(No) dimming of X-ray clusters beyond $z \sim 1$ at fixed mass: crude redshifts and masses from raw X-ray and SZ data

E. Churazov,$^{1,2}$* A. Vikhlinin$^{2,3}$ and R. Sunyaev$^{1,2}$

$^1$Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85741 Garching, Germany
$^2$Space Research Institute (IKI), Profsoyuznaya 84/32, Moscow 117997, Russia
$^3$Harvard–Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

Accepted 2015 April 1. Received 2015 March 31; in original form 2015 February 10

ABSTRACT
Scaling relations in the Λ cold dark matter cosmology predict that for a given mass the clusters formed at larger redshift are hotter, denser and therefore more luminous in X-rays than their local $z \sim 0$ counterparts. This effect overturns the decrease in the observable X-ray flux so that it does not decrease at $z > 1$, similar to the SZ signal. Provided that scaling relations remain valid at larger redshifts, X-ray surveys will not miss massive clusters at any redshift, no matter how far they are. At the same time, the difference in scaling with mass and distance of the observable SZ and X-ray signals from galaxy clusters at redshifts $z \lesssim 2$ offers a possibility to crudely estimate the redshift and the mass of a cluster. This might be especially useful for pre-selection of massive high-redshift clusters and planning of optical follow-up for overlapping surveys in X-ray (e.g. by SRG/eRosita) and SZ (e.g. Planck, SPT and ACT).

Key words: galaxies: clusters: general – distance scale – large-scale structure of Universe – X-rays: galaxies: clusters.

1 INTRODUCTION
The abundance of massive clusters of galaxies is a sensitive probe of the normalization of density perturbations power spectrum and the Universe geometry (e.g. Kaiser 1986). In the observable Universe, there are about $10^5$ clusters with masses$^1$ larger than $\sim 2 \times 10^{14} M_\odot$. Only a small fraction of these clusters is known today, but the situation will change drastically with forthcoming massive surveys in X-ray and microwave bands.

Main source of cluster candidates comes from X-ray (e.g. Ebeling et al. 1998; Vikhlinin et al. 2009), SZ (e.g. Carlstrom, Holder & Reese 2002; Planck Collaboration XXIX 2014) and optical surveys (e.g. Rozo et al. 2010). Each approach has its own strengths and weaknesses. Finding clusters in X-rays is a very powerful tool, capable of finding virialized cluster-scale objects at great distances. For example, in the upcoming SRG/eRosita all-sky survey, the most distant cluster will be at $z \sim 2$ with the mass $M_{500} \sim 3 \times 10^{14} M_\odot$ (e.g. Merloni et al. 2012). This estimate assumes that one needs $\sim 50$ counts to detect and classify an object as an extended source and a cluster candidate. We argue below that this limit in redshift comes primarily from the lack of massive haloes at higher redshifts, rather than due to the dimming of X-ray signal with distance. Therefore, with the upcoming SRG/eRosita data all massive clusters in the observable Universe can be detected, no matter at what redshift they are. The same is of course true for SZ surveys (e.g. SPT or ACT).

Working with large number of candidates which are detected at the limit of SRG/eRosita sensitivity is a challenge and requires a massive optical follow-up programme to measure redshifts. In many cases having even a crude estimate of the redshift for distant clusters would be very helpful.

Recent progress in sensitivity and angular resolution of SZ facilities makes it possible to quickly detect clusters using the ground-based instruments like CARMA (Combined Array for Research in Millimeter-wave Astronomy) or MUSTANG (Multiplexed SQUID/TES Array at Ninety Gigahertz) (exposures on the order of 20 min). However, significant part of the new discovered clusters in X-ray and microwave surveys will overlap. We expect the discovery of many tens of thousands of such objects for which both X-ray and SZ fluxes will be available. It will be very difficult task to find observing time on big telescopes to measure redshifts (even photometric) for all these objects. Mentioned above possibility of the rough redshift and mass estimate using just raw X-ray and SZ data might permit to separate immediately clusters which need small, medium or big telescopes for much more precise redshift measurements. This will help a lot to plan optical follow-up. Situation obviously will be much easier on the regions of sky covered by extended optical redshift surveys like for example JPAS (Benitez et al. 2014).

