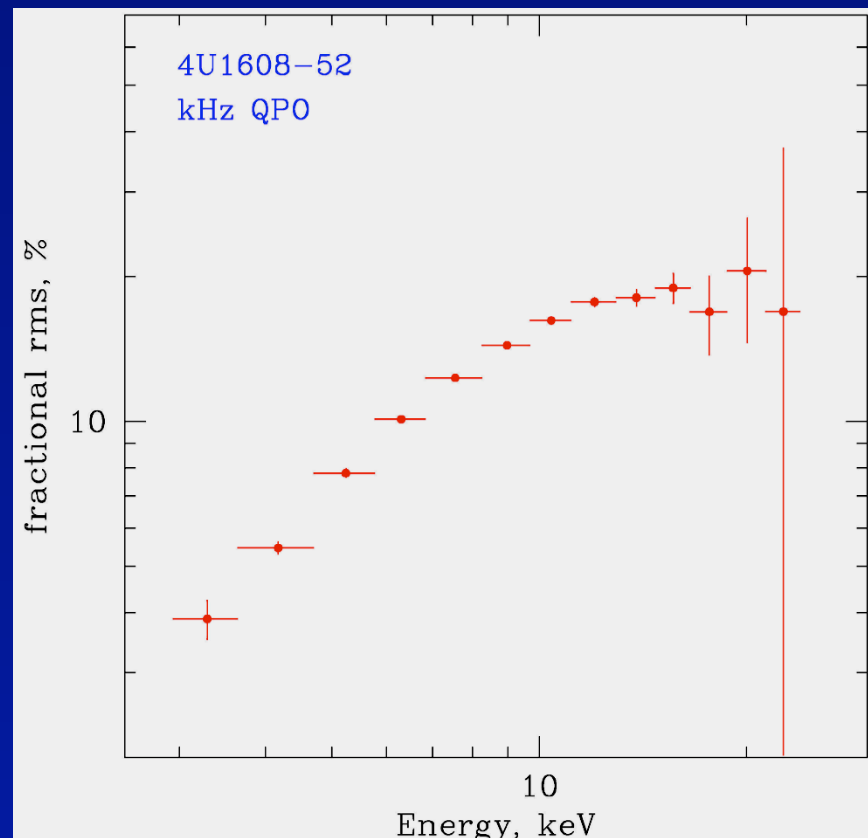




IXO/HTRS simulations by D. Barret

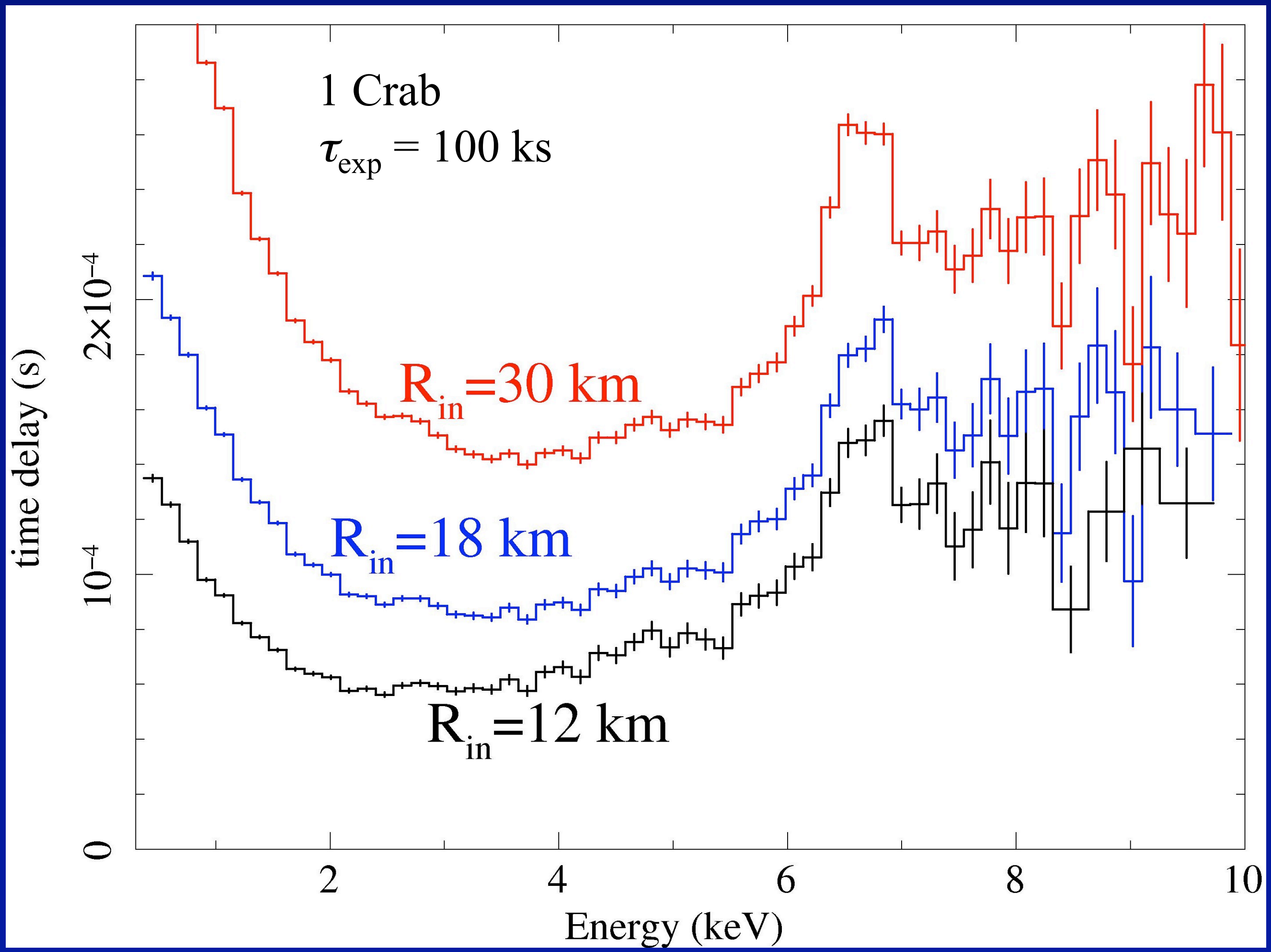
Measuring the inner disc radius





Gilfanov et al.

Frequency-resolved time-delay spectrum



IXO/HTRS simulations by P. Uttley

Neutron star EOS measurements and constraints