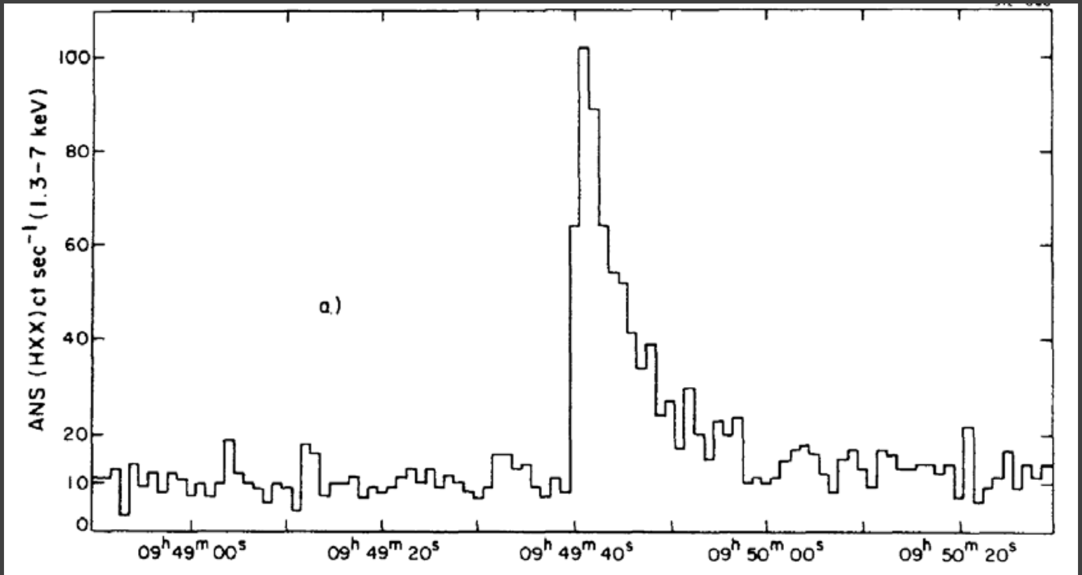
Neutron star cooling and rp features in the tails of X-ray bursts

(MINBAR spin-off)

Jean in 't Zand , Tullio Bagnoli , Jérôme Chenevez, Andrew Cumming, Duncan Galloway, Laurens Keek, Erik Kuulkers, Celia Sánchez-Fernández, Hauke Wörpel, Roger Mateijsen, Thomas Triemstra, Maaike Visser (2014, 2017)

Motivation



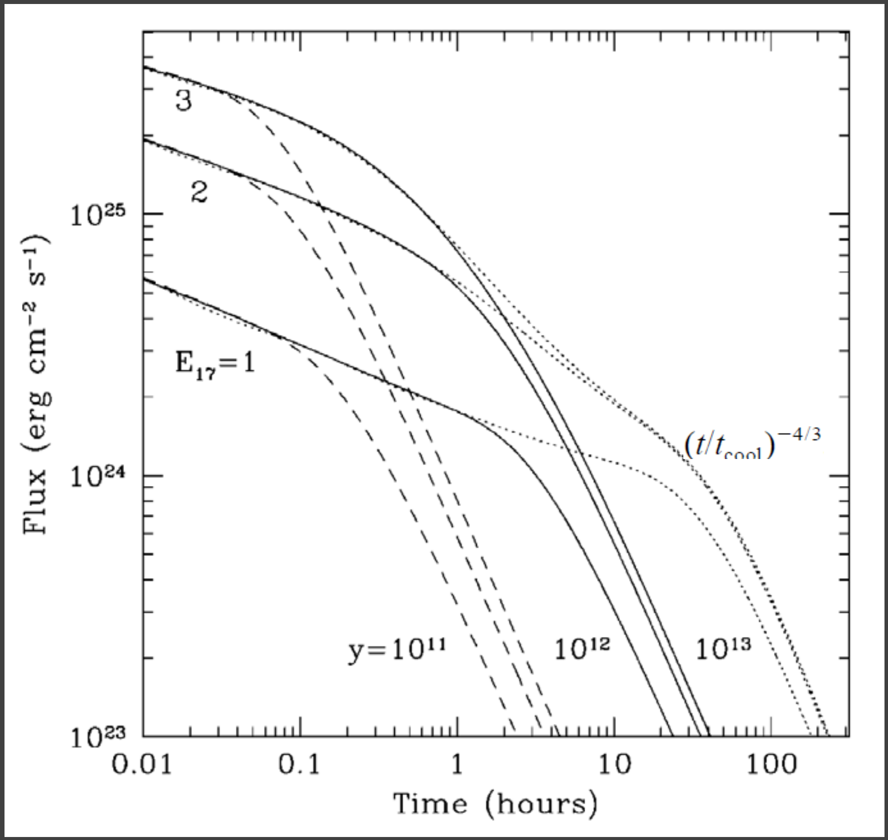
Everybody fits exponentials to burst decays.

Is that justified?

Are there better functions?

Motivation

- Cumming & Macbeth (2004) and Cumming et al. (2008) fit broken power laws to decays of superbursts and intermediate duration bursts
- What about 'ordinary' bursts?



Simple power law prediction

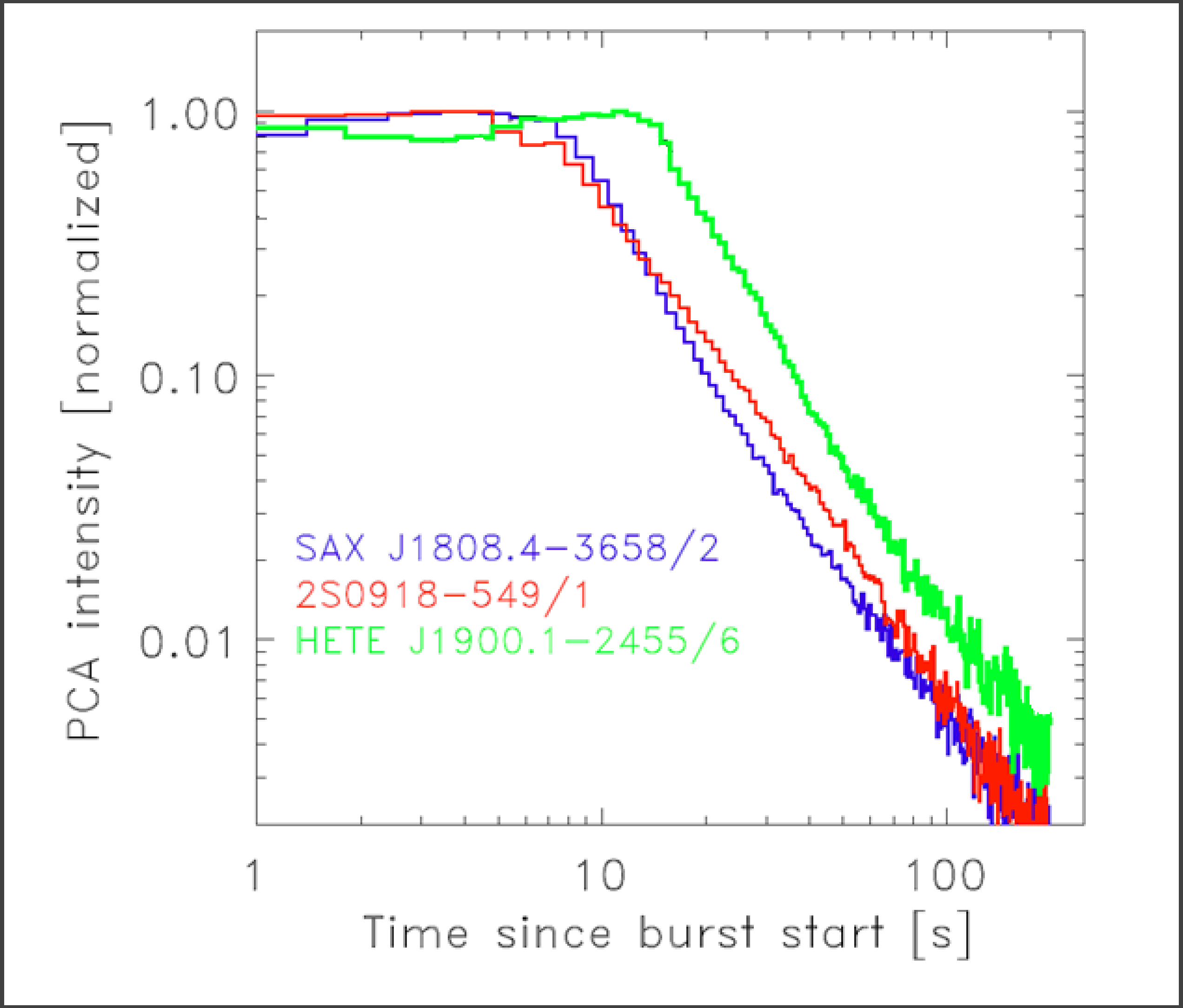
- Heat $Q = m C_p T$
- $dQ/dt = m C_P\ dT/dt = -A \sigma_{SB} T^4 \rightarrow T \propto t^{-1/3}$
- $L = dQ/dt \propto t^{-4/3}$

- Assumptions
  - Instantaneous heating
  - Constant C_p

- If cooling is through conduction →
- $dQ/dt \propto -T$
- $L \propto \exp(-t/tau)$

2014 study – data selection and treatment

- Use best available data: the RXTE subset of MINBAR
- Select those bursts that
  - Show no signs of rp burning → no bumps
  - Show no signs of scattering and obscuration by disk → low-i systems
  - Show no signs of wildly varying accretion rate → no strong and variable pre-burst flux and high peak/persistent flux (generally >50)
  - Add one intermediate duration and one superburst
- Result: 37 bursts out of 2280, from 15 of all kinds of sources, always with fast rise (<2 s) → pure helium flashes, 29 Eddington-limited
- Do time-resolved spectroscopy with a fixed (and faint) persistent spectrum throughout the burst and a Planck function


1.00
0.10
0.01
PCA intensity [normalized]
1
10
100
Time since burst start [s]
SAX J1808.4−3658/2
2S0918−549/1
HETE J1900.1−2455/6

