Measuring the Dense Matter Equation of State with the International X-ray Observatory

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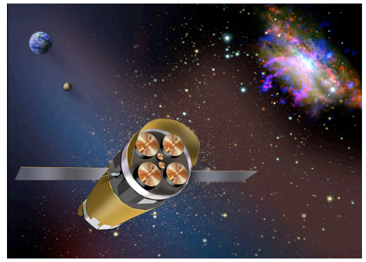
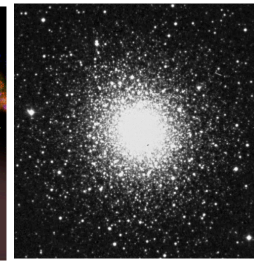
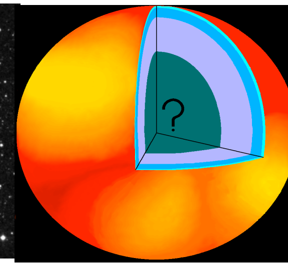
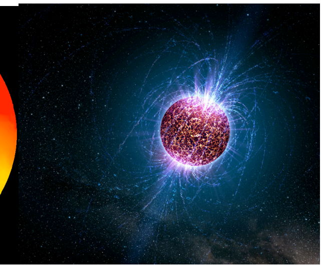
Summary



- 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 a proposed mission (International X-ray Observatory).

Solving Quantum Chromodynamics At Finite Density - Neutron Stars are Unique Astrophysical Laboratories

- 1932: Since discovery of neutron (Chadwick 1932), how the strong force works to mediate attraction between protons and neutrons has been a major question.
- 1930s-1960s: Strong force is a non-superpositional force, multi-body in nature -- parameterization with Skyrme potential with some success explaining the properties of small nuclei.
- 1960s: Discovery of quarks, and development of QCD explained the formation of neutrons, protons, mesons, hyperons.... This is QCD at finite energy (temperature, QCDt). It does an outstanding job of explaining the existence of these particles, and their one-to-one interactions, but we have no exact theoretical apparatus to perform the many-body interaction calculations. Thus we rely on approximate methods of effective-field-theories (Brueckner-Betha-Goldstone Theory, Green's function theory, and relativistic mean-field theory).
- Today: QCD is not an exact theory at finite density (QCDd). Where this becomes relevant is above nuclear density ($>2.35\times10^{14}$ g cm^{-3}).
- It is technically impossible to create a cold matter above nuclear density terrestrial laboratories. In the cores of neutron stars, gravitational force compresses matter to supernuclear densities.
- Thus: Neutron Stars are unique sites for exploring QCDd in the universe, precisely as black holes are the unique sites for strong field gravity. (Question: really? what about nuclei? at supernuclear densities?)
- If we want to solve QCDd, neutron stars will be the astrophysical tool for how we do it.

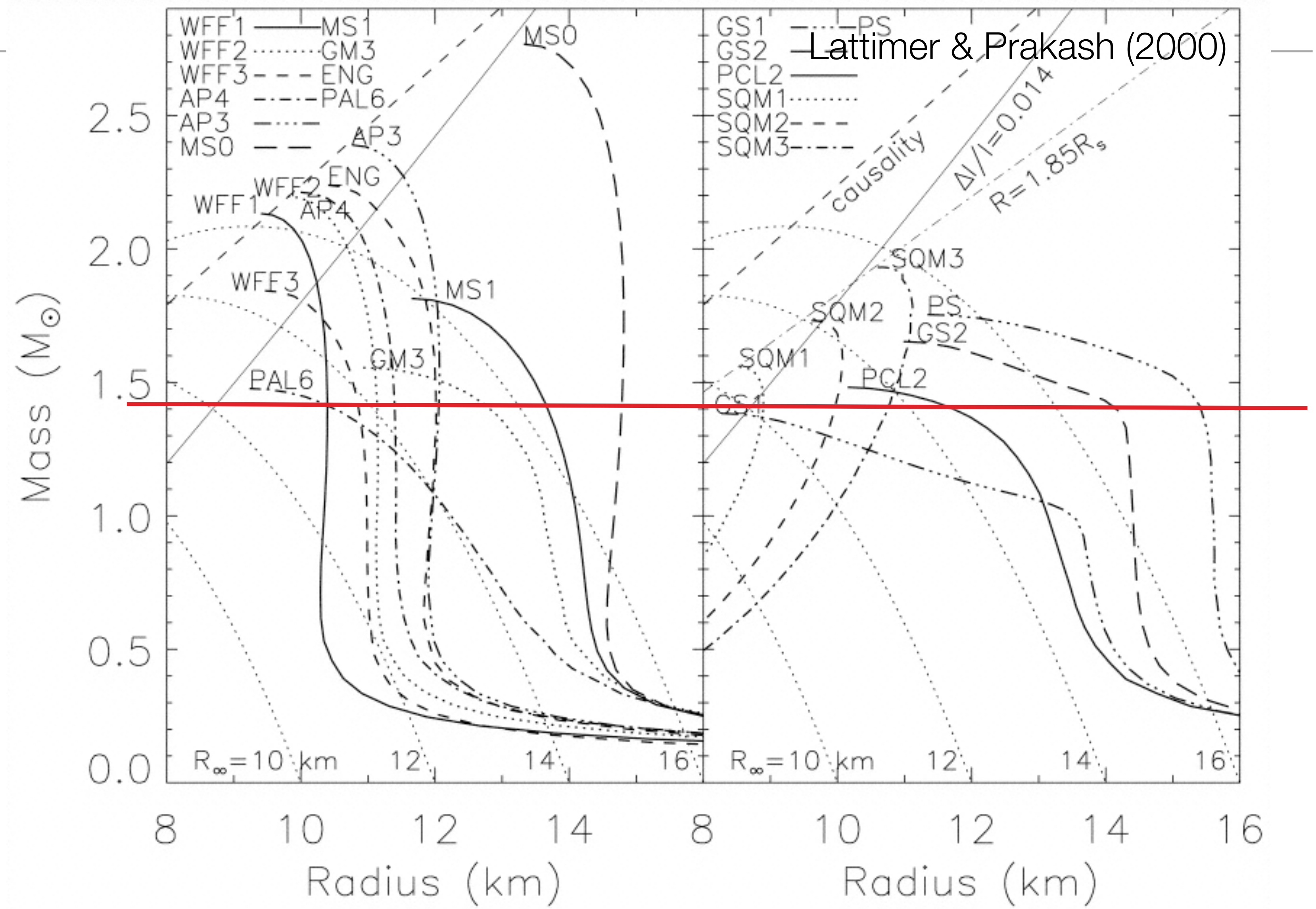
From Neutron Star Mass-Radius Relation to the Equation of State

- Lindblom (1992) showed that each Dense Matter Equation of State maps to a unique Mass-Radius relationship for neutron stars.

- Postnikov, Prakash and Lattimer (in progress) demonstrate how to perform the inverse problem: take the mass-radius relationship, and produce an equation of state. Only ~5-7 such objects are needed, but "with different masses", to derive a new dense matter equation of state.

- Thus, measurement of the neutron star mass-radius relationship would implicate a unique dEOS.

