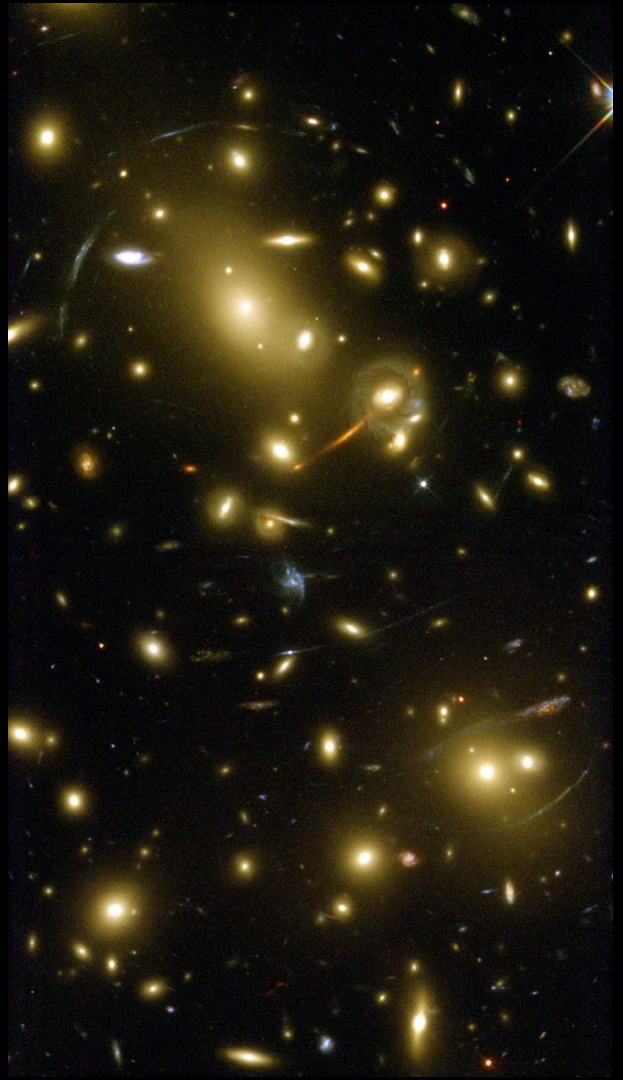
AMICO galaxy clusters in KiDS-1000: Cosmological constraints from two-point correlation function



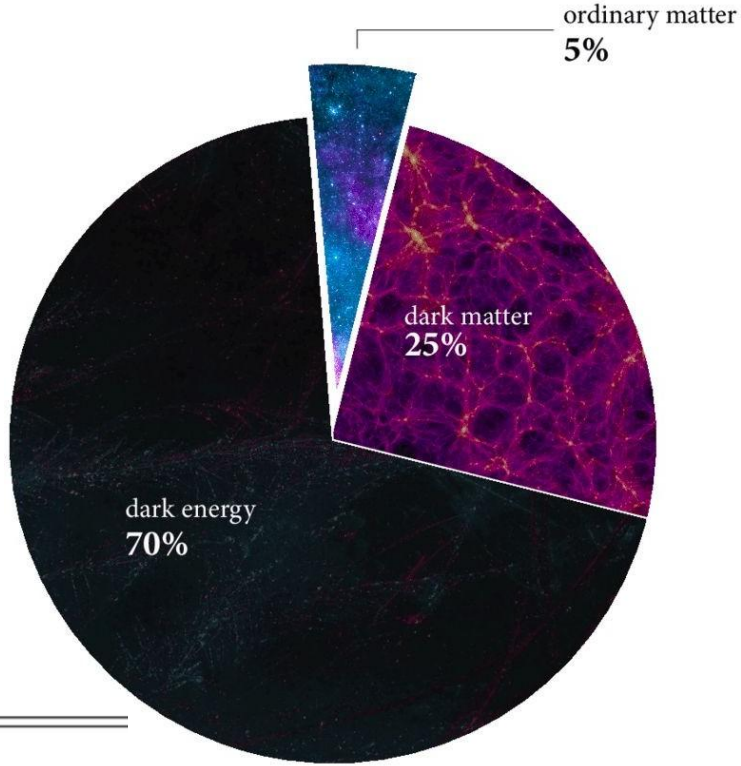
CosmoVerse@Bilbao - Addressing observational tensions in cosmology with systematics and fundamental physics

15 September 2026

Massimiliano Romanello - University of Bologna

The cosmological framework: the ΛCDM model

The currently most acknowledged cosmological model is the ΛCDM model. It predicts a Universe composed of cosmological constant (Λ ≈ 70%) and cold dark matter (CDM ≈ 25%) and provides a coherent large-scale description of the Universe with respect to the available data.



