Galaxy Systems in the Optical and Infrared

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Disclaimer:

No X-ray
Disclaimer:

No X-ray

No radio
Disclaimer:

No X-ray

No radio

No lensing
Plan of the lectures:

I. Identification, global properties, and scaling relations
II. Structure and dynamics
III. Properties of the galaxy populations
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I. Identification, global properties, and scaling relations
II. Structure and dynamics
III. Properties of the galaxy populations
Identification
Messier discovers the Virgo cluster in 1784
Herschel discovers the Coma cluster in 1785: “that remarkable collection of many hundreds of nebulae which are to be seen in what I called the nebulous stratum of Coma Berenices”
George Abell: First modern method of galaxy clusters identification (1958)

POSS photographic plates $m_{10}$ as a distance indicator

Count galaxies from $m_3$ to $m_3+2$ within 2.13 Mpc radius

Subtract counts from neighboring field
2712 clusters identified
(4073 w. southern extension)

Important reference catalog
(e.g. ENACS in 1989...)

but 2 main problems:

a) incompleteness
b) contamination (projection effects)
Ideally:
push incompleteness & contamination $\rightarrow 0$

*In practice:*

estimate incompleteness & contamination on mock galaxy cluster samples

$\Rightarrow$ cluster identification must be:

AUTOMATED and OBJECTIVE
How to be a good identification method:

1) automatization
2) objectiveness
3) minimal constraints on cluster properties
4) well-understood selection function
5) provide cluster $<z>$ and mass estimates
The Matched Filter method
(Postman+96, Kepner+99)
The Matched Filter method

Developed for photometric catalogs

\[ D(r,m) = \text{background} + \text{cluster} \]

\[ \approx b(m) + \Lambda_{\text{cl}} P(r/r_c) \phi(m-m^*), \]

\[ \sigma^2 = b(m) \]

\[ \ln \mathcal{L} \propto \int_{\text{Area},m} \ln \sigma \]

\[ + \int_{\text{Area},m} \left[ \frac{b(m) + \Lambda_{\text{cl}} P(r/r_c) \phi(m-m^*) - D(r,m)}{\sigma^2} \right]^2. \]
The Friends-of-friends method

(Huchra & Geller 82; Eke+04)
The Friends-of-friends method

Developed for spectroscopic catalogs

\[ D_{12} = 2 \sin(\theta/2) V/H_0 \leq D_L(V_1, V_2, m_1, m_2), \]

\[ V = (V_1 + V_2)/2, \]

\[ V_{12} = |V_1 - V_2| \leq V_L(V_1, V_2, m_1, m_2), \]

Systems are identified within physical overdensity.
- MF applied to EIS, SDSS, 2MASS ...
- Clusters detected to z\sim1 down to $10^{14} \, M_{\odot}$
- Completeness $\sim$90\% out to z\sim0.5
  
  $\sim$50\% out to z\sim1.5 for $10^{15} \, M_{\odot}$
- Miss <10\% X-ray selected clusters

- FoF applied to SDSS, 2dFGRS, 2MRS
- Several 1000 systems, low-z,
  
  mostly groups ($\sigma_{V}\sim$200 km/s, $\sim$10$^{13} \, M_{\odot}$)
- Essentially complete
The Cluster Red Sequence method:

(Gladders & Yee 00)
The Cluster Red Sequence method

Developed for photometric catalogs

(from Thomas & Katgert 06)
The Cluster Red Sequence method

Developed for photometric catalogs
The Cluster Red Sequence method

Developed for photometric catalogs
The Cluster Red Sequence method:
The Cluster Red Sequence method:

1) Slice a catalog in color,
2) compute galaxy surface density of the slice,
3) identify significant overdensities.

