Cosmological Constraints with Galaxy Cluster Counts with the Euclid Imaging Survey

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If linear density perturbation exceeds threshold density the region will collapse and form a cluster.

Mass function sensitive to amplitude of perturbations ($\sigma_8$) and mass contents of the Universe ($\Omega_m$); but also other cosmological parameters ($\omega$)!
Counting Dark Matter Halos

- Count halos in N-body simulations
- Measure “universal” mass function - density of cold dark matter halos of given mass

\[
\frac{dn}{dM}(z, M) = -0.316 \rho_{m,0} \frac{d\sigma_M}{dM} \frac{1}{\sigma_M} \exp \left\{ -\left[ 0.67 - \log[D(z)\sigma_M] \right]^{3.82} \right\}
\]

Jenkins et al. 2001; also Sheth & Tormen 1999 for analytical function
Warren et al. 2004, Tinker et al. 2008

more low mass clusters

more low redshift clusters

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Cosmology Dependence of the Mass Function

\[
\frac{dn}{dM}(z, M) = -0.316 \left( \frac{\rho_{m,0}}{M} \right) \frac{d\sigma_M}{dM} \frac{1}{\sigma_M} \exp \left\{ - |0.67 - \log[D(z)/\sigma_M]|^{3.82} \right\}
\]

- mass density
- power law dependence on fluctuation amplitude
- power law dependence on growth factor
Predicting Cluster Number Counts

\[ \Delta N(z) = \Delta \Omega \int_{z-\Delta z/2}^{z+\Delta z/2} dz \frac{d^2V}{d\Omega dz} \int_{M_{\text{lim}}}^{\infty} \frac{dn}{dM} dM \]

- Survey sky coverage
- Redshift bins
- Volume element
- Limiting mass of survey (redshift dependent)
- Cosmology dependence driven by volume element and mass function
Cosmology Dependence of Number Counts

- concordance cosmology:
  $\Omega_m = 0.3$;
  $\sigma_8 = 0.78$; $n=1$, $h=0.72$;
  $w = -1$, $\Delta \Omega = 4.000 \text{ deg}^2$
  $M_{\text{lim}} = 1.7 \times 10^{14} h^{-1} M_\odot$

- $\Omega_m = 0.4$
- $\sigma_8 = 0.85$
- $w = -0.8$
- $w = -0.7$
- $w = -1 + 0.2(1-a)$

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Cluster Counts in DGP Model

- DGP number counts for $\sigma_8 = 0.75$, $n=1$, $M_{\text{lim}} = 1.7 \times 10^{14} h^{-1} M_\odot$ (from ‘SPT’)
- mock data assuming Poisson errors
- mimic DE model

significant difference between mimic DE and DGP: $>1\sigma$
Selection Clusters with Euclid

- Weak lensing: e.g. peak statistics
- Galaxy overdensities
  - maxBCG
  - Voronoi Tessellation
  - Matched filters
  - Counts in Cells
  - Percolation Algorithms (FoF)
  - smoothing kernels
  - surface brightness enhancements
  - …

- Strong Lensing
maxBCG as Baseline Method

- Brightest Cluster Galaxy (BCG) at centre of every cluster
- tight color-magnitude relation of BCG
  - used to (pre-) select
- Identifying ridgeline galaxies
  - use model for radial and color distribution
- maximize the two models as a function of redshift: estimate of redshift of cluster
- Iterative scheme: removal of most likely clusters and their satellites
- Apply probability chain, which has been calibrated with mock observations
- Successfully applied to SDSS sample (Rozo et al.)
- Biggest problem: Completeness and Purity of Sample
  - projection effects along line of sight; misestimate of cluster members
maxBCG Selection SDSS: A Lesson for Euclid?

