see Bayliss et al. 2019 in *Nature Astronomy* for the complete published result

The First X-ray Detection of Star Formation In a Highly Magnified Giant Arc

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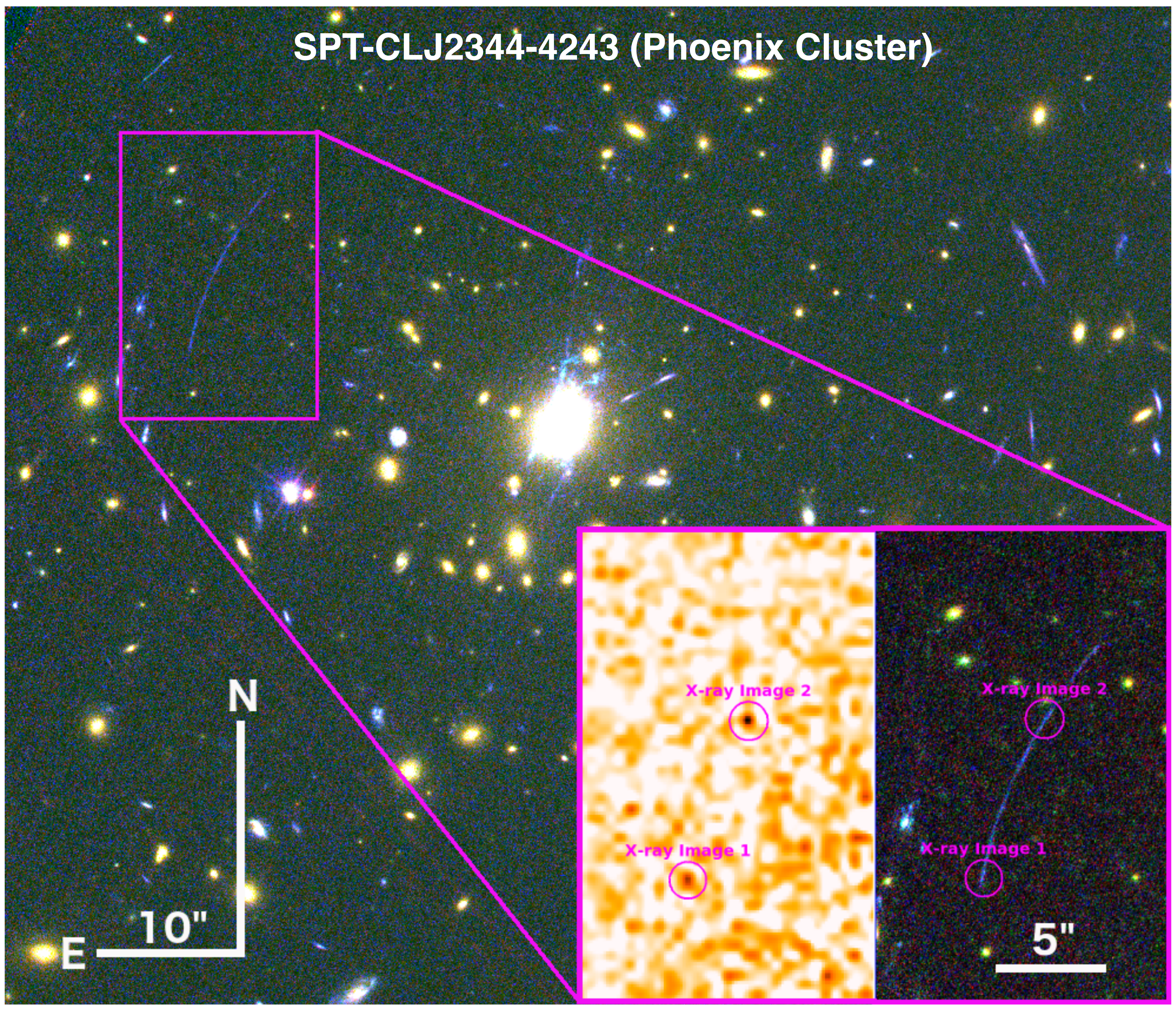


