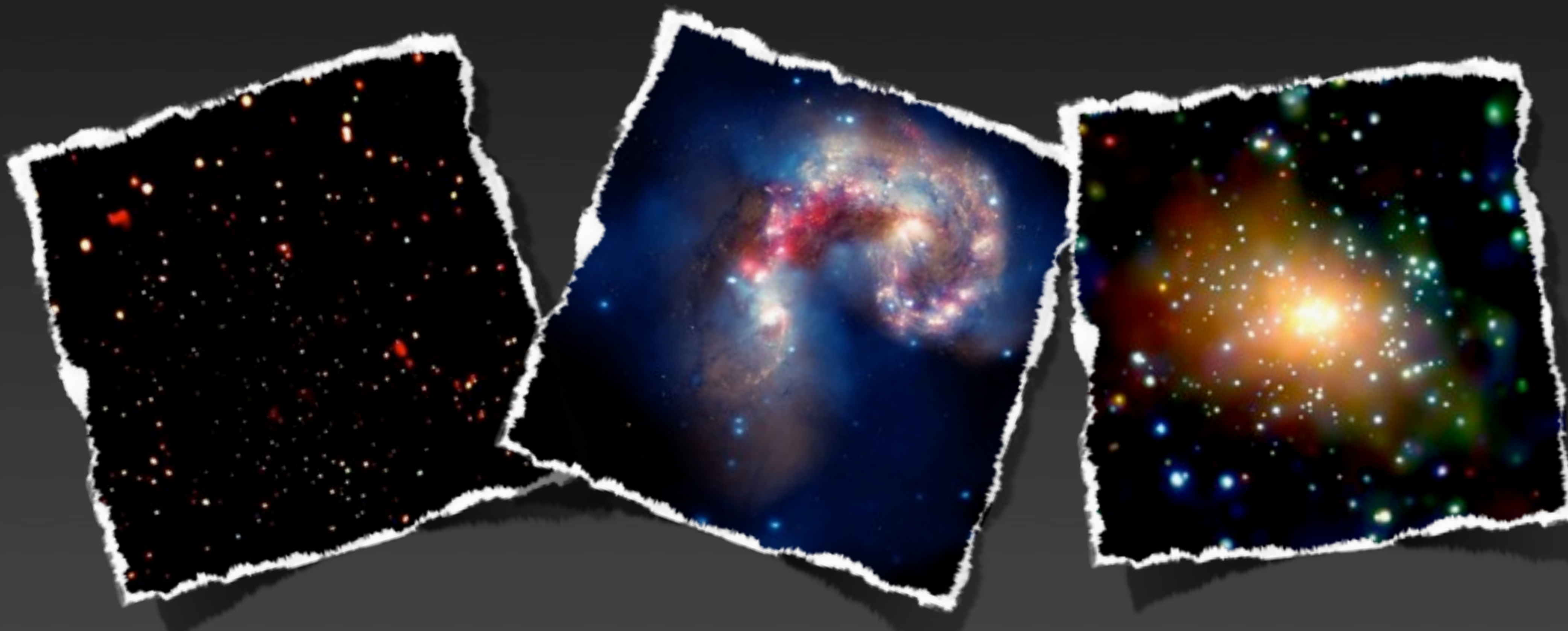
Evolution of X-ray Binaries Across Cosmic Time

Tassos Fragos

Harvard ITC / Harvard-Smithsonian CfA

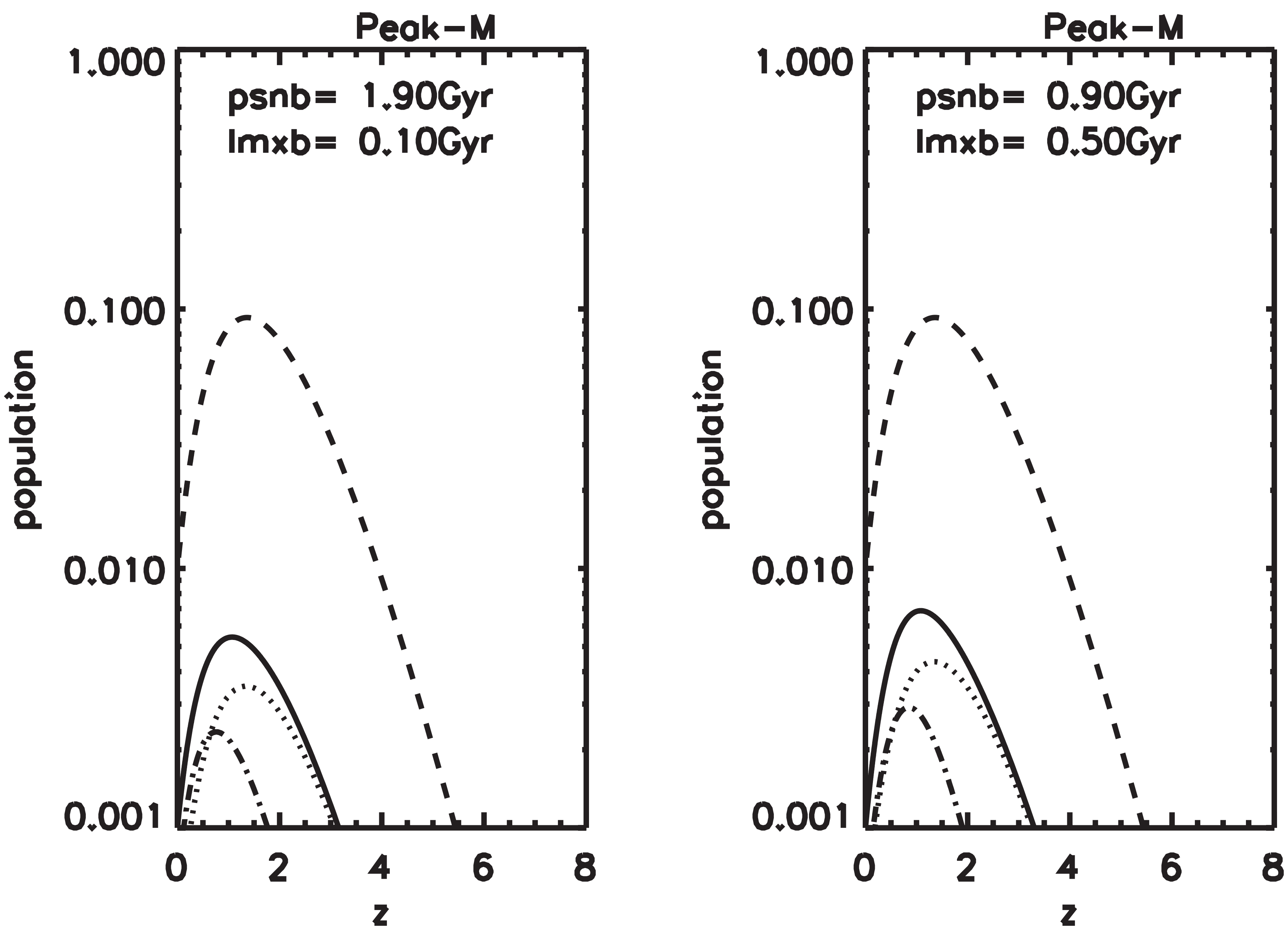


with B. Lehmer, M. Tremmel, P. Tzanavaris, A. Basu-Zych, K. Belczynski, A. Hornschemeier, L. Jenkins, V. Kalogera, A. Ptak, A. Zezas

***X-ray Binaries**: Celebrating 50 Years Since the Discovery of Sco X-1* 7/11/2012

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 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)

Parameter space study: 288 PS models for 9 metallicity values and ~45 Million binaries per model

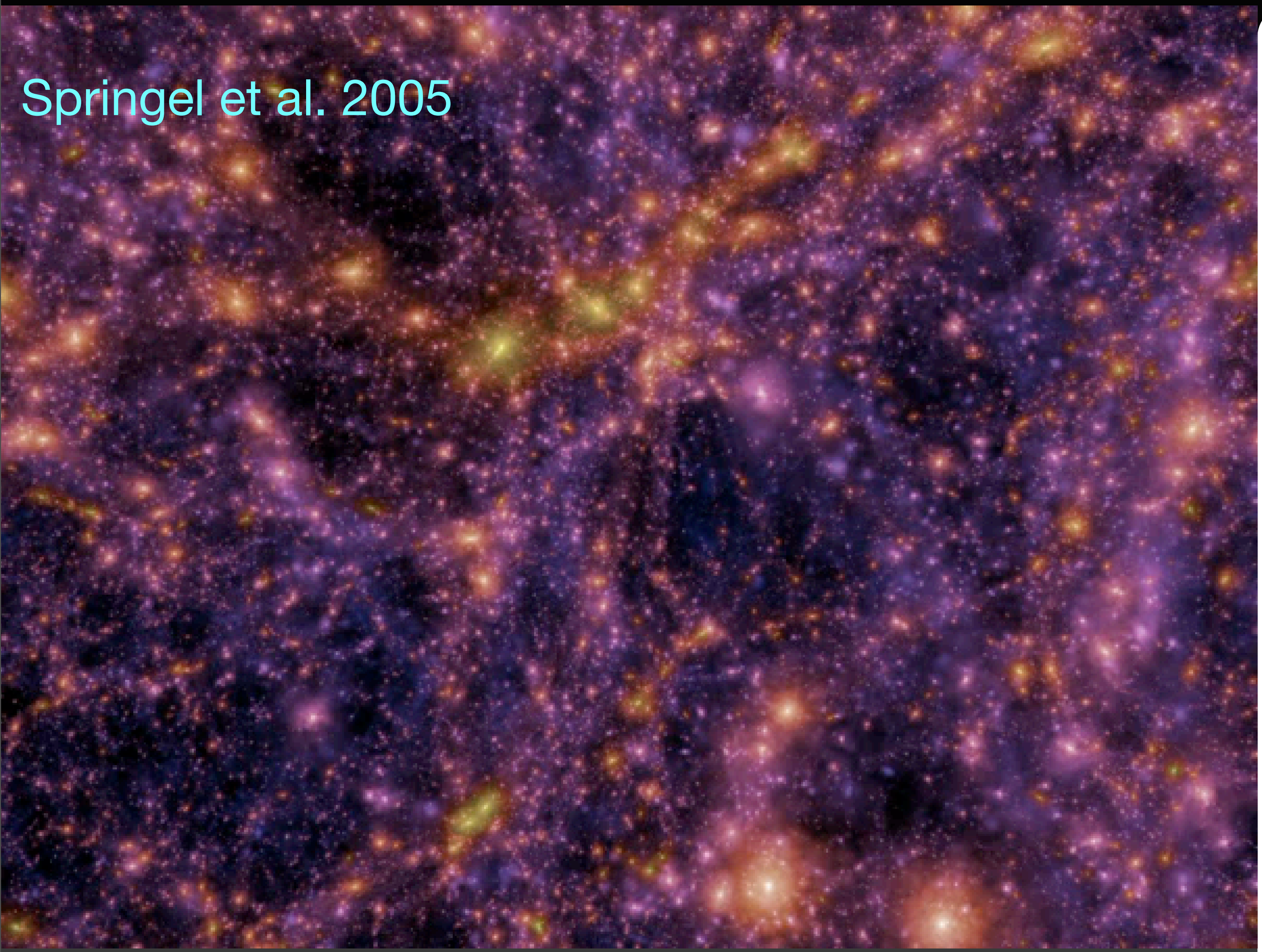
- Available computational resources:
  - Quest HPC cluster (NU)
  - Discover HPC cluster (NCCS)
  - Fugu HPC cluster (astro-NU)
  - **Total of ~2,000,000 cpu hours required**

