Measurements of Neutron Star Masses and Radii from Thermonuclear X-ray Bursts

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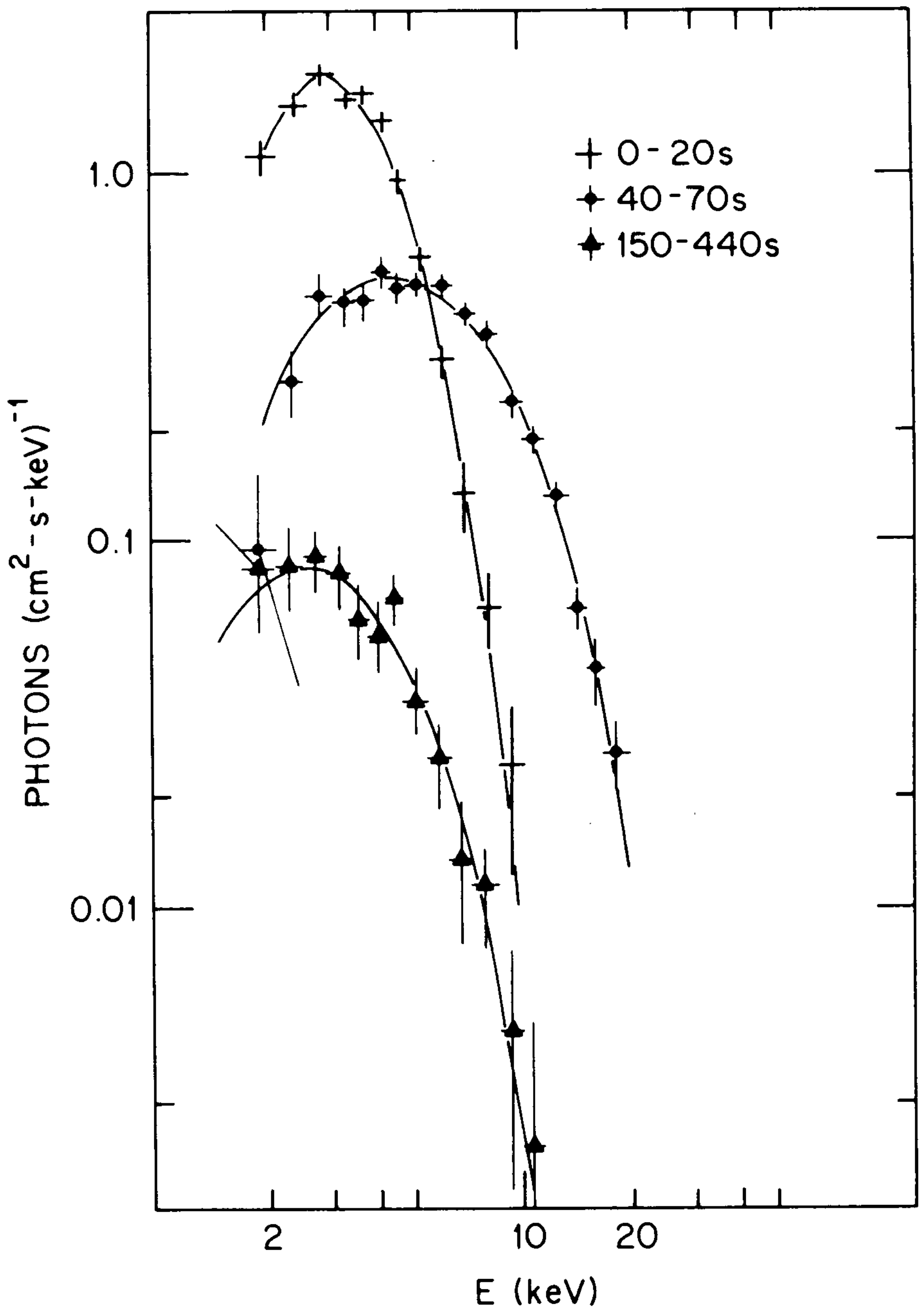
Use of X-ray Bursts as Probes of Neutron Star Mass / Radius

Swank et al. (1977) and Hoffman et al. (1977) noticed that the X-ray spectra is described by a Planck function.

Hoffman et al. (1977) also noticed that the flux in the tail of the X-ray bursts was proportional to T^4.

A result interpreted as a radiation from a cooling surface of constant size (van Paradijs 1978).



Swank+ 1977

Use of X-ray Bursts as Probes of Neutron Star Mass / Radius

- van Paradijs (1978) performed an analysis of 10 bursters and derived the following results :

Table 3 Distance, radius and total burst energy of X-ray burst sources

Source (MXB)	Distance (kpc)	Radius (km)	Total burst energy (10^{39} erg)
1636 − 53	4.5 ± 0.4	7.4 ± 1.2	1.20 ± 0.38
1659 − 29	10.9 ± 1.6	4.5 ± 1.0	2.09 ± 0.73
1728 − 34	4.2 ± 0.2	6.5 ± 0.4	1.45 ± 0.26
1735 − 44	7.2 ± 0.2	7.2 ± 1.6	0.80 ± 0.10
1742 − 29	7.4 ± 0.5	5.5 ± 1.8	1.19 ± 0.33
1743 − 28	8.0 ± 1.0	13.9 ± 9.5	1.62 ± 0.89
1743 − 29	6.0 ± 0.3	5.8 ± 1.0	2.12 ± 0.47
1837 + 05	7.0 ± 0.4	6.1 ± 1.1	0.96 ± 0.13
1906 + 00	7.6 ± 0.8	8.9 ± 1.9	1.09 ± 0.28
1916 − 05	8.4 ± 0.3	6.6 ± 1.8	1.07 ± 0.14

van Paradijs 1978

Use of X-ray Bursts as Probes of Neutron Star Mass / Radius

- van Paradijs (1979) followed the same idea and came up with the first neutron star mass and radius constraint :

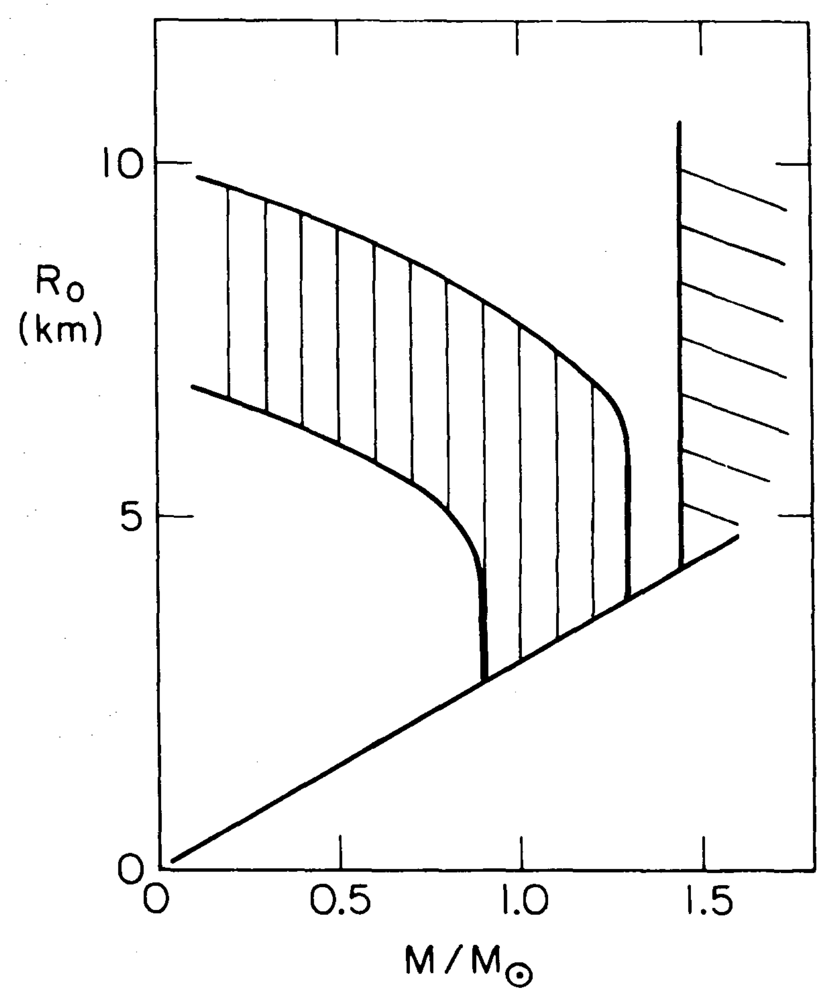


FIG. 2.—Allowed regions in the (M, R) plane of neutron stars. The area shaded by vertical lines corresponds to a range of observed blackbody radii between 7 and 10 km. The observed lower limit of 1.45 $M_\odot$ on the mass of Vela X-1 defines the area indicated by the slanted lines. The straight line $R \approx 3(M/M_\odot)$ km indicates the Schwarzschild radius.

van Paradijs 1979

Three questions

- Is the energy distribution of the X-ray spectrum during burst decay really Planckian?

- Do we observe the whole neutron-star surface during the decay of an X-ray burst?

- How are the maximum fluxes of X-ray bursts related to the Eddington Limit ?

van Paradijs 1981,1982

Use of X-ray Bursts as Probes of Neutron Star Mass / Radius

van Paradijs & Lewin (1987)	4U 1820-30
Sztajno et al. (1987)	4U 1746-37
Kaminker et al. (1989, 1990)	4U 1728-34, MXB 1730-335
Damen et al. (1990)	4U 1636-536, 4U 1820-30, 4U 1735-44

…

Three questions remain elusive

- “Is the energy distribution of the X-ray spectrum during burst decay Planckian?
- “Do we observe the whole neutron-star surface during the decay of an X-ray burst?
- How are the maximum fluxes of X-ray bursts related to the Eddington Limit ?

van Paradijs 1982, Damen+ 1990, Lewin+ 1993, …

Rossi X-ray Timing Explorer

- RXTE observed 63 low mass X-ray binaries for ~39.9 million seconds (till 2008).
- RXTE detected 1035 X-ray bursts from 45 sources (till 2008).
- RXTE obtained high S/N data for almost all of these events.

Galloway+ 2008

A systematic study of all X-ray burst

Selection Criteria

- Persistent emission < %10 of the Eddington Limit as noted by Galloway+ 2008.
- No dippers or high inclination systems (Galloway, Özel, Psaltis 2008).
- Did not include any known millisecond pulsars.
- No bursts that may have been affected by source confusion.

A systematic study of all X-ray burst

Method

- Extracted X-ray spectra depending on the count-rate, created responses using latest RXTE calibration.

- Applied Deadtime Correction

- Fit the spectra with a Planckian function, together with independently found nH (using tbabs and ISM; Wilms+ 2000).

X-Ray Bursters

Name	R.A.	Decl.	Number of Bursts	N_H (10^{22} cm^{-2})	N_H Method[a]
4U 0513−40	05 14 06.60	−40 02 37.0	6	0.014[(1)]	GC[b]
4U 1608−52	16 12 43.00	−52 25 23.0	26	1.08 ± 0.16[(2)]	X-ray edges[c]
4U 1636−53	16 40 55.50	−53 45 05.0	162	0.44[(3)]	X-ray edges[c]
4U 1702−429	17 06 15.31	−43 02 08.7	46	1.95	X-ray continuum[d]
4U 1705−44	17 08 54.47	−44 06 07.4	44	2.44 ± 0.09[(4)]	X-ray edges[c]
4U 1724−307	17 27 33.20	−30 48 07.0	3	1.08[(1)]	GC[b]
4U 1728−34	17 31 57.40	−33 50 05.0	90	2.49 ± 0.14[(4)]	X-ray edges[c]
KS 1731−260	17 34 12.70	−26 05 48.5	24	2.98	X-ray continuum[d]
4U 1735−44	17 38 58.30	−44 27 00.0	6	0.28[(3)]	X-ray edges[c]
EXO 1745−248	17 48 56.00	−24 53 42.0	22	1.4 ± 0.45[(5)]	X-ray continuum[d]
4U 1746−37	17 50 12.7	−37 03 08.0	7	0.36[(6)]	GC[b]
SAX J1748.9−2021	17 48 52.16	−20 21 32.4	4	0.79[(6)]	GC[b]
SAX J1750.8−2900	17 50 24.00	−29 02 18.0	4	4.97	X-ray continuum[d]
4U 1820−30	18 23 40.45	−30 21 40.1	5	0.25 ± 0.03[(7)]	X-ray edges[c]
Aql X-1	19 11 16.05	+00 35 05.8	51	0.34 ± 0.07[(8)]	Counterpart[e]

Notes.

[a] References: (1) Harris 1996; (2) Güver et al. 2010a; (3) Juett et al. 2004, 2006; (4) Wroblewski et al. 2008; (5) Wijnands et al. 2005; (6) Valenti et al. 2007; (7) Güver et al. 2010b; (8) Chevalier et al. 1999.

[b] Optical/IR observations of the globular cluster.