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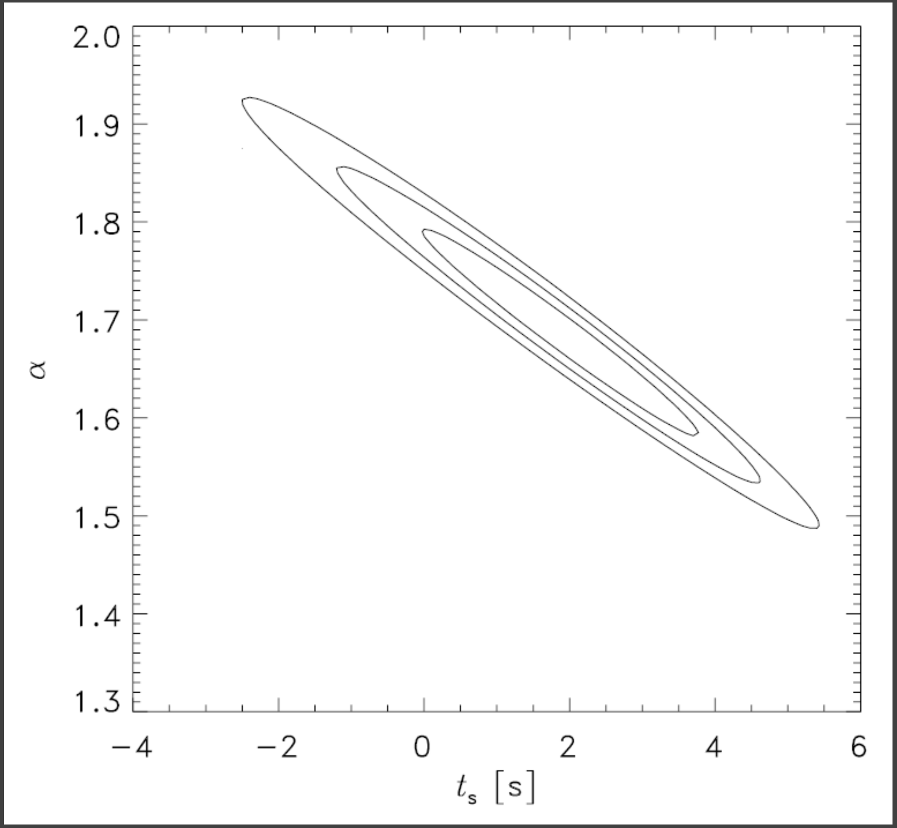
Fit procedure

- Fit exponential $F(t) = F_0 \ e^{-(t-t_0)/\tau} + F_{bg}$
- Fit power law $F(t) = F_0 \left(\frac{t - t_s}{t_0 - t_s} \right)^{-\alpha} + F_{bg}$
- Do it on count rate as well as bolometric flux
- Skip early phases
- Power law tricky function: it diverges at t=0 and the choice of t_s influences measurement of α



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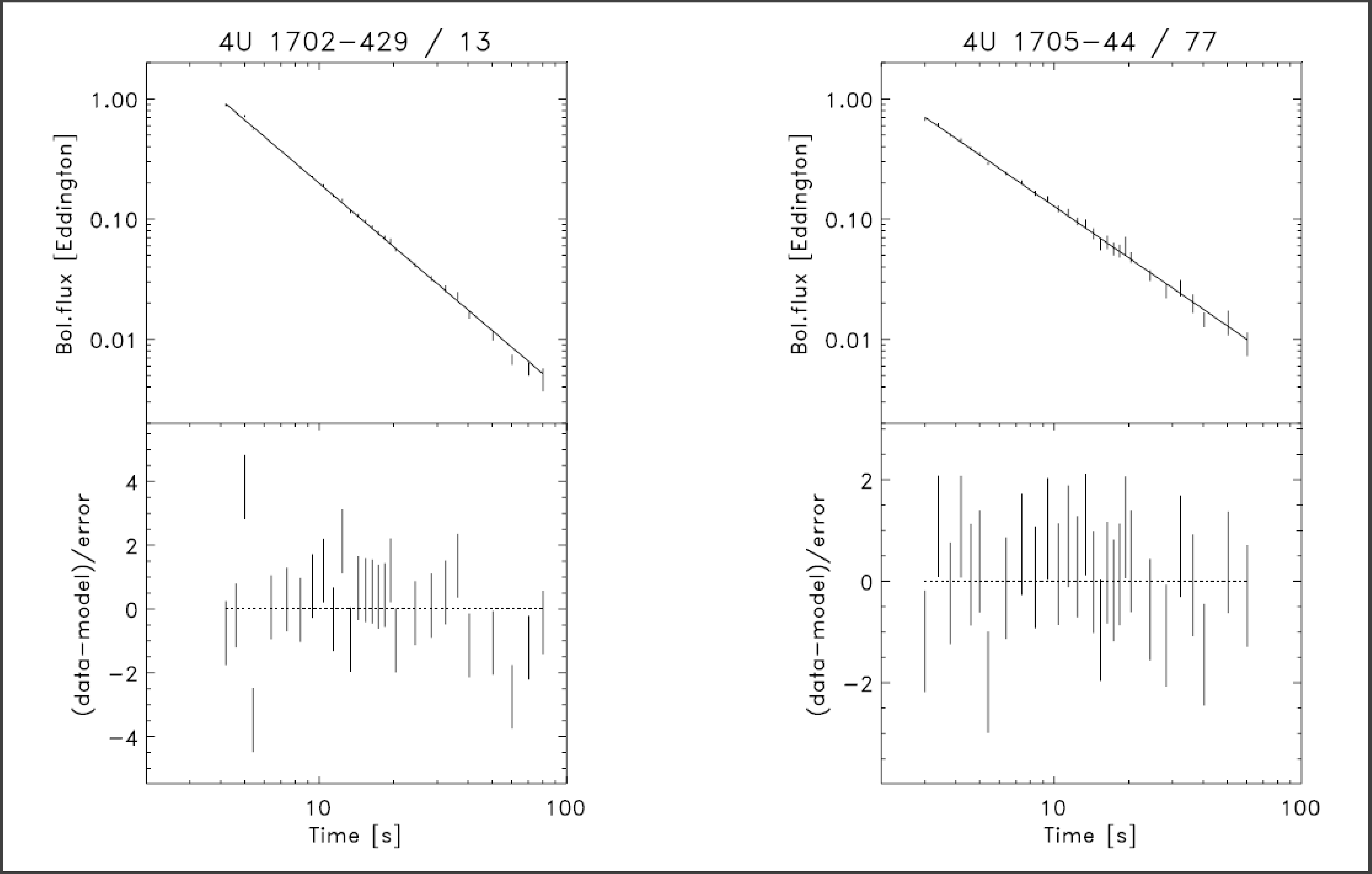
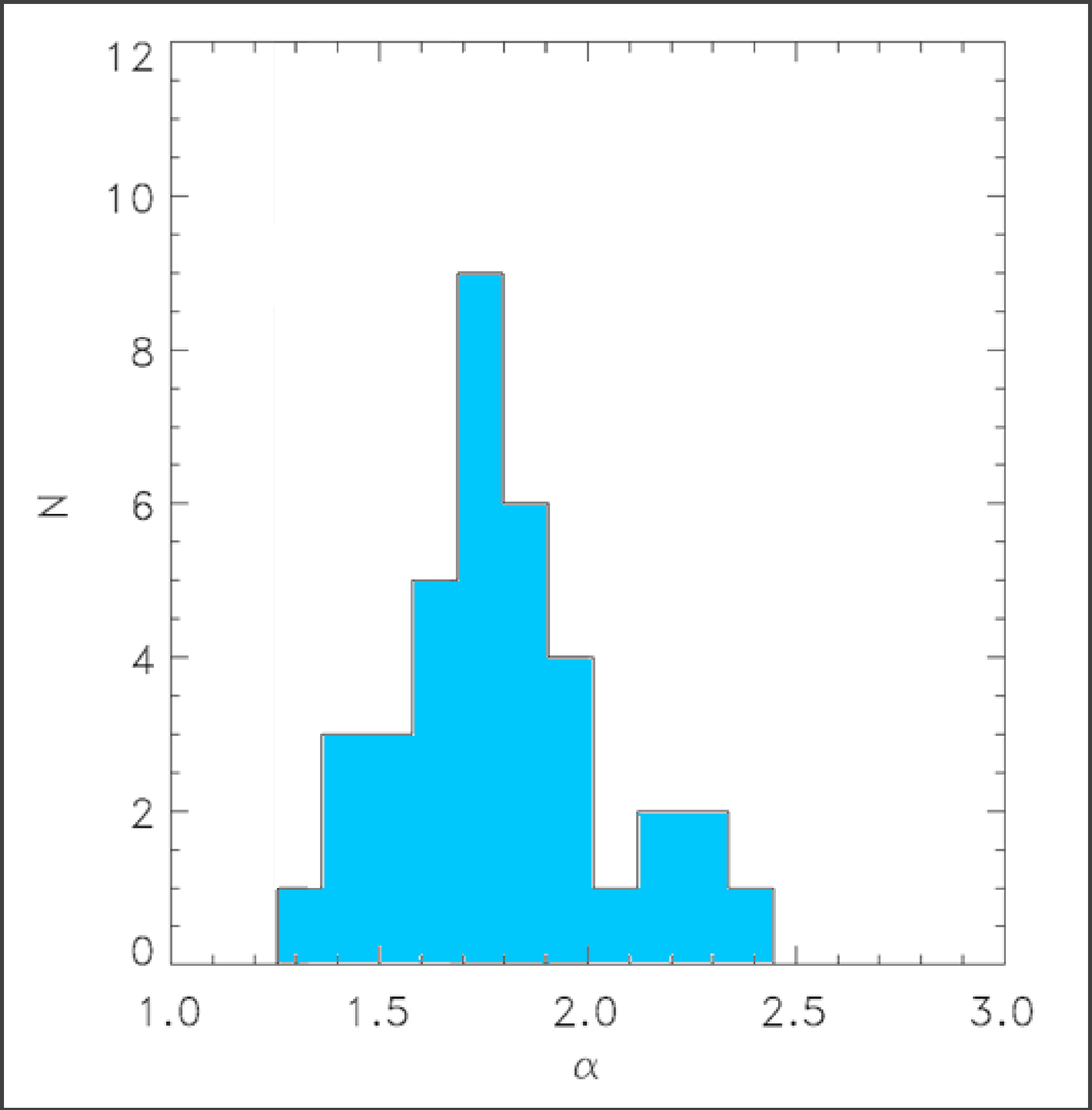
Examples



4U 1702−429 / 13
1.00
0.10
0.01
Bol.flux [Eddington]
4
2
0
−2
−4
(data−model)/error
10
100
Time [s]
4U 1705−44 / 77
1.00
0.10
0.01
Bol.flux [Eddington]
2
0
−2
(data−model)/error
10
100
Time [s]

