

# The Equation Of State (EOS) of neutron stars

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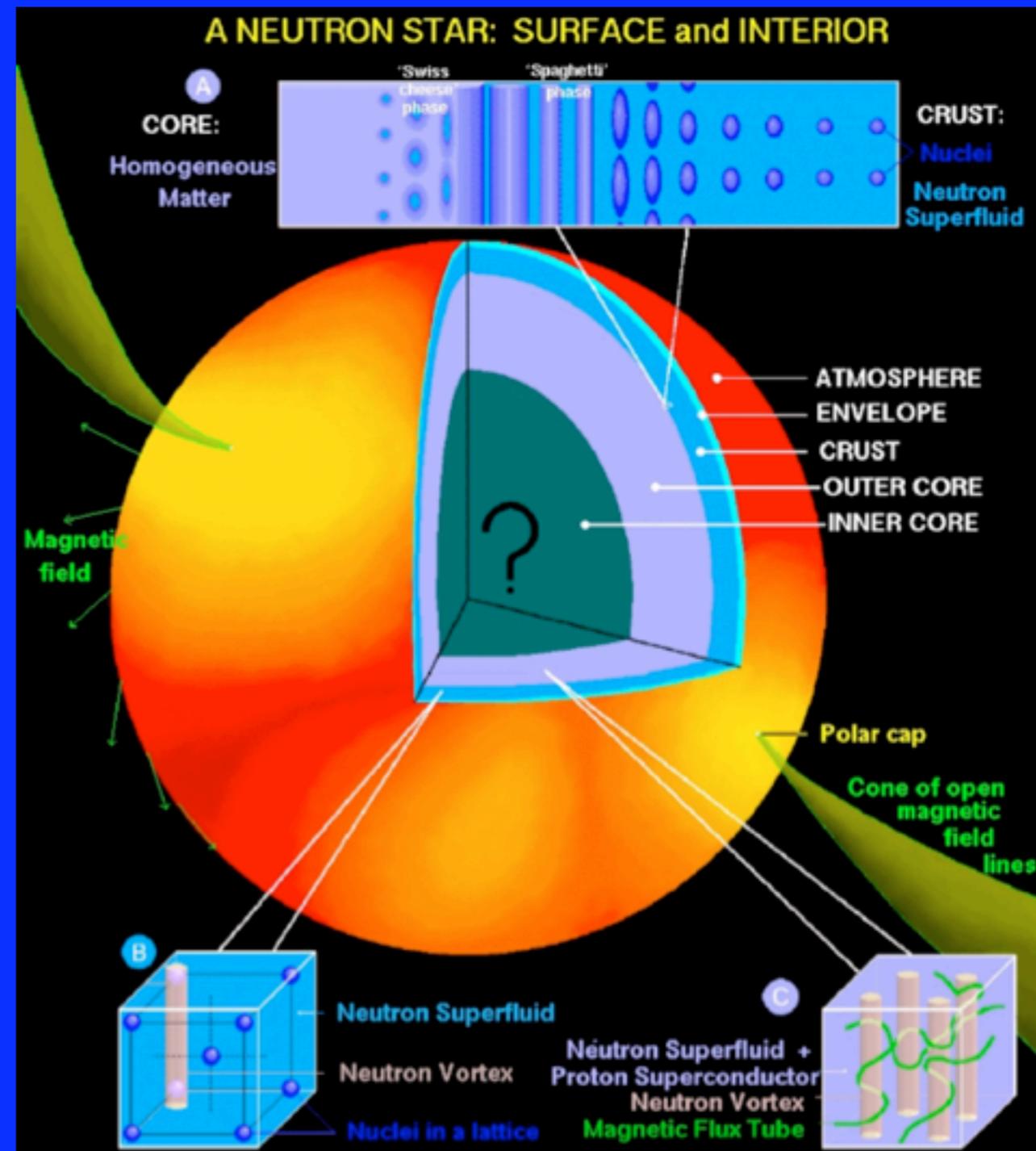
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# Neutron star structure

- Atmosphere from where the X-ray/optical emission arises
- Envelope whose composition affects the latter emission
- Crust extends down to 1/3 of the nuclear saturation density is composed of nuclei and dripped neutrons
- Terminates as phase transition to uniform nucleonic matter
- Inner core?  $\rho \sim 10^{15} \text{ g/cm}^3$



