Cluster Cosmology in the *Chandra* Era: Potential, Problems & Prospects

An incomplete & biased sampling

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Overview

• Cosmology & clusters in principle
• The real world according to Chandra
• Dealing with it
• Where we stand
• Prospects
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Leon van Speybroeck
Cosmological Observables

Two paths to knowledge of recent cosmic history:

• Geometry:
  * Measure (something that depends on) coordinate distance vs. redshift: $D(z) \sim \int dz'/H(z')$
  * Examples: Standard candle, ruler, baryon fraction

• Growth:
  * Measure rate of growth of cosmic structure:
    \[ \delta_0 = g(a) \delta_a ; \quad g(a) \sim \Omega_m H(a) \int da'/{a'H(a')}^3 \quad (a = 1/(1+z)) \]
  * Examples: Cosmic shear, Cluster abundance
Cosmological Observables

Distance: \( D(z) \sim \int dz' / H(z') \)

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\([\text{e.g.: } \text{SNe, BAO, Cluster } f_{\text{baryon}}]\)

\[ g(a) \sim \Omega_m H(a) \int da' / \{ a' H(a') \}^3 \]

\([\text{e.g.: cluster abundance, cosmic shear}\]

No Dark Energy
\( \Lambda, \text{CMB-matched} \)
\( w=0.9, \text{CMB-matched} \)

Figures: DETF Report
Albrecht, Kolb et al., 2006

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Eight Years of Chandra
25 October 2007
Cosmological Observables

Distance: \( D(z) \sim \int dz'/H(z') \)

\[ e.g.: \textit{SNe, BAO, Cluster } f_{\text{baryon}} \]

Growth: \( g(a) \sim \Omega_m H(a) \int da'/\{a'H(a')\}^3 \)

\[ e.g.: \textit{galaxy clusters, cosmic shear} \]

Extreme Precision Required!

\( \text{Figures: DETF Report} \)

Albrecht, Kolb et al., 2006

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Why Clusters for Cosmology? (The Elevator Pitch)

- Selected clusters can be geometric standards ($SZE, f_{\text{baryon}}$)
- Cluster distribution ($dN/dz$ and $P(k)$) is sensitive to both distance ($\frac{dV}{d\Omega}dz$) and growth history:
  - Physically independent of "distance-only" metrics
  - In principle allows test of GR: $D(z)$ & $g(z)$ should match
- Clusters are 'easy' to find (if you know how to look)
- Cluster physics is relatively simple (just ask McNamara & Burns!):
  - Dominated by gravity
  - Amenable to simulation
- Complementary to other cosmological probes
The Cluster Hubble Diagram

Two measures of cluster distance:

• X-ray \((S_X)\) + Microwave SZE \((\Delta T_0)\):
  \[ d \sim \frac{\Delta T_0^2}{S_X} \]  [Bonamente, Joy et al.]

• Baryon fraction:
  \[ d \sim f_{\text{gas}}^{2/3}; \quad (f_{\text{gas}} + f_{\text{stars}}) = \Omega_b / \Omega_m = \text{constant} \]
  NB: also yields \(\Omega_b / \Omega_m\) [Allen et al.]
Clusters
Trace
Structure
Formation

- Cosmic structure grows via gravitational instability
- The rate of growth is sensitive to the cosmic expansion history & thus to the cosmological model
- The cluster population (e.g. $dN/dVdM$) is sensitive to cosmology
- Key observational requirement: measure cluster masses
  [Henry, Reiprich & Boehringer, Mohr et al., Vikhlinin et al., Allen & Mantz...]

Andrei Kravtsov
Cluster complexity: merging

Clowe, Markevtich et al. 2006

The Bullet Cluster
(Magellan + Chandra)

Dark Matter
(from lensing)

Intracluster plasma
(from Chandra)
Cluster complexity: AGN heating

The Perseus cluster as seen by Chandra (Fabian et al. 2006)
Clusters in reality according to Chandra

Chandra (& XMM) have shown that clusters aren’t so simple:

• Both subtle & spectacular complexity in ICM density
  ==> mergers, fronts & AGN heating (Markevitch, Vikhlinin, McNamara, Fabian...)
  ==> evolution of spatial structure (Jeltema, Maughan)
  ==> ‘absence’ of high-z ‘bright’ (cool) cores (Vikhlinin)

• Spectral evidence against simple cooling models
  ==> AGN heating (Peterson...)

