Lessons on galaxy formation from weak gravitational lensing

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Questions in galaxy formation

- If we see a galaxy, at a variety of wavelengths…
  - What dark matter, if any, is associated with that galaxy? What is the relationship between the visible and the dark components?
- What about “special” galaxy types, such as active galactic nuclei?
- Relation to central black hole properties

How did these galaxies arise?




Pictures from Sloan Digital Sky Survey data release 6

The fundamental problem:

- Telescopes see baryons (galaxies)
- Baryon physics is imperfectly understood
- We need observations to refine models of the physics of galaxy formation/evolution.

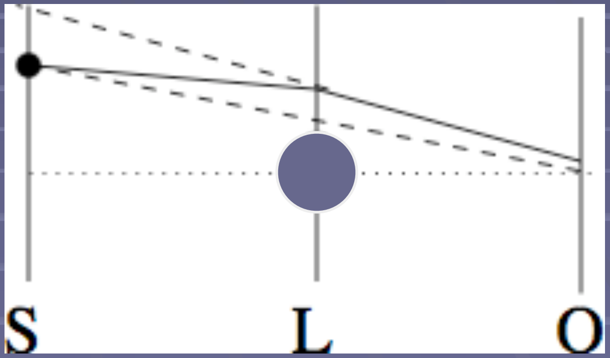
Conclusion: our toolbox needs some new tools!

Outline

- Motivation
- Lensing introduction
- Theoretical interpretation
- Application: halo mass and satellite fraction versus optical observables