X-Ray Detection of a Strongly Lensed Galaxy at z=1.52

The massive galaxy cluster, SPT-CLJ2344-4243 (the "Phoenix Cluster"), acts as a gravitational lens, magnifying our view of a background star forming galaxy. Remarkably, a deep (~600 kilosecond) observation taken with the *Chandra X-ray Observatory* reveals the presence of X-ray emission from the giant arc (Figure 1). A lensing analysis using *Hubble* and *Spitzer* imaging, as well as follow-up spectroscopy, confirms that the giant arc is formed from a pair of highly magnified (~60x) merging images of a background star-forming galaxy (Figures 2-5). The combination of a deep *Chandra* exposure and high lensing amplification produces an X-ray view of the lensed galaxy at a depth equivalent to a ~1.3 year (40 megasecond) *Chandra* exposure (Figure 6). The lensed galaxy is a low–mass ($M/M_\odot < 10^8$), low–metallicity starburst with elevated X-ray emission (Figure 7), and is a likely analog to the first generation of galaxies. The high X-ray luminosity reflects a phase in the life-cycle of star-forming galaxies dur- ing which HMXBs are present in large numbers. High-mass stellar binaries are thought to be important, if short-lived, contributors to high energy emission by galaxies that are dominated by young stellar populations, a stage through which all galaxies pass at some point in their evolutionary history. The source detected here was discovered serendipitously in archival data, but it demonstrates the potential for lensing-assisted X-ray observations of the brightest strongly lensed sources in the sky. This result paves the way for future work that will exploit strong lensing magnification in combination with *Chandra,* and its successor missions, to deliver spatially resolved X-ray measurements of star formation and stellar populations in the distant universe. These lensing-assisted studies will isolate the X-ray emission from distinct star-forming regions—thereby linking HMXBs and stellar populations with the fundamental physical scales (i.e., sub-galactic) on which stars formed in the distant universe.

Figure 1: The X-ray emitting giant arc is shown relative to the center of the foreground lensing galaxy cluster in a false color image at optical wavelengths. The inset shows Chandra X-ray 0.5–7 keV (left) and Hubble optical (right) images of the giant arc at a scale 1.5 times larger. The optical colors here are given by Hubble imaging data in the F850LP (red), F775W (green), and F475W (blue) filters. Two magenta circles indicate the locations of the X-ray emission from the giant arc in both inset panels. The lensing geometry of the giant arc is a pair of merging images, where the lower and upper halves of the arc are each a single image with mirror symmetry.