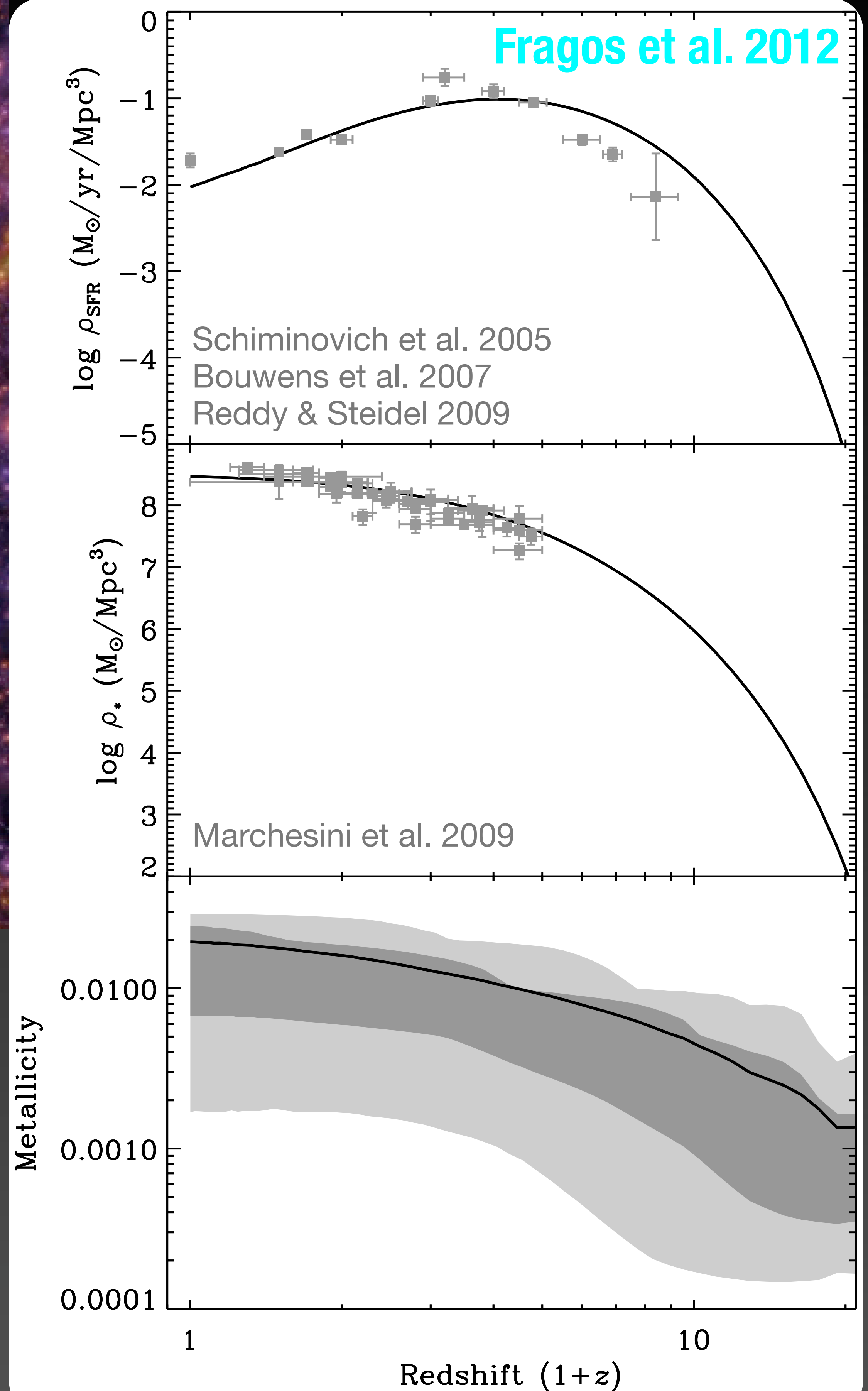
Parameter Study

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

288 Models with 5M (per metallicity) binaries each

The Millennium Simulation





Millennium-II Simulation

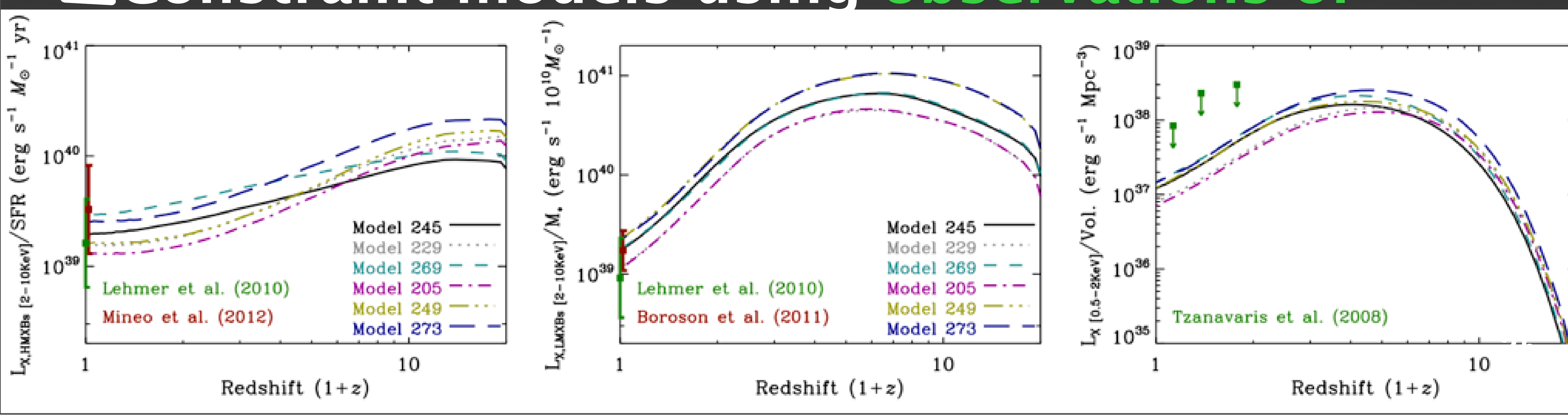
100Mpc^3/h volume - 125x better mass resolution - 5x better spatial resolution (Boylan-Kolchin et al. 2009)

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

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 populations according to the star formation history
- The resulting XRB population is a **mix of populations at different ages and different metallicities**
- Constraint models using **observations of**

Fragos et al. 2012



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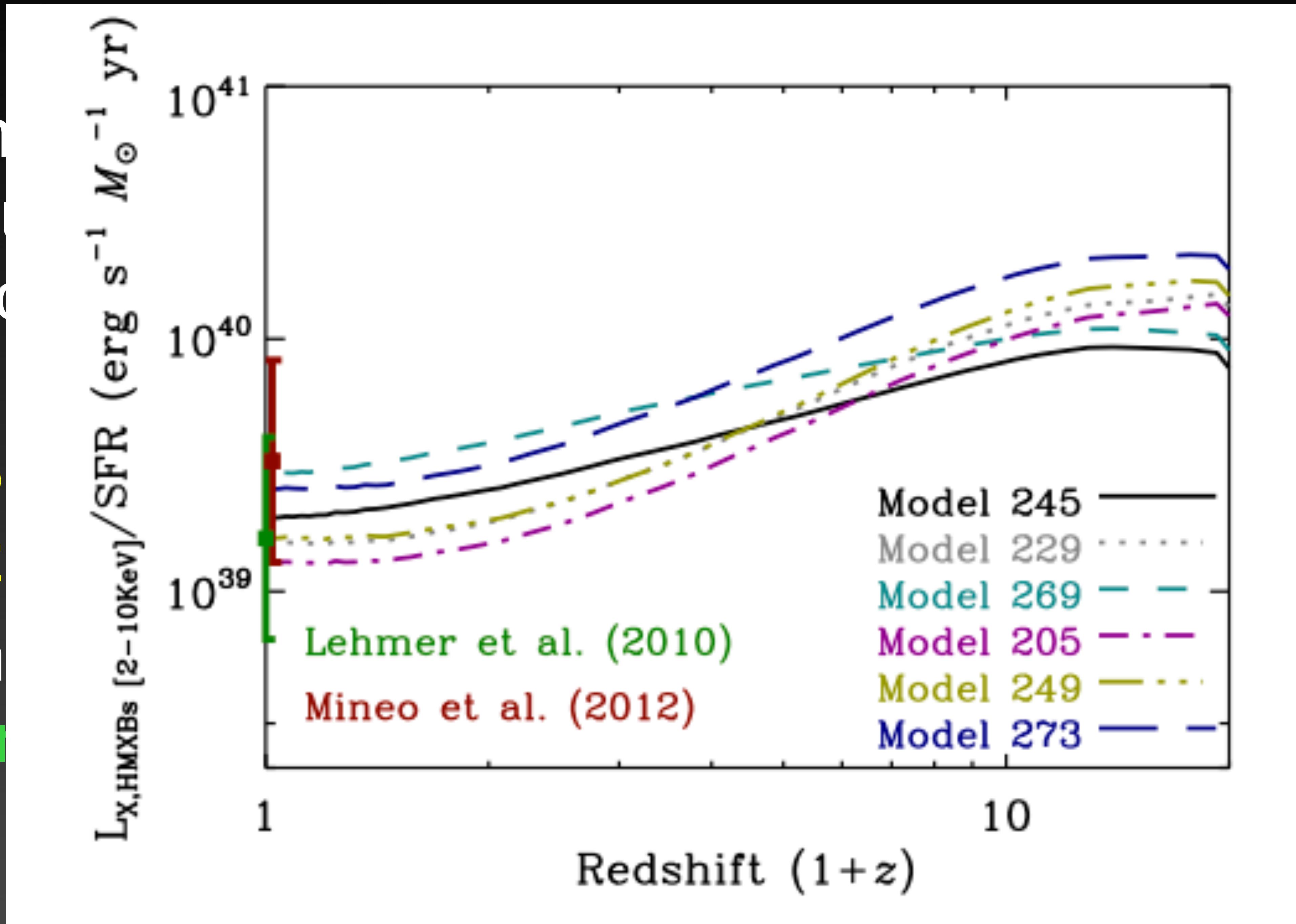
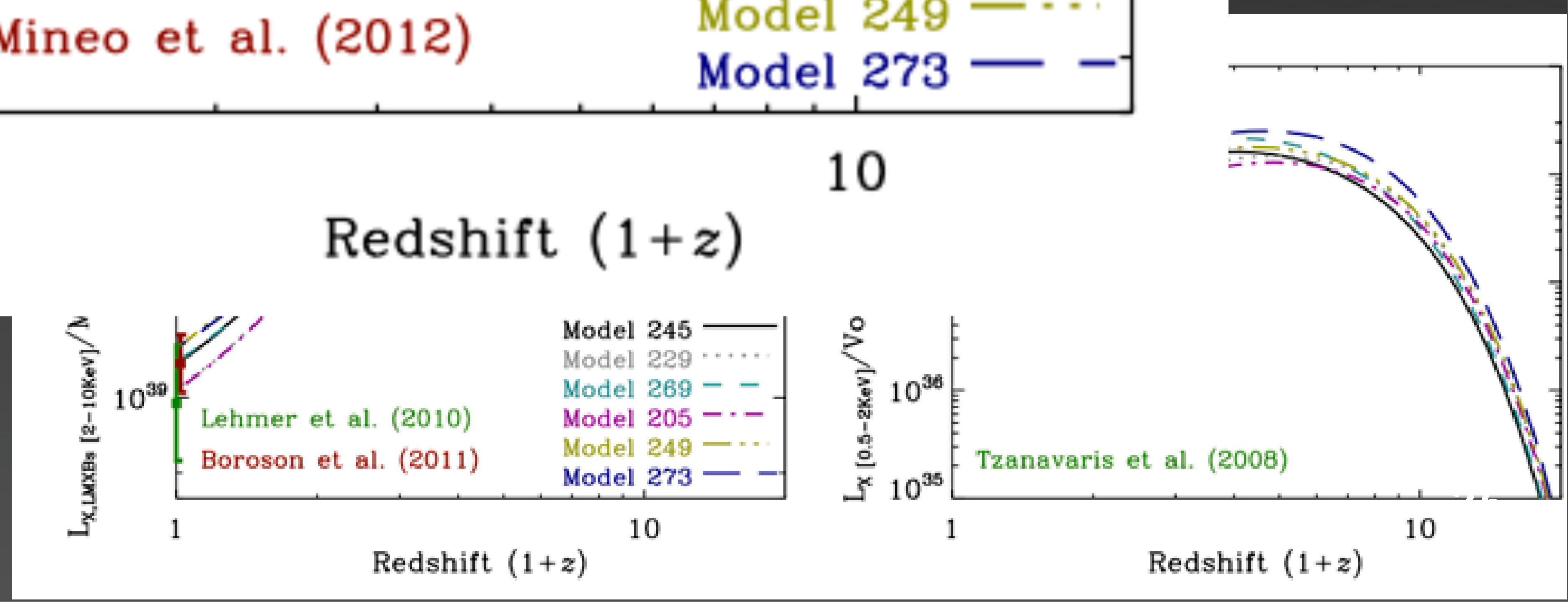
- Usin … tellar popu … n histo
- The … **pop** … **nt** **met**
- Con … **norr**