The ΛCDM model is fully characterised by six parameters:

Parameter	Description
Ω_m	Total matter density parameter
σ_8	Amplitude of the power spectrum on the scale of 8 h^{-1} Mpc
Ω_b	Baryon density parameter
n_s	Primordial spectral index
h	Normalised Hubble constant
τ	Reionization optical depth

Challenging the ΛCDM model

- Limits at *k*pc scale (e.g. missing satellite, cusp-core problem)
- H_0 tension: 5σ tension between the CMB data and local probes (e.g. Supernovae/Cepheids)
- **S_8 tension**: 2-3σ tension between CMB measurements and low redshift probes (e.g. weak lensing, galaxy clustering, cluster number counts)

Lesci, G. F.; Marulli, F.; Moscardini L.; et al. *AMICO galaxy clusters in KiDS-DR3: Cosmological constraints from counts and stacked weak lensing*, 2022a.

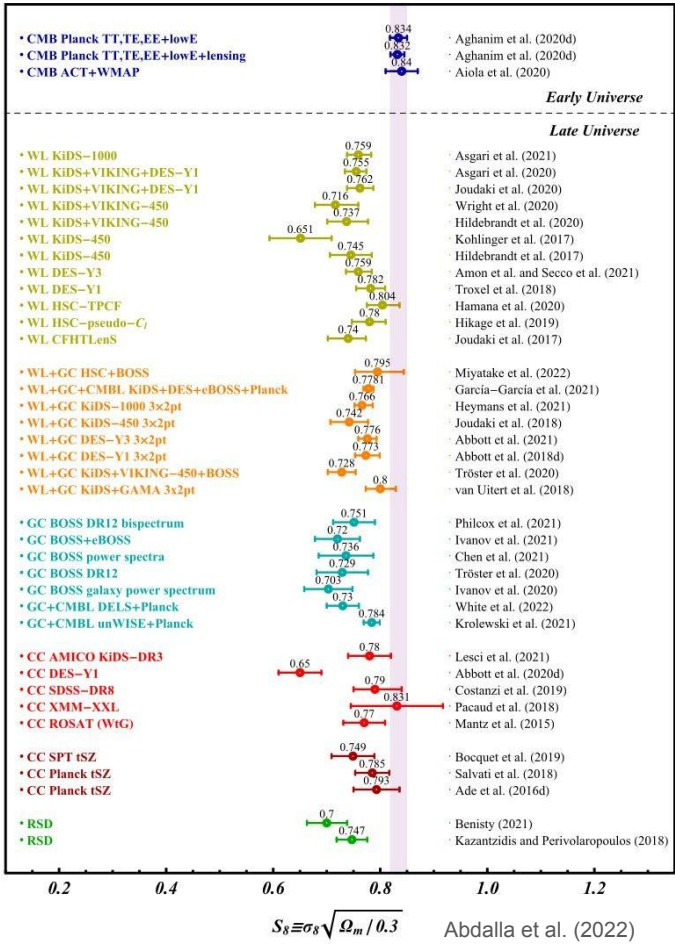
Lesci, G. F.; Nanni, L.; Marulli, F.; et al. *AMICO galaxy clusters in KiDS-DR3: Constraints on cosmological parameters and on the normalisation of the mass-richness relation from clustering*, 2022b.

Romanello, M.; Marulli, F.; Moscardini, L.; et al. *AMICO galaxy clusters in KiDS-DR3: Cosmological constraints from the angular power spectrum and correlation function*, 2024.

Romanello, M.; Marulli, F.; Moscardini, L.; et al. *Tomographic cluster clustering as a cosmological probe*, 2025.

Lesci, G. F.; Marulli, F.; Moscardini L.; et al. *AMICO galaxy clusters in KiDS-1000: Cosmological constraints and mass calibration from counts and weak lensing*, 2025.

