X-ray Cluster Cosmology

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Galaxy clusters: the largest objects in the Universe

By comparing the observed distribution, evolution and structure of galaxy clusters with cosmological model predictions, we can constrain the nature of dark energy, gravity, dark matter, neutrino properties, inflation …
The importance of X-ray observations

Most baryons in clusters (like Universe) are in form of gas, not stars (6-10\(\times\)). In clusters, gravity squeezes gas, heating it to X-ray temperatures (\(10^7-10^8\) K).

Clusters are easy to identify using X-ray observations \(\rightarrow\) clean, complete cluster catalogues (critical for cosmology with cluster counts).

X-ray observables (brightness, temperature) relate to the total mass (dark plus baryonic) via relatively simple physics that can be well modelled by simulations.
Outline of talk:

1) Cosmological constraints from measurements of the baryonic mass fraction in the largest dynamically relaxed clusters (aka the fgas test).
   (Cosmology with `cherry picked’ cluster samples, as with SNIa)
   → constraints on \( \Omega_m, \Omega_{de}, w \).

2) Cosmological constraints from cluster counts.
   (Cosmology with complete, statistical cluster samples)
   → constraints on \( \Omega_m, \Omega_{de}, w, \sigma_8, \text{gravity (and } \Sigma m_\nu) \).

X-ray Cluster Cosmology

1. The baryonic mass fraction


See also e.g. White & Frenk ’91; Fabian ’91; Briel et al. ’92; White et al ’93; David et al. ’95; White & Fabian ’95; Evrard ’97; Mohr et al ’99; Ettori & Fabian ’99; Roussel et al. ’00; Grego et al ’00; Allen et al. ’02, ’04; Ettori et al. ’03, ‘09; Sanderson et al. ’03; Lin et al. ’03; LaRoque et al. ’06 …
Constraining cosmology with $f_{\text{gas}}$ measurements

BASIC IDEA (White & Frenk 1991): galaxy clusters are so large that their matter content should provide a ~ fair sample of matter content of Universe.

Define:

- $f_{\text{gas}} = \frac{X\text{-ray gas mass}}{\text{total cluster mass}}$
- $f_{\star} = \frac{\text{stellar mass}}{\text{total cluster mass}}$

Then:

$f_{\text{baryon}} = f_{\star} + f_{\text{gas}} = f_{\text{gas}}(1+s)$

Since clusters provide ~ fair sample of Universe:

$f_{\text{baryon}} = b \frac{\Omega_b}{\Omega_m}$

$f_{\text{gas}} = \frac{b \Omega_b}{(1+s) \Omega_m}$
Constraining dark energy with $f_{\text{gas}}$ measurements

The measured $f_{\text{gas}}$ values depend upon the assumed distances to clusters as $f_{\text{gas}} \propto d^{1.5}$, which brings sensitivity to dark energy through the $d(z)$ relation (for clusters at $z > 0.2$). To use this information, we need to know the expected $f_{\text{gas}}(z)$.

What do we expect to observe?

Simulations: (non-radiative)

For large ($kT > 5\text{keV}$) clusters, we expect $b(z)$ and therefore $f_{\text{gas}}(z)$ to be approximately constant with $z$.

The precise prediction of $b(z)$ is a key task for hydro. simulations.
The observations

1.6Ms of Chandra data for 42 hot (kT>5keV), dynamically relaxed clusters spanning redshift range 0<z<1.1.

Selected on X-ray morphology: sharp central X-ray surface brightness peaks, minimal X-ray isophote centroid variations and high overall symmetry.

Restriction to hot, relaxed clusters minimizes all systematic effects.
Brute-force determination of $f_{\text{gas}}(z)$ for two reference cosmologies:

→ Inspection clearly favours $\Lambda$CDM over SCDM cosmology.
To quantify: fit data with model which accounts for apparent variation in $f_{\text{gas}}(z)$ as underlying cosmology is varied → find best fit cosmology.

$$f_{\text{gas}}(z) = \frac{KA\beta b(z)}{1 + s(z)} \left( \frac{\Omega_b}{\Omega_m} \right) \left[ \frac{d_A^{\text{LCDM}}(z)}{d_A^{\text{model}}(z)} \right]^{1.5}$$

For details see Allen et al. (2008).
Allowances for systematic uncertainties

Our analysis includes a comprehensive and conservative treatment of potential sources of systematic uncertainty (marginalized over in analysis).

