Neutron Star Radii: At The Crossroads

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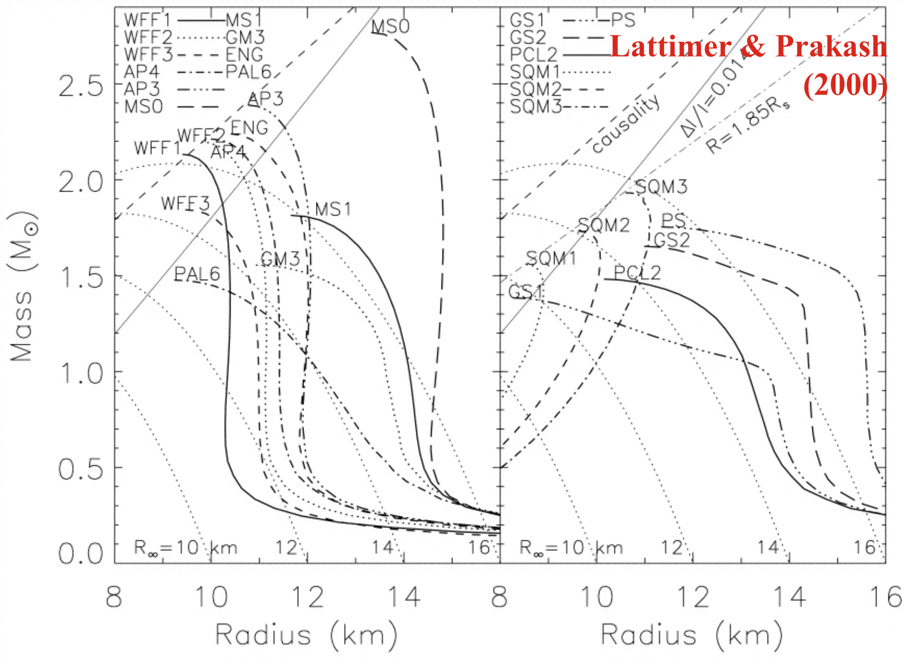


Pulsars

Pulsars

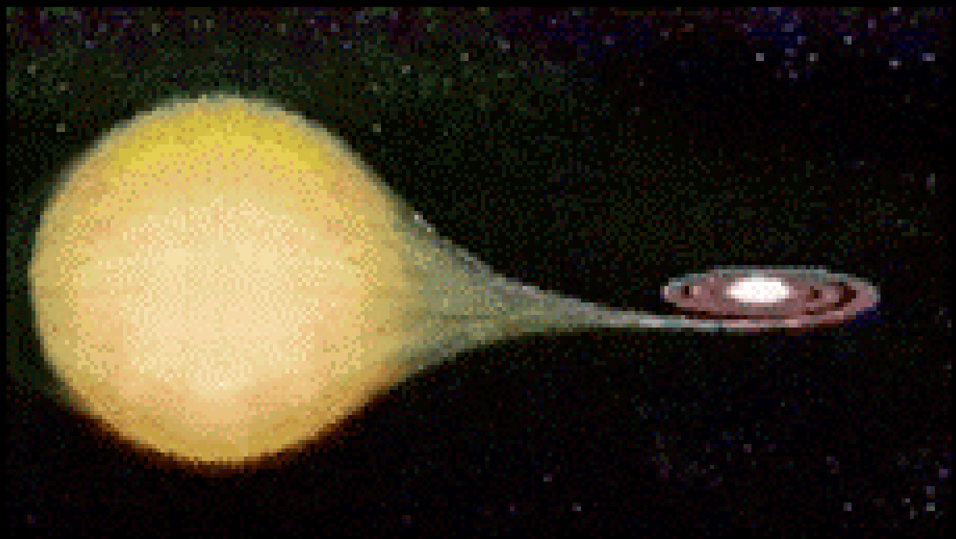
Outstanding Clocks for (doppler-shift) mass measurements

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

However, not so useful for radius measurements.

