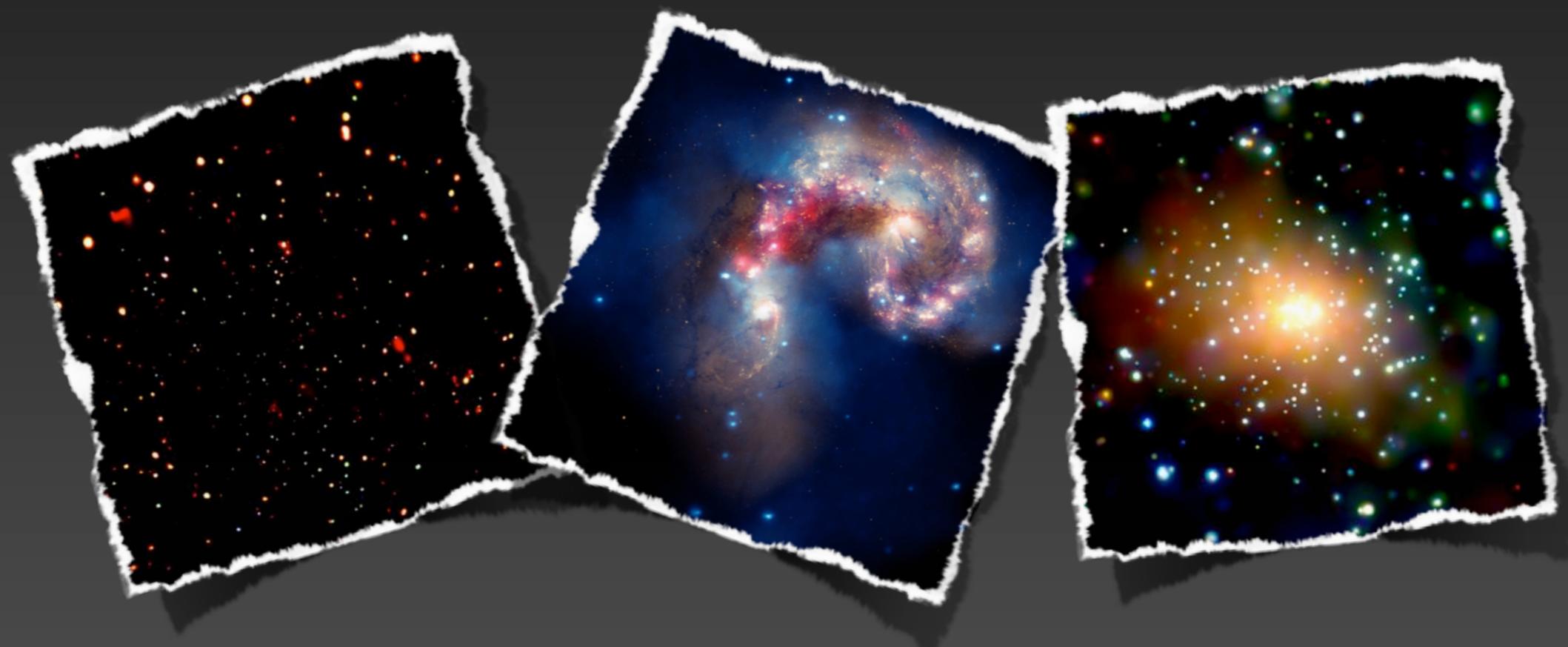


# *Evolution of X-ray Binaries Across Cosmic Time and Energy Feedback at High Redshift*

Tassos Fragos

*CfA/ITC Fellow*



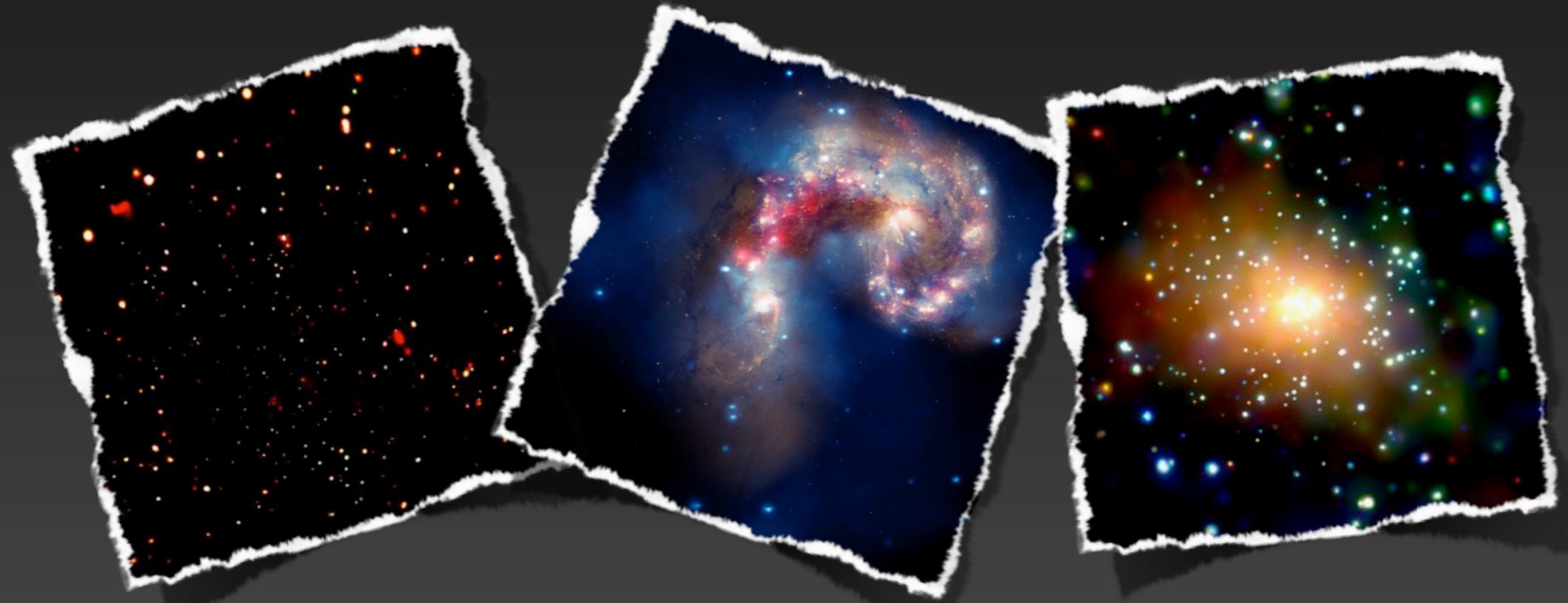
*Harvard-Smithsonian CfA  
Center for Astrophysics*

*Institute for Theory and Computation  
Harvard University*

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

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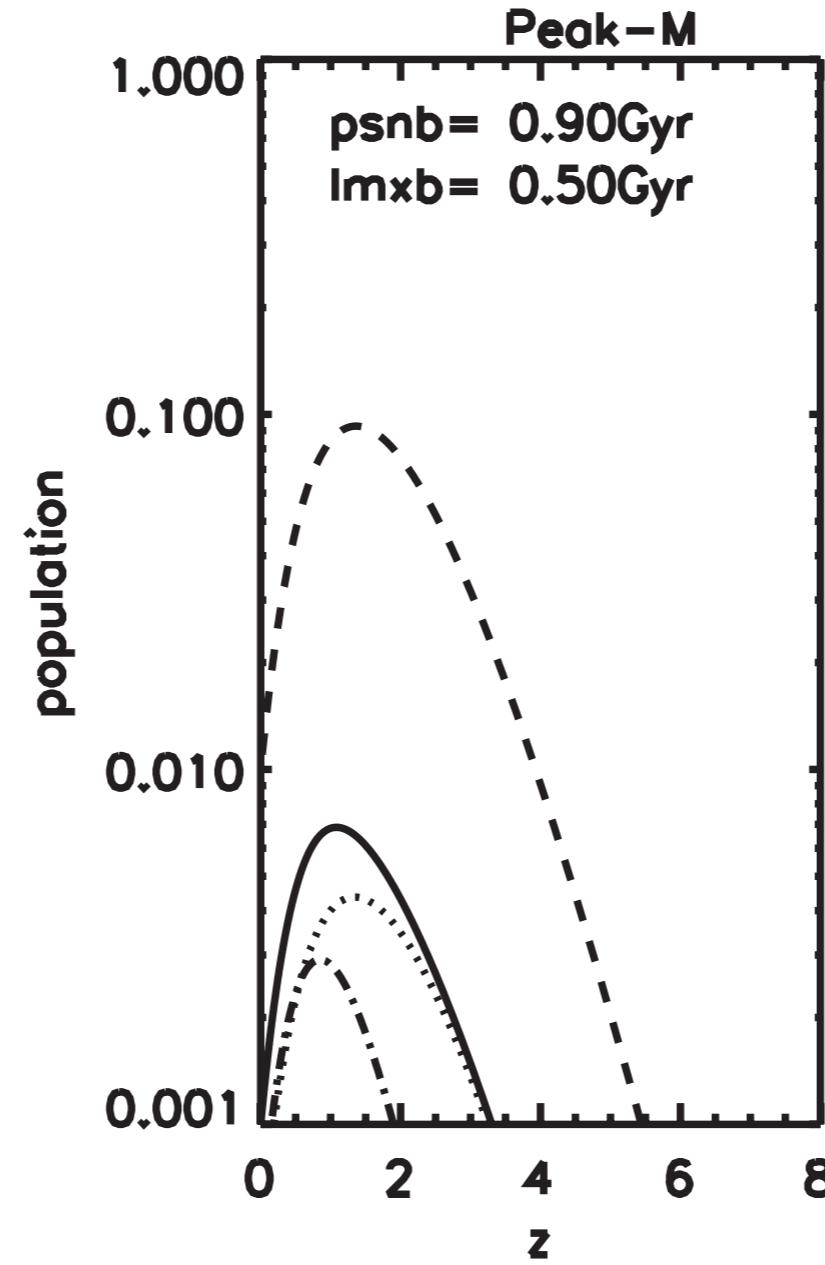
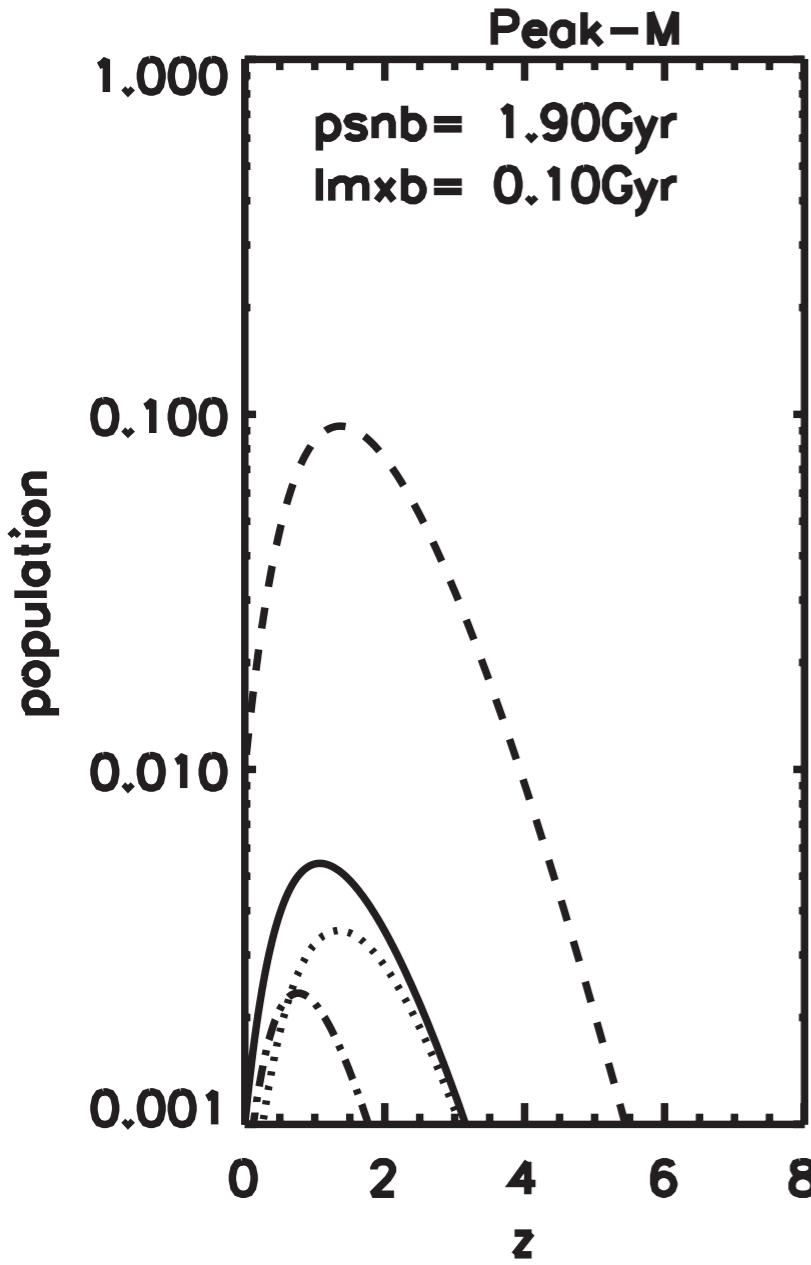
**with M. Tremmel, B. Lehmer, P. Tzanavaris,  
A. Hornschemeier, V. Kalogera A. Zezas, K. Belczynski**

*Harvard-Smithsonian CfA  
Center for Astrophysics*

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Harvard University*

# Existing Theoretical Models

White & Ghosh 1998  
Ghosh & White 2001



Timescale estimates  
for binary evolution

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

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

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

Several Star Formation  
history models

New observational constraint and advances in theoretical understanding  
allow the development of **detailed population synthesis models**

# 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)

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

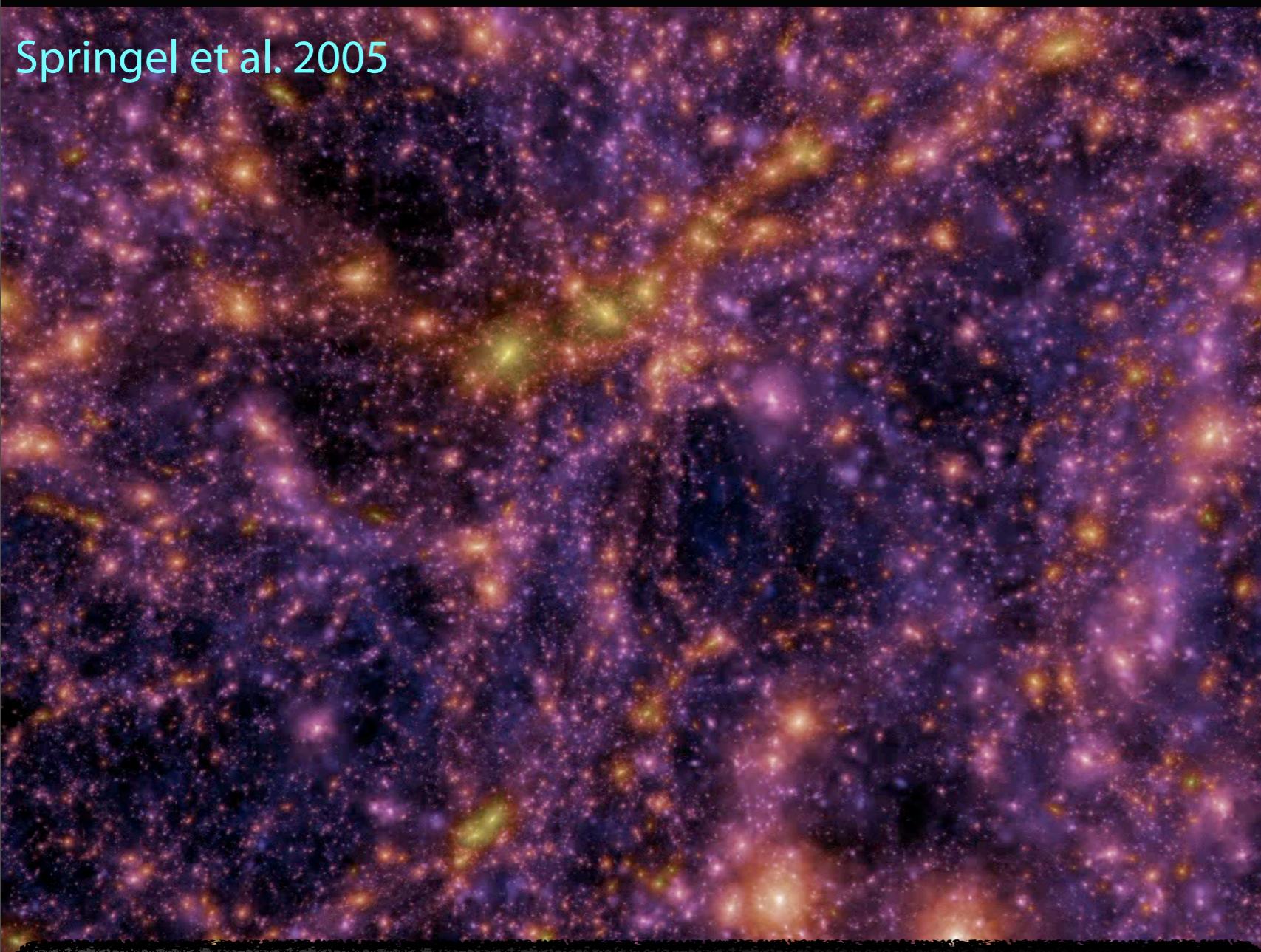
# Grid of New Simulations

Parameter	Value
$\alpha_{ce}$	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

