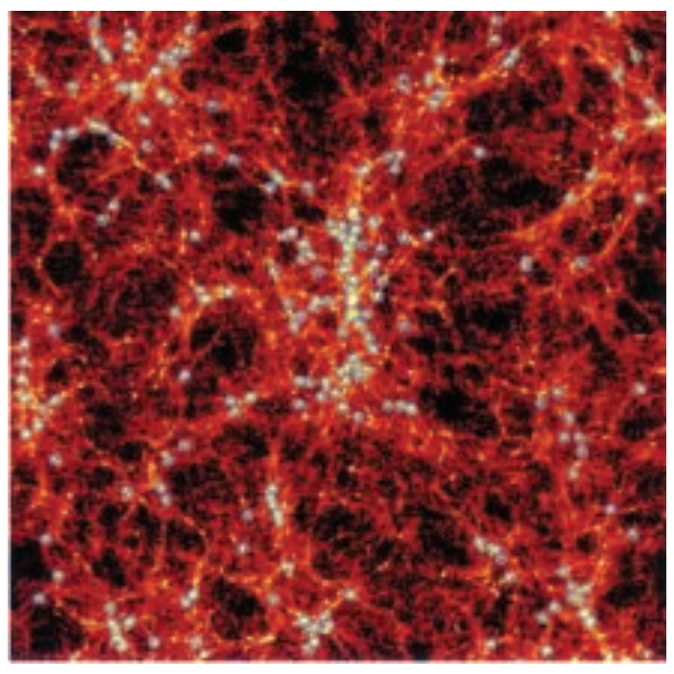
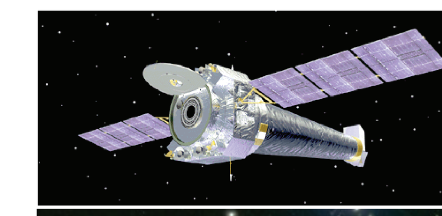


The *Chandra* Deep Protocluster Survey: Constraints on the AGN activity in the SSA22 Protocluster at $z = 3.09$



Bret Lehmer (Durham), Jim Geach (Durham), David Alexander (Durham), Franz Bauer (Columbia), Yuichi Matsuda (Japan), Ian Smail (Durham), Mark Swinbank (Durham), Toru Yamada (Japan), and members of the *Chandra* Deep Protocluster Survey Team

Abstract

We present results from a new ≈400 ks Chandra observation of the SSA22 protocluster at $z = 3.09$. We have studied the X-ray properties of 234 $z \sim 3$ Lyman Break Galaxies (LBGs) and 158 $z = 3.09$ Lyα Emitters (LAEs) in SSA22 to test how the high-density protocluster environment influences accretion activity of supermassive black holes (SMBHs). We detect individually six LBGs and five LAEs that are emitting powerfully in the X-ray band via an active galactic nucleus (AGN). These sources have rest-frame 8–32 keV luminosities in the range of $L_{8-32\ \mathrm{keV}} = 3$–$50 \times 10^{43}$ ergs s^{-1} and median observed-frame 2–8 keV to 0.5–2 keV band-ratios of 0.8 (median effective photon index of $\Gamma_{\rm eff} \sim 1.1$), suggesting significant absorption columns of $N_{\rm H} > 10^{22}$–10^{24} cm^{-2}. We find that the fraction of LBGs and LAEs in the protocluster harboring an AGN of $L_{8-32\ \mathrm{keV}} > 3 \times 10^{43}$ ergs s^{-1} is 11^{+16}_{-8}% and 6^{+8}_{-4}%, respectively. These AGN fractions are suggestively larger (by a factor of $3.9^{+6.8}_{-2.1}$) than similar LBGs and LAEs at $z \sim 3$ found in lower-density environments of SSA22 and the Chandra Deep Fields (CDFs). These results imply that in the high-density protocluster environment SMBHs may be more massive and/or growing more rapidly than similar galaxies found in low-density regions. Such a result is expected in a scenario where enhanced major-merger activity in the protocluster drives accelerated galaxy and SMBH growth at $z > 2$–3, which would eventually lead to SSA22 becoming an Abell-like cluster by $z = 0$.