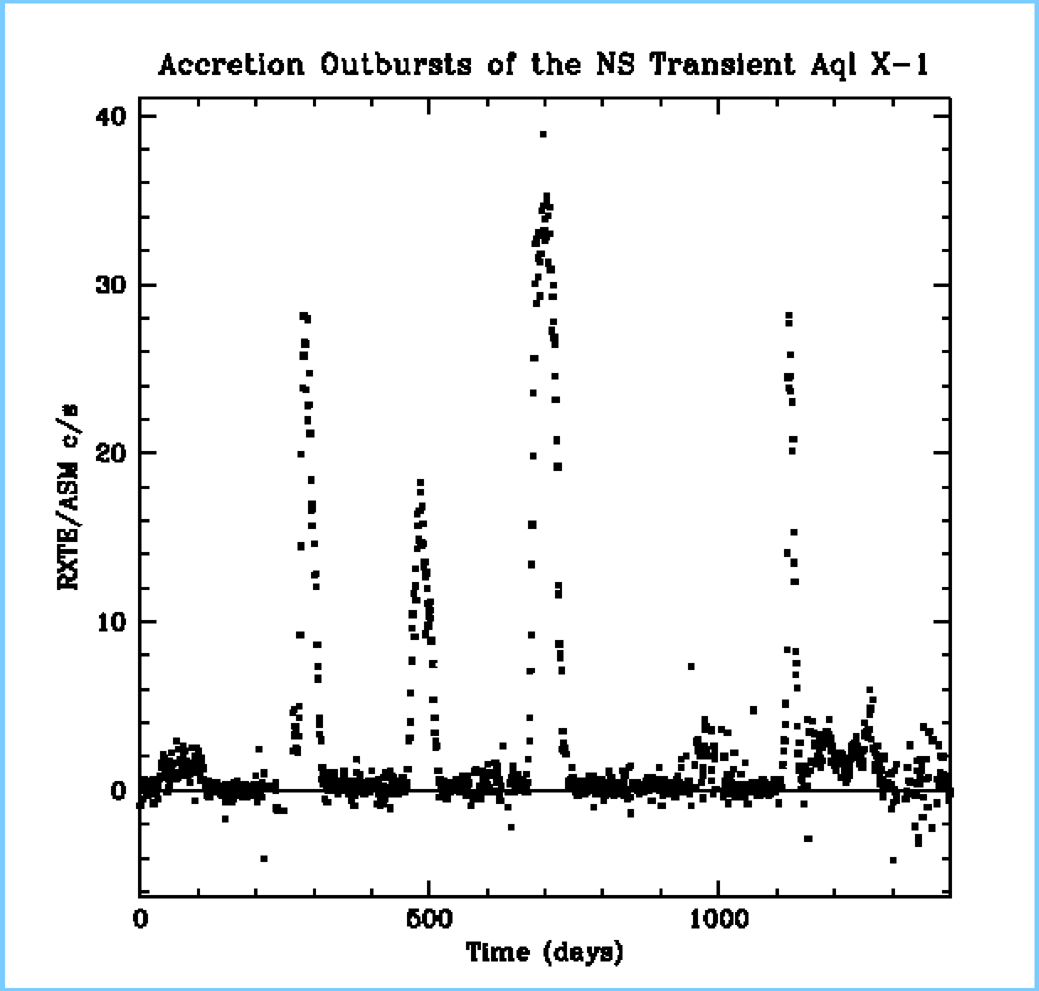
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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.

Fun Fact: Many names for these systems: qLMXBs, qNSs, Soft X-ray Transients, Neutron-Star Binaries. GLOAMARS



Neutron Star Transients

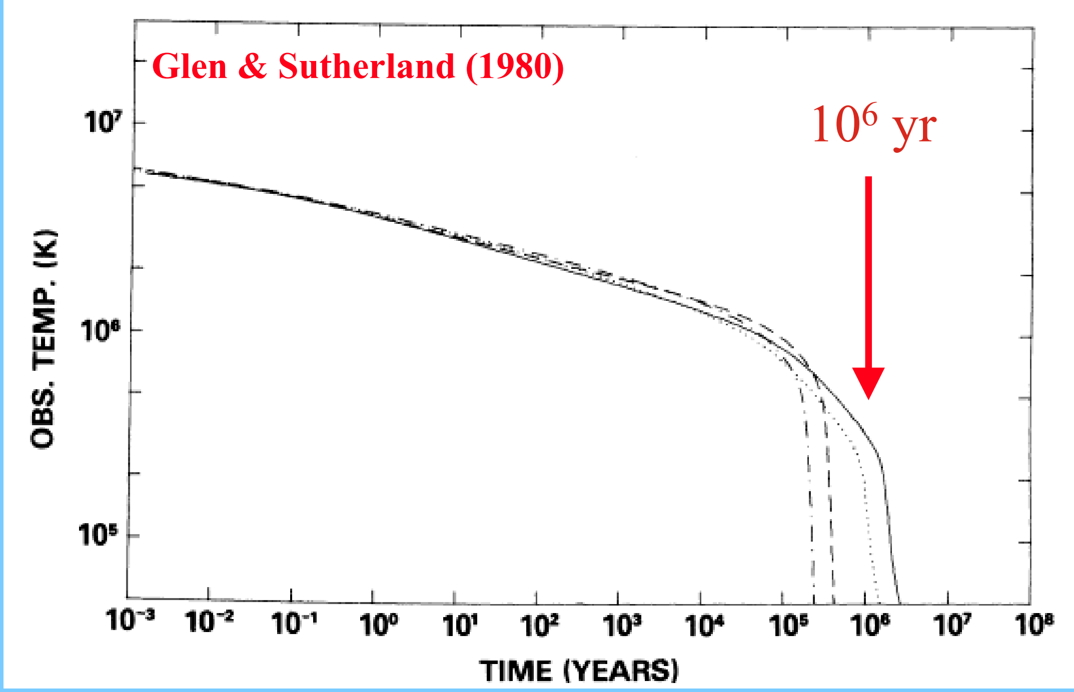
- Outbursts are due to disk instability; peak luminosities are 10^{36}-10^{38} ergs s^{-1}.
- Outbursts last ~30 days (or as long as years).
- Exhibit type-I X-ray bursts (thermonuclear flashes).
- After outburst, X-ray sources return to quiescence (10^{31}-10^{33} ergs s^{-1}) -- accretion has stopped.