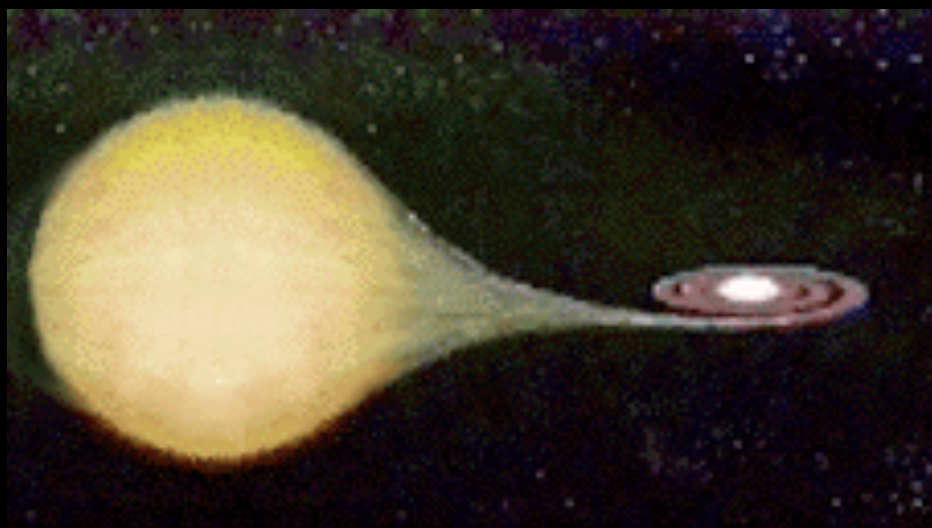
Mass-Radius Relation from the Equation of State



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

However, not so useful for radius measurements.

Quiescent Low Mass X-ray Binaries

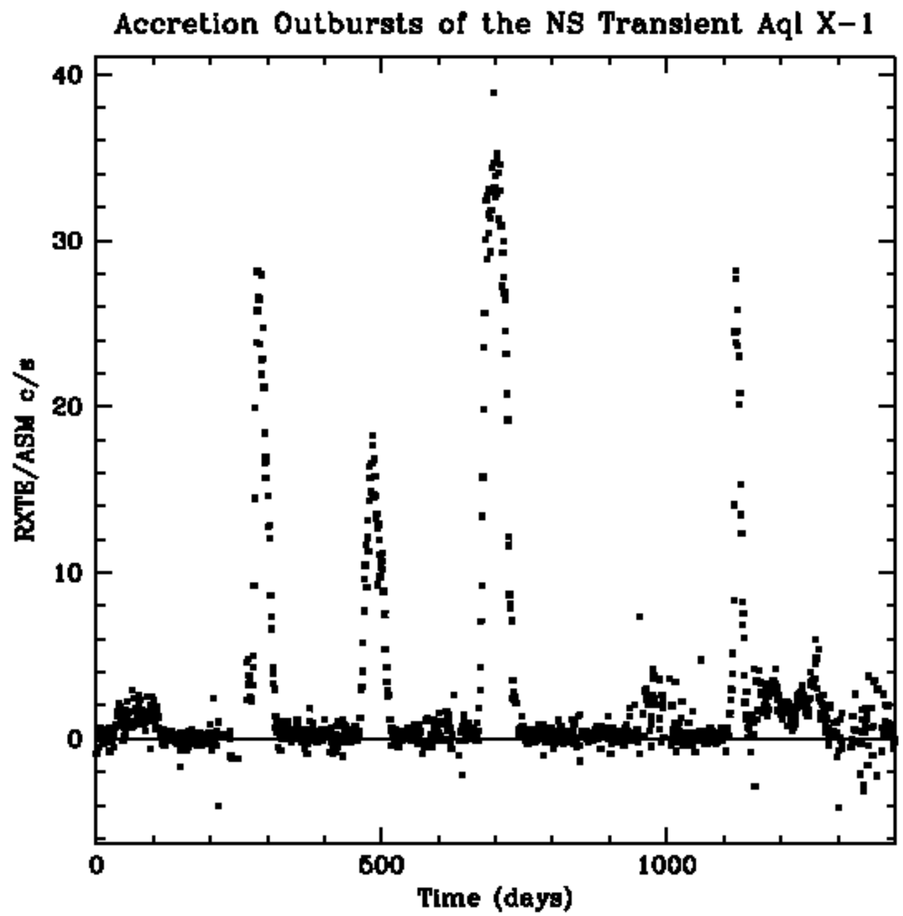


- When accreting (pictured) we mostly observe X-rays from the disk.
- In some sources ("transients") accretion can stop -- and then we see only the neutron star.

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})

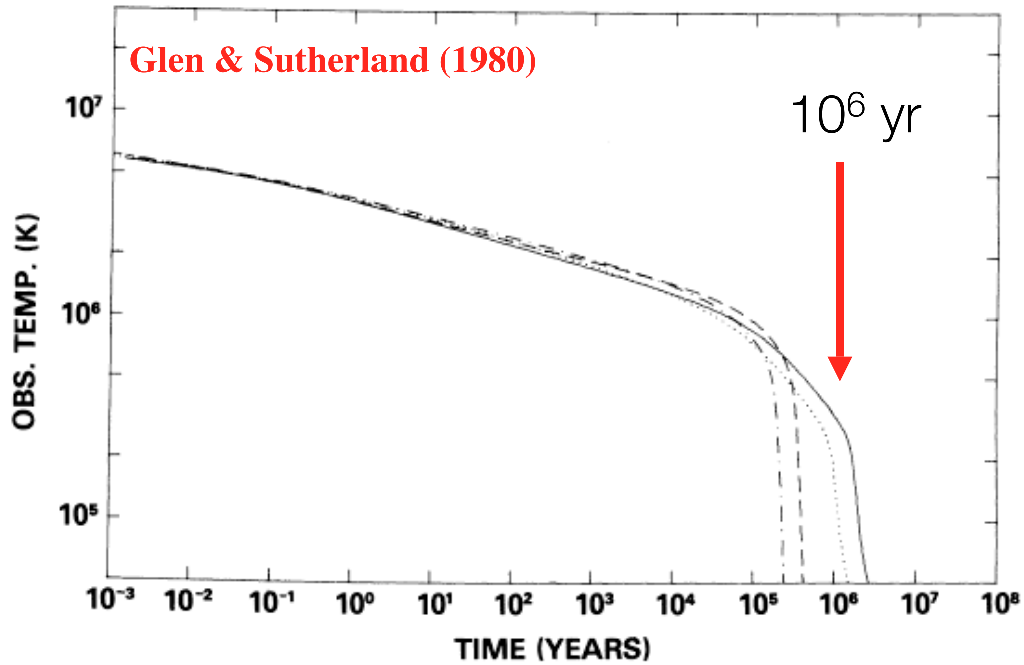


Why are qLMXBs promising for measuring NS radii?

Brown, Bildsten & RR (1998)

First detection: transient neutron star was discovered in quiescence (Cen X-4; $L_x \sim 10^{33}$ 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

Non-Equilibrium Processes in the Outer Crust
Beginning with ^{56}Fe (Haensel &Zdunik 1990, 2003)

ρ (g cm^{-3})	Reaction	Δρ/ρ	Q (Mev/np)
$1.5\cdot10^{9}$	$^{56}Fe \Rightarrow {}^{56}Cr - 2e- + 2\nu_e$	0.08	0.01
$1.1\cdot10^{10}$	$^{56}Cr \Rightarrow {}^{56}Ti - 2e- + 2\nu_e$	0.09	0.01
$7.8\cdot10^{10}$	$^{56}Ti \Rightarrow {}^{56}Ca - 2e- + 2\nu_e$	0.10	0.01
$2.5\cdot10^{10}$	$^{56}Ca \Rightarrow {}^{56}Ar - 2e- + 2\nu_e$	0.11	0.01
$6.1\cdot10^{10}$	$^{56}Ar \Rightarrow {}^{52}S + 4n - 2e- + 2\nu_e$	0.12	0.01

