INTERNATIONAL X-RAY OBSERVATORY

EXTREME STATES OF MATTER

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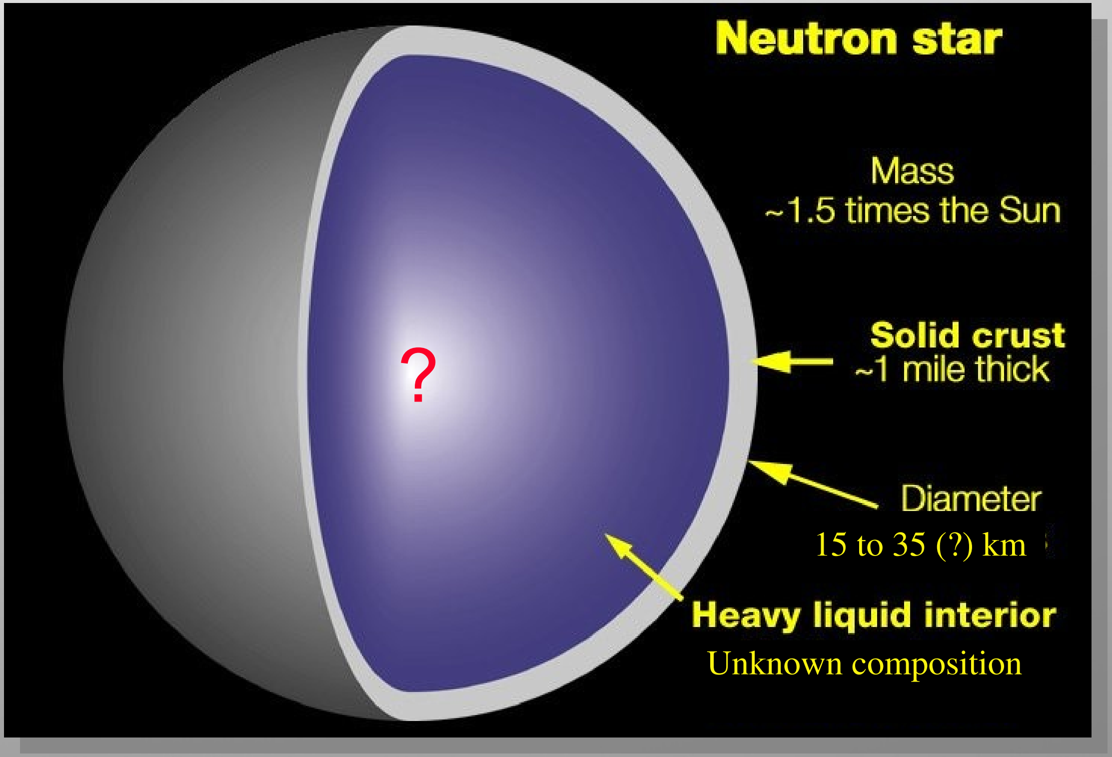
IXO FST Meeting, Garching, September 2008

Extreme States of Matter – Key Question

What is the equation of state of matter at supranuclear densities?

