Studying the Evolution of Normal Galaxy Populations in X-rays: Results from the Deepest *Chandra* Surveys

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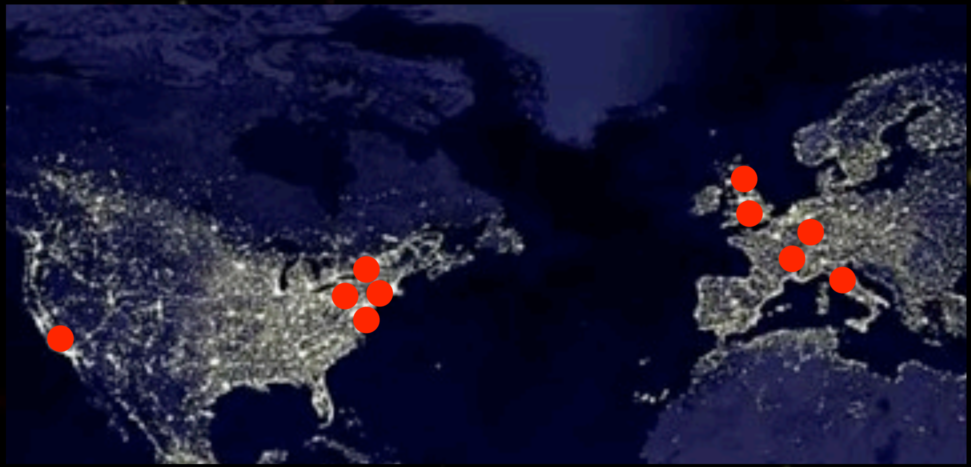
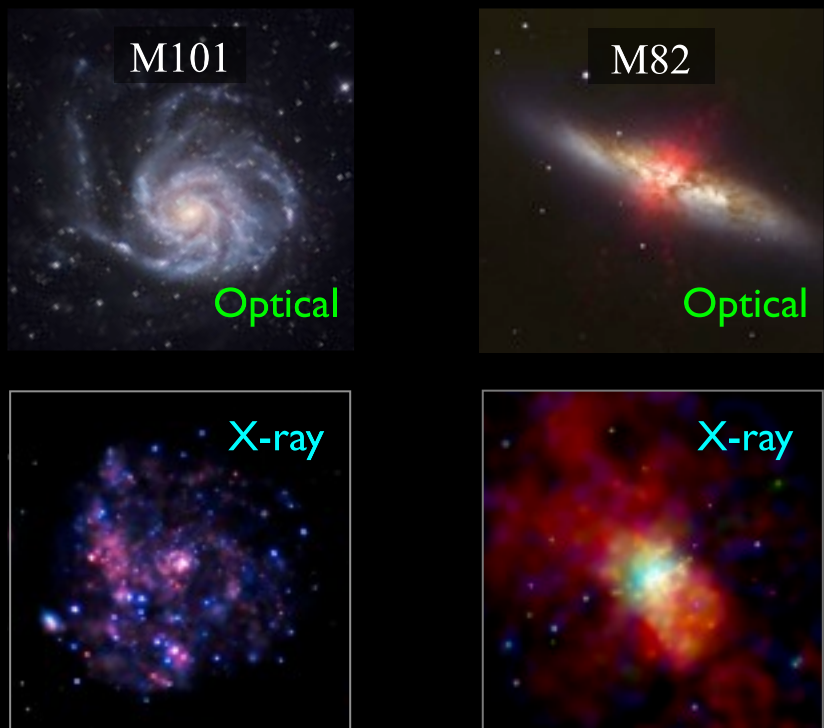
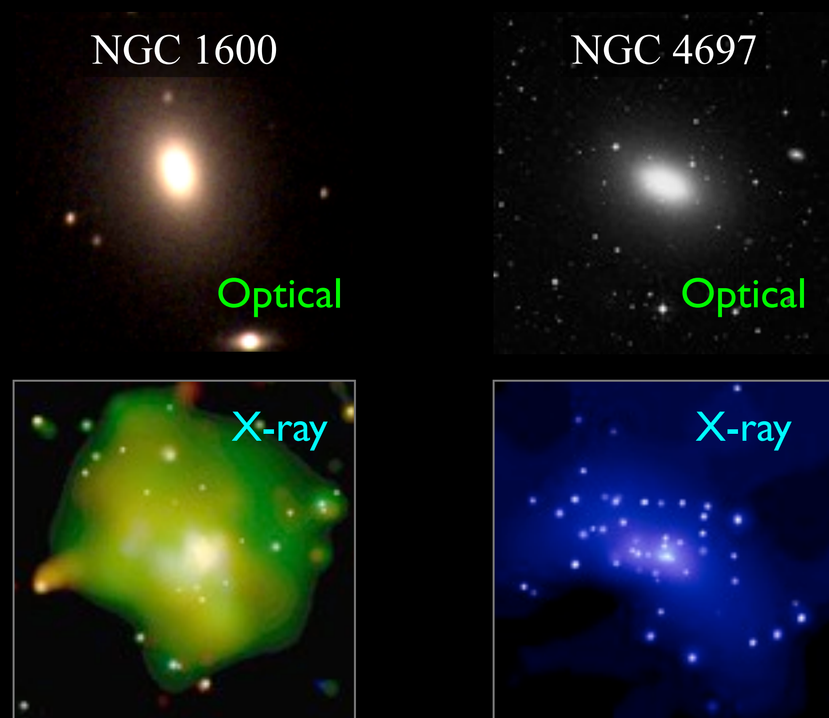


X-rays From Normal Galaxies

- Can be divided into early and late types.
- Late-types dominated by HMXBs, supernovae and remnants, hot gas, and young stars (current star-formation activity). Also contribution from LMXBs (past star formation and stellar mass).
- Early-types dominated by hot interstellar gas and LMXBs.