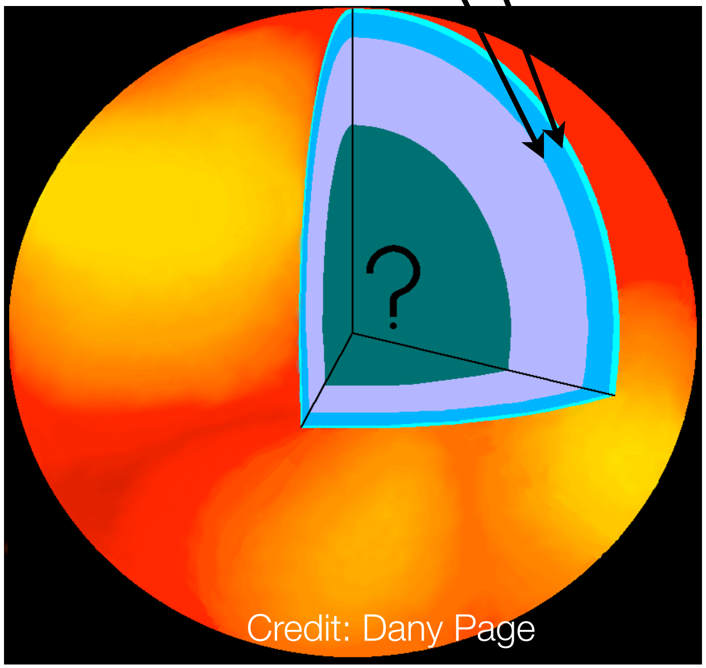
Non-Equilibrium Processes in the Inner Crust

ρ (g cm^{-3})	Reaction	X_n	Q (Mev/np)
$9.1\cdot10^{11}$	$^{52}S \Rightarrow {}^{46}Si + 6n - 2e- + 2\nu_e$	0.07	0.09
$1.1\cdot10^{12}$	$^{46}Si \Rightarrow {}^{40}Mg + 6n - 2e- + 2\nu_e$	0.07	0.09
$1.5\cdot10^{12}$	$^{40}Mg \Rightarrow {}^{34}Ne + 6n - 2e- + 2\nu_e$		
	$^{34}Ne + {}^{34}Ne \Rightarrow {}^{68}Ca$	0.29	0.47
$1.8\cdot10^{12}$	$^{68}Ca \Rightarrow {}^{62}Ar + 6n - 2e- + 2\nu_e$	0.39	0.05
$2.1\cdot10^{12}$	$^{62}Ar \Rightarrow {}^{56}S + 6n - 2e- + 2\nu_e$	0.45	0.05
$2.6\cdot10^{12}$	$^{56}S \Rightarrow {}^{50}Si + 6n - 2e- + 2\nu_e$	0.50	0.06
$3.3\cdot10^{12}$	$^{50}Si \Rightarrow {}^{44}Mg + 6n - 2e- + 2\nu_e$	0.55	0.07
$4.4\cdot10^{12}$	$^{44}Mg \Rightarrow {}^{36}Ne + 6n - 2e- + 2\nu_e$		
	$^{36}Ne + {}^{36}Ne \Rightarrow {}^{72}Ca$		
	$^{68}Ca \Rightarrow {}^{62}Ar + 6n - 2e- + 2\nu_e$	0.61	0.28
$5.8\cdot10^{12}$	$^{62}Ar \Rightarrow {}^{60}S + 6n - 2e- + 2\nu_e$	0.70	0.02
$7.0\cdot10^{12}$	$^{60}S \Rightarrow {}^{54}Si + 6n - 2e- + 2\nu_e$	0.73	0.02
$9.0\cdot10^{12}$	$^{54}Si \Rightarrow {}^{48}Mg + 6n - 2e- + 2\nu_e$	0.76	0.03
$1.1\cdot10^{13}$	$^{48}Mg + {}^{48}Mg \Rightarrow {}^{96}Cr$	0.79	0.11
$1.1\cdot10^{13}$	$^{96}Cr \Rightarrow {}^{88}Ti + 8n - 2e- + 2\nu_e$	0.80	0.01

Deep Crustal Heating

Begins Here

Ends Here



1.47 Mev per np

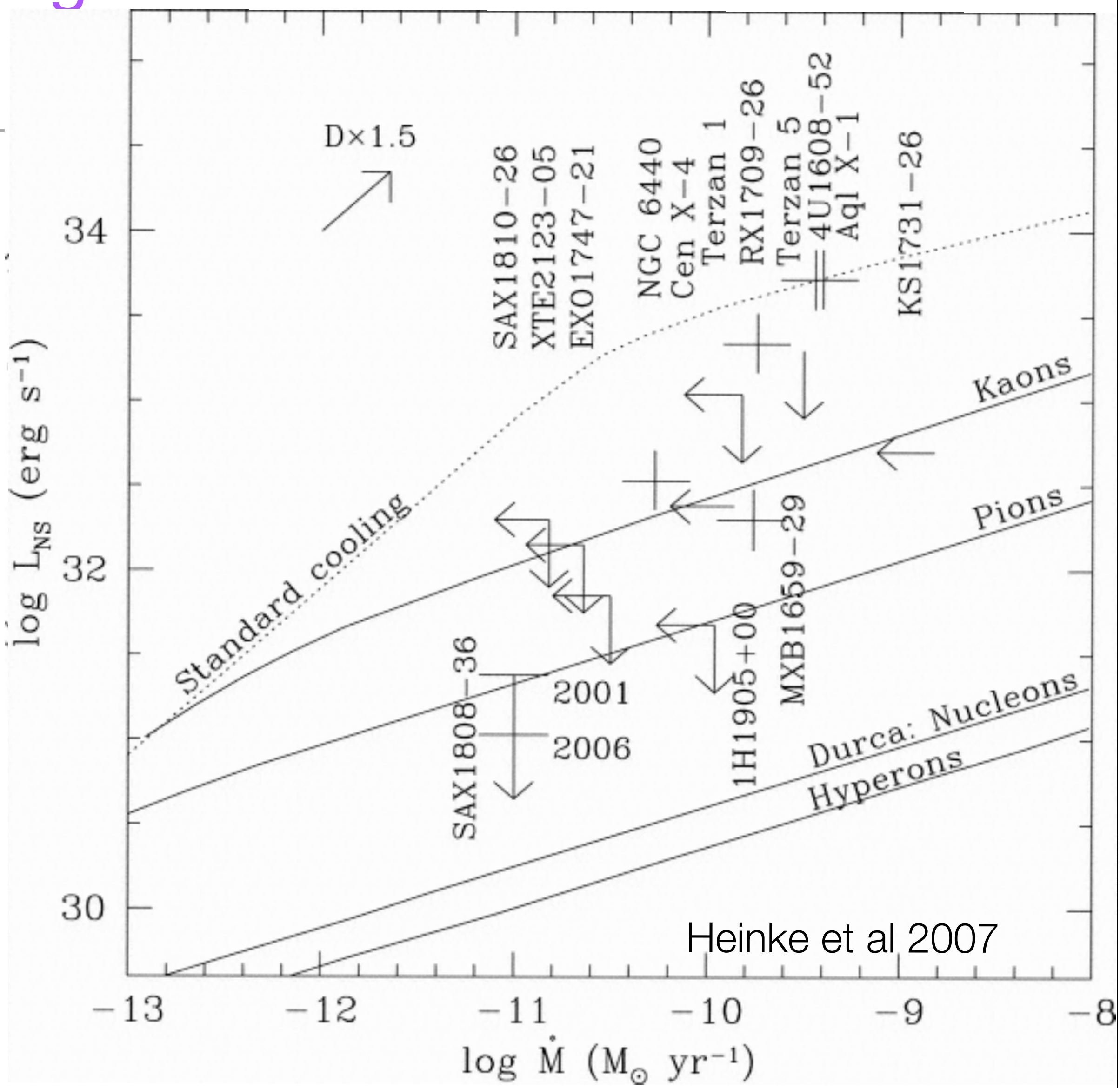
Brown, Bildsten & RR (1998)

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).

