International X-ray Observatory (IXO)

Extreme States of Matter and the Cold Equation of State with IXO

E. Cackett (Michigan) and the IXO Extreme States of Matter Working Group*

* F. Paerels, M. Méndez, D. Barret, S. Bhattacharyya, J. Cottam, D. Fox, W. Ho, P. Jonker, A. Juett, O. Kargaltsec, S. Kitamoto, J. Miller, F. Özel, G. Pavlov, B. Rutledge, T. Strohmayer, P. Uttley, M. Garcia, R. Smith

Neutron Star Equation of State

The cores of neutron stars (NSs) harbor the highest matter densities in the Universe, up to several times the densities in atomic nuclei. Similarly, the magnetic fields can exceed by ten orders of magnitude the strongest fields generated in terrestrial laboratories. Hyperon-dominated matter, deconfined quark matter, superfluidity, even superconductivity are predicted in NSs. Similarly, quantum electrodynamics predicts that in strong magnetic fields the vacuum becomes birefringent. The properties of matter under such conditions is governed by Quantum Chromodynamics (QCD), and the close study of the properties of neutron stars offers the unique opportunity to test and explore the richness of QCD in a regime that is utterly beyond the reach of terrestrial experiments. *NSs are ideal laboratories not only for astrophysics, but also for nuclear and particle physics.*

Different Equations of State (EoS) predict different maximum masses and mass-radius relations. Determining the EoS requires measuring the mass (M) and radius (R) of the NSs simultaneously. IXO, with its high count rate capability and high spectral resolution will probe NS radii and masses, and hence determine the physical state of matter in its densest form found in the observable Universe (Fig. 1). X-rays alone provide several complementary diagnostics for the same object. For the EoS, these diagnostics include:

- X-ray burst spectroscopy, enabling us to detect gravitationally redshifted absorption lines from photospheric X-ray emission
- Pulse-phase resolved spectroscopy of X-ray pulsations produced by rotating hot spots, either during X-ray bursts or in the persistent emission of pulsars
- X-ray spectroscopy of cooling NSs and measurements of the associated cooling curves whose shape depends on the NS structure and internal composition
- the study of the sub-ms variability from the innermost regions of accretion disks (high frequency quasi-periodic oscillations, QPOs)
- the detection of kilo-Hz seismic vibrations in magnetars after giant flares.

