Measuring the Neutron Star Mass-Radius Relationship with X-ray Spectroscopy

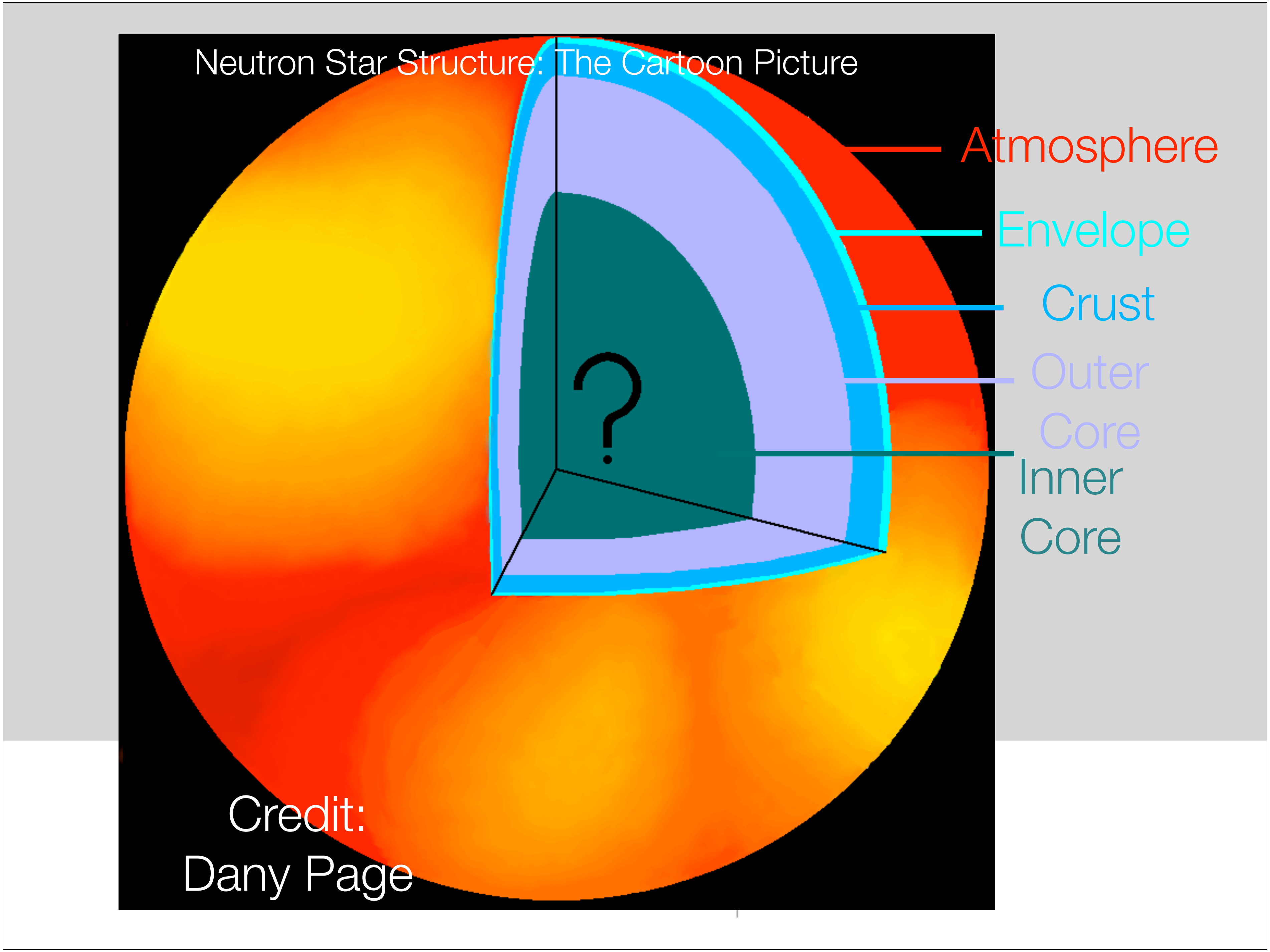
Bob Rutledge
McGill University

Collaborators:
Lars Bildsten (ITP/UCSB)
Ed Brown (MSU)
George Pavlov (PSU)
Slava Zavlin (MSFC)
Greg Ushomirsky (Lincoln Lab.)

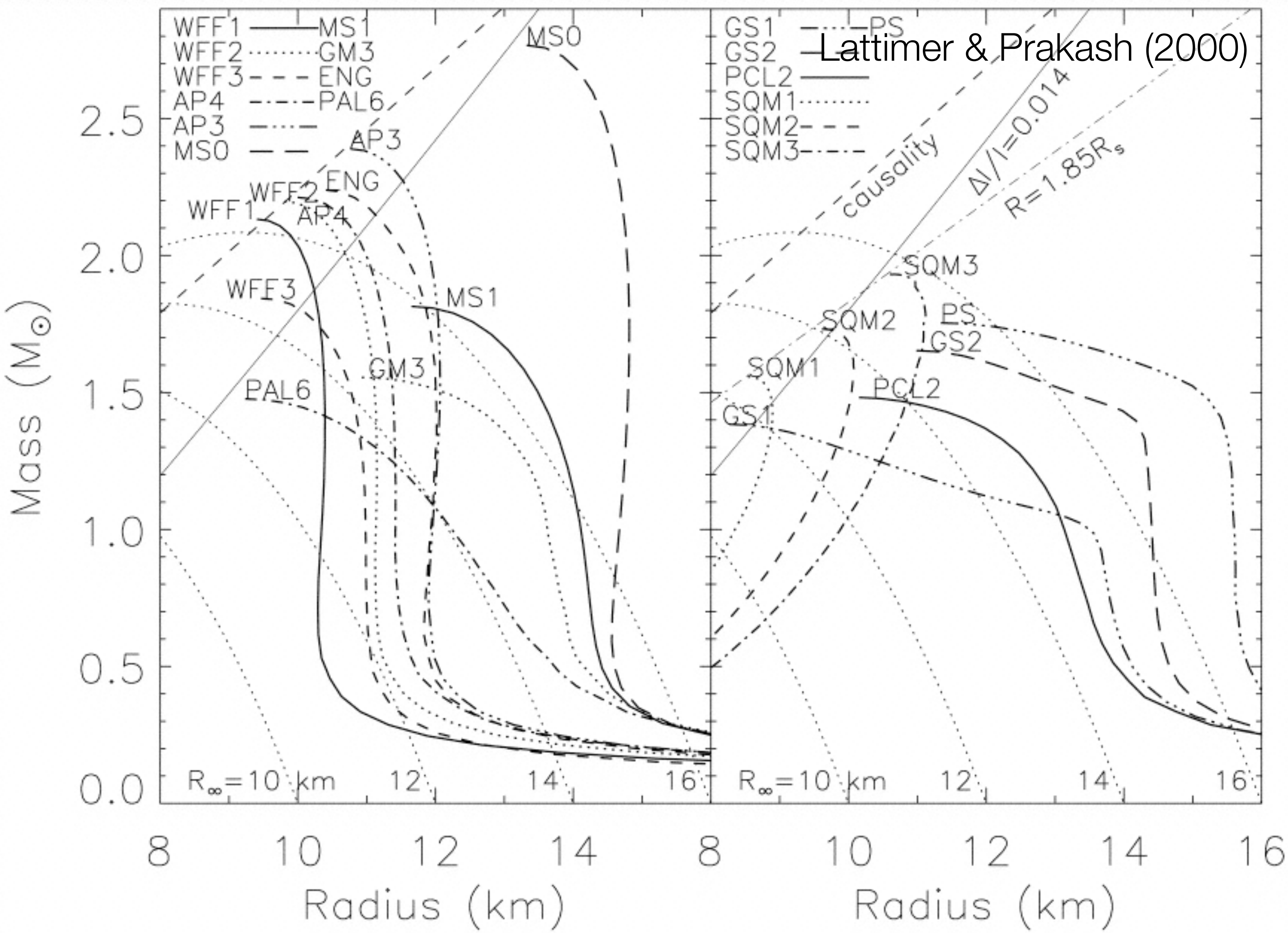
Summary

- Neutron Star Masses and Radii can be measured - independently, simultaneously - from Hydrogen atmosphere neutron stars, to < few% accuracy, each.

- Signal to noise required is out of reach of existing X-ray observatories, but can be done with proposed missions (Constellation-X/International X-ray Observatory).

