Observational Properties of Galaxy Clusters: Formation and Evolution

Outline

Part 1: Observational techniques
- Observational definition, observable physical properties
- Methods for cluster searches
- Cluster surveys: results, future prospects

Part 2: Clusters as Cosmological tools
- Evolution of the cluster abundance
- Independent constraints on cosmology from clusters
- Distribution and metallicity of baryons in distant clusters

Part 3: The Galaxy Content of Distant Clusters
- Multi-wavelength observations of distant clusters
- Galaxy populations and Environmental effects
- Formation and Evolution of cluster galaxies

Piero Rosati (ESO)
Clusters as Cosmological Tools

Mass profile from Weak/Strong Lensing:
Test CDM, nature of DM

N(M,z) from evolution of cluster abundance:
$\sigma_B$, $\Omega_M$, $\Lambda$

Gas fraction, $f_B$, $f_B(z)$
$\Omega_M h$, $\Lambda$

Clustering, $\xi_{CL}(r)$:
$P(k)$, CDM, $\Omega_M$, $\Lambda$

Cluster 3JF ($z=0-1.2$)
Evolution of cluster abundance (DM only)

Normalized to cluster abundance at $z=0$; circles: clusters with $T>3$ keV, size $\propto T$ (Borgani & Guzzo 2001)
(Left) Locally, one can determine the $\sigma_8 - \Omega_m$ relation ($\sigma_8 \Omega_m^{0.5} \approx 0.5$), because only the amplitude on a given scale $R \approx (M/\Omega_m \rho_{\text{crit}})^{1/3}$ can be measured.

(Right) the degeneracy can be broken measuring the evolution of $n(M)$, due to the dependence of the growth factor primarily on $\Omega_m$, weakly on $\Omega_\Lambda$ at $z<\sim 1$.

$D_+(z) = \frac{5}{2} \Omega_m E(z) \int_z^\infty \frac{1+z'}{E(z')^3} dz'$

$\Omega_m = 1$
$\Omega_m = 0.3$
$\Omega_\Lambda = 0$
$\Omega_m = 0.3$
$\Omega_\Lambda = 0.7$

r.m.s density fluctuation within a top-hat sphere of $8h^{-1}\text{Mpc}$ radius $\Leftrightarrow$ Amplitude of $P(k)$
X-ray selection provides the best way so far to trace the evolution of the space density of clusters of a given mass, i.e. to estimate the evolution of the cluster mass function \( [\text{constraints on cosmological params: } \sigma_8, \Omega_m, \Omega_\Lambda] \)

\[
\frac{d^3N}{dMd\Omega dz}(M,z) = \frac{dn_M}{dM}(M,z) \cdot \frac{d^2V_{\text{com}}}{dzd\Omega}(z)
\]

\[
dV = \frac{d^2M}{(1+\Omega_k H_0^2 d_M^2)^{1/2}} \, d(d_M) \, d\Omega
\]

\[
\frac{dV}{d\Omega dz} = (cH_0^{-1})^3 A(z) |\Omega_k|^{-1} S^2 \left\{ |\Omega_k|^{1/2} E(z) \right\} = cH_0^{-1} A(z) d_M^2
\]

\[
E(z) = \int_0^z [\Omega_k (1+y)^2 + (1+y)^3 +]^{-1/2} \, dy = \int_0^z A(y) \, dy
\]

\[
d_M(z) = D_L/(1+z) = \frac{cH_0^{-1}}{|\Omega_k|^{1/2}} S \left\{ |\Omega_k|^{1/2} \int_0^z [\Omega_k (1+z\ell)^2 + (1+z\ell)^3 +]^{-1/2} \, d\ell \right\}
\]

where:

\[
\Omega_k = 1 - \Omega_M - \Omega_\Lambda; \quad S^2 = \sinh^2 \text{ if } \Omega_k > 0 \text{ (open)}, \quad = \sin^2 \text{ if } \Omega_k < 0 \text{ (close)}, \quad S^2 \to E^2(z) \text{ (flat)}
\]
Since mass is not a direct observable, to measure the cluster mass function we resort to a proxy for the mass, $X$:

$$\frac{dn_M}{dM}(M, z) = \frac{dn_X}{dX}(M, z) \frac{dX}{dM}(M, z)$$

- Need a method to identify clusters over a wide redshift range
- The survey volume must be easy to compute
- The cluster mass is not a direct observable
  - $\Rightarrow$ one needs a robust estimator $X$ of the cluster mass
  - $\Rightarrow$ a full knowledge of the mass-observable relation $M(X, z)$ and its scatter as a function of redshift
  - $\Rightarrow$ Cluster mass definition: definition of cluster’s outer boundary
- Mass estimators: $L_x$, $T$, $L_{opt}$ (“Richness”), $\sigma_V$, baryonic mass, $Y_{SZ}$, ...
Cluster abundance from X-ray Luminosity Function

The cluster XLF is modelled as a Schechter function:

$$\phi(L_X) dL_X = \phi^* \left( \frac{L_X}{L_X^*} \right)^{-\alpha} \exp \left( - \frac{L_X}{L_X^*} \right) \frac{dL_X}{L_X^*},$$

A binned representation used to derive the LF from a flux-limited cluster sample is:

$$\phi(L_X) = \left( \frac{1}{\Delta L_X} \right) \sum_{i=1}^{n} \frac{1}{V_{\text{max}}(L_i, f_{\text{lim}})},$$

where $V_{\text{max}}$ is the total search volume defined as

$$V_{\text{max}} = \int_0^{z_{\text{max}}} S[f(L, z)] \left( \frac{dL(z)}{1+z} \right) \frac{cdz}{H(z)}.$$
• Different surveys, using independent methods, same results!

⇒ The determination of the local cluster abundance is solid today
Summary of Cluster XLFs of Distant Clusters

- The determination of the cluster space density out to $z=0.9$, for systems at $(0.1-5)L^*$, is rather solid today

(Mullis et al. 04)
Best fit to the Space Density of Clusters out to $z \approx 1$

$\Phi(L,z) = K L^{-\alpha} \exp(-L/L_*)$ with $K(z) = K_0(1+z)^A$, $L_*(z) = L_{*,0}(1+z)^B$

(Rosati, Borgani & Norman 02)

ML fit to the unbinned $L_X - z$ cluster distribution

The bulk of the cluster population ($L<L^*$) does not evolve much, most massive systems become more and more rare at high redshifts
Evolution of the most massive clusters

- Evolution from ROSAT serendipitous survey agrees with the one from wide-area ROSAT surveys
The measurement of $\sigma_8$ and $\Omega_m$ (and $\Omega_\Lambda, w$) is reduced to the estimate of the evolution of the space density of clusters of a given mass:

$$\frac{d^3N}{dMd\Omega dz}(M, z) = \frac{dn_M}{dM}(M, z) \frac{d^2V_{\text{com}}}{dzd\Omega}(z)$$

Comoving volume
(geometry in FRW)

Constraining Cosmological Parameters with the Cluster Mass Function
LX-M relation

Observed space density of clusters (i.e. XLF)

See S. Borgani's lectures
Cosmological constraints from the XLF evolution

Source of systematics:

conversion of observables to cluster mass:

- L–T slope: $L \sim T^{\alpha}$
- L–T evolution: $L \sim (1+z)^A$
- M–T normalization $\beta$
- L–M intrinsic scatter $\Delta_{M-L}$

$\sigma_8 = 0.70 \pm 0.05$ (± 0.05) (for $\Omega_m = 0.3$)

(Borgani et al 01, Rosati et al 02)
Clusters
Cosmological constraints from cluster evolution

• XLF evolution from a 400 sq.deg survey out to z=0.9 (Vikhlinin et al. 08). Mass estimator: $Y_x = M_{\text{gas}} T_x$ (calibrated with simulations)

• Cluster counts at z<0.9 from optically selected RCS sample (Gladders et al. 06). Mass estimator: BcgR (richness of red galaxies) calibrated with measured velocity dispersions on a subsample
Recent results on $\sigma_8$, $\Omega_m$ from ROSAT combination of samples
(Allen et al. 08)