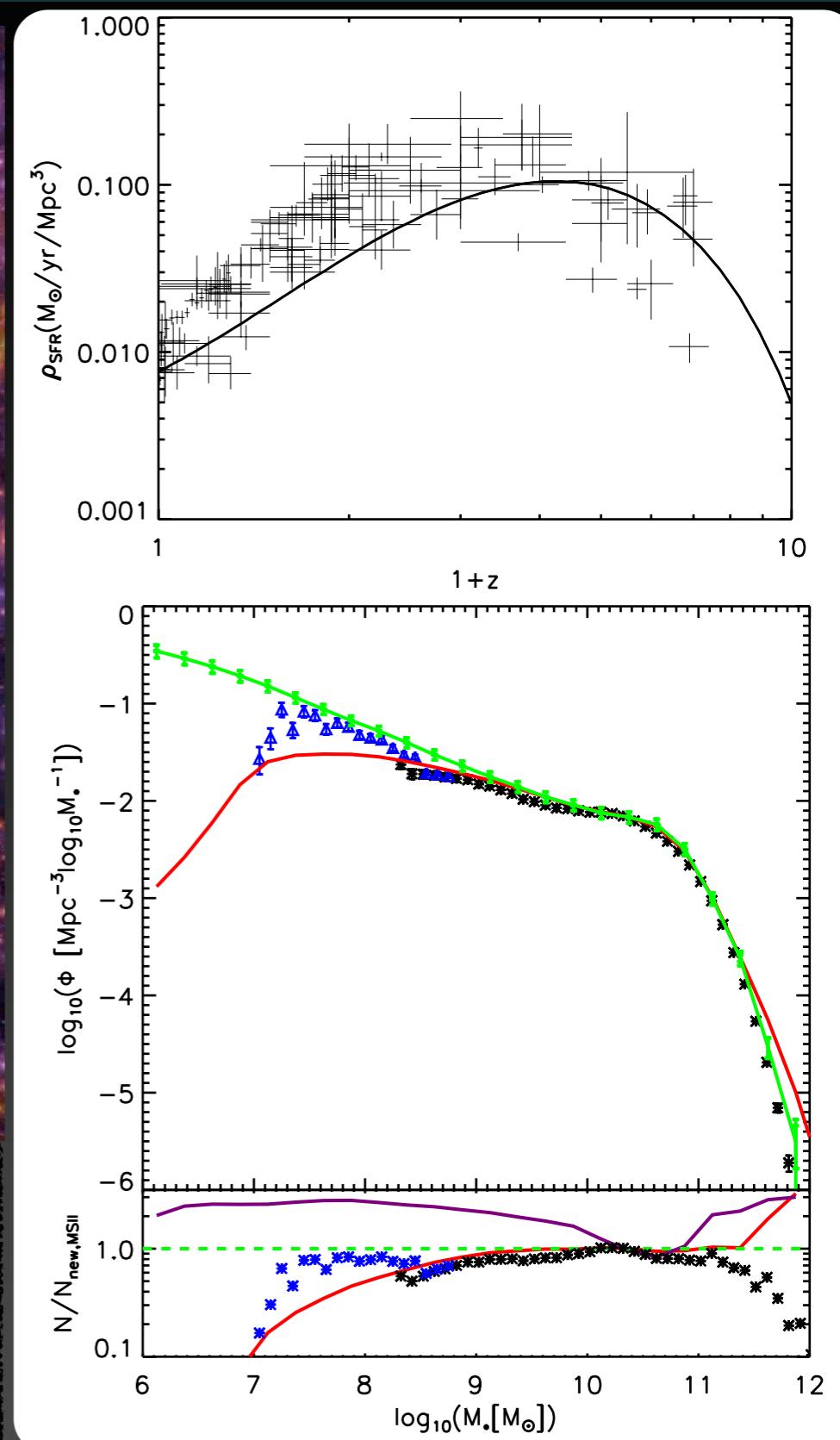
Springel et al. 2005



## Millennium-II Simulation

100Mpc<sup>3</sup>/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

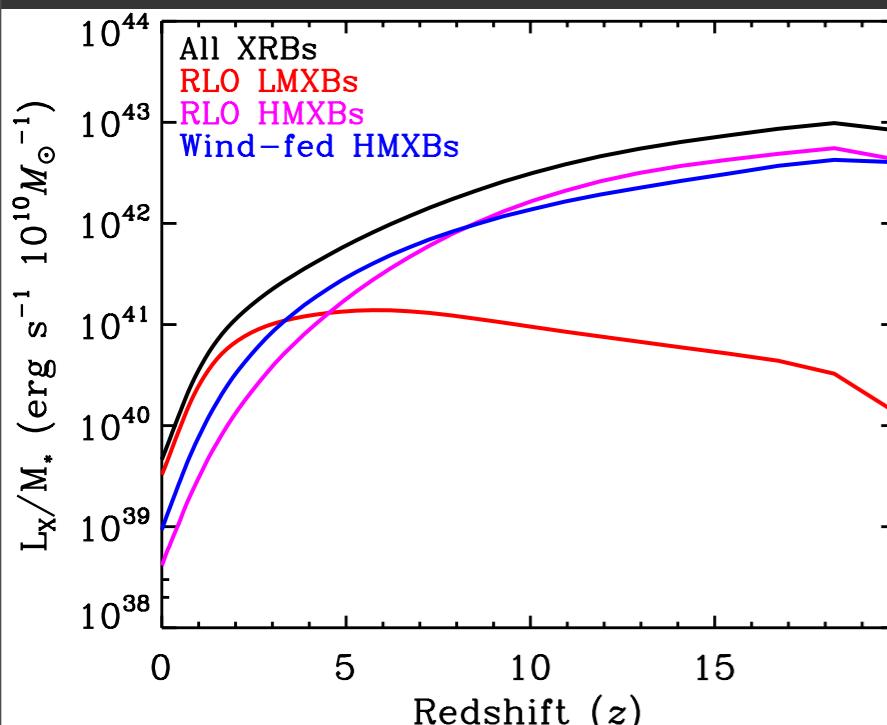


Hopkins 2007  
Li & White 2009 (SDSS DR7)  
Baldry et al. 2008 (DR4)

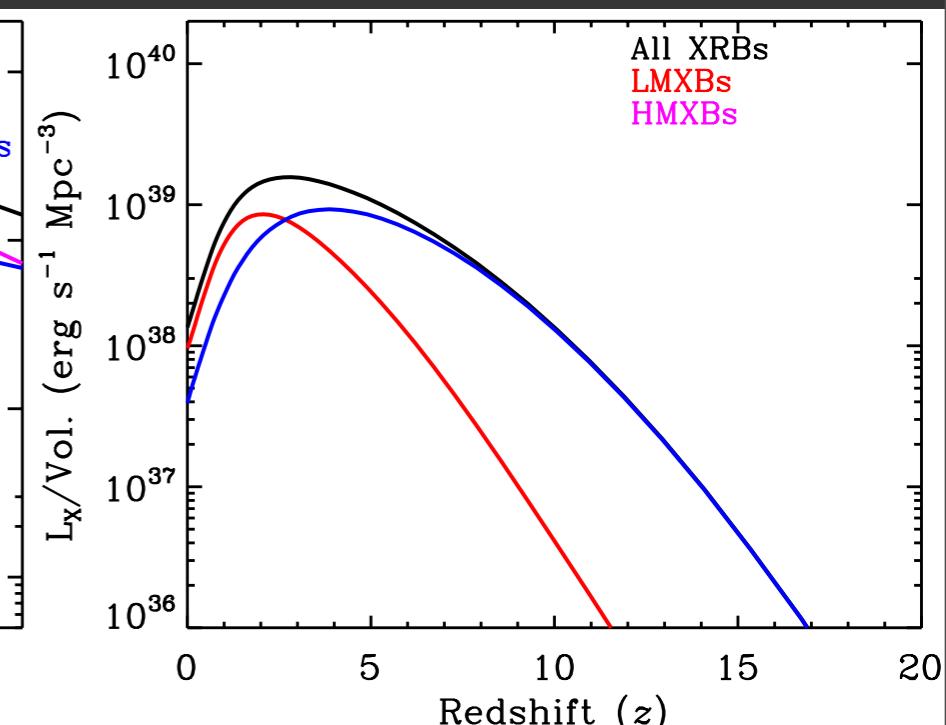
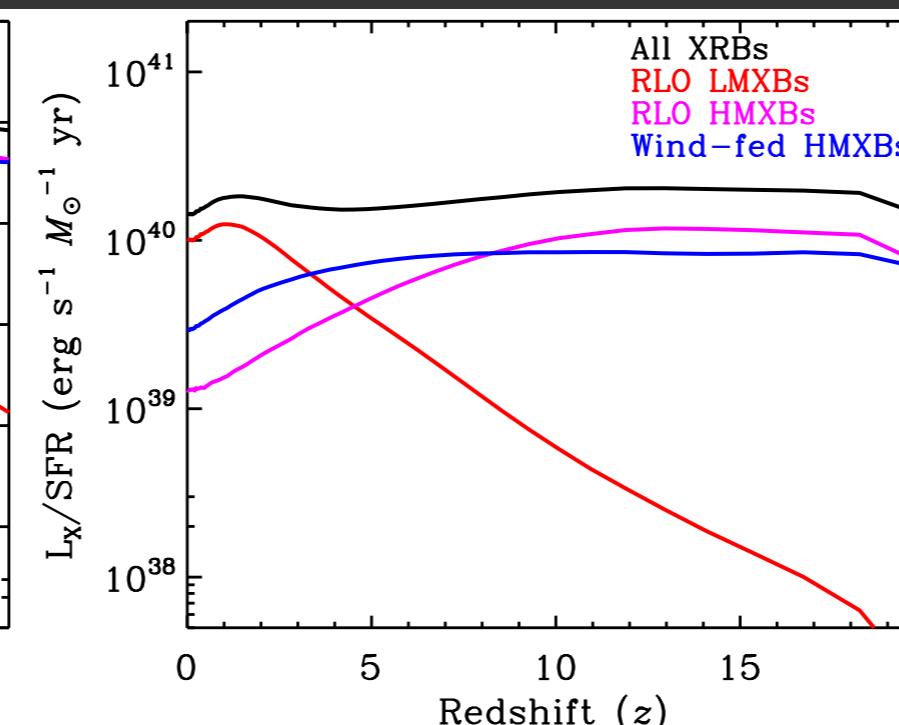
# Combining the two simulations

- 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:  $M_{\text{donor}} < 3M_{\odot}$



HMXB:  $M_{\text{donor}} > 3M_{\odot}$



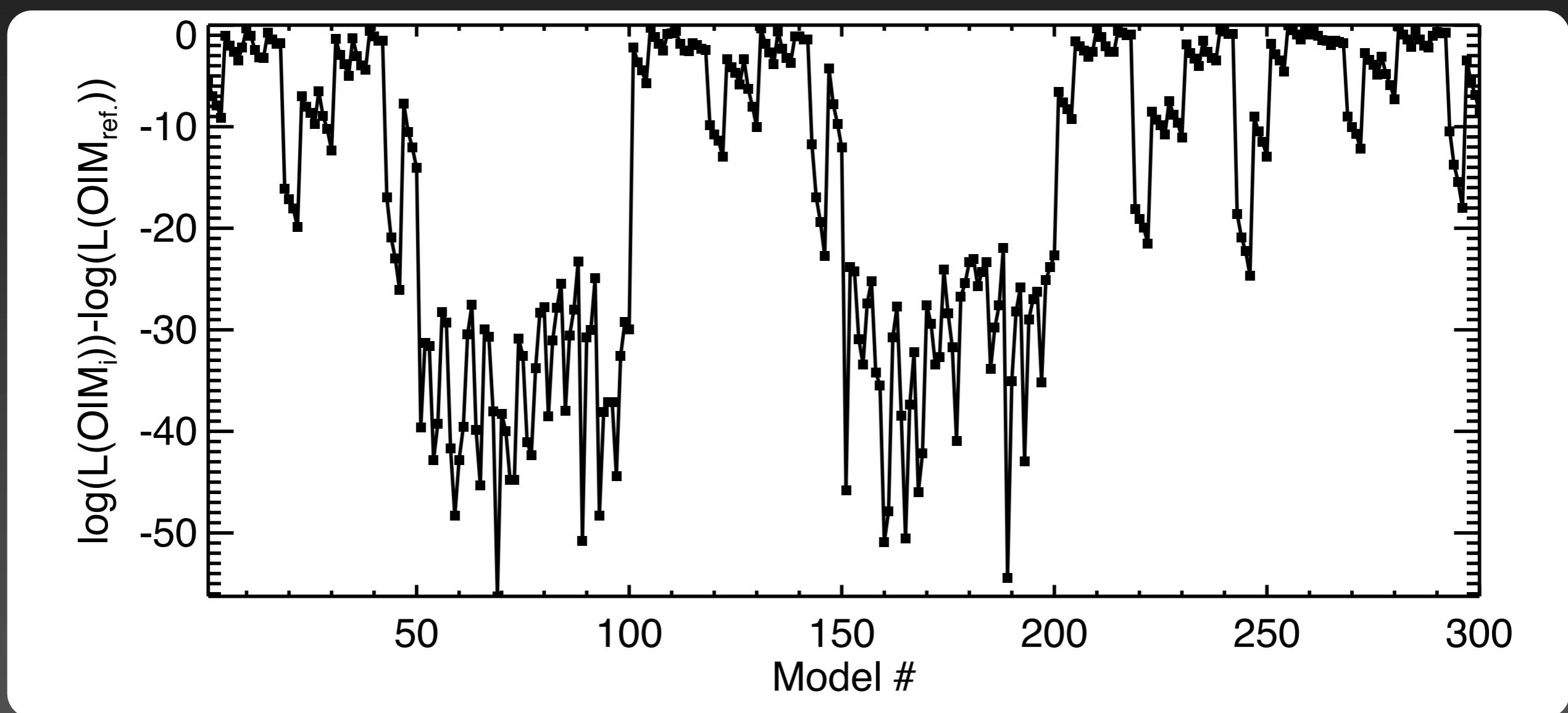
# Model Comparison

**L<sub>x</sub>/SFR :**

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

**L<sub>x</sub>/M<sub>\*</sub> :**

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



# Parameter Space

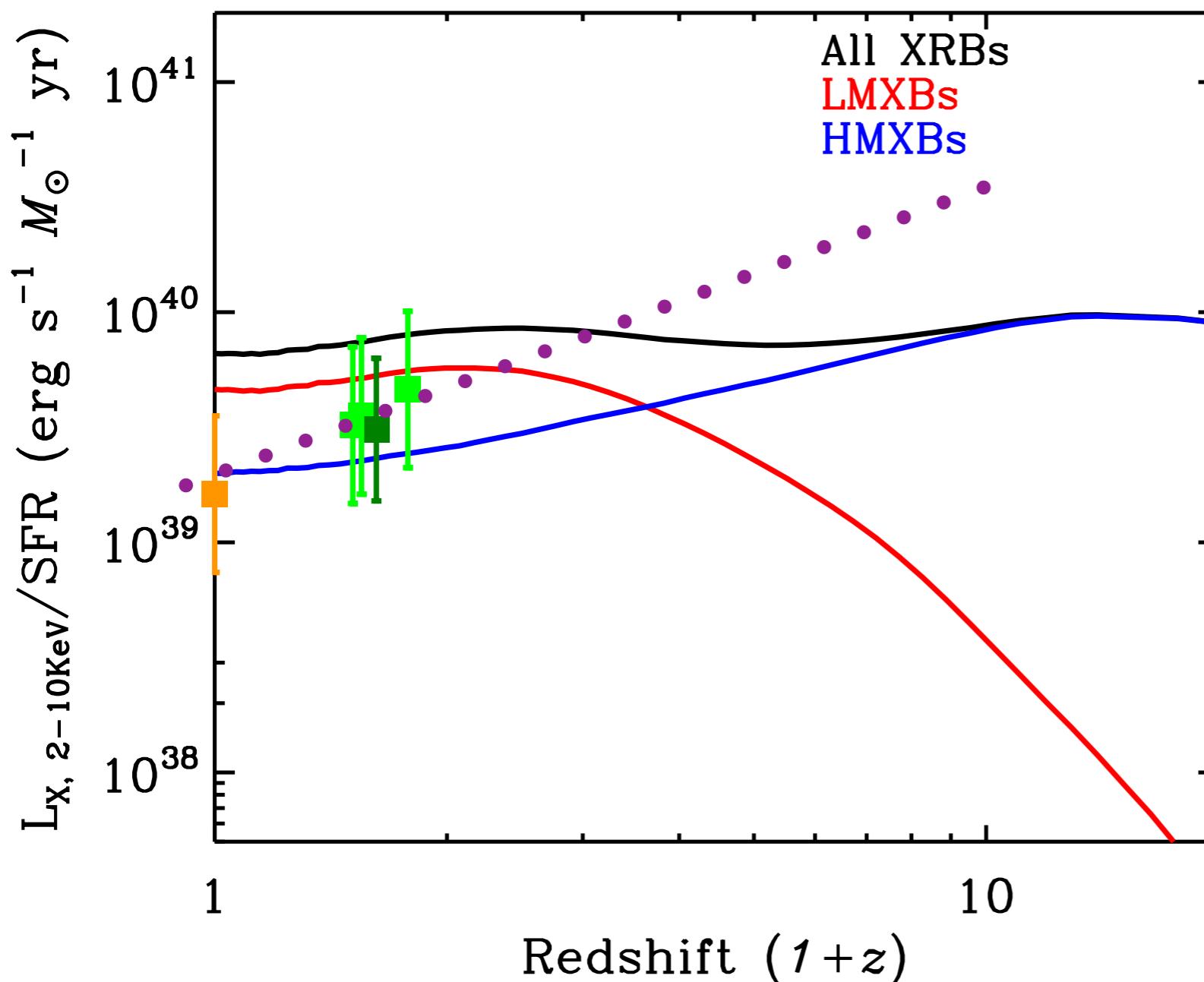
Parameter	Value
$\alpha_{ce}$	<b>0.1, 0.2, 0.3, 0.5</b>
IMF	<b>-2.7, -2.35</b>
Stellar Winds	<b>0.25, 1.0, 1.5, 2.0</b>
CE for HG primaries	0, 1
Mass Ratio	<b>Flat, Twin, mixture</b>
Kicks ECS/AIC	Yes, No
Kicks Direct C.C. BH	Yes, No

Low  $\alpha_{ce} \sim 0.1$  -- “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



$L_{\text{X}}/\text{SFR} \sim (1+z)^b$ ,  $b \leq 1.3$

Dijkstra et al., 2011

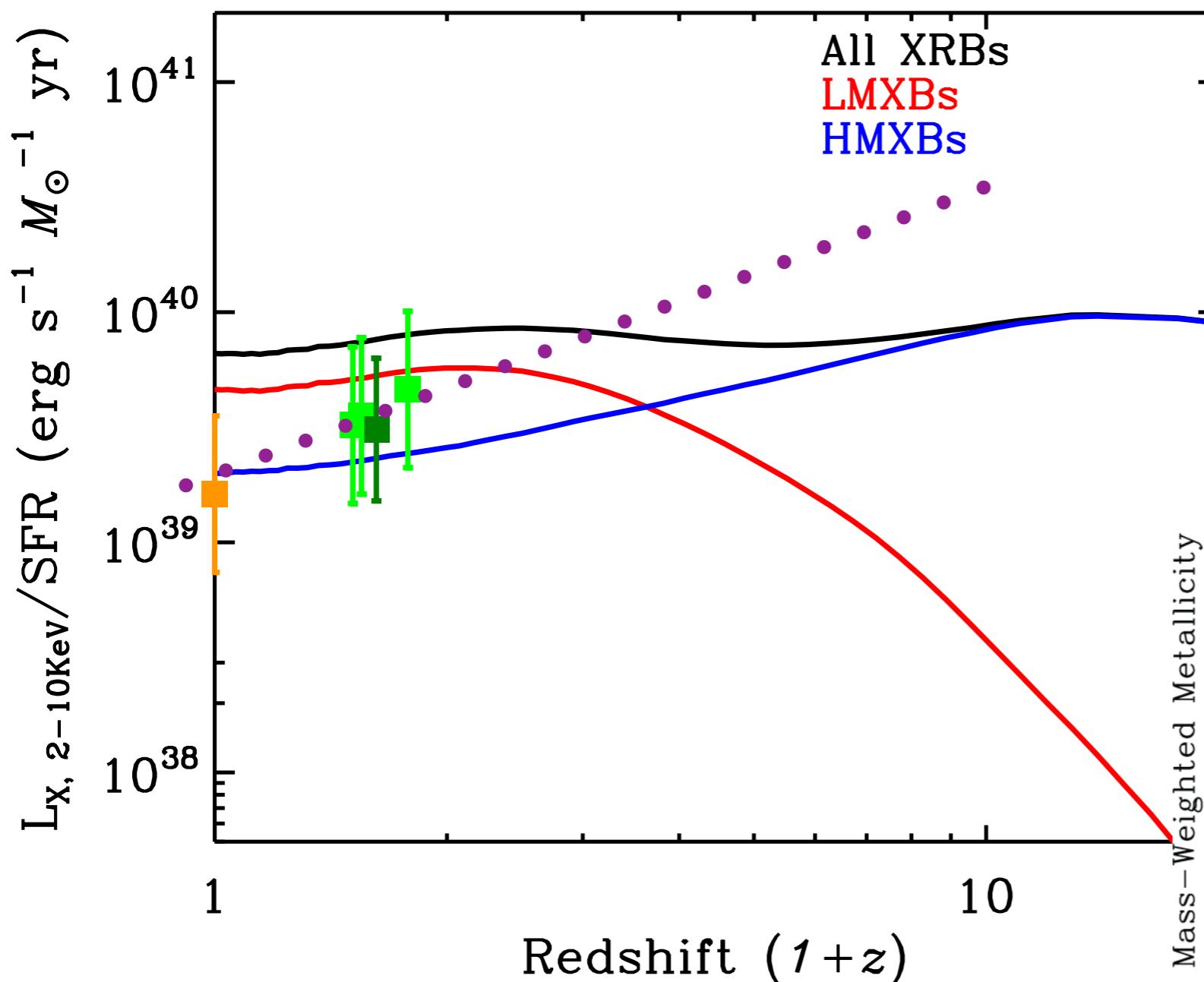
Lehmer et al., 2010

(Mineo et al. 2010)