Romanello, M.; Lesci, G. F.; Marulli, F.; et al. *AMICO galaxy clusters in KiDS-1000: Cosmological constraints from two-point correlation function, 2026.* To be submitted



Abdalla et al. (2022)

Cosmology with galaxy clusters

Galaxy clusters are the largest gravitationally bound systems that emerge from the cosmic web of the large-scale structure (LSS). They trace locations of peaks in the large-scale matter density, produced by gravitational infall and hierarchical merging of dark matter haloes.

Galaxy formation

Clusters statistics provide an important tool to:

- constrain fundamental cosmological parameters
- investigate the nature of dark matter and dark energy and of gravity
- constrain the neutrino mass
- understand the structure formation process

Cluste formation

Dark Energy
Accelerated Expansion

Galaxy clusters as a cosmological probe

Advantages

Galaxy clusters, hosted by the most massive virialized haloes, are more clustered than galaxies.

Relatively unaffected by nonlinear dynamics at small scales, so redshift-space distortions (RSDs) have a minor impact.

Easily identifiable in several bands: calibrate mass-observable scaling relations.

Disadvantages

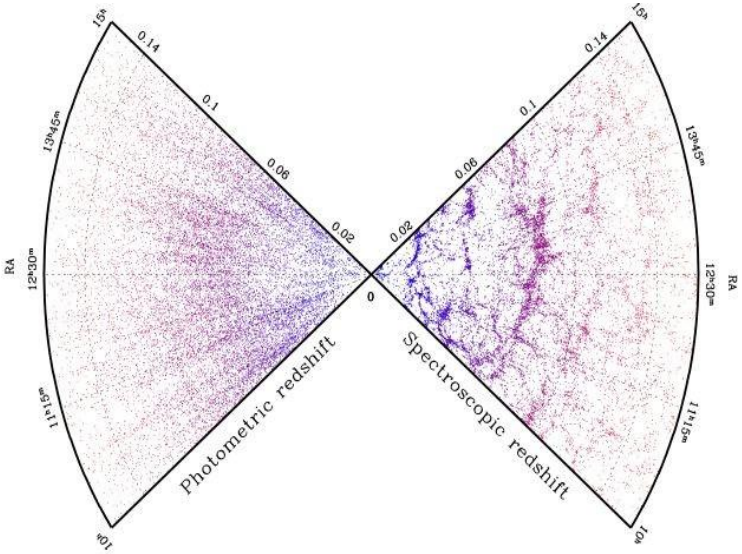
Cluster catalogues have few objects (with respect to galaxy catalogues).

Spatial distribution of LSS as a cosmological probe

The spatial distribution of LSS is investigated thanks to observational campaigns dedicated to measure the angular positions and redshifts of extragalactic objects.

Spectroscopic surveys allow us an accurate reconstruction of the pattern of cosmic structure, but require a large amount of observational time. They have limitations in terms of sky coverage and number of detected objects.

Photometric surveys (e.g. KiDS) allow us to cover a wider area and to go deeper, imaging also faint sources at high redshift. Photo-z errors are larger than spectroscopic errors.



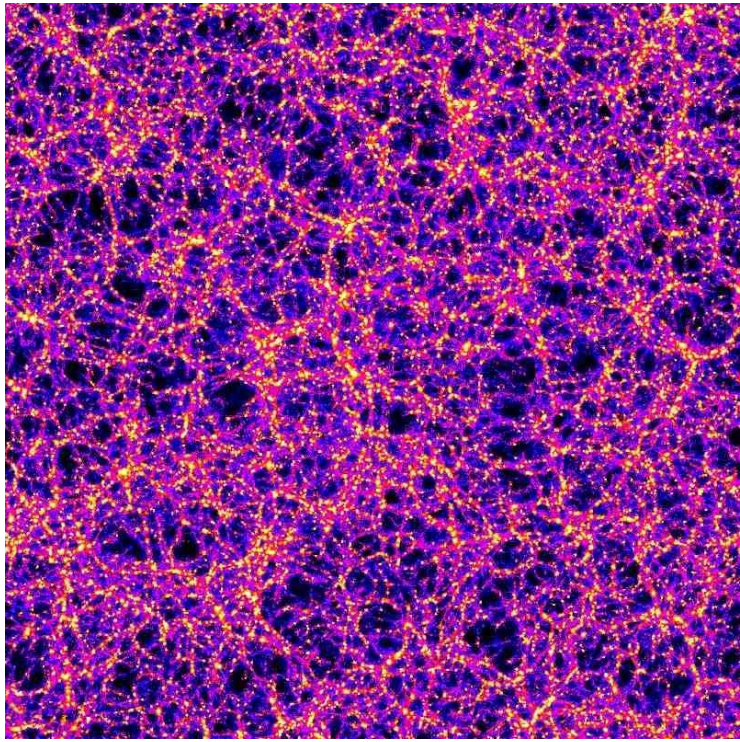
Balaguera-Antolínez et al. (2018)

Tomographic 2D and 3D clustering

Tomographic approach in different redshift shells.

