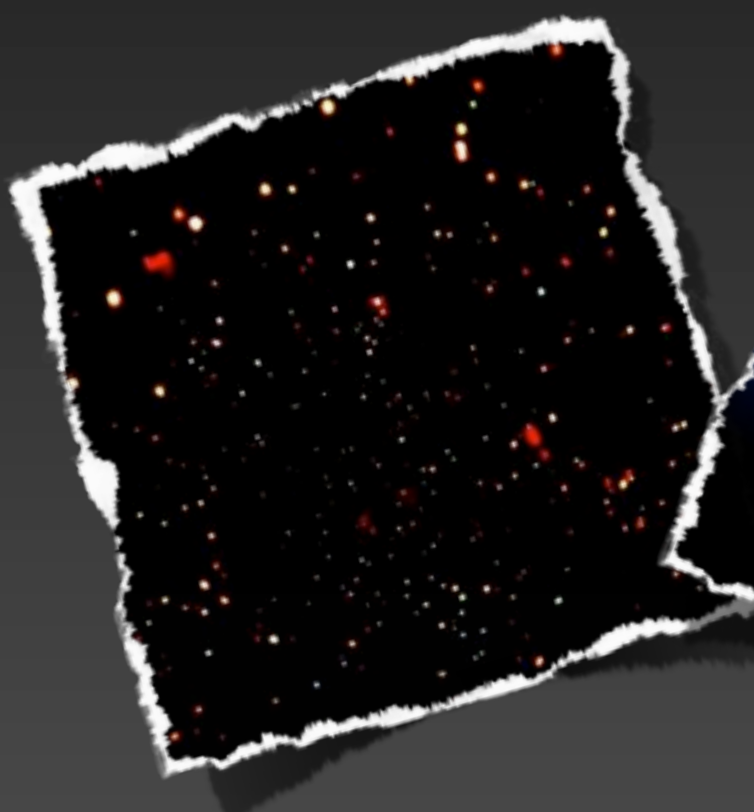
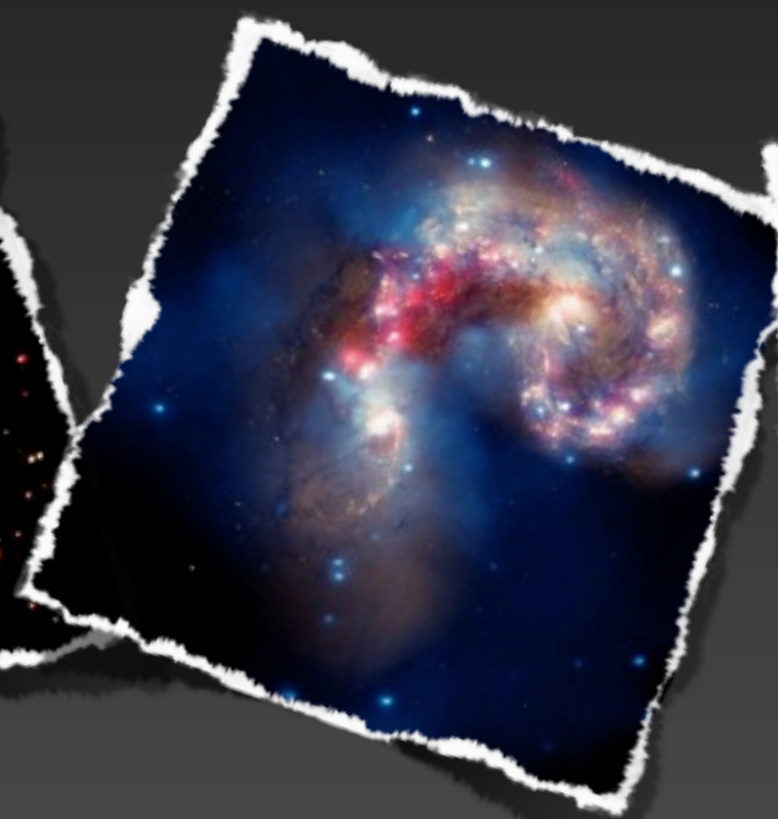
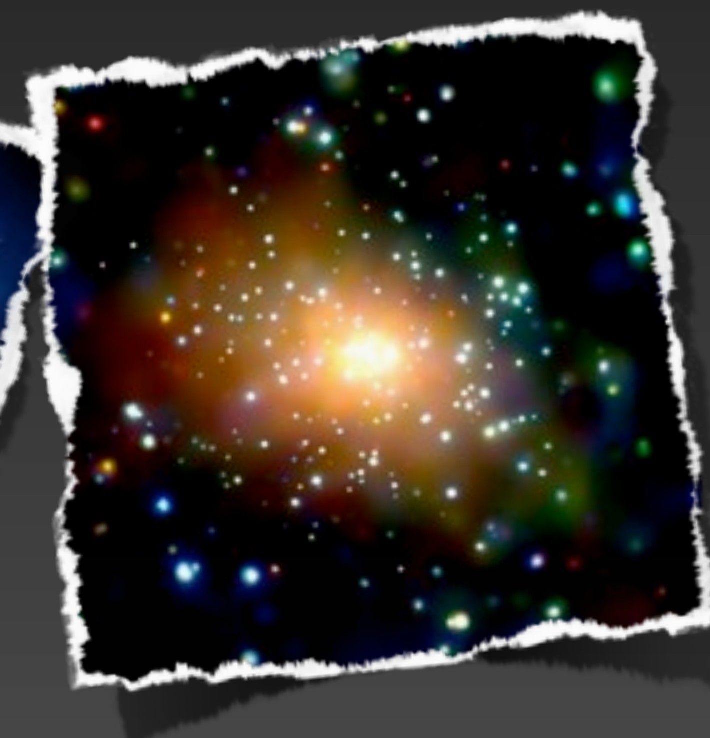
Evolution of X-ray Binaries Across Cosmic Time and Energy Feedback at High Redshift

Tassos Fragos

CfA/ITC Fellow







Harvard-Smithsonian CfA

Institute for Theory and Computation

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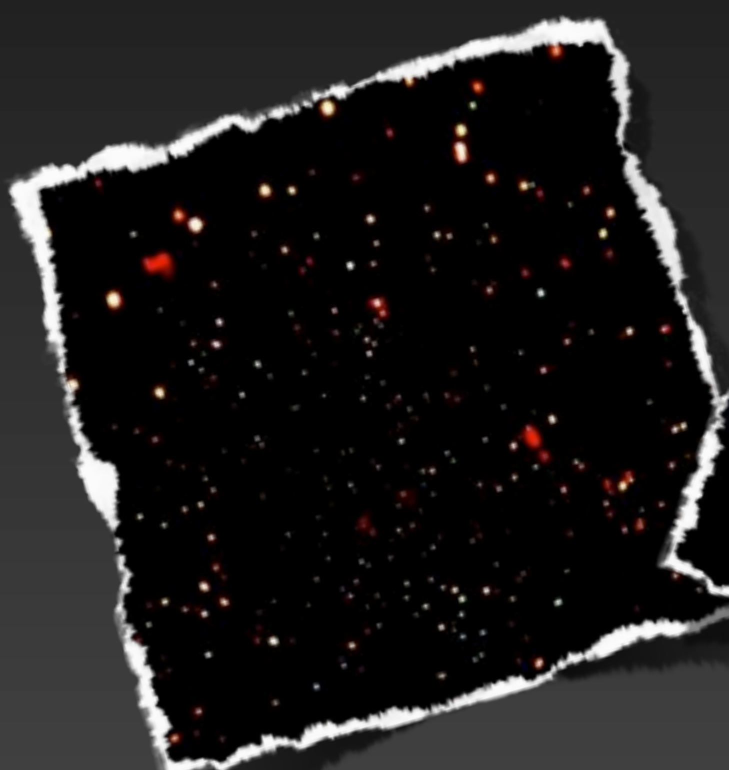

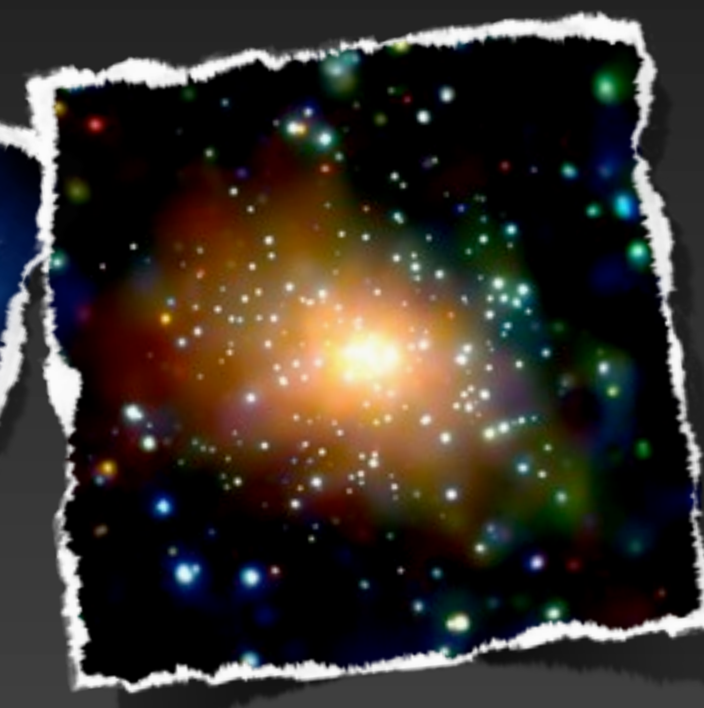

with M. Tremmel, B. Lehmer, P. Tzanavaris, A. Hornschemeier, V. Kalogera A. Zezas, K. Belczynski

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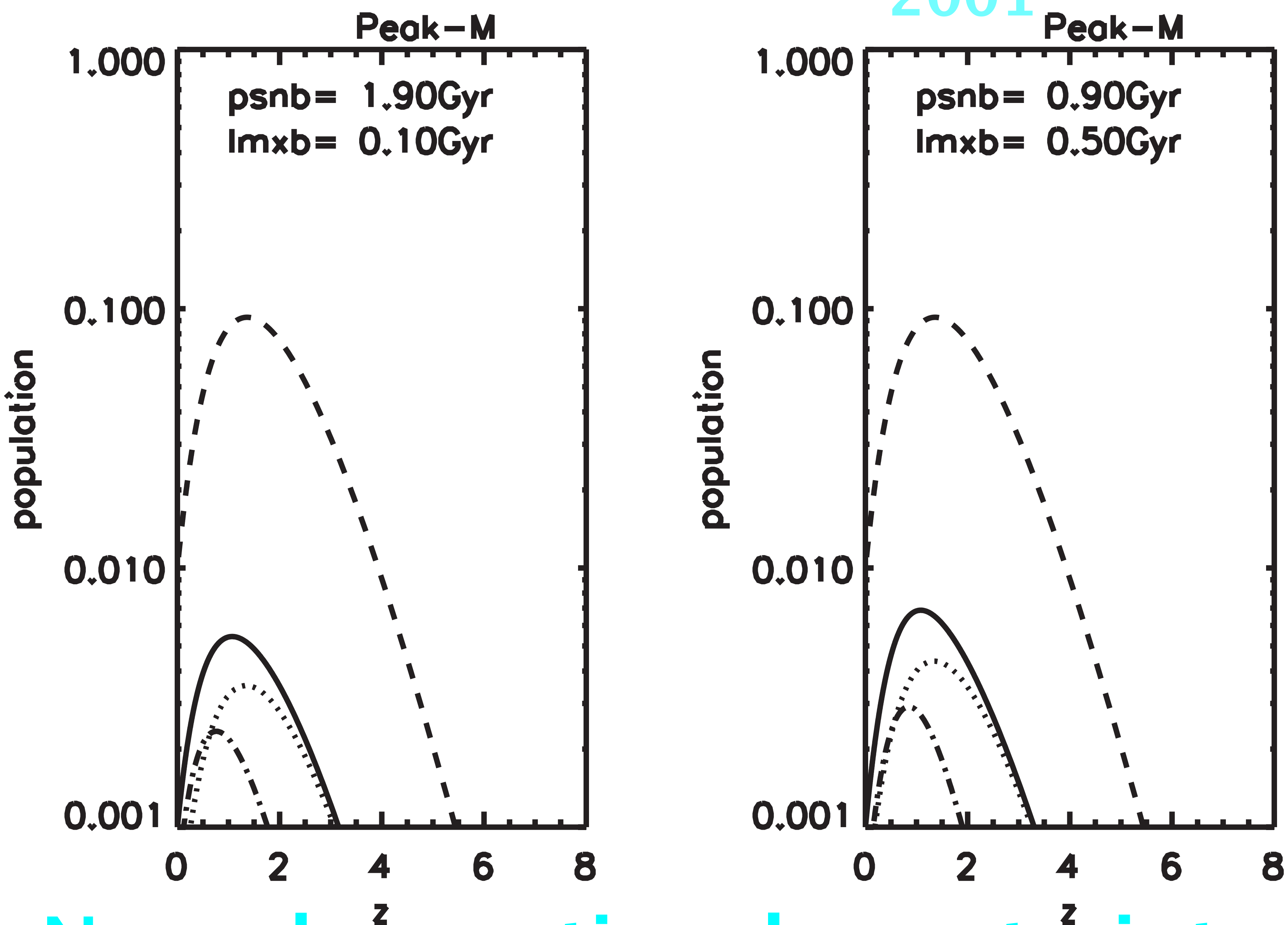
Existing Theoretical Models

White & Ghosh 1998
Ghosh & White 2001



Timescale estimates for binary evolution

$$\frac{\partial n_{\rm HMXB}(t)}{\partial t} = \alpha_h {\rm SFR}(t) - \frac{n_{\rm HMXB}(t)}{\tau_{\rm HMXB}},$$

$$\frac{\partial n_{\rm PSNB}(t)}{\partial t} = \alpha_l {\rm SFR}(t) - \frac{n_{\rm PSNB}(t)}{\tau_{\rm PSNB}},$$

$$\frac{\partial n_{\rm LMXB}(t)}{\partial t} = \frac{n_{\rm PSNB}(t)}{\tau_{\rm PSNB}} - \frac{n_{\rm LMXB}(t)}{\tau_{\rm LMXB}},$$

Several Star Formation history models

New observational constraint and advances in theoretical understanding

allow the development of **detailed population**

The Largest X-ray Binary Population Synthesis Simulations Ever!

The largest library of X-ray binary PS models with the StarTrack PS code (Belczynski et al. 2008)

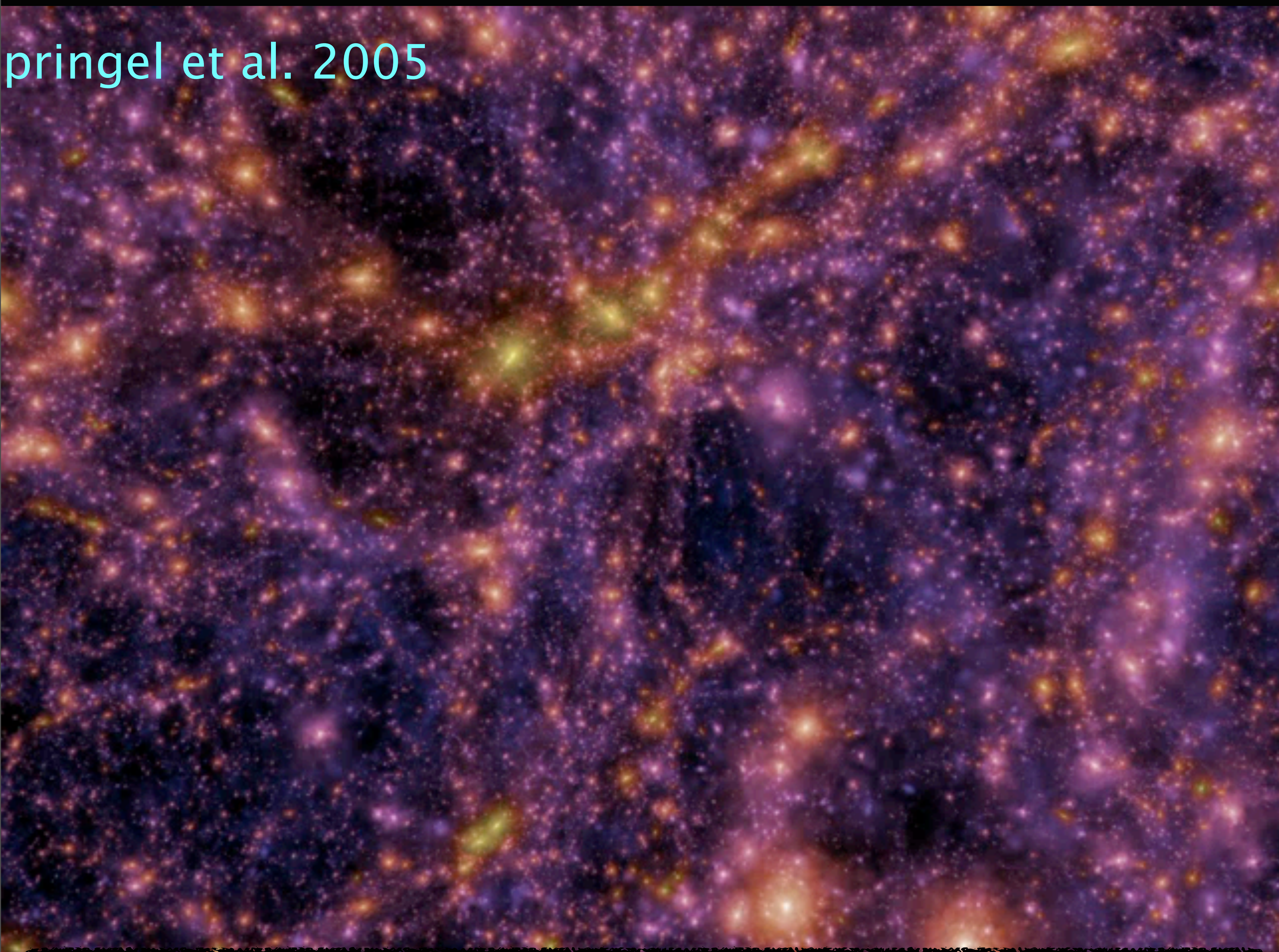
- **Parameter space study:** 300 PS models for 9 metallicity values and ~45 Million binaries per model
- Available computational resources:
  - Quest HPC cluster (NU)
  - Discover HPC cluster (NCCS)
  - Fugu HPC cluster (astro-NU)
  - **Total of ~2,000,000 cpu hours required**

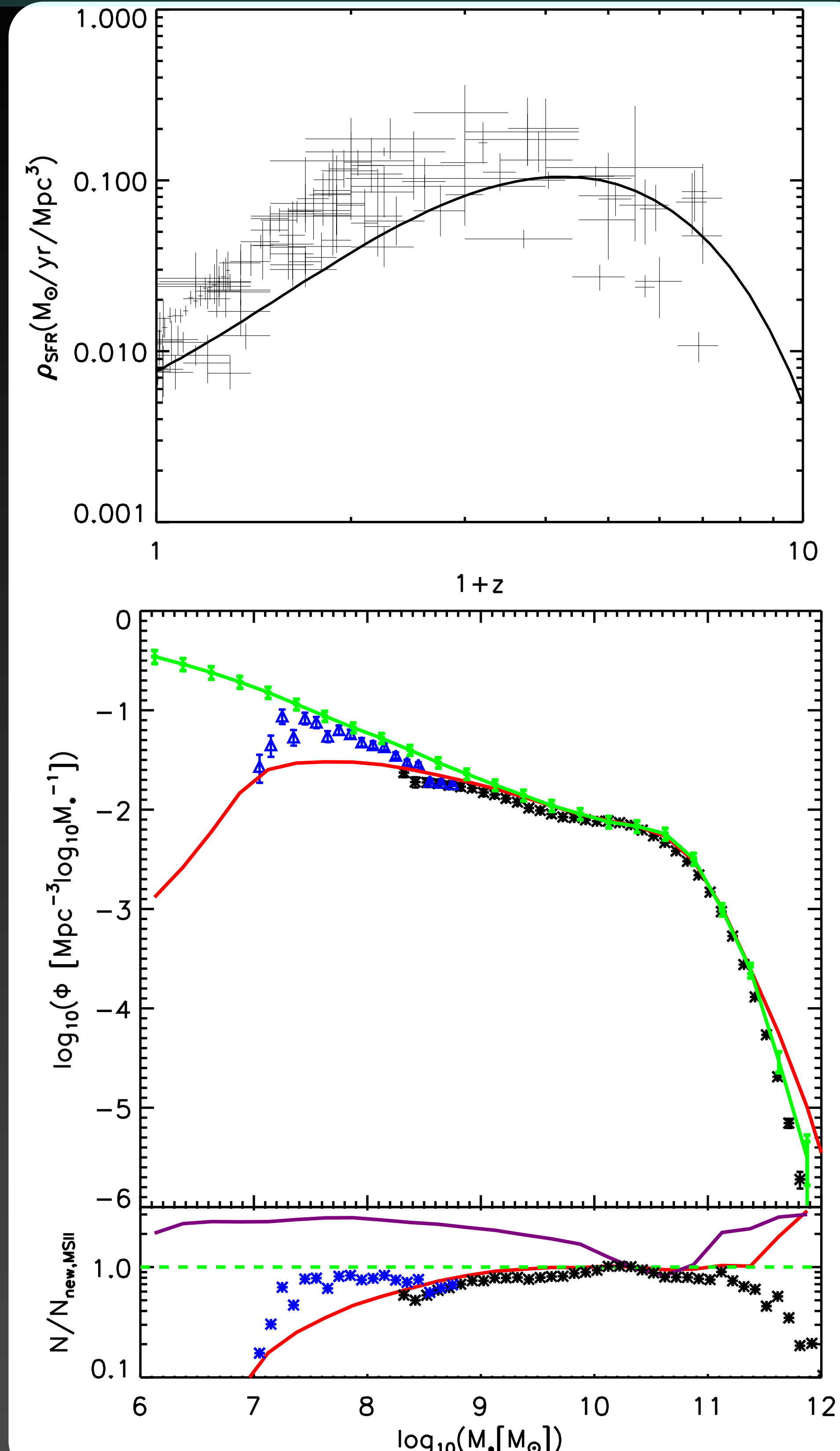
Grid of New Simulations

Parameter	Value
α_{ce}	0.1, 0.2, 0.3, 0.5
IMF	-2.7, -2.35
Stellar Winds	0.25, 1.0, 1.5, 2.0
CE for HG primaries	0 , 1
Mass Ratio	Flat, Twin, mixture
Kicks ECS/AIC	Yes, No
Kicks Direct C.C. BH	Yes, No