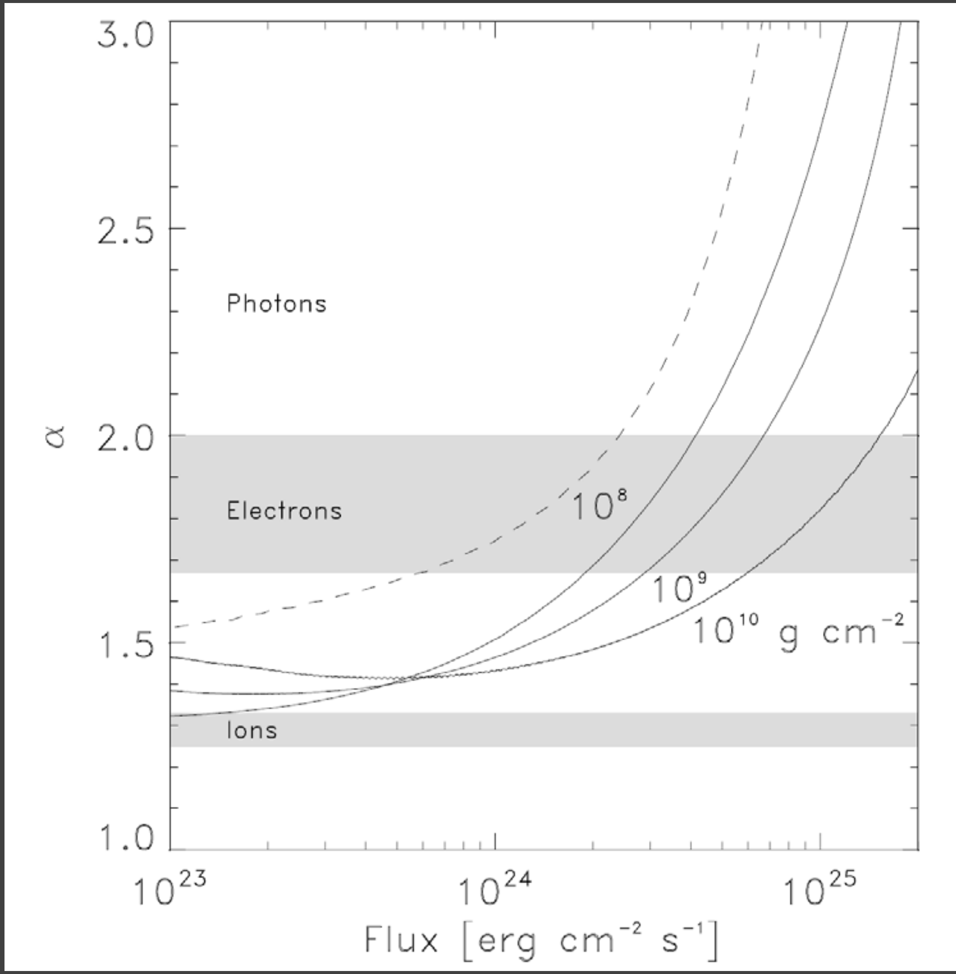
Object	Bu. No.[†]	MJD	R	Photon count rate history[‡]				Bol. flux history[‡]			
				Exponential		Power law		Exponential		Power law	
				τ	χ^2_ν	α	χ^2_ν	τ	χ^2_ν	α	$\chi^{2\S}_\nu$
4U 0512-40*	2	51 324.286947	22.3	13.8	3.0	1.707 ± 0.018	1.15	7.9	14.3	1.439 ± 0.022	0.38
4U 0512-40*	15	54 839.516222	27.7	11.4	2.5	1.715 ± 0.024	0.97	7.7	7.1	1.792 ± 0.042	0.65
2S 0918-549	1	51 676.826588	122.6	19.2	17.7	1.902 ± 0.007	1.41	13.8	65.9	1.832 ± 0.013	1.69
4U 1608-52	8	50 914.274663	86.9	14.7	90.2	1.894 ± 0.004	1.08	14.5	114.9	1.808 ± 0.016	1.74/8.31
4U 1608-52	9	51 612.030846	59.5	10.1	63.2	1.829 ± 0.004	1.49	3.8	1.2	2.141 ± 0.049	2.45
4U 1608-52	10	51 614.071258	111.5	14.0	103.5	1.995 ± 0.003	0.95	9.9	248.8	2.000 ± 0.013	1.05/8.86
4U 1608-52	31	53 104.407932	90.7	17.8	64.5	1.859 ± 0.004	5.14	13.0	256.9	1.869 ± 0.015	2.13/9.52
4U 1636-536	68	52 286.054034	35.5	9.2	10.2	1.681 ± 0.010	1.34	4.9	82.6	1.652 ± 0.011	2.45
4U 1636-536	327	55 394.904042	31.2	12.1	4.9	1.681 ± 0.016	1.06	5.2	43.7	1.592 ± 0.014	1.67
4U 1702-429*	13	51 939.193940	42.9	12.5	12.6	1.816 ± 0.009	1.17	6.1	82.8	1.751 ± 0.009	2.02
4U 1702-429	44	53 212.793589	43.6	12.0	33.4	1.825 ± 0.006	1.43	7.8	106.2	1.874 ± 0.012	1.81/3.00
4U 1705-44*	51	54 046.201890	33.9	12.4	4.4	1.863 ± 0.017	1.46	9.4	17.9	1.801 ± 0.021	0.79
4U 1705-44*	77	55 062.220583	29.8	11.4	2.7	1.807 ± 0.025	1.05	5.7	19.7	1.421 ± 0.017	0.68
4U 1724-30	2	53 058.401400	16.9	11.4	3.0	1.823 ± 0.028	0.96	4.6	28.5	1.651 ± 0.018	0.99
4U 1724-30	3	53 147.218284	27.8	12.9	11.5	1.764 ± 0.014	1.31	5.4	71.1	1.857 ± 0.012	1.19
4U 1728-34	76	51 657.203264	33.0	8.1	93.1	1.786 ± 0.006	2.19	6.7	76.1	1.781 ± 0.011	1.18
4U 1728-34	126	54 120.25887	29.6	7.6	68.4	1.784 ± 0.007	2.02	6.4	67.0	1.835 ± 0.010	1.00
IGR J17511-3057*	10	55 099.313613	43.3	12.4	3.9	2.303 ± 0.026	1.09	10.2	14.2	2.320 ± 0.033	1.89
IGR J17511-3057*	12	55 101.289836	47.4	12.4	3.6	2.134 ± 0.028	1.40	9.8	7.9	2.065 ± 0.031	2.05
SAX J1808.4-3658	2	52 564.305146	63.8	25.2	13.8	1.820 ± 0.010	1.57	20.4	32.6	1.789 ± 0.023	1.27
SAX J1808.4-3658	3	52 565.184268	74.8	24.9	27.0	1.896 ± 0.008	2.39	22.0	50.3	1.814 ± 0.050	0.88/6.50
SAX J1808.4-3658	4	52 566.426770	82.8	27.0	22.9	1.984 ± 0.008	1.93	17.0	113.1	1.961 ± 0.033	1.75/9.30
SAX J1808.4-3658	6	53 526.638240	76.5	29.1	18.6	1.868 ± 0.010	2.20	17.0	71.6	1.954 ± 0.048	0.67/6.27
SAX J1808.4-3658	7	54 732.708128	95.0	30.2	8.2	2.089 ± 0.017	1.78	16.4	53.3	2.231 ± 0.041	2.67/8.13
SAX J1808.4-3658	9	55 873.916348	79.7	25.3	24.1	1.903 ± 0.008	1.45	19.1	40.8	1.739 ± 0.029	4.22/10.34
SAX J1810.8-2609	3	54 590.729819	62.5	11.2	13.6	1.833 ± 0.010	1.14	11.6	9.2	1.633 ± 0.029	1.24
4U 1820-30	5	53 277.438562	13.3	6.4	5.4	2.002 ± 0.016	3.33	5.4	25.5	1.991 ± 0.020	0.75
4U 1820-30	12	54 981.187286	15.1	5.2	14.3	1.901 ± 0.011	5.28	7.2	27.0	1.885 ± 0.021	2.09
HETE J1900.1-2455	3	54 506.856149	56.1	11.4	30.3	2.155 ± 0.007	3.22	7.9	100.9	2.276 ± 0.015	1.74/3.01
HETE J1900.1-2455	5	54 925.796423	72.2	14.7	16.5	1.858 ± 0.008	1.31	9.8	46.6	1.727 ± 0.015	1.77
HETE J1900.1-2455	6	55 384.878220	86.5	14.7	38.2	2.216 ± 0.007	2.99	9.3	137.4	2.404 ± 0.015	6.31/11.16
HETE J1900.1-2455	7	55 459.228637	59.3	11.3	50.1	2.234 ± 0.005	3.59	9.3	201.6	2.289 ± 0.014	3.71/11.09
Aql X-1	11	51 336.590743	64.8	11.0	25.8	1.802 ± 0.007	1.18	12.3	14.2	1.531 ± 0.027	1.73
Aql X-1	25	52 100.799520	56.2	8.5	45.5	1.836 ± 0.005	1.25	14.5	14.3	1.641 ± 0.026	1.01
Aql X-1	64	54 259.247877	162.5	24.6	67.7	2.078 ± 0.004	2.56	21.6	108.3	1.904 ± 0.044	0.26/6.64
2S 0918-549	5	54 504.126944	158.8	110.6	3.4	1.372 ± 0.007	1.79	99.3	3.9	1.516 ± 0.005	1.47
4U 1636-536*	sb	51 962.702961	5.2	4387.1	1.5	1.428 ± 0.004	1.23	4879	5.0	1.321 ± 0.004	1.59

