GALAXY CLUSTER COSMOLOGY WITH THE FUTURE EUCLID SAMPLE

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Observing the millimeter universe with the NIKA2 camera

Credits: Hubble Space Telescope
EUCLID: THE NEXT LARGE SPACE-BASED OPTICAL/INFRARED SURVEY

- Euclid will observe 2 billion galaxy shapes
- Measure the spectrum of 50 million galaxies
- Euclid will detect $\sim 10^5$ galaxy clusters, a large fraction of which is going to be usable for cosmology (about 60% in this presentation)

Courtesy: Euclid France communication
1. Euclid will deliver exquisite optical data for lensing mass estimation

2. We need to exploit this information efficiently

3. Lensing masses depend on cosmology

- Build a framework directly including individual lensing mass estimates for Euclid to fit the cosmological parameter and the scaling relation at the same time

- Investigate systematics related to large samples
OUTLINE

I. Scientific context

II. Cosmology with individual lensing mass estimates
   ▶ Develop the statistical approach for Euclid

III. Forecasts for Euclid
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

GENERAL FRAMEWORK

Cluster detection with a given signal $A$

Clusters in the Flagship simulation

Mass & distance measurements

Assume $A = \mathcal{F}(M) = A_0 (M/M_0)^\alpha$

Get $(A_0, \alpha)$

Scaling relation

See F. Kéruzoré’s talk
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

GENERAL FRAMEWORK

Cluster detection with a given signal $A$

Clusters in the Flagship simulation

- **Mass** & distance measurements
- Get information from the full distribution of the weak lensing masses
- Avoid potential selection effects and astrophysical biases

Joint fit of $A = \mathcal{F}(M) = A_0 (M/M_0)\alpha$ and the cosmological parameters

Mantz et al., 2015
Bocquet et al, 2019
Abbott et al., 2020
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

INDIVIDUAL LENSING MASS ESTIMATES (C. MURRAY)

- Observed ellipticity of a source galaxy:
  \[ \epsilon_{\text{obs}} = \epsilon_{\text{int}} + \frac{\gamma}{1 - \kappa} \sim \epsilon_{\text{int}} + \gamma \]  
  Weak lensing regime

- Assuming an NFW profile, the shear can be computed \((\text{Wright & Brainerd, 2000})\)

- We recover the scale radius with a matched filter from \(\text{Murray et al., in prep:}\)
  \[ \tilde{r}_S = \sum_{i=1}^{N_{\text{gal}}} \omega_i \epsilon_{\text{obs},i} \]

- Very robust
- Designed to maximise the SNR ratio
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

INDIVIDUAL LENSING MASS ESTIMATES

We use the Raygalgroup sims:

- High spatial resolution
- Ray tracing

Shear ellipses around a cluster as calculated by the RayGalGroup Sims from Breton et al., 2018

Distribution of the lensing mass estimates with respect to the DM halo mass

(Figure from C. Murray)
JOINT-CALIBRATION : MASTER EQUATION

\[
\frac{d\tilde{N}}{dM_L dA dz}(\Theta) = \int_{-\infty}^{+\infty} \frac{dN}{d \ln M dA dz}(\Theta) f(A, M_L | M, z, \Theta) \chi(M, z) d \ln M
\]

Halo Mass Function

PDF of the observable and lensing mass estimate

Completeness (fraction of objects detected at a given mass and a given redshift)

The mean number of observed objects is obtained with a convolution of the ingredients listed above
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

LENSING MASS ESTIMATES

\[
\frac{d\tilde{N}}{dM_LdAdz}(\Theta) = \int_{-\infty}^{+\infty} \frac{dN}{d\ln M dz}(\Theta)f(A, M_L| M, z, \Theta)\chi(M, z) \, d\ln M
\]

**GOAL**: Present how we model the distribution of the lensing estimates
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

PDF OF THE LENSING MASS ESTIMATES

- Scatter on the lensing mass estimates modelled as:

\[
\sigma_{ML}(M, z)^2 = A_L \theta_{\Delta}(M, z)^\beta / n_{gal}(z) + \sigma_{int}^2(M, z) / n_{gal}(z)
\]

- Model tested on the Raygalgroup sims (Breton et al., 2018)

- The best fit parameter for the power is

\[\beta = -2.09\]

