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SELF-SIMILARITY OF CLUSTERS OF GALAXIES AT DIFFERENT REDSHIFTS AND THE L_X-T RELATION



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Abstract

Classical scaling laws from structure formation predict that X-ray emission measure profiles of clusters of galaxies are similar once scaled to virial mass and radius. In a previous paper we have shown that indeed the cluster emission measure profiles show small scatter when we scale them to the classical laws. However, this result is contradictory to the observed $L_X - T$-relation found for clusters of galaxies, which does not follow the predicted scaling laws. The observed relation found and confirmed by many authors is close to $L_X \propto T^3$, not $L_X \propto T^2$, predicted from classical scaling. In this paper we want to investigate this "discrepancy". We introduce the relationship between gas mass M_{gas} and T: $M_{gas} \propto T^{1.94}$ to explain the $L_X - T$ relation. We look at the corresponding emission measure profiles, which scale with M_{gas}^2. Introducing this relationship we can reduce the scatter in the emission measure profiles by a factor of 2 when compared to the classical scaling. We interpret this finding as strong indication that the gas mass deviates from classical scaling with $M_{gas} \propto T^{1.94}$.

We furthermore investigate whether also distant clusters show self-similarity. For this study we look at all clusters which were observed with ROSAT with sufficient statistics and have a temperature measurement provided by ASCA with $z > 0.3$. We indeed find that the emission measure profiles of these distant clusters also show a high degree of self-similarity once we scale them to virial mass and radius. This result is a hint for an evolution of the $L_X - T$ relation with redshift, since distant clusters are smaller in the self-similar picture. We also propose that the self-similarity of clusters up to high redshift might be used as an independent measure to determine the cosmological parameters Ω_m and Λ.

1 Introduction

The simplest theory of structure formation purely based on gravitation predicts that galaxy clusters follow simple scaling laws. In particular the masses of clusters and the temperature of their hot, X-ray emitting intra-cluster medium (hereafter ICM) should follow the relation

$$M \propto T^{3/2}(1+z)^{-3/2}. \tag{1}$$

And the radius and the ICM temperature should scale as

$$R \propto T^{1/2}(1+z)^{-3/2}. \tag{2}$$

The mass and the radius of these relations corresponds to a fixed mass over-density compared to the critical density of the universe.

Hydrodynamic simulations ([16] and references therein) support the fact that the baryon fraction in clusters is similar to the mean baryon fraction in the universe and thus constant for all hot clusters, in which feedback processes of galaxies are negligible [14]. Therefore, it is logical to suppose the relation $M_{gas} \propto M \propto T^{3/2}$ for clusters of galaxies.

An important question is now whether real, observed clusters follow in fact these predicted scaling laws. In [15] it was recently found $R \propto T^{0.57\pm0.04}$, which is close to the predicted scaling. Also in [13] – hereafter paper I – have shown that the emission measure profiles of the ICM of a sample of nearby clusters with k$T > 3.7$ keV show a high degree of self-similarity if scaled to the predicted scaling laws.

But there are also observed departures from this simple scaling laws like the observed bolo-metric $L_X - T$ relation of clusters. While scaling laws predict $L_X \propto T^2$ different authors using different cluster samples find $L_X \propto T^{2.9}$ [4], [9], [2] with a low dispersion, which completely rules out $L_X \propto T^2$.

There exist two possibilities to explain the differences between observed and predicted $L_X - T$ relation: either the cluster shape itself is a function of T or the gas mass temperature relation deviates from predictions [4], [14].

We want to address this issue by examining the surface brightness profiles and the corresponding emission measure profiles of clusters, which are sensitive to both, form and gas mass content.

We also investigate the hypothesis of self-similarity for distant clusters. For this we examine the emission measure profiles of all clusters of galaxies with a temperature measurement by ASCA at redshifts greater than z=0.3.

This self-similarity of distant clusters will allow us to use clusters in the future as standard candles to measure the curvature of the universe.

2 The sample

The sample is in detail described in paper I. To summarize it briefly: our sample comprises Abell clusters [1] in the redshift shell $0.04 < z < 0.06$, which were observed in a pointing mode with the ROSAT PSPC with good statistics. Here we look only at the subsample for which we have accurate temperature measurements from the literature.