300 Models with 5M (per metallicity) binaries each

The Millennium Simulation





Millennium-II Simulation

100Mpc^3/h volume - 125x better mass resolution - 5x better spatial resolution (Boylan-Kolchin et al. 2009)

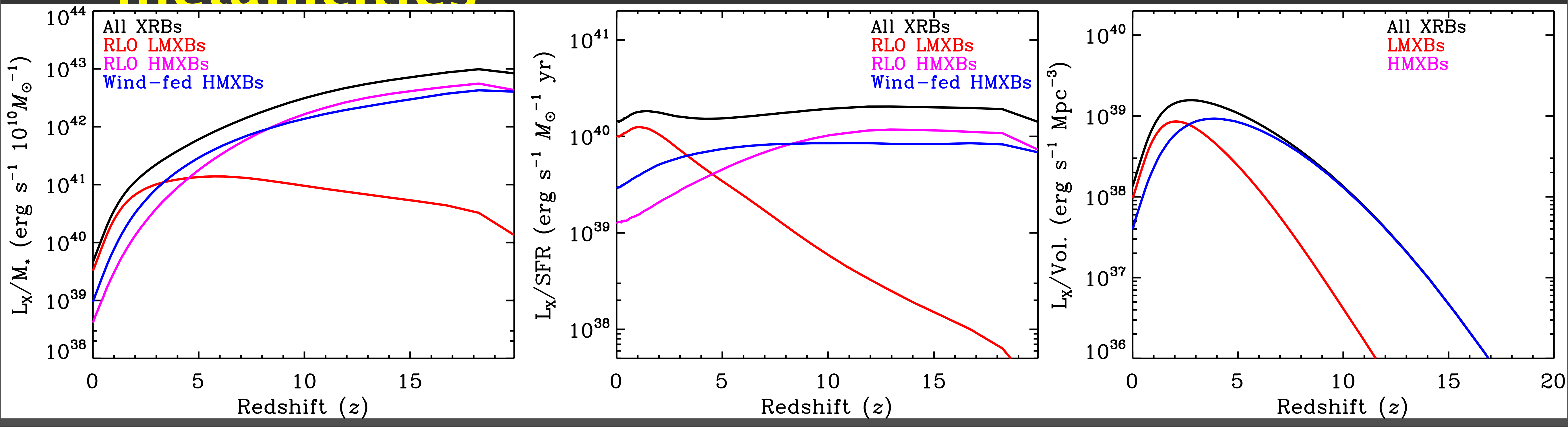
Updated semi-analytic galaxy catalogs by Guo et al. 2011

Hopkins 2007
Li & White 2009 (SDSS DR7)
Baldry et al. 2008 (DR4)

Combining the two simulations

- From the **Millennium Simulation** we track the new stellar mass formed at each metallicity bin as a function of time.
- Using the **StarTrack** models, we add new stellar population according to the star formation history
- The resulting XRB population is a **mix of populations at different ages and different metallicities**

LMXB: $M_{donor}<3M_\odot$ HMXB: $M_{donor}>3M_\odot$



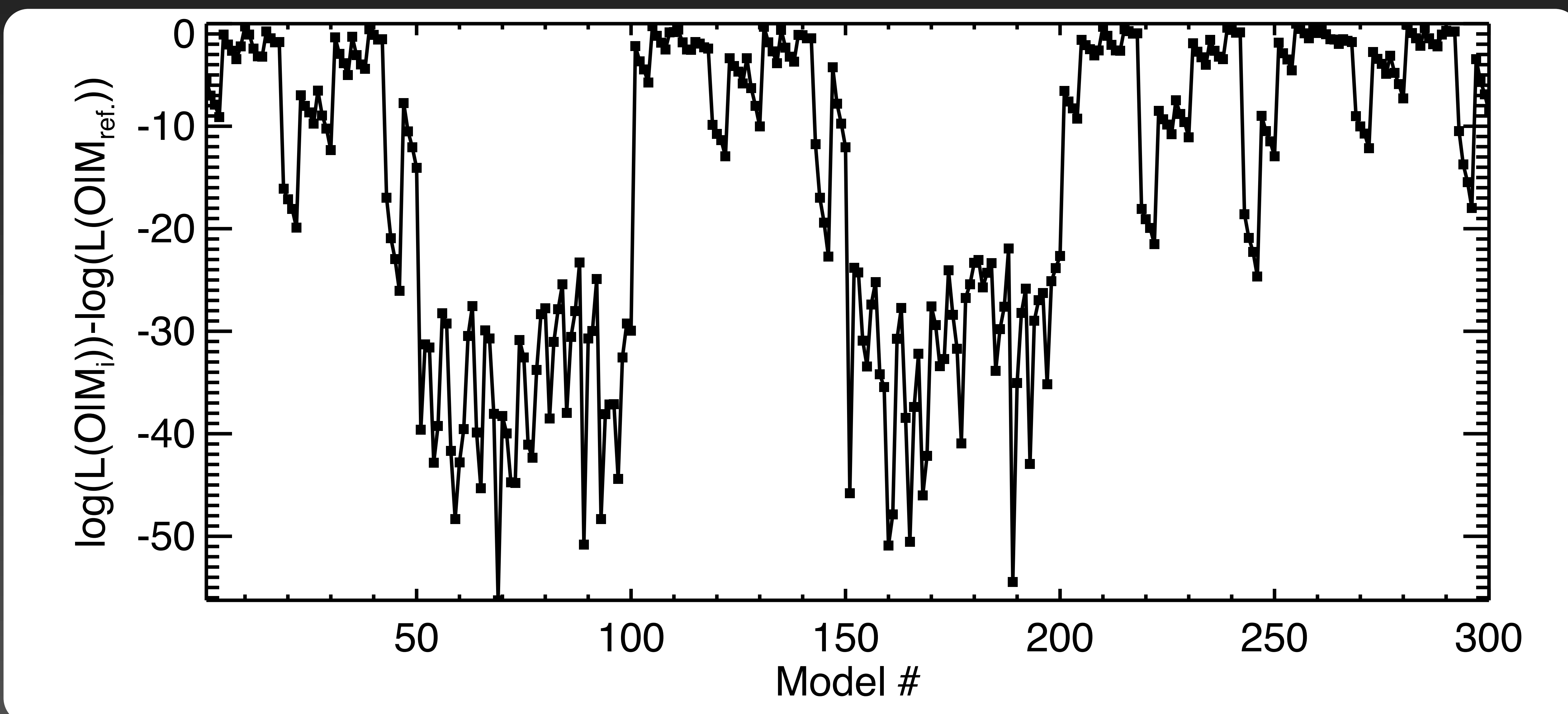
Model Comparison

Lx/SFR :

- z=0 : Lehmer et al. 2010, Mineo et al 2011
- z>0 : Symeonidis et al. 2011, Lehmer et al. 2008

Lx/M* :

- z=0 : Lehmer et al. 2010, Boroson et al 2011
- z>0 : Lehmer et al. 2007



Parameter Space

Parameter	Value
α_{ce}	**0.1**, ~~0.2, 0.3, 0.5~~
IMF	**-2.7**~~, -2.35~~
Stellar Winds	~~0.25,~~ 1.0, 1.5~~, 2.0~~
CE for HG primaries	0 , 1
Mass Ratio	Flat~~, Twin,~~ **mixture**
Kicks ECS/AIC	Yes, No
Kicks Direct C.C. BH	Yes, No

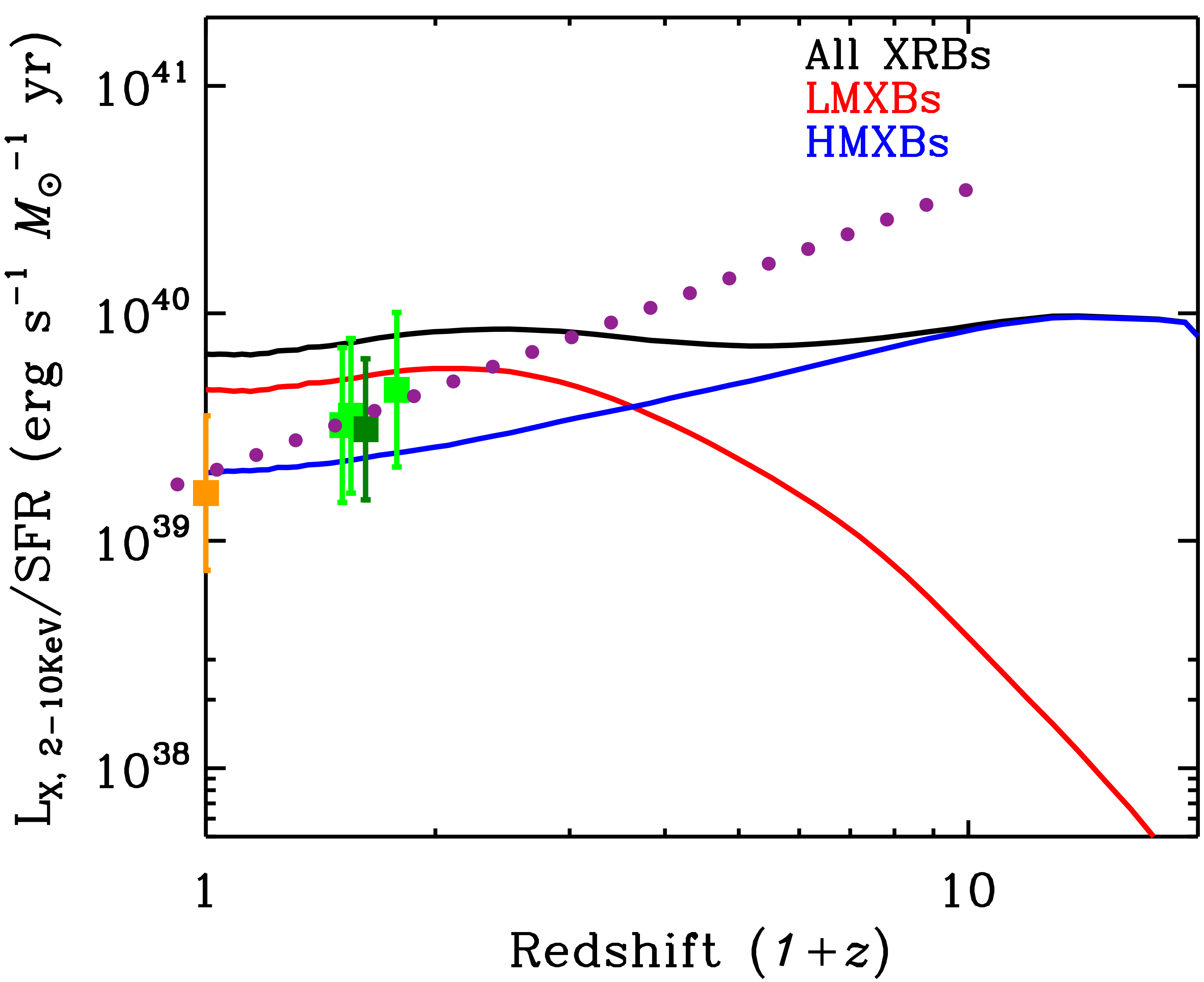
Low α_{ce} ~0.1 -- “Standard” Stellar Winds or ~50% increased

Maybe a mixed mass ratio distribution

Consistent with previous PS studies:

Belczynski et al., 2004, Fragos et al. 2008,2009, Linden et al., 2009, 2010

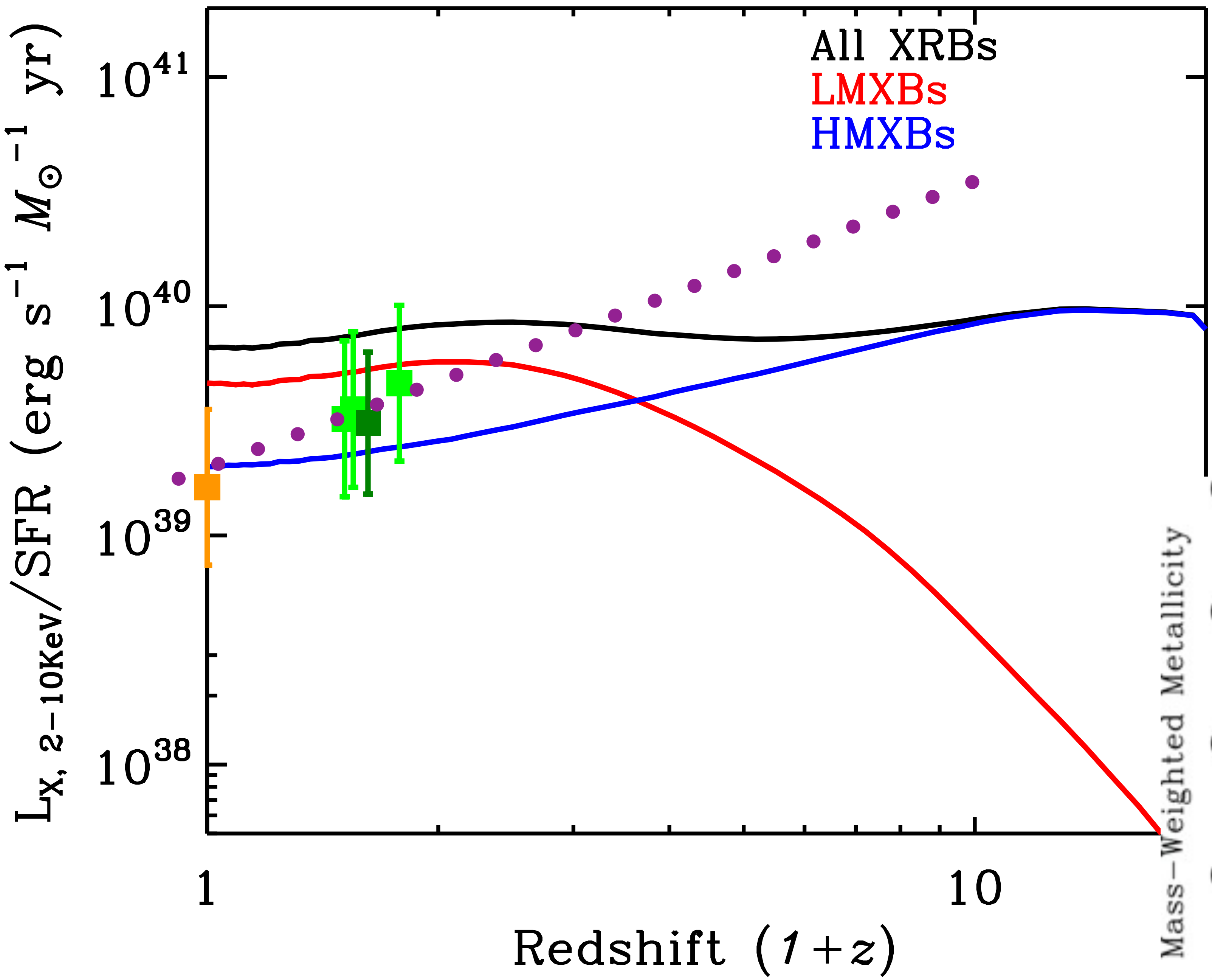
Observational Constraints I: HMXBs



$L_X/SFR \sim (1+z)^b$, $b \lesssim 1.3$
Dijkstra et al., 2011

Lehmer et al., 2010
(Mineo et al. 2010)
Lehmer et al., 2008
Symeonidis et al. 2011

Observational Constraints I: HMXBs



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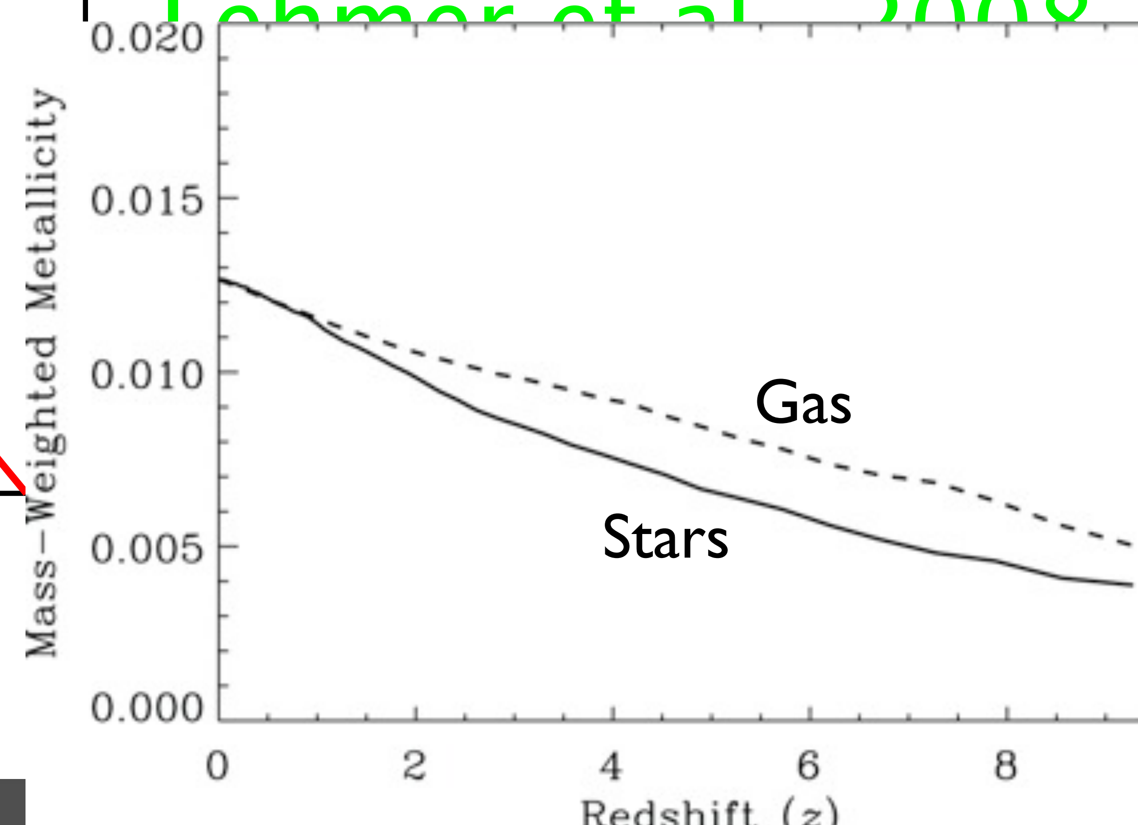