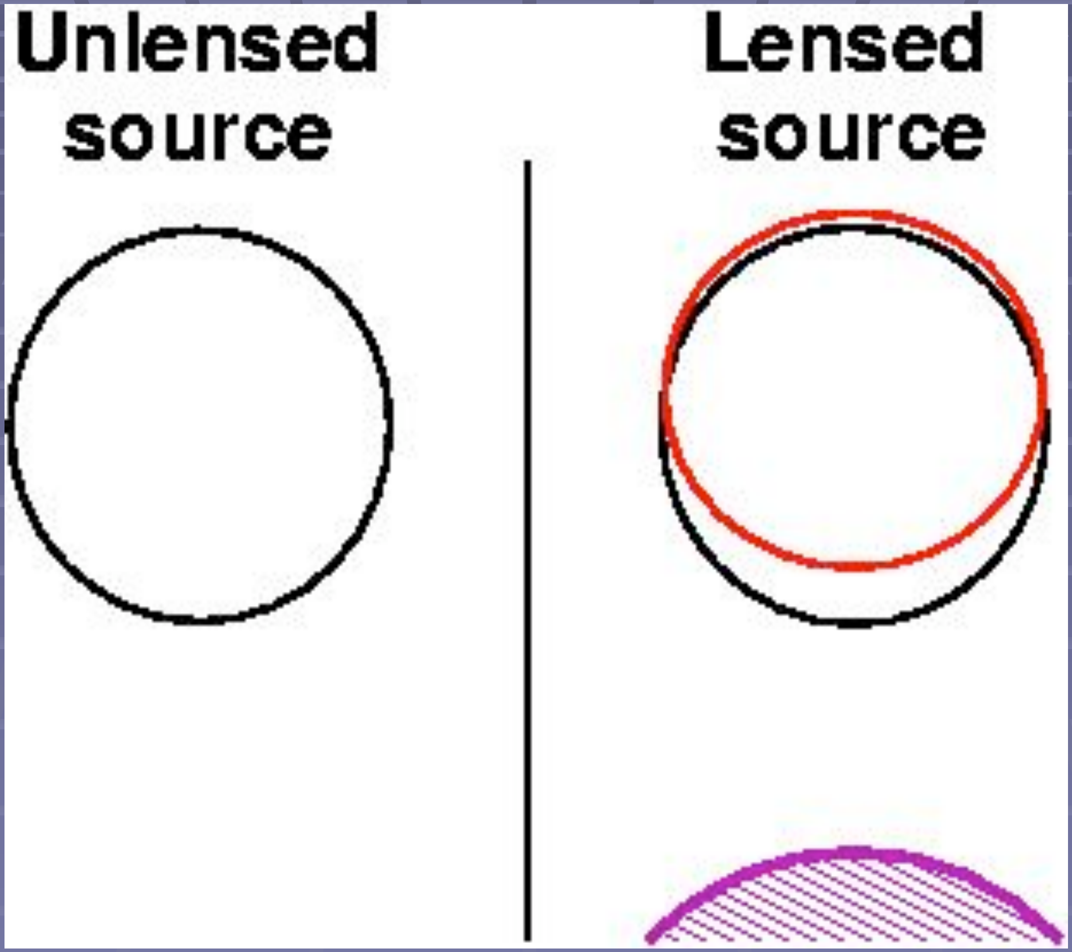
One (relatively) new tool…

- Gravitational lensing:
  Sensitive to all matter along line of sight, including dark matter!



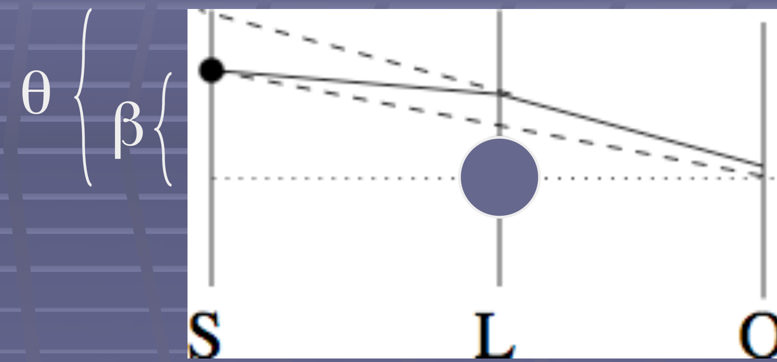
- Depends on projection along line of sight
- Weak: small effect, can be treated perturbatively

The (weak) lensing effect



Caution: magnification not depicted accurately!

The basics



- Source galaxy at β
- Observed image at θ
- Instead of $I(\beta)$, we see $I'[\theta(\beta)]$
- We care about the Jacobian:

$$\frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

~~κ = convergence;~~ γ = shear

Definitions

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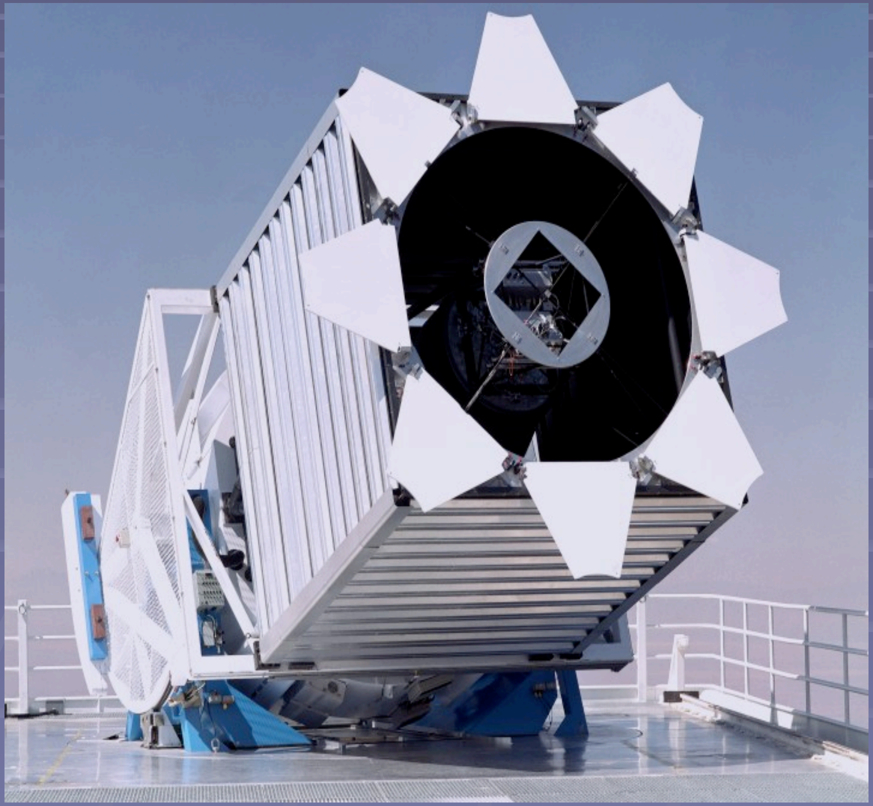
γ = "shear"

