Measuring the distances, masses and radii of neutron stars

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Distances, Masses, and Radii of NSs

- *Measuring the distances to X-ray binaries*
  - *Globular Clusters*
  - *Extinction as a tool ?*
    - *Red Clump stars as distance ladders*
    - *How to measure the extinction to X-ray sources*
    - *Distance to the X-ray binary : 4U 1608-52*
- *The Masses and Radii of Neutron Stars (Current Results)*
- *Future Prospects*

Measuring the Distances to Globular Clusters

- *Measuring the distances to the globular clusters rely on the comparison of Horizontal Branches of the clusters with those of a reference, which is 47 Tuc (for the metal-rich sample in the bulge).*
- *Such a comparison simultaneously gives the distance and the reddening.*
- *Recent near-IR observations enabled reliable measurements of distances to a number of globular clusters in especially towards the galactic bulge (see e.g. Valenti et al. 2007).*

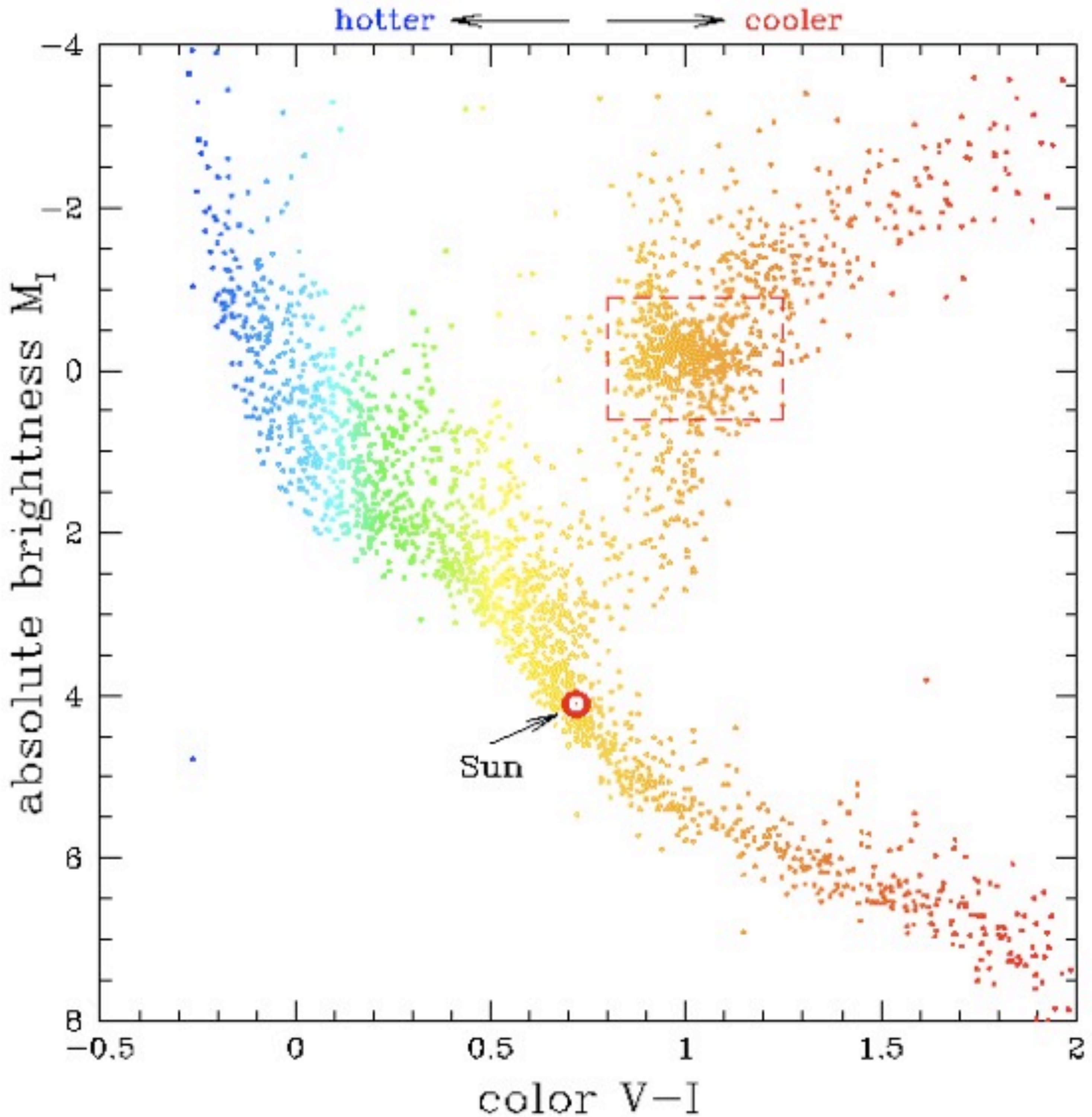
Are globular clusters really helpful for mass & radius measurements ?

- *We know only 9 X-ray bursters, out of ~72, that are known to be located in globular clusters :*

Source Name	N PRE	Notes
4U 0513-40	1	
4U 1746-37	3	Very low flux
GRS 1747-312	3	Varying touchdown flux
4U 1724-307	2	Cooling curve is not good
SAX J1748.9-2021	6 (4)	Two Groups of Touchdown Fluxes
XB 1832-330	1	
4U 1820-30	**5**	**Suitable**
4U 2129+12	1	
EXO 1745-248	**2**	**Suitable**

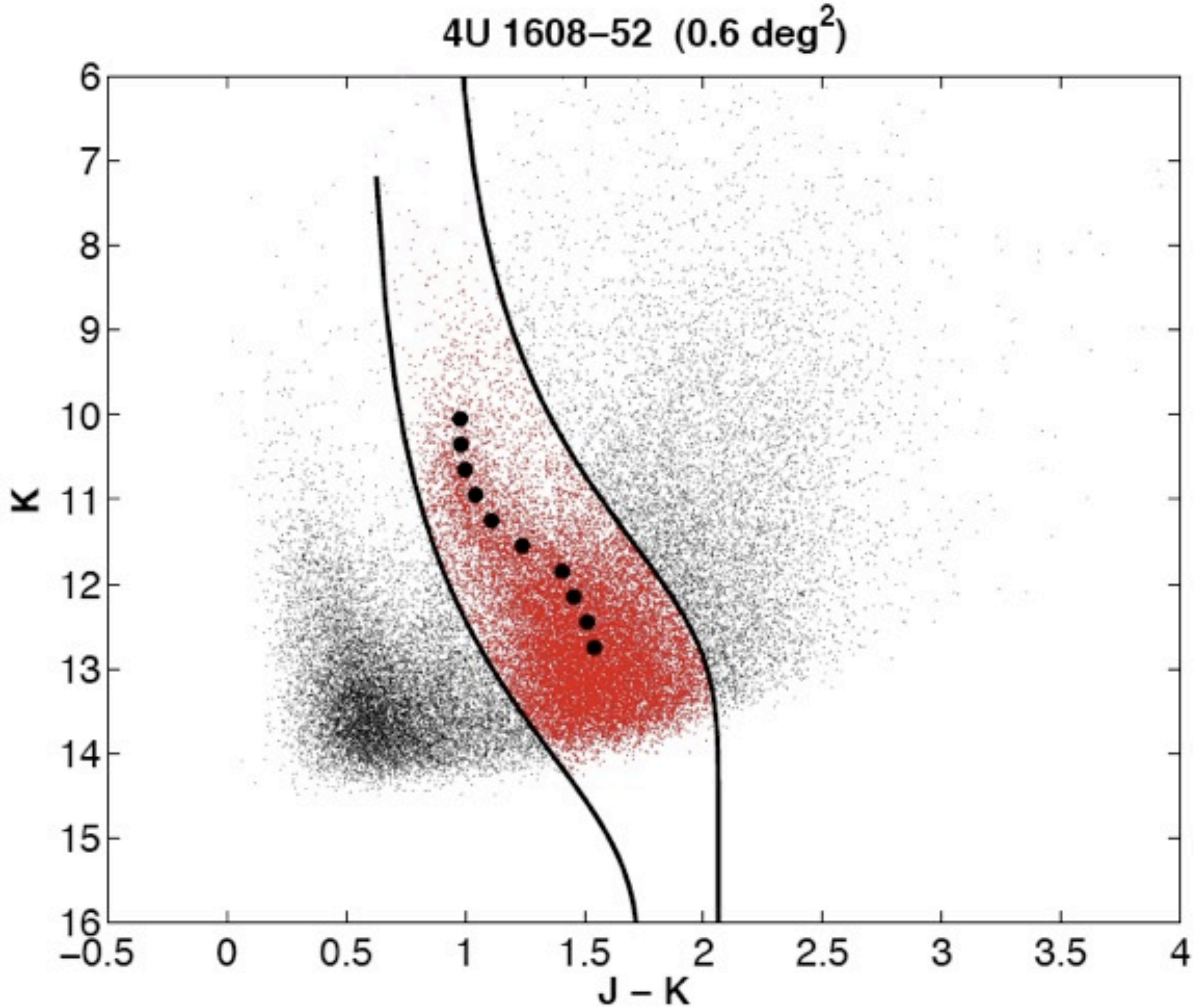
Red Clump Stars as standard candles

- *Core-helium burning giant stars with a very narrow luminosity function.*
- *They are relatively bright, which means they can be identified to large distances.*
- *The absolute magnitude and intrinsic color of the red clump stars are well established (see e.g. Alves 2000, Grocholski & Sarajedini 2002).*



Red Clump Stars in a Near-IR CMD

- *Position on a CMD of a star depends on four parameters :*
    - *Absolute Magnitude*
    - *Intrinsic Color*
    - *Distance*
    - *Extinction*



- **So in principle one can use red clump stars as a standard candle to map the variation of extinction with distance** (Paczynski & Stanek 1998, Lopez-Corredoira et al. 2002, Cabrera-Lavers, et al. 2005)**.**