Courtesy of D. Page

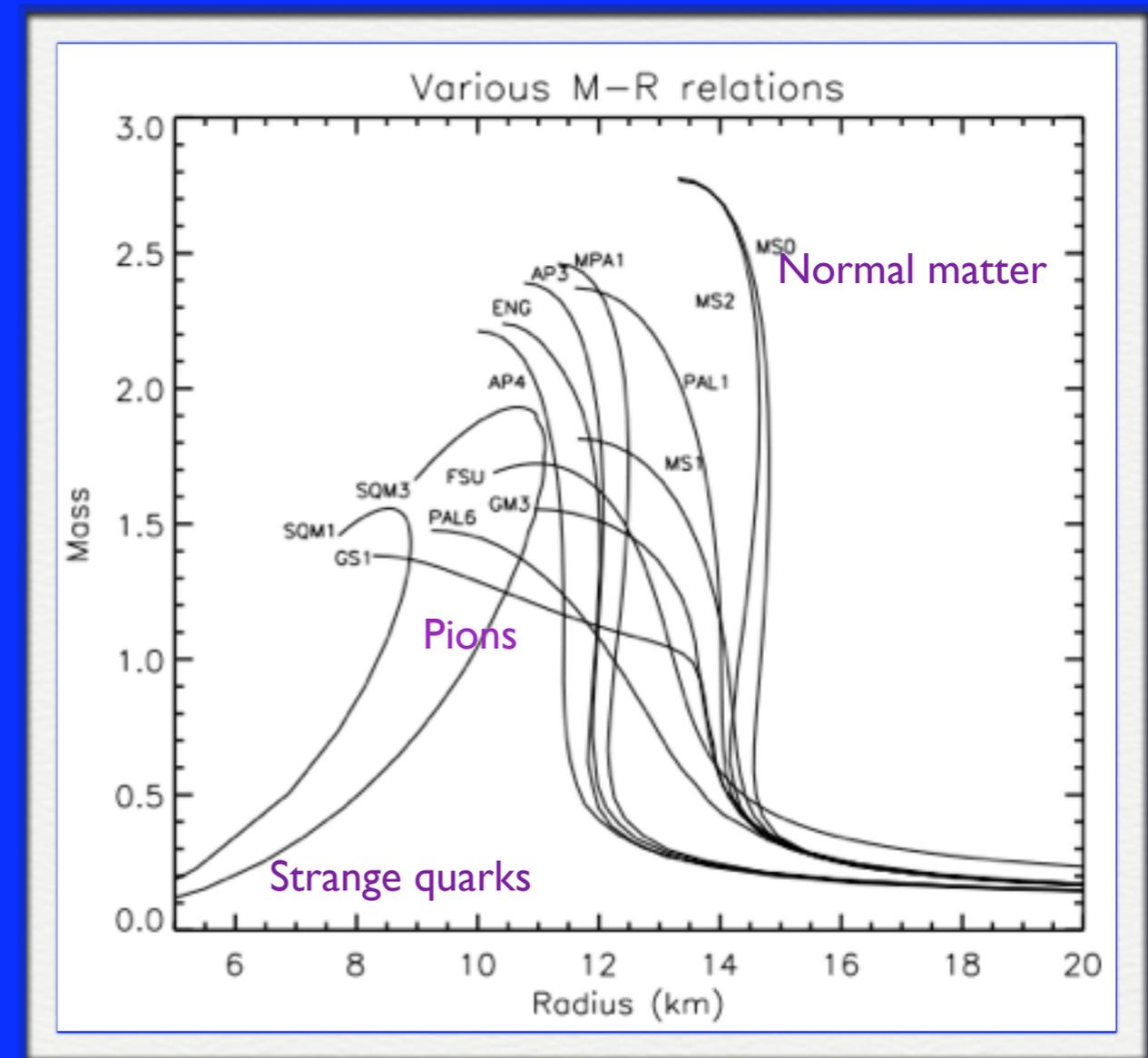
# The equation of state

- Interactions between the particles making up stars determine the EoS; a relation between the  $P$  and  $\rho$

✓ which can be translated into a mass-radius relation:  $M=M(R)$

- Difficulty to extrapolate standard nuclei matter with 50% proton fraction to exotic matter at  $\sim 0\%$  proton fraction

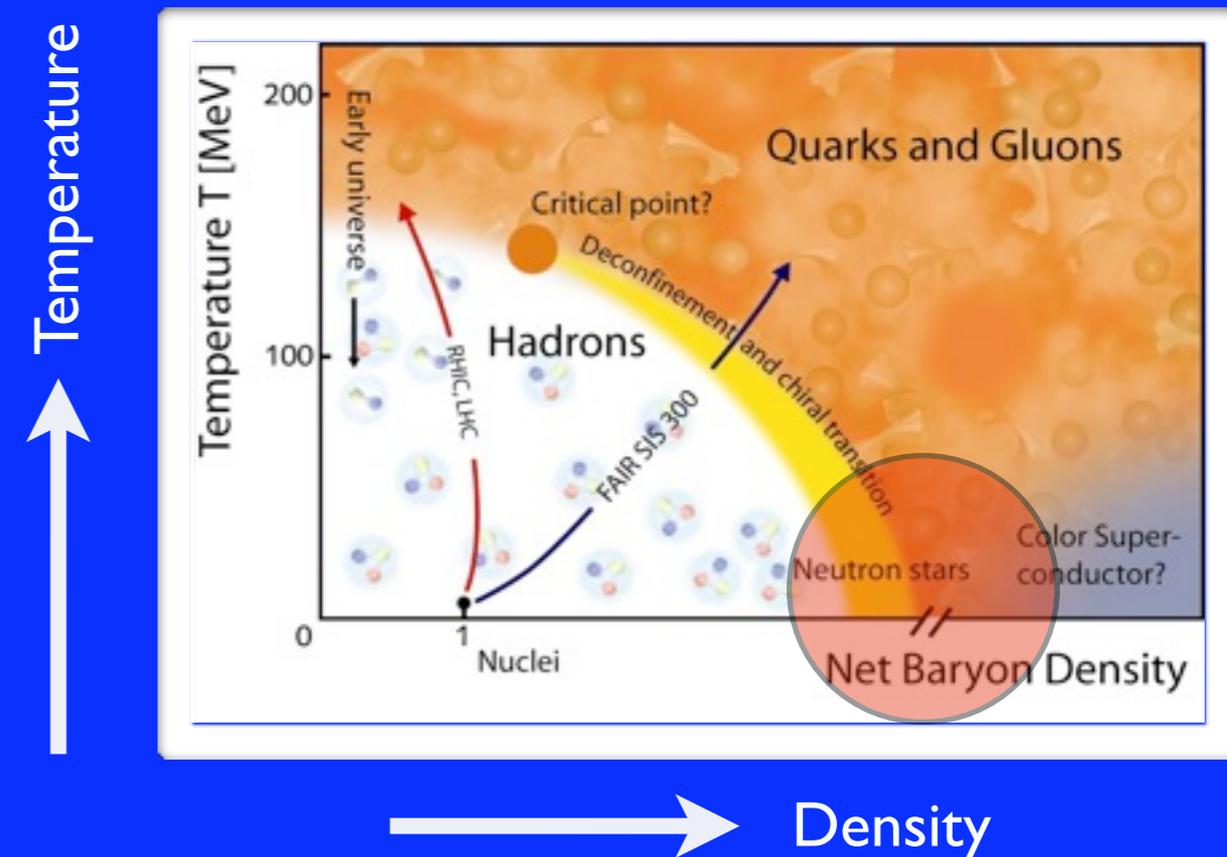
✓ Exotic matter may be present - strange quark matter, pions, hyperons