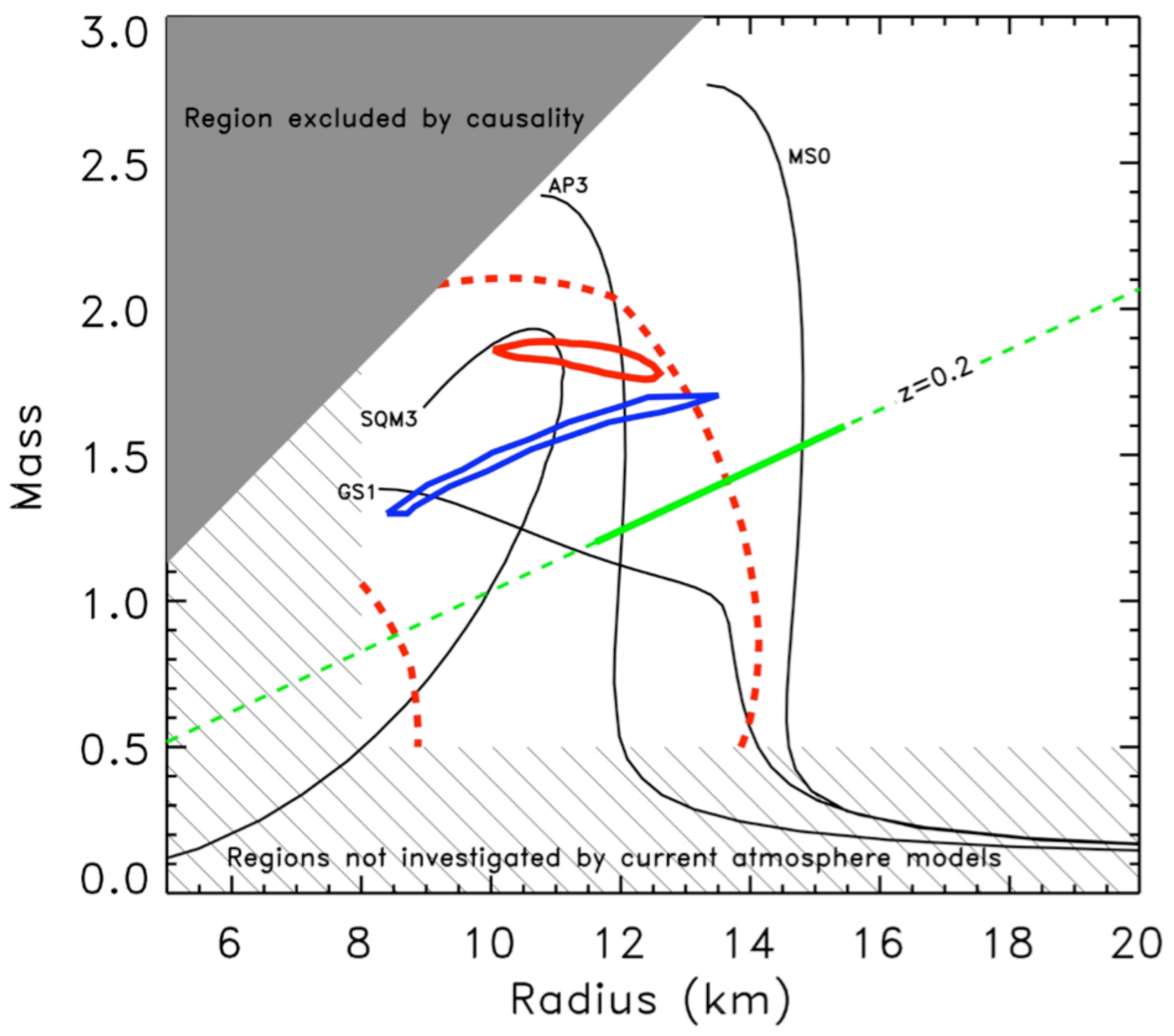

Fig. 1 (left): *Mass-radius relations for representative EoS involving standard nucleonic matter (AP3 and MS0), strange quark matter (SQM3) and Kaon condensates (GS1). For illustrative purposes, the constraints derived from IXO are from (i) a gravitational redshift (z=0.2) for a source for which mass function is known (green bold solid and dashed lines), (ii) waveform fitting of pulsations obtained from a 2 hr observation of an accreting millisecond pulsar (blue contours), (iii) hydrogen atmosphere model fitting of the X-ray spectrum of a quiescent NS in the globular cluster Omega Cen (red contours, 99%). The best available constraints from XMM-Newton to date for the same object are also shown (red dashed lines).*