Key Results

- ⇒ We detect a total of ten $z \sim 3$ AGNs in our sample of 382 galaxies.
- ⇒ The majority of the AGNs are located in high-density regions of the SSA22 protocluster at $z = 3.09$ (Fig. 1).
- ⇒ The AGNs have luminosities and inferred intrinsic column densities characteristic of obscured quasars (Fig. 2).
- ⇒ We have compared the luminosity-dependent AGN fractions of protocluster galaxies with galaxies in low-density regions and find that the $L_{8-32\ \mathrm{keV}} \geq 10^{43.5}$ ergs s^{-1} AGN activity is ≈4 times more prevalent in the protocluster than in the field (Fig. 3).
- ⇒ We hypothesize that an elevated AGN fraction in SSA22 may be due to a combination of (1) an increase in the AGN duty cycle of SMBHs in high redshift high-density environments and (2) an increase in the typical X-ray luminosity of protocluster SMBHs due to the presence of more massive SMBHs on average.

Introduction and Motivation

Theories of large-scale structure formation in a ΛCDM Universe predict that galaxy formation is accelerated in high-density regions (Kauffmann 1996; de Lucia et al. 2006). Observational studies have provided convincing support for this hypothesis, showing that there is a strong relationship between galaxy stellar age and local environment in the nearby universe; the most evolved and massive galaxies reside in the highest density regions of local clusters, while more typical galaxies that are undergoing significant star formation are more generally found in lower density environments (Kauffmann et al. 2004).

The progenitors of the highest density clusters in the local universe are also expected to be the highest density structures at $z > 2$–3 and should be undergoing vigorous star-formation during their assemblage (e.g., Governato et al. 1998). These protoclusters are presently identifiable as overdense redshift "spikes" in high-redshift galaxy surveys of blank fields (e.g., Adelberger et al. 1998; Steidel et al. 2003) and in fields surrounding powerful radio galaxies (e.g., Venemans et al. 2007). It is therefore plausibly expected that if the growth of galaxies and their central SMBHs are causally linked, then the highest density structures will also be the sites of significant SMBH accretion, identifiable as active galactic nuclei (AGNs).

The $z = 3.09$ SSA22 protocluster was originally identified by Steidel et al. (1998) as a significantly overdense region (a factor of 4–6 times more numerous than in the field) through spectroscopic follow-up observations of $z \sim 3$ candidate Lyman break galaxies (LBGs). Theoretical modelling indicates that the structure should collapse into a $z = 0$ structure resembling a local Abell cluster (e.g., Coma) making it an ideal site for studying how SMBH growth depends on environment in the $z \gtrsim 2$–3 universe.

In this project, we utilize new ≈400 ks Chandra observations of the $z = 3.09$ SSA22 protocluster region to identify luminous AGNs that are growing via accretion processes and place constraints on how the AGN properties (e.g., luminosity and X-ray spectra) and frequency in the protocluster compares with AGNs identified in lower density regions of the Chandra Deep Field-North (CDF-N; Alexander et al. 2003) and Extended Chandra Deep Field-South (E-CDF-S; Alexander et al. 2003; Lehmer et al. 2005).