Adapted from J. Lattimer

# Why bother?

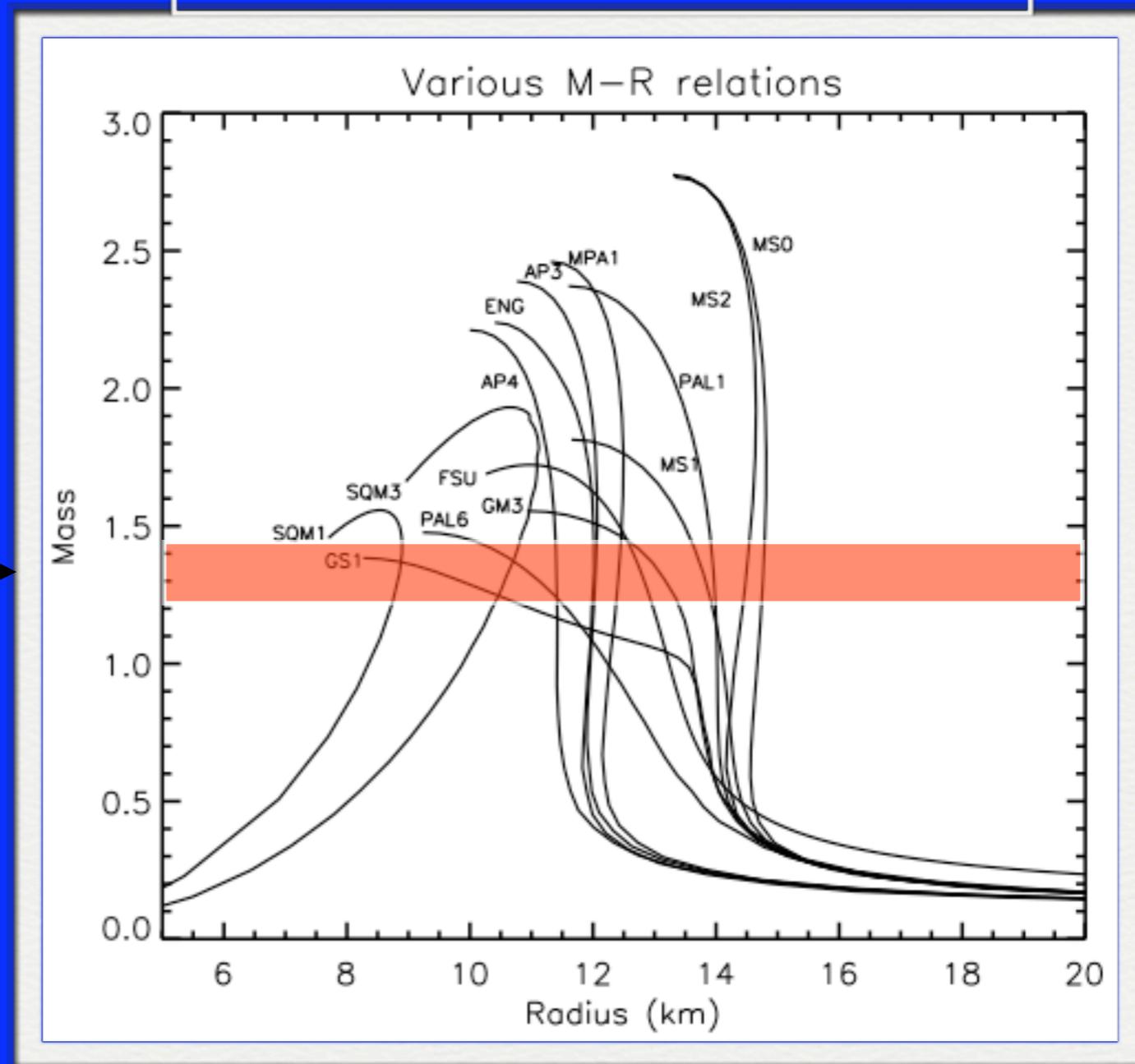
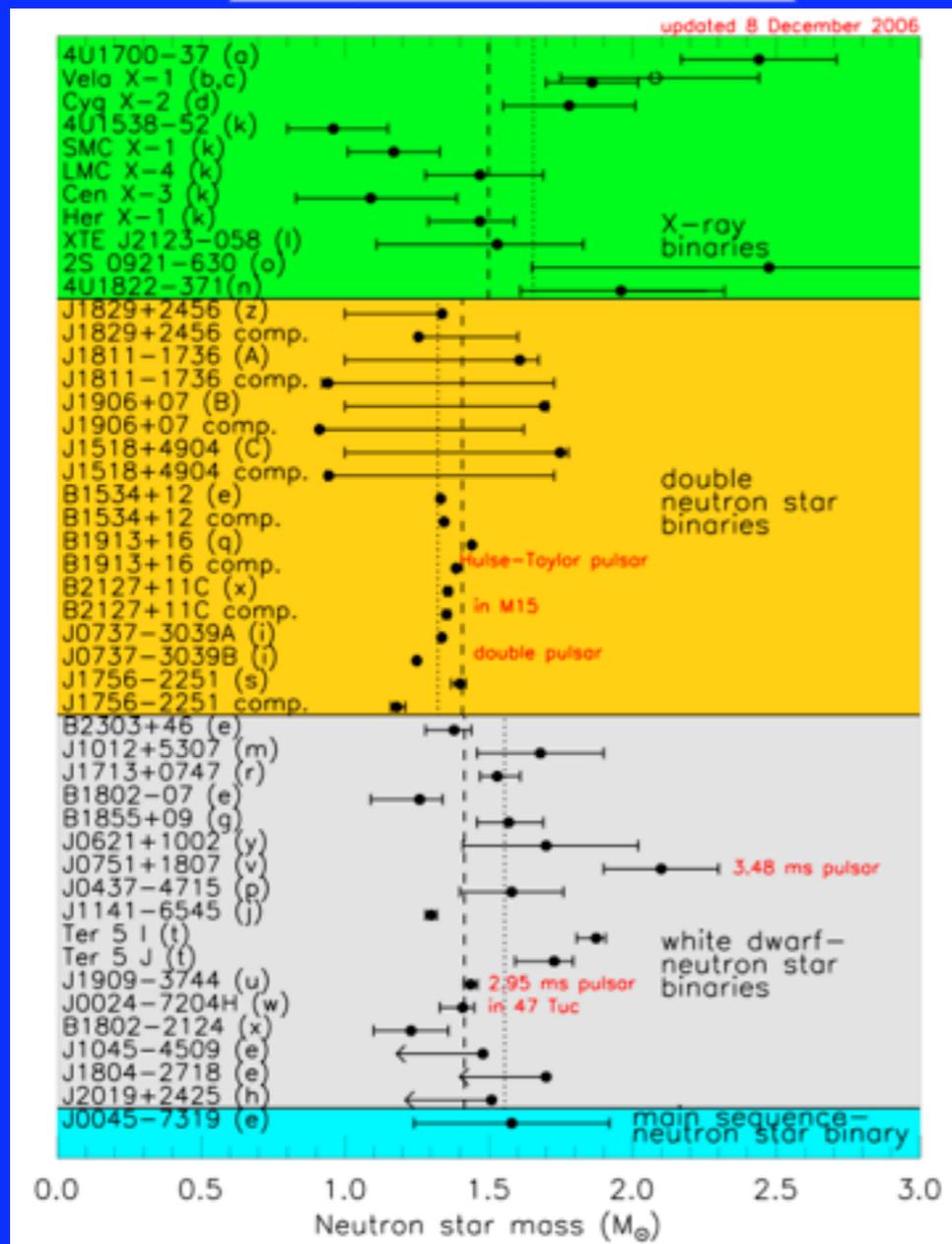
- Neutron stars probe the low temperature and large density region of the QCD phase diagram
  - ✓ This regime is expected to be marked by the appearance of exotic matter and phase transitions.
  - ✓ This regime can only be probed by astrophysical observations of neutron stars
    - ➔ key goal of physics in general
- Relevance also to the physics of supernovae, to short GRBs (NS mergers and GW emitters)



