Ensemble Properties of Cluster Galaxies and Their Redshift Evolution

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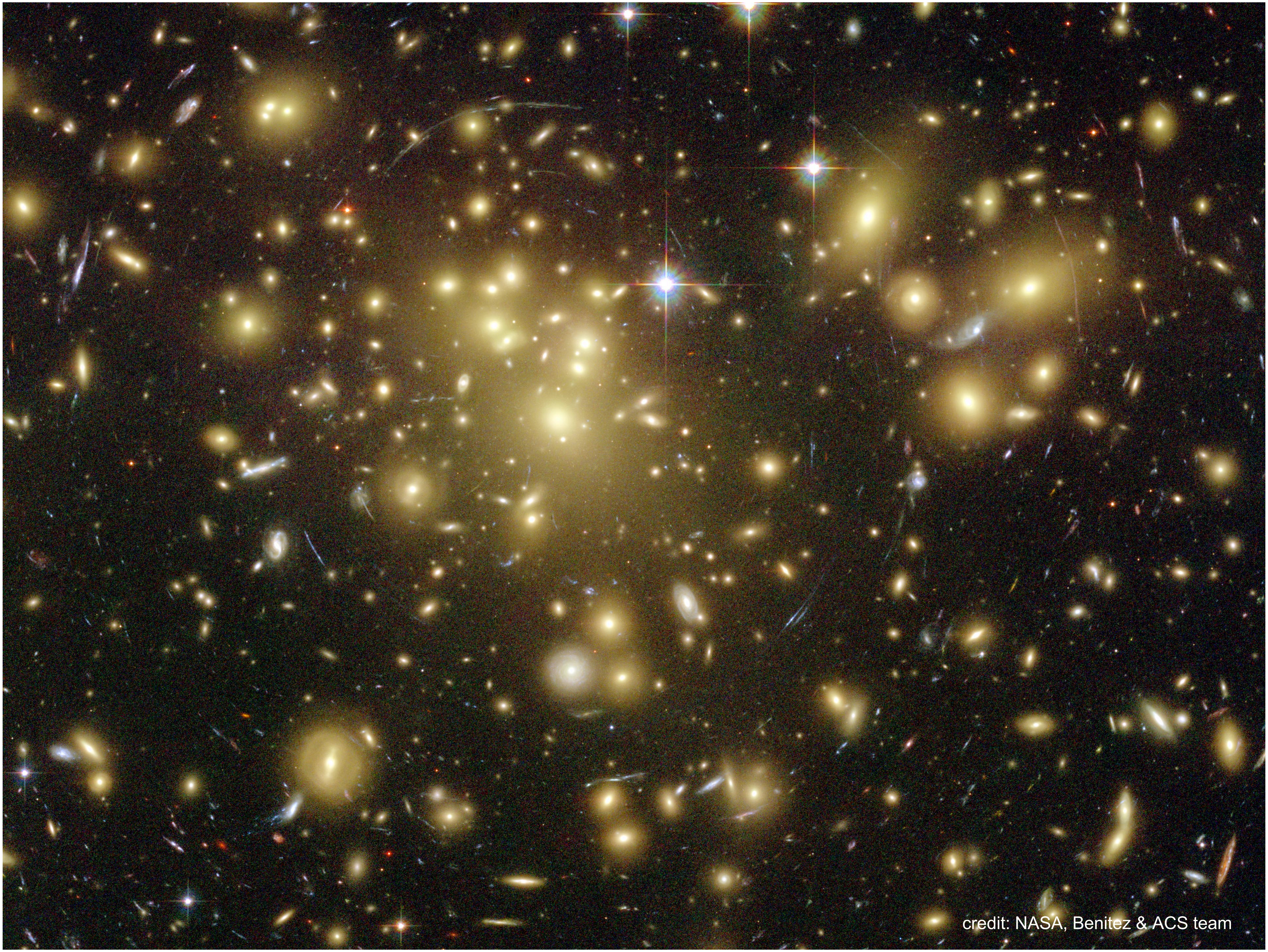
why study clusters?

- they are gorgeous!


credit: NASA, Benitez & ACS team

why study clusters?

- they are gorgeous!
- excellent astrophysical laboratory
  - ram pressure stripping
  - tidal disruption
  - galaxy harassment
  - transformation from the “field’’ population to “red and dead”
- intriguing classes of objects

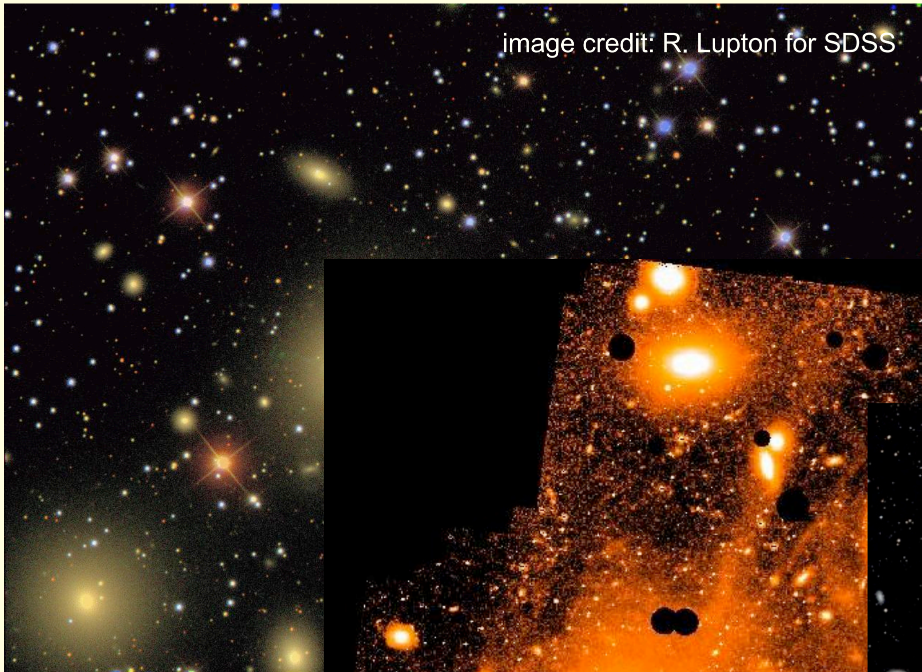
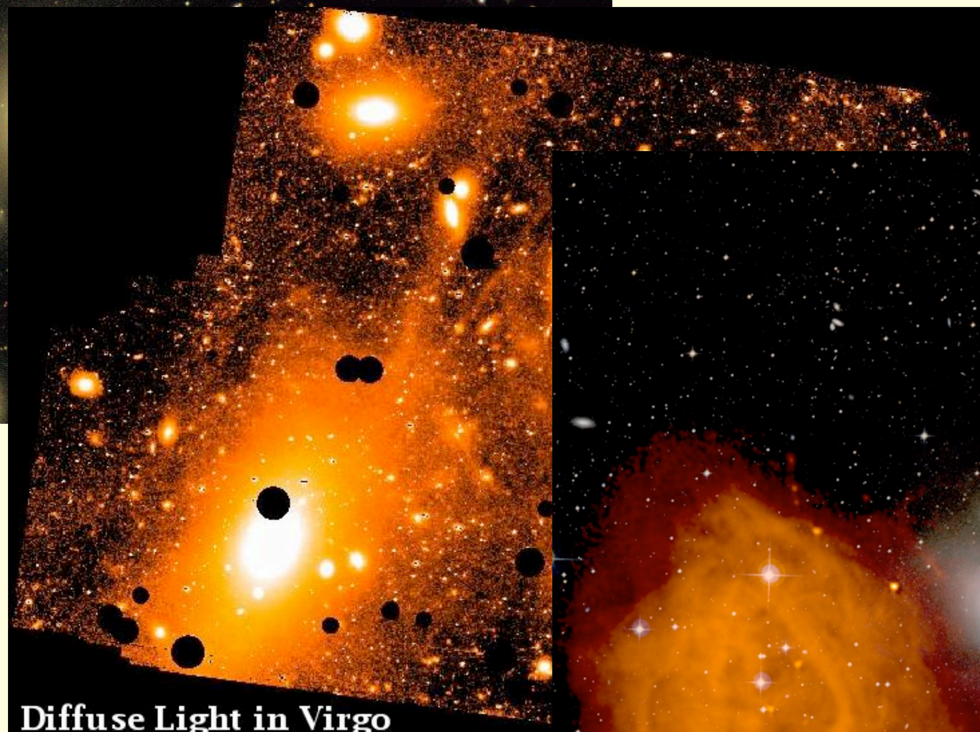


image credit: R. Lupton for SDSS


Diffuse Light in Virgo

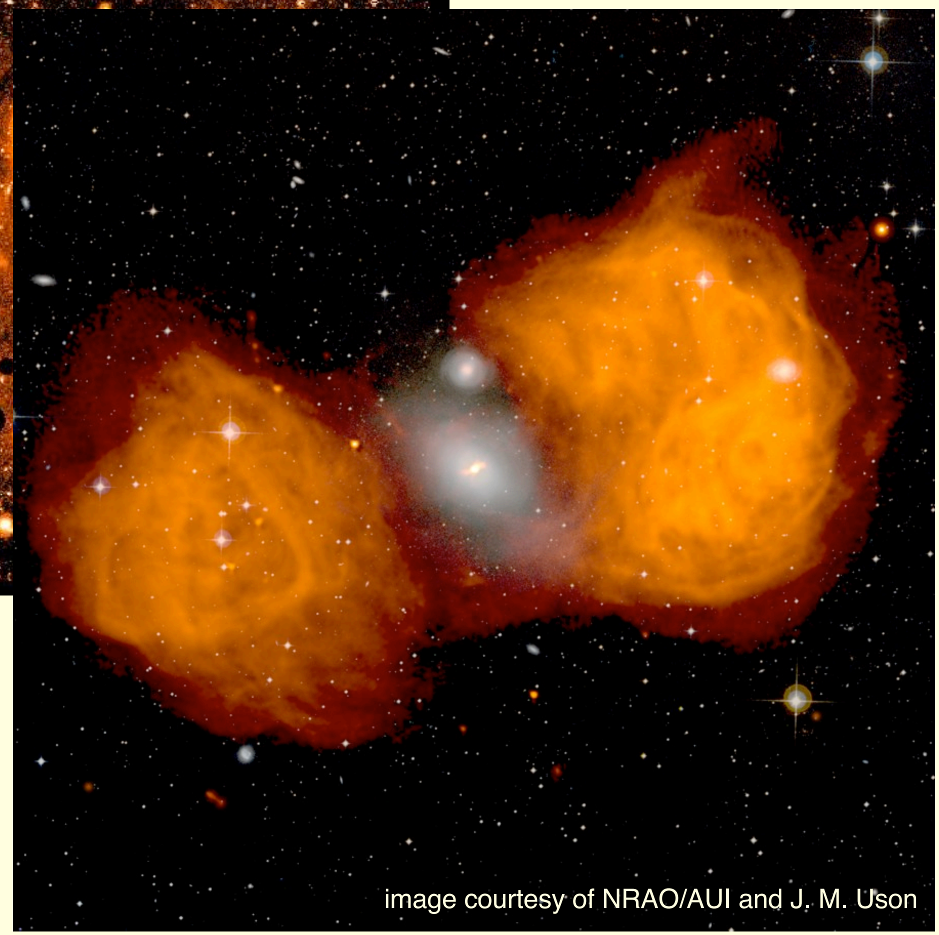


image courtesy of NRAO/AUI and J. M. Uson

why study clusters?

- they are gorgeous!
- excellent astrophysical laboratory
  - ram pressure stripping
  - tidal disruption
  - galaxy harassment
  - transformation from the “field’’ population to “red and dead”
- intriguing classes of objects
  - cD, giant elliptical galaxies, luminous red galaxies
  - intracluster stars
  - radio galaxies
- powerful cosmological probes
  - mass function, clustering/power spectrum, baryon fraction
  - crucial to understand clusters before using them!

questions to be addressed

- how are cluster galaxies formed/assembled in the context of hierarchical structure formation?
- redshift evolution of cluster galaxy populations? implication of massive galaxy formation?
- what is the (radio-loud) AGN content of clusters? implication for Sunyaev-Zel’dovich effect (SZE) cluster surveys?