$$\Sigma_c^{-1} = \left(\frac{4\pi G}{c^2}\right) \frac{D_L D_{LS}(1+z_L)^2}{D_S}$$ (comoving)

Sloan Digital Sky Survey (SDSS)



(from http://www.sdss.org/)

- Imaging, spectroscopy over ~ 1/4 of the sky
- Imaging in 5 passbands (ugriz)

Our approach: Reglens

- **Lenses**: SDSS spectroscopic sample (~4x10^5 galaxies, <z>~0.1)
- **Sources**: SDSS photometric galaxies (~3x10^7 galaxies, <z>~0.4)
- **Statistics**: Stack 3K-100K lenses
- **Systematics**: Random points, 45-degree, and ratio test

Pipeline developed with Uros Seljak, Christopher Hirata

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Extracting information from lensing

- Small scales (below r_{vir}): halo mass
- Intermediate scales (r_{vir} - cluster scales): group/cluster membership
- Large scales (>~ several Mpc): large-scales structure
- Typically determine simultaneously using halo model

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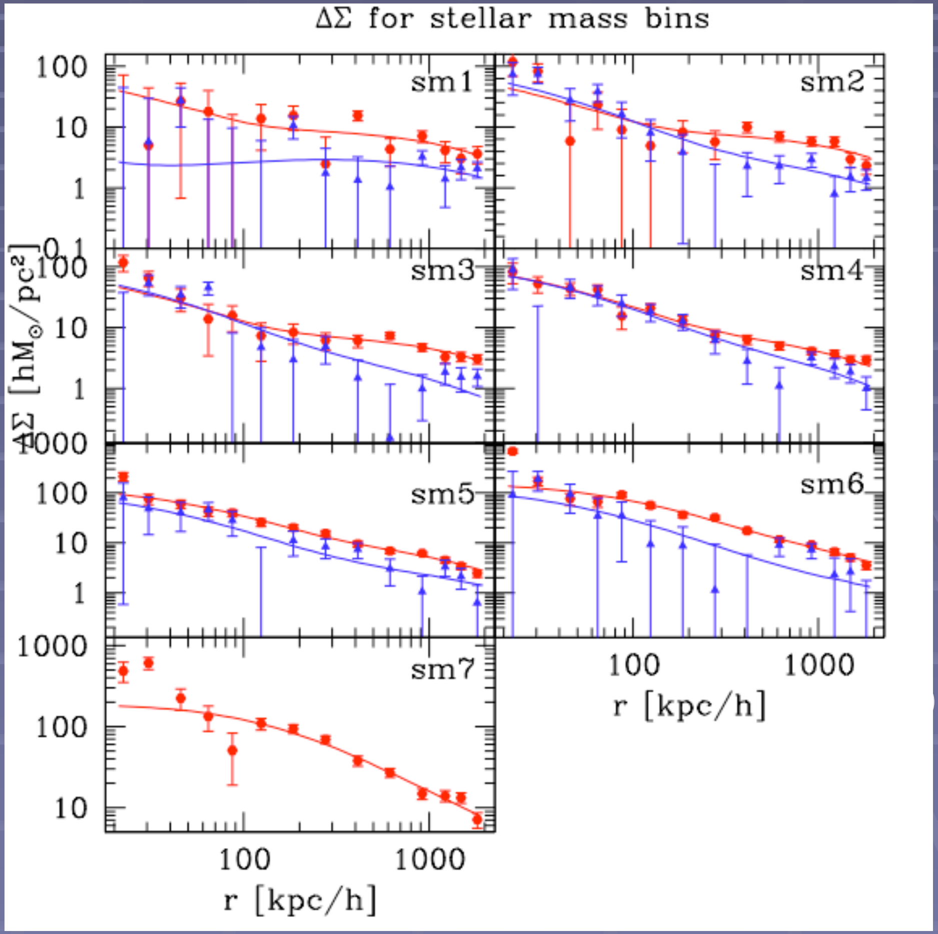
RM, Uros Seljak, Guinevere Kauffmann, Christopher Hirata, et al. (2006) MNRAS 368, 715

