

## CLUSTERS OF GALAXIES AS A TOOL IN COSMOLOGY\*

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Using the data comprising measurements of the gas mass fraction  $f_{\text{gas}}$  for 42 hot and dynamically relaxed galaxy clusters with redshift spanning the range of  $0.05 < z < 1.1$ , collected and analysed by Allen (2008) from the Chandra X-ray observations, we obtained constraints on the matter density parameter  $\Omega_m$  and baryonic matter density parameter  $\Omega_b$ . In our calculations, we took into account two most popular cosmological scenarios: quintessence model in which dark energy equation of state is constant and the model in which cosmic equation of state evolves with redshift according to Chevalier–Polarski–Linder (CPL) parametrization. Our results for quintessence model:  $\Omega_m = 0.301 \pm 0.086$ ,  $\Omega_b = 0.042 \pm 0.011$  as well as for time-varying CPL scenario:  $\Omega_m = 0.268 \pm 0.094$ ,  $\Omega_b = 0.038 \pm 0.012$  are in a very good agreement with the latest Planck results. This demonstrates that galaxy clusters can be an excellent tool to constrain the values of relevant cosmological parameters.

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### 1. Introduction

Clusters of galaxies are the largest and the most massive bound objects in the Universe. Therefore, they can serve as excellent probes of cosmology. Typically, clusters contain 10–100 galaxies. However, galaxies account only for 2–3% of their mass: next c.a. 15–20% is in the form of intergalactic gas and the rest of their mass is dark matter. One way to test a cosmological model is by studying the cluster abundance. Growth of structure in an expanding Universe depends on the initial density distribution and the

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expansion rate  $H(z) = H_0 E(z)$  ( $H_0$  is the so-called Hubble constant related to the present value of the cosmic expansion rate and  $E(z)$  is dimensionless expansion rate). Clusters originated from the peak matter overdensities  $\delta = (\rho - \rho_{\text{cr}})/\rho_{\text{cr}}$  ( $\rho_{\text{cr}} = \frac{3H^2}{8\pi G}$  denotes the critical density, needed for a spatially flat, asymptotically static expansion of the Universe) and thus they are sensitive to the high-end tail of the  $\delta$  distribution, observationally measured by the parameter  $\sigma_8$  (the rms of the density contrast in the sphere of 8 Mpc radius).

Since the dominant baryonic mass fraction of galaxy clusters is in hot intracluster gas (ICG)<sup>1</sup>, it bears very important information: temperature of ICG (which falls within the range of  $T \approx (20\text{--}100) \times 10^6$  K, *i.e.*  $kT \approx 2\text{--}10$  keV) reflects the depth of the gravitational well of the cluster and hence its total mass. Such energetic electrons of ICG radiate via bremsstrahlung which can be seen in the X-rays. The observed X-ray surface brightness and deprojected X-ray temperature profiles can be used to determine the mass of intracluster gas and the total mass profiles in the cluster [1]. Thus, for a particular cluster, the ratio of the ICG mass and the total mass of this cluster should universally reflect the ratio of cosmological density parameters  $\Omega_b/\Omega_m$ , where  $\Omega_b$  is independently constrained by the primordial nucleosynthesis [2] and the observations of anisotropies in the Cosmic Microwave Background (CMB) by *e.g.* [3, 4]. This sort of information underlies our study.

## 2. The method and the sample

The gas mass fraction of a given cluster is defined as a ratio of the mass of X-ray emitting gas to the total mass of a cluster, *i.e.*,  $f_{\text{gas}} = M_{\text{gas}}/M_{\text{tot}}$ . The mass of the gas,  $M_{\text{gas}}$ , is estimated from the X-ray surface brightness, while the total mass,  $M_{\text{tot}}$ , can be obtained by assuming that the gas is in hydrostatic equilibrium with the cluster Navarro–Frenk–White (NFW) potential [5]. The gas mass density profile is often approximated by spherical isothermal  $\beta$  model [6], in which the 3-dimensional electron number density  $n_e$  can be written as

$$n_e(r) = n_{e0} \left( 1 + \frac{r^2}{r_c^2} \right)^{-3\beta/2}, \quad (1)$$

where  $n_{e0}$  is the central electron number density,  $r$  is the radius from the center of the cluster,  $r_c$  is the core radius of the intracluster gas and  $\beta$  is a power law index.

