The combination of the abundance of optically-selected clusters, weak lensing measurements, and X-ray information results in a powerful probe for precision cosmology.

New constraints from the SDSS maxBCG catalog

\[ \sigma_8 = 0.809 \pm 0.019 \]

joint maxBCG-WMAP5 constraint

\[ \sigma_8 (O_m/0.25)^{0.405} = 0.834 \pm 0.032 \]

best-constrained combination from maxBCG alone

Realistic mock catalogs based on our understanding of the galaxy-halo connection provide key input, but final result is “self-calibrated”
maxBCG collaborators

- new cluster finder, sample of ~14000 SDSS clusters
  - Koester, McKay et al 2007a, b
- cosmological constraints using abundances
  - Rozo, RW et al 2007a,b
- lensing masses and mass to light ratios
  - Johnston et al 2007, Sheldon et al 2007a, b
- dynamical masses
  - Becker, McKay et al 2007
- X-ray masses, Lx-richness scatter
  - Rykoff, McKay et al 2008; Rykoff, Evrard et al 2008
- properties of cluster galaxies
  - Hansen, Sheldon, RW et al 2007
- scatter in mass-richness, improved richness estimator
  - Rozo, Rykoff, Koester et al 2008a, b
- combined cosmological constraints
  - Rozo et al 2009 (in preparation)

mock catalog collaborators

Michael Busha

theory collaborators

- see poster: Efficacy of Self-Calibration and Follow-up Observations on Dark Energy Figure of Merit
  - Wu, Rozo & RW 2009
Local cluster abundance primarily constrains $\sigma_8$

$\sigma_8$ : measures the “clumpiness” of mass in the universe at present.

High $\sigma_8$ - Universe is very clumpy at present.

Low $\sigma_8$ - Universe is more homogeneous at present.

The number of clusters at low redshift depends sensitively on $\sigma_8$. 
The CMB measures the amplitude of matter fluctuations at $z \approx 1200$

WMAP value of $\sigma_8$ is an extrapolation assuming a $\Lambda CDM$ cosmology.

Consistency with the local measured value $\sigma_8$ is an important test of the $\Lambda CDM$ model.

Measuring evolution of the cluster abundance is one of the most powerful constraints on the dark energy equation of state.

The local abundance of clusters can be used to measure $\sigma_8$. Why is this interesting in general?
σ₈ has been, comparatively, a hold-out on the precision cosmology front

main difficulty is that we can’t directly see mass peaks, and thus we can’t determine how clumpy the mass distribution is.

key challenge is understanding the relation between cluster observables and the well-understood properties of dark matter halo (e.g. mass)

this is particularly challenging for optically-identified clusters: larger scatter between mass and optical observables & easier to misidentify

current estimate in scatter in richness @ fixed mass ~ 0.33
so why is optical interesting?

- Comes for “free” from large photometric surveys
- Standard Lore: clusters can only constrain the product $\sigma_8 \Omega_m^{0.5}$.
- Optically-selected cluster catalogs have an effective lower mass limit that is well below that of X-rays, SZ, or weak lensing
- This significantly reduces the degeneracy between $\sigma_8$ and $\Omega_m$. 

![Graph showing the relationship between cluster density and mass for different values of $\sigma_8$ and $\Omega_m$.]
what do we need to achieve to make this viable for optically-selected clusters?

key thing is to make a robust connect between cleanly predicted quantities (like the halo mass function) and the observables (e.g., the cluster abundance as a function of the number of galaxies)

1. need a reasonably complete and pure cluster catalog
2. need a constraint on the mean relationship between mass and richness
3. need a constraint on the scatter

combination of:

- additional data to provide information about \( P(M|\text{observable}) \)
- realistic simulations of galaxy populations mock catalogs to:
  1. understand *and improve* the cluster finding: completeness & purity, scatter, miscentering
  2. develop and test these **observational constraints** on the selection function
the maxBCG sample of SDSS clusters

- ~7400 square degrees of photometric data
- maxBCG cluster finder (Koester et al 2007a): uses photo data to identify BCGs and red sequence galaxies
- optimized to detect clusters from $z=0.1-0.3$ in SDSS
- ~180,000 with $\geq 2$ bright red galaxies; 
  ~14,000 with $\geq 10$ bright red galaxies
public catalog: Koester et al 2007b

clusters are actually easy to find in the optical!
estimating the halo mass function

- We measure $N(\nu) =$ No. of clusters with $\nu$ galaxies.
- Can predict the cluster mass function
- To connect the two we need to know $P(\nu|M)$ - probability a halo of mass $M$ contains $\nu$ galaxies.
- Hard to measure, but we can measure several quantities related to this distribution!
- e.g., by stacking the clusters fields as observed by SDSS we can get a clean, high S/N measurement of the mean mass $\langle M|\nu \rangle$. (Sheldon et al. 08, Johnston et al. 08, Mandelbaum et al. 08)
- *The Problem:* knowing the mean mass as a function of richness is not enough. We also need the variance (scatter).
Add X-ray observations and measure the mean and scatter of $L_X$-richness relation.