3 Scaling taking into account the $L_X - T$-relation

For the $L_X - T$ relation we use the relation found by [4]

$$L_X \propto T^{2.88} \tag{3}$$

which is in good agreement with other work [9], [2].

We can write the relation between X-ray luminosity, gas mass M_{gas}, cluster extend R, cooling function $\Lambda(T)$ and a form factor for the gas $Q(T)$ as follows:

$$L_X \propto \frac{M_{gas}^2(r < R)}{R^3} \Lambda(T) Q(T) \tag{4}$$

whereas $Q(T)$ is defined as: $Q(T) = \langle \rho_{gas}^2 \rangle / \langle \rho_{gas} \rangle^2$ averaged over the whole cluster (see also [4]). If clusters have similar shapes, $Q(T)$ should be constant. Simple theoretical scaling predicts $R \propto T^{1/2}$.

Generally it can be assumed that $\Lambda(T) \propto T^{0.5}$.

For the emission measure (EM) we can write:

$$EM(r) \propto \int_r^R \frac{n_g^2(x) x dx}{\sqrt{x^2 - r^2}} \propto \frac{M_{gas}^2}{R^5} F(r/R, T) \tag{5}$$

$F(r/R, T)$ is again a dimensionless form function. Again, if clusters are self-similar $F(r/R, T)$ should be independent of T.

We transform the surface brightness ($S(\Theta)$) into emission measure profiles via equ. (3) in paper I ($EM \propto (1+z)^4 S(\Theta)/\Lambda(T,z)$). Fig.1 shows the emission measure profiles of our cluster sample (upper panel) and their corresponding relative dispersion (lower panel). We use r_{200} for R with the normalization from [8]. We see that the profiles are parallel, especially as the relative dispersion stays almost constant with radius (we restrict ourselves to $r = 0.5R$ since due to detection limits our sample becomes incomplete at larger radii). We conclude subsequently that the clusters in our sample have similar shapes since this is the only possibility to have a relative dispersion which does not change with radius. Therefore in the following we assume that $Q(T)$ and $F(r/R, T)$ are constant.

Also we assume from now on:

$$R \propto T^x; M_{gas} \propto T^{3/2+y} \tag{6}$$

Combining equ.3, equ.4 and equ.6 we find the relationship:

$$2y - x = 0.38 \tag{7}$$

to explain the observed $L_X - T$ relation. If we assume that $x = 0.5$, which is the classical scaling we find that $y = 0.44$. The emission measure scales in this case not as $EM \propto T^{1/2}$ but as $EM \propto T^{1/2+0.88=1.38}$.– The rescaled emission measure profiles are shown in Fig.2 (upper panel) with their corresponding relative dispersion (lower panel). For this we divided the profiles shown in Fig.1 by $T^{0.88}$ (in keV). In this case the dispersion is a factor of 2 lower when compared to the original scaling in Fig.1.[a]

In order to see whether we can also see the dependence of the emission measure profiles on the temperature directly we display the emission measure at $r/R = 0.3$ versus T in Fig.3. As we are temperature limited in our sample we add Abell 2163 (kT=12.9 keV), one of the hottest clusters observed so far [3] to our sample. Fig.3 shows a clear dependence of the emission measure on T. Furthermore, the full line represents the relationship needed to explain the observed $L_X - T$ relation, which matches with the data points.

The large dispersion at the low temperature end in Fig.3 is possibly due to the larger number of clusters or due to additional effects, for example Cooling Flows or galactic feedback, which are much more important in cooler clusters [14].

4 The distant cluster sample

To enlarge our sample to distant clusters we looked at all distant ($z > 0.3$) clusters observed by ROSAT, with ASCA temperature measurement [5]. We excluded very irregular clusters and too poor quality data.

5 The self-similarity of distant clusters

As above the emission measure along the line of sight was deduced from the surface brightness profile and then scaled according to classical scaling laws. This scaling depends on the cosmological parameters Ω and Λ. The angular distance and thus the conversion between angular and physical radius depends on these parameters. So does the mean density of the universe at any z, as well as the cluster overdensity and thus the normalization of the M_V–T and R_V–T relations used in the scaling process (see e.g. [6]). We assumed that the normalization of the virial relation ($GM_{\rm V}/R_{\rm V} \propto kT$) does not evolve with z and is independent of the cosmology.