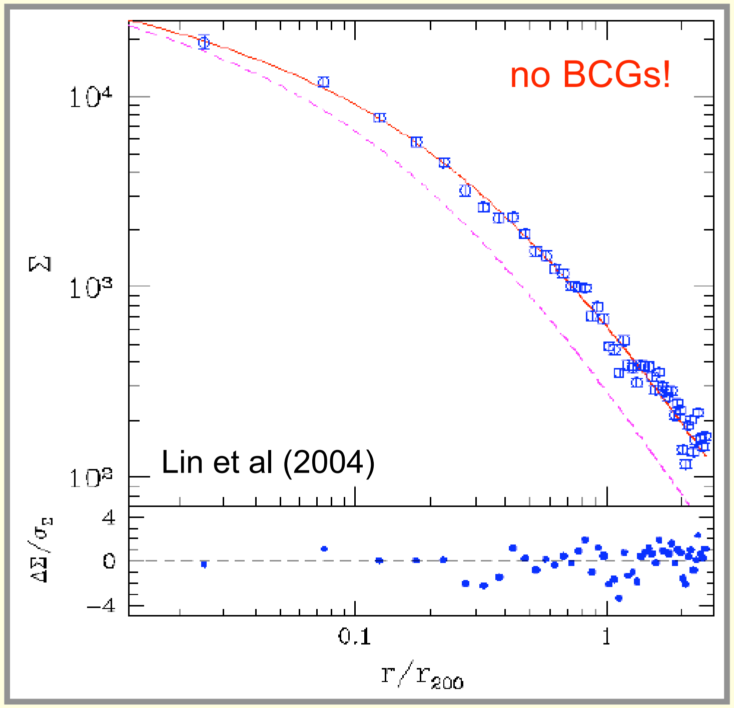
methods and samples

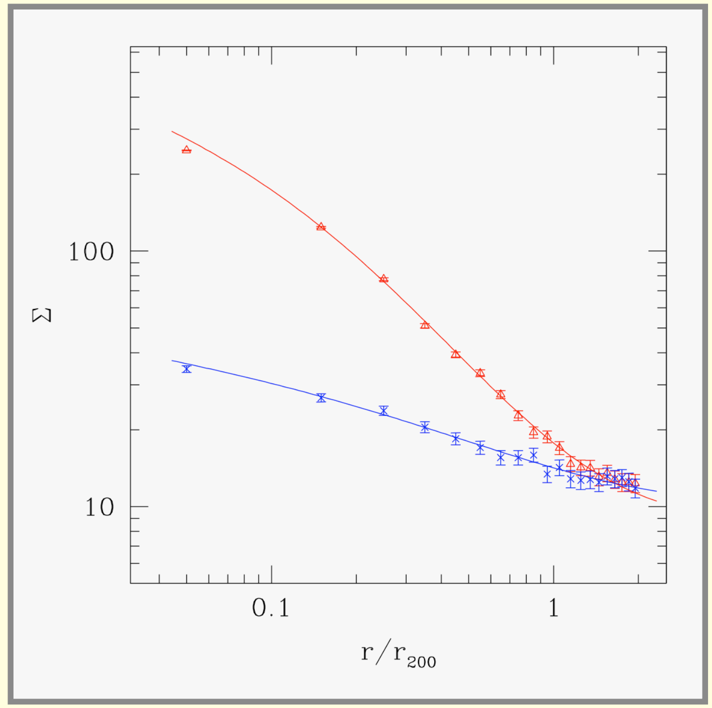
- the mass of the clusters is important
  - to obtain a fundamental length scale to normalize the galaxy radial distribution ⇒ calculation of spatial distribution
  - to estimate the cluster volume probed by the survey ⇒ luminosity function (LF)
- X-ray is useful: mass estimate, centroid determination, ICM info
- use samples constructed from existing catalogs, requiring clusters have measured T_X or L_X from ASCA, ROSAT, Chandra, or XMM ⇒ estimate mass using M_{500}-T_X or M_{200}-L_X relations
  - ensemble properties of cluster galaxies: 93 clusters at $z<0.1$ (K-band data from 2MASS)
  - redshift evolution of scaling relations: 41 clusters at $0.1 \le z \le 0.9$ (deep K-band imaging)
  - luminous red galaxy (LRG) population in intermediate-z clusters: 47 clusters at $0.2 \le z \le 0.6$ (optical data from SDSS)
  - radio-loud AGN (RLAGN) content in clusters: 573 clusters at $z \le 0.2$ (1.4GHz data from NVSS)
- "stack" clusters to enhance signal over background, which is estimated statistically

questions to be addressed

- how are cluster galaxies formed/assembled in the context of hierarchical structure formation?
  - review some of the basic properties such as spatial distribution within clusters, and LF
  - dark matter halo formation and evolution well-understood
  - seek for quantities that can be linked to the halo mass $\Rightarrow$ observable-mass scaling relations
  - implications of the galaxy evolution in clusters

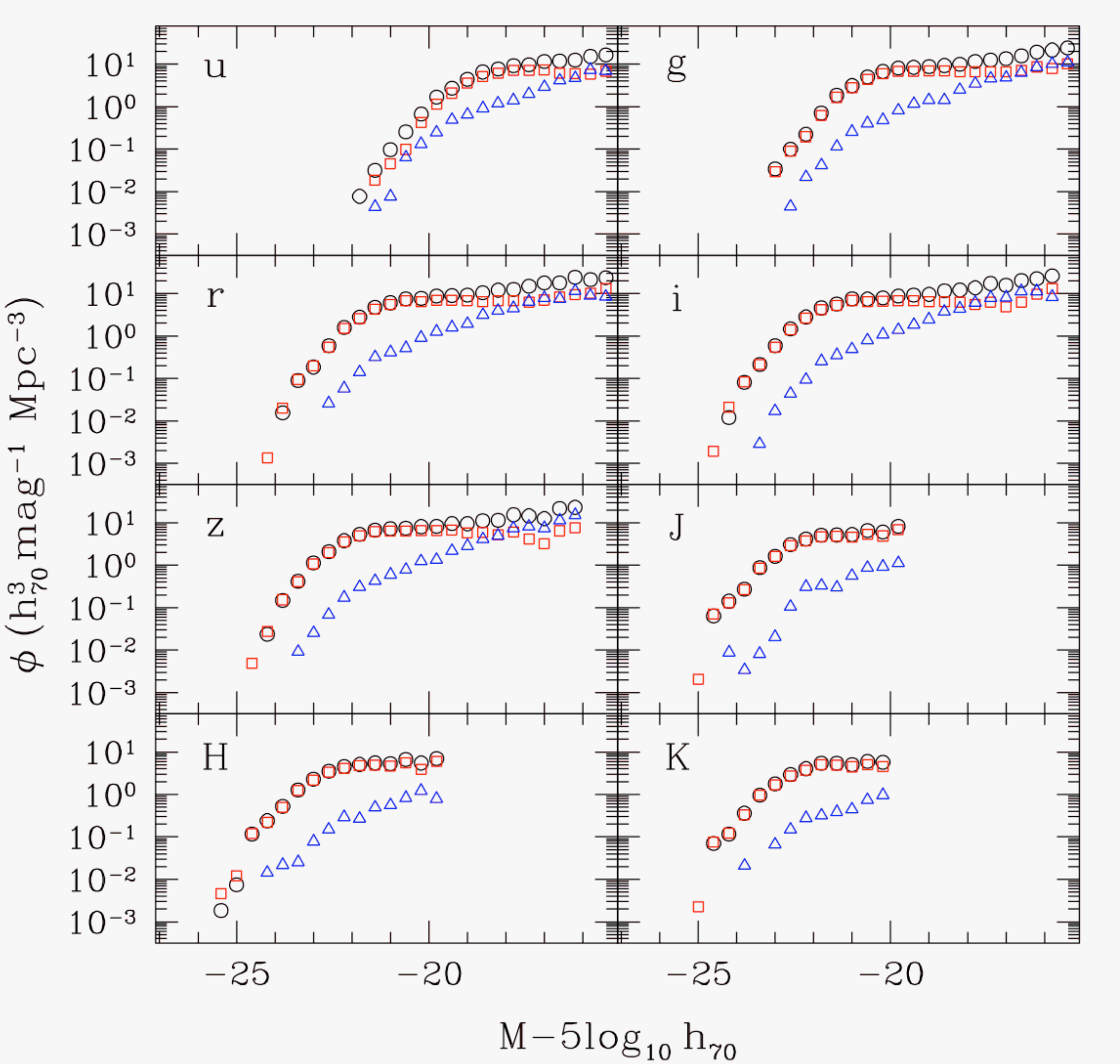
cluster galaxy formation: spatial distribution





- clusters are of different sizes; use virial radius r_{200} to rescale radial distance
- Σ: surface density per unit “virial area”
- non-BCG galaxies well described by NFW profile
  - c~3–4 for all galaxies; c~3–4 for red galaxies; c~1 for blue galaxies ⇒ color-density relation
  - weak luminosity segregation
- including BCGs makes profile steeper, c~6
- lensing & X-ray observations suggest cluster-scale dark matter halos have c~5–10

cluster galaxy formation: optical/near-IR LFs



Lin et al (in prep)

- LF within r_{500}; no BCGs
- all magnitudes in AB system
- red squares: red galaxies

  blue triangles: blue galaxies

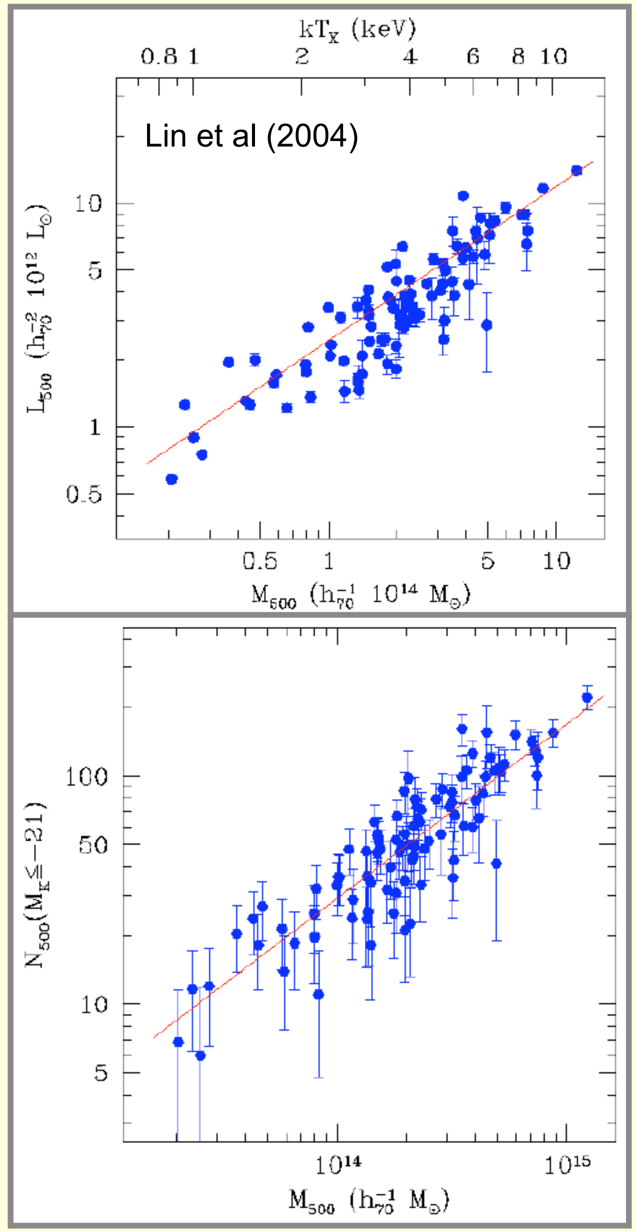
  black circles: all galaxies
- use u-r=2.2 to separate blue from red population
- galaxies become more luminous toward longer λ
- red galaxies dominate over blue ones in all bands (number density ~30 times higher down to M_*)
- faint-end slope:

  red: –0.9; blue: –1.5; all: –1.1

cluster galaxy formation: scaling relations

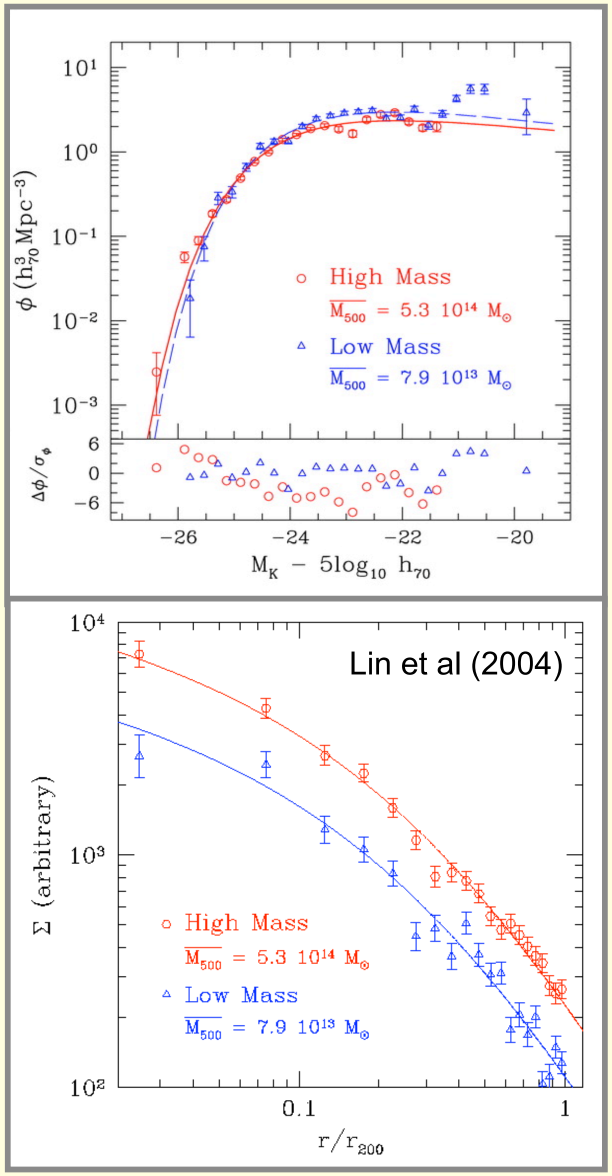
- recall Schechter function $\phi(L)\,dL = \phi_* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*}\, d\left(\frac{L}{L_*}\right)$

  three parameters: α, M_*, φ_*
- fixing α=–0.9 for all clusters, from the observed, background corrected galaxy number and flux, we can solve for M_* and φ_*
  $\Rightarrow$ can then integrate the LF to get total N and L more luminous than e.g., M_K=–21
- N and L correlate with cluster mass
  - $N \propto M^{0.76}$
  - $L \propto M^{0.82}$
  - 30–35% fractional scatter
  - regularity of cluster galaxy formation and evolution processes
- why isn't N proportional to M?
  - high mass clusters not simply direct sum of lower mass systems?

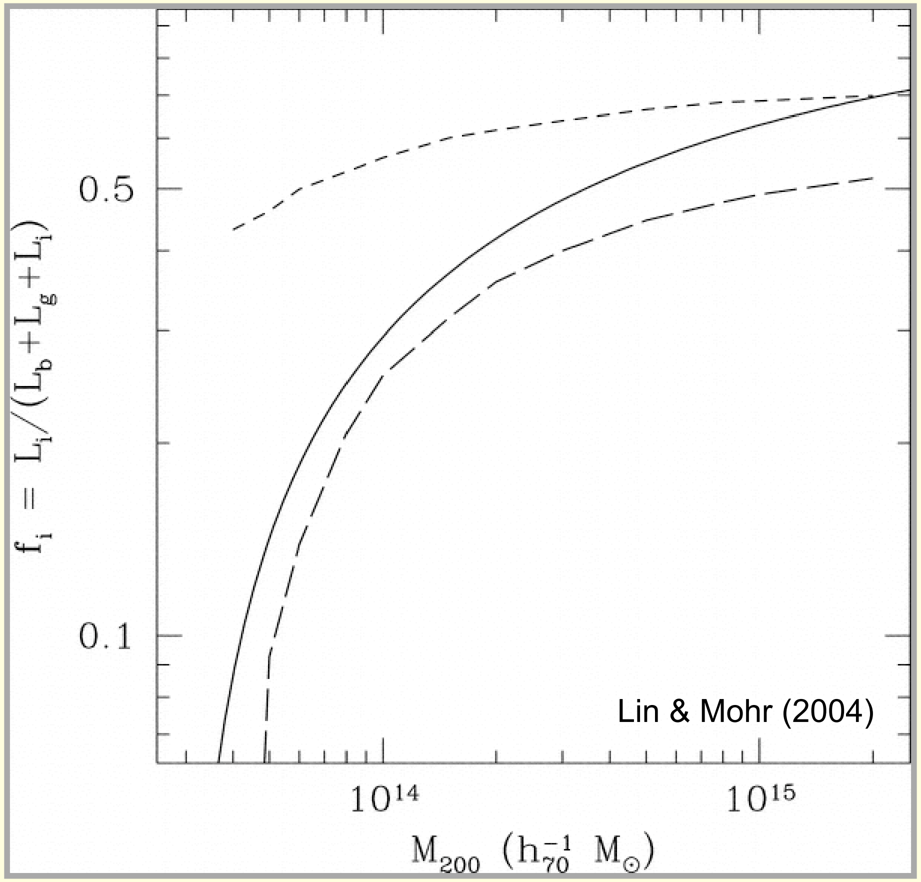


cluster galaxy formation: why is galaxy number *not* proportional to mass?

- possible scenarios
  - star formation efficiency higher in low mass clusters
  - galaxy disruption more efficient in high mass clusters: tidal processes, ram pressure, etc
- constraints from LFs and spatial distribution of *most* and *least* massive clusters (no BCGs)
  - very luminous galaxies appear only in most massive clusters; lower mass clusters have higher abundance of ~M_* galaxies
  - evolving LMLF into HMLF:
    - galaxy harassment, tidal stripping can remove ~40% of galaxy mass (but less certain in light) (√?)
    - ram pressure stripping more efficient in transforming morphology (X)
    - K-band insensitive to stellar aging (X)
    - merger between brightest galaxies (√)
  - galaxy spatial distribution does not depend on cluster mass
    - tidal interactions (X)
    - ram pressure stripping (X)
    - cannibalism (X)
- *maybe:* progenitors of high mass clusters differ from z~0 low mass clusters?



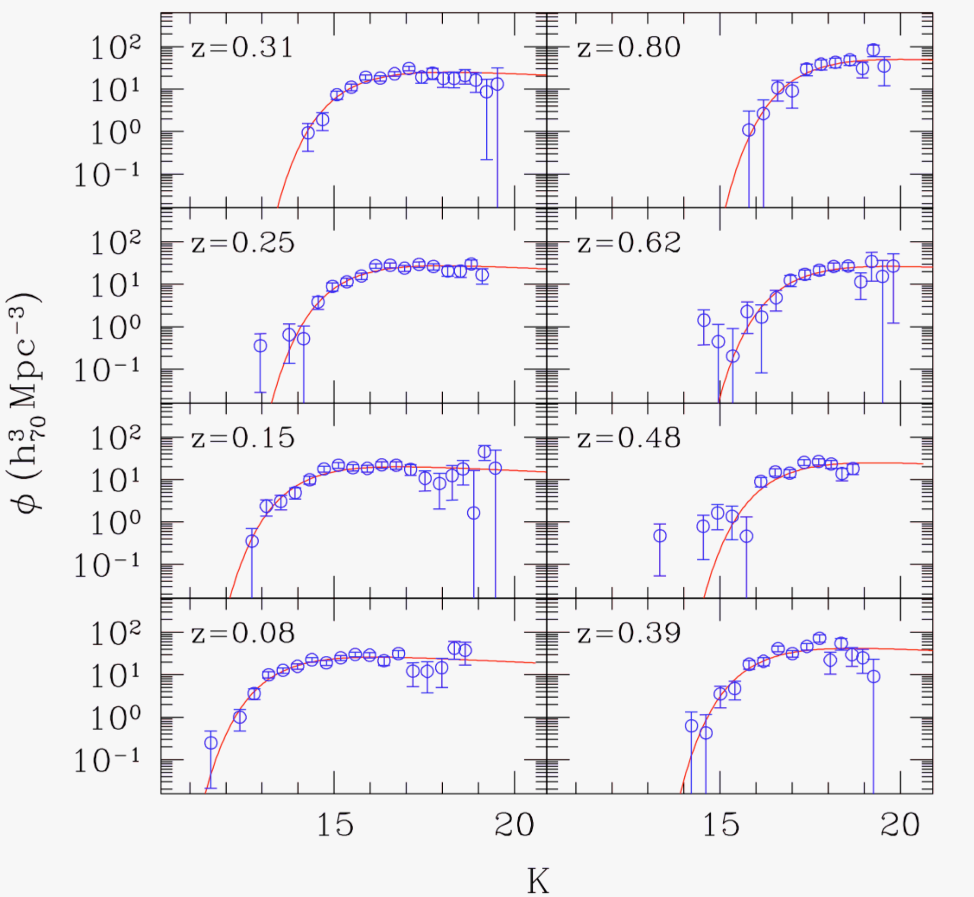
effect of intracluster light



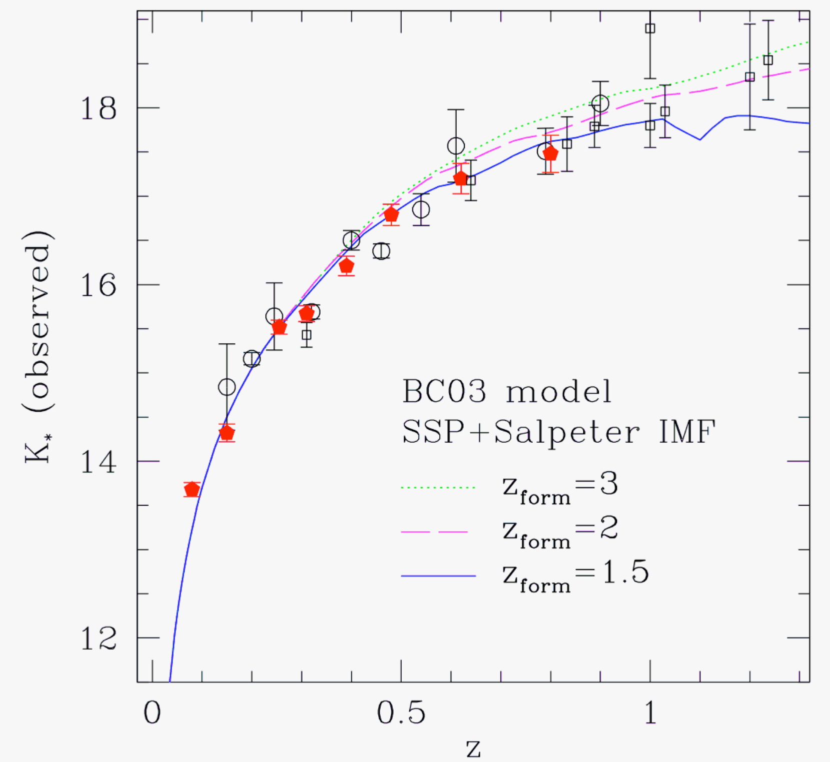
questions to be addressed

- redshift evolution? implication of (massive) galaxy formation?
  - are progenitors of present-day massive clusters differ from low mass clusters at z~0?
  - evolution of K-band LF and scaling relations out to z=0.9 for bulk of cluster galaxies
  - evolution of massive galaxies: LRG populations in clusters at z=0.2–0.6 from Vikhlinin's ROSAT PSPC 400 deg^2 survey

redshift evolution:
LF & $K_*(z)$



Lin et al (2006)

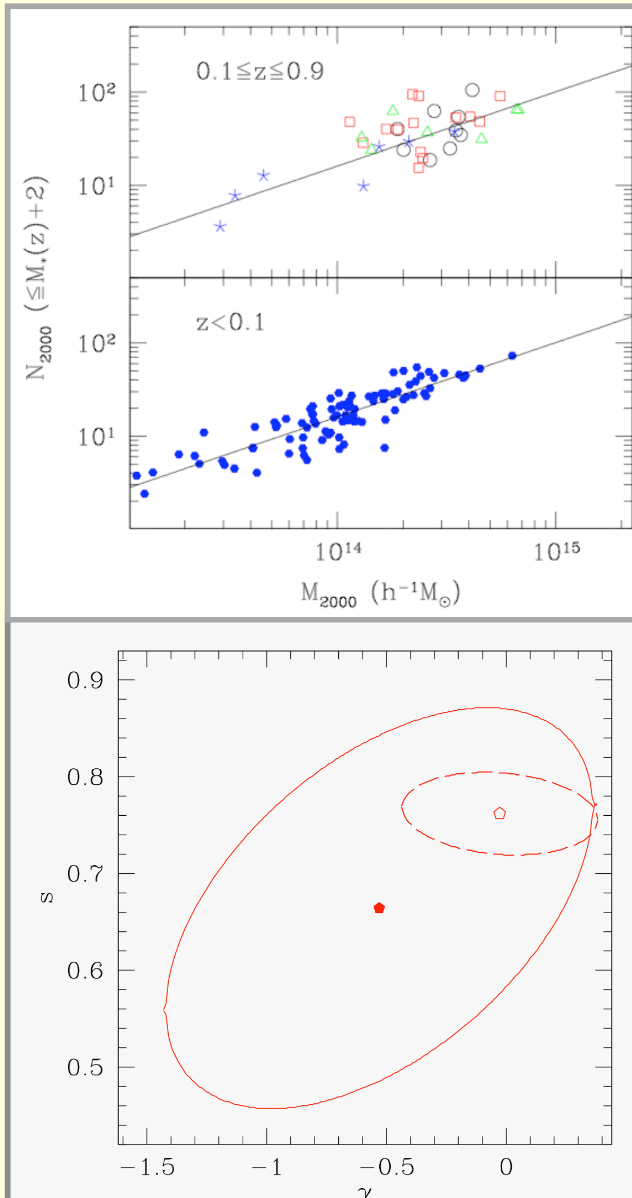


Lin et al (2006)

