




An Exploration of the X-ray Emission from Normal Galaxies in the Early Universe with Lynx

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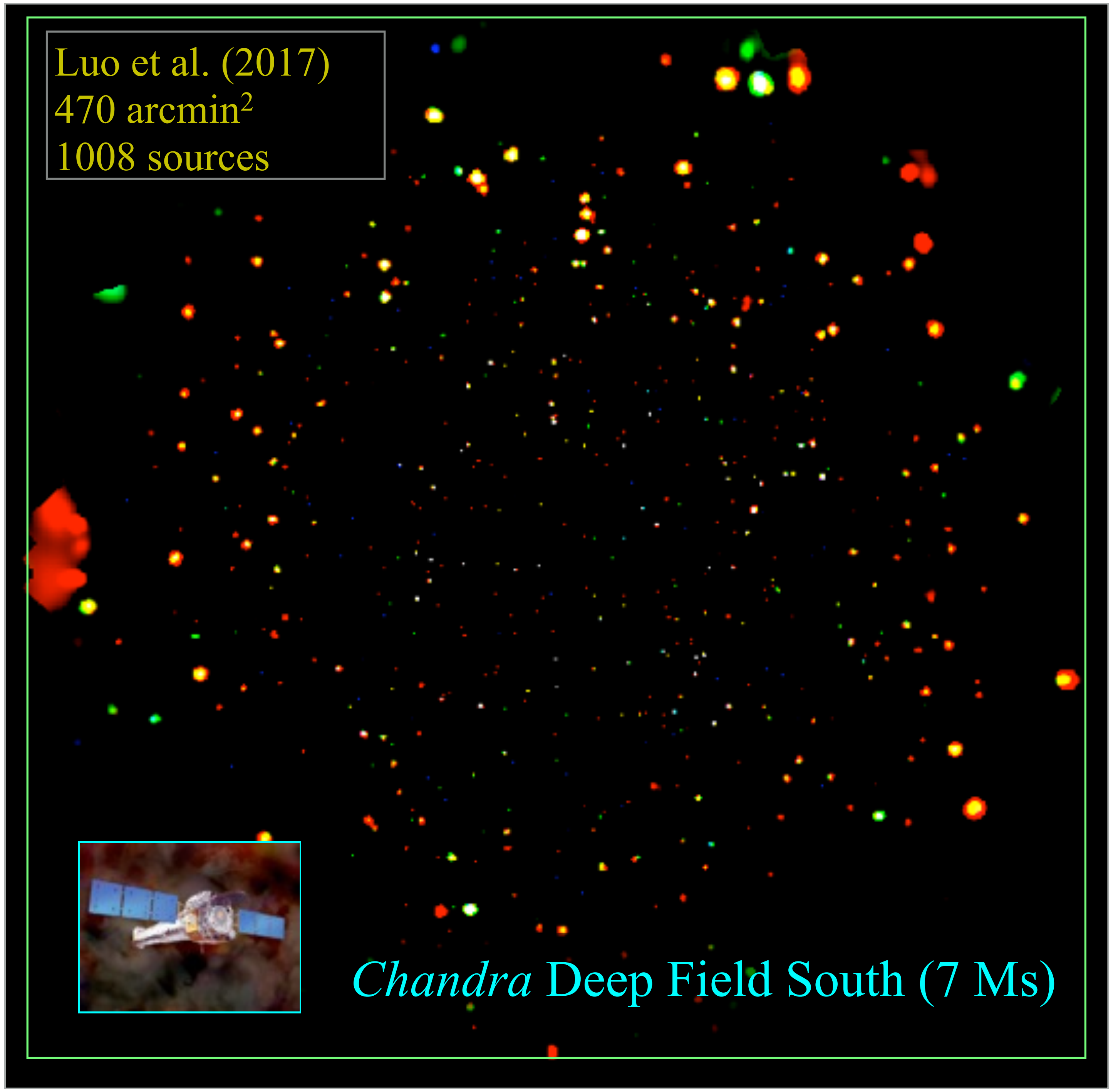
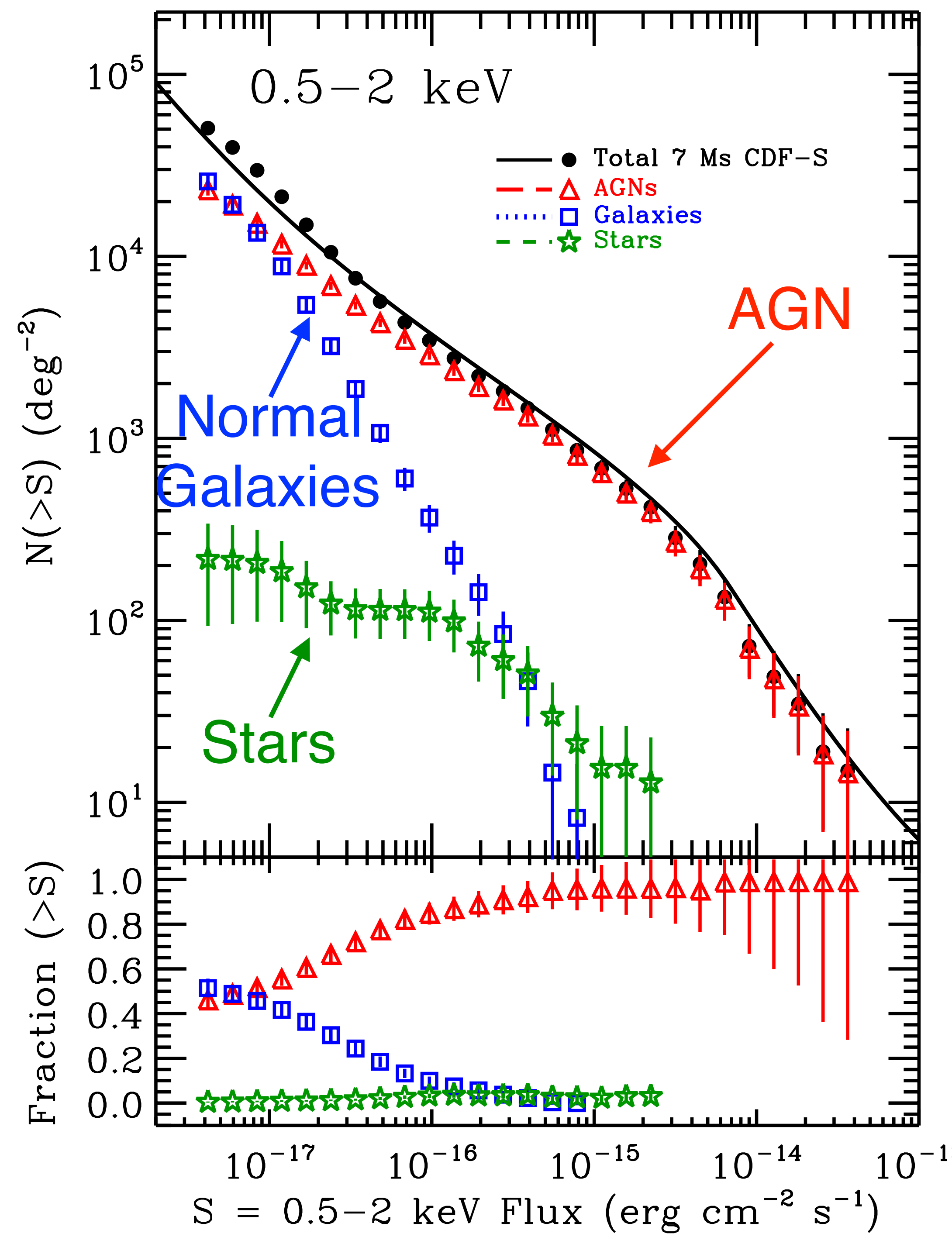
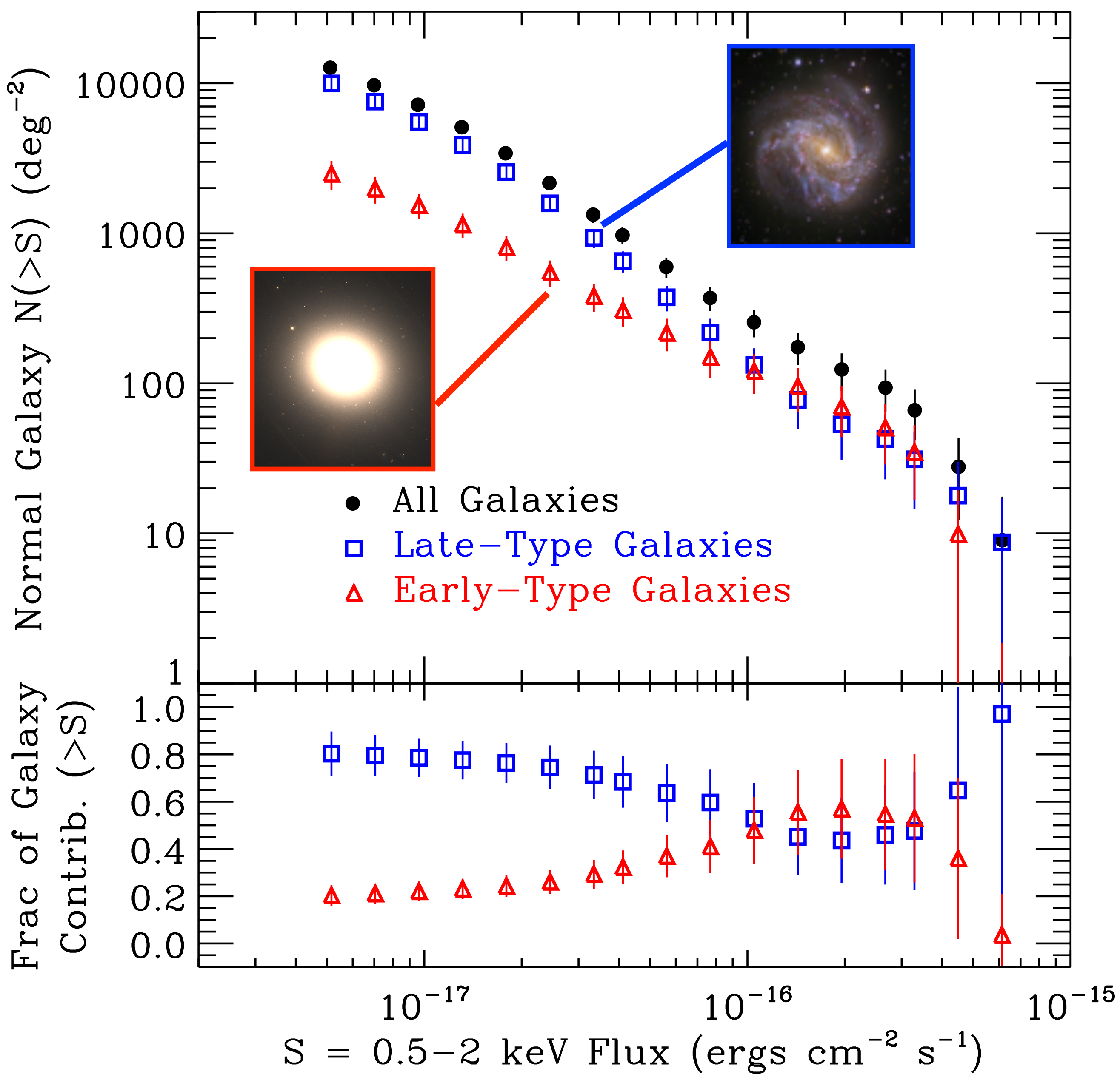
7 Ms CDF-S: Deepest X-ray Survey of the Universe

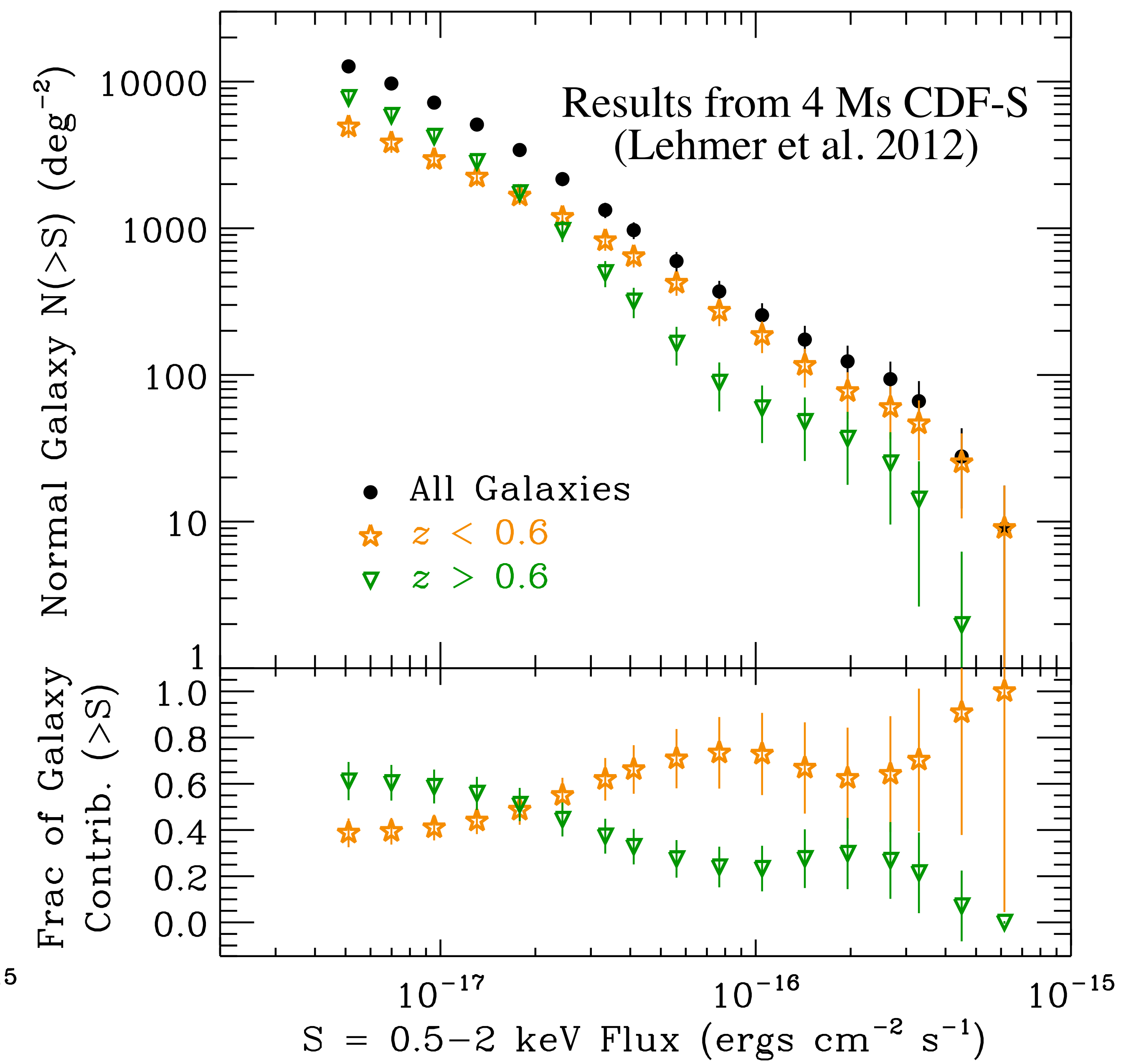




At fainter fluxes, normal galaxies counts will continue to rise rapidly and will dominate in moderately-deep (>100 ks) Lynx exposures.

