The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2354-23

Summer School on Cosmology

16 - 27 July 2012

Clusters of Galaxies - Lecture 2

J. Mohr
LMU, Munich

ICTP Summer School on Cosmology, Trieste, July 2012

Galaxy Clusters and Galaxy Cluster Surveys

The halo abundance experiment can be carried out using surveys of galaxy clusters. Key challenges include identifying survey methods that select clean samples of clusters with an observable that is simply related to the cluster mass, calibrating cluster masses and measuring cluster photometric redshifts.

Joe Mohr
Ludwig-Maximilians University, Munich
Max Planck Institute for Extraterrestrial Physics, Garching

Outline

- Halo abundance as cosmological constraints
- Galaxy clusters and galaxy cluster surveys
- Cosmological constraints from Cluster Surveys
- Future Prospects

Overview: Galaxy Clusters and Galaxy Cluster Surveys

- Reminder- what is a galaxy cluster
- What is a survey and how does it constrain cosmology?
- Survey selection and redshift estimation

Cluster Surveys as a Test of Cosmology

- A real world application requires a population of objects for which the masses can be estimated accurately
- Galaxy clusters are one such population
- Here we review the ingredients of a cluster survey, highlight some recent results, an ongoing project and briefly review some future projects

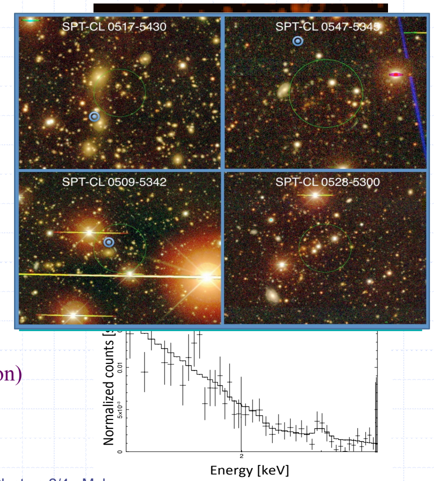
What Are Galaxy Clusters?

Galaxy clusters are the most massive, collapsed structures in the universe. They contain galaxies, hot ionized gas (10^{7-8}K) and dark matter.

In typical structure formation scenarios, low mass clusters emerge in significant numbers at z~2-3

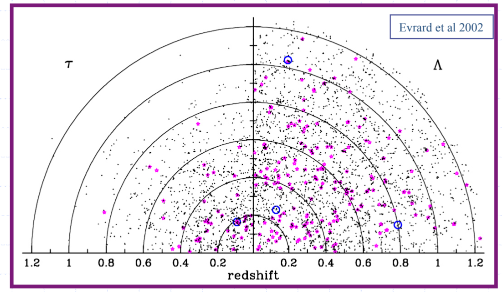
Clusters are good probes, because they are massive and "easy" to detect through their:

- X-ray emission (Bremsstrahlung)
- Sunyaev-Zel'dovich Effect (Inverse Compton)
- Light from galaxies (Black Body)



Galaxy Clusters Tracer Large Scale Structure

- Galaxy clusters are excellent tracers of structure formation
- A galaxy cluster survey is a powerful probe of the cosmic acceleration
  - As we probe to higher redshift we see clusters disappear, and the exact rate at which they disappear is (exponentially) sensitive to the growth rate of density perturbations



Galaxy Cluster Redshift Distribution and Cosmology

- Cluster redshift distribution dN(z)/dz/dΩ

abundance of detectable clusters — **cluster mass function**

$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_{m_{lim}(z)}^{\infty} dM \frac{dn(M,z)}{dM}$$

volume element

Minimum mass of detectable cluster (typically function of redshift)

