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The new fundamental plane dictating galaxy cluster evolution

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Abstract. In this study, we show that the characteristic radius r_s, mass M_s, and the X-ray temperature, T_X, of galaxy clusters form a thin plane in the space of $(\log r_s, \log M_s, \log T_X)$. This tight correlation indicates that the cluster structure including the temperature is affected by the formation time of individual clusters. Numerical simulations show that clusters move along the fundamental plane as they evolve. The plane and the cluster evolution within the plane can be explained by a similarity solution of structure formation. The angle of the plane shows that clusters have not achieved "virial equilibrium". The details of this study are written in Fujita *et al.* (2018a,b).

Keywords. galaxies: clusters: general — large-scale structure of universe

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1. Fundamental plane

The structure of galaxy clusters can be represented by the NFW profile (Navarro *et al.* 1997):

$$\rho_{\rm DM}(r) = \frac{\delta_c \rho_c}{(r/r_s)(1+r/r_s)^2} \,. \tag{1.1}$$

The characteristic density r_s and mass M_s, which is the mass inside r_s, include information of cluster formation history (e.g. Wechsler *et al.* 2002; Zhao *et al.* 2003). For example, older clusters are more concentrated. Since the X-ray temperature reflects cluster structure, it should also be affected by cluster formation history. Thus, we studied the relation among r_s, M_s, and T_X for the CLASH cluster sample (Donahue *et al.* 2014; Umetsu *et al.* 2016). We found that clusters form a plane (Fig. 1a), which means that

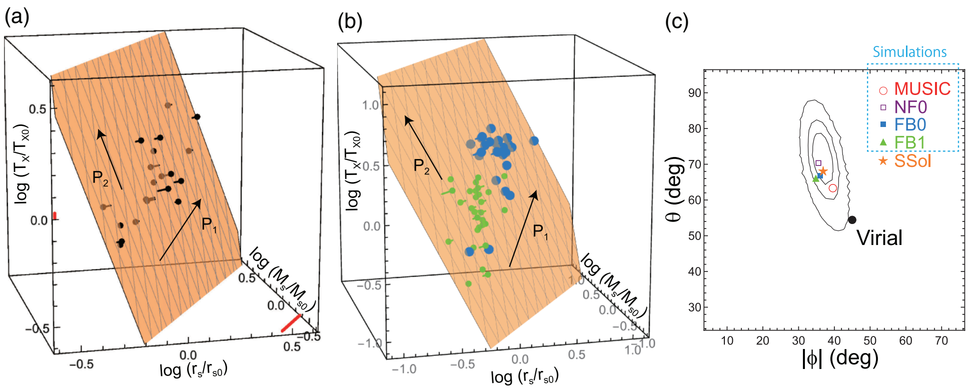

Figure 1. (a) CLASH clusters distributed on the fundamental plane. (b) Distribution of simulated clusters (blue: $z=0$, green: $z=1$). (c) Direction of the plane normal. While CLASH results (contours) are inconsistent with virial equilibrium (black dot), they are consistent with simulation results and the similarity solution (SSol). Figures are reconstructed from Fujita *et al.* (2018a).

T_X is actually determined by the formation history. Numerical simulations confirmed the plane and showed that clusters evolve along the plane in the direction of P_1 (Fig. 1b). We also found that the direction of the plane normal is not consistent with virial equilibrium ($T_X \propto M_s/r_s$; Fig. 1c).

2. Discussion

In Fujita *et al.* (2018a), we showed that the properties of the plane can be explained by a similarity solution by Bertschinger (1985). The solution shows that clusters are not in virial equilibrium because of matter accretion. It predicts a relation, $T_X \propto M_s^{3/2}/r_s^2$, that is consistent with observations and simulations (SSol in Fig. 1c). Moreover, it can also explain the direction of the cluster motion on the plane (P_1 in Fig. 1b).

The reason why clusters form a plane is the following. In the universe, smaller (less massive) density perturbations tend to have larger amplitudes (first dimension). However, there is a dispersion about the relation. For example, there is a range of mass scale for a given amplitude. This introduces another dimension and makes the planar distribution.

The well-known mass-temperature relation of clusters ($M_{200} \propto T_X^{3/2}$) can also be explained by the fundamental plane and the mass dependence of halo concentration without assuming that clusters are in virial equilibrium Fujita *et al.* (2018b).

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