- 2D clustering (Peebles, 1973). The measurement loses radial information, but it is cosmologically independent. *The thinner the shells, the closer to a full 3D study*. Angular correlation function, $w(\theta)$ and power spectrum, C_ℓ.

- 3D clustering, based on RA, Dec and redshift. It exploit radial information, but it is based on cosmological assumption for the redshift-distance relation. 3D two-point correlation function, $\xi(r)$.



CosmoBolognaLib

Free Software C++/Python libraries for cosmological calculations

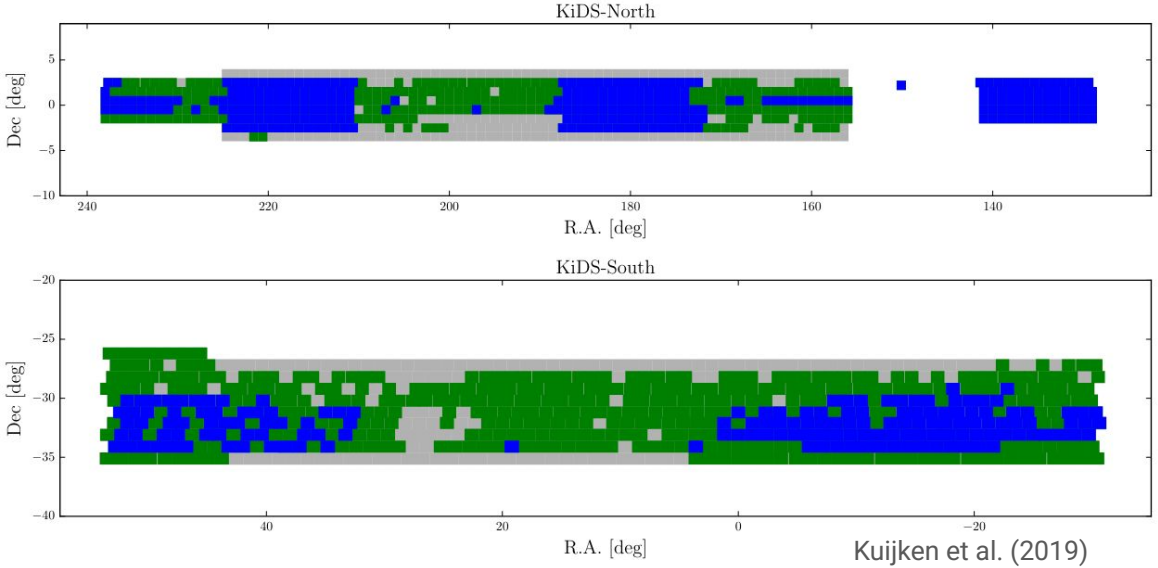
Marulli, F.; Veropalumbo A.; Moresco, M. *CosmoBolognaLib: C++ libraries for cosmological calculations, 2016.*

The Kilo Degree Survey (KiDS)

KiDS is a large optical imaging survey obtained with the VLT Survey Telescope (VST), located at the ESO Paranal Observatory, with photometry in four bands (*u, g, r, i*).

It also includes the photometry of the near-IR ($ZYJHK_s$) VIKING images, from the ESO VISTA telescope.