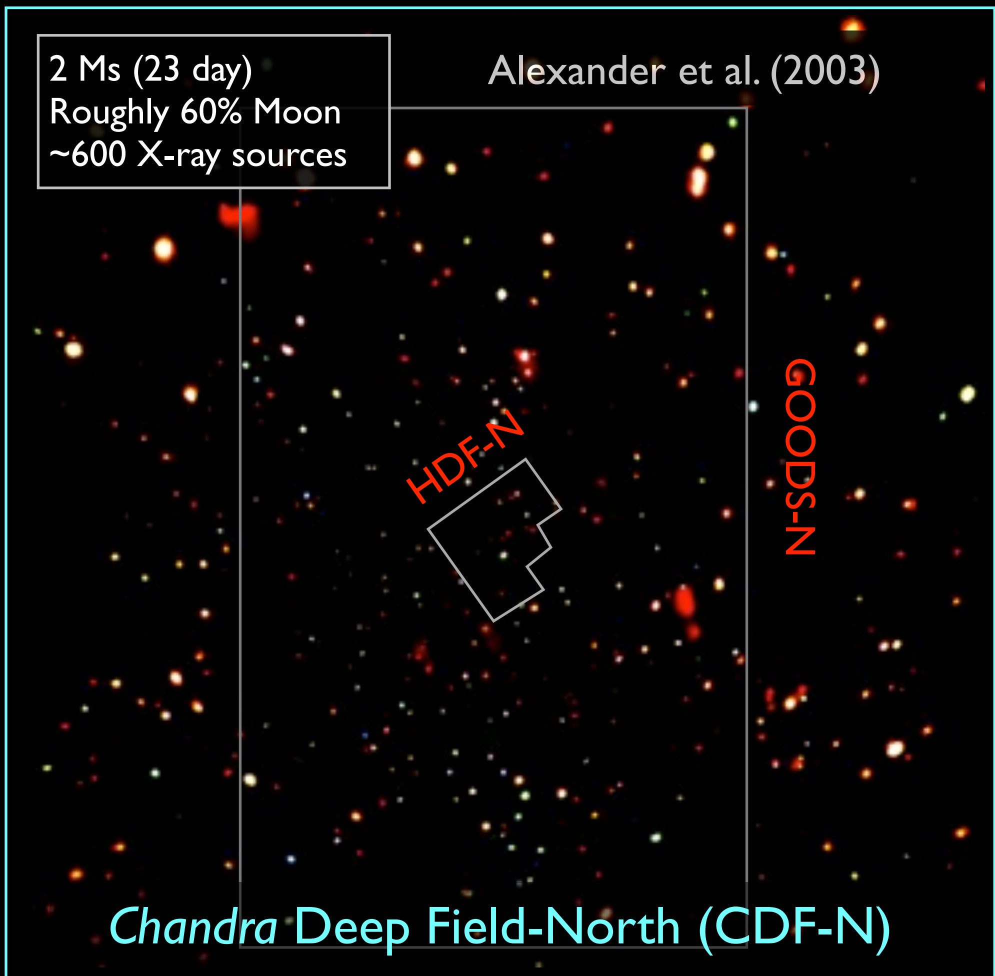
Kuntz+2008 Strickland+2006



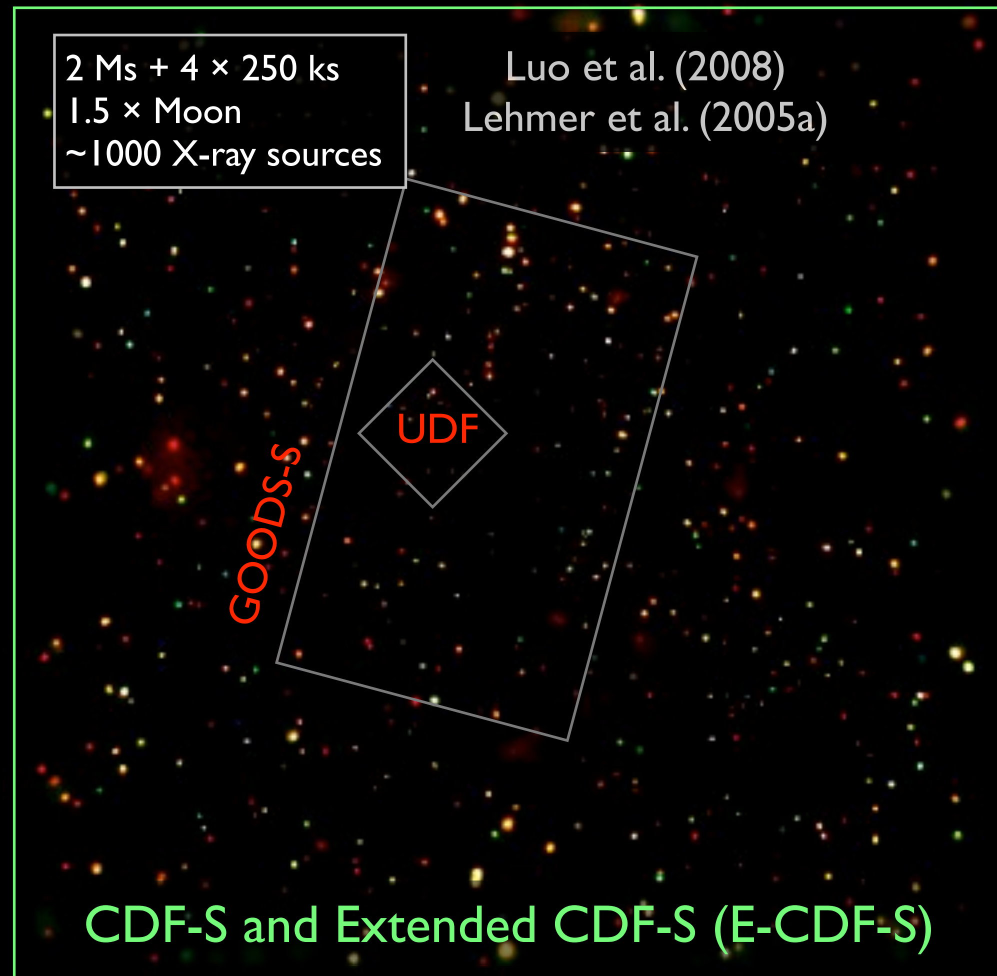
Sivakoff+2004 Sarazin+2001

The Chandra Deep Fields (CDFs)

• The CDFs are the deepest *Chandra* surveys yet conducted and are the sites of several multiwavelength space- and ground-based programs (using, e.g., *HST*, *Spitzer*, radio, optical, near-IR, etc.).

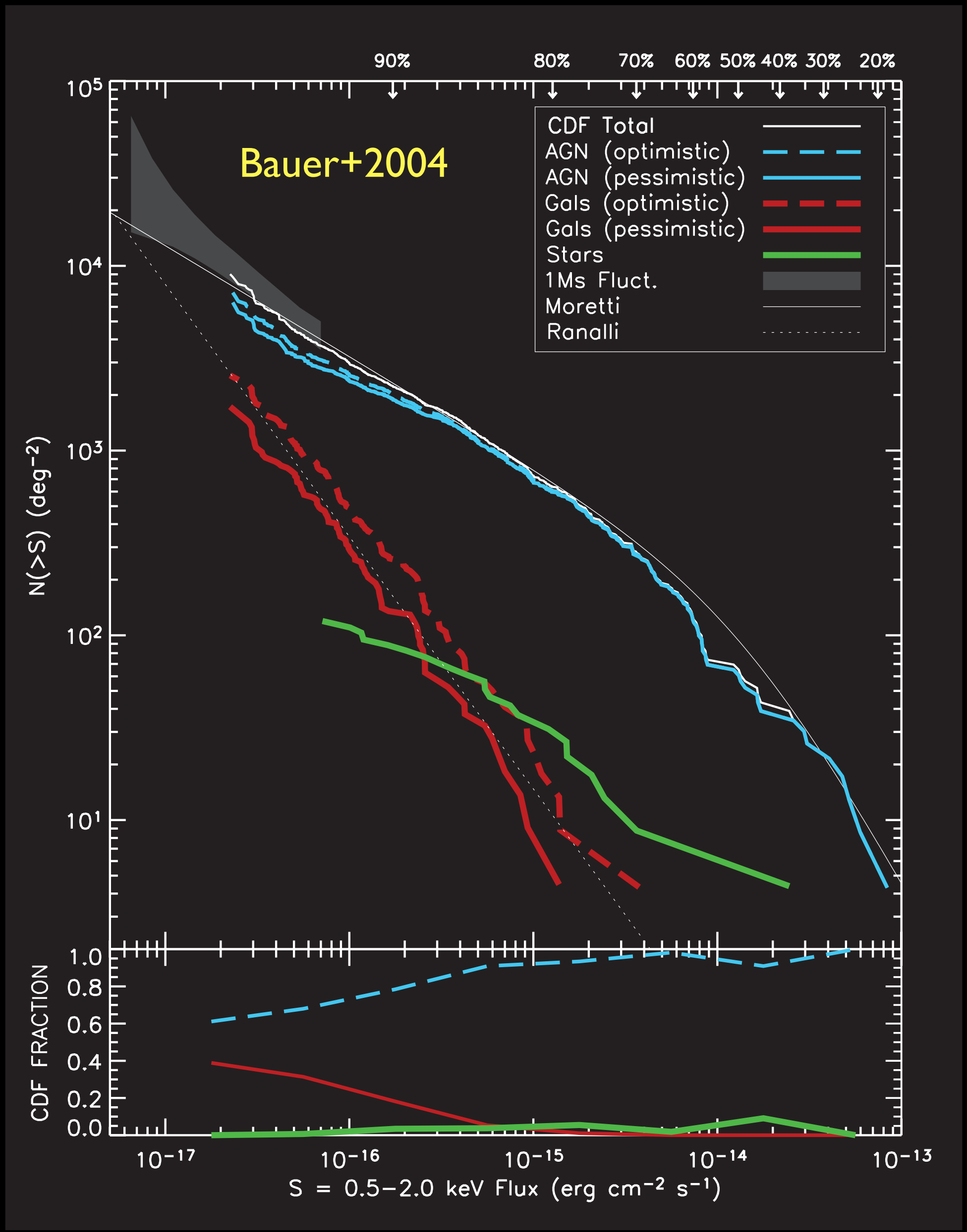


Chandra Deep Field-North (CDF-N)



CDF-S and Extended CDF-S (E-CDF-S)

X-ray Source Number Counts



- The majority of the X-ray detected sources in the CDFs are AGNs; however, at the lowest fluxes (i.e., below 10^{-16} ergs cm^{-2} s^{-1}), normal galaxies start make up ≈25–35% of the detected sources.

- At flux levels below 10^{-17} ergs cm^{-2} s^{-1} normal galaxies are expected to dominate over AGNs, making them an important population to study with deeper *Chandra* observations and future X-ray observatories.

Methods for Studying Distant Normal Galaxies

1.—Direct detection (e.g., Ranalli+2003; Ptak+2007; Tzanavaris+2008)

- Study of distant normal galaxy properties on an individual basis.
- Evolution of the X-ray luminosity function.
- Limited to the most luminous X-ray sources in deepest fields.

2.—X-ray stacking (e.g., Lehmer+2007, 2008; Danielson+2010)

- Representative populations of galaxies to highest possible redshift.
- Study X-ray properties and evolution as a function of physical properties (optical lum, SFR, $M_{\star}$).
- Only study in an average sense and removing potential AGN contamination is difficult.

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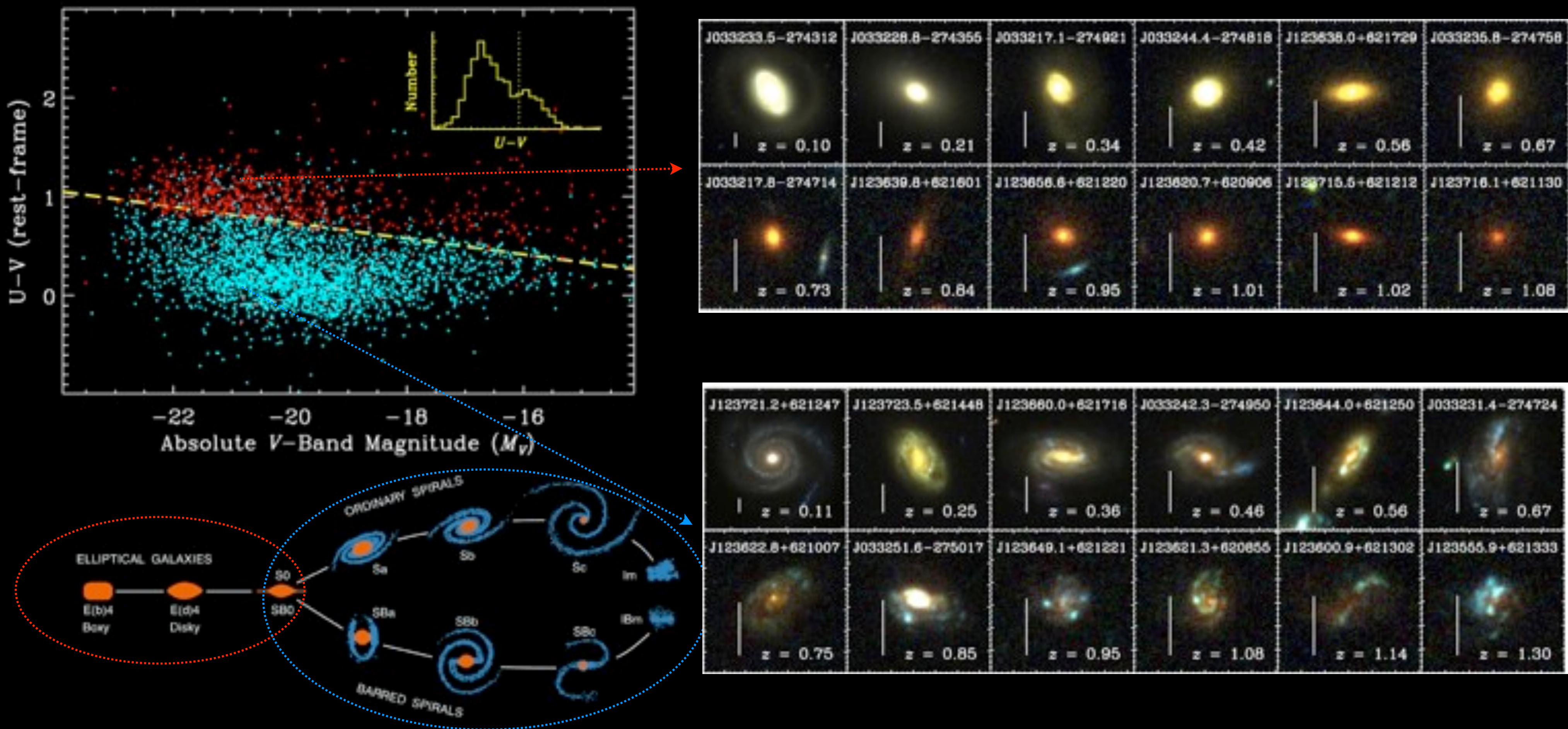
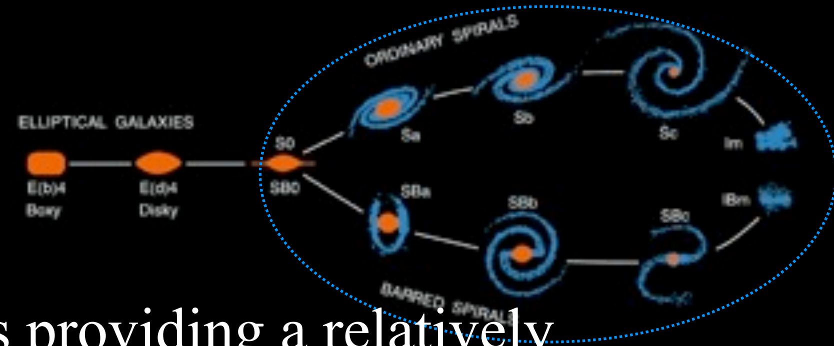
Galaxy Selection in the CDFs