Relating mass to light

- Questions: baryon conversion efficiency, satellite fractions
- Stellar masses (Kauffmann, et. al. 2003) tell us the mass in stars better than luminosities
- Lensing: relate (on average) to dark matter halo mass
- Can do as function of environment, age of stellar population

Results

- Lensing signal in stellar mass bins split by morphology
- Signal on small scales reflects halo mass
- Signal on large scales reflects fraction in group/cluster



Early types

Late types

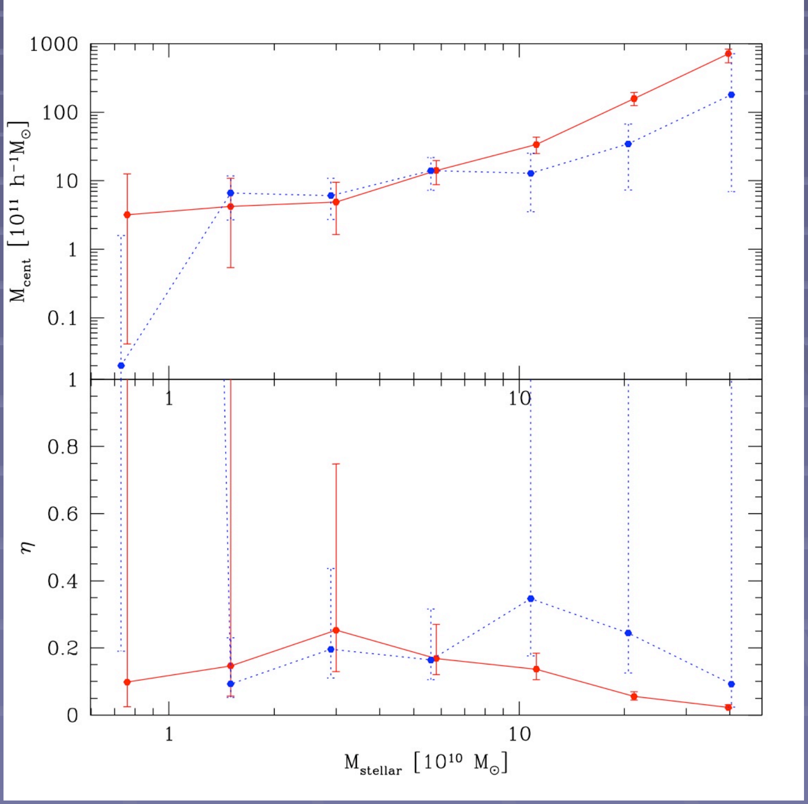
Plot from Mandelbaum et al. 2005, astro-ph/0511164

Results, cont.

- Stellar mass traces halo mass for $M_{stellar}$ <~ 10^{11} M_{sun}
- Baryon conversion efficiencies peak around 30-40%

$$\eta = \frac{M_{stellar}}{M_{halo} f_b}$$

(Errors: 95% CL)



Early types

Late types

Other g-g lensing measurements

- Hoekstra et al. 2005: isolated galaxies in RCS with photometry only; $<z>\sim 0.3$, results for L* galaxies consistent with SDSS
- Heymans et al. 2006: lensing data from GEMS, stellar masses from COMBO-17, $0.2<z<0.8$; little evolution in η, upper limits on growth via star formation