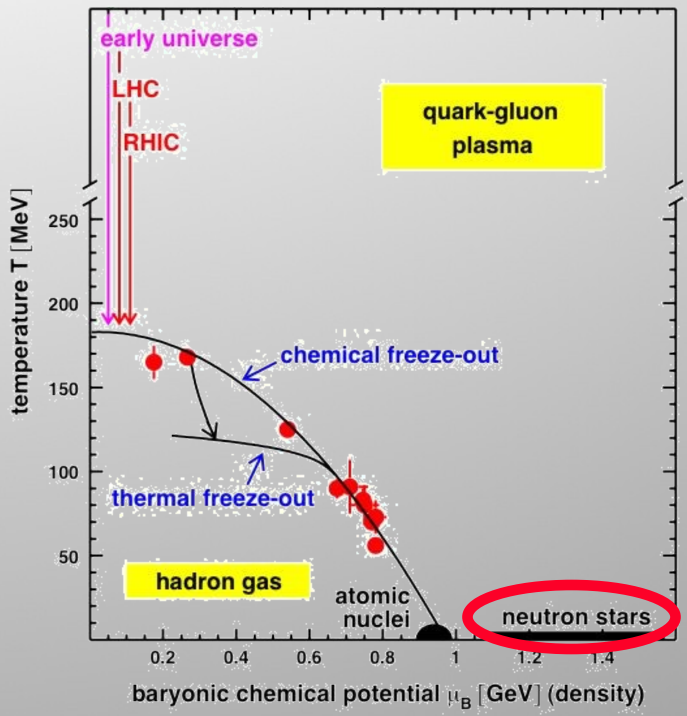


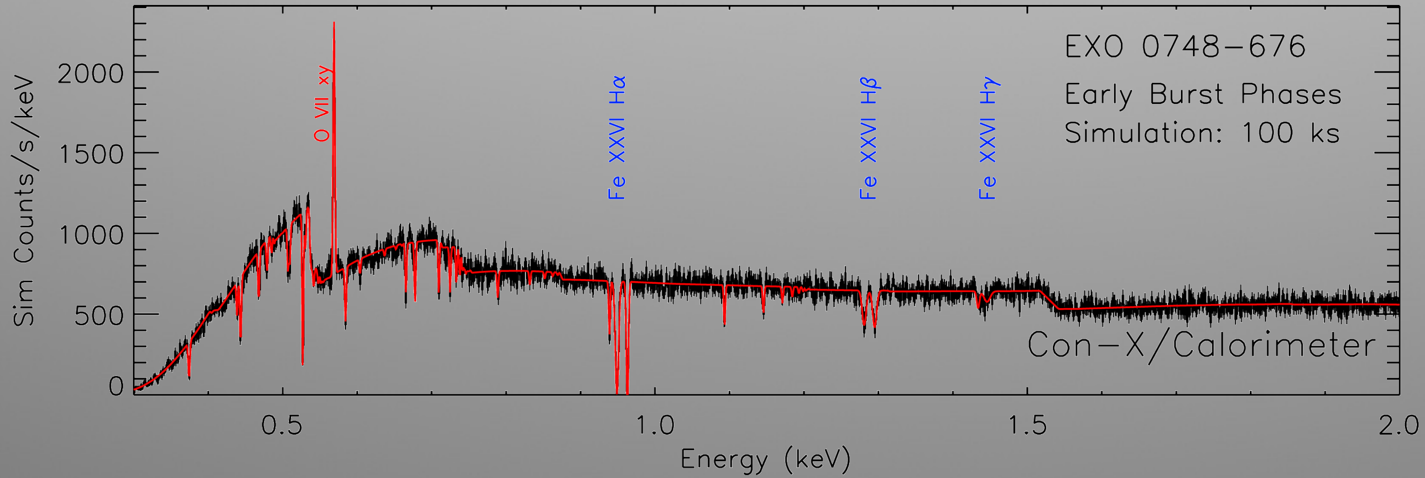
- Interiors of neutron stars present extremes of density not found anywhere else in the Universe
- Nature of matter in these conditions a deep mystery – entirely new states may be present
- Neutron star mass+radius measurements will test current models of QCD
- Unique opportunity with *IXO*: unveil fundamental properties of matter at highest densities

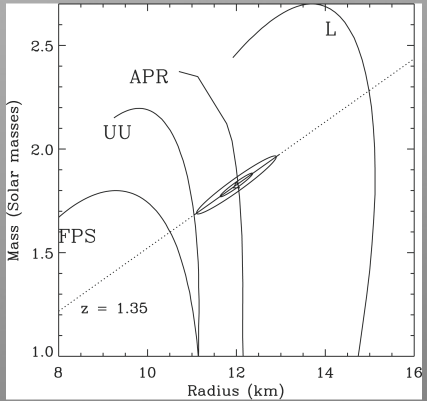
Where ? could be: hyperon condensate, pion condensate, kaon condensate, strange quark matter, quark-gluon plasma…