Combined constraints (68%)
(flattened $\Lambda$CDM model, incl. systematics)

$\Omega_m = 0.28 (+0.11, -0.07)$
$\sigma_8 = 0.78 (+0.11, -0.13)$

In agreement with cosmic shear results within the errors

$\sigma_8 = 0.92 \pm 0.10 \Rightarrow 0.77\pm0.05 \Rightarrow 0.80\pm0.04$

WMAP1     WMAP3     WMAP5

Excellent agreement between many different independent X-ray cluster surveys (all from ROSAT, deep/moderate area and large/shallow surveys)
Results on dark energy with current (ROSAT) samples
(Allen et al. 08)

Flat, constant $w$-model:
REFLEX+BCS+MACS ($z<0.7$).
242 clusters, $L_x>2.55e44$ erg/s.
2/3 sky. $n(M,z)$ only.
(Mantz et al. ’08)

68.3, 95.4% confidence limits

Marginalized constraints (68%)

$\Omega_m = 0.24 (+0.15, -0.07)$
$\sigma_8 = 0.85 (+0.13, -0.20)$
$w = -1.4 (+0.4,-0.7)$

CMB: WMAP3 (Spergel et al. 07), SNIa: (Davis et al. 07), $f_{\text{gas}}$ (Allen et al. ’08)
Cl–abundance: “past generation” X–ray samples
Power Spectrum of the distribution of Clusters  
(see H.Bohringer’s lectures)

- Clusters have a clustering amplitude much larger than galaxies (corr. length for clusters $r_0 \approx 20 h^{-1} \text{Mpc} \approx 4$ times $r_{0,\text{gal}} \approx 5 h^{-1} \text{Mpc}$)

- Strong clumpiness: clusters trace only the high-density peaks of underlying mass density field (more “biased” tracers of the mass distribution than galaxies)

- “bias factor” $= (\delta \rho / \rho)_{\text{Xray}} / (\delta \rho / \rho)_{\text{mass}}$ easier to compute for clusters using the $L_X - M$ relation $\Rightarrow P(k)$ can be predicted for a given cosmological model

![Power Spectrum of the distribution of Clusters](image)
Estimating $\Omega_M$ with the cluster gas fraction
(White et al. 1993, Ettori et al., Allen et al.)

→ See S. Borgani’s lectures

1) $f_{\text{bar}} = b \cdot \Omega_b / \Omega_M$, $f_{\text{bar}} = f_{\text{gas}} + f_{\text{star}}$, $f_{\text{star}} = 0.16 \, h_{70}^{-1} f_{\text{gas}}$, $f_{\text{gas}} = 0.11 \, h_{70}^{-1.5}$

$\rightarrow \Omega_M = b \, \Omega_b / f_{\text{gas}} (1 + f_{\text{star}} / f_{\text{gas}}) = 0.9 \times 0.044 / 0.11 (1 + 0.16) = 0.27 \ (\pm 0.05)$

2) $f_{\text{gas}} \propto d_A(z, h, \Omega_M, \Omega_\Lambda)$, if $f_{\text{gas}}(z) = \text{const} \rightarrow f_{\text{gas}}$ is like a standard rod
Clustering, $\xi_{CL}(r)$, or $P(k)$: $\sigma_8$, $\Omega_M$, $\Omega_\Lambda$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Accuracy *</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_8$</td>
<td>3-8%</td>
</tr>
<tr>
<td>$\Omega_M$</td>
<td>5-10%</td>
</tr>
<tr>
<td>$\Omega_\Lambda$, $w$</td>
<td>40-100%</td>
</tr>
</tbody>
</table>

*with current (ROSAT) samples

$N(M,z)$ from evolution of cluster abundance:

$\sigma_8$, $\Omega_M$, $\Omega_\Lambda(w)$

Gas fraction, $f_B$, $f_B(z)$

$\Omega_M h (\Omega_\Lambda, w)$

Parameter accuracy:

- $\sigma_8$: 3-8%]
- $\Omega_M$: 5-10%]
- $\Omega_\Lambda$, $w$: 40-100%]