gos et al. 2012





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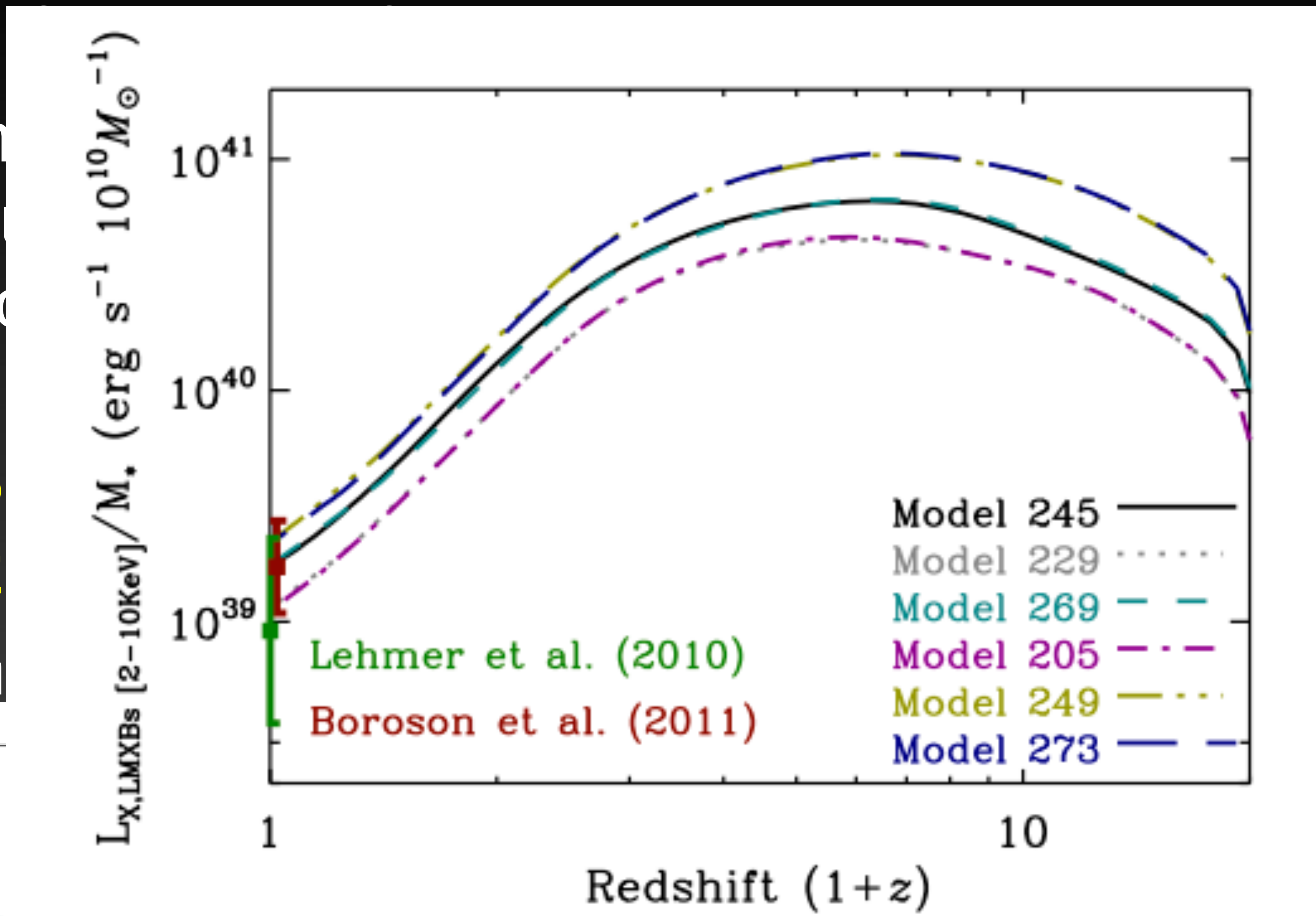