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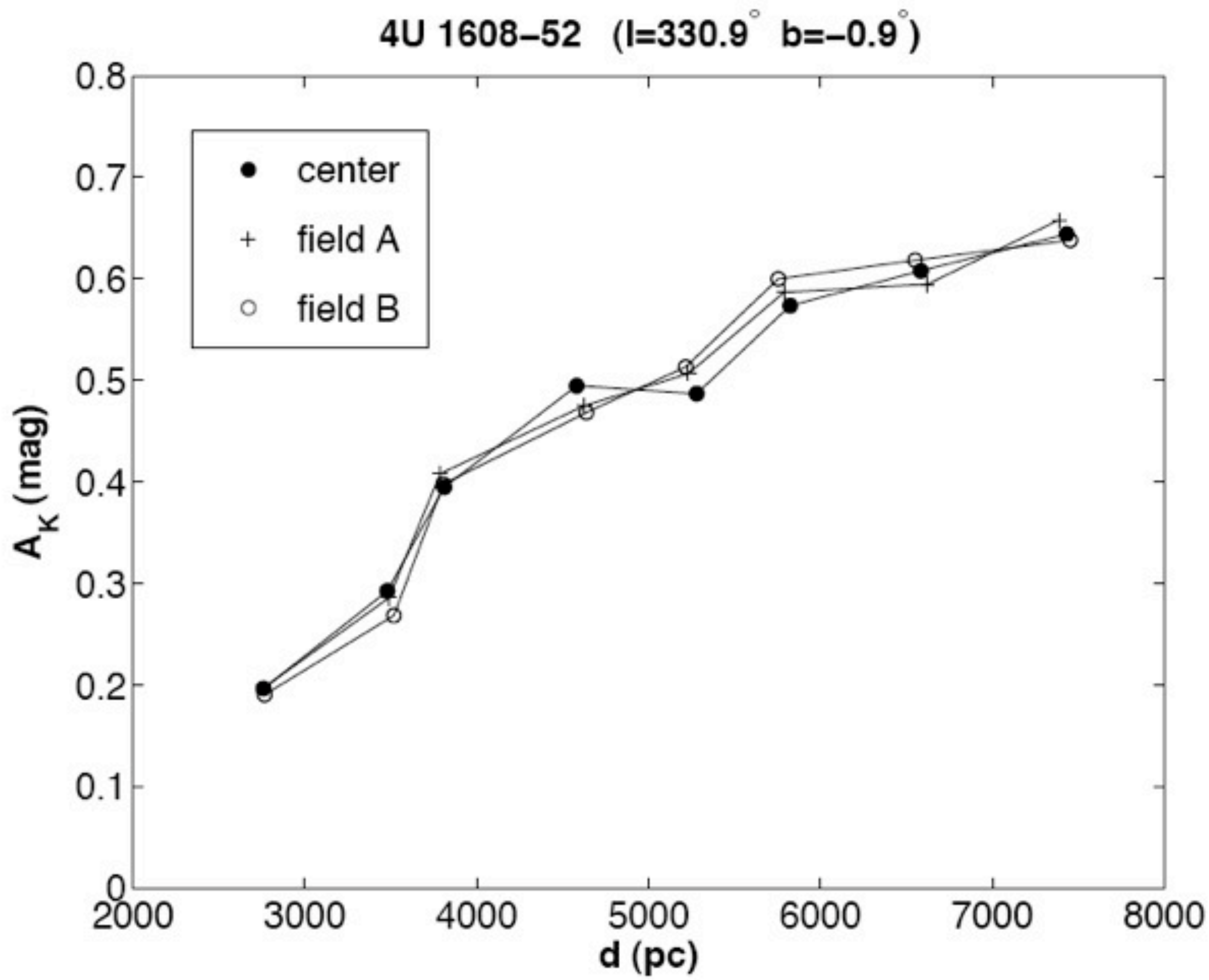


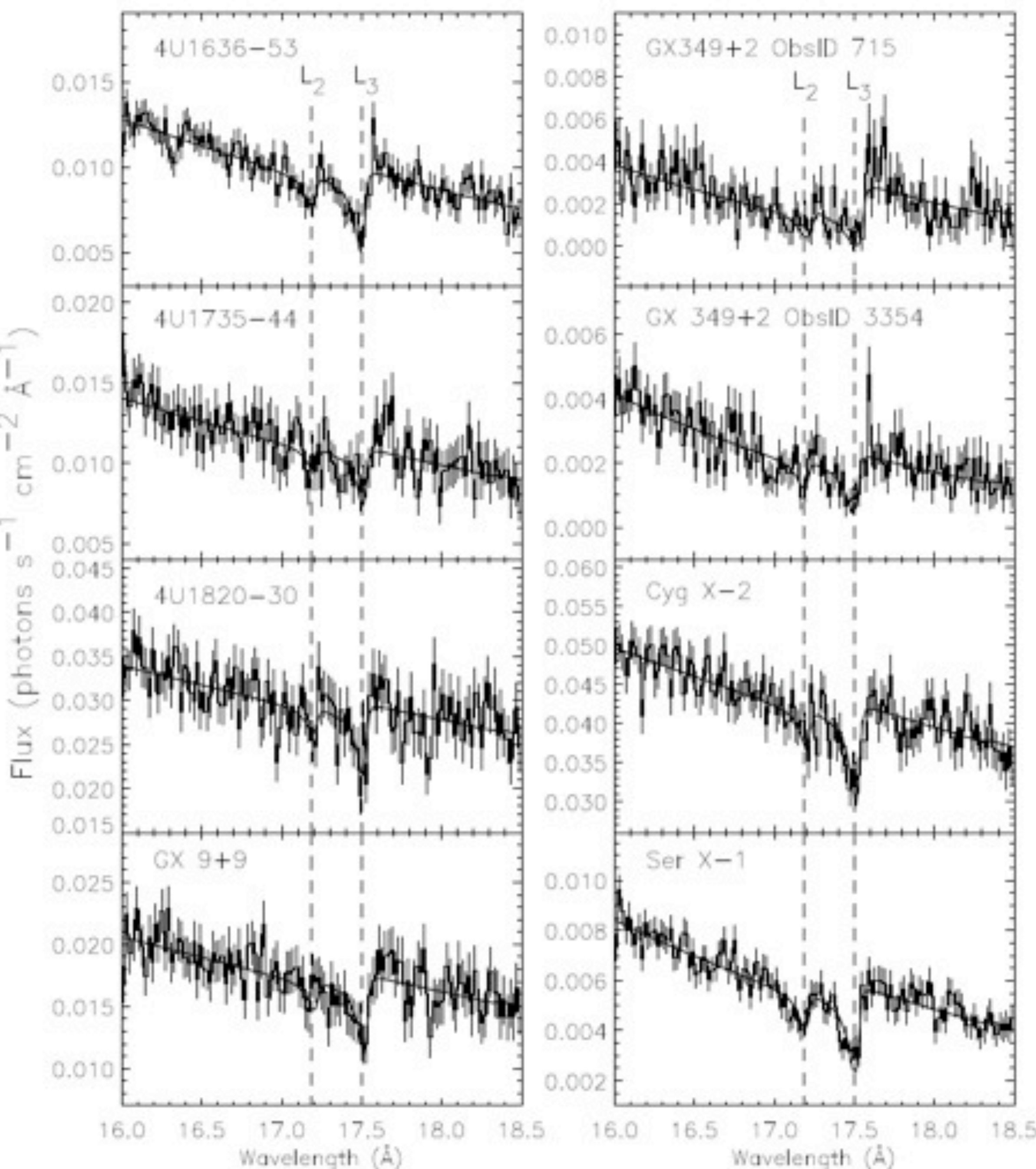
Extinction towards X-ray sources

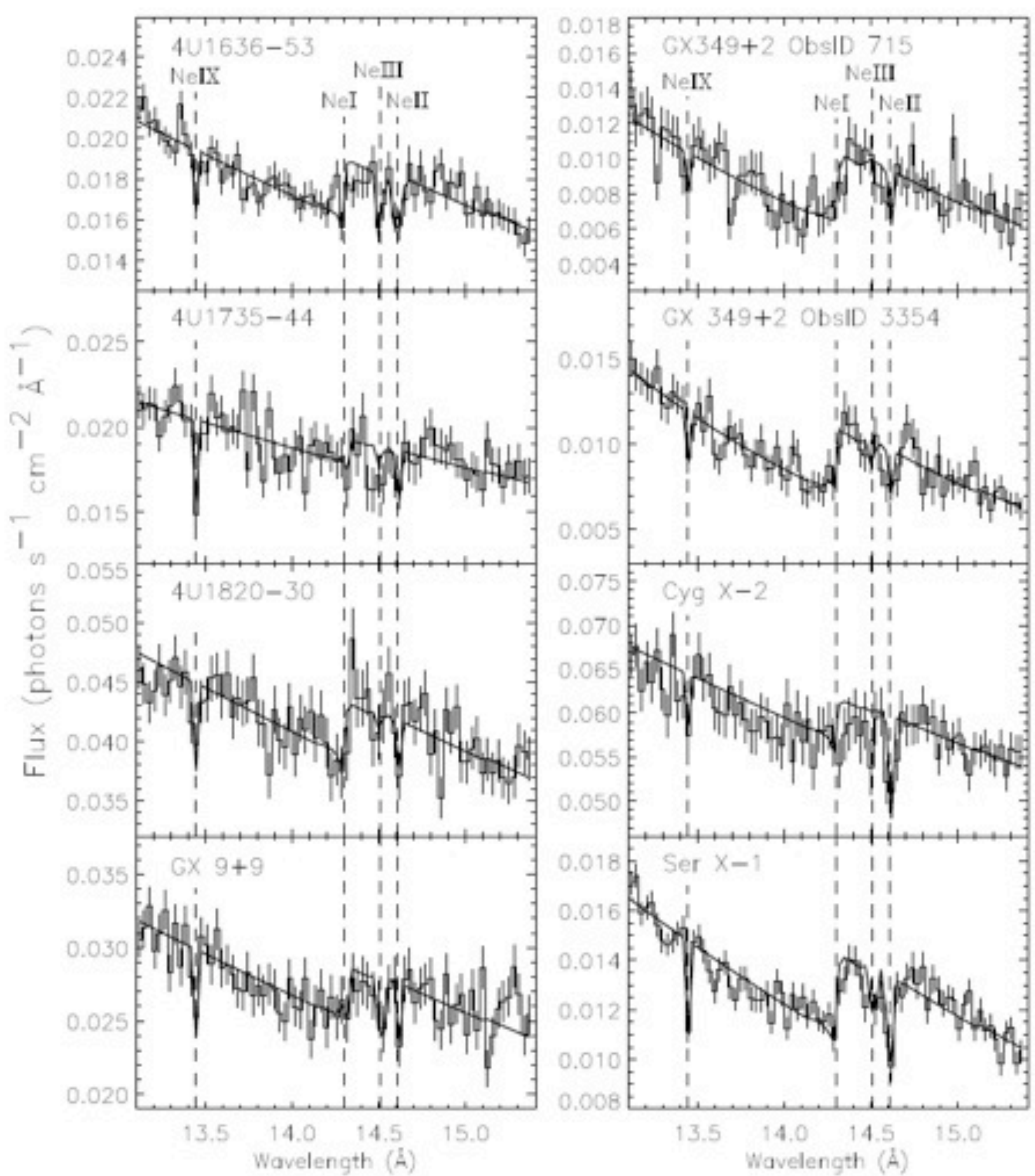
- *Can we measure the total column density of the gas in the ISM towards X-ray sources ?*
  - *Binding energies of electrons in the K, L etc. shells of some of the most abundant metals lie in the soft X-ray range.*