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<sup>1</sup> It is hot because it was heated during the cluster formation and did not have enough time to cool.

Theoretical formula for the gas mass fraction has the following form:

$$f_{\text{gas}}^{\text{th}}(z) = \frac{KA\gamma b_0(1 + \alpha_b z)}{1 + s_0(1 + \alpha_s z)} \frac{\Omega_b}{\Omega_m} \left[ \frac{D_A^{\Lambda\text{CDM}}(z)}{D_A(z)} \right]^{1.5}, \tag{2}$$

where seven parameters, further collectively denoted as  $\tilde{p} = \{K, A, \gamma, \sigma_0, b_0, \alpha_s, \alpha_b\}$  are related to the details adopted in modelling procedure for the cluster gas mass fraction (see [7] and [8] for further discussion). We treat them as nuisance parameters in our analysis. The angular diameter distance  $D_A(z) := \frac{1}{1+z} \frac{c}{H_0} \int_0^z \frac{dz'}{E(z')}$ , has been calculated in  $\Lambda$ CDM fiducial model ( $E(z)^2 = \Omega_m(1+z)^3 + \Omega_\Lambda$ ), as well as for two other cosmological scenarios. First one is the quintessence model in which the dark energy equation of state  $p = w\rho$  has constant  $w$  coefficient ( $E(z)^2 = \Omega_m(1+z)^3 + \Omega_Q(1+z)^{3(1+w)}$ ). The second one allows for temporal evolution of the  $w$  parameter according to Chevalier–Polarski–Linder model  $w(z) = w_0 + w_a \frac{z}{1+z}$  [9] and the expansion rate in this model is  $E(z)^2 = \Omega_m(1+z)^3 + \Omega_Q(1+z)^{3(1+w_0+w_a)} \exp \frac{-3w_a z}{1+z}$ . Now, the point is that for dynamically relaxed clusters,  $f_{\text{gas}}$  should evolve very little with redshift (or even not at all), as it was indicated from hydrodynamic simulations of cluster formation [10]. Thus, comparison between theoretical predictions for  $f_{\text{gas}}^{\text{th}}$  with the apparent evolution of  $f_{\text{gas}}^{\text{obs}}$  measurements can be used as a cosmological tool [7]. Namely, the cosmological parameters can be adjusted so that any trend of  $f_{\text{gas}}^{\text{obs}}$  with redshift vanishes. Because our goal is to constrain density parameters  $\Omega_m$  and  $\Omega_b$ , we assumed fixed priors for the equation of state parameters as the best fits to the SNIa data [11].

We used the gas mass fractions  $f_{\text{gas}}(z)$  for 42 hot and dynamically relaxed galaxy clusters having redshifts within the range of  $0.05 < z < 1.1$ . Data for these clusters were obtained by Allen [7] from the Chandra X-ray observations. Figure 1 shows the  $f_{\text{gas}}^{\text{obs}}$  which we used.

Then, we minimized the  $\chi^2$  function

$$\chi^2 = \sum_{i=1}^{42} \frac{(f_{\text{gas}}^{\text{obs}}(z_i) - f_{\text{gas}}^{\text{th}}(z, \Omega_b, \Omega_m, \tilde{p}))^2}{\sigma_i^2} \tag{3}$$

as a function of  $\Omega_m$  and  $\Omega_b$ , marginalized over nuisance parameters  $\tilde{p}$ .