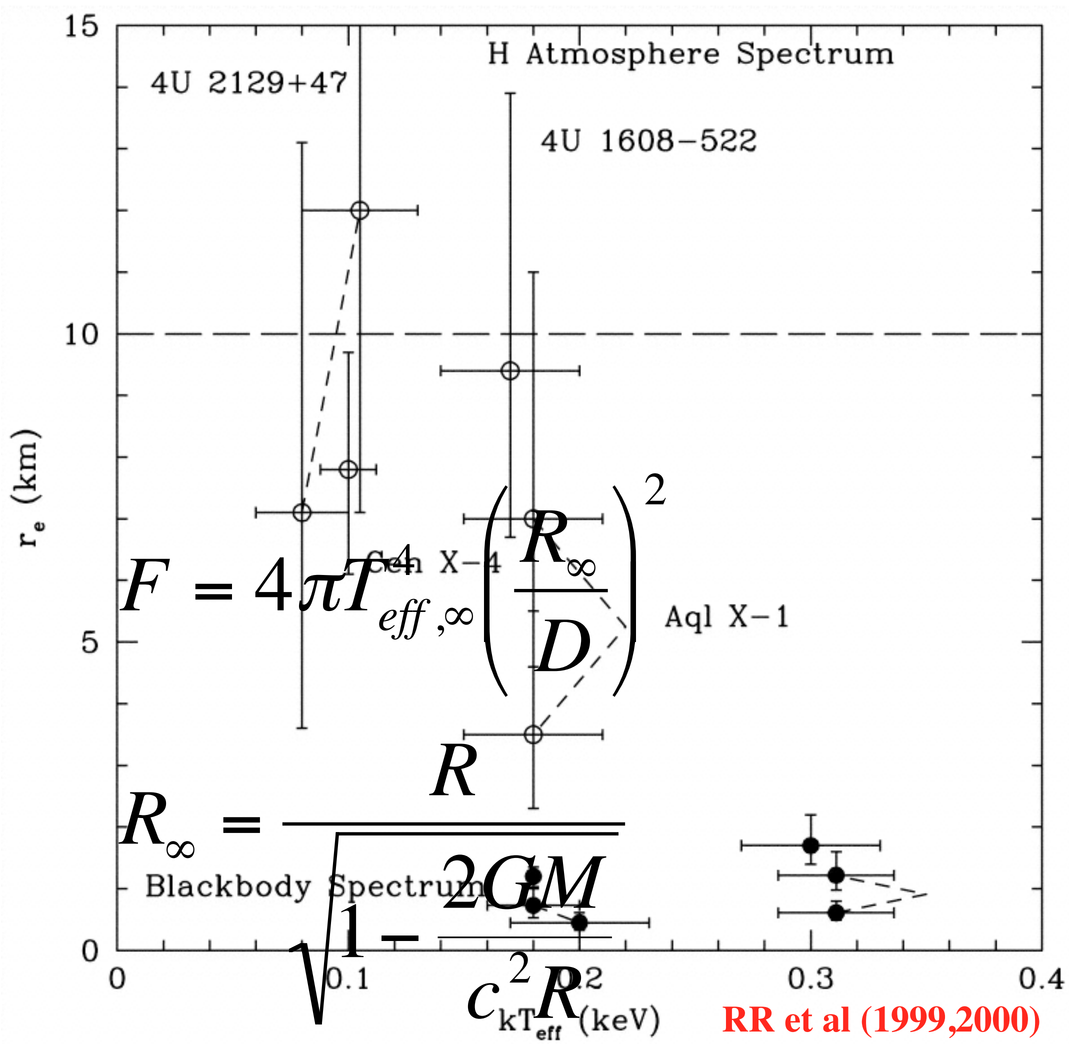
Solution: qNSs are not blackbodies.

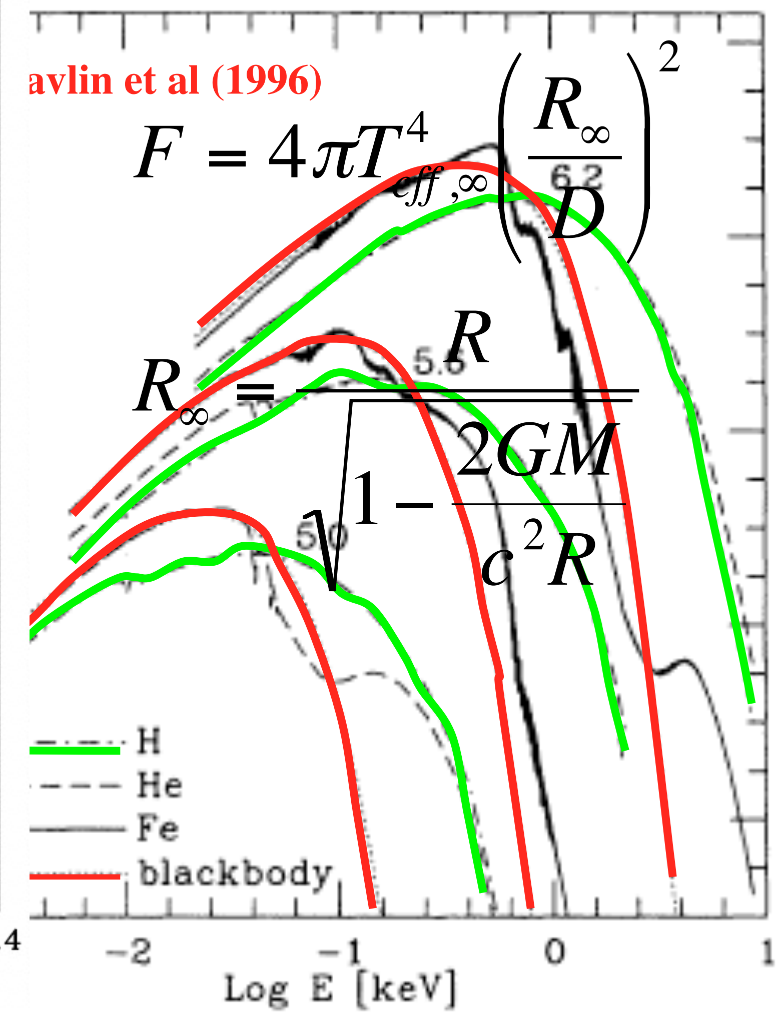
When the accretion rate onto the NS drops below a certain rate (~10^{34} erg s^{-1}) metals settle out of the photosphere on a timescale of 10-100 sec (Bildsten et al 1992). This leaves a photosphere of pure Hydrogen. The dominant opacity of a ~100 eV H photosphere is free-free processes, which is strongly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