# Constraining the EoS

Adapted from J. Lattimer

Constraints from accurate mass measurements



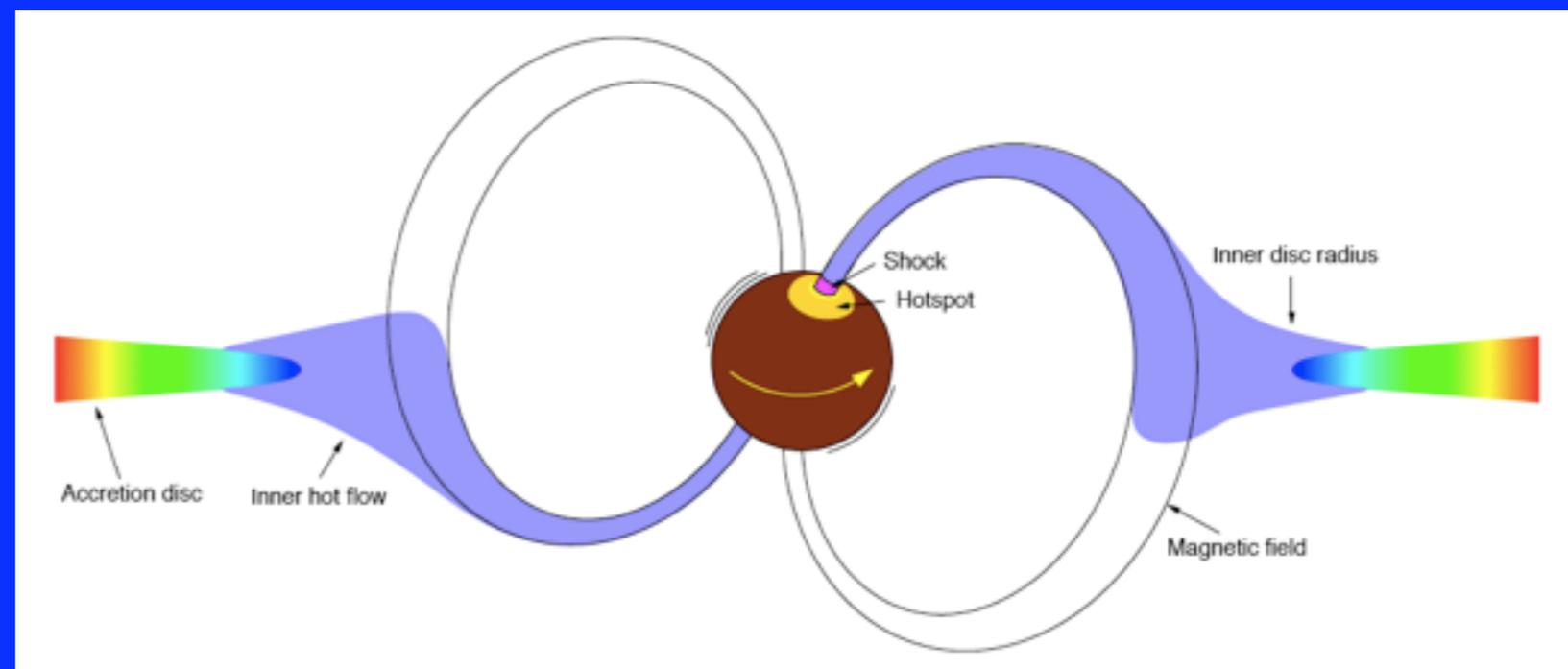
➔ Need simultaneous measurements of M and R

# Using X-rays to constrain the EoS

- Generated during type I X-ray bursts, by rotating surface hot spots, by the accretion disk, by surface emission, by crust vibration modes



Type I X-ray burst



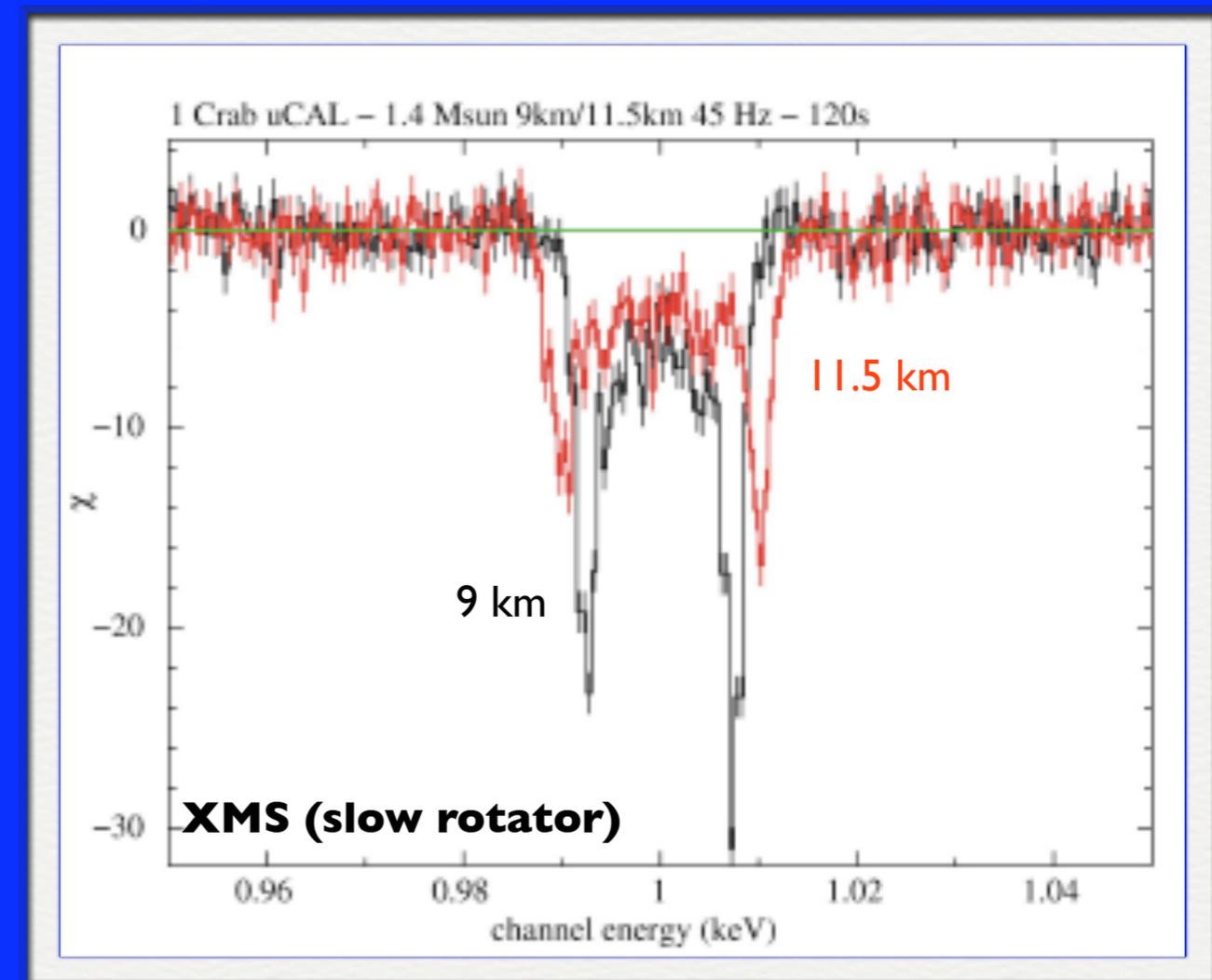
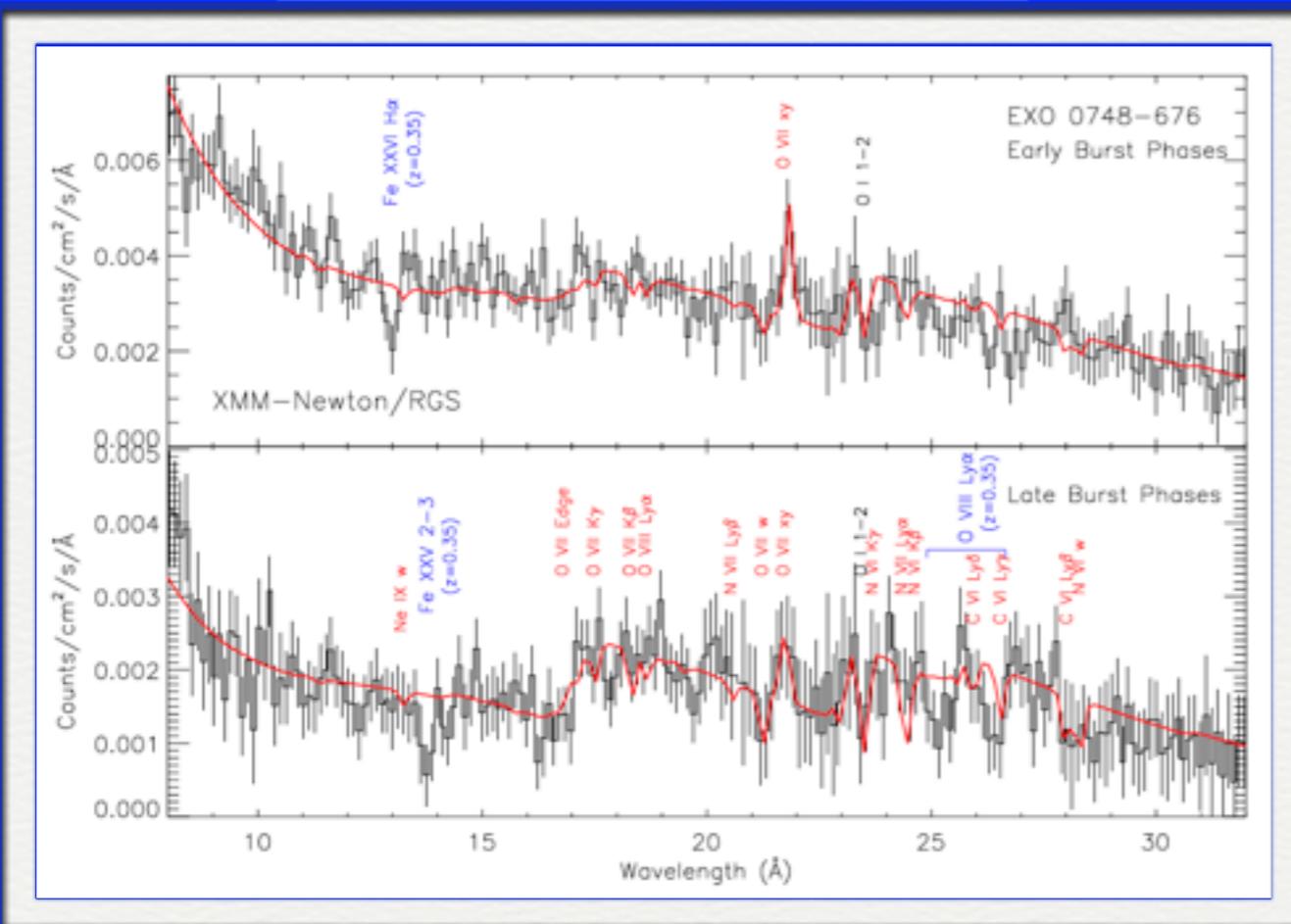
Accreting millisecond pulsar - Gierlinski, Done & Barret (2002)