*with current (ROSAT) samples
Independent Probes of cosmological parameters

• **Geometrical methods:**
  - Type Ia Supernovae: comoving distance-redshift relation
  - Cosmic Microwave Background angular spectrum
  - Baryon Acoustic Oscillations (modulation of P(k)) from galaxy redshift surveys (galaxy clustering), act as standard rod

• **Dynamical methods:**
  - Number density of clusters: measure combination of growth factor, $D(a)$, and expansion history (volume evolution)
  - Weak lensing tomography: trace the evolution of the growth rate, $f_g(a) = \frac{d\ln(D)}{d\ln(a)}$, of DM perturbations
  - Redshift-space distortions: measure the growth rate (derivative of growth factor) from $z$-distortions due to peculiar motions
Independent Probes of cosmological parameters

- The combination of Independent Probes, $H(z)$ and $D(z)$, of cosmological parameters allows:
  - to control and measure a wide range of systematics inherent in each method
  - breaking degeneracies in parameter space
  - within GR, geometric and dynamical methods should provide consistent values on the dark energy parameters ($w(z)$), if they differ we learn about modifications to GR on very large scales
  - modified gravity theories predict different patterns for $H(z)$ and $f_g(z)$
Euclid
ESA’s mission to map the Dark Universe

All-sky all-sky opt-nearIR imaging
for gravitational lensing
(PI: Refregier)

All-sky near-IR slit-spectra to H=22 for BAO
(PI: Cimatti)

• Designed to probe cosmological parameters with a number of independent probes
  (determine $w$ at 1%, $w'$ at 10%)
• Test GR on cosmological scales
• Huge legacy value!
• Launch 2017, L2 orbit
• JDEM mission concepts from NASA (2015?)
Spatial distributions of Baryons (and DM) in Clusters

- If the ICM is in hydrostatic equilibrium and the relation $T \sim \sigma_r^2$ holds, then the two baryonic components (gas and galaxies) should trace each other very closely
  → generally true with some exception in case of cluster mergers

- The gas is a collisional fluid (with particle velocities are isotropically distributed), whereas galaxies in clusters are collisionless

- ICM from X-ray imaging ($\sim \rho^2$) is expected to be smoother than galaxy distribution (sound wave crossing time $\ll$ cluster age)

- Gas/galaxy distributions trace each other even in the most distant X-ray clusters known to date ($z=1.2-1.4$)
  → remarkably shows that clusters at look-back times of $2/3 T_U$ ($\approx 9$ Gyr at $z=1.4$) are already in an advanced dynamical state
Chandra ACIS-I, 51 ks, 3-10 keV
(Mullis et al. 03)
RXJ0152
z=0.83

Mass over X-ray

(Jee et al. 04)
RXJ0152
z=0.83

X-ray over Light

(Jee et al. 04)
Distribution of baryons and DM in a distant cluster (z=1.24)
Measuring metallicity of the ICM at z>1
Most distant X-ray clusters

XMM2235: VLT follow-up spectroscopy yielded $z=1.396$ (Mullis et al. 1995)
XMM2215: Keck follow-up spectroscopy yielded $z=1.45$ (Stanford et al. 1997)
190 ksec Chandra Observations of xmm2235

Fe K \( M_{\text{tot}} < 1 \text{ Mpc} \approx 10^{15} \, M_{\odot} \)

Surface brightness profile

\( kT = 9.3^{+1.6}_{-1.2} \, \text{keV}, \text{ and } Z_{Fe} = 0.32 \pm 0.20 \, Z_{\odot} \)

Rosati et al. 08
Chandra contours onto HST(i,z)+VLT(K) image

The most massive cluster to date at z>1

Rosati et al. 08
Evolution of ICM metallicity from Chandra Observations of distant clusters

Method: stacking spectral analysis of a sample of 20 high-z clusters (0.3<z<1.2)

Fe abundance at z~1.4 is already 0.2-0.3 solar

(ICM enrichment complete by $T_{z=1.2}+T_{cross}$ i.e. $z\approx2$

Much SF at high-z and/or efficient/fast mechanism to circulate metals

(>~50% of the present day stellar mass density assembled by z~1 (Dickinson+ 03, Rudnick+ 03))