- Classified ~3300 z = 0.1–1.4 CDF galaxies as early-types or late-types using rest-frame colors and *HST* morphologies.
- We generated samples of 2568 late-type and 691 early-type galaxies.



X-rays from Late-Type Galaxies

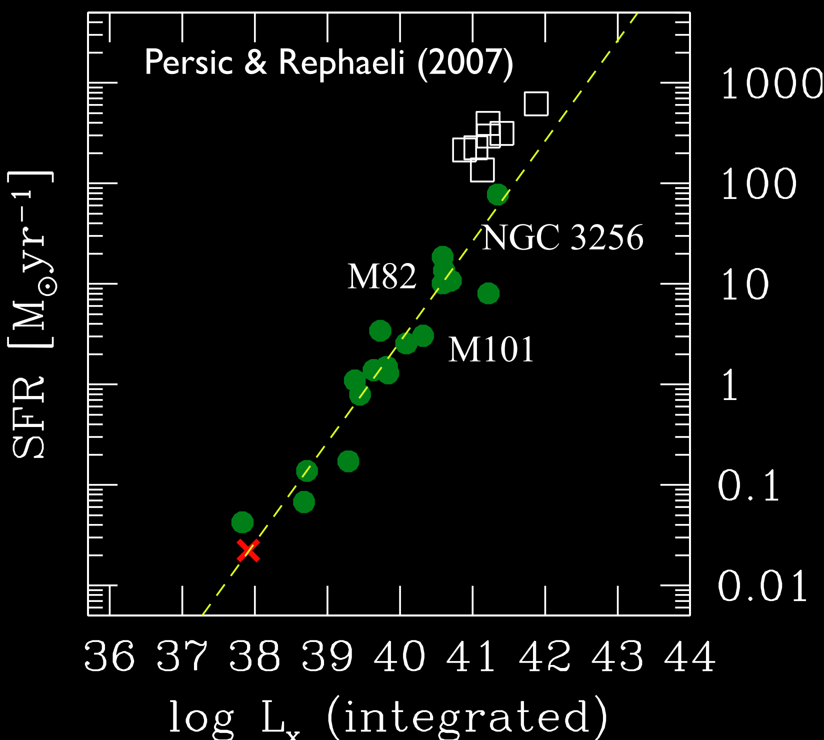


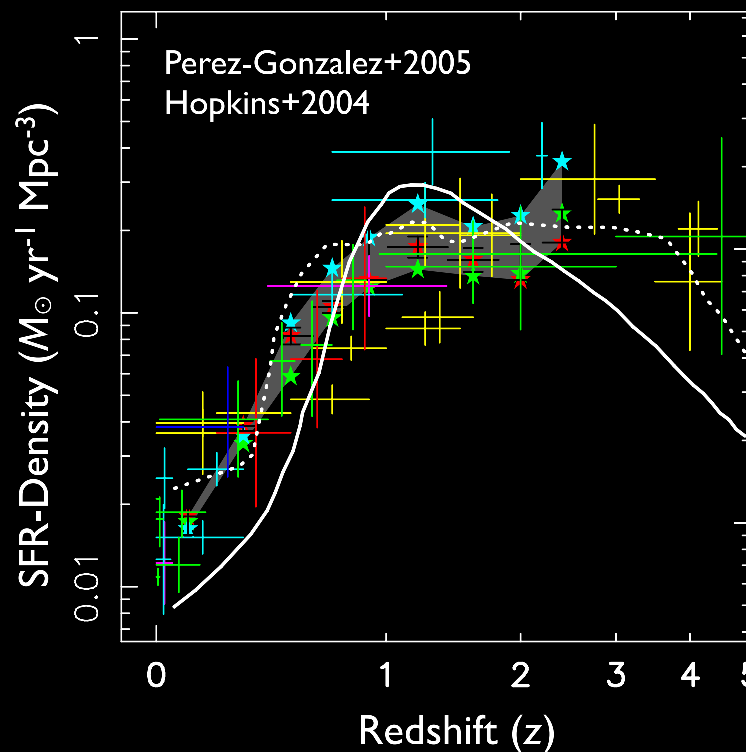
(Lehmer+2008; ApJ, 681, 1163)

• X-rays can penetrate thick star-forming regions providing a relatively unobscured view of star formation activity.

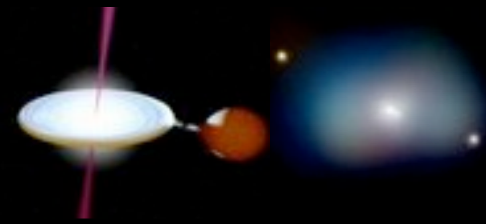
• X-ray power of LTGs is strongly correlated with SFR.

• UV and infrared observations indicate that the global SF activity evolves strongly out to at least $z = 1$.