Radio-loud AGN

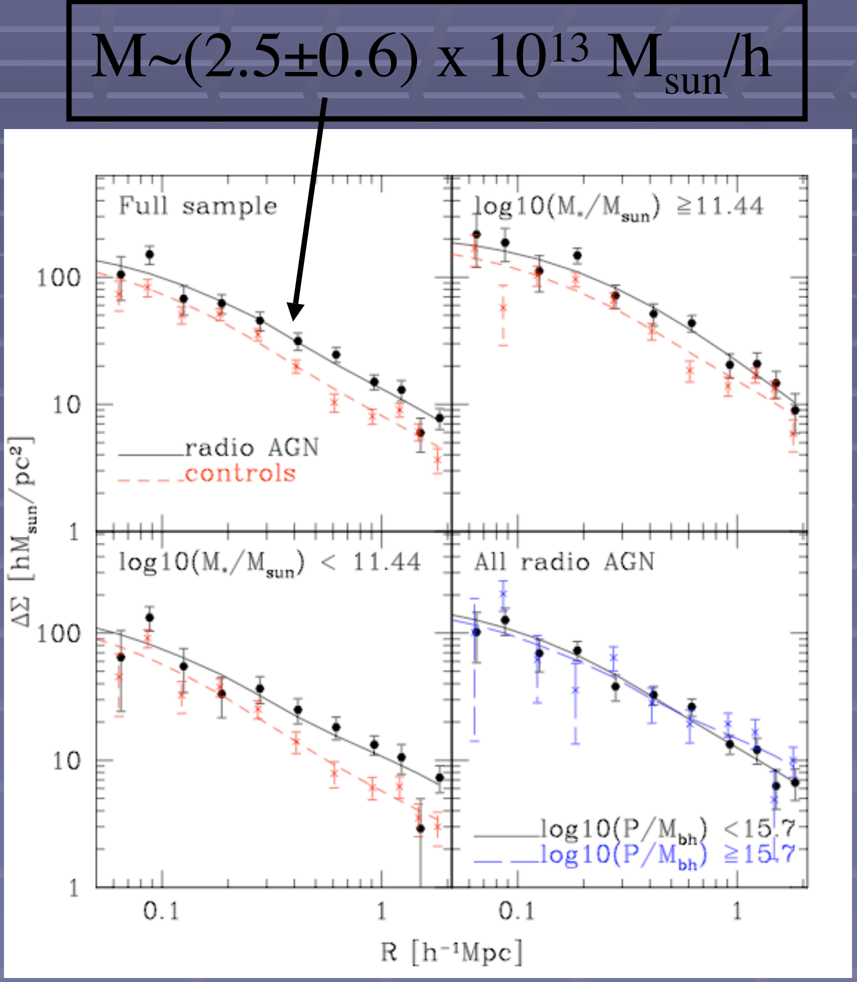
- Question: in what small- and large-scale environments do these galaxies live?
- Match SDSS Main (spectroscopic) sample against radio surveys: ~5500 with $0.1<z<0.3$ in SDSS DR4
- Usual tool for investigating AGN at low, high redshift: galaxy clustering (less direct way to measure halo masses)