1) The depletion factor (simulation physics, feedback processes etc.)

\[ b(z) = b_0 (1 + \alpha_b z) \pm 20\% \text{ uniform prior on } b_0 \text{ (simulation physics)} \]

\[ \pm 10\% \text{ uniform prior on } \alpha_b \text{ (simulation physics)} \]

2) Non-thermal pressure support in gas: (primarily bulk motions)

\[ \beta = \frac{M_{\text{true}}}{M_{\text{X-ray}}} \quad \text{10\% (standard) or 20\% (weak) uniform prior [1<\gamma<1.2]} \]

3) Baryonic mass in stars: define \( s = \frac{f_{\text{star}}}{f_{\text{gas}}} = 0.16h_{70}^{0.5} \)

\[ s(z) = s_0 (1 + \alpha_s z) \pm 30\% \text{ Gaussian uncertainty in } s_0 \text{ (observational uncertainty)} \]

\[ \pm 20\% \text{ uniform prior on } \alpha_s \text{ (observational uncertainty)} \]

4) Instrument calibration, X-ray modelling

\[ K \quad \pm 10\% \text{ Gaussian uncertainty} \]
Results ($\Lambda$CDM)

Including all systematics + standard priors:

$$(\Omega_b h^2 = 0.0214 \pm 0.0020, h = 0.72 \pm 0.08)$$

Best-fit parameters ($\Lambda$CDM):

$$\Omega_m = 0.27 \pm 0.06, \quad \Omega_\Lambda = 0.86 \pm 0.19$$

(Note also good fit: $\chi^2 = 41.5/40$)

Result limited by $b(z), K$ priors

Important
The low systematic scatter in the $f_{\text{gas}}(z)$ data

\[ \chi^2 \text{ for best fit acceptable.} \]

Intrinsic scatter is undetected.

68% upper limit on $f_{\text{gas}}$ scatter $\sigma_{f_{\text{gas}}} \sim 10\%$ (7% in distance).

(Consistent with expectations from hydro. simulations)

$f_{\text{gas}} \rightarrow$ precise tracer of expansion history (individually, better than SNIa).

$M_{\text{gas}} \rightarrow$ excellent mass proxy for hot, massive clusters.
Expanded sample: 3x more fgas data.
Automated target selection applied to archives.
Optimized X-ray analysis engine.
Improved external priors.
Blind cosmology analysis.

Mantz et al., in preparation.
Allen et al., in preparation.
Suzaku study of Perseus Cluster

Simionescu et al. 2011

Science (2011) 331, 1576
Suzaku Key Project data for Perseus Cluster

1Ms exposure
Simionescu et al., arXiv:1208.2990
Urban et al., in prep.
X-ray Cluster Cosmology

2. Cluster counts


See also e.g. Borgani et al. ’01; Reiprich & Bohringer ’02; Seljak ’02; Viana et al. ’02; Allen et al. ’03; Pierpaoli et al. ’03; Schuecker et al. ’03; Voevodkin & Vikhlinin ’04; Henry ’04; Dahle ’06; Mantz et al. ’08; Henry et al. ’09; Vikhlinin et al. ‘09; Rozo et al. ’10 ...
Measurements of the number counts of massive galaxy clusters, and especially their evolution with redshift, provides powerful, complementary constraints on cosmological parameters.
Ingredients for cluster count experiments 1

[THEORY] The predicted mass function of clusters, \( n(M,z) \), as a function of cosmological parameters (\( \sigma_8, \Omega_m, w \) etc).

[CLUSTER SURVEY] A large, clean, complete cluster survey with a well defined selection function.

Current leading work based on ROSAT X-ray surveys and the Sloan Digital Sky Survey (optical) + new SZ surveys.

[SCALING RELATION(S)] Tight, well-determined scaling relation(s) linking survey observable (e.g. \( L_x \)) and mass.
Ingredients for cluster count experiments 2

[THEORY] The predicted mass function of clusters, $n(M, z)$, as a function of cosmological parameters ($\sigma_8, \Omega_m, w$ etc).

[CLUSTER SURVEY] A large, clean, complete cluster survey with a well defined selection function.