Neutron Star Observations

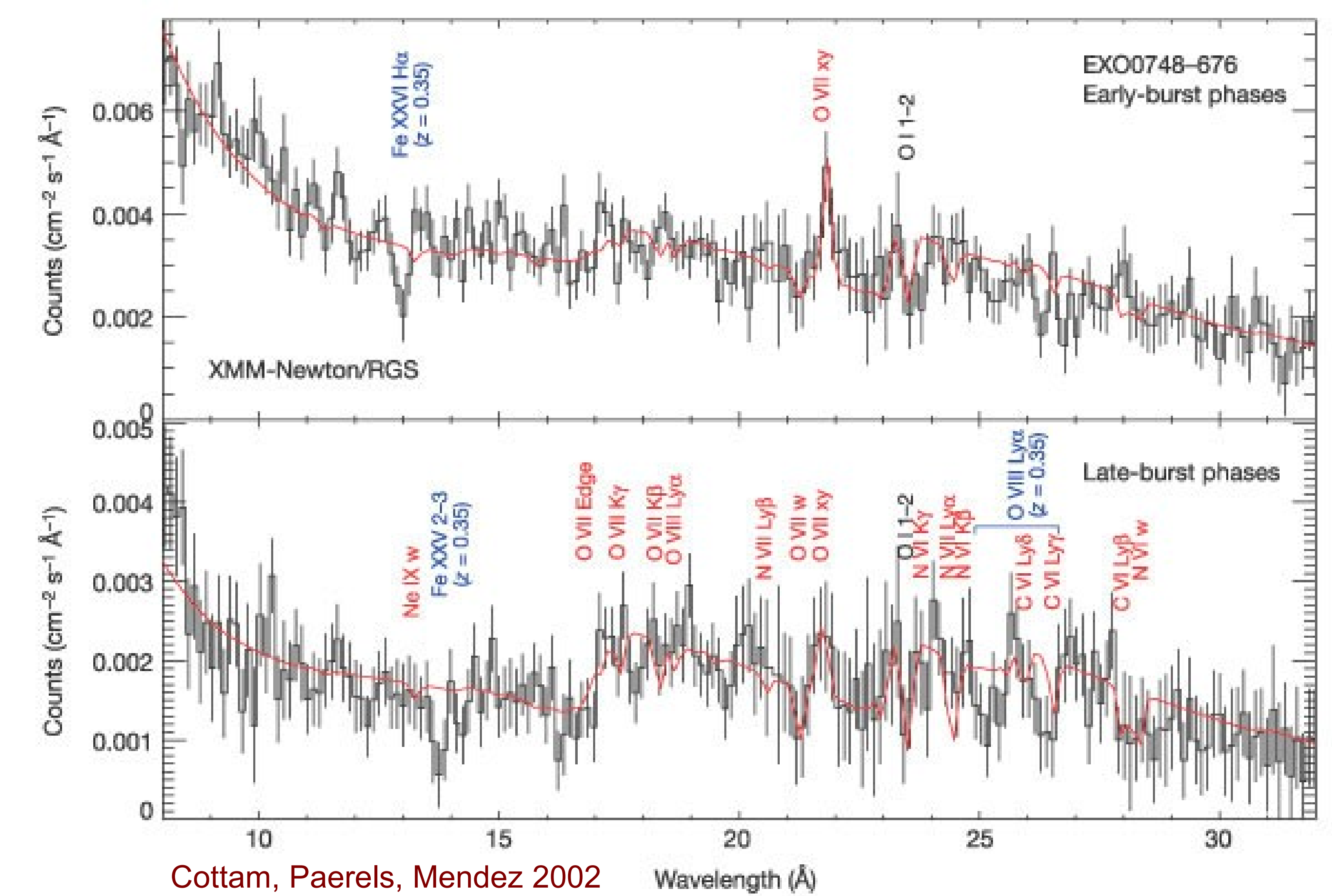
- Probe high-density, low-temperature regime inaccessible to particle experiments
- Joint **mass+radius** constraints are needed to test QCD – pulsar timing does not do it (c.f.: double pulsar's moment of inertia)
- *IXO* enables multiple independent approaches:
  - X-ray burst **spectroscopy** (simulation)
  - X-ray burst **pulse profiles**
  - **Continuum spectra** of NS @ known distance