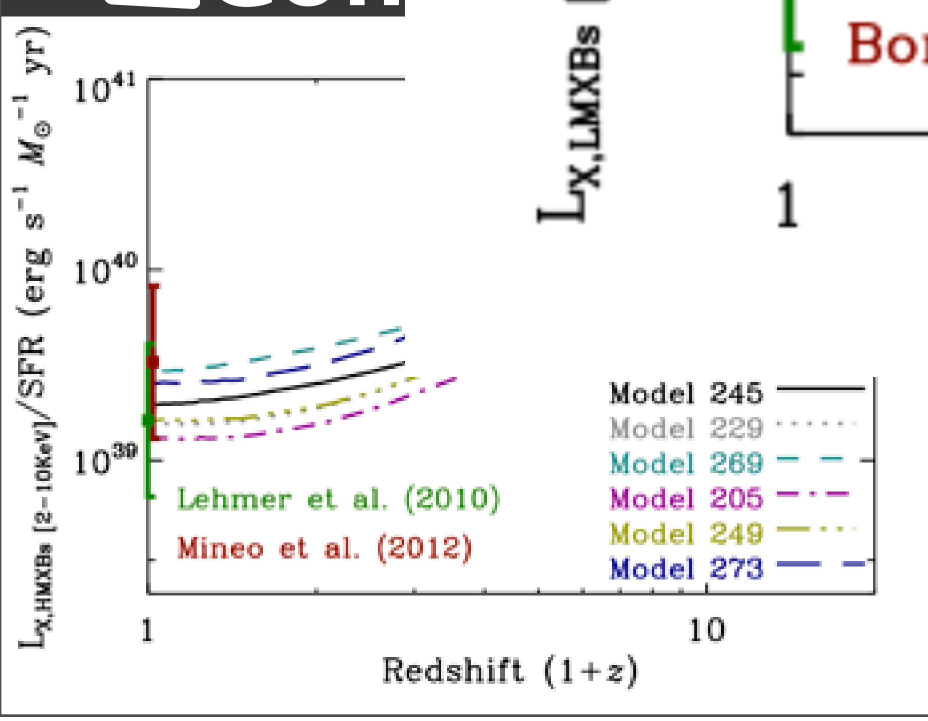

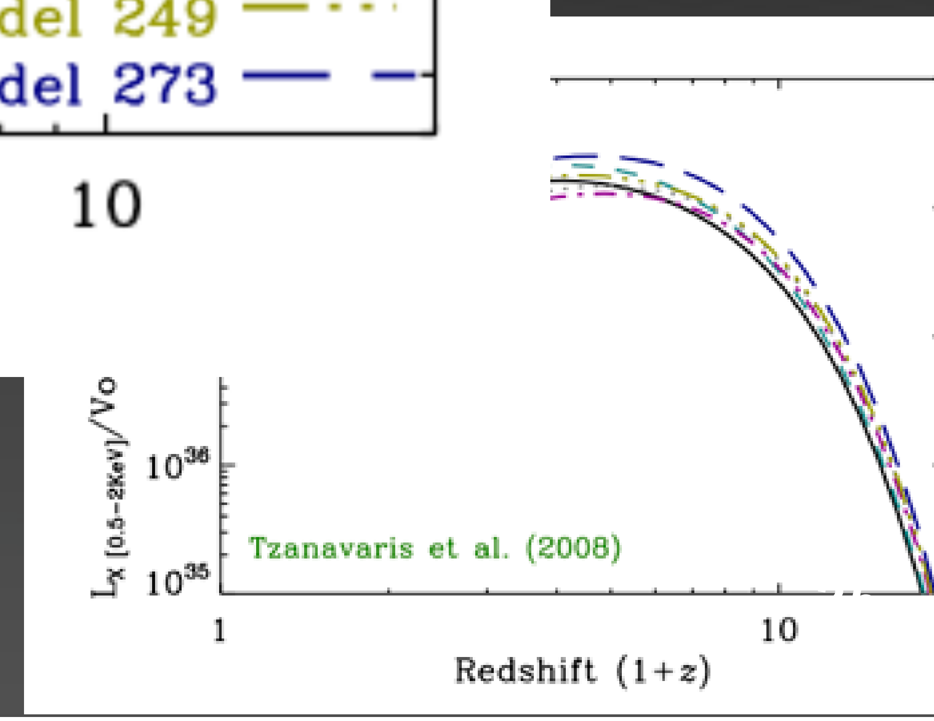

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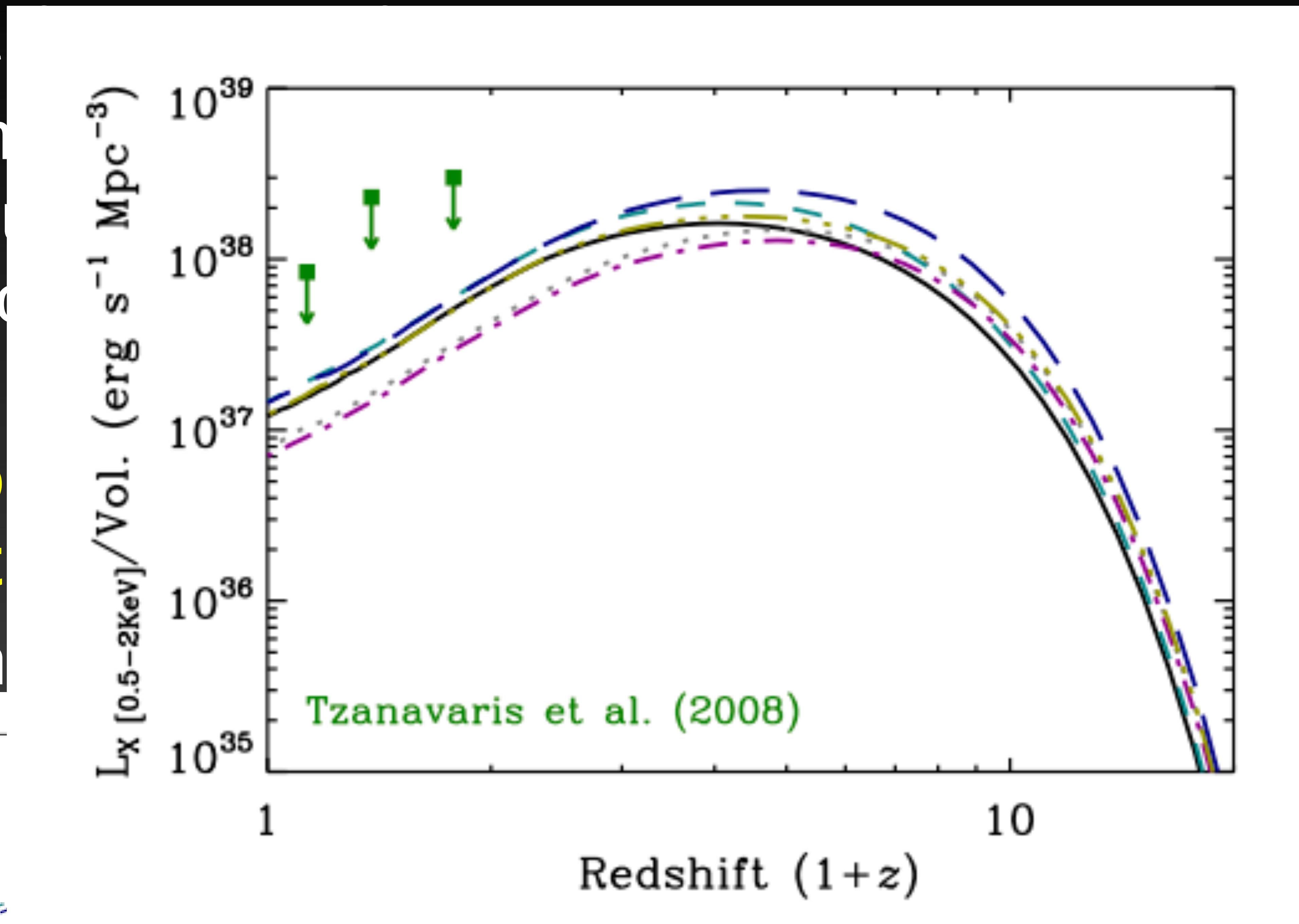

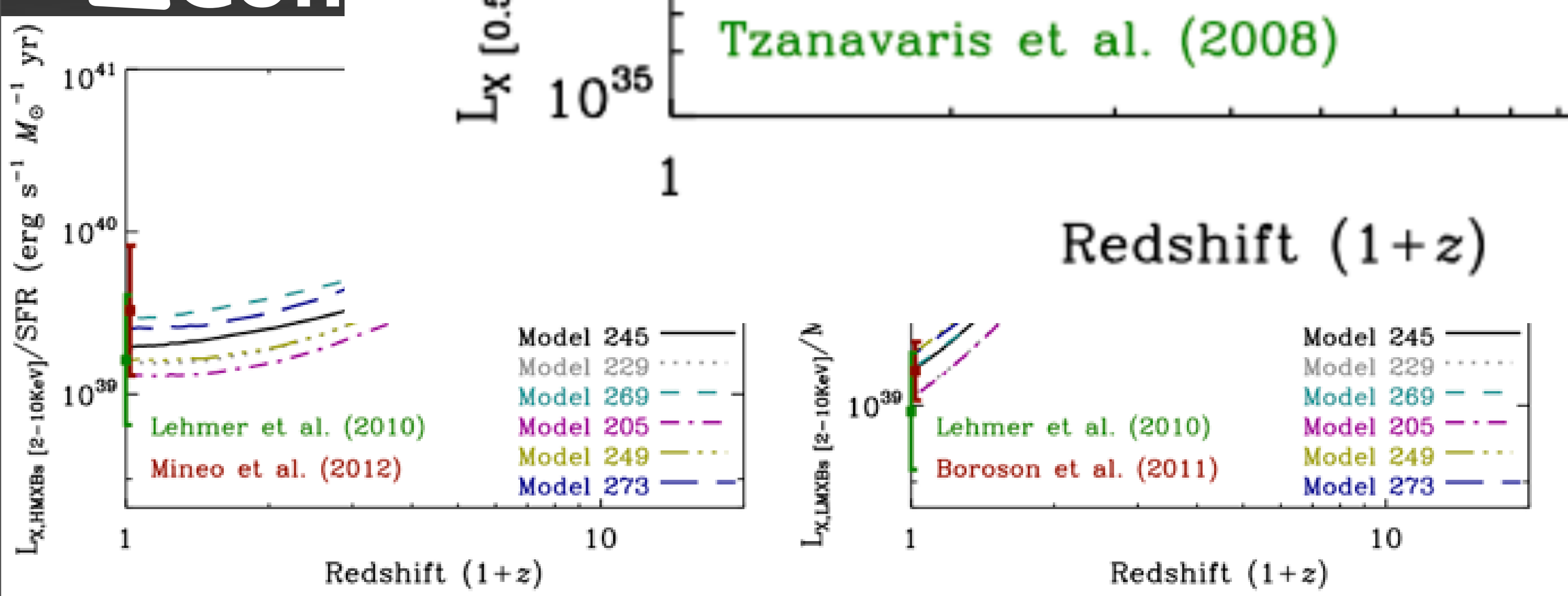

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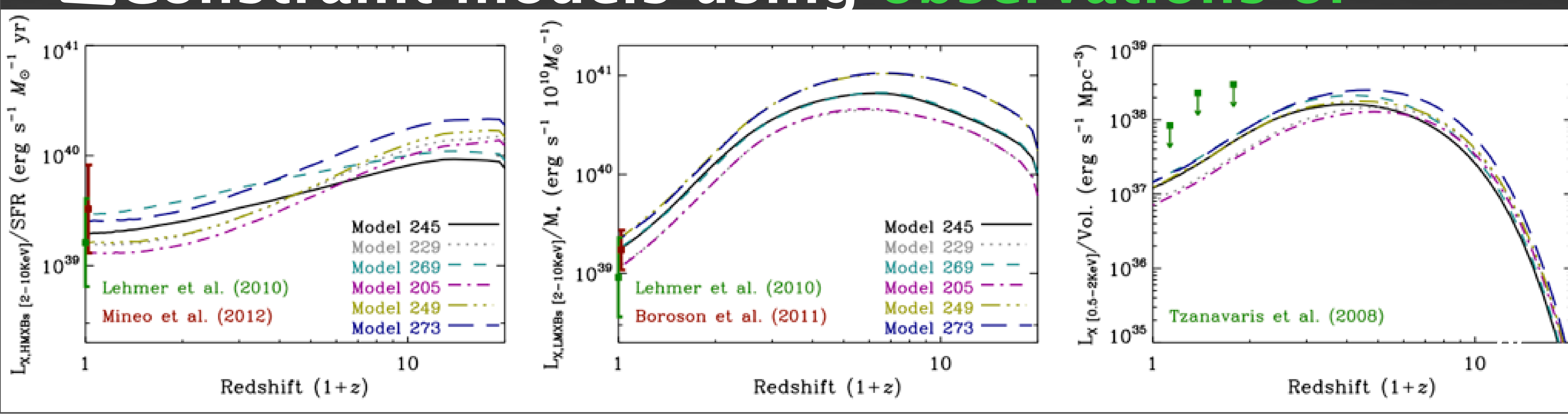
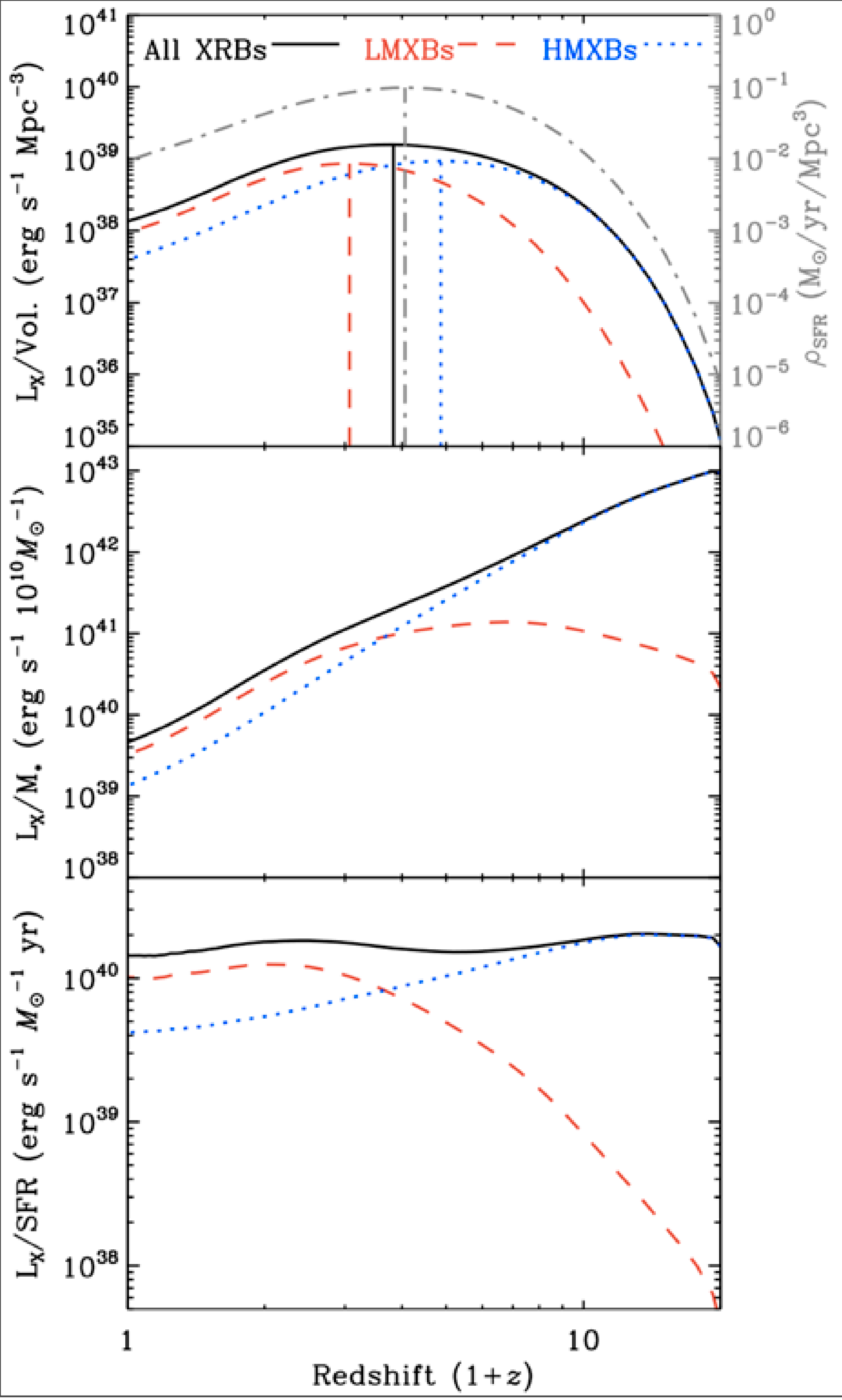