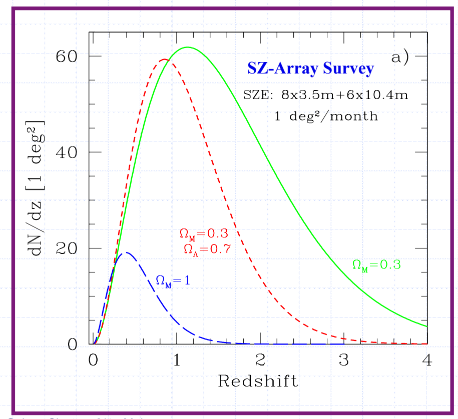
Critical components: **Volume element**, **Mass function**, **Limiting mass**

Galaxy Cluster Surveys and Survey Yields

Cluster surveys probe (1) **volume-redshift relation**, (2) **abundance evolution**, (3) **structural evolution**

Surveys Constrain:

- Cluster surface density
- LogN-LogS
- Angular distribution
- Redshift distribution
- (Mass) function



The Volume-redshift Relation

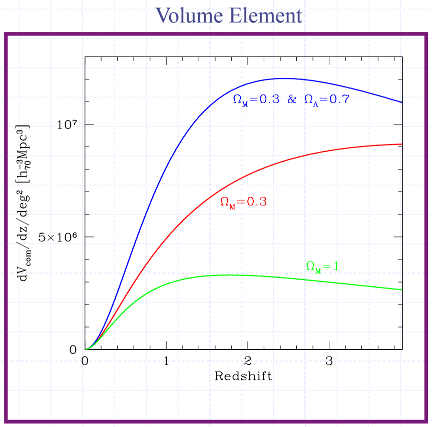
- Volume-Redshift Test
  - Count non-evolving tracers
    - measure volume

$$\frac{dV}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2$$

$$d_A(1+z) \sim \int_0^z dz' \frac{c}{H(z')}$$ is proper distance

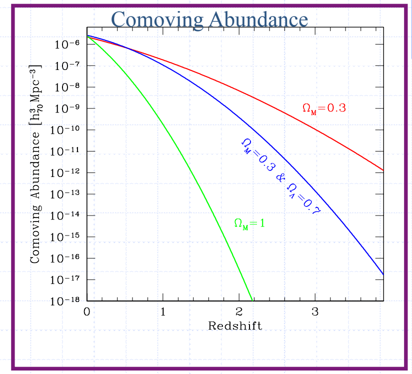
$$H(z) = H_o E(z)$$ is the Hubble parameter

  - But cluster abundance (number density) evolves as well



Abundance Evolution and Cosmology

- Normalize locally
  - Measure the abundance of galaxy clusters
- Abundance evolution directly reflects growth rate of density perturbations



Importance of the Survey Detection Limit

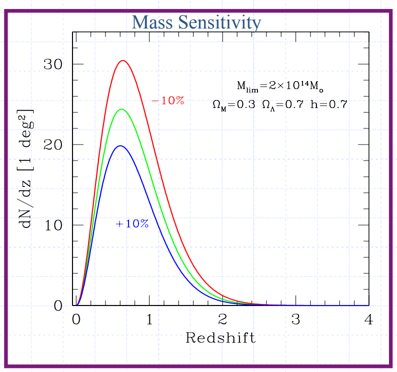
Cluster redshift distribution dN(z)/dz/dΩ

$$\frac{dN(z)}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_{m_{\rm lim}}^{\infty} dM \frac{dn(M,z)}{dM}$$

Minimum mass of detectable cluster

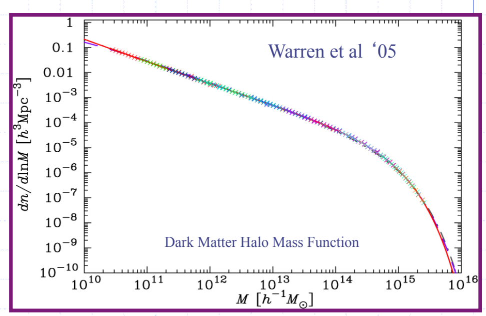
Limiting mass $M_{\rm lim}(z)$

- Connecting cluster virial mass to observables is critically important
  - X-ray luminosity or emission weighted temperature
  - SZE luminosity
  - Weak lensing shear amplitude
  - Galaxy light / dynamical estimators