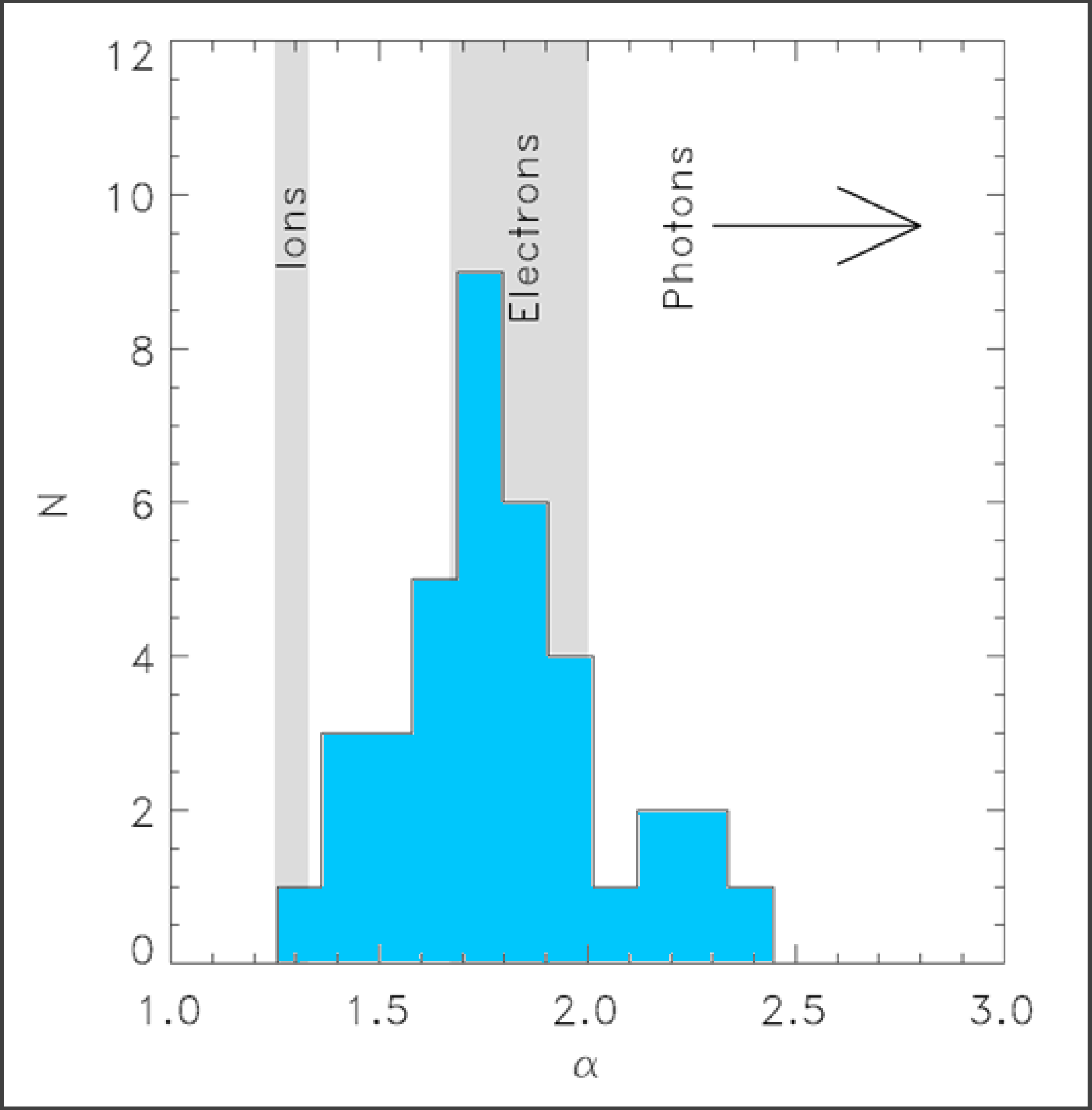

12
10
8
6
4
2
0
N
1.0
1.5
2.0
2.5
3.0
α

Not quite a 4/3 decay index..

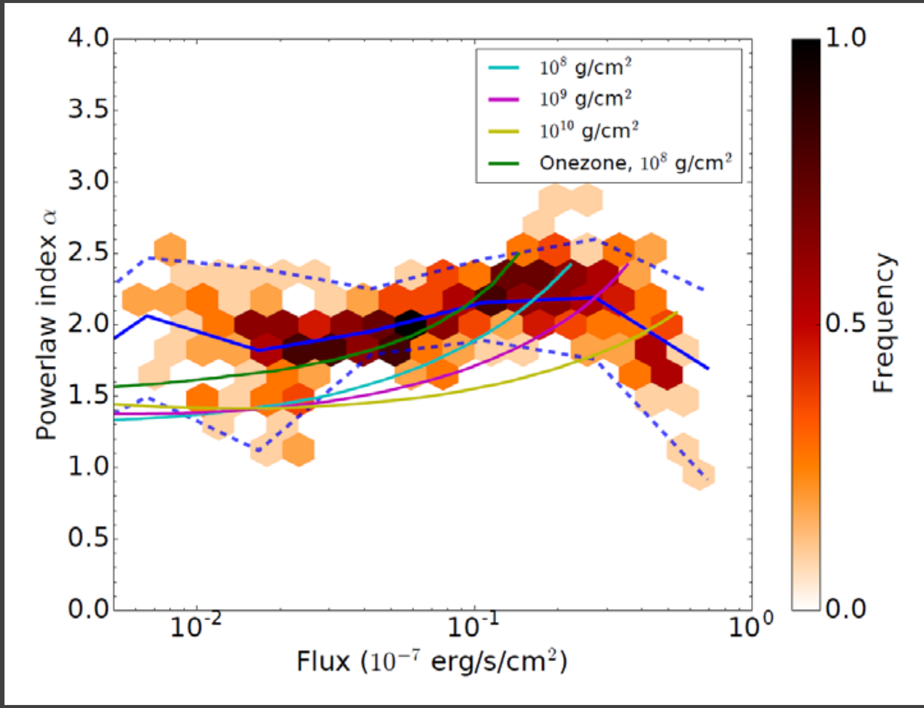
- Cooling is not everywhere (:) T^4 but L (:) T^{gamma} with gamma=4-5

- Cp is not always constant:
- Ions → ideal →
  Constant C_P → alpha=1.25-1.33
- Electrons → degenerate →
  C_P (:) T → alpha=1.67-2.0
- Photons →
  C_V (:) T^3 → alpha>2.0




12
10
8
6
4
2
0
N
1.0
1.5
2.0
2.5
3.0
α
Ions
Electrons
Photons

Kuuttila, Nättilä, Sanchéz-Fernandéz, Cumming et al. 2017



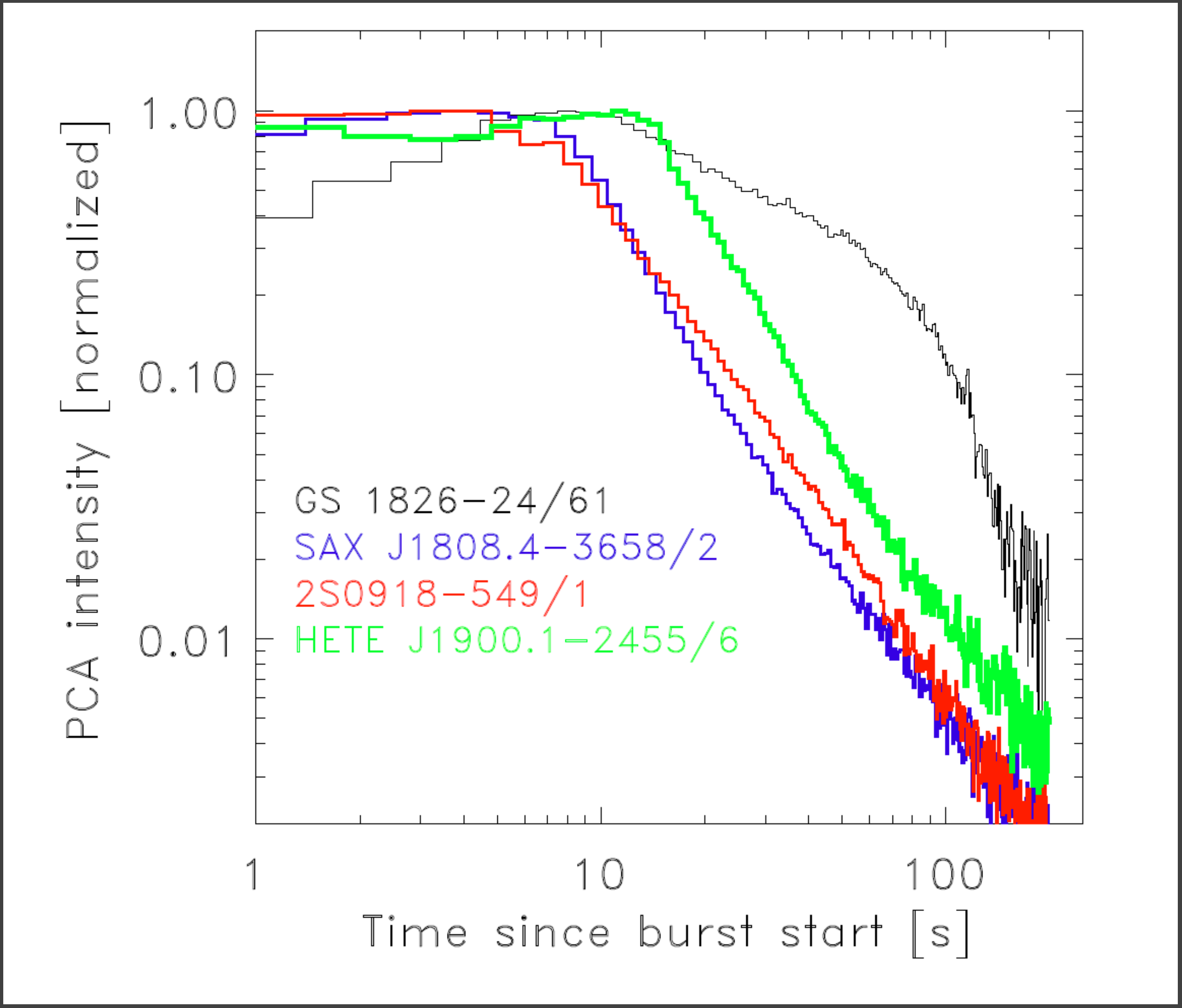
- Determine alpha as a function of time/flux, including data >55%
- Plot data of all bursts per source in one diagram, for 5 sources (2 UCXBs and 3 ordinary LMXBs)
- UCXBs and H-poor bursts reasonably follow some trends

2017 study

- include all 2280 RXTE bursts from the MINBAR project
- Also those which do not show smooth decay
- Include only those 1254 cases with:
  - Good quality (peak flux 5% accurate)
  - Continuous data stretch
- Model spectra with black body and pre-burst model spectrum (disk black body plus power law) with a free normalization ('f_a method') and fixed N_H
- Determine accurately start times of bursts
- Fit with exponential, single power law (2 parameters) and single power law plus half-Gaussian centered at t=0 (4 parameters)

$$F_3(t) = F_3(t_0)\left(\frac{t}{t_0}\right)^{-\alpha_3} + \frac{G}{\sqrt{2\pi}s}\, e^{-\frac{t^2}{2s^2}},$$

- Motivation for Gauss!
- Select bursts with accurate enough decay index (<0.1) and burst fluence (<20%) 1254 → 501


PCA intensity [normalized]
1.00
0.10
0.01
1
10
100
Time since burst start [s]
GS 1826−24/61
SAX J1808.4−3658/2
2S0918−549/1
HETE J1900.1−2455/6

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2280 bursts from 59 sources, select 1254

Source	Numbers a	Numbers b	Source	Numbers a	Numbers b
4U 0513-40	20	17	GX 3+1	3	3
4U 0614+09	1	0	EXO 1745-248	22	18
EXO 0748-676	160	109	4U 1746-37	29	14
4U 0836-429	17	1	IGR J17473-2721	45	41
2S 0918-549	4	1	GRS 1747-312	7	4
4U 1254-69	7	5	SAX J1747.0-2853	27	15
4U 1323-62	40	29	SAX J1748.9-2021	29	29
Cir X-1	13	3	IGR J17480-2446	303	15
4U 1608-52	56	44	IGR J17498-2921	2	0
4U 1636-536	381	302	SAX J1750.8-2900	7	6
MXB 1658-298	26	10	IGR J17511-3057	10	9
XTE J1701-462	3	3	IGR J17597-2201	9	9
4U 1702-429	50	44	SAX J1806.5-2215	4	4
4U 1705-44	94	64	SAX J1808.4-3658	9	7
XTE J1709-267	3	3	XTE J1810-189	8	3
XTE J1710-281	46	9	SAX J1810.8-2609	6	6
IGR J17191-2821	5	5	XTE J1814-338	28	25
XTE J1723-376	3	0	GX 17+2	15	5
4U 1722-30	4	3	4U 1820-303	16	15
4U 1728-34	174	137	GS 1826-24	78	58
MXB 1730-335	127	47	XB 1832-330	1	0
KS 1731-260	27	25	Ser X-1	19	14
SLX 1735-269	1	1	4U 1850-086	1	0
4U 1735-444	23	19	HETE J1900.1-2455	8	8
XTE J1739-285	6	5	Aql X-1	75	54
KS 1741-293	1	0	XB 1916-053	14	10
GRS 1741.9-2853	8	0	XTE J2123-058	6	3
1A 1742-294	87	10	4U 2129+12	6	1
SLX 1744-299/300	24	14	Cyg X-2	70	0
1A 1744-361	3	3			