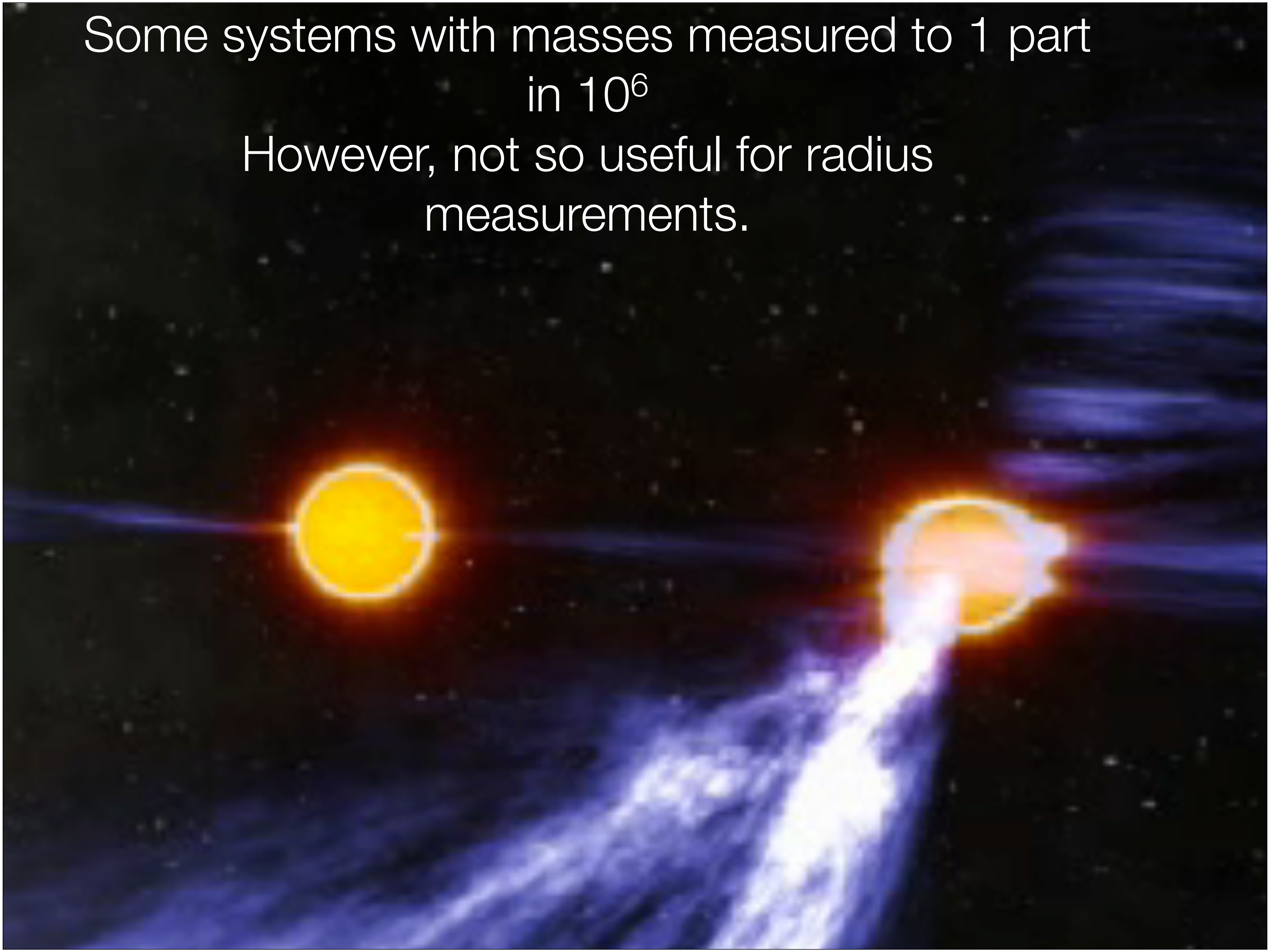

Neutron Star Structure: The Cartoon Picture
Atmosphere
Envelope
Crust
Outer
Core
Inner
Core
?
Credit:
Dany Page

Mass-Radius Relation from the Equation of State

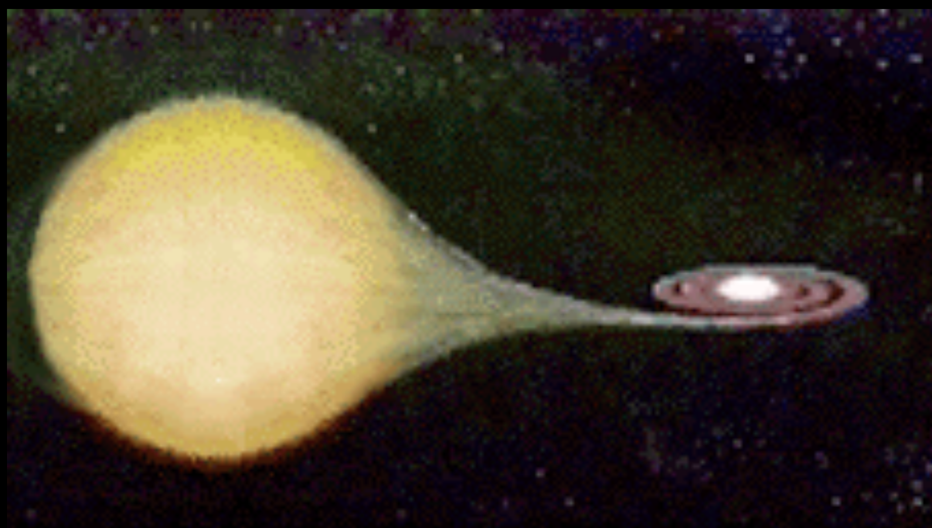


Some systems with masses measured to 1 part in 10^6

However, not so useful for radius measurements.



Quiescent Low Mass X-ray Binaries

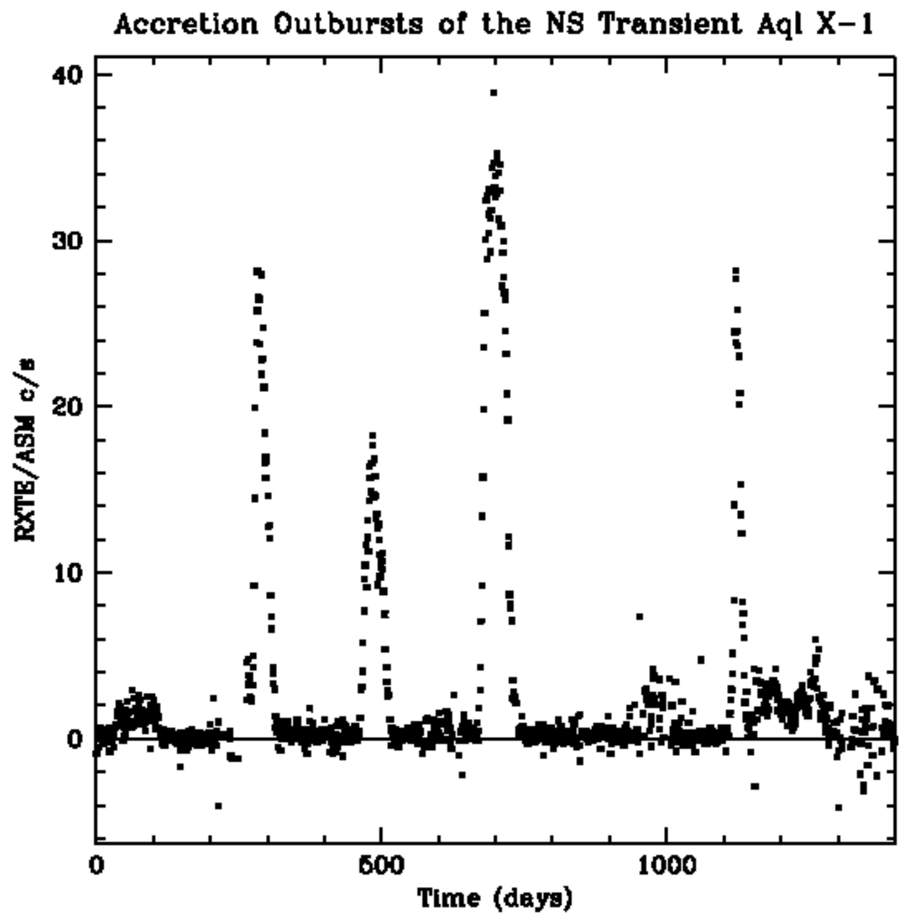


- When accreting (pictured) we mostly observe X-rays from the disk.
- In some sources ("transients") accretion can stop -- and then we see only the neutron star.

