A Chandra Perspective on the X-ray Binary Activity and Evolution in Star-Forming Galaxy Populations

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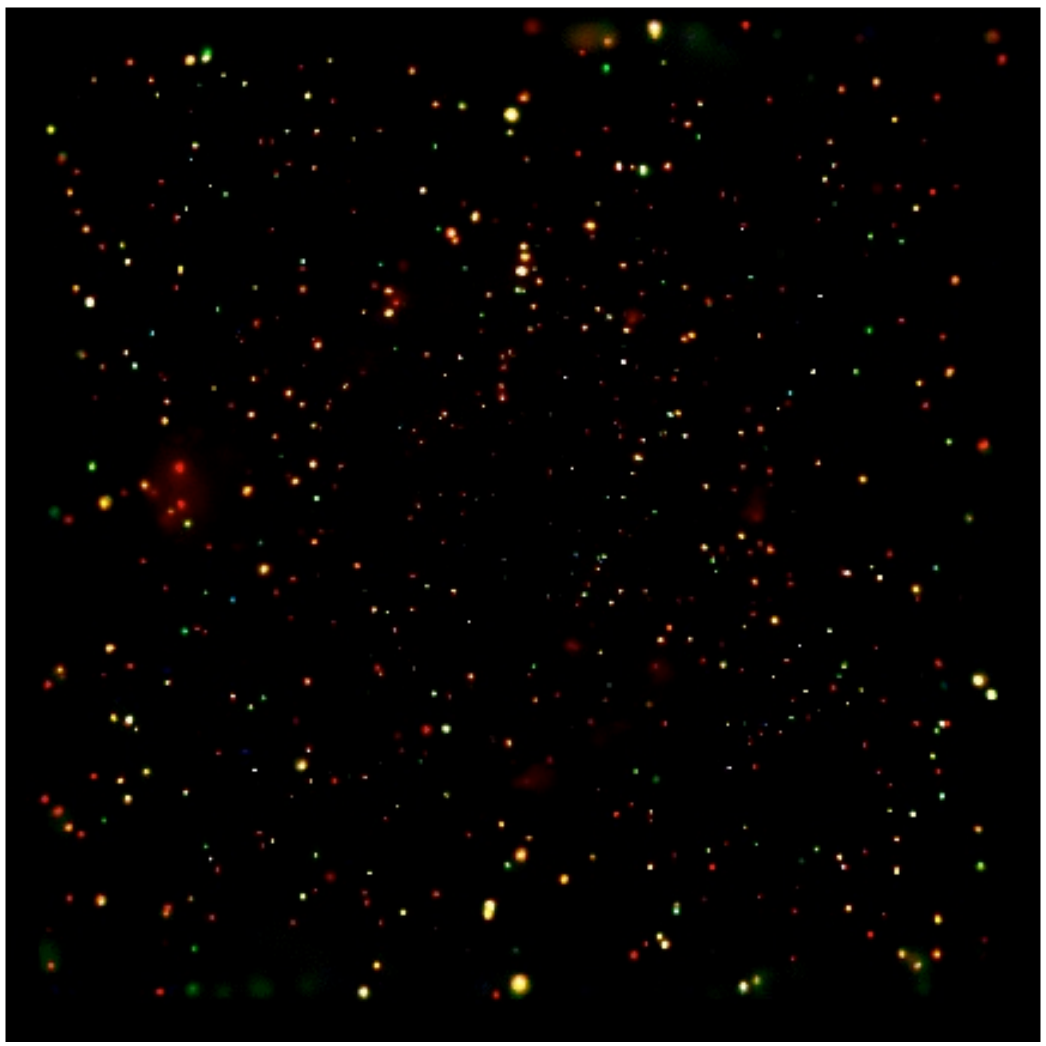

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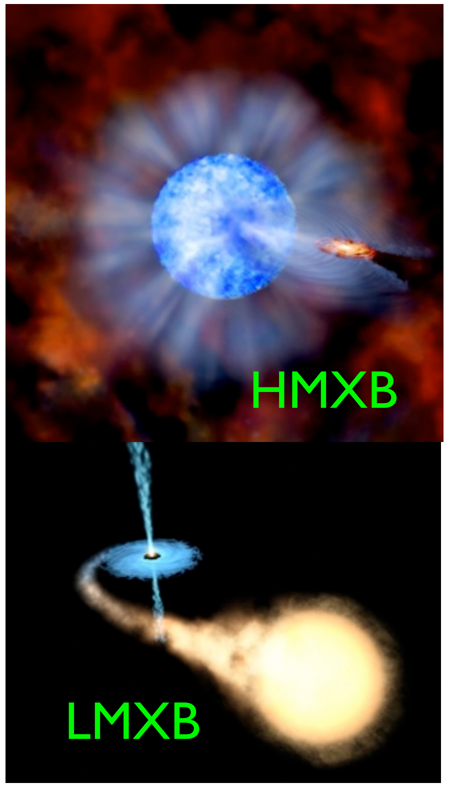
Connecting X-ray Emission and Physical Properties of Galaxies

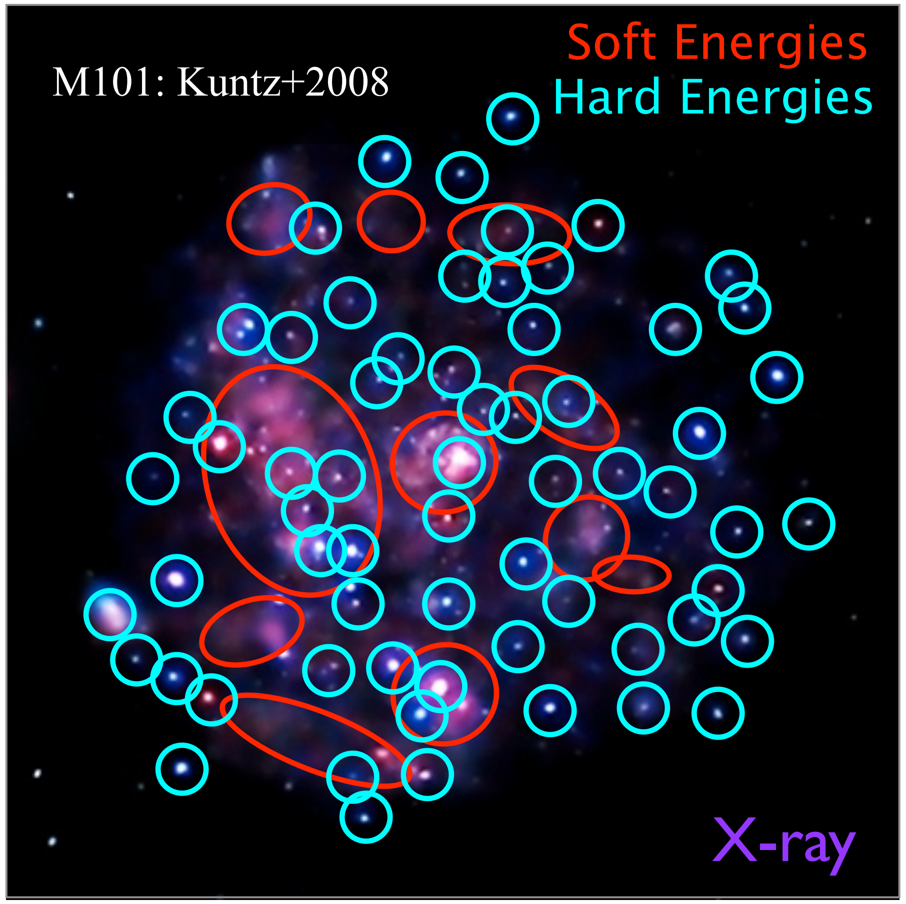
- Galaxy-wide X-ray emission arises from a variety of sources.
  - Extended soft emission from hot (~0.2−1 keV) gas.
  - Point sources: HMXBs, LMXBs, SN and remnants.

    XRBs dominate hard (>2 keV) emission and trace galaxy properties:

    HMXBs−trace current SF activity; emission scales with SFR (e.g., Ranalli+2003; Grimm et al. 2003; Persic & Rephaeli 2007)

    LMXBs−trace SF history with ~1 Gyr delay; emission scales with stellar mass, $M_\star$ (e.g., Gilfanov 2004).