Lehmer et al., 2008

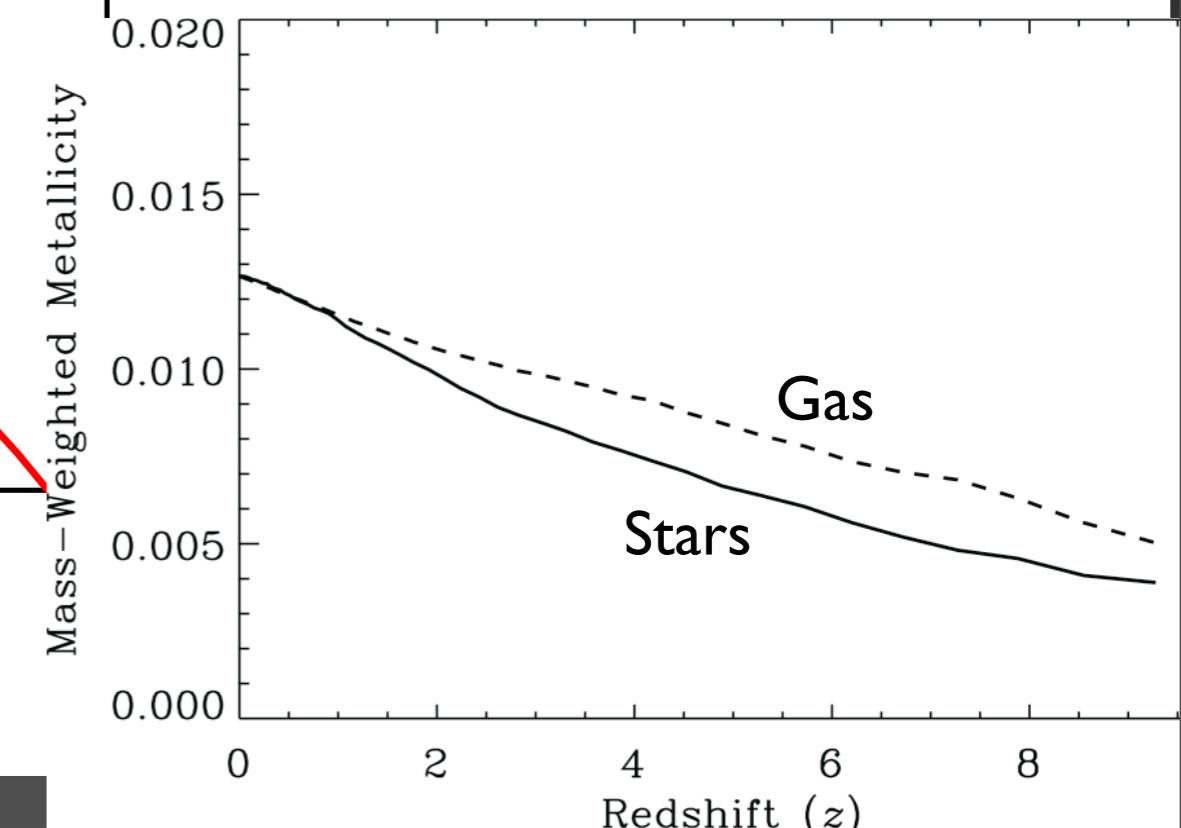
Symeonidis et al. 2011

# Observational Constraints I: HMXBs

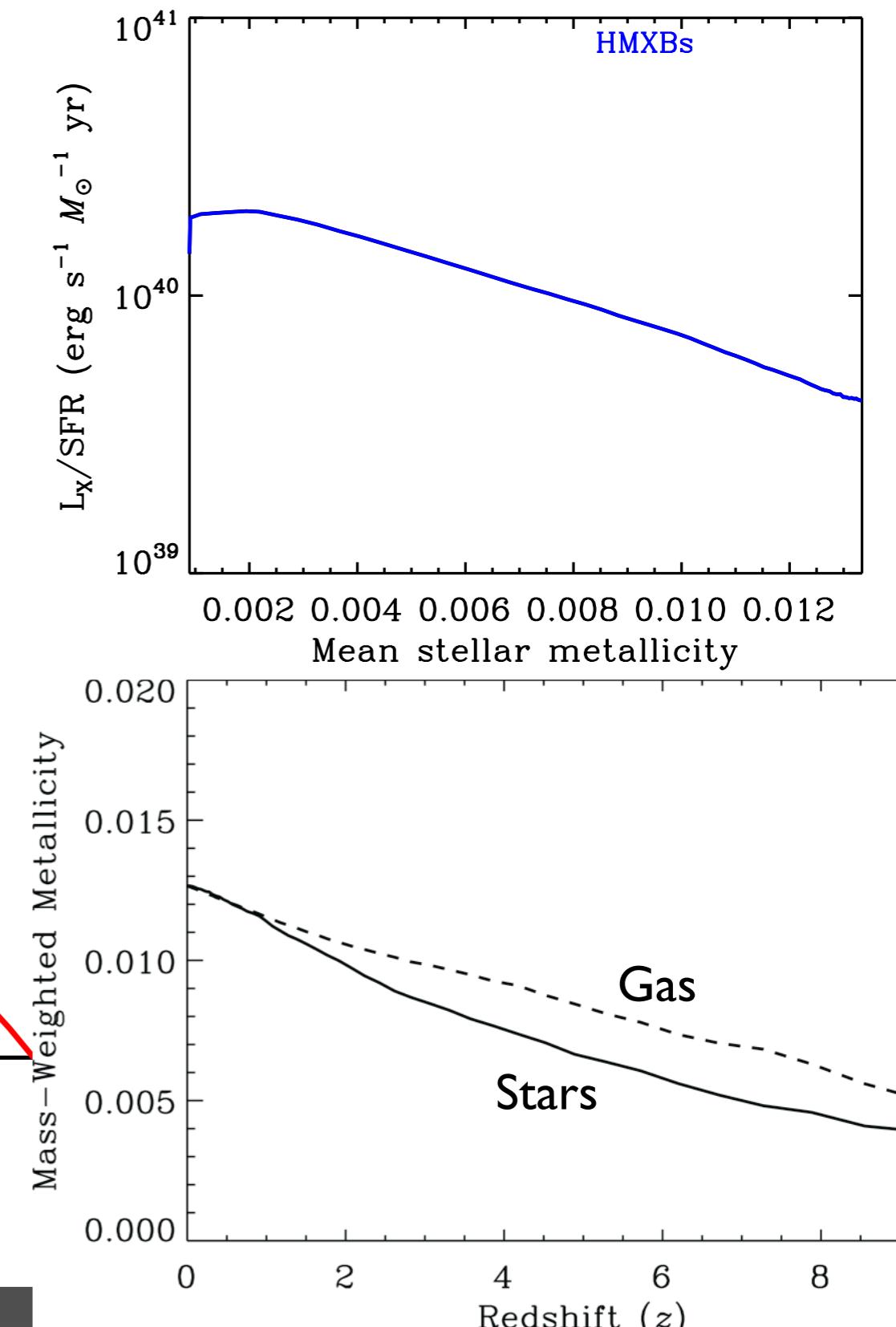
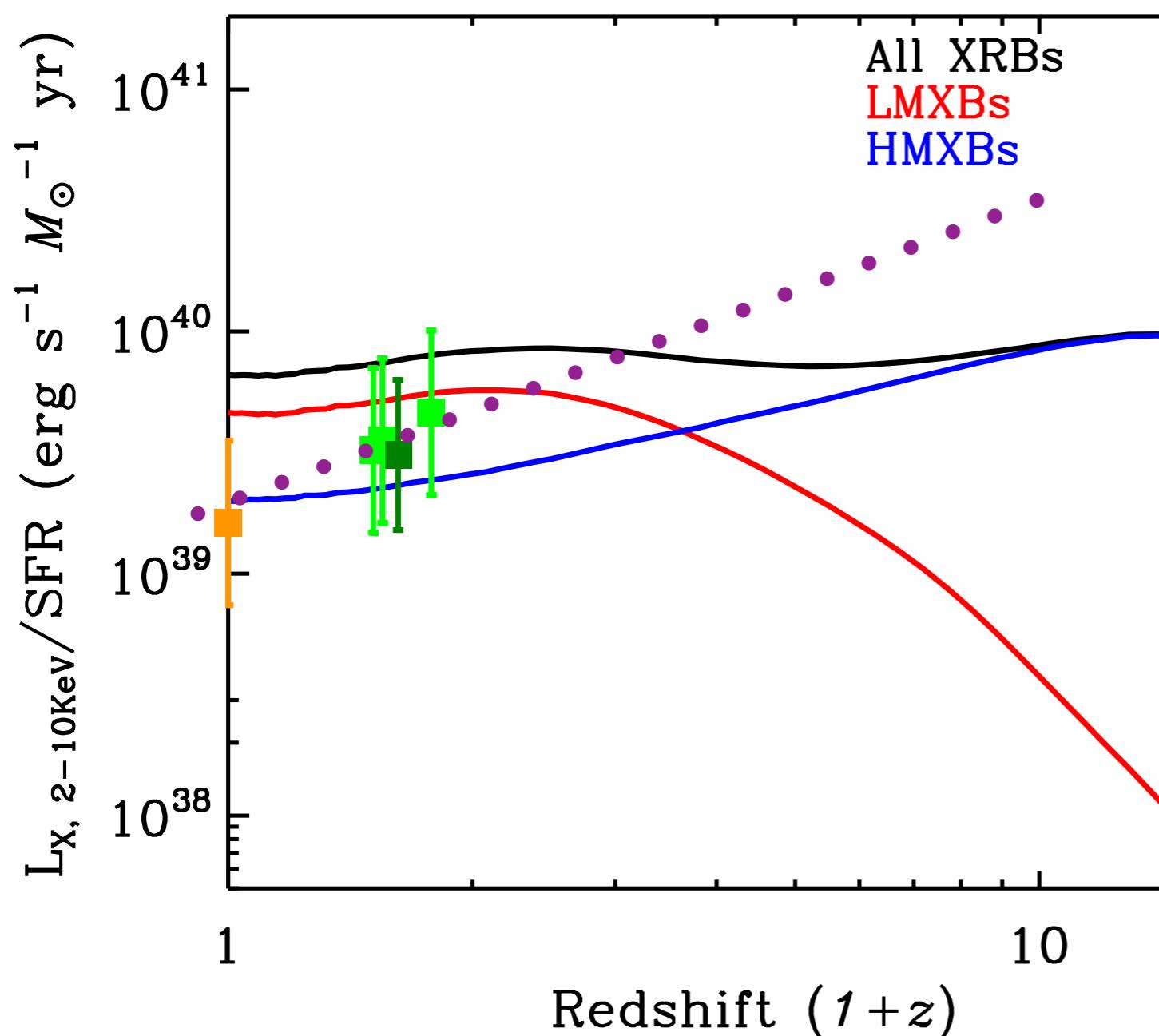


$L_{\text{X}}/\text{SFR} \sim (1+z)^b$ ,  $b \lesssim 1.3$   
Dijkstra et al., 2011

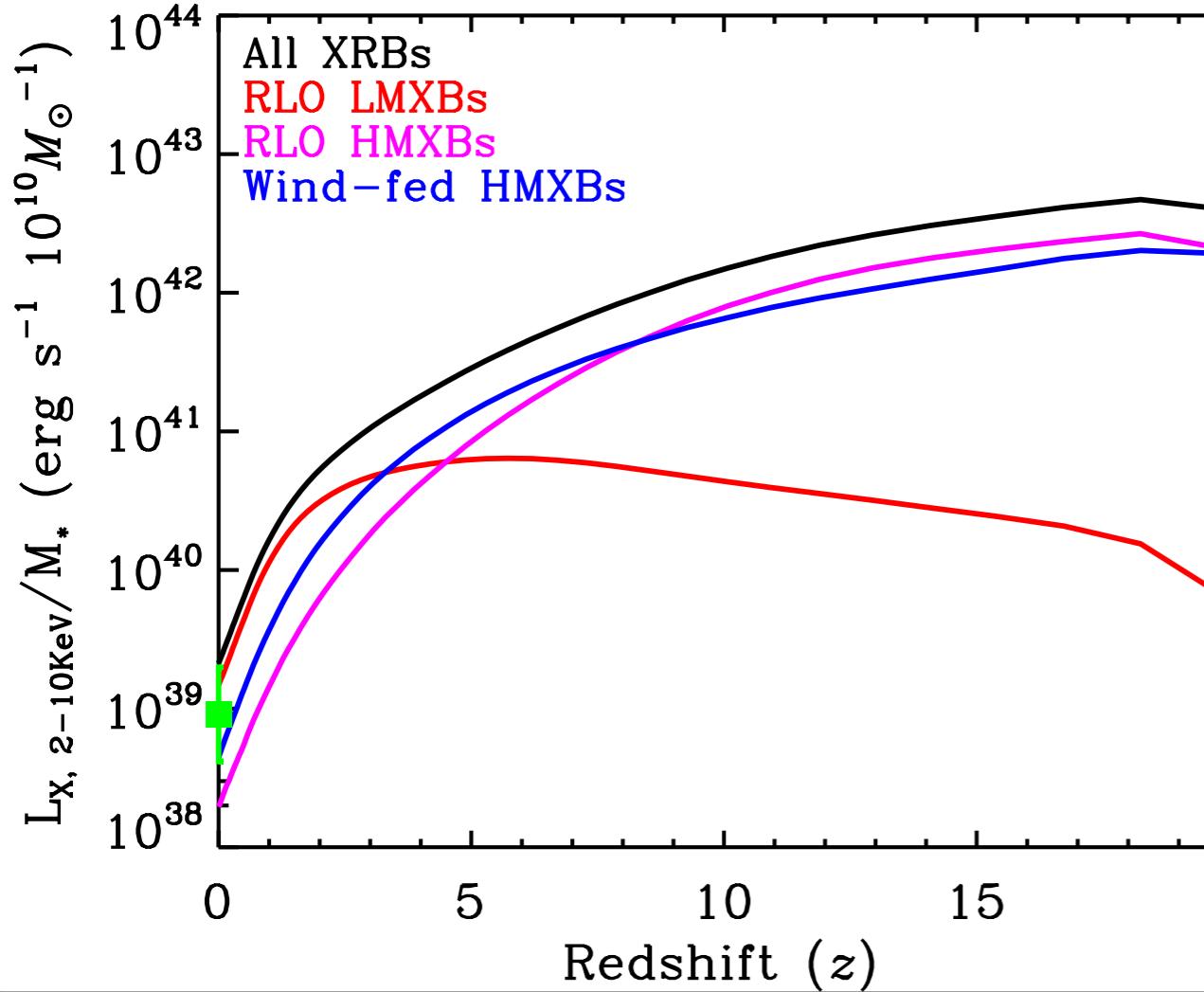
Lehmer et al., 2010  
(Mineo et al. 2010)