Element	Absorption Edge Wavelength
O (K edge)	23.1 Angstrom (~0.5 keV)
Fe (L edge)	17.52 Angstrom
Ne (K edge)	14.31 Angstrom
Mg (K edge)	9.5 Angstrom
Si (K edge)	6.72 Angstrom (~1.85 keV)

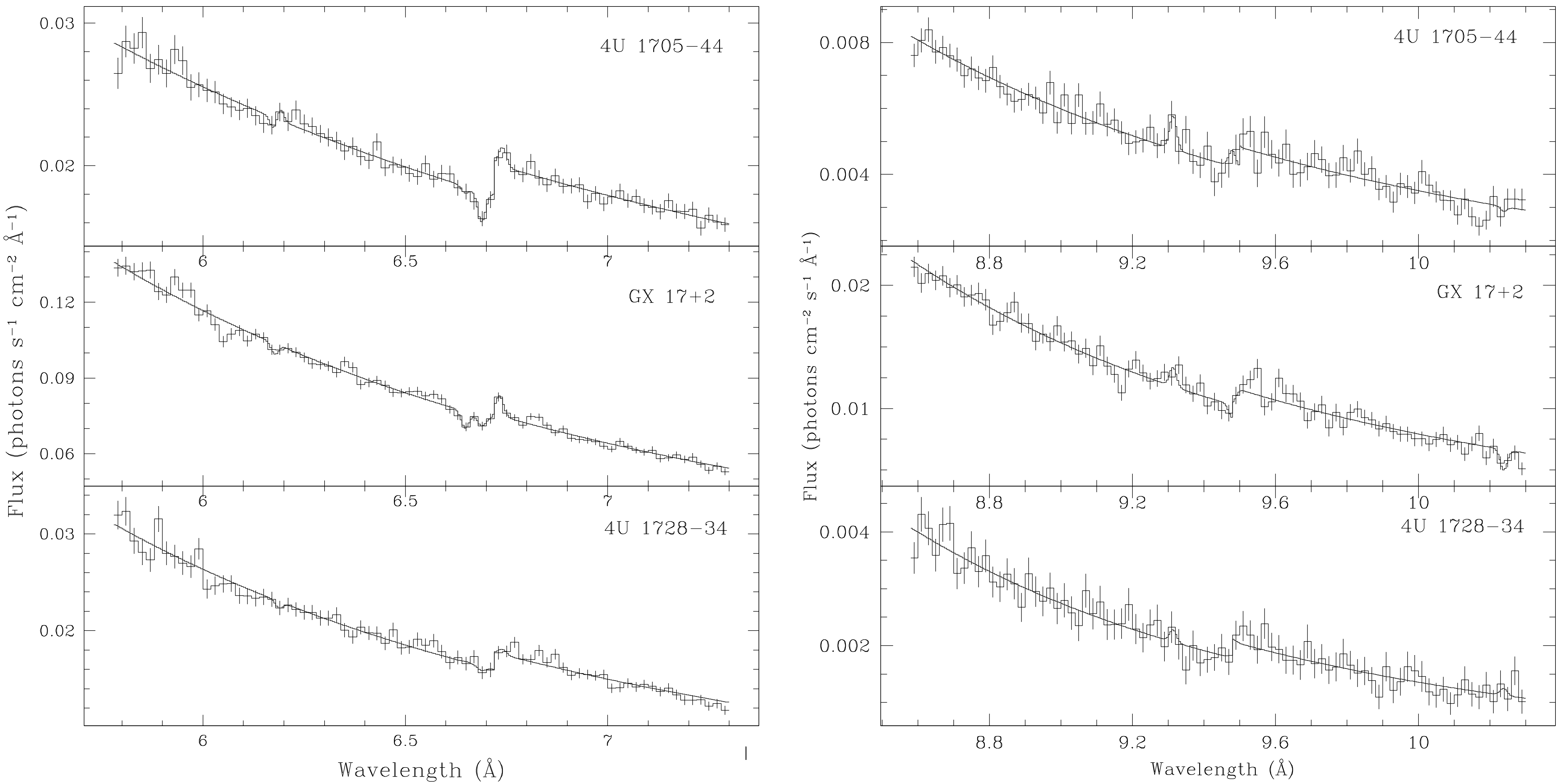
Measuring the X-ray absorption towards X-ray Bursters

- *X-ray bursters are bright X-ray sources with a number of high resolution X-ray spectra (see e.g. Juett et al. 2004, 2006) :*



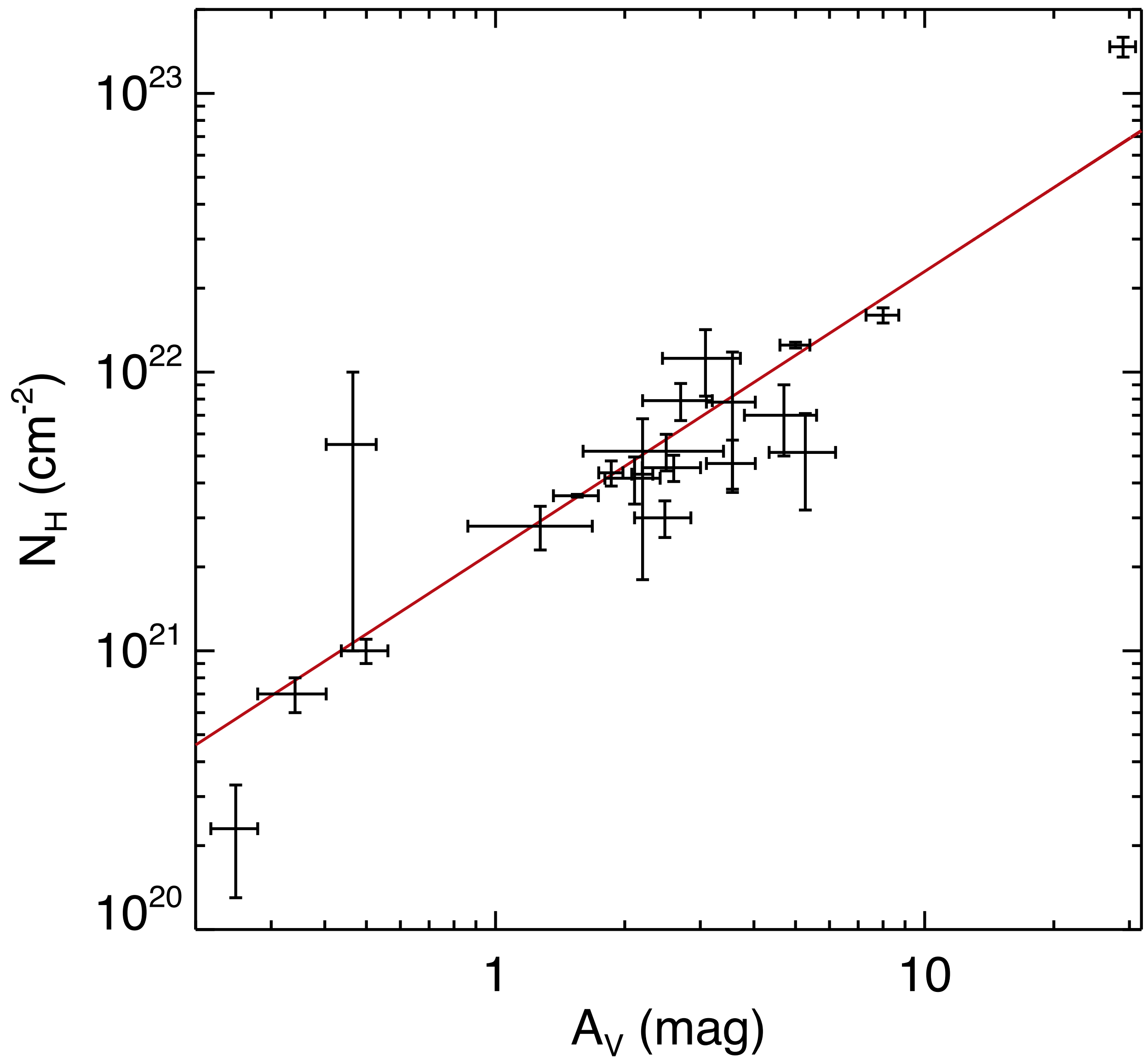


- *Si and Mg edges (Wroblewski, Güver, & Özel, 2008):*



Converting the Column Density to optical Extinction

- *Although usually expressed in units of hydrogen column density, X-ray absorption is caused by the most abundant heavier elements.*
- *On the other hand, optical extinction is also caused by grains composed of these same heavier elements.*
- *Therefore one expects a relation between the optical extinction and the X-ray absorption a.k.a gas to dust ratio.*