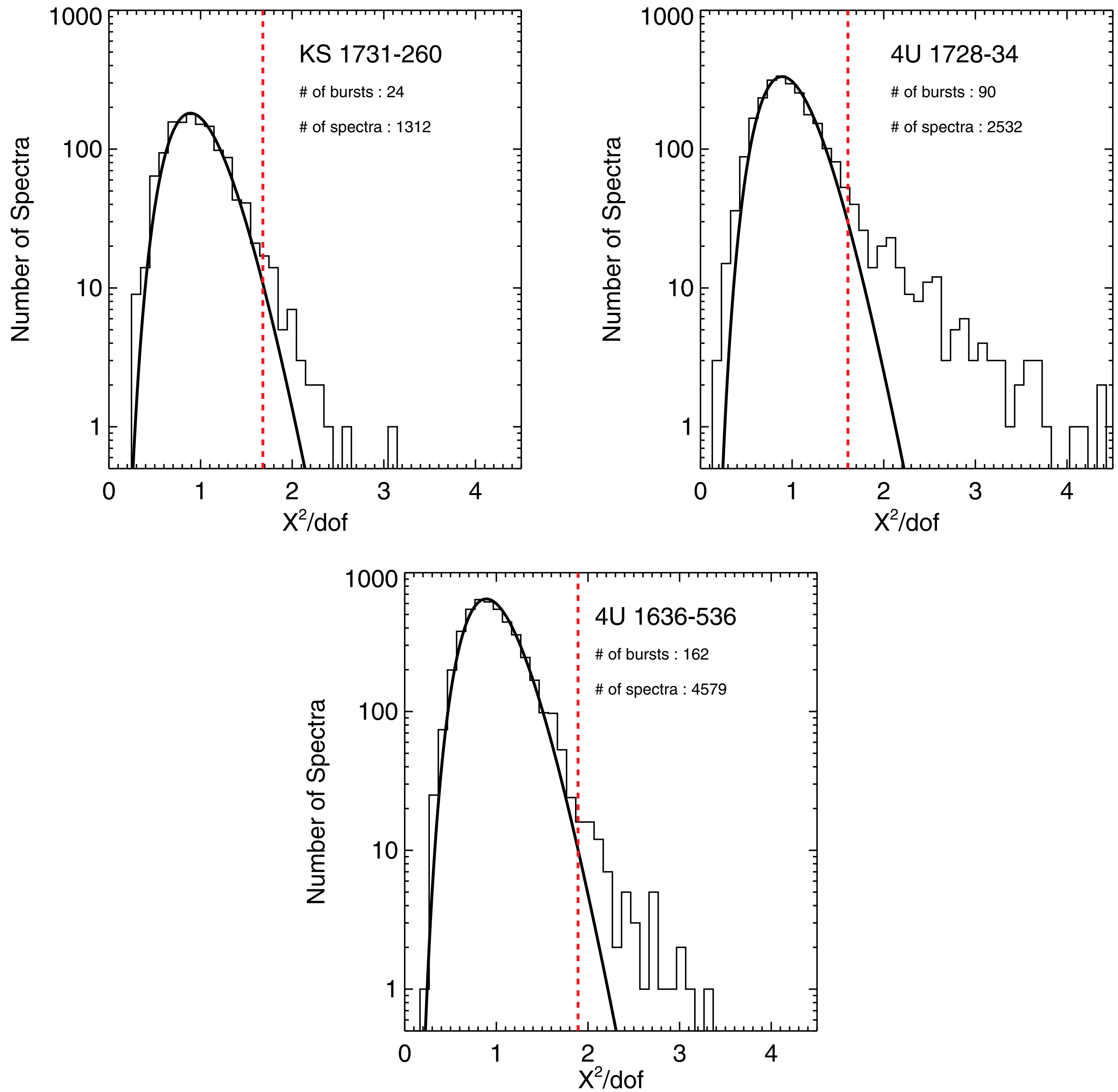
[c] High-resolution spectroscopy of X-ray absorption edges.

[d] Average of continuum X-ray spectroscopy.

[e] Optical spectroscopy of the counterpart.

A total of 13095 X-ray spectra from 12 sources and 446 X-ray bursts.

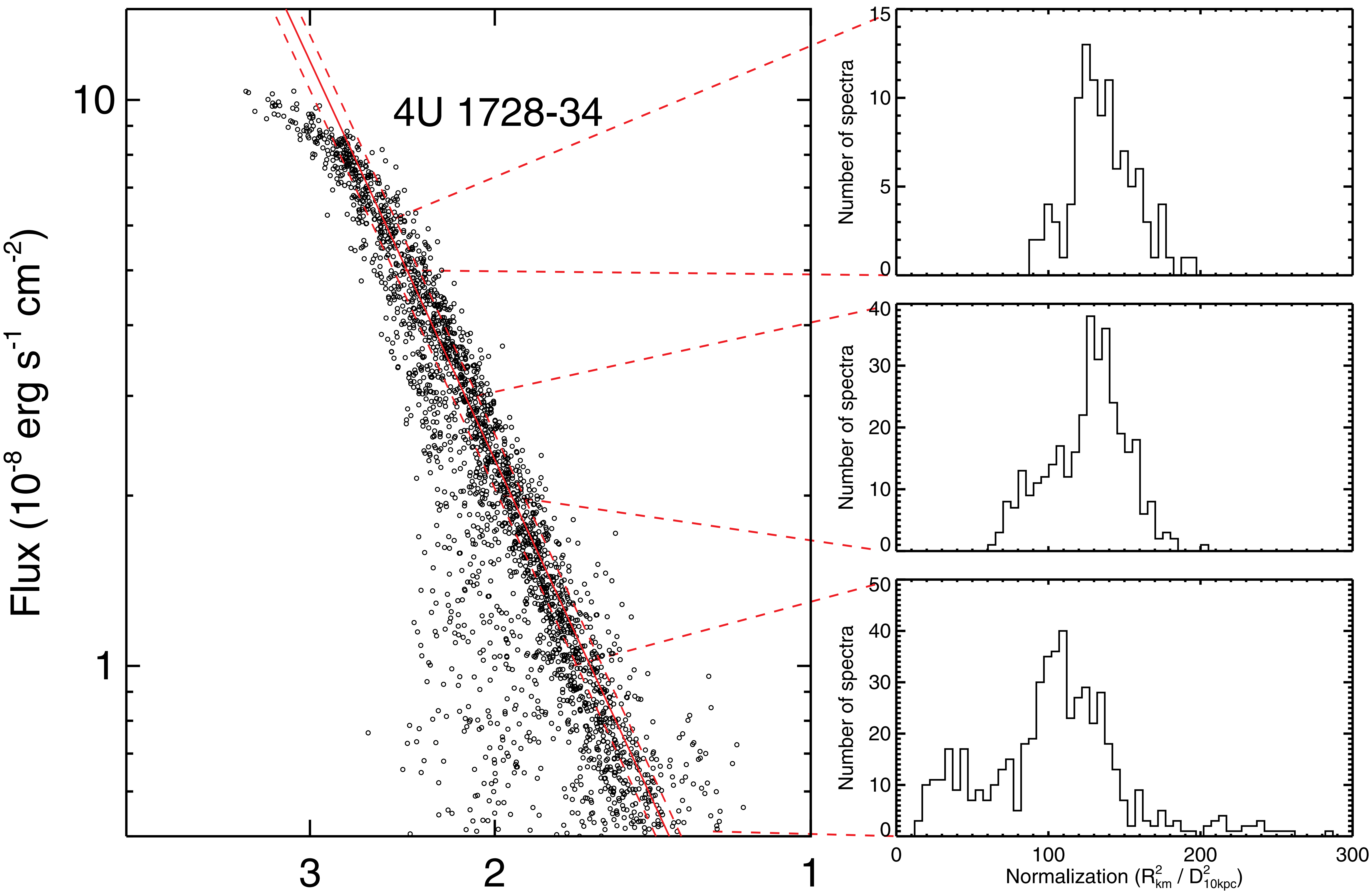
How good are the blackbody fits ?



The systematic uncertainty required to render the observed spectra as a blackbody is ~3-5%

A similar amount (~3-5%) of X-ray spectra are just not consistent with a blackbody function.

Do the cooling tails really follow T^4 ?



Güver+ 2012a

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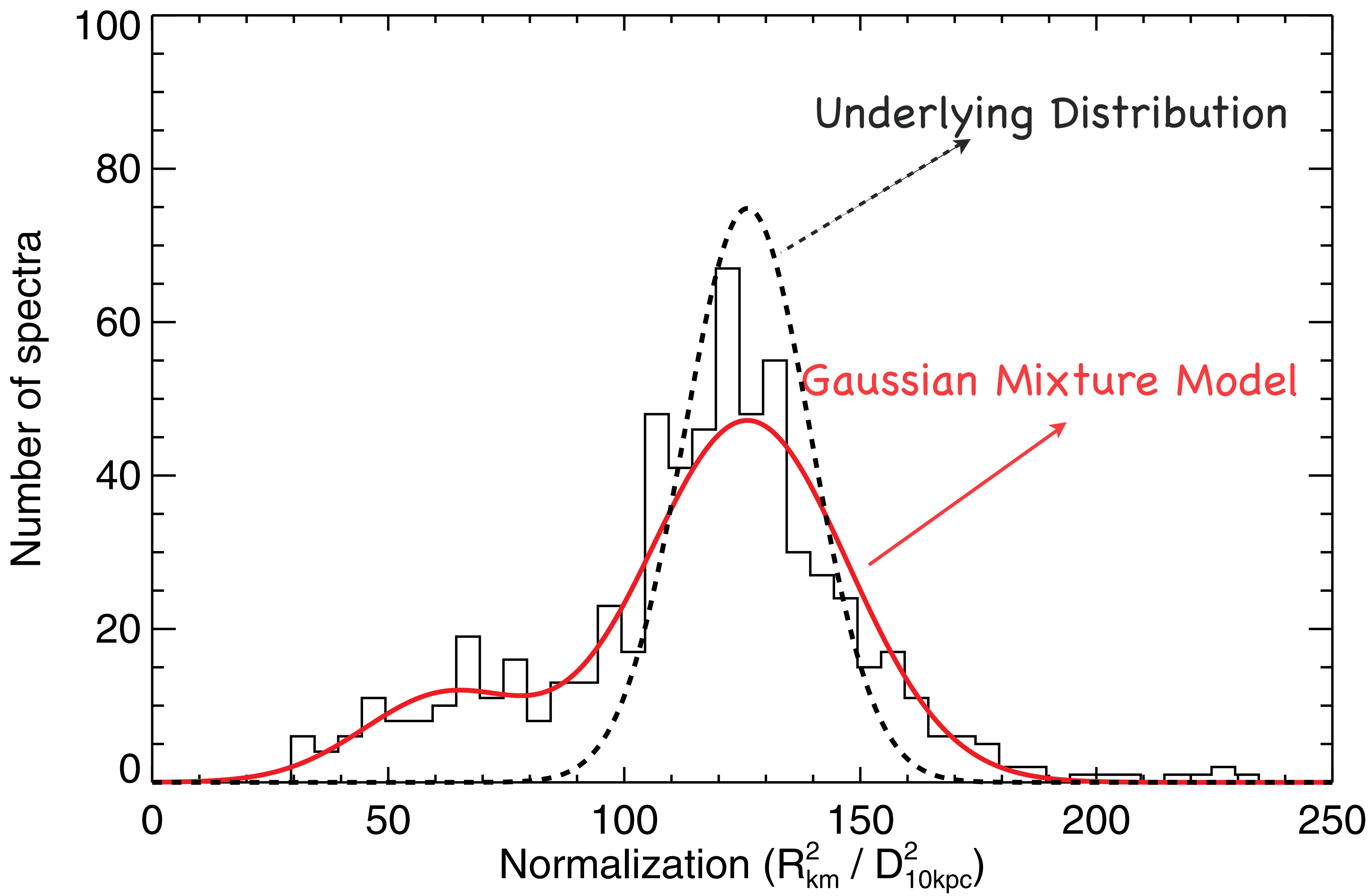