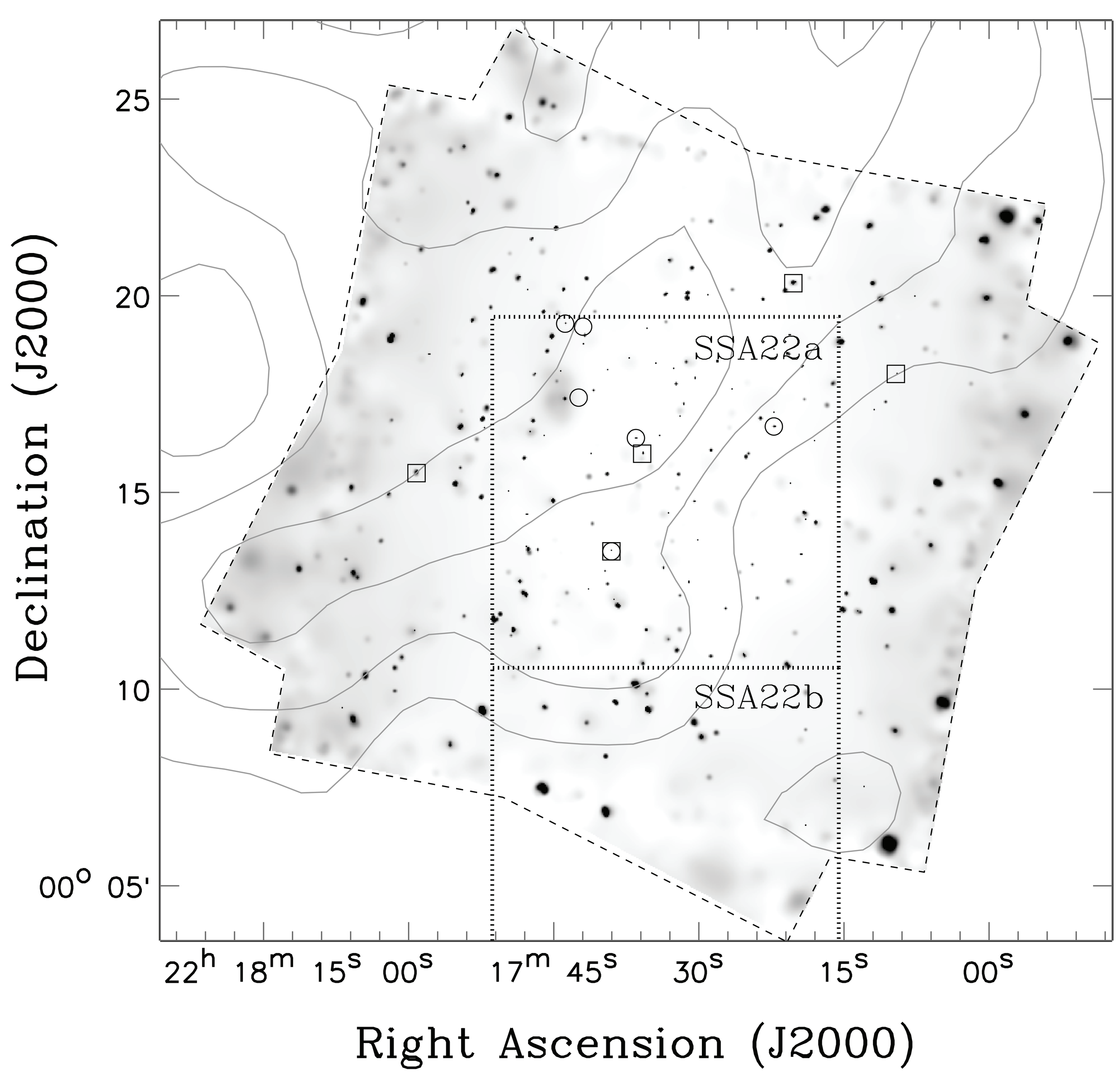


Figure 1 — Adaptively-smoothed 0.5–8 keV Chandra image (with boundaries shown as a dashed polygon) of the SSA22 field. X-ray detected LBGs and LAEs have been highlighted with open circles and squares, respectively. LAE source-density contours are shown in gray (computed using the Hayashino et al. 2004 LAE catalog); most of the X-ray sources lie in regions of high LAE density. The dotted regions show the extent of the Steidel et al. (2003) "SSA22a" and "SSA22b" LBG surveys. We note that the Hayashino et al. (2004) sample of LAEs covers a region larger than that shown here.