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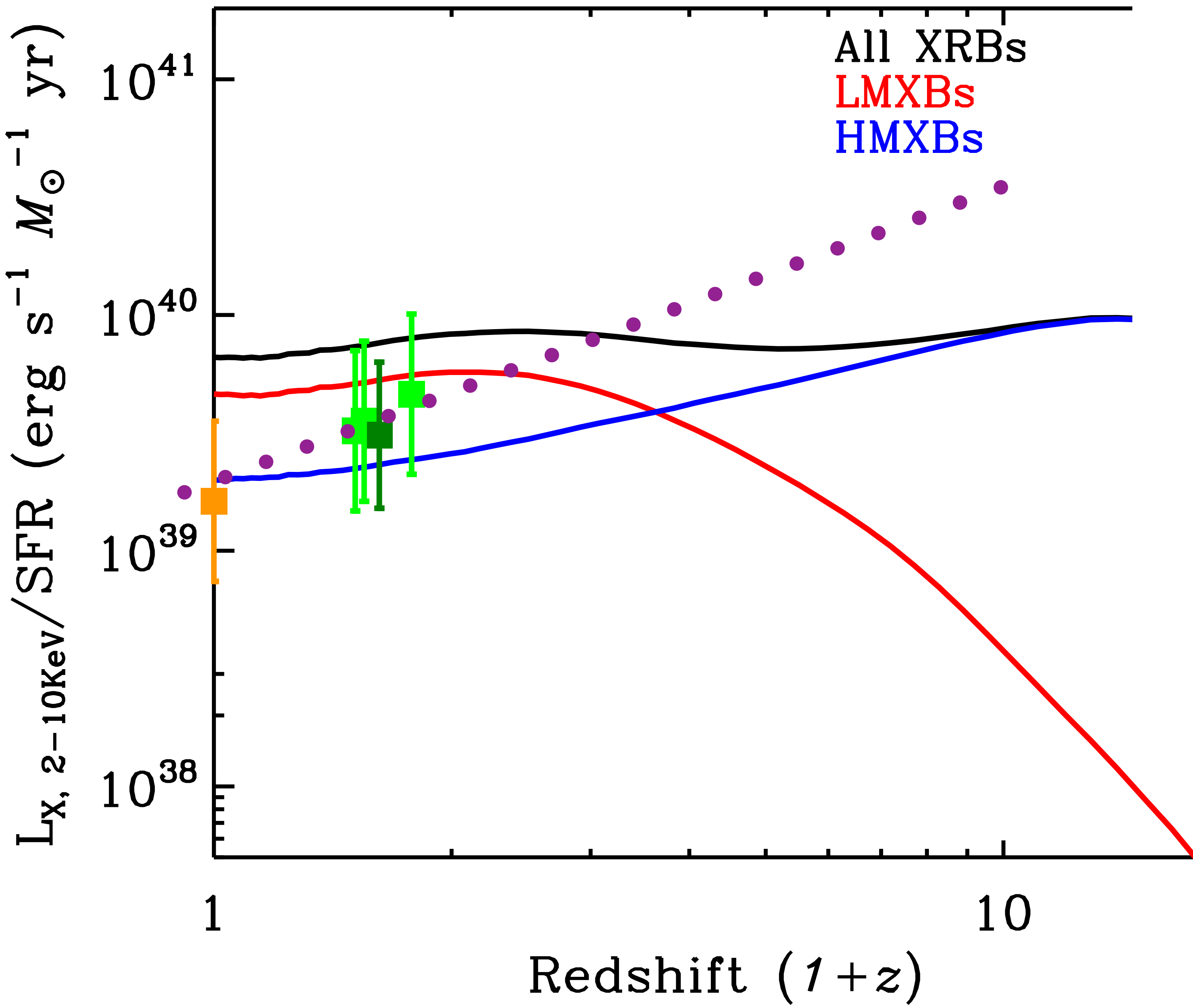
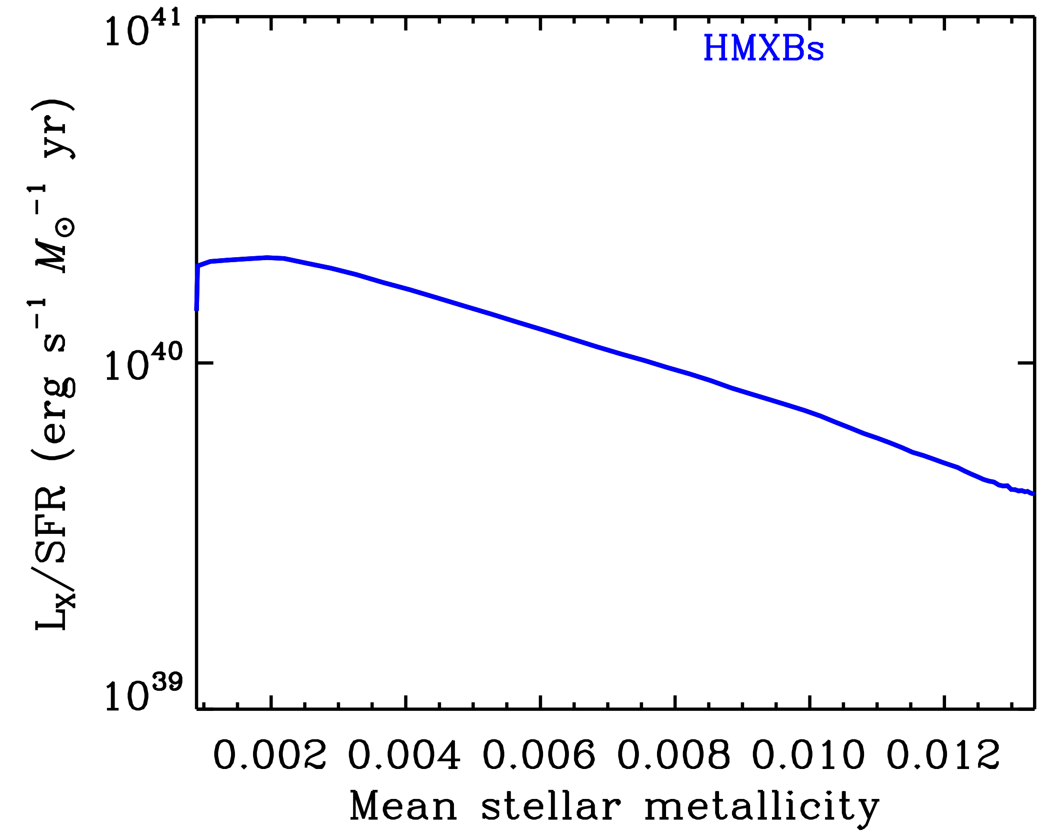
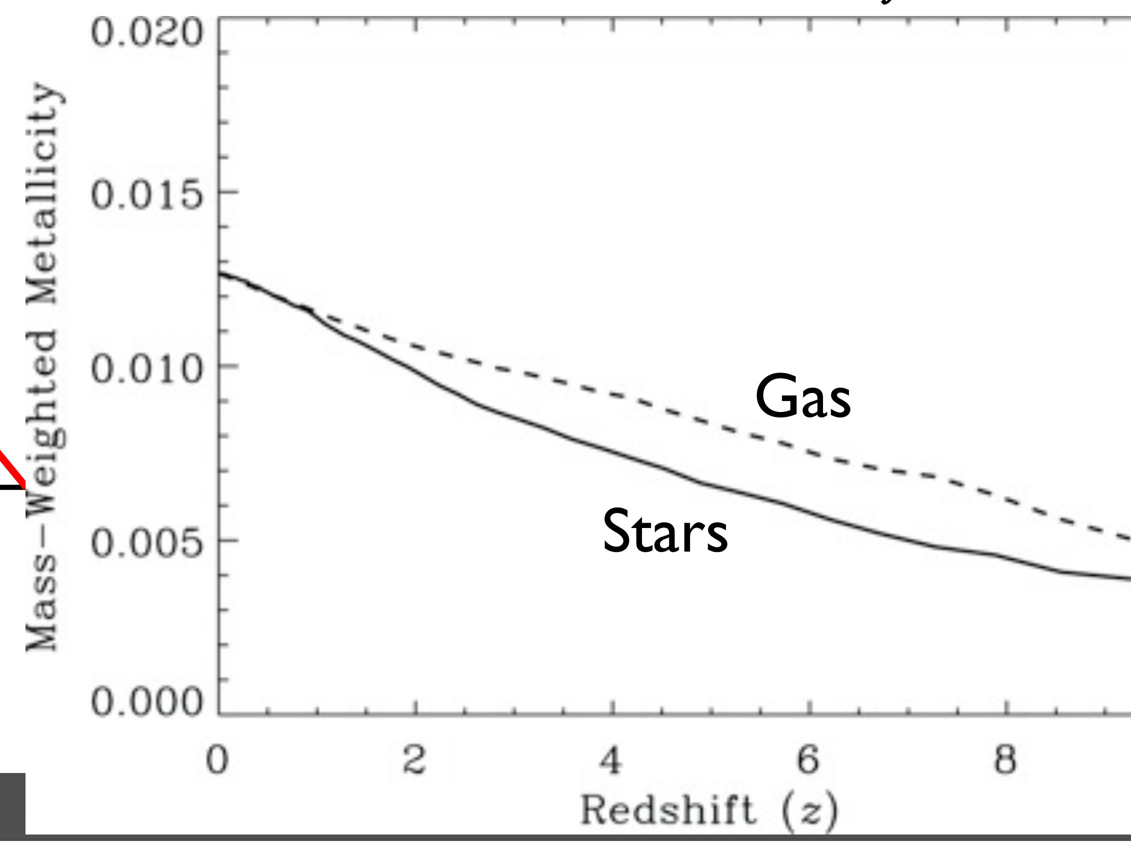
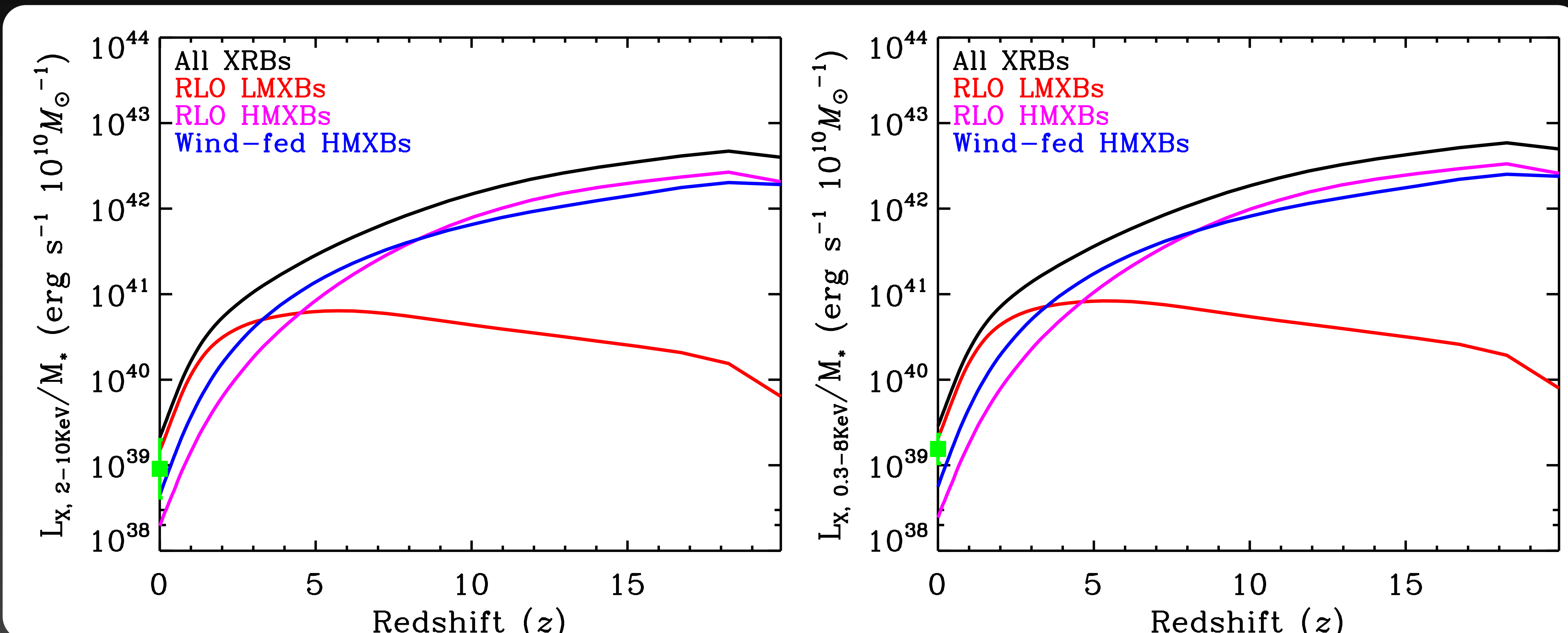






Observational Constraints III: LMXBs



Lehmer et al. (2010)

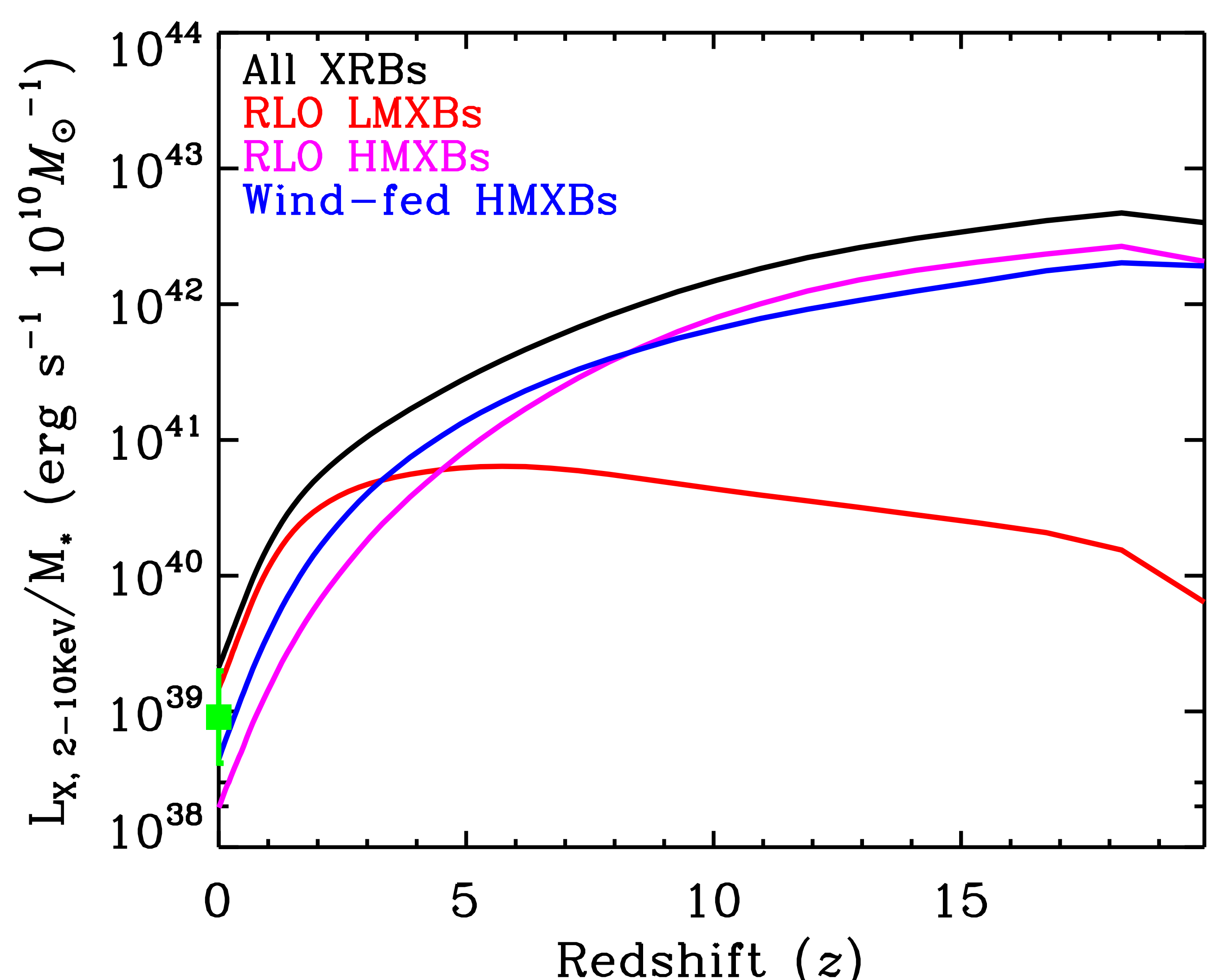
$$L_{HX}^{gal} = L_{HX}^{gal}(\text{LMXB}) + L_{HX}^{gal}(\text{HMXBs}) = \alpha M_* + \beta \text{SFR},$$

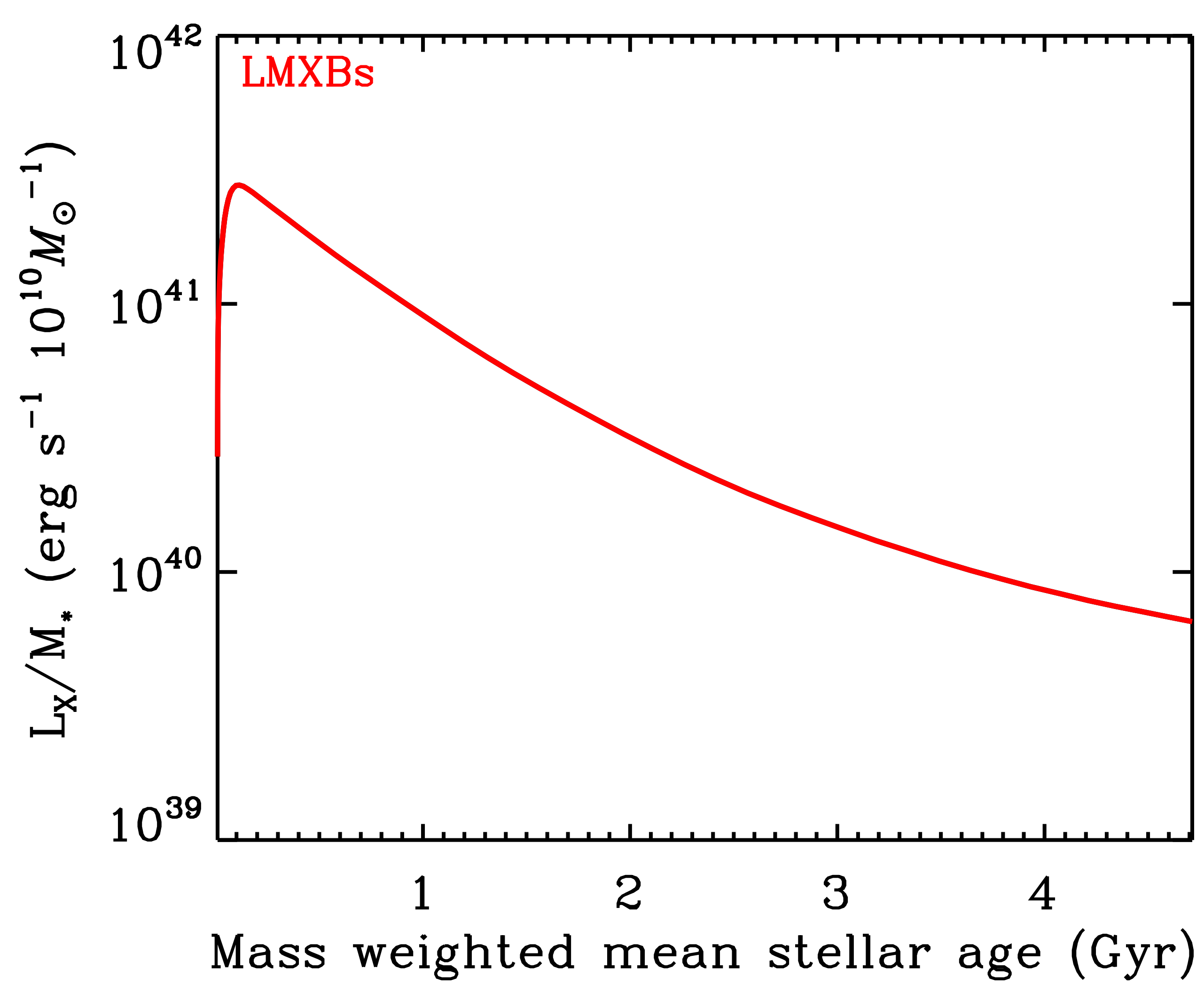
$$\alpha = (9.05 \pm 0.37) \times 10^{28} \text{ ergs s}^{-1}\ M_\odot^{-1}$$
$$\beta = (1.62 \pm 0.22) \times 10^{39} \text{ ergs s}^{-1}\ (M_\odot \text{ yr}^{-1})^{-1}$$

Boroson, Kim & Fabbiano (2011)