Güver+ 2012a

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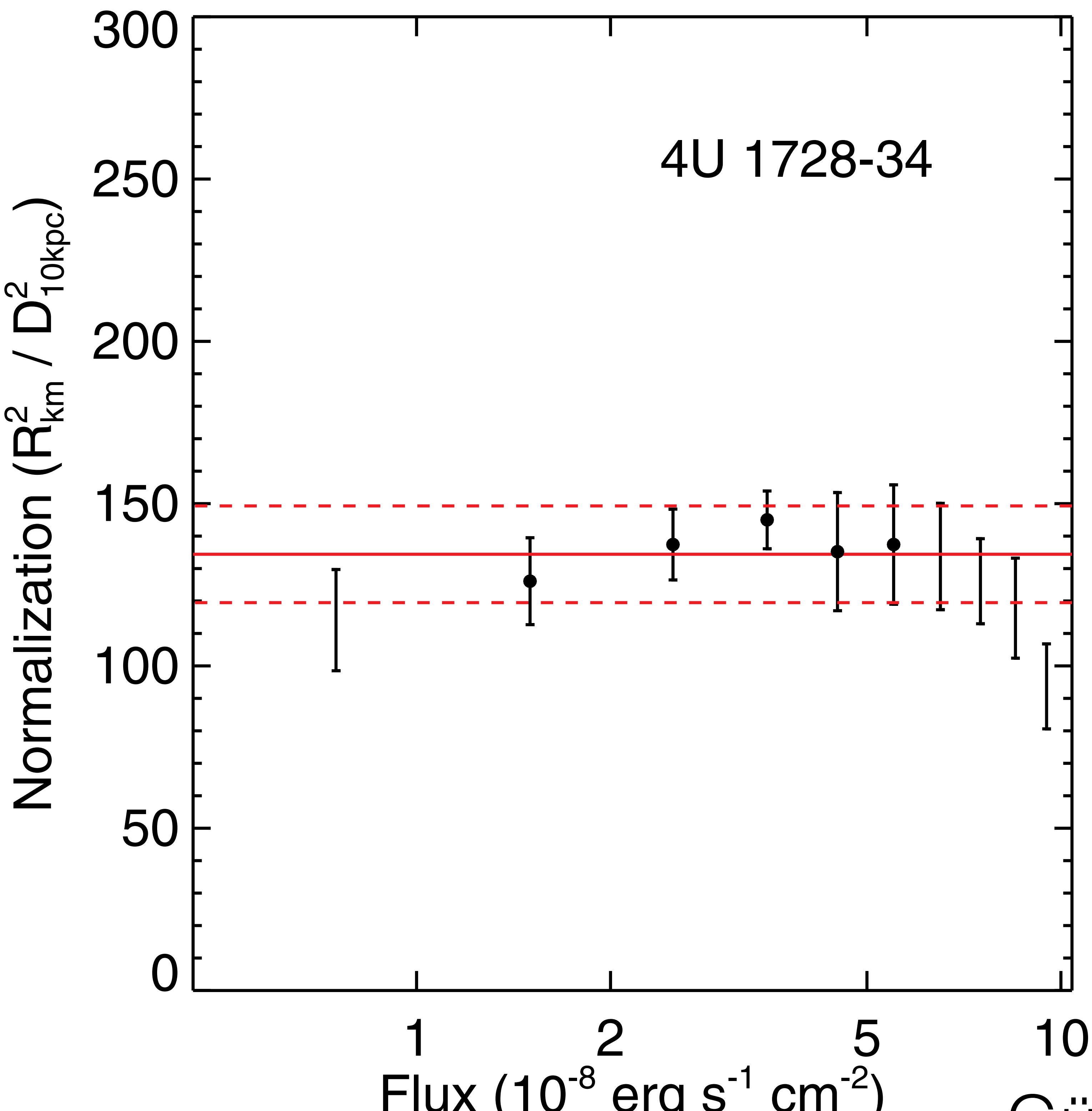
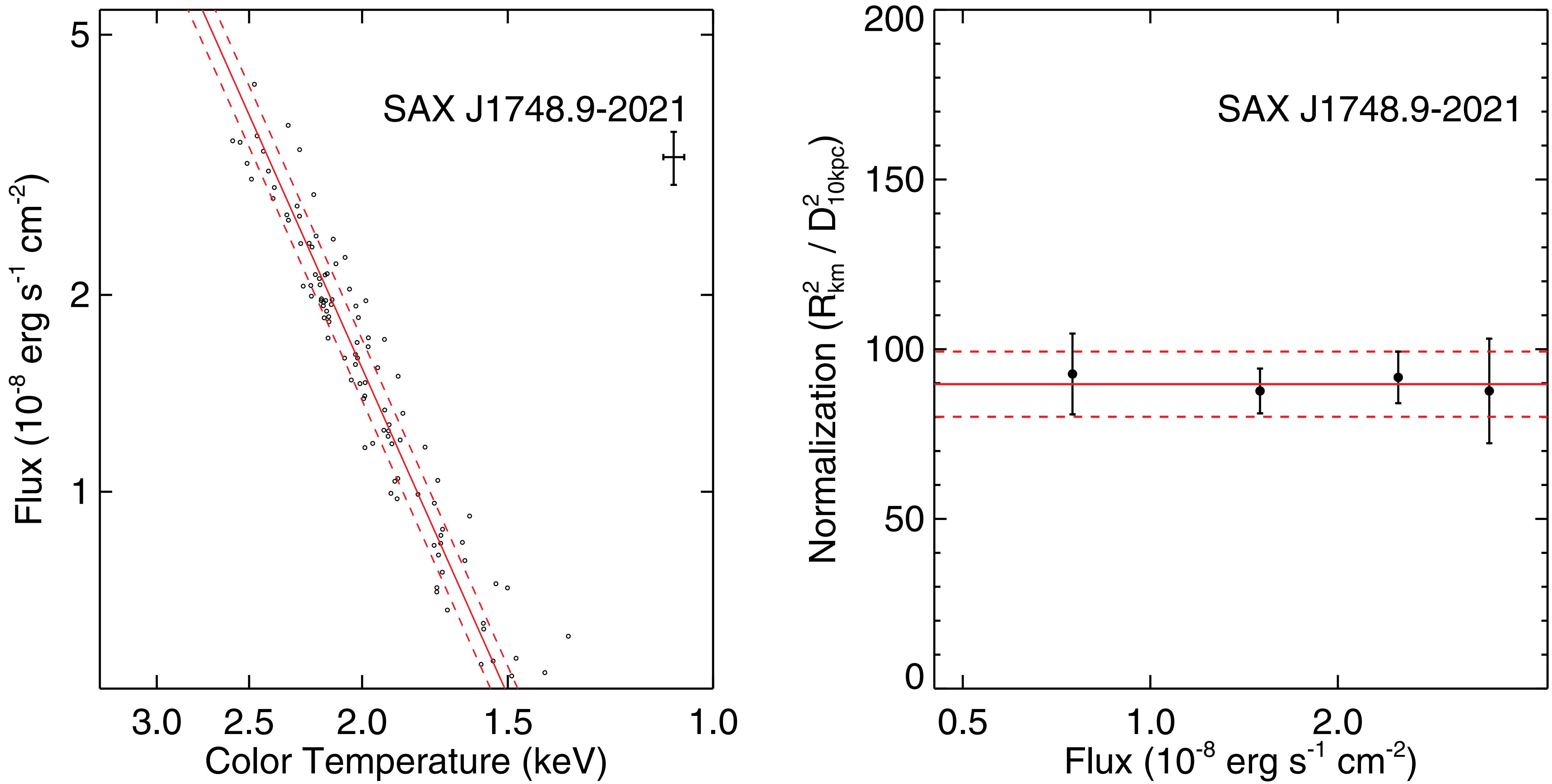


Güver+ 2012a

Evolution of the Color Correction Factor



Güver+ 2012a

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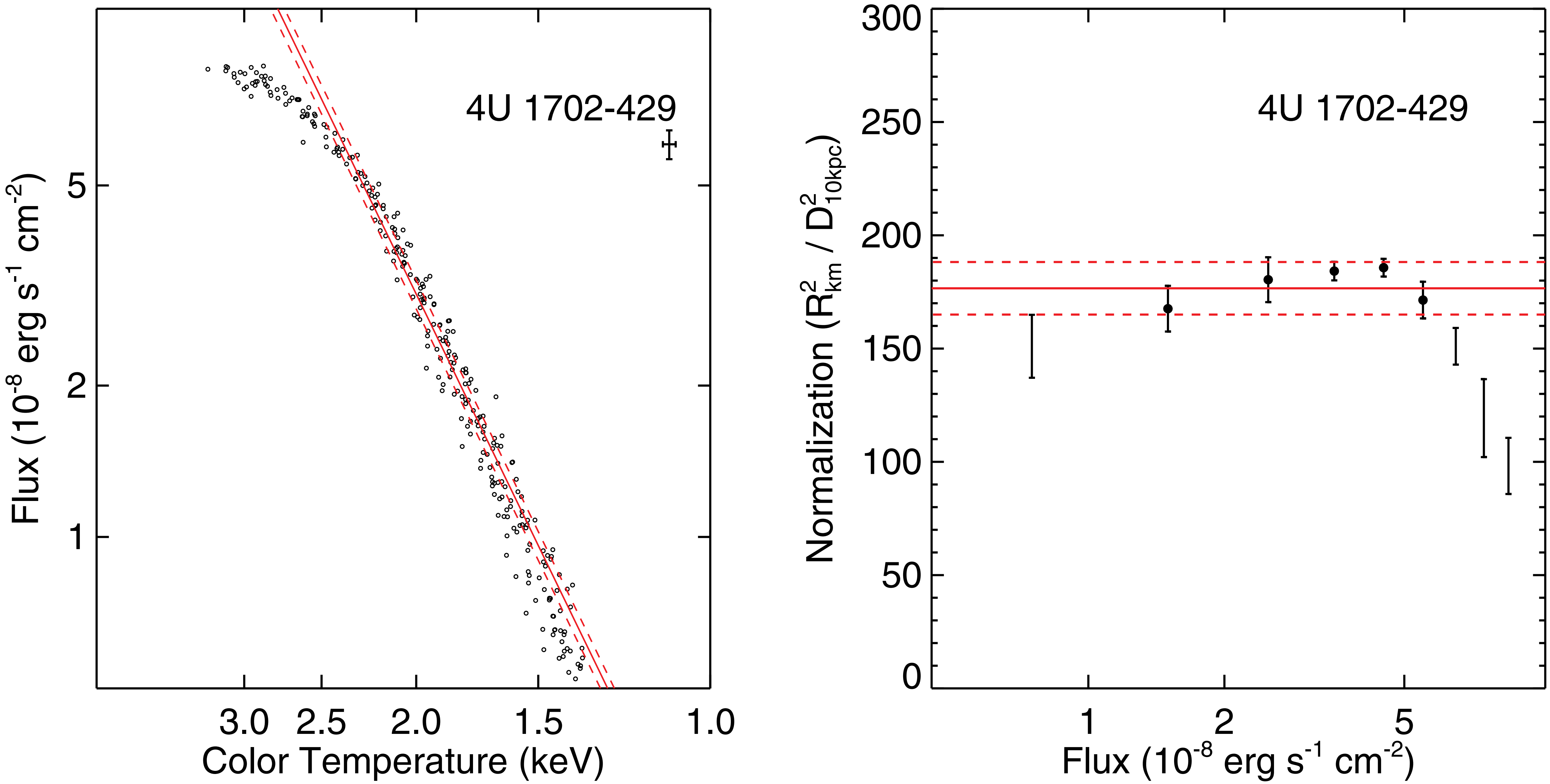
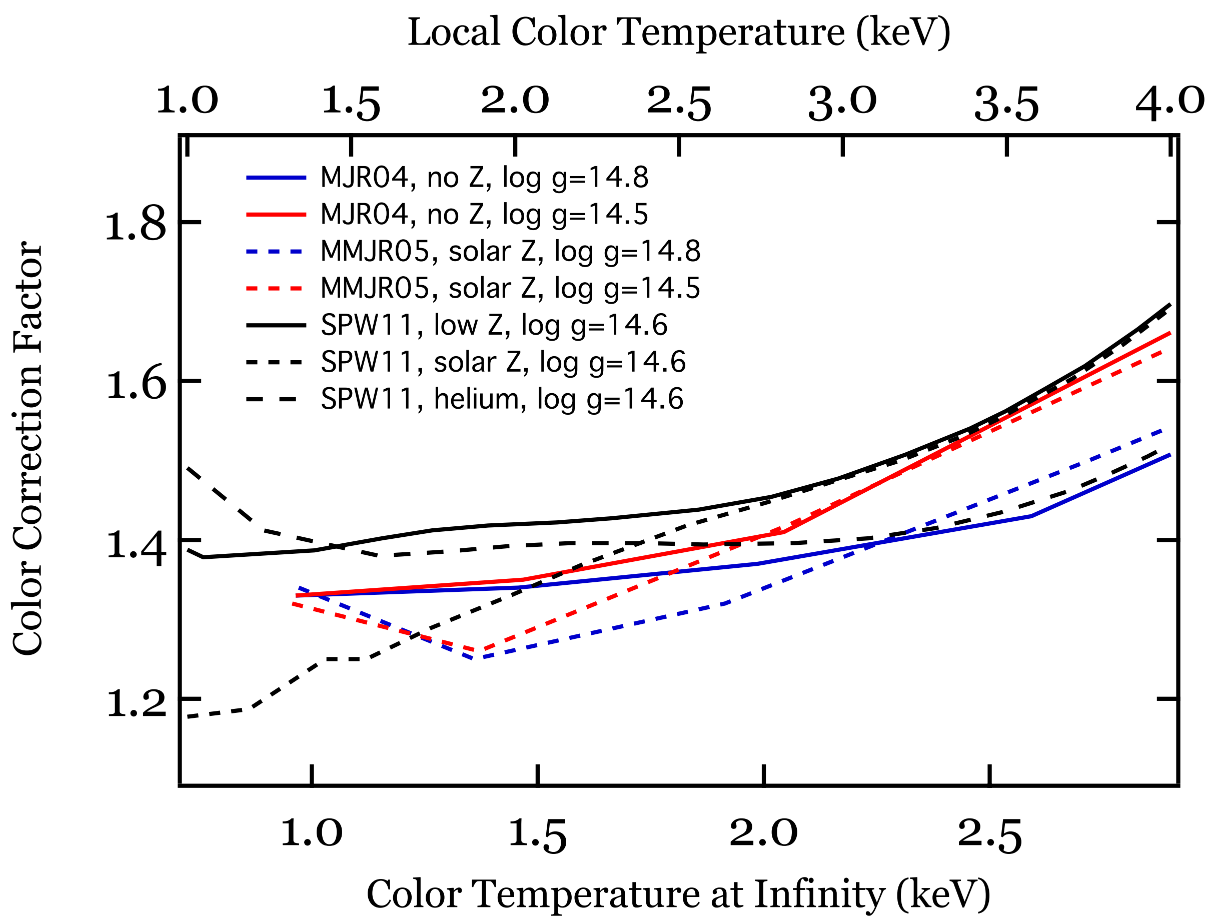
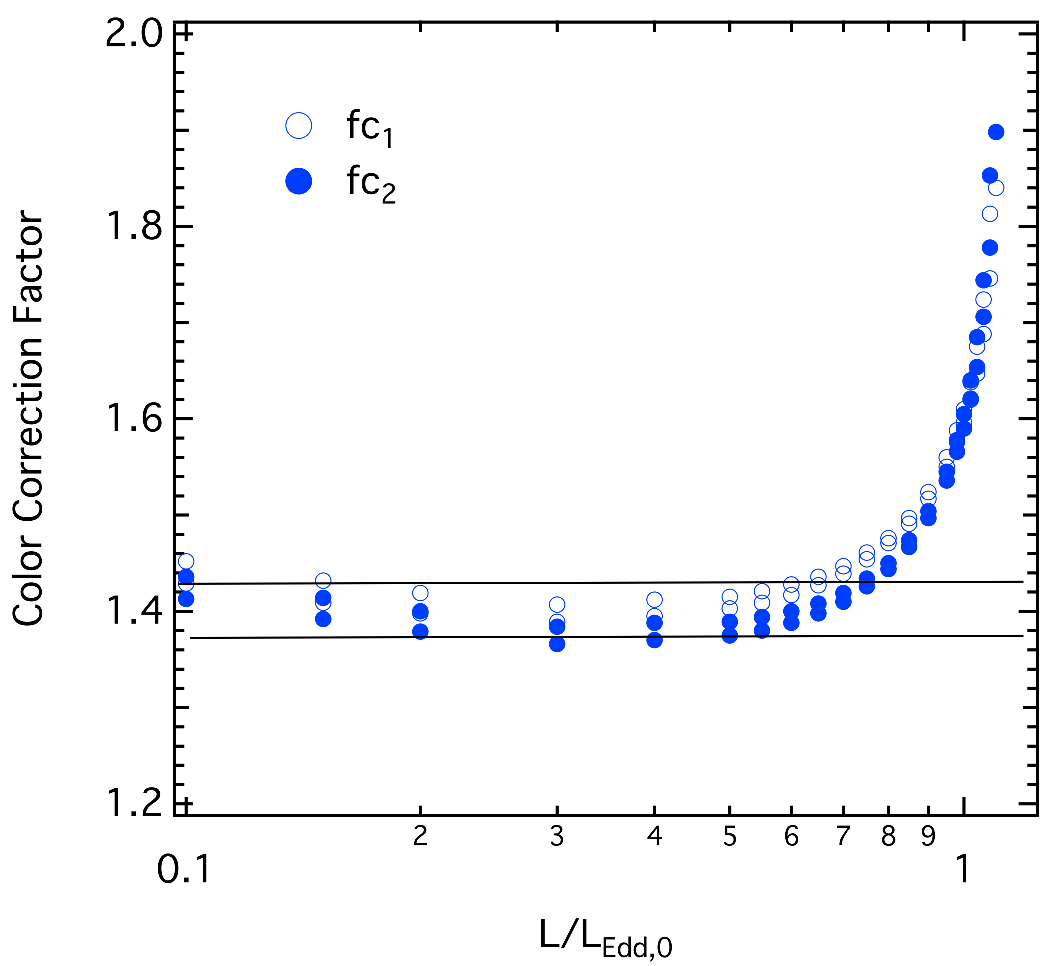