(Güver & Özel 2009)

The distance to the X-ray Binary : 4U 1608-52

- *4U 1608-52 is a Soft X-ray Transient.*
- *It has an Optical Counter-part QX Normae with I = 18.2 (Grindlay & Liller 1978).*
- *Source exhibited 32 Type I X-ray bursts of which 12 are Eddington Limited Photospheric Radius Expansion bursts (Galloway et al. 2008).*

Hydrogen Column density Measurement

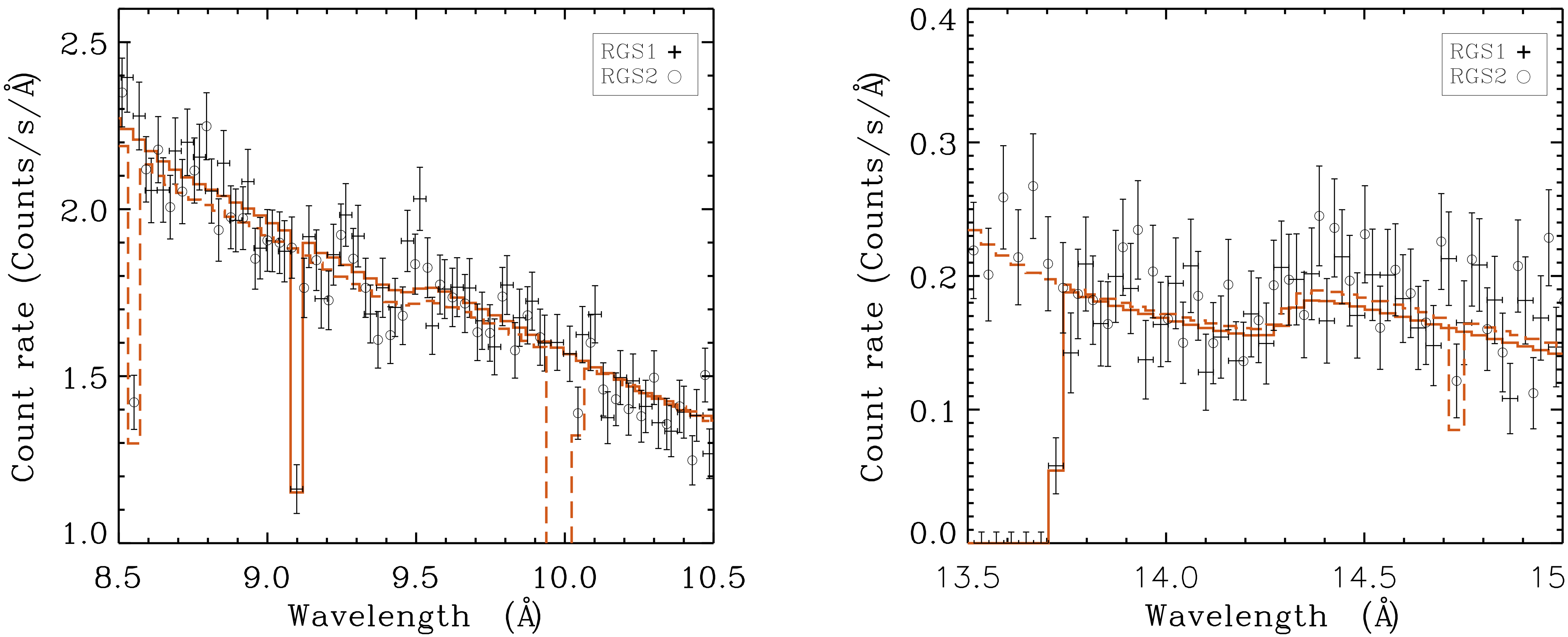


Fig. 1.— RGS1 and RGS2 spectra of 4U 1608−52 together with the best fit models (solid line for RGS1 and dashed line for RGS2) are given for the regions we used to determine the column densities of Mg (left panel) and Ne (right panel). Features are due to CCD gaps and the malfunctioning CCD in the RGS detector.

Optical Extinction towards 4U 1608-52

- *Based on the NH measurement as :*

  $$(1.08 \pm 0.09) \times 10^{22}\ \mathrm{cm}^{-2}$$

- *and the using the relation :*

  $$N_{\mathrm{H}} = (2.30 \pm 0.04) \times 10^{21} \times A_{\mathrm{V}}$$

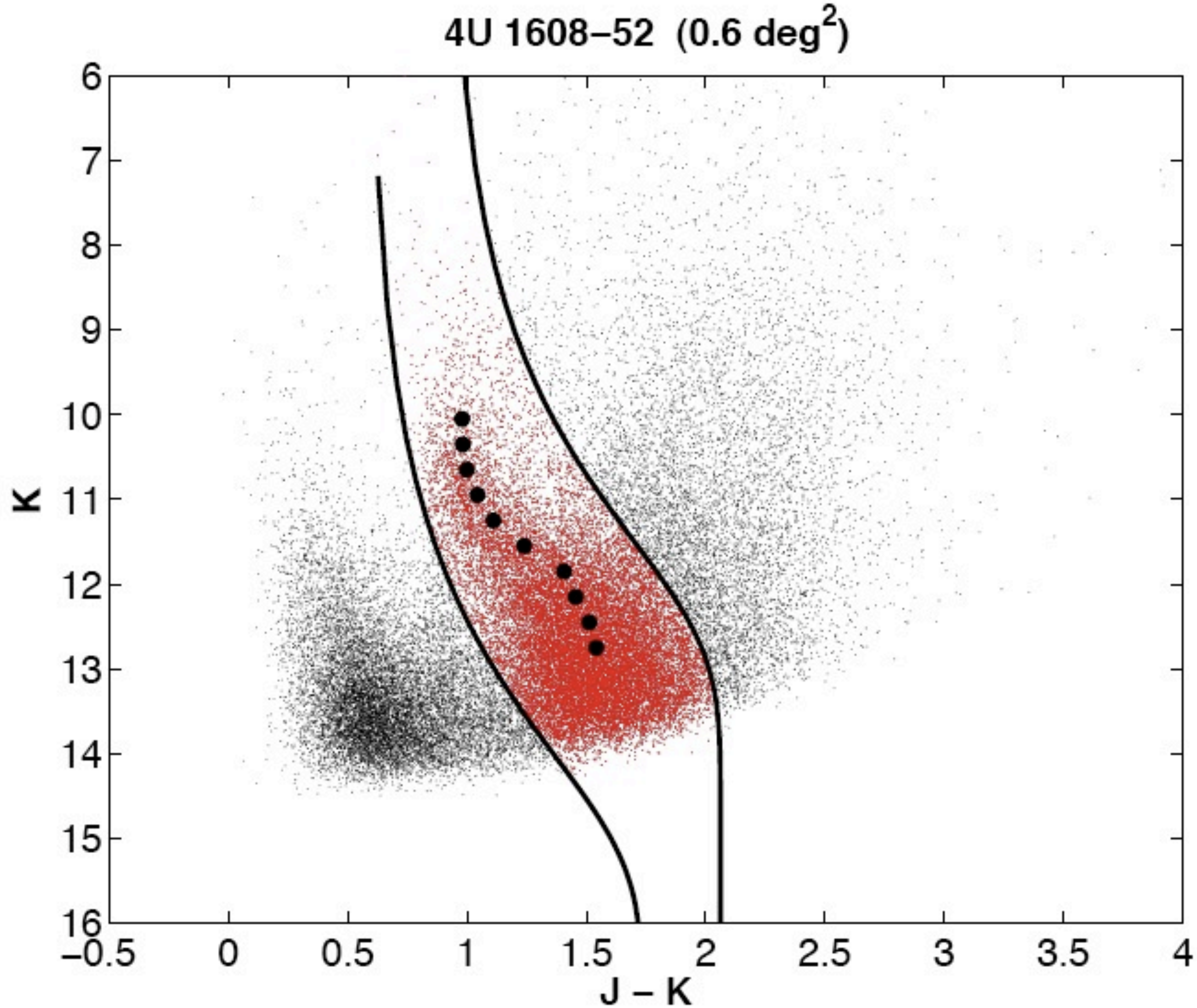
  A_V = 4.66 +/- 0.39 mag.

- *Using conversion presented by Rieke & Lebofsky (1985),*

  A_K = 0.52 +/- 0.04 mag.