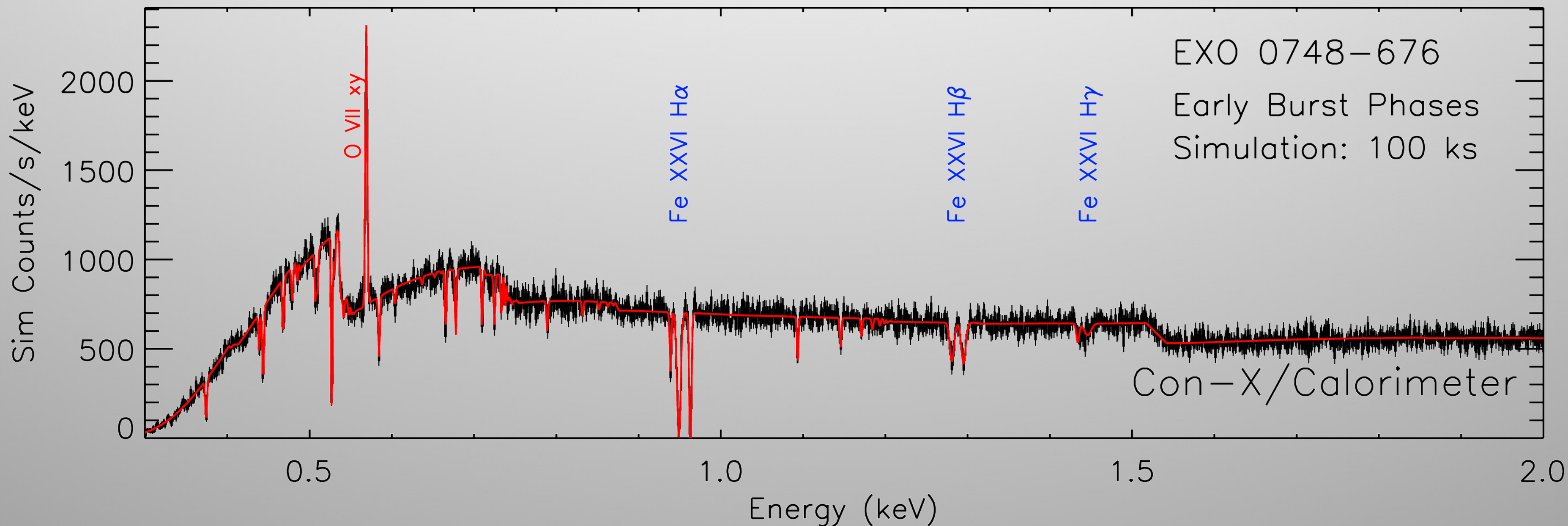
Burst Spectroscopy



Cottam, Paerels, Mendez 2002

Pressure broadening (Stark effect) !

Measure *z* and *g*: *M* and *R*



Simulated spectrum: EXO0748-676,
100 ksec with microcalorimeter

Sensitivity requirement: ~ 20 eV EW in n=2-3;
Can easily see important higher order series members

Burst Spectroscopy with *IXO*:

Scale expected number of burst photons to EO0748-676:

At least a dozen good targets:

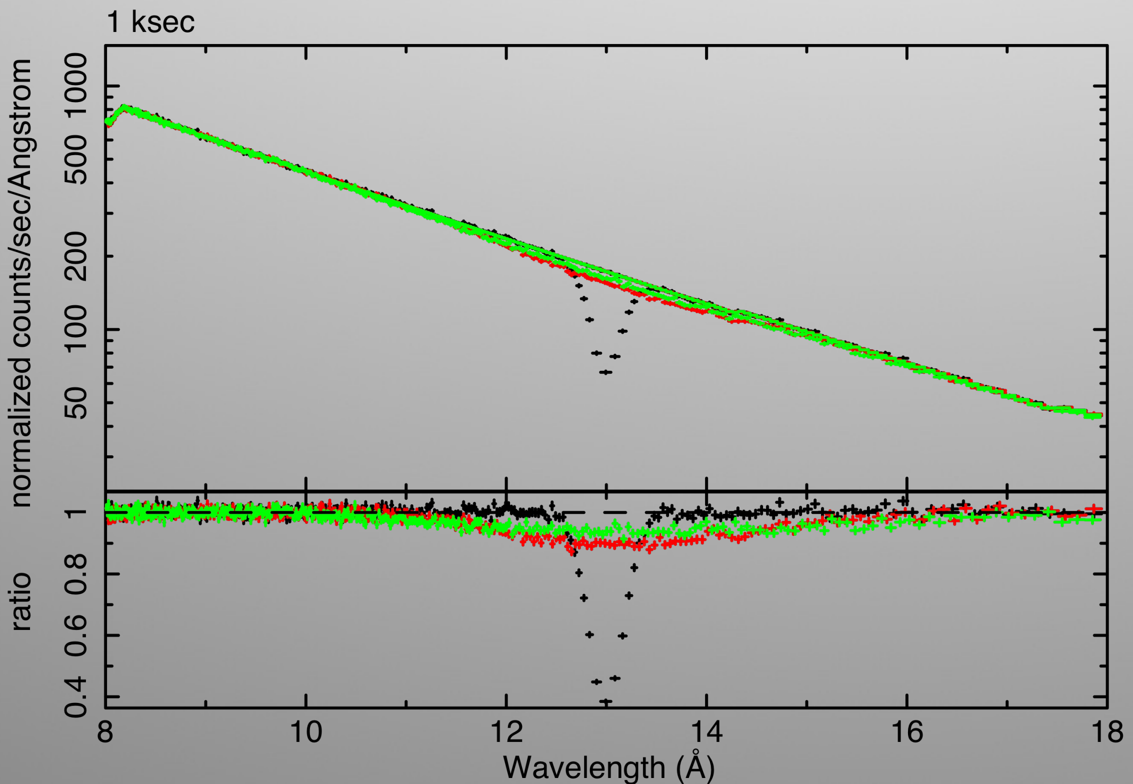
Source	FoM	Peak (C)	Wait (h)
1745-248	8.00	1.21	0.54
1826-24	3.55	1.04	3.98
1608-52	3.12	3.98	5.82
1748.9-2021	2.90	1.60	1.39
1731-26	2.90	1.60	2.89
GX_17+2	2.65	11.45	9.82
1705-44	2.34	1.44	1.31
1728-34	2.00	2.79	3.52
1636-536	1.90	2.56	2.50
0836-429	1.77	0.69	2.20
1735-44	1.21	1.30	1.18
1808-369	1.11	1.84	25.46
0748-676	1.00	1.60	2.54

Burst Spectroscopy with *IXO*: NS Spin

Absorption line profile broadens with increasing NS spin frequency:

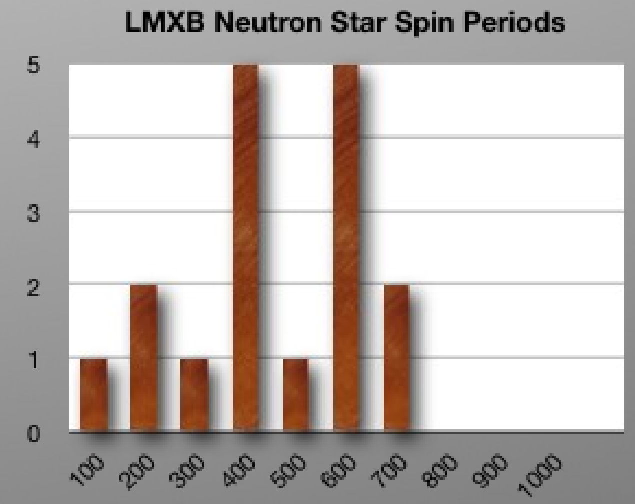
Both a bonus (profile shape gives R) and a drawback (reduced contrast);

Detection and profile measurement remain feasible up to ~ 500 Hz!!



Spin frequencies:
0, 300, 500 Hz

(75 deg inclination,
10 deg equatorial belt,
1.4 M_{O}, R = 11 km)

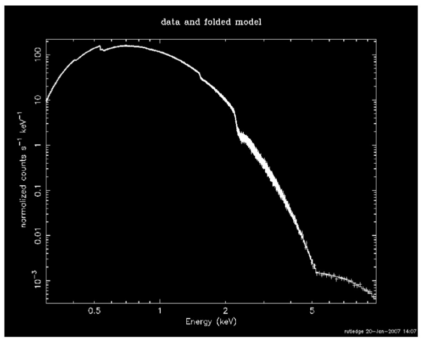


from Ed Cackett (Umich/ FST),
Sudip Bhattacharya (Tata/FST)