By demanding consistency of:
1. cluster abundance as a function of richness $N(\nu)$
2. mean mass-richness relation from weak lensing $\langle M|\nu \rangle$.
3. mean and scatter of $L_X$-richness relation.
4. mean and scatter of $L_X$-mass relation (known from other X-ray studies),
we can determine the scatter in mass at fixed richness

$\sigma_{M|\nu} = 0.45 \pm 0.19$ (95% CL)

Rozo et al. 08, arXiv: 0809.2794
deriving cosmological constraints

We observe:

1. abundance of clusters a function of richness
2. mean mass as a function of richness (from stacked weak lensing)
3. scatter in mass at fixed richness (from X-rays)

Do a simultaneous fit for cosmology and \( P(\nu|M) \) (assume log-normal) using all three observational constraints (self-calibration).

six free parameters:

- amplitude and slope of \( \langle \nu|M \rangle = AM^\alpha \)
- scatter in richness at fixed mass
- bias in the lensing mass estimates due to uncertain photo-zs
- cosmological parameters: \( \sigma_8 [0.4,1.2] \) and \( \Omega_m [0.1,0.5] \).
- 2 weak cosmological priors: \( h=0.70\pm0.15 \) and \( n=0.96\pm0.05 \).
Cosmological Constraints on $\sigma_8$ and $\Omega_m$

\[ \sigma_8 = 0.809 \pm 0.019 \]

\[ \sigma_8 = 0.84 \pm 0.07 \]

lots of tests for systematics: systematics in the lensing masses from photometric redshift uncertainties; relaxing the assumptions of a linear mass-richness relation and constant scatter; changing priors on the completeness & purity; relaxing cosmological priors; removing the scatter constraint (combined constraint increases by 10%)

Rozo et al 2009
What masses are contributing to the sample?

observed mass function weighted by selection function

Best constrained mode

\[ \sigma_8 \left( \frac{\Omega_m}{0.25} \right)^{0.405} = 0.834 \]
The Role of Mock Catalogs

- understanding *and improving* the cluster finding: completeness & purity, scatter, miscentering, detailed form of $P(N|M)$
- directly test methods for cosmological constraints
- however, the analysis does not use the $P(N|M)$ from these simulations!

Desired Properties

- ideally, you want a suite of simulations (with a range in cosmological parameter space) which produce a galaxy population that reproduces all relevant statistical properties of the observed universe
- they should reproduce the observed properties that are used for cluster finding, e.g.:
  1. evolution of LF and color distribution
  2. BCG and red sequence colors and luminosities and their connection to background galaxies; the joint luminosity-color-density relation

- for current and future photometric surveys, need to model fairly dim galaxies in large volumes: for SDSS maxBCG, need at least $-19.5$ galaxies in a $\sim 1\text{Gpc}/h^3$ volume

**currently neither hydrodynamical simulations nor semi-analytic models are adequate for this task:** resort to semi-empirical methods that connect well-understood dark matter distribution to properties of the observed galaxy distribution
**ADDGALS mock catalogs: realistic galaxy populations in clusters**

- add central galaxies to massive halos using observationally constrained L-M relation.
- assign luminosities to dark matter distribution using observed luminosity-dependent clustering as a constraint.
- complementary to other methods, SHAM (Kravtsov et al 04, Conroy, RW & Kravtsov 06), HOD (Berlind & Weinberg 02, Zehavi 04) main advantage is pushing the resolution to simulate large volume. works very well except on small scales.
- assign colors to galaxies by matching to SDSS galaxies with same luminosity & galaxy density.
- works very well with the possible exception of color-dependent profiles.

RW et al 2009
public catalogs in Jan
the maxBCG cluster selection function in simulations

- more than 90% pure and complete for halos > 5e13

Rozo, RW et al 2007a
Cosmological “constraints” from a mock Universe

- Inputs from full-sky mock catalog with WMAP1 cosmology:
  1. maxBCG cluster counts
  2. mean halo mass in richness bins
  3. prior on scatter in mass at Ngals ~ 40

\[ \sigma_8 = 0.90 \pm 0.11 \]

\[ \Omega_m = 0.29 \pm 0.12 \]
Future Prospects

- **SDSS**
  - already in hand: ~33,000 clusters at $z < 0.5$ (8000 sq. deg)
  - improved richness estimator, with decreased scatter
  - impact of photo-zs on lensing estimates is currently dominant systematic error; may be able to improve

- **DEEP**: see Gerke talk!

- **Dark Energy Survey (DES)**
  - 5000 square degrees imaging 2011--2016
  - $g$, $r$, $i$, $z$, $Y$ photometry to $i = 24$
  - 4000 sq. degrees overlap with the South Pole Telescope S-Z survey
  - should identify clusters robustly out to $z > 1$
  - expected FOM constraint from optical counts and counts-in-cells is roughly $\sim \text{FOM} \, \frac{1}{\sigma(w_s)\sigma(w_p)} = 27$ (but depends a lot on assumed priors!)
Dark Energy Figure of Merit for DES-like survey:
Effect of Follow-up Information Cluster Masses

- assumes 5000 sq. degrees, $0 < z < 1$
- baseline FOM, using optical counts + counts in cells: 27
- how much can this be improved with follow-up mass measurements?
- is there an optimal way to sample?

50% improvement in FOM from 100 followup clusters

for small number of followups, where you put them makes a big difference

Wu, Rozo & RW 2009
see poster for further estimates.
Summary

- Optically selected cluster catalogs, in conjunction with weak lensing and Lx measurements, are a powerful tool for precision cosmology.

- Although mock catalogs have been used throughout in understanding our selection function and improving the cluster finding, at the end of the day this additional data allows us to “self-calibrate” the mass-observable relation.

- Current constraints from maxBCG are orthogonal to WMAP5 constraints, and nearly as tight on normalization; maxBCG and WMAP5 results are consistent with each other -> consistent with no departure from the standard ΛCDM model.

- Future prospects with large photometric surveys and selected complementary data look very promising.

\[ \sigma_8 = 0.809 \pm 0.019 \]

joint maxBCG-WMAP5 constraint
Comparison between optical and X-ray data

prediction of the Lx function from maxBCG richness + Lx-richness relation is in excellent agreement with the measured Lx function from REFLEX. data is consistent with 100% completeness & purity +/- 6%