Current leading work based on ROSAT X-ray surveys and the Sloan Digital Sky Survey (optical) + new SZ surveys.

[SCALING RELATION(S)] Tight, well-determined scaling relation(s) linking survey observable (e.g. $L_x$) and mass.
Cluster surveys based on RASS

BCS (Ebeling et al. ’98, ’00).  
z<0.3, Fx>4.4×10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}  
[northern sky: 201 clusters]

REFLEX (Bohringer et al ’04).  
z<0.3, Fx>3.0×10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}  
[southern sky: 447 clusters]

Bright MACS (Ebeling et al. ’09)  
z>0.3, Fx>2.0×10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}.  
[all-sky: 34 clusters]

All three surveys based on ROSAT All-Sky Survey (RASS) (0.1-2.4keV). To minimize systematics (associated with scaling relations) analysis limited to most luminous systems with Lx > 2.5×10^{44} h_{70}^{-2} \text{ erg s}^{-1} (238 clusters total).
Ingredients for cluster count experiments

[THEORY] The predicted mass function of clusters, $n(M,z)$, as a function of cosmological parameters ($\sigma_8, \Omega_m, w$ etc).

[CLUSTER SURVEY] A large, clean, complete cluster survey with a well defined selection function.

Current leading work based on ROSAT X-ray surveys and the Sloan Digital Sky Survey (optical) + new SZ surveys.

[SCALING RELATION(S)] Tight, well-determined scaling relation(s) linking survey observable (e.g. $L_x$) and mass.
Data used to measure scaling relations

3.4Ms of pointed Chandra and ROSAT observations for 94/238 survey clusters → measure $M_{\text{gas}}$, $T_x$, $Y_x$ at $r_{500}$ ($\leq 10$-$15\%$ mass proxies) and re-measure $L_x$.

$M_{\text{gas}}$ (measured at $r_{500}$) is our primary mass proxy: easy to measure + small (<10%) intrinsic scatter for clusters with $kT>5\text{keV}$ ($M=M_{\text{gas}}/f_{\text{gas}}$).
Analysis

To determine robust cosmological constraints one should solve simultaneously for the cosmology+scaling relations, accounting fully for survey biases and covariance, and marginalizing over systematic uncertainties.

This is best done using likelihood function that encompasses the entire theoretical model (mass function, cosmology, scaling relations).

Such analyses can be carried out efficiently using Markov Chain Monte Carlo (MCMC) methods.

For details see Mantz et al. (2010a).
Parameters, priors and allowances for systematics

Our analysis includes the following parameters and priors with conservative allowances for systematic uncertainties:

<table>
<thead>
<tr>
<th>Type</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmology (§3.1)</td>
<td>$H_0$</td>
<td>Hubble parameter $a,b$</td>
<td>N(72, 8)</td>
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<tr>
<td></td>
<td>$\Omega_b h^2$</td>
<td>Baryon density $b$</td>
<td>N(0.0214, 0.002)</td>
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<tr>
<td></td>
<td>$\Omega_c h^2$</td>
<td>Cold dark matter density</td>
<td></td>
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<td></td>
<td>$\ln(10^{10} A_S)$</td>
<td>Scalar power spectrum amplitude</td>
<td></td>
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<tr>
<td></td>
<td>$n_s$</td>
<td>Scalar power spectrum slope $b,c$</td>
<td>= 0.95</td>
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<tr>
<td></td>
<td>$\tau$</td>
<td>Optical depth to reionization $c$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$A_{SZ}$</td>
<td>Sunyaev-Zel’dovich signal amplitude $c$</td>
<td>U(0, 2)</td>
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<tr>
<td></td>
<td>$w$</td>
<td>Constant dark energy equation of state</td>
<td></td>
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<tr>
<td></td>
<td>$w_0$</td>
<td>Evolving $w$: current value</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$w_a$, $w_{et}$</td>
<td>Evolving $w$: value at early times</td>
<td></td>
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<tr>
<td></td>
<td>$a_4$</td>
<td>Evolving $w$: transition scale factor</td>
<td>U(0.5, 0.95)</td>
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<tr>
<td>Mass function (§3.2)</td>
<td>$A$</td>
<td>Global amplitude</td>
<td>N$_4$(0.20, ...)</td>
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<tr>
<td></td>
<td>$a$</td>
<td>Low mass amplitude</td>
<td>N$_4$(1.52, ...)</td>
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<tr>
<td></td>
<td>$b$</td>
<td>Low mass slope</td>
<td>N$_4$(2.25, ...)</td>
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<tr>
<td></td>
<td>$c$</td>
<td>Exponential cutoff scale</td>
<td>N$_4$(1.27, ...)</td>
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<tr>
<td></td>
<td>$\varepsilon$</td>
<td>Evolution strength</td>
<td>N(1.0, 0.1)</td>
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<td>Scaling relation (§3.3)</td>
<td>$\beta^{m}_0$, $\beta^{l}_0$</td>
<td>Nominal mass–luminosity relation</td>
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<td></td>
<td>$\beta^{m}_1$, $\beta^{l}_1$</td>
<td>Nominal mass–temperature relation</td>
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<tr>
<td></td>
<td>$\sigma_{m l}$, $\sigma_{l m}$</td>
<td>Marginal scaling relation scatters</td>
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<td></td>
<td>$\rho_{tt}$</td>
<td>Scaling relation scatter correlation</td>
<td></td>
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<tr>
<td>Other (§3.4, 3.5)</td>
<td>—</td>
<td>Chandra temperature calibration</td>
<td>10% Normal</td>
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<td></td>
<td>$\eta_g$</td>
<td>Cluster gas mass logarithmic slope</td>
<td>N(1.092, 0.006)</td>
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<tr>
<td></td>
<td>$\eta_L$</td>
<td>Cluster luminosity logarithmic slope</td>
<td>N(0.1135, 0.0005)</td>
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<td></td>
<td>$\kappa$</td>
<td>$r_{200}$ to survey flux conversion $d$</td>
<td></td>
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<tr>
<td></td>
<td>$\xi$</td>
<td>Completeness/purity $d$</td>
<td>U(0.95, 1.05)</td>
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</table>

**Dominant systematic**: $\pm 15\%$ uncertainty in absolute cluster mass calibration.
Cosmology: results on $\sigma_8$, $\Omega_m$

Good agreement between results from 3 RASS surveys, as well as independent X-ray (e.g. Vikhlinin et al. ’09) and optical (Rozo et al. ’10) cluster surveys.

Flat $\Lambda$CDM model:

Combined constraints (68%)

$$\Omega_m = 0.23 \pm 0.04$$
$$\sigma_8 = 0.82 \pm 0.05$$

Results marginalized over all systematic uncertainties.
Results on dark energy

Flat, constant $w$ model:

$\Omega_m = 0.23 \pm 0.04$

$\sigma_8 = 0.82 \pm 0.05$

$w = -1.01 \pm 0.20$

Results marginalized over all systematic uncertainties.

Clear detection of the effects of dark energy on cluster growth (suppression). See also Vikhlinin et al. '09 (comparable constraints).
Comparison with independent techniques

Flat, constant $w$ model:
- Cluster growth (Mantz 2010)
- Cluster $f_{\text{gas}}$ (Allen et al ’08)
- CMB (WMAP-5yr)
- SNIa (Kowalski et al. ’08)
- BAO (Percival et al. 2010)

All 5 independent techniques consistent with cosmological constant ($w = -1$)
Neutrino Masses
Constraining the neutrino mass

Neutrinos free-stream on the scales of galaxy clusters, suppressing the growth of structure on these (and smaller) scales. The larger the contribution of neutrinos to the total matter density, the stronger the effect.

By comparing the amplitude of matter fluctuations on large scales at early times (CMB) and small scales at late times (cluster counts), we can constrain the species-summed neutrino mass, $M_\nu = \sum m_i$.
Constraints on the species-summed neutrino mass

The inclusion of cluster count data leads to robust constraints on the species-summed neutrino mass (Mantz et al. 2010).

For basic (flat $\Lambda$CDM) cosmology with no tensors:

$$M_{\nu} = \sum_i m_i < 0.33\text{eV} \ (95\%)$$
The Origin of Cosmic Acceleration
Distinguishing between dark energy and modified gravity models for cosmic acceleration requires measurements of both the expansion and growth histories.

The best current constraints on the growth history come from clusters (CL), galaxy redshift surveys (GRS) and the CMB.