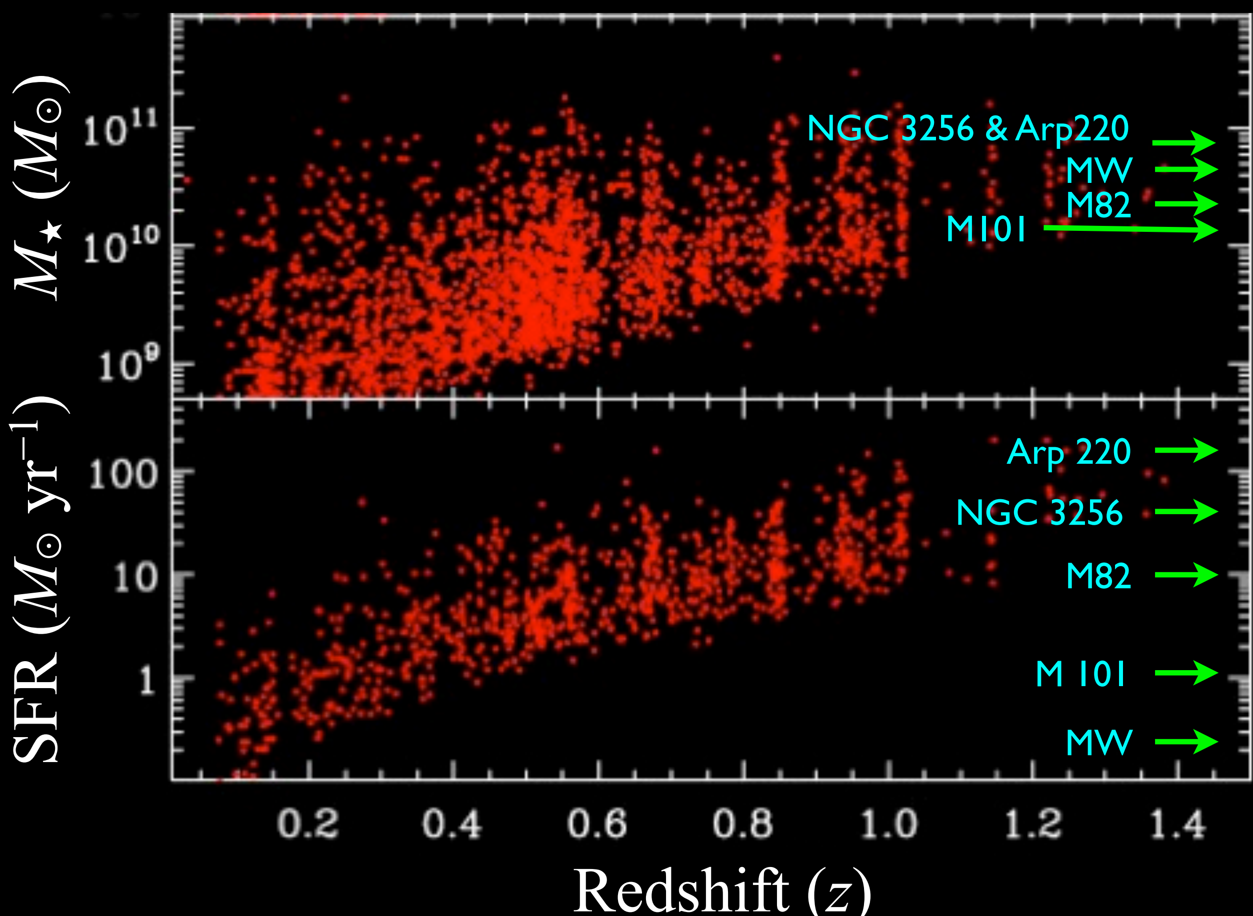


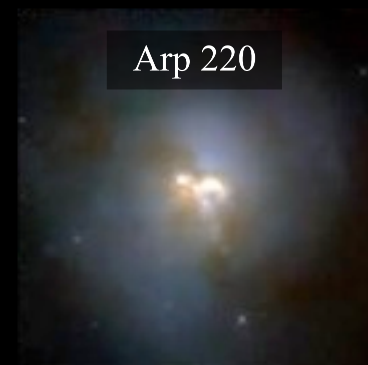


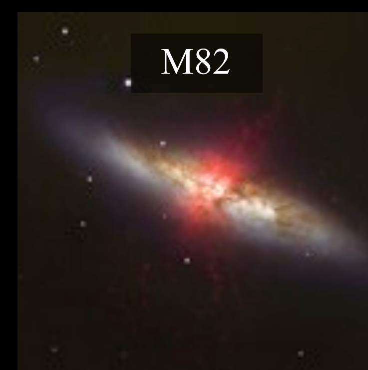
Physical Properties of LTG Sample



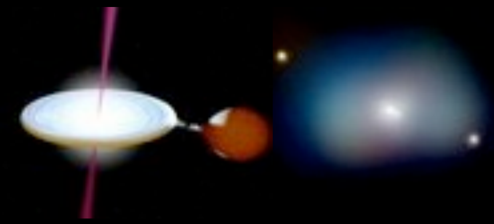
• For our 2568 LTGs, we estimated stellar masses using a combination of *K*-band luminosities and rest-frame optical colors and for 888 LTGs we estimated star-formation rates (SFRs) using UV+IR (MIPS 24 μm-detected) emission.



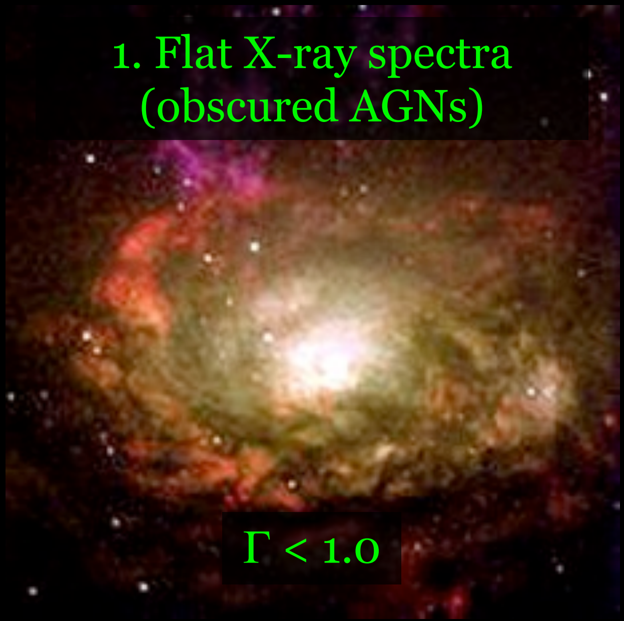


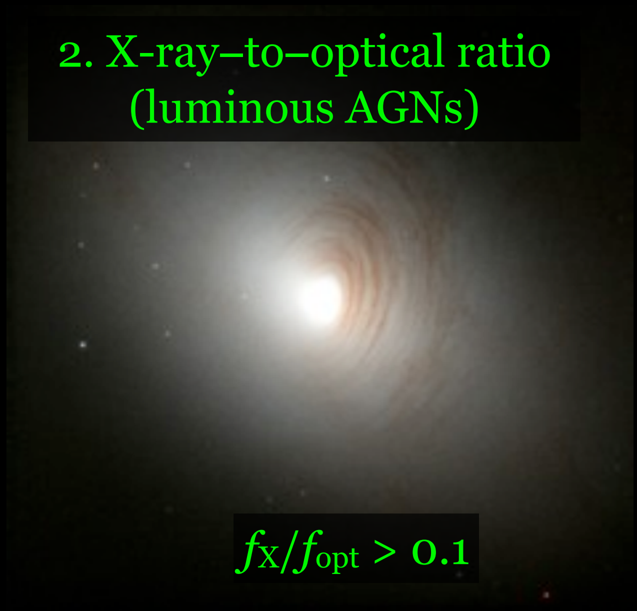


X-ray Properties of LTGs



- We detected 225 of the 2568 late-type galaxies in the CDFs.
- Candidate AGNs were identified using three primary criteria:





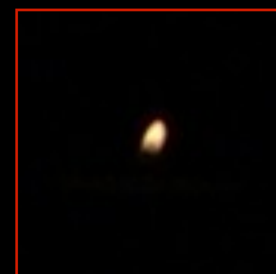
- 121 AGNs and 104 normal LTGs (out of 2568 LTGs).

Want to study the X-ray undetected LTGs: Use stacking technique.

Stacking by Candlelight

3/100 second exposure

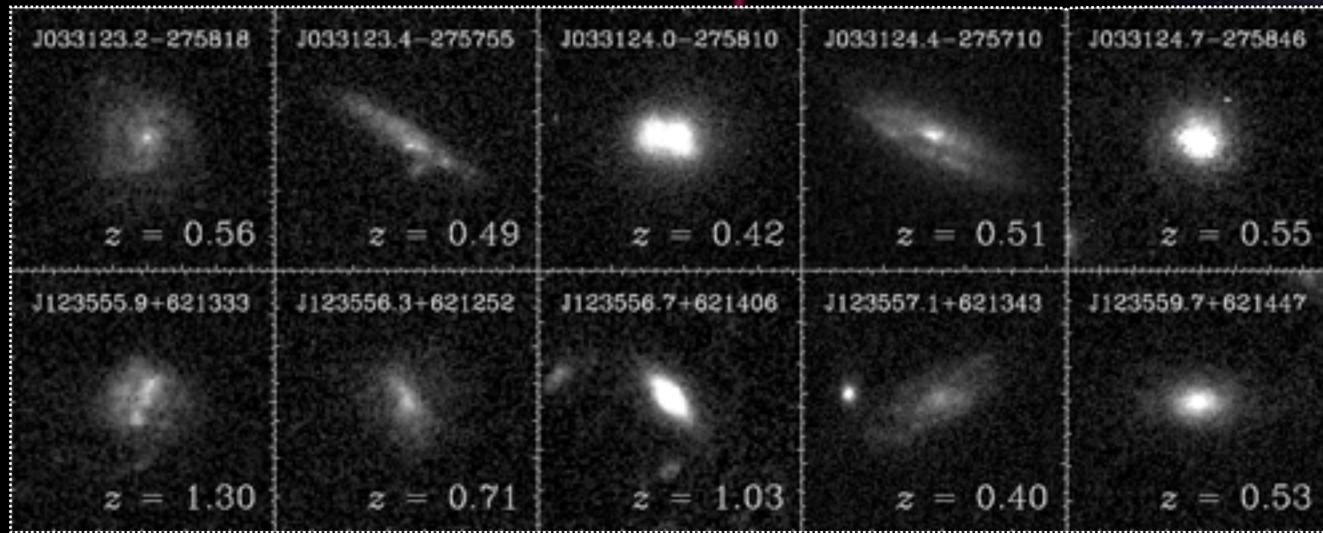
1/1000 second exposure

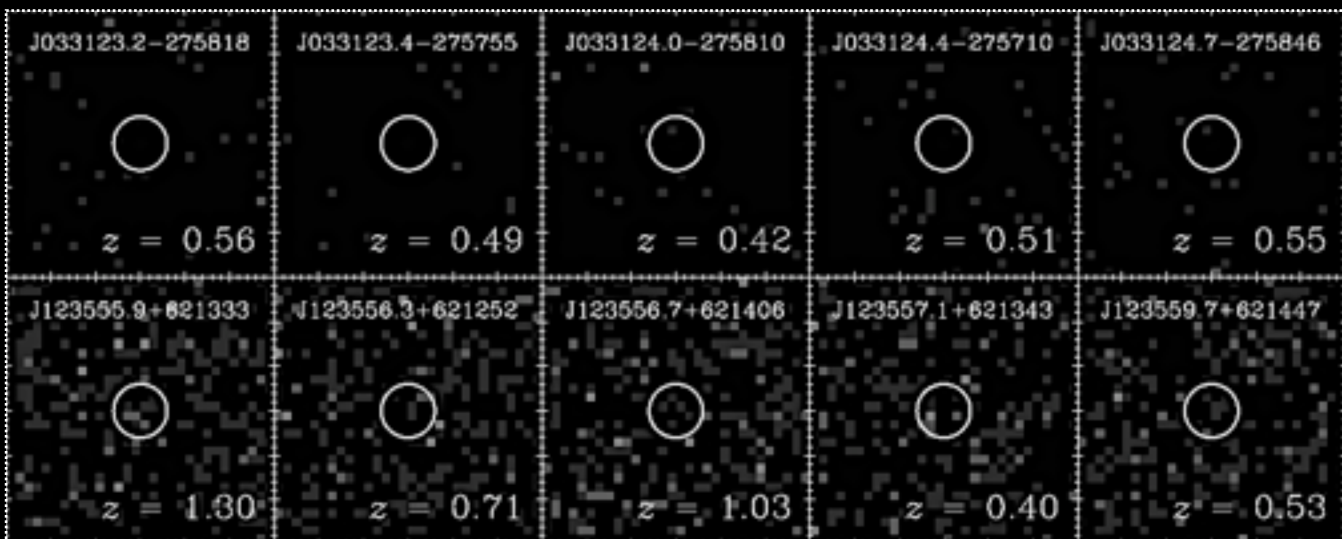


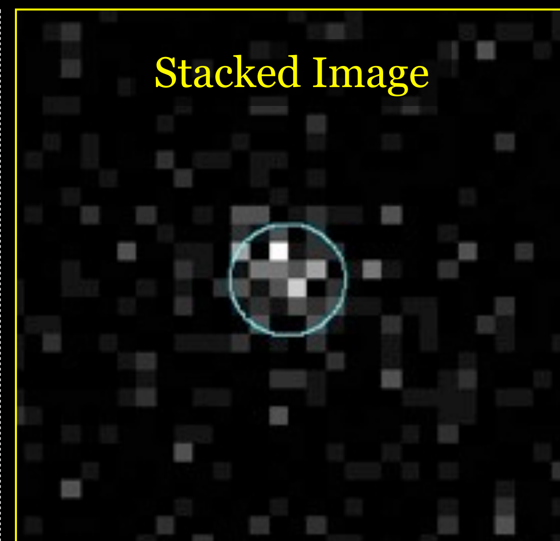
Stacked image of 30 candles with 1/1000 sec exposure

⇒ effective stacked exposure of (30 × 1/1000 sec) 3/100 sec.