It is divided in two fields, one equatorial (KiDS-North) and the other near the South Galactic Pole (KiDS-South)



Kuijken et al. (2019)

Blue: KiDS-450 (DR3), 438 deg^2 -> *effective area* 377 deg^2

Green+**Blue**: KiDS-1000 (DR4), 1006 deg^2 -> *effective area* 839 deg^2

Gray: KiDS-Legacy, 1350 deg^2

The AMICO-KiDS cluster catalogue

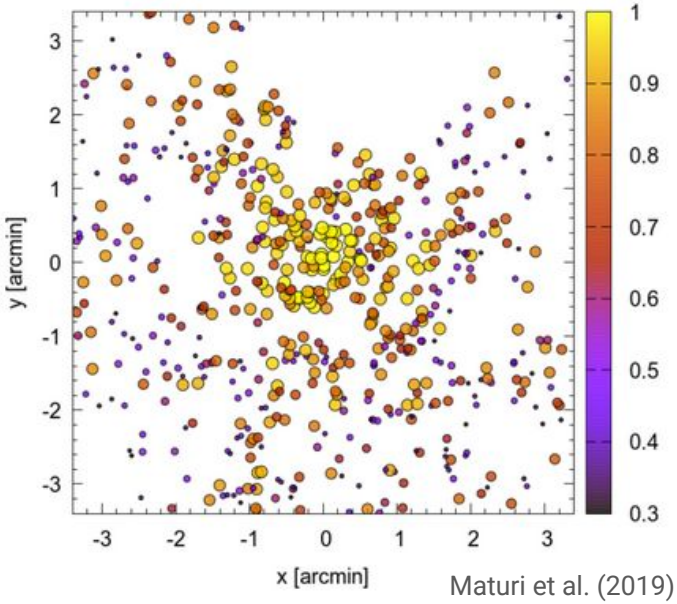
AMICO (Adaptive Matched Identifier of Clustered Objects, Bellagamba+18, Maturi+19) is an Optimal Filtering algorithm for cluster detection.

$$D(\boldsymbol{x}) = AM_c(\boldsymbol{x}) + N(\boldsymbol{x})$$

Noise from field galaxies

Signal: amplitude and cluster model

- It relies only on *angular coordinates, magnitude, and photometric redshift distribution*. No colour-based selection!
- Convolution of the 3D galaxy distribution with a redshift-dependent filter.
- Cluster candidates are selected by looking for peaks with the highest signal-to-noise ratio, S/N.
- Output: cluster catalogue and membership probabilities, $\mathbf{P_i(j)}$.



Maturi et al. (2019)

KiDS-DR3: **5162** clusters, z∈ (0.10, 0.60]
KiDS-1000: **9049** clusters, z∈ (0.10, 0.80]

The mass-richness scaling relation

Scaling relations relate an appropriate photometric observable to the total mass of clusters, mostly made of dark matter.

$$\log \frac{M_{200}}{10^{14}\,\mathrm{M}_{\odot}\,h^{-1}} = \alpha + \beta \log \frac{O}{O_{\mathrm{piv}}} + \gamma \log \frac{E(z)}{E(z_{\mathrm{piv}})}$$

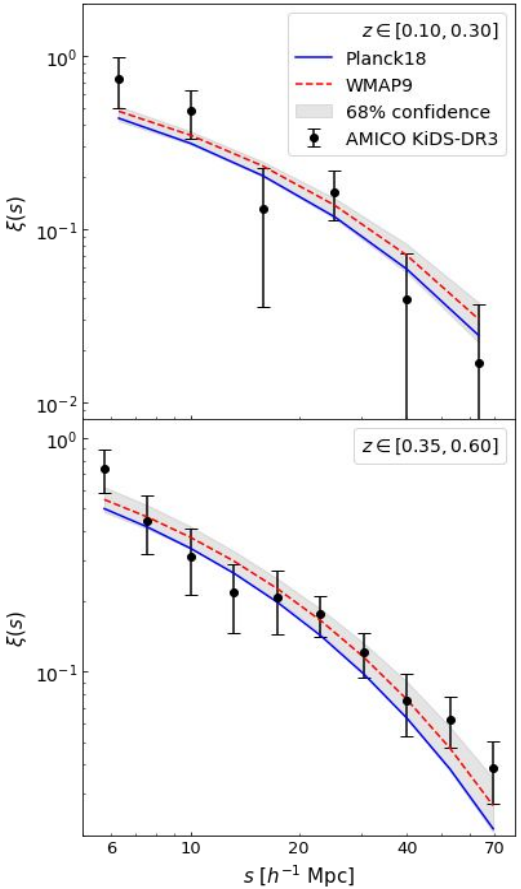
We used the intrinsic richness, defined as the sum of the galaxy membership probabilities, which roughly correspond to the number of visible member galaxies in a given detection.

$$\lambda_{*j} = \sum_{i=1}^{N_{gal}} P_i(j) \quad \text{with} \quad \begin{cases} m_i < m_*(z_j) + 1.5 \\ r_i(j) < R_{200}(z_j) \end{cases}$$

The mass-richness scaling relation allows us to derive the effective bias, which connects the matter power spectrum to the power spectrum of galaxy clusters.