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

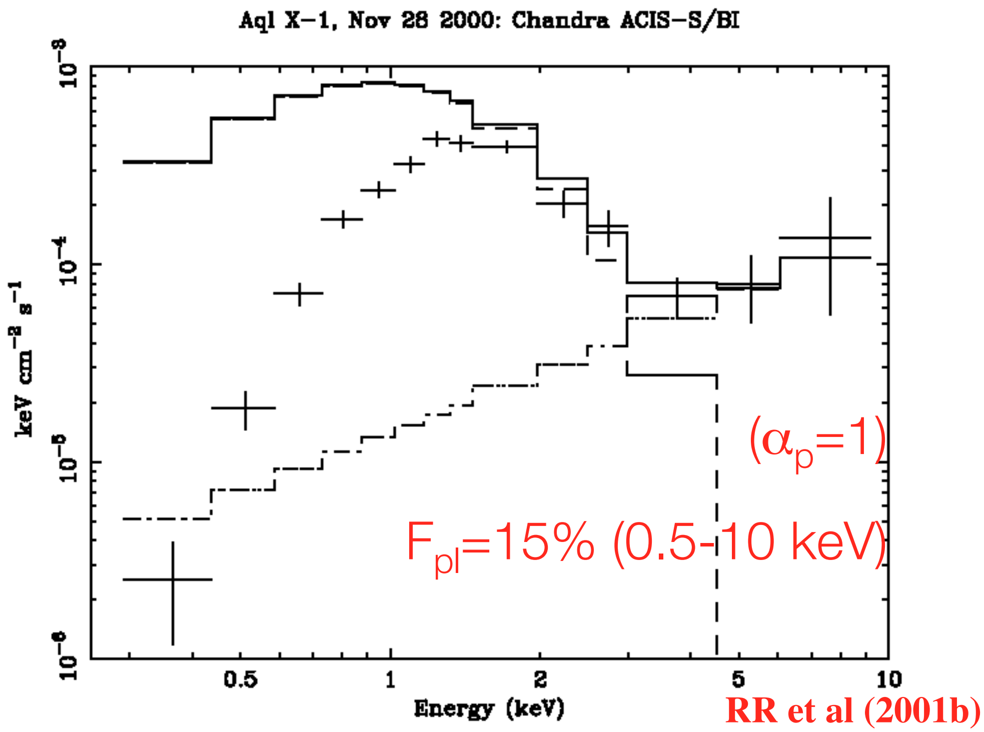
Brown, Bildsten & RR (1998)

Emergent Spectra from Neutron Star Hydrogen Atmosphere





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}

H atmosphere Spectral Analyses of qLMXBs in the field

- Cen X-4 (Campana et al. 2000; Rutledge et al. 2001b);
- Aql X-1 (Rutledge et al. 2001a)
- 4U 1608-522 (Rutledge et al. 1999);
- 4U 2129+47 (Rutledge et al. 2000);
- SAX J1748−2021, in NGC 6440 (in't Zand et al. 2001);
- X1732-304 in Terzan 1 (Wijnands et al. 2002);
- XTE J2123−058 (Tomsick et al. 2004);
- EXO 1747−214 (Tomsick et al. 2005);
- MXB 1659−29 (Cackett et al. 2006);
- 1M 1716−315 (Jonker et al. 2007a);
- 2S 1803−245 (Cornelisse et al. 2007);
- 4U 1730−22 (Tomsick et al. 2007);
- 1H 1905+000 (Jonker et al. 2007b).

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.

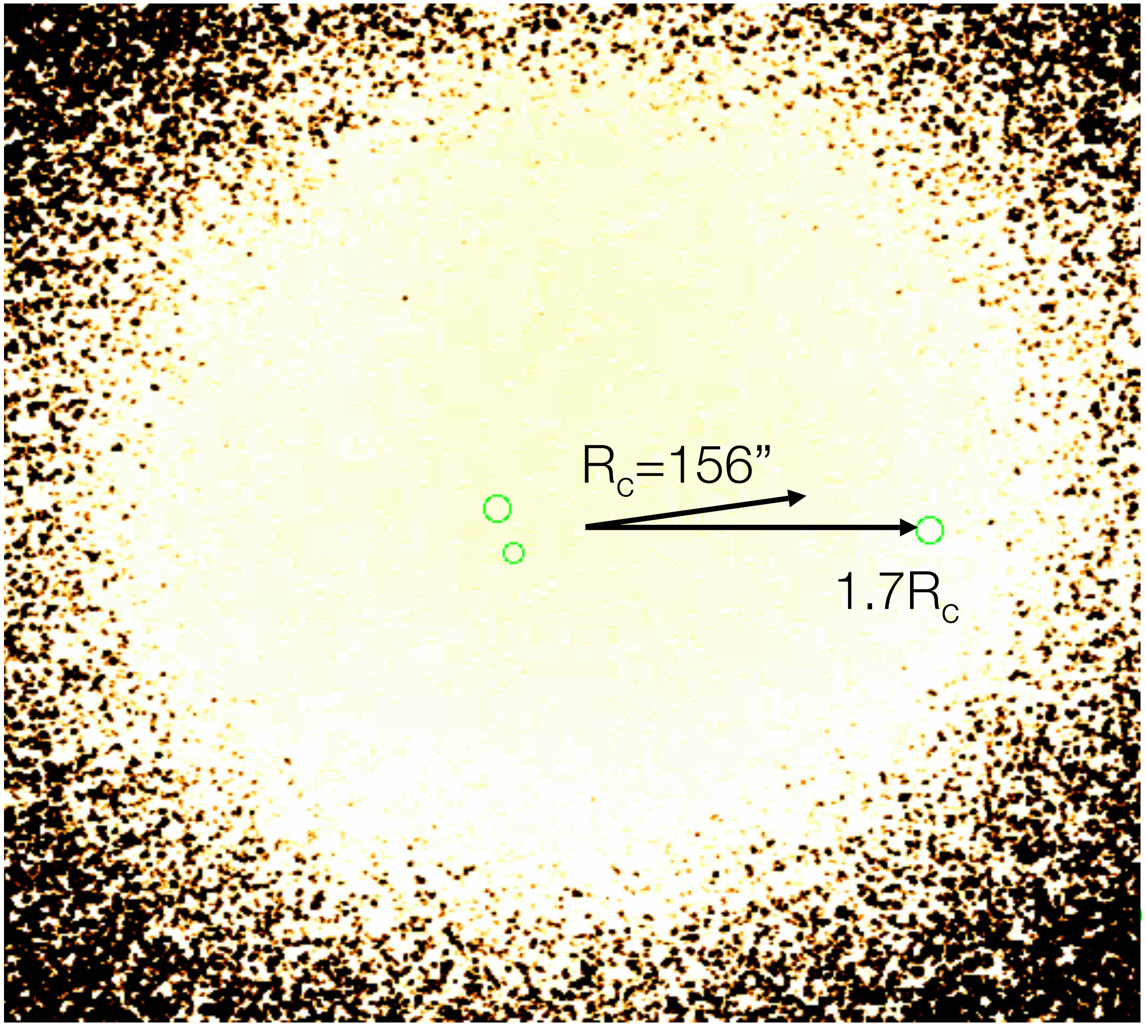
- Accurate distances are important for a number of studies (Stellar evolution, WD cooling).

qLMXBs 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

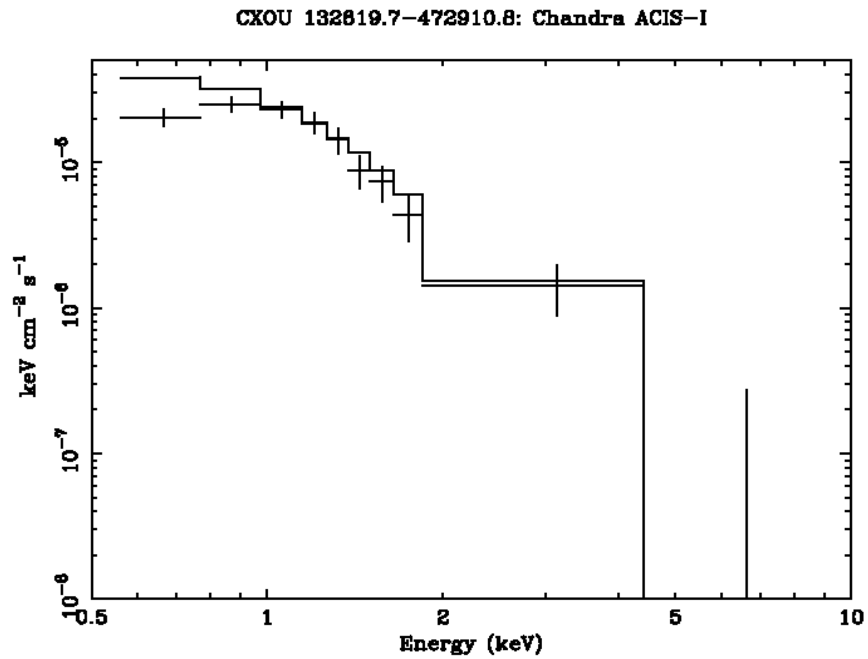
Carretta et al (2000)