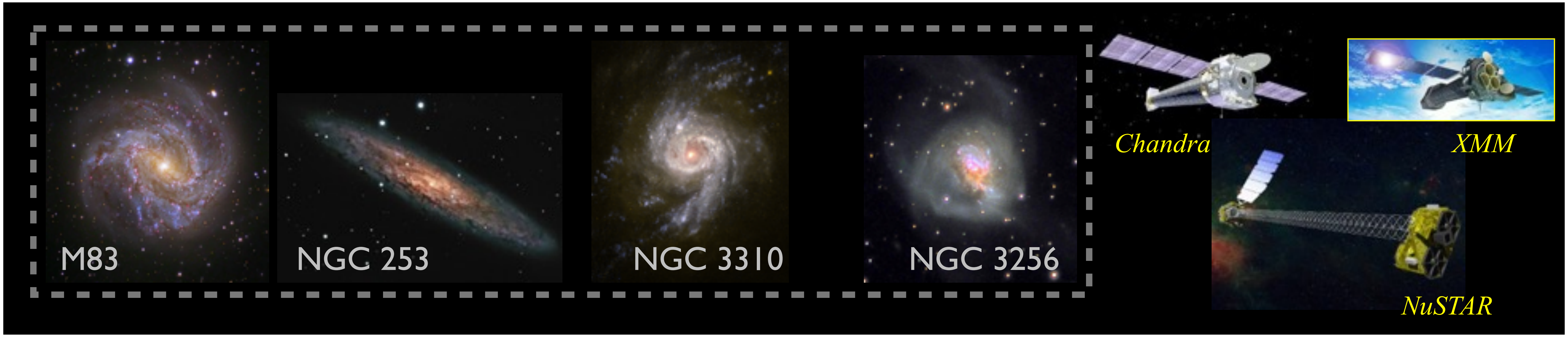
Contributions from Normal Galaxy Subgroups



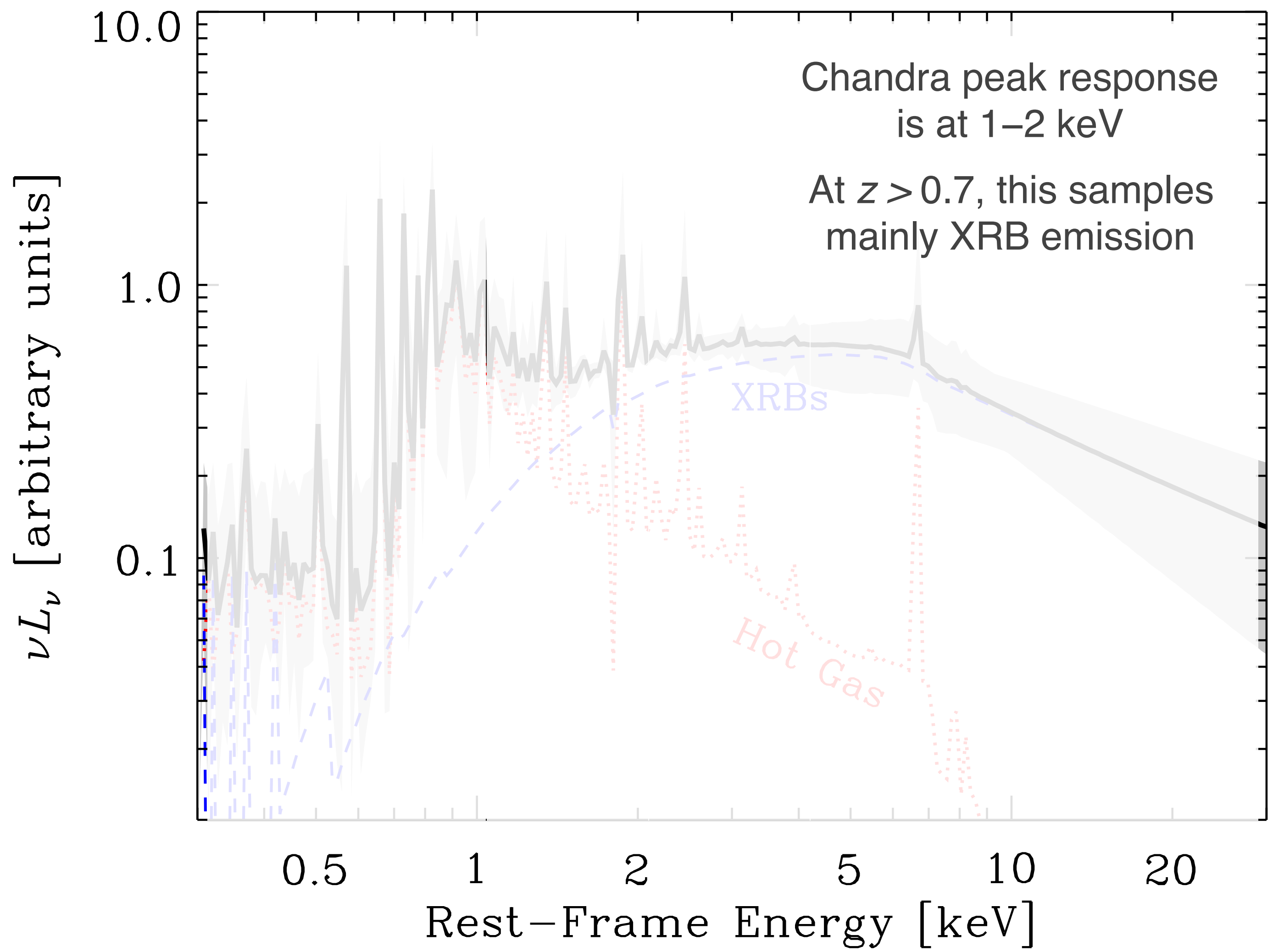


Above the detection limit, majority of the galaxies are late-type galaxies at $z > 0.7$.
At fainter flux levels, we expect counts to be dominated by higher redshift sources.

Average Spectrum of Late-Type Galaxies

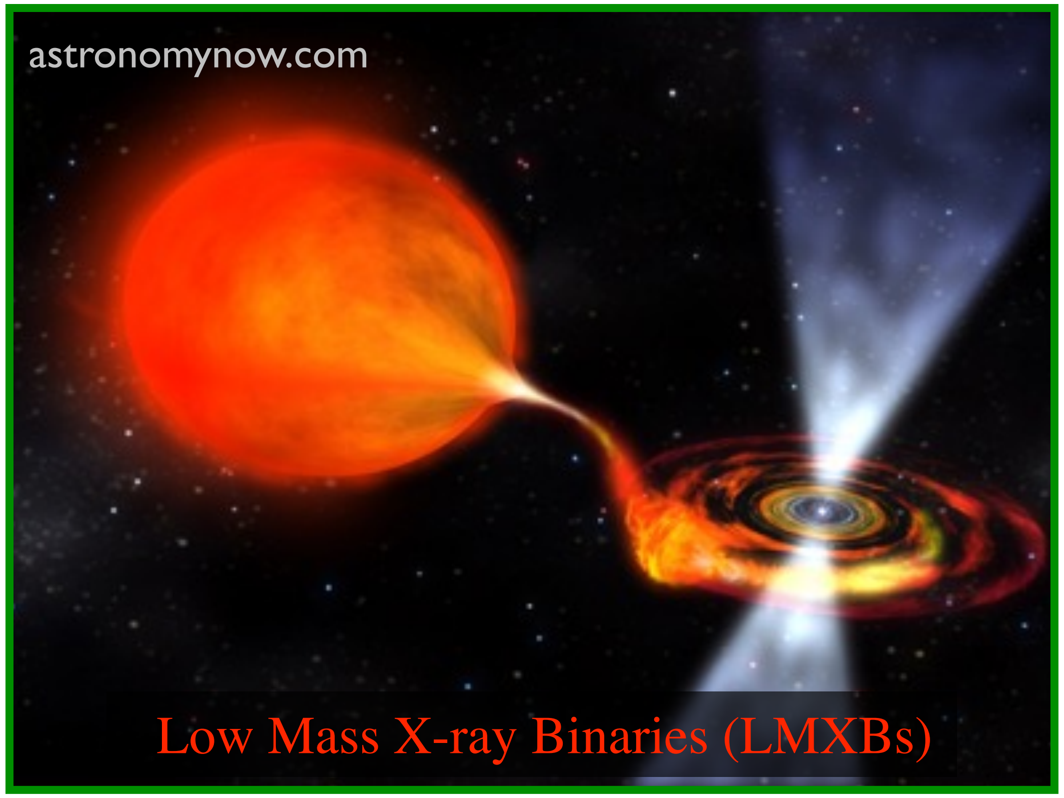


(Wik et al. 2014; Lehmer et al. 2015; Yukita et al. 2016)



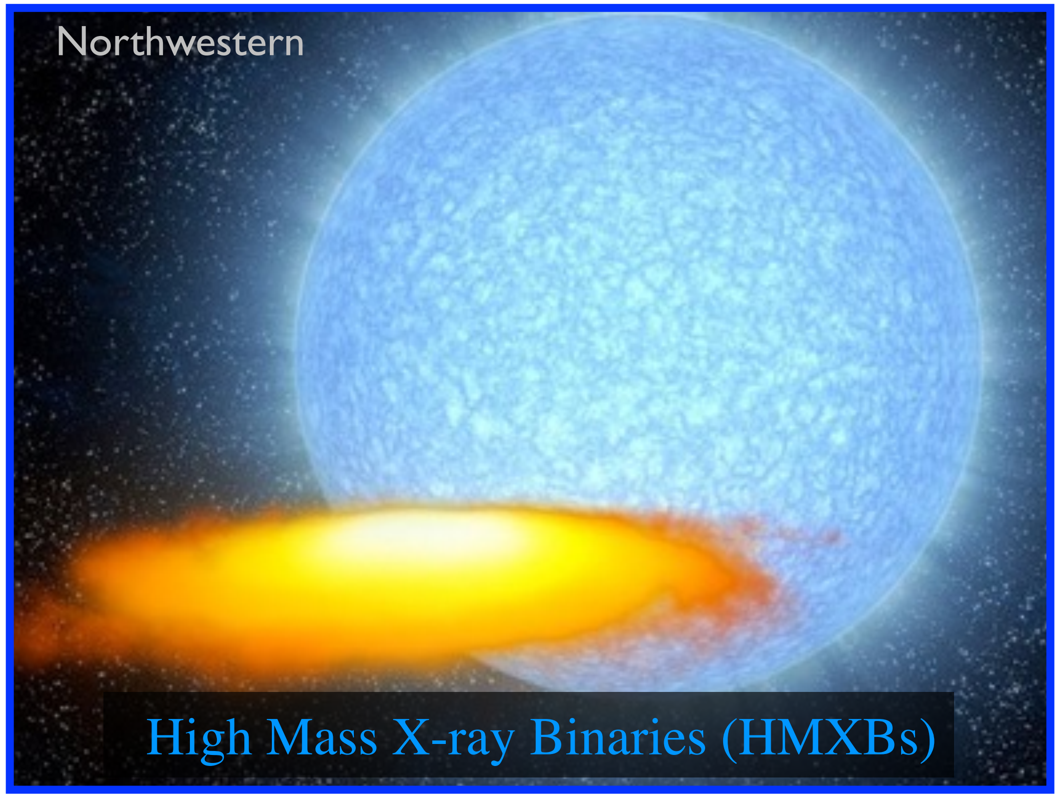
- *Chandra, NuSTAR* and *XMM* have observed several local late-type galaxies and we have a sense of their spectral shape.
- Dominant contributions from hot gas (<1.5 keV) and X-ray binaries (both LMXBs and HMXBs; >1.5 keV).
- At high redshift, observed-frame bands sample harder rest-frame bands, favoring XRBs as dominant source.

Evolution of X-ray Scaling Relations



OLD POPULATION - Stellar Mass

$L_X = \alpha\, M_\star$



YOUNG POPULATION - Star Formation

$L_X = \beta$ SFR

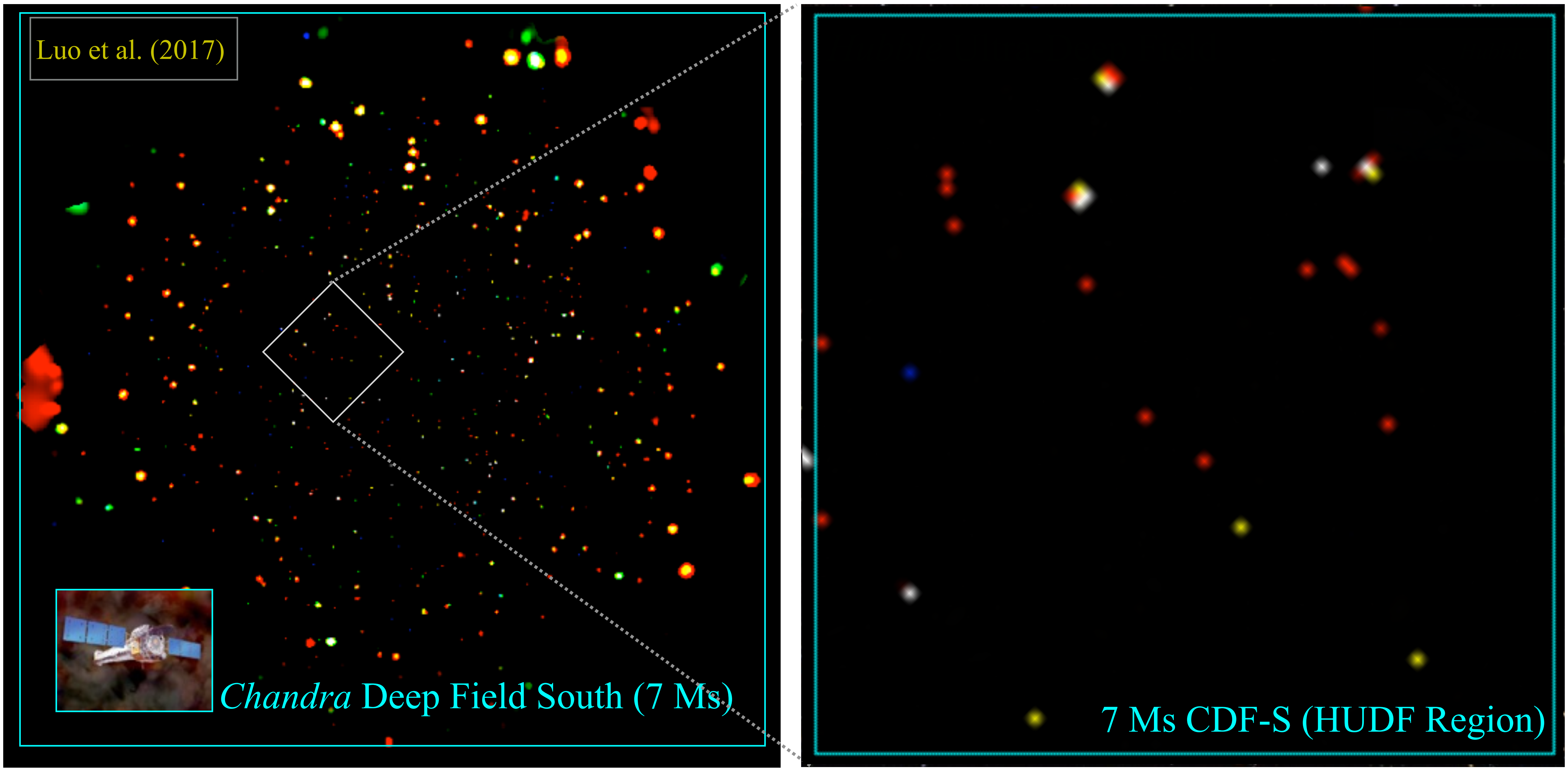
1. XRBs may offer a means to measure galaxy properties like SFR and $M_\star$ relatively free of obscuration.

2. Scaling relation evolution is sensitive to evolution of metallicity, stellar ages (donors change), and IMF.

3. Progenitors to millisecond pulsars, gravitational-wave producing mergers, and short-duration gamma-ray bursts.

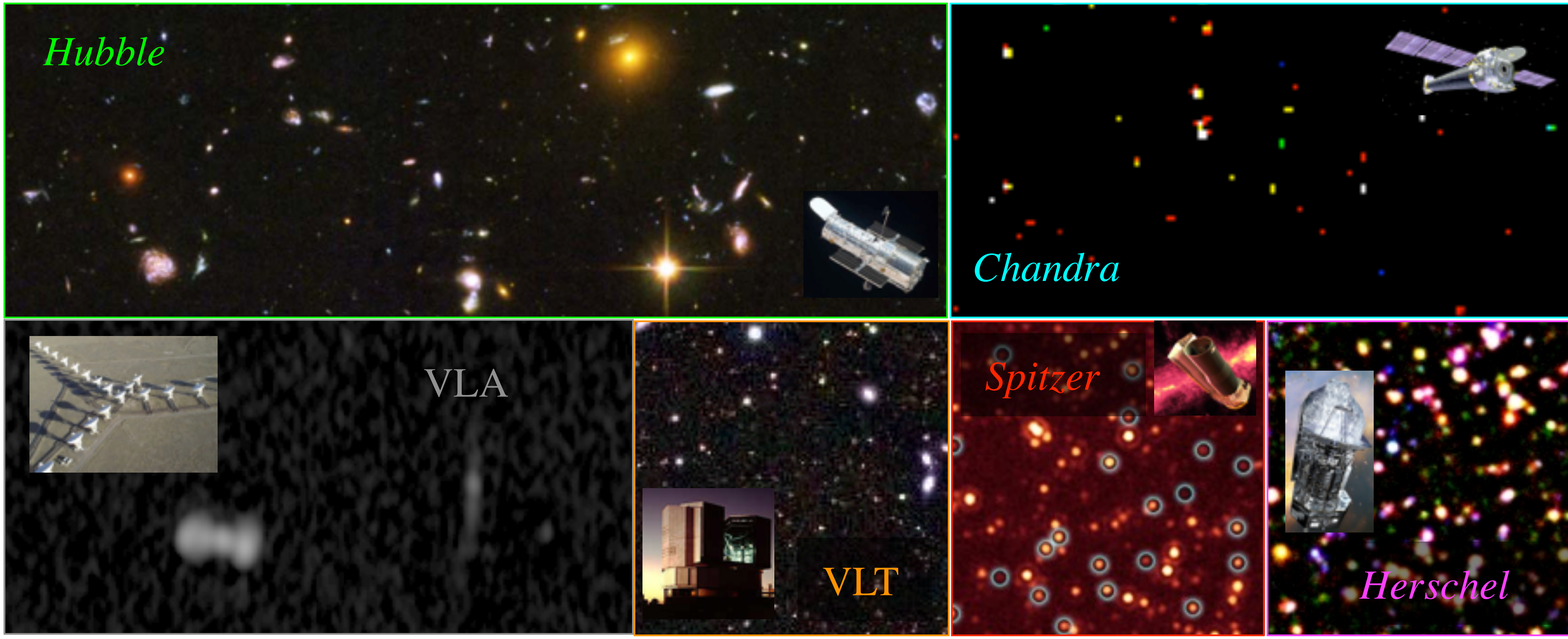
4. XRB radiation field may be important to heating the IGM in the early Universe.