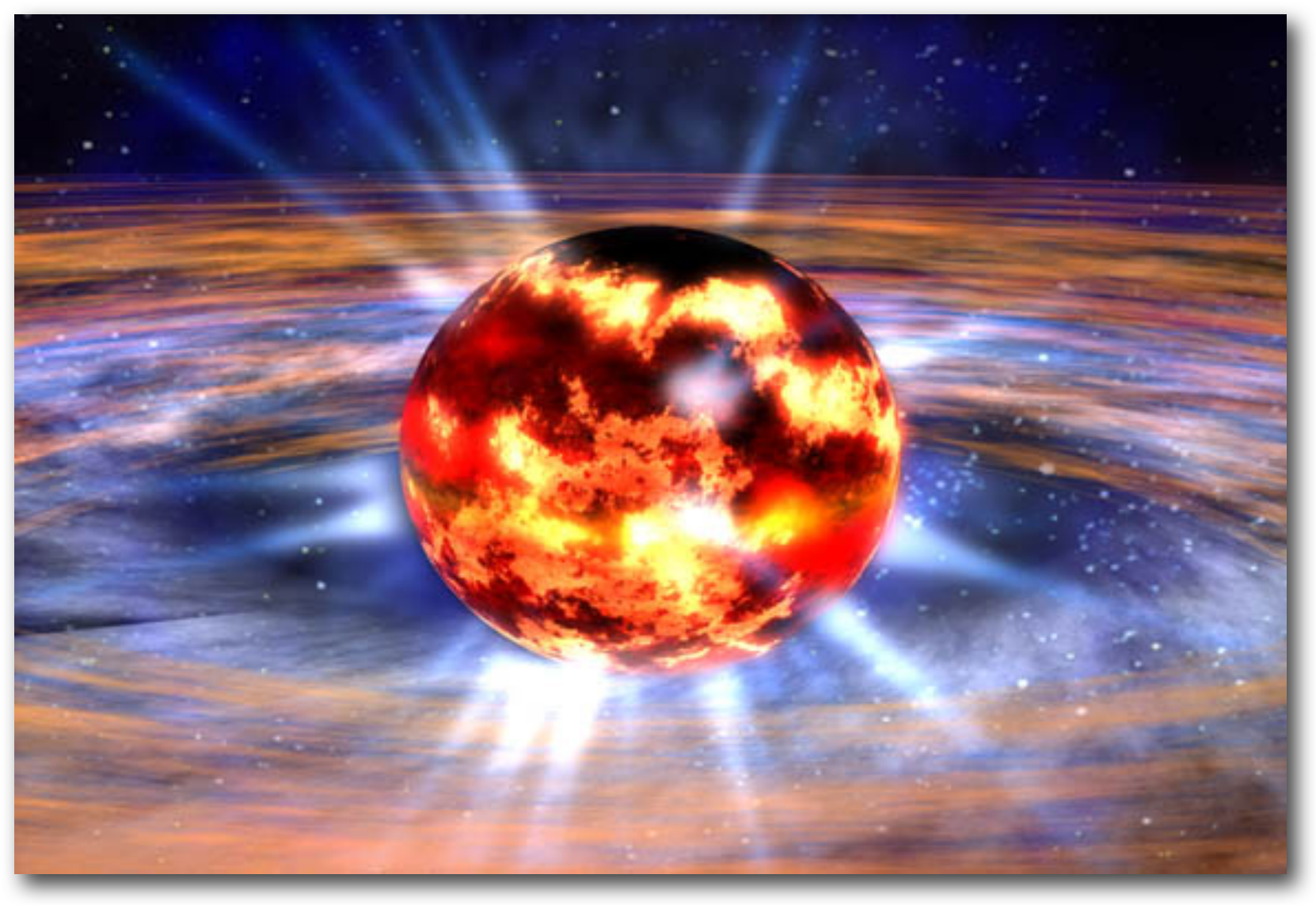

Fig. 2 (right): *An artist's conception of a thermonuclear X-ray burst on the surface of an accreting neutron star.*

A detailed example: photospheric X-ray emission

Photons will be redshifted while escaping from a neutron star's powerful gravitational field, and if the redshift z can be measured, it will provide a direct measure of the stellar mass to radius ratio, since z depends on the ratio GM/c^2R. Cottam, Paerels & Mendez (2002) found evidence for narrow, redshifted Fe absorption lines in co-added spectra of 28 thermonuclear X-ray bursts from the low-mass X-ray binary EXO 0748-676 with the *XMM-Newton* RGS. Their proposed identifications for these lines with the Hα-analog transitions of Fe XXVI and XXV implies a surface redshift of z = 0.35 that is consistent with most modern EOS. With IXO, detailed line profile spectroscopy can now be used to constrain other combinations of mass and radius, and the redshift measurement will be trivial (Fig. 3). We can test a variety of effects that will produce observable distortions of the line profiles (Fig. 4), including:

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

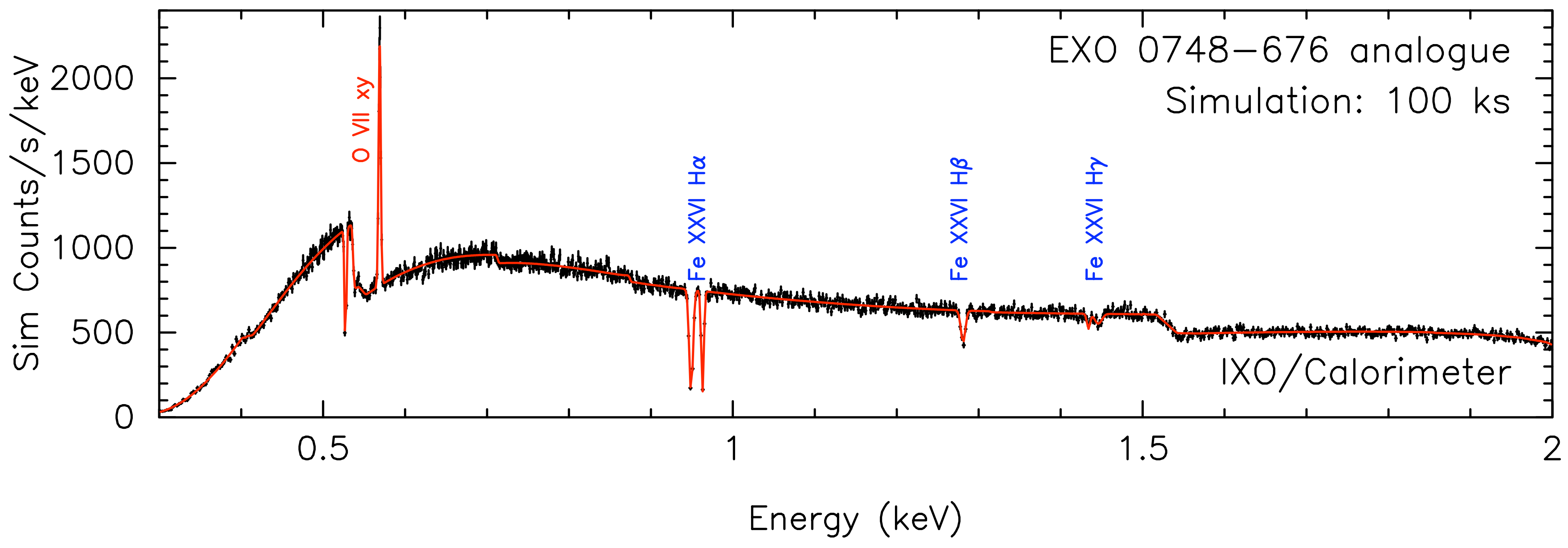

Fig. 3: *The simulated spectrum of X-ray bursts from an accreting neutron star using IXO (100 ks observation yields 1 ks of burst time). The blue labeled lines are gravitationally redshifted absorption lines from the neutron star atmosphere. The remaining spectral structure originates in the circumstellar material.*

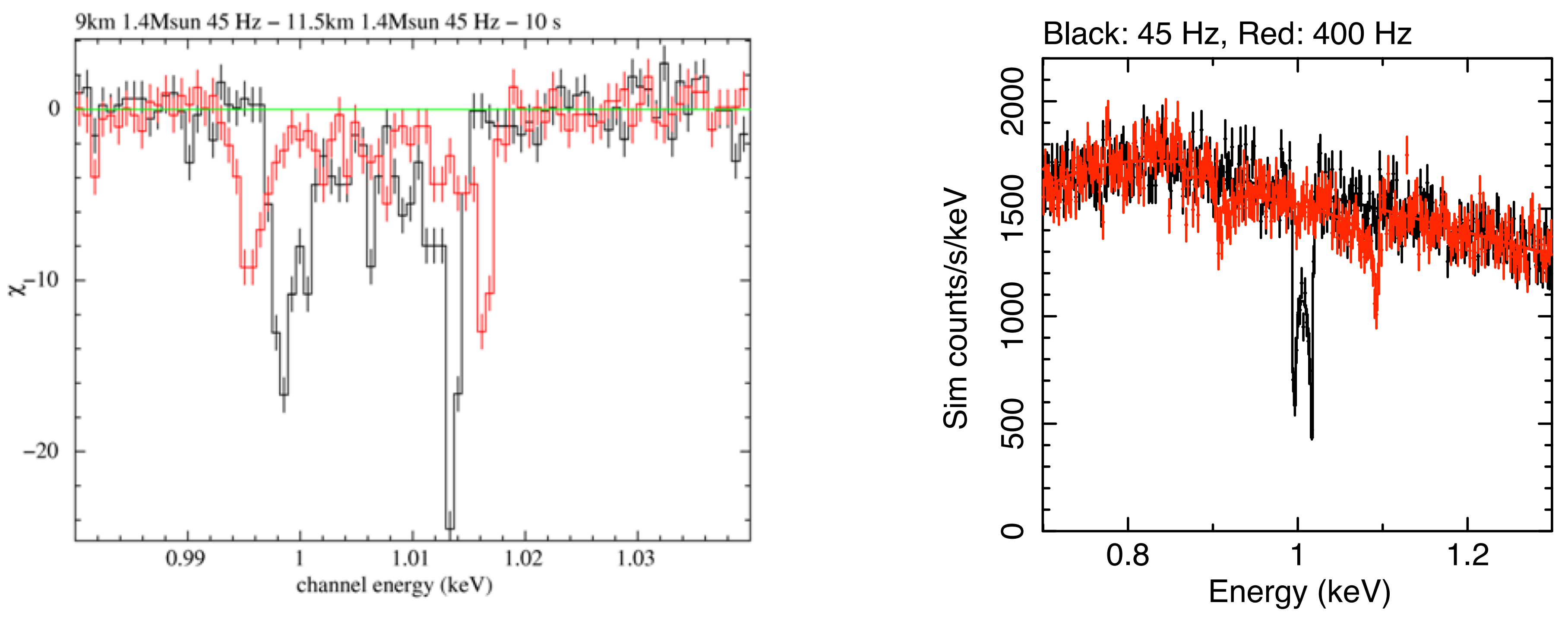

Fig. 4: *Left: The line profile is sensitive to the neutron star radius. This HTRS simulation shows that even with only 10-s (i.e. only with 1 X-ray burst) we can distinguish between a 9 km radius (black) and 11.5 km radius neutron star. Right: The profile is also sensitive to the spin frequency of the neutron star. The black data is for a neutron star with a 45 Hz spin frequency, where as the red line is for a neutron star with a 400 Hz spin frequency. This 120-s IXO/Calorimeter simulation demonstrates how we can easily detect the lines even in a relatively highly spinning neutron star.*