Red Clump Stars towards 4U 1608-52

- *We used 2MASS archive to create a near-IR color-magnitude diagram of the observed stars in the field of view towards 4U 1608-52.*
- *We ended up with 40548 stars.*



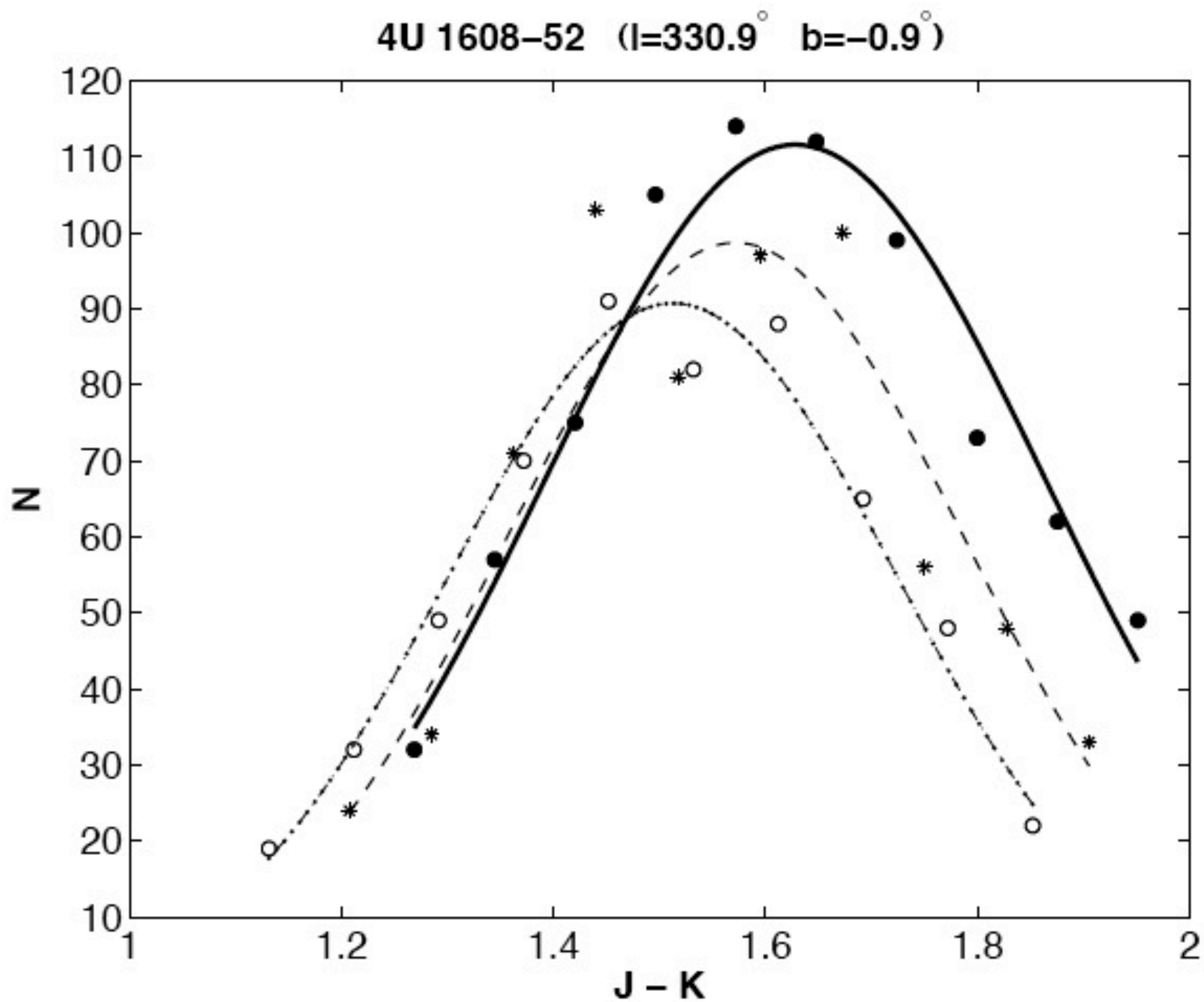
Distance vs. Extinction

- *Assuming :*
  - *MK = -1.62 (+/- 0.03)*
  - *(J-Ks)0 = 0.7 (+/- 0.05) mag*

(Alves 2000; Grocholski & Sarajedini 2002).

$$A_K = c_e \times [(J-K)_{m_K} - (J-K)_0]$$

$$r = 10^{[m_K - M_K + 5 - A_K(r)/5]}$$



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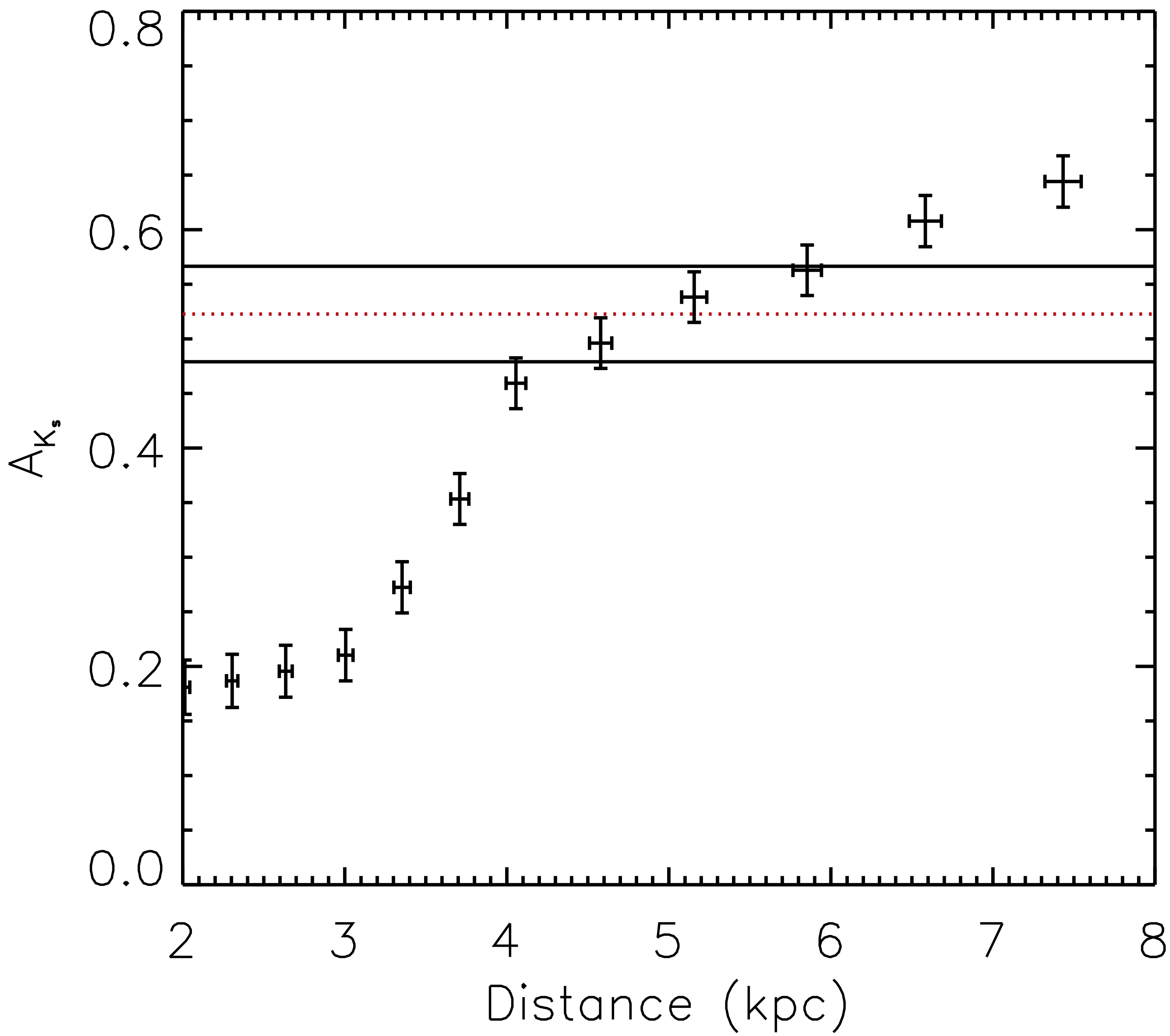
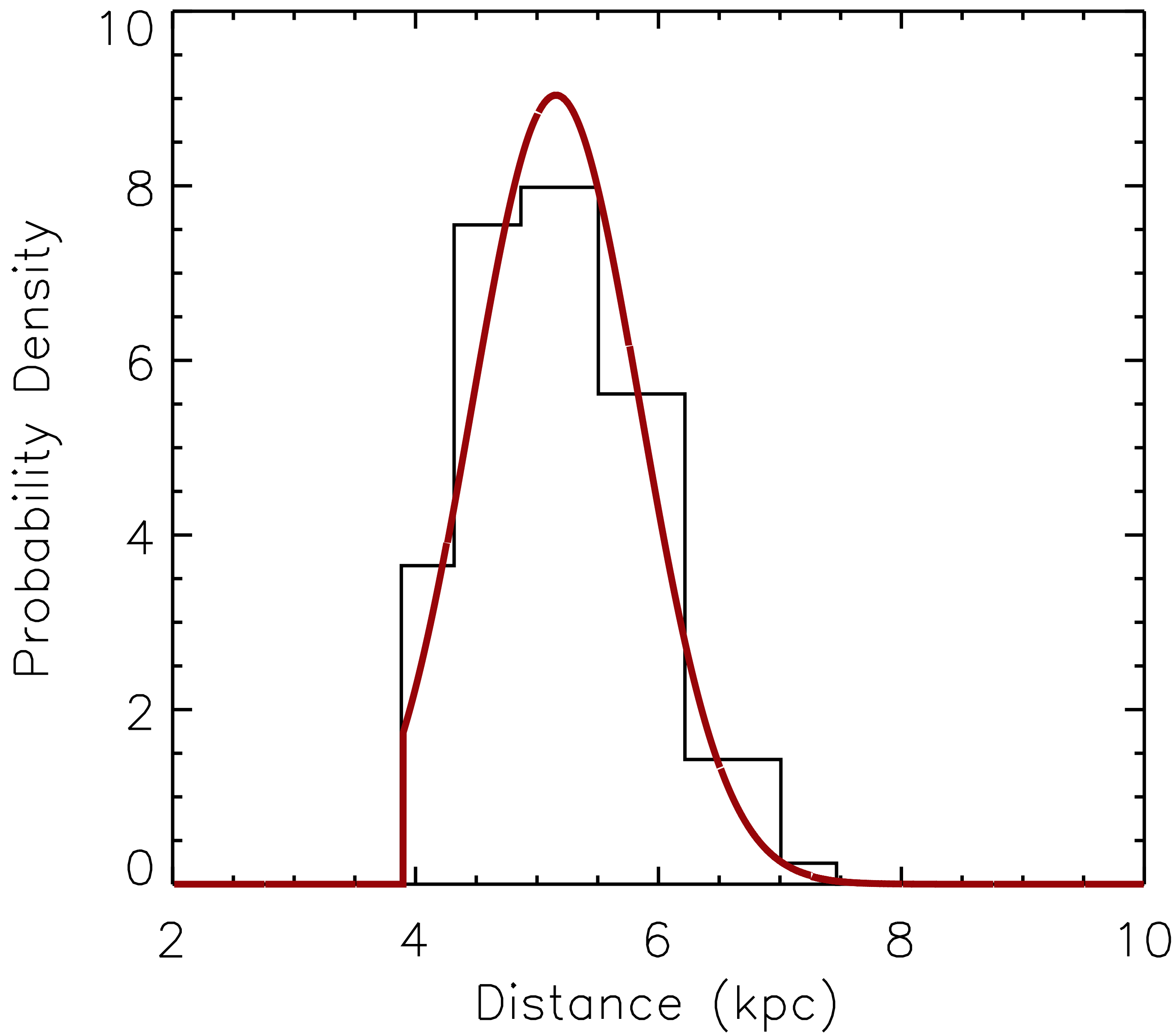