- 41 clusters at $0 \le z \le 0.9$ with deep K-band data (the "high-z sample")
- apparent composite LFs suggest that a simple stellar population formed in a single burst at z_{form}=1.5~2 (based on the Bruzual-Charlot model) describes data well
- we do not distinguish galaxy types in composite LFs ⇒ inferred z_{form} is an average over all galaxies

redshift evolution: scaling relations

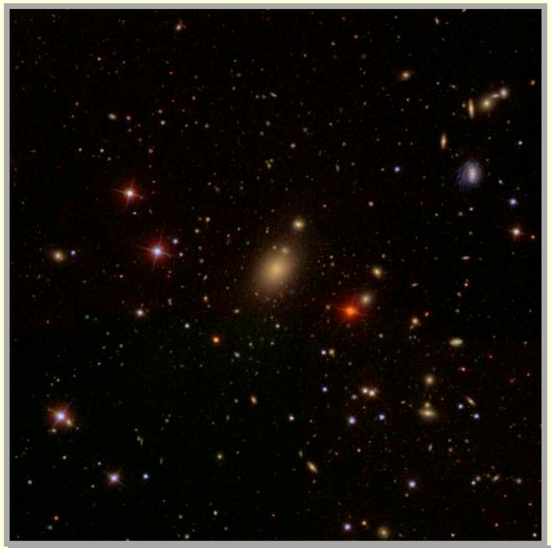
- using the z_{form}=1.5 BC model for evolution and k-corrections to infer fluxes in restframe K-band
- for each cluster, calculate N and L for galaxies more luminous than $M_*(z)+2 \Rightarrow$ to sample the same fraction of the LF (take out passive evolution)
- infer the evolution of N–M correlation from the high-z and nearby cluster samples; assuming
  $N(M,z) = N_0\,(M/M_0)^s\,(1+z)^\gamma$
  solving for N_0, γ, and s (assuming s independent of z)
- the nearby cluster sample largely determines s=0.76
- when marginalized over s, γ=–0.03±0.27
- understanding the no-evolution:
  – $N(M,z) = V\,\varphi_*\,\Gamma[\alpha+1, L_{low}(z)/L_*(z)]$
  – α and L_{low}/L_* the same for all clusters
  – clusters *i* and *j*: same mass, at z_i and z_j ($z_i>z_j$) $\Rightarrow V_j>V_i$; data suggest that $\varphi_{*,i}>\varphi_{*,j}$
  – the increase in the galaxy number density (φ_*) is offset by the decrease in the virial volume at higher-z

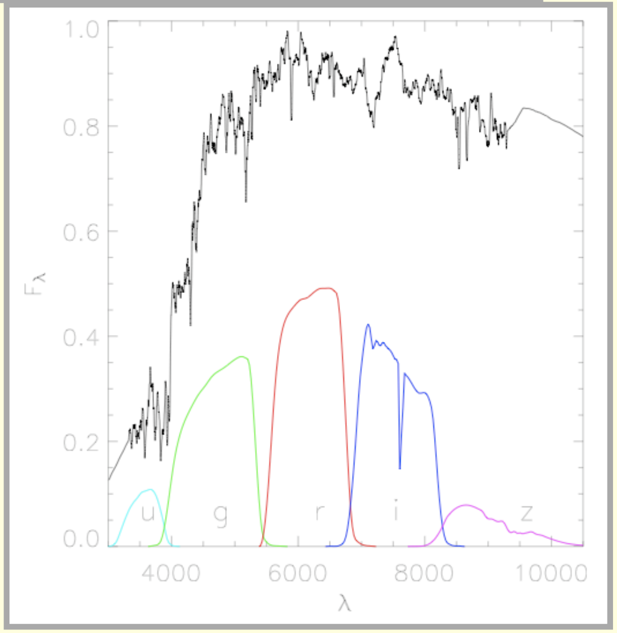


Lin et al (2006)

redshift evolution: LRGs at 0.2≤z≤0.6

- why study LRGs?
  - we just examined the evolution of the bulk of the cluster galaxies; how about the massive ones?
- what are LRGs?
  - massive, luminous, red, early type
  - majority of stars formed at high redshift
  - spectra characterized by strong break at 4000Å
    - help redshift measurement
    - selectable by color
- goals
  - are their properties related to host clusters?
  - do they show any redshift evolution?
- galaxy sample
  - SDSS photometric catalog
  - selecting LRGs via g-r and r-i colors, following Padmanabhan et al (2005)
  - z=0 restframe g-band magnitude $-23.5 \le M_g \le -21$
  - utilizing photometric redshift [$\delta z/(1+z) \le 0.03$] for cluster membership assignment

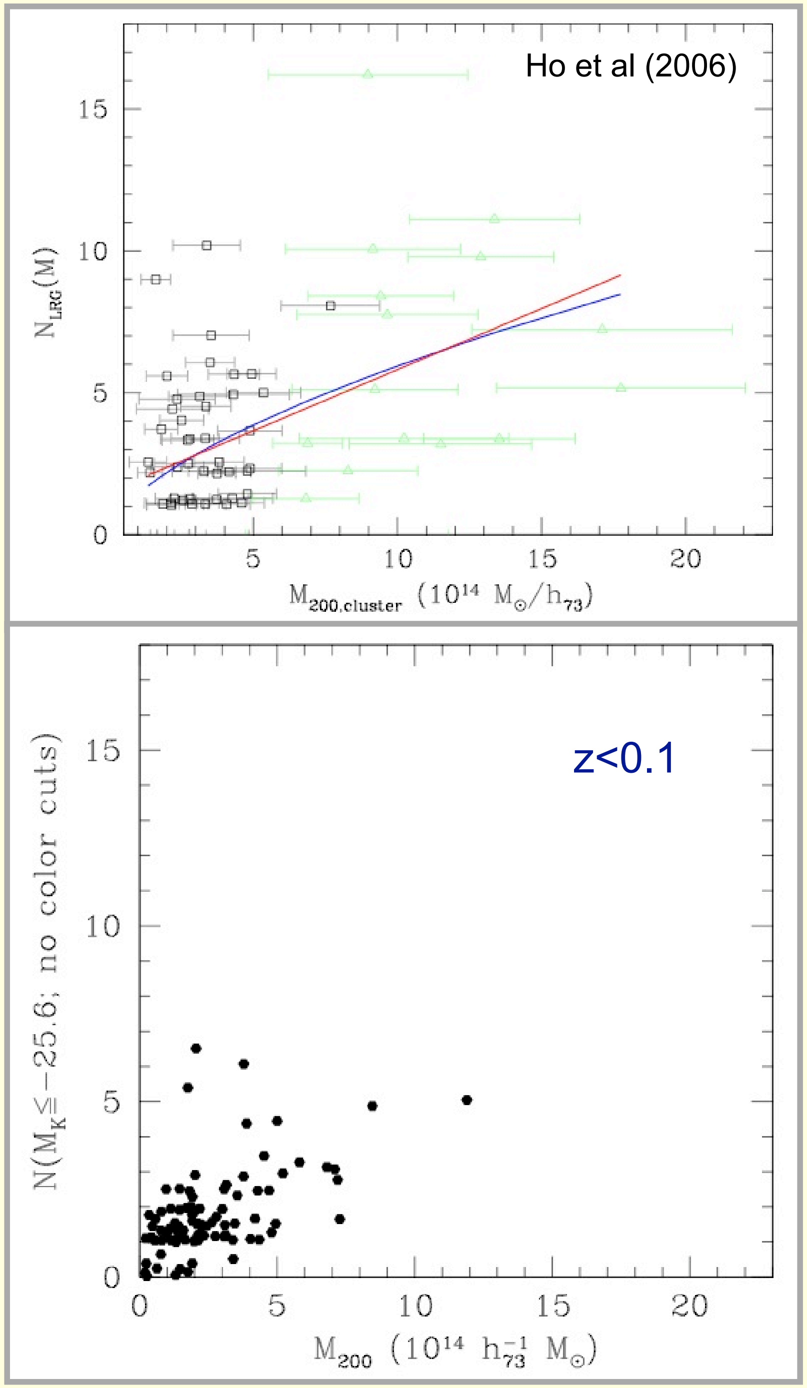




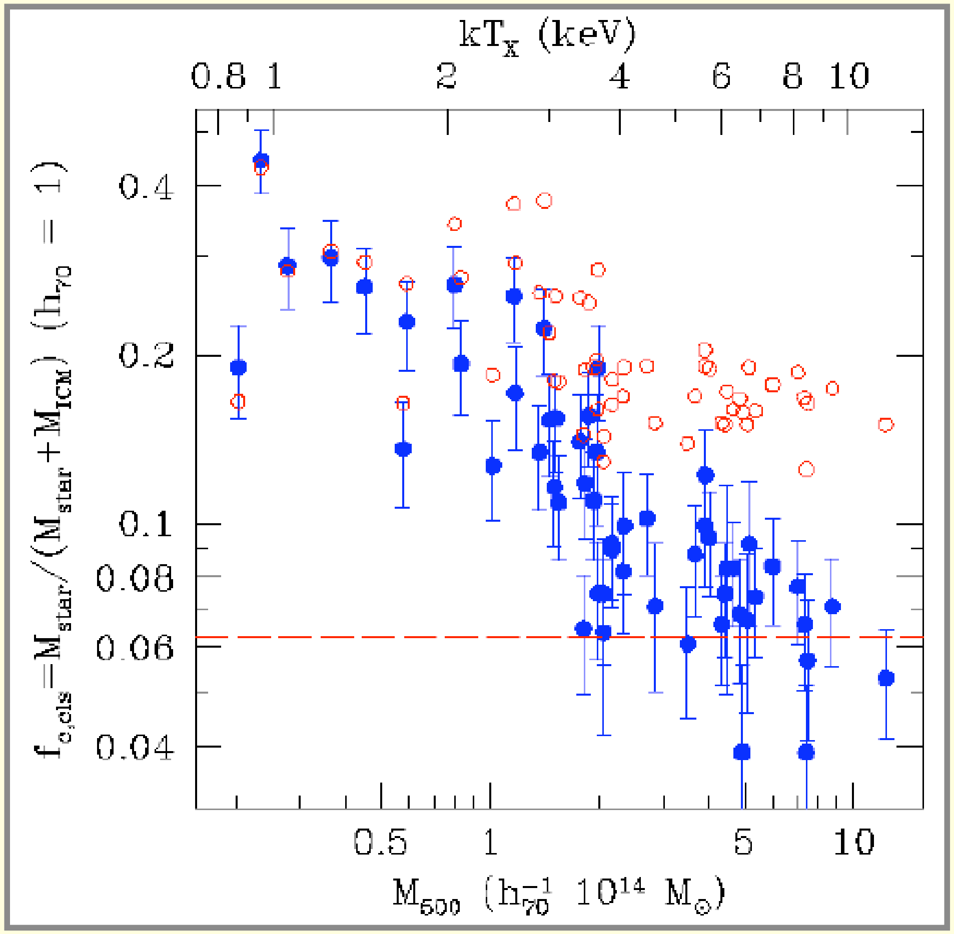
Padmanabhan et al (2005)

