

Gravitational Potential Estimator for Galaxy Clusters

An alternative to the observable-mass scaling relations

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1. Motivation

Ideally, to constrain cosmology using clusters we want to measure the abundance of observable signals from clusters, e.g. constraining cosmology through direct comparison of the cluster temperature function predicted from theory against observations. The current paradigm of cluster cosmology relies on estimating the cluster mass function from cluster observables via well-calibrated observable-mass relations. Instead of focusing on cluster mass, alternatively we can characterize clusters by their gravitational potential, a quantity which is also well predicted by theory. This has several advantages over mass (Angrick & Bartelmann 2009), e.g.,

- Observable quantities depend directly on the gravitational potential.
- The shape of gravitational potential is more spherical than the matter distribution, which may lead to smaller scatter in observable scaling relations.

In this study we propose a new way to characterize gravitational potential of clusters by introducing a gravitational potential estimator using intracluster gas profiles.

2. The Estimator

Following Churazov et al. (2008, 2010), our estimator for the gravitational potential difference for clusters is based on hydrostatic equilibrium,

$$\nabla\phi = -\frac{\nabla P}{\rho_g}$$

where ϕ is the gravitational potential and P and ρ_g are the pressure and density of the intracluster gas. Integrating by parts and assuming ICM is an ideal gas,

$$\phi(r_2) - \phi(r_1) = -\frac{kT}{\mu m_H} \Big|_1^2 - \int_{r_1}^{r_2} \frac{kT}{\mu m_H} \frac{d \ln \rho_g}{dr} dr$$

where T is the gas temperature, $\mu = 0.59$ is the mean molecular weight for the intracluster plasma and m_H is the mass of a hydrogen atom. We have assumed spherical symmetry when we calculate the integral. We denote the right hand side of the above as

$$\Delta\psi \equiv -\frac{kT}{\mu m_H} \Big|_1^2 - \int_{r_1}^{r_2} \frac{kT}{\mu m_H} \frac{d \ln \rho_g}{dr} dr$$

which we call it the estimator of the gravitational potential of the cluster.

3. Testing the Estimator

The test our proposed estimator, we employ high-resolution cosmological hydro simulations of 16 clusters using the ART code (Nagai et al. 2007a,b) with two sets of gas physics: *Non-Radiative* (NR), and *Cooling plus Star Formation* (CSF).

We compare the real potential difference $\Delta\phi$ with our estimator $\Delta\psi$ by fitting a scaling relation,

$$\log \Delta\phi = \alpha \log (\Delta\psi / \Delta\psi_0) + \log \Delta\phi_0$$

where we set $\Delta\psi_0 = 20 \text{ keV} / \mu m_H$, and we fit using linear-least-square for α and $\log \Delta\phi_0$.

4. Results

In the following sections we investigate the robustness of this estimator.

4.1 Dependence on Cluster physics

Upper panels of Fig. 1 shows the $\Delta\phi - \Delta\psi$ scaling relations for the CSF (blue circles) and NR (red triangles) clusters, for the inner radius r_1 taken to be $0.2 r_{500}$ and $0.4 r_{500}$, and the outer radius r_2 fixed at r_{500} . The lower panels show the corresponding residuals. The difference between the CSF and NR relations is small, and for each case the scaling between the true potential difference and the estimated potential difference is very good, with lognormal scatter varying from 9 to 14%.

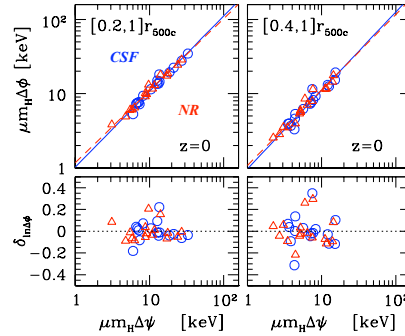


Figure 1

4.2 Hydrostatic Equilibrium

Setting $[r_1, r_2] = [0, r_{500}]$ gives a large difference between the CSF and NR clusters as shown in Fig. 2. This is because of the strong gas rotation in the cluster core induced by cooling (e.g. Lau et al. 2010). Including pressure support due to gas motions resulted in essentially no difference between the CSF and NR relations. Scatter in both relations also decrease to $\sim 5\%$. Our estimator is robust to dissipative gas physics if non-thermal pressure support is included or the cluster core is excluded.

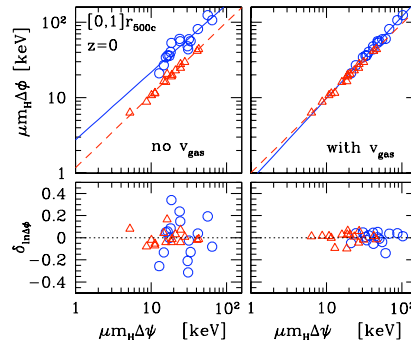


Figure 2

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4.3 Redshift Evolution

Fig. 3 shows the $\Delta\phi - \Delta\psi$ relation for $z=0.6$ and 1.0 for $[r_1, r_2] = [0.2 r_{500}, r_{500}]$. There is little evolution in the relation; and the scatters are comparable to the $z=0$ case (cf. Fig. 1.)

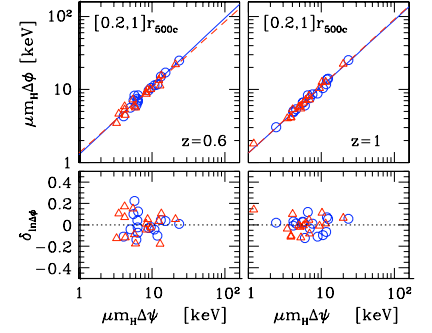


Figure 3

4.4 Choice of radial separation

To test whether the estimator is sensitive to the choice of the inner and outer radii, we take $[r_1, r_2]$ to be metric distances (left panel) and multiples of the NFW scale radius r_s instead of fractional multiples of r_{500} in Fig. 4. Both give a low scatter $\Delta\phi - \Delta\psi$ relation. In general the larger the separation the less is the scatter (cf. Fig. 1).

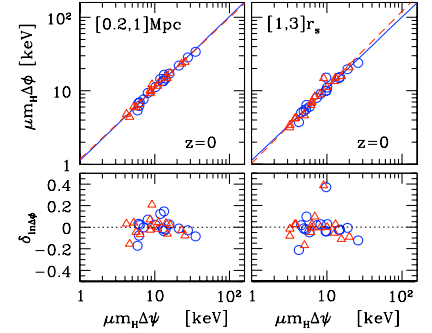


Figure 4

5. Summary

A new low-scatter estimator for the gravitational potential of cluster is proposed using the temperature and density profiles of the intracluster gas based on the assumptions of hydrostatic equilibrium and spherical symmetry. Using high resolution cosmological simulations of galaxy clusters, we show that the scaling relation between this estimator and the true gravitational potential has a small intrinsic scatter, and it is insensitive to baryon physics outside the cluster core, varies weakly with redshift, and it is relatively independent of the choice of radial range. The results presented here provide a way for using the cluster potential function as an alternative to the cluster mass function in constraining cosmology using clusters.

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