Güver+ 2012a

Evolution of the Color Correction Factor

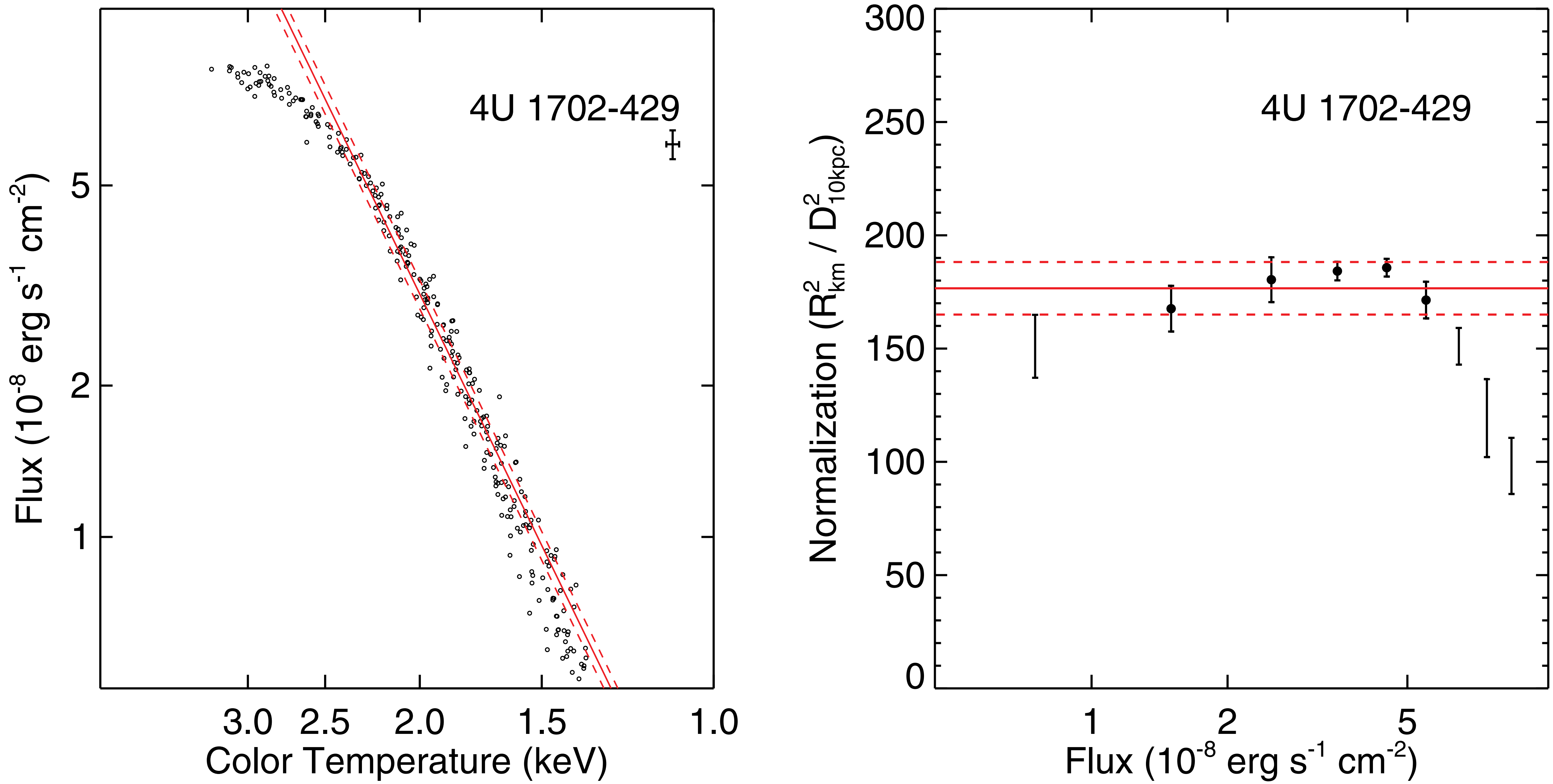




Güver+ 2012, Özel+ 2015

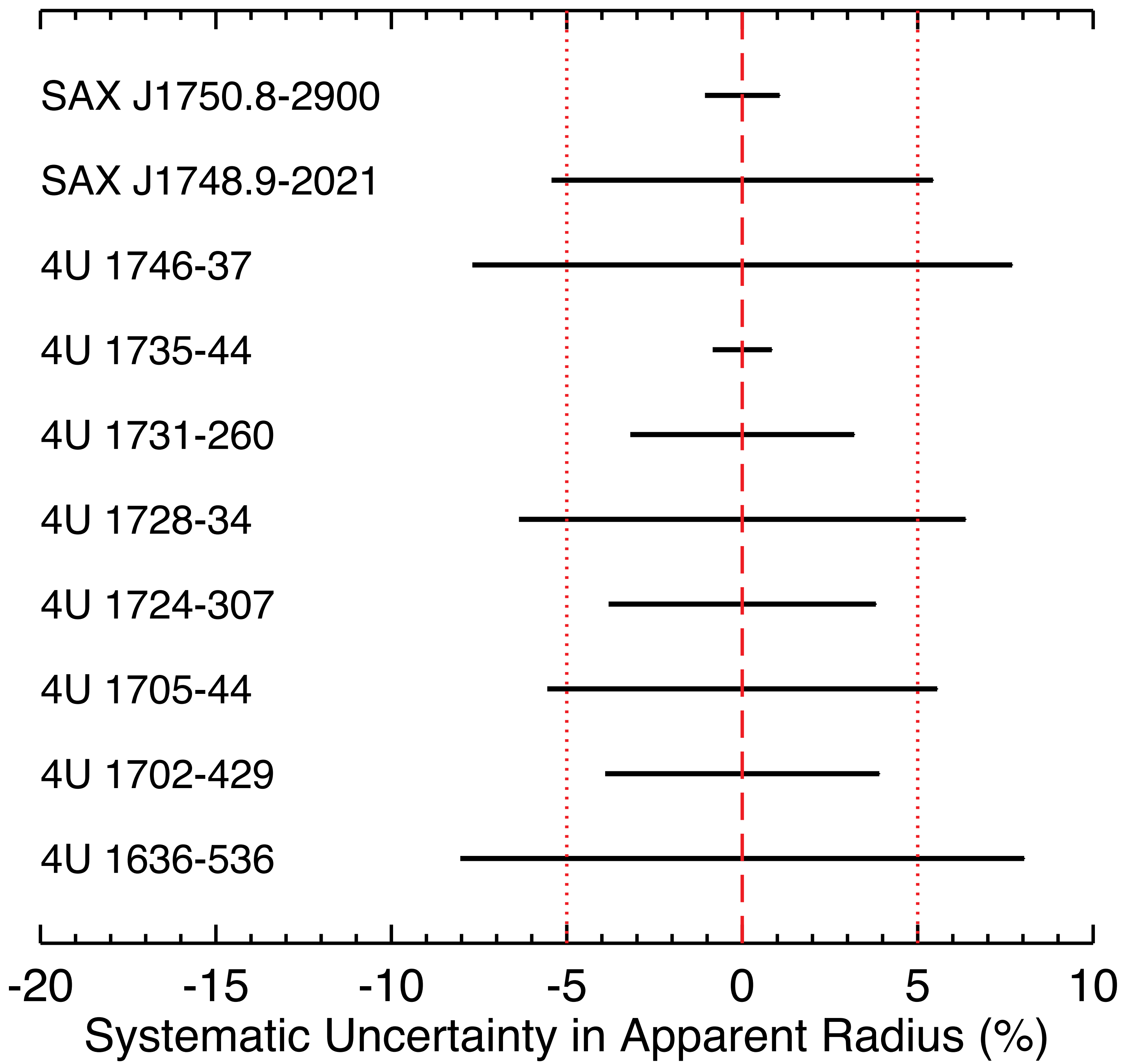
data from Suleimanov+ 2012

Evolution of the Color Correction Factor

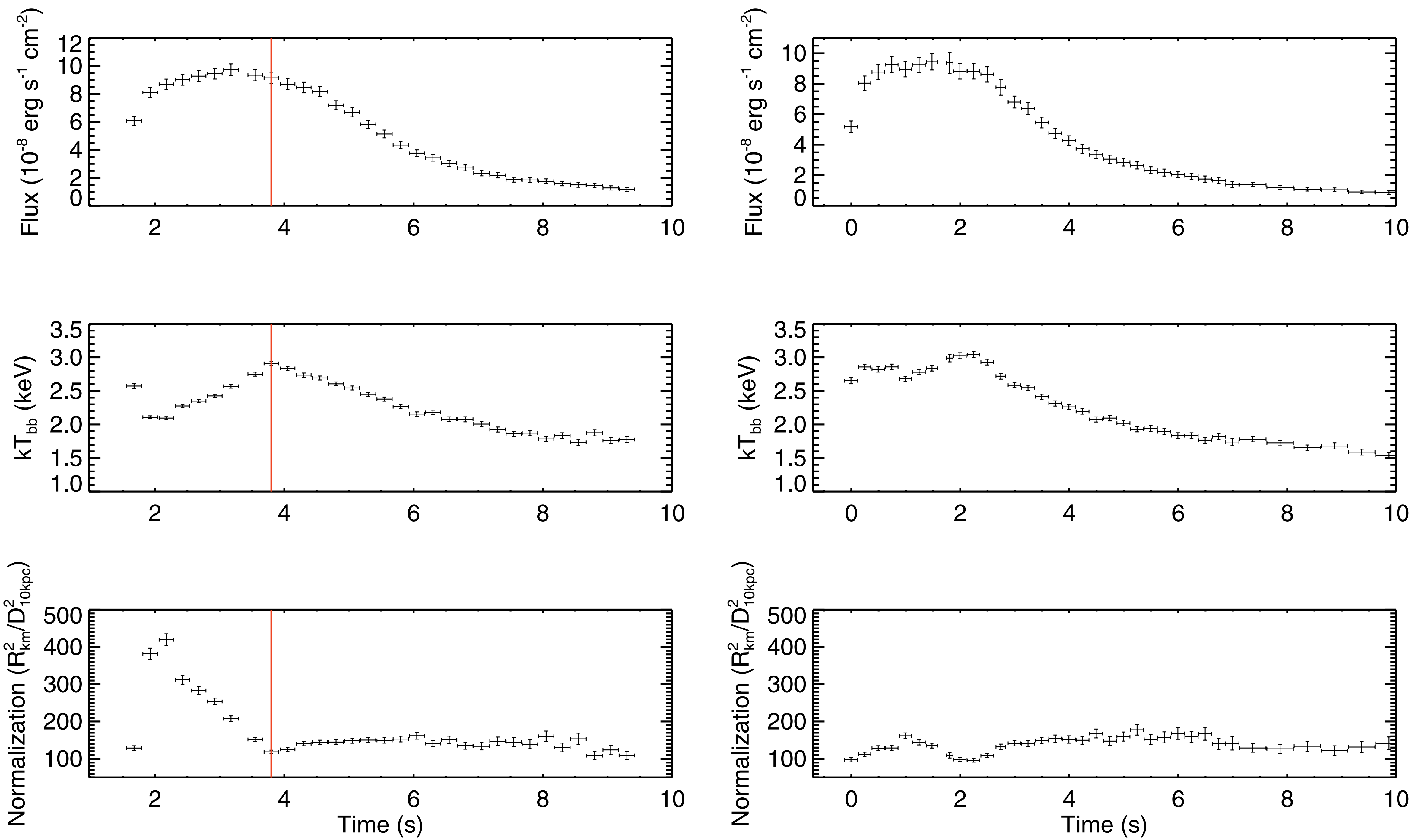


Güver+ 2012a

Uncertainties in the apparent radii of neutron stars