Small X-ray Detection Fraction of Optical Sources



Dramatic mismatch between number of galaxies. The density of $M_\star > 10^9\ M_\odot$ galaxies detected is a factor of ~30 times larger in optical compared to X-rays.

X-ray Stacking of High-Redshift Galaxy Populations

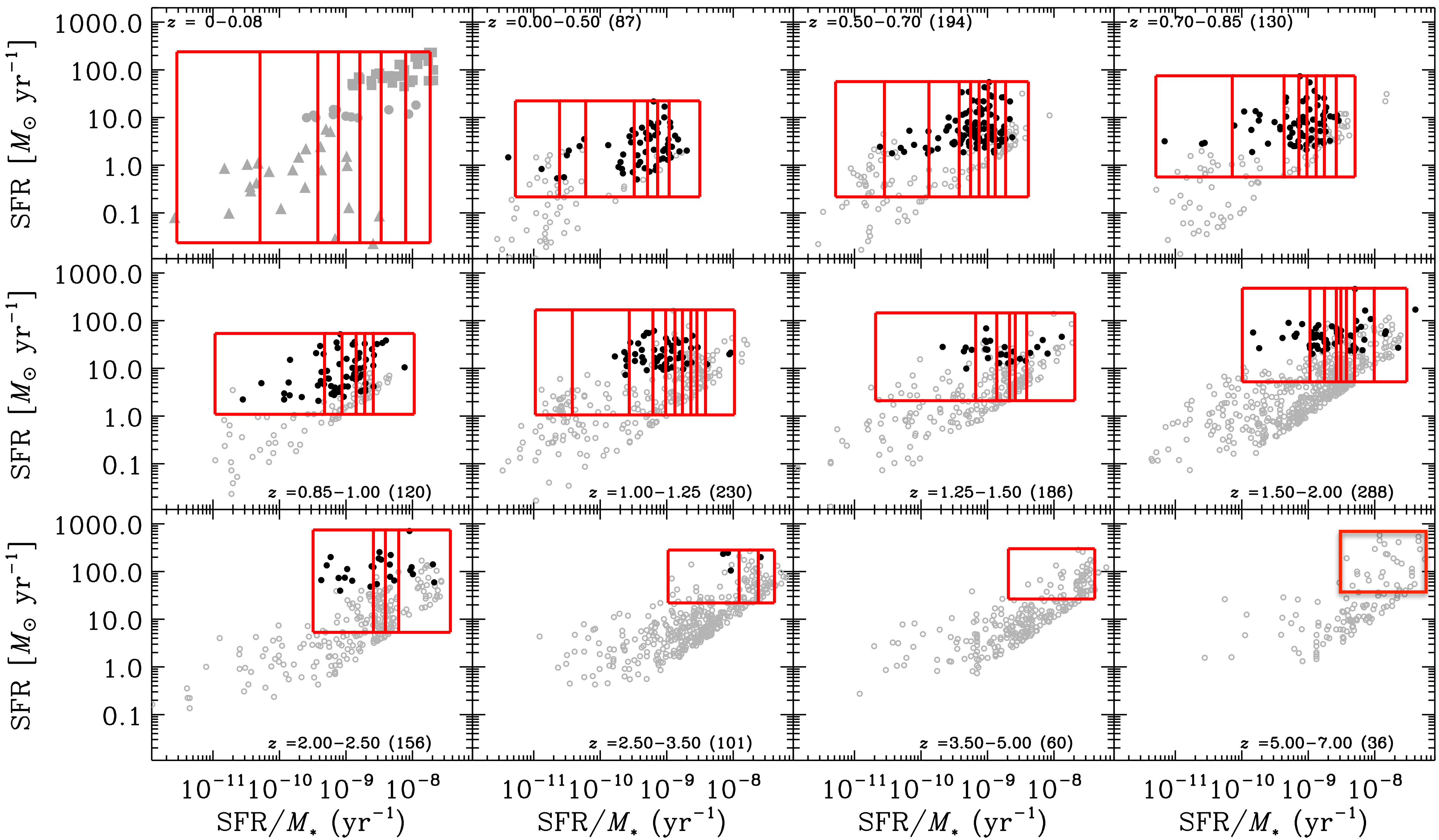


- Multiwavelength data allows us to identify large populations of galaxies and measure their redshifts and physical properties like SFR and $M_\star$.

- Can divide the galaxy sample into bins of redshift, SFR, and stellar mass and stack to measure $\alpha = L_X(\mathrm{LMXB})/M_\star$ and $\beta = L_X(\mathrm{HMXB})/\mathrm{SFR}$ at different redshifts.

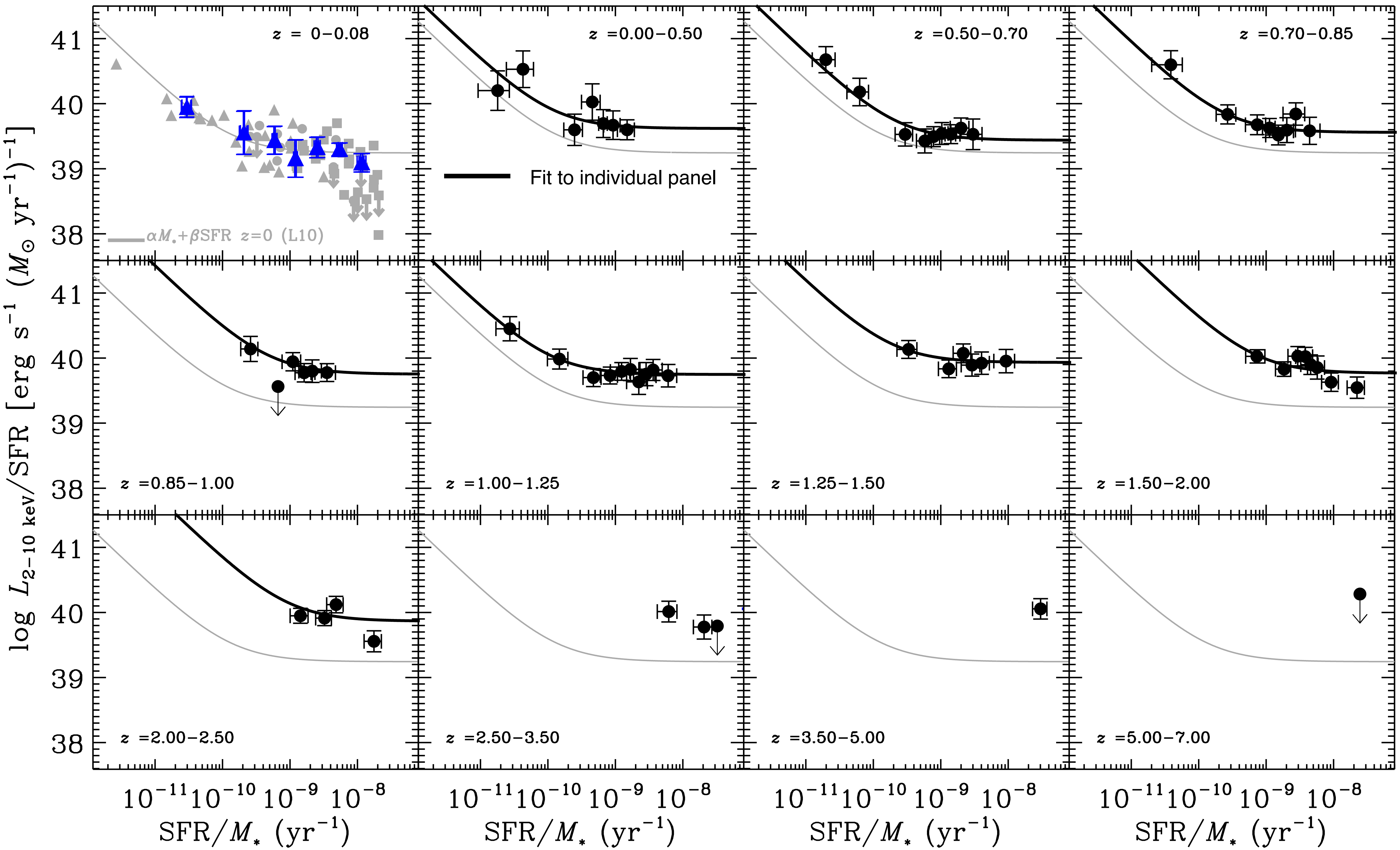
$$L_X = \alpha M_\star + \beta \mathrm{SFR} \quad \text{and} \quad L_X/\mathrm{SFR} = \alpha\,(\mathrm{SFR}/M_\star)^{-1} + \beta$$

Chandra Deep Field-South Galaxy Selection



Lehmer et al. (2016)

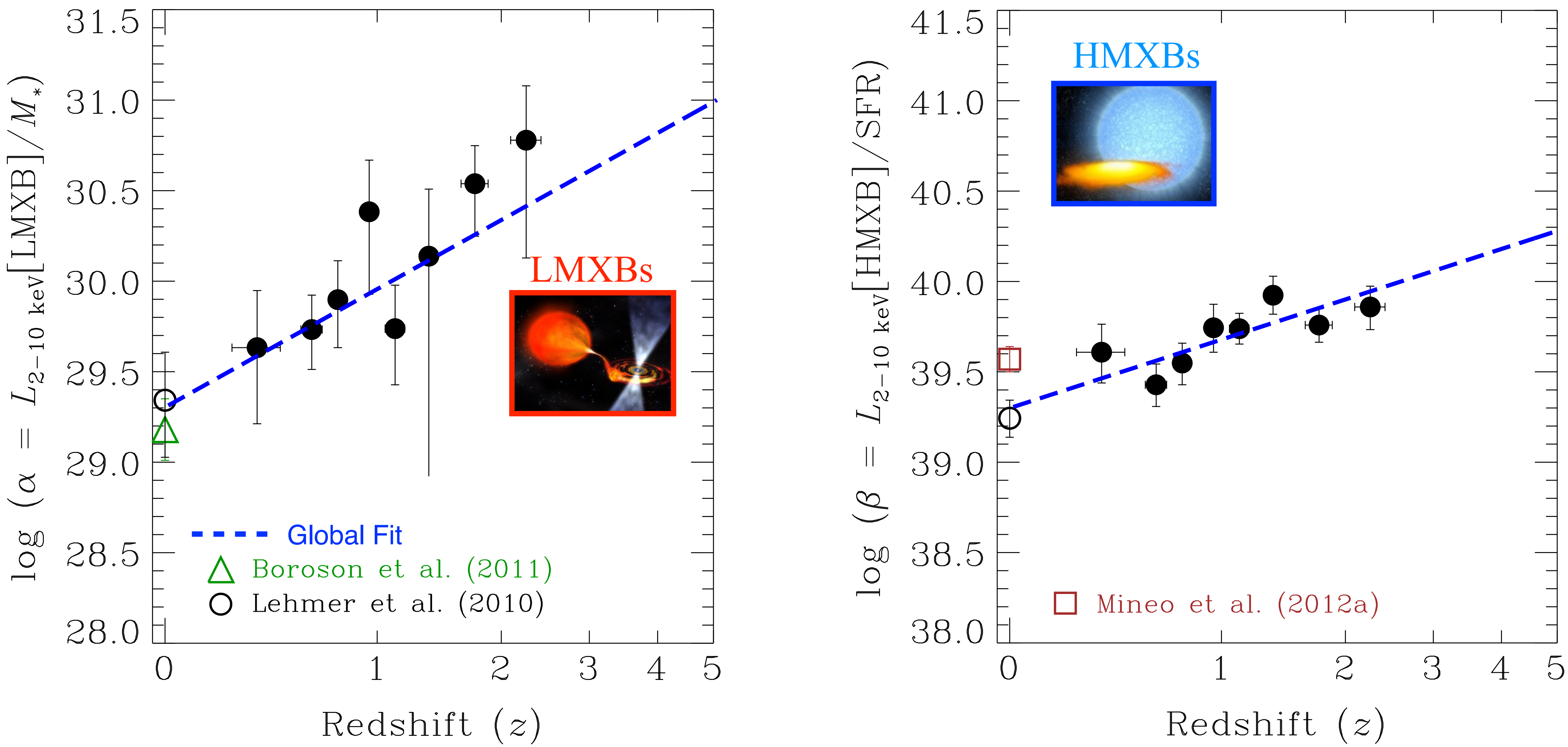
X-ray Evolution of Galaxy Populations



$$L_X/\mathrm{SFR} = \alpha\,(\mathrm{SFR}/M_\star)^{-1} + \beta \qquad \alpha = L_X(\mathrm{LMXB})/M_\star \qquad \beta = L_X(\mathrm{HMXB})/\mathrm{SFR}$$

X-ray Evolution of Galaxy Populations

Lehmer et al. (2016)



• We find clear evidence for increases in both α and β with redshift:

$\alpha(z) = L_X(\mathrm{LMXB})/M_\star \sim \alpha_0\,(1+z)^{2\text{-}4}$

$\beta(z) = L_X(\mathrm{HMXB})/\mathrm{SFR} \sim \beta_0\,(1+z)$

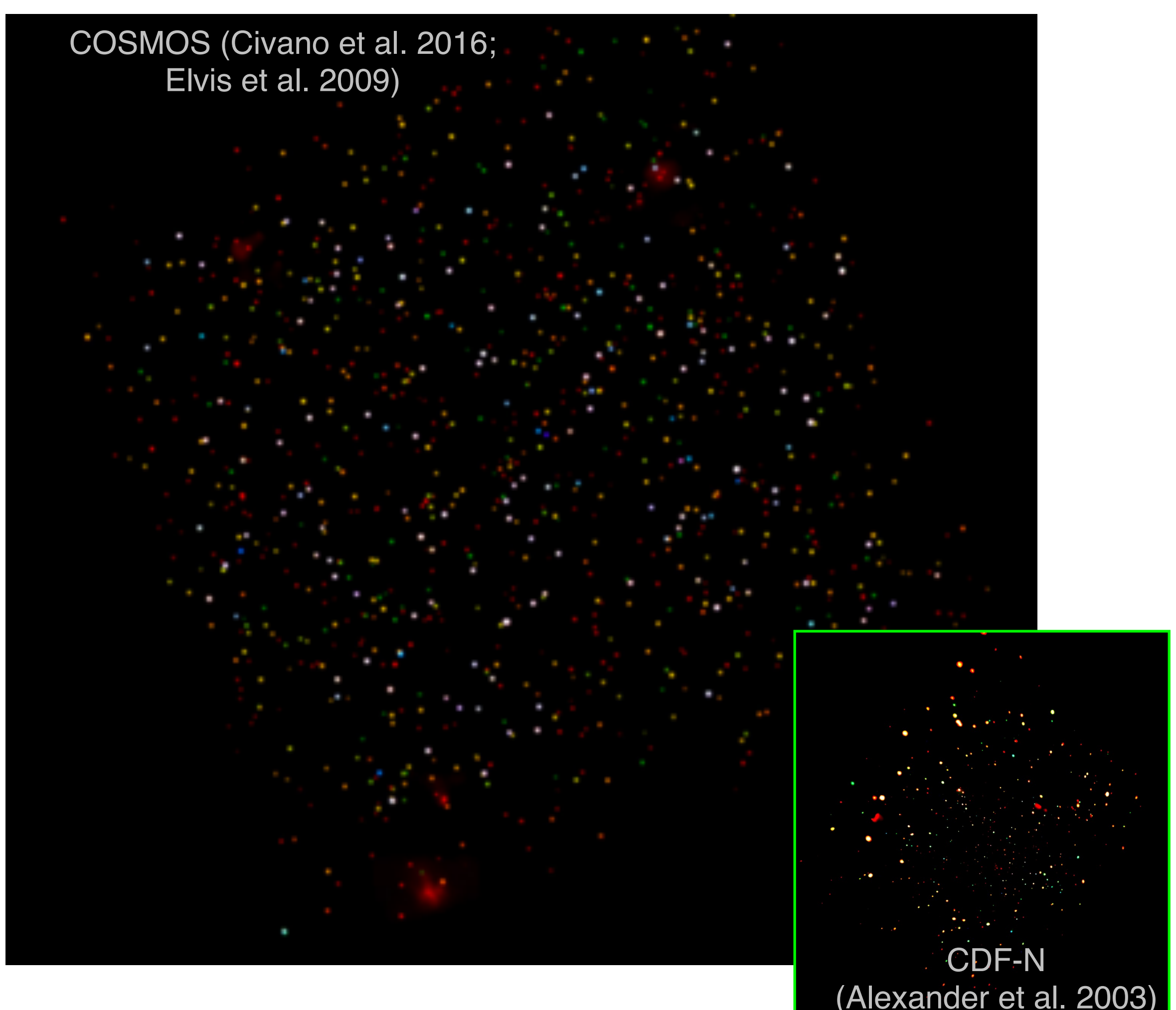
Only valid out to $z \sim 2.5$

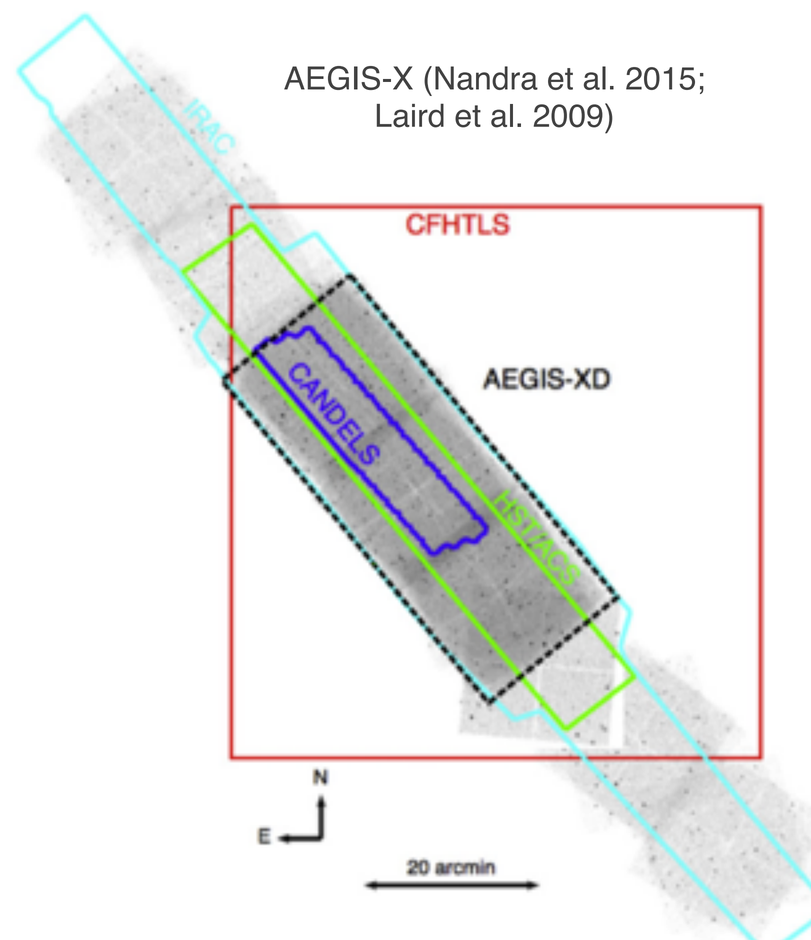
Results from other Deep-Field Studies

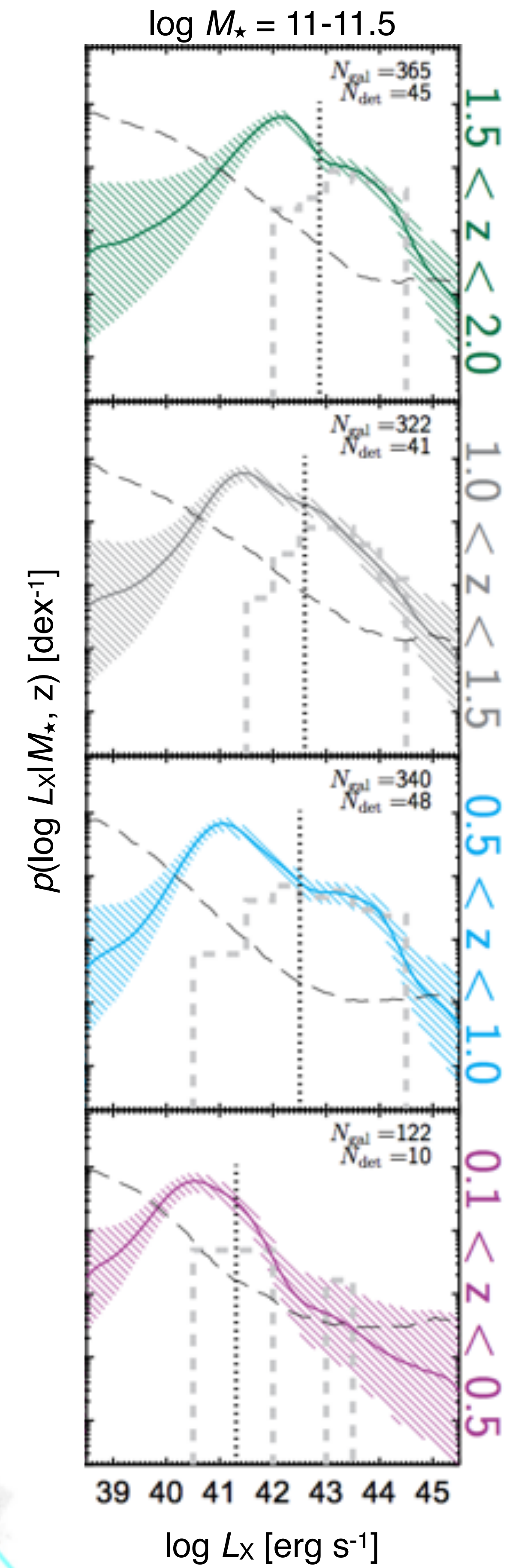
- Additional studies of galaxy samples in, e.g., COSMOS (e.g., Civano et al. 2016; Mezcua et al. 2016; Paggi et al. 2016), AEGIS (e.g., Lair et al. 2006; Symeonidis et al. 2011, 2014), and CDFs (Cowie et al. 2012; Basu-Zych et al. 2013; Mineo et al. 2014) have shown results broadly consistent with our conclusions; however, most studies focus only on SFR or $M_\star$ scaling [see also poster by Francesca Fornasini].

- Aird et al. (2017) used COSMOS, AEGIS, CDF-N, and CDF-S and independent technique to measure evolution of L_X(LMXB)/$M_\star$ and L_X(HMXB)/SFR.

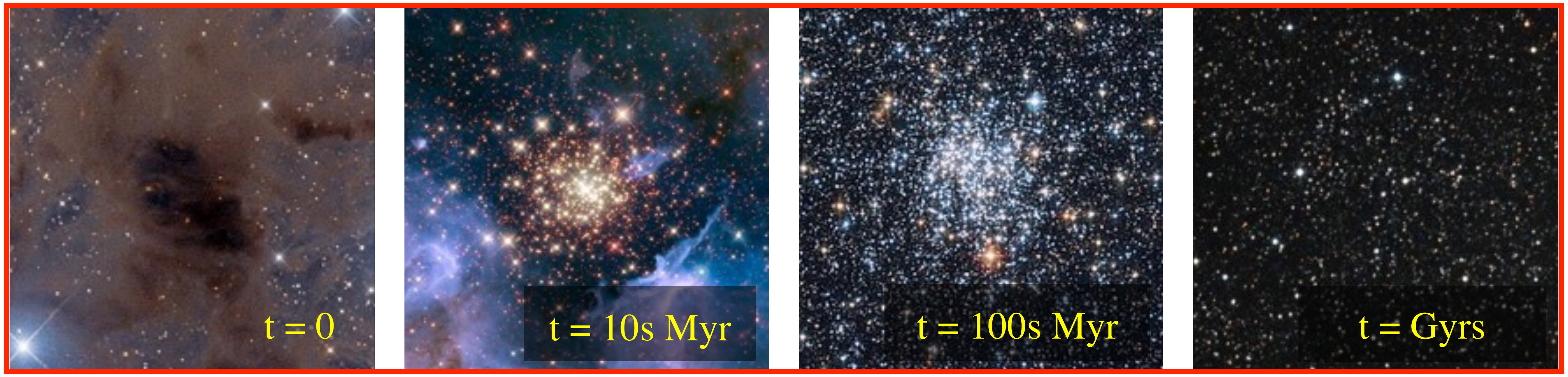
- These independent results also find strong evolution of L_X(LMXB)/$M_\star$ ~ $(1+z)^4$ and more mild evolution of L_X(HMXB)/SFR ~ $(1+z)$.