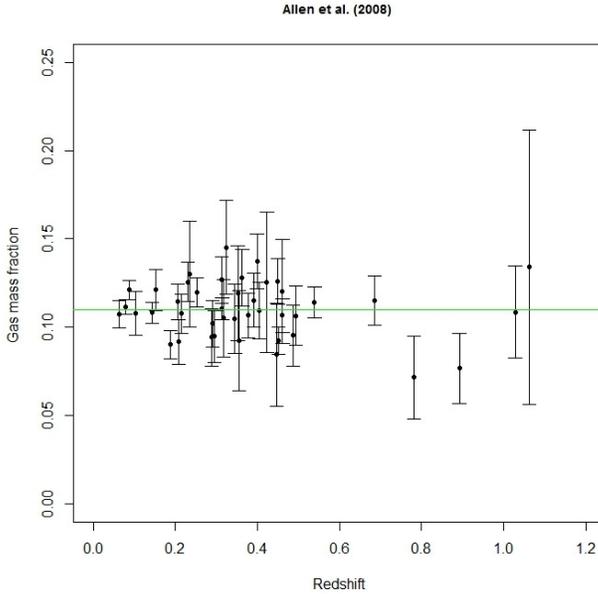


Fig. 1. Relation of  $f_{\text{gas}}^{\text{obs}}(z)$  for 42 clusters taken after [7].

### 3. Results and discussion

Results for the quintessence and the CPL model (the confidence regions around the central fits on the  $(\Omega_m, \Omega_b)$  parameters plane) are shown respectively in the top and in the bottom panel of Fig. 2. The values:  $\Omega_m = 0.301 \pm 0.086$ ,  $\Omega_b = 0.042 \pm 0.011$  in the quintessence scenario and  $\Omega_m = 0.268 \pm 0.094$ ,  $\Omega_b = 0.038 \pm 0.012$  for time-varying equation of state CPL scenario should be compared with the results obtained with other, independent techniques. The most recent one is from Planck data, based on the analysis of CMB anisotropies [3] which gives:  $\Omega_m = 0.315 \pm 0.016$ ,  $\Omega_b = 0.0455 \pm 0.0003$ . Comparing these values with Fig. 2, one can see perfect agreement — Planck results lie within the one-sigma regions obtained by us from gas mass fraction  $f_{\text{gas}}$  data for clusters.

Our results demonstrate that galaxy clusters are promising as a cosmological probe complementary to other techniques like supernovae Ia, CMB or BAO. As it was shown in [12, 13], strong gravitational lensing systems are also a reliable alternative cosmological tool that, additionally, may help to break degeneracy existing between dark energy parameters [13, 14]. A work in this direction using the clusters and the lenses is in progress.

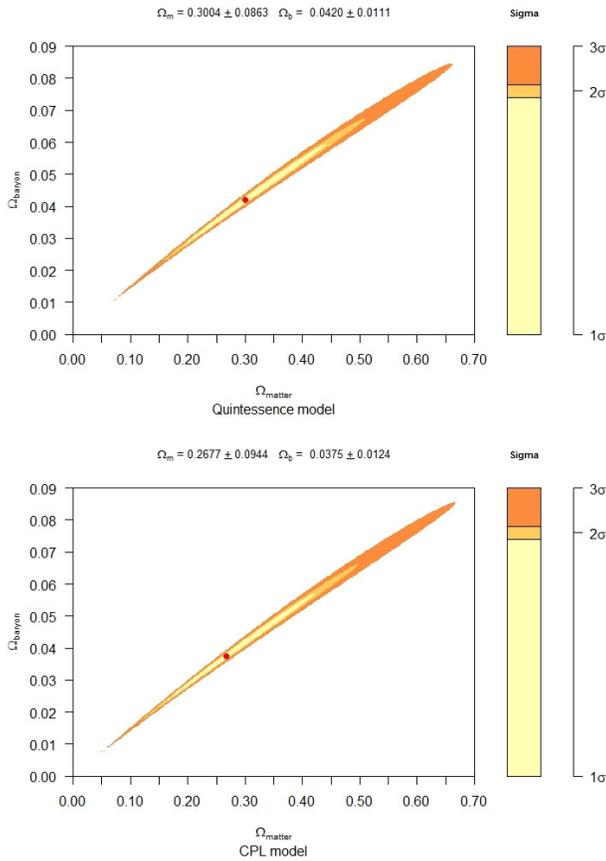


Fig. 2. Top panel: Fits of baryonic and total mass density parameters in the quintessential Universe. Bottom panel: Fits of baryonic and total mass density parameters in the Universe with evolving cosmic equation of state (CPL parametrization).

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