• Confirmation of ‘non-self-similar’ scaling relations (e.g. $L_X$ vs $T$)
  ==> (e.g.) non-gravitational thermodynamics (Vikhlinin, Markevitch, Allen, Ettori..)

• Scatter in mass/observable relations (Maughan, Mantz, O’Hara)

• Variation of $f_{\text{baryon}}$ with cluster mass/ temperature (Allen, Vikhlinin)
The message from Chandra

In sum:
• Gravity is *not* solely responsible for cluster structure & evolution
• Clusters are not, in general, ‘relaxed’

So, can we deal with this?:

*Can we measure cluster masses well enough to do cosmology?*
Cluster Mass Proxies

- Mass is not directly observable, so use observable proxies: \( N_{\text{gal}} \), \( \sigma_{\text{opt}} \), \( Y_{\text{SZE}} \), \( L_X \), \( T_X \), \( M_{\text{gas}} \), \( Y_X \) ...
- One must know both evolution & scatter in mass-observable relations to do cosmology (& knowing physics would also help!)
- So far, evolution in X-ray observables seems modest, generally consistent with 'gravity only' self-similar picture
- Until recently, scatter seemed large:
  - Optical richness: \( \sim x2 \) scatter at fixed mass (SDSS better?)
  - Millimeter: \( Y_{\text{SZE}} \sim 30\% \) (est.)
  - Weak lensing: \( \sim 40\% \) (est)
  - X-ray: \( \delta M/M \) from \( L_X \) \( \sim 50\% \); \( T_X \) \( \sim 15\% \)
- Refined X-ray mass proxies show much lower scatter
Accurate & Precise Mass Estimator (Kravtsov, Vikhlinin & Nagai 2006)

- In N-body+hydro simulations, $Y_X = M_{\text{gas}(r_{500})} T_X$ is an accurate mass proxy.
- Scatter $\sigma_M = 7\%$, including unrelaxed clusters.
- Must ignore core (<0.15$r_{500}$).
- Observed M-Y relation ~15% lower than simulated (non-thermal pressure).
- In simulations, z-evolution close to self-similar.

Kravtsov et al. 2006
L_X as a Mass Estimator
(Maughan 2007)

- Conventional L_X/M relation shows large scatter (σ_M ~ 40-60%)
- Excluding cluster core (r<0.15r_500) yields tight L_X/Y_X rel'n, & σ_Y ~ 12%
- Even without accurate kT measure, expect L_X to measure mass to 16% if core is excluded (cf O’Hara et al. 2006)
Recent Cosmological Results from Clusters

- **Improved constraints on $\sigma_8$**
  * Fine-tuning WMAP results (Henry, Evrard et al.)

- **Latest from geometric methods**
  * CXO/SZE (Bonamente, Joy et al)
  * $F_{\text{gas}}$ (Allen, Rapetti et al.)

- **Latest on growth of structure**
  * Mantz et al. (next talk)
  * Vikhlinin et al. (coming soon)
Results from SZE & Chandra

Bonamente, Joy et al. 2006

$H_0 = 77.6 \pm 4 \pm 9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ($\Lambda$CDM $\Omega_m = 0.3$)

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Fig. 4.— Angular diameter distances of the 38 clusters, using the simple $r < 100$ kpc-cut isothermal $\beta$ model (green) and the isothermal $\beta$ model (red) described in Section 4.2. The error bars are the total statistical uncertainties, obtained by adding the X-ray and SZE data modelling uncertainties (Table 4, Table 5) and the additional sources of random error described in Section 3.3 and Table 3. The systematic errors of Table 3 are not shown. Dashed lines are the best-fit angular diameter curves using the best-fit Hubble constant $H_0 = 77.6$ km s$^{-1}$ Mpc$^{-1}$ (green) and $H_0 = 75.7$ km s$^{-1}$ Mpc$^{-1}$ (red) and $\Omega_M = 0.3$, for $\Omega_L = 0.7$. In black are the distances obtained with the hydrostatic equilibrium model of Section 4.1 (Figure 3).