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

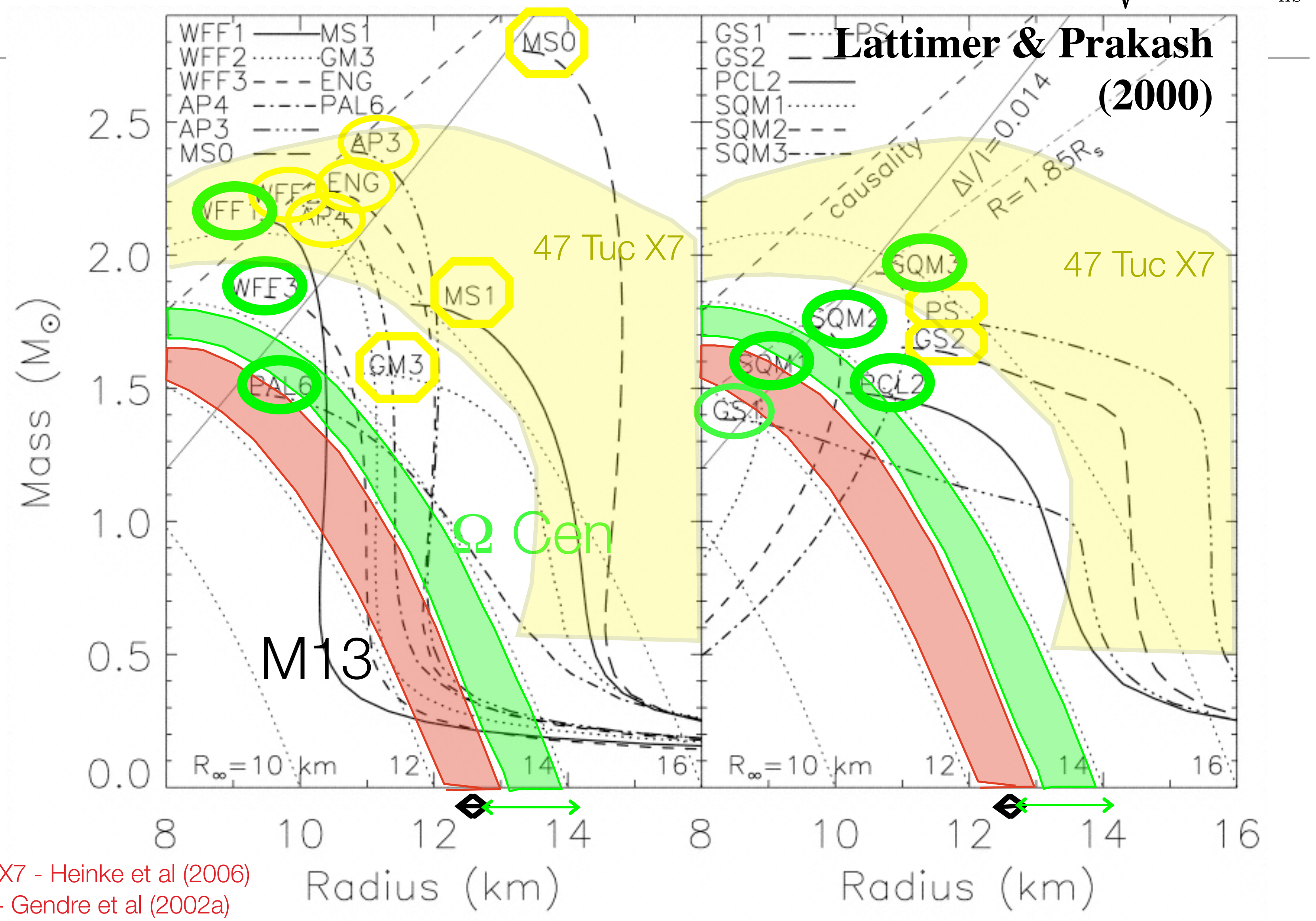
Distances:
Carretta et al (2000), Thompson et al (2001)

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”

Best Mass-Radius Constraints on the Equation of State

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



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

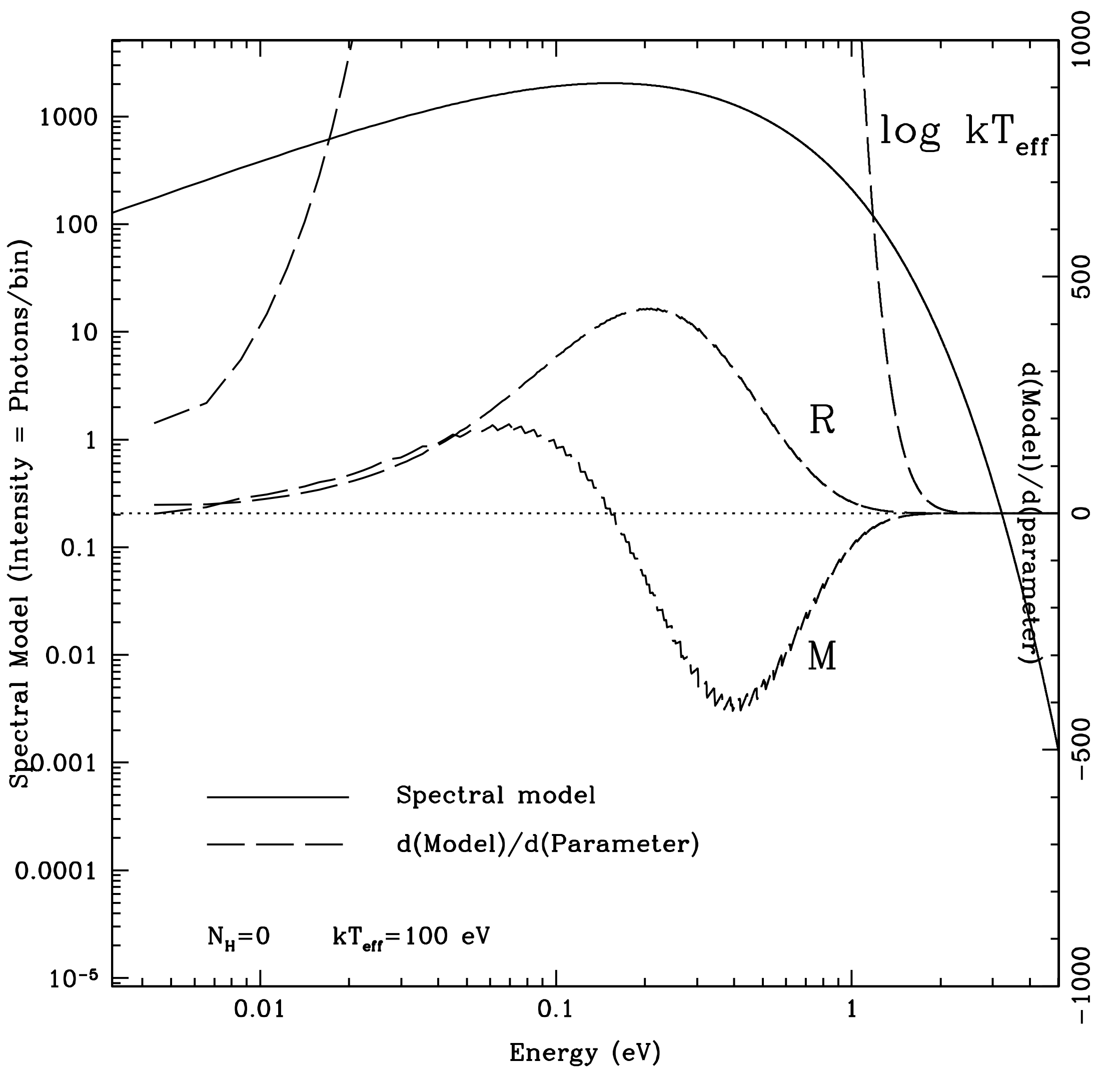
$$R_\infty \rightarrow \quad \text{Normalization}$$