LRGs at 0.2≤z≤0.6: scaling relation

- power-law fit to the distribution gives $N_{LRG} \propto M^{0.62\pm0.11}$
- defining a low-z comparison sample: select massive galaxies with luminosity cut ($M_K \leq -25.6$) that gives same number density as LRGs
- for z<0.1 massive, K-band selected galaxies, $N \propto M^{0.40\pm0.10}$ with similar normalization as LRGs
- lessons from LRGs: both spatial distribution and scaling relation are similar to that of massive, K-band selected cluster galaxies at z≤0.2
- no obvious redshift evolution



cluster galaxy formation: star formation efficiency



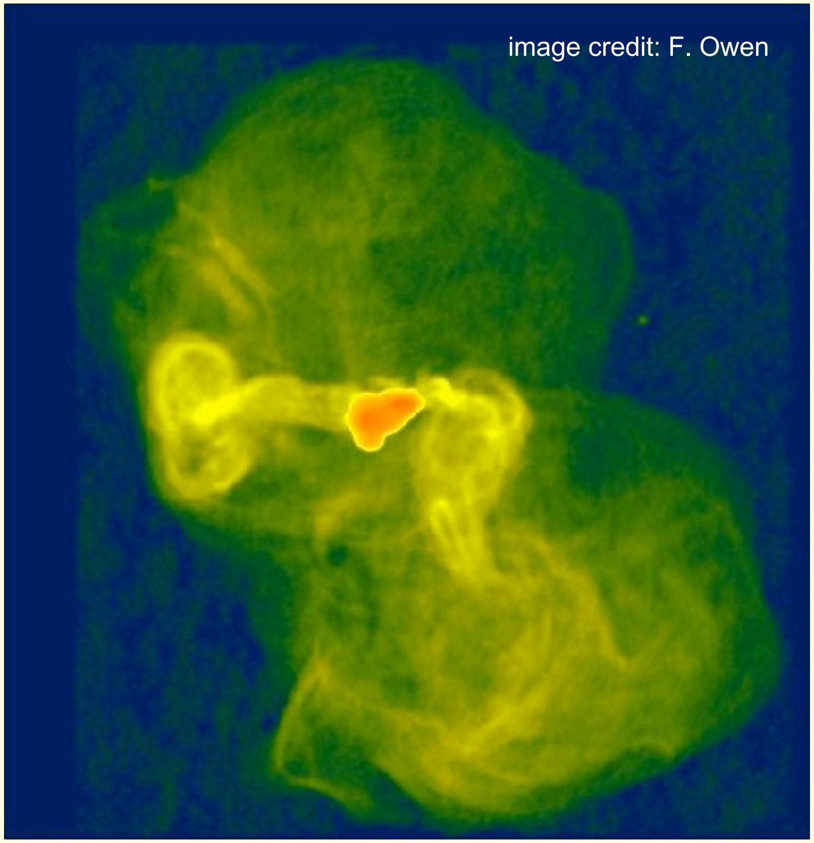
- ensemble properties of galaxy populations in clusters may be set at z~1 or earlier
- another possibility to explain the slope of the N–M relation is a varying star formation efficiency: massive halos form stars less efficiently than lower mass ones
- look at the *cold baryon fraction*: fraction of cluster baryons that are in the form of stars (in galaxies)
- X-ray data from Mohr et al (1999) and Sanderson et al (2003) for ~60 clusters and groups
- cold fraction decreases with cluster mass

questions to be addressed

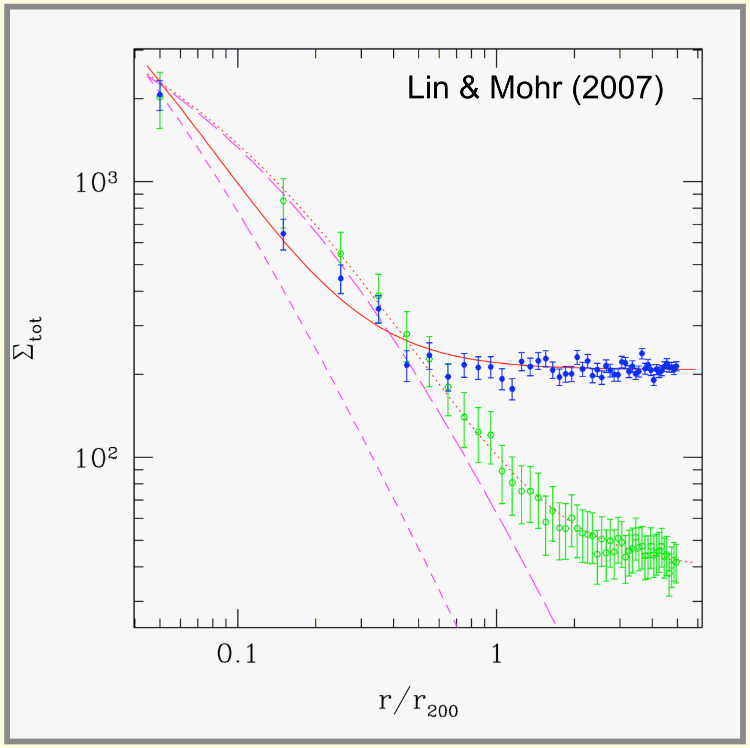
- what is the RLAGN content of clusters?
  - radio and near-IR K-band LFs $\Rightarrow$ radio-active fraction and duty cycle
  - BCGs as radio-active galaxies
- clustering properties of RLAGNs
- implication for SZE cluster surveys?

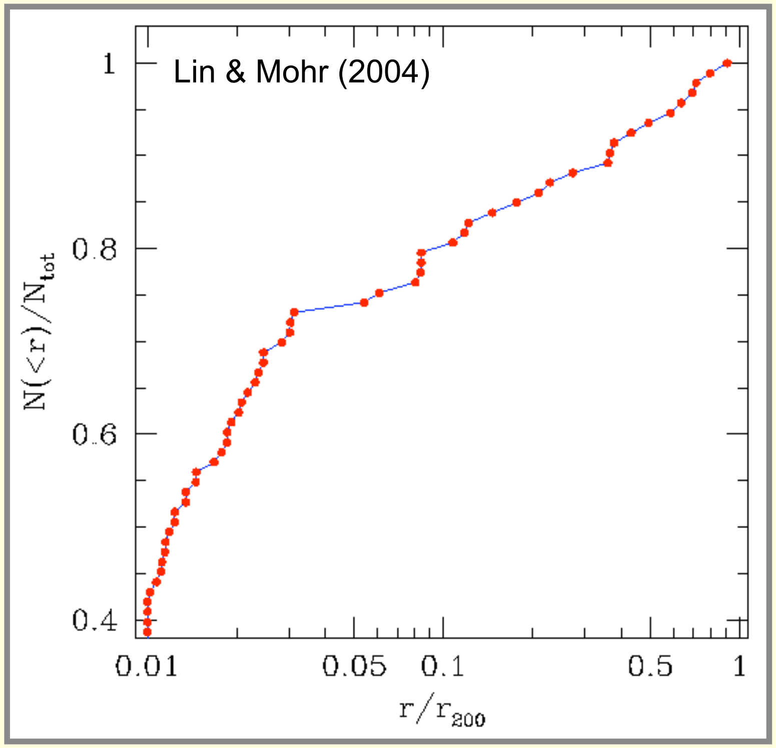
radio-loud AGNs: motivation

- at low frequencies (e.g., $\nu \leq 30$ GHz), RLAGNs may overwhelm the SZE signal from the cluster
  - cosmological constraints based on cluster abundance weakened if not properly account for clusters lost due to AGNs
  - realistic forecast for survey yields needs accurate estimates of degree of contamination
- long been invoked as candidate source for heating up the ICM
- need to study their abundance and relation to the general cluster galaxy population: radio LF (RLF) at 1.4 GHz, spatial distribution, and duty cycle
- caution: at $\log P \leq 26$, AGNs selected via radio represent a different population from those selected by optical emission lines (Best et al 2005)



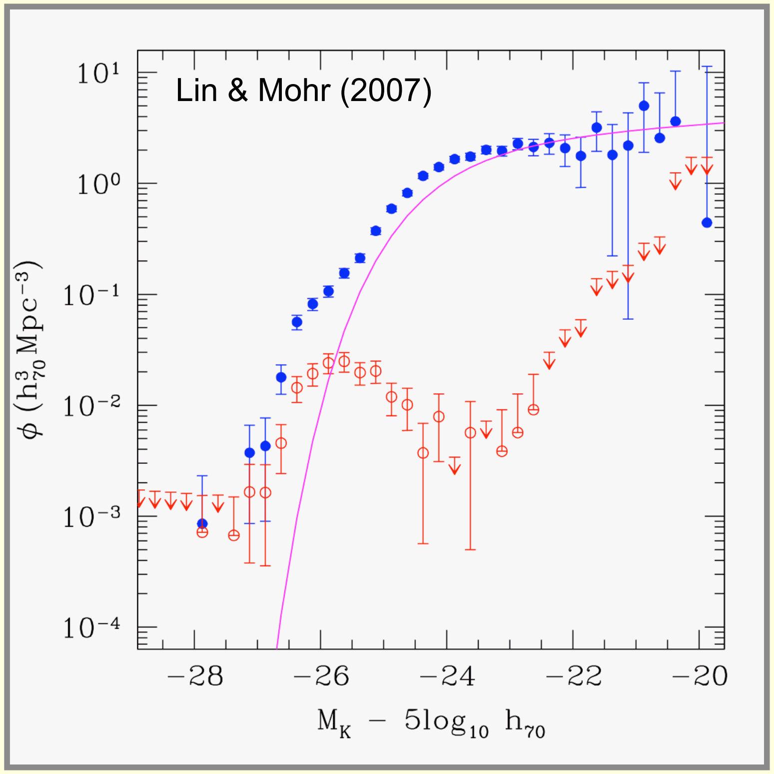
radio-loud AGNs: radial distribution

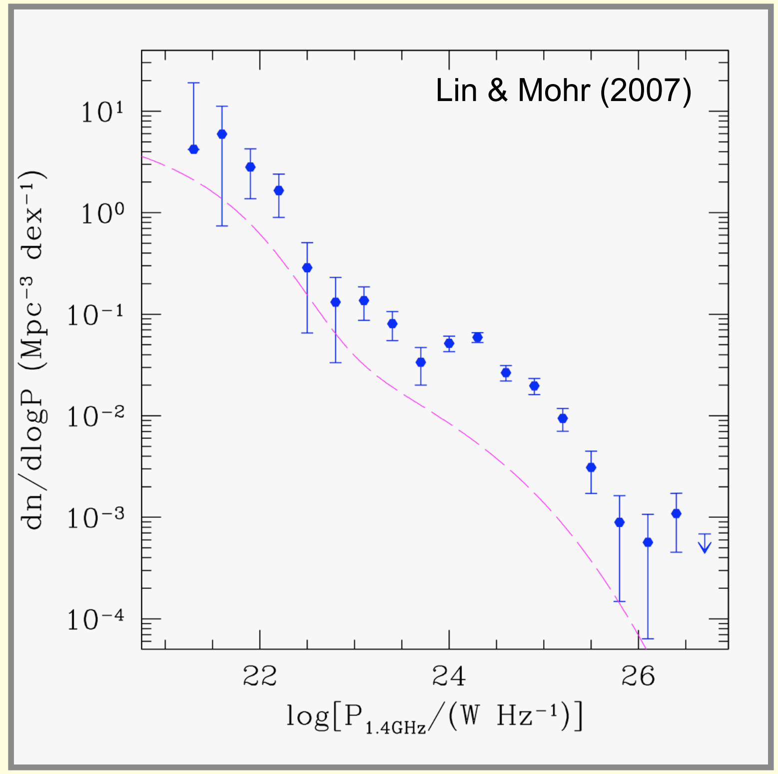




- RLAGN distribution much more concentrated than galaxies, c~30 ⇒ central region of clusters promotes AGN activity (within "cooling radius")
- being centrally located, BCGs have higher probability of being radio-active