Growth index parameterization:

\[ \frac{\partial \ln \delta}{\partial \ln a} = \Omega_m(a)^\gamma \]

For General Relativity, \( \gamma = 0.55 \) (dashed curve)
Testing the standard $\Lambda$CDM+GR cosmological model

The best current data are simultaneously consistent with General Relativity + dark energy in the form of a cosmological constant.

Flat geometry:

Gold: CL+GRS+CMB.
Grey: (above)+SNIa+BAO+H0

$w = -0.968 \pm 0.049$
$\gamma = 0.546 \pm 0.072$

Results marginalized over all systematic uncertainties.
Incorporation of Subaru weak gravitational lensing mass measurements into cluster cosmology experiments.

→ factor 2 improvement in absolute mass calibration.

→ improved constraints on cosmology (and neutrino mass).

For methods see:

Kelly et al. 2012  (arXiv:1208.0602)
Conclusions

Measurements of galaxy clusters provide powerful and robust constraints on cosmological models, competitive with and complementary to those from other leading techniques.

The combination of galaxy cluster data and other techniques is already providing strict tests of the standard $\Lambda$CDM+GR paradigm.

$$w = -0.968 \pm 0.049, \quad \gamma = 0.546 \pm 0.072$$

The prospects for near- and mid-term improvements are strong, with powerful, new surveys (e.g. eROSITA, LSST, Euclid) and targeted, follow-up facilities (e.g. ASTRO-H) on the way.

A coordinated, multi-wavelength approach to exploiting these data will be essential. However, X-ray observations will remain central.
Bonus Slides
Surveys on the near and mid-term horizons (mm)

**SZ surveys:** Over the next 1-2 years, the completion of the South Pole Telescope (SPT), Atacama Cosmology Telescope (ACT) and Planck surveys will extend our statistical knowledge of galaxy clusters out to z=1 and beyond.

These surveys should (in combination with low-z X-ray surveys) provide significant improvements in our knowledge of cluster growth and corresponding improvements in cosmological constraints.
**Surveys on the near and mid-term horizons (optical)**

**Optical and near-IR:** A suite of powerful, new ground- and space-based surveys are about to come on-line. These include the Panoramic Survey Telescope and Rapid Response System (PanSTARRS), the Dark Energy Survey (DES), the Kilo-Degree Survey (KIDS/VIKING), the Hyper Suprime-Cam survey (HSC) and eventually the Large Synoptic Survey Telescope (LSST) and Euclid.

These surveys offer significant potential for finding clusters and will provide critical photometric redshift and gravitational lensing data.
Surveys on the near and mid-term horizons (X-ray)

**X-ray:** The eROSITA telescope on the Spektrum-Roentgen-Gamma satellite (launch 2014) will perform a 4-year all-sky survey to a depth two orders of magnitude fainter than RASS. It is expected to find of order 100,000 clusters, with excellent purity and completeness.
A coordinated, multiwavelength approach will be essential

Follow-up observations with X-ray observatories such as Chandra, XMM-Newton and the new ASTRO-H (launch 2014) will be critical in providing low-scatter mass proxy measurements for individual clusters (Tx, Mgas, Yx), as well as new astrophysical information.

Likewise, the photometric redshift and gravitational lensing data from optical surveys will provide a cornerstone for all cluster cosmology work.
Example of Subaru weak lensing data (color image and overlays)
MACSJ\textsubscript{0911.2+1746} cluster galaxies.
Glossary of relevant cosmological parameters

\[ \Omega_m = \frac{\rho_m}{\rho_{\text{crit}}} \]

is the mean matter density in units of the critical density.

\[ \Omega_{\text{de}} = \Omega_{\Lambda} = \frac{\rho_{\text{de}}}{\rho_{\text{crit}}} \]

is the dark energy density in units of the critical density.

\[ \sigma_8 \]

is the amplitude of matter fluctuations (in $8h^{-1}\text{Mpc}$ spheres, linear theory)

\[ w = \frac{p_{\text{de}}}{\rho_{\text{de}}} \]

is the dark energy equation of state. $w = -1$ for cosmological constant.

\[ \gamma \]

is the gravitational growth index. $\gamma \approx 0.55$ for General Relativity

Note: in the absence of dark energy, $\Omega_m > 1$ would eventually cause the Universe to re-collapse.