Model Predictions

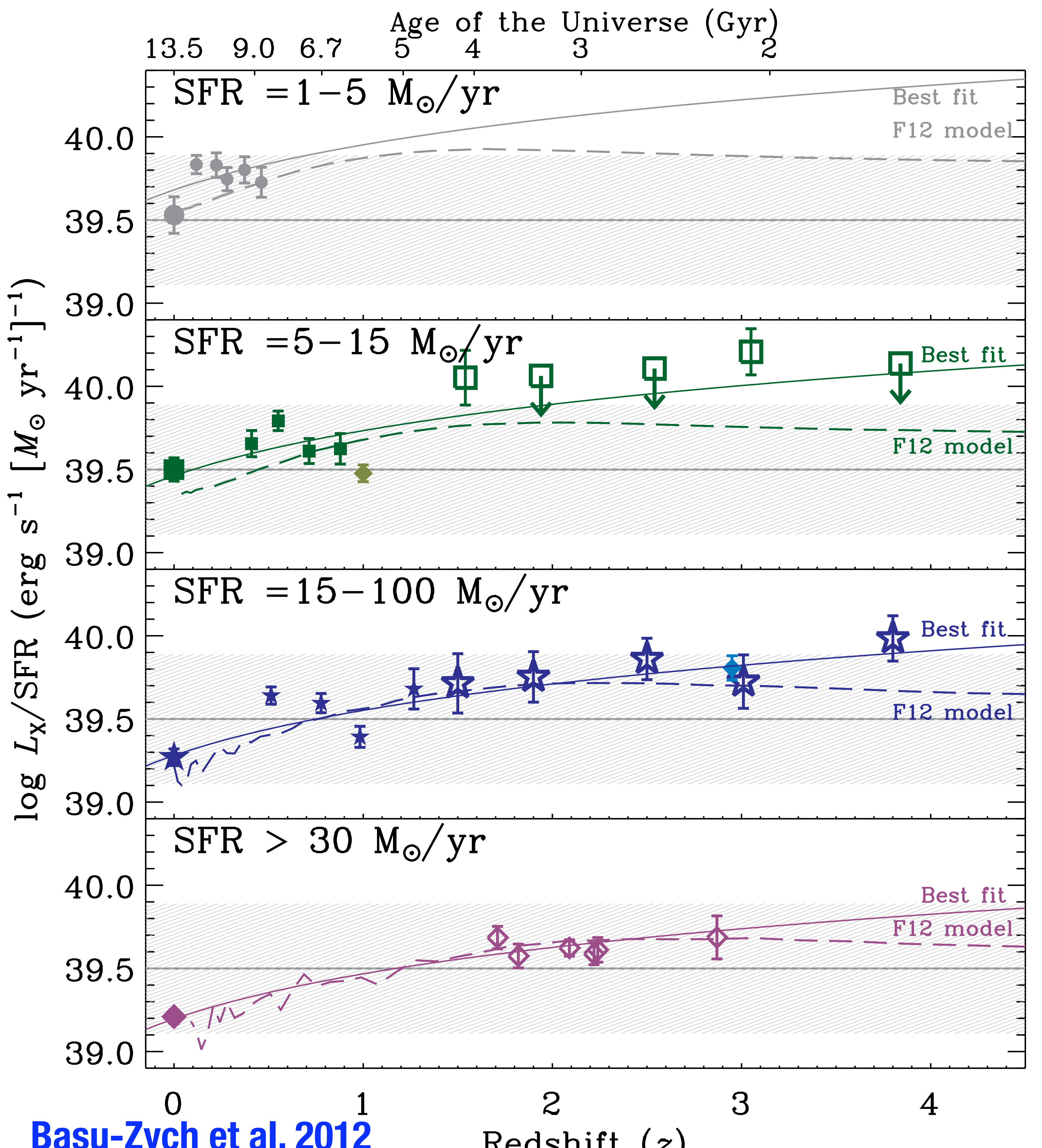
Fragos et al. 2012



- There is a delay between the peak of the SFR and the peak of X-ray luminosity density from LMXBs
- L_X/SFR constant with redshift, although $L_{X,HMXBs}$/SFR shows a slight evolution due to metallicity.
- $L_X/M_{Stellar}$ increases with redshift. Younger stellar populations have higher $L_X/M_{Stellar}$.
- The X-ray luminosity from XRBs in our Universe today is dominated by LMXBs, rather than HMXBs.

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

4 Ms CDF-S vs. PS Models :
Lyman-Break Galaxies

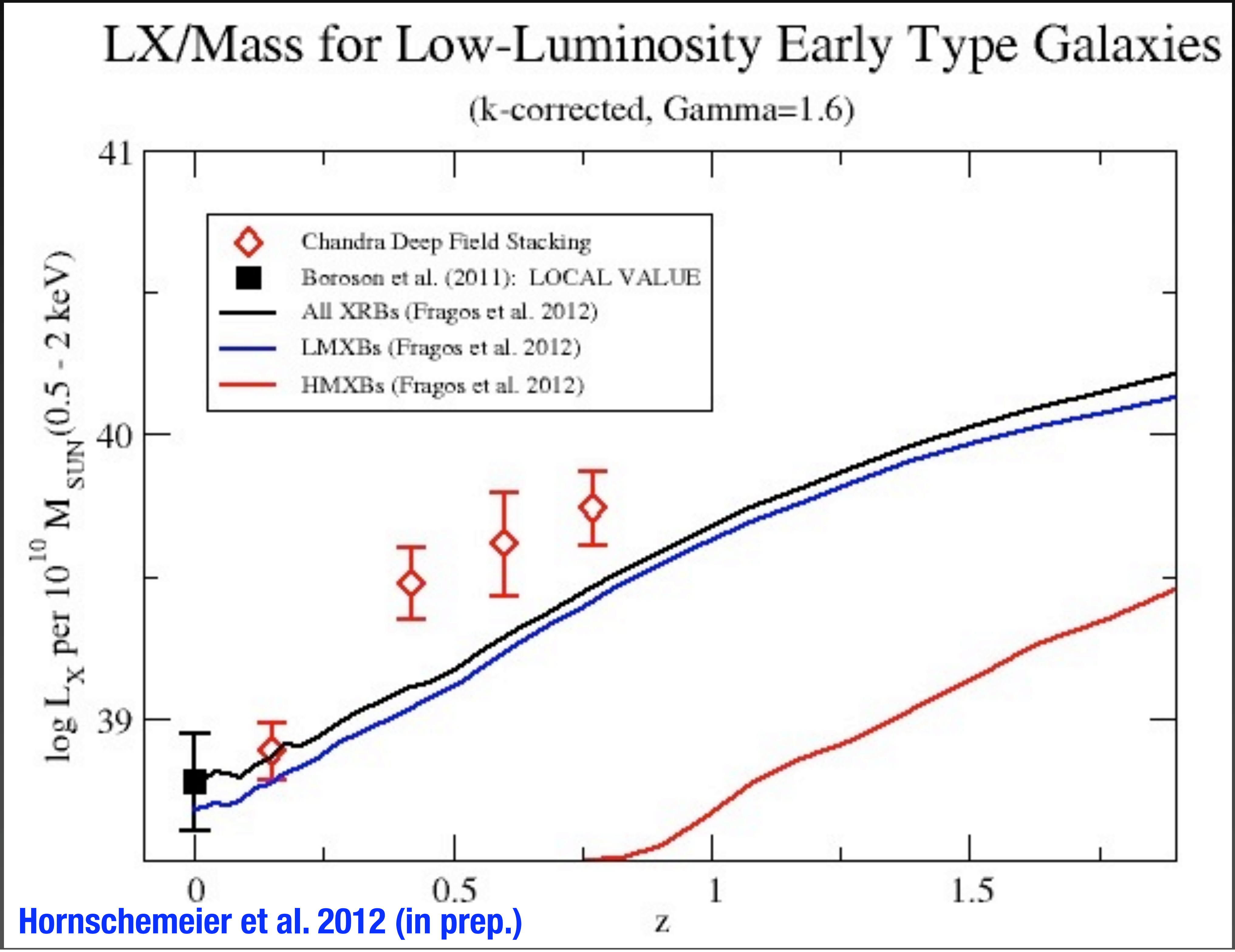


Basu-Zych et al. 2012

4 Ms CDF-S vs. PS Models :
Early-type Galaxies

Red Sequence Selection (from Bell et al. 2004)

$10^{9.5}$ $L_{K\odot}$ < L_K < $10^{10.5}$ $L_{K\odot}$ ($10^{9.3}$ $M_\odot$ < M < $10^{10.3}$ $M_\odot$)



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.

- There is a **time difference** between the **peak** of the **SFR (z~3.1)** and the **peak of X-ray luminosity density** from **HMXBs (z~3.9)** and that of **LMXBs (z~2.1)**.
- The X-ray luminosity from XRBs in the **Universe today** is **dominated by LMXBs**, rather than HMXBs.
- **$L_{X,HMXBs}$/SFR shows an evolution** due to metallicity, but **$L_{X,total}$/SFR is constant** with redshift.
- PS models **constrained from local observations** are in **excellent agreement with high-z CDF-S data**.