Analysis and Results

We created an *SSA22 sample* of 234 $z \sim 3$ LBGs from Steidel et al. (2003) and 158 $z = 3.09$ LAEs from Hayashino et al. (2004) that lie within the Chandra-observed region of the SSA22 protocluster. In total our sample consisted of 382 unique sources. When cross-correlating our sample with Chandra catalogs, we found ten galaxies detected in the X-ray band down to a median luminosity limit of $L_{8-32\ \mathrm{keV}} = 3 \times 10^{43}$ ergs s^{-1}. These sources lie in the highest density regions of the protocluster (see Fig. 1) and have X-ray luminosities and effective photon indices indicative of heavily obscured quasars (Fig. 2).

To compare the X-ray properties of our SSA22 sample with those found in lower density regions, we created a *field sample* of $z \sim 3$ galaxies in the Chandra Deep Fields. This sample includes 146 LBGs in the CDF-N from Steidel et al. (2003) and 257 LAEs in the E-CDF-S from Gronwall et al. (2007). We found 11 X-ray detected LBGs and LAEs down to a median luminosity limit of $L_{8-32\ \mathrm{keV}} = 10^{43}$ ergs s^{-1}.

To assess whether the AGN activity in the SSA22 protocluster environment was quantitatively different from that observed in the field, we compared the 8–32 keV luminosity dependent AGN fraction, f_C, for LBGs and LAEs in the protocluster with that of the field. Using exclusively the 168 LBGs in our SSA22 and CDF-N samples that had spectroscopic redshifts from Steidel et al. (2003), we computed f_C for both "spike" LBGs (27 sources) that were within the physical boundaries of the SSA22 protocluster ($z =$ 3.074–3.108) and "non-spike" LBGs (141 sources) in the SSA22 field (i.e., outside the protocluster redshift spike) and the CDF-N. For the LAEs, we computed f_C for the SSA22 protocluster and E-CDF-S field samples. In Figure 3, we present f_C versus $L_{8-32\ \mathrm{keV}}$ for the above LBG and LAE samples. We find that for both the LBGs and LAEs there is suggestive evidence for an enhancement of the AGN fraction for log $L_{8-32\ \mathrm{keV}}$ = 43.5-44 in the protocluster environment versus the field. At $L_{8-32\ \mathrm{keV}} = 3 \times 10^{43}$ ergs s^{-1}, this enhancement is measured to be $3.3^{+8.2}_{-2.5}$ and $3.6^{+8.5}_{-2.8}$ for LBGs and LAEs, respectively. Of the 27 LBGs in the SSA22 redshift spike, only 9 (≈33%) are identified as also being LAEs. We can therefore consider our measurements of the AGN fraction enhancement for LBGs and LAEs to be two roughly independent results; these combined give a mean enhancement of $3.9^{+6.8}_{-2.1}$ (enhanced at the ≈90% confidence level) for the AGN activity in the SSA22 protocluster environment.