Fig: EA et al, in prep
COSMOLOGICAL DEPENDANCE

- The lensing mass estimates intrinsically depend on the cosmology.
- The dependence is approximated as

\[ M_L(\Theta) \propto D_A(z, \Theta)^{-3} \rho_C(z, \Theta)^{-2} , \]

where \( \Theta \) is the cosmological model and which should be valid for low to intermediate redshift clusters.
II. NUMBER COUNTS USING INDIVIDUAL LENSing MASS ESTIMATES

OBSERVABLE: AMPLITUDE

\begin{equation}
\frac{d\tilde{N}}{dM_L dA dz}(\Theta) = \int^{+\infty}_{-\infty} \frac{dN}{d \ln M dz}(\Theta)f\left(A, M_L | M, z, \Theta\right) \chi(M, z) \ d \ln M
\end{equation}

GOAL: Understand how clusters are detected and what is the observable in case of the Euclid survey
II. NUMBER COUNTS USING INIVIDUAL LENSING MASS ESTIMATES

CLUSTER DETECTION IN EUCLID: AMICO (BELLAGAMBA ET AL., 2017)

- Galaxy distribution around one cluster:
  
  \[ D(\theta, z) = A(\theta_c, z_c)M(\theta - \theta_c, z) + N(z) \]

- Optimal filtering:

  \[ A(\theta_c, z_c) = \frac{1}{\alpha(z_c)} \int \Psi(\theta - \theta_c, m, z)D(\theta, m, z)d\theta dm dz - B(z_c) \]

Amplitude: Normalisation of the cluster galaxy distribution
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

AMICO: THE AMPLITUDE AS OUR OBSERVABLE

Fig: Bellagamba et al. (2017)

Amplitude mass produced by Amico with at $z = 0.33$

- The amplitude correlates with the number of galaxies in a cluster, and thus, correlates with the mass of the halo
- We assume:

$$A = A_0 (M/M_0)^\alpha$$
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

AMICO: THE AMPLITUDE AS OUR OBSERVABLE

Fig: Bellagamba et al. (2017)

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$$A = A_0 (M/M_0)^\alpha$$

Must be calibrated!
II. NUMBER COUNTS USING INDIVIDUAL LENSSING MASS ESTIMATES

JOINT PDF OF THE AMPLITUDES AND LENSSING MASSES

- AMICO also provides the noise related to the amplitude \[\sigma_A(M, z)\].

- \(f(A, M_L | M, z, \Theta)\) is then a \textit{gaussian} pdf with covariance matrix:

\[
C(M, z) = \begin{pmatrix}
\sigma_A(M, z)^2 & \rho \sigma_A(M, z) \sigma_M(M, z)

\rho \sigma_A(M, z) \sigma_M(M, z) & \sigma_M(M, z)^2
\end{pmatrix},
\]

This parameter is going to be \textit{primordial} for next generation.
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

SELECTION FUNCTION

\[
\frac{d\tilde{N}}{dM_L dA dz}(\Theta) = \int_{-\infty}^{+\infty} \frac{dN}{d\ln M dz}(\Theta)f(A, M_L | M, z, \Theta)\chi(M, z) d \ln M
\]

GOAL: Present how we compute the fraction of cluster that are detected
III. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

**SELECTION FUNCTION**

- The SNR is simply defined as $q \equiv A/\sigma(A, z)$.
- The completeness, assuming **gaussian** noise, reads

$$\chi(M, z) = \mathbb{P}(q > \tilde{q})$$

Comparison between our selection and Bellagamba et al., (2017)
II. NUMBER COUNTS USING INDIVIDUAL LENSING MASS ESTIMATES

SUMMARY

\[
\frac{d\tilde{N}}{dM_L dA d\tilde{z}}(\Theta) = \int_{-\infty}^{+\infty} \frac{dN}{d \ln M d\tilde{z}}(\Theta) f(A, M_L | M, z, \Theta) \chi(M, z) \, d \ln M
\]

- Individual lensing mass estimates directly included in the likelihood
- Model of the masses repartition fitted on the Raygalgroup sims follows physical intuition

Can we use these masses to self calibrate the observable-mass relation?
OUTLINE

I. Scientific context

II. Cosmology with individual lensing mass estimates

III. Forecasts for Euclid
II. FORECASTS FOR EUCLID

THE FLAGSHIP SIMULATION

- Full sky light-cone

- $\sim 44$ billion DM halos detected using the Rockstar halo finder \cite{Behroozi2013}.