The Origin of the X-ray Emission - The Evidence Favors High Mass X-ray Binaries

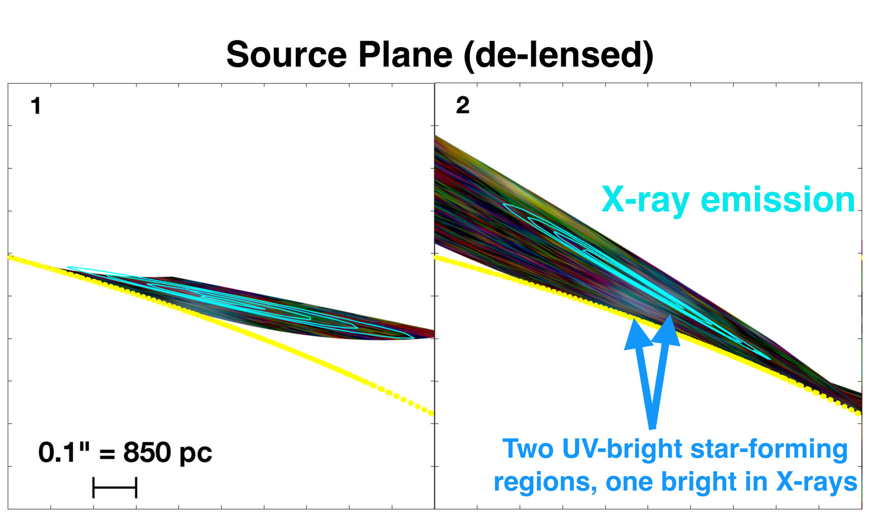
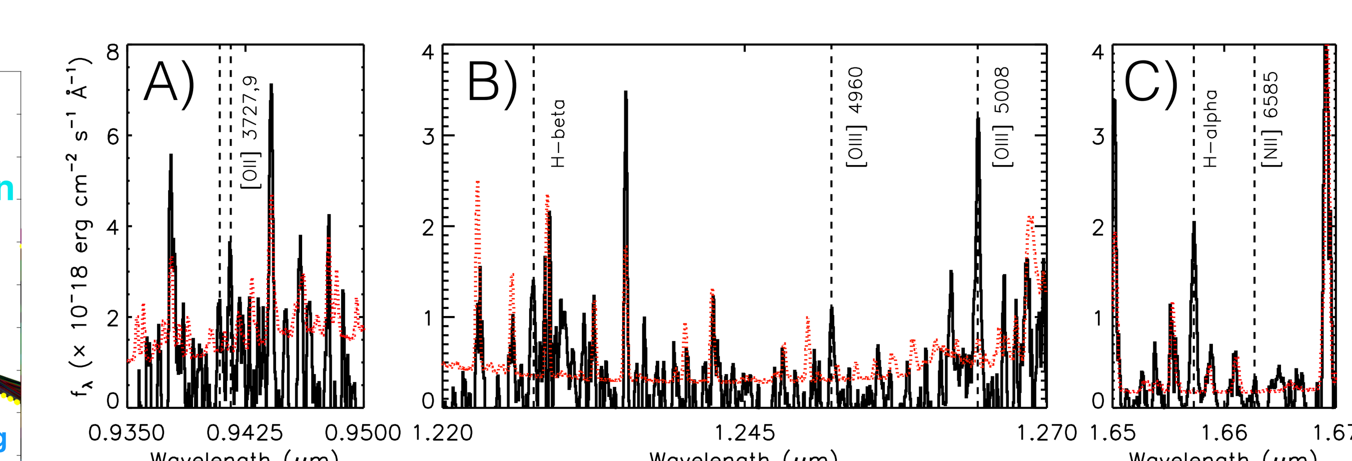


Figure 2: Source–plane reconstructions of images 1 & 2 of the lensed X-ray arc, with the X-ray detections indicated by the cyan contours. These contours indicate the shape and extent of the *Chandra* detections ray-traced back to the source plane. The X-ray emission is unresolved but isolated to one of two large (D ~ 400 pc) UV–bright star forming regions in the lensed galaxy with intrinsic (lensing corrected) luminosities of $L_{X,0.5,8} = 6.5 \pm 2.3 \times 10^{40}$ erg s^{-1}. and $L_{X,2,10} = 4.7 \pm 1.7 \times 10^{40}$ erg s^{-1}.



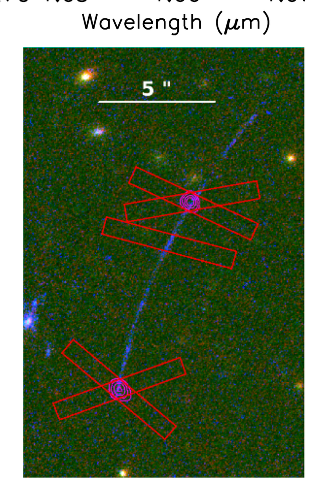


Figure 3 & 4: *(Right:)* Hubble image zoomed in on the X-ray emitting giant arc indicating where slits were placed to measure its rest-frame optical emission line spectrum. The location of the X-ray emission is indicated by the magenta contours. *(Top:)* Spectra from all slit positions returned the same rest–frame optical emission line pattern, shown here in several panels. Panel A shows the [O II] 3727,3729 doublet, panel B shows H–β and the [O III] 4960,5008 doublet, and panel C shows H–α and [N II] 6585.