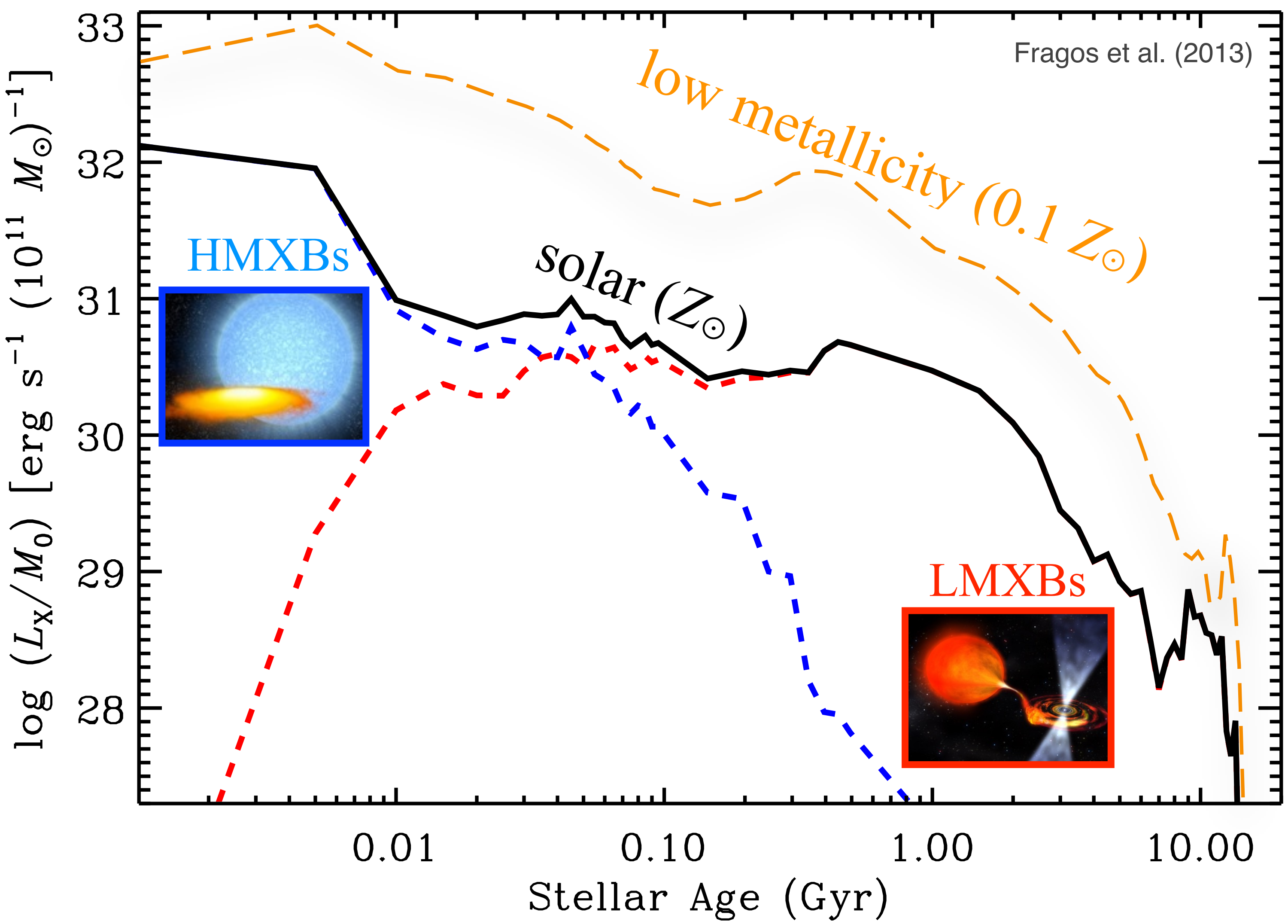






Basic Population Synthesis Predictions





- XRB population synthesis modeling predicts strong decline in X-ray emission with age due to donor mass decreasing.
- Also, XRB emission predicted to increase with decreasing metallicity (e.g., pr
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L_X(HM
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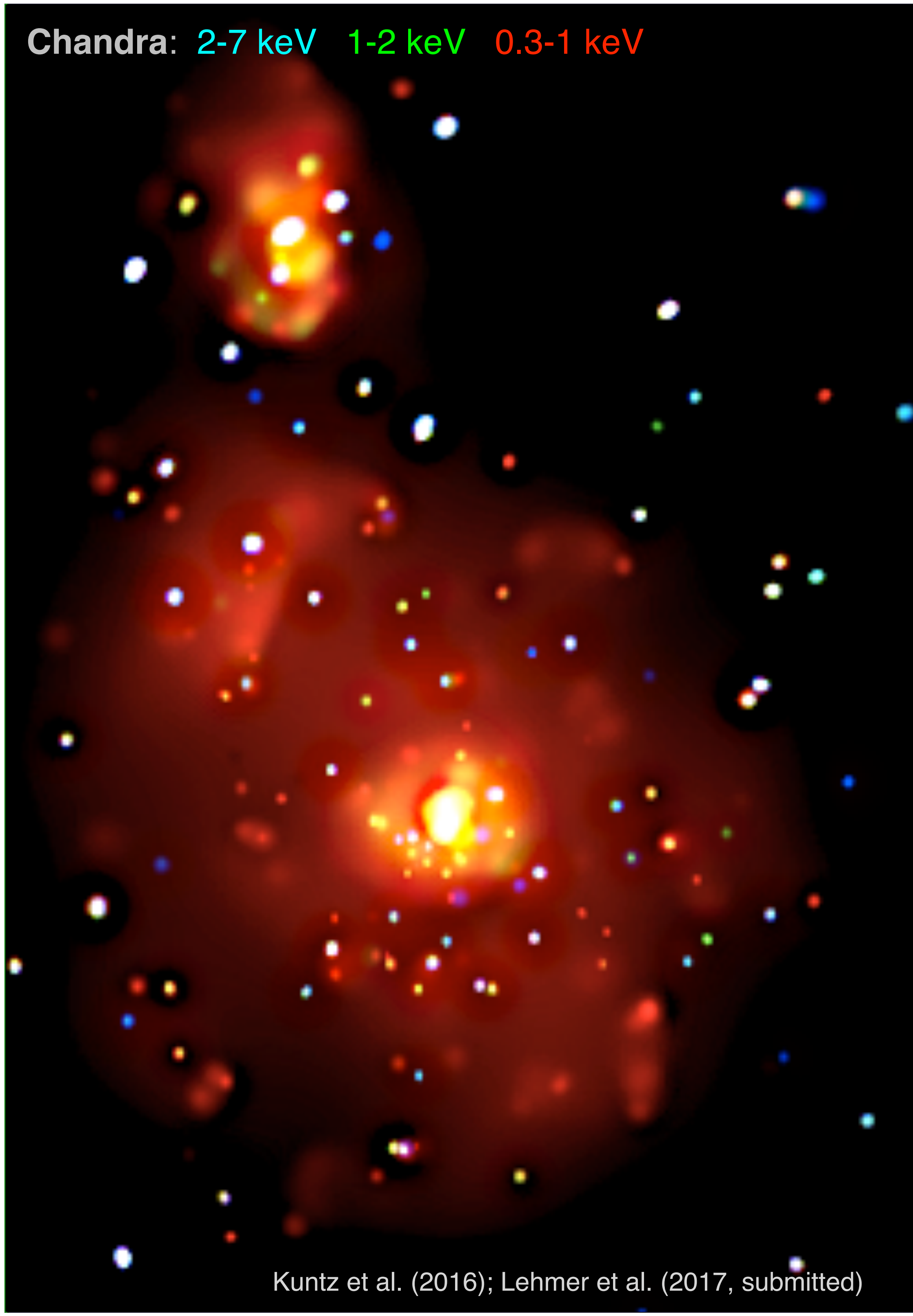
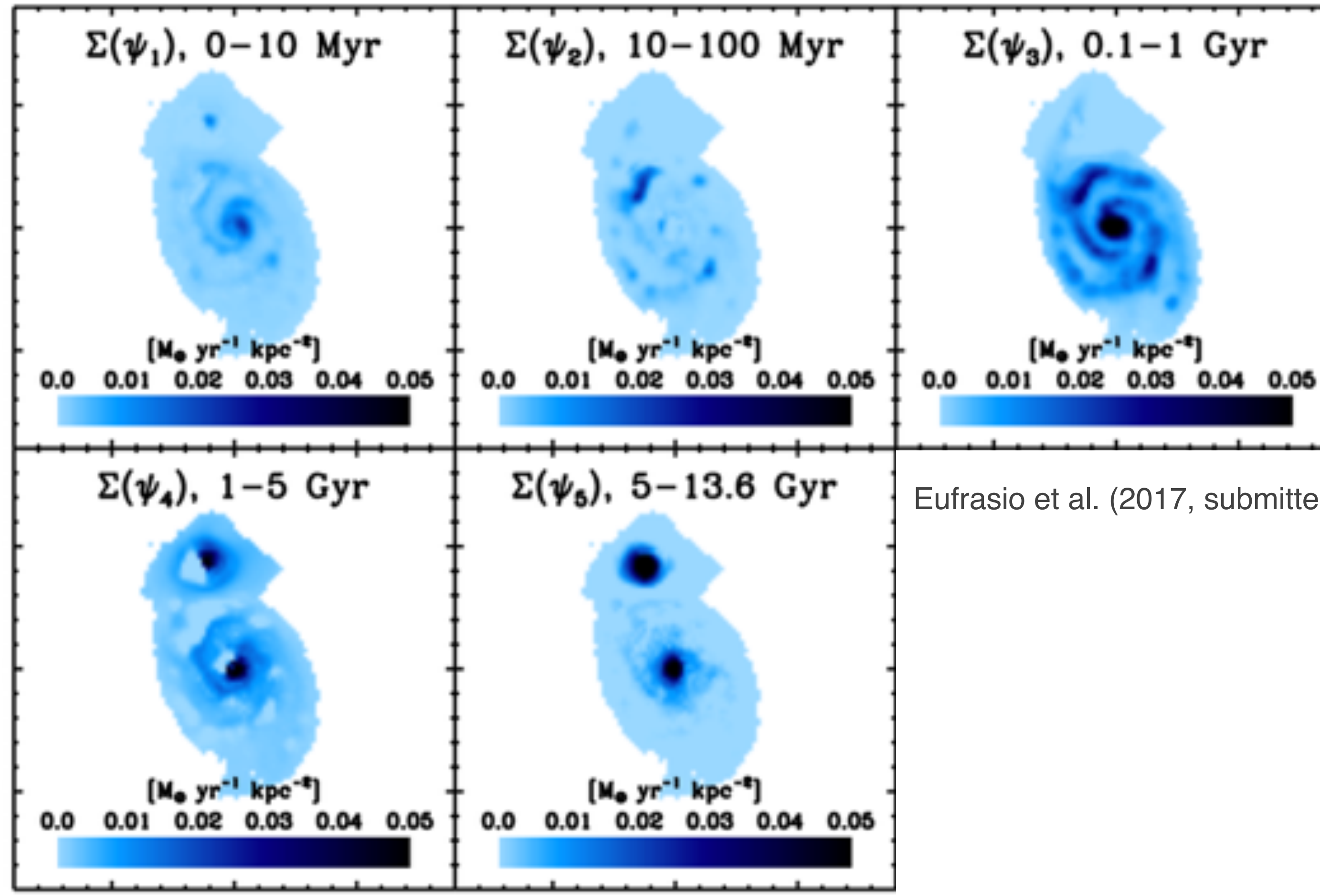
XRB Evolution Based on Data in M51



Eufrasio et al. (2017, submitted)



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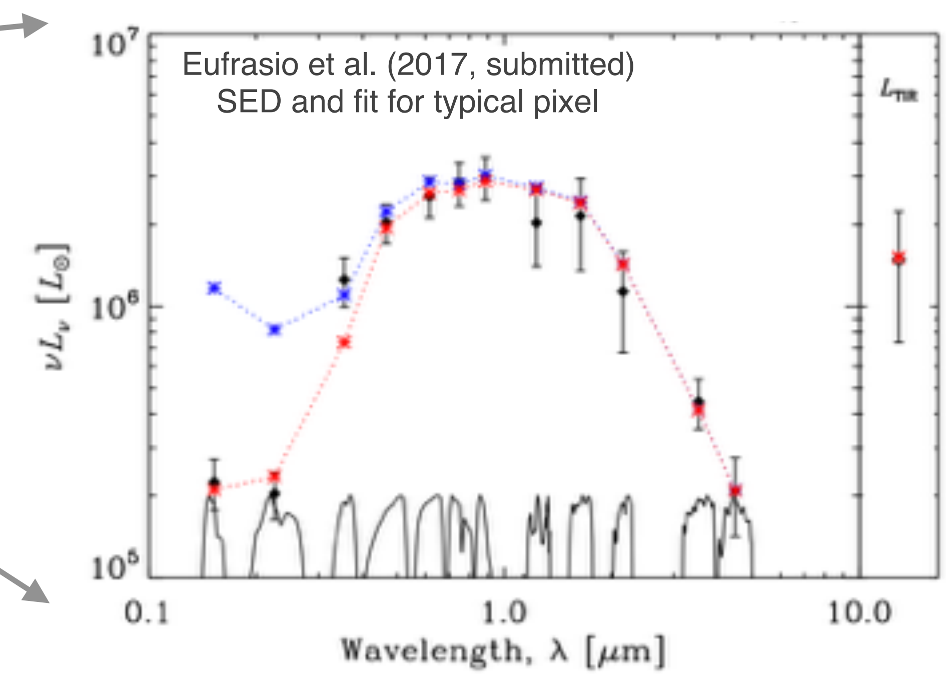
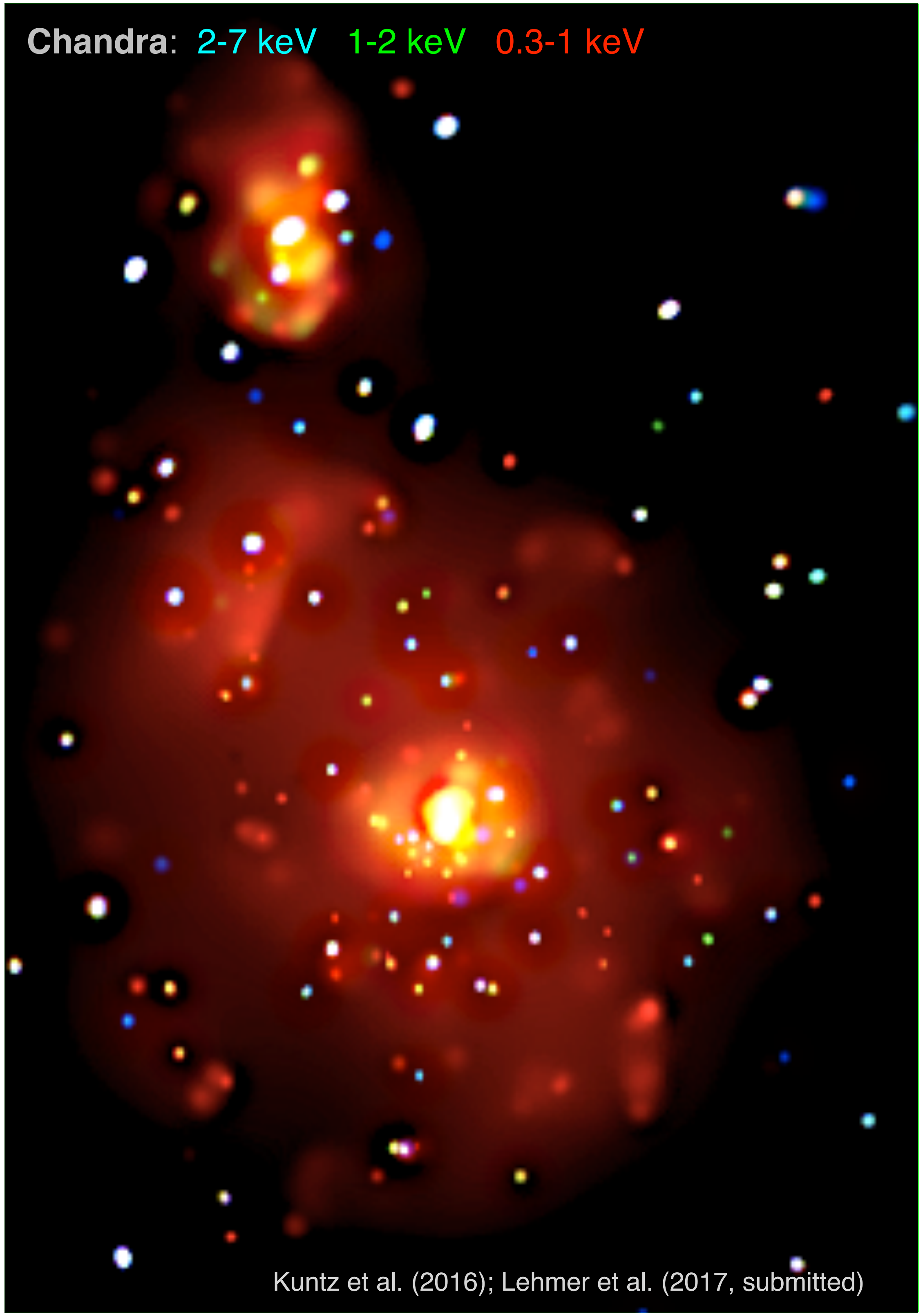
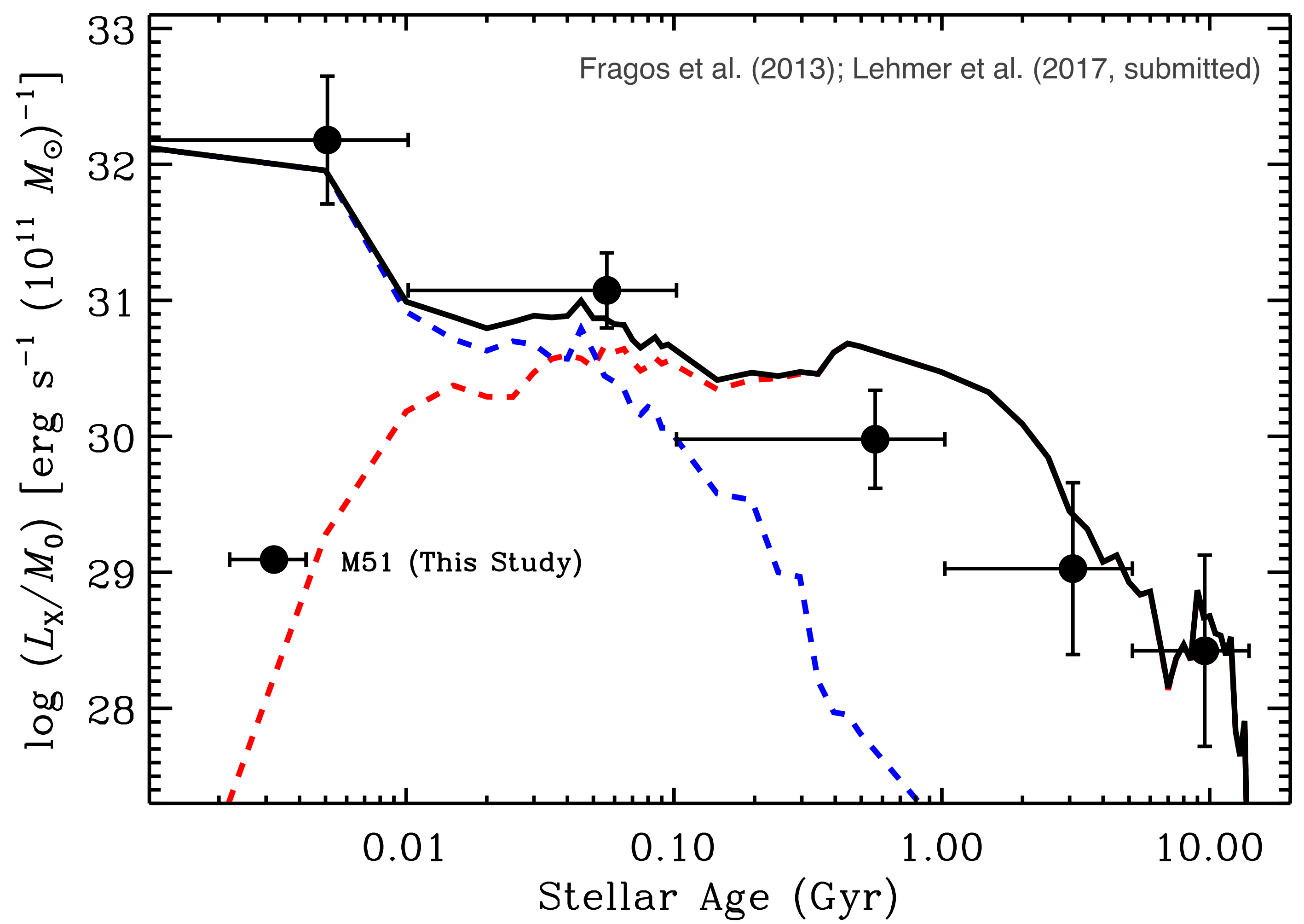


XRB Evolution Based on Data in M51

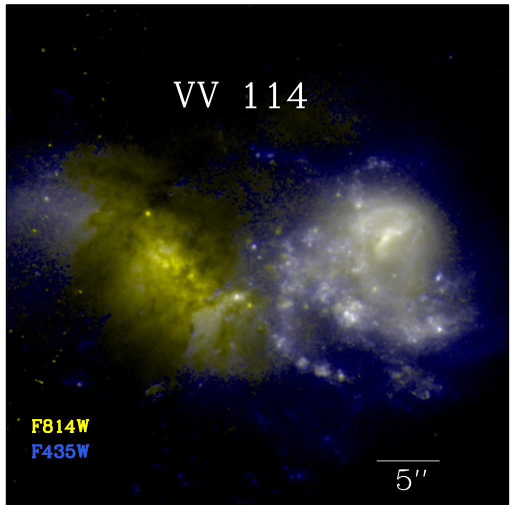


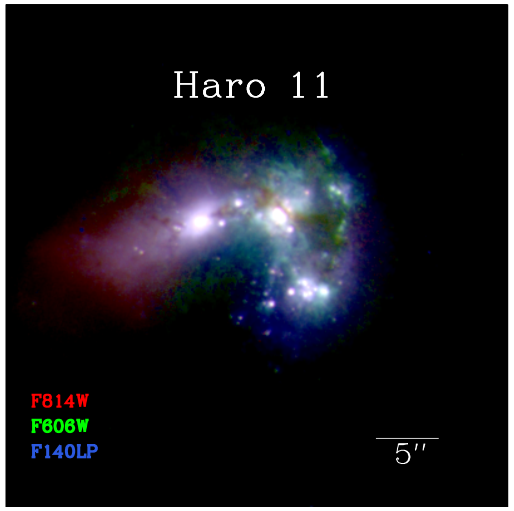


- M51 observations suggest that XRB evolution follows similar pattern to that predicted by population synthesis models.