selection of ellipticals with total Lx, M*, Age, [Fe/H] measurements

Observational Constraints III: LMXBs





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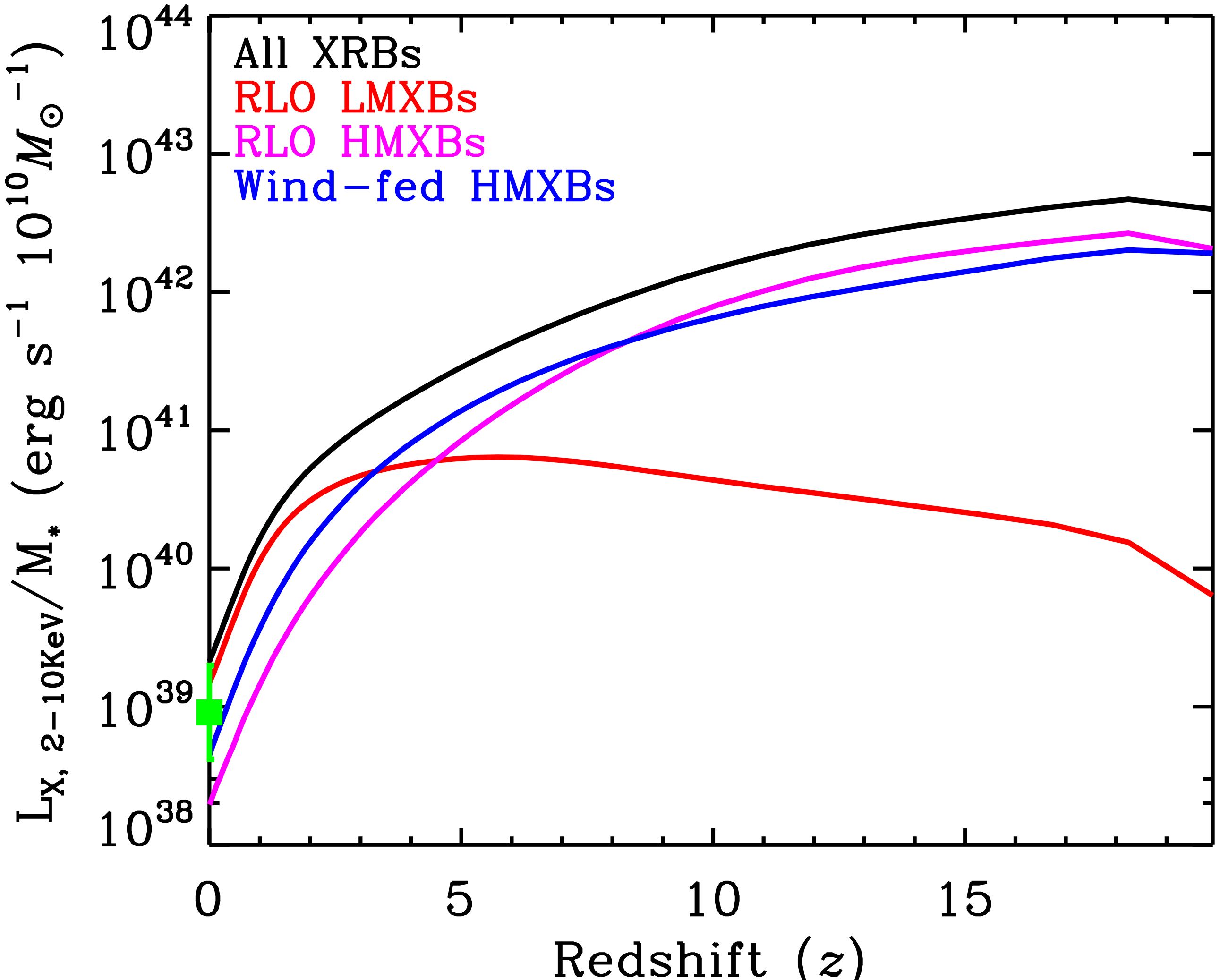
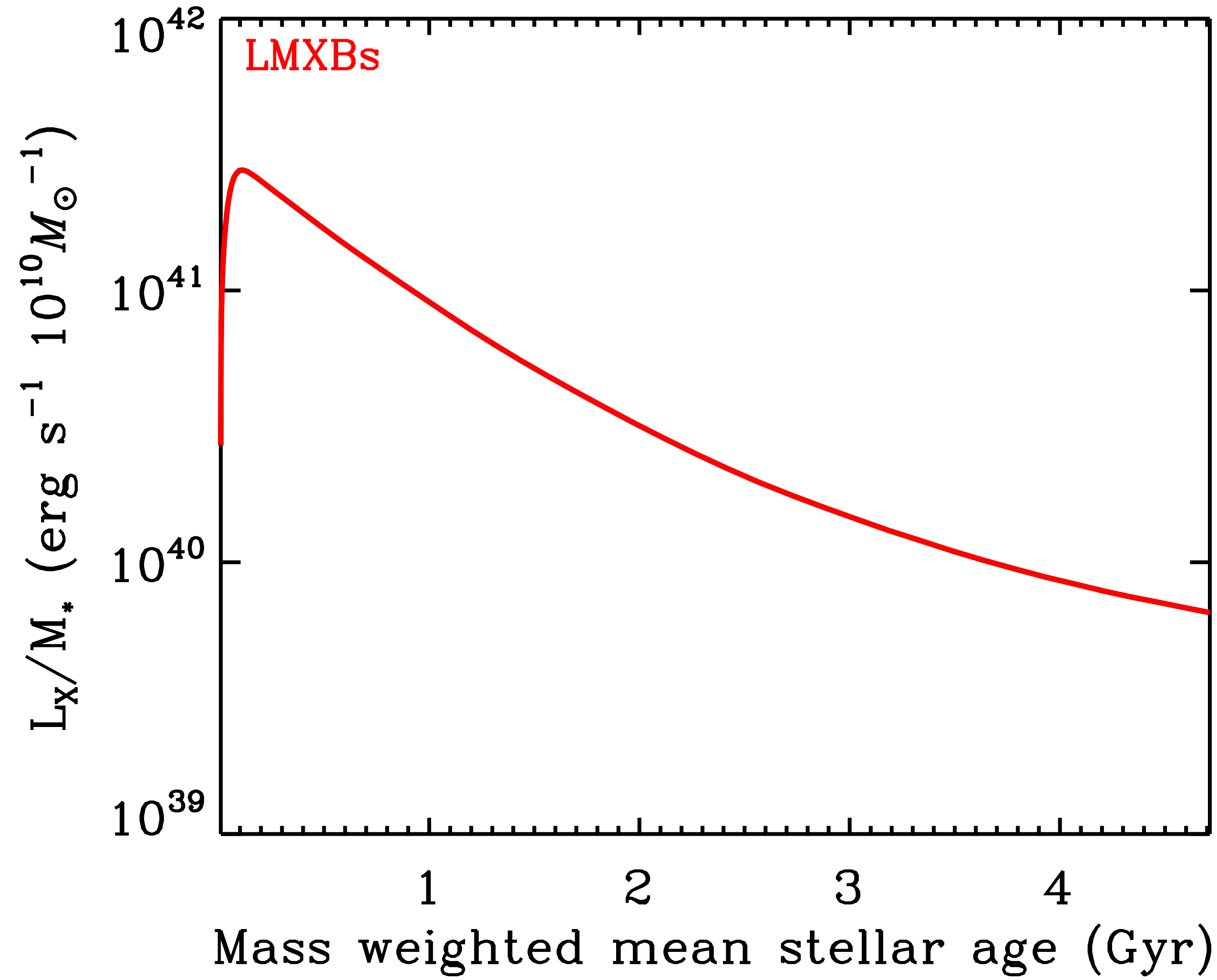
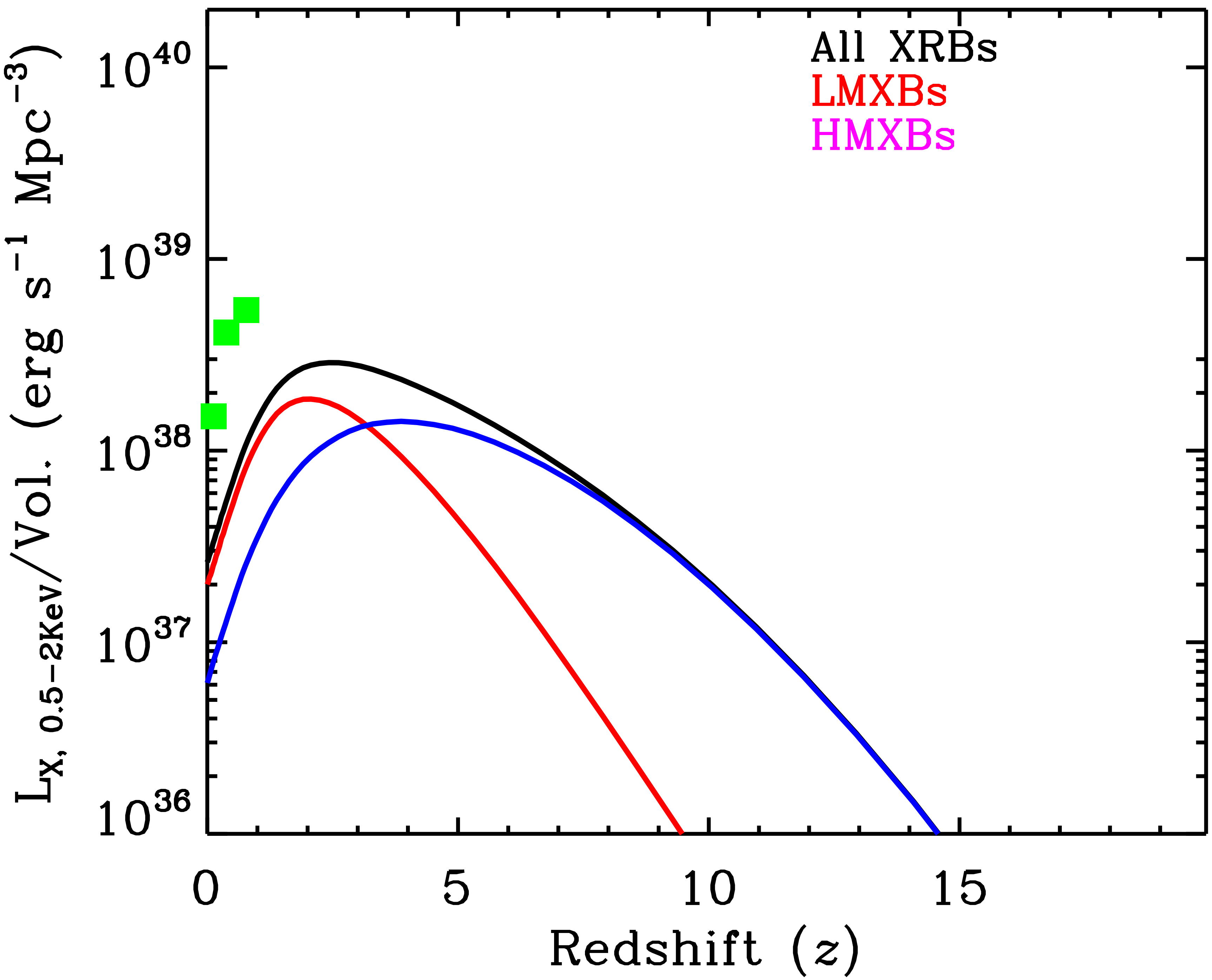
Observational Constraints III: LMXBs

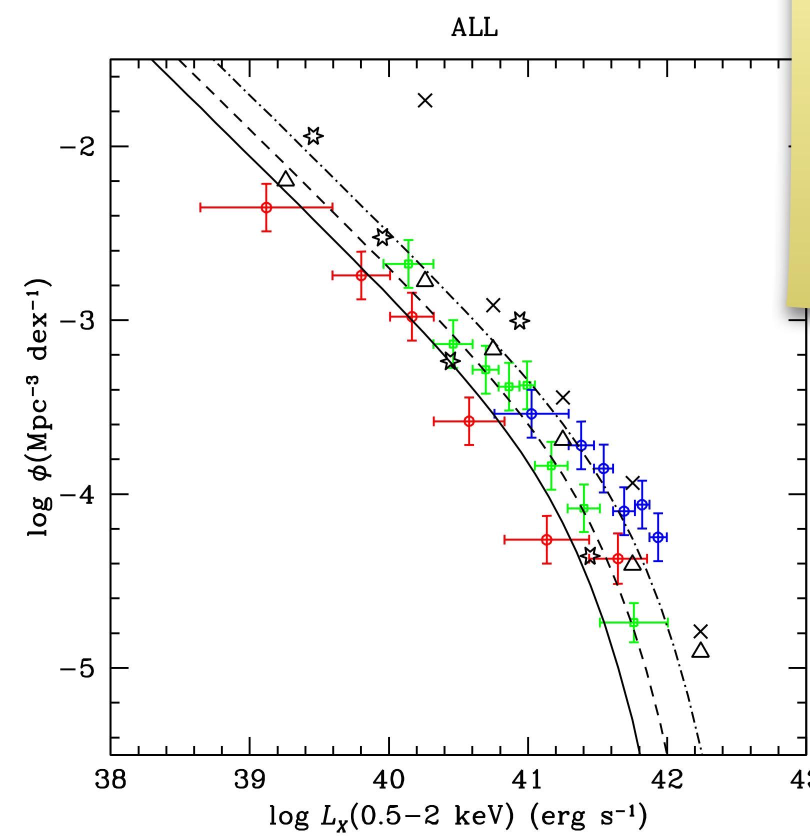




Comparing with X-ray stacking results from early-type
galaxies require careful modeling of selection effects
see Hornschemeier et al. 2011 (in prep.)

Observational Constraints III: Total X-ray luminosity





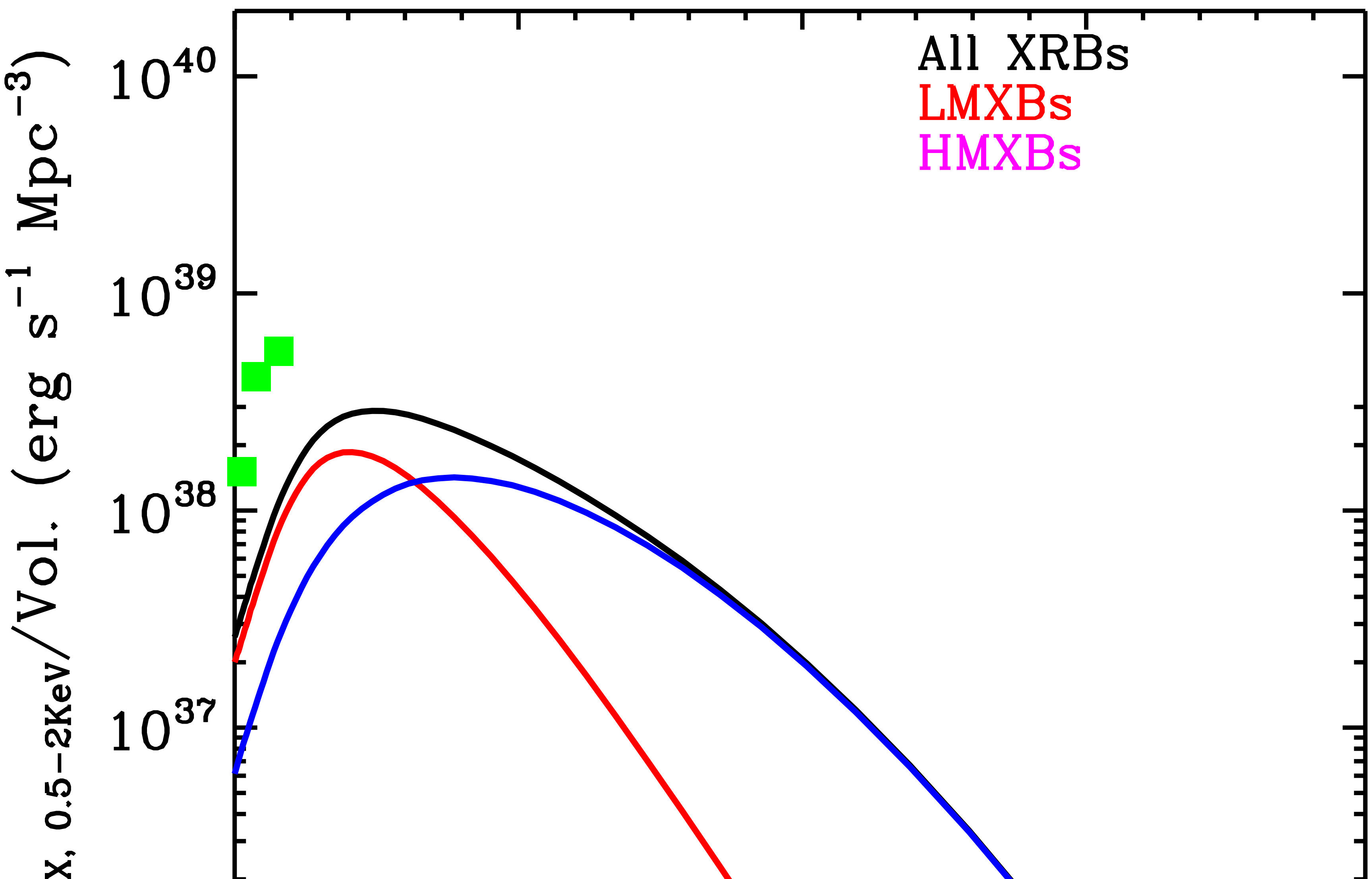
Other
work
of Kim
Norma
shown
triangle

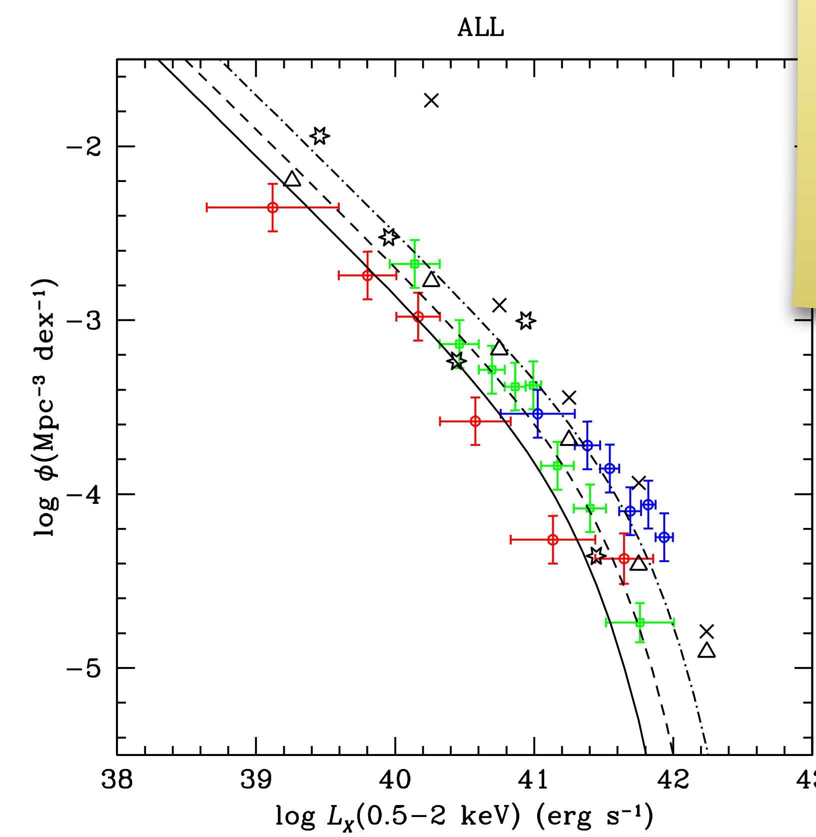
Tzanavaris & Georgantopoulos 2008

XLF of normal galaxies at 3 redshift bins:

0<z<0.2, 0.2<z<0.6, 0.6<z<1.4

Observational Constraints III: Total X-ray luminosity





Tzanavaris & Georgantopoulos 2008

XLF of normal galaxies at 3 redshift bins:

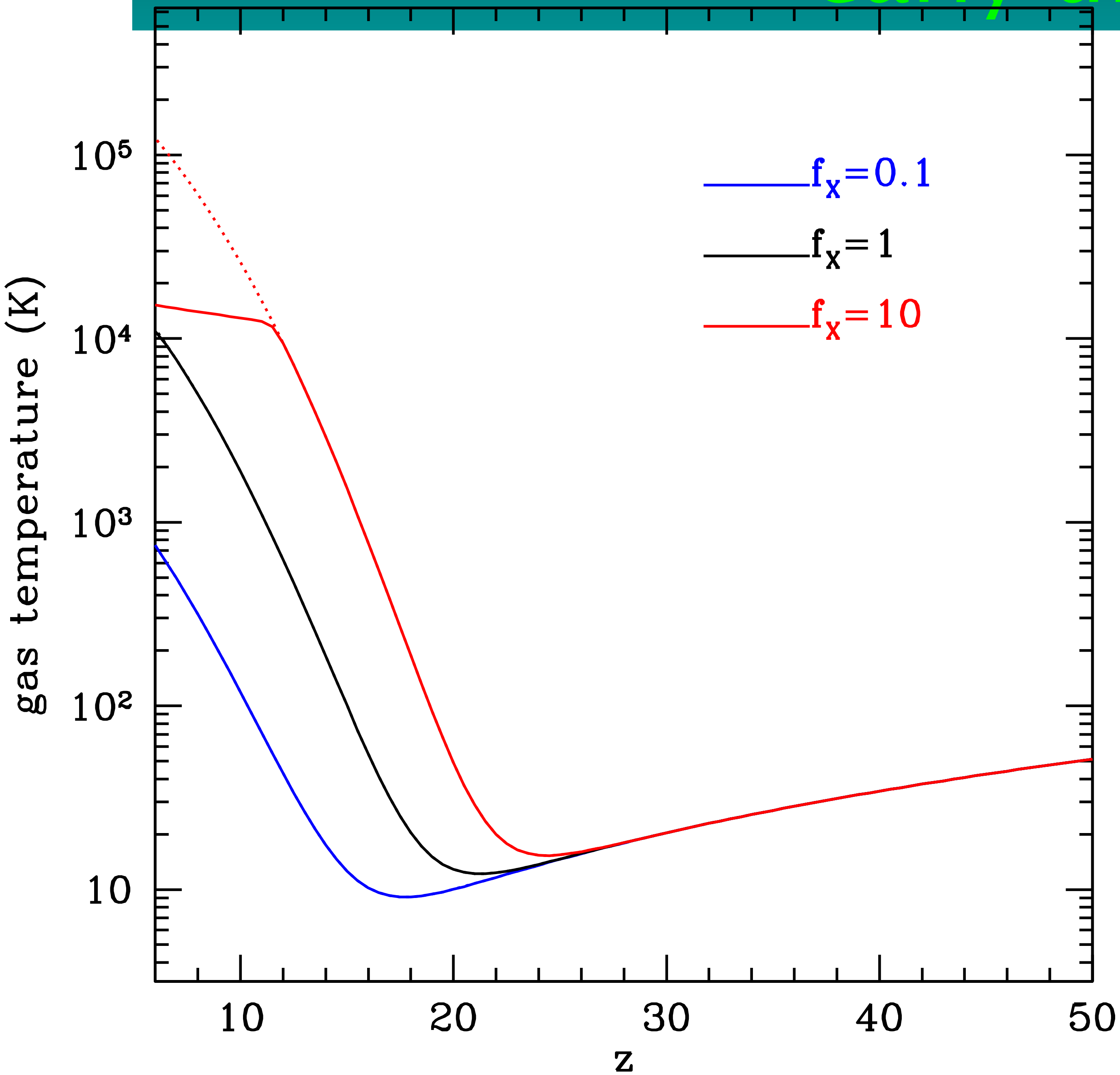
Other work of Kim Norma shown triangle

Directly comparing with galaxy XLF studies requires modeling of selection effects and hot gas **see Tremmel et al. 2011 (in prep.)**

Energy feedback from XRBs

X-ray photons have long mean free path

The radiation field by XRBs may be important in the thermal evolution of the early universe



Mirabel et al., 2011

$$L_X = 3.4 \times 10^{40} f_X \left(\frac{\mathrm{SFR}}{1\,\mathrm{M_\odot\,yr^{-1}}} \right) \mathrm{erg\,s^{-1}}$$