To be observed with eV spectral resolution (XMS), sub-ms time resolution and CDD like energy resolution (HTRS), polarimetric capabilities (XPOL), ...

# X-ray spectroscopy of NS

Cottam, Paerels & Mendez (2002)

Redshifted photospheric lines

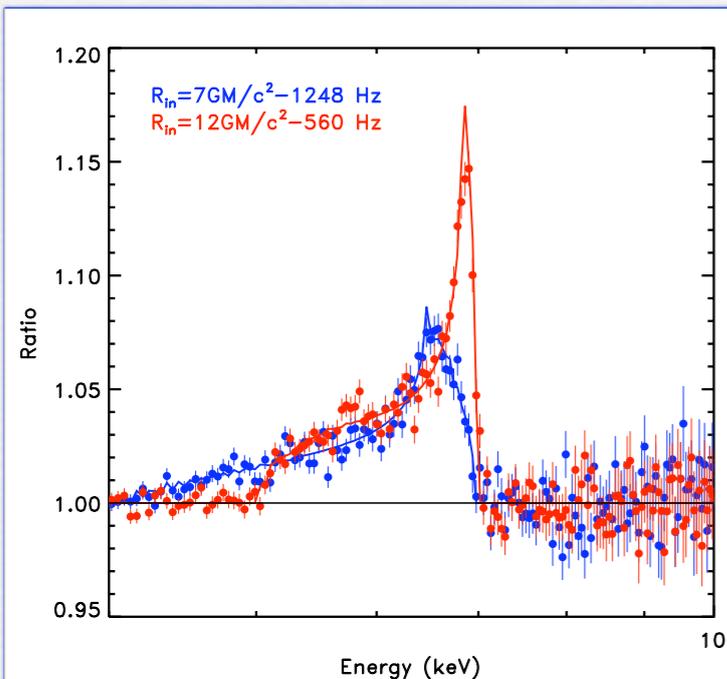


The XMM-Newton RGS spectra of EXO 0748-676 for 28 type I X-ray bursts. The red line is the empirical continuum, with additional O VII intercombination line emission, modulated by absorption in photoionized circumstellar material (Cottam et al., Nature).

