Studying the Nature of Dark Energy with Galaxy Clusters

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Summary. We report on the status of our effort to constrain the nature of dark energy through the evolution of the cluster mass function. *Chandra* temperature profiles for 31 clusters from a local cluster sample are shown. The X-ray appearance of the proto supermassive binary black hole at the center of the cluster Abell 400 is described. Preliminary weak lensing results obtained with Megacam@MMT for a redshift $z = 0.5$ cluster from a distant cluster sample are given.

1 Introduction

Understanding the nature of dark energy is one of the major goals of contemporary cosmological and particle physics. The fate of the universe seems to be entirely determined by dark energy and a deeper understanding of its properties may shed light on the unification of general relativity and quantum theory.

At the moment, astronomical measurements seem most likely to provide further information about dark energy. Measurements of the evolution of the galaxy cluster abundance are among the most promising tools; they have the potential to yield tight constraints on the equation of state of dark energy. Here, we report on the status of our project to measure the evolution of the cluster mass function with very high quality observations of moderately sized local and distant cluster samples.

2 Local Cluster Sample

X-ray selection is well suited for the construction of complete cluster samples useful for cosmological tests, because the X-ray luminosity of clusters is tightly correlated with their total gravitational mass [1, 2]. The HIghest X-ray FLUx Galaxy Cluster Sample (*HIFLUGCS*) has been selected from

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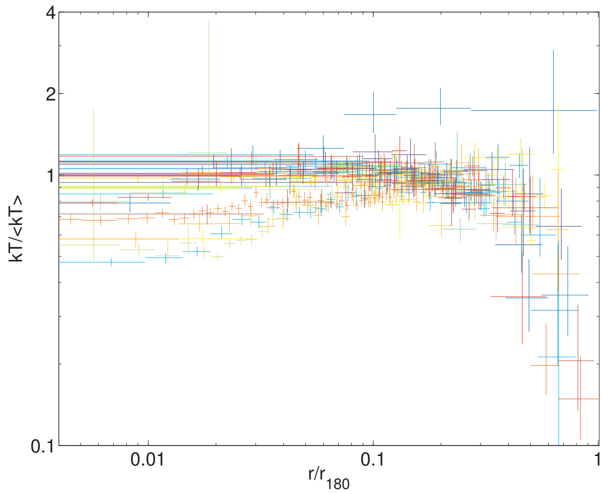

Fig. 1. Normalized intracluster gas temperature profiles for 31 clusters measured with *Chandra*.

the *ROSAT* All-Sky Survey and contains the X-ray brightest galaxy clusters in the sky, excluding ±20 deg around the Galactic plane as well as the regions of the Virgo cluster and the Magellanic clouds [1]. All clusters have been re-observed with *Chandra* and almost all with *XMM-Newton*. We are currently analyzing these data to determine the most precise local X-ray galaxy cluster mass function.

Currently, cosmological constraints from X-ray galaxy clusters are limited by systematic effects, especially those affecting the total mass determination. The high quality *Chandra* and *XMM-Newton* observations now allow us to study the gas and temperature structure of clusters in much greater detail than previously possible.

Fig. 1 shows the normalized temperature profiles of about half of the *HIFLUGCS* clusters (Hudson et al., in prep.). A log scale is used to emphasize details of the innermost regions, showing *Chandra*'s unrivaled spatial resolution. This plot gives one of the most detailed views into the statistics of central temperature structures obtained to date (see also [3, 4, 5]). As expected, there is no universal temperature profile in the inner part – some profiles drop towards the center, others stay flat. Usually, the former are identified as relaxed clusters and the latter as merging clusters. More interesting is the fact that even the relaxed clusters do not appear to show a universal profile in the inner parts – quite a large spread becomes obvious in this log scale plot. This seems contrary to the universal profile for relaxed clusters that [3] found, although they used only 6 clusters. Scatter was also seen by [4] when they analyzed 13 clusters and, in fact, considering the complicated physics in cluster centers, non-universality might be expected. Note that these central regions account for only a small fraction of the total cluster mass.

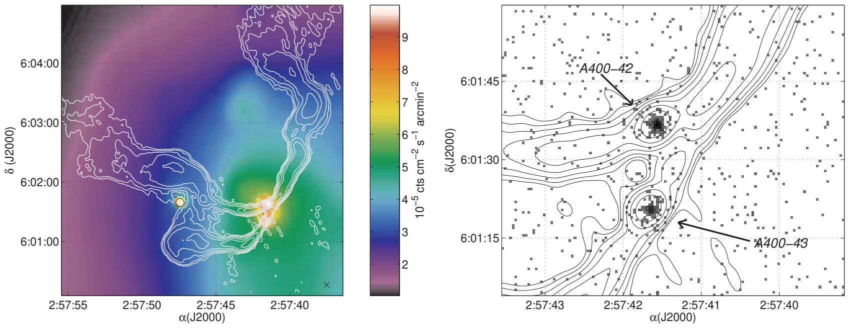

Fig. 2. *Left:* Adaptively smoothed *Chandra* image of the central region of Abell 400 [6]. Overlaid are the 4.5 GHz VLA radio contours. *Right:* Zooming further into the very center of the unsmoothed *Chandra* image.