Why are qLMXBs promising for measuring NS radii?

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)**

Brown, Bildsten & RR (1998)



Alternative: Deep Crustal Heating

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

1.47 Mev per np

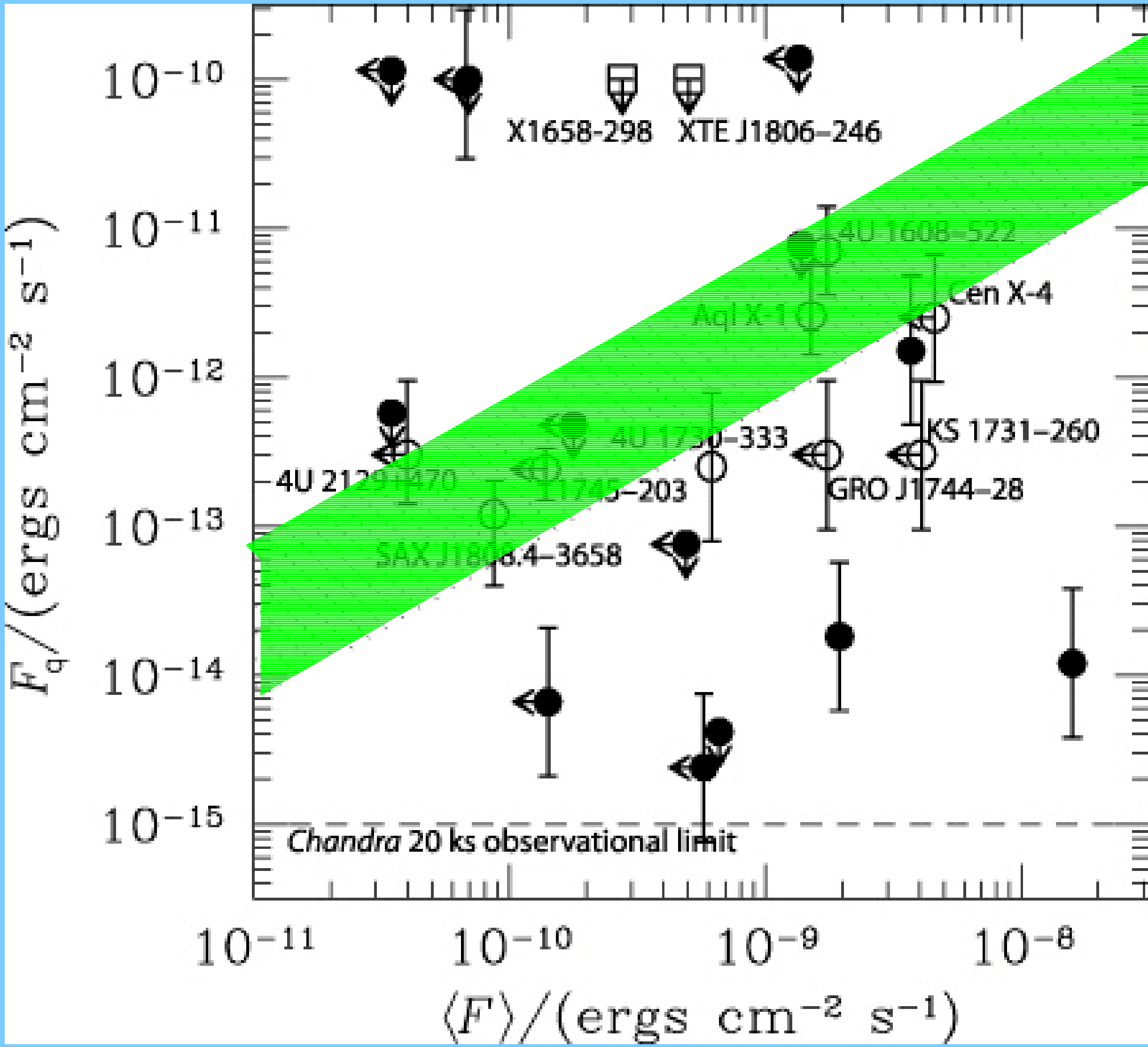
Brown, Bildsten & RR (1998)

Deep Crustal Heating

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 and RR (2005, in prog.)

Brown, Bildsten & RR (1998)

Why are qNSs promising for measuring NS radii?