Furlanetto 2006

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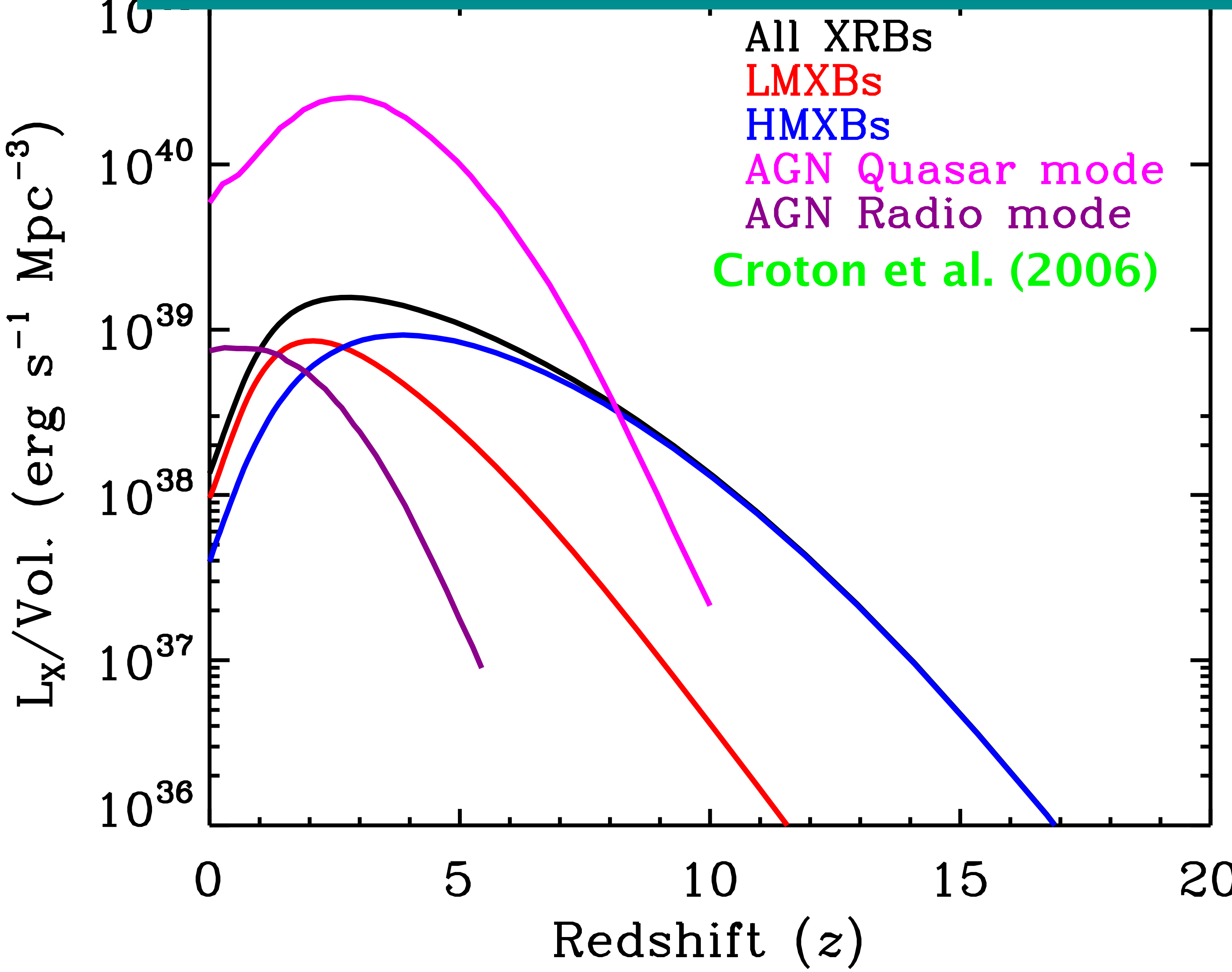
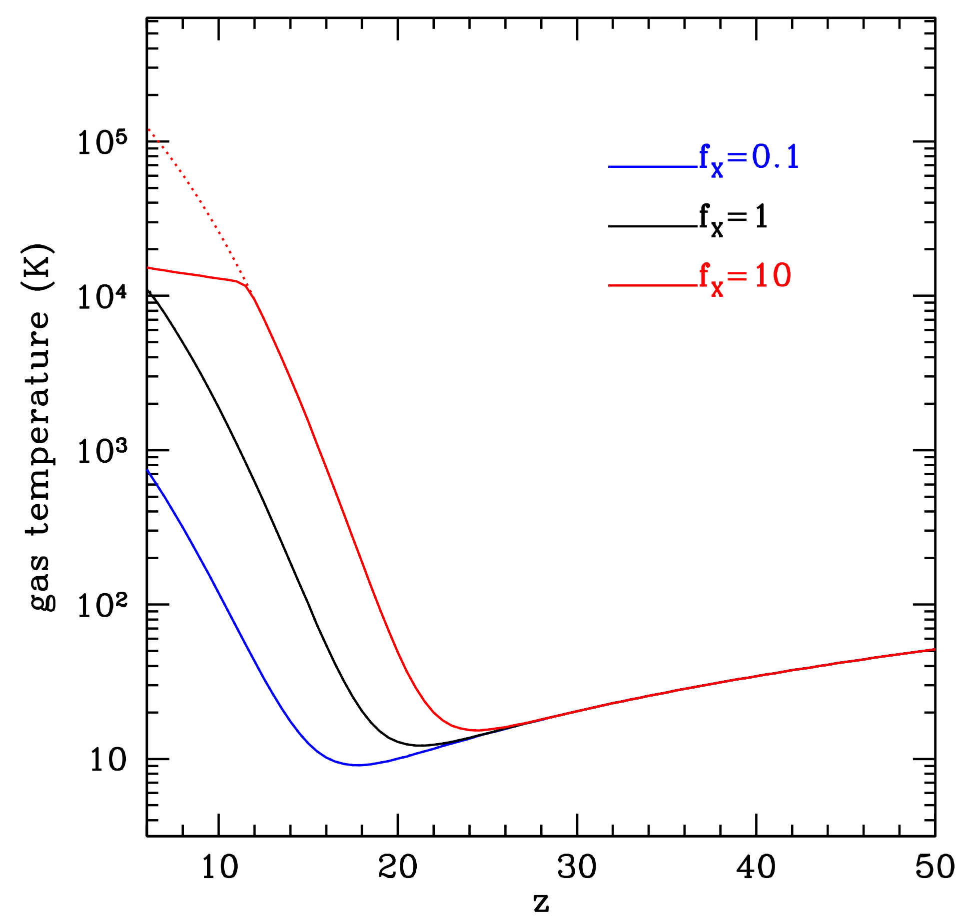


Mirabel et al., 2011

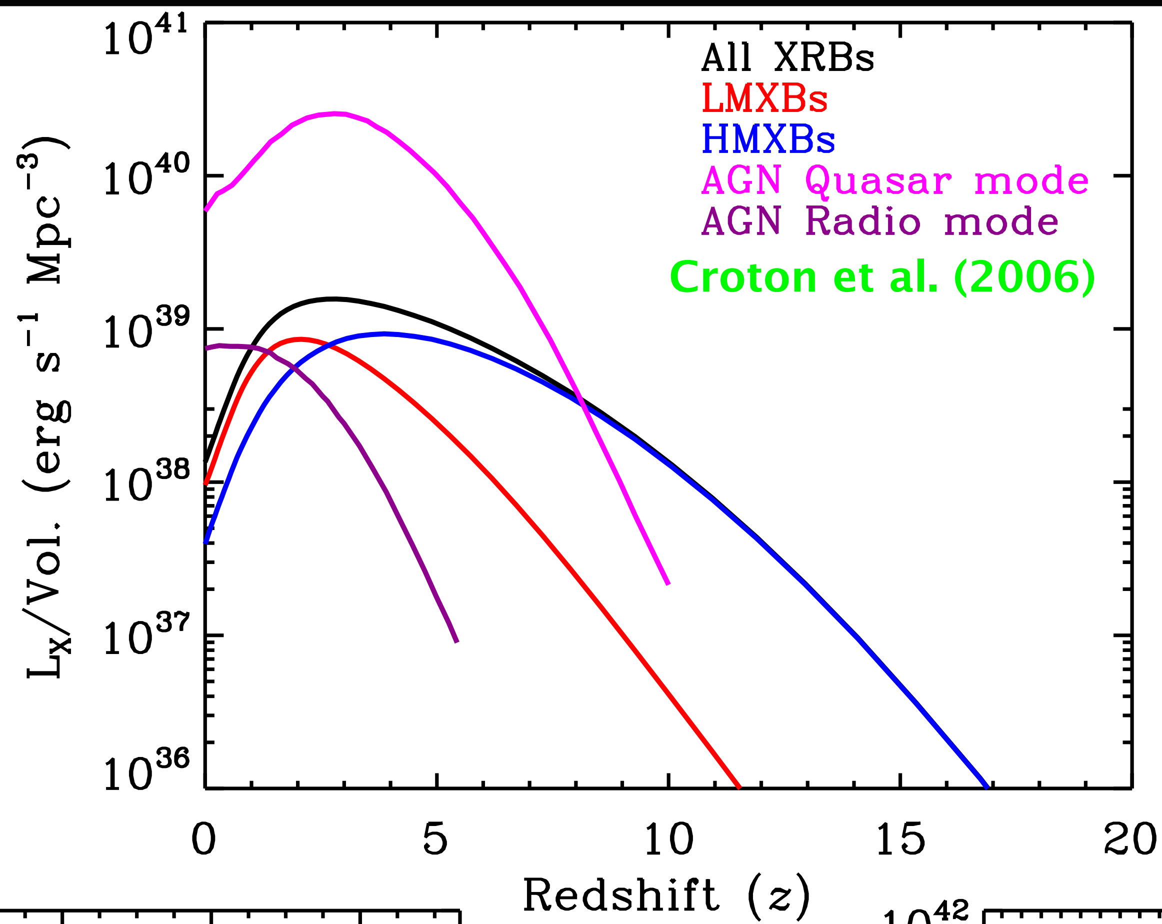


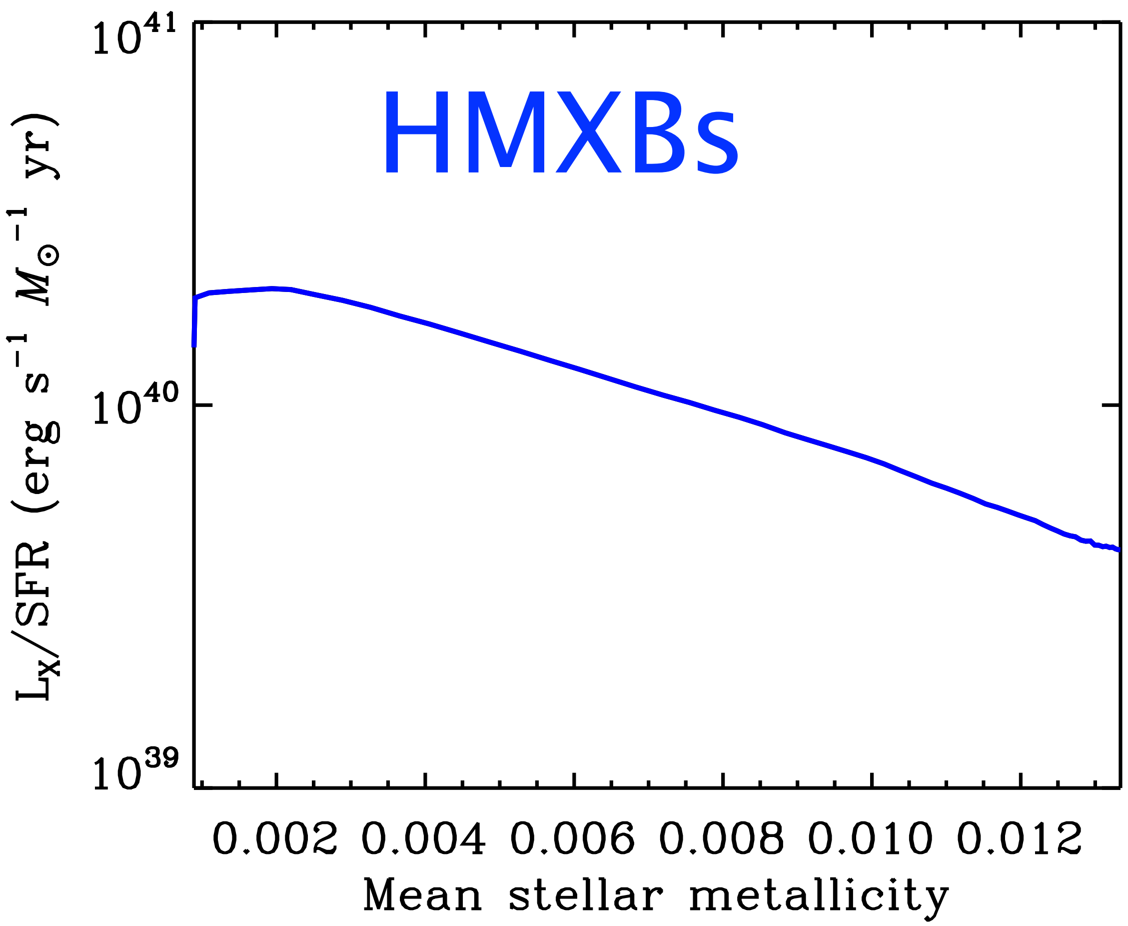
Summary

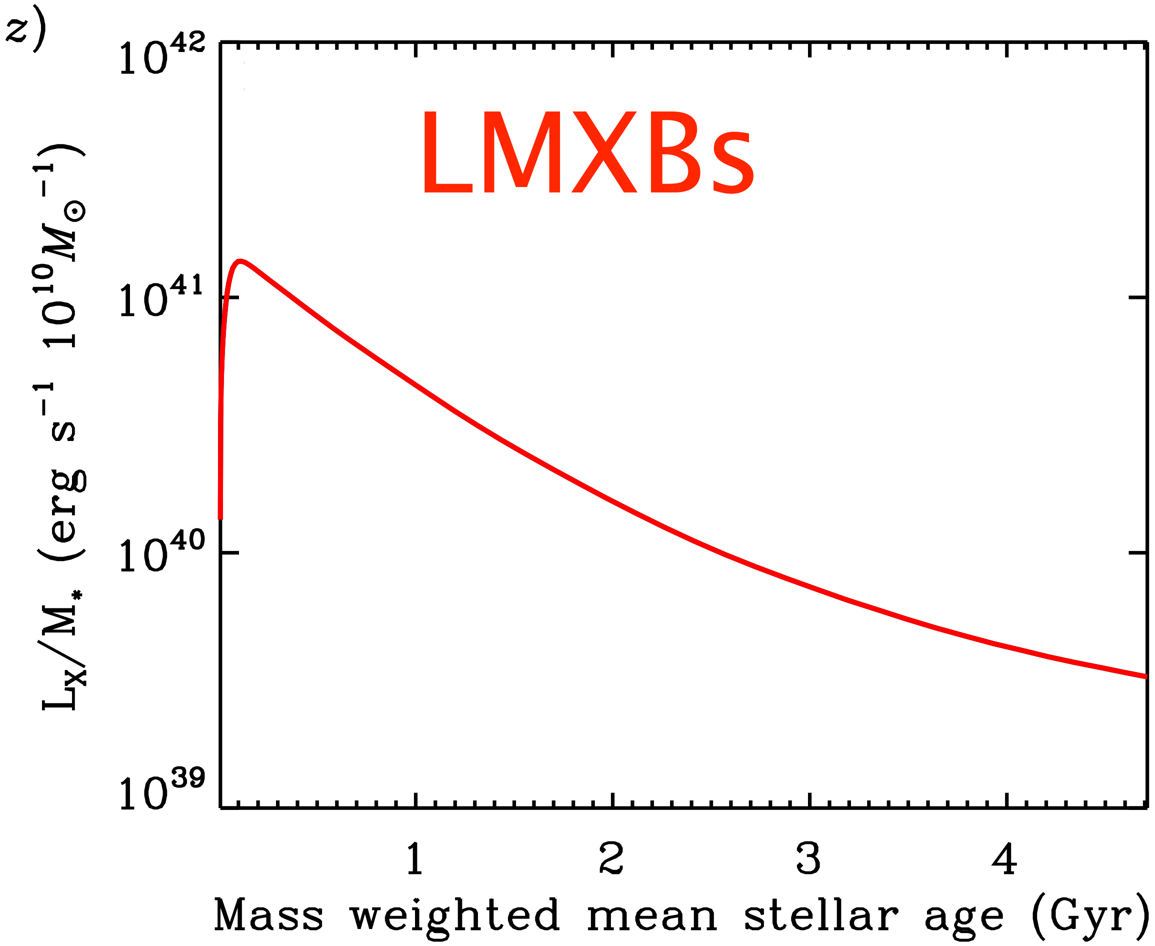
We built **the largest PS model library** in order to study the **evolution of XRBs at high redshifts**, **using cosmological simulations as input** in our modeling.

- We predict an inversion in the evolution of galaxy XLFs at a redshift of ~2.5
- The contribution of wind-fed HMXBs ($L_{X,HMXBs}$/SFR) is increasing with z, as a result of metallicity evolution.
- Average delay between star formation and peak Lx from LMXBs is ~1.5Gyr
- XRBs are the dominant sources of X-ray photon production at redshifts >10