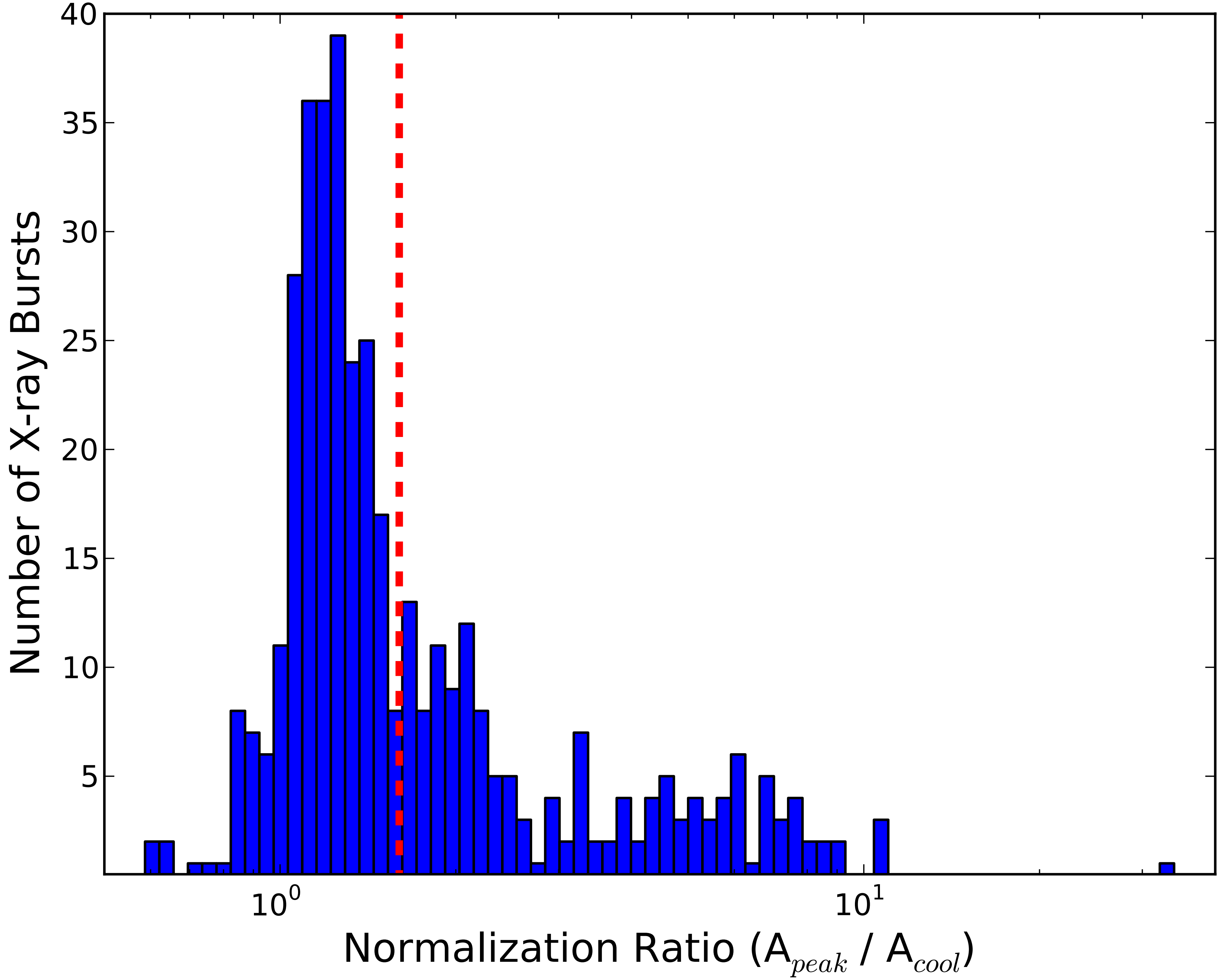


Touchdown Flux Measurements



Güver+ 2012b

Touchdown Flux Measurements



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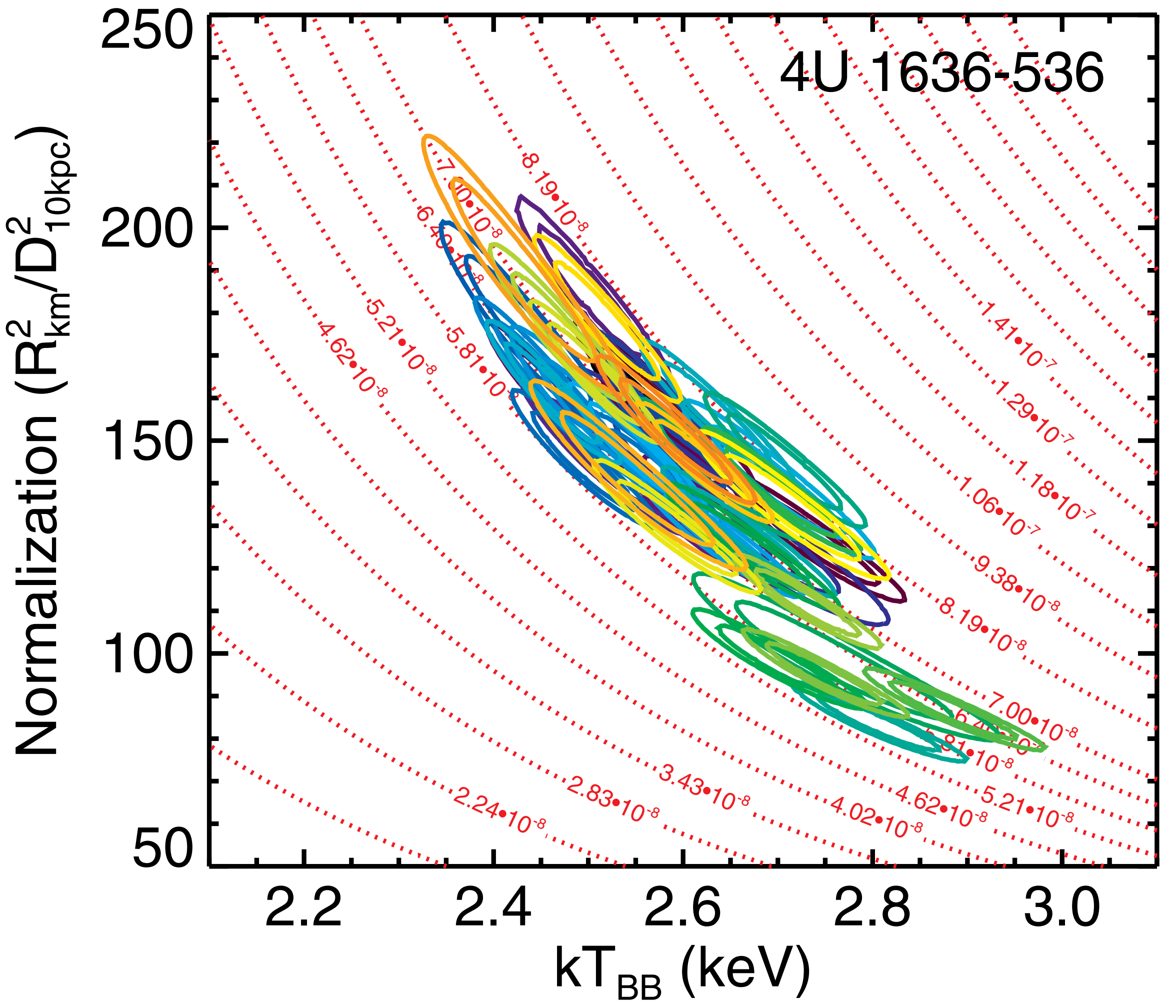
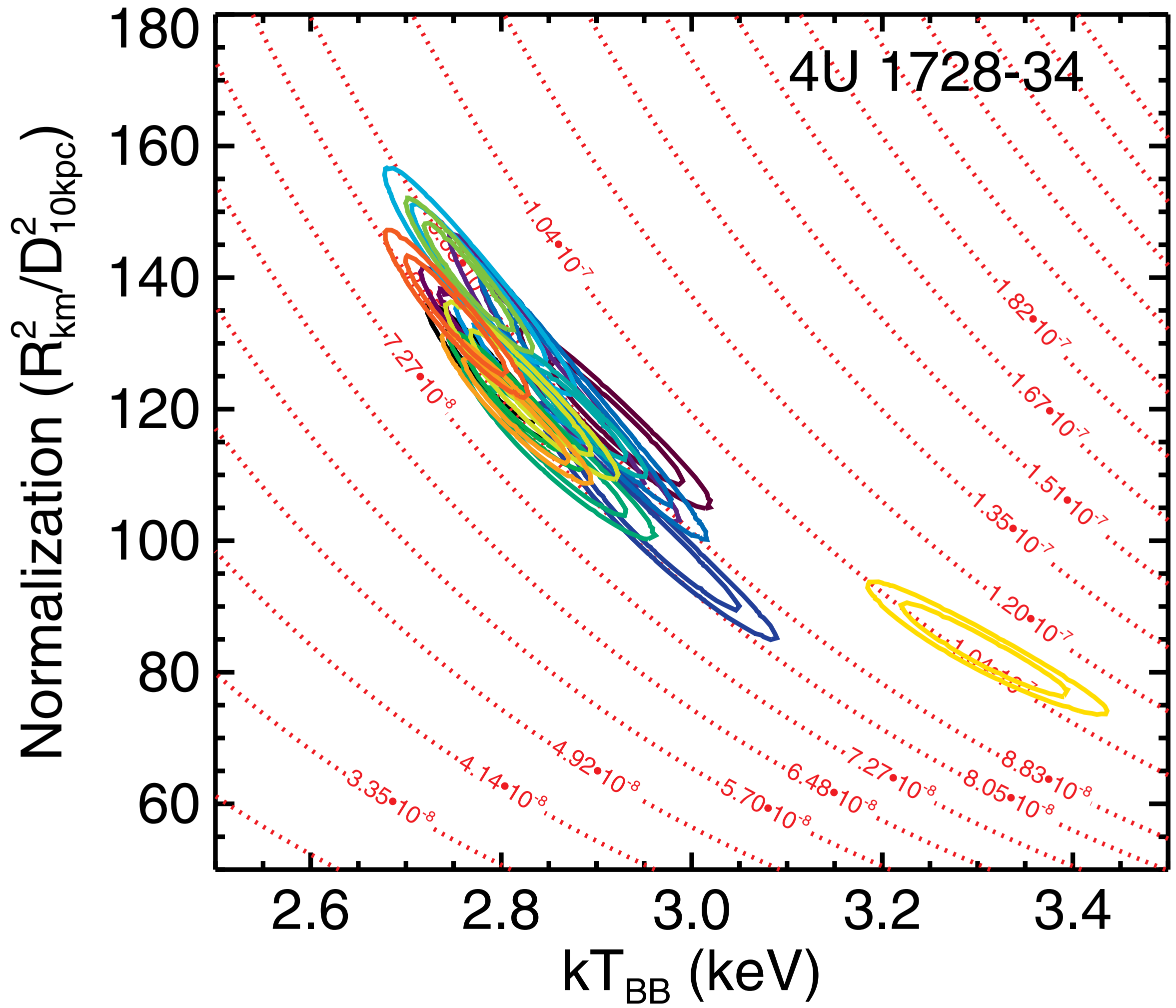
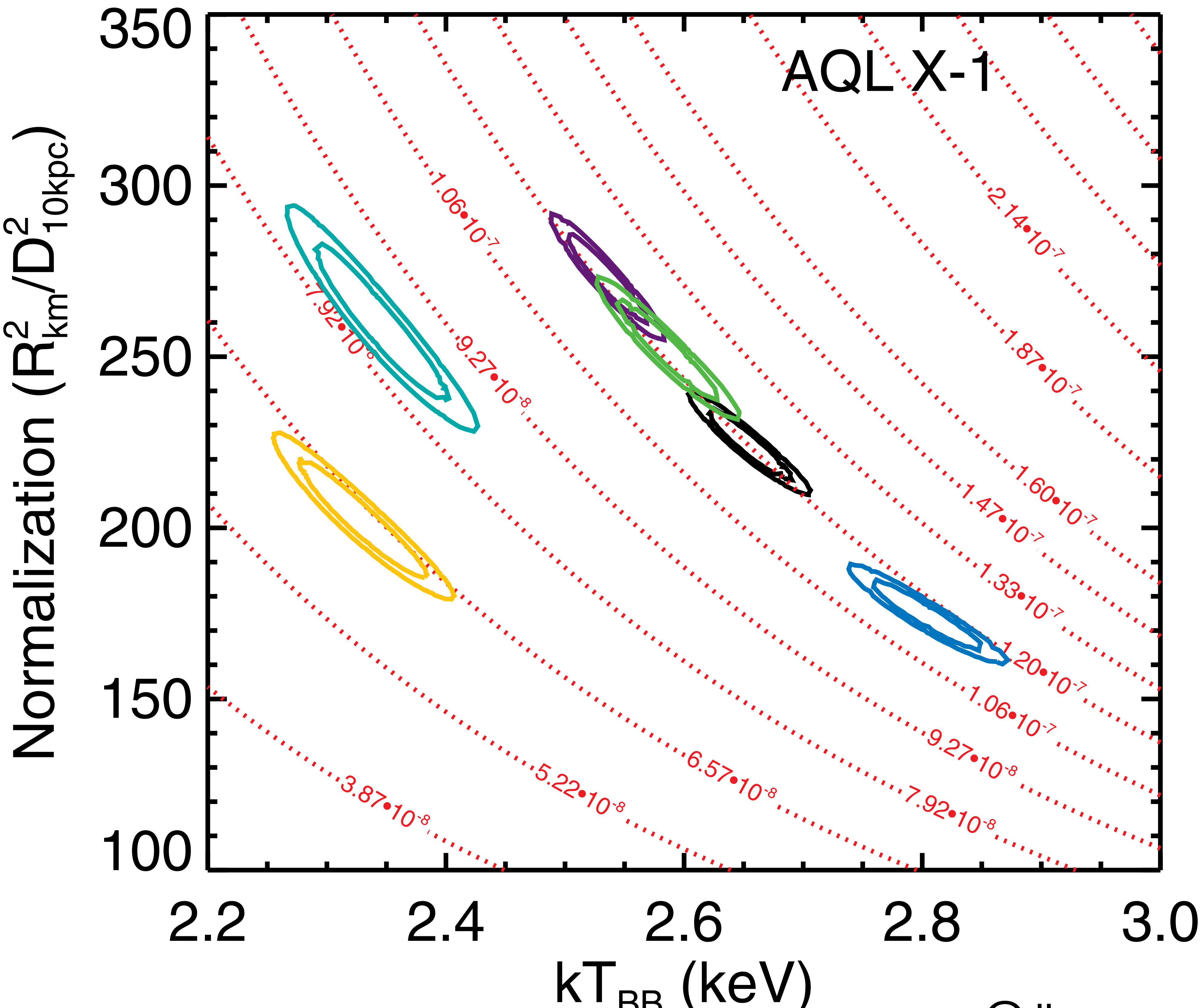