radio active fraction and radio LF



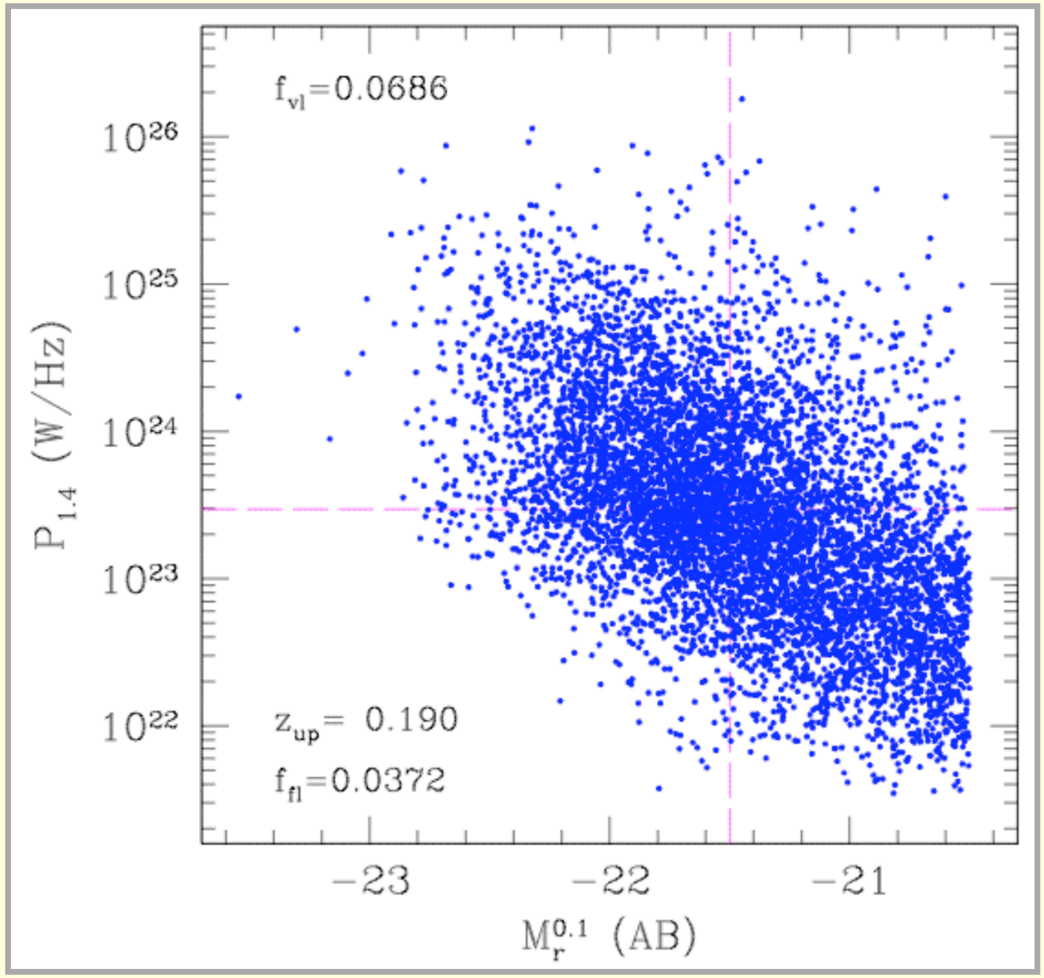


- comparison of K-band LF for all galaxies and radio galaxies (more powerful than a radio luminosity threshold, e.g. ≥10^{24} W/Hz)

  ⇒ RAF: fraction of galaxies that are active in the radio
- ~5% of galaxies more luminous than M_* host RLAGNs (~1.3% in the field); ~35% of BCGs are radio-active
- cluster central region is special: RAF of central galaxies 2–3 times larger than other cluster galaxies of similar optical luminosity
- more powerful than log P = 23, RLF dominated by RLAGNs; weaker sources mainly star-forming galaxies
- density of cluster AGNs ~6x higher than expectations from the scaled field value ⇒ another indication that RLAGNs favor cluster environment

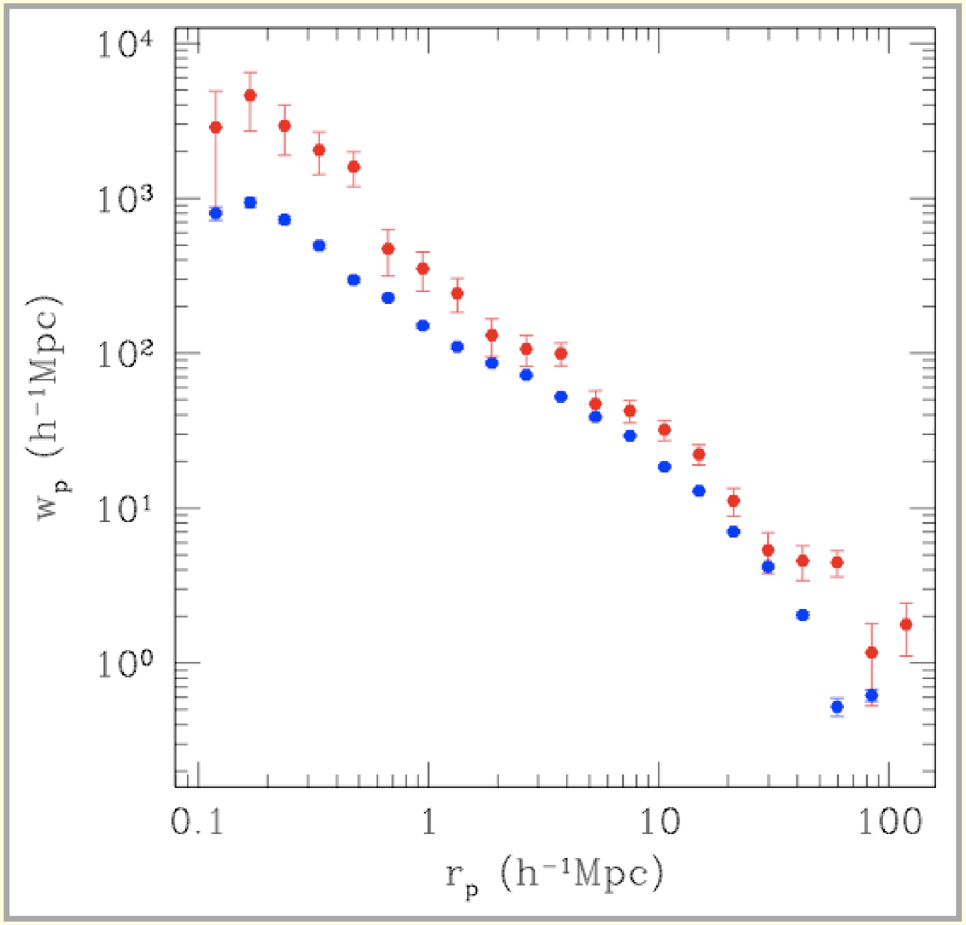
radio-loud AGNs: optical-radio bivariate luminosity distribution

- clearer picture of optical-radio bivariate luminosity distribution
- cross-matching SDSS DR6 with NVSS+FIRST surveys at 1.4 GHz generates the largest radio galaxy catalog to date: 9,300 RGs from ~215,300 galaxies to $M_r \leq -20.5$
- NOTE: not just cluster radio sources
- radio luminosity ∝ (optical luminosity)^2
- projection on either axis generates optical and radio LFs



Lin et al (in prep)

radio-loud AGNs: correlation function



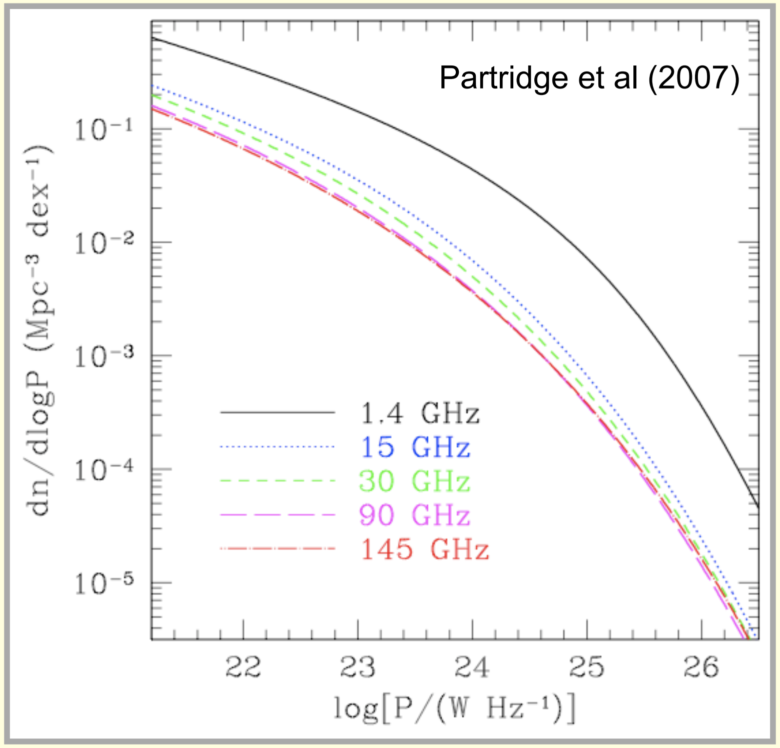
- both galaxies and RLAGNs are volume-limited
  - both subject to same optical luminosity cut ($M_r \leq -21.5$)
  - RLAGNs more powerful than $10^{23.47}$ W/Hz
- RLAGNs (red points) more strongly clustered than galaxies (blue points)
- clustering length comparable to groups of galaxies (~10h^{-1}Mpc)
- trend remains with further color/luminosity cuts

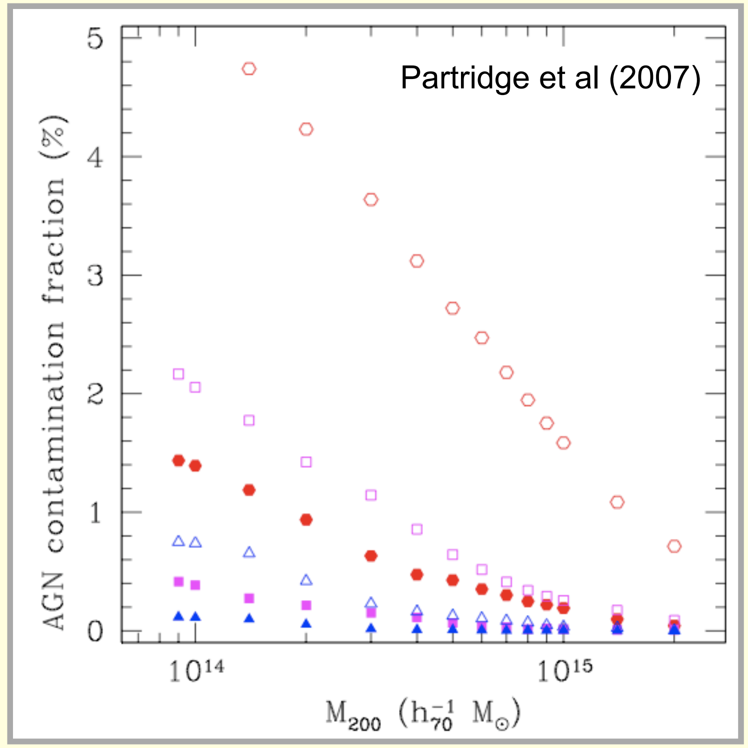
Lin et al (in prep)

radio-loud AGNs: forecast for SZE contamination

- extrapolate observed 1.4 GHz RLF to higher frequency by convolving the RLF with the distribution of the spectral shape
- assume redshift evolution of RLF $\propto(1+z)^{\gamma}$ with $\gamma=2.5$
- compute RLAGN contamination in a Monte Carlo fashion:
  - given cluster mass and redshift, expect $\langle N \rangle$ AGNs based on the RLF
  - draw Poisson random number N_p with mean of $\langle N \rangle$
  - assign fluxes to N_p sources according to RLF
  - for each redshift and mass, repeat the MC process for 10^5 times; estimate the contamination fraction as the proportion of all clusters whose AGN fluxes are large compared to the SZE flux: $\Sigma S_{AGN} \geq q|S_{SZE}|$
    - consider q=0.2 and 1.0
- advantage of our forecast: use of observed spectra of cluster radio galaxies up to 43 GHz (Partridge et al 2007)
- caveat: redshift evolution of the RLF and the spectral shape are still unknown

radio-loud AGNs: forecast for SZE contamination





- extrapolated RLFs have amplitudes much reduced compared to 1.4 GHz
- consider two degrees of contamination: 100% and 20%
  - solid points: $\Sigma S_{AGN} \geq |S_{SZE}|$
  - open points: $\Sigma S_{AGN} \geq 0.2|S_{SZE}|$
  - fraction of contaminated clusters is small at all redshifts (red, magenta, blue: z=0.1, 0.6, 1.1)