Neutron Stars at Known Distance: qLMXB

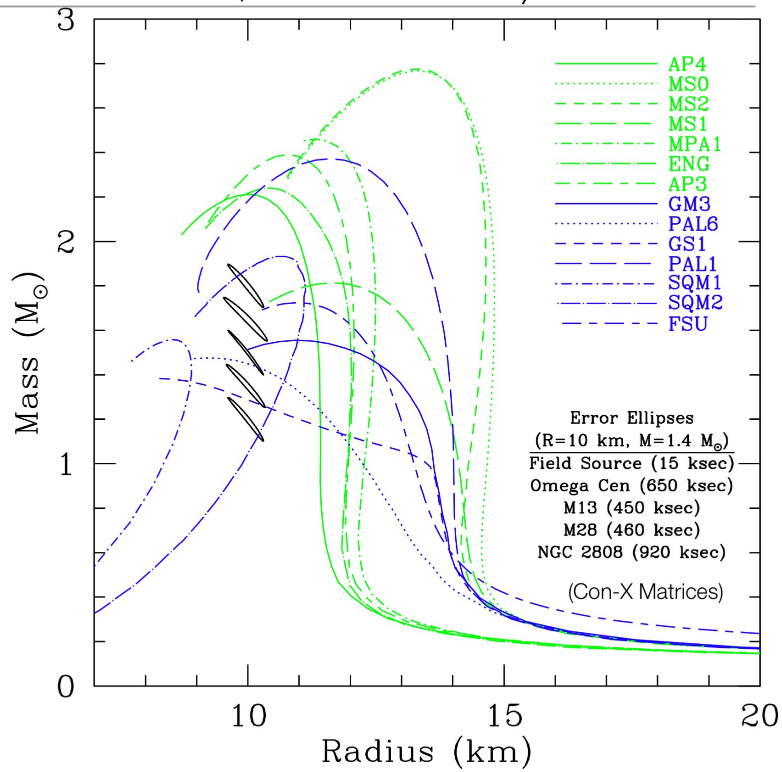
Characteristic distortions of continuum (not BB) allow simultaneous redshift and T_{eff}; know *d*, get *R* and *M*

Simultaneous Mass and Radius Measurements
(Micro-calorimeter response curves, ~1/2 IXO area)



Requirement: 250k-300k counts with calorimeter energy resolution.
(Model: kT_{eff}=80 eV, $N_H=10^{21}$ cm^{-2})

(At XMM/pn resolution: 1M -2M counts)



Courtesy Bob Rutledge (McGill/FST)

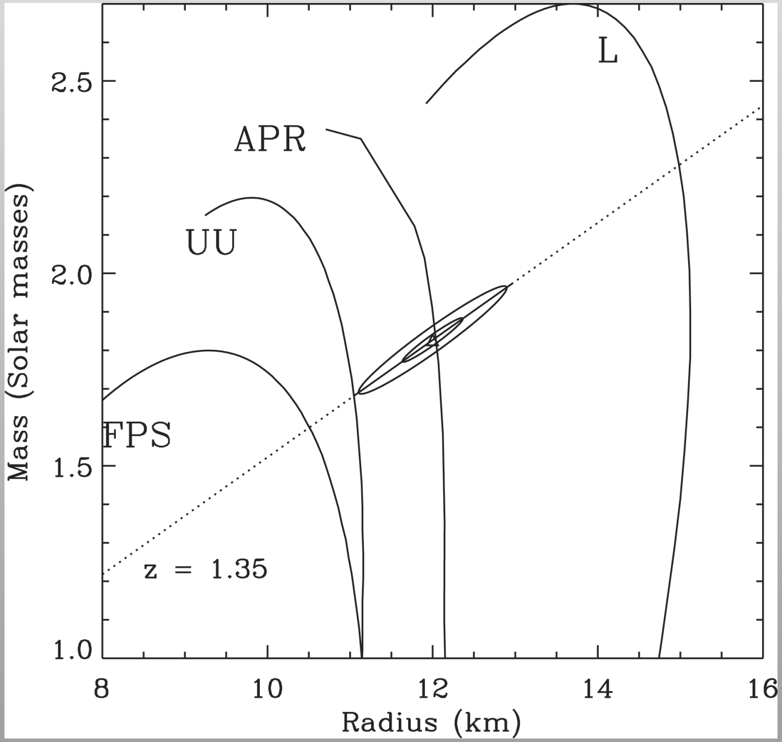
For now: qLMXB in GC

INS: Isolated Neutron Star; qLMXB: quiescent Low Mass X-ray Binary; GC: Globular Cluster