System Names: LMXBs, Soft X-ray Transients, Neutron-Star Binaries.

Soft X-ray Transients

- Outbursts are due to disk instability; peak luminosities are 10^{36}-10^{38} ergs s^{-1}.
- Outbursts last ~30 days (or as long as years).
- Exhibit type-I X-ray bursts (thermonuclear flashes).
- After outburst, X-ray sources return to quiescence (10^{31}-10^{33} ergs s^{-1})

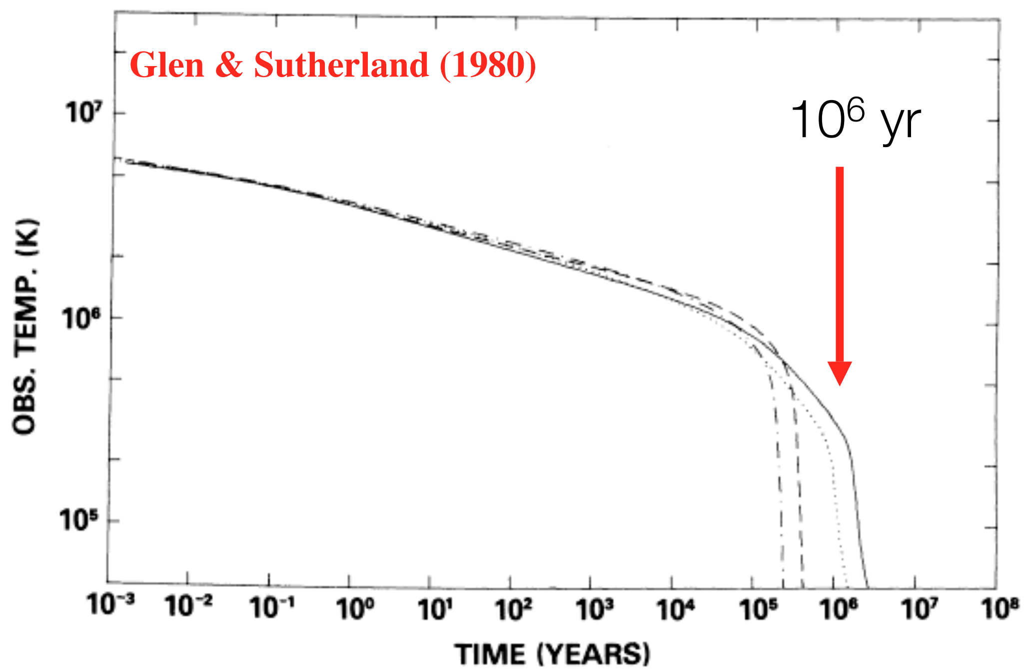


Why are qLMXBs promising for measuring NS radii?

Brown, Bildsten & RR (1998)

First detection: transient neutron star was discovered in quiescence (Cen X-4; L_x~10^{33} erg s^{-1}. Van Paradijs et al 1984), resulted in two problems :

1. The neutron stars should be cold. Luminosity provided by accretion? (van Paradijs et al 1984)



Alternative:

Deep Crustal Heating

Deep Crustal Heating (Haensel & Zdunik 1990, 2003)

Non-Equilibrium Processes in the Outer Crust Beginning with ^{56}Fe			
ρ (g cm^{-3})	Reaction	$\Delta\rho/\rho$	Q (Mev/np)
$1.5 \cdot 10^{9}$	$^{56}Fe \Rightarrow {}^{56}Cr - 2e^- + 2\nu_e$	0.08	0.01
$1.1 \cdot 10^{10}$	$^{56}Cr \Rightarrow {}^{56}Ti - 2e^- + 2\nu_e$	0.09	0.01
$7.8 \cdot 10^{10}$	$^{56}Ti \Rightarrow {}^{56}Ca - 2e^- + 2\nu_e$	0.10	0.01
$2.5 \cdot 10^{10}$	$^{56}Ca \Rightarrow {}^{56}Ar - 2e^- + 2\nu_e$	0.11	0.01
$6.1 \cdot 10^{10}$	$^{56}Ar \Rightarrow {}^{52}S + 4n - 2e^- + 2\nu_e$	0.12	0.01

Series of reactions deposit Q=1.45 MeV/np within the crust

Non-Equilibrium Processes in the Inner Crust			
ρ (g cm^{-3})	Reaction	X_n	Q (Mev/np)
$9.1 \cdot 10^{11}$	$^{52}S \Rightarrow {}^{46}Si + 6n - 2e^- + 2\nu_e$	0.07	0.09
$1.1 \cdot 10^{12}$	$^{46}Si \Rightarrow {}^{40}Mg + 6n - 2e^- + 2\nu_e$	0.07	0.09
$1.5 \cdot 10^{12}$	$^{40}Mg \Rightarrow {}^{34}Ne + 6n - 2e^- + 2\nu_e$		
	$^{34}Ne + {}^{34}Ne \Rightarrow {}^{68}Ca$	0.29	0.47
$1.8 \cdot 10^{12}$	$^{68}Ca \Rightarrow {}^{62}Ar + 6n - 2e^- + 2\nu_e$	0.39	0.05
$2.1 \cdot 10^{12}$	$^{62}Ar \Rightarrow {}^{56}S + 6n - 2e^- + 2\nu_e$	0.45	0.05
$2.6 \cdot 10^{12}$	$^{56}S \Rightarrow {}^{50}Si + 6n - 2e^- + 2\nu_e$	0.50	0.06
$3.3 \cdot 10^{12}$	$^{50}Si \Rightarrow {}^{44}Mg + 6n - 2e^- + 2\nu_e$	0.55	0.07
$4.4 \cdot 10^{12}$	$^{44}Mg \Rightarrow {}^{36}Ne + 6n - 2e^- + 2\nu_e$		
	$^{36}Ne + {}^{36}Ne \Rightarrow {}^{72}Ca$		
	$^{68}Ca \Rightarrow {}^{62}Ar + 6n - 2e^- + 2\nu_e$	0.61	0.28
$5.8 \cdot 10^{12}$	$^{62}Ar \Rightarrow {}^{60}S + 6n - 2e^- + 2\nu_e$	0.70	0.02
$7.0 \cdot 10^{12}$	$^{60}S \Rightarrow {}^{54}Si + 6n - 2e^- + 2\nu_e$	0.73	0.02
$9.0 \cdot 10^{12}$	$^{54}Si \Rightarrow {}^{48}Mg + 6n - 2e^- + 2\nu_e$	0.76	0.03
$1.1 \cdot 10^{13}$	$^{48}Mg + {}^{48}Mg \Rightarrow {}^{96}Cr$	0.79	0.11