[a] Another solution for equ.7 in principle is to assume that $y = 0$, which implies $x = -0.38$. This seems to be an unreasonable case, since it would mean that smaller clusters are bigger than hotter ones, a clear contradiction of the found $R - T$ relation found by [15] or [11]. Therefore we discard this possibility in the following.

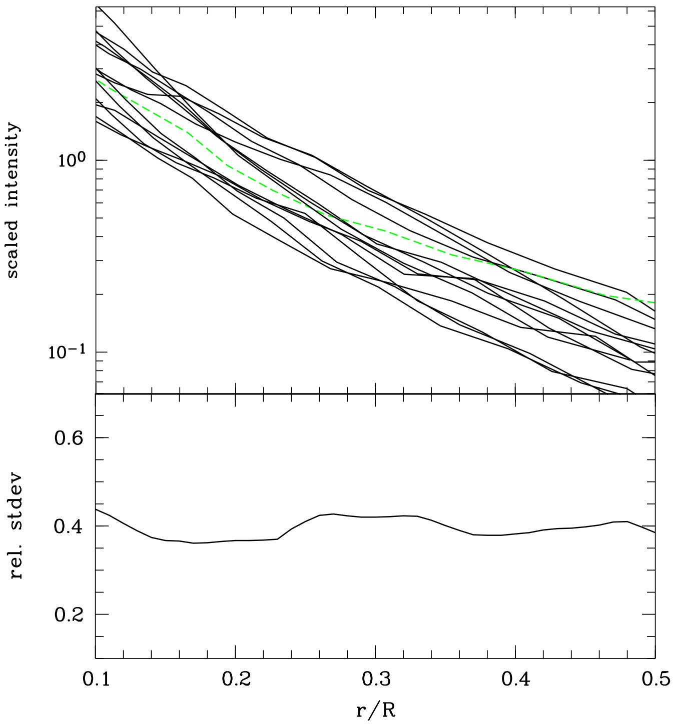

Figure 1: **Upper panel:** emission measure profiles following the classical scaling laws (arbitrary units). The dashed line represents A3562, which we excluded for further analysis, as it clearly deviates from the other profiles. **Lower panel:** The standard deviation of the emission measure profiles (above) as a function of radius.

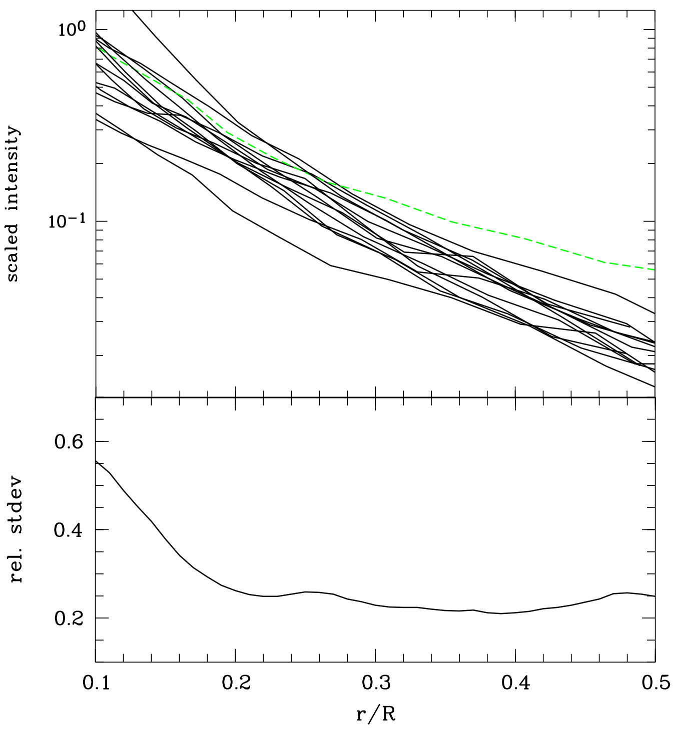

Figure 2: **Upper panel:** emission measure profiles (arbitrary units) for $M_{gas} \propto T^{1.94}$ ($x = 0.5$, $y = 0.44$). The dashed line represents A3562, which we excluded for further analysis, as it clearly deviates from the other profiles. The dynamic range of Fig.1 (upper panel) and this diagram are identical. **Lower panel:** The standard deviation of the emission measure profiles (above) as a function of radius.