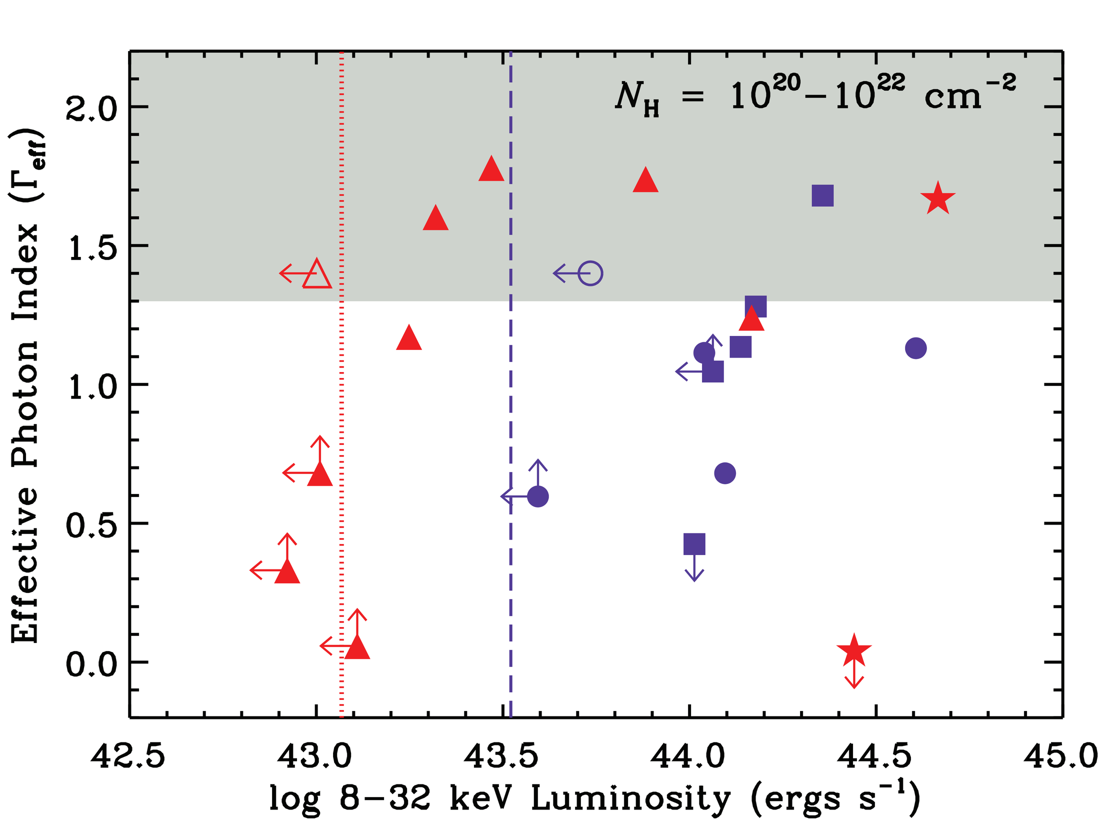


Figure 2 — Effective photon index ($\Gamma_{\rm eff}$) versus 8–32 keV luminosity for X-ray-detected SSA22 (*blue symbols*) and CDF field comparison (*red symbols*) samples. The shaded region indicates the range of $\Gamma_{\rm eff}$ values expected for a source at $z = 3$ with intrinsic $\Gamma = 1.8$ and $N_{\rm H} = 10^{20}$–10^{22} cm^{-2}. SSA22 LBGs and LAEs have been indicated using circles and squares, respectively. CDF-N field LBGs and E-CDF-S LAEs are shown as triangles and five-pointed stars, respectively. Open symbols indicate sources that were detected only in the 0.5–8 keV bandpass and therefore have an adopted photon-index of $\Gamma_{\rm eff} = 1.4$. The vertical dashed and dotted lines indicate the median sensitivity limit for all 382 and 403 $z \approx 3$ sources in the SSA22 and CDF samples, respectively.