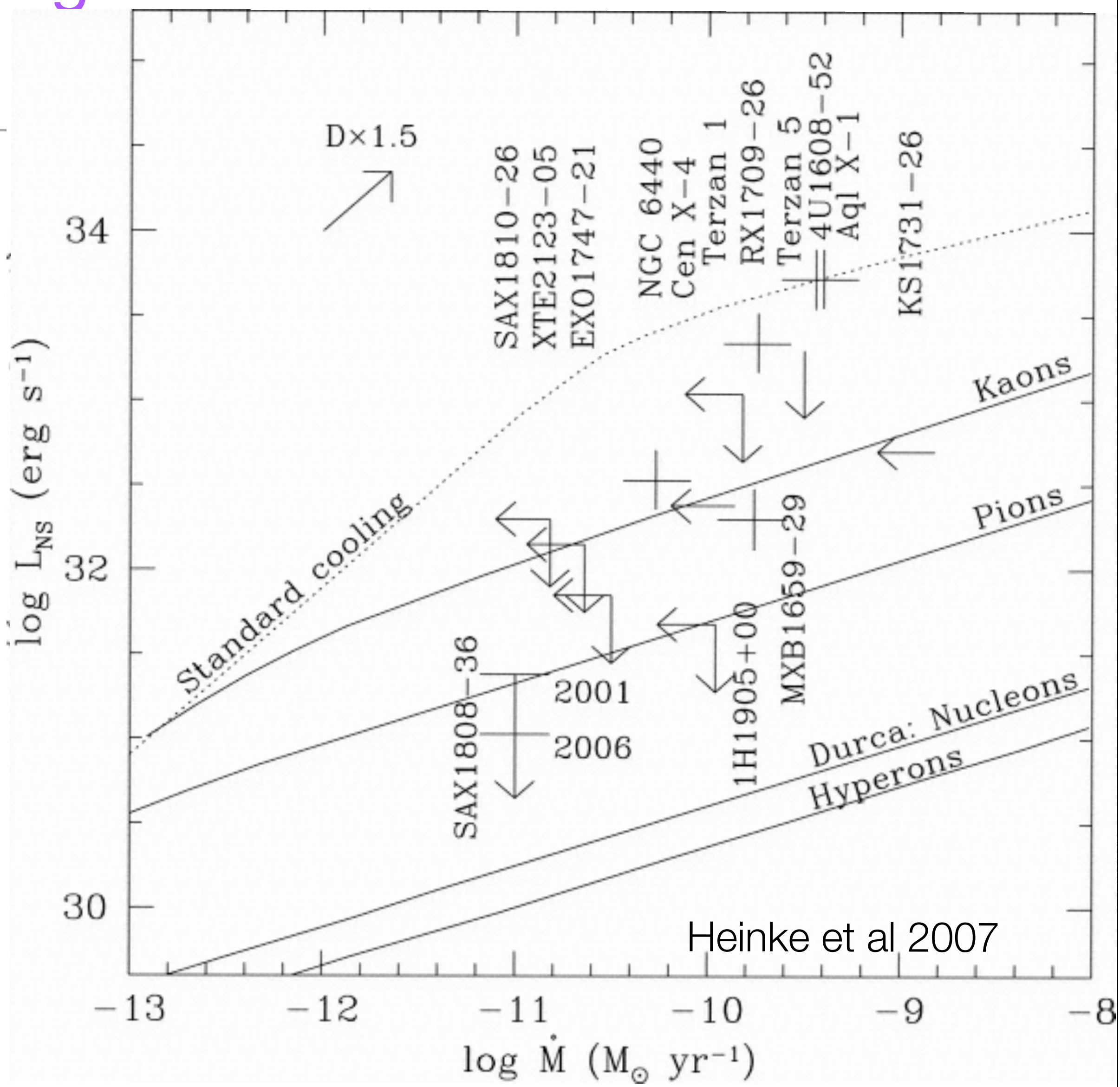
1.45 Mev per np

Deep Crustal Heating

Reactions in the crust provide ~1 MeV/np. Because the crust is in close thermal contact with the NS core, this will heat a cold core until a steady-state is reached (10^4 yr; cf. Colpi 1999) in which the energy emitted between outbursts (the quiescent luminosity) is equal to the energy deposited in the crust during outbursts.

$$L_q \approx 6\times10^{33}\frac{\langle\dot{M}\rangle}{10^{-10}\ M_{sun}\ \mathrm{yr}^{-1}}\frac{Q}{1\ \mathrm{MeV}}\quad \mathrm{erg\ s^{-1}}$$

$$F_q \approx \frac{\langle F\rangle}{200}\frac{Q}{1 MeV}$$



Brown, Bildsten & RR (1998)

Why are qNSs promising for measuring NS radii?

2. Spectral fits using blackbody spectra produced too small of radii for a neutron star (<1 km vs. ~10-20 km, with kT_{eff}~100 eV).

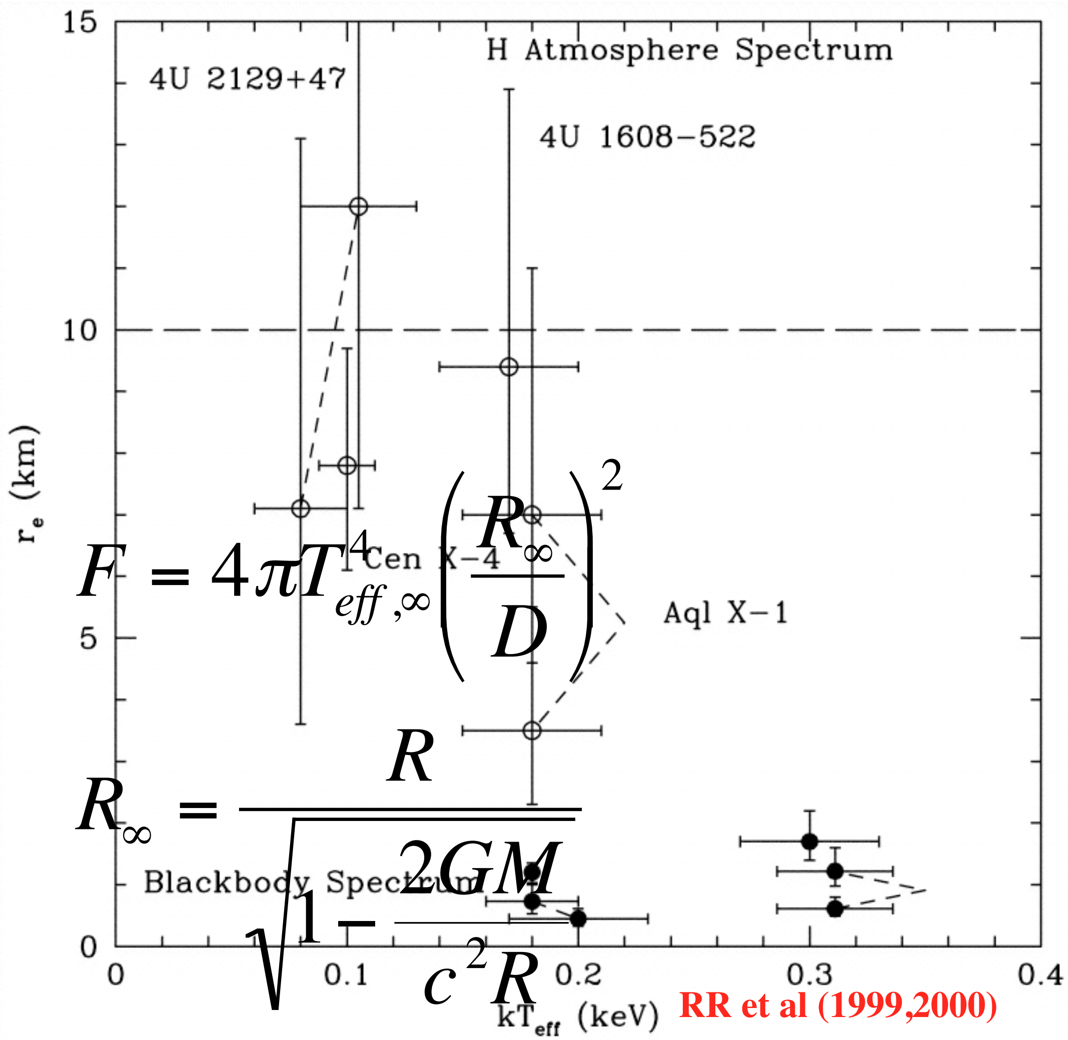
Solution: qNSs are not blackbodies.

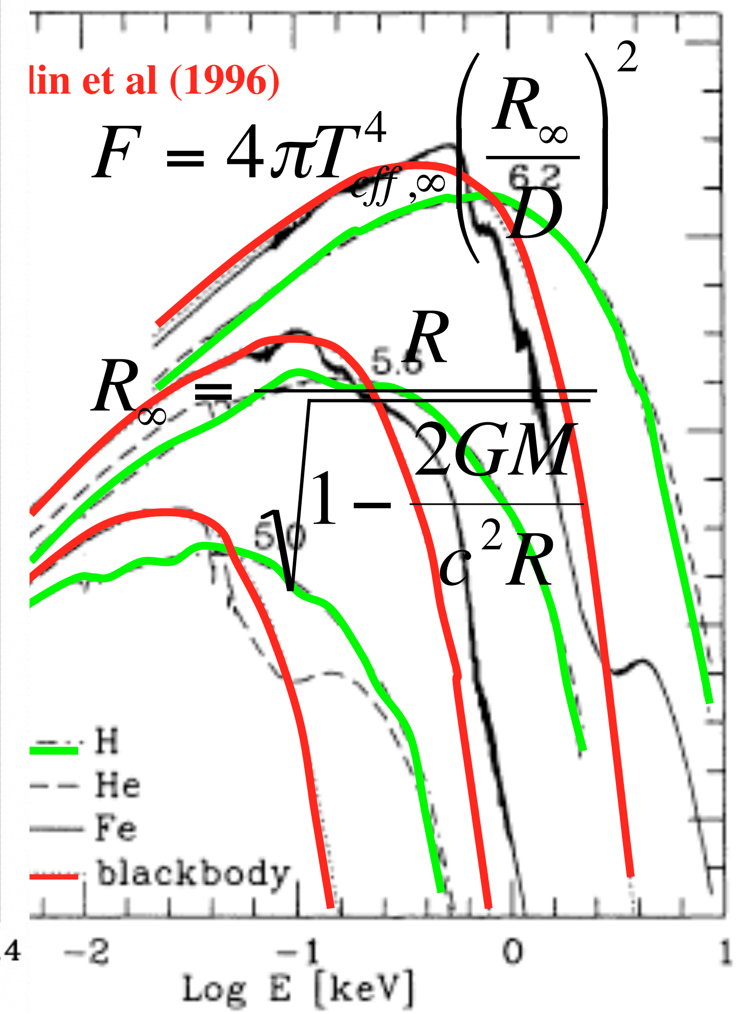
When the accretion rate onto the NS drops below a certain rate (~10^{34} erg s^{-1}) metals settle out of the photosphere on a timescale of 10-100 sec (Bildsten et al 1992). This leaves a photosphere of pure Hydrogen. The dominant opacity of a ~100 eV H photosphere is free-free processes, which is strongly energy dependent.

