Weighing the Giants: Weak Lensing and X-ray Studies of the most Massive Clusters

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Cosmology with clusters

- number of clusters $N(> M, z)$ sensitive to cosmology
  $\rightarrow$ cluster surveys promising cosmological probes

Mantz et al. 2008, 2010; Vikhlinin et al. 2009; Rozo et al. 2010

• direct mass detection (weak lensing) too noisy (shear peak statistics?)

• cluster selection in X-rays, SZ, or optical more efficient, complete, pure
  $\rightarrow$ *but need to rely on mass proxies*
• mass proxies currently calibrated from hydrostatic mass estimates of relaxed clusters

• error budget (on $\sigma_8$) dominated by possible biases in hydrostatic masses

• need to reduce mass calibration uncertainty to $<5\%$ for future cluster count experiments (e.g. eROSITA)

• currently: bias known to $\sim 10\%$ at $z \sim 0.25$  
  
  Mahdavi et al. 2007

• redshift evolution of bias?
Method

⇒ compare X-ray and weak lensing mass measurements of a large cluster sample

• X-ray mass measures:
  + some have very small scatter:
    gas mass, \( Y_X \), core-excised luminosity / temperature
  – may be biased at the 5 – 10% level

• weak lensing mass measures:
  + unbiased (if done right)
  – large scatter

CANNOT select on lensing properties
The Sample

- massive, X-ray selected clusters used in cosmology analysis of Mantz et al. 2010abc, Rapetti et al. 2010
- MAssive Cluster Survey (MACS) at $z > 0.3$ (Ebeling et al. 2001, 2007, 2010)
- Bright Cluster Sample (BCS) at $z < 0.3$ (Ebeling et al. 1998)
- REFLEX at $z < 0.3$ (Böhringer et al. 2004)

follow-up data:

- optical multi-band imaging ($\sim 50$ clusters)
  - SuprimeCam @ Subaru ($BVRIz$)
  - MegaPrime @ CFHT ($u$)
- Chandra X-ray imaging ($\sim 70$ clusters)
Data challenges

• need accurate shape measurements and accurate photometry
• 5 generations of SuprimeCam configurations
• some of the issues:
  • scattered light correction
  • non-linearity
  • unstable flat-fields
  • stellar halos/ghosts (and other artifacts)
  • parts of a chip astrometrically offset (???)
  • limited dynamic range
  • non-square pixels
  • ghosting
  • CTE
  • ...
Weak lensing: biases / scatter

• substructure, triaxiality:
  → cause scatter, but average mass unbiased
  Clowe et al. 2004, Corless & King 2007, Meneghetti et al. 2010

• associated structures (two-halo term):
  → cause scatter, deviation from one-halo at \( r \gtrsim 5 \text{Mpc} \)

• unassociated structures along line-of-sight:
  → cause scatter, but average mass unbiased
  Hoekstra 2003

• shear estimates:
  → can be calibrated from Shear TEsting Program
  Heymans et al. 2006, Massey et al. 2007

• redshifts of background sources:
  → bias in \( z \) leads to bias in mass
  → not accounting for shape of \( p(z) \) can also lead to bias
Lensing by $z \sim 0.5$ clusters

- lensing signal small
- redshift errors $\rightarrow$ larger shear errors
- foreground contamination
- cluster area small $\rightarrow$ fewer background sources
Background redshift distribution

- to first order:

\[ g(z) \approx \beta_s(z) \gamma_\infty \]
\[ \beta_s(z) = \beta(z) / \beta_\infty \]
\[ \beta(z) = \frac{D_{LS}}{D_S} \]

- standard method: color cuts
- apply to cluster field and to standard deep field with good photo-z’s
- assume \( \langle \beta_s \rangle \) of standard field for cluster field
two effects:

- larger scatter in $\beta_{\text{true}}/\beta_{\text{assumed}}$  
  (think galaxy sample)

- cosmic variance: larger scatter in $\langle \beta_{\text{true}} \rangle/\beta_{\text{assumed}}$  
  (think cluster sample)

COSMOS-30: $\sim 3 \times 3$ SuprimeCam pointings 

applied color cuts for 0.2 and 0.5 cluster 

measure $\beta_{\text{assumed}}$ on remaining 8 pointings 

test variation of $\beta_s$ in each pointing 

(still too small to properly estimate cosmic variance)
Photometric redshifts

+ avoids scatter/bias from $\langle \beta_s \rangle$ assumption
+ evaluated per galaxy

- $uBVRIz$ photometry; BPZ code (Benitez 2000)
- no training set (most clusters have little spectroscopic data)
- color calibration via stellar locus (High et al. 2009)
- one-point redshift estimate unbiased
Photo-z errors

if we had \( p(z) \) . . .

- \( p(z) \) has finite width:
  - flux measurement errors
  - intrinsic width
  - template errors
  - prior
- even gaussian \( p(z) \) are transformed to non-gaussian distributions of \( g(z) \)
- \( p(z) \) generally not gaussian
- simple averaging or \( \chi^2 \) minimization lead to bias
- need to account for full \( p(z) \) distribution
Status of analysis

• goal: unbiased weak lensing masses of X-ray selected clusters
• as demonstrated: several small effects need to be taken into account
• “expected result” (consistency with previous, lower redshift samples)
→ “blind analysis”, develop algorithms on mock clusters

• current question:
  • can we trust \( p(z) \) returned by photo-z code?
  • if not, can we improve them empirically?
Summary

• future cluster count experiments require mass proxies calibrated to < 5% bias

• only observational method: weak lensing mass measurements (unbiased, large scatter) of large cluster samples (possibly biased masses, no scatter)

• this sample: redshift (and mass) range of current and future cluster count experiments

• complementary to low-redshift studies (CCCP, LoCuSS)

• with increasing cluster redshift:
  • source redshifts ever more important
  • color cuts very noisy
  • photo-z’s promising way forward, but need to understand errors