Table 1: X-ray Properties of SSA22 $z \sim 3$ sources

Survey Field (1)	Source Name (J2000.0) (2)	z (3)	Band Ratio (2–8 keV)/(0.5–2 keV) (4)	$\Gamma_{\rm eff}$ (5)	$L_{2-8\ \mathrm{keV}}$ (log ergs s^{-1}) (6)	$L_{8-32\ \mathrm{keV}}$ (log ergs s^{-1}) (7)	Notes (8)
X-ray–Detected Lyman Break Galaxies ($z \approx$ 2–3.5)							
SSA22	J221722.25+001640.6	3.353	$0.78^{+0.17}_{-0.15}$	$1.13^{+0.18}_{-0.17}$	44.1	44.6	QSO
	J221736.51+001622.9	3.084	$0.80^{+0.30}_{-0.24}$	$1.11^{+0.30}_{-0.29}$	43.5	44.0	QSO
	J221739.04+001330.1	3.091	> 1.83	< 0.42	< 43.1	44.0	GAL
	J221741.97+001912.8	≈ 3[a]	≈ 1	1.4[b]	< 43.1	< 43.7	
	J221742.43+001724.6	≈ 3[a]	< 1.48	> 0.60	42.8	< 43.6	
	J221743.82+001917.4	2.857	$1.33^{+0.57}_{-0.44}$	$0.68^{+0.31}_{-0.30}$	43.3	44.1	GAL
X-ray–Detected Lyα Emitters ($z = 3.1$)							
SSA22	J221709.64+001800.7	3.106	< 0.86	> 1.05	43.5	< 44.1	GAL
	J221720.24+002019.1	3.105	$0.42^{+0.10}_{-0.09}$	$1.68^{+0.21}_{-0.20}$	44.2	44.4	GAL
	J221735.86+001559.1	3.094	$0.78^{+0.26}_{-0.21}$	$1.13^{+0.26}_{-0.25}$	43.6	44.1	GAL
	J221739.04+001330.1	3.091	> 1.83	< 0.42	< 43.1	44.0	GAL
	J221759.19+001529.4	3.096	$0.66^{+0.23}_{-0.19}$	$1.28^{+0.30}_{-0.28}$	43.8	44.2	GAL

[a] Redshift of $z = 3$ was assumed for all LBG candidates that did not have a spectroscopic counterpart.
[b] Sources that were detected in only the 0.5–8 keV bandpass were assumed to have an effective photon-index of $\Gamma_{\rm eff} = 1.4$.

Discussion

We have found initial evidence for an enhancement in the AGN activity for the $z = 3.09$ SSA22 protocluster, in which the fraction of LBGs and LAEs harboring an AGN with $L_{8-32\ \mathrm{keV}} > 10^{43.5}$ ergs s^{-1} is a factor of ≈4 times larger in the high-density protocluster environment versus that of the field. We hypothesize that the elevation in the SSA22 protocluster AGN fraction could be due to a combination of (1) an increase in the AGN duty cycle of SMBHs in high-density environments and (2) an increase in the typical X-ray luminosity of protocluster SMBHs due to the presence of more massive SMBHs on average.

Theoretical studies of the assembly and merger history of galaxies (e.g., Volonteri et al. 2003) suggest that SMBHs build up mass more quickly in high-density regions due to major-merger activity. Steidel et al. (1998) estimate that the SSA22 prot ocluster LBGs reside in relatively massive dark matter halos of $\sim 10^{12}\ M_\odot$ per galaxy. It is expected that galaxies in such massive halos will undergo a peak in major-merger frequency at $z \approx 2$–4. Therefore, in the SSA22 protocluster these merger events may potentially be responsible for funneling cold gas into the central SMBH and fueling AGN activity at a larger duty cycle than in a field environment.

As a consequence of the above scenario, it is also expected that galaxy and SMBH growth will be accelerated in the protocluster environment leading to more massive galaxies and SMBHs than in lower density environments. Detailed multiwavelength studies of the $z = 2.3$ protocluster HS 1700+643, a cluster similar in overall size and mass to SSA22, have found the protocluster galaxies to be a factor of ≈2 times older and more massive (in stellar content) than galaxies outside the protocluster (e.g., Steidel et al. 2005). It is therefore also likely that SSA22 protocluster galaxies also have older and more massive stellar assemblages and more massive SMBHs than those found in field galaxies, as predicted by models. This point of view also suggests that typically the growth of SMBHs in the SSA22 protocluster occurs in relatively massive SMBHs, which generally produce more luminous AGNs. Such an effect would translate to a larger observable AGN fraction or a "shift" along the *x*-axis in the f_C versus log $L_{8-32\ \mathrm{keV}}$ curves in Figure 3.