Tested on spectroscopic samples using only photometry:
⇒ only 1/23 clusters missed out to z=0.5
  <z> estimates accurate to Δz~0.03

Tested on Millennium simulations:
⇒ 80-90 % detected systems unaffected by strong projection effects
The Cluster Red Sequence method:

\(<z> = 0.89\)

THE CORE OF THE CLUSTER CANDIDATE
CRS 1620+2929 + SURROUNDING LARGE
SCALE STRUCTURE AT REDSHIFT 1

Detection Significance in Sigma
The Cluster Red Sequence method

CFHT and CTIO large-format camera data

\( \Rightarrow \) Red Sequence Cluster survey

~1000 cluster candidates (100 @ \( z \sim 1 \))

IR needed to find \( 1 < z < 2 \) clusters with CRS:

Spitzer SWIRE data: 70 candidate clusters
Beyond the red sequence:

maxBCG (Bahcall+03)
Relies also on presence of central BCG

Cut & Enhance (Goto+02)
C4 (Miller+05)
Use all colors in SDSS, not only 2 bands
maxBCG applied to SDSS:

13823 clusters $z<0.3$, $\Delta z \sim 0.01$, $\sigma_v > 400$ km/s

Mocks $\Rightarrow$ 90% pure, 85% complete, $>10^{14} M_\odot$

maxBCG vs. MF:

~80% overlap

imperfect matching due to substructures and presence of false positives
IR searches for z>1 clusters
(Brodwin+08, Eisenhardt+08, Elston+08, Stanford+05)

7.25 sq deg Spitzer IRAC Shallow survey
\( z_{\text{phot}} \) slices, overdensity selection
→ 335 candidates, \( \sim 10^{14} \, M_\odot \)
100 z>1 (12 confirmed so far) \( \sim 10 \) at z>1.5
IR searches for $z>1$ clusters

$z_p = 1.24$

$5' \times 5'$

$2.5 \times 2.5 \text{ Mpc}^2$
The Voronoi Galaxy Cluster Finder
(Ramella+01)
The Voronoi Galaxy Cluster Finder

Developed for photometric catalogs

Galaxies = Voronoi generators

1/Area(Voronoi Region) = density

Clusters = ensembles of adjacent cells with density > threshold
The Voronoi Galaxy Cluster Finder

Non-parametric
Imposes no constraints on cluster shape

Using $z_{\text{phot}}$ slices $\Rightarrow z \sim 1$ detections

Using spectroscopic catalogs (DEEP2 GRS)
$\Rightarrow$ 105 systems $z \sim 0.9$, $\sigma_v \sim 500$ km/s
One step up in the cosmic hierarchy: superclusters

FoF and overdensity techniques using clusters rather than galaxies

LSS statistical characterization
(e.g. the \textbf{genus} statistics:
\begin{center}
\textit{the number of holes a surface has}
\end{center}
Global properties:
richness, luminosity, mass
Cluster catalogs + cluster masses

→ cosmology
Cluster catalogs + cluster masses ➡ cosmology

When direct Mass measurements too expensive,
Cluster catalogs + cluster masses ➔ cosmology

When direct Mass measurements too expensive, use M-proxies:

1) richness (multiplicity), N
2) total luminosity of cluster galaxies, L
N and L:
- count galaxies,
  sum galaxy luminosities;
- correct for incompleteness;
- subtract field contribution;

L only:
- fit analytic function;
- extrapolate beyond $m_c$

Schechter (1976) function:

$$\phi(L)\,dL = \phi_* \left(\frac{L}{L_*}\right)^\alpha \exp\left(-\frac{L}{L_*}\right) \,d(L/L_*)$$
An alternative richness estimate: $B_{gc}$
(Yee & López-Cruz 2003)

Amplitude of 3-d spatial correlation function between the cluster center and cluster galaxies,

$$\xi(r) = B_{gc} \ r^{-\gamma}$$

Requires background correction and luminosity function (LF)

Robust vs. change of: assumed LF
spatial aperture
limiting magnitude
Direct M estimate from the virial theorem

(Zwicky 33, 37; Smith 36)

\[ M = 3\pi f_{sp} \sigma_p^2 R_h / G \]

\[ R_h = \frac{1}{2} \frac{N(N-1)}{\sum_{i>j} R_{i,j}^{-1}} \]

\[ f_{sp} = 1 - 4\pi r_l^3 \frac{\rho(r_l)}{\int_0^{r_l} 4\pi x^2 \rho dx} \frac{\sigma_r^2(r_l)}{\sigma^2(<r_l)} \]

\[ f_{sp} \approx 0.8-0.9 \text{ at } r_l \approx r_{200} \]
Direct M estimate from the virial theorem:

The surface pressure term

cluster center
Direct $M$ estimate from the virial theorem:

The surface pressure term

$r_i$  

cluster center
Direct M estimate from the virial theorem:

The surface pressure term

$r_l$  
cluster center
Direct M estimate from the virial theorem:

The surface pressure term

$r_i$  

cluster center
Direct M estimate from the virial theorem:

The surface pressure term
Direct M estimate from velocity dispersion
(from numerical SPH simulations; Biviano+06)
Direct M estimate:
are the tracers distributed like the mass?