Parameter Study

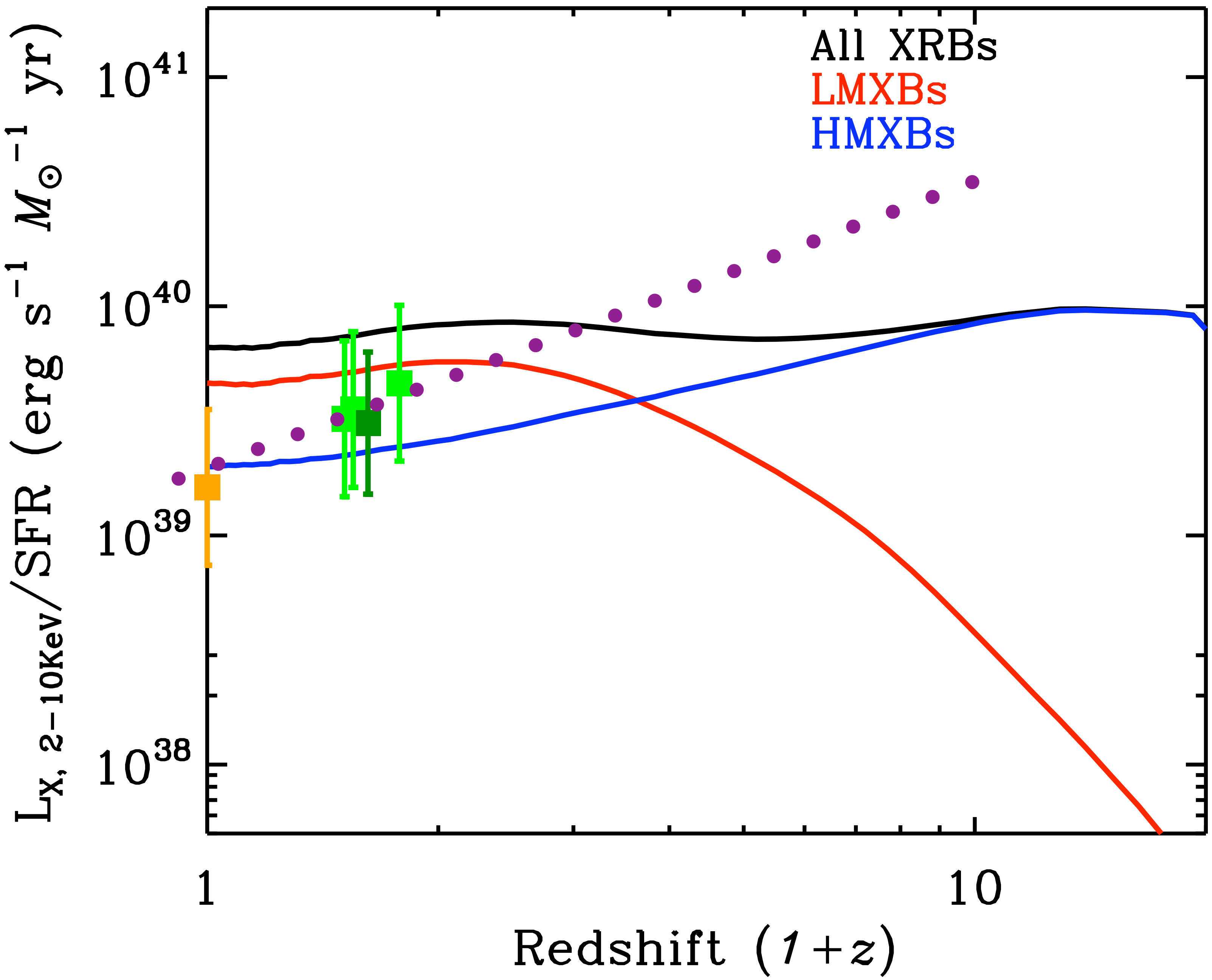
Parameter	Value
α_{ce}	**0.1**~~, 0.2, 0.3, 0.5~~
IMF	**-2.7**, -2.35
Stellar Winds	~~0.25,~~ **1.0**, 2.0
CE for HG primaries	Yes, No
Mass Ratio	**Flat**~~, Twin,~~ **mixture**
Kicks Direct C.C. BH	Yes, No

Low α_{ce} ~0.1 -- "Standard" Stellar Winds or x2 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

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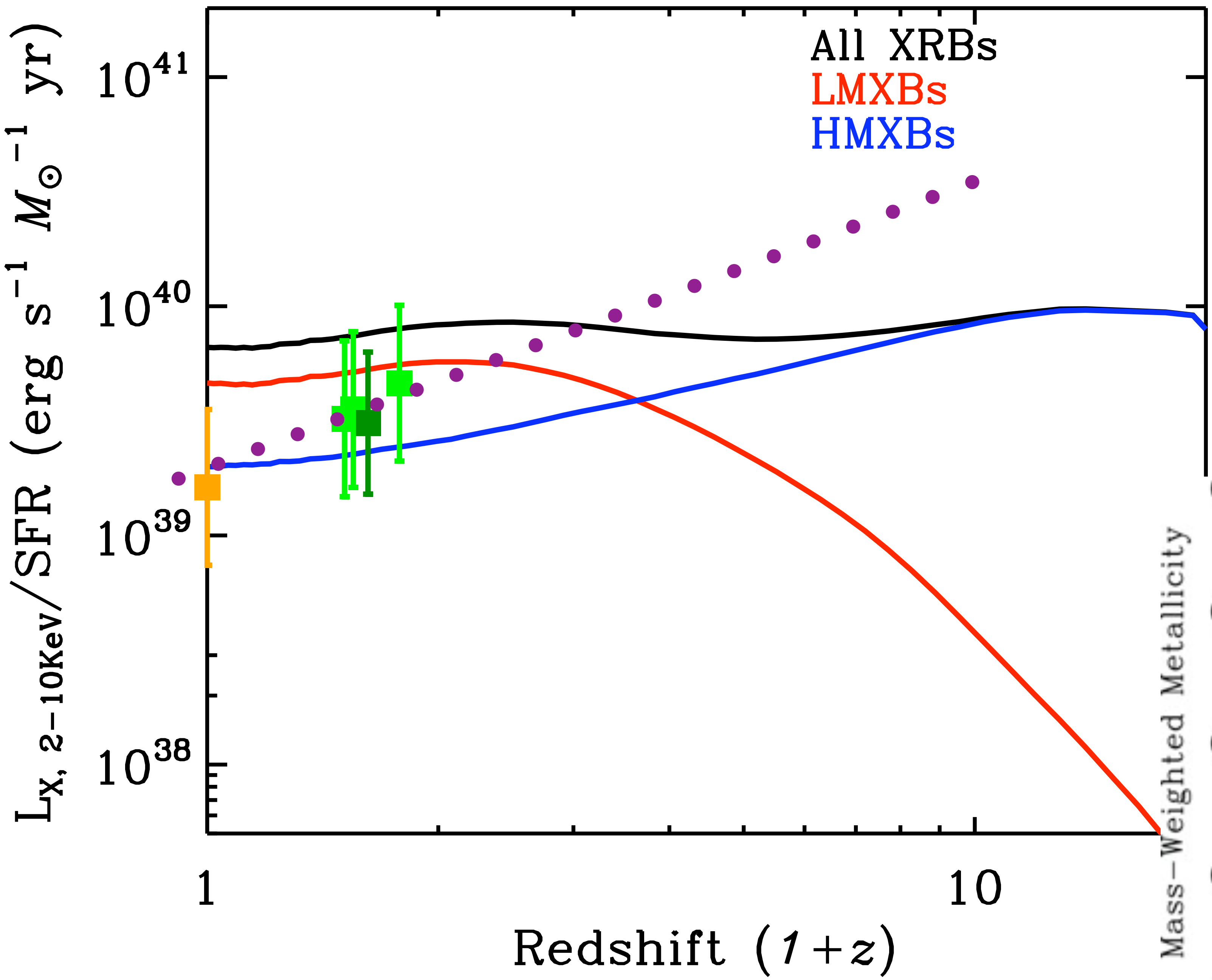

L_X/SFR~$(1+z)^b$, b≲1.3

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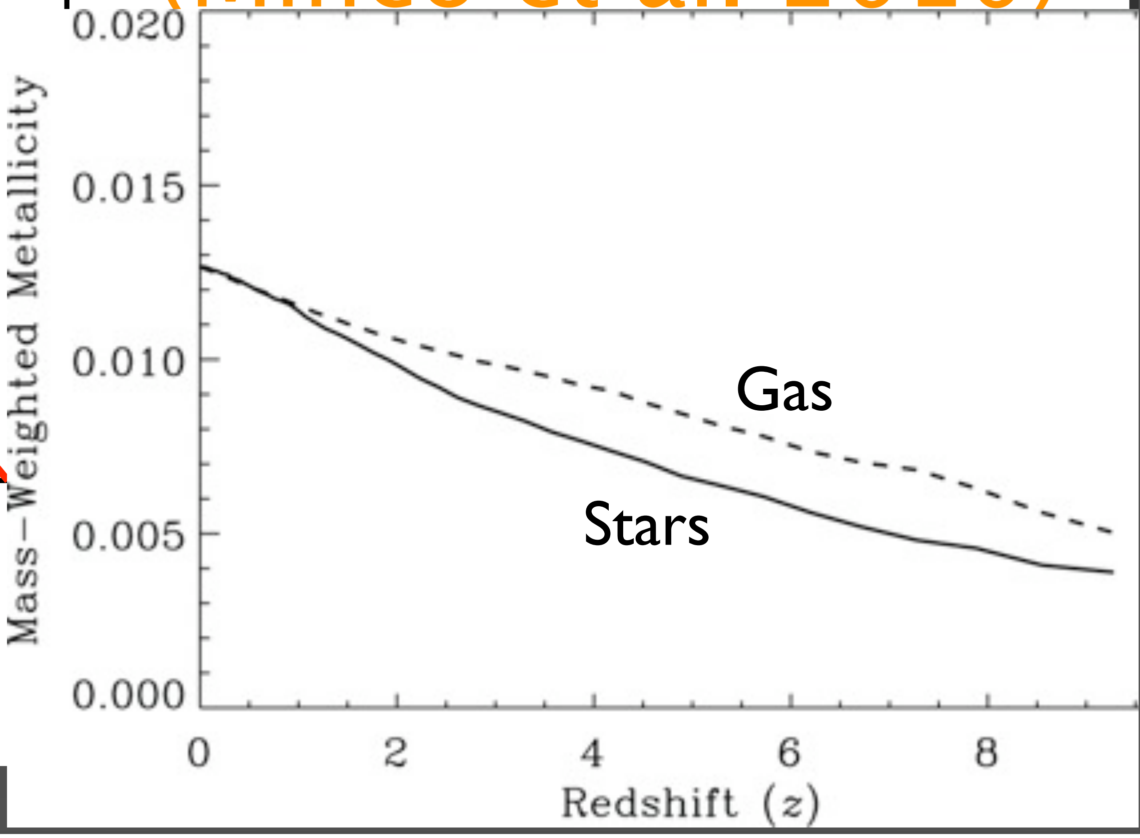