- **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).**

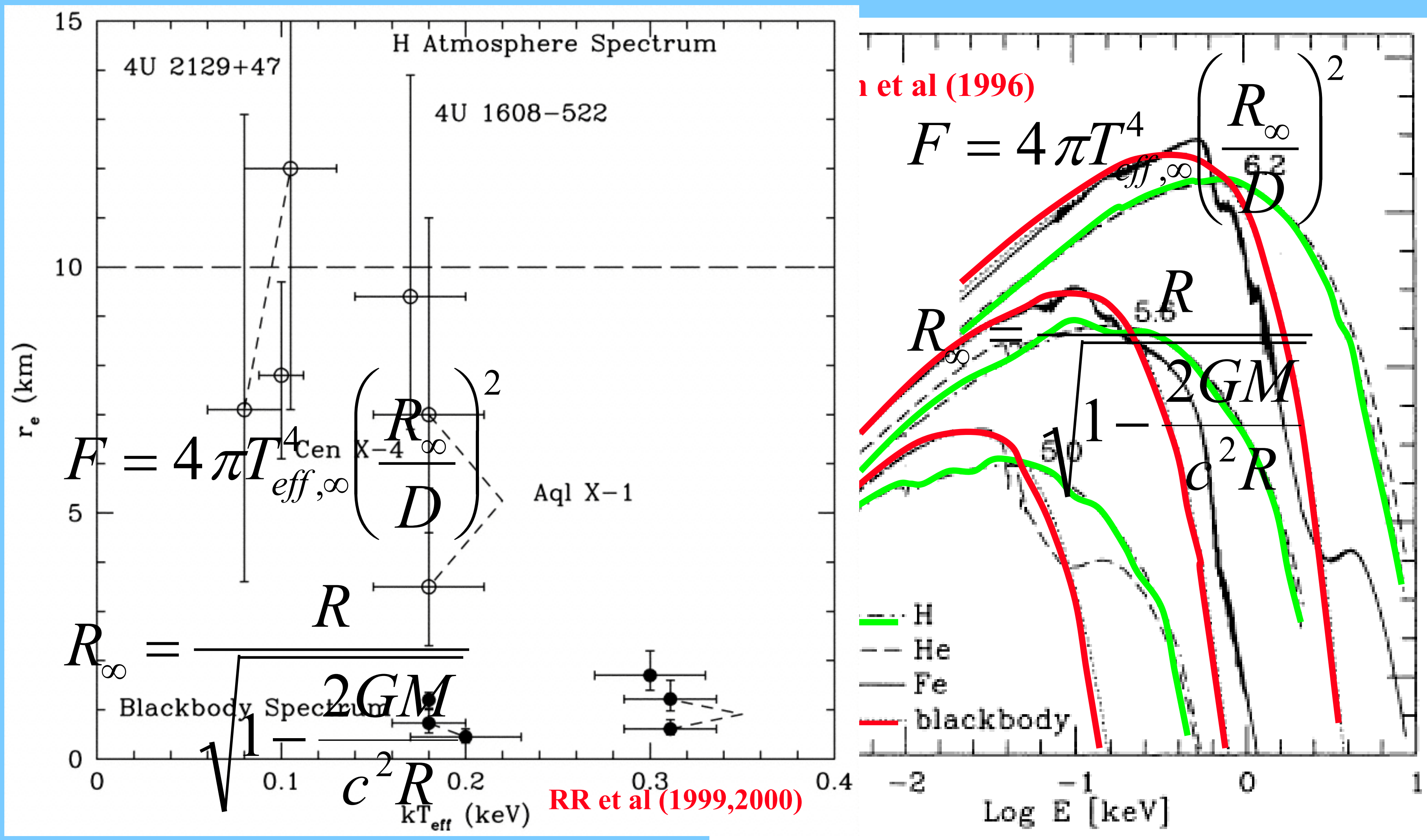
Solution: qNSs are not blackbodies.

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.

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

Brown, Bildsten & RR (1998)

Emergent Spectra from Neutron Star Atmospheres



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

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

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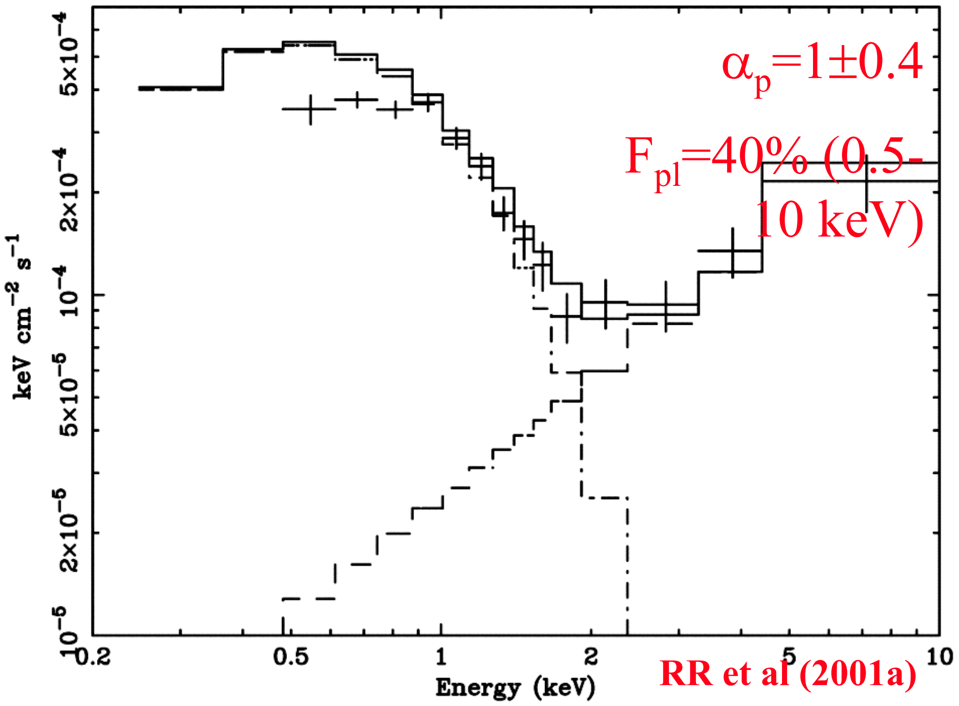
$$R_\infty = \frac{R}{\sqrt{1-\frac{2GM}{c^2R}}}$$

Why Quiescent Transient Neutron Stars Are Useful for Radius Measurments.