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

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

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

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



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

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

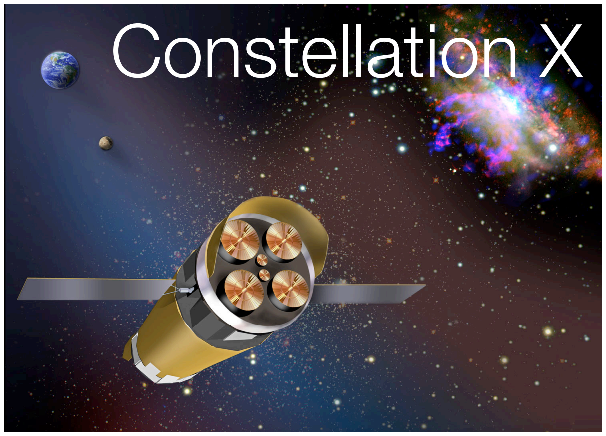
$$\sigma^2_{\alpha,\beta} = (C^{-1})_{\alpha,\beta}$$

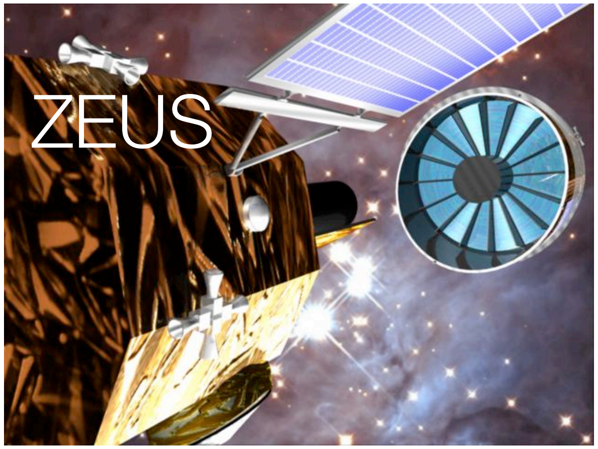
History: Pre- International X-ray Observatory

- The science case for a large X-ray Observatory is compelling:
    - Con-X: NASA concept, number two in 2000 Decadal survey
    - XEUS: ESA with JAXA candidate as large Cosmic Vision mission

Very similar science goals, very different derived requirements and implementation

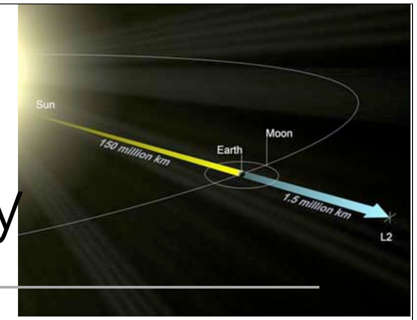
Unlikely there will be two large X-ray missions at the same time, and it would be more cost effective to join forces





Source: Randall Smith (NASA)

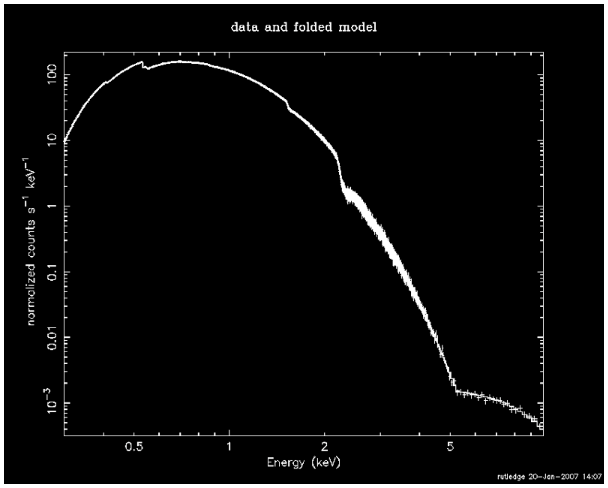
Today:
The Proposed International X-ray Observatory



- NASA, ESA and JAXA are no longer pursuing Con-X or ZEUS, and replaced its efforts with a joint effort toward a new proposal, the “International X-ray Observatory”: to be put forward to the Decadal Review processes.
- Basic specifications:
    - Area: 3 m² @ 1.25 keV
    - 1 m² @ 6-7 keV
    - 150-1000 cm² @ 40 keV
    - Energy resolution: <2.5 eV @ 0.5-2 keV
    - Spatial Resolution: <5 arcsec half-power diameter
    - Oribit: Out at L2 (anti-Geo/Solar direction)
    - Science Teams are coalescing.

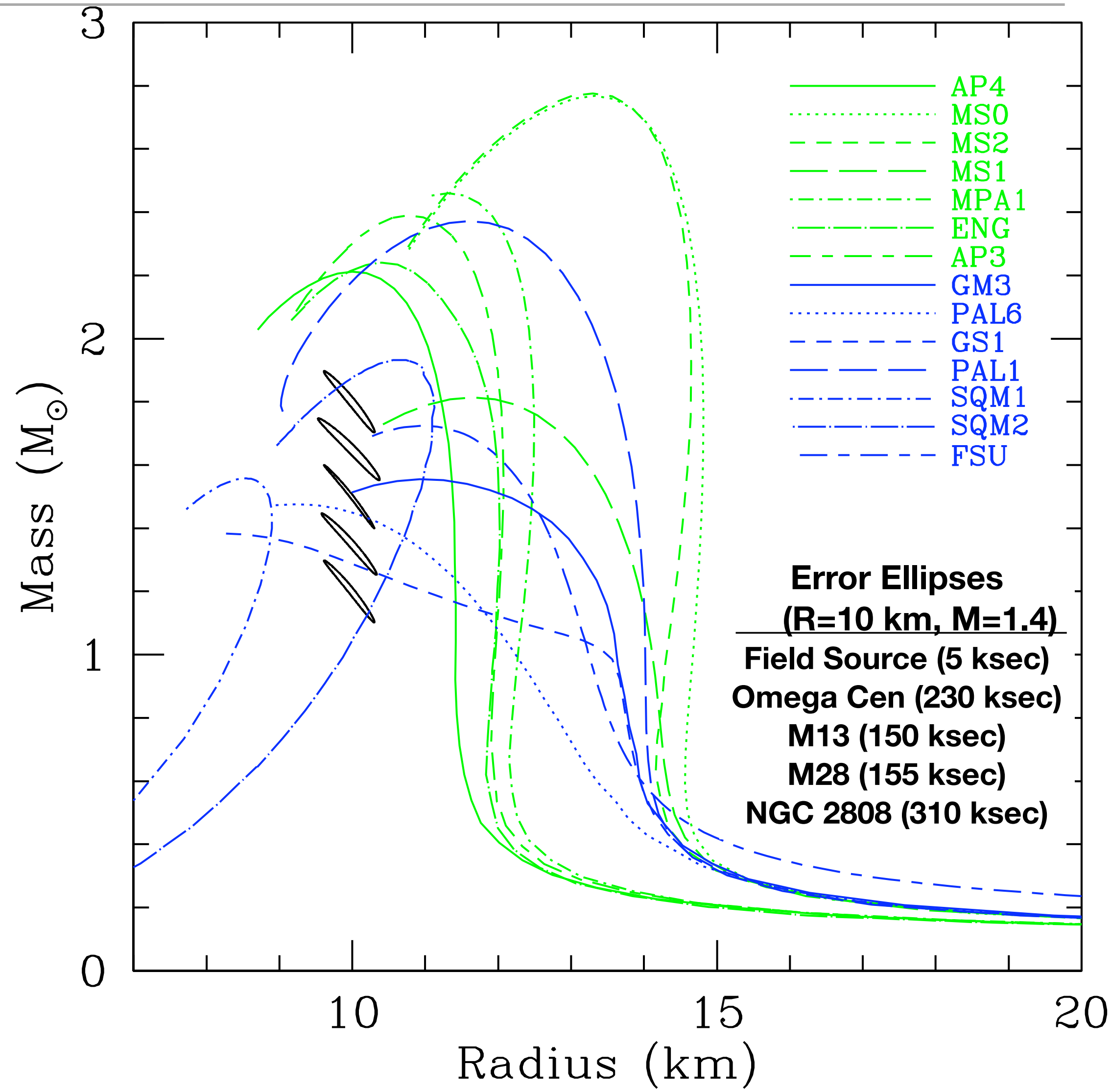
Source: Randall Smith (NASA)