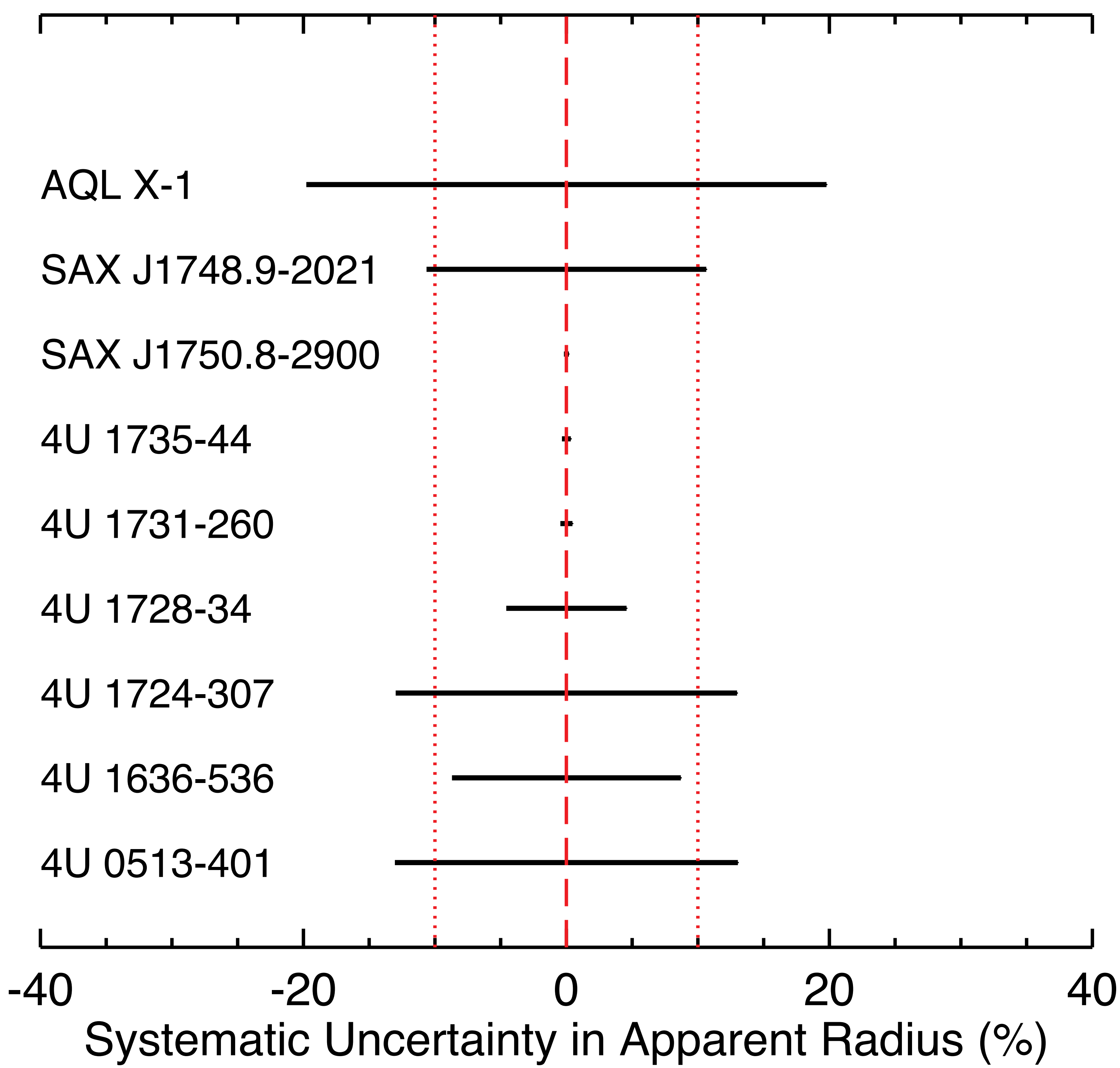
Güver+ 2012b

Touchdown Flux Measurements

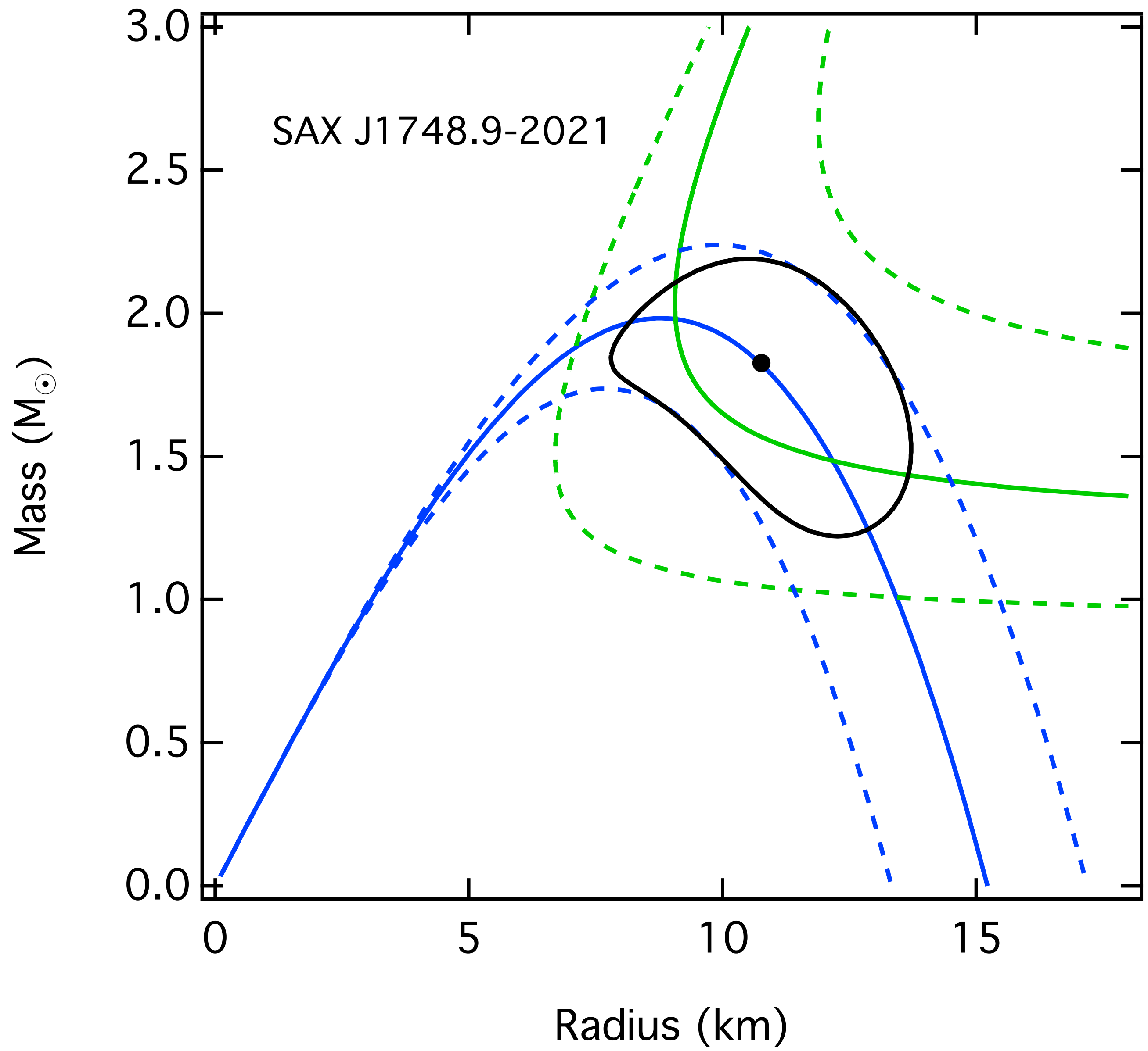


Güver+ 2012b

Uncertainties in the touchdown flux measurements

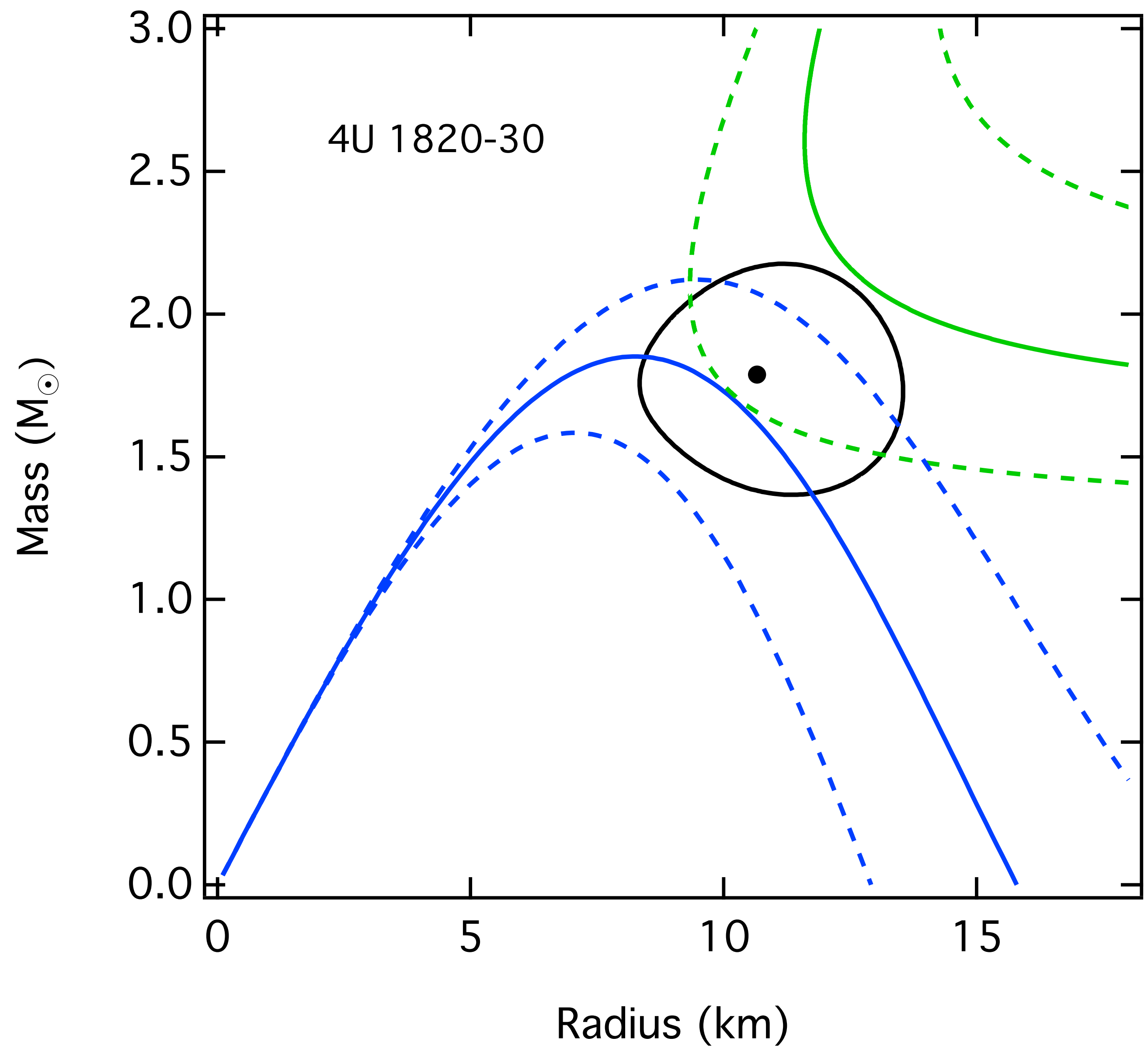


SAX J1748.9-2021



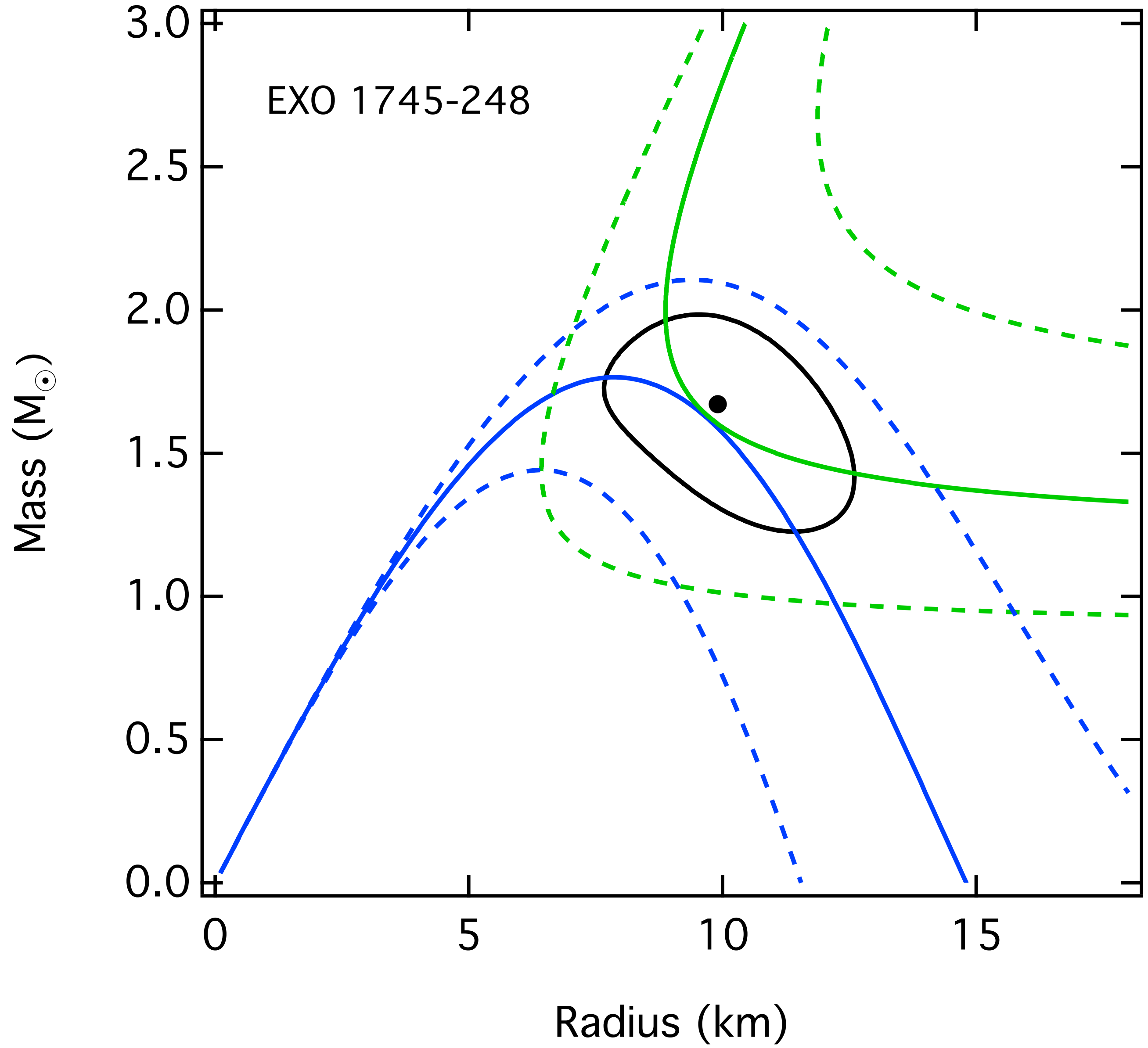
Özel+ 2015, submitted

4U 1820-30



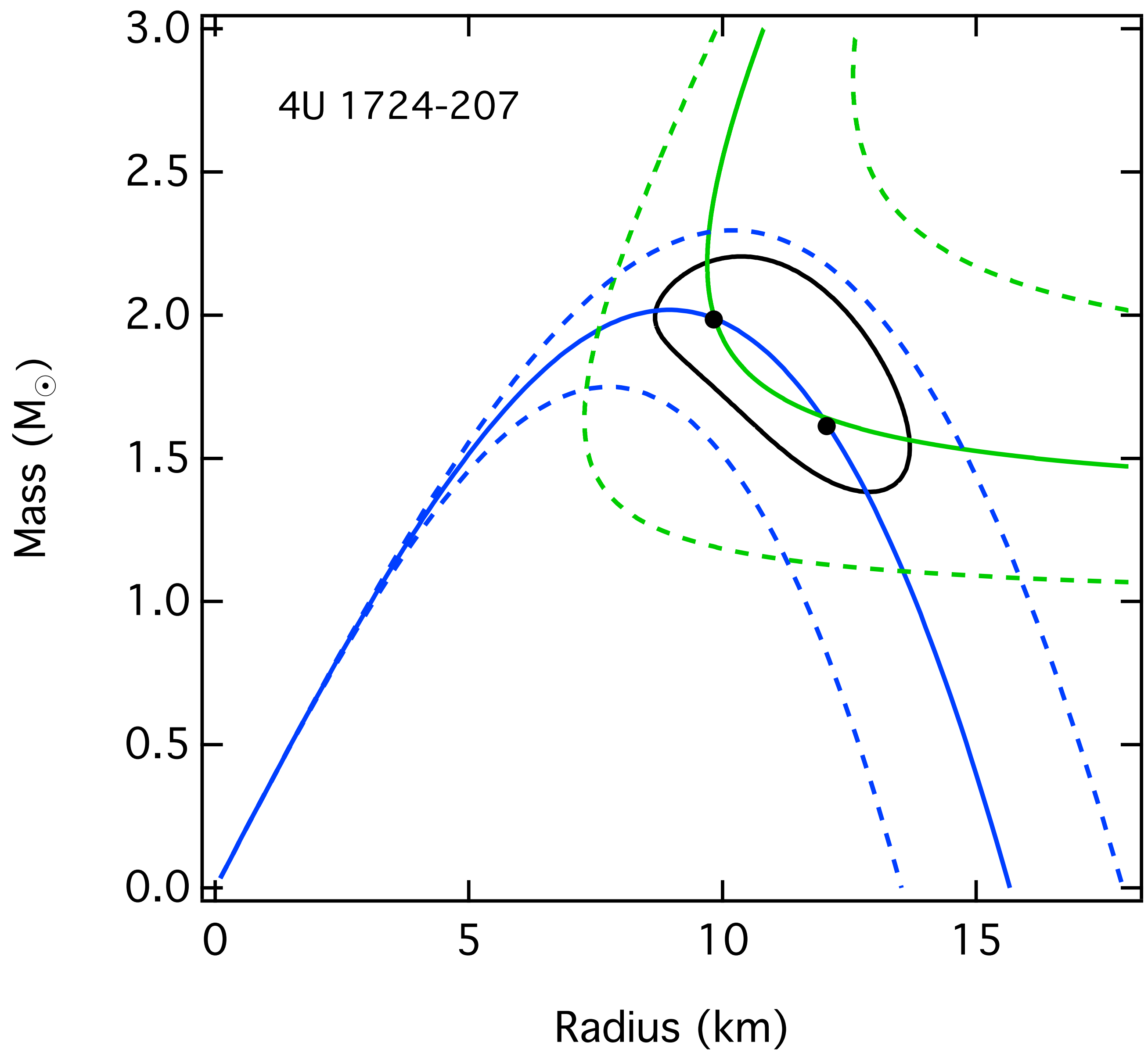
Özel+ 2015, submitted

EXO 1745-248



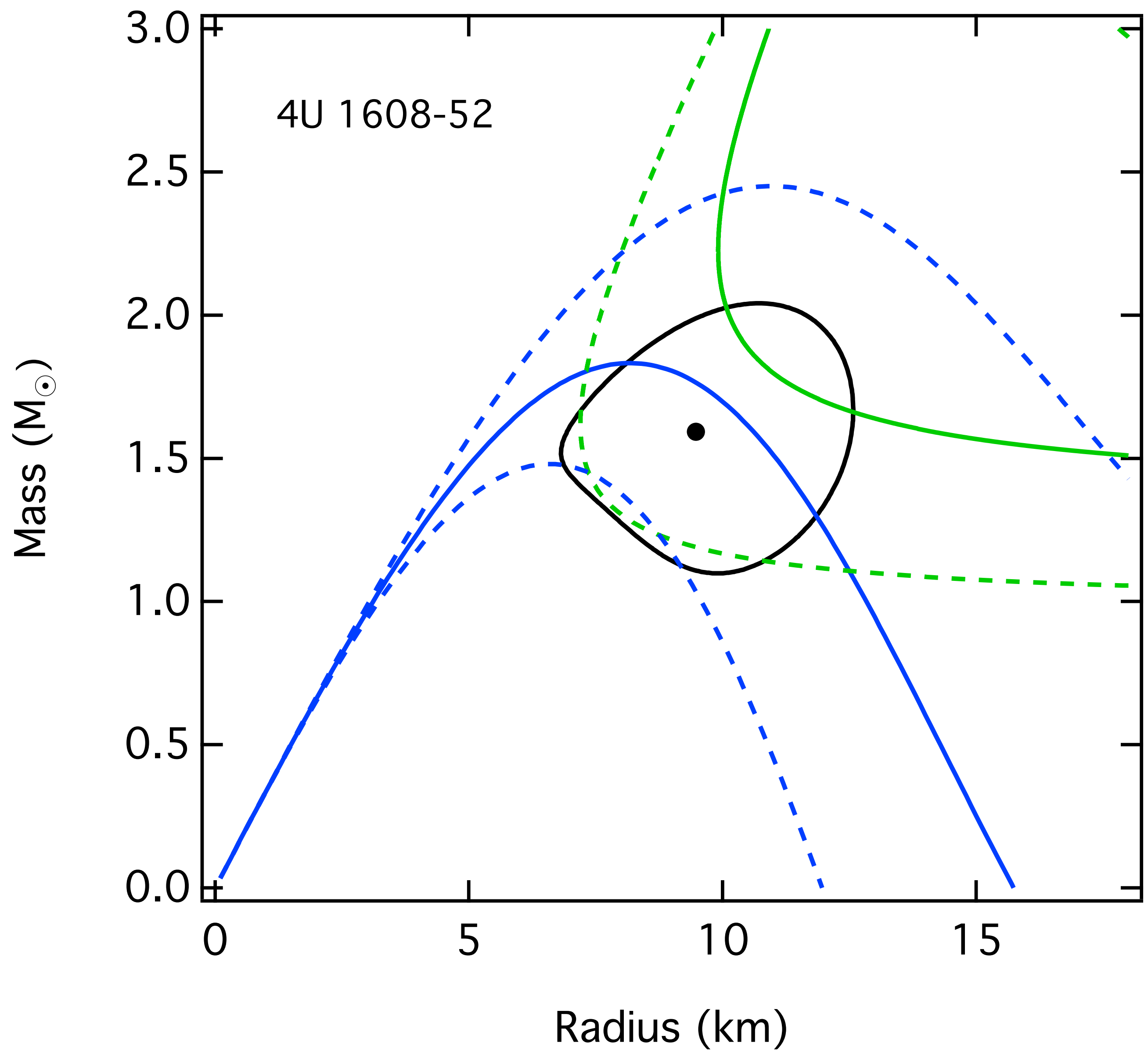
Özel+ 2015, submitted

4U 1724-207