* E-mail: churazov@mpa-garching.mpg.de
$^1$All masses quoted in the paper are at overdensity of 500, unless stated otherwise.
Already in 1970 it was recognized that different dependences of surface brightness of clusters in X-rays and microwave bands on the gas density $n_e$, temperature $T_e$ and the physical size of the cluster $L$, namely, $I_X \propto n_e^2 L$ (for X-rays) and $Y \propto n_e T_e L$ (for microwave band), can be used to determine $L$ independently of its redshift (Sunyaev & Zeldovich 1970, p. 16). It was assumed that X-ray data provide us with the value of $T_e$. It is possible to compare X-ray and cosmic microwave background fluxes from clusters of galaxies and come to the same conclusion (Sunyaev & Zeldovich 1980). Knowing $L$ and the angular size of the cluster in X-rays or in microwave band, it is possible to estimate the distance to the cluster. This permits to measure the Hubble constant for any individual cluster if its redshift is known (Gunn 1978; Silk & White 1978; Birkinshaw 1979; Cavaliere, Danese & de Zotti 1979; Bonamente et al. 2006). More than 1000 counts are needed to measure the gas temperature in clusters using observatories like Chandra or XMM–Newton. NUSTAR spacecraft, hard X-ray grazing incidence telescopes aboard of Astro-H and SRG/ART-XC will open a way to measure electron temperature in most massive selected clusters with $kT_e > 10$ keV. This will give an additional information about evolution of the hot gas temperatures inside clusters of galaxies as a function of the redshift and will permit to take into account the relativistic corrections to SZ effect. However, for faint objects the required exposure is long and the information on gas temperature will not be available for majority of objects in the SRG/eRosita survey.

Cosmological evolution of cluster properties with redshift and scaling relations found for real clusters add another aspect to the problem. In particular, for clusters obeying observed scaling relations (see Fig. 1) the X-ray flux (similarly to SZ signal) levels off at $z \sim 1$, and this minimal level of X-ray flux can be used as a crude proxy to the mass of distance clusters. At the same time the ratio of the X-ray and SZ fluxes turns out to be weakly dependent on the mass (see Planck Collaboration I 2012 and Section 3) and can serve as a crude proxy to the redshift. While these proxies suffer from the large intrinsic scatter of cluster parameters, they might nevertheless be useful for SRG/eRosita, SPT, ACT, which are planning to detect more than 100 000 clusters on the whole sky. For these numerous (and mostly faint) objects, a combination of X-ray and SZ fluxes will provide a simple and convenient tool to approximately position clusters in the mass–redshift diagram. This approach is similar to colour–magnitude diagrams extensively used in infrared and optical astronomy.

For the purposes of this paper, the relevant mass range is $M_{500} \sim 2 \times 10^{14}–2 \times 10^{15} M_\odot$; the relevant redshift range is $0.1–2$.

Throughout the paper, we adopt the following cosmological parameters: $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, $\Omega_b h^2 = 0.022$, $h = 0.7$, $w_0 = -1$, $w_a = 0$, $n = 0.95$, $\sigma_8 = 0.79$. These parameters are close to values derived/used in Vikhlinin et al. (2009) from the analysis of X-ray selected clusters at $0.02 < z < 0.9$. The choice of this particular set is motivated by the use of the cluster scaling relations based on the same data.