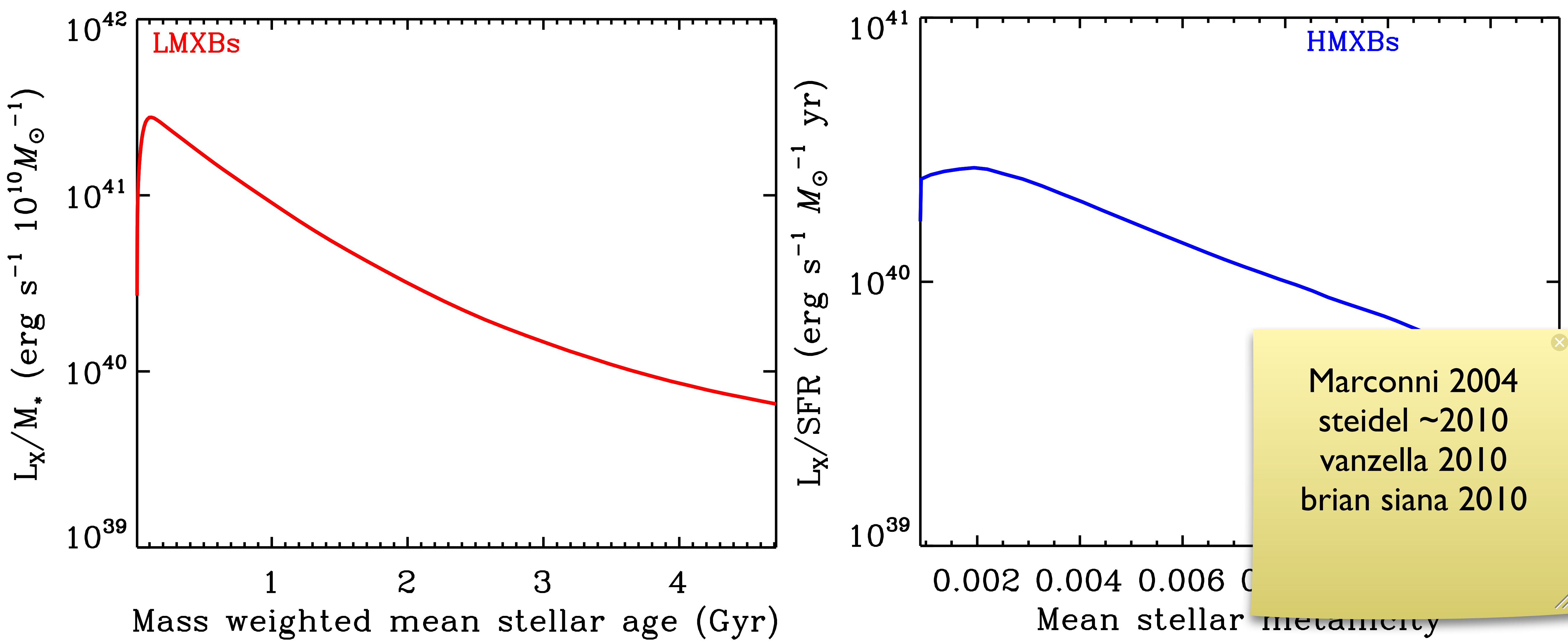
Energy feedback from XRBs





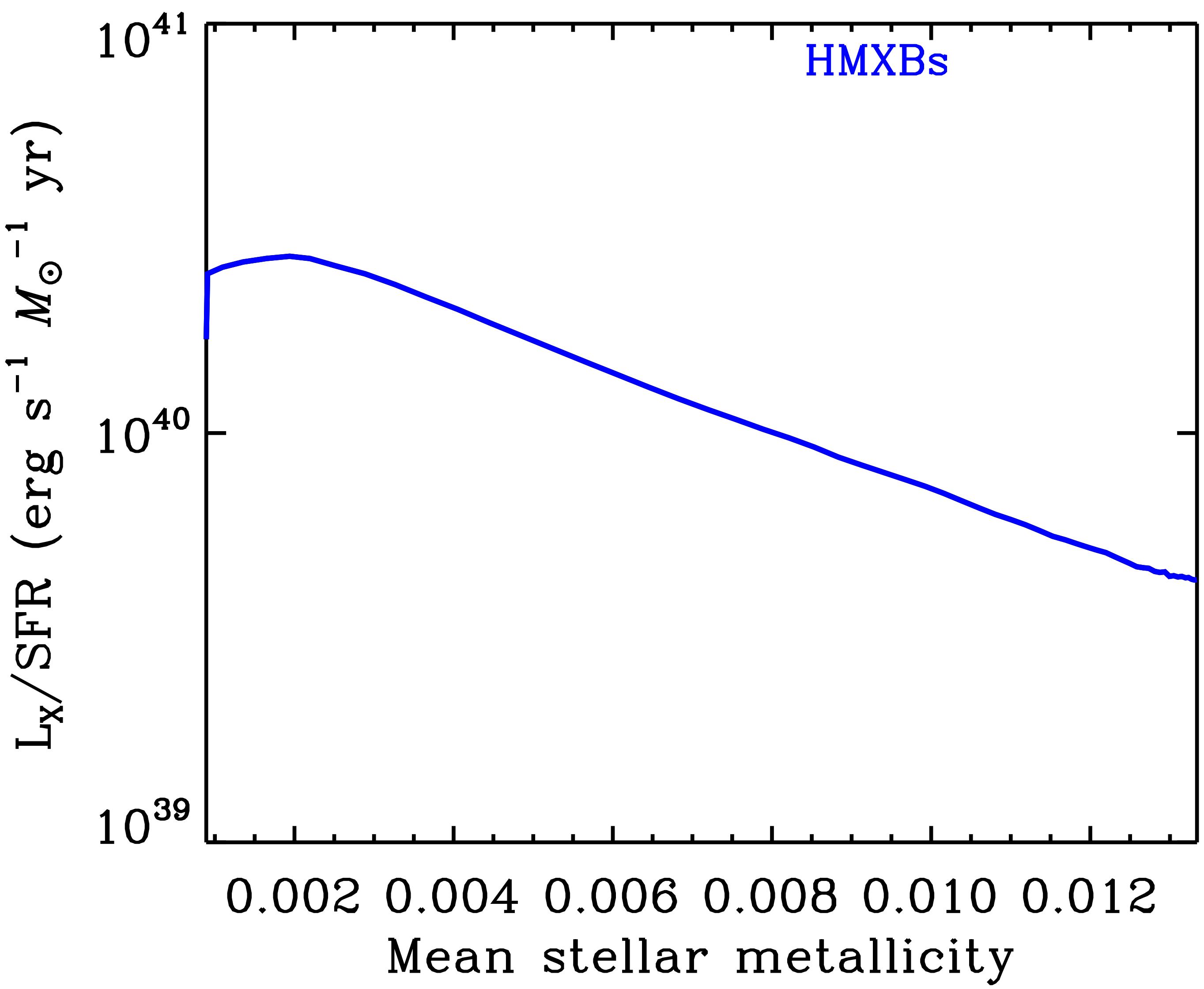


Energy feedback from XRBs

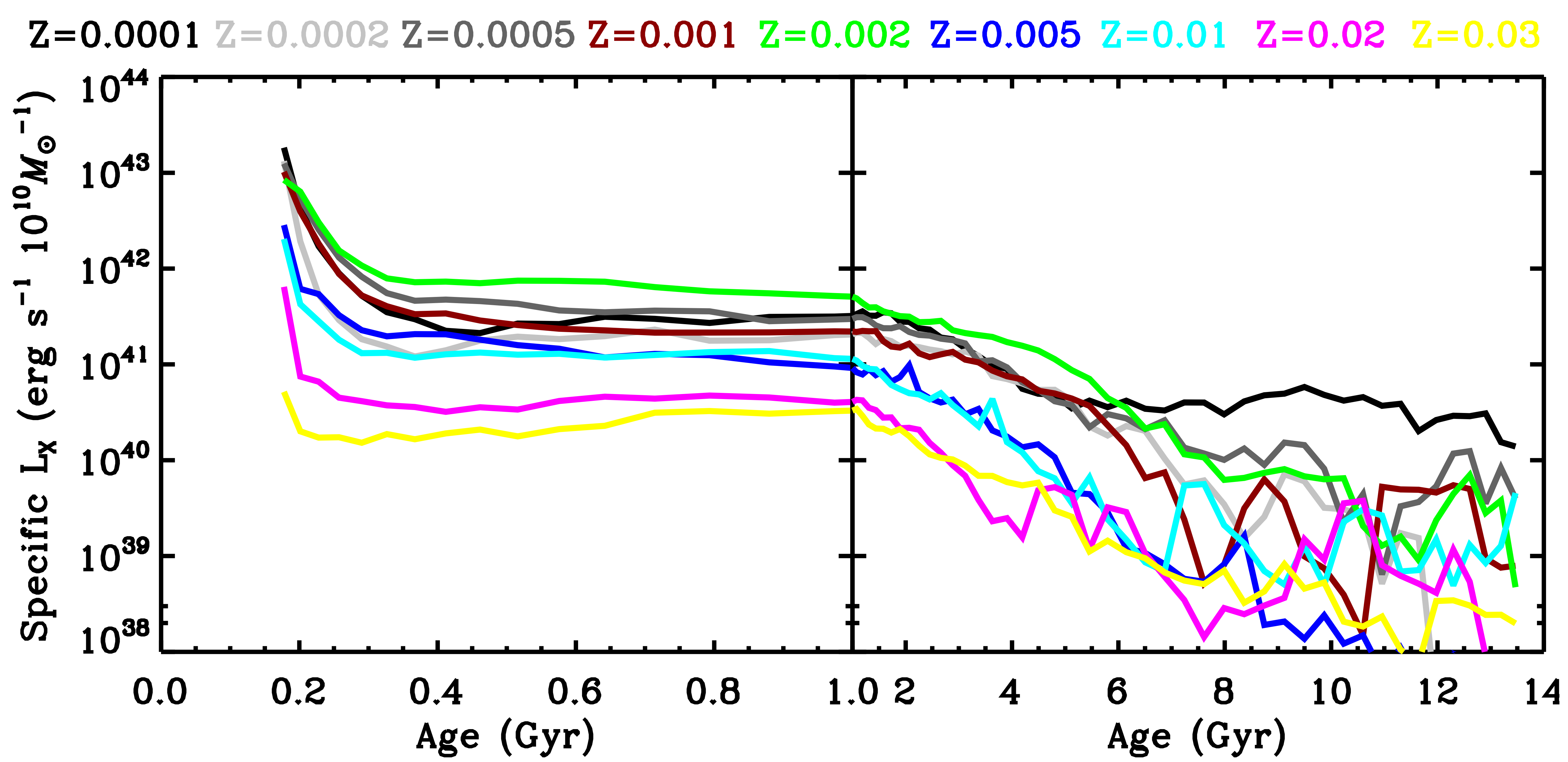


Marconni 2004
steidel ~2010
vanzella 2010
brian siana 2010

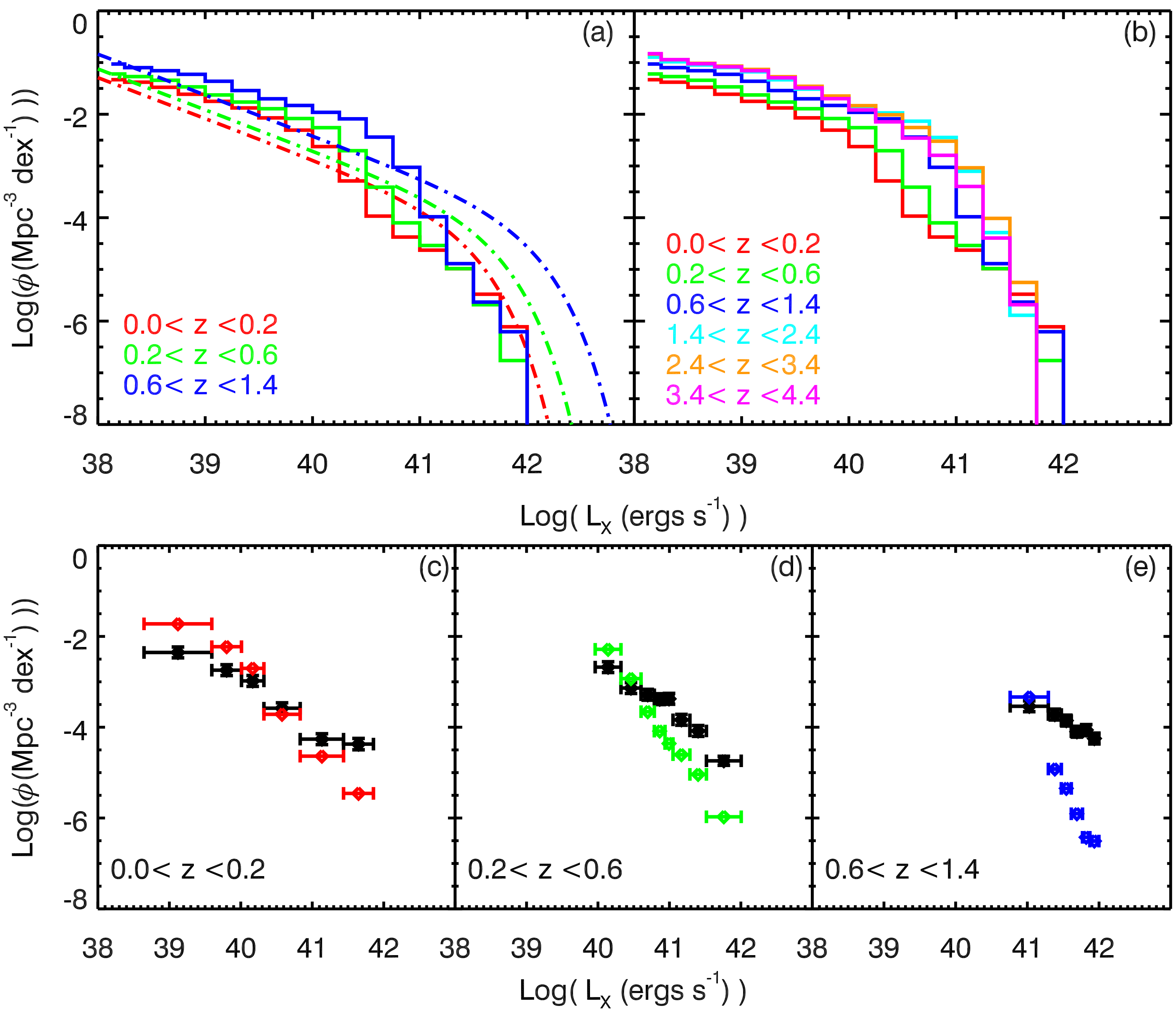
Feedback from HMXBs



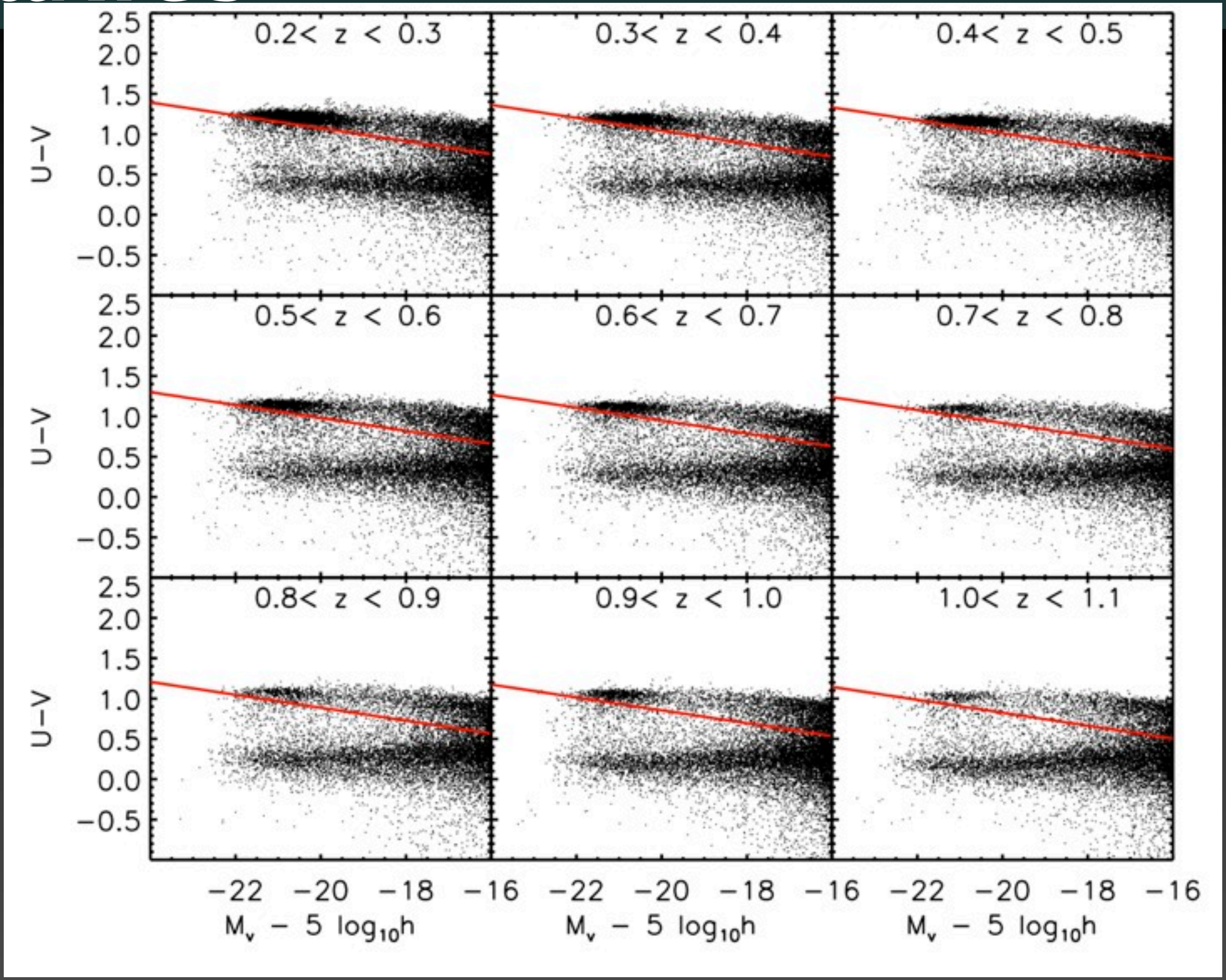
Modeling the X-ray Luminosity from a Single Stellar Population



X-ray luminosity functions of distant galaxies

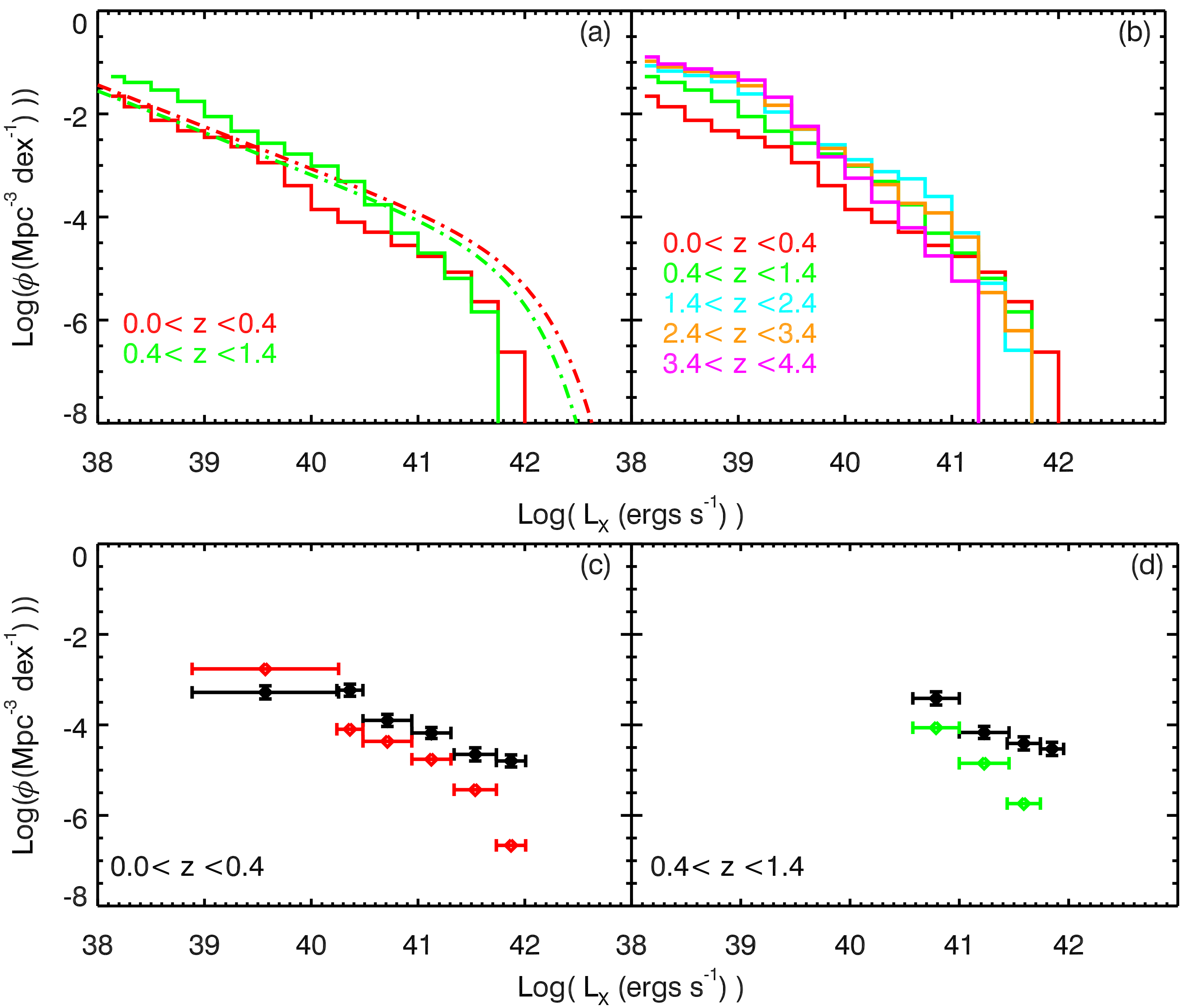


Separating early from late type galaxies

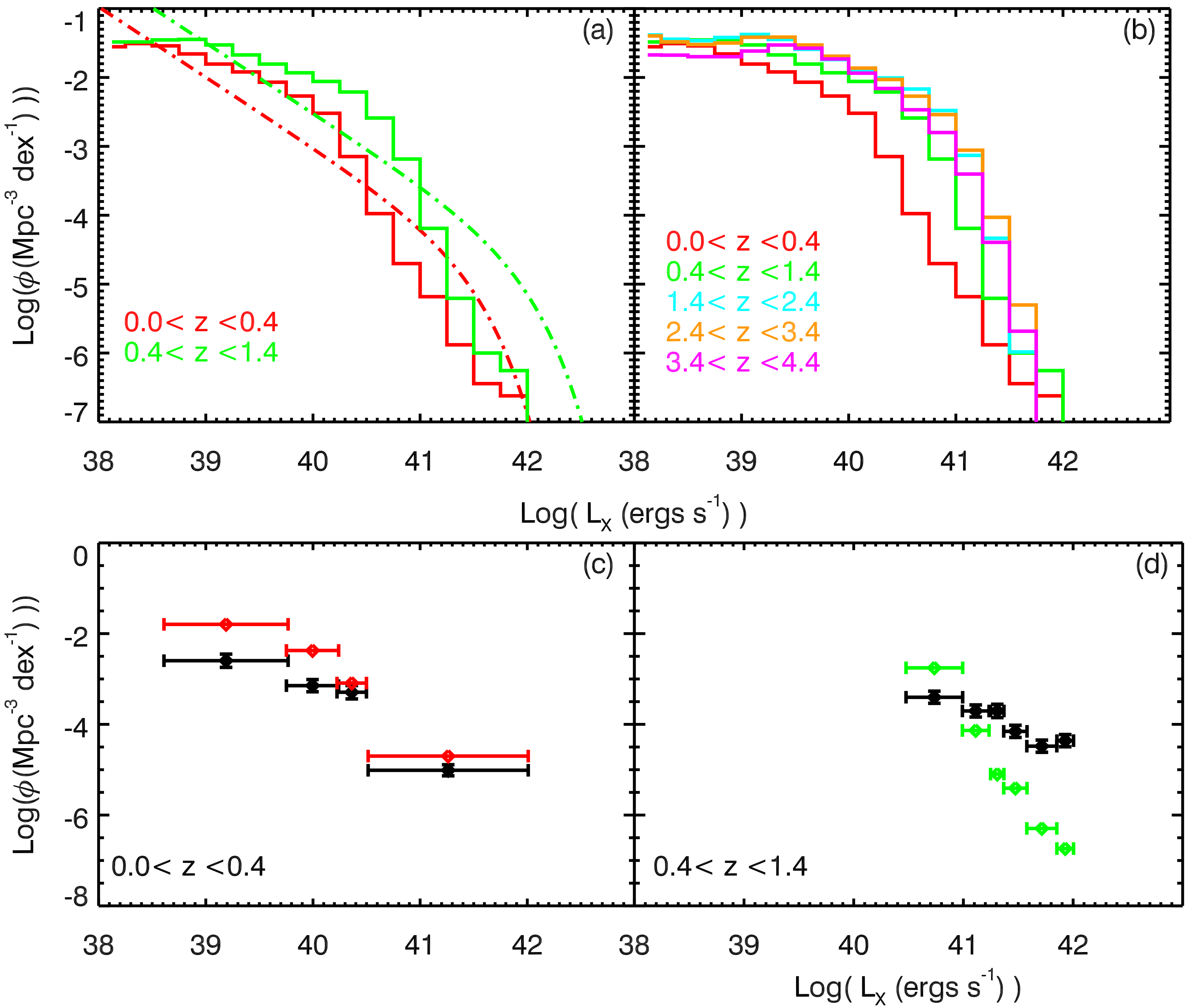


Bell et al. (2004): 1.15 – 0.31*z – 0.08*(M_V – 5*log(h) +20)