Pulse Shape of Burst Oscillations

known spin period and Doppler shift: *R*;

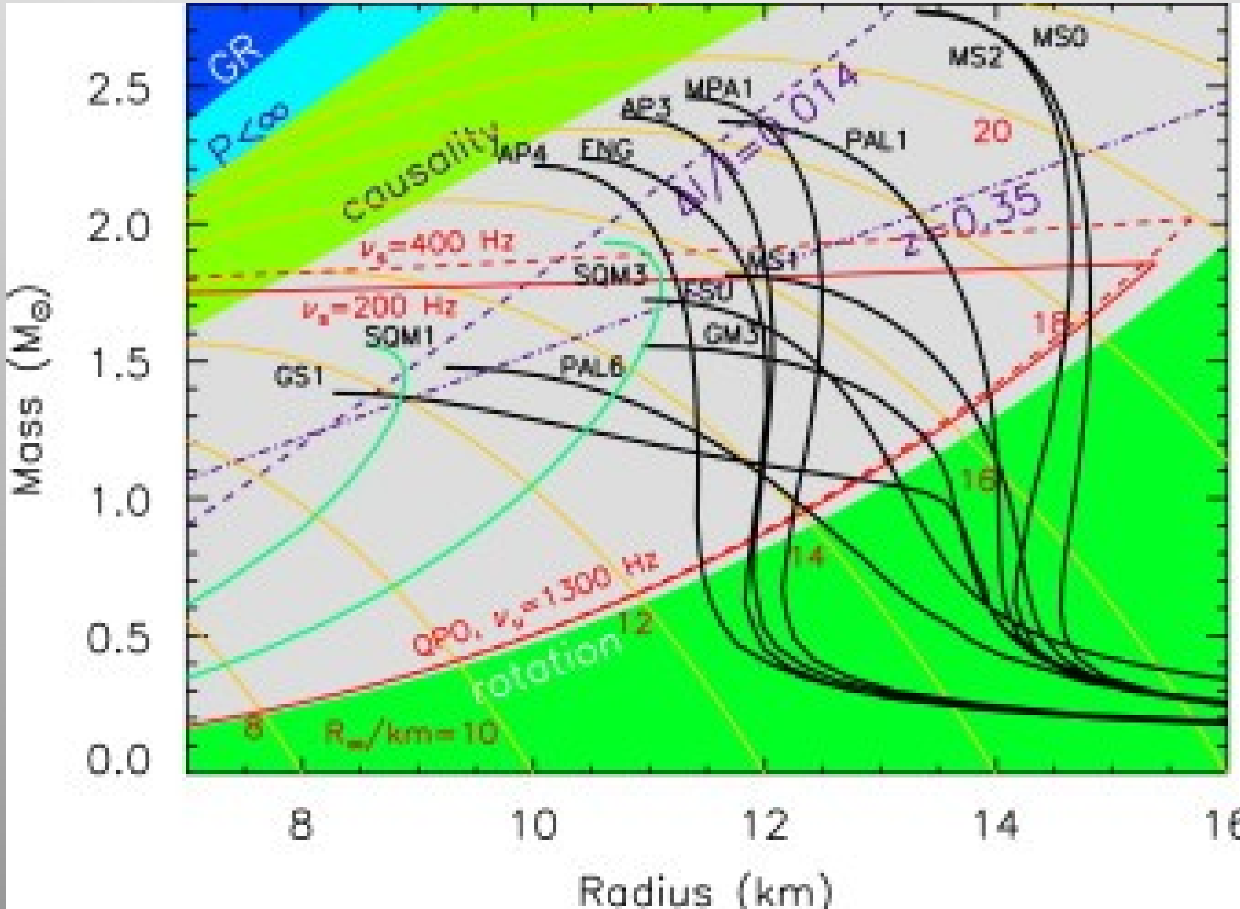
GR light bending: *z*; find *M* and *R*



Tod Strohmayer (GSFC/FST)