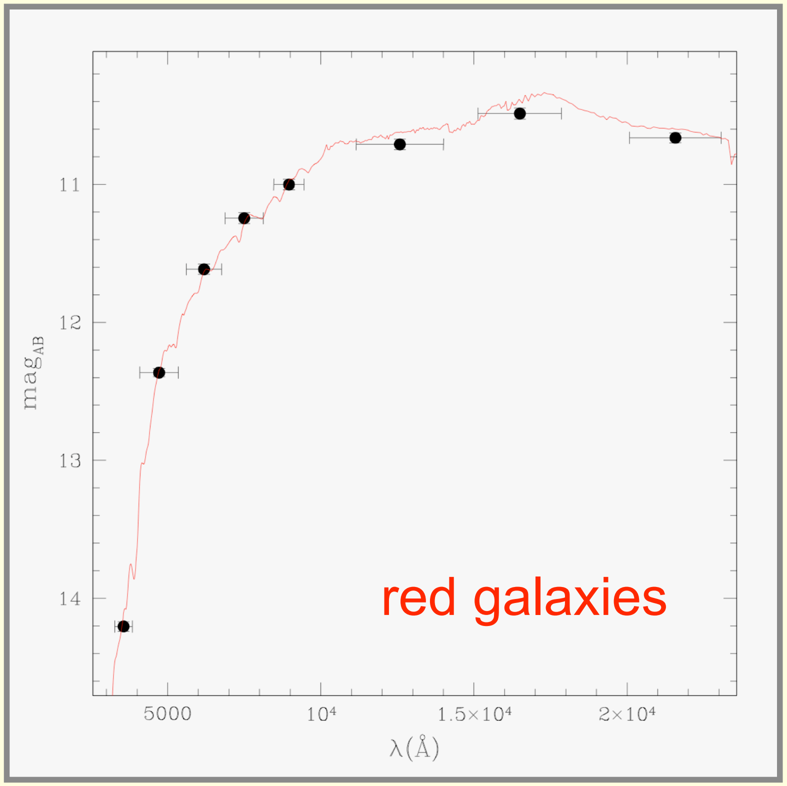
summary

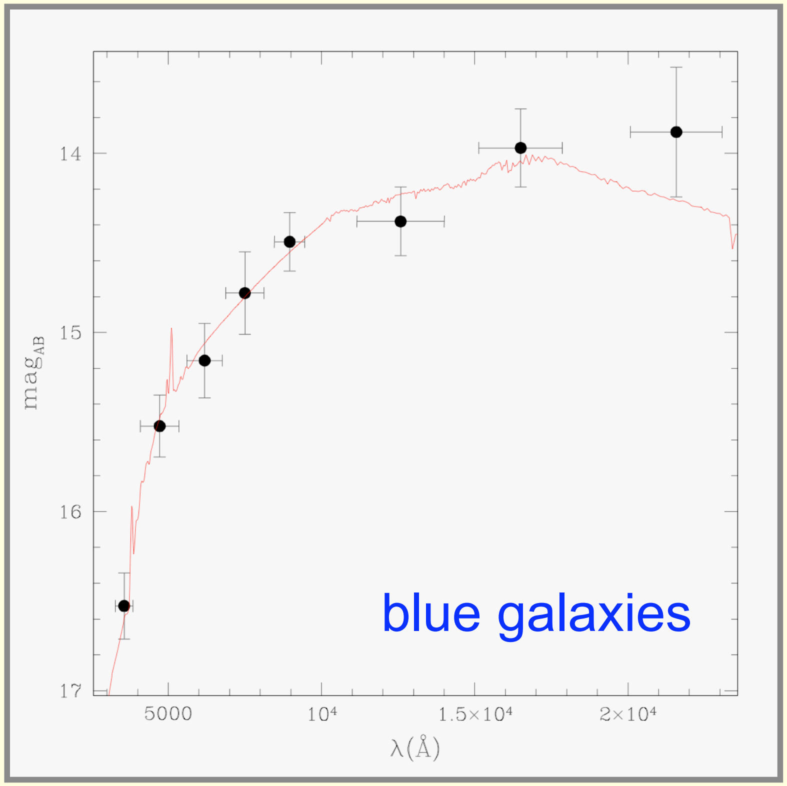
- what sets the slope of N–M relation?
  – mergers, tidal disruption, varying star formation efficiency
- the redshift evolution of cluster galaxy populations
  – ensemble properties set by z=1
- the radio-loud AGN content of clusters?
  – central regions of clusters promote AGN activity
- results mainly from
  – Lin, Mohr, and Stanford (2004 ApJ 610, 745) — LF, scaling relations
  – Lin & Mohr (2004 ApJ 617, 879) — BCGs
  – Lin, Mohr, Gonzalez, and Stanford (2006 ApJL 650, 99) — cluster galaxy evolution
  – Ho, Lin, Spergel, and Hirata (2007, ApJ, submitted; 0706.0727) — cluster LRG evolution
  – Lin & Mohr (2007 ApJS, 170, 71) — radio sources in low-z clusters
  – Partridge, Lin, et al (2007 ApJ, submitted) — spectral shape of radio sources

Summary: How to Populate a Cluster?

- BCGs:
  - Mainly located at cluster center
  - Luminosity weakly correlates with cluster mass; growth of luminosity slower than the cluster as a whole (overall importance of BCG in cluster luminosity content decreasing with cluster mass)
  - High probability of being radio active
- Red and blue galaxies:
  - Spatial distribution can be described by NFW profile; red galaxies more concentrated than blue ones
  - Space density of red galaxies much higher than that of the blue ones
  - Mean spectral types approximated by E2 and Scd
  - Red galaxy luminosity correlates well with cluster mass; not so much for blue light
- Radio-loud AGNs:
  - Very concentrated (c~30) spatial distribution
  - Number density of cluster radio sources ~6x higher than the expectation from the field
  - Radio active fraction of cluster galaxies is higher than field galaxies of similar luminosity
  - Central region of clusters promotes radio activity: Cooling instability? ICM confining pressure?
- Evolution to z~1:
  - Cluster galaxies *on average* appear to form their stars at z=1.5–2 in a burst, and evolve passively afterwards
  - Mean number of galaxies shows no evolution with redshift; the increase in the galaxy number density at higher-z is offset by the decrease in the virial volume

Mean Spectra





- Calculating luminosity density by integrating the LFs
- Place composite cluster at z=0.02 (e.g. Coma)
- Red galaxies described by an E2 SED
- Blue galaxies described by a Scd SED
- Can then use appropriate stellar M/L to obtain stellar mass
- May also infer mean star formation history from the spectra

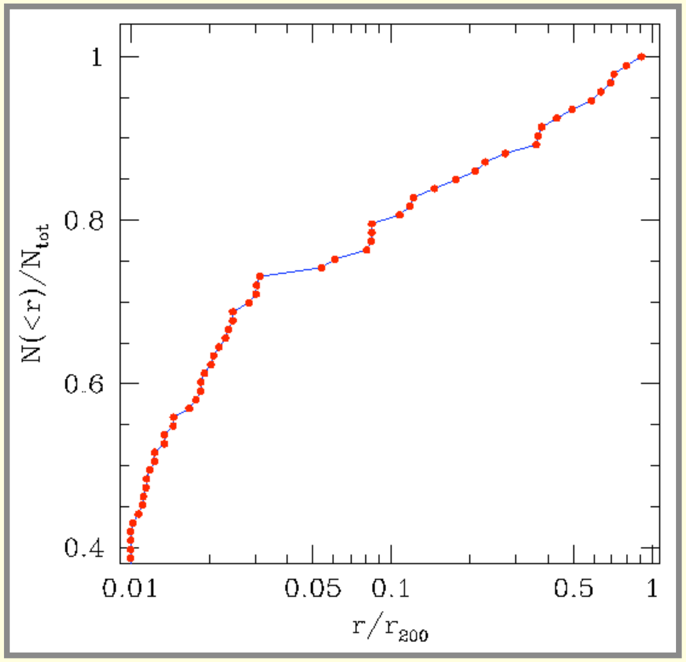
questions to be addressed

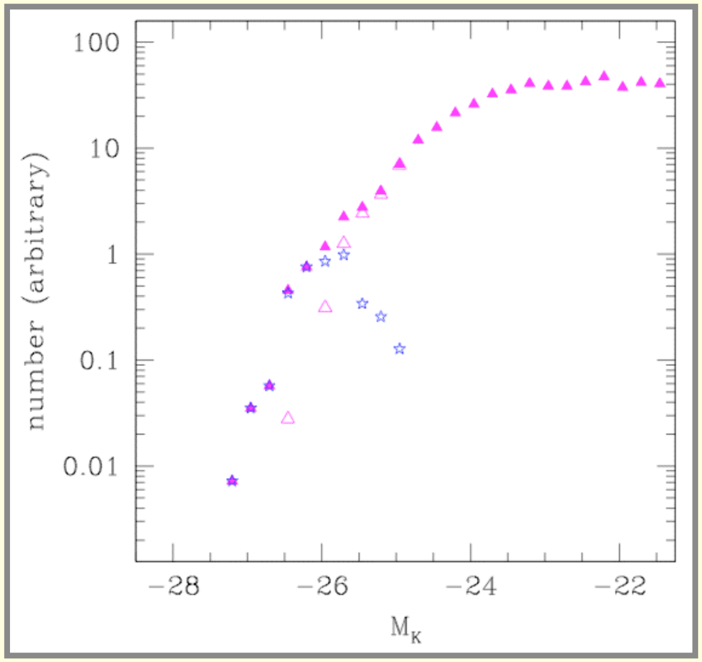
- how are brightest cluster galaxies (BCGs) formed?
  - special location within clusters
  - LF, scaling relations
  - clues on the formation from luminosity distribution and dark matter halo merger history considerations

BCG formation

- how are brightest cluster galaxies (BCGs) formed?
  - cooling flows (Fabian)
    - existence of the flow
    - color of the BCGs
  - cannibalism (Ostriker): ~M_* galaxies sink to the bottom of potential and merge with the central galaxy
    - multiple nuclei seen in BCGs
    - dynamical friction time actually quite long for mergers
  - rapid merger during cluster collapse and virialization (Merritt)
    - demonstrated by N-body simulation (e.g., Dubinski)

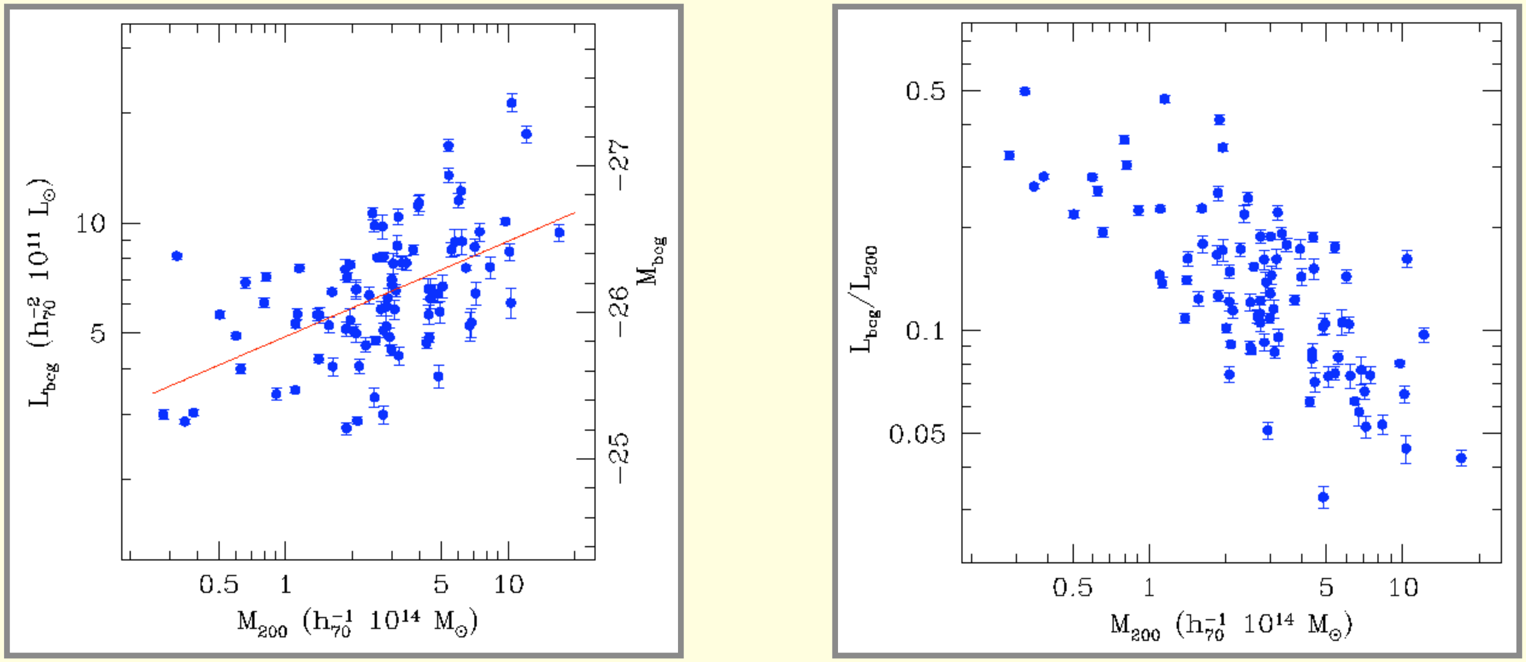
BCG formation: observations





- X-ray emission peak as cluster center
- 45% of BCGs within $0.01r_{200}$; 75% within $0.06r_{200}$ ⇒ can use BCG position as proxy of cluster center
- make the bright end of LF deviate from Schechter form
- Tremaine-Richstone test indicates they are not drawn from the same population as the rest of the galaxies; likely made by mergers