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Read the fine print!
Results from Cluster $f_{\text{gas}}$

Allen et al. astro-ph/0706.0033

$\Omega_\Lambda > 0$ @ 99.99% confidence, $f_{\text{gas}}$ + priors

$\sigma_w = 0.07$ ($\Omega_K = 0$ assumed)

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Figure 6. The 68.3 and 95.4 per cent (1 and 2σ) confidence constraints in the $\Omega_m, \Omega_\Lambda$ plane for the Chandra $f_{\text{gas}}$ data (red contours; standard priors on $\Omega_0h^2$ and $h$ are used). Also shown are the independent results obtained from CMB data (blue contours) using a weak, uniform prior on $h$ ($0.2 < h < 2.0$), and SNIa data (green contours; the results for the Davis et al. 2007 compilation are shown). The inner, orange contours show the constraint obtained from all three data sets combined (no external priors on $\Omega_0h^2$ and $h$ are used). A flat CDM model is assumed, with the curvature included as a free parameter.

Figure 8. The 68.3 and 95.4 per cent (1 and 2σ) confidence constraints in the $\Omega_m, w$ plane obtained from the analysis of the Chandra $f_{\text{gas}}$ data (red contours) using standard priors on $\Omega_0h^2$ and $h$. Also shown are the independent results obtained from CMB data (blue contours) using a weak, uniform prior on $h$ ($0.2 < h < 2.0$) and SNIa data (green contours; Davis et al. 2007). The inner, orange contours show the constraint obtained from all three data sets combined: $\Omega_m = 0.253 \pm 0.021$ and $w = -0.98 \pm 0.07$ (68 per cent confidence limits). No external priors on $\Omega_0h^2$ and $h$ are used when the data sets are combined. A flat cosmology with a constant dark energy equation of state parameter $w$ is assumed.
Key Questions

• How good are absolute mass estimates?
  * e. g., X-ray/weak-lensing comparison
• Are X-ray selected samples fair?
  * e. g., compare to SZE- and optical selection
• How do we tell which clusters are 'relaxed'?
• How do mass-observable relations evolve?
• How do mergers & feedback affect scatter & evolution of mass-observable relations?
More data coming soon

- **SZ surveys for clusters:**
  * SPT: 4000 deg$^2$, > 10$^4$ clusters, 1$^{st}$ light ’07
  * ACT: ~1000 deg$^2$, 1$^{st}$ light ’07
  * Planck: All-sky, launch 2008
  * ALMA:

- **X-ray surveys:**
  * SRG-e-ROSITA: ~half-sky, S$_X$ > 4e-14 cgs, > 8 x 10$^4$ clusters, launch 2011
  * Others?

- **Optical surveys:**
  * LST: all-sky, 1$^{st}$ light ~2014
Future X-ray Observations

Near-term:

- *Chandra* observations of ~100 higher-z clusters (~5 Ms) from, e.g., SZ survey) can:
  * Measure evolution & scatter of mass proxies
  * Improve cosmological constraints from growth-of structure (better masses)
- *e-ROSITA* will provide ~x100 more X-ray selected clusters than we have now (most @ z < 1)
Future X-ray Observations

Longer term:

- Constellation-X is essential to resolve bulk motions & turbulence in the ICM to \( z=1 \):
  - Size (collecting area) matters!
  - Reduce mass systematics in \( f_{\text{gas}} \) samples
  - Improve mass-observable relations for structure growth experiments
- Future low-background, high-angular-resolution mission would reveal very first clusters at \( z \sim 2 \)
Conclusions

• Cluster studies have already contributed to our knowledge of cosmology & structure formation.
• As with every cosmological measurement, systematic errors dominate; progress is rapid:
  * Chandra has vastly improved cluster mass metrics
  * Better absolute normalization of mass-obs. rel’n is needed & coming (lensing, SZE, future observatories)
• Chandra has shown us clusters are complicated, but (so far, it seems) not too complicated.
  * We now know mergers AGN feedback affect ICM
  * We need to understand the physics & quantify effects on mass estimates