# Observational Constraints I: HMXBs



# Observational Constraints III: LMXBs

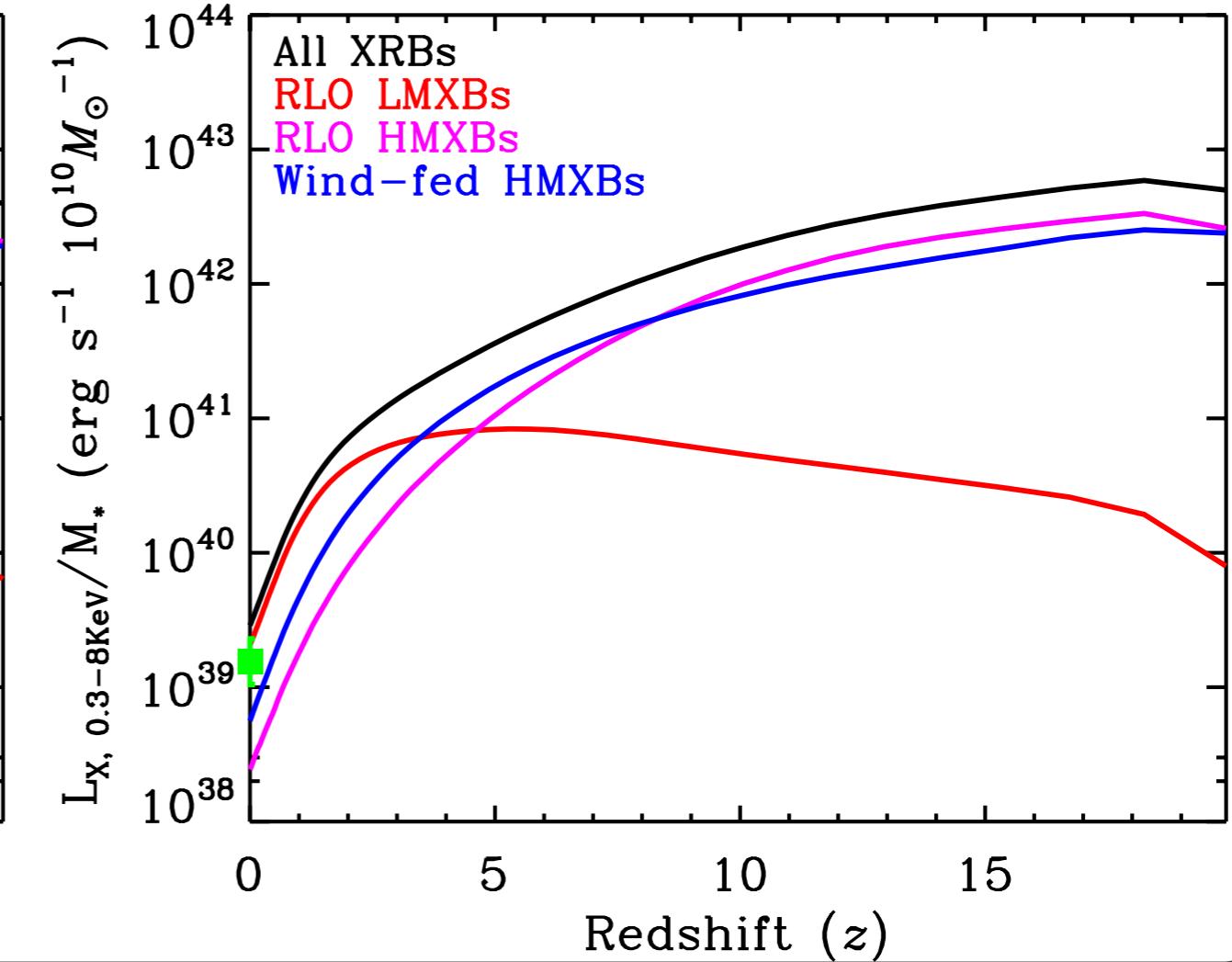


**Lehmer et al. (2010)**

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

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

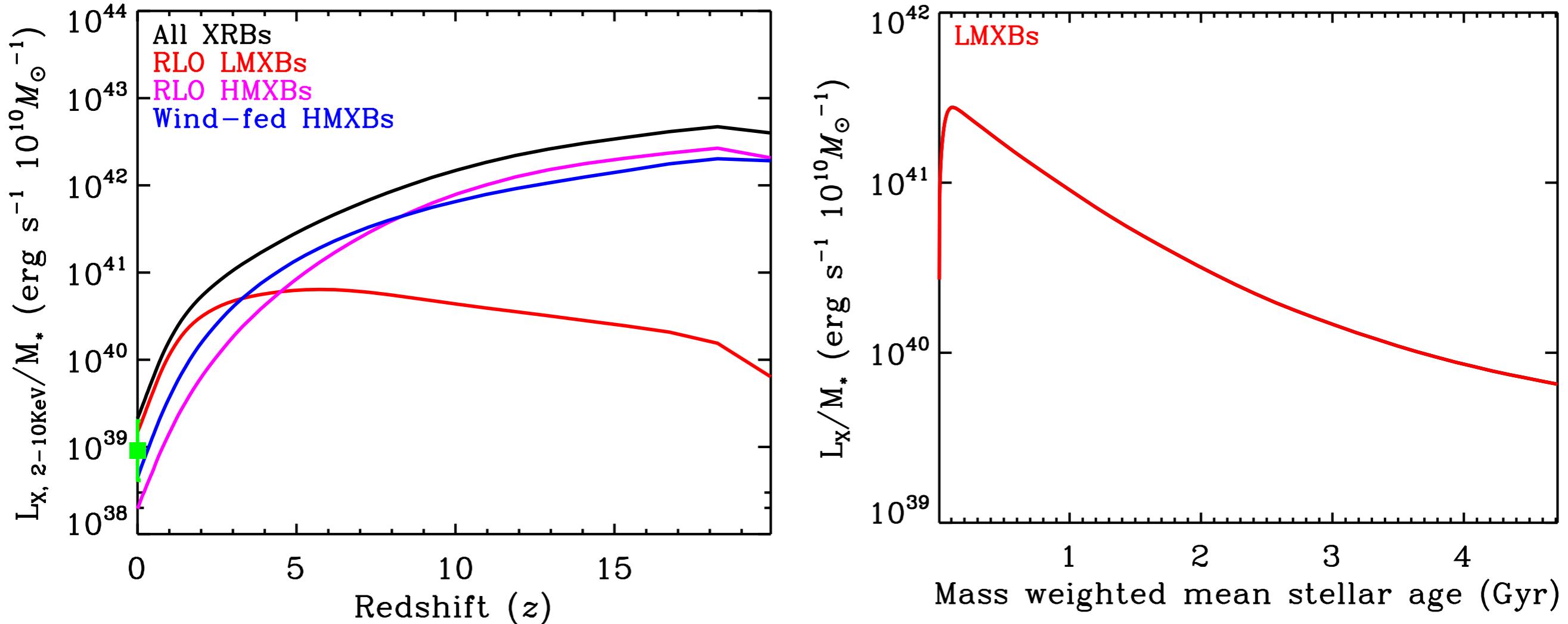
$$\beta = (1.62 \pm 0.22) \times 10^{39} \text{ ergs s}^{-1} (M_\odot \text{ yr}^{-1})^{-1}$$



**Boroson, Kim & Fabbiano (2011)**

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

# Observational Constraints III: LMXBs



**Lehmer et al. (2010)**

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

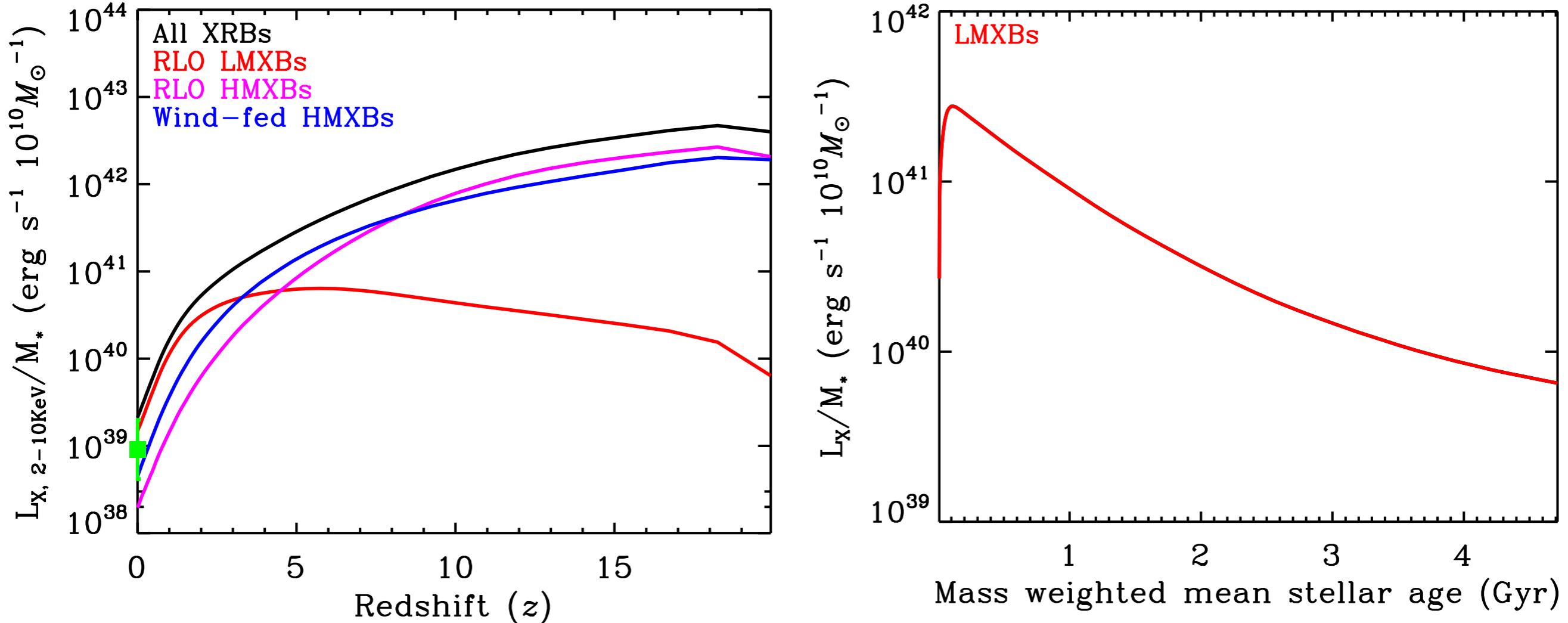
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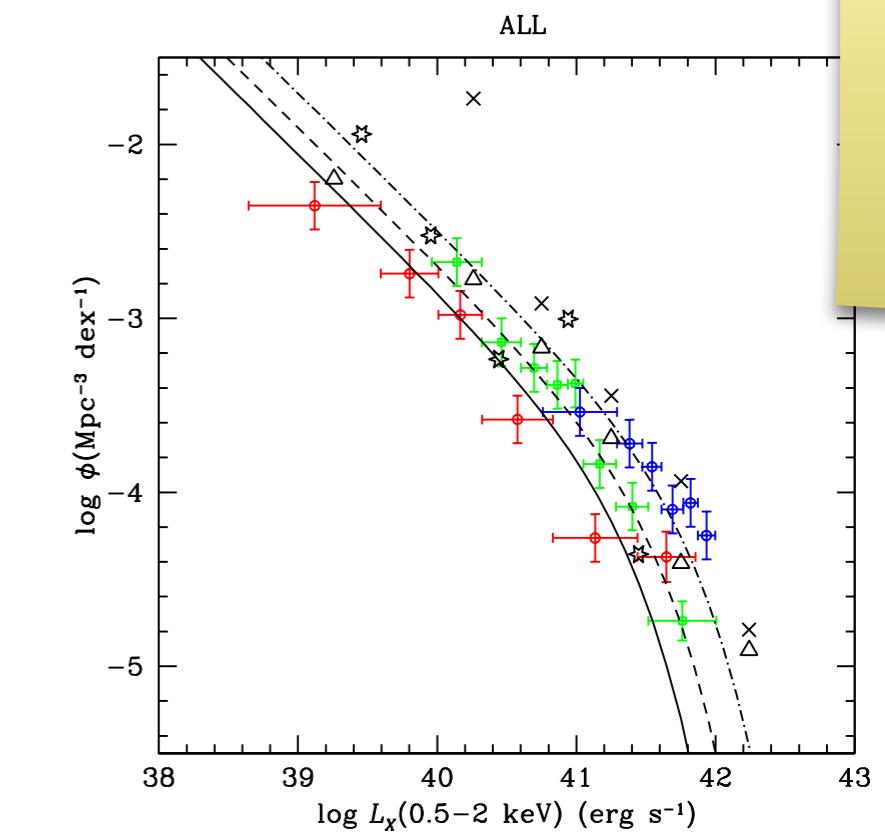
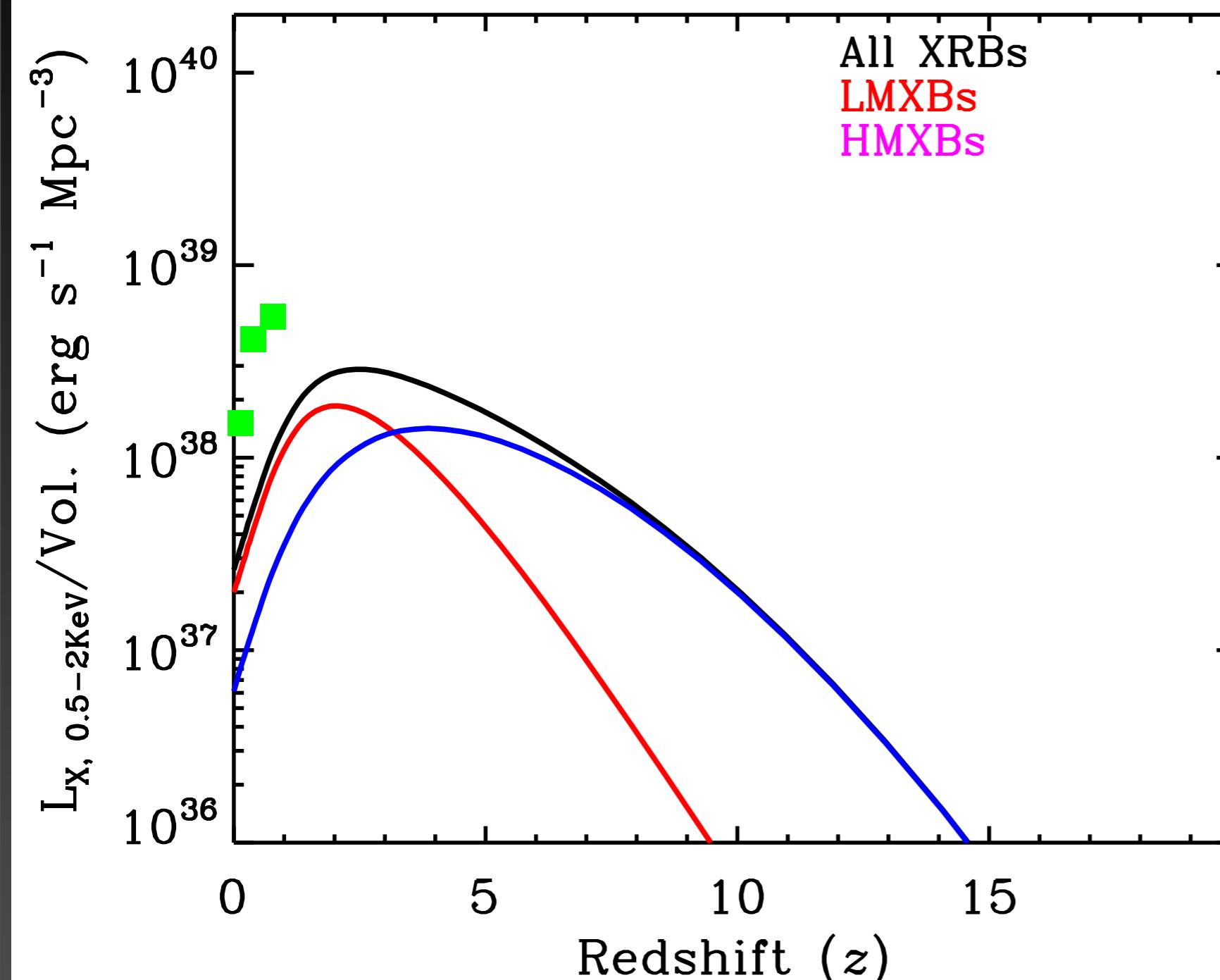
# Observational Constraints III: LMXBs



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

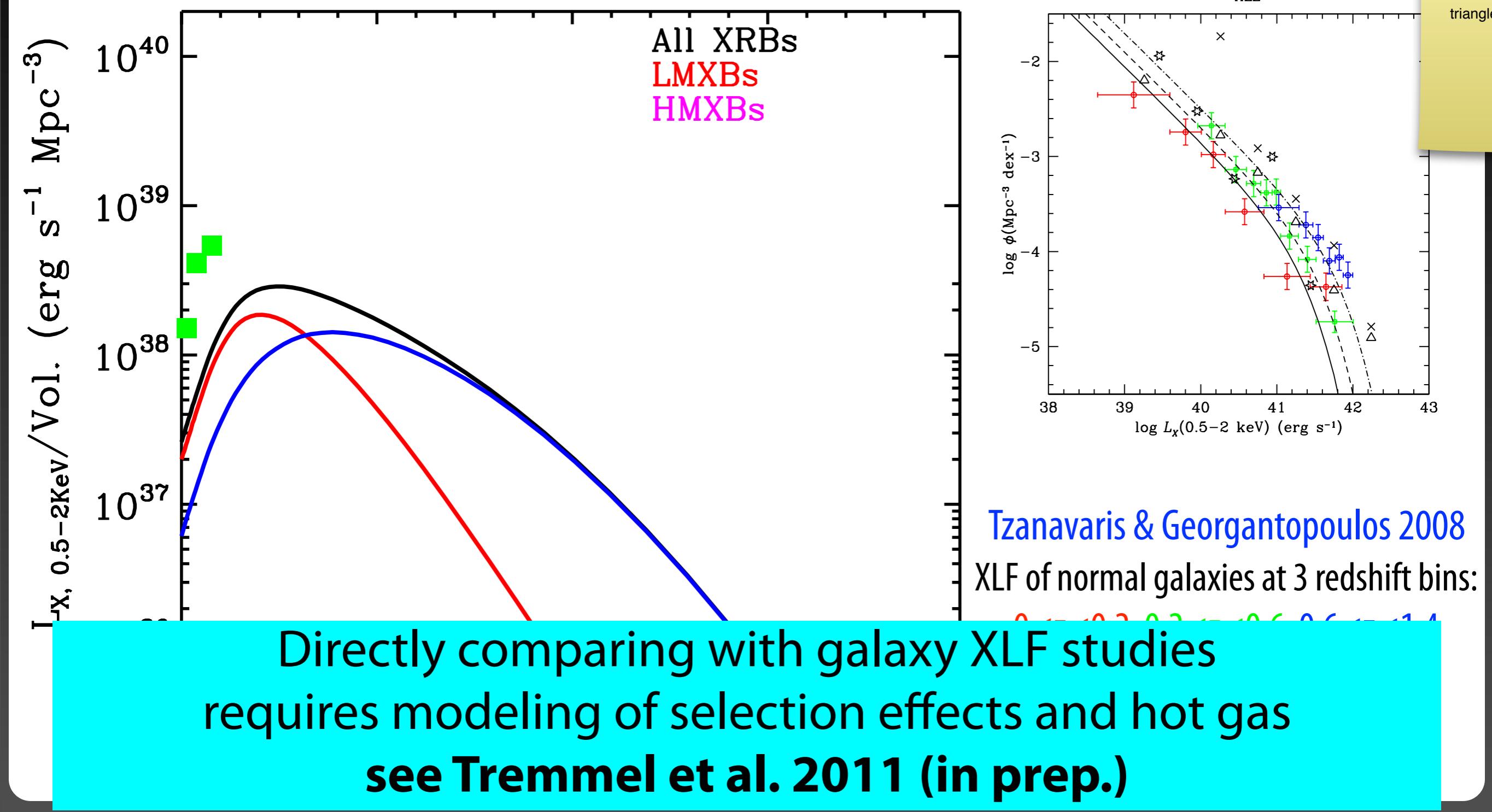
Other  
work  
of Kim  
Normal  
shown  
triangle