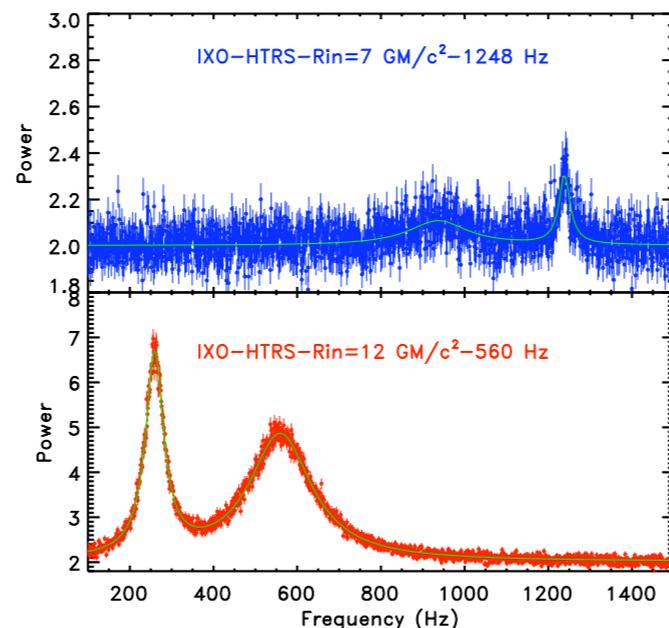
Courtesy of M. Mendez

$\Rightarrow M/R$

# Time resolved X-ray spectroscopy

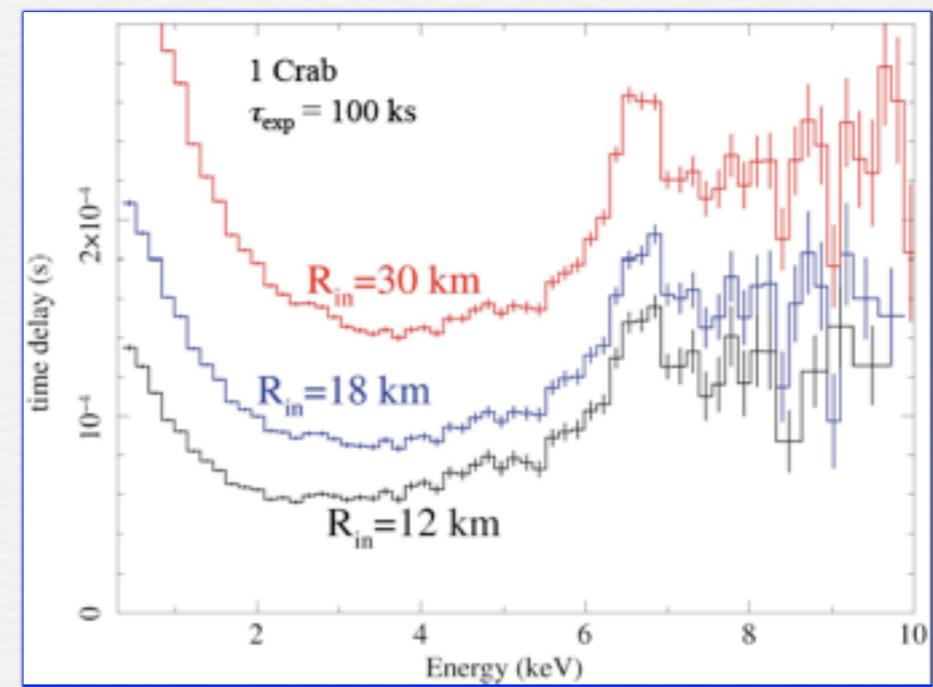


## Relative measures



## Absolute measures

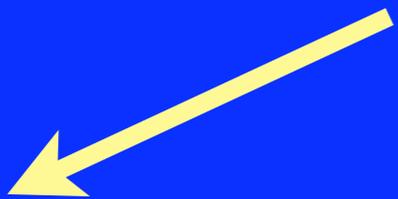
Provided by Phil Uttley



The residuals for two simulated relativistically broadened iron lines at two different inner disk radii (line parameters from Cackett et al. (2008))

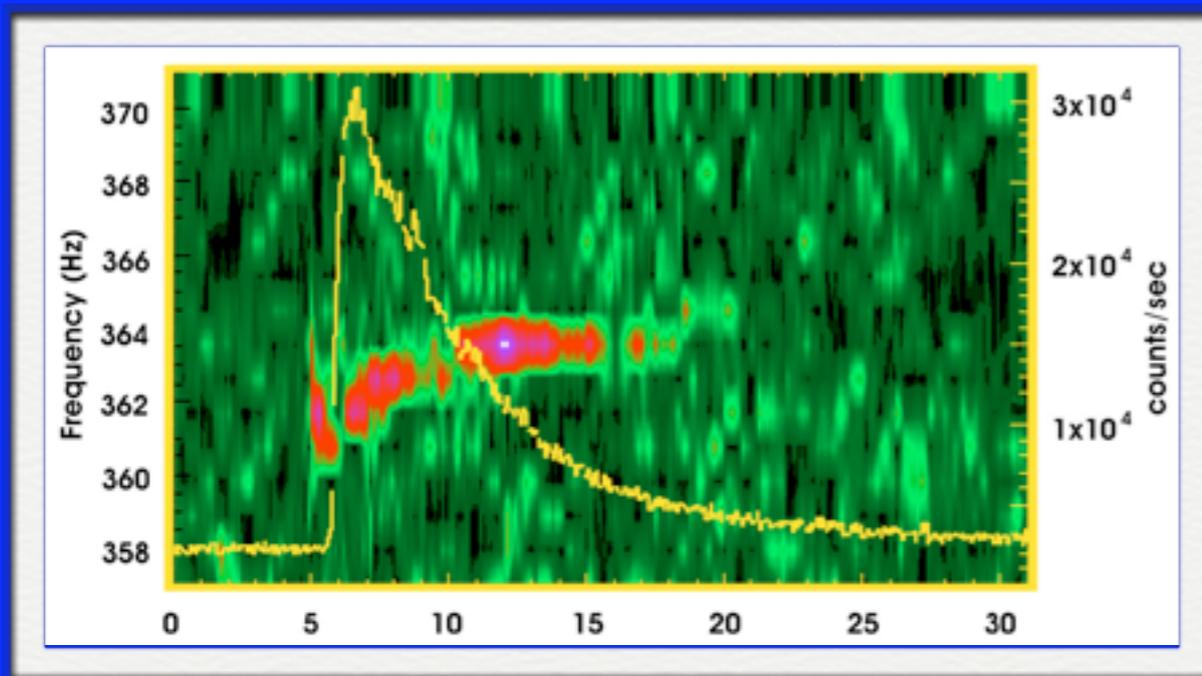
Simulated Fourier PDS, assuming that the upper QPO is a Keplerian frequency at the same inner disk radii.

Lag spectrum simulated for different inner disk radii

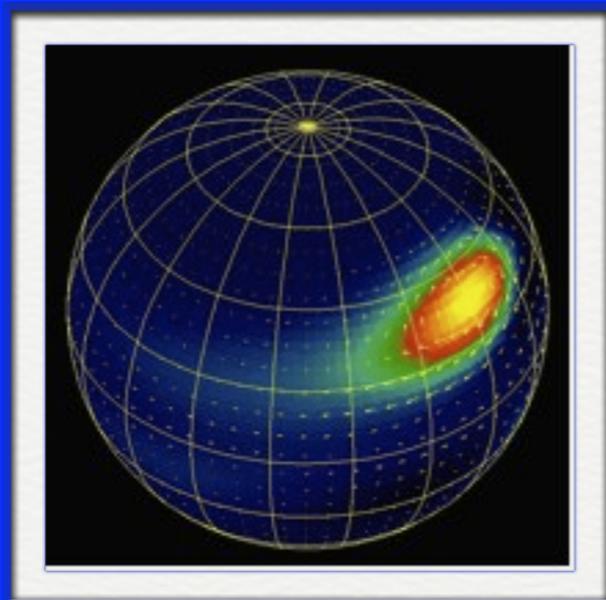


$$M_{NS} = \frac{32.2}{(\nu_K / 1000 \text{ Hz})} \left(\frac{R_{in}}{R_g}\right)^{-3/2} M_{\odot}$$