BCG formation: scaling relations



- BCG luminosity correlates with cluster mass $L_{bcg} \propto M^{0.26}$
- formation history tied to that of host clusters?
- different mass scaling between total light from non-BCG galaxies and BCGs ($L \propto M^{0.82}$)
  - importance in total luminosity budget decreases with cluster mass
  - ~50% in groups; few percent in most massive clusters

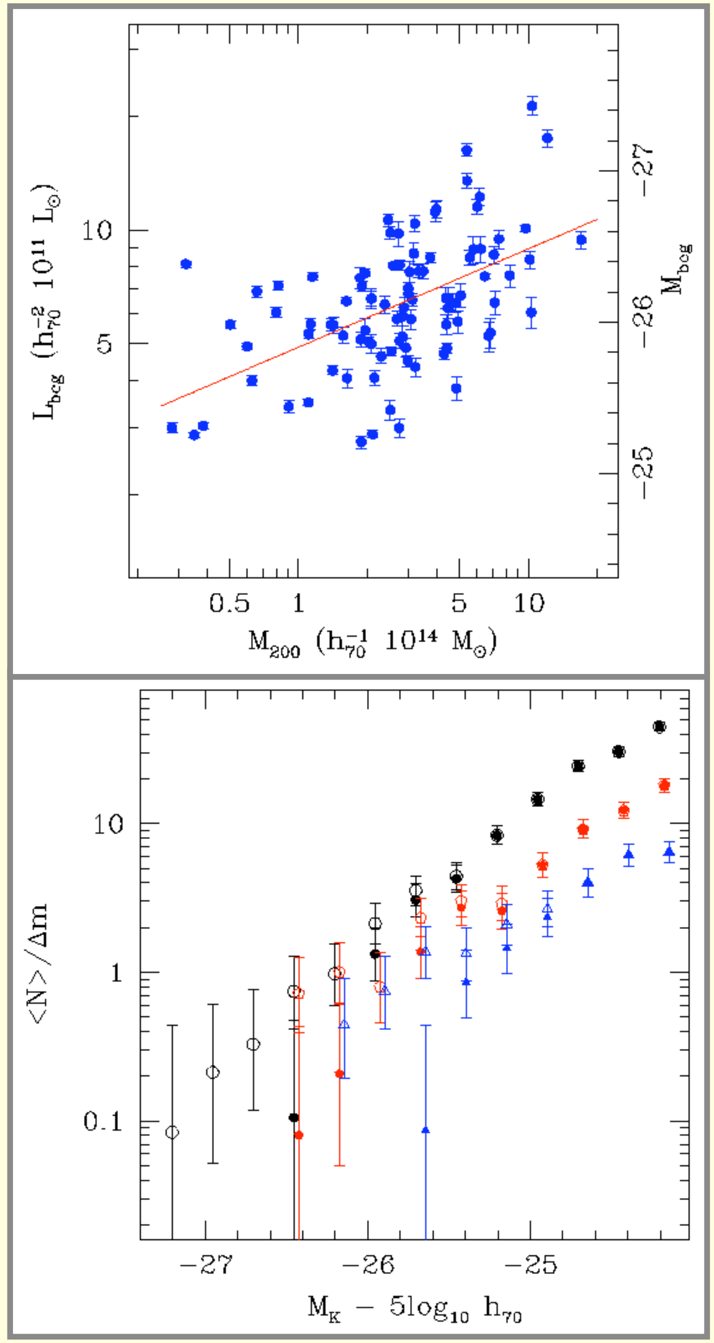
BCG formation

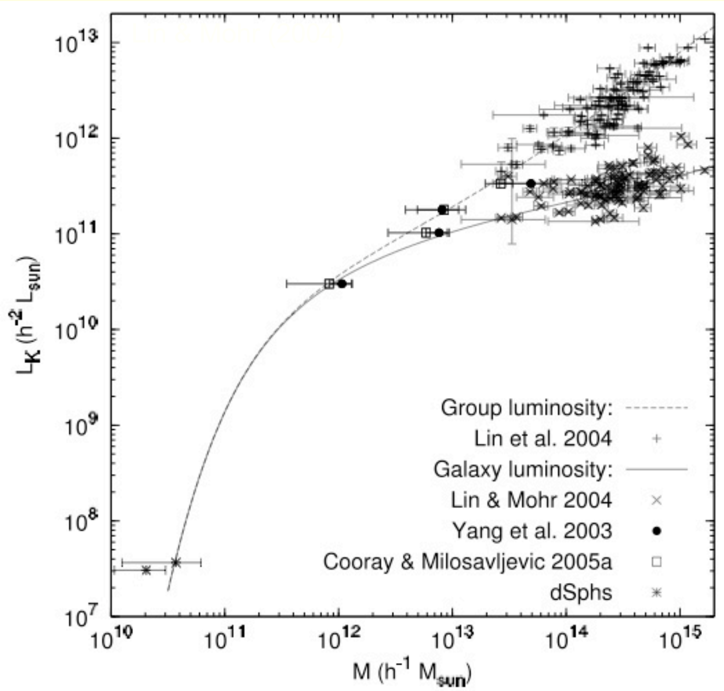
- BCG must grow in luminosity, but slower than the cluster itself
- luminosity distributions (LDs):

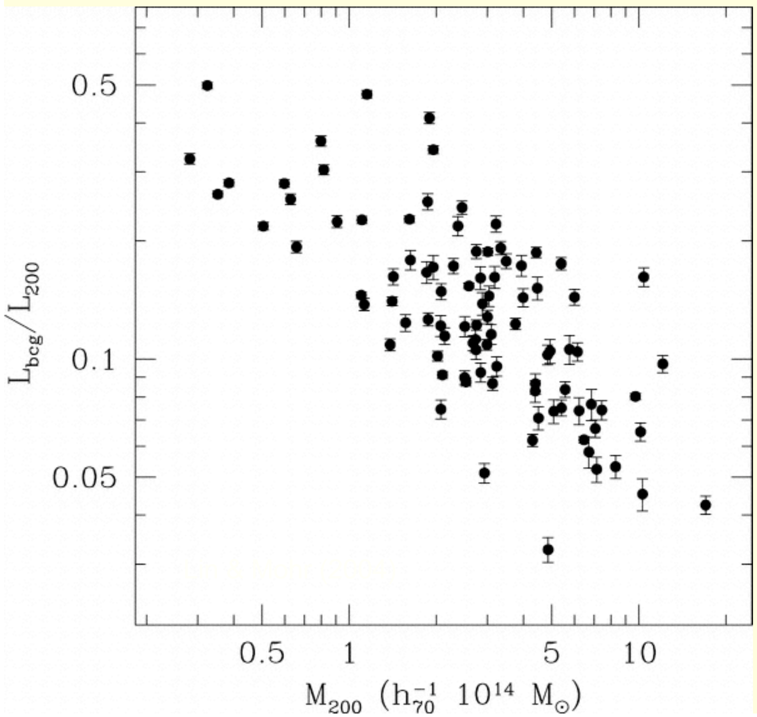
  25 least massive

  25 intermediate

  25 most massive
- mergers of ~M_* galaxies enough to produce BCGs in intermediate clusters, but not enough for BCGs in high mass clusters
- brightest galaxies in lower mass clusters enough to make up ΔL
- ΛCDM supplies enough mergers between clusters/groups
- possible evolution routes
  - after a central galaxy forms, cannibalism adds only little light
  - it can grow by merging with normal (L_*) galaxies
  - but most efficiently, merger with ex-BCGs when parent cluster grows hierarchically



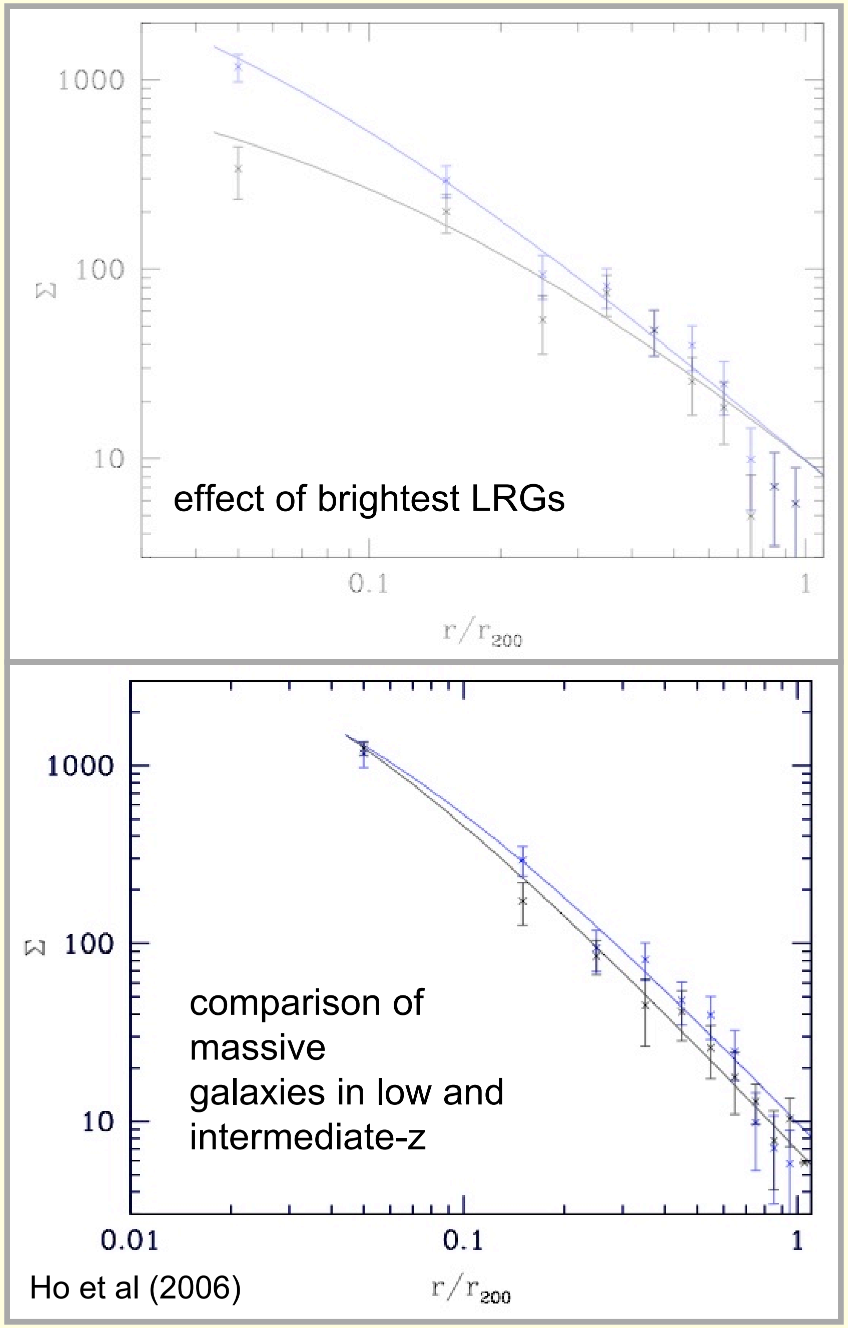




- BCG luminosity weakly dependent on cluster mass: $L_b \propto M^{0.26}$
- Recall that L (w/ BCG) $\propto M^{0.69\pm0.04} \Longrightarrow$ importance of BCG luminosity decreases with cluster mass
- Model of Vale & Ostriker can reproduce both the L_{tot}-M and L_b-M relations
- Cooray uses these relations to construct a conditional luminosity function model

LRGs at $0.2 \le z \le 0.6$: data & methods

- galaxy sample
  - SDSS photometric catalog
  - selecting LRGs via g-r and r-i colors, following Padmanabhan et al (2005)
  - z=0 restframe g-band magnitude $-23.5 \le M_g \le -21$
  - utilizing photometric redshift, typically of uncertainty $\delta z/(1+z) \le 0.03$, for cluster membership assignment
- cluster sample
  - flux-limited cluster sample from the ROSAT 400 square degree survey: a serendipitous cluster survey using archival PSPC images, covering 400 deg^2 (Burenin et al 2006)
  - 47 clusters (out of 266) with SDSS DR5 coverage, at $0.2 \le z \le 0.6$
  - L_X available as proxy of cluster mass



LRGs at 0.2≤z≤0.6: spatial distribution

- LRGs are concentrated toward cluster center
  - Including brightest LRGs, c~18
  - excluding brightest LRGs, c~6
- LRGs at intermediate-z are distributed within clusters similar to that of massive galaxies (M_*–1; K-band selected, no color cuts) in clusters at lower redshifts