$$\kappa_E^{ff} \approx 114 \left(\frac{kT}{50\ \mathrm{eV}} \right)^{-3/2} \left(\frac{E}{1\ \mathrm{keV}} \right)^{-3} \ \mathrm{cm^2\ g^{-1}}$$

Brown, Bildsten & RR (1998)

Emergent Spectra from Neutron Star Hydrogen Atmosphere





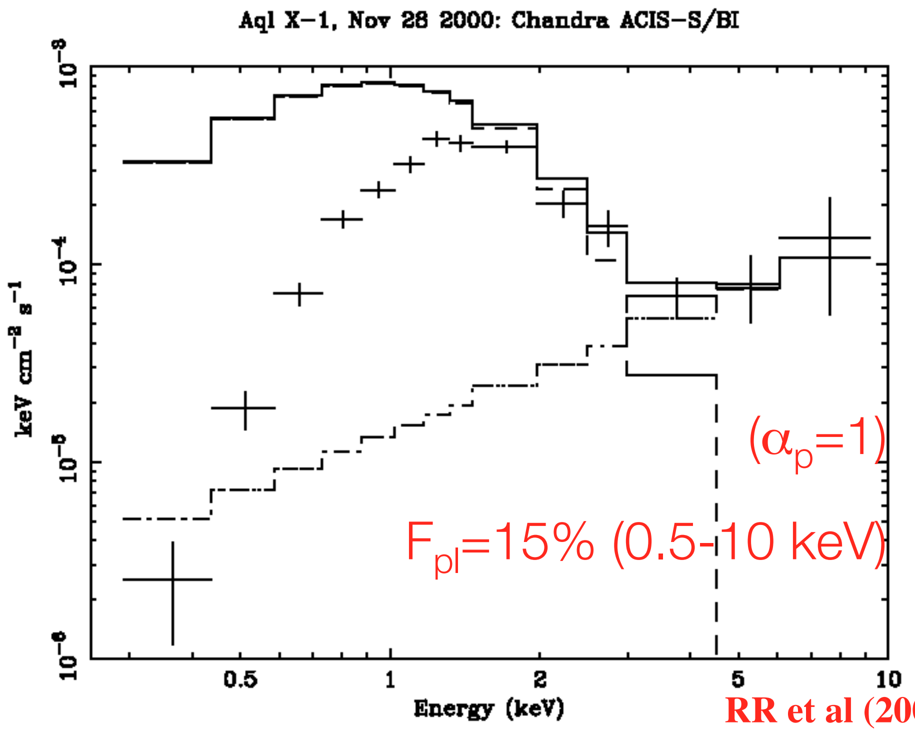
$$F = 4\pi T_{eff,\infty}^4 \left(\frac{R_\infty}{D}\right)^2$$

$$R_\infty = \frac{R}{\sqrt{1-\frac{2GM}{c^2 R}}}$$


Chandra X-ray Observatory
• Launched 1999 (NASA)
• 1” resolution


XMM/Newton
• Launched 1999 (ESA)
• 6” resolution
• ~4x area of Chandra.

Aql X-1 with Chandra -- Field Source



RR et al (2001b)

R_∞ (d/5 kpc)	$kT_{eff,\infty}$	N_H (1e20 cm^{-2})
13^{+5}_{-4} km	135^{+18}_{-12} eV	35^{+8}_{-7}

The LMXB Factories: Globular Clusters

- GCs : overproduce LMXBs by 1000x vs. field stars -- contain 10% of the known LMXBs vs. 0.01% of the stars in the galaxy.

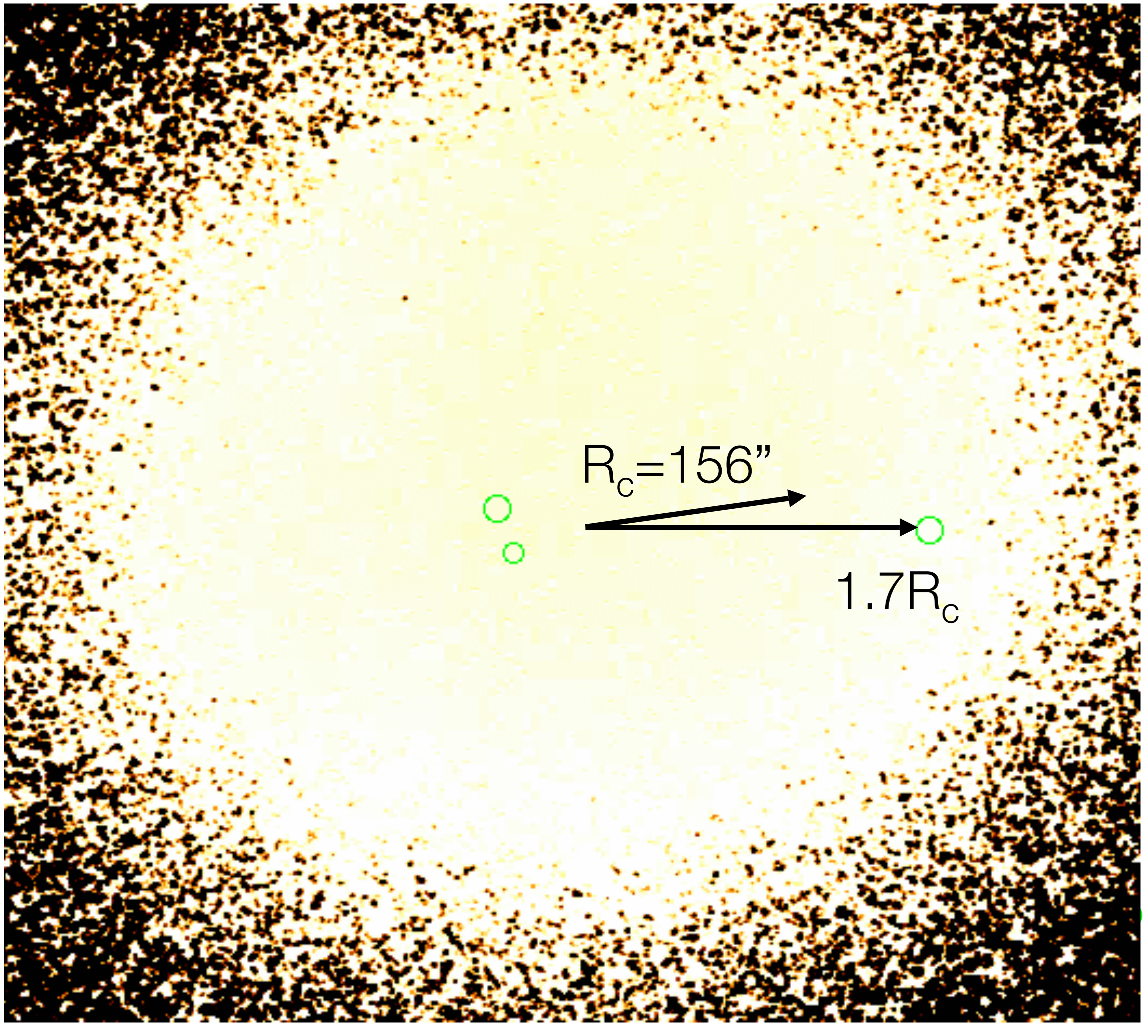
- Accurate distances are important for a number of studies (Stellar evolution, WD cooling).

qNSs can be identified by their soft X-ray spectra, and confirmed with optical counterparts.