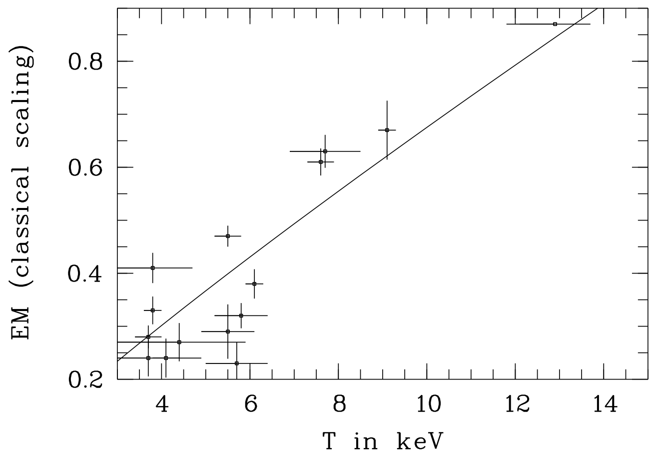

Figure 3: The emission measure of the clusters versus temperature at $r/R = 0.3$ (approx. 1 Mpc). The full line represents EM$\propto T^{0.88}$.

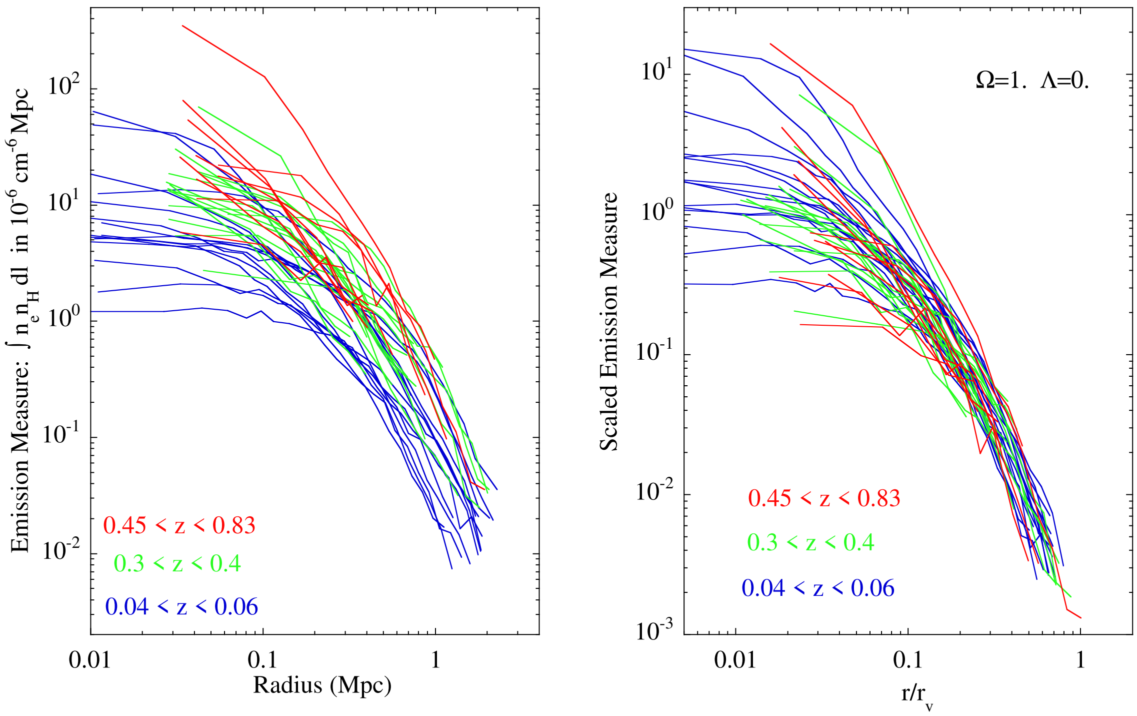

Figure 4: **Left:** The emission measure profiles of our entire cluster sample in physical units. **Right:** The scaled emission measure profiles. For the scaling see text.

