Cluster abundance cosmology: Including super-sample covariance in the unbinned likelihood

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Cluster abundance cosmology

- Galaxy clusters are the largest self-gravitating objects in the Universe and form under the gravitational collapse of the largest matter density fluctuations in the Universe.
- Their formation history, mass, and spatial distribution are highly sensitive to the growth rate of large-scale structures, the expansion rate in the universe as well as the nature of gravity. Their abundance, I.e. the number count of clusters in intervals of mass and redshift is particularly sensitive to the average matter density in the Universe Ω_m and the amplitude of matter density fluctuations σ_8 (see **Fig. 1**).

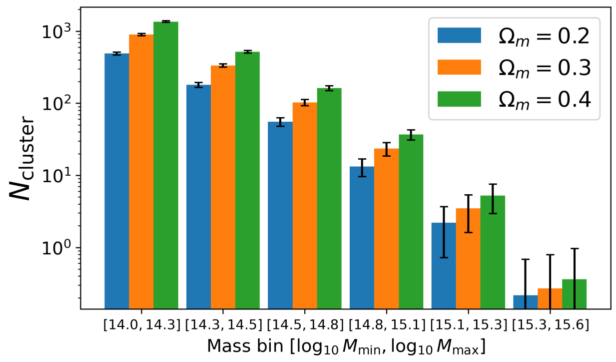

Figure 1: Predicted cluster counts in different mass intervals for the redshift interval $0.28 < z < 0.36$, for different values of Ω_m (colors)

Super-sample covariance (SSC) and shot noise (SN)

- There are two principle noise contributions to the variance of cluster counts. The first one is the Poisson shot noise (SN), which is characteristic of a counting experiment of discrete objects in bins. It is the principal source of noise for small cluster samples, given by

$$\sigma^2_{\rm SN} = \boxed{N}$$

Mean cluster count at given cosmology

- The matter density fluctuations across the finite survey volume induce additional noise to the cluster count, referred to as SSC (Hu & Kravstov, 2003). It is given by

$$\sigma^2_{\rm SSC} = b_h^2\, N^2 \boxed{\sigma^2_{\mathscr{W}}}$$

Amplitude of matter density fluctuations in the survey volume

Halo bias

- In the abundance likelihood, SSC and SN can be accounted for using the Gauss-Poisson Compound (GPC) formalism (see e.g. Payerne et al. 2023), where each Poisson likelihood has a scattered mean $\hat{\lambda} = N(1 + b_h\hat{\delta})$. This approach was used for binned analyses (Lesci et al., 2022), i.e. counting clusters in fixed mass-redshift bins, where $b_h\hat{\delta} \ll 1$.

The unbinned regime

- The unbinned abundance regime (Mantz et al., 2010) is obtained when considering infinitesimal mass-redshift bins, contrary to binned.
- In that case, the observed count in each bin is at most 1, with respective cosmological prediction

Halo number density

$$N \approx \frac{\partial^2 \bar{n}(m_k, z_k)}{\partial m \partial z} \boxed{\Delta m \Delta z}$$

$\ll 1$, volume of each halo in the mass-redshift space

- This halo-to-halo description enables to account for each cluster's properties (uncertainties on mass and redshift) but to study the correlations between different observables such as the cluster optical, SZ and X-ray proxies, or the weak lensing and SZ masses (Bocquet et al., 2024).
- Unbinned likelihoods have been used to analyze the number counts of clusters detected by e.g. ACT, SPT, Planck, or eROSITA.
- The unbinned regime is usually used to analyze small samples of a few thousand clusters, thus neglecting the impact of SSC. The standard unbinned likelihood is derived from the binned Poisson one.
- For the upcoming surveys, the impact of SSC will be important and needs to be accounted for in the unbinned likelihood.

Including SSC in the unbinned likelihood

- In the unbinned regime, we can try to derive the likelihood with SSC by expanding the GPC likelihood up to the second order in $b_h\hat{\delta}$ (Takada & Spergel, 2014).
- In the unbinned regime, the variance of $\hat{\delta}$ is maximal compared to the binned version (see **Fig. 2**). In that case, the scattered mean $\hat{\lambda} = N(1 + b_h\hat{\delta})$ may reach negative values for a non-negligible fraction of clusters.
- We propose to use a hybrid likelihood, using infinitesimal mass bins but **standard redshift bins** that allow us to exploit the GPC formalism in the unbinned regime, similar to the methodology described in Garrell et al., 2022.