- Mass – Richness relation
  - calibrated with statistical weak lensing measurements (for 130,000 groups)
  - Johnston et al. 2007

- Good purity and completeness to about:\n  - $M \sim 10^{13.5} \, h^{-1} M_\odot$

- however for SDSS only to: $z \sim 0.3$

- depth of Y, J and H filters
  - should be able to find ridgeline galaxies out to $z=1.3-2.0$
  - how far out do we find robust red sequence?
Mass Limit for Euclid

- EIS-WL (Berge et al)
- Planck
- eROSITA (Muehlegger, Boehringer, Hasinger)
- EIS-maxBCG

$M_{\text{lim}}(h^{-1} M_{\odot})$ vs. $z$
Cluster Numbers for Euclid

solid: $\Lambda$ CDM

in total: well over 750,000

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Uncertainty in Mass Limit

- Mean mass observable relation
  - scaling laws dependent on method – not entirely determined: redshift and mass dependence
  - different methods can be used for cross calibration

- Individual scatter in mass observable relation
  - how behave the tails
    - high redshift, low mass, high mass, etc.
  - degenerate with cosmology
  - can also be estimated by surveys
    - Rozo et al.: optical, x-ray and weak lensing find 0.45±0.20

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General Form for Scaling and Scatter

- assign likelihood for observed mass for a true mass \( p(M_{obs} | M) \) with a bias and a scatter included; allow to differ in redshift and mass bins

\[
p(M_{obs} | M) = \frac{1}{\sqrt{2\pi}\sigma_{\ln M}^2} \exp \left[ -\frac{x^2(M_{obs})}{\sigma_{\ln M}^2} \right]
\]

\[
x(M_{obs}) = \frac{\ln M_{obs} - \ln M - \ln M_{bias}}{\sigma_{\ln M}}
\]

- completely free form does not allow cosmology fit (Lima & Hu)

- \( \ln M_{bias} = A + n \ln(1+z) \)
  - better form for particular selections possible

- \( \sigma_{\ln M}^2 = A + Bz + Cz^2 + \ldots \)
  - so far this is ad hoc
Exploit shape of mass function to calibrate for bias and scatter in constant mass bins

Further use clustering of clusters (cross-correlated to other probes? Not used here!)

Result: scatter in mass-observable relation is not the problem: Increases number of clusters, hence better statistics

Uncertainty in scatter is PROBLEM
Constraints from EIS Cluster Counts

Including Planck priors and 5 cluster nuisance parameters; prior on scatter: 25%
Cosmology and Priors on the Mass – Observable Relation

1, 2 and 3 scatter parameters

$w_0$ -0.6 -0.4 -0.2 -0.0 0.2 0.4 0.6

-1.00 -0.95 -0.90

orange contours: 50% prior on scatter, 25% bias
dashed contours: 25% prior on scatter, 25% bias
blue contour: fixed scatter
dark contour: fixed scatter and bias

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Self-Calibrate Uncertainty in Mass – Temperature Relation

- Relevant for SZ and x-ray surveys
- In addition to cosmological parameters fit for cluster parameters $T_*$, $\xi$, $\varepsilon$
Weak Lensing Calibration of Mass - SZ Observable Relation

- Here simple estimate: 15 background (DES) galaxies/sq. arcmin
- Distribution: $\frac{dn}{dz} = \exp(-z/z_c)$; $z_c = 0.5$

Projected errors on single cluster

Dodelson & Weller: DES and SPT

Fractional errors on cluster mass after stacking in redshift bins
$\Delta z = 0.1$ and $\Delta M = 10^{14} M_\odot$

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Weak Lensing Calibration
How can Euclid help Planck-SZ Clusters – Very Preliminary!

NO SCATTER; NO Planck Prior, see also Cunha et al., Wechsler et al.
But also vice versa: Improvement of FoM could be 50% from WL and x-ray

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Conclusions

- EIS cluster counts complementary to primary science drivers
- sensitive in particular to modified gravity
- crucial to understand and control systematic, scatter and scaling
  - next step: simulations to understand selection and optimize method
  - lessons to be learned from surveys like DES
- in particular complementary to other full sky cluster probes
- ‘self-calibration together with Euclid Spectroscopic Survey!'