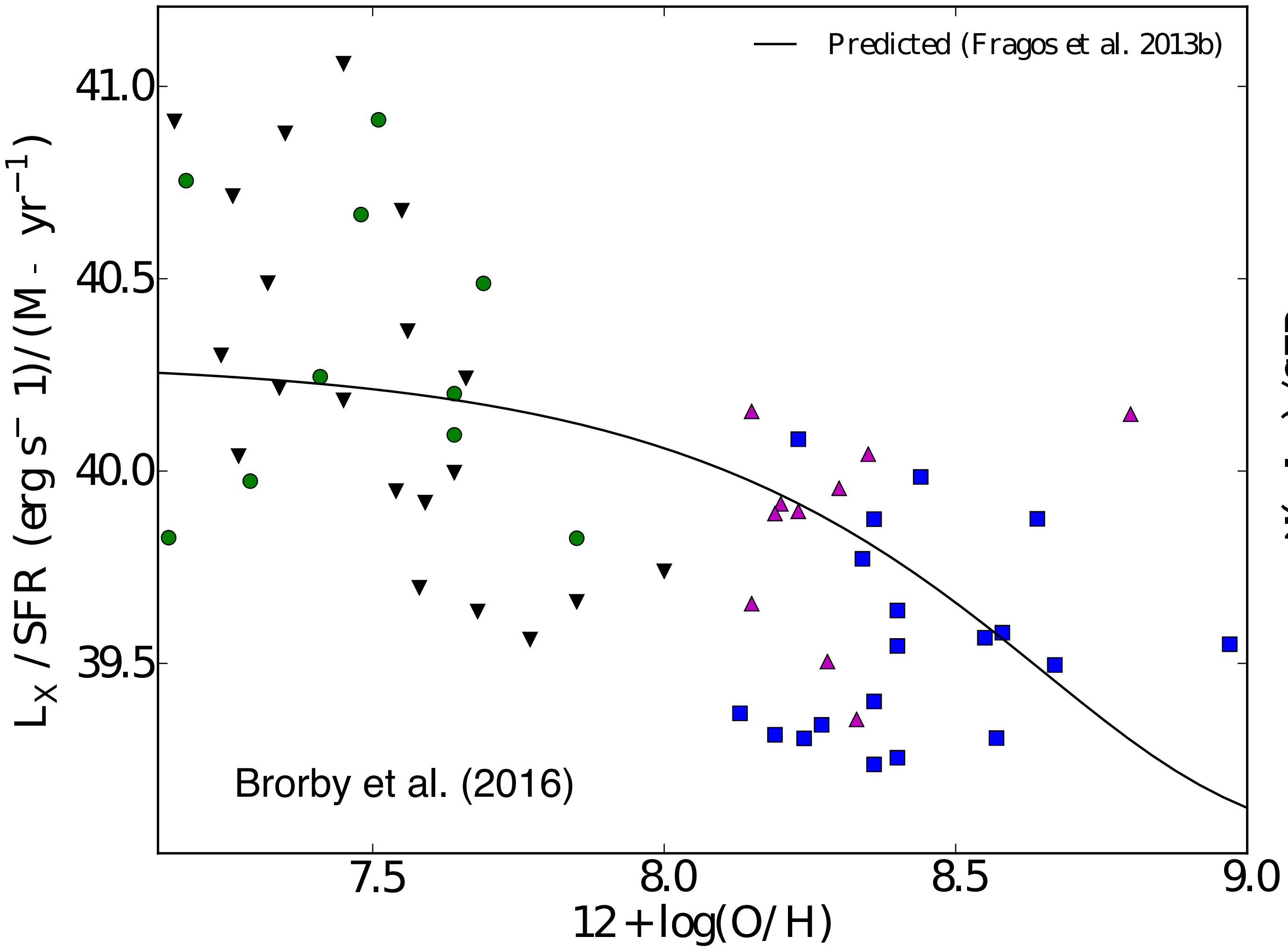
- Additional studies of elliptical galaxies of various ages have also found evidence for a decline in LMXB emission with age (e.g., Kim & Fabbiano 2010; Lehmer et al. 2014); however, see, e.g., Zhang et al. (2012) for caveats.

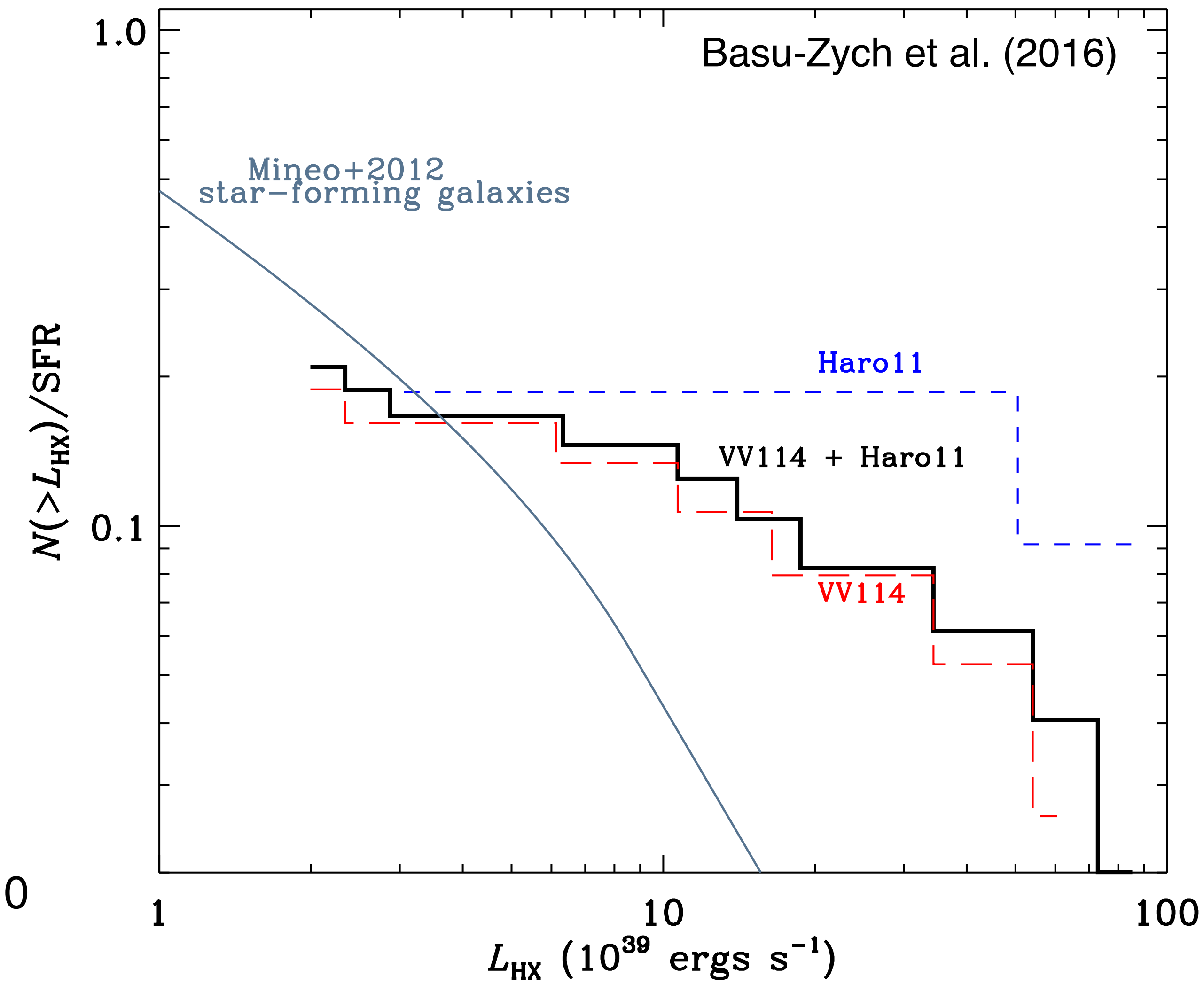
Metallicity-Dependence from Local Galaxy Studies



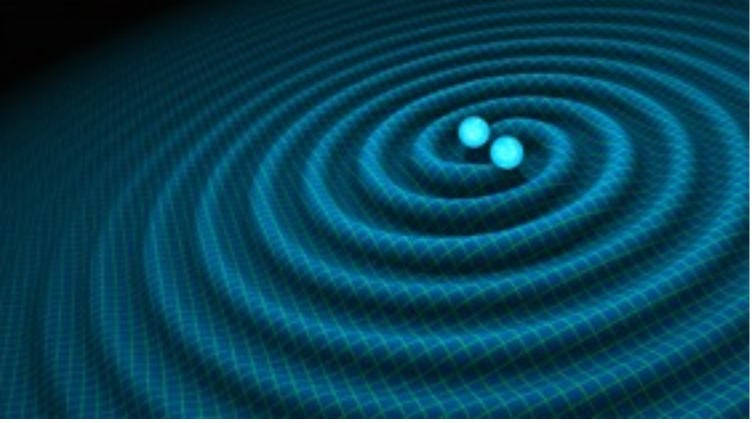


- Correlation studies of local galaxy samples show that L_X/SFR declines with gas-phase metallicity, similar to Fragos et al. prediction (e.g., Brorby et al. 2016).
- Low metallicity galaxies appear to have an excess of luminous (>10^{40} erg/s) ULXs, but not yet clear whether there is an excess of low-luminosity XRBs.





[see also Mapelli et al. 2010; Kaaret et al. 2011; Basu-Zych et al. 2013; Prestwich et al. 2013; Brorby et al. 2014; Douna et al. 2015]