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$$F_3(t) = F_3(t_0)\left(\frac{t}{t_0}\right)^{-\alpha_3} + \frac{G}{\sqrt{2\pi}s}\,\mathrm{e}^{-\frac{t^2}{2s^2}},$$

- Motivation for Gauss!
- Select bursts with accurate enough decay index (<0.1) and burst fluence (<20%) 1254 → 501

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Caveats

- Force G and s to be positive
- Pre-burst spectra simplified and shape fixed during bursts
- Ignore incidental absorption edges
- Ignore anisotropy
- Ignore oblateness NS
- Ignore deviations from Planck spectrum, should be OK within a few percent for decay index for L>0.1 Ledd

Alternatives

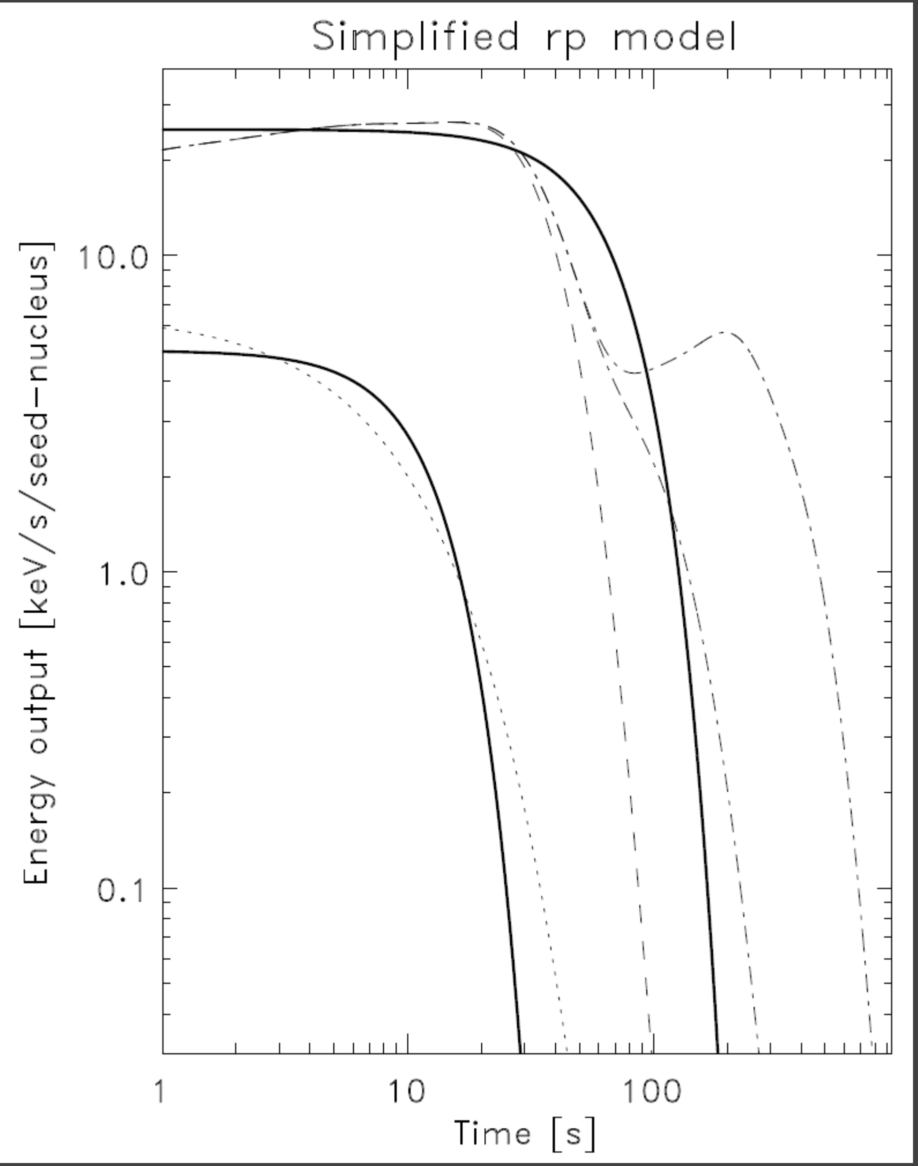
- Leaving free Gaussian centroid results in unconstrained fits
- Broken power law fits no improvement
- Simplified physical model for rp process fits worse

Simplified rp model

- Chain of rp process from Wallace & Woosley 1981 and Schatz 2001
- Decay times and energies from Sakharuk et al. 2006

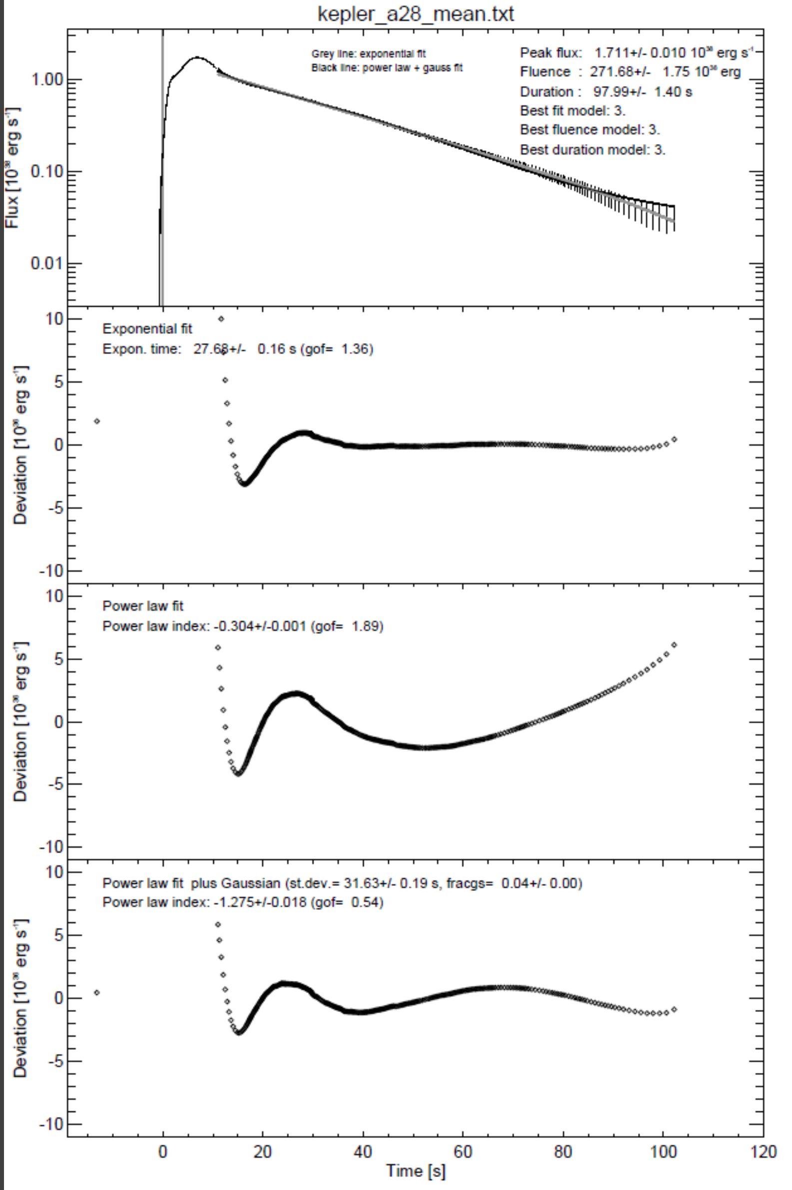
Table A.1. Half-life and energy Q per β^{+} decay.

Isotope	$t_{\frac{1}{2}}$	Q (keV)	Isotope	$t_{\frac{1}{2}}$	Q (keV)
^{21}Mg	5.658	5504.18	^{66}Se	17.328	1818.97
[illegible]Mg	0.180	12 860.3	^{67}Se	6.931	4892.27
^{25}Si	3.180	5514.43	^{68}Se	0.007	8996.11
^{26}Si	0.314	12 816.8	^{71}Kr	7.146	–213.75
^{29}S	3.707	4399	^{74}Sr	1.386	1707.62
^{30}S	0.587	11 050.04	^{75}Sr	0.347	4314.16
^{33}Ar	4.007	4662.76	^{76}Sr	0.139	8745.81
^{34}Ar	0.821	7564.61	^{79}Zr	3.466	4449.44
^{36}K	2.027	1857.63	^{80}Zr	0.693	8011.69
^{37}K	0.568	10 904.68	^{83}Mo	6.931	4136.41
[illegible]Ca	0.806	13 181.45	^{84}Mo	0.693	7063.91
^{42}Ti	3.466	9181.46	^{87}Ru	19.804	3813.97
[illegible]Cr	13.862	4883.08	^{88}Ru	0.693	5083.941
^{46}Cr	2.666	6828.34	^{90}Rh	41.258	4768.94
^{48}Mn	23.104	6234.31	^{92}Pd	0.693	5673.911
[illegible]Fe	6.931	9091.04	^{95}Cd	47.803	3292.97
^{53}Ni	15.403	3854.93	^{96}Cd	0.827	3320.97
[illegible]Ni	6.931	4615.01	^{97}Cd	0.248	7827.497
^{55}Ni	3.667	10 136.09	^{100}Sn	0.737	2679.14
^{58}Zn	6.931	2887.37	^{101}Sn	0.231	3428.97
^{59}Zn	3.301	7887.05	^{102}Sn	0.182	3568.97
^{62}Ge	13.862	2238.67	[illegible]Sn	0.098	4324.97
^{63}Ge	3.466	4855.66	^{104}Sn	0.033	6224.911