Galaxy Evolution and the Response of X-ray Binaries

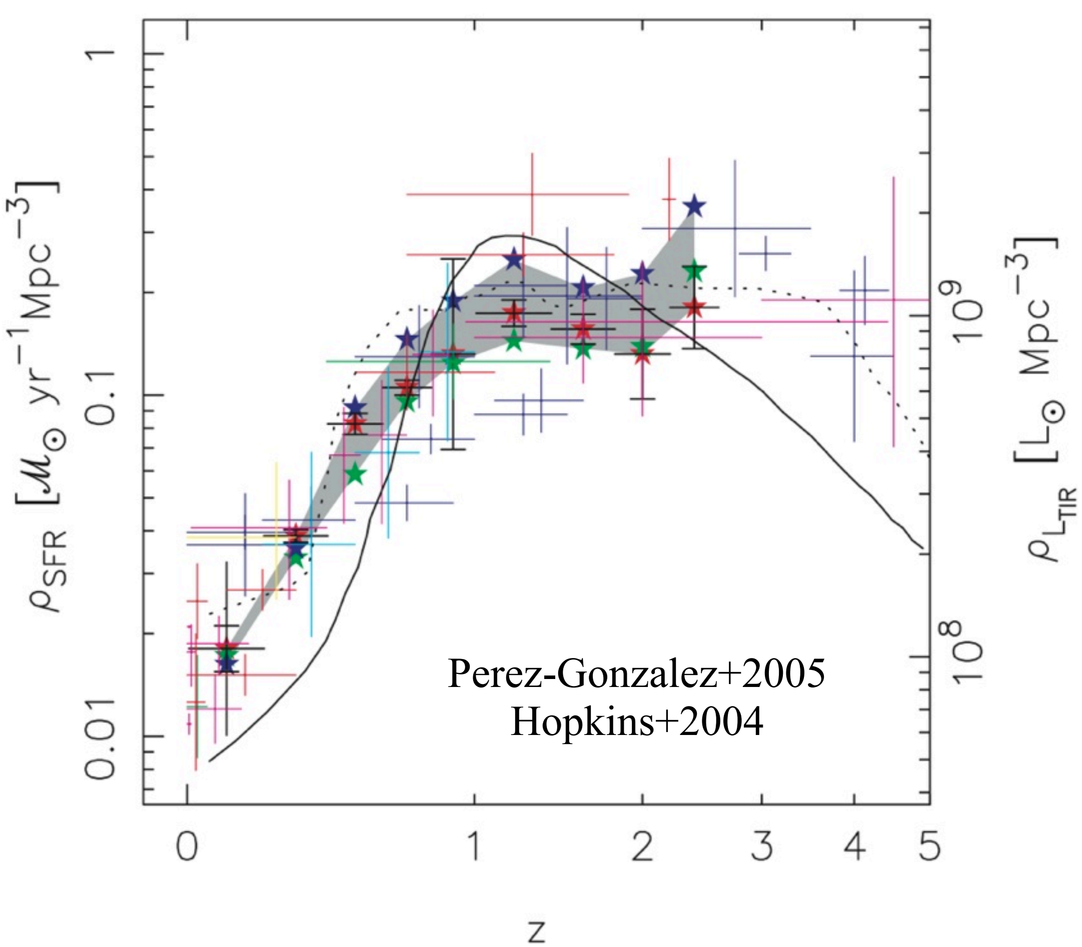
- Multiwavelength studies (particularly UV, infrared, and radio) have shown SF activity of the Universe evolves significantly with cosmic time.

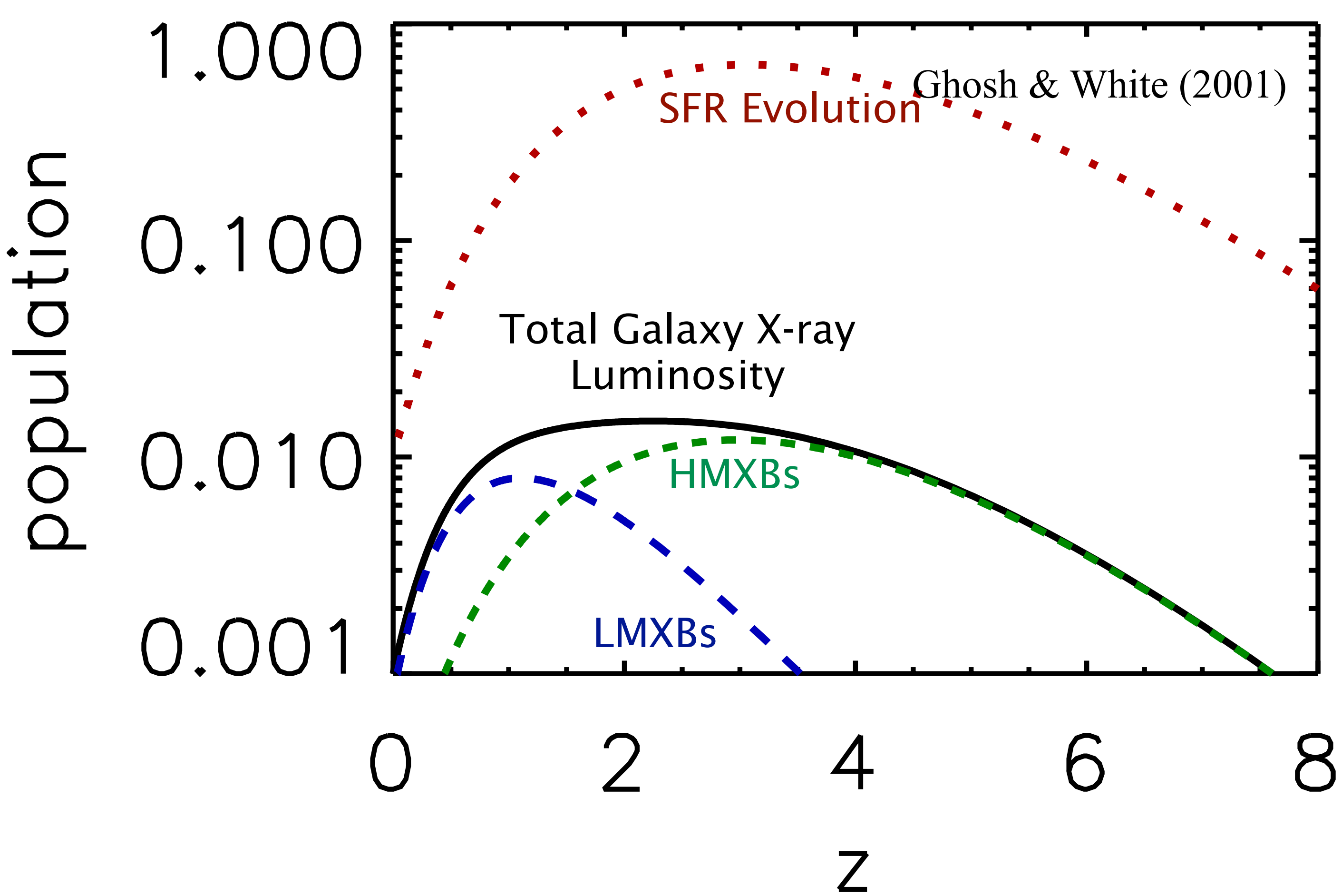
- X-ray binary activity should also change with cosmic time in response to the evolution of galaxies (e.g., Ghosh & White).

Goal: Use Chandra observations to place new constraints on

1. How the HMXB and LMXB emission from local galaxies scales with SFR and stellar mass, respectively, and

2. How the X-ray binary emission from star-forming galaxies evolves in response to global changes in SF activity.





How does Galaxy-Wide LMXB and HMXB Emission Scale with $M_\star$ and SFR?