Support from Early LIGO Results

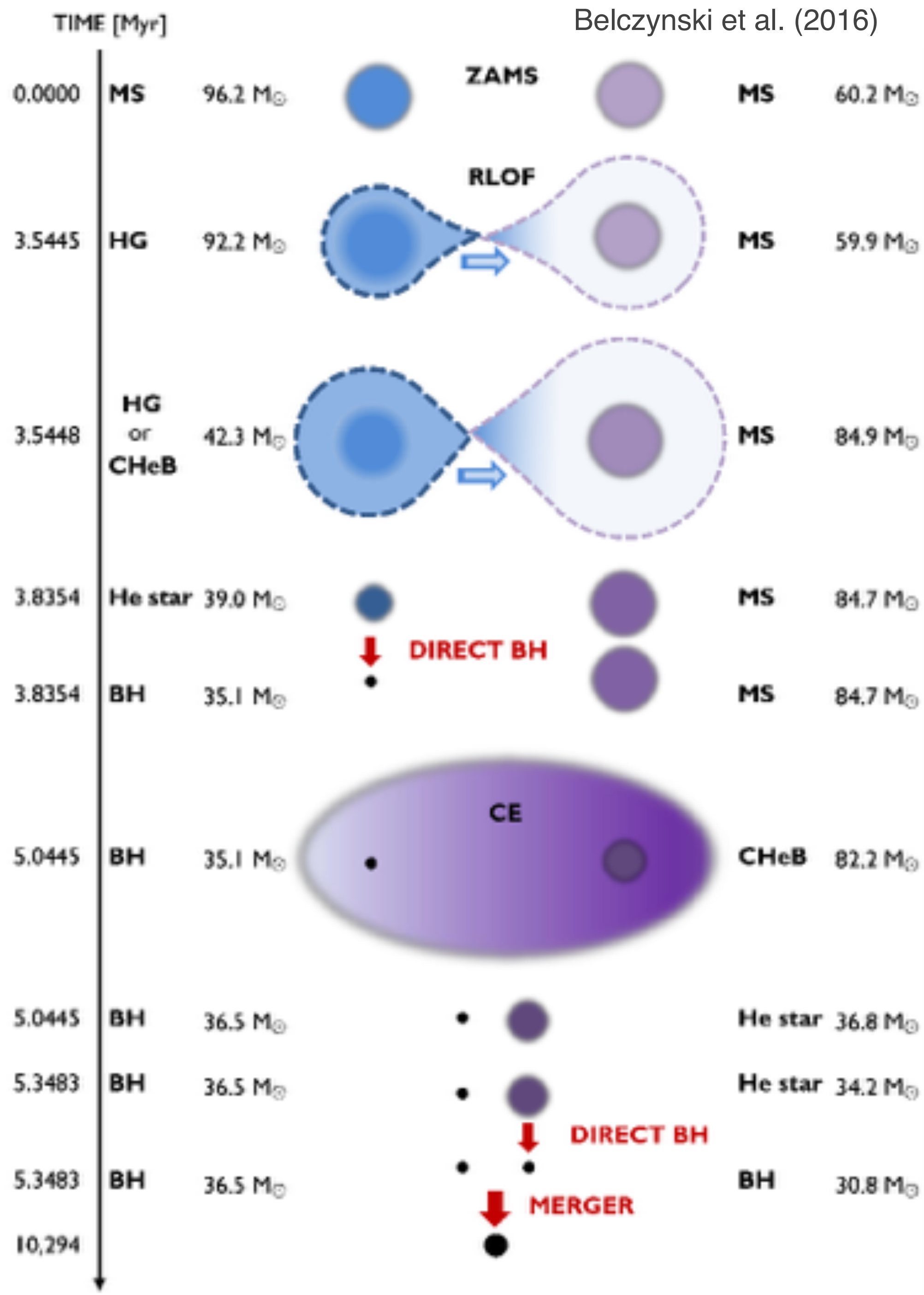
Best Model Timeline of GW150914

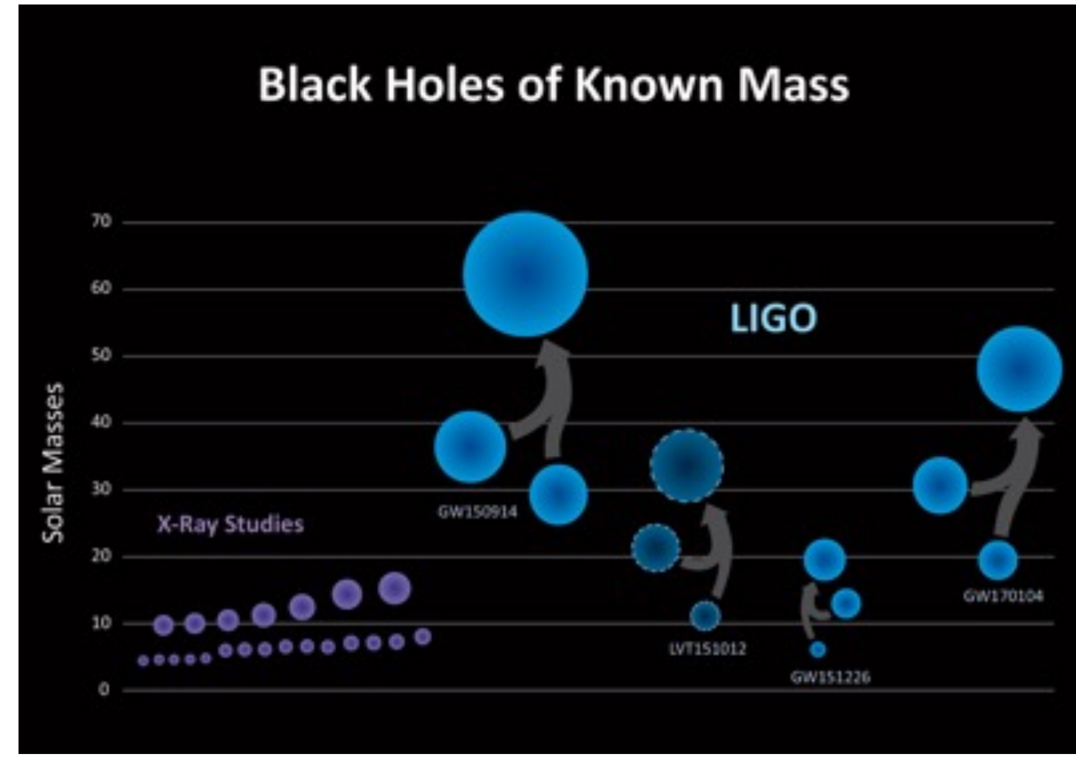
$z \sim 3$

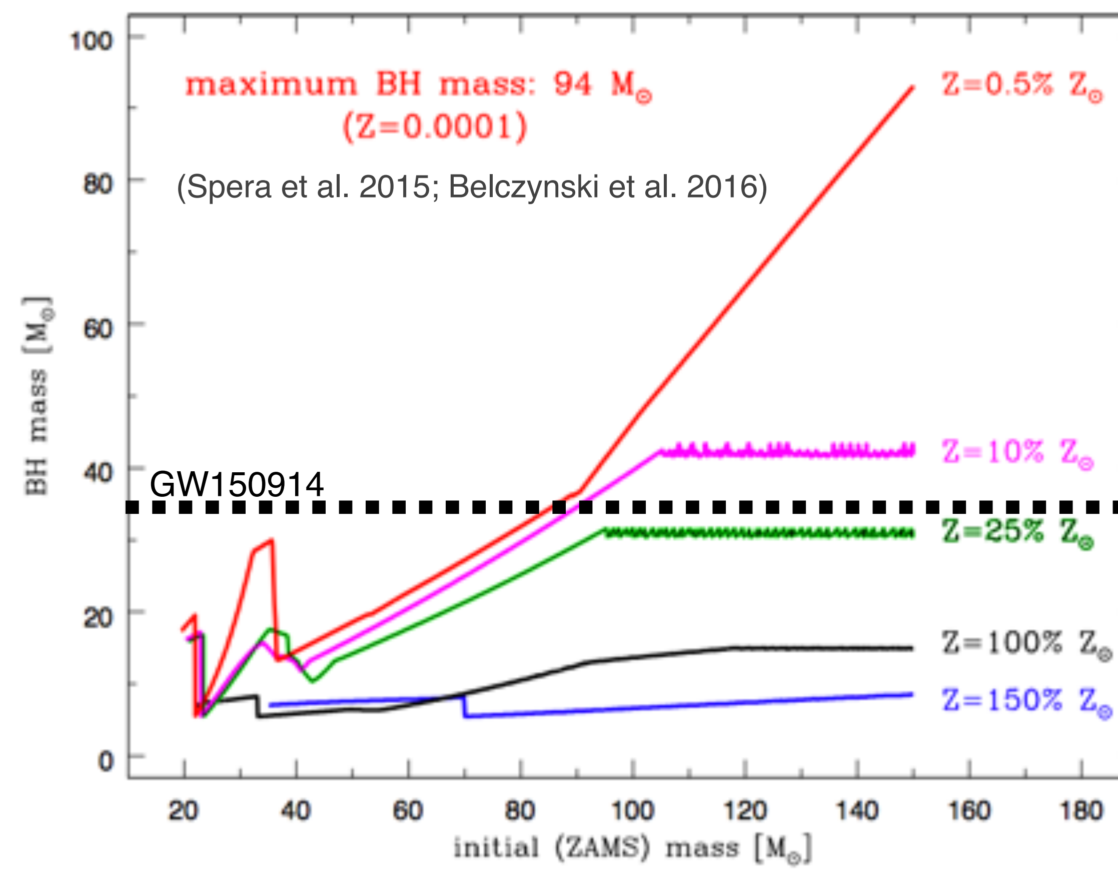
X-ray binary phase

$z \sim 3$

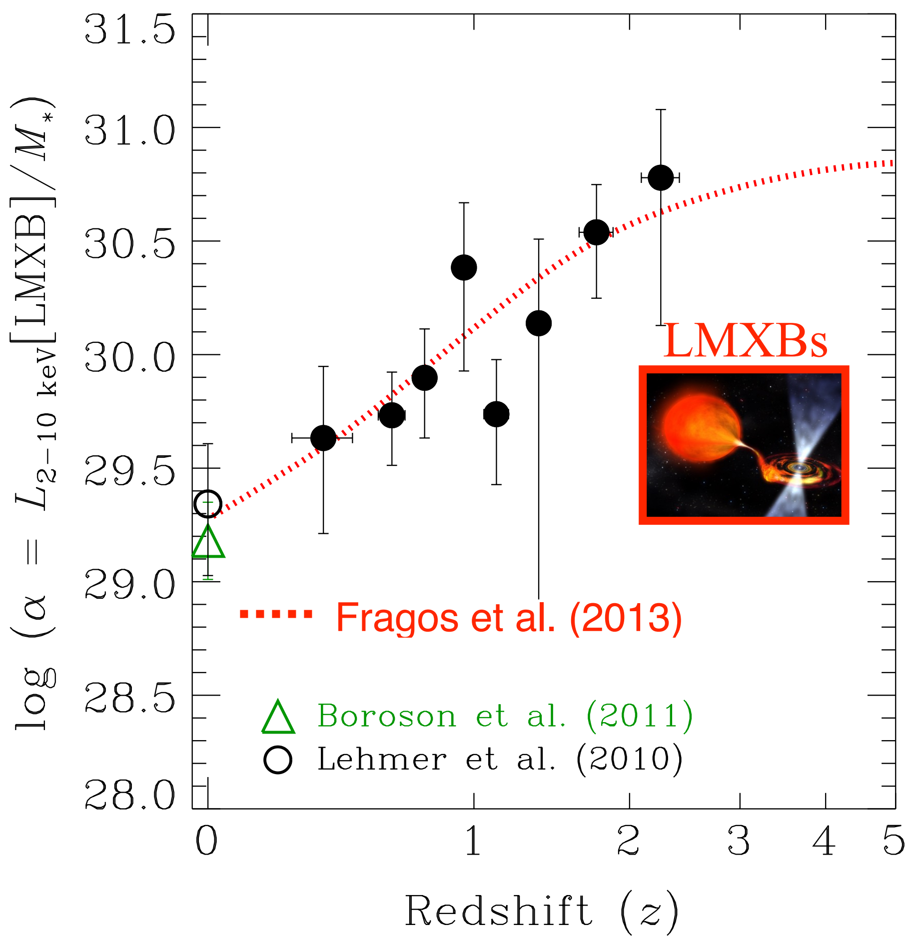
$z = 0.09$

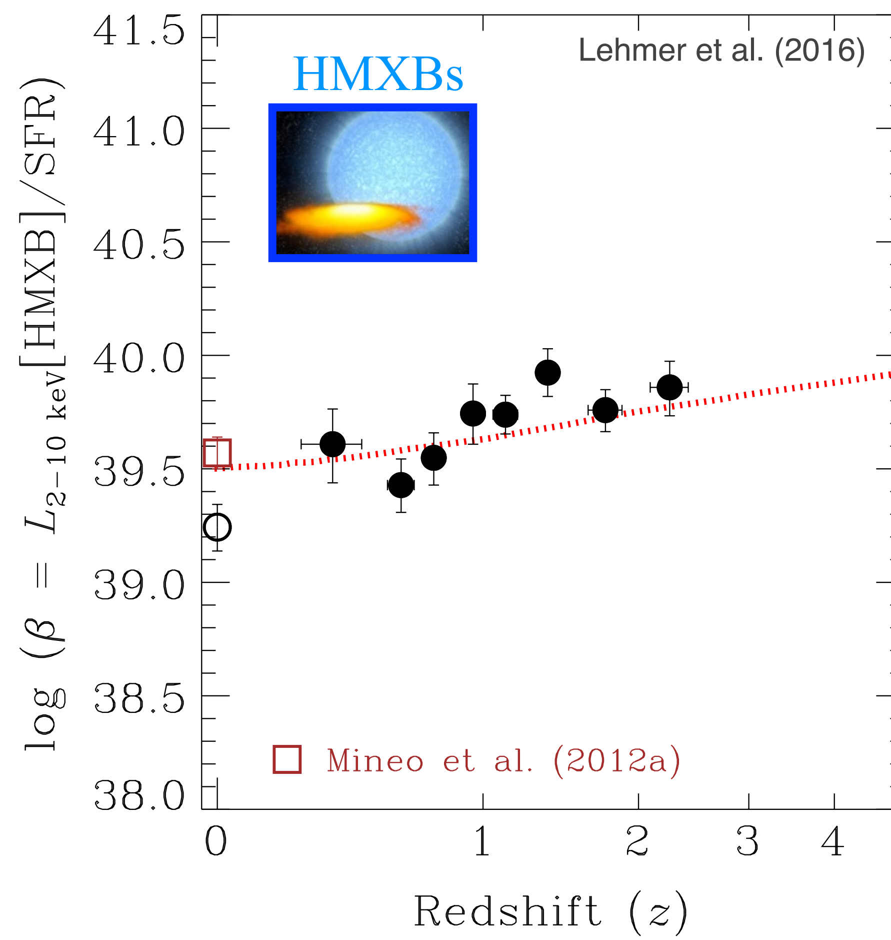






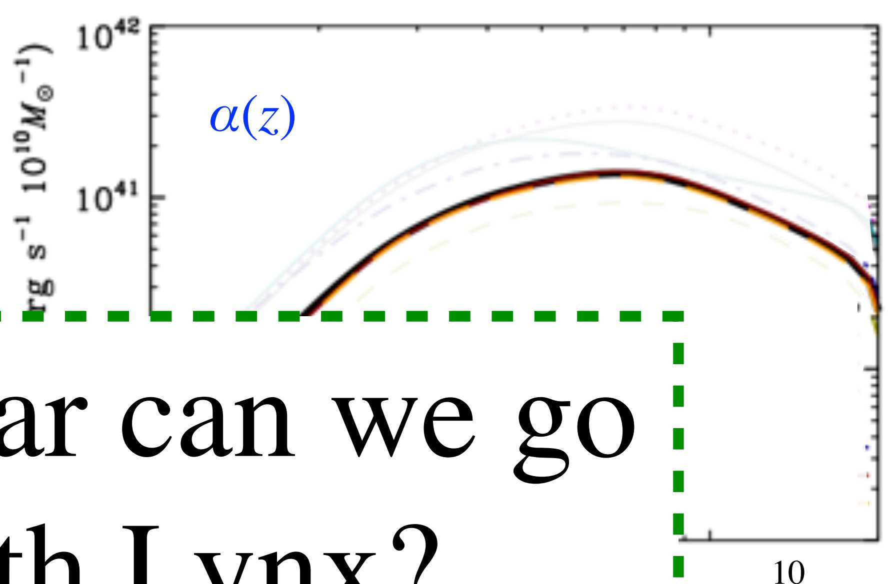
X-ray Evolution of Galaxy Populations

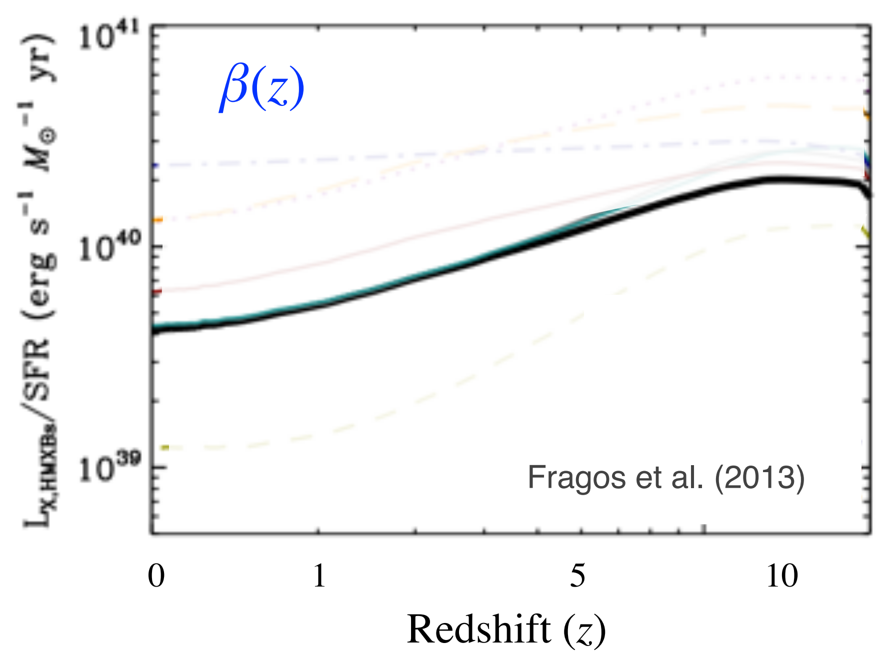




Younger galaxies, more luminous LMXBs

Lower metallicity, more/bigger black holes, more luminous HMXBs





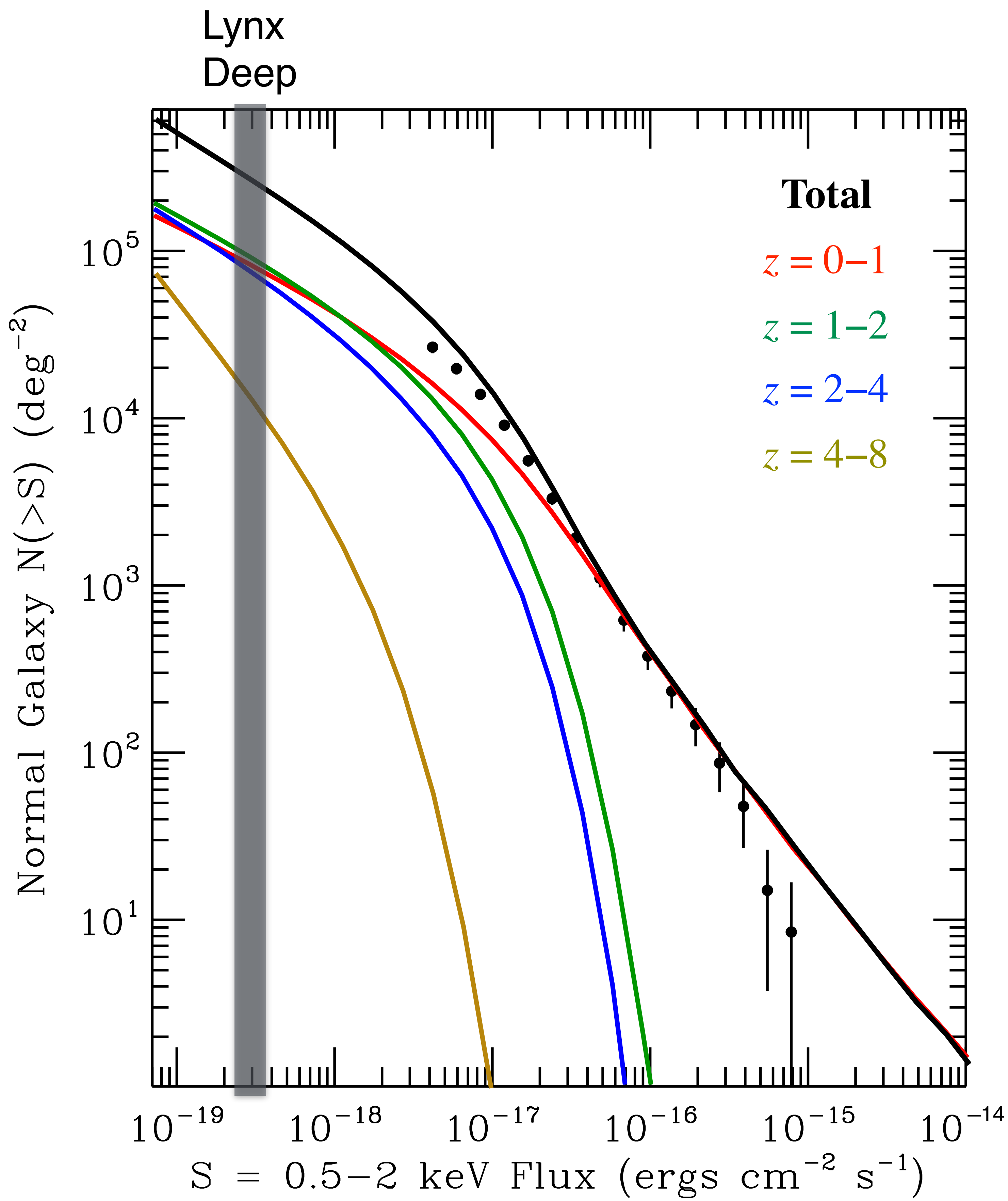
How far can we go with Lynx?

Predictions for Lynx Deep Survey

• Combining the X-ray scaling relations with measured evolution of stellar mass functions (Ilbert et al. 2010; Song et al. 2016) and SFR per stellar mass of the galaxy main sequence (Karim et al. 2011; Salmon et al. 2015) gives predictions for X-ray counts for normal galaxies to $z \sim 8$.