### 2 X-RAY AND SZ SIGNALS AND SCALING RELATIONS

The total X-ray flux (in erg s$^{-1}$ cm$^{-2}$ in a given energy band from $\epsilon_1$ to $\epsilon_2$ keV) from a galaxy cluster at redshift $z$ can be written as

$$F_X \propto \frac{n_e^2 R^3}{D_L^2} C_X(T, z),$$

where $R$ is the physical size of the cluster, $n_e$ is the electron density, $T$ is the gas temperature, $D_L$ is the luminosity distance to the cluster. A factor $C_X(T, z)$ is the conversion coefficient from the rest-frame flux into observer frame for a given $T$ and $z$:

$$C_X(T, z) = \int_{\epsilon_1(T + z)}^{\epsilon_2(T + z)} S(\epsilon, T) d\epsilon,$$
where \(S(\epsilon, T)\) in units of \(\text{erg} \, \text{s}^{-1} \, \text{cm}^{-2}\) is the emissivity at energy \(\epsilon\) of an optically thin plasma with unit electron density. For hot clusters \((T > 3 \text{ keV})\), the emissivity is largely due to thermal bremsstrahlung. In the arguments below, we use the expression

\[
S(\epsilon, T) \propto \frac{e^{-\epsilon/kT}}{T^{1/2}} \approx \frac{1}{T^{1/2}}, \tag{3}
\]

which corresponds to the thermal bremsstrahlung spectrum for \(\epsilon \ll kT\). We note, however, that this expression is not accurate. First of all, with account for the gaunt factor the bremsstrahlung spectrum (in the relevant temperature and energy ranges) is better described by the expression \(S(\epsilon, T) \propto e^{-\epsilon/kT} - 0.35 e^{-\epsilon/kT}\). Secondly, the contribution of heavy elements (lines and recombination continuum) is important. Therefore, for all plots the realistic approximation of \(S(\epsilon, T)\) is used, calculated for APEC model (Foster et al. 2012) in XSPEC (Arnaud 1996). The main difference of these more accurate approximations compared to equation (3) is a much weaker temperature dependence of the emissivity in the soft X-ray band.\(^2\) Nevertheless, for the sake of simplicity of argument we use below equation (3). With this definition, \(C_X(T, z) \propto (1 + z) / \sqrt{T}\).

The total \(Y_{SZ}\) parameter for the same cluster is

\[
Y_{SZ} = \frac{F_{SZ}}{D_\lambda} \propto \frac{n_e R}{D_\lambda} \frac{C_X(T, z)}{T} \propto \frac{n_e C_X(T, z)}{(1 + z)^2 T} \propto \frac{1}{(1 + z)^{3/2}}, \tag{4}
\]

where \(\sigma_T\) is the Thomson cross-section and \(D_\lambda\) is the angular diameter distance.

If \(n_e, R, T\) and \(T\) are fixed, then the changes of the \(F_X\) and \(F_{SZ}\) are primarily driven by the factors \(\frac{C_X(T, z)}{T}\) and \(\frac{n_e}{D_\lambda}\), respectively (Fig. 1, left-hand panel). As expected, the X-ray flux declines much faster than the \(SZ\) signal. Indeed, the ratio of X-ray and \(SZ\) signals changes with \(z\) as

\[
R_{XSZ} = \frac{F_X}{F_{SZ}} \propto \frac{D_\lambda}{D_\lambda^2} \frac{n_e C_X(T, z)}{T} \propto \frac{n_e C_X(T, z)}{(1 + z)^2 T} \propto \frac{1}{(1 + z)^{3/2}}. \tag{5}
\]