**Ongoing work with Cheng Li,
Guinevere Kauffmann

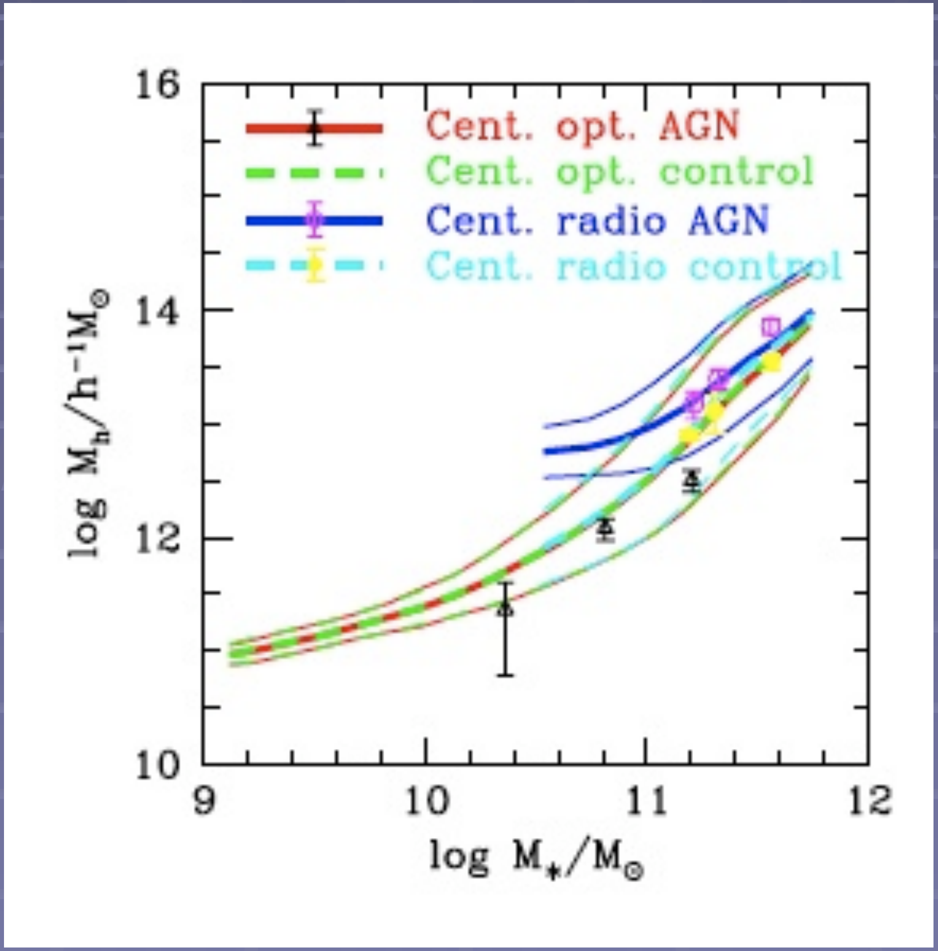
Radio-loud AGN

- Construct control samples (same z, M* properties)
- Mean halo masses differ by factor of ~2
- Consistent with correlations
- Can be used in modeling their formation/evolution

$M \sim (2.5 \pm 0.6) \times 10^{13}\ M_{sun}/h$



Optical vs. radio AGN



Galaxy cluster observables

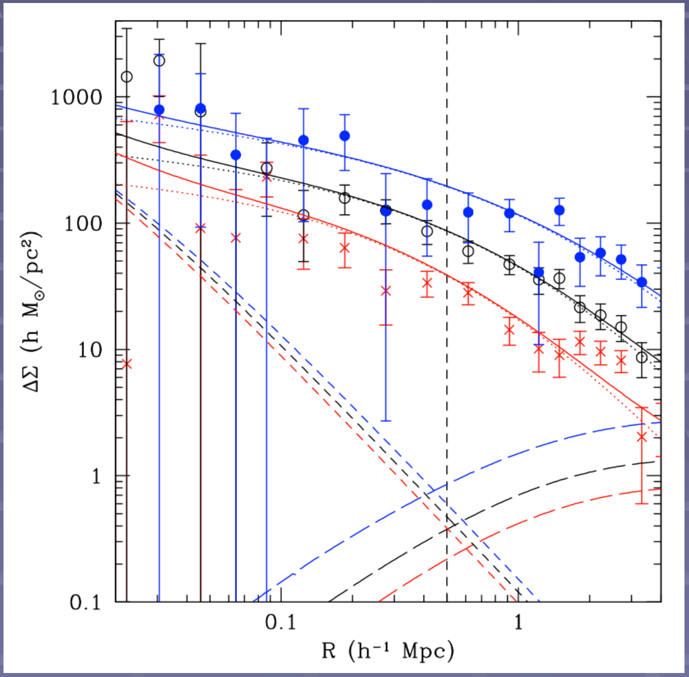
- Relate optical observables to cluster mass
- Understand cluster formation physics, dynamics, evolution
- Useful for cluster-count cosmology