• Lynx survey of ~1 deg^2 to depth of 3×10^{-19} erg cm^{-2} s^{-1} would yield ~256,000 galaxies:

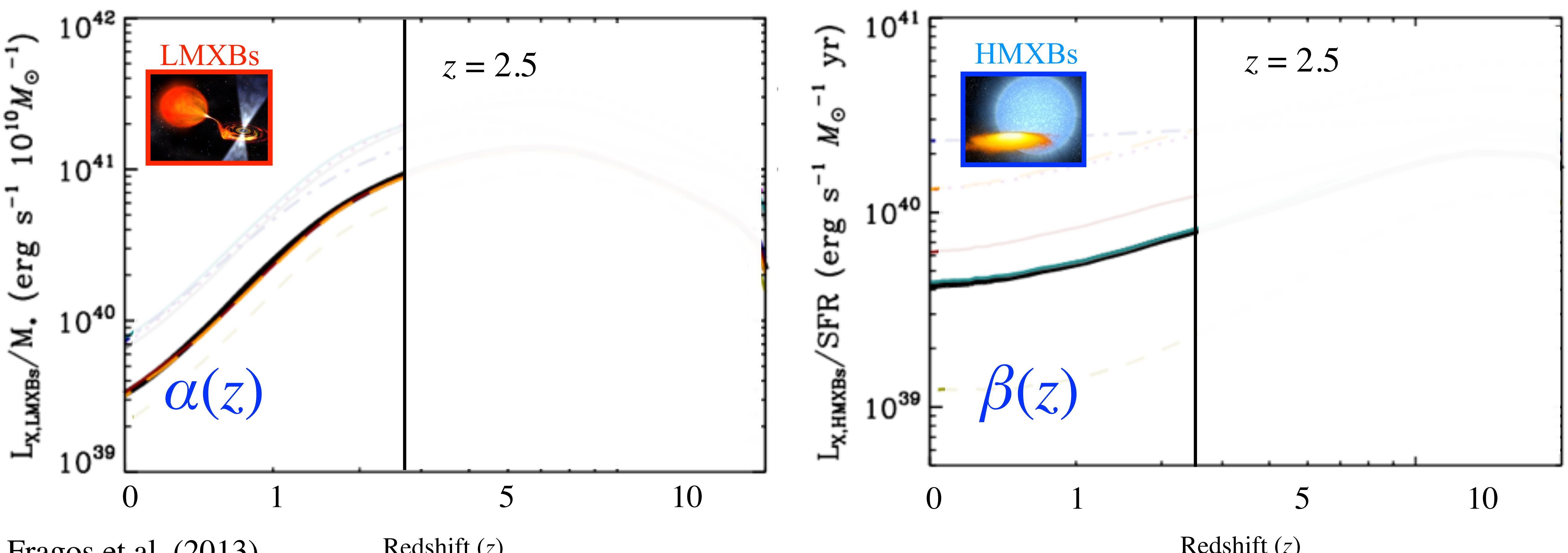
Redshift	Lynx Deep	7 Ms CDF-S (Luo et al. 2017)
z = 0–1	80,000	219
z = 1–2	90,000	59
z = 2–4	73,000	7
z = 4–8	13,000	0
Total	256,000	285



From *Chandra* to *Lynx*: Scaling Relations

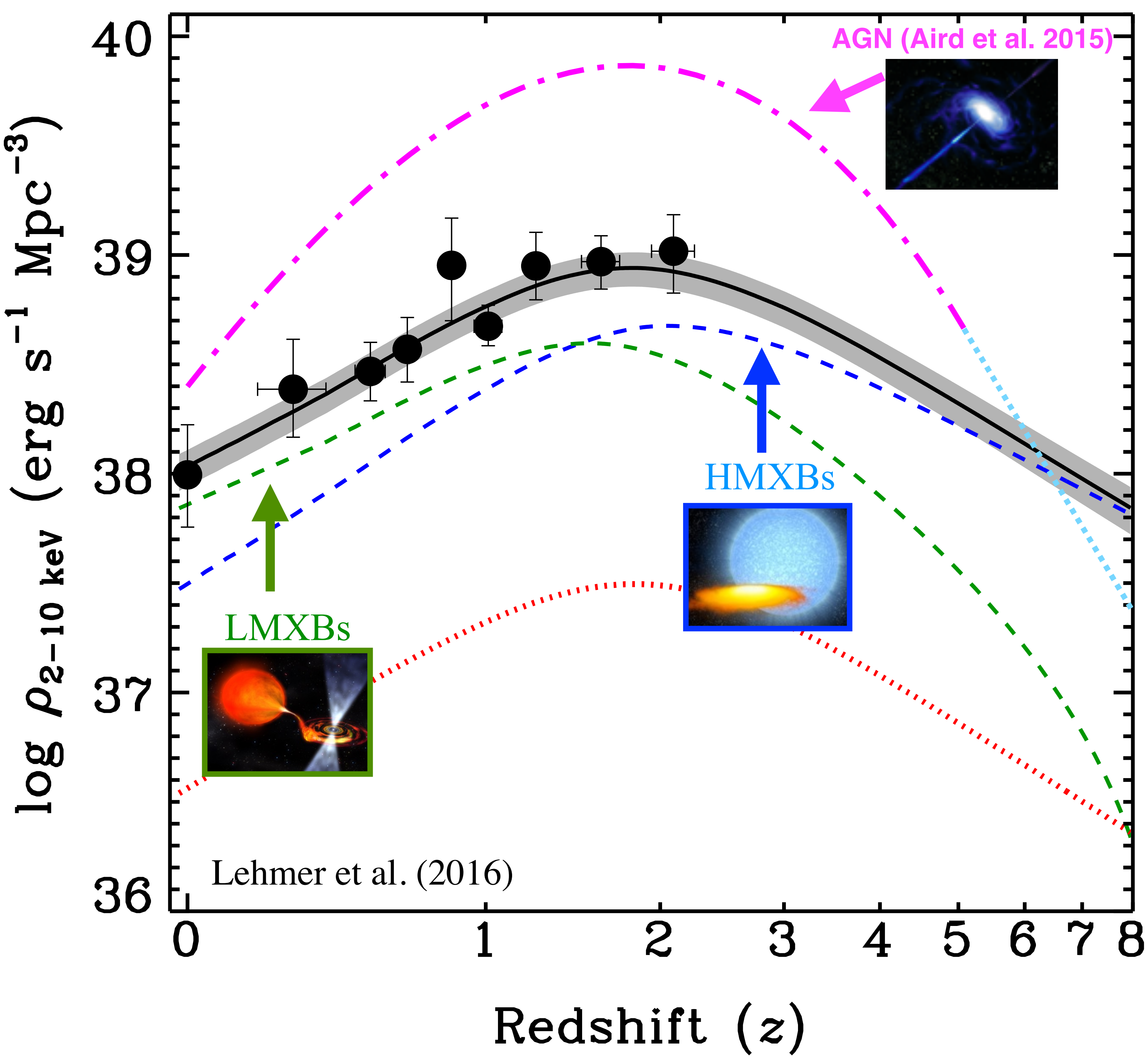
- The combination of Lynx-detected galaxies and stacking of populations detected by other multiwavelength facilities (e.g., JWST and other ELTs) would push estimates to $z \sim 10–20$.

- New insights into metallicity, age, and IMF effects on XRB formation and the X-ray radiation field in the early Universe.



Fragos et al. (2013)

X-ray Emissivity Evolution of XRBs and AGN

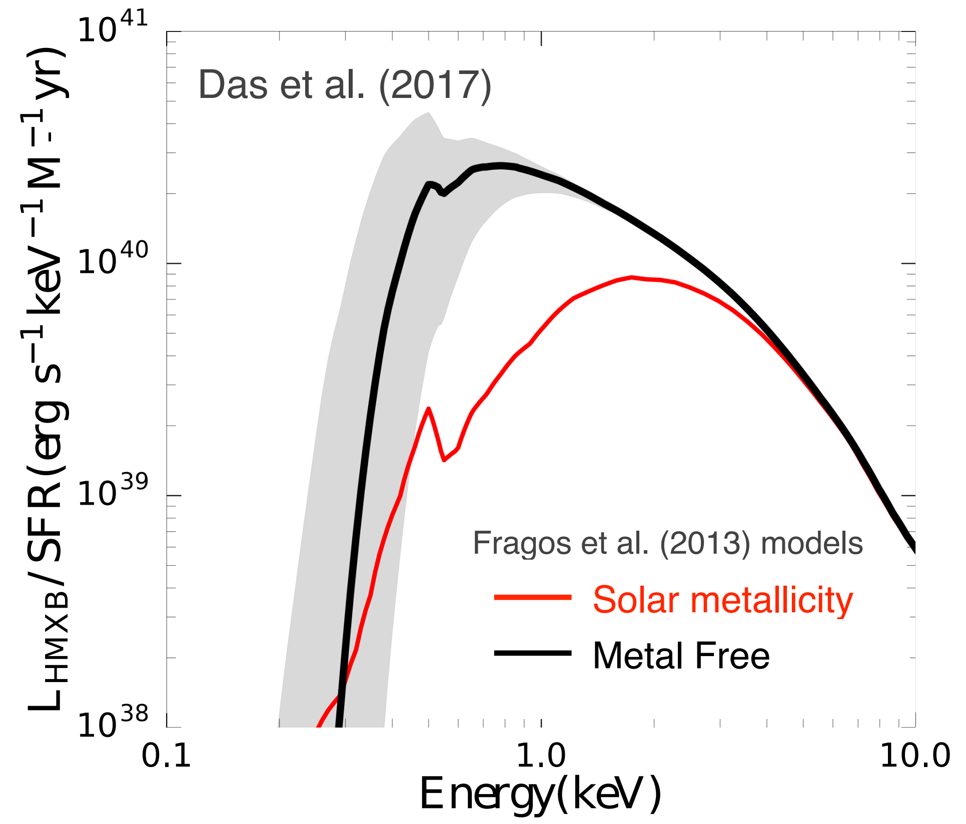


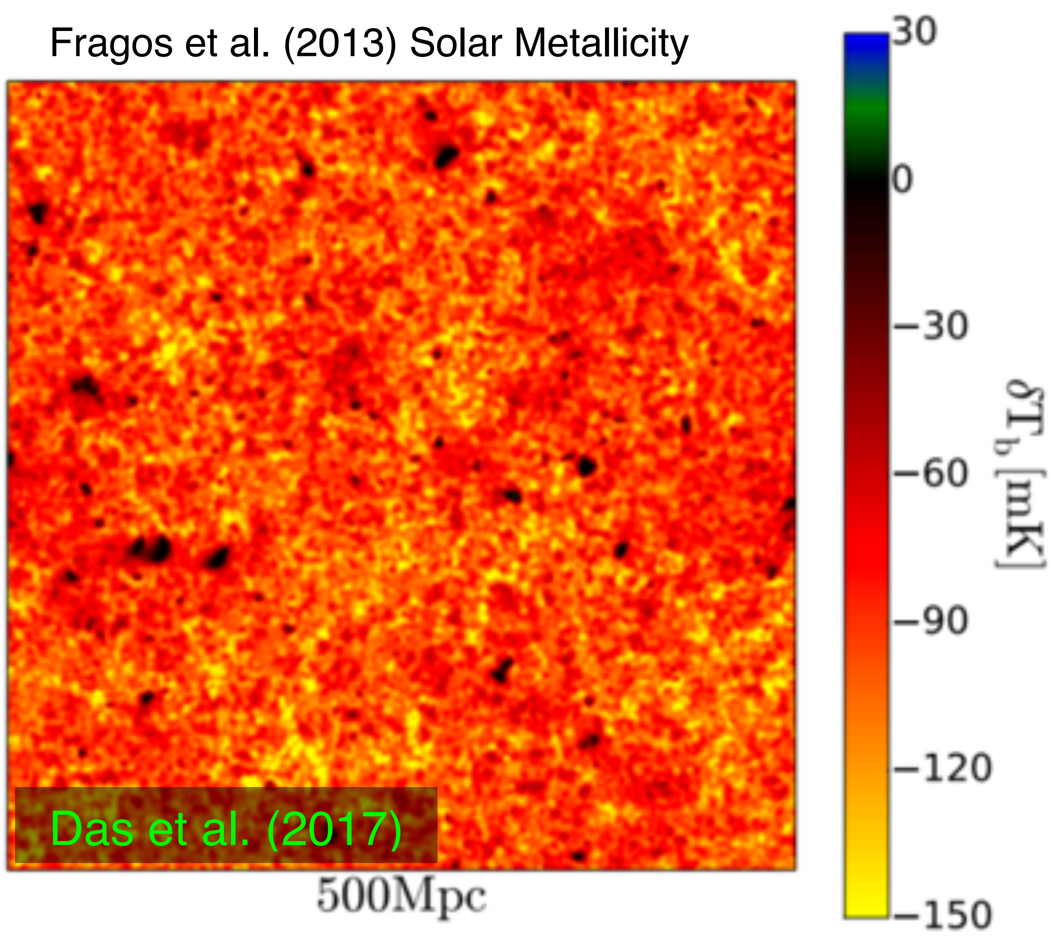
- AGN XLF measured to $z \sim 5$–6, providing estimates of the X-ray emissivity (e.g., Aird et al. 2015; Vito et al. 2017).
- Scaling the stellar mass and SFR densities with scaling relations provides estimate of the XRB emissivity.
- Pop. synth. models suggest galaxies will likely overpower AGN at $z > 6$–8.

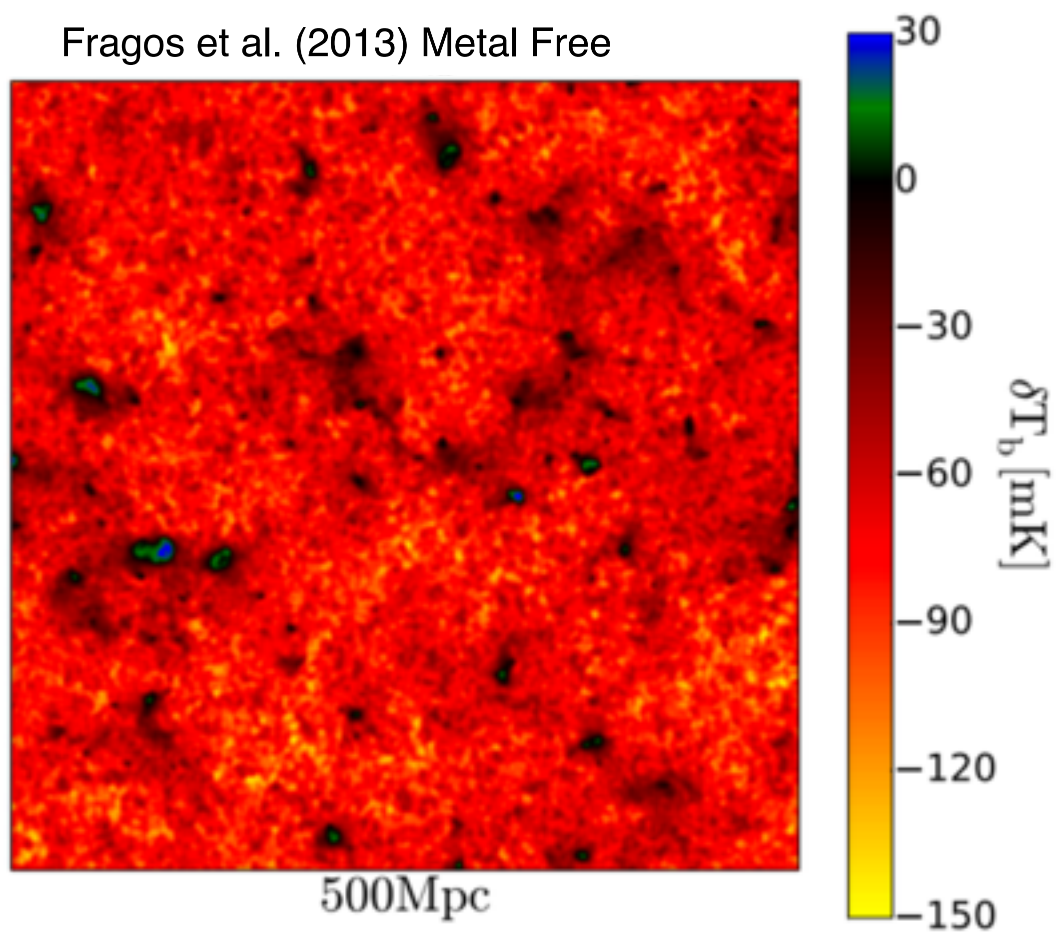
X-ray Heating in the Early Universe

- X-ray heating in the early Universe could be important due to longer X-ray path lengths compared to UV and less absorption due to metals.

- XRBs are expected to affect the cosmic 21 cm signal at $z \sim 10$–20, and several planned experiments (e.g., MWA, HERA, SKA) will directly measure this.







Summary

- Deep *Chandra* surveys, studies of XRBs in local galaxies, and population synthesis models are converging on a picture in which scaling relations L_X(LMXB)/$M_\star$ and L_X(HMXB)/SFR clearly depend on stellar age and metallicity. The role of IMF, and other variables, will also affect these relations, but have yet to be tested rigorously.

- X-ray detected galaxies will be important for deep surveys with *Lynx*, with several thousand galaxies expected to $z > 8$.

- The evolution of scaling relations with cosmic time provide important information on changes in metallicity, stellar ages, IMF, etc. Quantifying these changes and their impact on the radiation field at $z \sim 3$–20 will be among the key insights to be gained by *Lynx*.

- Distant XRB studies with *Lynx* will provide an important complement to insights gained by several future observatories, including *JWST*, ELTs, gravitational-wave detectors, and 21 cm observatory arrays.