The Distance to 4U 1608-52

- *Distance can be found as :*
- *5.16 +/- 0.72 kpc*

(Guver et al. 2009)



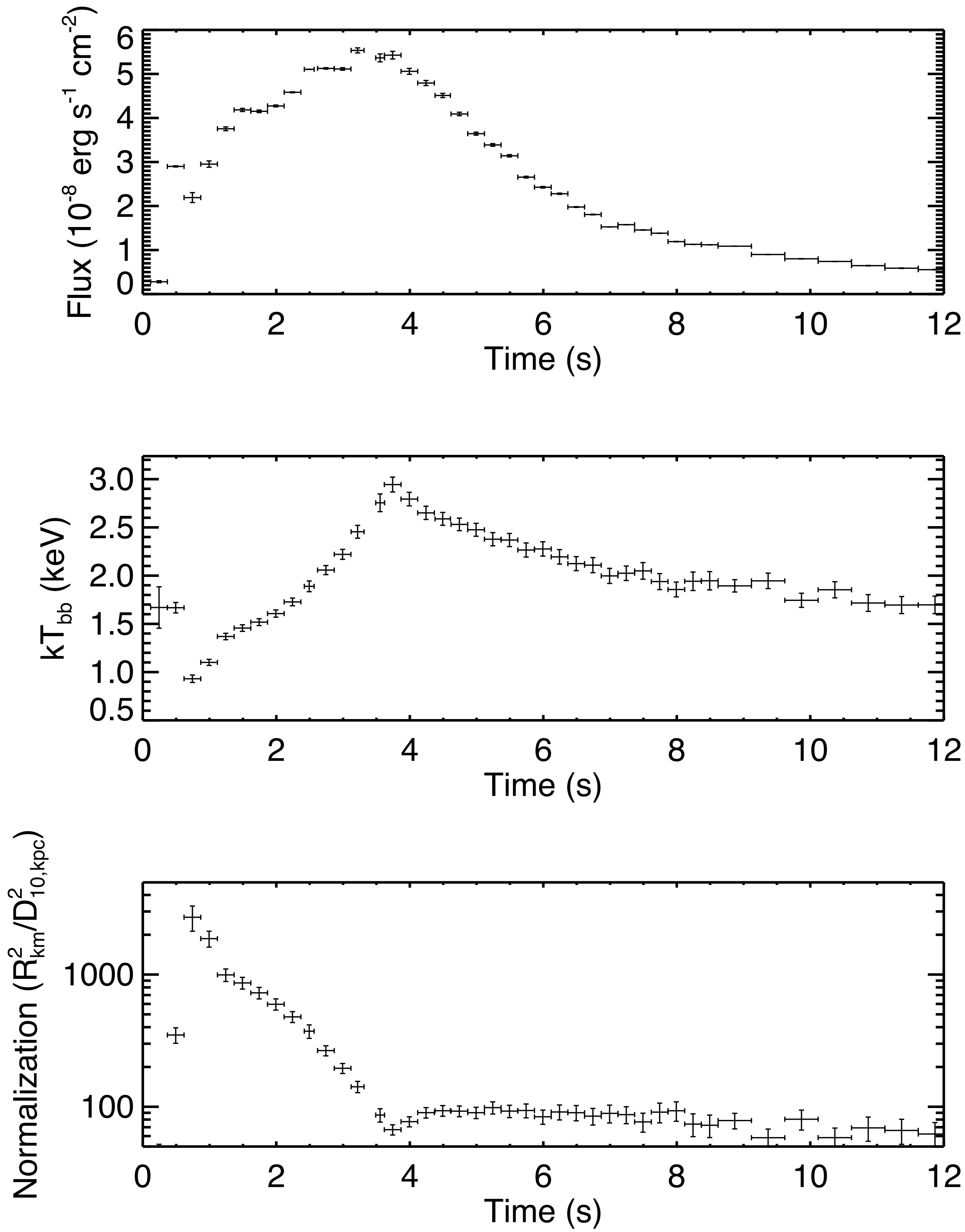
Masses and Radii of neutron stars in X-ray Bursters

$$\frac{F_{cool}}{\sigma T^4} = \frac{k^4 A}{\sigma}$$

$$M = \frac{Rc^2}{2G}\left(1 - \frac{R^2 \sigma T^4}{F_{cool} f_\infty D^2}\right)$$

$$\frac{1}{R} = \frac{c^2}{2GM}\left(1 - \frac{F_{Edd}^2 D^4 \kappa_{es}^2}{MG^2 c^2}\right)$$

4U 1820-30



(Güver et al. 2009, in prep.)

Figure 1. Spectral evolution during the first 12 seconds of an example burst of 4U 1820−30 (Obsid : 90027-01-03-05). Note that, due to the broad range of measured normalization values, a logarithmic scale is used.

4U 1820-30

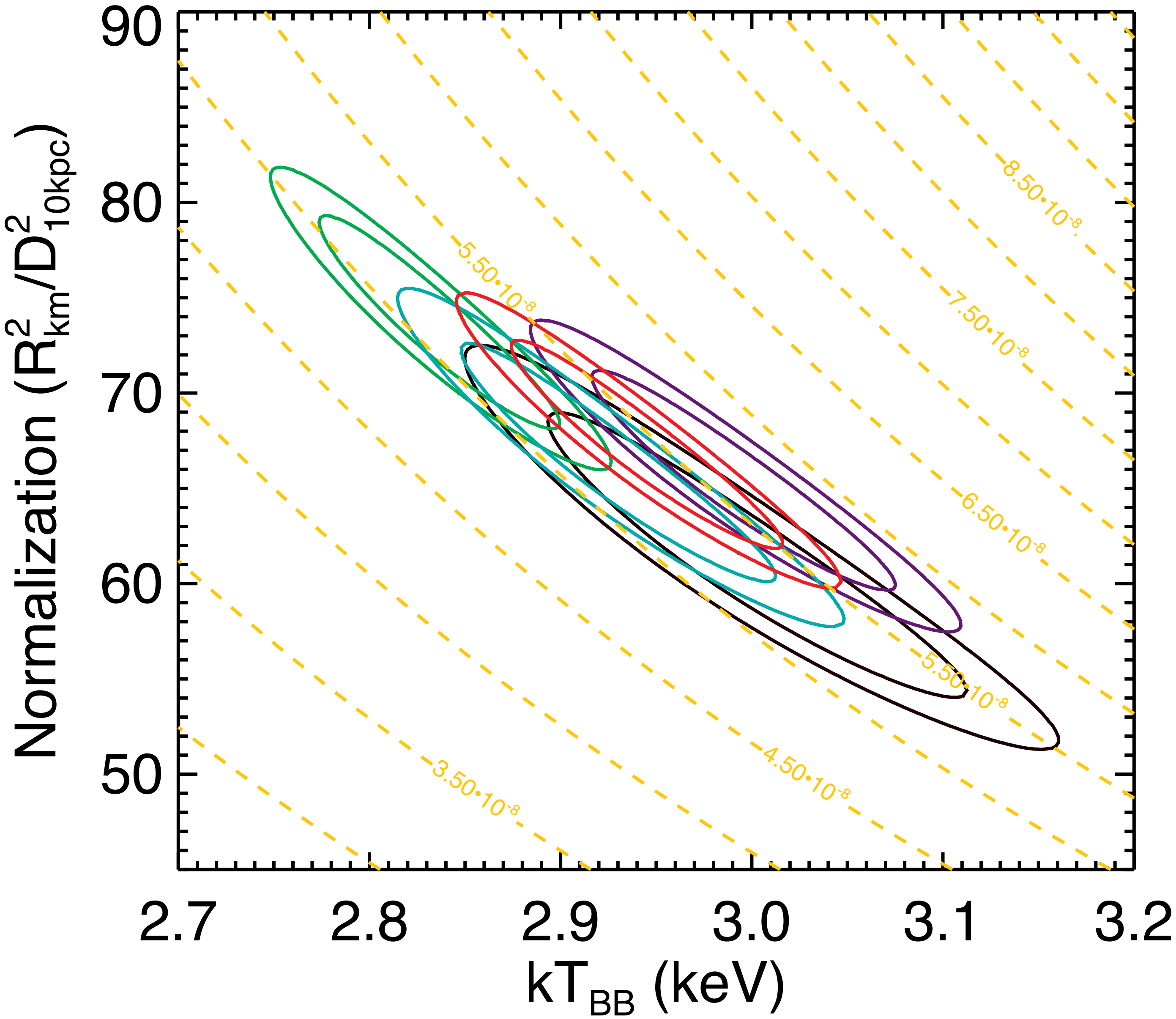


Figure 2. 1 and 2$-\sigma$ confidence contours of the normalization and blackbody temperature obtained from fitting the five X-ray spectra extracted from the touchdown moments of 5 PRE bursts observed from 4U 1820$-$30. The dashed lines show contours of constant bolometric flux.