Cluster Survey Cosmology Requirements

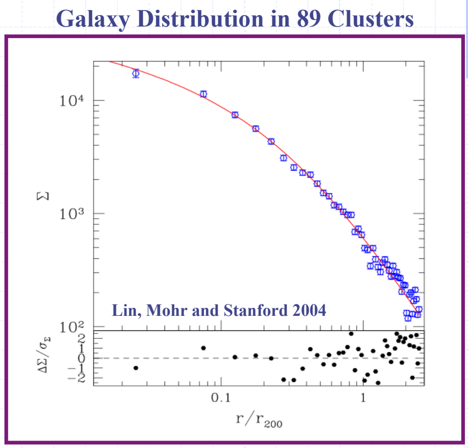
- Comparing observed and simulated mass function shape and evolution requires:
  - Ability to estimate mass
  - Well understood selection
  - Cluster redshift measurements



Masses: Clusters Have No Outer Surface

- Dark matter, ICM, and galaxy distributions all fall off with distance from the cluster center, but there's no clear signature of the edge of the cluster
- There are preferred definitions of cluster mass- we choose a region which is a few hundred times denser than the background or critical density
  - motivated by spherical collapse model but also from structure formation simulations

$$M_{200} = \frac{4}{3}\pi R_{200}^3 * 200\rho_{crit}$$

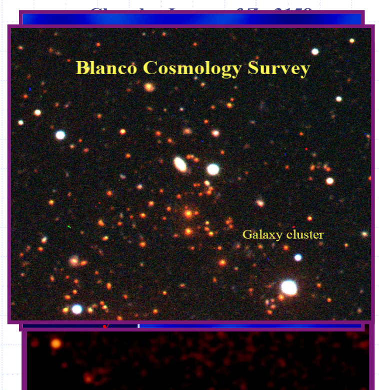


Cluster Mass Measurements

- There are three methods of measuring cluster masses directly:
  - Assume hydrostatic equilibrium, use X-ray observations:
    - Measure the temperature and density profiles using X-ray observations
    - Infer the mass profile
  - Assume virial equilibrium, use galaxy kinematics:
    - Measure the velocities of a large number of galaxies within each cluster
    - Relate the kinetic energy in the galaxies to the potential energy (mass)
  - Use weak lensing (no equilibrium assumption needed)
    - Map the gravitational lensing distortions due to the cluster lense
    - Infer the mass profile – non-trivial, too
- All these methods are time and data intensive. In a cluster survey we rely on inexpensive observables that serve as mass proxies:
  - X-ray luminosity, temperature, SZE flux, Optical light
  - Must calibrate the Mass-Observable relation!
    Single cluster mass estimate need not be precise but must be unbiased/accurate

Clean Cluster Selection

- In addition to accurate cluster masses, the selection of the sample is also very important
- Clusters can be selected in the optical, X-ray or SZE
- None of these provide a pure mass selection, because the mass-observable relations exhibit significant scatter
- Currently the SZE selection is the closest we can come to mass selection



$$\frac{\Delta T(R)}{T_{cmb}} = -2\frac{\sigma_T}{m_e c^2}\int dl\, n_e(l,R)\, k_B T_e(l,R)$$

Mass-Observable Relation Evolution

- At high redshift the Universe is younger and denser, and this impact mass-observable relation evolution
- Stars within the galaxies are more luminous per unit stellar mass at high redshift than nearby, but of course their brightness goes as d_L^{-2}
- Remember that the cluster virial region has an overdensity of ~200. Because the mean matter density is $(1+z)^3$ higher at redshift z, this means that ICM is denser, too. This boosts X-ray and SZE!
  - In case of SZE the mass-obs relation is almost redshift independent