Fig.4 shows the emission measure profiles for all our clusters in physical units, and once scaled to virial radius and mass for an $\Omega = 1$ $\Lambda = 0$ universe assuming that the gas mass fraction is constant and that $M_{tot} \propto T^{3/2}$. Once scaled to virial mass and radius distant massive clusters are remarkably similar to nearby ones, suggesting that the classical scenario for cluster formation is basically correct. It also indicates that distant clusters are systematically smaller than nearby ones. This is a hint for an evolution in the $L_X - T$ relation with redshift.

If we include furthermore our knowledge on the local $L_X - T$ relation and assume that there is evolution in the $L_X - T$ relation according to the scaling relations, we can see differences in the distribution of the emission measure profiles (see Fig.5), which also depends on the adopted cosmology.

Up to know we can trace the surface brightness profiles of distant clusters only up to several 100 kpc. Once we can measure the emission measure profiles up to large radii we can use these profiles as a tool to determine Ω_m and Λ. The correct cosmological parameters being the ones that show the lowest dispersion in the self-similar emission measure profiles of clusters.

6 Discussion

Recently[12] found indications for a relation between gas mass fraction and temperature at r_{500} with $f_{gas} \propto T^{0.34\pm0.22}$.[15], furthermore, showed indications for a deviation of the $M_{gas} - T$-relation ($M_{gas} \propto T^{1.71\pm0.13}$) after fitting a power law to the X-ray emission of the outer parts of cluster. The relations found by [12] and [15] are in good agreement with our results. Also, our result is in agreement with the work by [11], who found a tight correlation between some isophotal radius and the ICM temperature with $R_I \propto T^{0.93\pm0.11}$. We looked at this relationship between R_I and T in our sample and found the same behaviour.

However, the deviation of the $M_{gas} - T$-relation predicted from classical scaling has to be explained physically. A possible explanation would be for example galactic feedback. However, recently [14] showed that this effect is only important for cool/small groups below 4 keV.

Another possibility to explain the deviation from classical scaling would be the existence of relativistic particles creating radio halos. If the strengths or quantity of these particles is a function of temperature as indicated by [7] it might explain the deviation from the $M - T$ relation.

Also effects based on structure formation might be responsible for our found $M_{gas} - T$ relation, or it might be that the effect we observe is purely observational as we, for example, generally neglect up to now temperature variations in the ICM. It might be that there exists for example, a universal law for a temperature gradient (as already indicated by [10]), dependent on the overall observed mean temperature of the ICM. A substantial temperature gradient, which we ignore up to now, due to the limitations of current X-ray observatories might introduce important biases. New X-ray observatories such as XMM or Chandra will be able to investigate this possibility in detail.

7 Summary

We investigate why the observed $L_X - T$ relation ($L_X \propto T^{2.9}$) of clusters is different from theoretical scaling laws ($L_X \propto T^2$). There are in principle two possibilities for this difference: either clusters do not have similar shapes, or the gas mass content in clusters diverges from classical scaling.

For our investigation we use the surface brightness profiles of a sample of nearby clusters, which we defined in paper I. We transfer these surface brightness profiles into emission measure profiles and scale them to $R \propto T^{1/2}$ and $M \propto T^{3/2}$. We find that the profiles are parallel – a clear indication that all clusters have similar shapes. If we scale the gas mass in clusters in such a way that it matches the observed $L_X - T$ relation ($M_{gas} \propto T^{1.94}$) and apply this relationship to the emission measure profiles, which follow the relation $EM \propto M_{gas}^2$, we