(Lehmer+2010; ApJ, in-press, arXiv1009.3943)

Chandra View of X-ray Binary Emission in Local Star-Forming Galaxies

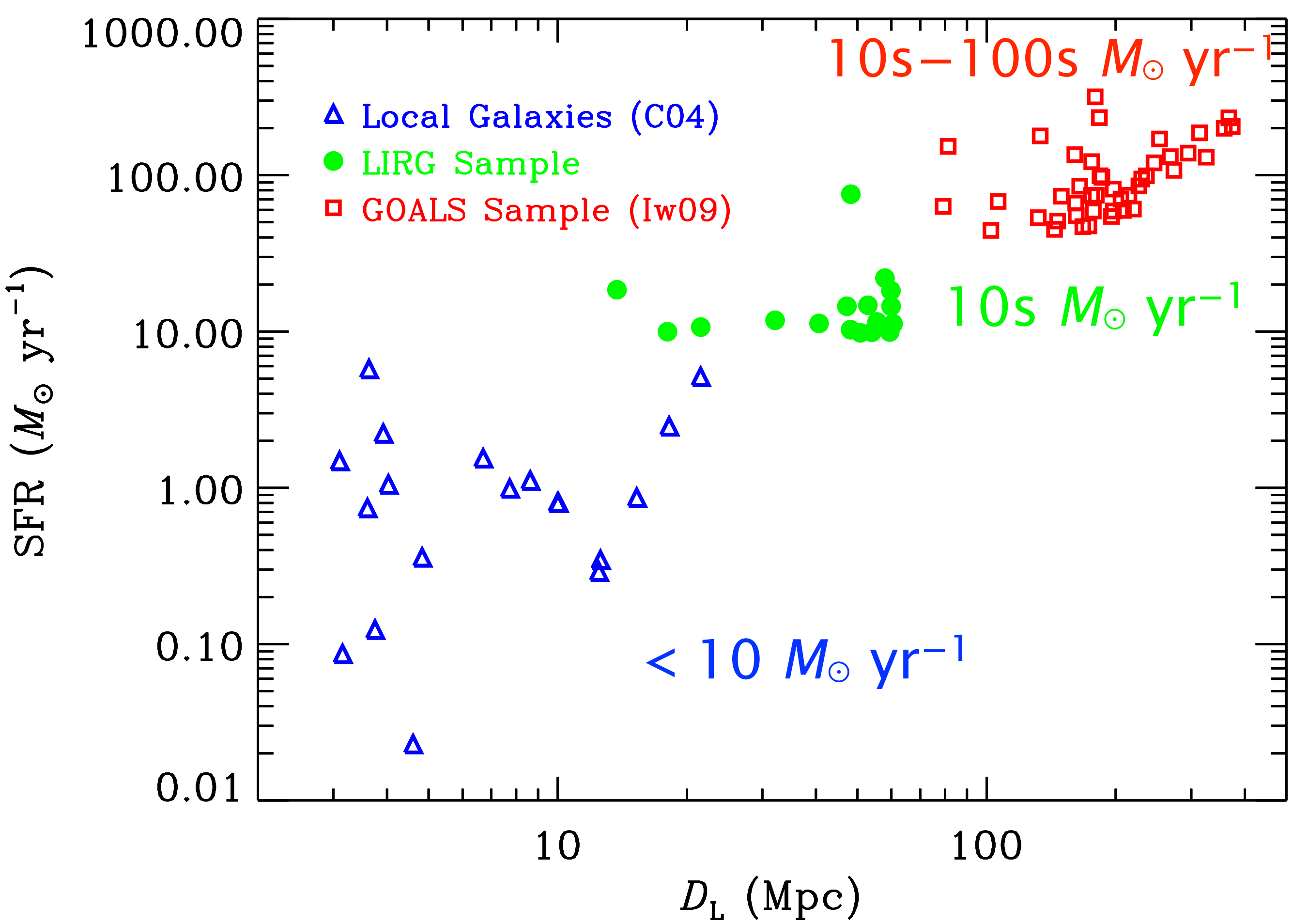
- Combine *Chandra*-observed star-forming galaxy samples to study relations between X-ray binary emission and galaxy properties:

    nearby late-type galaxies (Colbert+2004)

    luminous infrared galaxies (LIRGs; our study, Lehmer+2010)

    ultraluminous infrared galaxies (ULIRGs; Iwasawa+2009)

- 85 galaxies collected with SFR = 0.01−400 $M_{\odot}$ yr^{-1} and $M_{\star}$ = 10^{8}−10^{11} $M_{\odot}$; 66 of these galaxies do not host AGNs (via optical, IR, and X-ray spectra).



An Updated Measure of the X-ray Binary/SFR Correlation

- Galaxy-wide 2−10 keV emission L_X and $M_\star$ both scale with SFR.

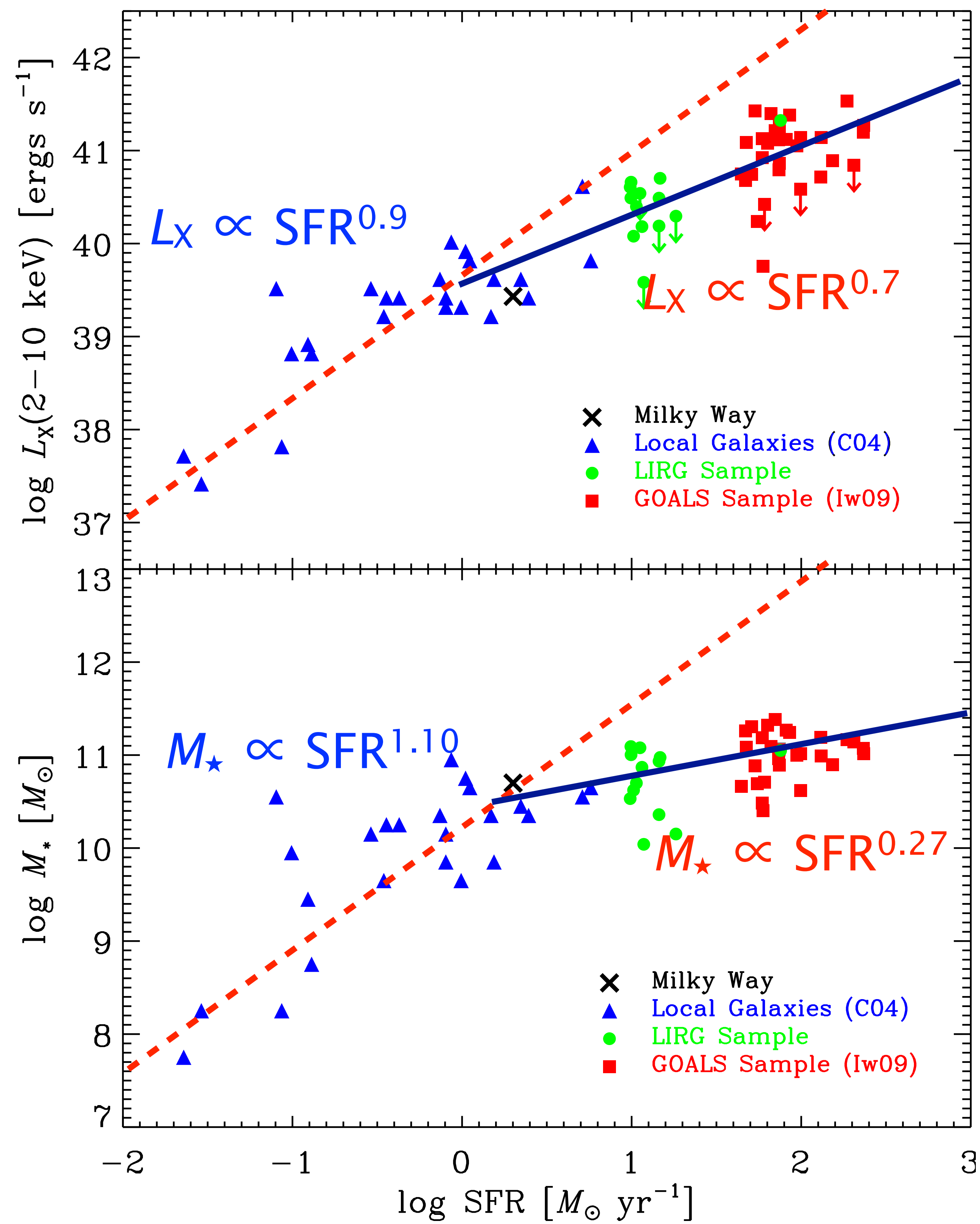
$L_X \propto \mathrm{SFR}^{0.9}$
$M_\star \propto \mathrm{SFR}^{1.10}$ (SFR < 1 $M_\odot$ yr^{-1})

AND

$L_X \propto \mathrm{SFR}^{0.7}$
$M_\star \propto \mathrm{SFR}^{0.27}$ (SFR ≥ 1 $M_\odot$ yr^{-1})

- To first-order, a physically-motivated scaling of L_X will include both $M_\star$ and SFR to account for LMXBs and HMXBs:

$$L_X = L_X(\mathrm{LMXBs}) + L_X(\mathrm{HMXBs}) = \alpha M_\star + \beta \mathrm{SFR}$$



A More Physically-Motivated Scaling of X-ray Binary Emission with Galaxy Properties

$L_X = L_X(\text{LMXBs}) + L_X(\text{HMXBs}) = \alpha M_\star + \beta \text{SFR}$

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

$L_X/\text{SFR} \propto 1/[\text{SFR}/M_\star]$

The relative contributions of HMXBs and LMXBs can be quantified as...