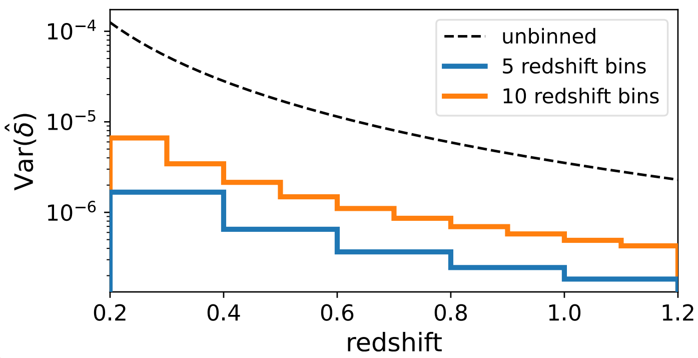

Figure 2: Variance of $\hat{\delta}$ as a function of redshift. Dashed lines correspond to the unbinned case, solid lines to two different binnings of the redshift plane.

Impact on cosmological parameter constraints with simulated catalogs

- For binned analyses, SSC has a measurable impact on cosmological parameter constraints when considering Rubin/Euclid-like cluster samples (Fumagalli et al., 2021). It may become important for unbinned analyses based on the upcoming large cluster samples.
- We use the simulated dark matter halo catalogs obtained by the PINOCCHIO algorithm (Monaco et al. 2002), and we consider three samples of clusters with redshifts $0.2 < z < 0.3$ within three different mass ranges given by $\log_{10} M \in [14.3{,}14.35]$ (labeled as S_1, with 850 clusters), $[14.3{,}14.40]$ (S_2 with 1,700 clusters) and $[14.3{,}14.45]$ (S_3, with 2,300 clusters). We subdivide the redshift range into three equal-size standard redshift bins.
- **Fig. 3** shows the constraints on Ω_m, for the three cluster samples using the standard unbinned (circles) or the new hybrid likelihood (squares). The parameter posterior dispersion is larger using the hybrid likelihood, by

$$\frac{\sigma_{\rm hybrid} - \sigma_{\rm standard}}{\sigma_{\rm standard}} = 10\,\%\,(S_1),\ 19\,\%\,(S_2),\ 26\,\%\,(S_3)$$

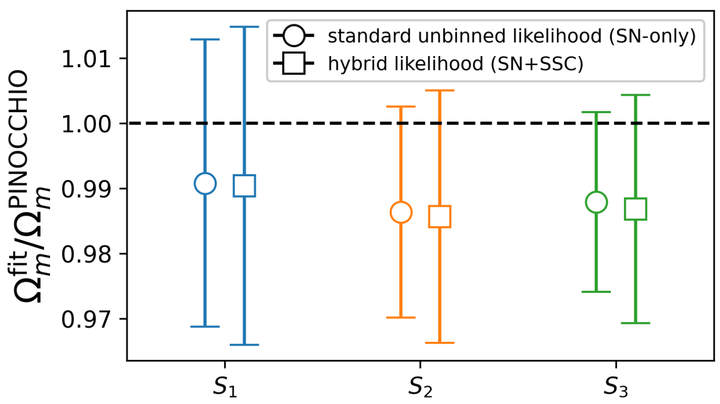

Figure 3: Posterior mean and posterior dispersion for the three cluster samples (colors). Circles stands for the standard unbinned likelihood, squares for the hybrid likelihood

- We have found that SSC can be included in the unbinned regime using a new hybrid likelihood and based on the GPC formalism, showing that parameter errors are impacted positively by $\sim 25\,\%$ when considering $< 2{,}500$ cluster samples. The effect of SSC will be important for larger samples ($\sim 10^5$), such as those provided by Stage IV surveys (e.g. the Rubin LSST or Euclid).

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