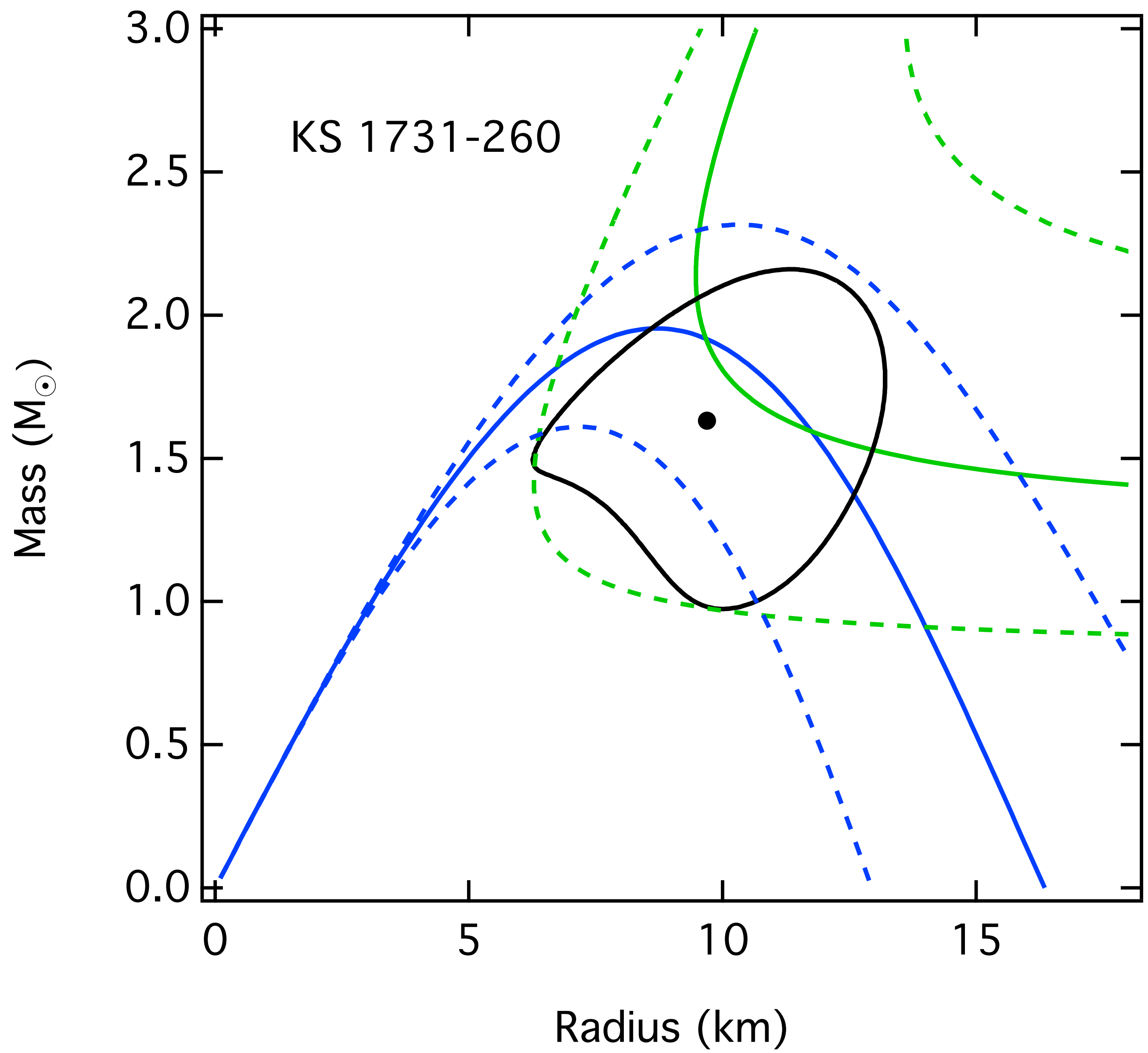
Özel+ 2015, submitted

4U 1608-52



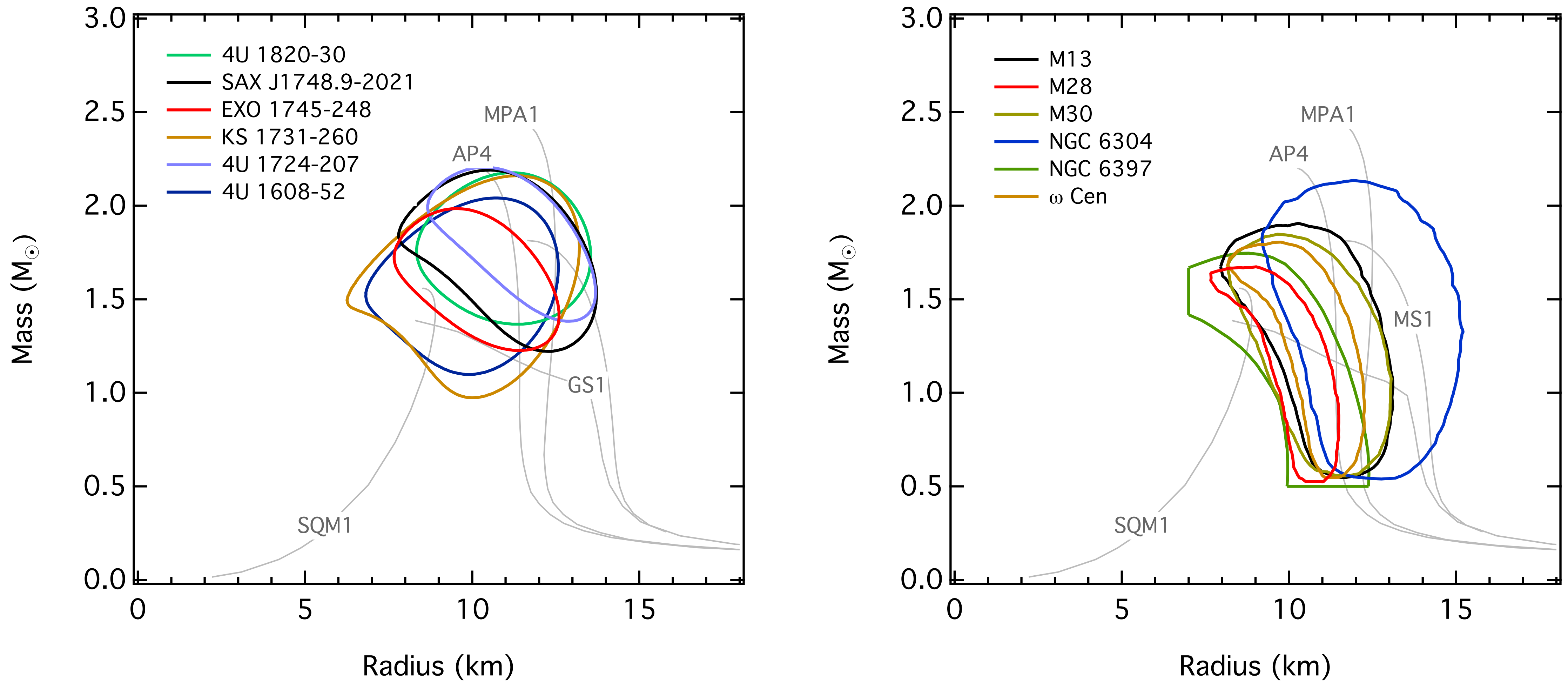
Özel+ 2015, submitted

KS 1731-260



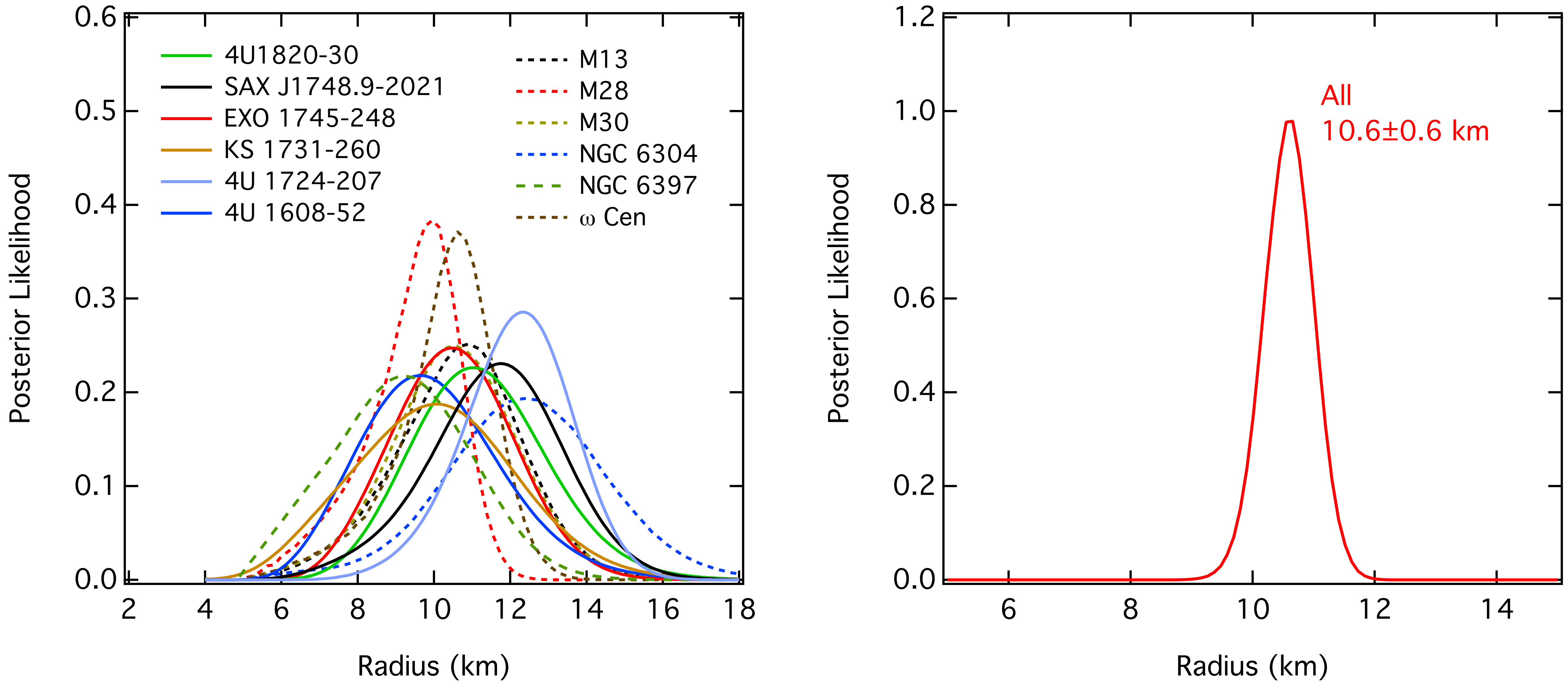
Özel+ 2015, submitted

Comparison with the qLMXBs



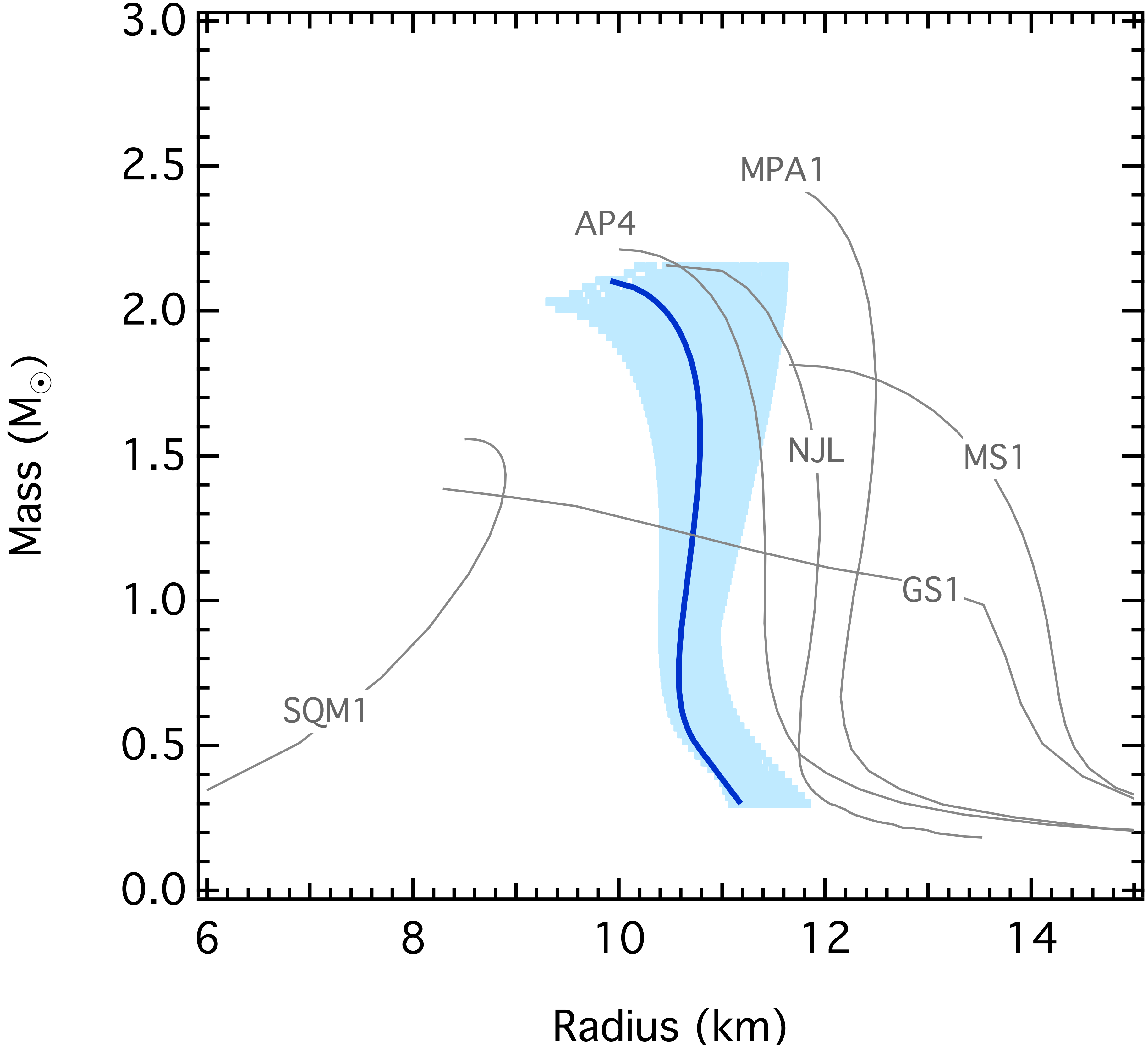
Özel+ 2015, submitted

Radius measurements assuming a mass distribution



Özel+ 2015, submitted

Observational MASS-RADIUS relation from these results



Conclusions

- X-ray bursts offer a unique laboratory to constrain the neutron star masses and radii.

But its complicated !!

- We have a better understanding on the systematic effects in these measurements but our measurements still rely on several assumptions. Independent measurements are necessary to confirm these results.

- Further observations especially in the 0.5 - 25 keV range should be performed and an **archive** like the RXTE/PCA has should be established.

COSPAR

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