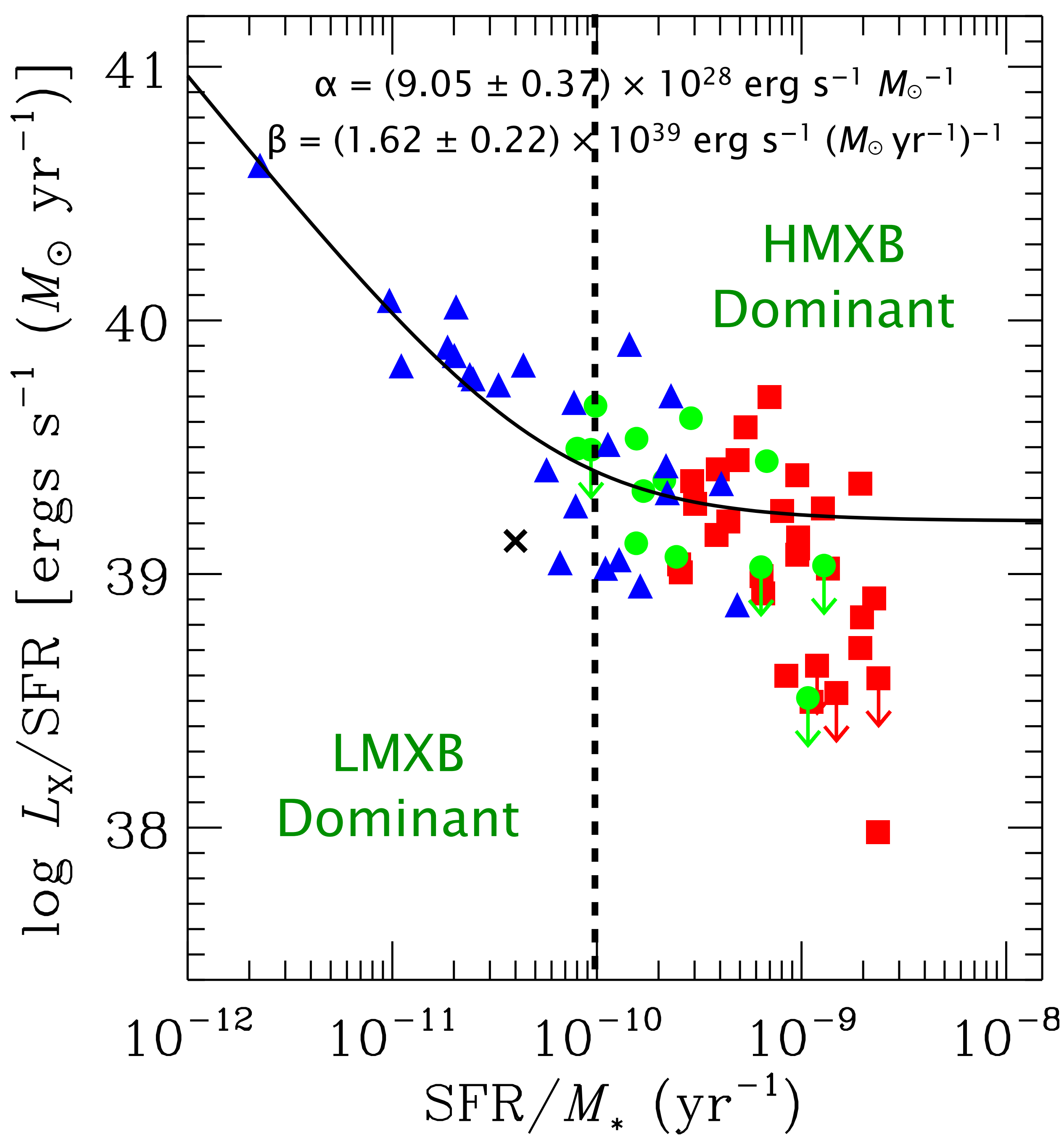
$L_X(\text{HMXBs})/L_X(\text{LMXBs}) = \beta\ \text{SFR}/(\alpha M_\star)$

implies

$\text{SFR}/M_\star > \alpha/\beta$ HMXB-dominated

or

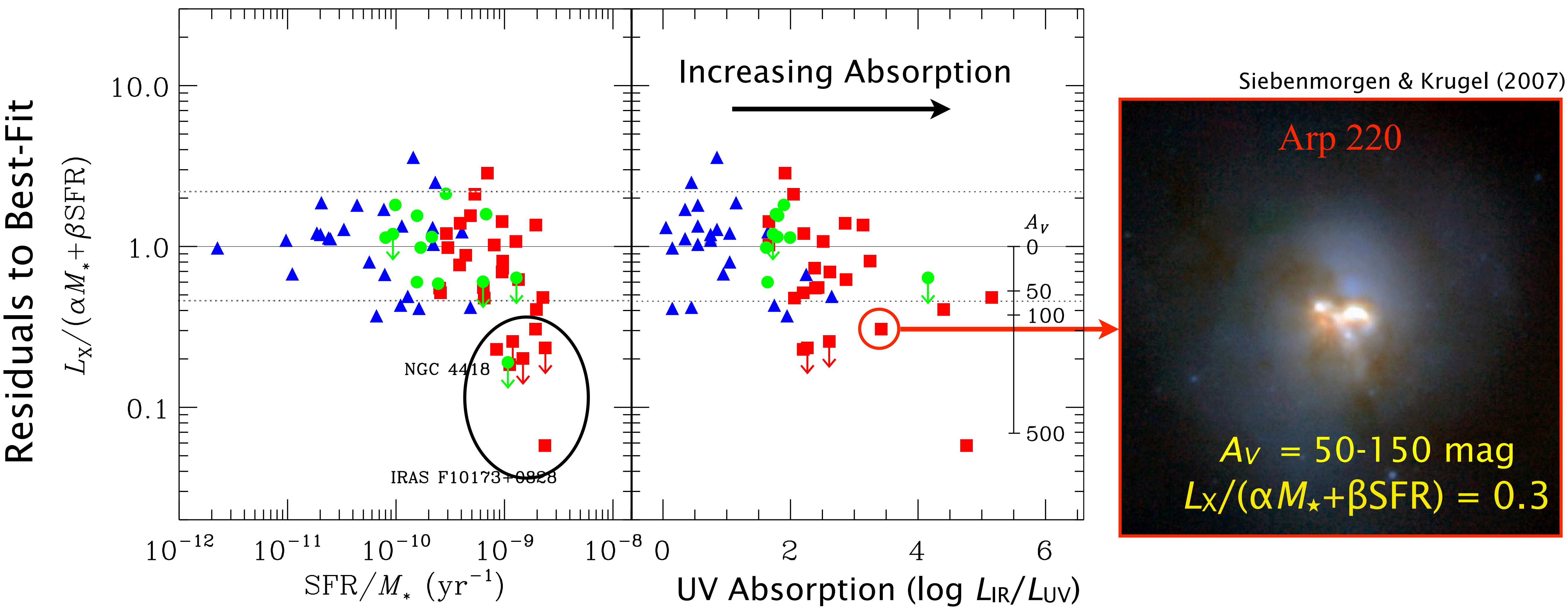
$\text{SFR}/M_\star > 0.1\ \text{Gyr}^{-1}$ HMXB-dominated



A Deficit of X-ray Binary Emission for the Most Star-Formation Active Galaxies

- Many residuals to our best fit relation $L_X/(\alpha M_\star+\beta \mathrm{SFR})$ are << 1.0 at the largest SFR/$M_\star$.

- Residuals correlate well (99.9% significance) with UV absorption (as measured by log L_{IR}/L_{UV}), suggesting that extinction in the 2−10 keV band is likely important in at least some high SFR/$M_\star$ galaxies.