X-ray Stacking Analyses







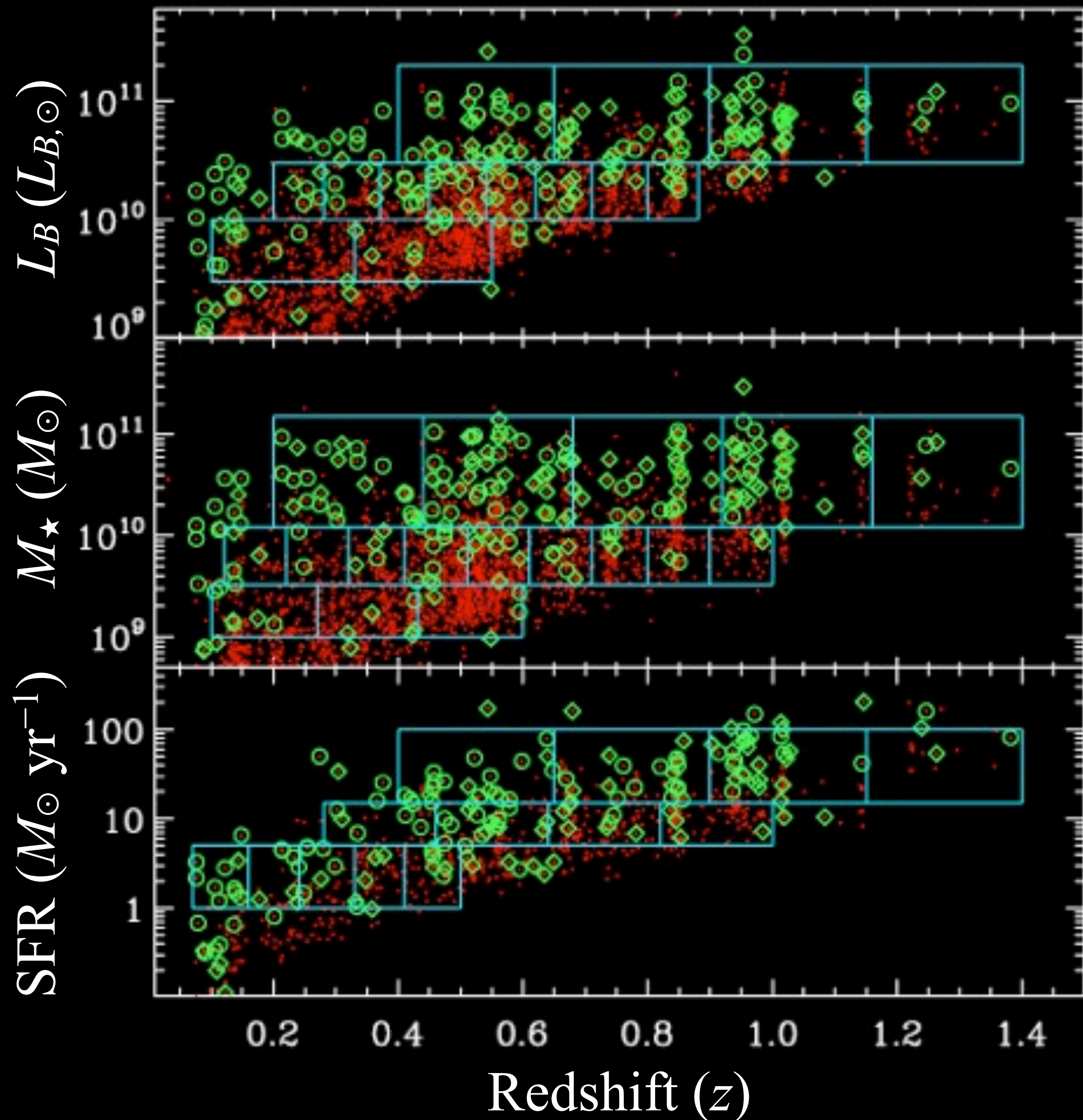
X-ray stacking has recently become popular in studying populations of distant normal galaxies from z = 0.1−6 (e.g., Brandt+2001; Hornschemeier+2002; Nandra+2002; Laird+2005, 2006; Lehmer+2005, 2007, 2008; Watson+2009)

Late-Type Galaxy Stacking

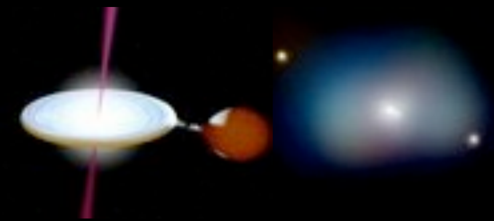
- We identified AGN-dominant systems using X-ray spectra, X-ray to optical/IR flux ratios, and IR properties.

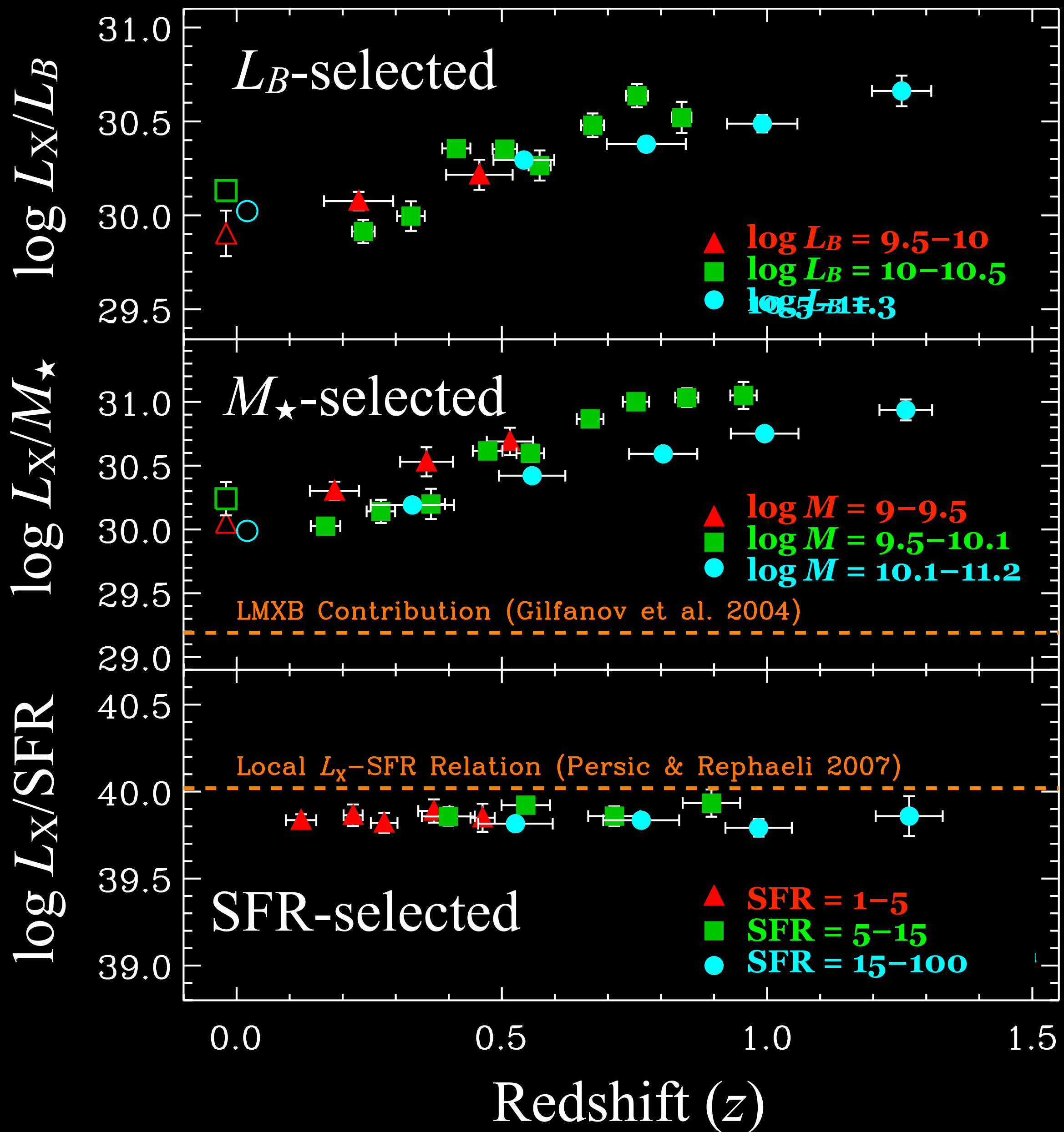
- The LTGs were divided into bins L_B, $M_\star$, and SFR in various redshift slices. These samples were then stacked after removing AGN-dominant systems.

- AGN Contamination expected at < 5–30% level.