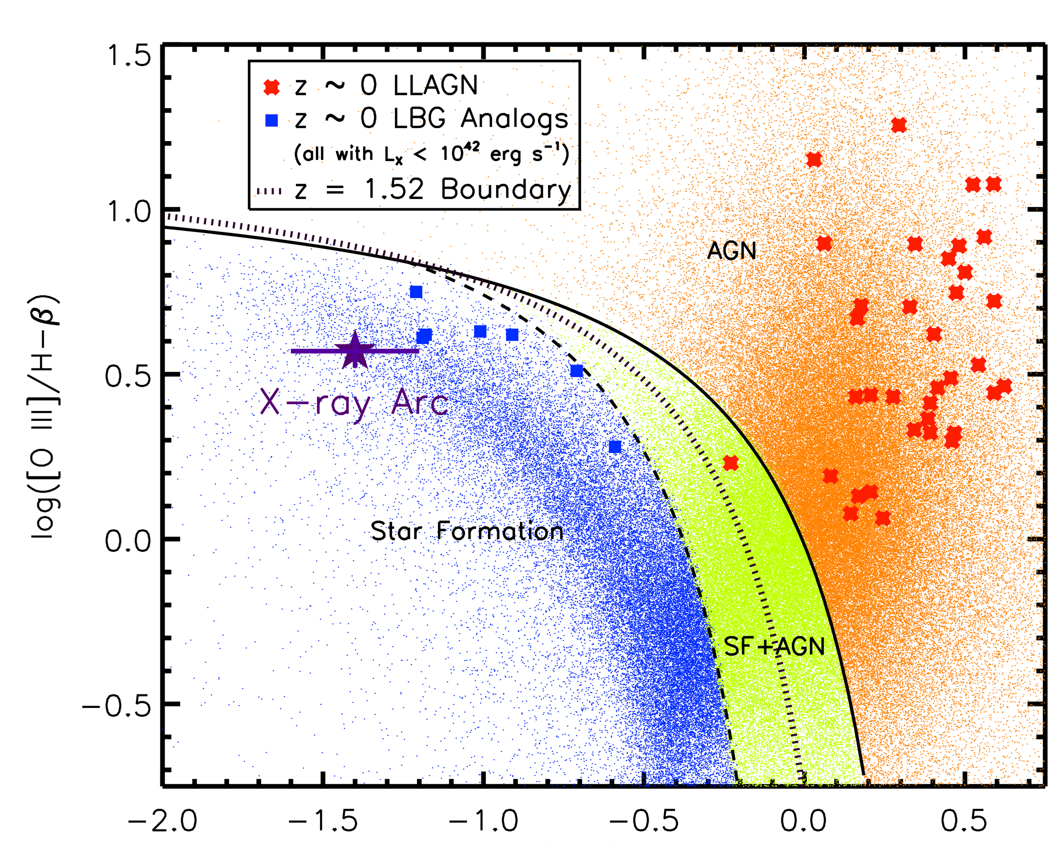
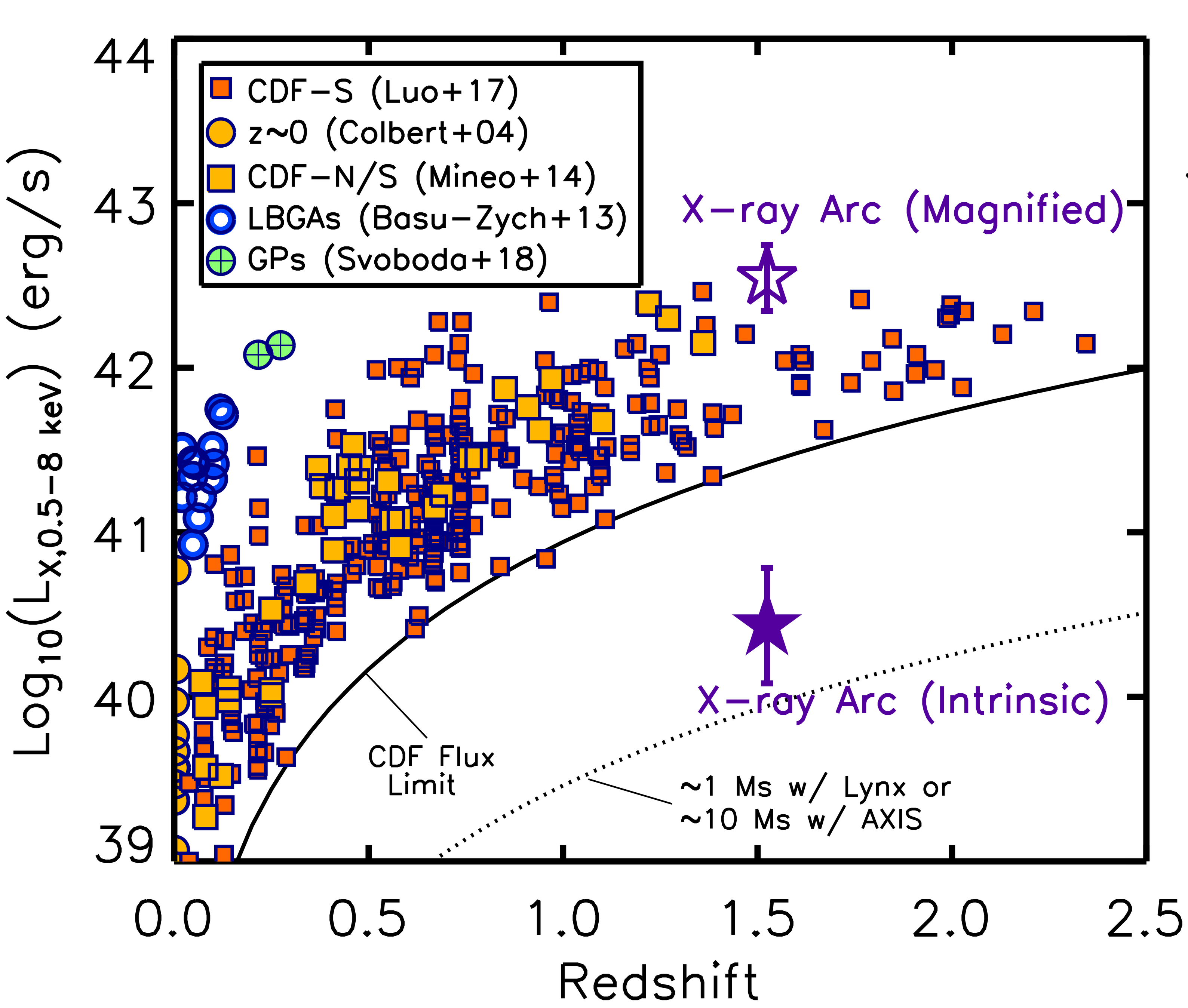