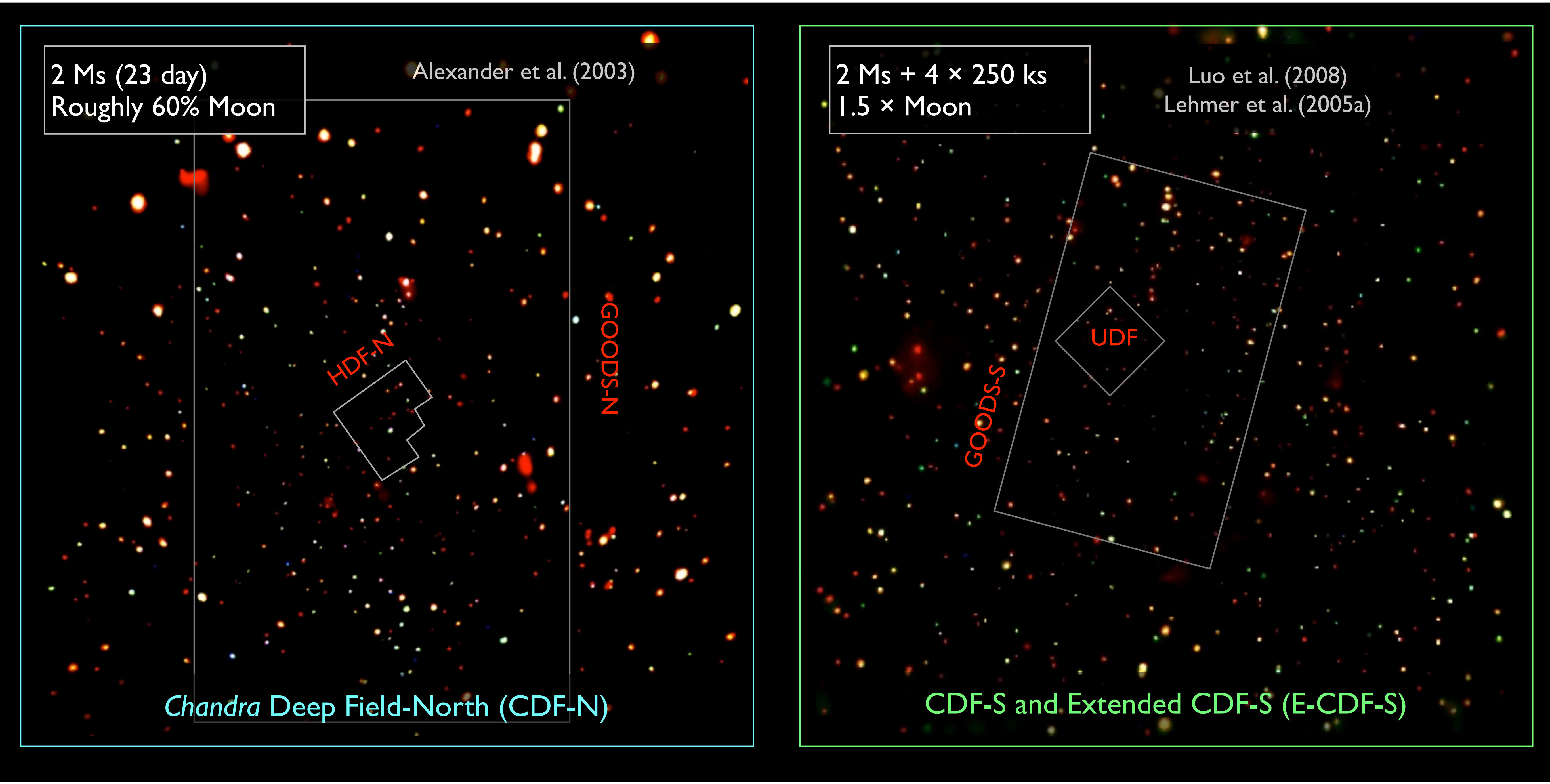


How do X-ray Binary Populations in Star-Forming Galaxies Evolve in Response to Changes in Star-Formation Activity?

(Lehmer+2008; ApJ, 681, 1163)

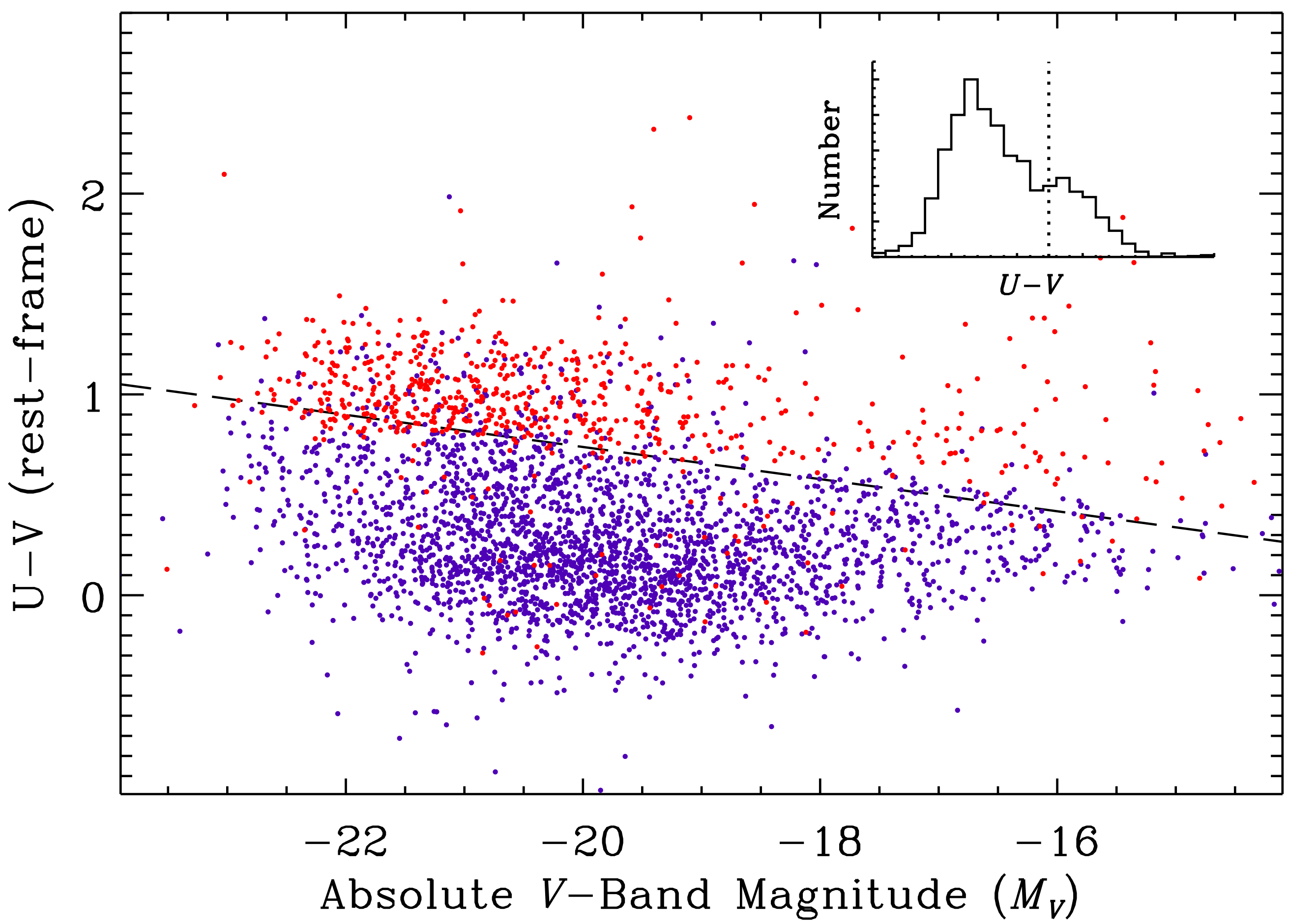
Deepest Chandra Surveys: the Chandra Deep Fields