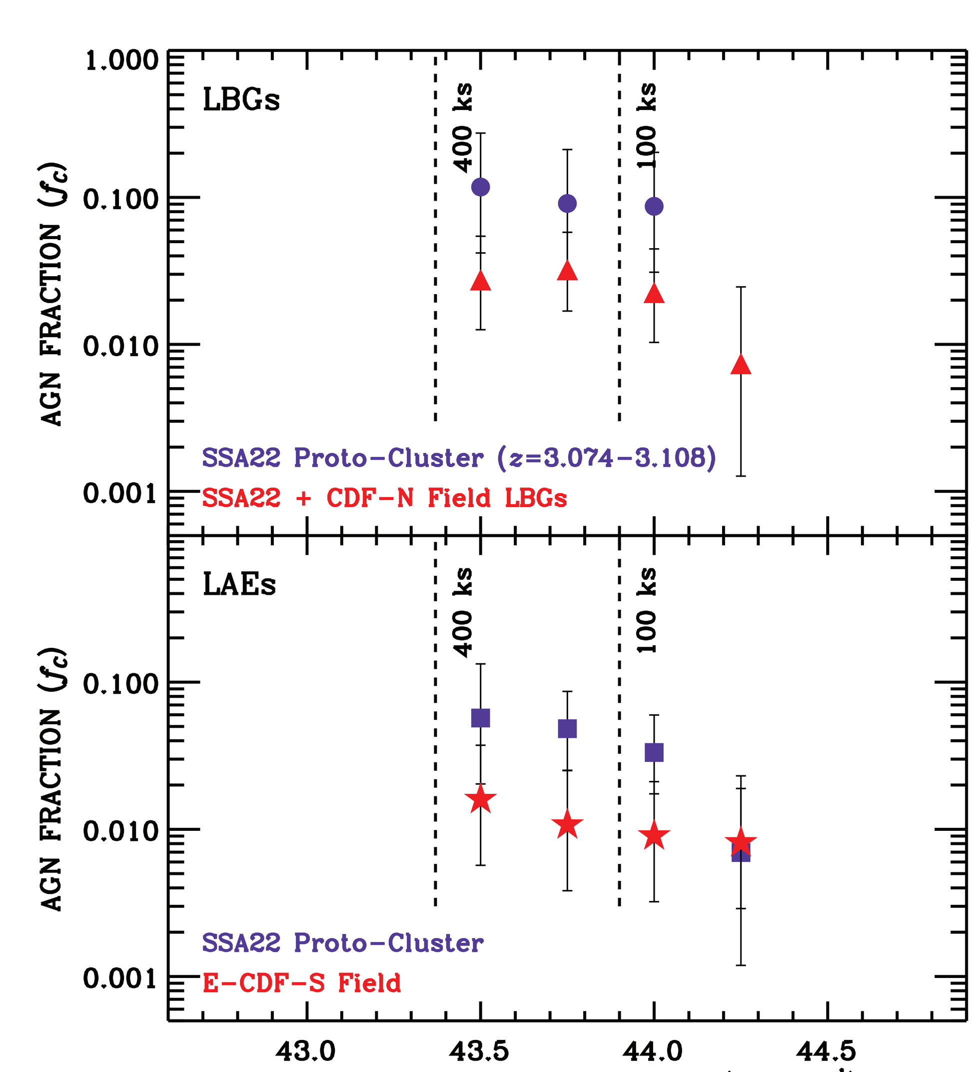


Figure 3 — (*top panel*) Fraction of LBGs harbouring an AGN with logarithm of the 8–32 keV luminosity larger than that indicated on the *x*-axis (i.e., the AGN fraction, f_C). The SSA22 protocluster (z = 3.074–3.108) and CDF-N AGN fractions have been shown as blue circles and red triangles, respectively. (*lower panel*) LAE AGN fractions for the SSA22 proto-cluster (*blue squares*) and E-CDF-S field (*red five-pointed stars*) surveys.

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