NGC	D (kpc)	+/-(%)
104	5.13	4
288	9.77	3
362	10.0	3
4590	11.22	3
5904	8.28	3
7099	9.46	2
6025	7.73	2
6341	8.79	3
6752	4.61	2

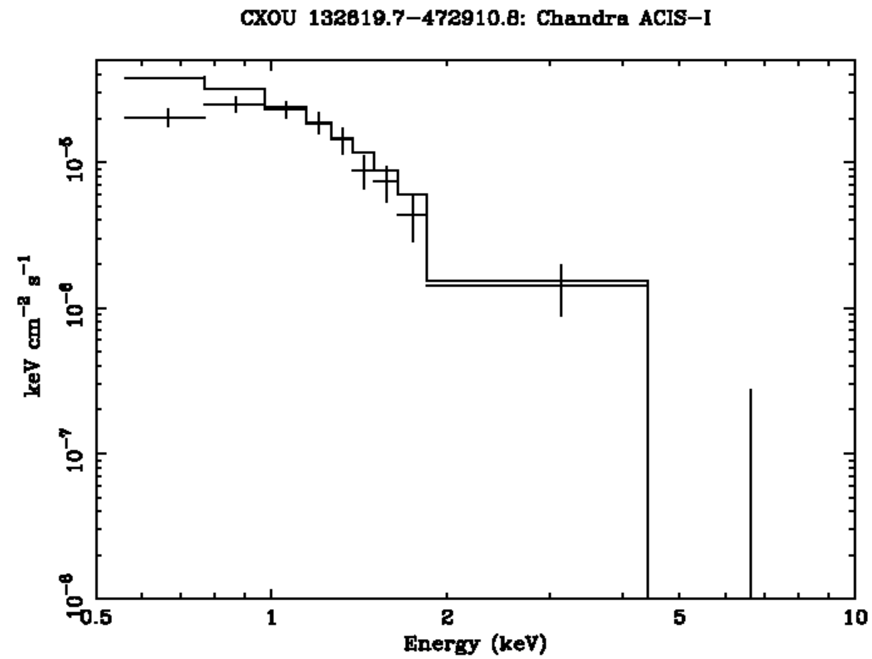
Carretta et al (2000)

NGC 5139 (Omega Cen)



The optical counterpart has been identified! (second one)

NGC 5139 (Omega Cen)



R_∞ (d/5 kpc)	$kT_{eff,\infty}$	N_H (1e20 cm^{-2})
14.3 ± 2.1 km	66^{+4}_{-5} eV	(9)

RR et al (2002)

The Best Measured Neutron Star Radii

Name	R_∞ (km/D)	D (kpc)	$kT_{eff,\infty}$ (eV)	N_H (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	5.36 ±6%	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen** (XMM)	13.6 ± 0.3	5.36 ±6%	67 ±2	9 ± 2.5	Gendre et al (2002)
M13** (XMM)	12.6 ± 0.4	7.80 ±2%	76 ±3	(1.1)	Gendre et al (2002)
47 Tuc X7 (Chandra)	34_{-13}^{+22}	5.13 ±4%	84^{+13}_{-12}	$0.13^{+0.06}_{-0.04}$	Heinke et al (2006)
M28** (Chandra)	$14.5_{-3.8}^{+6.9}$	5.5 ±10%	90_{-10}^{+30}	26 ± 4	Becker et al (2003)
NGC 7099 (Chandra)	$16.9_{-4.3}^{+5.4}$	--	94_{-12}^{+17}	$2.9^{+1.7}_{-1.2}$	Lugger et al (2006)
NGC 2808 (XMM)	??	9.6 (?)	103_{-33}^{+18}	18^{+11}_{-7}	Webb et al (2007)

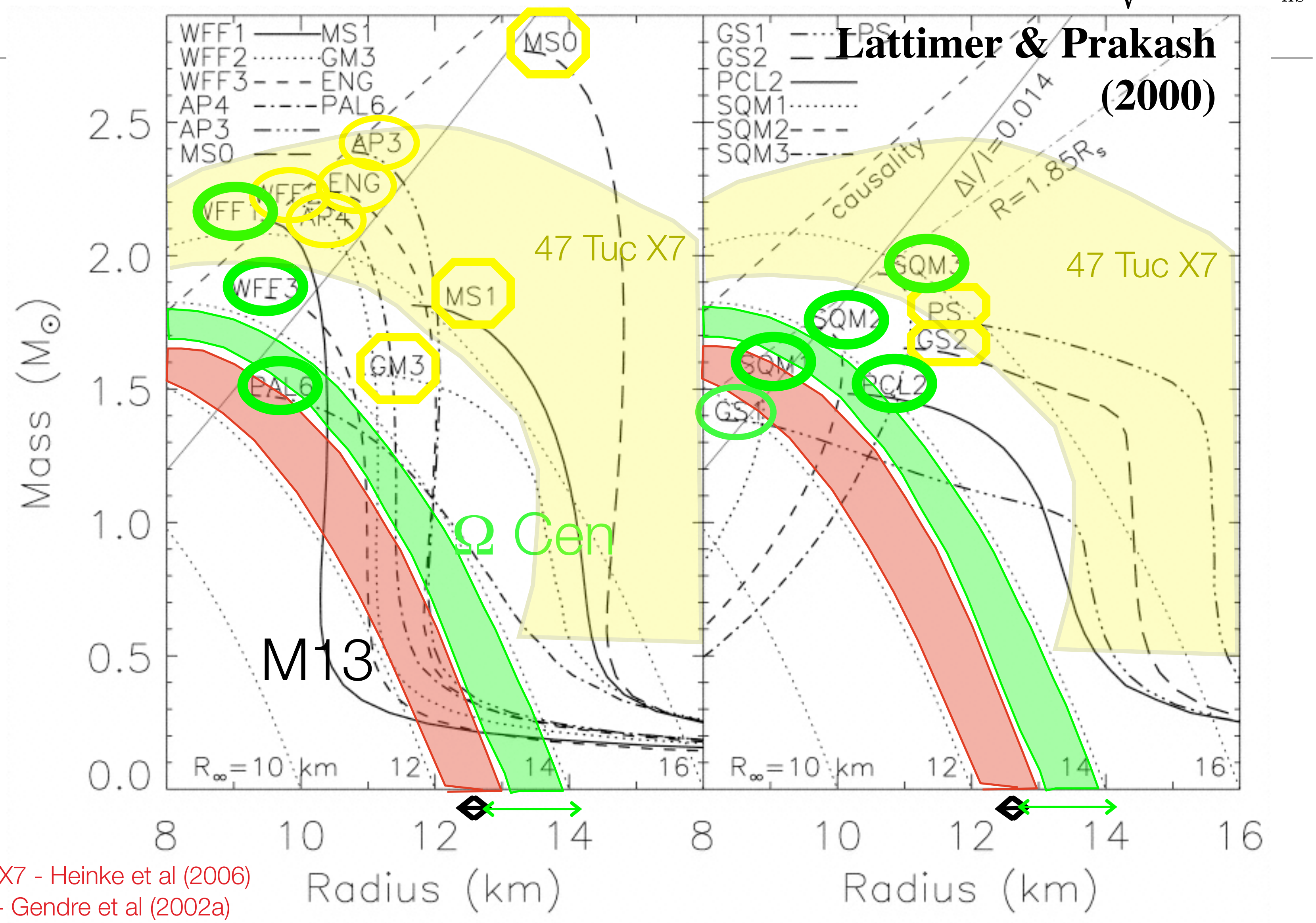
Caveats:

- All IDd by X-ray spectrum (47 Tuc, Omega Cen now have optical counterparts)
- calibration uncertainties

Distances:
Carretta et al (2000), Thompson et al (2001)