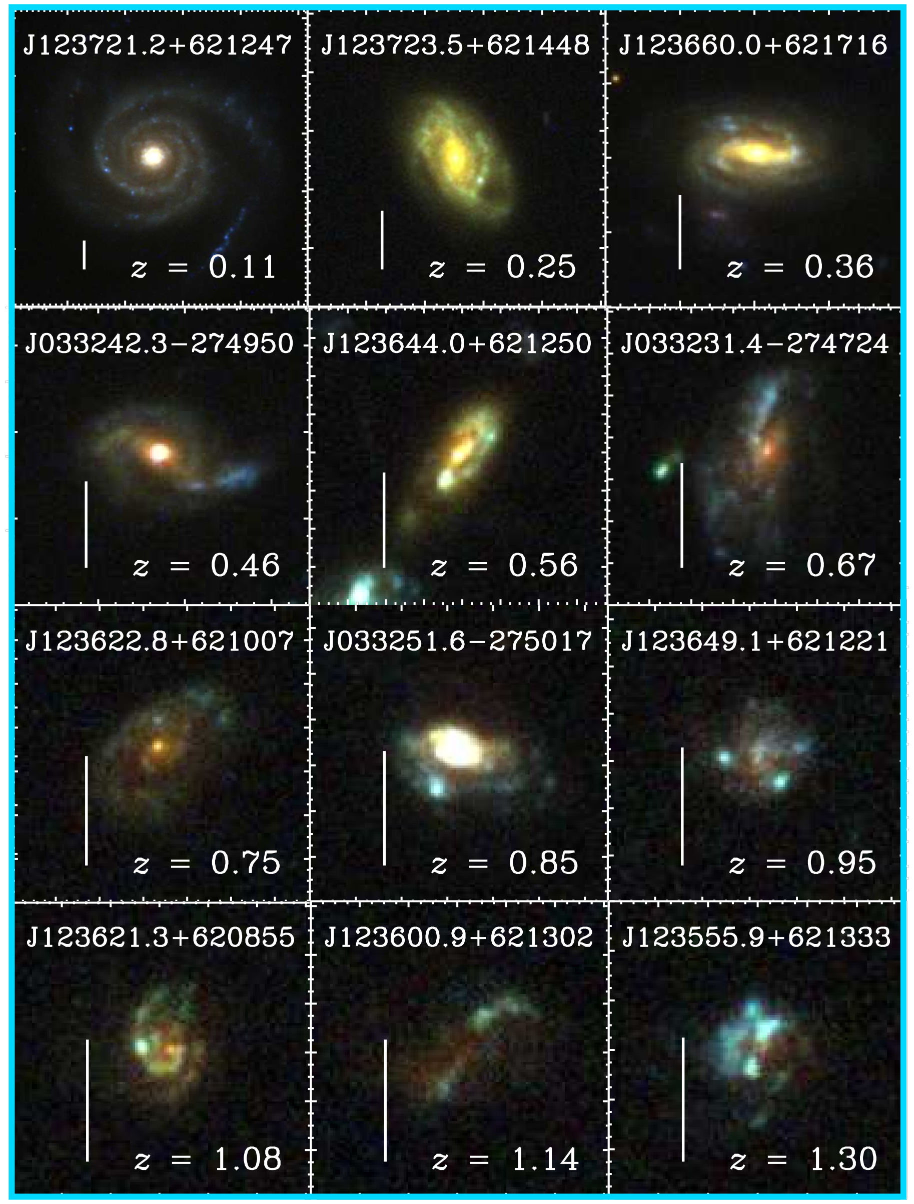
- CDFs host a plethora of deep multiwavelength data sets (e.g., from HST, Spitzer, VLT, VLA, etc.) allowing for highly accurate redshift and galaxy property estimates (e.g., SFRs and stellar mass) for large numbers of galaxies.
- Majority of X-ray sources AGN, but SF-active galaxies are detectable to $z \sim 1$.



Selection of Distant (z = 0−1.4) Star-Forming Galaxies

- Using rest-frame $U-V$ colors combined with HST morphologies, we constructed a sample of 2568 star-forming galaxies at z = 0−1.4.
- Stellar masses were approximated using a combination of K-band luminosity and optical colors.
- SFRs were derived using the total rest-frame UV luminosity plus the infrared luminosity (based on *Spitzer* 24um).





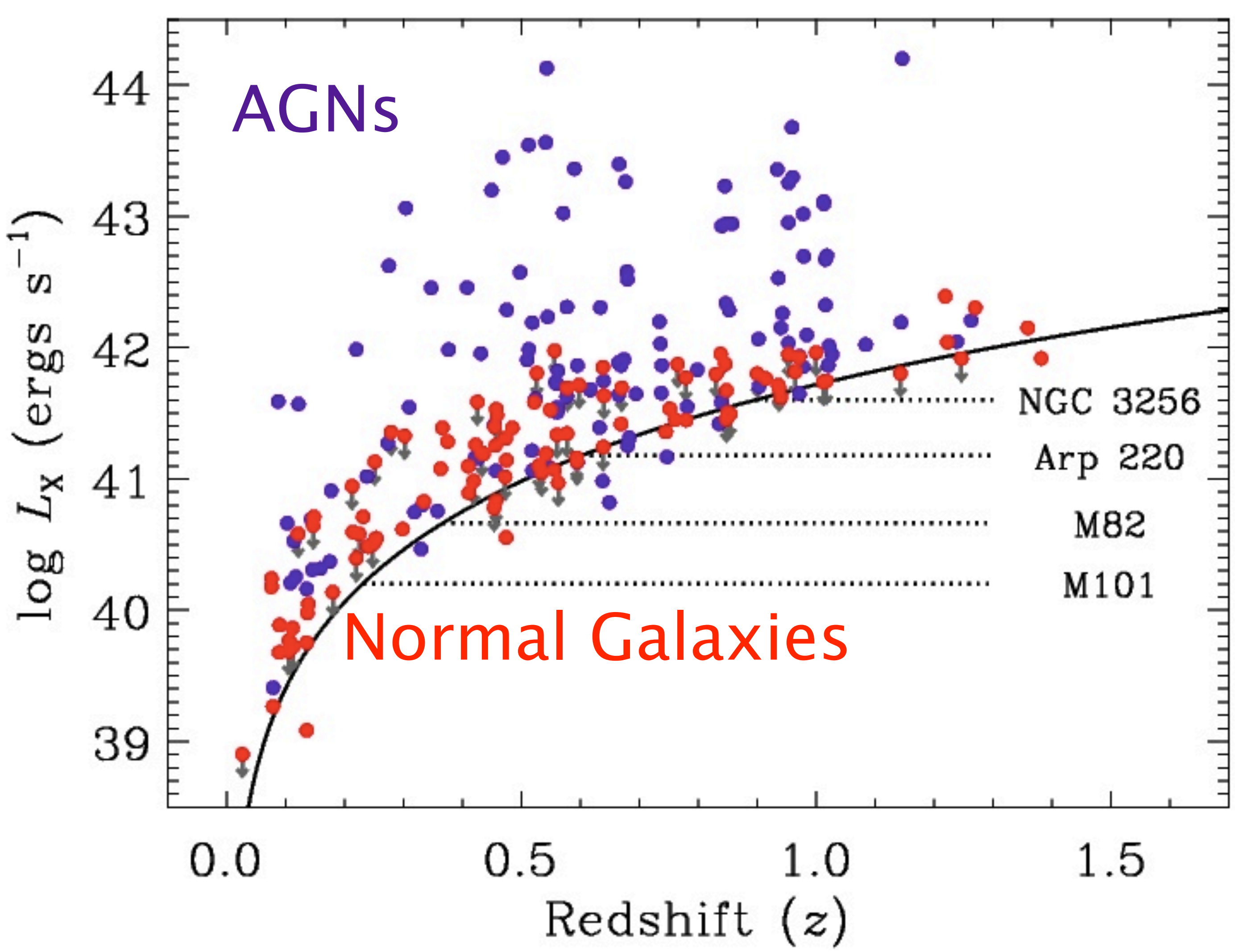
Characteristics of X-ray Detected Galaxies

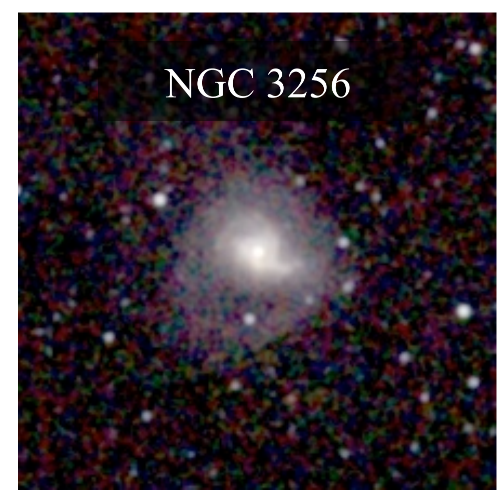
- In total 225 out of 2568 star-forming galaxies were detected in X-rays.

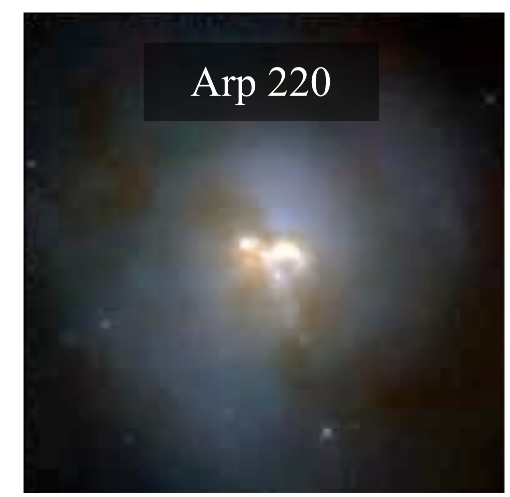
- Using X-ray band ratios, X-ray-to-optical flux ratios, and optical spectroscopy, we classified 121 galaxies as AGNs and 104 as normal star-forming galaxies.