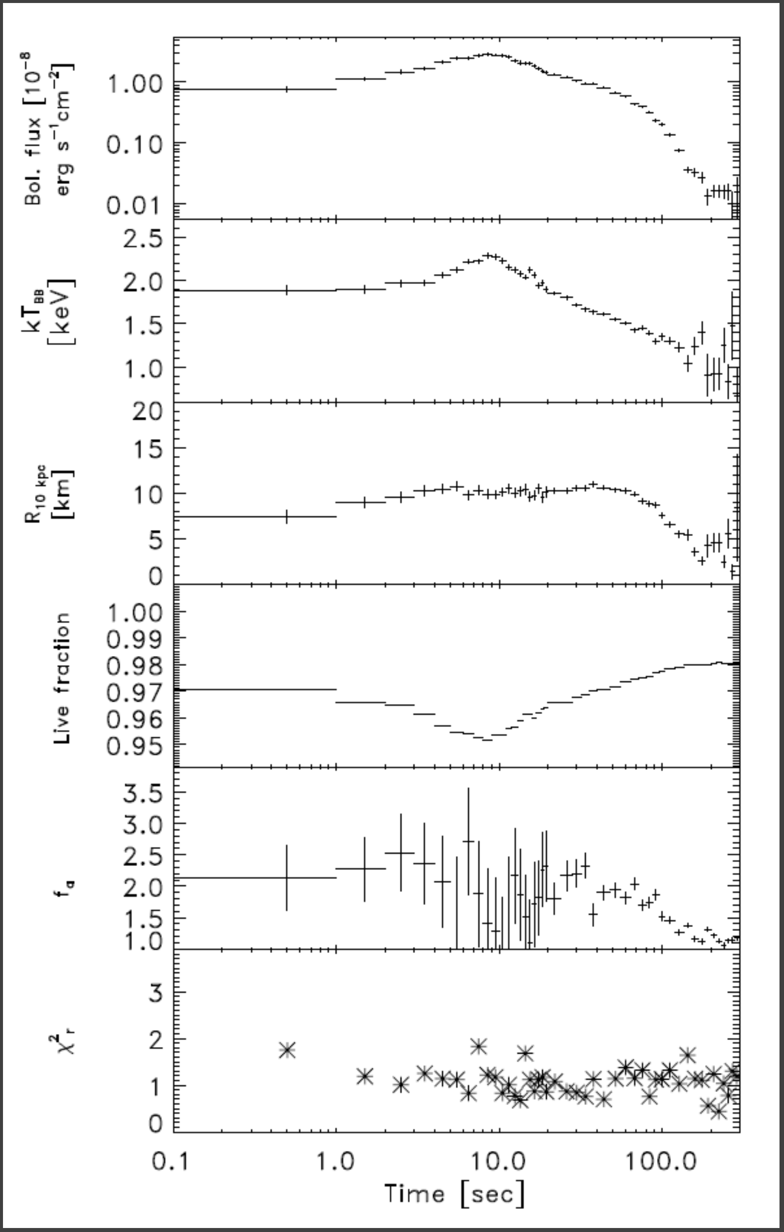


Kepler comparison (Lampe, Heger, Galloway 2016)

- Moderately good
- How good are Kepler light curves?



First things first: spectral modeling



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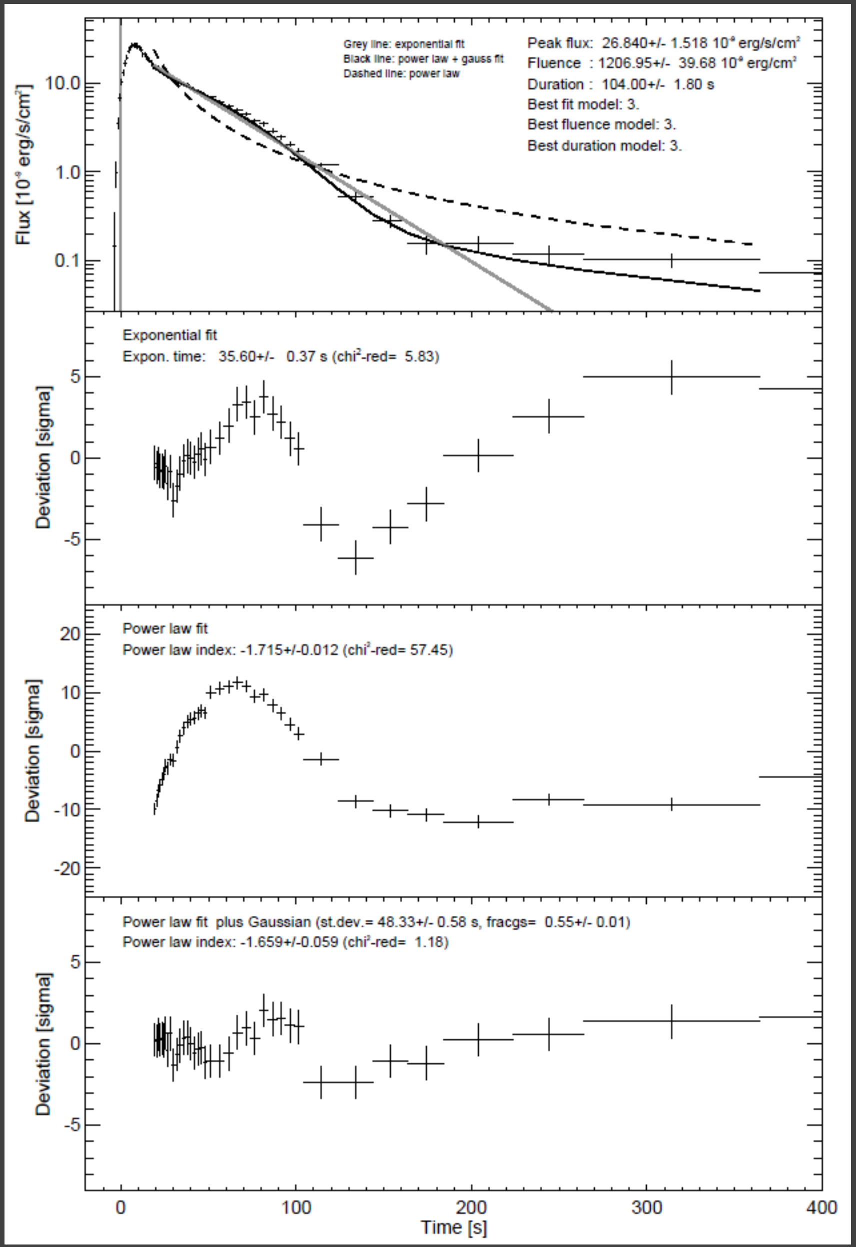
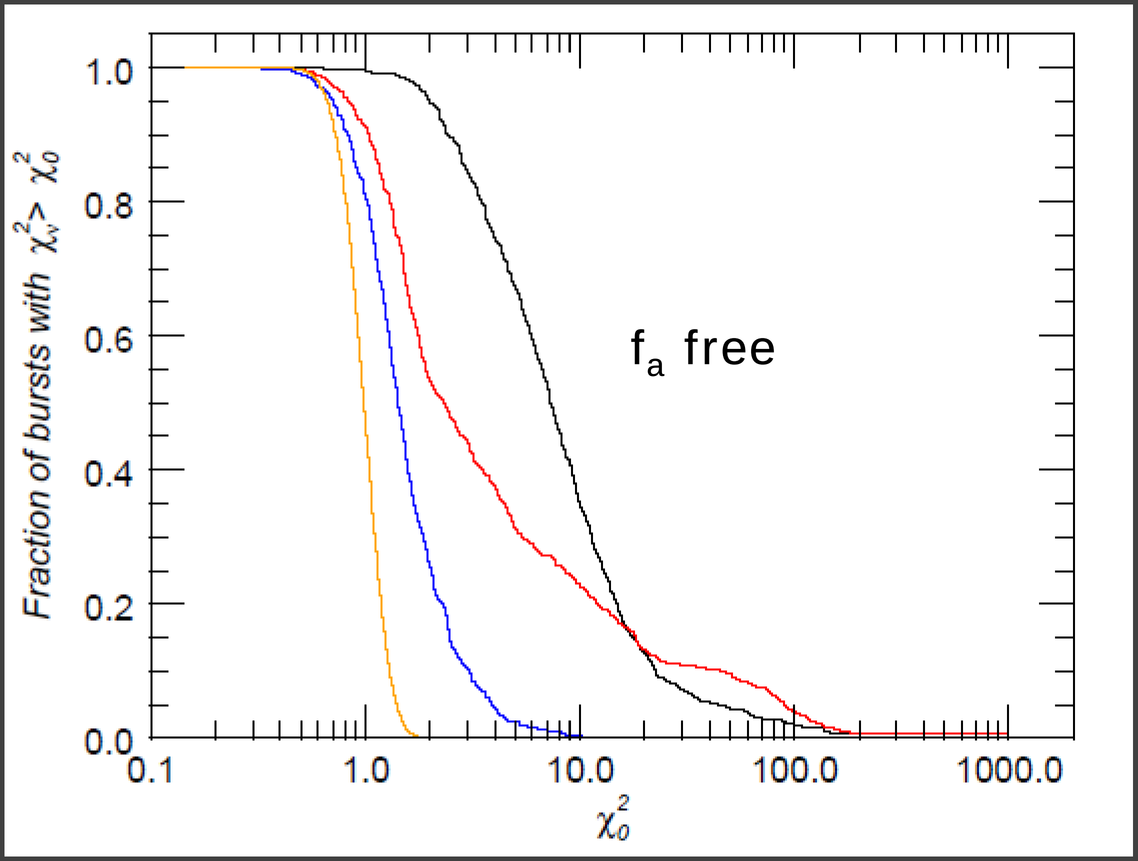
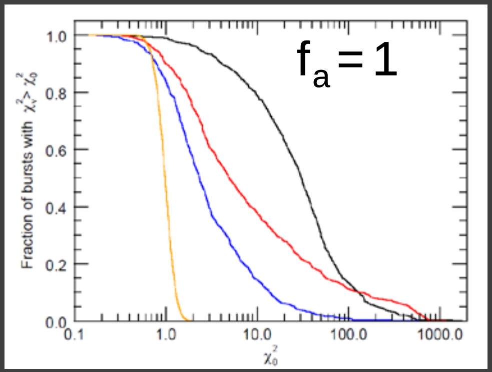
Tryout