Self-similar Expectations

- If we assume that cluster dark matter and gas profiles evolve self-similarly with redshift, one can simply model that evolution
- Two constraints needed:
  - Mass-radius-density:
  - Virial relation:

$$M_\delta \equiv \delta\rho_{crit}\,\tfrac{4}{3}\pi R_\delta^3 \qquad \frac{GM_\delta}{R_\delta} \approx \sigma^2 \quad \text{or} \quad T_x$$

- Using evolution of critical density in terms of $H(z)=H_0E(z)$ we have

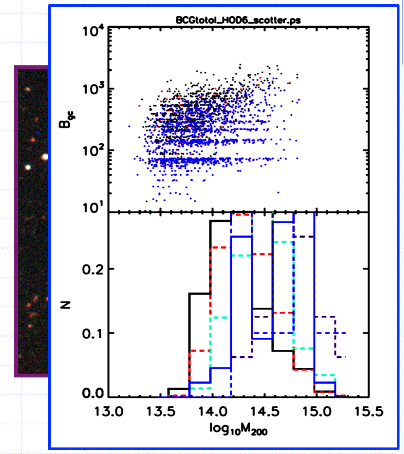
$$M_\delta \propto \frac{\sigma^3}{\sqrt{\rho_{crit}}} \propto \frac{\sigma^3}{E(z)}$$

  - Dispersion-mass relation from N-body sims consistent with this
  - Gas related mass-obs relations tend to depart from self-similar evolution (with redshift or mass)

Cluster Selection: Optical/IR

- Optical/IR Surveys
  - Optical/IR signature only crudely related to cluster mass- clean mass selection impossible
  - Galaxies (even red ones) exist everywhere, not just in clusters- contamination an issue
  - Sims show contamination at ~30% (Song et al 2012)
  - Completeness of red sequence methods seems quite good

BGC versus Mass in Simulated Catalog



Song et al 2012

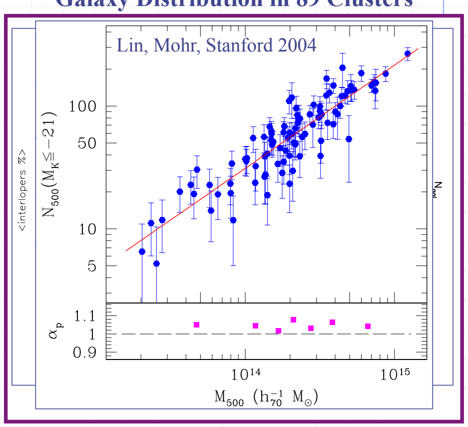
Galaxies as Observables

- The cluster halo occupation number is regular with Poisson fluctuations, but this is only clear if you have external knowledge of the cluster virial radius and mass

  Not available in optical survey, where there is no natural signature of the virial radius of the cluster

- Also, even with spectroscopic redshifts and red sequence selection the contamination from surrounding non-cluster galaxies is significant

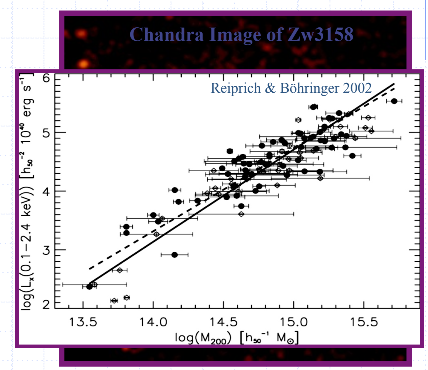
Galaxy Distribution in 89 Clusters



Cluster Selection: X-ray

- ROSAT experience:
  - high completeness (~95%), low contamination (~1%) (see Vikhlinin et al 1998)
- X-ray surveys
  - X-ray luminosity tracks cluster mass with ~45% scatter
  - AGN can boost flux, leading to contamination by low mass systems
  - Unresolved clusters can be missed unless there is complete multiband optical imaging available to followup all sources
  - Low scatter mass estimate (Y_x or M_{icm} at ~15% available for a subset)