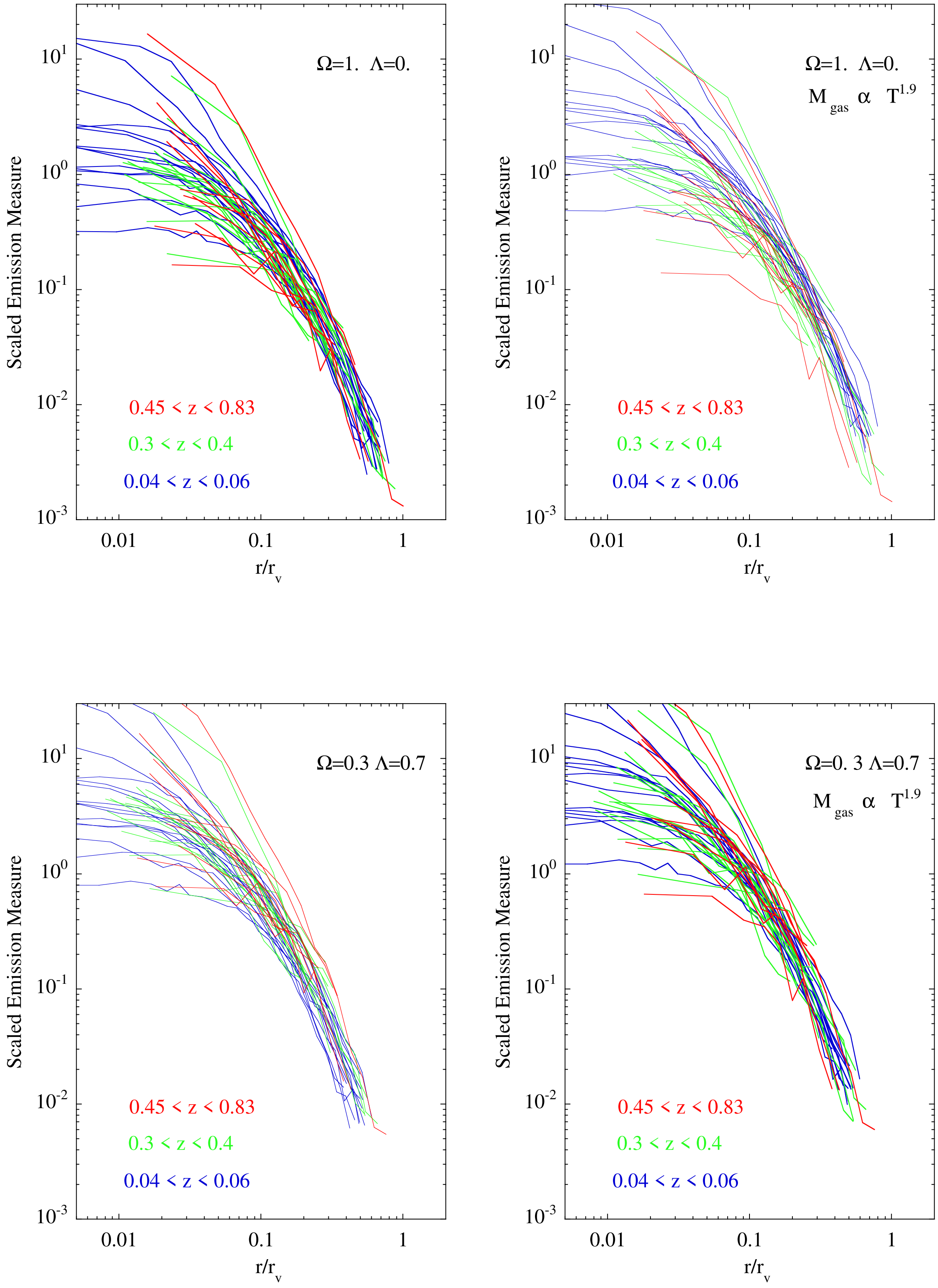

Figure 5: **Left:** The scaled emission profiles without introducing our knowledge on the $L_X - T$ relation for two different cosmologies. **Right:** The scaled emission profiles with our knowledge on the $L_X - T$ relation for the same two different cosmologies.

Figure 6: Thank you

can diminish the dispersion of the profiles by a factor of two when compared to the classical scaling ($M_{gas} \propto T^{1.5}$).

We interpret this result as indication that clusters do in fact have similar shapes but that the gas mass does not follow the self-similar prediction $M_{gas} \propto T^{3/2}$. This finding is in agreement with previous works such as [12] or [15], which were based on the direct measurement of M_{gas} in clusters. However, our test is more sensitive to deviations from the predicted $M_{gas} - T$ relation since the emission measure has the dependence $EM \propto M_{gas}^2$.

Up to know it is not clear whether also the total mass diverges from predicted scaling or not – for this detailed knowledge, especially on the temperature distribution of clusters has to be acquired, which will be possible now with modern X-ray observatories such as XMM-Newton or Chandra.

For our complete sample of clusters, including the distant ones, we find that clusters of galaxies show in their emission measure profiles a large degree of self-similarity up to high redshift. In the future this self-similarity might be used as an independent measure to determine the cosmological parameters Ω_m and Λ.

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