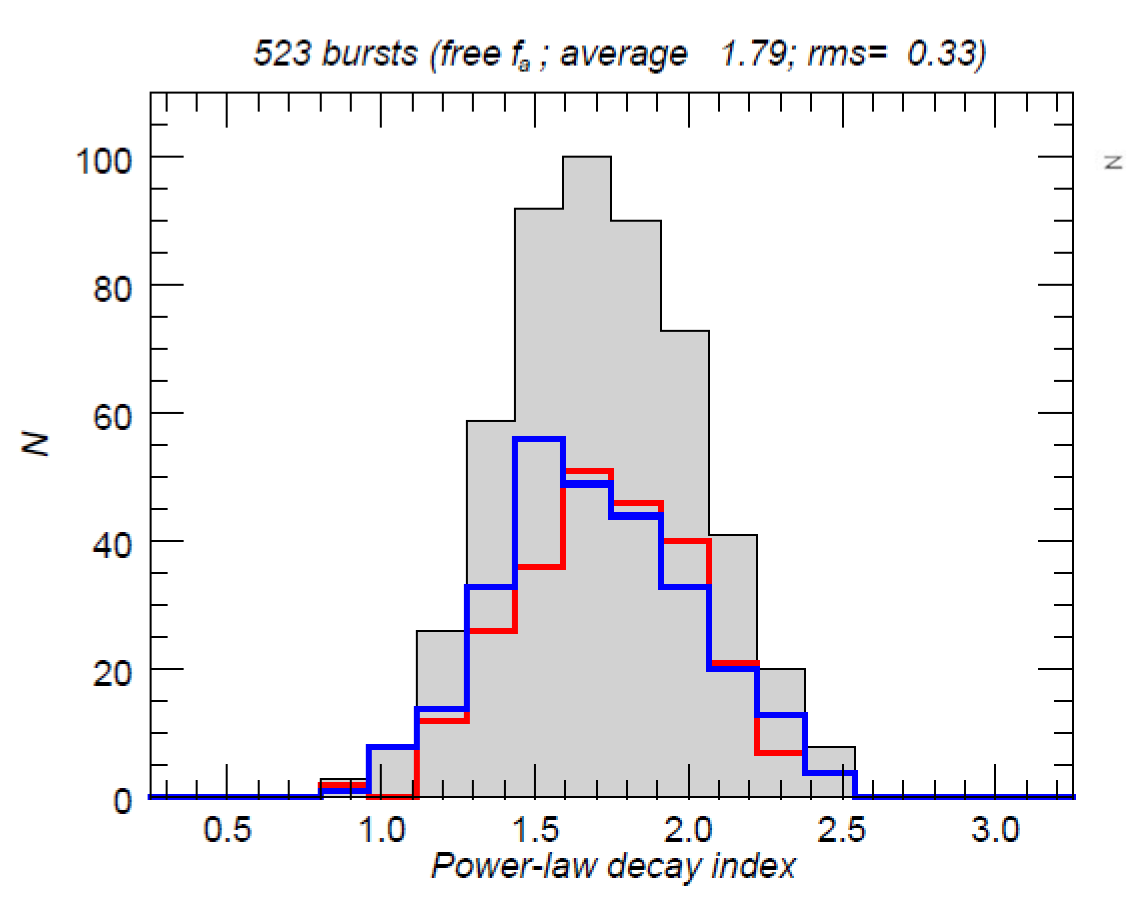


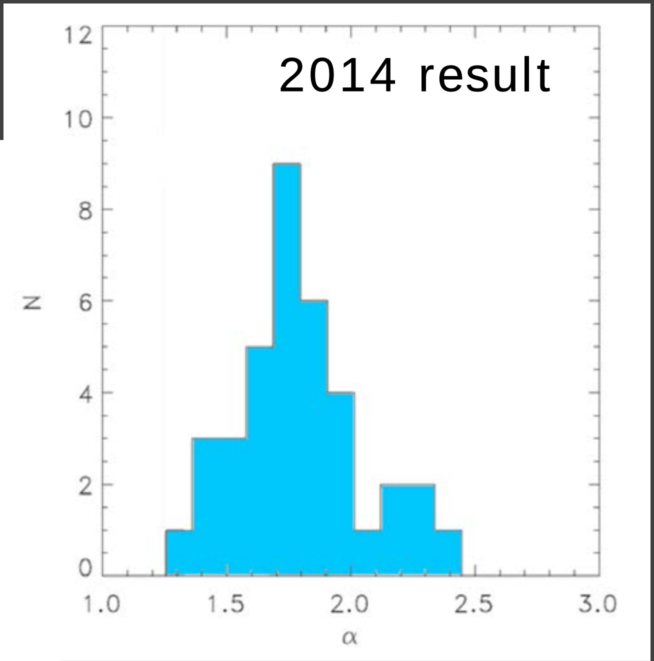
Grey line: exponential fit
Black line: power law + gauss fit
Dashed line: power law
Peak flux: 26.840+/- 1.518 10^9 erg/s/cm^2
Fluence : 1206.95+/- 39.68 10^9 erg/cm^2
Duration : 104.00+/- 1.80 s
Best fit model: 3.
Best fluence model: 3.
Best duration model: 3.
Flux [10^9 erg/s/cm^2]
10.0
1.0
0.1
Exponential fit
Expon. time: 35.60+/- 0.37 s (chi^2-red= 5.83)
Deviation [sigma]
5
0
-5
Power law fit
Power law index: -1.715+/-0.012 (chi^2-red= 57.45)
Deviation [sigma]
20
10
0
-10
-20
Power law fit plus Gaussian (st.dev.= 48.33+/- 0.58 s, fracgs= 0.55+/- 0.01)
Power law index: -1.659+/-0.059 (chi^2-red= 1.18)
Deviation [sigma]
5
0
-5
0
100
200
300
400
Time [s]

Goodness of fit



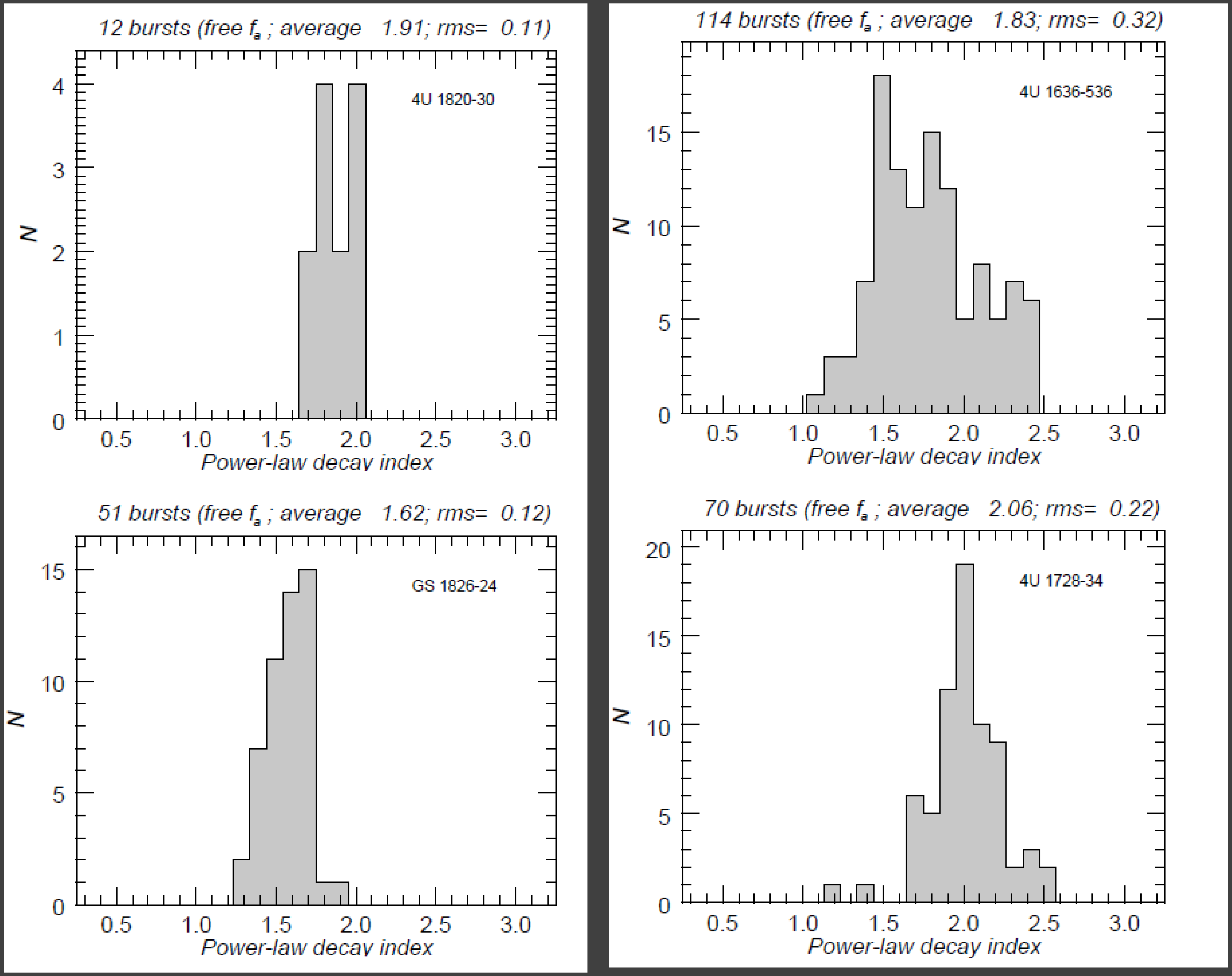



523 bursts (free f_a ; average 1.79; rms= 0.33)
N
100
80
60
40
20
0
0.5
1.0
1.5
2.0
2.5
3.0
Power-law decay index