Method

R. Reyes, RM, et al. (2008)

- ~13,000 clusters from the SDSS MaxBCG catalog, photometric *z* = 0.1 to 0.3 (Koester, et al. 2007)
- optical tracers: N_{200}, L_{200}, L_{BCG} and combinations $N_{200}{}^{\alpha}L_{BCG}{}^{\gamma}$, $L_{200}{}^{\alpha}L_{BCG}{}^{\gamma}$
- group clusters by tracer → measure stacked WL signal →determine best-fit M_{200}

ΔΣ



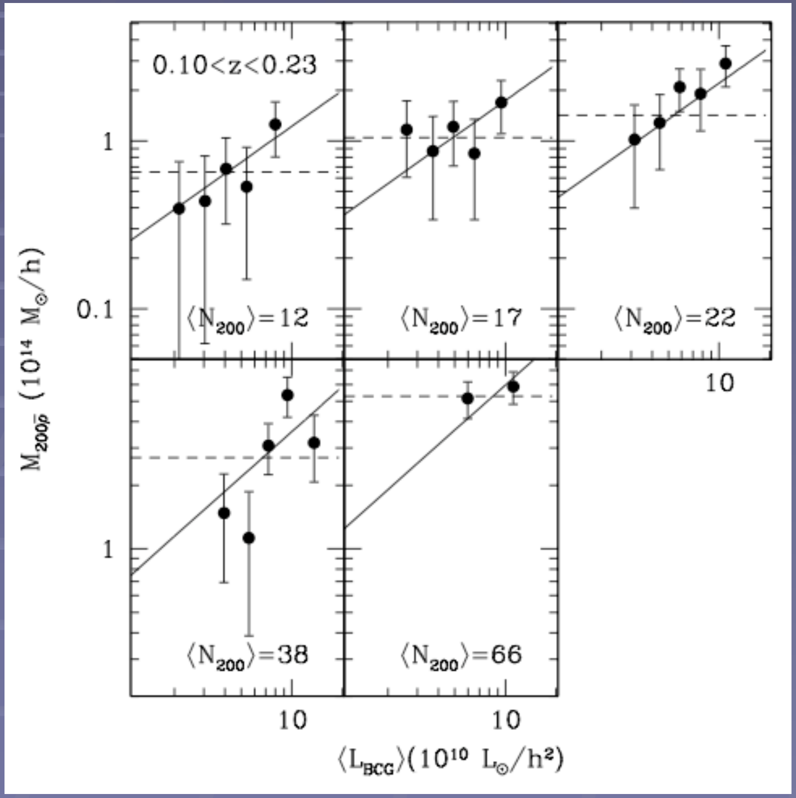
R

N_{200} = 10-11, 26-40, 71-190

M_{200} = 0.65±0.30, 2.48±0.57, 10.96±1.87 × 10^{14} Mpc/h

Results

Cluster mass



BCG luminosity

- scaling with N_{200}, L_{200}, L_{BCG}
- residual scaling of cluster mass with L_{BCG} at fixed N_{200} / L_{200}

γ_N = 0.71±0.14 (~5σ, 0.10<z<0.23)
γ_N = 0.34±0.24 (0.23<z<0.30)

γ_L = 0.40±0.23 (~2σ, 0.10<z<0.23)
γ_L = 0.26±0.41 (0.23<z<0.30)

$$M_{14} = (1.27 \pm 0.08)\left(\frac{N_{200}}{20}\right)^{1.20\pm0.09}\left(\frac{L_{\rm BCG}}{\bar{L}_{\rm BCG}(N_{200})}\right)^{0.71\pm0.14}$$

Implications

- Evidence for effect from N-body simulations giving anticorrelation between L_{bcg} and N_{200} (formation time effect)
- Can use combined tracer for more optimal constraints on cosmology using optical cluster surveys

Lessons:

- Galaxy-galaxy lensing measurements can yield parameters that are directly useful for constraining theories of galaxy formation
- There is great promise for future advances in our understanding using this method in combination with others