- If you observe a qNS when accretion has shut off, it will emit isotropic thermal radiation from its surface, due to deep crustal heating.
- The composition of the atmosphere is known -- unmagnetized (or negligibly magnetized) H -- and the radiative transfer and resulting emergent spectrum is straightforward, as is the resulting measurement of $\mathbf{R}_{\square}$.

Cen X-4 with Chandra (June 2000)

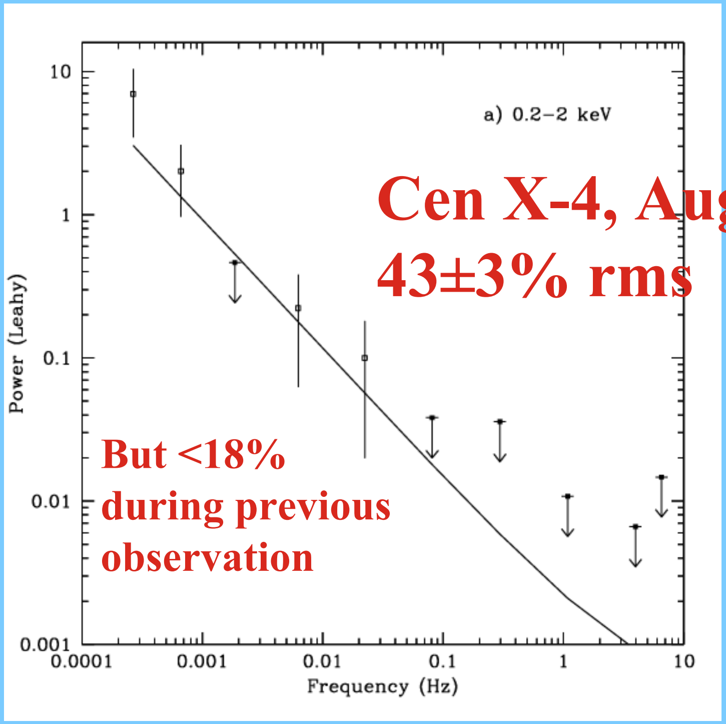


%rms<18%
(3 sigma)

$R_{\square}$ (d/1.2 kpc)	$kT_{eff,\square}$	N_H (1e20 cm^{-2})
$13.3^{+2.4}_{-3.9}$ km	74^{+12}_{-5} eV	(5.5)
19^{+45}_{-10} km	67 ± 19 eV	10^{+10}_{-7}

40+/-8% decrease in flux over 5 years (ASCA)