Yes, if tracers = ETG; using LTG ⇒ M overestimate
Direct M estimate:

**reliability** (from numerical SPH simulations; Biviano+06)

All galaxies
Direct M estimate: reliability (from numerical SPH simulations; Biviano+06)

ETG only
Direct M estimate:

comparison with X-ray estimates

Nearby clusters (Girardi+98)  Medium-z clusters (Hicks+06)
Scaling relations:
richness & luminosity vs. mass
$N, L \Rightarrow M$

with 30-40% accuracy

$\approx L_x \Rightarrow M$

accuracy

$M \uparrow$ scatter $\downarrow$

Scatter $\downarrow$

in more regular clusters

(Popesso+07)
Linear relation on cluster scales

(Yee & Ellingson 03)
Linear relation on cluster scales
...not on group scales

(Girardi+02)
Agreement with SAM:
SF efficiency regulated by cool gas reheating (small scales) and (long) cooling time of hot gas (large scales)
N vs. M does not evolve out to z=0.9

(Lin+06)
Biases in cluster selection?

Compare different M proxies

Low-$L_X$ clusters at given $N$:

systems in formation or projection effects?

(Ledlow+03)
Biases in cluster selection?

Compare different M proxies

Low-$\sigma_v$ groups at given $L_X$: dynamically evolved (dynamical friction) or projection effects?

(Ledlow+03)
Cosmological constraints
The Oort technique: $\Omega_m = \langle M/L \rangle \rho_L / \rho_c$

Cluster $\langle M/L \rangle \sim$ Universal value
( assembled from regions $>10$ Mpc)

Abell 65: $1^{st}$ result, $0.1 < \Omega_m < 1.0$
The cluster mass function, $n(M,z)$

Constrains $\Omega_m$ and $\sigma_8$

(Borgani & Guzzo 01)
The cluster mass function, $n(M,z)$

(Evrard+02)
E.g.: The CIRS virial mass function (Rines+08)
72 nearby clusters with accurate M determination
Too many massive superclusters?

Millennium simulation lacks very rich superclusters cmpd to real Universe (Einasto+07)

RCS1-discovered z=0.9 massive supercluster <9% probability in WMAP5 Universe (Gilbank+08)
Summary of current constraints

Shaded regions: WMAP5 (Dunkley+08)
Perspectives:

forthcoming/planned optical/IR spectroscopic and photometric surveys from the ground and from space
Cluster-dedicated photometric survey:

CFHT MegaCam
1000 deg$^2$
g$'$=25.3, r$'$=24.8, z$'$=22.5
detection out to z~1
constrain $\Omega_m$ to $\pm0.02$, $\sigma_8$ to $\pm0.05$, and w to 10%
(Yee+07)
Other photometric surveys:

Univ Hawaii Inst Astronomy:
1200 deg², g=27, 4 bands

KiDS
1500 deg², 5 SDSS bands
VLT Survey Telescope
2 mag deeper than SDSS

CTIO 4m wide-field camera:
5000 deg², 4 bands

The Dark Energy Survey
Spectroscopic surveys:

**BOSS,**
Baryon Oscillation Spectroscopic Survey
10000 deg$^2$ 1.5 million z's ($z \leq 0.7$)
Part of SDSS-III, 1$^{st}$ DR in 2011

1 million z's in 100 nights
Surveys from space:

Warm mission: $\sim 10^4$ hrs observations

3.6, 4.5 $\mu$m $\Rightarrow$ more IR-selected $z>1$ clusters (e.g. Papovich 08)

JDEM, NASA+DoE joint dark energy mission
Surveys from space:

ESM M-class mission
20000 deg^2, H=22, R=400
~150 million z's
~2 billion galaxies z~2