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*

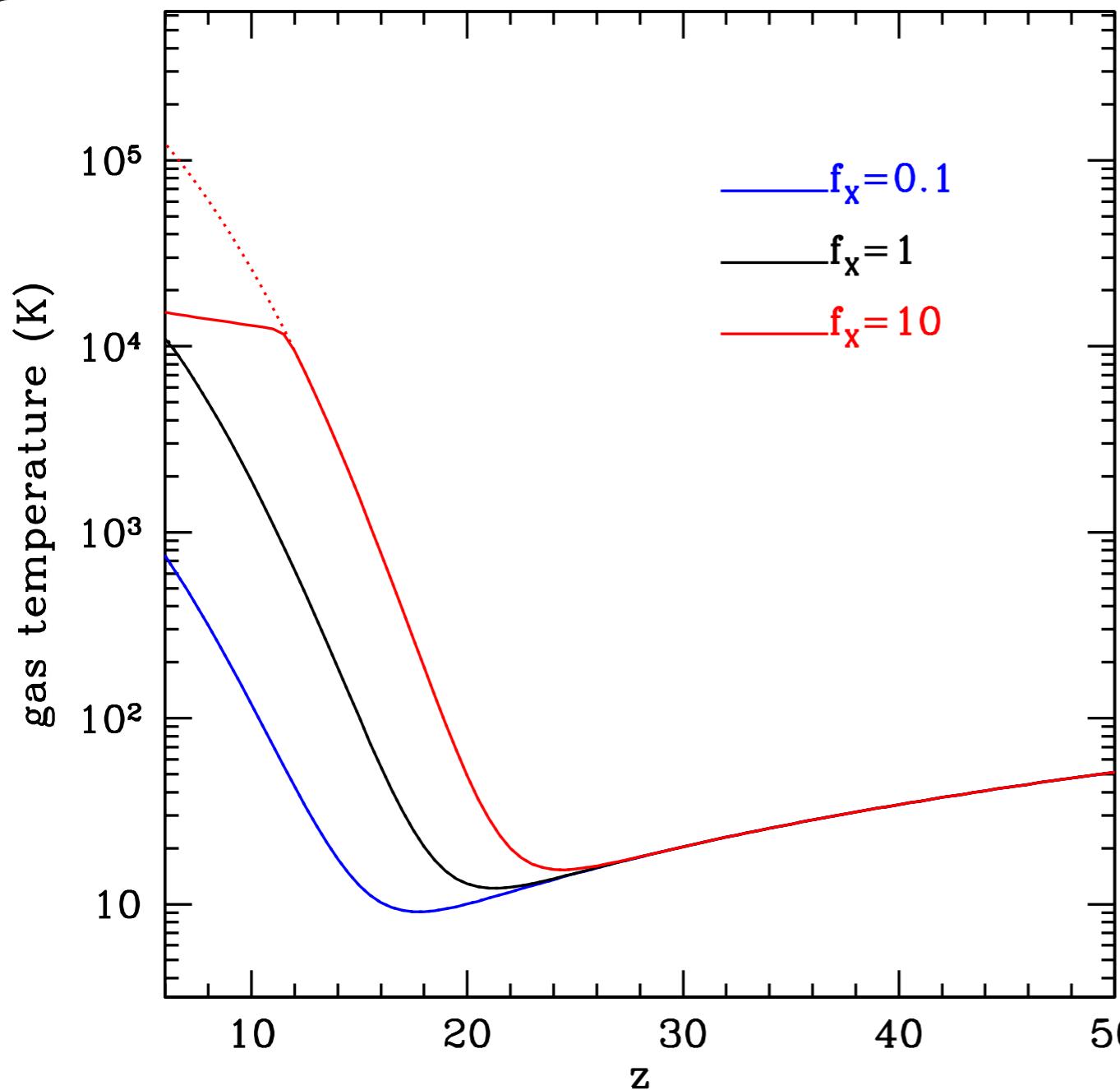
Other  
work  
of Kim  
Normal  
shown  
triangle



# 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

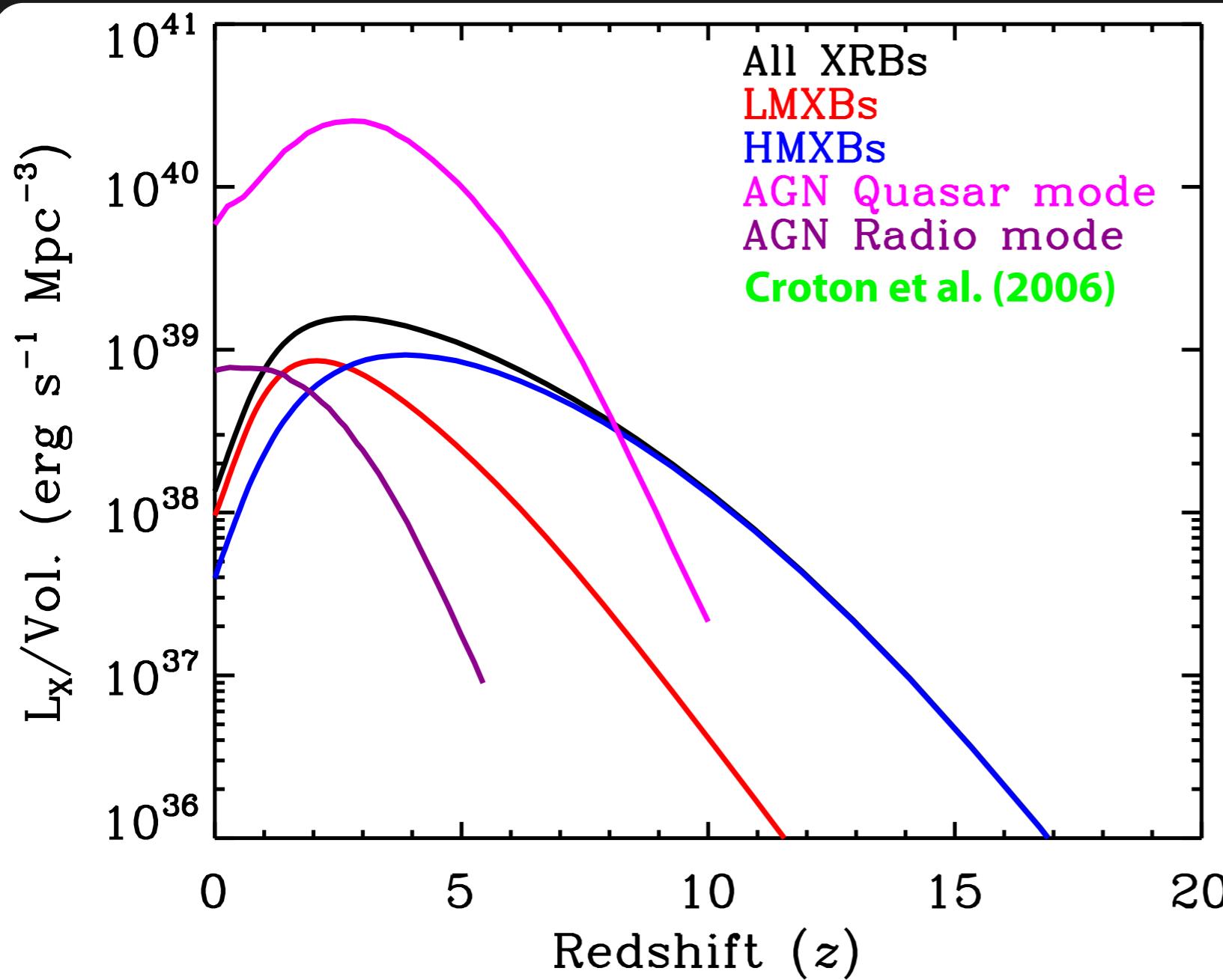
$$L_X = 3.4 \times 10^{40} f_X \left( \frac{\text{SFR}}{1 M_\odot \text{ yr}^{-1}} \right) \text{ erg s}^{-1}$$

Furlanetto 2006

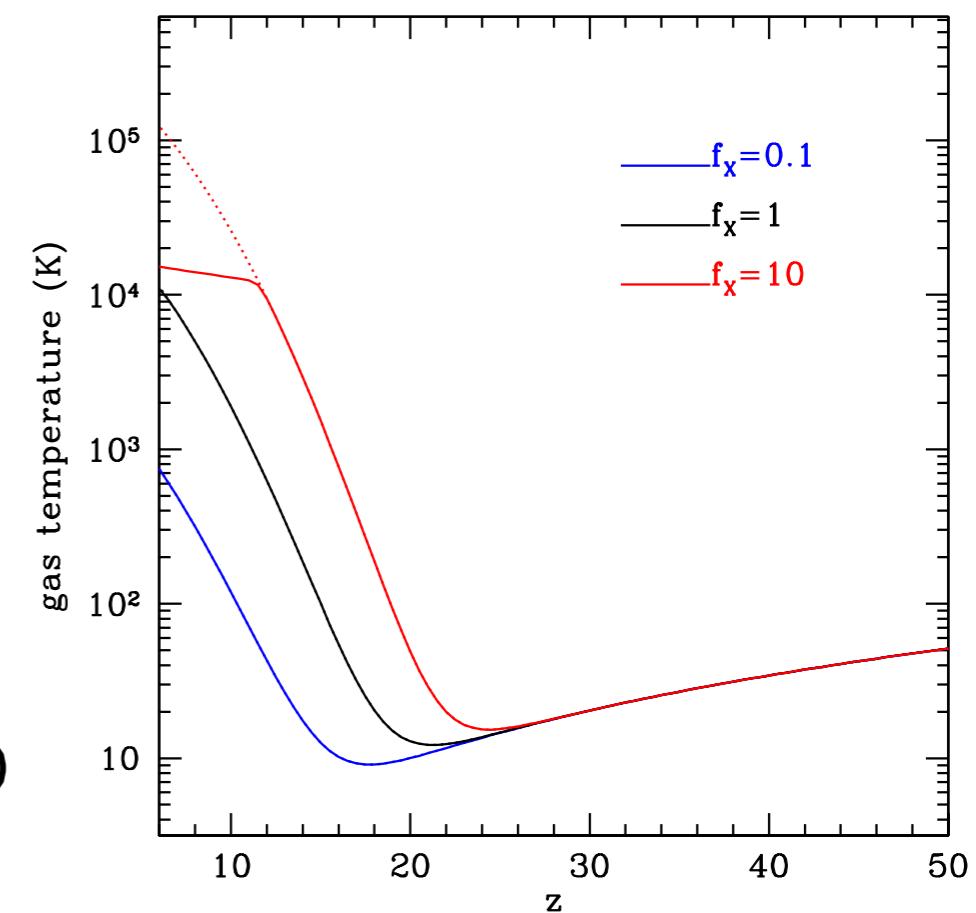
# Energy feedback from XRBs

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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  $\sim 2.5$
- 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  $L_X$  from LMXBs is  $\sim 1.5\text{Gyr}$
- XRBs are the dominant sources of X-ray photon production at redshifts  $> 10$

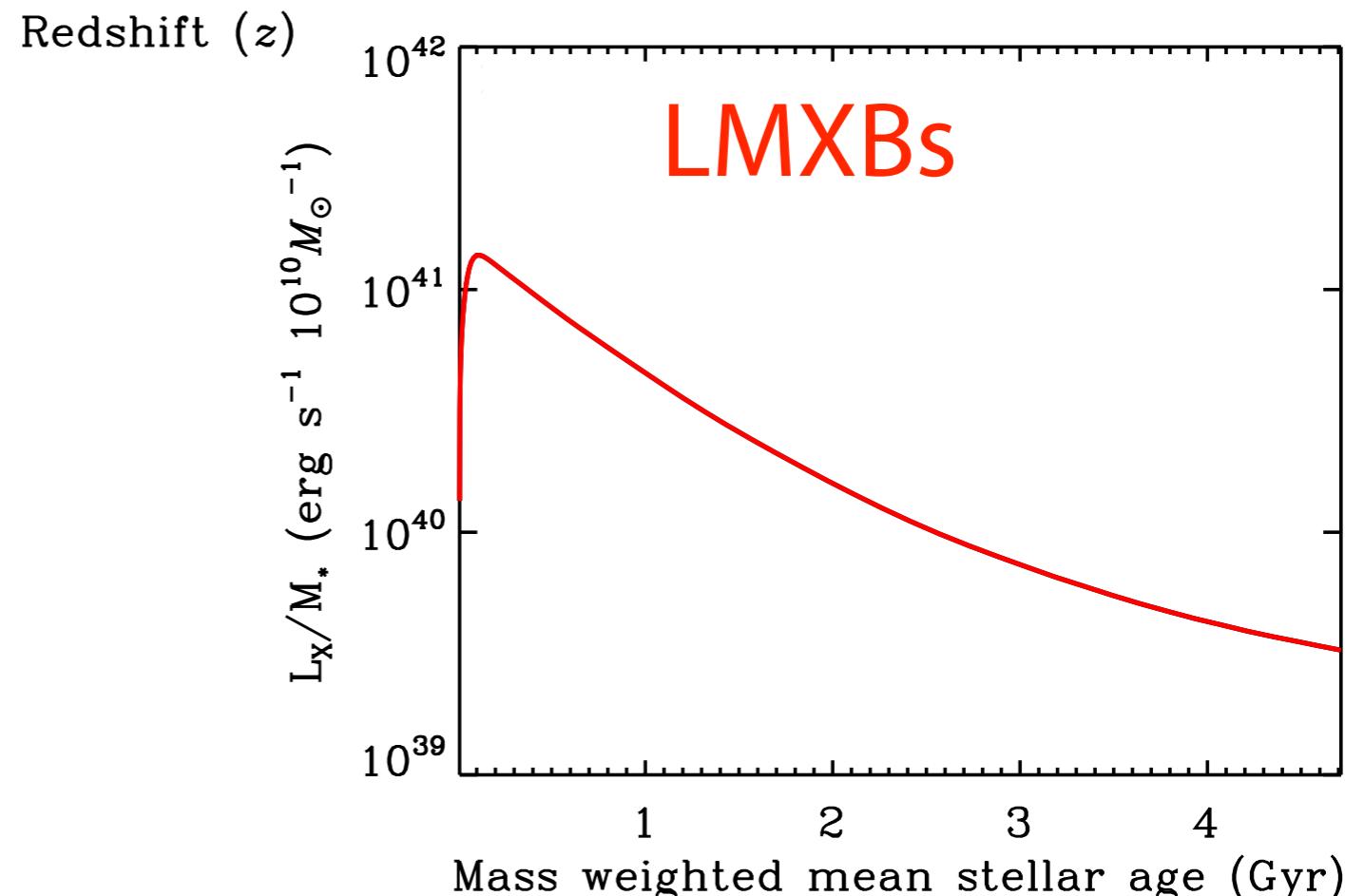
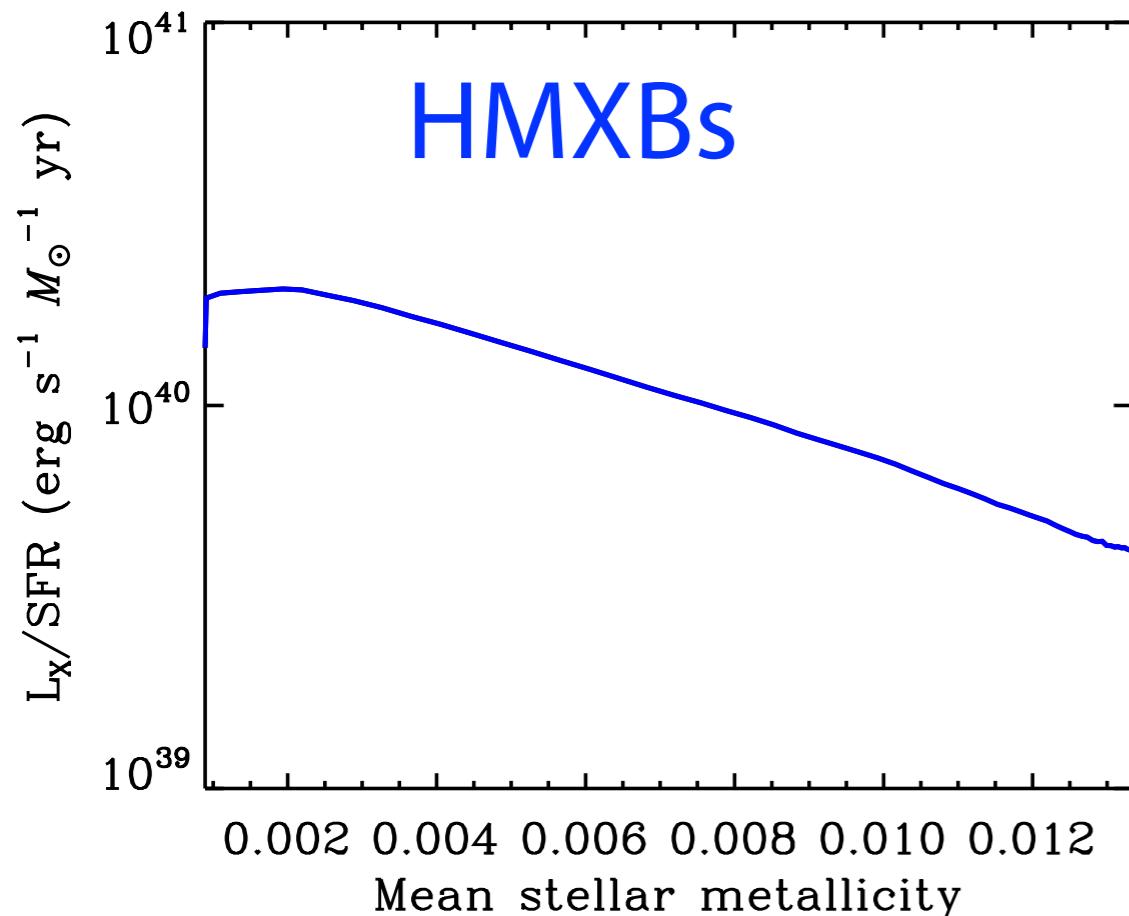
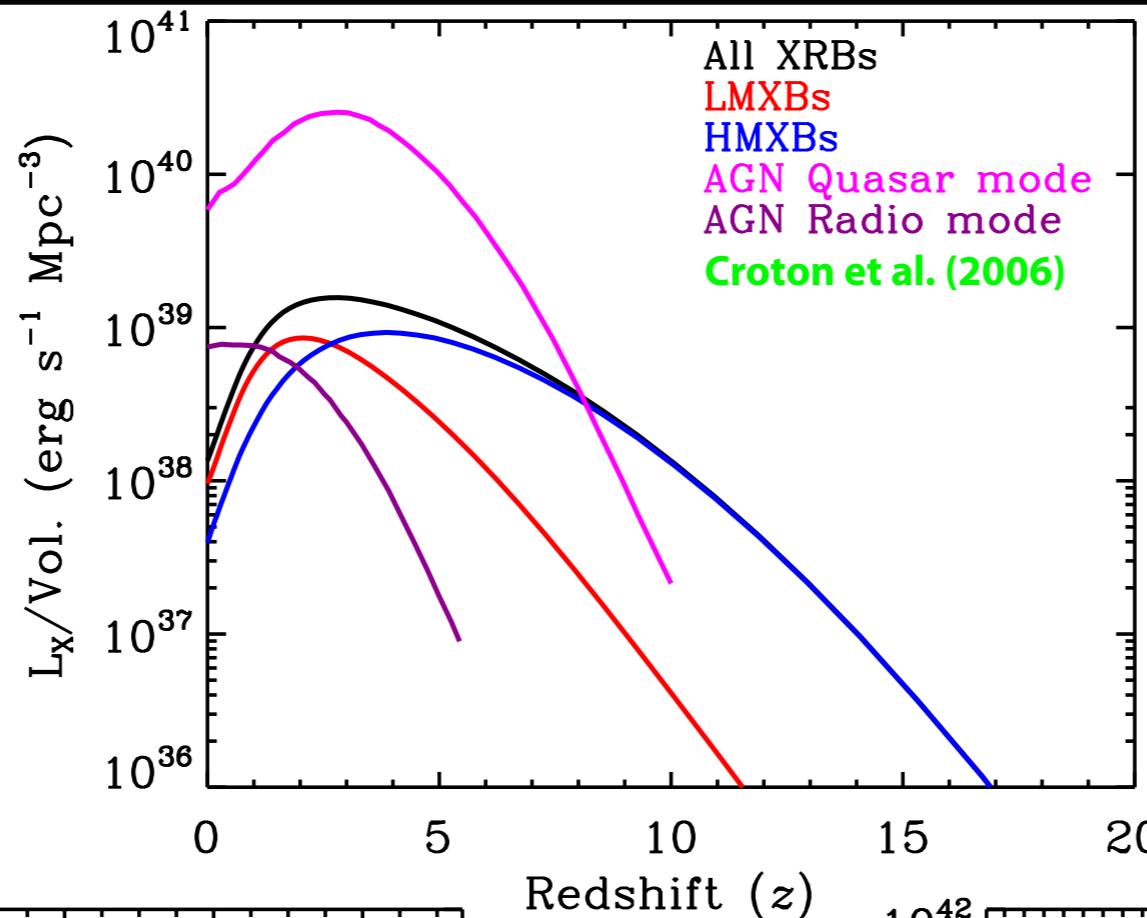