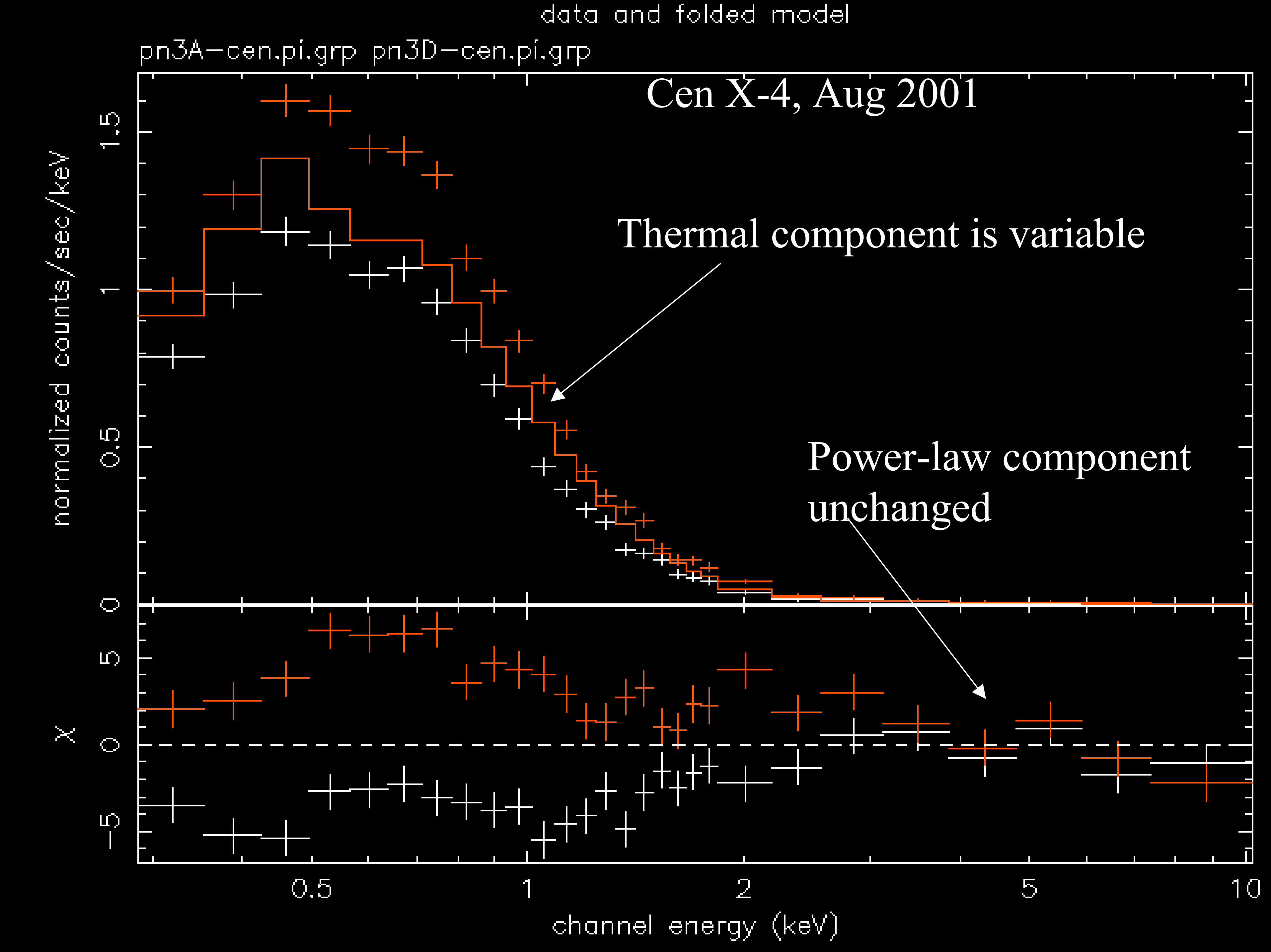
Short Timescale Variability



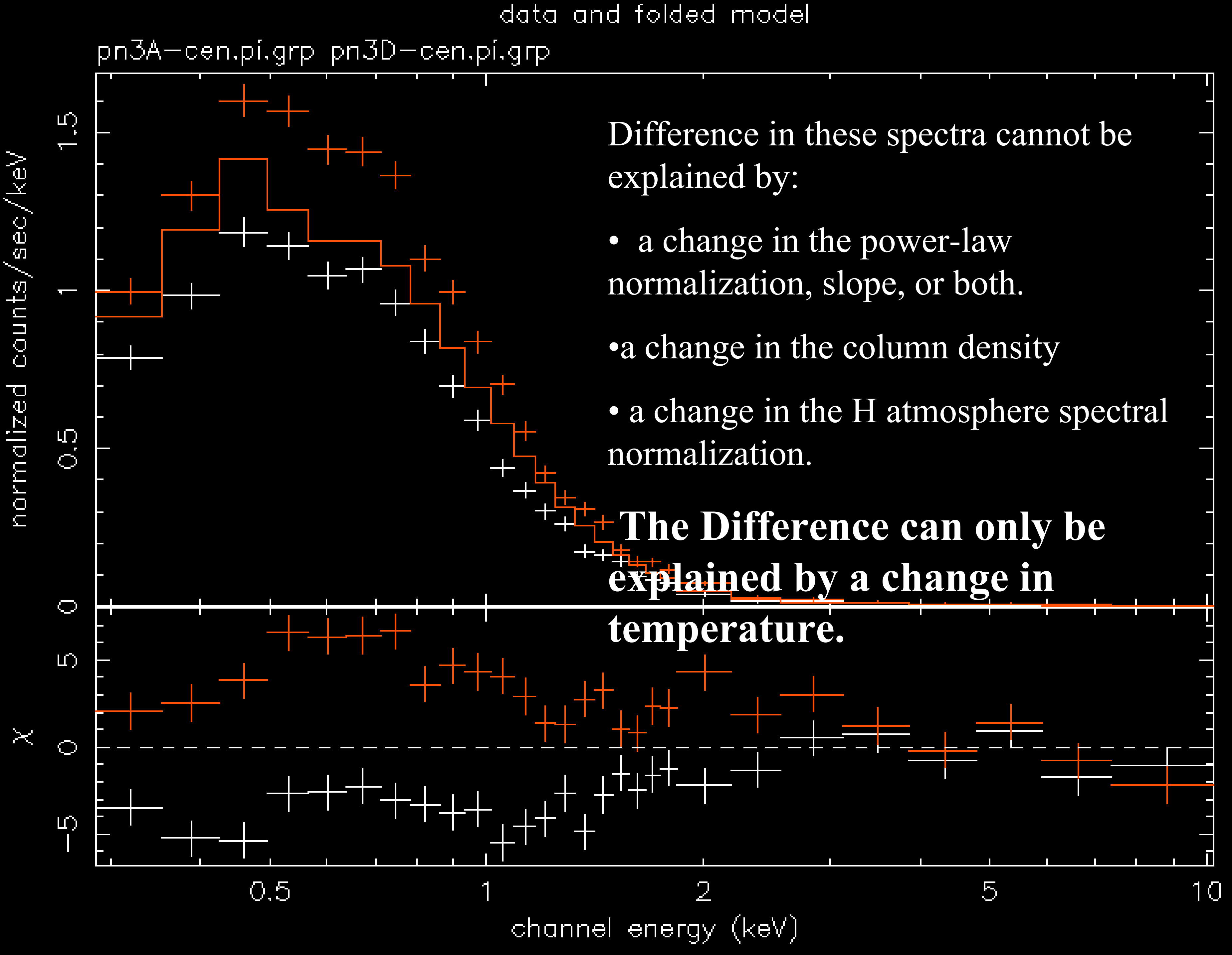
Cen X-4, Aug 2001
43±3% rms

But <18% during previous observation

- **Variability:** **qLMXBs sometimes vary on short timescales, sometimes don't!** **(Campana et al 1998; Rutledge et al 2002a, b. 2003)**