However, the situation changes if instead of fixing all parameters, we fix only the mass of a cluster and let the other properties to vary with redshift according to the cosmological scaling relations. In the simplest scenario of a self-similar growth of haloes, the characteristics of a virialized object, collapsing at redshift \(z\) obey the following scaling relations: \(R \propto M^{1/3} \rho^{-2/3}, T \propto \rho^{-2/3}\) and \(n_e \propto E^2\) (e.g. Kaiser 1986; Bryan & Norman 1998), where \(E(z) = \frac{H(z)}{H_0} = \frac{\Omega_{\Lambda} + \Omega_m(1 + z)^3}{\Omega_m}\). Obviously, at a fixed mass the cluster collapsing at larger \(z\) is expected to be hotter, denser and more compact, boosting the X-ray luminosity of the cluster. This boost in luminosity largely compensates for the \(D_z^2\) factor in \(F_X\). Indeed,

\[
F_X \propto n_e^2 R^3 C_X(T, z) \sim M \frac{E^2 C_X(T, z)}{(1 + z)^2 D_\lambda^2} \propto M \frac{E^2 C_X(T, z)}{(1 + z)^2 D_\lambda^2}, \tag{6}
\]

At \(z \sim 1-2, D_\lambda \approx \text{const}\) and then declines as \(\sim 1/z\), \(E\) approximately scales as \((1 + z)^{1/2}\) and \(T \propto (1 + z)\). Therefore,

\[
F_X \propto \frac{M}{D_\lambda^2 (1 + z)^{1/2}}. \tag{7}
\]

The redshift dependence of the \(F_X\) curve changes dramatically (Fig. 1, right-hand panel), the steep decline is reverted and overall behaviour at \(z \gtrsim 1\) resembles that of \(F_{SZ}\). In other words, if a cluster can be detected in X-ray survey at \(z \sim 1\), then objects with similar mass can be detected at any redshift, assuming that the self-similar cluster evolution model is valid for extreme masses and very high redshifts. This implies that with a sufficient sensitivity both SZ and X-ray surveys have access to all massive clusters at all redshifts in the observable Universe, even at redshifts where massive clusters are not expected to exist.

In terms of the ratio of \(F_X\) and \(F_{SZ}\) at \(z \gtrsim 1\),

\[
R_{XSZ} = \frac{F_X}{F_{SZ}} \propto \frac{E^2 C_X(T, z)}{(1 + z)^2 E^{2/3}} \propto \frac{1}{(1 + z)^{3/2}}, \tag{8}
\]

i.e. much weaker than for the case when all cluster properties are fixed (c.f. equation 5). Similar expression was used by Planck Collaboration I (2012) (see equation 3 there) to verify possible redshift solutions for cluster candidates detected by Planck.

The same conclusions can be formulated in terms of the X-ray surface brightness at a given energy \(\epsilon\) and Compton \(\gamma\)-parameter \(y = \int \sigma_T n_e \frac{d\epsilon}{\epsilon} \Lambda\),

\[
I_X(\epsilon) \propto \frac{n_e^2 R}{(1 + z)^3}, \tag{9}
\]

\(y \propto n_e R T\).

For a cluster obeying self-similar scaling, both the X-ray surface brightness and the \(\gamma\)-parameter grow strongly with distance. The ratio of these two quantities, of course, behaves similarly to the ratio of total fluxes – see equation (8).

In reality, scaling relations, involving physics of baryons, deviate to various degree from the self-similar relations (see, e.g. Ettori 2015, for a recent work). For a sample of X-ray selected clusters at \(0.02 < z < 0.9\), the following relations have been derived (Vikhlinin et al. 2009):

\[
L_X(0.5-2) = 1.2 \times 10^{44} \text{ erg} \, \text{s}^{-1}, \tag{10}
\]

\[
X_T = 5 \text{ keV} \left(\frac{M}{3.0 \times 10^{14} h^{-1} M_\odot}\right)^{0.65} E^{0.65}, \tag{11}
\]

\[
Y_X = 3 \times 10^{14} M_\odot \text{ keV} \left(\frac{M}{5.8 \times 10^{14} h^{1/2} M_\odot}\right)^{5/3} E^{2/3}, \tag{11}
\]

where \(L_X(0.5-2)\) is the rest-frame cluster luminosity in the 0.5–2 keV band, \(Y_X = M_{500}/T_X\) and \(F_{SZ} = \eta Y_X\). Here \(\eta = \frac{\mu m_p n_e}{m_e} D_\lambda^2\), where \(\mu \approx 0.61\) is the mean atomic weight of a gas particle, and \(n_e/n_i \approx 0.52\) is the fraction of electrons in the total gas number density.