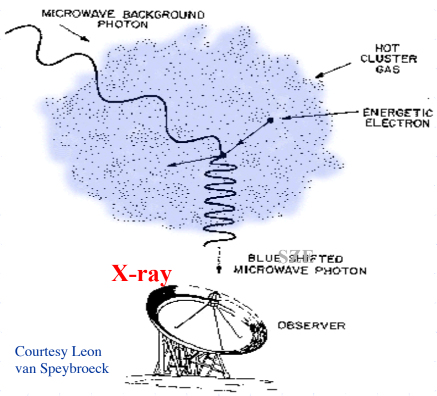
Chandra Image of Zw3158



$$I_x(R) = \frac{1}{4\pi(1+z)^4}\frac{\mu_e}{\mu_H}\int dl\, n_e^2(l,R)\Lambda(T_e)$$

Sunyaev-Zel'dovich Effect (1972)

- SZ effect (SZE) is inverse Compton scattering between low energy CMB photons and high energy cluster electrons
- SZE leads to a distortion of CMB spectrum and therefore it is redshift independent.
- SZE signal is a direct probe of total thermal energy in cluster electron population and hence a good proxy for cluster mass.



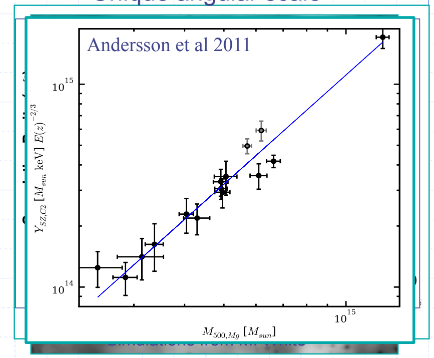
Courtesy Leon van Speybroeck

$$\frac{\Delta T(R)}{T_{cmb}} = -2\frac{\sigma_T}{m_e c^2}\int dl\, n_e(l,R)\, k_B T_e(l,R)$$

Cluster Selection: SZE

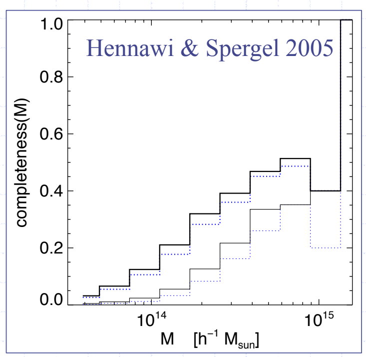
- Unique signature in frequency and angle
  - Contamination just a function of S/N
- Clean mass selection
  - SZE flux proportional to the total thermal energy in the electron population
  - No cosmological dimming (indep of z)
  - Radio galaxies can bias flux, but these are rare at high frequency
- SPT selection very clean- redshift independent mass selection with ~20% scatter, purity high from SZE alone, close to 100% after optical followup

Unique spectrum
Unique angular scale



A Note on Shear Selection of Galaxy Clusters

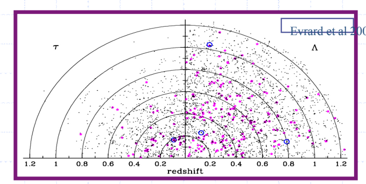
- Clusters are the most massive collapsed objects in the Universe, and so one might expect them to be visible through weak lensing
- Hennawi & Spergel (2005) showed that shear selected cluster samples are highly incomplete and contaminated- embedded in surrounding large scale structure and working in the low signal to noise regime
- Deitrich & Hartlap (2009) have shown that shear peak statistics (sourced from clusters and LSS) are cosmologically important



Efficiency $\varepsilon = n_{clus}/n_{peak}$
Top curve: ε=60%
Bottom curve: ε=75%