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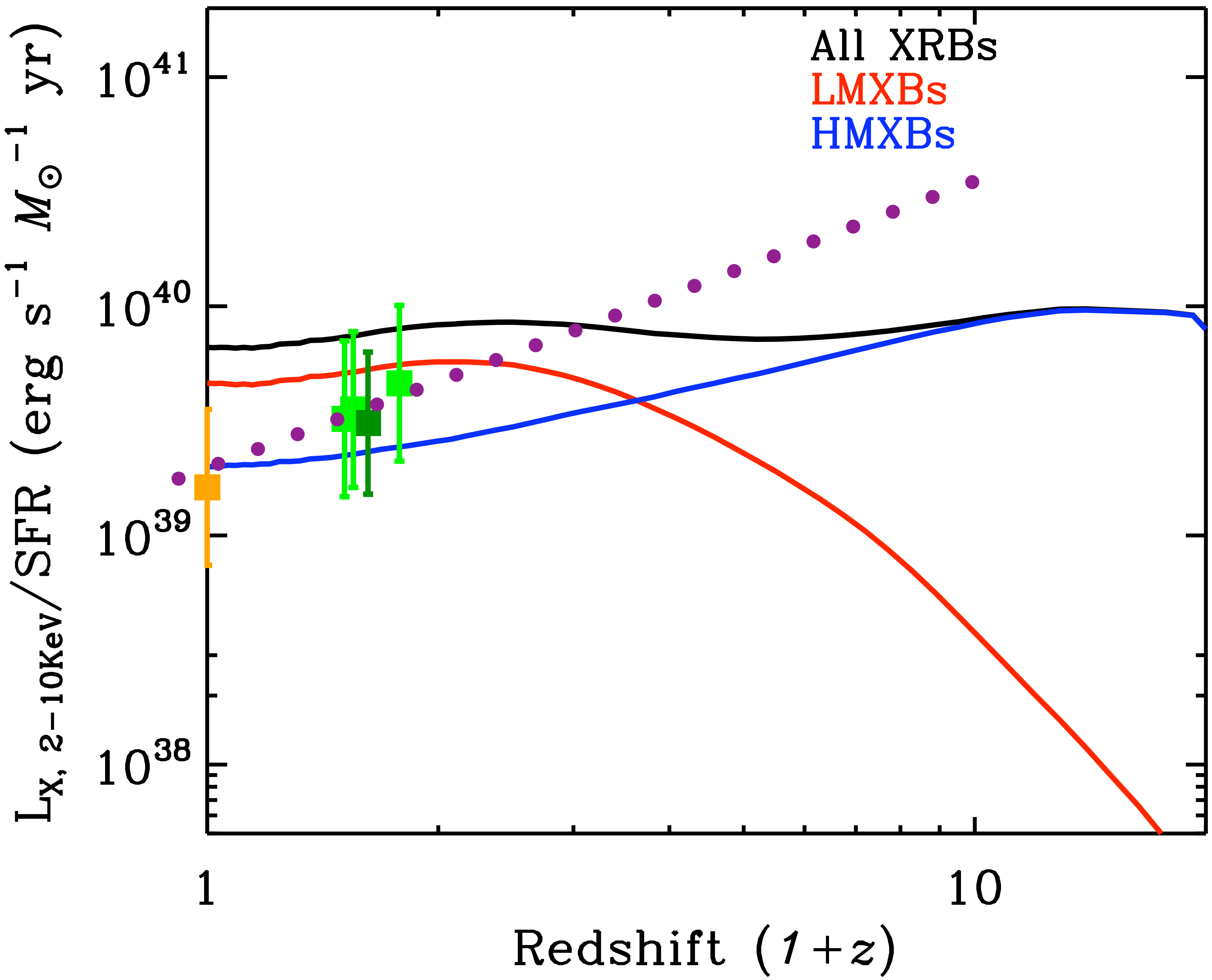

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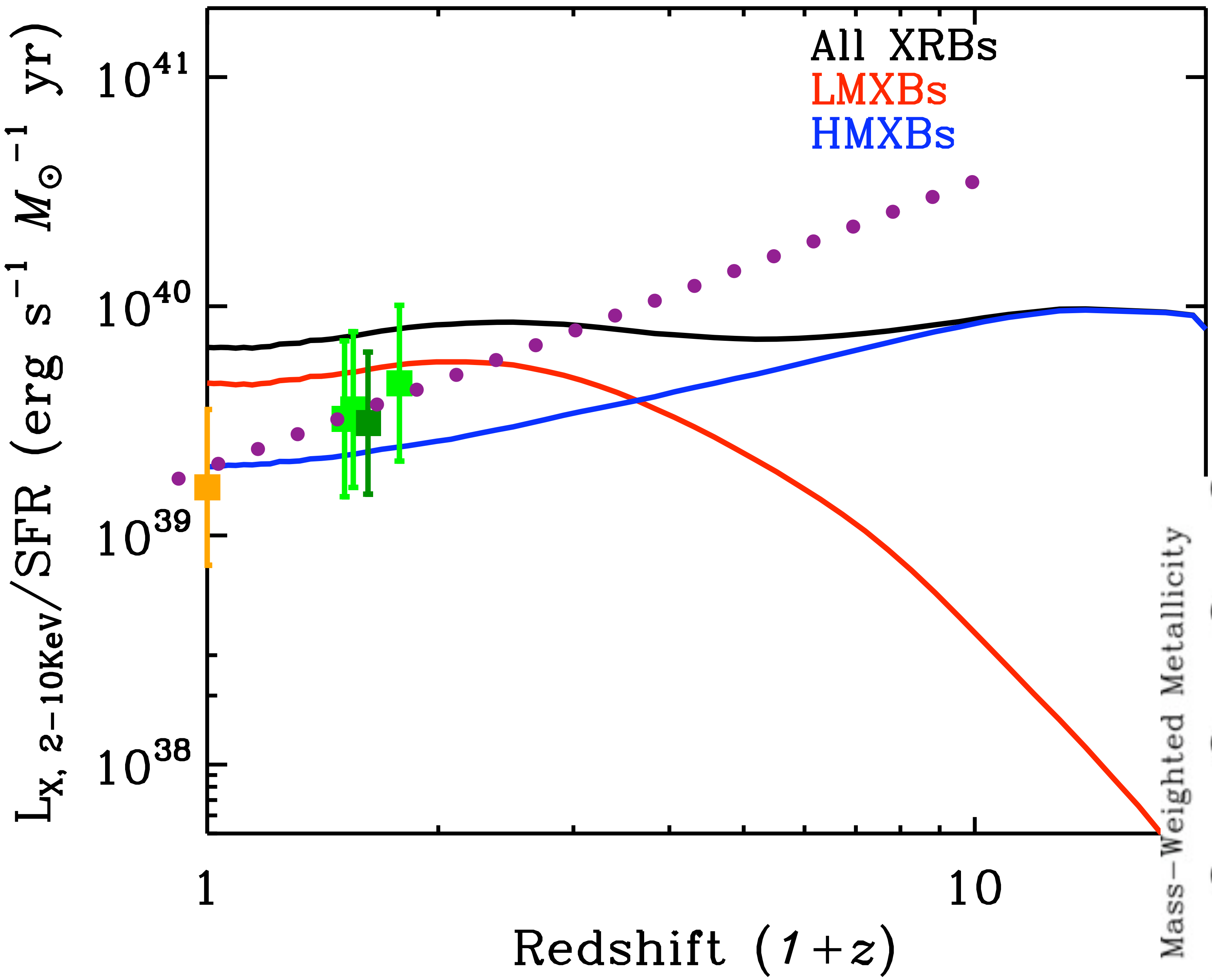

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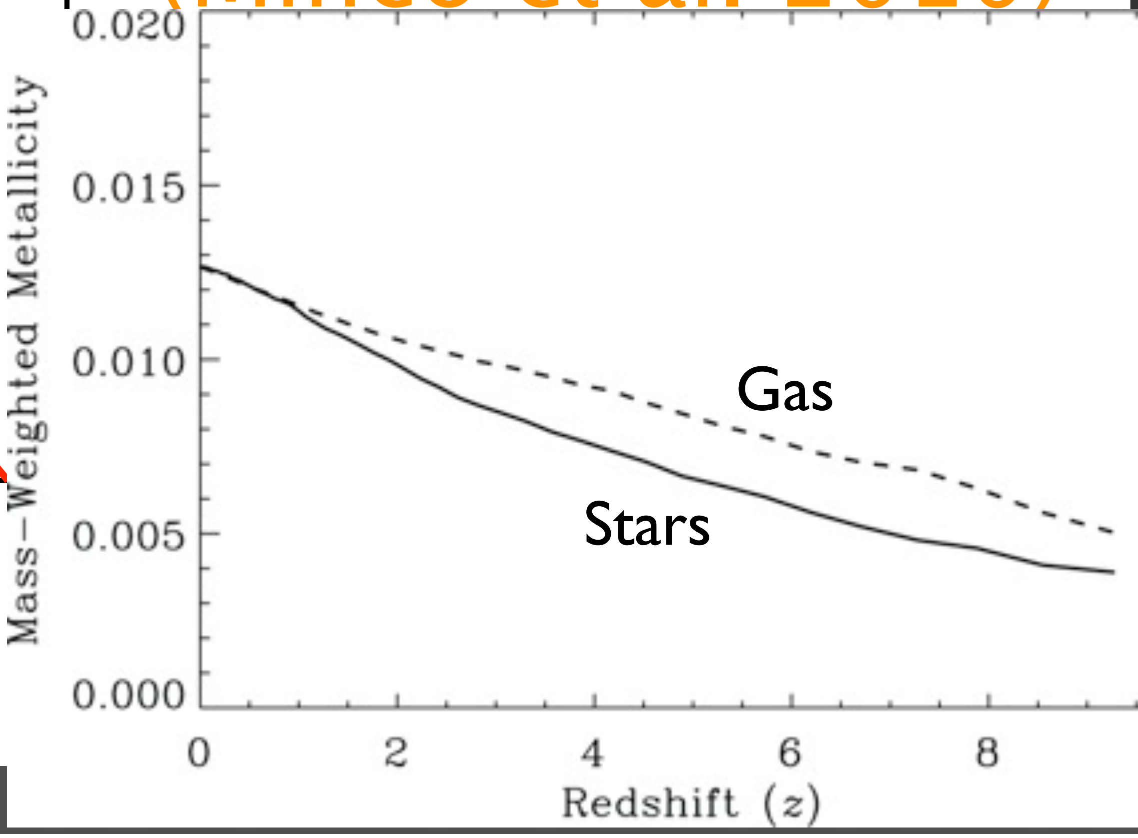