The above relations can be used straightforwardly to predict the dependence of \(F_X\) and \(F_{SZ}\) on \(z\) for a fixed cluster mass, as shown in Fig. 1 (right-hand panel). The conclusion that \(F_X\) does not decrease with redshift beyond \(z \sim 1\) holds both for pure self-similar and empirical scaling relations. It is a generic consequence of self-similar evolution in the \(\Lambda\) cold dark matter (ΛCDM) cosmological model.

3 \(F_X\) AND \(R_{XSZ}\) PLANE

Given that for empirical relations \(F_X \propto L_X \propto M^{0.6}\) and \(F_{SZ} \propto Y_X \propto M^{5/3}\), one can expect that in the ratio of these two observables \(R_{XSZ} = \frac{F_X}{F_{SZ}}\) the mass dependence approximately cancels...
out and $R_{\text{SZ}}$ is primarily a function of $z$ (see also Planck Collaboration I 2012). This is further illustrated in Fig. 2, which shows the value of $R_{\text{SZ}}$ for clusters with given mass $M_{\text{SZ}} = 10^{14} - 2 \times 10^{15} M_{\odot}$ and slightly different definitions of $Y$ and $F_X$. Different colours correspond to: red-scaling relations (11) and $F_X$ in the 0.5–2 keV band; green – the same scaling relations, but $F_X$ in the 0.1–2.4 keV band; blue – $F_X$ in the 0.5–2 keV band and $Y_{\text{SZ}}$–$M$ relation from Planck Collaboration XI (2011) and the X-ray flux in the 0.5–2 keV band. Black squares show a small sample of SPT clusters with X-ray data from Andersson et al. (2011). Below we adopt the $R_{\text{SZ}}(z)$ dependence corresponding to red area as a base-line model, but the results can be readily reformulated for any other dependences, shown in the figure. The black dashed line shows a simple analytic approximation $R_{\text{SZ}} = 2.8 \times 10^{-3} (1 + (z/0.3)^{1.3})^{-1}$, which does not have physical meaning, but roughly reproduces the $R_{\text{SZ}}$ dependence over the redshift range of interest.

We now consider how clusters populate the $(F_X, R_{\text{SZ}})$ plane, using predictions of the abundance of virialized haloes at a given redshift/mass. To this end, we use the mass function of Tinker et al. (2008). We start by calculating cluster abundance $\frac{dN}{dM_{\text{SZ}}}$ for a grid over $z$ and $M = M_{\text{SZ}}$. For each pair of $z$ and $M$, we use scaling relations (11) to calculate $F_X$ and $F_{\text{SZ}}$. The results of these calculations are shown in Fig. 3. The size of the circle is proportional to the log of the number of clusters per grid cell, i.e. $\frac{dN}{dM_{\text{SZ}}} \times \Delta z \Delta M$. Only cells with more than one cluster are shown. Cells corresponding to the constant mass or redshift are connected with red and blue lines, respectively.

As expected, blue lines are almost horizontal, implying that the ratio $R_{\text{SZ}} = \frac{F_{\text{SZ}}}{F_X}$ changes with $z$, but is weakly dependent on mass (see also Fig. 2). Therefore, $R_{\text{SZ}}$ can serve as a redshift indicator, at least for clusters more massive than $\sim 2 \times 10^{14} M_{\odot}$. At the same time, the red lines (constant mass) are nearly vertical at $z \gtrsim 1$ and are slightly inclined at lower redshifts. This behaviour can be traced back to Fig. 1 (right-hand panel) which shows that at fixed mass the $F_X$ curve levels off at $z \sim 1$. The curves, corresponding to clusters with different masses will have different minimum flux, which is proportional to the mass of the cluster, if one adopts simplified $F_X$–$M$ relation according to equation (7). With the scaling relations adopted here (equation 11), the mass dependence is steeper (see below).