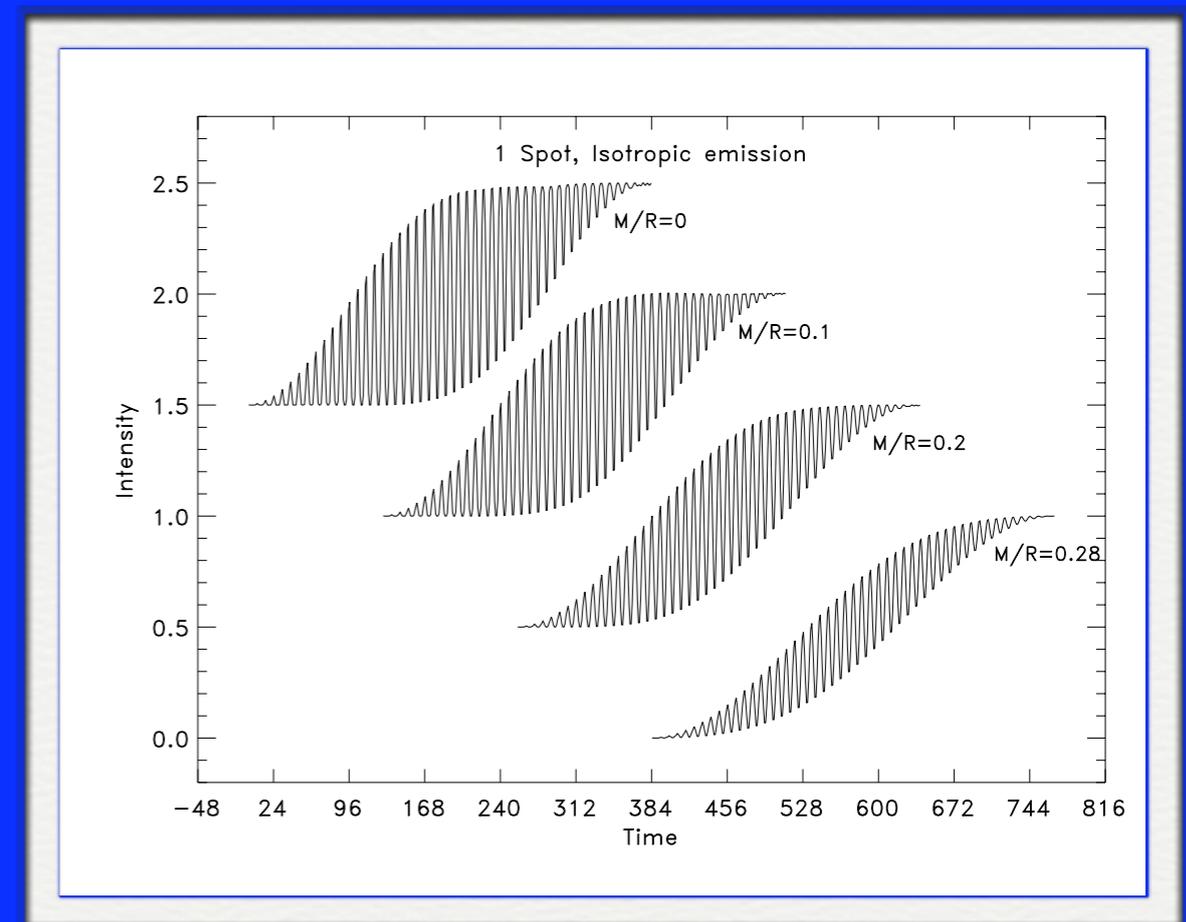
# Burst oscillations



Dynamical Fourier PDS of a type I X-ray burst showing an oscillation at 364 Hz



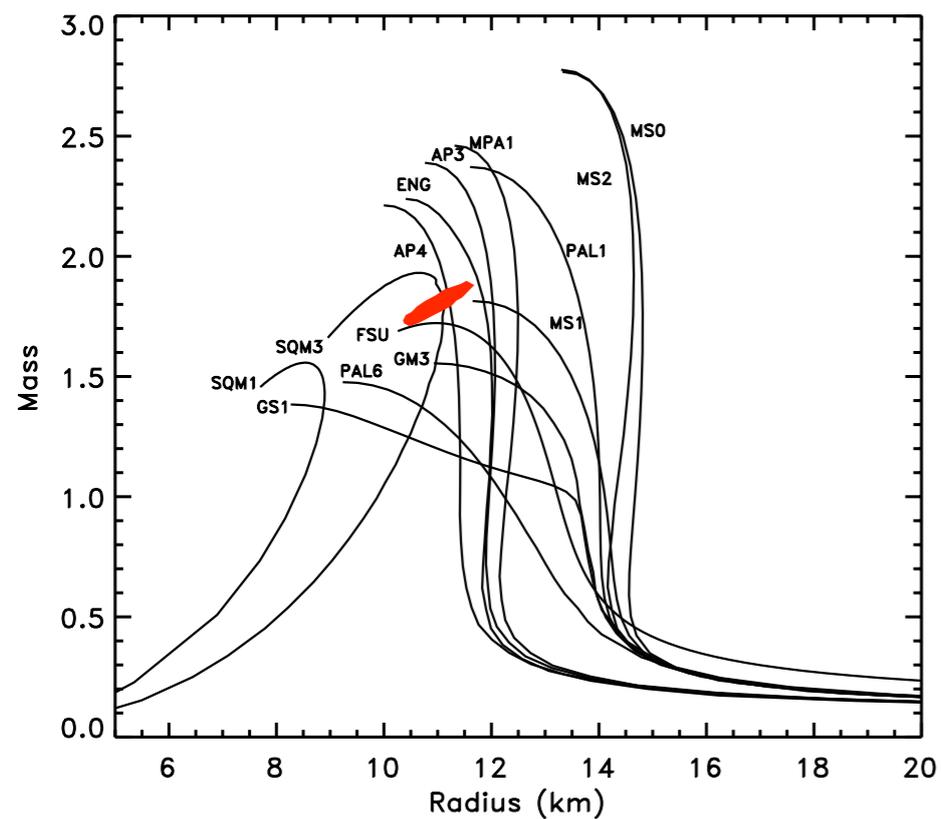
Courtesy of T. Strohmayer



Simulated light curve of burst oscillations for increasing neutron star compactness