data and folded model
pn3A−cen.pi.grp pn3D−cen.pi.grp
Cen X-4, Aug 2001
Thermal component is variable
Power-law component unchanged
normalized counts/sec/keV
1.5
1
0.5
0
χ
5
0
−5
0.5
1
2
5
10
channel energy (keV)



Difference in these spectra cannot be explained by:

- a change in the power-law normalization, slope, or both.
- a change in the column density
- a change in the H atmosphere spectral normalization.

The Difference can only be explained by a change in temperature.

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)

The Best Measured Neutron Star radii

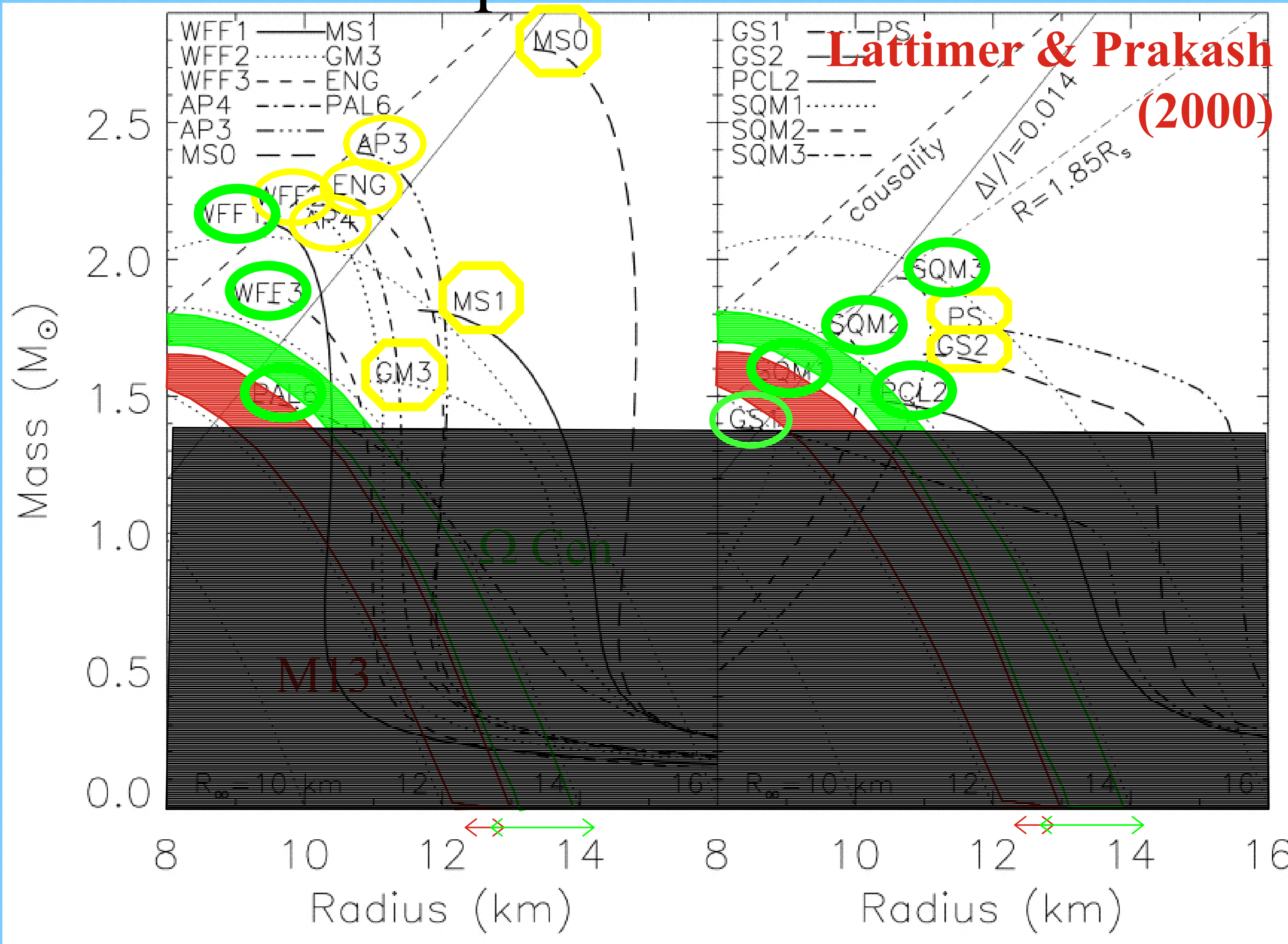
Name	$R_{\square}$ (km/D)	D (kpc)	$kT_{eff,\square}$ (eV)	N_H (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	5.36 ±6%	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen (XMM)	13.6 ± 0.3	5.36 ±6%	67 ±2	9 ± 2.5	Gendre et al (2002)
M13 (XMM)	12.6 ± 0.4	7.80 ±2%	76 ±3	(1.1)	Gendre et al (2002)
47 Tuc X7 (Chandra)	$R=14.5^{+1.6}_{-1.4}$ (M=1.4)	5.13 ±4%	kT=105 ±6	$4.2^{+1.8}_{-1.6}$	Rybicki et al (2005)
M28 (Chandra)	$14.5^{+6.9}_{-3.8}$	5.5 ±10%	90^{+30}_{-10}	26 ± 4	Becker et al (2003)