KiDS-DR3: 3D clustering

Lesci et al. (2022b)



$$P_{\rm hh}(k,\mu) = P(k)\, b_{\rm eff}^2 \left(1 + \frac{f}{b_{\rm eff}}\mu^2\right)^2 \exp(-k^2\mu^2\sigma^2)$$

Exponential damping: accounts for photo-z error

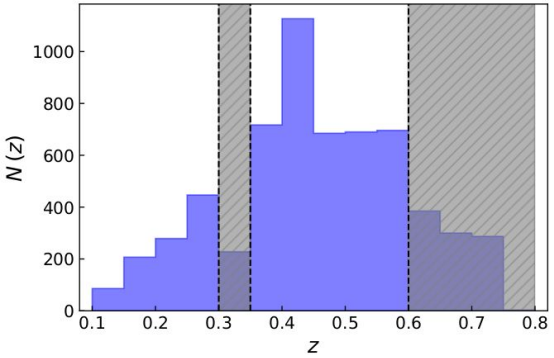
Kaiser factor: large-scale RSDs

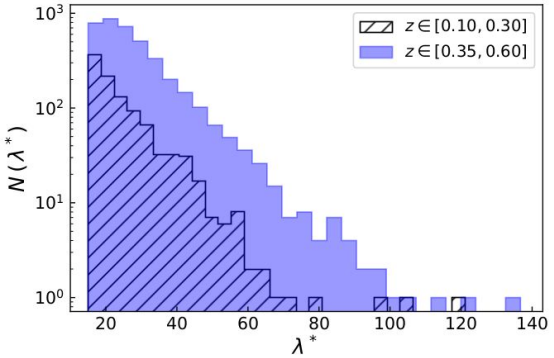
$$\sigma = \frac{c\sigma_z}{H(z)} \qquad \sigma_z = \sigma_{z,0}(1+z) \qquad \sigma_{z,0} = 0.02$$

$$\Omega_{\rm m} = 0.28^{+0.05}_{-0.04}$$

$$\sigma_8 = 0.82^{+0.14}_{-0.12}$$

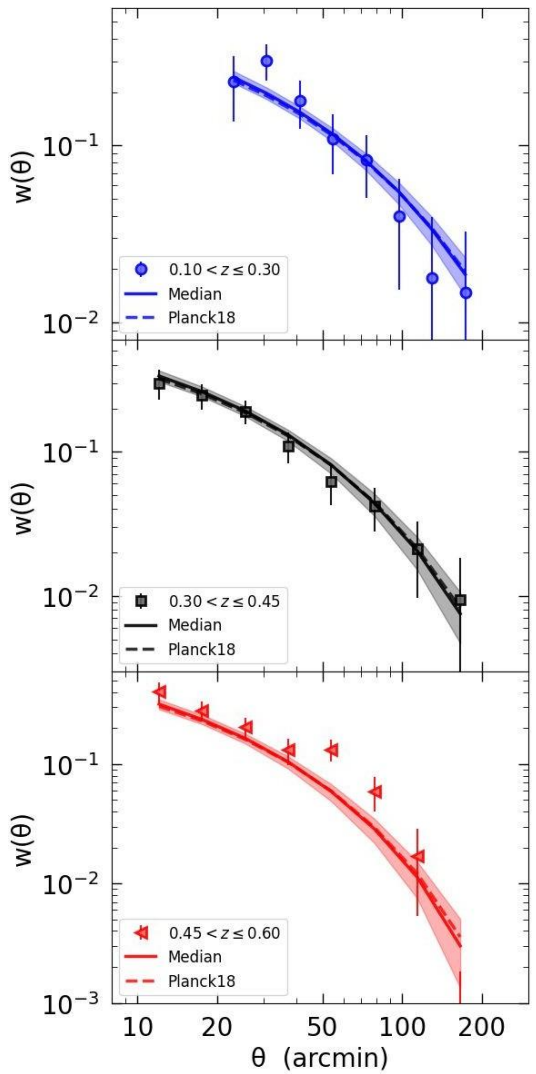
$$S_8 = 0.80^{+0.08}_{-0.08}$$





KiDS-DR3: 2D clustering

Romanello et al. (2024)