(Güver et al. 2009, in prep.)

4U 1820-30

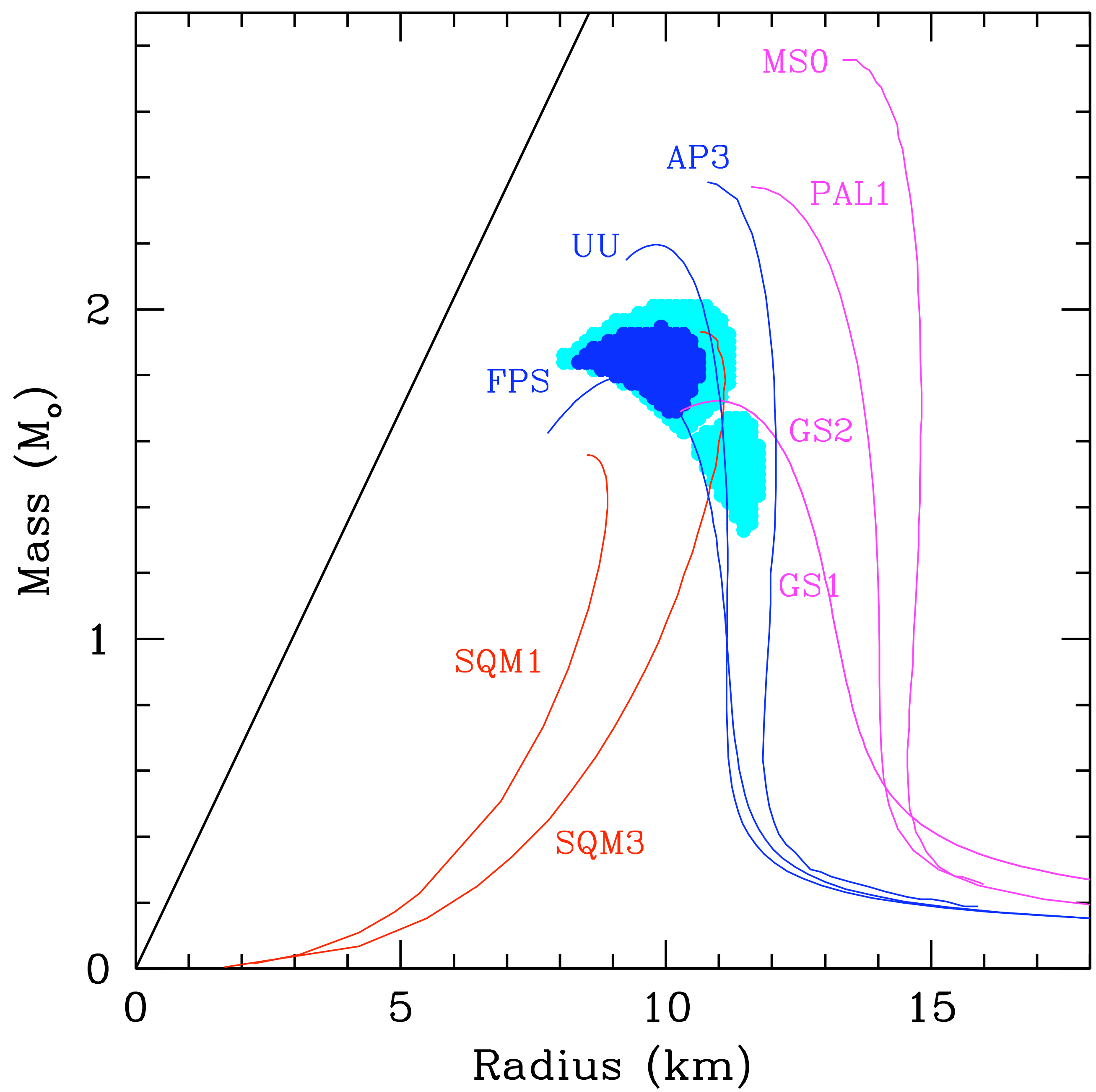
Obs. ID	MJD	Touchdown Flux (10^{-8} erg cm^{-2} s^{-1})	Normalization $(R_{km}/D_{10kpc})^2$
20075-01-05-00	50570.73110	5.33 ±0.27	–
40017-01-24-00	52794.73813	5.65 ±0.20	88.86 ±3.73
70030-03-04-01	52802.07557	5.12 ±0.15	96.68 ±3.39
70030-03-05-01	52805.89566	5.24 ±0.19	–
90027-01-03-05	53277.43856	5.42 ±0.16	90.40 ±2.00

(Güver et al. 2009, in prep.)

X-ray Bursters :

Source Name	Distance	Touchdown Flux	Normalization	PRE Bursts
	(kpc)	(10^{-8} erg/s/cm^2)	(R^2_{km} / D^2_{10kpc})	Number
4U 1608-52	5.16 +/-0.72	15.41 +/- 0.65	324.6 +/- 2.4	(2 T) (4 N)
EXO 1745-248	6.3 +/- 0.6	6.25 +/- 0.2	116.0 +/- 26.0	2
4U 1820-30	8.1 +/- 0.9	5.31 +/- 0.10	91.98 +/-1.86	(5 T) (3 N)
EXO 0748-676	---	2.25 +/- 0.25	107.99 +/- 8.09	2

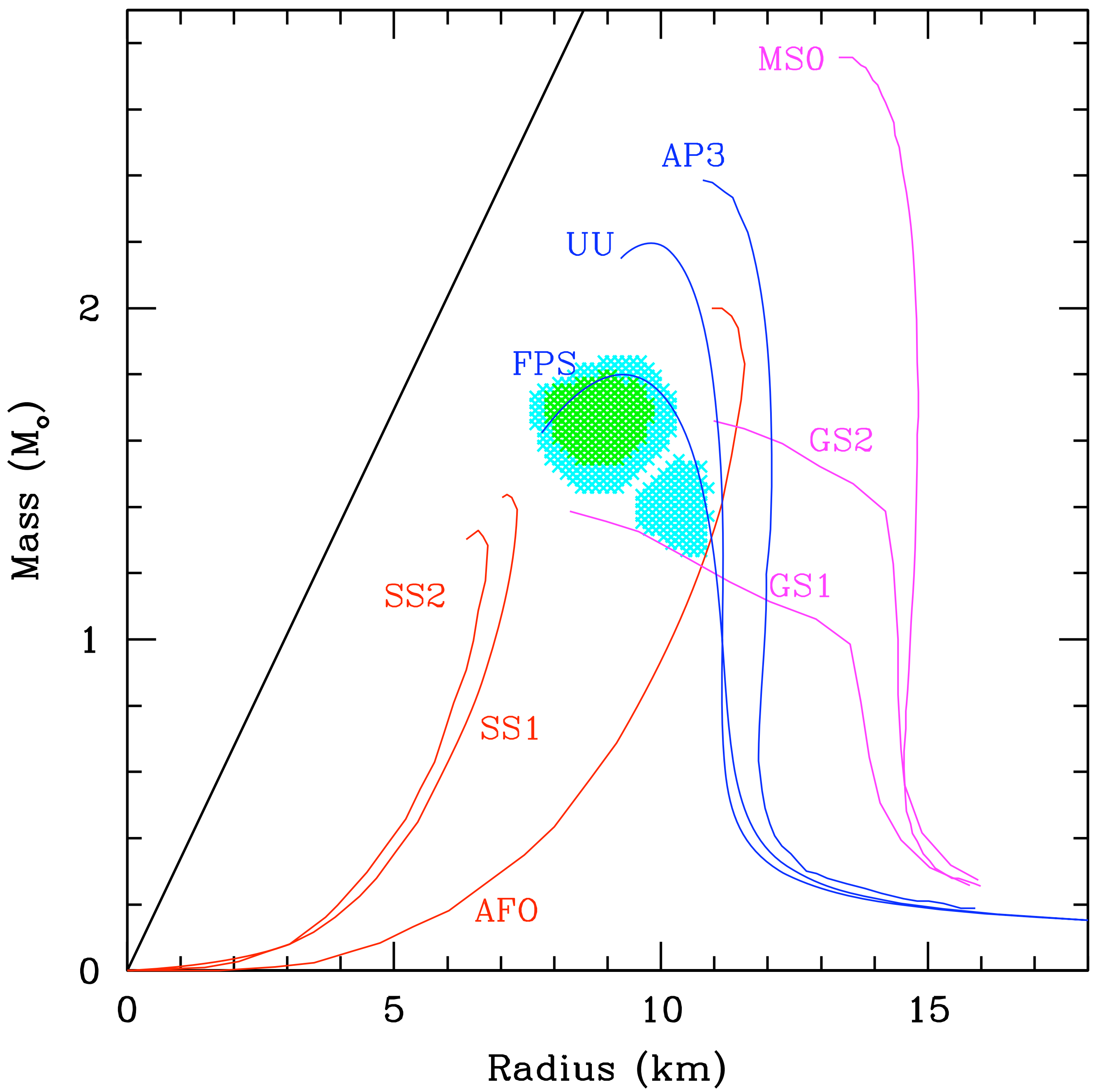
4U 1608-52



(Güver et al. 2009)

Fig. 13.— The 1− and 2−σ contours for the mass and the radius of the neutron star in 4U 1608−52. The descriptions of the various equations of state and the corresponding labels can be found in Lattimer & Prakash (2001).