The approximate orthogonality of the constant redshift and constant mass curves suggests that a combination of X-ray and SZ data

Figure 2. Ratio $R_{\text{SZ}}$ of the X-ray and SZ signals as a function of redshift. The shaded areas correspond to clusters in the mass range from $1 \times 10^{14}$ to $2 \times 10^{15} M_{\odot}$ and the redshift range from 0.01 to 4 (note, that at large redshifts massive clusters are not expected to be present). The red area is for clusters obeying scaling relations (11) and the X-ray flux $F_X$ in the 0.5–2 keV band. The green area is for the same scaling relations, but uses $F_X$ in the 0.1–2.4 keV band. The blue area uses $Y_{\text{SZ}}$–$M$ relation from Planck Collaboration XI (2011) and the X-ray flux in the 0.5–2 keV band. Black squares show a small sample of SPT clusters with X-ray data from Andersson et al. (2011). Below we adopt the $R_{\text{SZ}}(z)$ dependence corresponding to red area as a base-line model, but the results can be readily reformulated for any other dependences, shown in the figure. The black dashed line shows a simple analytic approximation $R_{\text{SZ}} = 2.8 \times 10^{-3} (1 + (z/0.3)^{1.3})^{-1}$, which does not have physical meaning, but roughly reproduces the $R_{\text{SZ}}$ dependence over the redshift range of interest.

Figure 3. Expected number of clusters with a given $(F_X, R_{\text{SZ}})$. Clusters with $T < 3$ keV are marked with circles, while hotter clusters are marked with squares. The size of the symbol is proportional to the log of the number of clusters per grid cell, i.e. $\frac{dN}{dM_{\text{SZ}}} \times \Delta z \Delta M$. Red and blue lines correspond to the constant mass and redshift, respectively. Purple circles mark 20 most massive clusters in each redshift bin. The approximate orthogonality of the constant redshift and constant mass curves suggest that a combination of X-ray and SZ data is a useful indicator of the object redshift and mass. The green dashed line is the cluster detection threshold for eRosita all-sky survey. Dark green ellipse shows typical uncertainty in the position of a cluster in the $(F_X, R_{\text{SZ}})$ plane due to the intrinsic scatter in $F_X$ (dominant component of the scatter) and $Y$. Without the scatter, the expected number of (most massive) clusters below black solid line is $\sim 10$ per each $[F_X; 2 \times F_X]$ bin. To compensate for the intrinsic scatter from the mean scaling relations, one has to use less strict selection cut (dashed line) to provide 90 per cent completeness of the sample for these massive clusters.
is a useful indicator of the object redshift and mass. In other words, there is an approximate mapping of $F_X$ to $M_{500}$ and $R_{\text{SZ}}$ to $z$, which is most straightforward in the interesting range of $z \sim 1$–2.

The expected correlation of the observed X-ray flux and the cluster mass is further illustrated in Fig. 4. The same mass/redshift bins as in Fig. 3 are used, but this time the mass is plotted as a function of X-ray flux. Clusters from different redshift groups are marked with different colours. For nearby clusters ($z < 0.6$, black circles), the spread in $F_X$ at a fixed mass is huge. On the contrary, for $z > 0.6$ (blue and red points) there is a good correlation between the X-ray flux and the mass. This correlation appears due to evolution of cluster properties with redshift. The black dashed line shows a simple analytic approximation of this correlation

$$M_{500} = 1.2 \times 10^{14} \left(\frac{F_X}{10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}}\right)^{0.57} \, \text{M}_\odot. \quad (13)$$