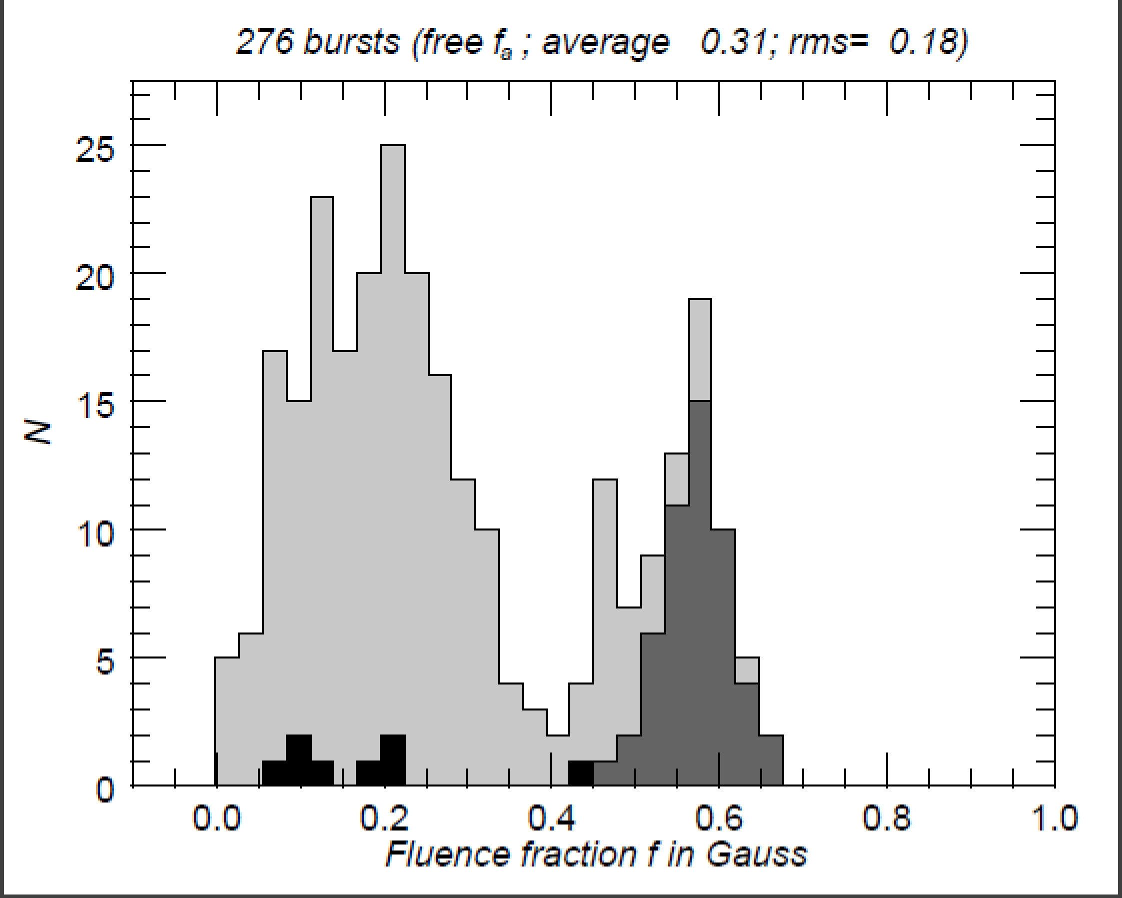

2014 result
12
10
8
6
4
2
0
N
1.0
1.5
2.0
2.5
3.0
α

SRON

Decay indices in individual sources



rp component



$$\frac{5.6X}{5.6X+1.6Y} < 0.65, \text{ so } \frac{X}{Y} < 0.53$$

$$\frac{X}{Y} = 2.6\text{–}2.9$$

For cosmo/solar abundances → suggests H depleted by factor >5

Time scale rp component

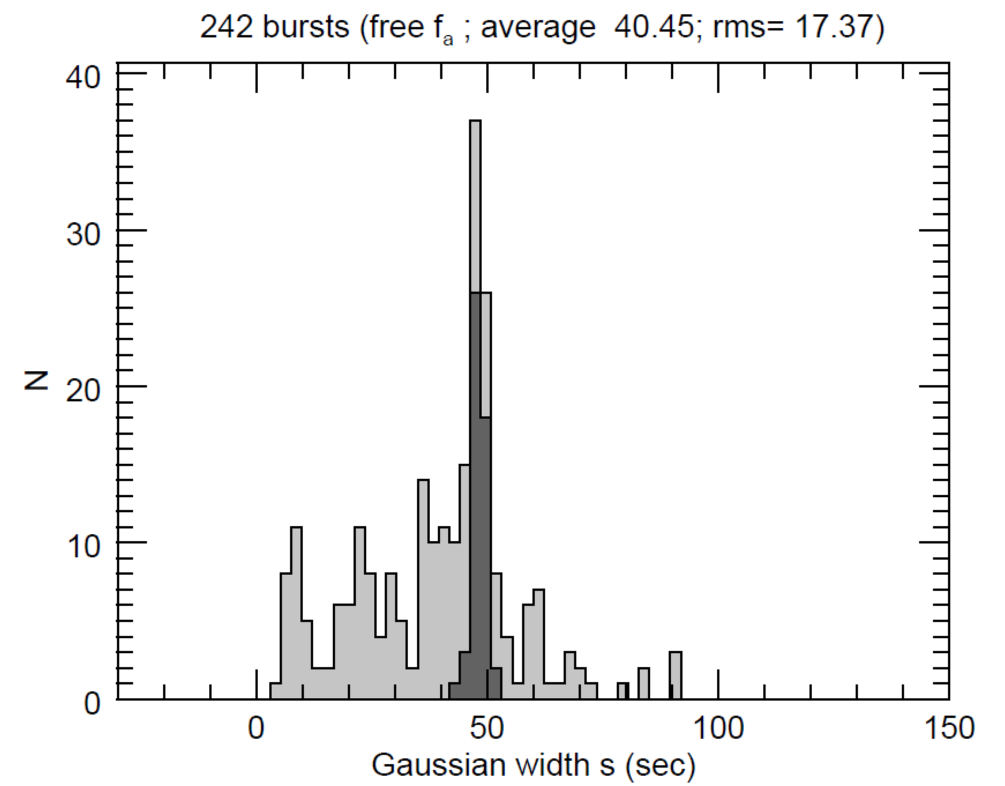
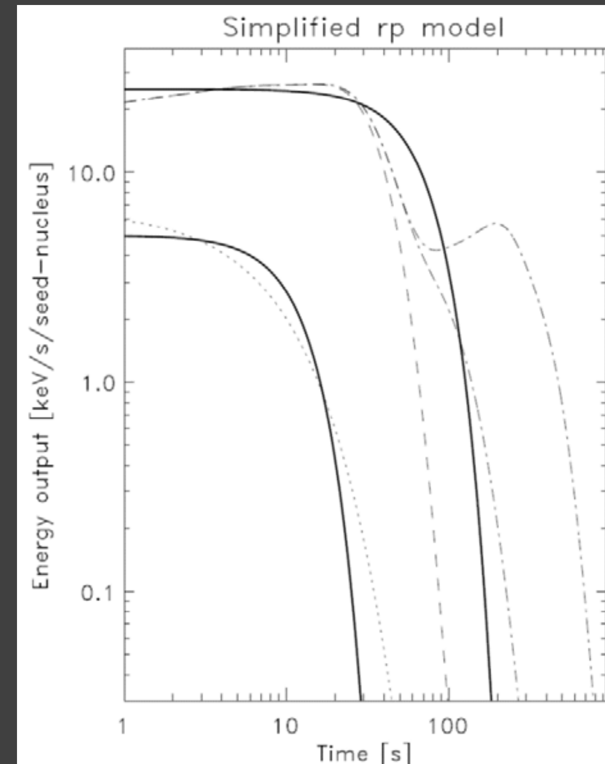


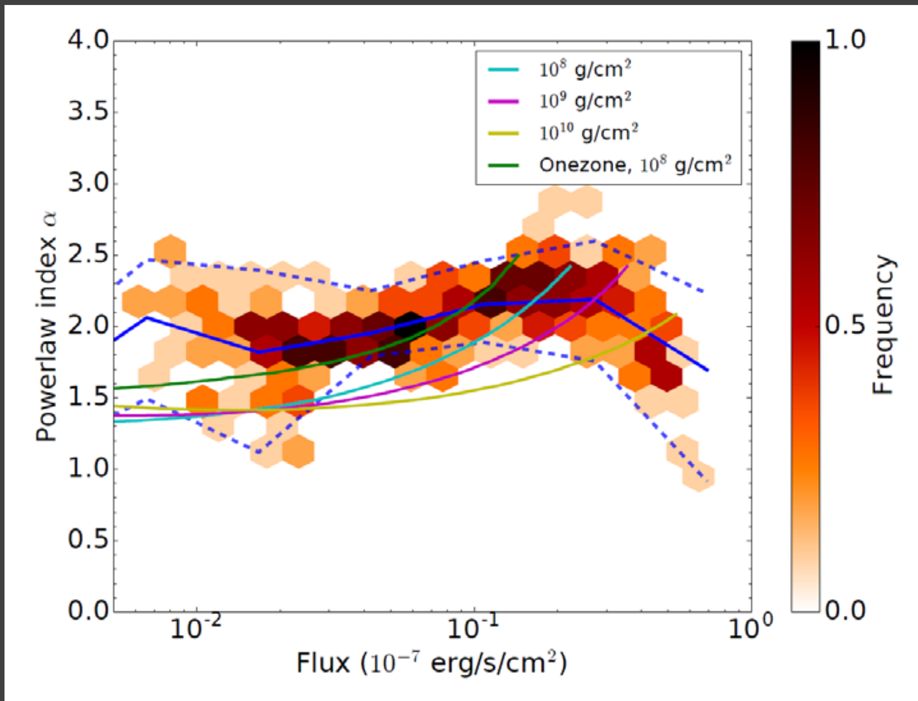
Fig. 7. Histogram of Gaussian width *s*, as found from fitting with Eq. (3). The peak at 48 s is due to bursts from GS 1826-24, as indicated by the dark gray shaded part of the histogram. Note the cutoff at 60–70 s.

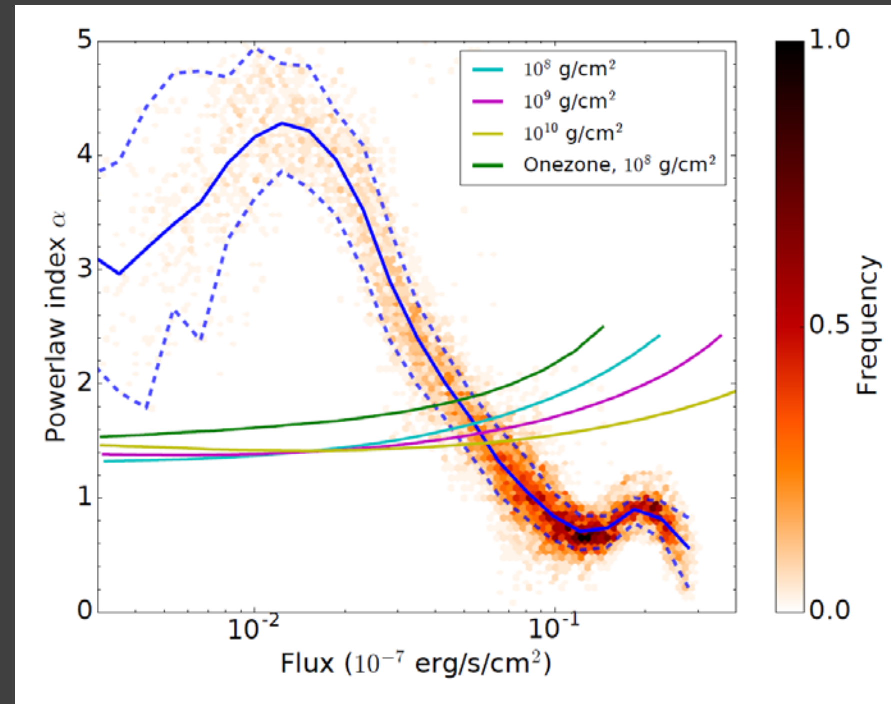


→ up to at least ^{42}Ti for GS 1826-24

→ But not as far for most other bursts

Kuuttila, Nättilä, Sanchéz-Fernandéz, Cumming et al. 2017





- UCXBs and H-poor bursts reasonably consistent with models. Others not → rp
- Lesson: it is not possible to model changing index and rp at the same time

Conclusions

- Decays better described by power law plus one-sided Gaussian than by exponential
- Hydrogen-deficient ultracompact X-ray binaries always lack Gaussian component
- Gaussian representative of rp process
- Decay index
  - Close to constant in each burst
  - Varies between 1.3 to 2.2 from burst to burst, except within GS 1826-24 and 4U 1820-30
  - Independent of being UCXB
  - Probably most strongly depends on ignition depth → m-dot
- No correlation between power law and Gaussian
- GS 18126-24 exceptional case
  - Narrow range
  - Very slowly changing accretion rate (up to 2015)
  - Largest Gaussian component → highest H content

SRON

Thank you