Need to carefully evaluate high count rate effects/limitations

Accreting NS versus Radiopulsars (binary pulsar): X-ray spectroscopy samples different masses



Lattimer & Prakash 2007

Constellation-X ➔ *IXO* capabilities:

- larger effective area at 1 keV: **GOOD** (more objects and/or more time resolution in bursts)
- increased angular resolution: **PROBABLY NOT GOOD**
- increased Field of View: **NOT RELEVANT**
- sensitivity > 10 keV: **NOT RELEVANT**

To be determined:

trade off between count rate and energy resolution in XMS:

effect on burst spectroscopy and timing

(a few night thoughts:

‘testing QCD’: we will test the many-body behavior of QCD-
not the foundations of the theory

Need to evaluate claims that LHC or RHIC could do high-
density/zero temperature regime

Range in M-R due to uncertainties in EOS may be SMALLER
than range due to untested variations on GR: if we
find a NS with M ~1.5 M_O, R > 15 km, we are testing
the correct relativistic EHE(*), not the EOS!
(point due to Dimitris Psaltis)
)

(*) Equation of Hydrostatic Equilibrium

Nobel Prizes in Physics, 1981-present
red indicates: directly or indirectly related to condensed matter physics, purple: AMO and astrophysics

2007 - *Albert Fert, Peter Grünberg*
Giant Magnetoresistance

2006 - *John C. Mather, George F. Smoot*
CMB anisotropy

2005 - *Roy J. Glauber, John L. Hall, Theodor W. Hänsch*
Quantum Optics

2004 - *David J. Gross, H. David Politzer, Frank Wilczek*
Asymptotic freedom in QCD

2003 - *Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett*
Superfluidity/Superconductivity

2002 - *Raymond Davis Jr., Masatoshi Koshiba, Riccardo Giacconi*
Neutrino/X-ray astronomies

2001 - *Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman*
Bose-Einstein

2000 - *Zhores I. Alferov, Herbert Kroemer, Jack S. Kilby*
Semiconductors/IC

1999 - *Gerardus 't Hooft, Martinus J.G. Veltman*
Electroweak renormalization

1998 - *Robert B. Laughlin, Horst L. Störmer, Daniel C. Tsui*
Fractional quantum Hall effect

1997 - *Steven Chu, Claude Cohen-Tannoudji, William D. Phillips*
Atom laser trapping and cooling

1996 - *David M. Lee, Douglas D. Osheroff, Robert C. Richardson*
He-3 superfluidity

1995 - *Martin L. Perl, Frederick Reines*
neutrino's, tau lepton

1994 - *Bertram N. Brockhouse, Clifford G. Shull*
neutron spectroscopy, diffraction

1993 - *Russell A. Hulse, Joseph H. Taylor Jr.*
Binary pulsar (GR gravitational wave emission)

1992 - *Georges Charpak*
particle detectors (multiwire PC)

1991 - *Pierre-Gilles de Gennes*
'glue'

1990 - *Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor*
deep inelastic scattering

1989 - *Norman F. Ramsey, Hans G. Dehmelt, Wolfgang Paul*
high precision maser spectroscopy; atom trapping

1988 - *Leon M. Lederman, Melvin Schwartz, Jack Steinberger*
muon neutrino

1987 - *J. Georg Bednorz, K. Alex Müller*
high-Tc superconductivity

1986 - *Ernst Ruska, Gerd Binnig, Heinrich Rohrer*
electron microscope; STM

1985 - *Klaus von Klitzing*
Quantum Hall

1984 - *Carlo Rubbia, Simon van der Meer*
W and Z bosons

1983 - *Subramanyan Chandrasekhar, William A. Fowler*
Stellar structure, nuclear astrophysics

1982 - *Kenneth G. Wilson*
critical phenomena at phase transitions

1981 - *Nicolaas Bloembergen, Arthur L. Schawlow, Kai M. Siegbahn*
Laser and electron spectroscopy