The most stringent limits on the growth of structure come from the most massive clusters at each redshift. Fig. 5 shows the mass and temperature dependence for the 20 most massive clusters in each redshift bin according the mass function of Tinker et al. (2008). The characteristic mass changes by an order of magnitude (red line in the top panel of Fig. 5), while the characteristic temperature stays above 4–5 keV over the redshift range 0–3. The relativistic corrections to the SZ signal can be important for most massive clusters at $z \sim 0.5$, while for more distant ($z \gtrsim 1$) massive clusters they are expected to be small. The locus of these massive clusters in the ($F_X$, $R_{\text{SZ}}$) plane is shown with purple circles. It is clear that these clusters form an elongated and narrow band in the plane, implying that picking clusters candidates from this band will provide a useful subsample for further studies. Without definition of X-ray and SZ signals, the most massive clusters at a given $F_X$ correspond to those below the line $R_{\text{SZ}, 10} = 3.7 \times 10^{-10} \left(\frac{F_X}{10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}}\right)^{0.36}$ (black solid line in Fig. 3). There are ~10 massive clusters below this line per each X-ray flux interval [$F_X$; $2 \times F_X$] over the whole range of interest.

The above discussion completely neglects the scatter of cluster properties around the adopted scaling relations. This scatter in $L_X$ is considerable (e.g. Stanek et al. 2006; Vikhlinin et al. 2009) and will spread the clusters in the ($F_X$, $R_{\text{SZ}}$) plane. We assume that the scatter in $\log F_X$ and $\log Y$ is 0.4 and 0.13, respectively (Vikhlinin et al. 2009) and that the scatter is independent in these two variables. With this assumptions, the expected level of the scatter in the ($F_X$, $R_{\text{SZ}}$) plane is shown with a green ellipse in Fig. 3 with log of the major and minor axes of 0.57 and 0.09, respectively. Note, that since the scatter in $F_X$ is substantially larger than the scatter in $Y$, we choose to plot an ellipse, corresponding to 68 per cent probability for 1 degree of freedom (rather than for 2). When scatter is included, the selection cut for massive clusters has to be modified. Assuming that we want 90 per cent of the most massive clusters to be captured by the selection (i.e. those objects which without intrinsic scatter would be below the solid line), we need to increase the selection cut by as factor 1.34 (black dashed line in Fig. 3), as demonstrated by Monte Carlo simulations. Thus, selecting objects with $R_{\text{SZ}} < 1.34 R_{\text{SZ}, 10}$ will ensure that 9 out of 10 most massive clusters will not be lost from the sample due to intrinsic scatter. Of course, this relaxed selection will contain factor $\sim 10^2$ more objects than our target sample at $F_X \sim 3 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, i.e. about $10^3$ cluster candidates has to be followed up in order to identify 10 most massive ones. This is nevertheless a substantial improvement compared to the total number of objects per $F_X$ bin without $R_{\text{SZ}}$ cut, which is another factor of $\sim 10^2$ larger.
We also used a Monte Carlo approach to estimate the uncertainties in evaluating $z$ via equation (12). For each redshift, the scatter is added to $F_X$ and $F_{SZ}$, the value of $R_{XSZ}$ is calculated and equation (12) is used to recover the redshift. The estimated uncertainties in $z$ correspond to lower/upper 17 per cent of the probability distribution. For $z = 1, 1.5$ and $2$, these intervals are $1.9^{+0.42}_{-0.32}, 1.5^{+0.61}_{-0.45}$ and $2.0^{+0.77}_{-0.57}$. As expected, the uncertainties are large, but suitable for pre-selection of massive and distant clusters for further studies.

For the mass determination using equation (13), the uncertainty is factor $\sim 1.4$ in the normalization of equation (13) (see previous section). Additional uncertainty due to the scatter in $F_X$ adds another $\sim 22$ per cent to the mass estimate.