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

Caveats:

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

Radius Constraints on the Equation of State



Chandra: Observed   Observed with insufficient time   Not Observed

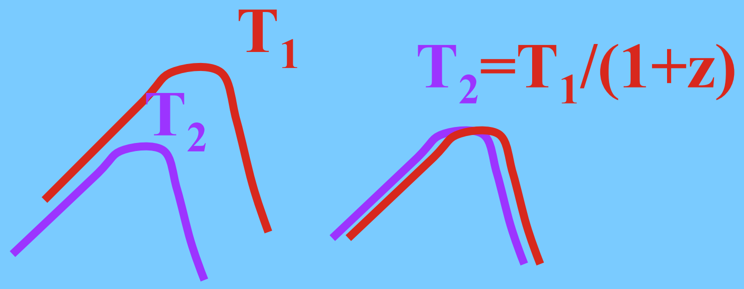
NGC	Rcore (“)	D (kpc)	Log N_H	Obs. Time ACIS-S/I?	qNS detect Tobs (ksec)	qNSs?
104	22.5	4.6	20.3	74 I/ 299 S	33	2
5904	24.2	7.6	20.2	45	87	
3201	86.3	5.0	21.1	0	56	
4372	104.2	5.2	21.4	0	89	
4833	60.2	5.8	21.3	0	91	
5139	156.3	4.9	20.9	70 S	48	1
6121	50.3	2.0	21.4	25	12	
6205	52.0	7.2	20.0	0	76	1 /XMM
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	24	68	
6397	3.0	2.2	21.0	109	10	1
6496	62.8	5.7	21.0	0	66	
6539	32.5	4.0	21.7	0	92	
6541	17.9	6.6	20.9	46 S	83	
6544	2.9	2.5	21.6	0	29	
6553	33.1	3.5	21.7	0	73	
6656	84.3	3.0	21.3	0	26	
6752	10.5	4.2	20.3	30 S	28	
6809	170.6	4.8	20.8	34	43	
6838	38.2	3.9	21.2	0	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.
- 5 have sufficient time, in which 4 qNSs detected.
- 6 have been observed with insufficient time.
- 0 qNSs in the remaining

Mass Measurements with Continuum Spectra

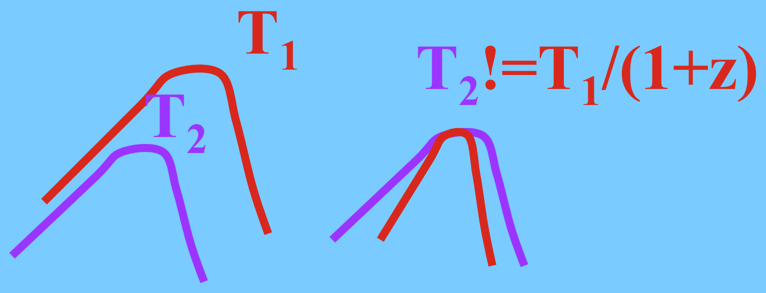
You cannot measure a redshift from blackbody emission due to photon energy (E) temperature (kT) degeneracy.

$$I(E_\gamma) \propto \left(\frac{E_\gamma}{kT}\right)^3 \frac{1}{e^{\frac{E_\gamma}{kT}} - 1}$$



• But, the free-free opacity breaks this degeneracy. This spectrum, redshifted, permits (in principle) determination of the redshift.

$$I(E_\gamma) \propto \left(\frac{E_\gamma}{kT}\right)^3 \frac{1}{e^{\frac{E_\gamma}{kT}} - 1} \kappa_{ff,o} \left(\frac{E_o}{E_\gamma}\right)^3$$



The Path Forward

- **Obtain Chandra Imaging Spectroscopy to:**
  - **spectroscopically identify qNSs**
  - **identify nearby sources which would be spectrally confused in the 6-15" PSFs of XMM, Con-X and XEUS**
- **Use HIPPARCOS dwarfs, SIM to obtain 2% accurate distances to the GCs (field sources?)**
- **Obtain deep X-ray spectra (XMM, Con-X, XEUS) to:**
  - **confirm spectroscopic identifications**
  - **constrain intensity variability, which would affect R_{∞} measurements**
  - **measure R_{∞} -- AGAIN AGAIN AND AGAIN**

Thank you!