The outer radial region where much of the cluster mass resides ($> r_{180}/2$) is rather compressed in this plot. There seems to be a clear indication for a temperature drop towards larger radii as observed by a number of previous works but the uncertainties become large, too. We aim to tighten these constraints by cross correlating the *Chandra* data with our *XMM-Newton* results for the same clusters, taking advantage of *XMM-Newton*'s higher throughput and larger field-of-view.

Analyzing the data for all clusters in this sample, it is no surprise that exciting details about individual clusters are discovered. As an example, we show in Figs. 2 the very center of the galaxy cluster A400 [6], where the well-known radio source 3C75 – exhibiting a pair of double radio jets – resides. Both AGNs, separated by 15 arcsec corresponding to a projected separation of 7 kpc, are detected separately for the first time in X-rays. Detailed analysis of the X-ray data reveals further evidence that the two AGNs are physically close to each other and form a bound system – a proto supermassive binary black hole moving through the intracluster medium at the supersonic speed of about 1200 km/s.

3 Distant Cluster Sample

The 400 Square Degree (400d) *ROSAT* Survey (Burenin et al., in prep.) is the continuation of the 160d Survey [7, 8]. It contains clusters serendipitously detected in basically all useful *ROSAT* PSPC pointed observations. The covered search volume is larger than the volume of the entire local ($z < 0.1$) Universe. A complete subsample of the 41 most luminous, most distant clusters has been observed with *Chandra* in a large program.

Since the fraction of galaxy clusters undergoing a major merger is expected to increase with redshift [9], it would be ideal to have additional cluster mass estimates – independent of their dynamical state – for these distant

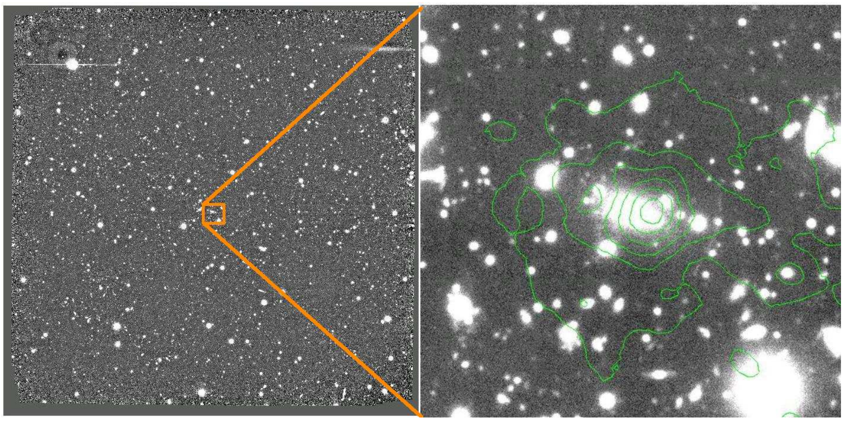

Fig. 3. *Left:* Coadded Megacam r'-band image of a $z = 0.5$ cluster (box size $\sim$30 arcmin). *Right:* Zoom into the very center. *Chandra* X-ray surface brightness contours are overlaid. Note the arc to the right of the bright central galaxy.

clusters. Therefore, we have engaged in a complete weak lensing follow-up of all 41 clusters. Observations of a redshift $z = 0.5$ cluster are shown as an example in Figs. 3 (Erben et al., in prep.). The images were taken at the 6.5m MMT telescope with the 36-CCD Megacam camera. The images of the 25 dithered observations were reduced and combined with the GaBoDS pipeline [10], adapted to Megacam. Zooming into the very center, a giant arc is detected. A preliminary weak lensing analysis shows that the cluster is clearly detected (Fig. 4), demonstrating for the first time that Megacam is ideally suited to perform weak lensing measurements for distant clusters.

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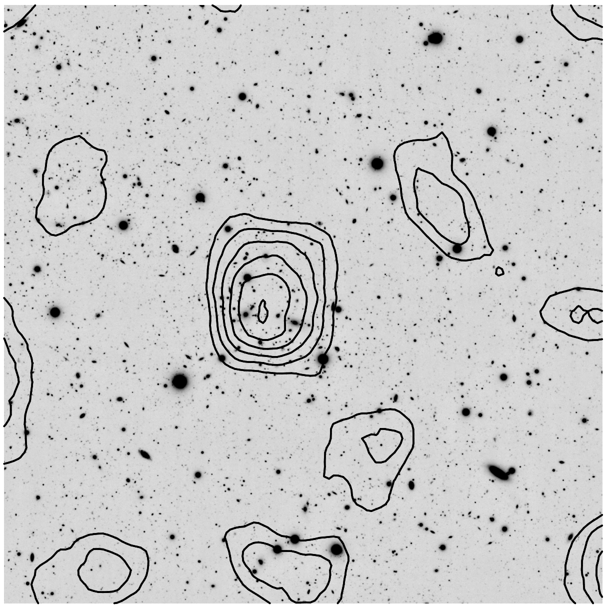

Fig. 4. Preliminary weak lensing contours (box size ∼10 arcmin). Contours indicate signal-to-noise ratio of 1.0, 1.5, .., 3.5; the cluster is clearly detected.

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