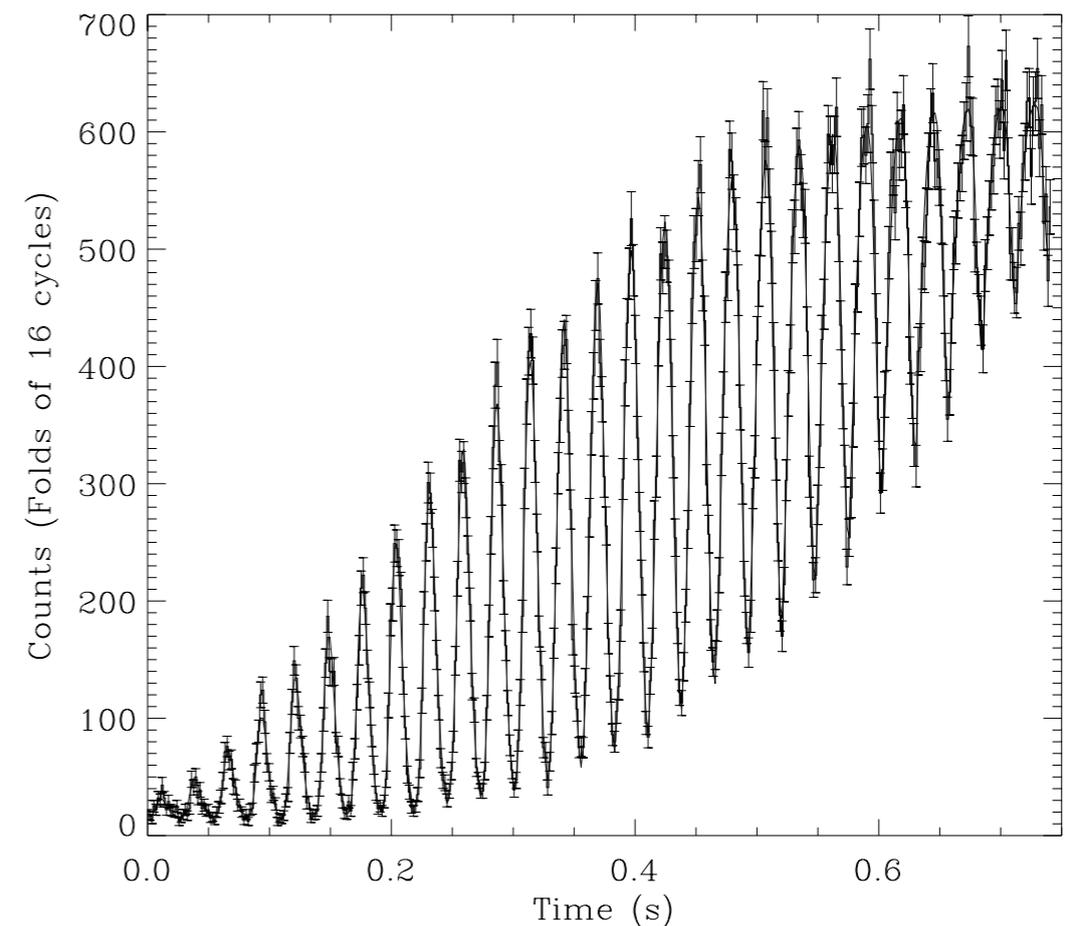
# Burst oscillations

Courtesy of T. Strohmayer & M. C. Miller



Constraints on mass and radius waveform fitting. The red ellipse shows the 95% confidence regions from 5 typical bursts. (Courtesy of Cole Miller).

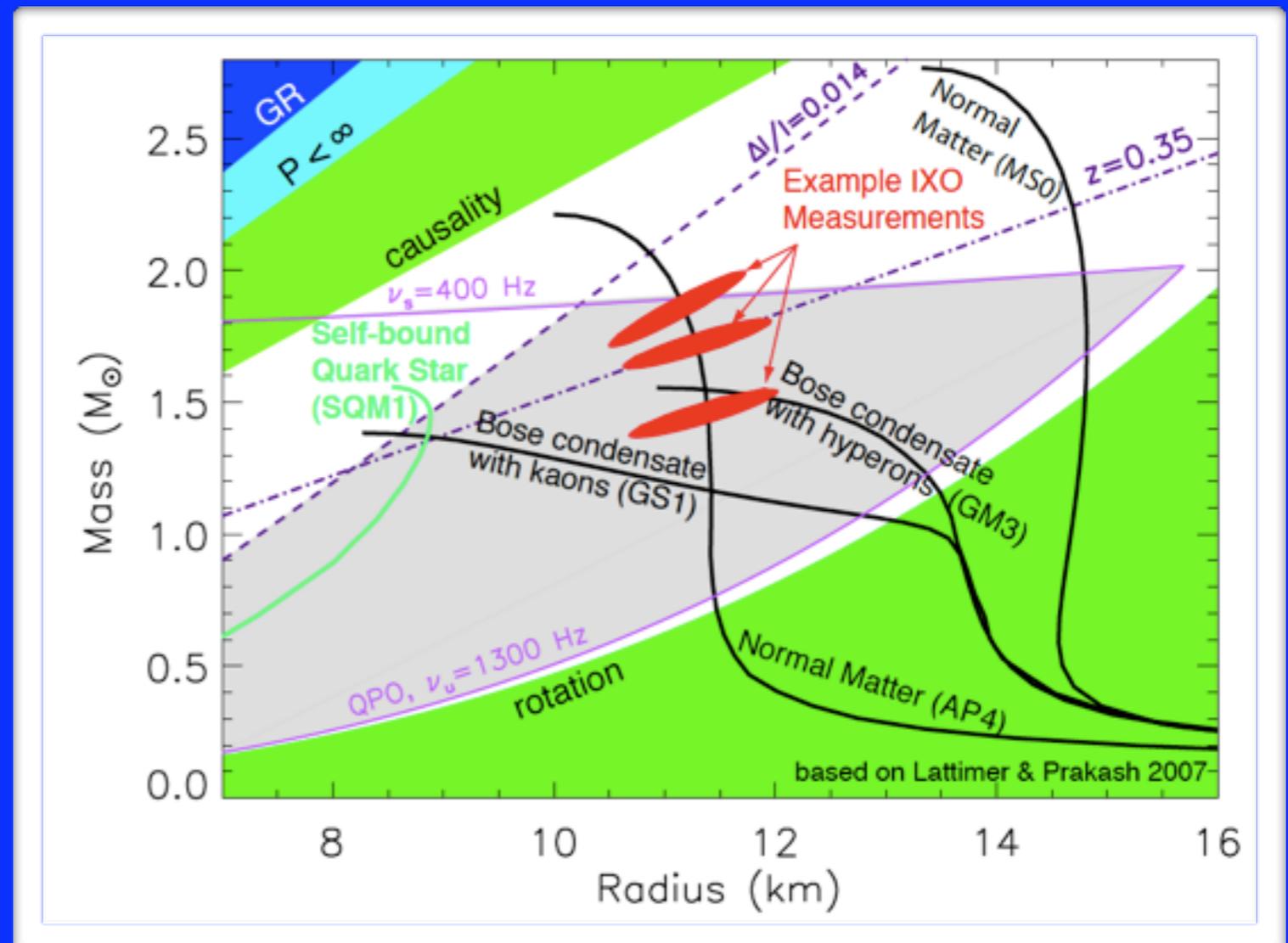
Courtesy of T. Strohmayer



Simulated X-ray light curve of a typical burst oscillation - Thanks to its unprecedented effective area, IXO will resolve individual pulses

# Conclusions

IXO, by combining multiple diagnostics for a large sample of systems, in a wide variety of states, will determine the EoS of dense matter at supra-nuclear density



More in the White paper by Paerels et al. (arXiv:0904.0435)