Best Mass-Radius Constraints on the Equation of State

$$R_\infty = \frac{R_{NS}}{\sqrt{1 - \frac{2GM_{NS}}{c^2 R_{ns}}}}$$



47 Tuc X7 - Heinke et al (2006)
M13 - Gendre et al (2002a)
Omega Cen - Gendre et al (2002b)

Observed   Observed with insufficient time   Not Observed

NGC	Rcore (")	D (kpc)	log NH	Obs. Time	qNS detect	qNSs?
104	22.5	4.6	20.3	74 I/ 299 S	33	2
5904	24.2	7.6	20.2	45	87	
3201	86.3	5.0	21.1	(XMM: 70)	56	1?
4372	104.2	5.2	21.4	(XMM)	89	
4833	60.2	5.8	21.3	0	91	
5139	156.3	4.9	20.9	70 S	48	1
6121	50.3	2.0	21.4	25	12	
6205	52.0	7.2	20.0	60 ksec 11/05	76	1 /XMM
6218	39.4	5.6	21.0	30	66	
6254	51.3	4.3	21.2	0	47	
6352	49.9	6.1	21.0	0	80	
6366	110.1	4.0	21.6	XMM 70; 24	68	
6397	3.0	2.2	21.0	109	10	1
6496	62.8	5.7	21.0	0	66	
6539	4.0	32.5	21.7	(scheduled)	92	
6541	17.9	6.6	20.9	46 S	83	
6544	2.9	2.5	21.6	17	29	
6553	33.1	3.5	21.7	XMM 21	73	
6656	84.3	3.0	21.3	XMM 470	26	
6752	10.5	4.2	20.3	30 S	28	
6809	170.6	4.8	20.8	XMM 27	43	
6838	38.2	3.9	21.2	55	39	
7099	3.4	7.4	20.5	50 S	88	

- 23 GCs for which one could easily detect 10^{32} erg/s qNS in <100 ksec w/ Chandra
- 12 have sufficient time, in which 5 (6?) qNSs detected.
- 5 observed with insufficient time.

6 not observed.

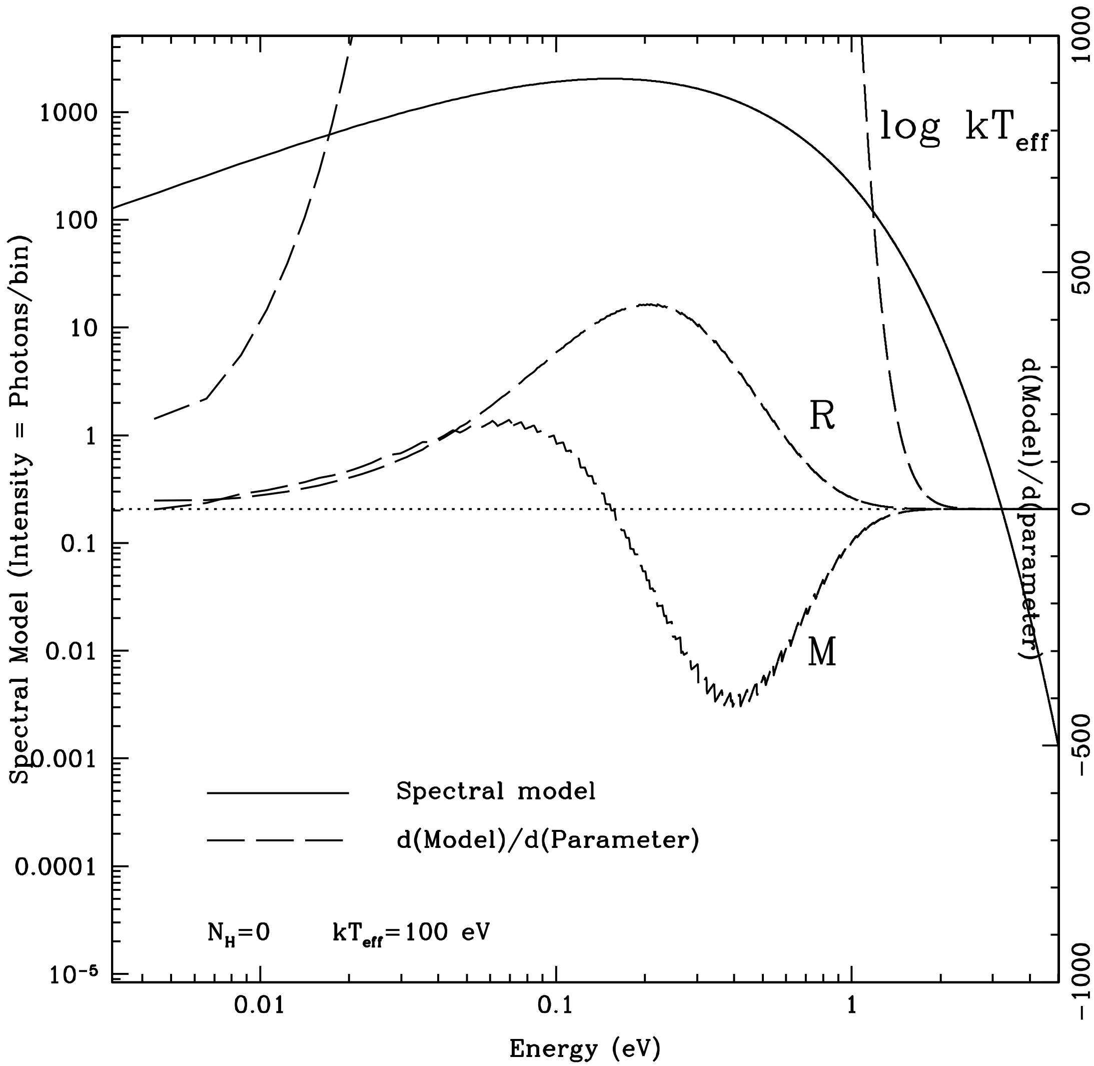
$$R_\infty \rightarrow \quad \text{Normalization}$$

$$T_\infty \rightarrow \quad \text{Peak of the spectrum}$$

$$z = \frac{G\,M_{NS}}{c^2 R_{\rm NS}} \rightarrow \quad \text{Second Derivative at the Peak of the Spectrum}$$

$$(R_\infty = \frac{R_{\rm NS}}{\sqrt{1 - \frac{2GM_{\rm NS}}{c^2 R_{\rm ns}}}}, z = \frac{GM_{\rm NS}}{c^2 R_{\rm NS}}) \rightarrow (R_{\rm NS}, M_{\rm NS})$$

Neutron Star Mass and Radius Measurement with Broad-Band X-ray Spectroscopy: Fisher Analysis



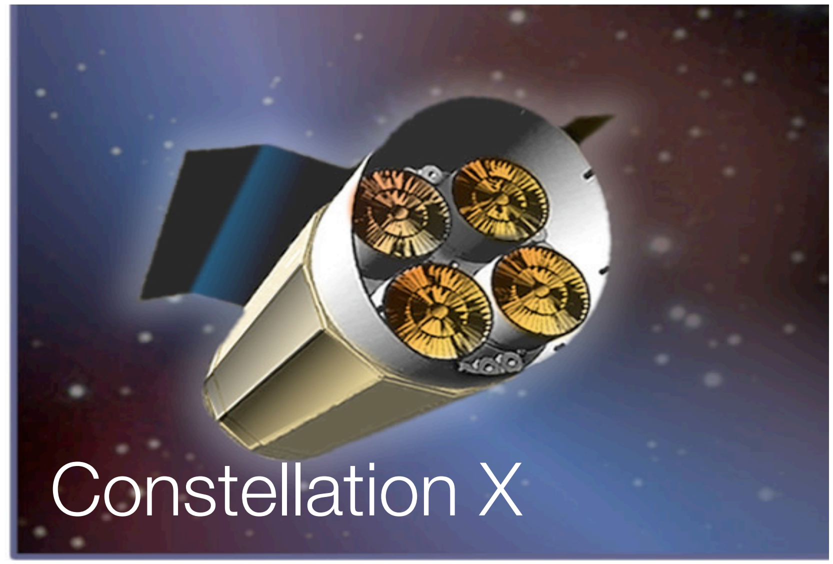
$$M_j = \sum_i F(E_i) A_{i,j}$$

$$C_{\alpha,\beta} = \sum_i \frac{1}{M_i} \frac{dM_i}{dP_\alpha} \frac{dM_i}{dP_\beta}$$

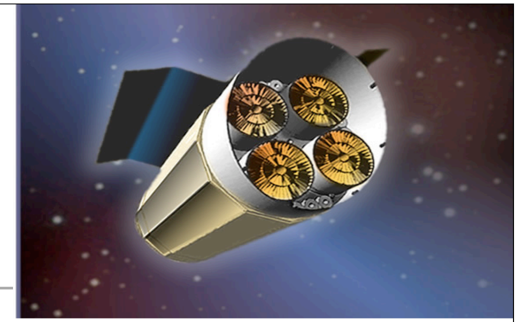
$$\sigma^2_{\alpha,\beta} = (C^{-1})_{\alpha,\beta}$$