- $m_p \sim 2.398 \times 10^9 h^{-1} M_\odot$

Extract a Euclid like catalog
III. FORECASTS FOR EUCLID

NEED A SUITABLE DATASET

- The Euclid cosmological cluster sample will include $6 \times 10^4$ clusters over $15,000 \text{ deg}^2$, from $z = 0$ to $z = 2$.
- No actual sample has such properties.
- The Flagship simulation not designed for cluster mass estimation.

Emulate the properties of the Raygalgroup and Amico sims from the Flagship.

Fig: Completeness as a function of mass and redshift.
### JOINTLY FIT EVERY PARAMETER

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
<th>True value</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cosmological parameters</td>
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<td></td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>Matter density</td>
<td>0.319</td>
<td>[0.1,0.5]</td>
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<tr>
<td>$\sigma_8$</td>
<td>r.m.s. matter fluctuation</td>
<td>0.83</td>
<td>[0.6,0.9]</td>
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<tr>
<td>$H_0$</td>
<td>Hubble constant (km $\cdot$ s$^{-1} \cdot$ Mpc$^{-1}$)</td>
<td>67</td>
<td>$\mathcal{N}(67,1000)$</td>
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<tr>
<td>$\Omega_b$</td>
<td>Baryonic density</td>
<td>0.049</td>
<td>$\mathcal{N}(0.049,0.0026)$ and $\Omega_b &gt; 0$</td>
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<tr>
<td>$n_s$</td>
<td>Spectral index</td>
<td>0.96</td>
<td>[0.871.07]</td>
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<td></td>
<td>Halo Mass Function parameters</td>
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<tr>
<td>$a_0$</td>
<td>High mass cut-off</td>
<td>0.938</td>
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<td>$a_z$</td>
<td>Redshift dependence $a_0$</td>
<td>-0.12</td>
<td>Covariance matrix fitted on flagship</td>
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<tr>
<td>$p$</td>
<td>Shape at low masses</td>
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<td>$A_{0,MF}$</td>
<td>Normalization</td>
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<td>Richness-mass parameters</td>
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<tr>
<td>$A_0$</td>
<td>Normalization</td>
<td>0.5</td>
<td>[0.05,5]</td>
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<tr>
<td>$\alpha$</td>
<td>Slope</td>
<td>0.5</td>
<td>[0.05,2]</td>
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<td>Lensing mass estimates uncertainties</td>
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<td></td>
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<tr>
<td>$A_L$</td>
<td>Normalization of the scatter</td>
<td>0.836</td>
<td>[0.001,4]</td>
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<tr>
<td>$\beta$</td>
<td>Slope</td>
<td>-2.09</td>
<td>[-6.0]</td>
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<td>$\sigma_{int}$</td>
<td>Intrinsic scatter</td>
<td>0.3</td>
<td>[0.001,2]</td>
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<td>Correlation richness-lensing estimates</td>
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<tr>
<td>$\rho$</td>
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<td>0.6</td>
<td>[0,1]</td>
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<td>Bias on the richness</td>
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<tr>
<td>$b_A$</td>
<td>-</td>
<td>0</td>
<td>[0,0.99]</td>
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<td>Bias on the lensing masses</td>
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<tr>
<td>$b_L$</td>
<td>-</td>
<td>0</td>
<td>Fixed</td>
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</tbody>
</table>
III. FORECASTS FOR EUCLID

RESULTS

EA et al, in prep.
III. FORECASTS FOR EUCLID

RELATIVE IMPORTANCE OF THE ERRORS (EA ET AL., IN PREP)

Comparison of the cases where everything is fixed but the cosmology (red), and when every systematic is taken into account.
III. FORECASTS FOR EUCLID

RELATIVE IMPORTANCE OF THE ERRORS \((\Omega_m - \sigma_8 \text{ PLANE})\)

Budget of errors (EA et al, in prep.)
$w_0w_a$ CDM RESULTS (EA ET AL., IN PREP.)

\[
w(a) = w_0 + (1 - a)w_a
\]

from Chevallier & Polarski, 2001
III. FORECASTS FOR EUCLID

SUMMARY

EA et al., in prep

- Cosmological forecasts for Euclid
  - Joint calibration of the cosmological and nuisance parameters without stacking

- We update the work of Sartoris et al., 2016 (for number counts only) in a more realistic framework
  - 3% precision on $\sigma_8$ (4%)  
  - 2% precision on $\Omega_m$ (12%)  
  - $|\Delta w_0| \sim 0.26$ (0.5)  
  - $|\Delta w_a| \sim 0.6$ (2)

- We examine the performance of future measurements
  - Lensing related errors less important than obs/mass
Thank you for your attention!