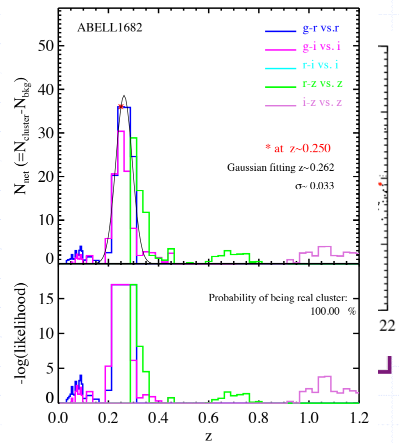
Redshifts Needed, too

- Redshifts are an additional need to enable evolution constraints
- Spec-z's are very costly (and not needed for abundance evolution)
- Photo-z's still costly unless there is a deep multiband optical survey covering your cluster survey



Measuring Photometric Redshifts

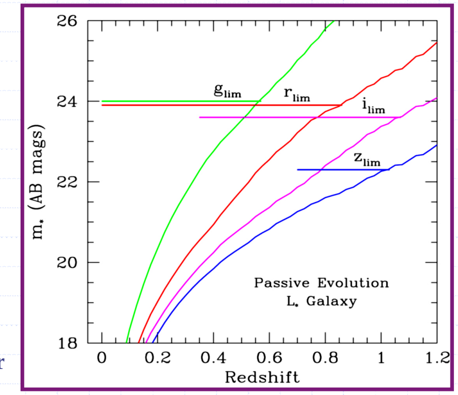
- Measure relative flux in the four filters *griz*: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\delta z \sim 0.05$-0.2 (more like $\delta z \sim 0.02$ for clusters)
- Use spectroscopic calibration samples (>10^5) to control systematic uncertainties
- Note: good detector response in *z* band filter needed to reach z~1.35



Required Survey Photometric Depths (no initial redshift guess)

- Photometry in the four bands must be deep enough to detect galaxies of interest at the redshift where the 4000A break shifts out of the band
  - *g* (z=0.35)
  - *r* (z=0.7)
  - *i* (z=1.0)
  - *z* (z=1.4)
- For example, 10σ galaxy limits of (*g,r,i,z*=24.0,23.9,23.6,22.3) for BCS survey (see figure)
  - DES pushes significantly deeper (*g,r,i,z*=25.2,24.8,24.0,23.4)

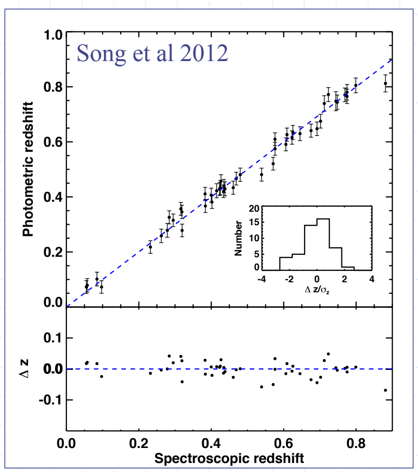
Blanco Cosmology Survey Depths



Desai et al 2012

Good Performance Demonstrated

- For the South Pole Telescope survey we have measured a large sample of cluster photo-z's (>300). The 56 with spec-z's enable a test.
- Characteristic accuracy is $\delta z/(1+z)$~0.017, uncertainties describe the scatter
- These experiences (see also SDSS and RCS redshift estimation) can be scaled up to much larger cluster samples.



Summary

- Cluster redshift distribution offers constraints on distance-redshift and growth of structure (as well as anything that impacts P(k))
- Key requirements include:
  - Ability to cleanly select using signature closely related to mass
  - Ability to precisely calibrate the mass-obs relation
  - Ability to measure photometric redshifts
- SZE offers cleaner selection (closest to mass selection) in comparison to X-ray and optical
- Photometric redshifts working well- multiband optical data provides a second stage in confirmation for SZE and X-ray surveys (thereby reducing contamination)

References

- *Articles from the current literature*