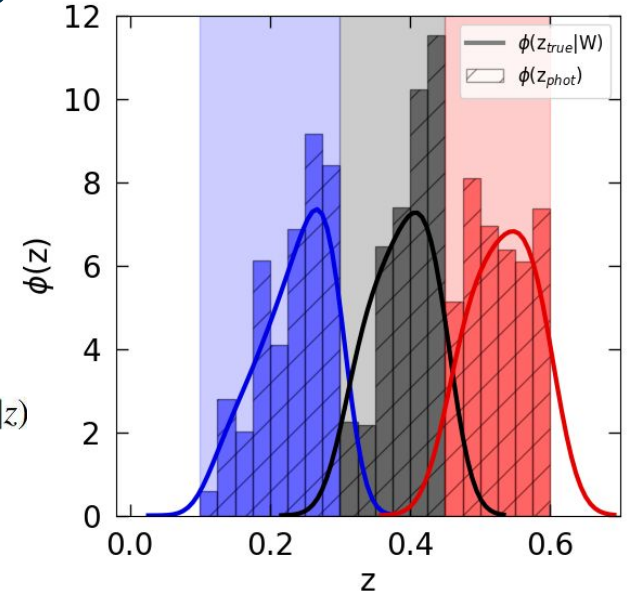
Measurements of 2D correlation in the spatial range $\theta \in [10\text{-}20, 200]$ arcmin.

$$P(z_{\rm phot}|z) = \frac{1}{\sqrt{2\pi}\sigma_z}\exp\left[-\frac{\delta z^2}{2\sigma_z^2}\right]$$

$$\frac{dN}{dz^i} = \Omega_{\rm sky}\frac{{\rm d}V}{{\rm d}z{\rm d}\Omega}\int_0^\infty {\rm d}M\frac{{\rm d}n(M,z)}{{\rm d}M}\int_{\Delta z_i}{\rm d}z_{\rm phot}P(z_{\rm phot}|z)$$

$$w^{ij}(\theta) = \int\int {\rm d}z_1{\rm d}z_2\phi^i(z_1)\phi^j(z_2)\xi(s)$$

Parameter	Posterior $w(\theta)$ - C_ℓ
$\Omega_{\rm m}$	$0.32^{+0.05}_{-0.04}$ - $0.24^{+0.05}_{-0.04}$
σ_8	$0.77^{+0.13}_{-0.09}$ - $1.01^{+0.25}_{-0.17}$
$S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5}$	$0.80^{+0.08}_{-0.06}$ - $0.93^{+0.11}_{-0.12}$