X-ray luminosity functions of early type galaxies



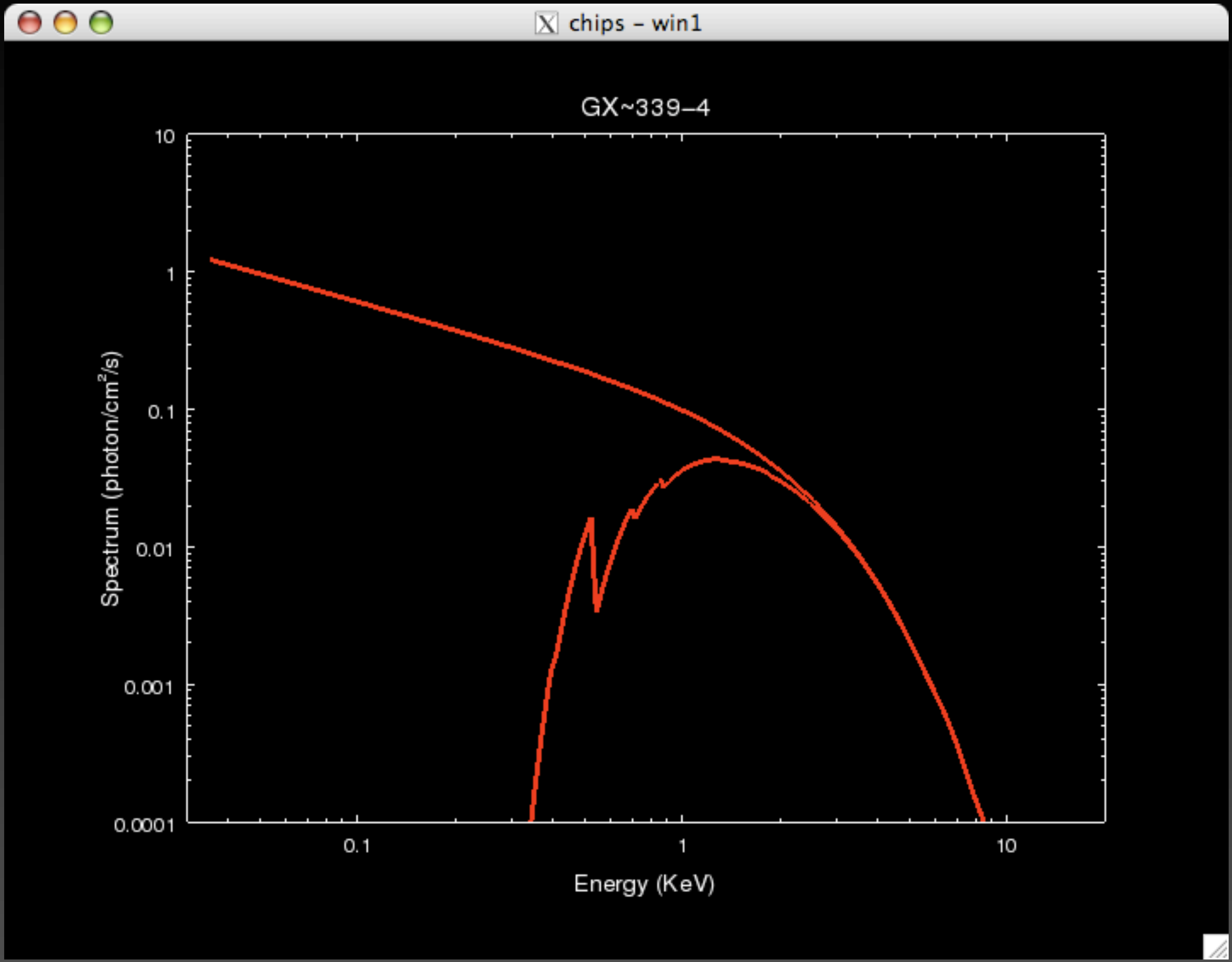
X-ray luminosity functions of late type galaxies



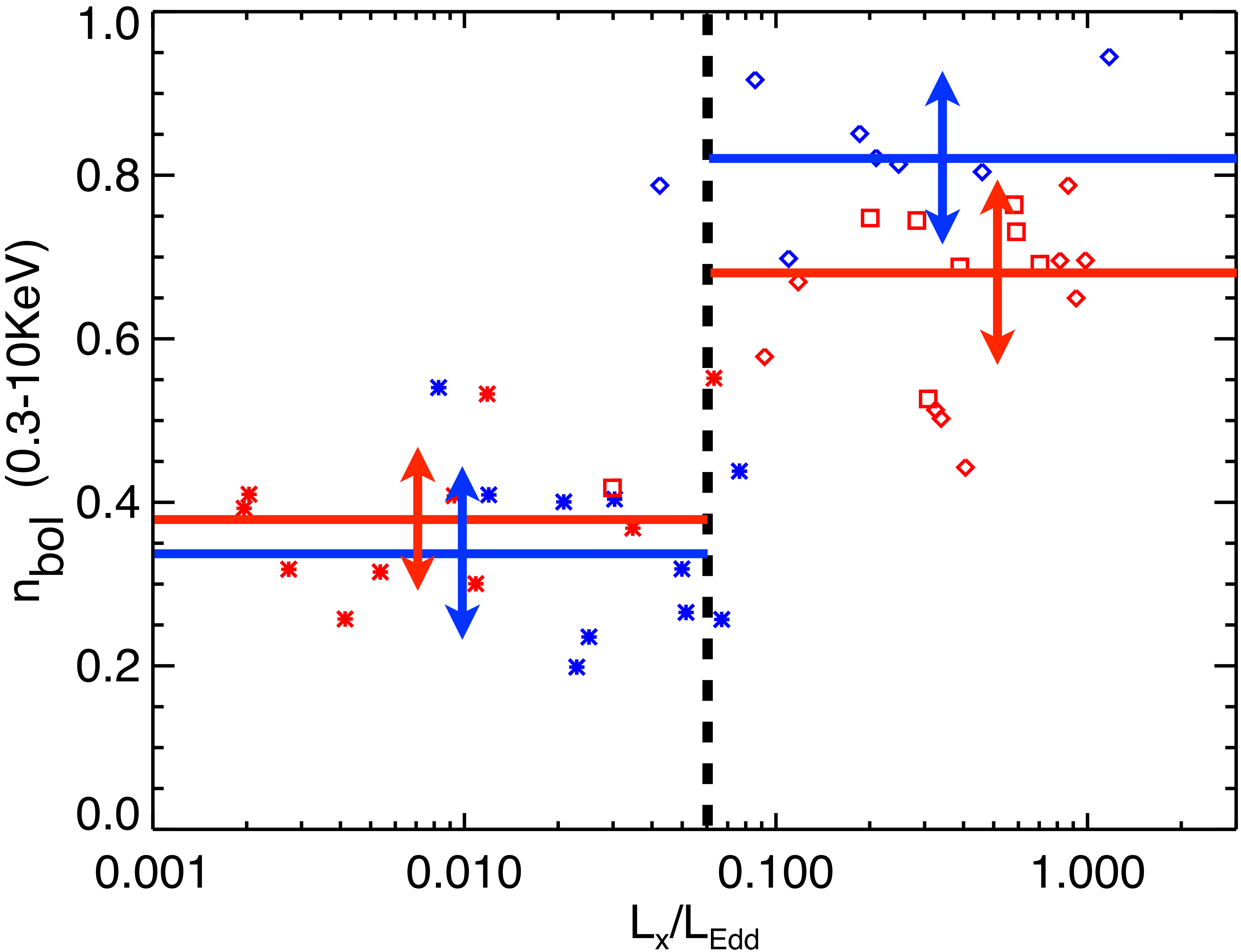
Bolometric Corrections

Object	REF	CO_Type	State	N_H	T_dbb	N_DBB	Gamma_PL	N_PL	Line_Temp	Fe_FWHM	N_Fe	Porb	D	D_err	Mco_min	Mco_max
IGR~J00291+5934	**Wu2010**	NS	HS	0.5	1.01	0.0012	1.38	0.085	0	0	0	2.46	3.1	0.5	1.4	1.4
EXO~0748-676	**Wu2010**	NS	TD	0.1	1.19	0.0073	3.1	0.7	6.4	4.59	0.02	3.82	6.8	0.9	1.4	1.4
EXO~0748-676	**Wu2010**	NS	HS	0.1	1.6	0.0006	1.36	0.017	0	0	0	3.82	6.8	0.9	1.4	1.4
XTE~J0929-314	**Wu2010**	NS	HS	0.12	0.72	0.0009	1.79	0.084	0	0	0	0.73	10	5	1.4	1.4
4U~1608-52	**Wu2010**	NS	TD	1.8	2.15	0.25	3.76	78	6.4	1.87	0.5	12.89	3.8	0.3	1.4	1.4
4U~1608-52	**Wu2010**	NS	HS	1.8	0.73	0.0022	1.97	0.303	6.4	1.1	0.0024	12.89	3.8	0.3	1.4	1.4
MXB~1659-298	**Wu2010**	NS	TD	0.2	2.15	0.0048	2.76	0.98	6.3	0.97	0.0033	7.11	10	0	1.4	1.4
XTE~J1710-281	**Wu2010**	NS	TD	0.24	1.65	0.00046	2.52	0.098	0	0	0	3.28	14	2	1.4	1.4
1A~1744-361	**Wu2010**	NS	TD	0.3	2.08	0.03	2.9	2.2	0	0	0	1.62	7	2	1.4	1.4
1A~1744-361	**Wu2010**	NS	HS	0.3	1.6	0.0011	1.76	0.064	0	0	0	1.62	7	2	1.4	1.4
GRS~1747-312	**Wu2010**	NS	TD	0.6	2.22	0.0113	2.58	0.43	0	0	0	12.36	9.5	0	1.4	1.4
GRS~1747-312	**Wu2010**	NS	HS	0.6	1.42	0.0002	2.08	0.022	0	0	0	12.36	9.5	0	1.4	1.4
XTE~J1751-305	**Wu2010**	NS	HS	0.6	1.38	0.002	1.45	0.164	0	0	0	0.71	8	1	1.4	1.4
XTE~J1807-294	**Wu2010**	NS	HS	0.3	1.1	0.0004	1.72	0.16	0	0	0	0.668	-	-	1.4	1.4
SAX~J1808.4-3658	**Wu2010**	NS	HS	0.12	0.79	0.0085	1.51	0.27	6.4	1.14	0.0073	2.014	3	0.6	1.4	1.4
XTE~J1814-338	**Wu2010**	NS	HS	0.15	1.15	0.0004	1.49	0.052	0	0	0	4.27	8	1.6	1.4	1.4
GS~1826-238	**Wu2010**	NS	HS	0.17	1.34	0.0014	1.29	0.14	0	0	0	2.088	6	2	1.4	1.4
HETE~J1900.1-2455	**Wu2010**	NS	HS	0.1	1.11	0.0026	1.41	0.075	0	0	0	1.39	5	0	1.4	1.4
4U~1908+005	**Wu2010**	NS	TD	0.3	1.97	0.154	3.89	49	6.4	1.62	0.22	18.95	5	0	1.4	1.4
4U~1908+005	**Wu2010**	NS	HS	0.3	1.39	0.01	1.29	0.68	6.4	1.16	0.016	18.95	5	0	1.4	1.4
XTE~J2123-058	**Wu2010**	NS	TD	0.06	1.91	0.0109	2.51	0.99	0	0	0	5.96	8.5	2.5	1.4	1.4
XTE~J2123-058	**Wu2010**	NS	HS	0.06	0.88	0.00015	1.72	0.015	0	0	0	5.96	8.5	2.5	1.4	1.4
XTE~J1118+480	**Wu2010**	BH	HS	0.013	0	0	1.748	0.298	0	0	0	4.1	1.8	0.5	6.5	7.2
GS~1354-64	**Wu2010**	BHC	HS	0.7	1.82	2.39	1.12	0.086	0	0	0	-	-	-	-	-
4U~1543-47	**Wu2010**	BH	TD	0.4	0.979	7876	2.63	5.6	6	0.83	0.09	26.8	7.5	0.5	7.4	11.4
4U~1543-47	**Wu2010**	BH	HS	0.4	1.67	1.14	1.56	0.076	0	0	0	26.8	7.5	0.5	7.4	11.4
XTE~J1550-564	**Wu2010**	BH	SPL	2	4.18	2.25	2.92	234	5.9	1.72	0.68	37	5.3	2.3	8.4	10.8
XTE~J1550-564	**Wu2010**	BH	TD	2	1.137	3822	2.18	3.86	0	0	0	37	5.3	2.3	8.4	10.8
XTE~J1550-564	**Wu2010**	BH	HS	2	0.78	1588	1.6	4.56	6.3	1.16	0.095	37	5.3	2.3	8.4	10.8
XTE~J1650-500	**Wu2010**	BHC	SPL	0.6	1.08	176	1.52	1.55	6.3	1.42	0.057	-	-	-	-	-
XTE~J1650-500	**Wu2010**	BHC	TD	0.6	0.664	8147	2.25	0.94	6.5	0.69	0.005	-	-	-	-	-
XTE~J1650-500	**Wu2010**	BHC	HS	0.6	1.66	21.1	1.33	0.85	6.53	0.8	0.012	-	-	-	-	-
GRO~J1655-40	**Wu2010**	BH	SPL	0.6	4.05	4.4	2.64	84	6.3	0.87	0.26	62.9	3.2	0.2	6	6.6
GRO~J1655-40	**Wu2010**	BH	TD	0.6	1.324	1089	2.4	2.55	0	0	0	62.9	3.2	0.2	6	6.6
GRO~J1655-40	**Wu2010**	BH	HS	0.6	1.33	222	2.06	4.7	0	0	0	62.9	3.2	0.2	6	6.6
GX~339-4	**Wu2010**	BH	TD	0.4	0.888	3377	2.16	0.43	6.4	0.6	0.009	42.1	4	-	2	-
GX~339-4	**Wu2010**	BH	HS	0.4	1.21	66	1.34	1.05	6.3	0.22	0.045	42.1	4	-	2	-
XTE~J1859+226	**Wu2010**	BH	TD	0.2	1.14	841	2.54	15.1	0	0	0	9.2	11	-	7.6	12
XTE~J1859+226	**Wu2010**	BH	HS	0.2	1.03	103	1.5	1.18	6.4	1.18	0.023	9.2	11	-	7.6	12
GRS~1915+105	**Wu2010**	BH	TD	8	2.79	14.1	3.33	328	6.4	1.27	0.356	804	11.5	0.5	10	18
GRS~1915+105	**Wu2010**	BH	HS	8	0.69	5767	1.97	6.5	6.3	1.28	0.092	804	11.5	0.5	10	18
4U~1543-47	**McClintock&Remillard**	BH	TD	0.3	1.01	7419	2.57	5.42	6.4	0.61	0.0479	26.8	7.5	0.5	7.4	11.4
XTE~J1550-564	**McClintock&Remillard**	BH	TD	2	1.12	3289	4.76	152	0	0	0	37	5.3	2.3	8.4	10.8
GRO~J1655-40	**McClintock&Remillard**	BH	TD	0.9	1.16	1559	2.85	1.01	0	0	0	62.9	3.2	0.2	6	6.6
GX~339-4	**McClintock&Remillard**	BH	TD	0.2	0.71	2520	2.02	0.08	6.4	1.05	0.0032	42.1	4	-	2	-
GRS~1915+105	**McClintock&Remillard**	BH	TD	6	2.19	62	3.46	33.4	0	0	0	804	11.5	0.5	10	18
4U~1630-47	**McClintock&Remillard**	BHC	TD	11	1.33	315	3.75	17.4	0	0	0	-	-	-	-	-
GRS~1739-278	**McClintock&Remillard**	BHC	TD	3	0.95	972	2.65	0.21	6.4	1.11	0.0068	-	-	-	-	-
XTE~J1748-288	**McClintock&Remillard**	BHC	TD	10.4	1.79	42.4	2.6	14.6	0	0	0	-	-	-	-	-
XTE~J1755-324	**McClintock&Remillard**	BHC	TD	0.2	0.75	1486	2.4	0.11	0	0	0	-	-	-	-	-
XTE~J2012+381	**McClintock&Remillard**	BHC	TD	0.8	0.85	1176	2.06	0.16	0	0	0	-	-	-	-	-
4U~1543-475	**McClintock&Remillard**	BH	HS	0.3	0.38	645	1.67	0.041	0	0	0	26.8	7.5	0.5	7.4	11.4
XTE~J1550-564	**McClintock&Remillard**	BH	HS	2	0	0	1.7	0.108	0	0	0	37	5.3	2.3	8.4	10.8
GRO~J1655-40	**McClintock&Remillard**	BH	HS	0.9	0.77	228	1.93	0.571	6.4	1	0.0065	62.9	3.2	0.2	6	6.6
GX~339-4	**McClintock&Remillard**	BH	HS	0.2	0	0	1.75	0.168	6.4	0.9	0.0013	42.1	4	0	2	0
GRS~1915+105	**McClintock&Remillard**	BH	HS	6	0	0	2.11	0.231	6.4	0.91	0.0458	804	11.5	0.5	10	18
XTE~J1118+480	**McClintock&Remillard**	BH	HS	0.01	0	0	1.72	0.267	0	0	0	4.1	1.8	0.5	6.5	7.2
GS~1354-644	**McClintock&Remillard**	BHC	HS	0.7	0	0	1.48	0.47	6.4	0.1	0.0008	-	-	-	-	-
XTE~J1748-288	**McClintock&Remillard**	BHC	HS	10.4	0.48	5302	1.88	0.293	6.4	0.66	0.0045	-	-	-	-	-
GRS~1758-258	**McClintock&Remillard**	BHC	HS	1	0	0	1.67	0.053	6.4	0.36	0.0004	-	-	-	-	-
Cyg~X-1	**McClintock&Remillard**	BH	HS	0.5	0	0	1.68	0.446	6.4	1.44	0.0206	134.4	2	0.1	6.9	13.2
4U~1543-47	**McClintock&Remillard**	BH	SPL	0.3	0.93	3137	2.47	6.85	6.4	0.82	0.0347	26.8	7.5	0.5	7.4	11.4
XTE~J1550-564	**McClintock&Remillard**	BH	SPL	2	3.31	7.76	2.82	200	6.4	1.3	0.2136	37	5.3	2.3	8.4	10.8
GRO~J1655-40	**McClintock&Remillard**	BH	SPL	0.9	2.22	9.89	2.65	75.3	6.4	1.32	0.2321	62.9	3.2	0.2	6	6.6
GX~339-4	**McClintock&Remillard**	BH	SPL	0.2	0.89	1917	2.42	2.34	6.4	0.97	0.0178	42.1	4	-	2	-
GRS~1915+105	**McClintock&Remillard**	BH	SPL	6	1.19	115	2.62	28.5	6.4	0.9	0.0396	804	11.5	0.5	10	18
4U~1630-47	**McClintock&Remillard**	BHC	SPL	11	1.73	46	2.65	17	0	0	0	-	-	-	-	-
GRS~1739-278	**McClintock&Remillard**	BHC	SPL	3	1.01	1116	2.61	2.95	6.4	1.53	0.0341	-	-	-	-	-
XTE~J1748-288	**McClintock&Remillard**	BHC	SPL	10.4	1.36	210	2.92	26.2	0	0	0	-	-	-	-	-
XTE~J1859+226	**McClintock&Remillard**	BH	SPL	0.5	1.03	1164	2.55	14.5	6.4	1.33	0.0426	9.2	11	0	7.6	12
Cyg~X-1	**McClintock&Remillard**	BH	SPL	0.5	0.49	55708	2.68	7.65	6.4	0.73	0.027	134.4	2	0.1	6.9	13.2

Bolometric Corrections



Bolometric Corrections



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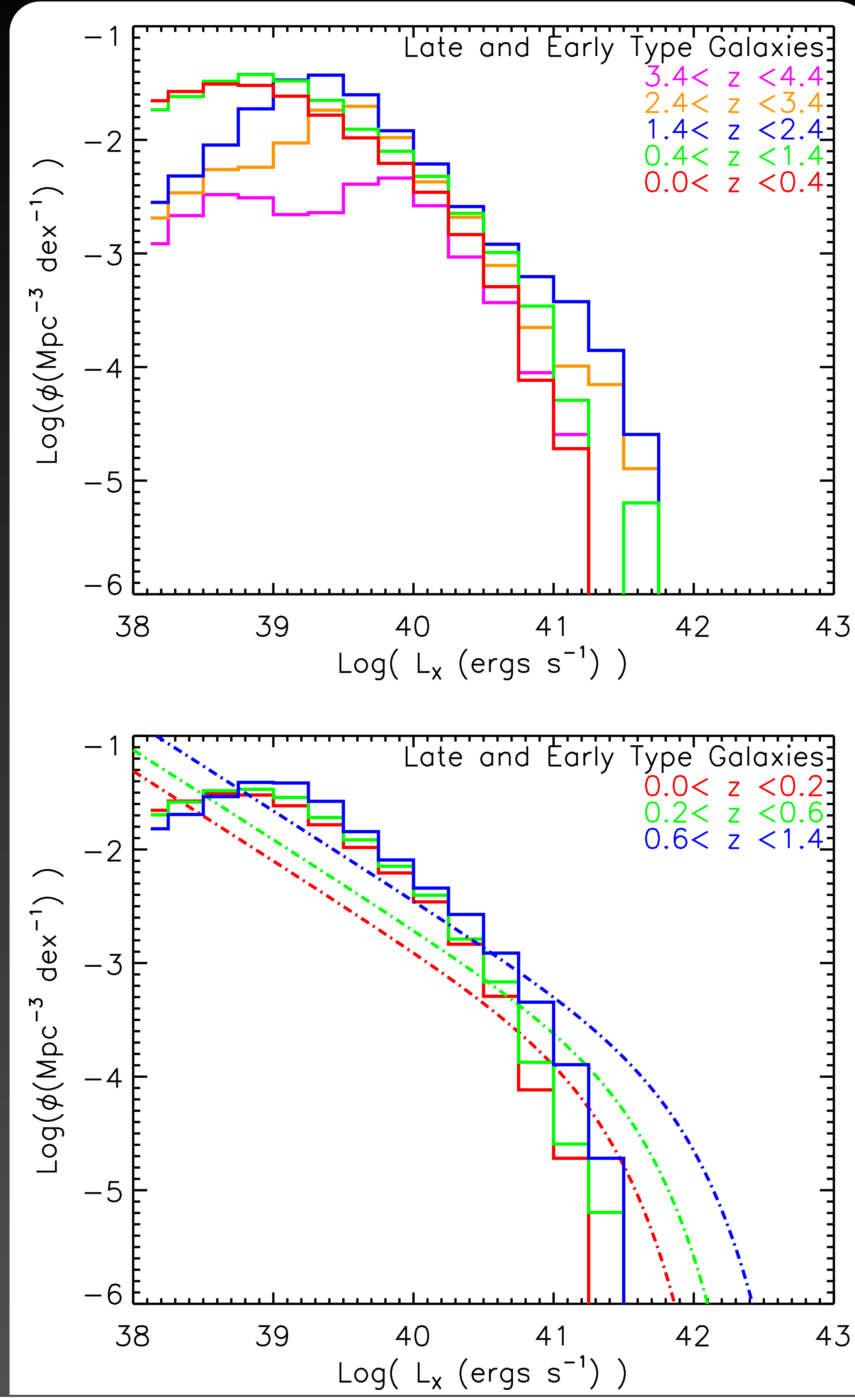
Work in Progress...