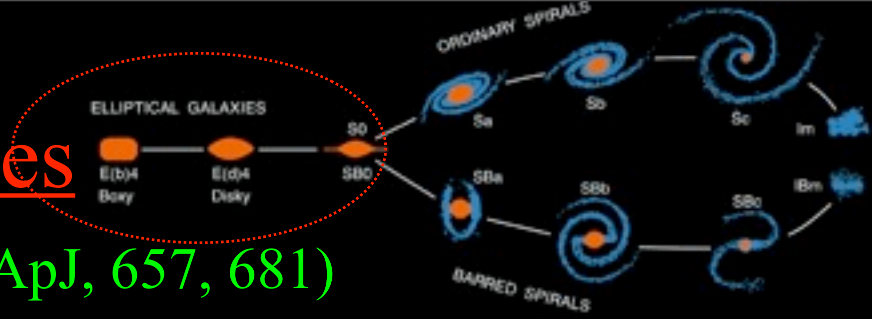
Stacking Results for LTG Samples



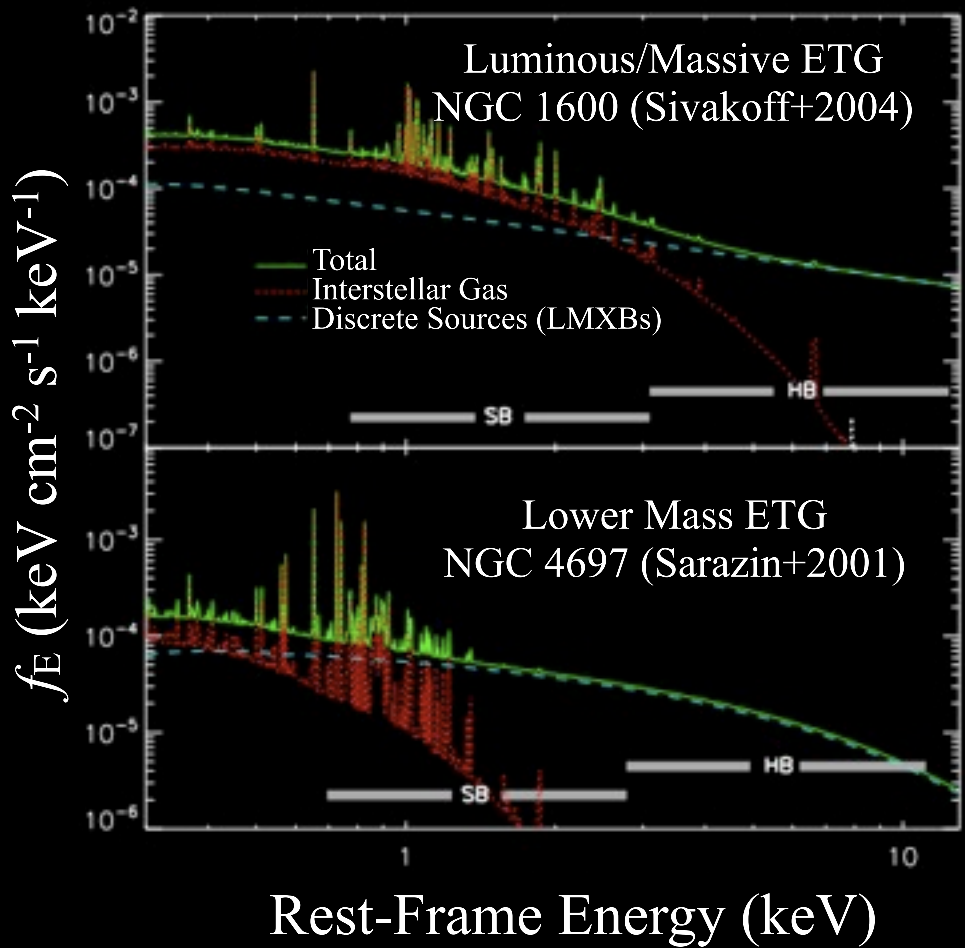


- Strong (factor of 4–10) redshift evolution in L_X for L_B and $M_\star$-selected samples from $z \approx 0$–1.4.
- Evidence for "cosmic downsizing" where low-mass systems are undergoing larger fractional growth than high-mass galaxies.
- L_X and SFR are well correlated out to at least $z \approx 1.4$.

X-rays from Early-Type Galaxies

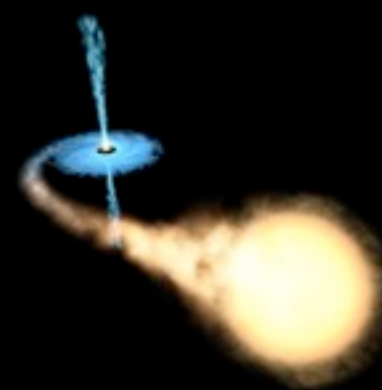


(Danielson+2010; ApJ, in-prep; Lehmer+2007; ApJ, 657, 681)



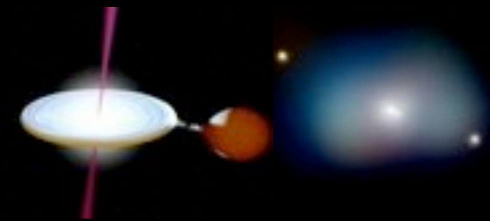
- Optically luminous and massive ETGs ($L_B > 3 \times 10^{10}\ L_{B,\odot}$); 0.5–2 keV emission dominated by hot (~1 keV) gas and 2–8 keV dominated by LMXBs

- Optically faint and lower mass ETGs ($L_B < 3 \times 10^{10}\ L_{B,\odot}$); dominated by LMXBs.



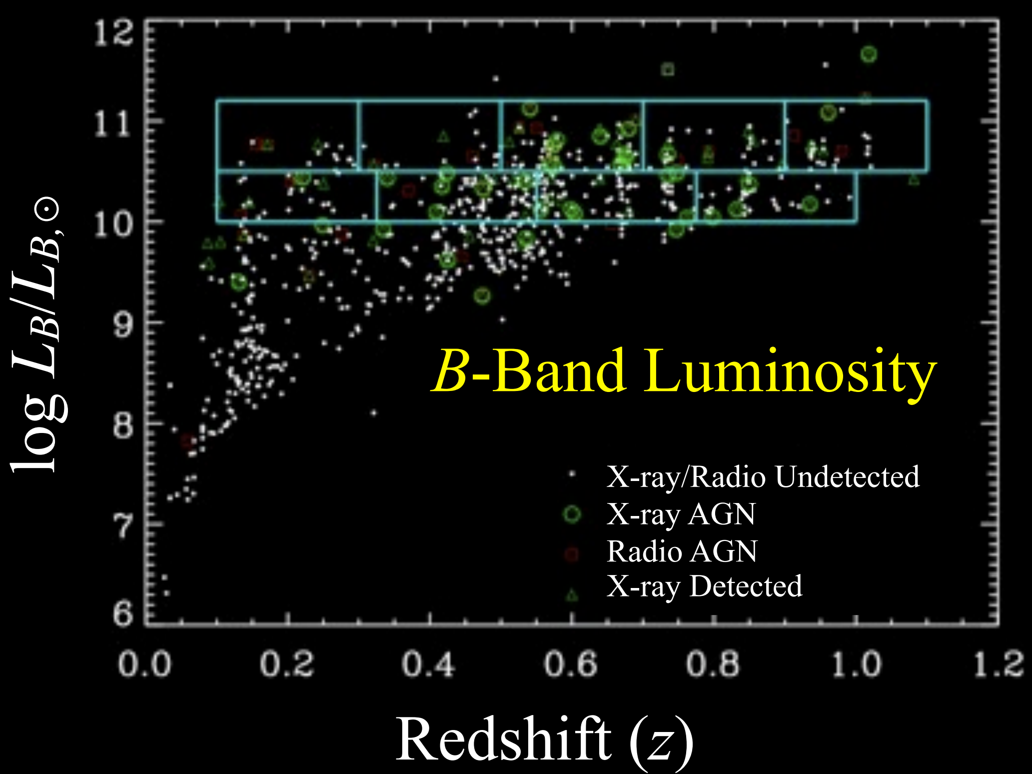
Constrain the evolution of hot gas emission in massive ETGs and LMXBs in lower-mass ETGs out to $z \approx 1$.

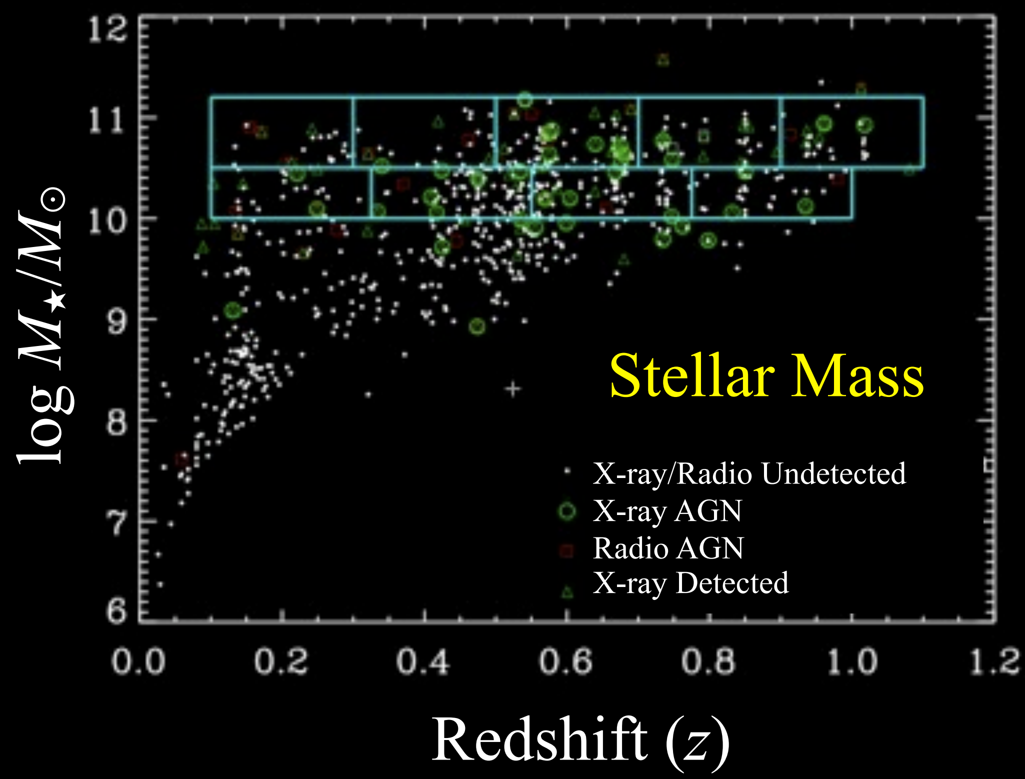
Early-Type Galaxy Stacking



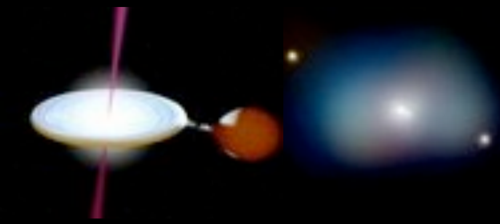
• We divided our sample of 691 ETGs into redshift bins and optically luminous/massive and optically faint/lower-mass galaxy populations.