Figure 5: BPT (Baldwin et al. 1981) diagnostic diagram with the X-ray detected giant arc plotted as a purple star; solid and dashed lines separate galaxies ionized by star formation, AGN, and by both in the local universe, with the local SDSS (Thomas et al. 2013) samples plotted as the blue, red and green points, respectively. The dotted line shows the predicted evolution in the boundary isolating pure star formation at the redshift of the X-ray arc (Kewley et al. 2013). Two other comparison samples that have X-ray luminosities similar to the X-ray detected arc are plotted: local low X-ray luminosity AGN, (LLAGN) red x's and local Lyman break galaxy, (LBG) analogs as blue filled squares.

The Lensed X-ray Giant Arc Compared to Local and Deep Field Samples of X-ray Detected Star Forming Galaxies

Figure 6: The observed X-ray luminosity vs redshift for X-ray detected non-AGN galaxies, including local LBG Analogs (blue open circles; Basu-Zych 2013a, Brorby et al. 2016, Kaaret et al. 2017), "Green Pea" extreme emission line galaxies (GPs; green filled circles with crosshairs; Svoboda et al. 2018), and "normal" star-forming galaxies in the local universe and in the northern and southern *Chandra* Deep Fields (orange filled circles/squares and red filled squares; Colbert et al. 2004, Lehmer et al. 2016, Luo et al. 2017). The X-ray arc is plotted as an open star for the observed (apparent) luminosity and as a filled star for the true (intrinsic), lensing-corrected luminosity. The lensing amplification has allowed us to detect X-ray emission from a dwarf star-forming galaxy (z = 1.524) with an intrinsic, lensing–corrected luminosity that current *Chandra* deep fields only probe out to z~0.5. Approximate depths for hypothetical deep fields from two proposed future X-ray observatories, AXIS and *Lynx*, are also plotted as the dotted black line.