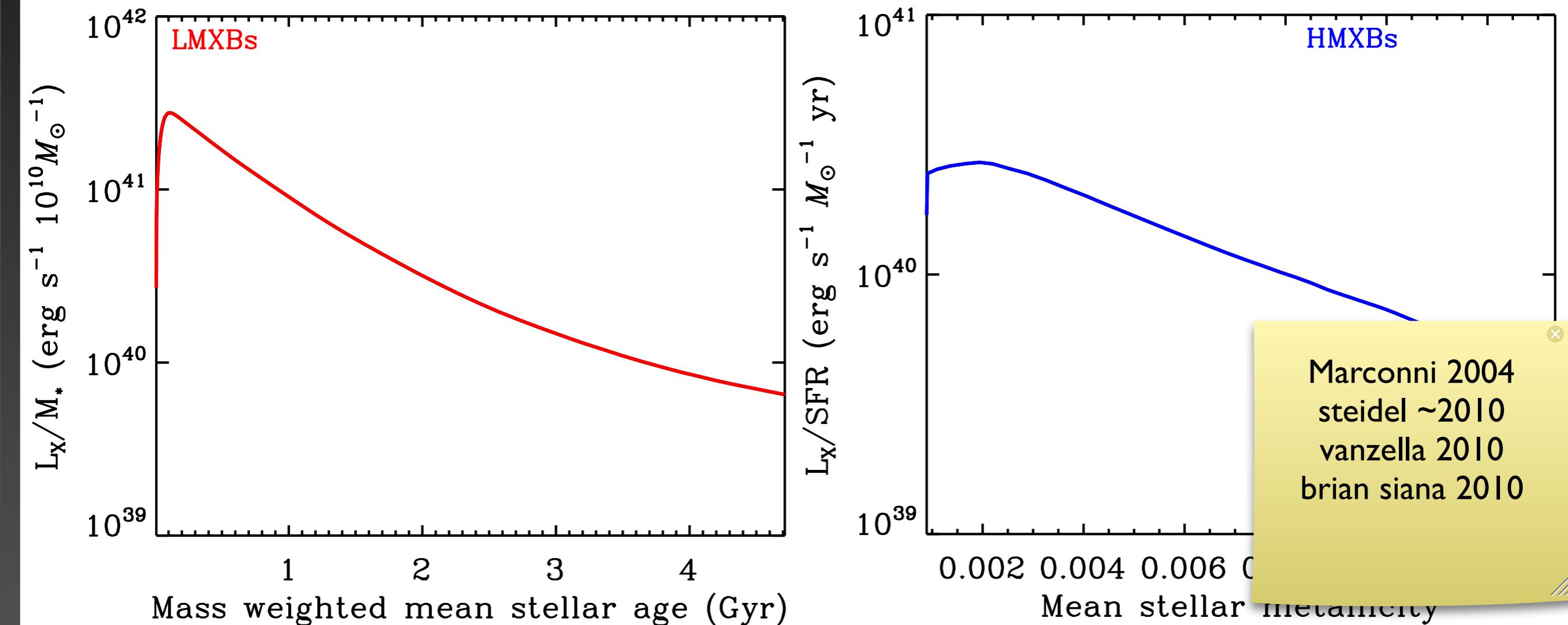




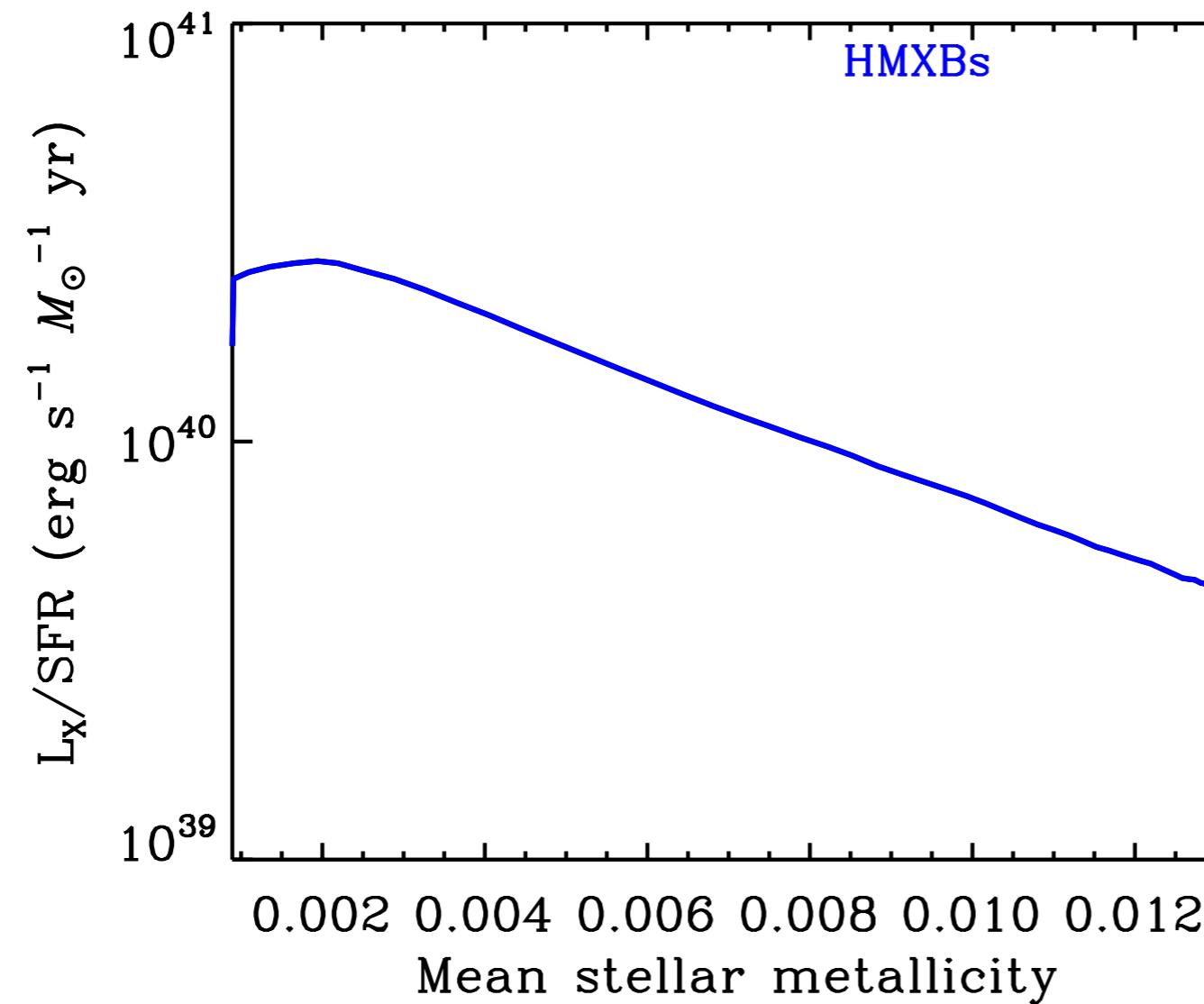
# Energy feedback from XRBs



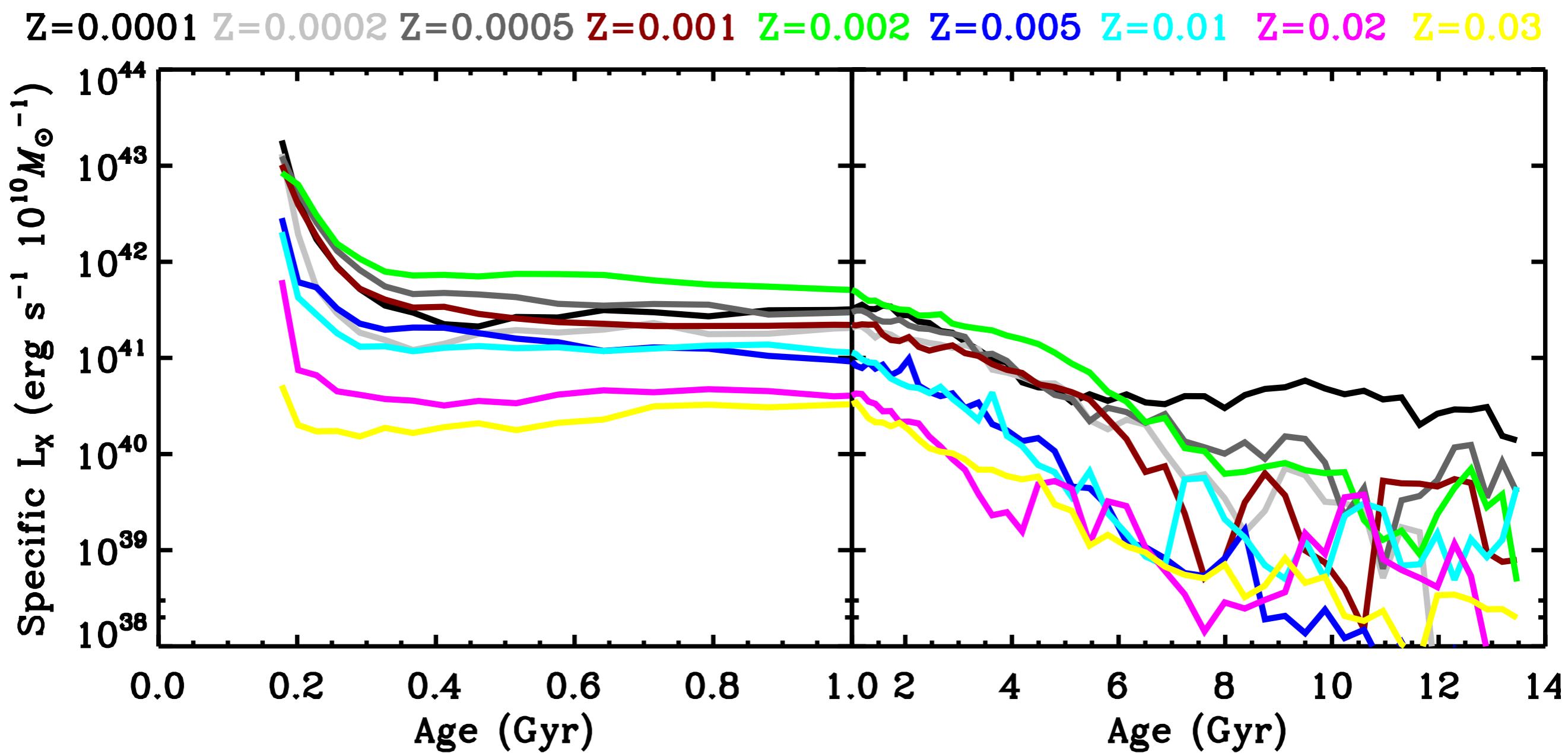
# Energy feedback from XRBs



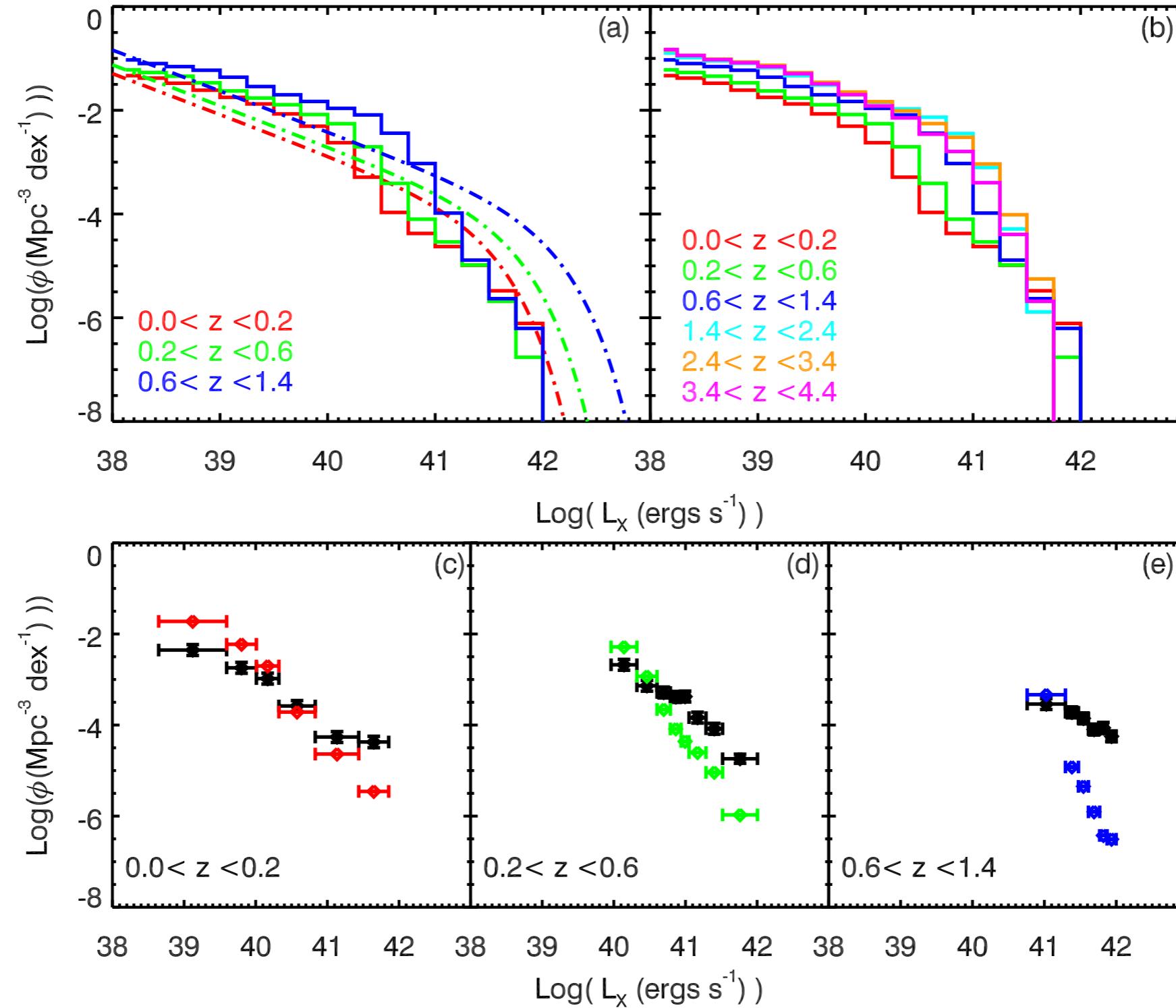
# Feedback from HMXBs



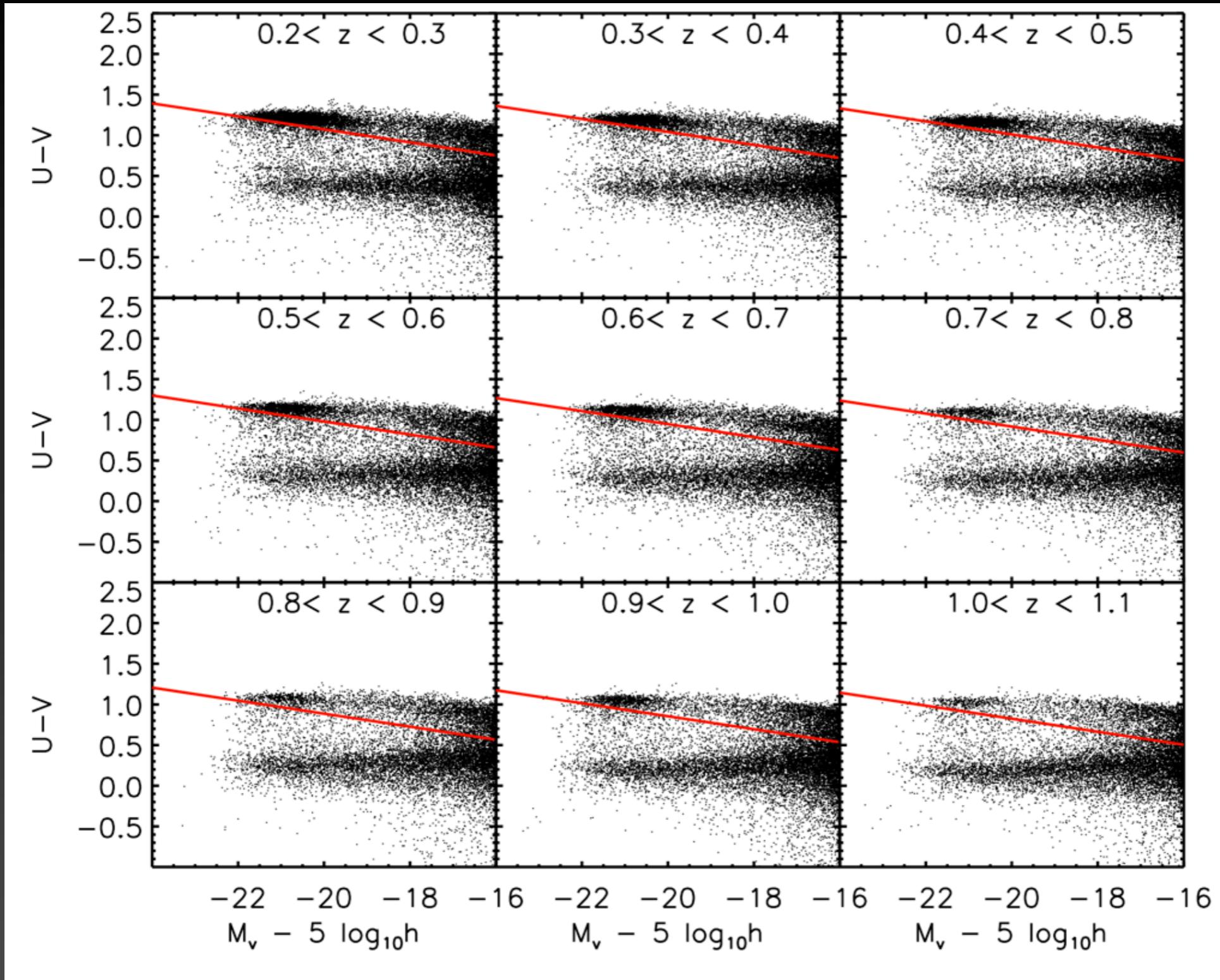
# Modeling the X-ray Luminosity from a Single Stellar Population