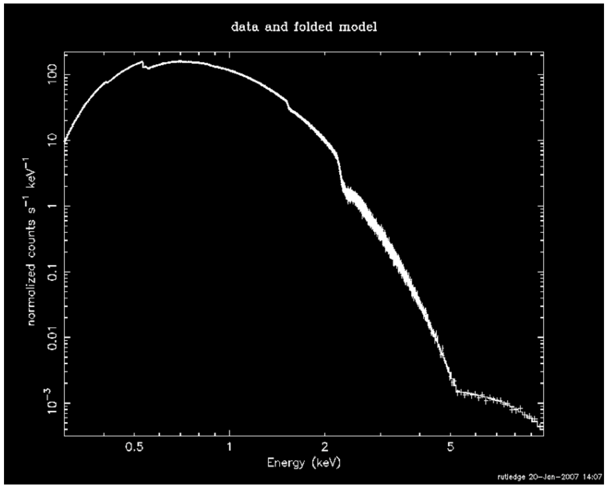
X-ray Observatories -- Beyond 2010 Constellation X / (International X-ray Observatory)?

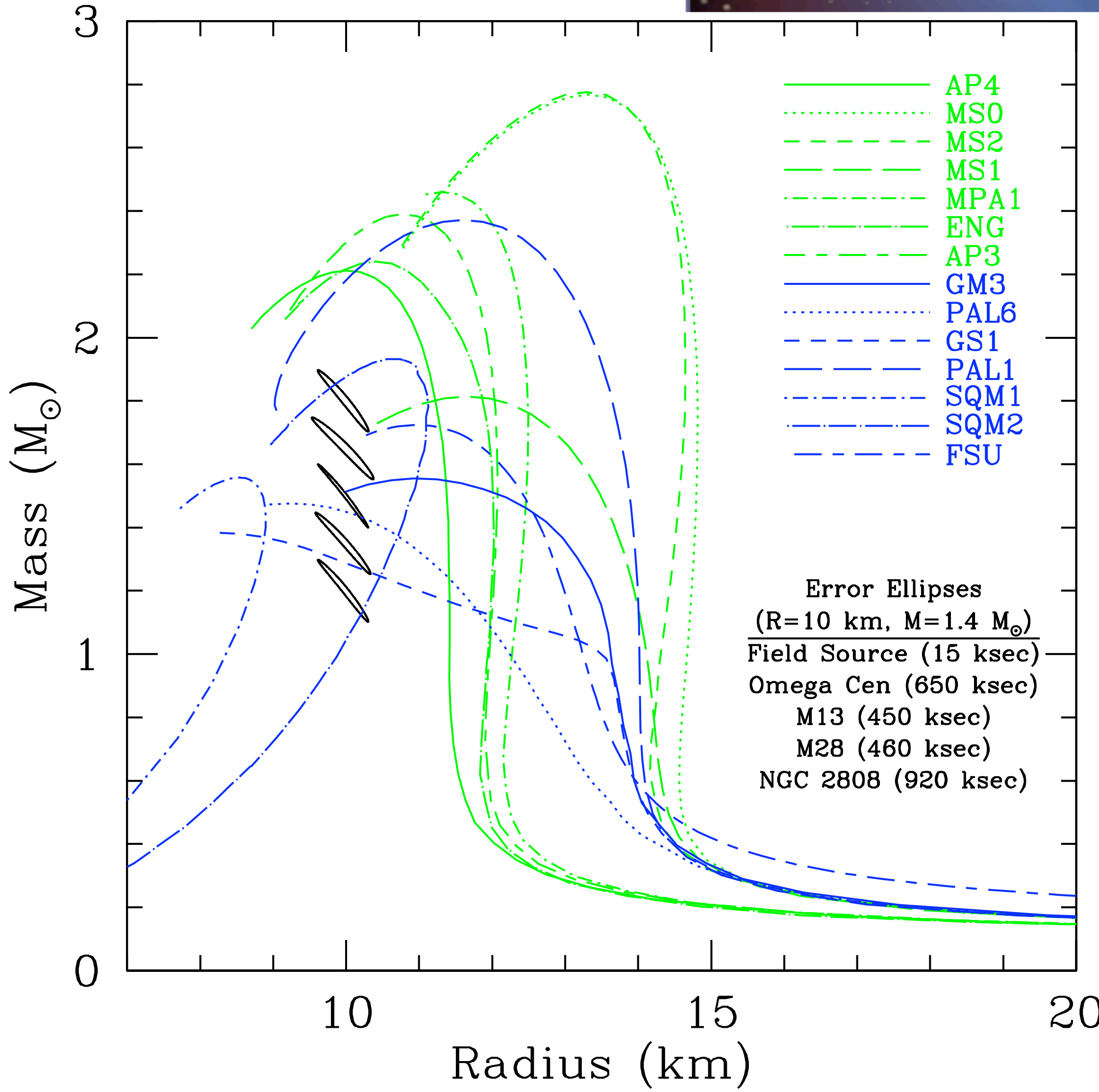
- Collecting area 50-100x present missions. High S/N X-ray spectroscopy will make possible precise (~5% accurate) simultaneous Mass and Radius measurements of neutron stars.
- Status: Under Review to determine priority under the Einstein program (Behind JDEM). Earliest launch: 2016.
- NASA Recently signed MOU with ESA & JAXA to explore an International X-ray Observatory.
- 15” sized PSF excludes all but ~3 of the known Globular Cluster sources for detailed study (OCen, M13, M28)
- A return to the field sources is required for progress. This will also require a high-precision (10 uarcsec) parallax mission, to obtain ~2% distances to field sources.



Constellation X
Simultaneous Mass and Radius Measurement



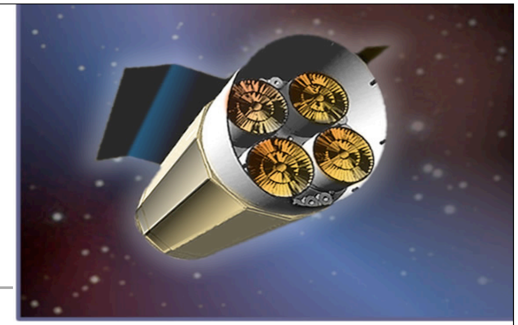




Observationally important qLMXBs in Globular Clusters

qLMXB	kT_eff(infty) (ev)	NH	Fx (10^{-13} cgsflux)	Band (keV)	Ref.	
47 Tuc X7	105(5)	0.04(2)	5.3	0.5-10	Heinke et al (2006)	<: 5”
47 Tuc X5	100(20)	0.09(7)	4.3	0.5-10	Heinke et al (2003)	< 5”
M28	90(+30-10)	0.26(4)	3.4	0.5-8	Becker et al (2003)	
NGC 6304 X4	120(50)	[0.266]	2.3	0.5-10	Guillot et al (2008)	
oCen	67(2)	0.09(3)	1.7	0.1-5	Rutledge et al (2002), Gendre et al (2003)	
NGC 6304 X9	100(20)	[0.266]	1.5	0.5-10	Guillot et al (2008)	
NGC 6397	74(18)	0.1-0.26	1.06	0.5-2.5	Grindlay et al (2001	< 15”
M13	76(3)	[0.011]	1.03	0.1-5	Gendre et al (2003)	
M30 A-1	94(15)	0.03(1)	0.73	0.5-10	Lugger (2007)	
NGC 6304 X5	70(25)	[0.266]	0.59	0.5-10	Guillot et al (2008)	
M80 CX2	82(2)	0.09(2)	0.23	0.5-6	Heinke et al (2003)	<5”
M80 CX6	76(6)	0.22(7)	0.07	0.5-6	Heinke et al (2003)	<15”
NGC 2808 C2	--	0.86	0.02	--	Servillat et al (2008)	<15”

Constellation X/IXO
Simultaneous Mass and Radius Measurement



- Neutron Star Masses and Radii can be measured from Hydrogen atmosphere neutron stars with ~few% accuracy with coming generation X-ray telescope.
- Field sources are the most promising targets, due to their brightness.
- Parallax mission will also be required to obtain accurate (1%) distances.