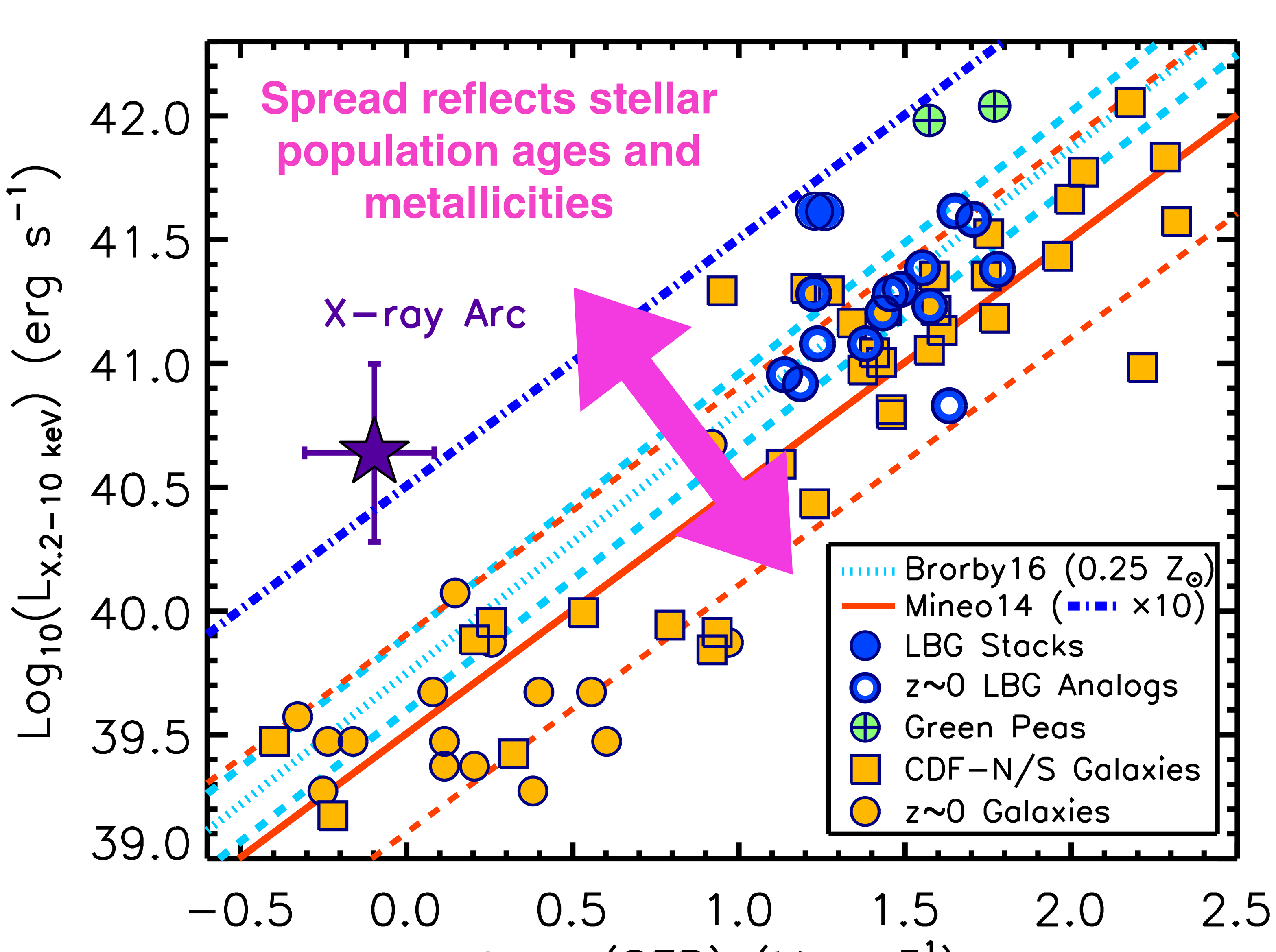


Figure 7: The L_X-to-SFR relationship for X-ray detected star forming galaxies, which follows a broad scaling (red lines; Mineo et al. 2014). We also show the best-fit relation at the measured metallicity of our X-ray emitting arc (cyan lines; Fragos et al. 2013, Brorby et al. 2016). Also shown are samples of galaxies with elevated L_X at fixed SFR, including Lyman break galaxy analogs (open blue circles; Basu-Zych et al. 2013a, Kaaret et al. 2017); stacked high-redshift Lyman break galaxies (blue filled circles; Basu-Zych et al. 2013b); and z~0.2-0.3 extreme emission line galaxies ("Green Peas"; green filled circles with crosshairs; Svoboda et al. 2019).

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