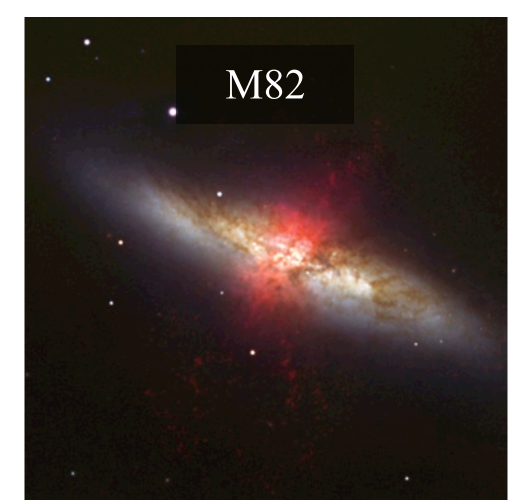
- The X-ray detected normal galaxies are quite diverse and include normal and starbursts (analogs to M82 and M101) at z < 0.3 and LIRGs/ULIRGs (analogs to NGC 3256 and Arp 220) beyond z < 0.8−1.

To study the average X-ray properties of the remaining 2343 normal galaxies, we implemented X-ray stacking analyses.

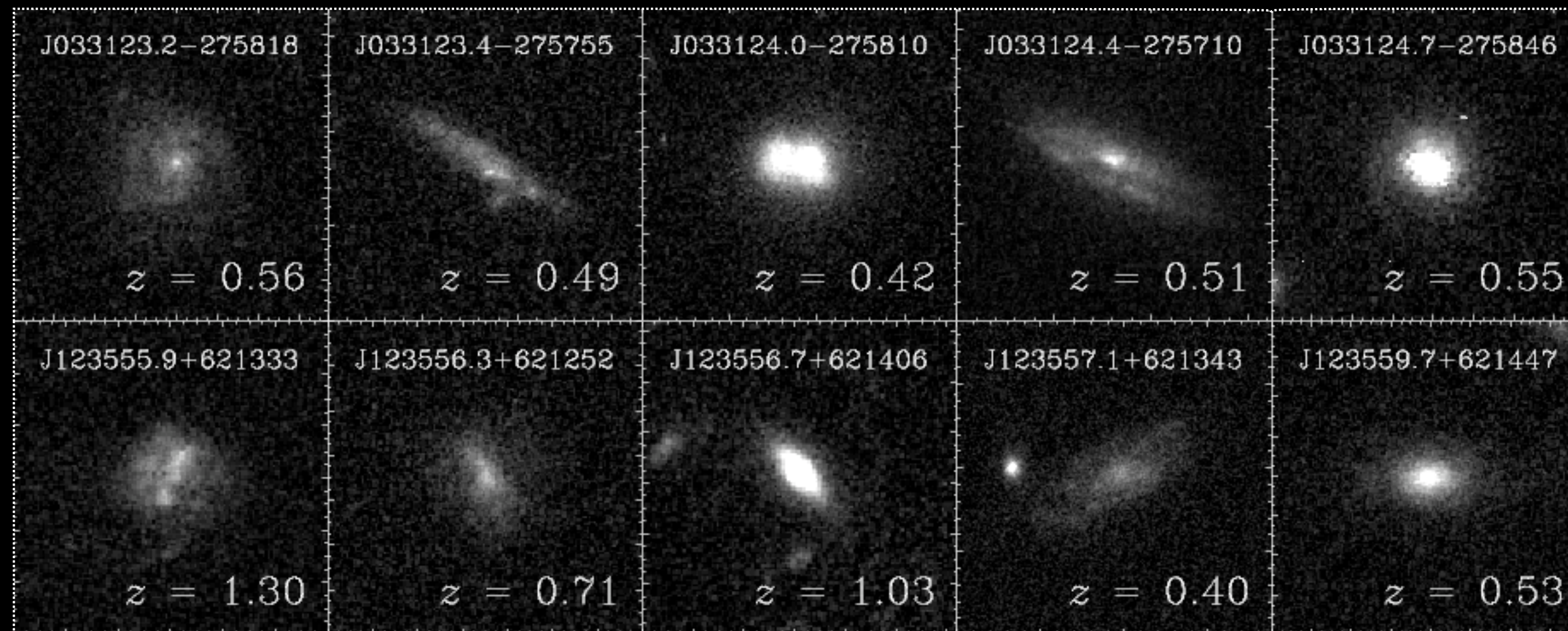


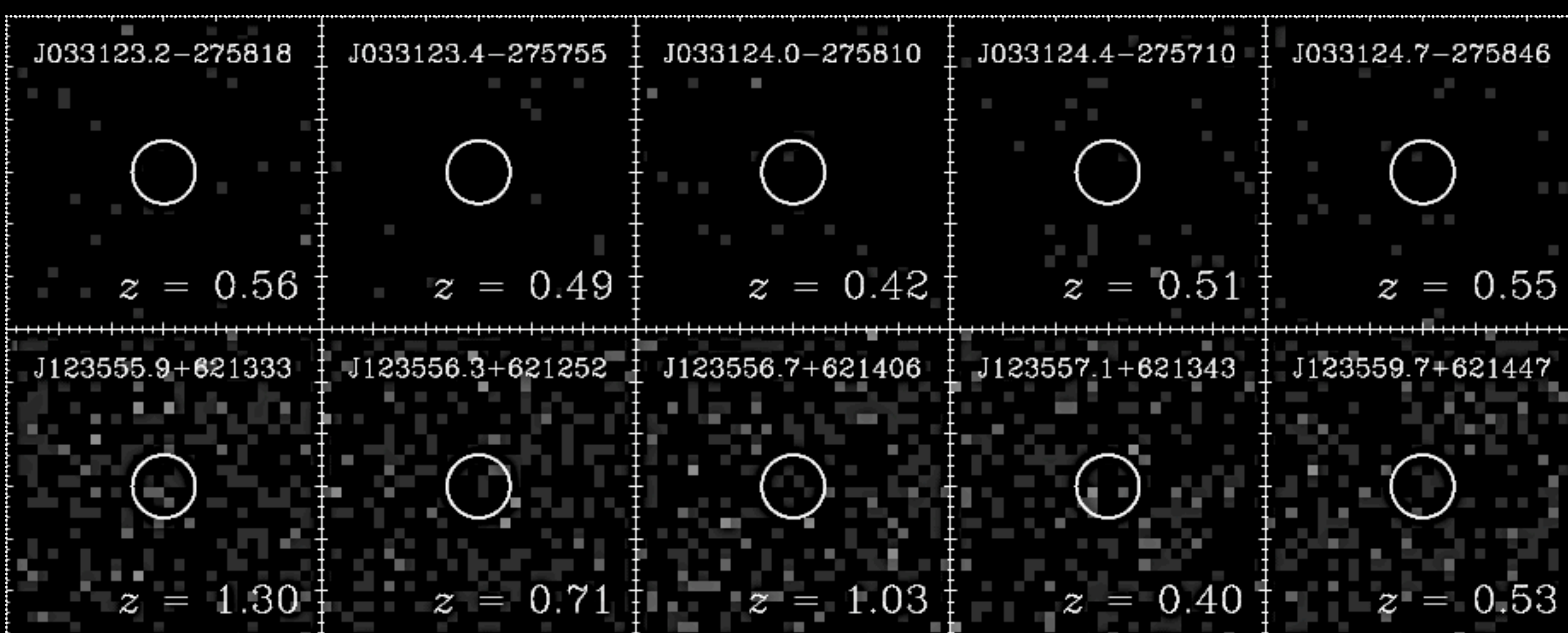


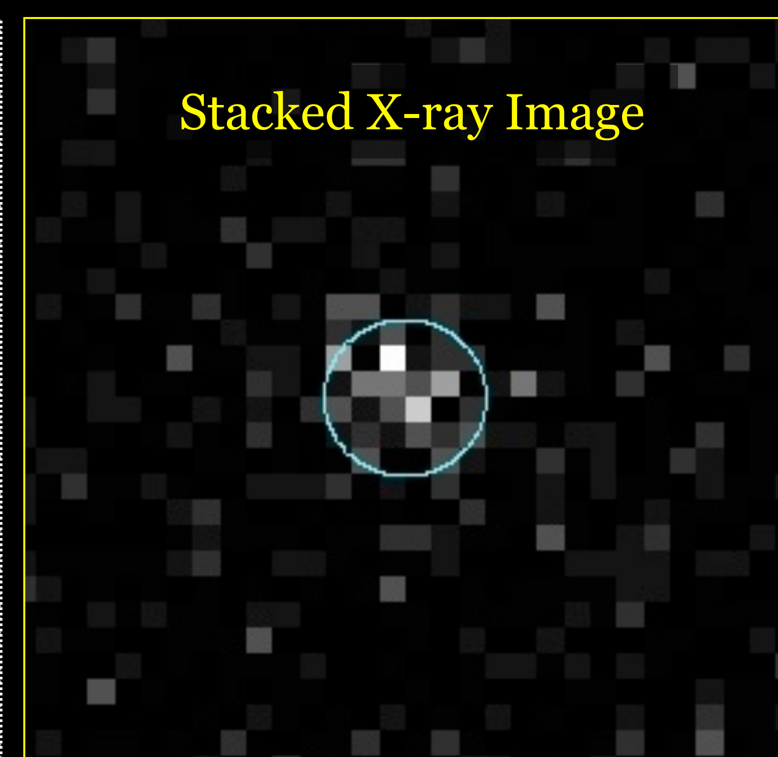




X-ray Stacking Analyses

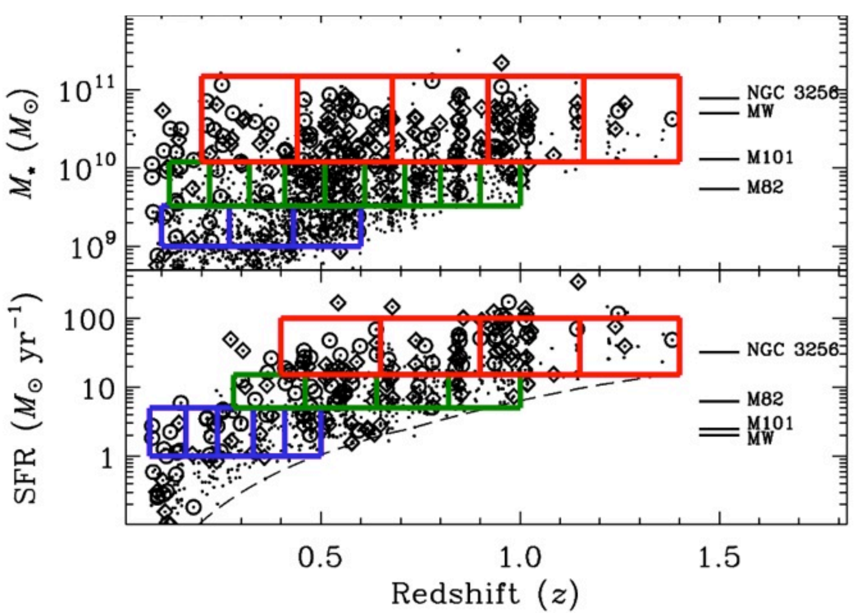


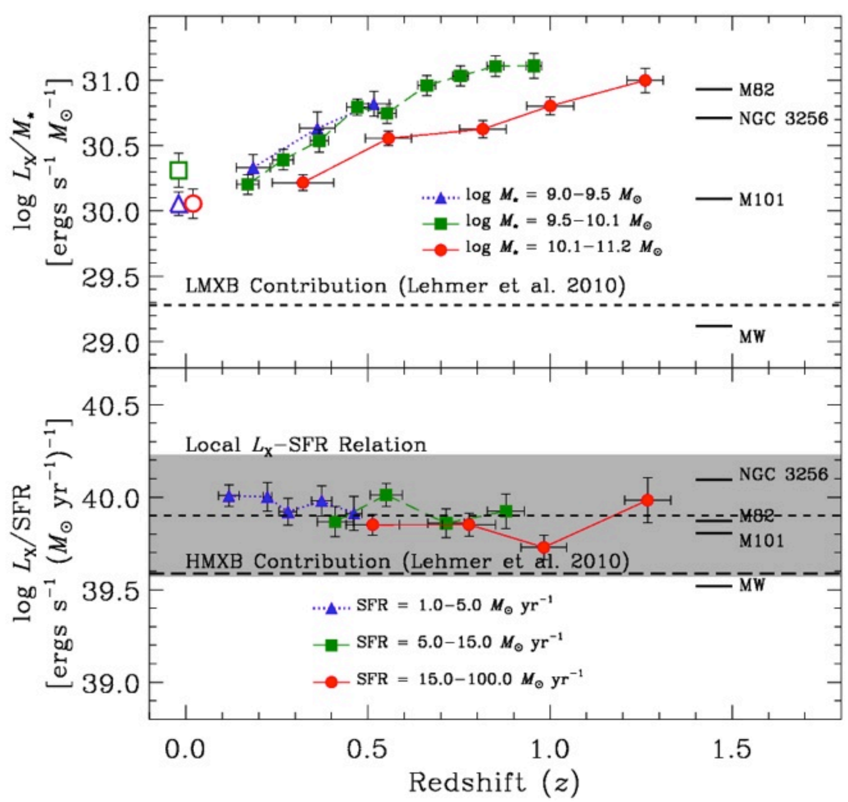


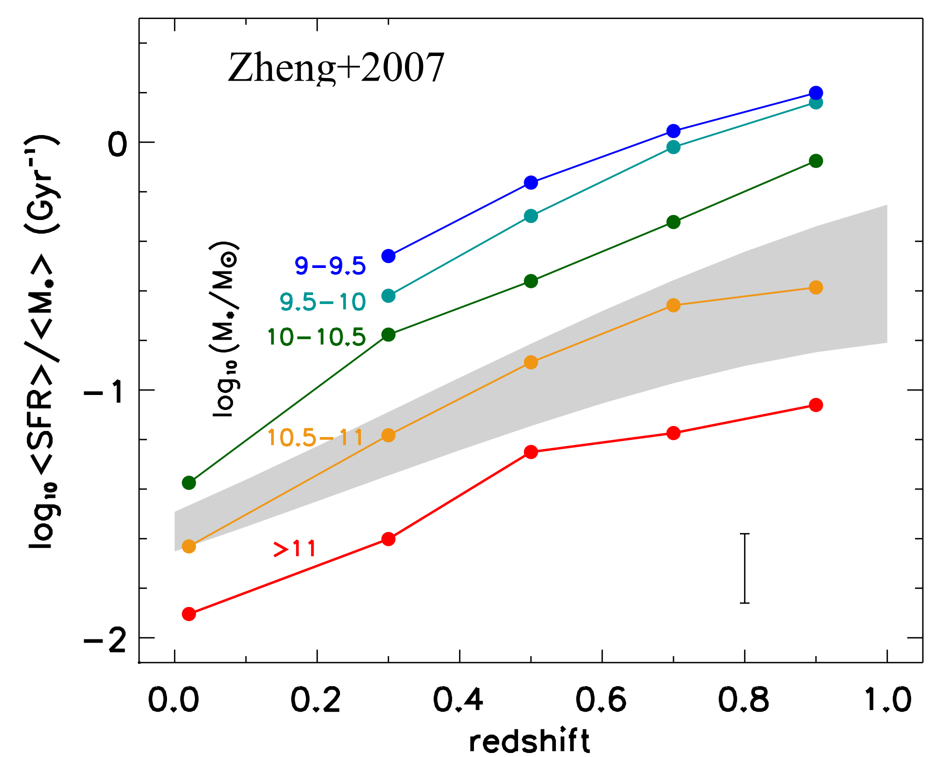


Stacking Constraints on the X-ray Evolution of Star-Forming Galaxies

- Divided galaxy sample into redshift bins and stellar mass and SFR bins and stacked the X-ray data.
- Find L_X and SFR appear to be well correlated for SFR = 1−100 $M_\odot$ yr^{-1} over the redshift range z = 0−1.4.
- For mass-selected samples, L_X evolves rapidly with redshift
  - $L_X/M_\star$ is 10 times larger at z = 1.3 than z = 0.
  - Massive galaxies have lowest $L_X/M_\star$; similar to IR-observed SFR/$M_\star$ evolution.







Summary

Galaxy-Wide X-ray Binary Emission Scaling with $M_\star$ and SFR

- Galaxy-wide 2−10 keV luminosity L_X can be described well as

$$L_X = L_X(\text{LMXBs}) + L_X(\text{HMXBs}) = \alpha M_\star + \beta \text{SFR}$$

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

- HMXBs dominate the XRB emission from galaxies with SFR/$M_\star$ > 0.1 Gyr^{-1}

- At largest SFR/$M_\star$, several ULIRGs fall below our best-fit relation, likely due to heavy extinction, even at 2−10 keV.

X-ray Evolution of XRB Emission in Star-Forming Galaxies

- X-ray/SFR relation appears to hold for star-forming galaxies out to $z \sim 1.4$.

- SFR/$M_\star$ (traced by $L_X/M_\star$) for star-forming galaxies increases by a factor of ~10 from $z = 0$ to $z \sim 1$, with the most massive galaxies undergoing less fractional growth than less massive galaxies.