Calorimeter response curves
Simultaneous Mass and Radius Measurement



Requirement: 250k-300k counts with calorimeter (2.5 eV) energy resolution.

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



IXO: Into the Future

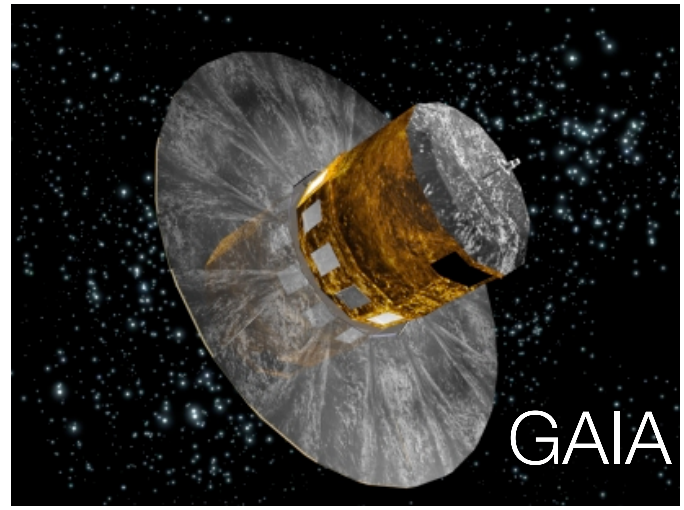
- Three equal Agency Representatives: Nick White (NASA), Arvind Parmar (ESA), Hideyo Kunieda (JAXA). For now, mutual agreement there is no “leader”.
- IXO will be the only major X-ray observatory presented to the Astronomy Decadal Survey.
  - The Astronomy Decadal Survey process is undertaken by the National Academy of Sciences every 10 years, and poses programmatic priorities in its report. These programmatic priorities give guidance to funding agencies and Congress for consideration in the budgetary process.
  - Roger Blandford selected as Chair (Sept 2008), and nominations were made for panel membership (Closed Nov 2008).
- Timeline to launch: Dec 2020.

Known Challenges to this Approach

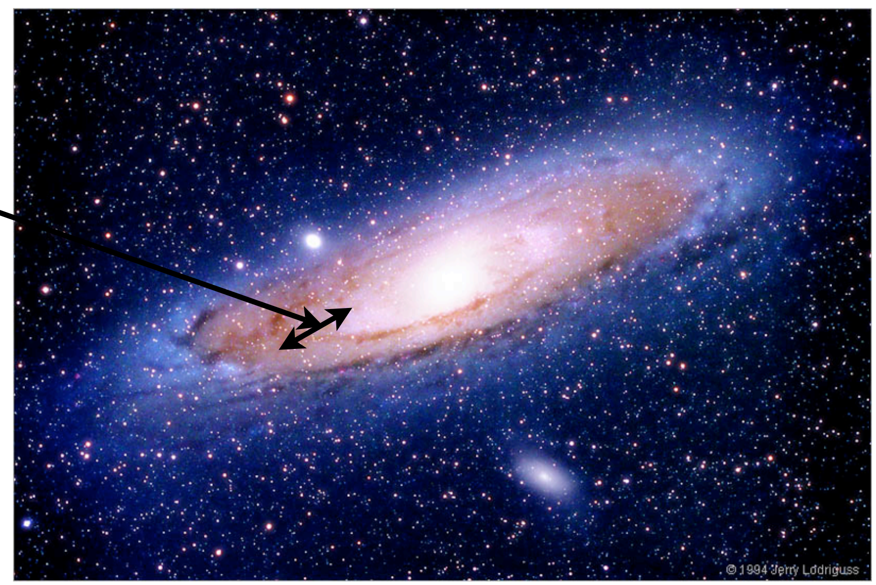
- Accurate Distances (<2-3%) are required.
- Astronomical Challenges
  - Background Spectral Contributions (the powerlaw?)
  - Coronal activity in the low-mass companion -- ~1-10% of the luminosity?
  - Non-DCH related Intensity Variability (observed in active field qLMXB Aql X-1, Cen X-4; but not yet detected in GC qLMXBs).
  - Will atmospheric isotropy hold?
  - Effects of rotation in the NS (simple doppler boosting)
- Systematic Challenges (instrumental Calibration)
- H Atmosphere Spectral models --- Heinke (Rybicki) et al (2006); Zavlin et al (2006) are calculated to ~1.5% accuracy in Lbol; disagree with each other at the 1-3% level at each photon energy, not likely to be resolved.
- “Next Generation” H atmosphere modeling is needed, with <0.1% uncertainty (Haakonsen et al, in progress).

Measuring Distances: GAIA Mission Capabilities

- An European Space Agency Cornerstone Mission, construction approved in 2006 and in process, with a launch (to L2) on schedule for 2011.



V	#	$\sigma_{\mu-arcsec}$	3% Distance (kpc)
10	0.34	7	4.2
15	26	22	1.4
20	1000	250	0.12



Are there enough qLMXBs within this distance?

IXO
Simultaneous Mass and Radius Measurements of Neutron Stars

Questions, comments:

1) Now is very much the time for this community to become active and vocal, directed toward the Decadal Survey Process (Chair: Roger Blandford; National Academy of Sciences). This means being specific about what capabilities (including theoretical ones!) will permit what breakthoughs in physics. 1) Write papers; 2) attend the open meetings and make presentations.

2) What will be learned about the dEOS prior to 2020 (PREX, FRIB)? Should we even bother launching IXO?

3) Is the following statement accurate: “Precisely as black holes are unique sites to study strong field gravity, neutron stars are the unique sites in the universe to study QCD at finite density, and determine the dense matter equation of state.”

4) If we precisely invert the dEOS from the NS M-R relationship, will we have learned anything about QCD at finite density?