- Comparison in a galaxy by galaxy basis
- Modeling the spectral states of XRBs to refine bolometric corrections
- Modeling of selection effects in galaxy surveys
- Use as a constraint the XLFs of the most well observed nearby ellipticals, after revisiting their observational age estimates.
- Do LMXBs or HMXBs dominate our universe today?
- What is their relative contribution as a function of redshift?
- Is energy feedback from XRBs important in galaxy formation and evolution?



Outline

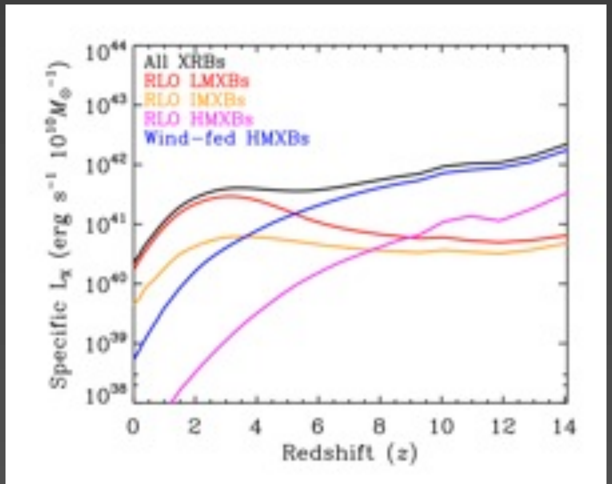
- Motivation
- StarTrack and Millennium simulations
- Constraining the model with observations
- Summary and next steps

Exploring the Parameter Space

- For the first time we are taking into account **simultaneously multiple observational constraints**
- Preliminary parameter study: 25 PS models varying:
  CE efficiency, Stellar winds, SN kicks
  IMF, initial mass ratio and orbital period distribution
- Dominant effects:
  CE efficiency for LMXB and **Stellar winds for HMXBs**

LMXBs **HMXBs**

$\alpha_{ce}=0.5$



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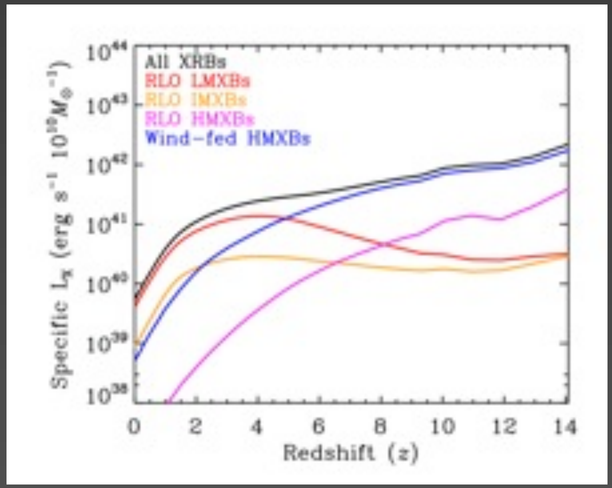
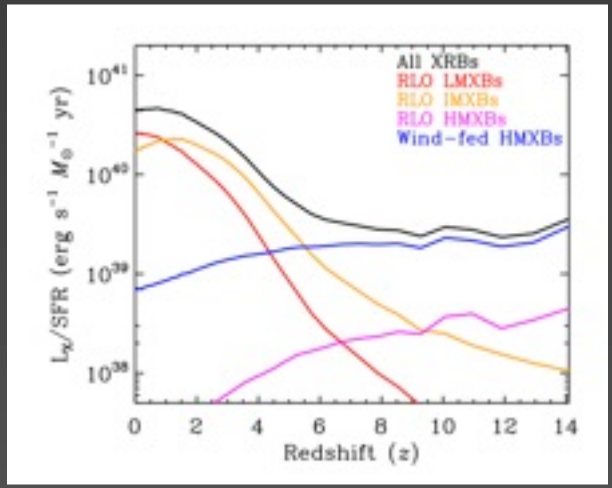


$\eta_{wind}=2.0$



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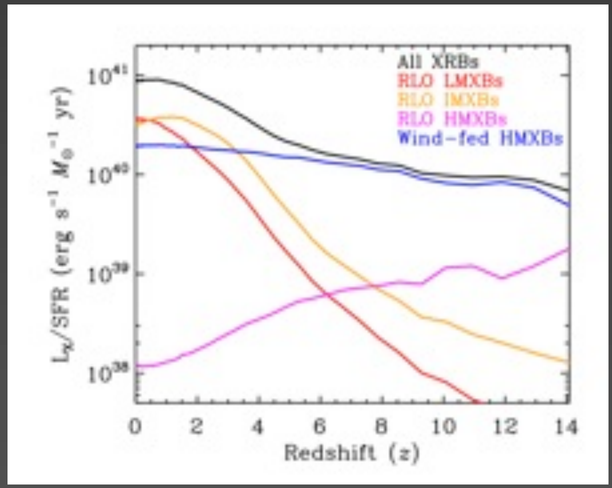

Exploring the Parameter Space

For the first time we are taking into account **simultaneously multiple observational constraints**

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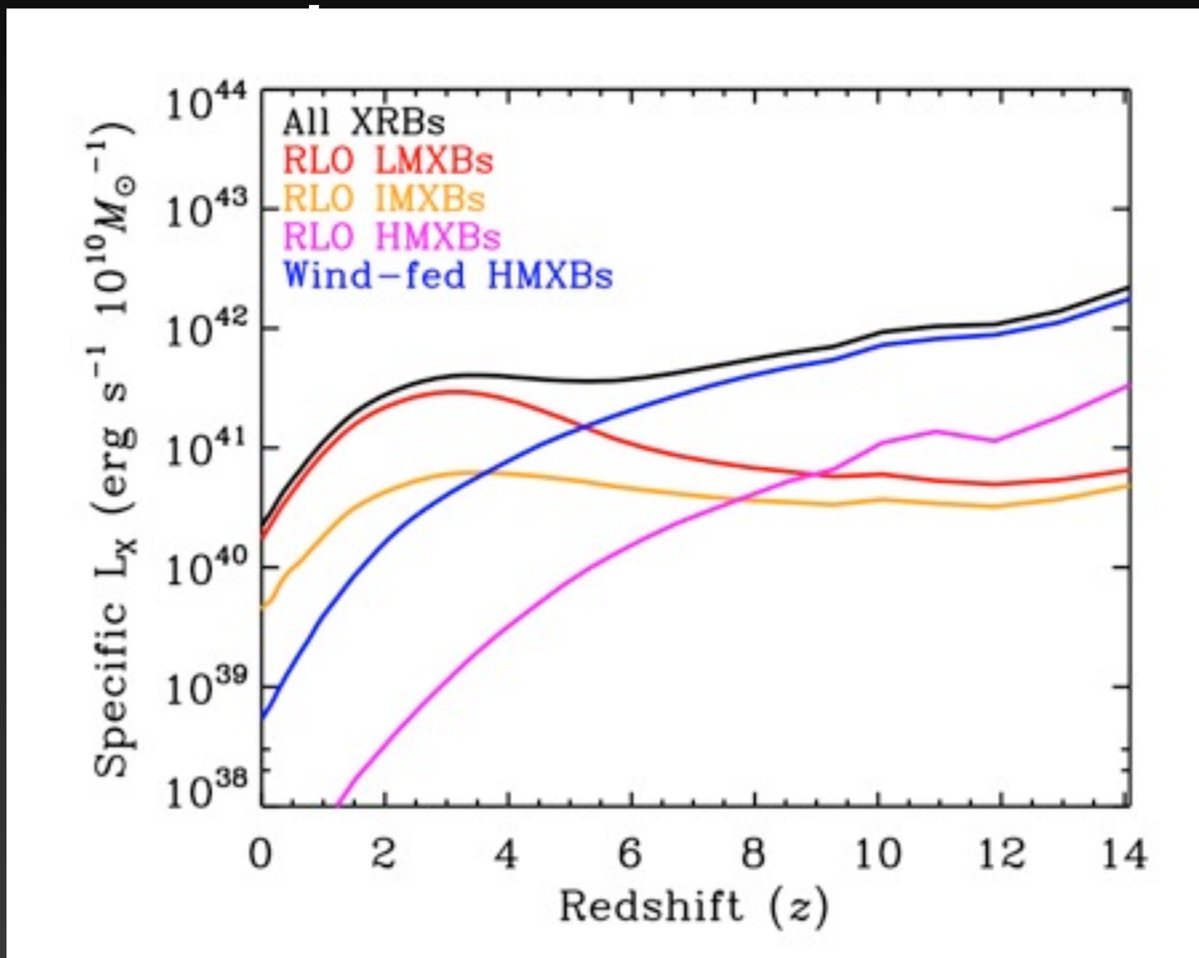
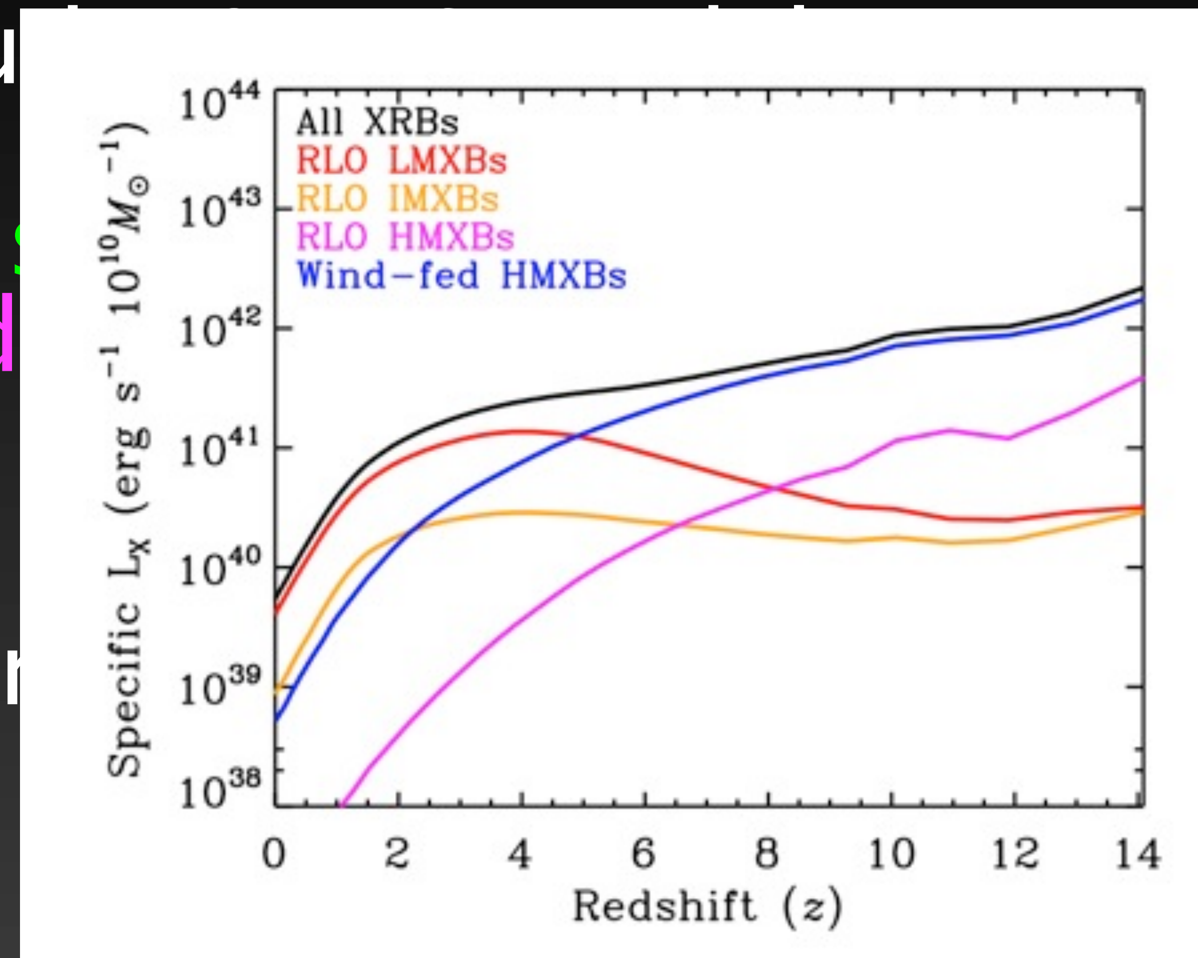
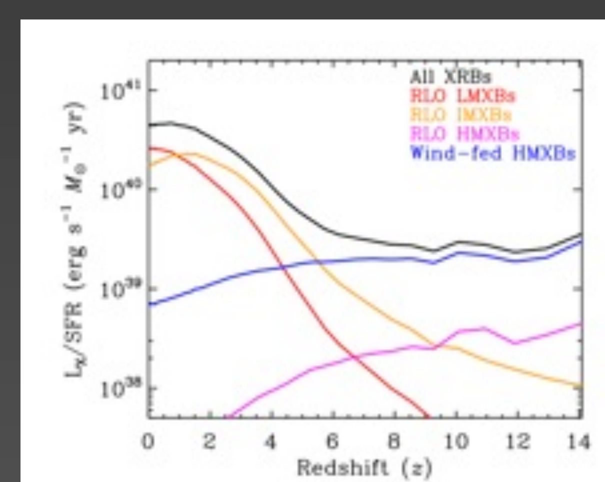
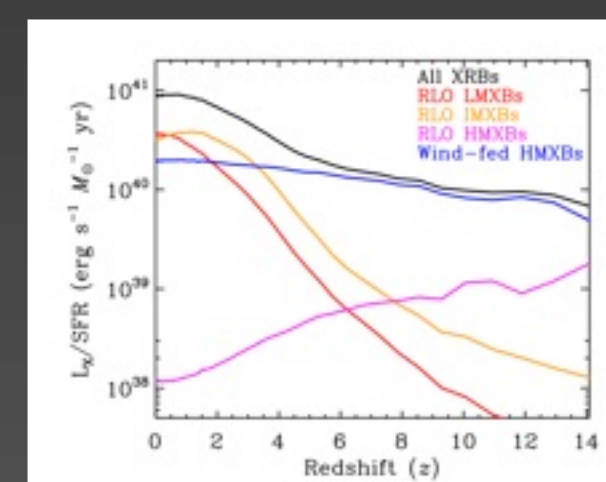




$\alpha_{ce}=0.5$ $\alpha_{ce}=0.1$ $\eta_{wind}=2.0$ $\eta_{wind}=0.25$





Exploring the Parameter Space

- For the first time we are taking into account **simultaneously multiple observational constraints**

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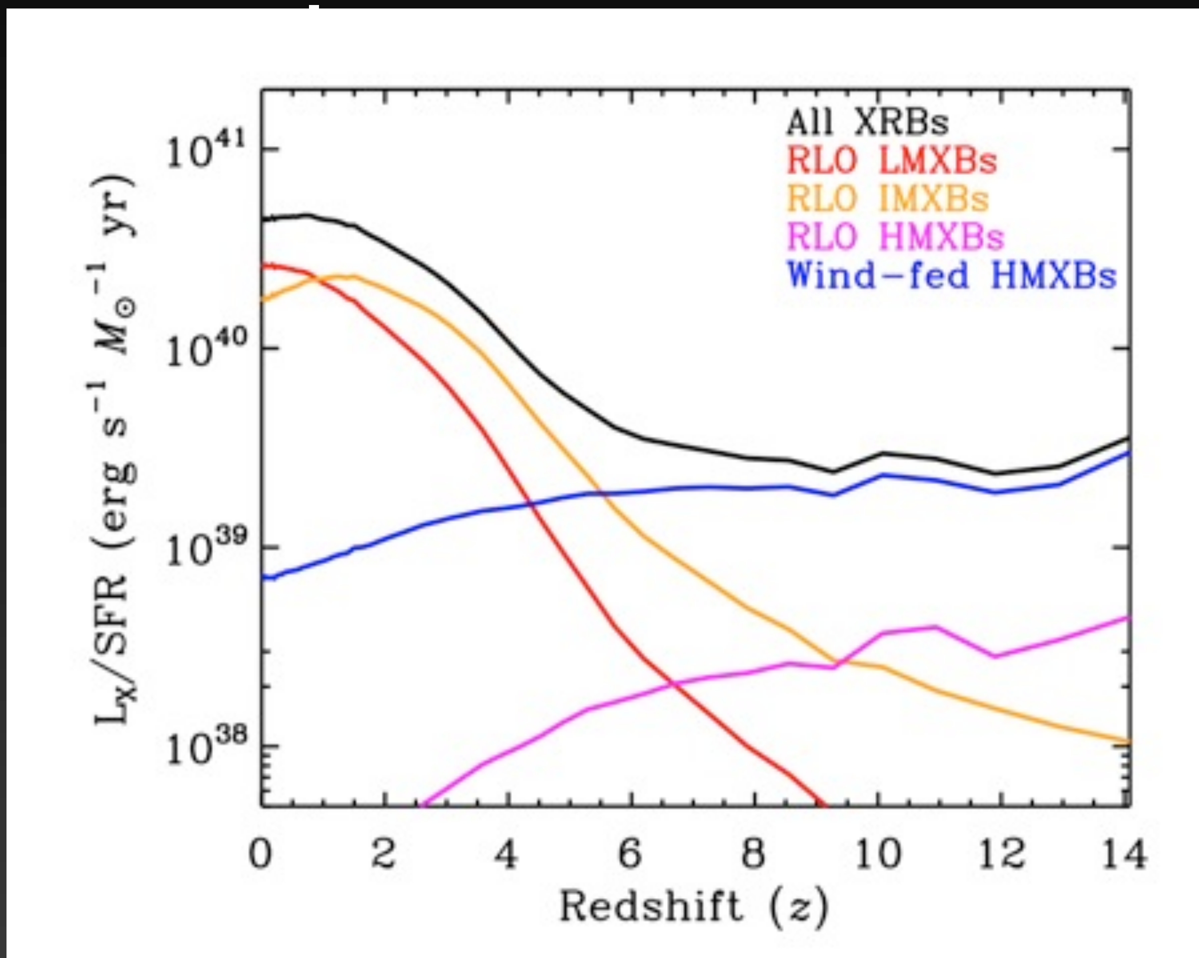

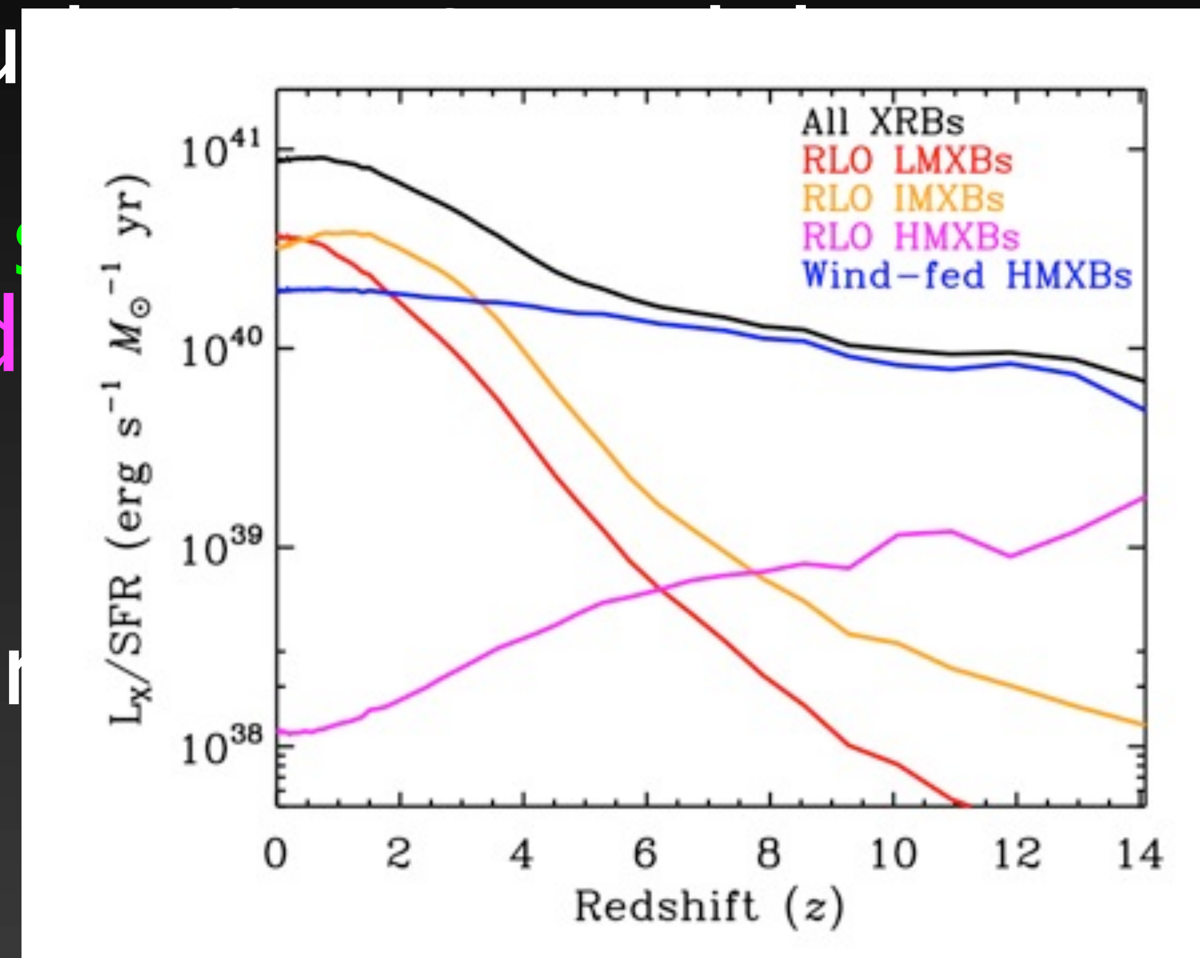

$\alpha_{ce}=0.5$ $\alpha_{ce}=0.1$ $\eta_{wind}=2.0$ $\eta_{wind}=0.25$

Modeling the X-ray Luminosity from a Single Stellar Population