# *X-ray luminosity functions of distant galaxies*

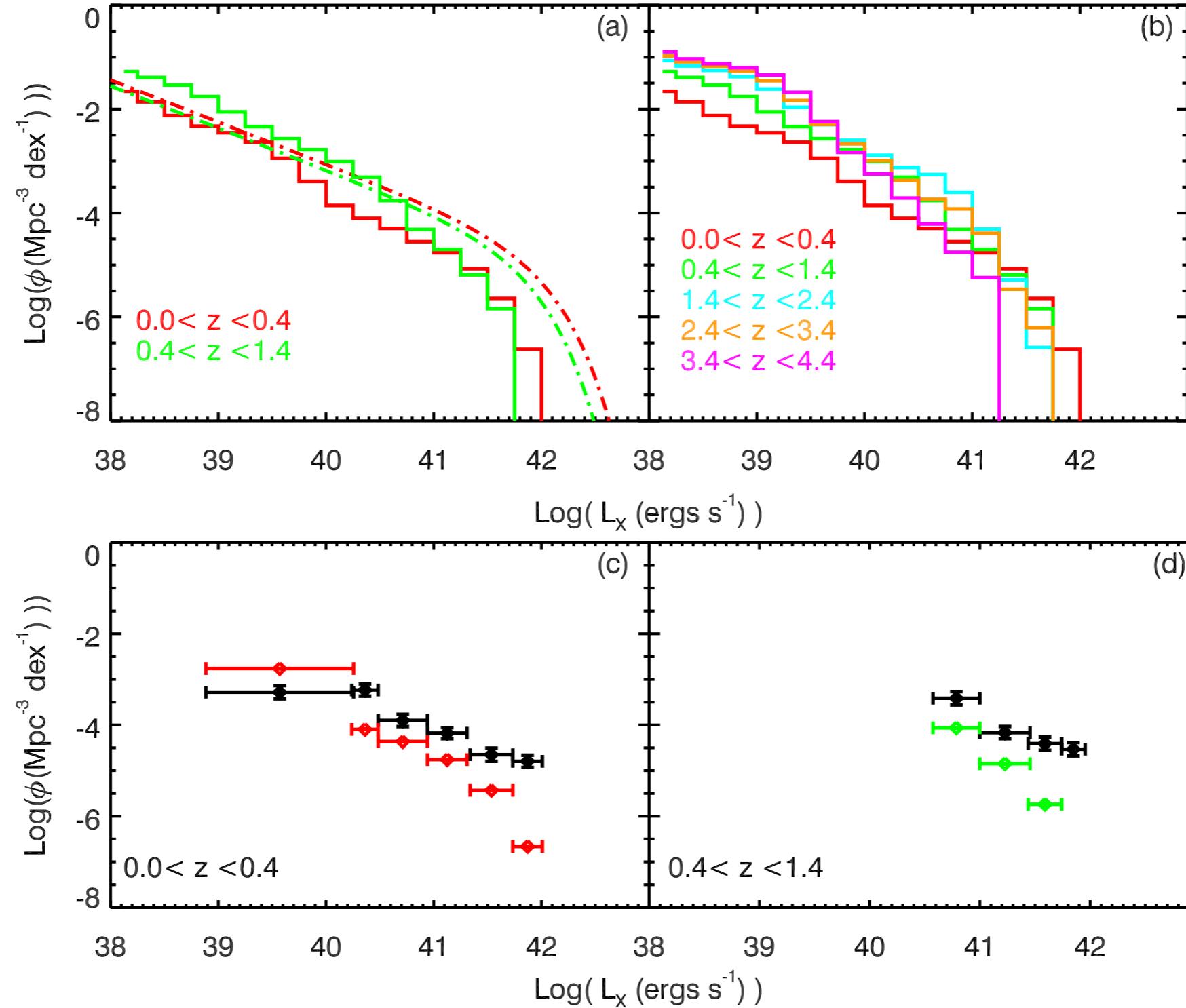


# Separating early from late type galaxies

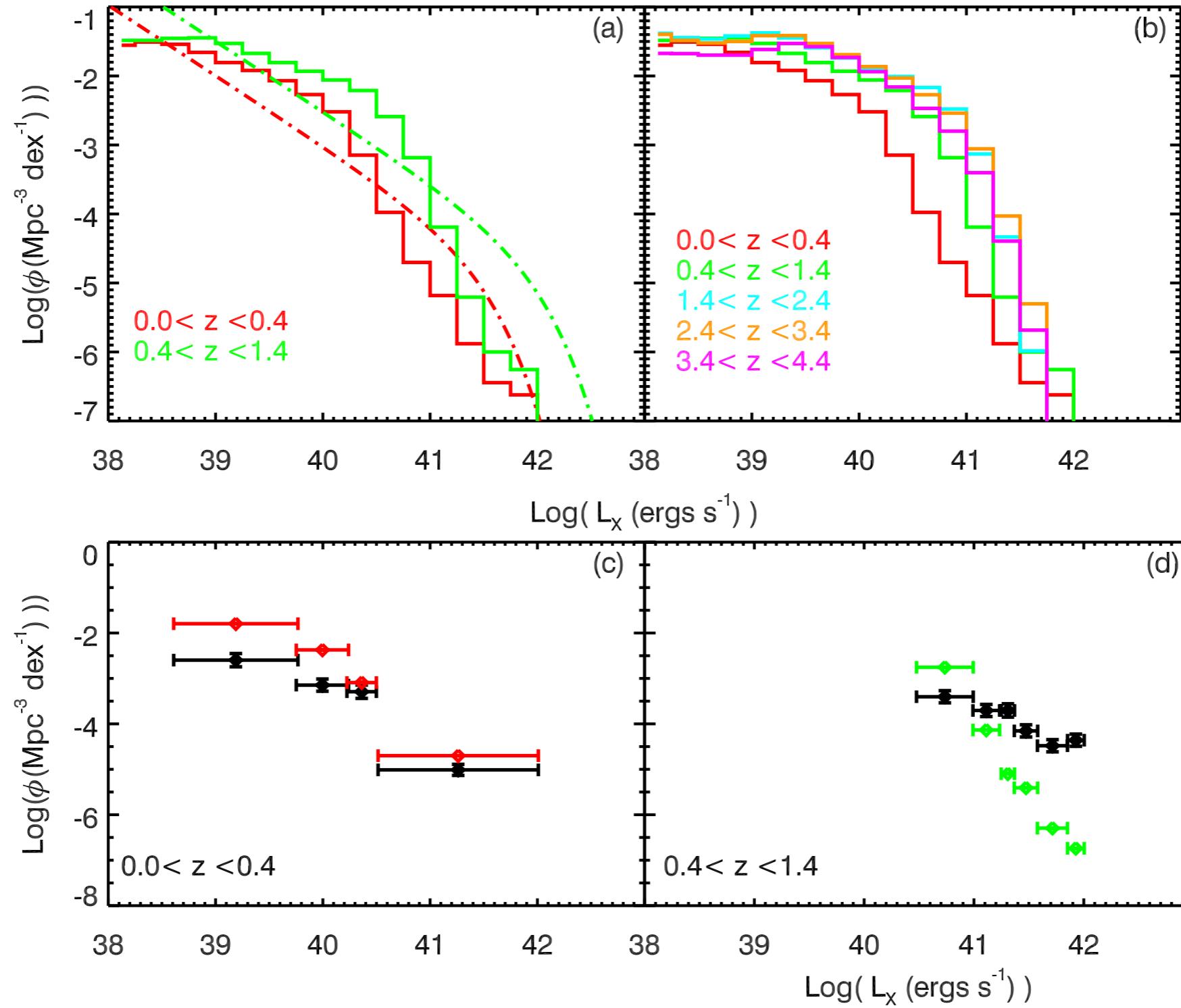


**Bell et al. (2004):**  $1.15 - 0.31*z - 0.08*(M_V - 5*\log(h)+20)$

# *X-ray luminosity functions of early type galaxies*



# *X-ray luminosity functions of late type galaxies*

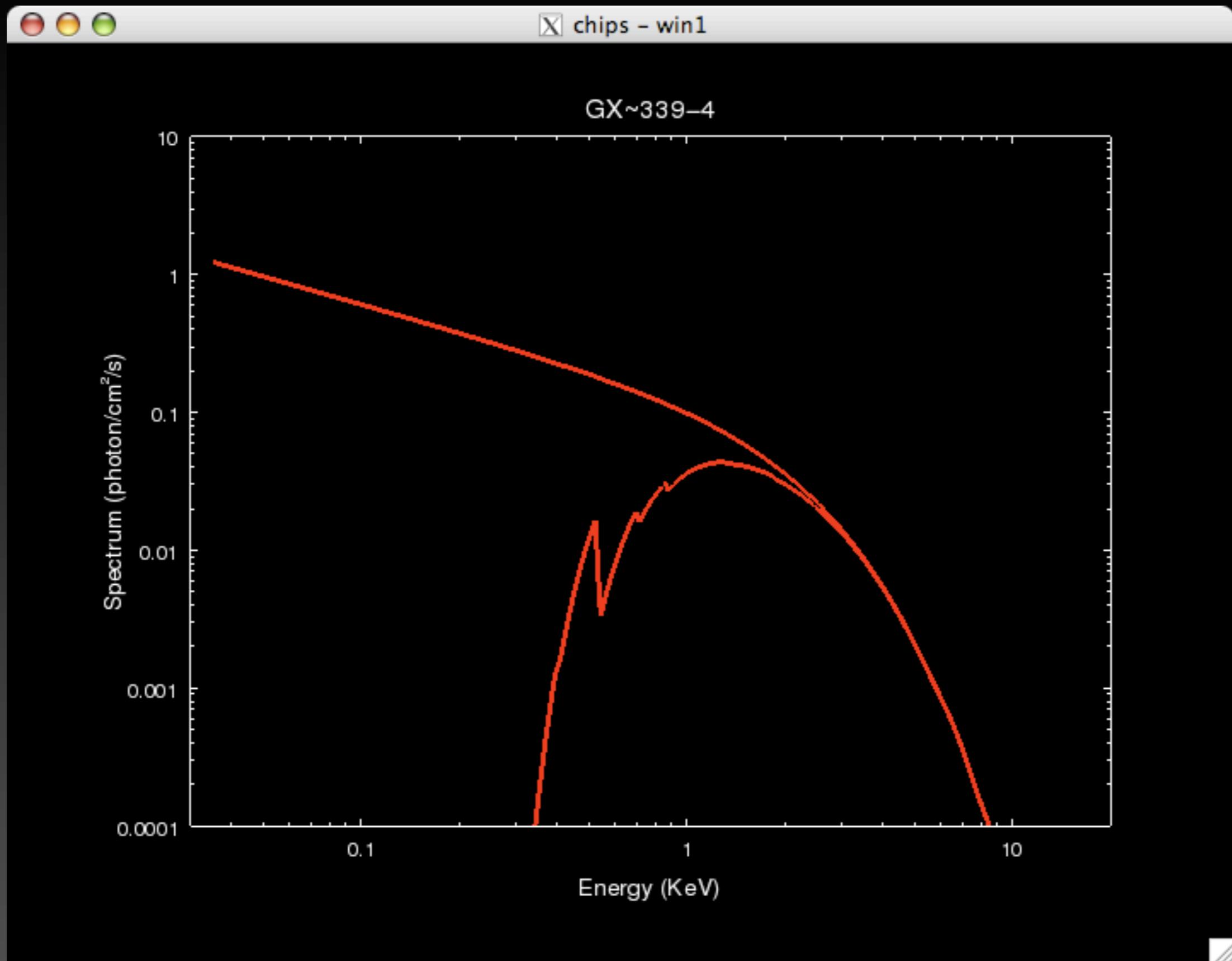




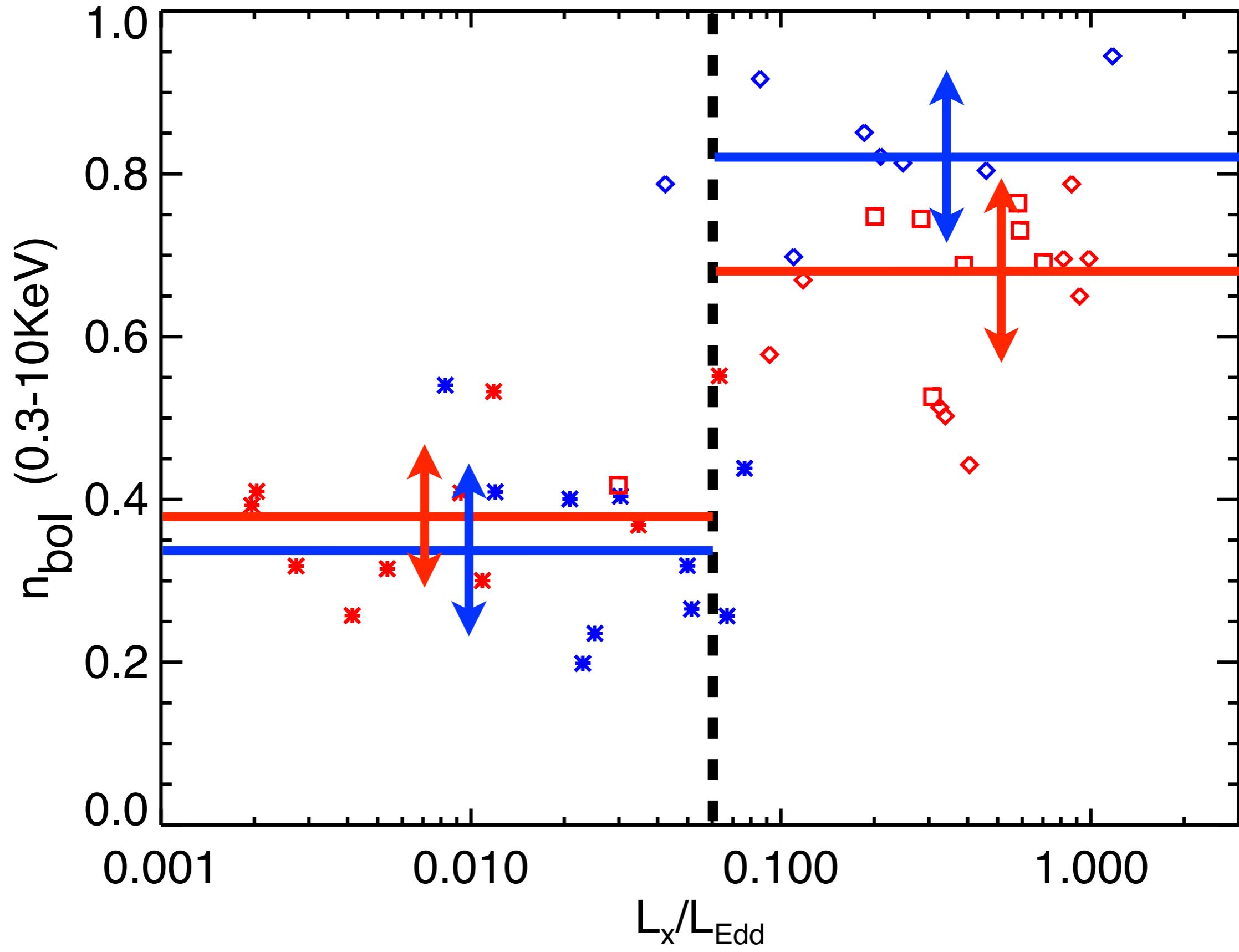
# Bolometric Corrections

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													

# Bolometric Corrections



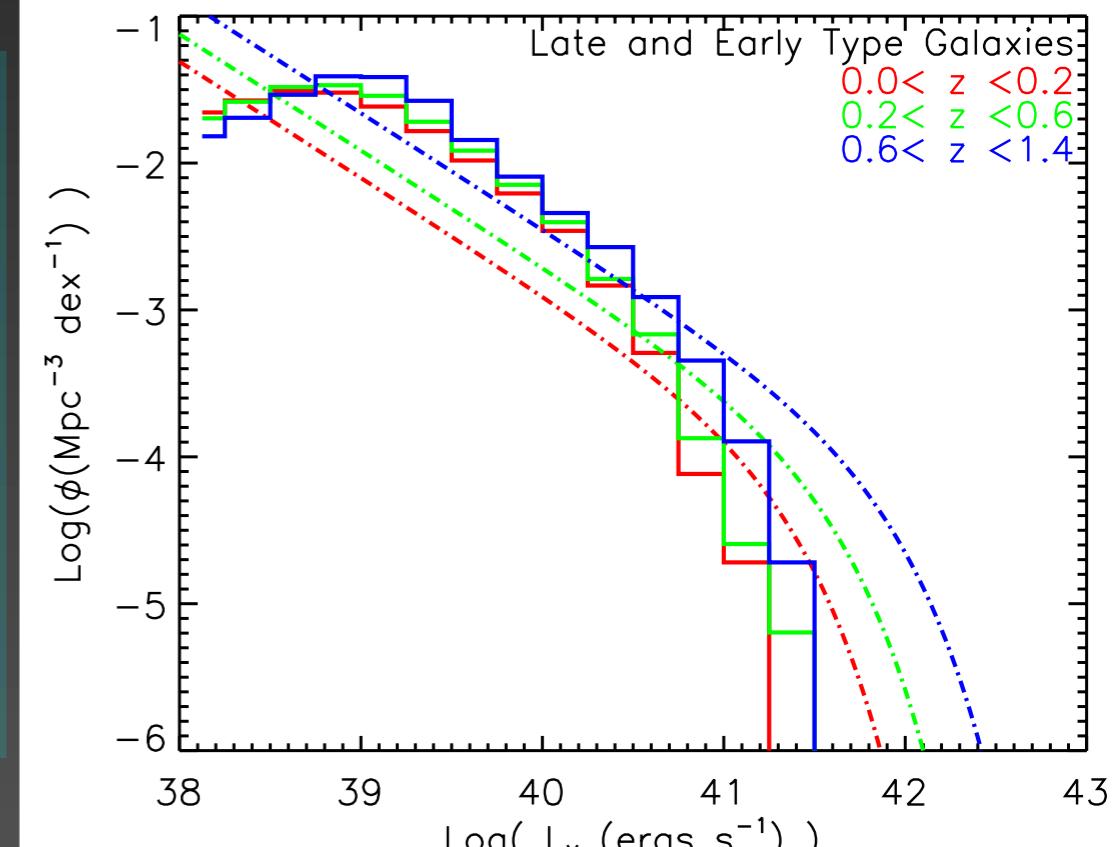
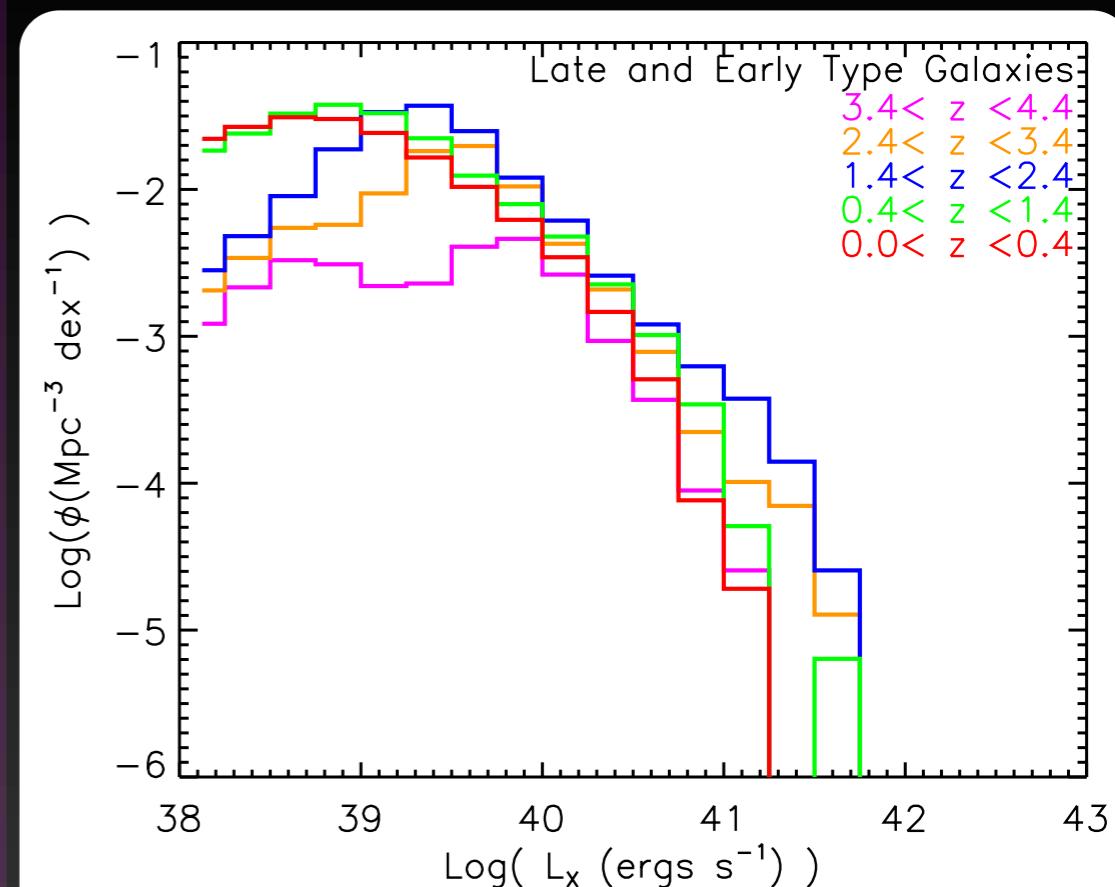
# Bolometric Corrections



# Work in Progress...

- Completion of PS model library
- 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

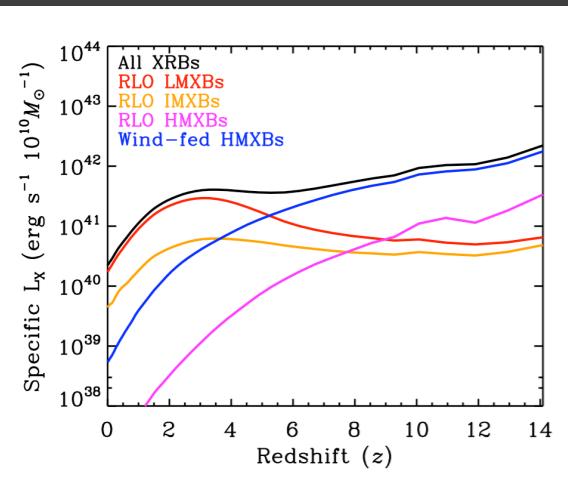
- Motivation
- *StarTrack* and *Millennium* simulations
- Constraining the model with observations
- Summary and next steps

# Exploring the Parameter Space

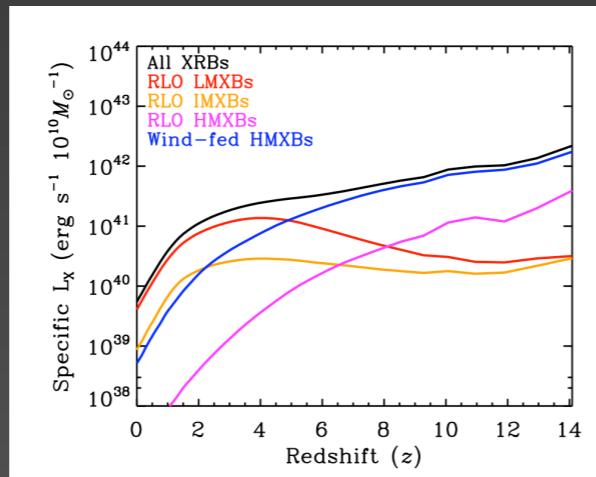