• The non-AGN sub-populations were then stacked to measure how the X-ray emission from hot gas (luminous/massive ETGs) and LMXB+hot gas (faint/lower-mass ETGs) changes with cosmic time.



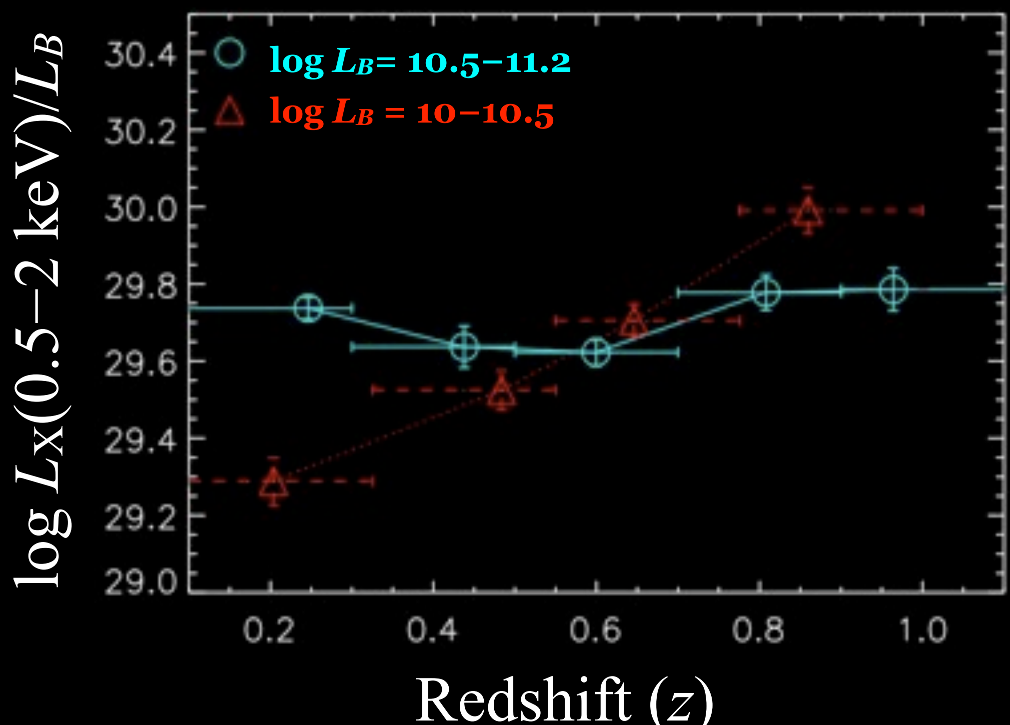


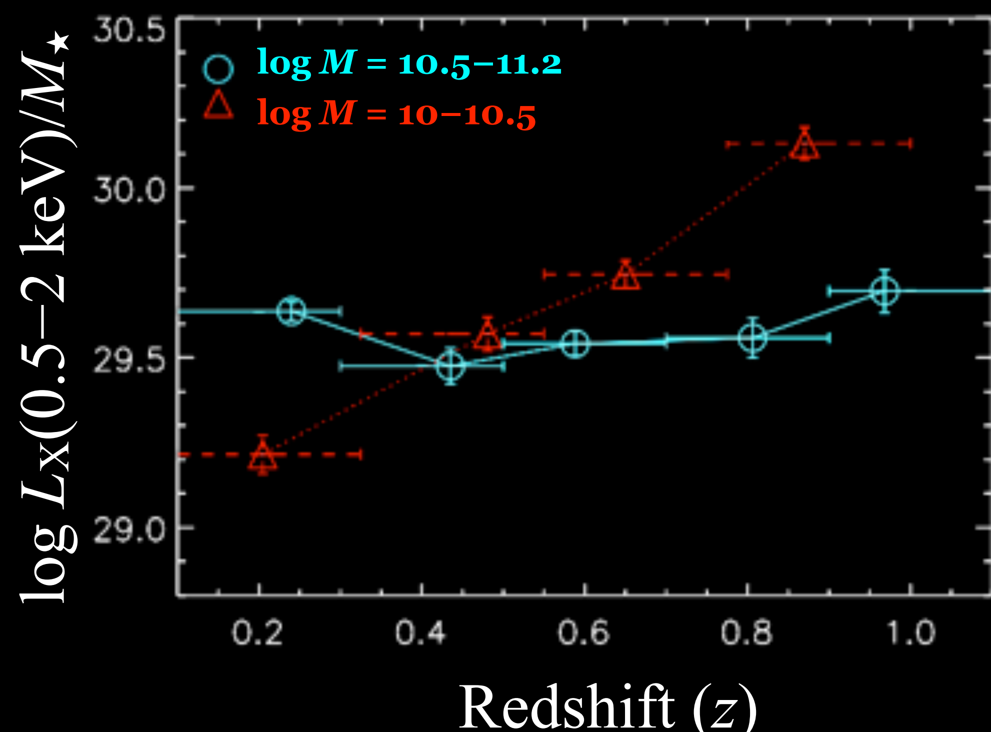
Early-Type Galaxy Stacking



• Little evolution in X-ray power from luminous/massive ETGs out to $z = 1$. If these sources are dominated by hot gas emission, then the hot gas emission has undergone little evolution over the last ~8 Gyr despite having a typical cooling time of 0.1−0.5 Gyr.

• By contrast X-ray emission from faint/lower-mass ETGs evolve strongly $(1+z)^{2-4}$; similar to the evolution of star-formation and AGN activity.

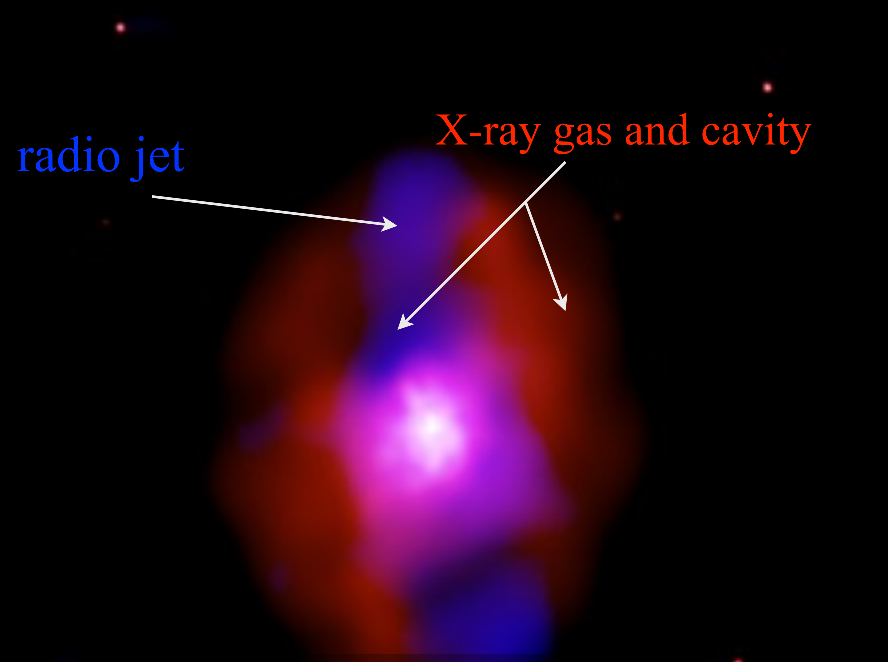




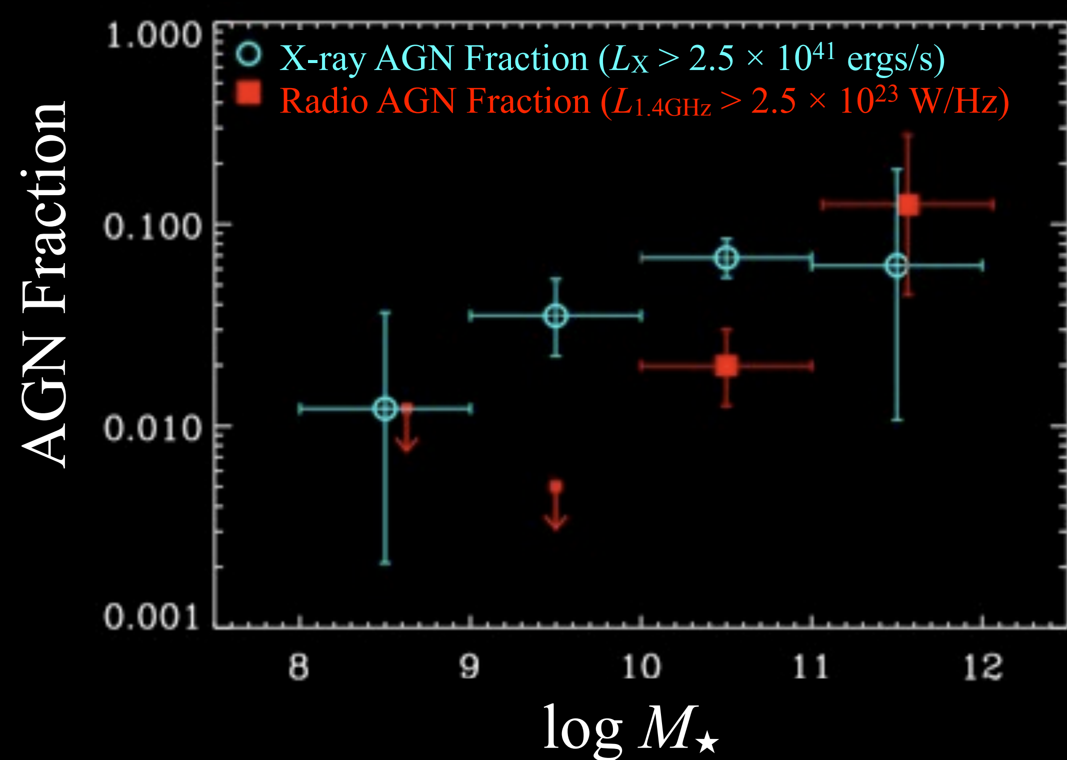
AGN Feedback in Massive ETGs?