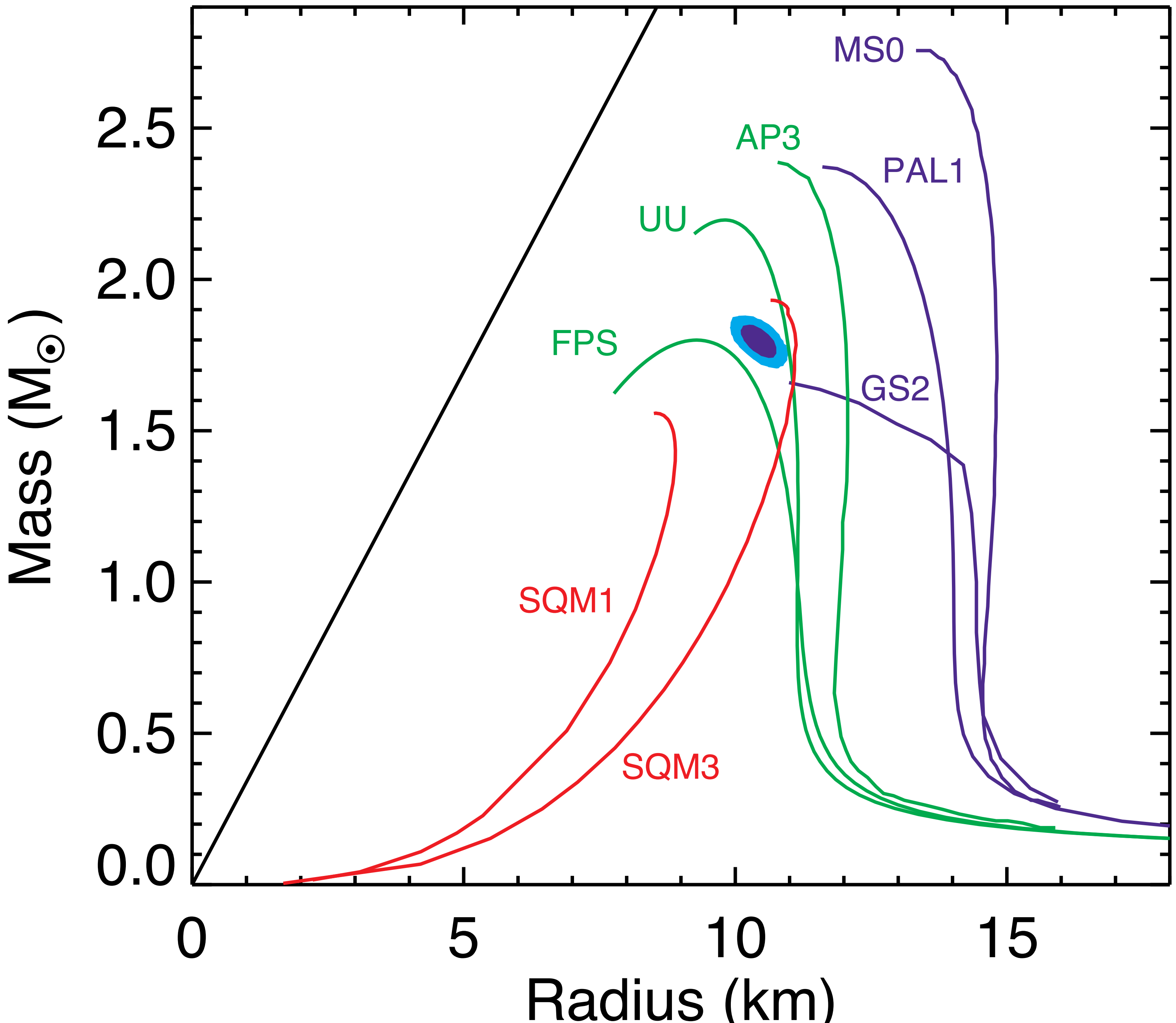
EXO 1745-248



(Özel et al. 2009)

Figure 5. Plot of 1σ and 2σ contours for the mass and radius of the neutron star in EXO 1745−248, for a hydrogen mass fraction of $X = 0$, based on the spectroscopic data during thermonuclear bursts combined with a distance measurement to the globular cluster. Neutron star radii larger than $\sim$ 13 km are inconsistent with the data. The descriptions of the various equations of state and the corresponding labels can be found in Lattimer & Prakash (2001).

4U 1820-30



(Güver et al. 2009, in prep.)

Figure 3. 1 and 2$-\sigma$ contours for the mass and radius of the neutron star in 4U 1820$-$30. The descriptions of the various equations of state and the corresponding labels can be found in Lattimer & Prakash (2001).

EXO 0748-676

- *The only gravitational redshift measurement (Cottam et al. 2002).*

Unfortunately two identifications :

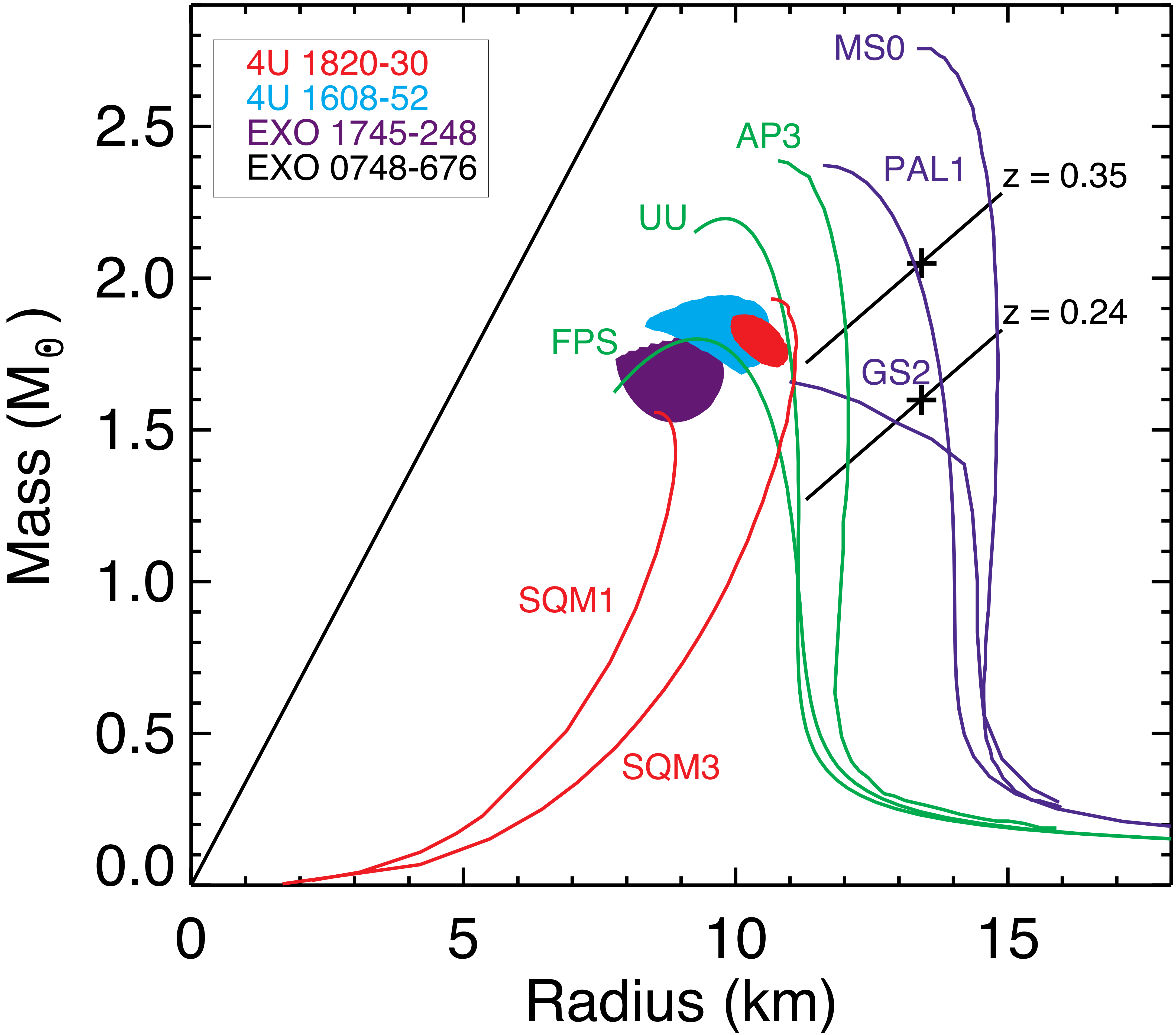
- *n = 2 - 3 transition H and He-like Fe lines => z = 0.35 (Cottam et al. 2002)*
- *n = 2 - 3 resonance transition of Fe XXIV => z = 0.24 (Rauch et al. 2008)*

$$M = \frac{f_\infty^4 c^4}{4G\kappa_{\rm es}} \left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right) \frac{[1-(1+z)^{-2}]^2}{(1+z)^3} F_{\rm Edd}^{-1} \qquad (1)$$

$$R = \frac{f_\infty^4 c^2}{2\kappa_{\rm es}} \left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right) \frac{1-(1+z)^{-2}}{(1+z)^3} F_{\rm Edd}^{-1} \qquad (2)$$

$$D = \frac{f_\infty^2 c^2}{2\kappa_{\rm es}} \left(\frac{F_{\rm cool}}{\sigma T_{\rm c}^4}\right)^{1/2} \frac{1-(1+z)^{-2}}{(1+z)^2} F_{\rm Edd}^{-1} \qquad (3)$$

Özel, 2006


4U 1820-30
4U 1608-52
EXO 1745-248
EXO 0748-676
MS0
AP3
PAL1
UU
z = 0.35
z = 0.24
FPS
GS2
SQM1
SQM3
Mass ($M_\odot$)
Radius (km)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15

Future Prospects

- *Measure more distances !!!*
  - *Measure the Hydrogen Column densities towards low-mass X-ray binaries (see Wroblewski et al. 2008)*
  - *We will perform near-IR observations of the fields around the X-ray bursters with Magellan Telescopes.*
- *Continue modeling the Type-I X-ray bursts*