Finally, we note that $(F_X, R_{XSZ})$ is not the only pair of variables which can be used for pre-selection of clusters, but it is one of the most straightforward and simple combinations of the observables. In practice the selection strategy has to be optimized for a particular set of instruments/observables used in the X-ray and SZ surveys.

4 CONCLUSIONS

In $\Lambda$CDM universe distant clusters with a given mass are denser and hotter compared to their local counterparts. This boosts strongly the rest-frame X-ray luminosity of distant clusters and compensates for the dimming of the X-ray signal with distance. This implies that similarly to SZ surveys, X-ray telescopes are able to detect massive cluster over entire observable Universe. If the cluster can be detected at $z \sim 1$, similar mass objects can be detected at any redshift.

A combination of X-ray and SZ observables happens to be a simple indicator of $z$ and $M$ (see equations 12 and 13 and Figs 2 and 4), which can be used to approximately classify clusters in broad mass/redshift bins for the spectroscopic follow-up. Provided that local-scaling relations hold for larger redshift, the ratio $R_{XSZ}$ of X-ray flux to the total $Y$ is almost independent on the mass and serves as convenient redshift indicator, while the X-ray flux itself can be used as the mass proxy (for objects with sufficiently large redshift $z \gtrsim 0.5$, or, equivalently, with sufficiently low $R_{XSZ}$).

ACKNOWLEDGEMENTS

We are grateful to the referee for a number of helpful comments and suggestions. We acknowledge partial support by grant No. 14-22-00271 from the Russian Scientific Foundation.

REFERENCES

Andersson K. et al., 2011, ApJ, 738, 48
Arnaud K. A., 1996, Jacoby G. H., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
Benitez N. et al., 2014, preprint (arXiv:1403.5237)
Birkinshaw M., 1979, MNRAS, 187, 847
Bonamente M., Joy M. K., LaRoque S. J., Carlstrom J. E., Reese E. D., Dawson K. S., 2006, ApJ, 647, 25
Bryan G. L., Norman M. L., 1998, ApJ, 495, 80
Carlstrom J. E., Holder G. P., Reese E. D., 2002, ARA&A, 40, 643
Cavaliere A., Danese L., de Zotti G., 1979, A&A, 75, 322
Ebeling H., Edge A. C., Bohringer H., Allen S. W., Crawford C. S., Fabian A. C., Voges W., Huchra J. P., 1998, MNRAS, 301, 881
Ettori S., 2015, MNRAS, 446, 2629
Foster A. R., Ji L., Smith R. K., Brickhouse N. S., 2012, ApJ, 756, 128
Gunn J. E., 1978, in 8th Saas-Fee Advanced Course Lectures (A79-23276-08-90): Observational Cosmology Geneva Observatory, Sauverny, Switzerland, p. 1
Haiman Z., Rees M. J., 1996, ApJ, 469, 565
Haiman Z., Khosroshahi A., 2001, ApJ, 554, 61
Kaiser N., 1986, MNRAS, 222, 323
Merloni A. et al., 2012, preprint (arXiv:1209.3114)
Planck Collaboration XI, 2011, A&A, 536, AA11
Planck Collaboration I, 2012, A&A, 543, AA102
Planck Collaboration XXIX, 2014, A&A, 571, AA29
Rozo E. et al., 2010, ApJ, 708, 645
Silk J., White S. D. M., 1978, ApJ, 226, L103
Stanek R., Evrard A. E., Böhringer H., Schuecker P., Nord B., 2006, ApJ, 648, 956
Sunyaev R. A., Zeldovich Y. B., 1970, Ap&SS, 7, 3
Sunyaev R. A., Zeldovich I. B., 1980, ARA&A, 18, 537
Tinker J., Kravtsov A. V., Klypin A., Abazajian K., Warren M., Yepes G., Gottlöber S., Holz D. E., 2008, ApJ, 688, 709
Vikhlinin A. et al., 2009, ApJ, 692, 1033

This paper has been typeset from a TeX/LaTeX file prepared by the author.