- For the first time we are taking into account **simultaneously multiple observational constraints**
- Preliminary parameter study: 25 PS models varying: **CE efficiency, Stellar winds, SN kicks**  
**IMF, initial mass ratio and orbital period distribution**
- Dominant effects:  
**CE efficiency for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

## LMXBs

$\alpha_{ce}=0.5$

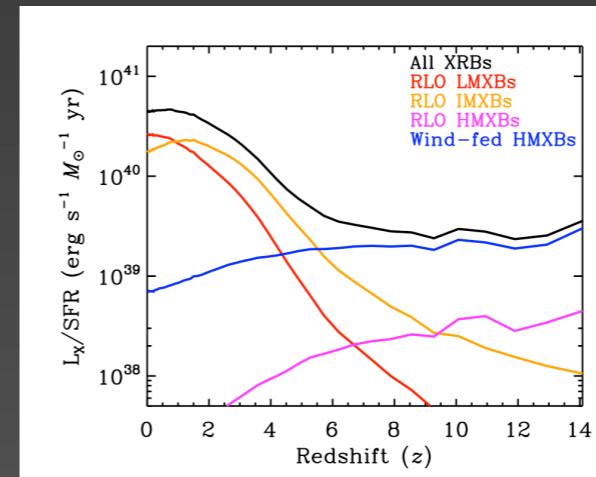


$\alpha_{ce}=0.1$

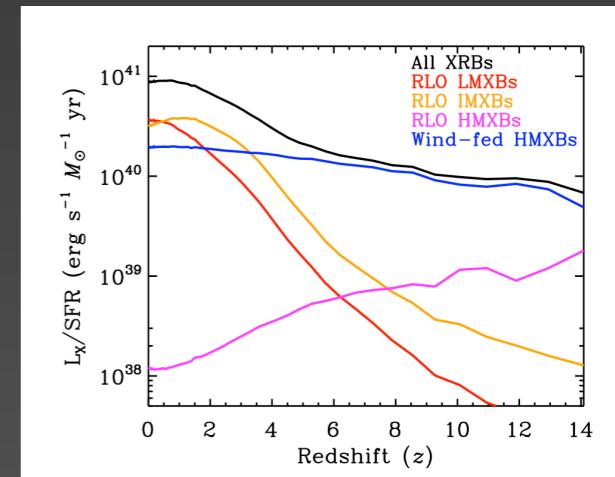


## HMXBs

$\eta_{wind}=2.0$

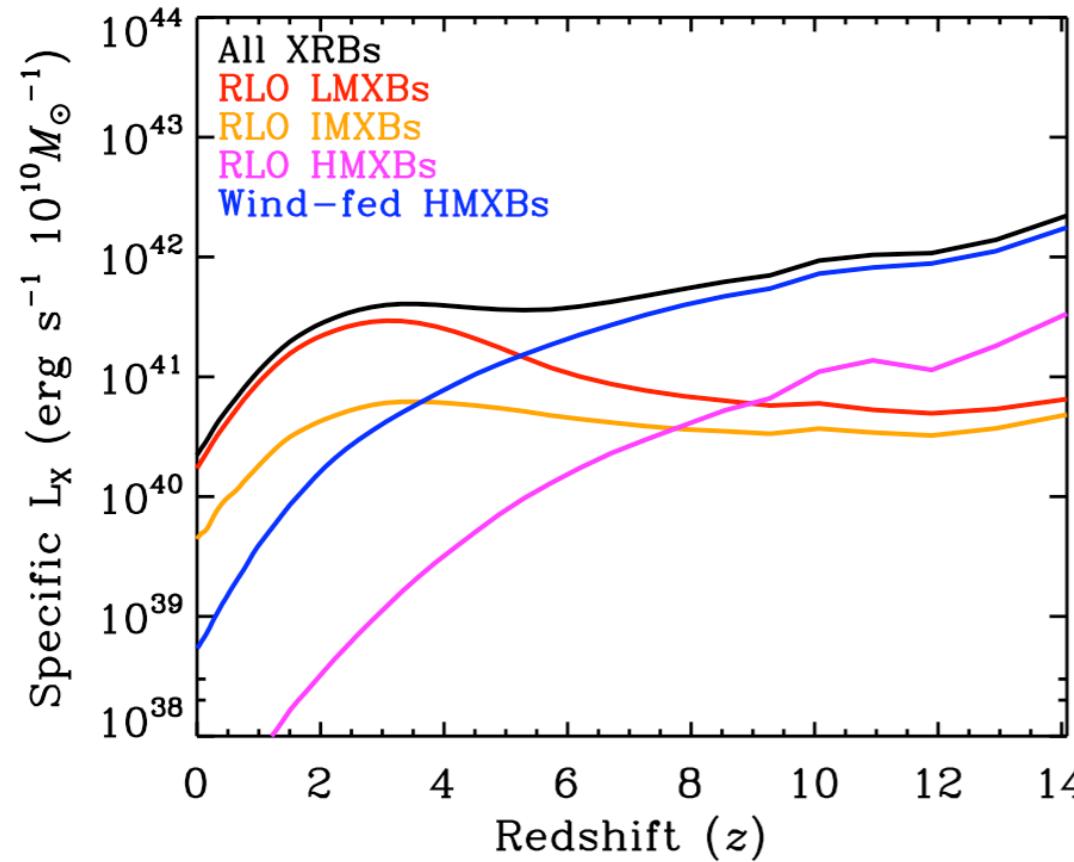


$\eta_{wind}=0.25$



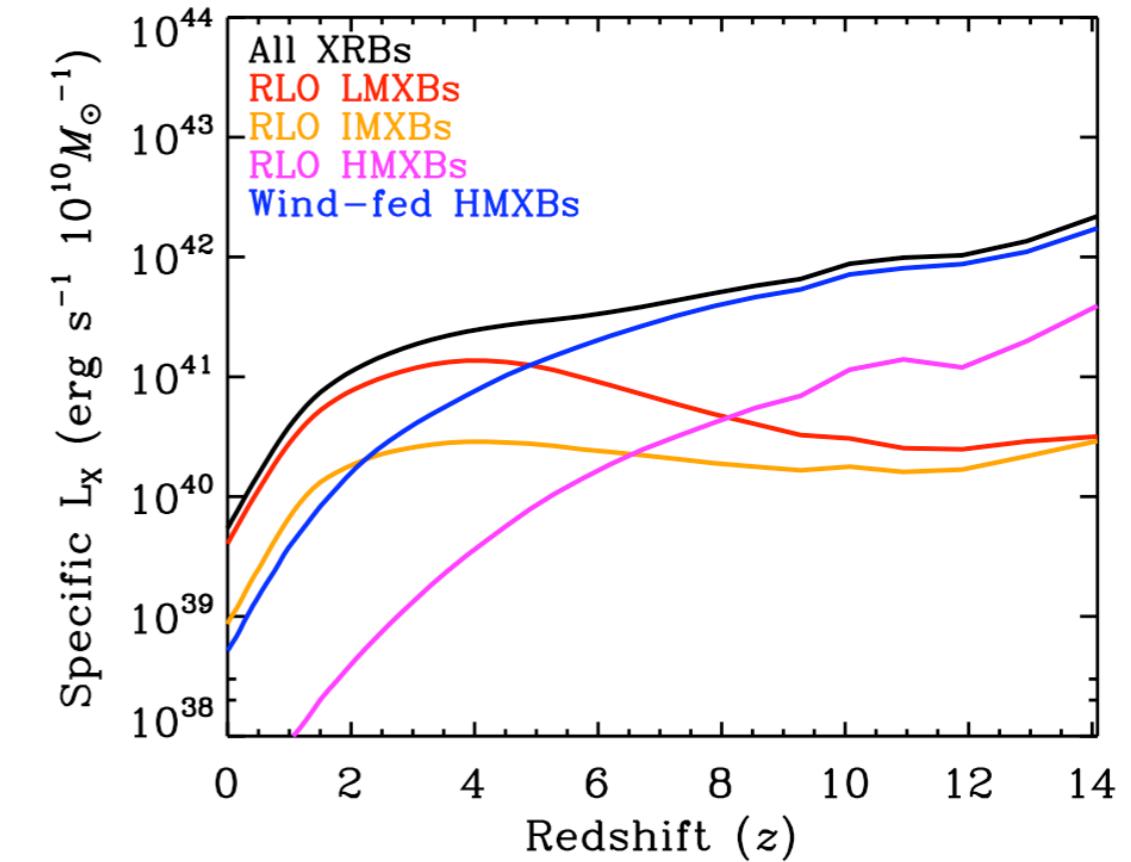
# Exploring the Parameter Space

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



$\alpha_{ce} = 0.5$

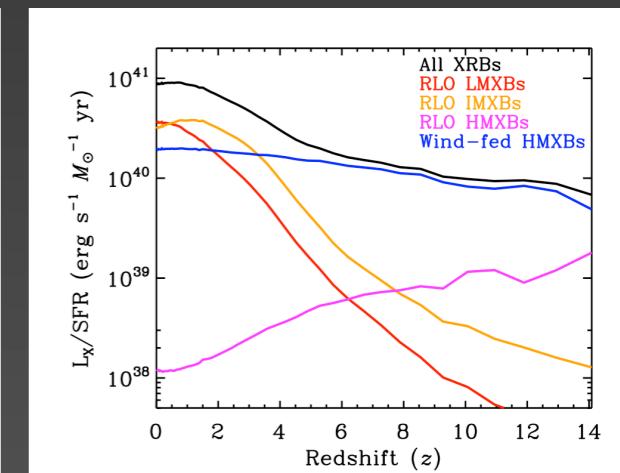
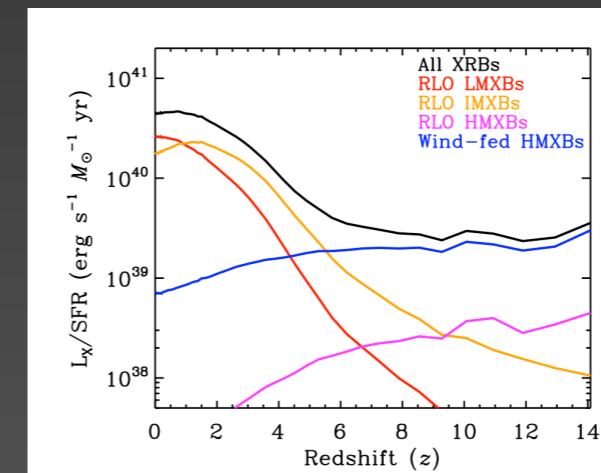
Study:  
S, SN  
orbit  
and S.



$\alpha_{ce} = 0.1$

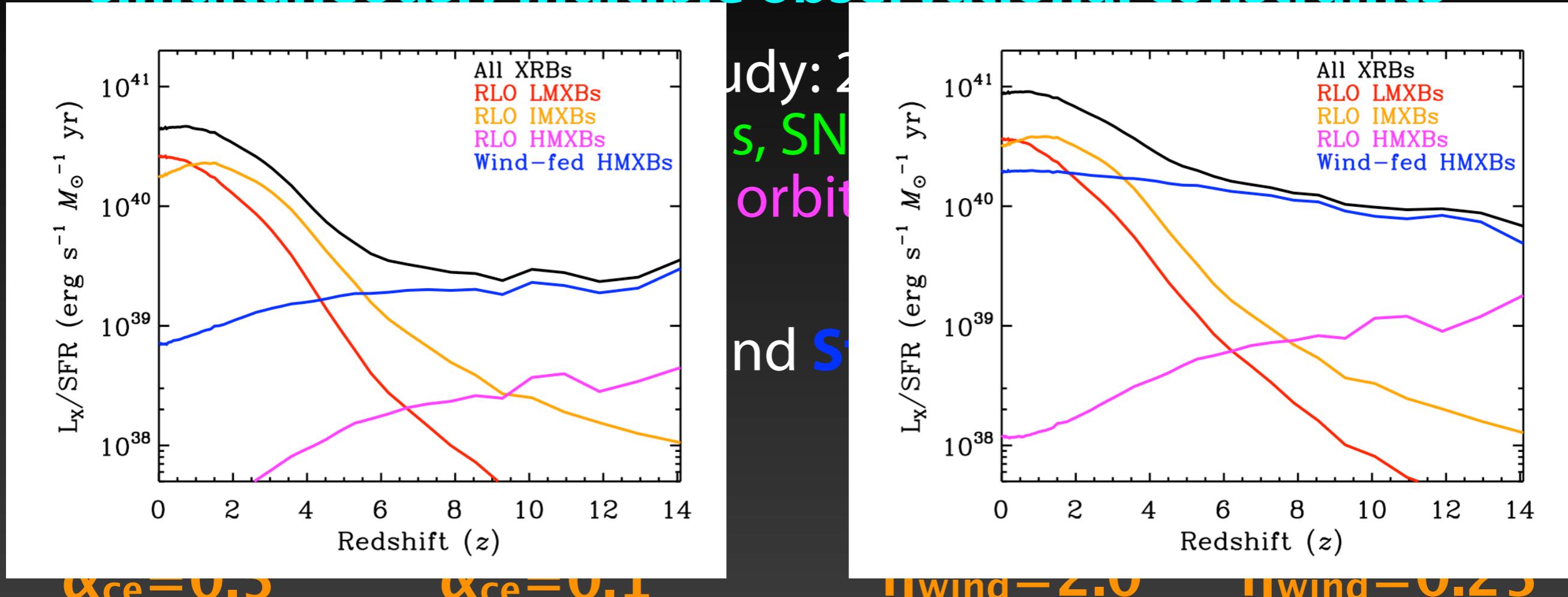
$\eta_{wind} = 2.0$

$\eta_{wind} = 0.25$



# Exploring the Parameter Space

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



# Modeling the X-ray Luminosity from a Single Stellar Population