• In local massive ETGs, feedback from radio AGNs is likely responsible for keeping the gas hot and inhibiting significant star formation and SMBH growth.

• We find the fraction of radio AGN fraction of ETGs increases monotonically with galaxy mass, while the X-ray AGN activity (tracing SMBH growth) appears to flatten at high galaxy mass, similar to that of local ETGs (e.g., Best+2005).



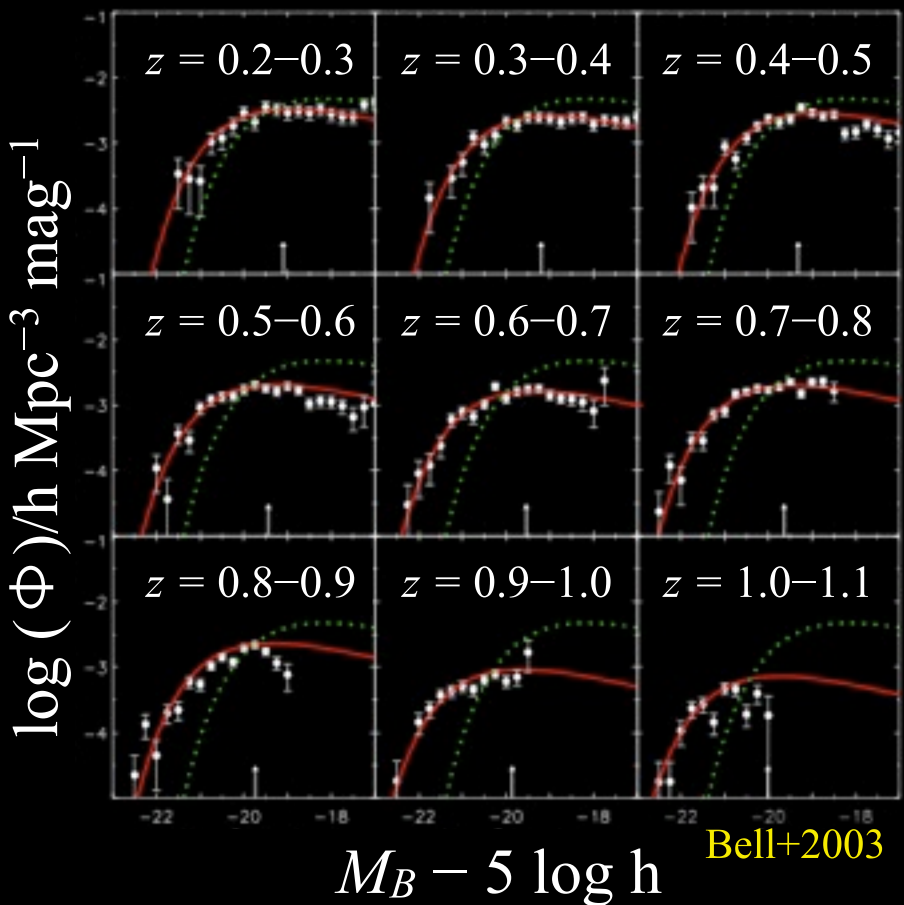
MS 0735.6+7421 (McNamara+2005)



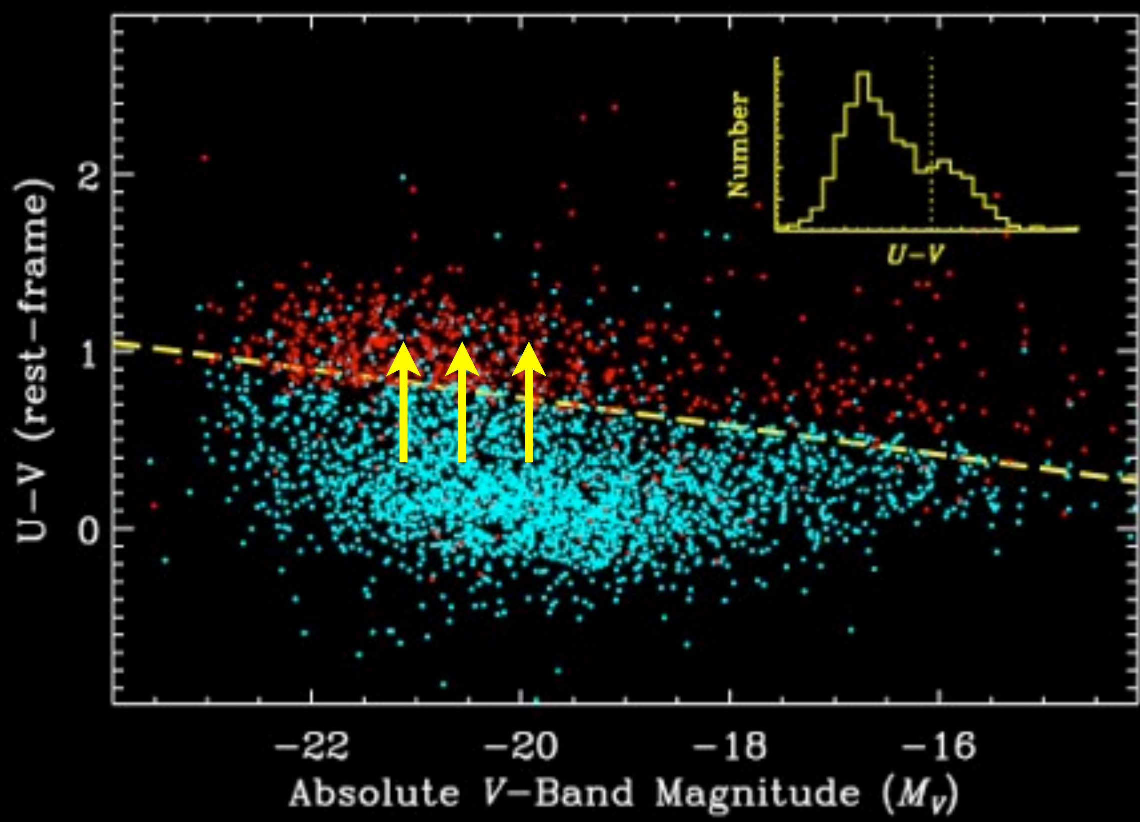
LMXB Evolution in Lower-Mass ETGs?

- We find evidence for strong evolution in the X-ray emission from lower-mass ETGs (LMXB dominant).

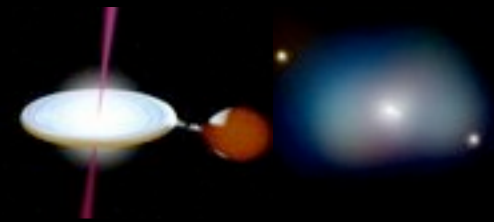
- If this is indeed due to LMXB evolution, we may be seeing the signatures of past star-formation activity.



Bell+2003



Summary of Key Results




Late-Type Galaxies (Lehmer+2008; ApJ, 681, 1163)

1.−X-ray power is well correlated with SFR (1−100 $M_\odot$ yr^{-1}) over the redshift range z = 0−1.4, suggesting X-ray emission provides a reasonable tracer of star-formation out to at least z = 1.4.

2.−We have found significant evolution $(1+z)^{3-5}$ in the X-ray emission from the LTG population in general and find evidence for "cosmic downsizing."

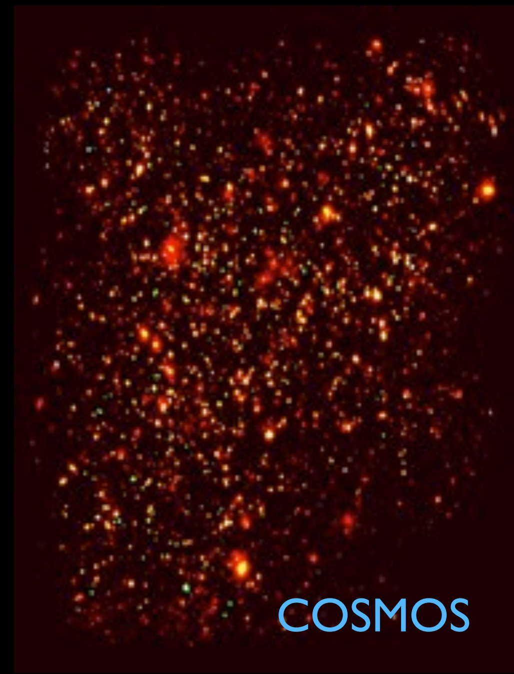
Early-Type Galaxies (Danielson+2010, in-prep; Lehmer+2007; ApJ, 657, 681)

1.−Mean L_X from massive/optically luminous ETGs does not evolve significantly from z = 0−1 possibly due to hot gas being kept hot by AGN feedback.

2.−We find significant X-ray evolution $(1+z)^{2-4}$ for lower-mass/faint ETGs possibly due to evolution of LMXB population.

Future Direction of this Work

• Incorporate constraints from additional deep *Chandra* surveys (e.g., COSMOS, AEGIS, etc.) to widen the accessible volumes, increase number statistics, and enable studies of X-ray properties of normal galaxies as a function of environment.



• Utilize local observations (both archival and new) to place new local constraints on mean X-ray luminosities of populations and understand contributions from various X-ray emitting populations.

• Conduct deeper *Chandra* surveys to increase number of individually detected normal galaxies available for study and improve constraints on X-ray luminosity function evolution for normal galaxies.

ChaMP