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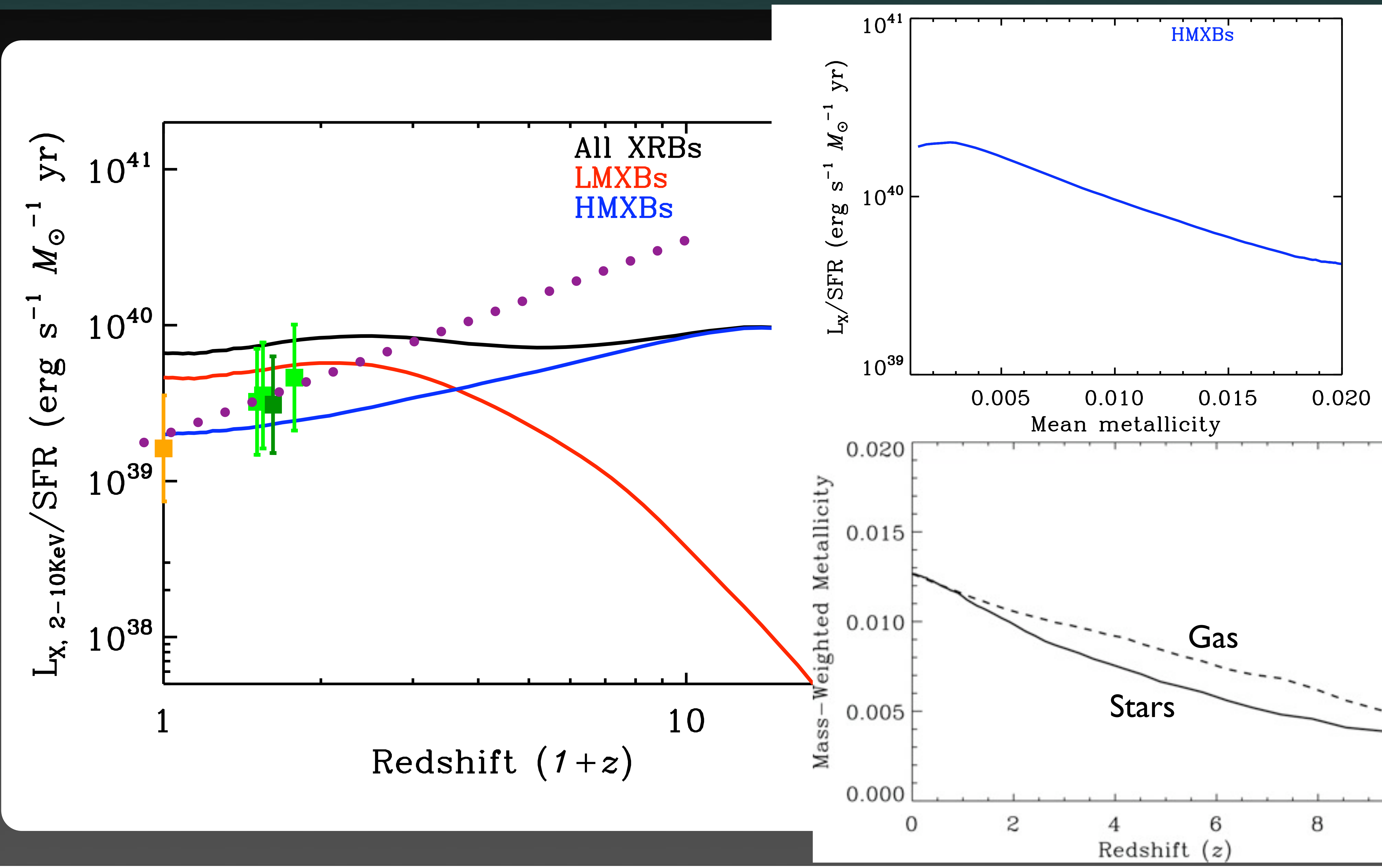
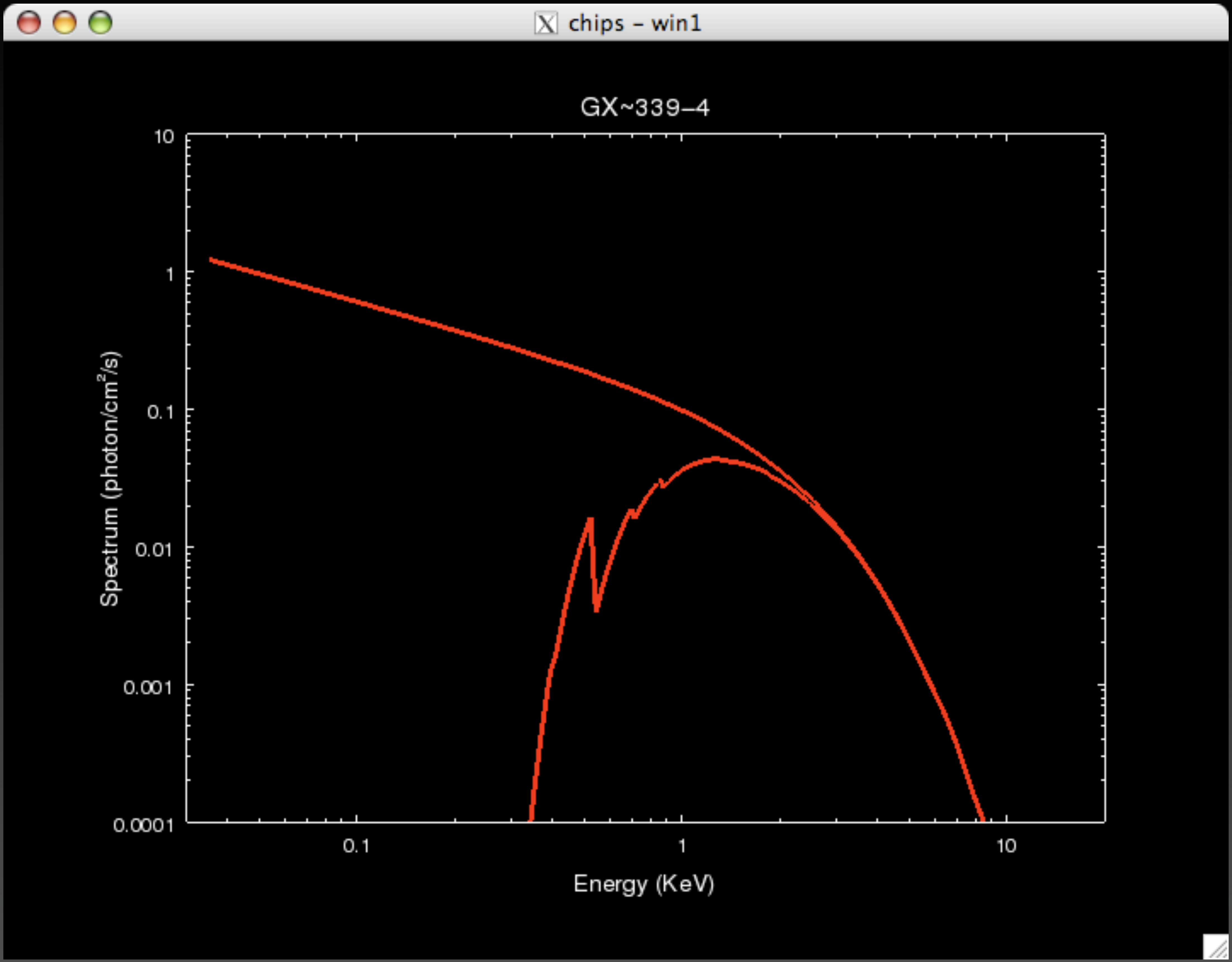


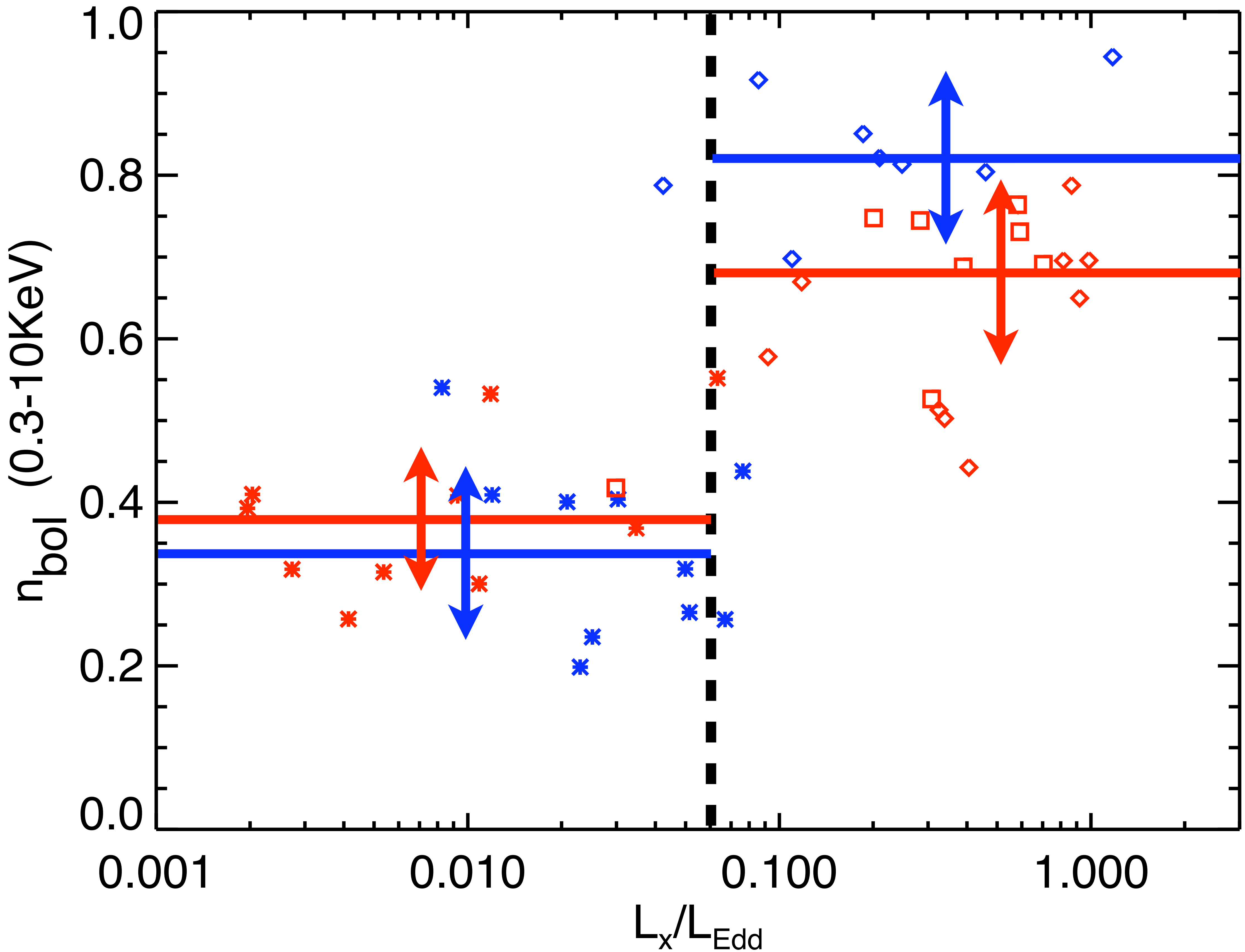
Bolometric Corrections

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



Work in Progress...

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?