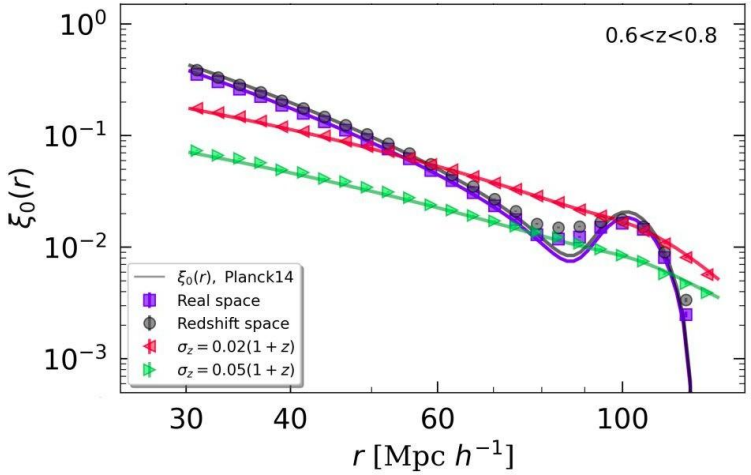


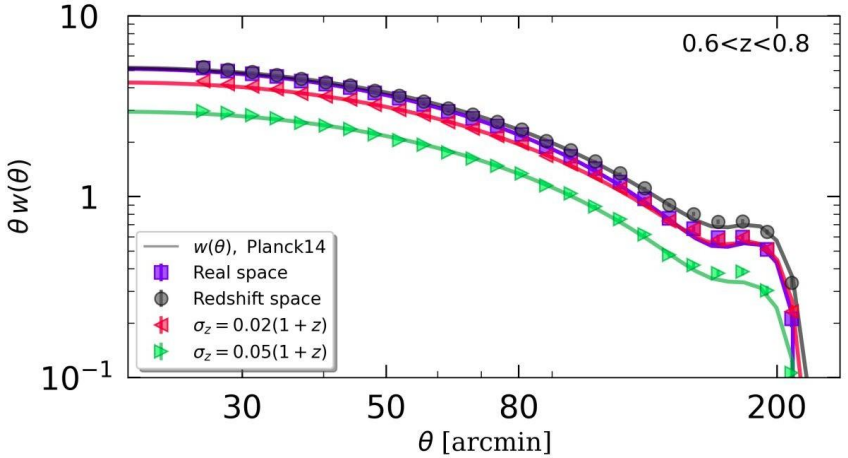
$z \in (0.10, 0.30]$ 1019 clusters +
$z \in (0.30, 0.45]$ 2072 clusters +
$z \in (0.45, 0.60]$ 2071 clusters =

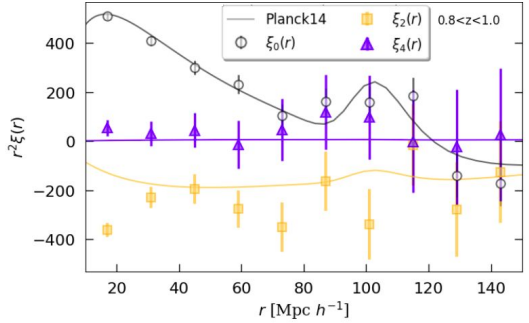
5162 clusters

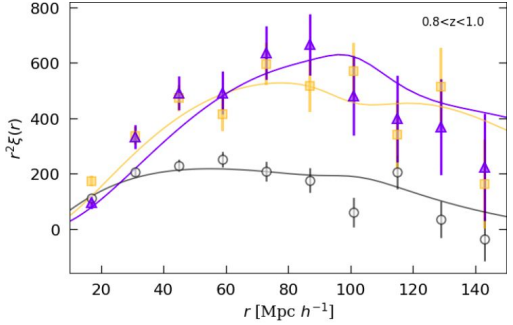
Photo-z effect, PINOCCHIO simulations

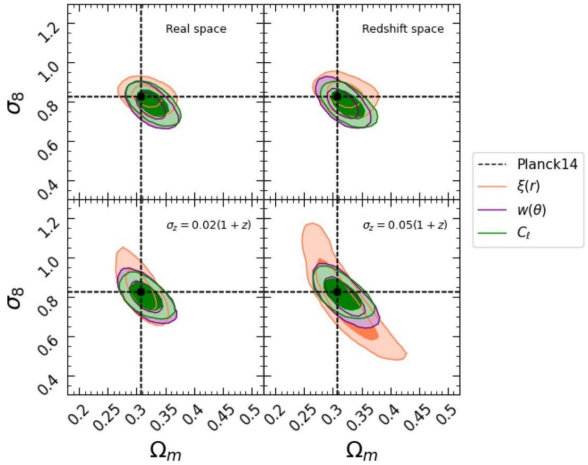
Romanello et al. (2024-2025)









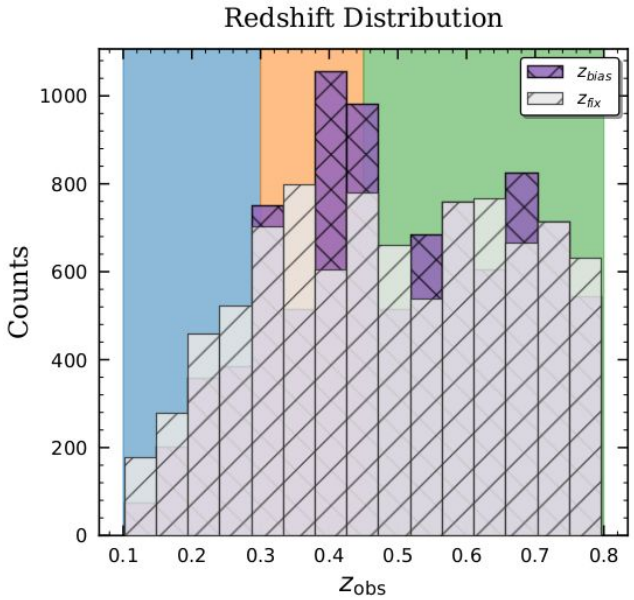


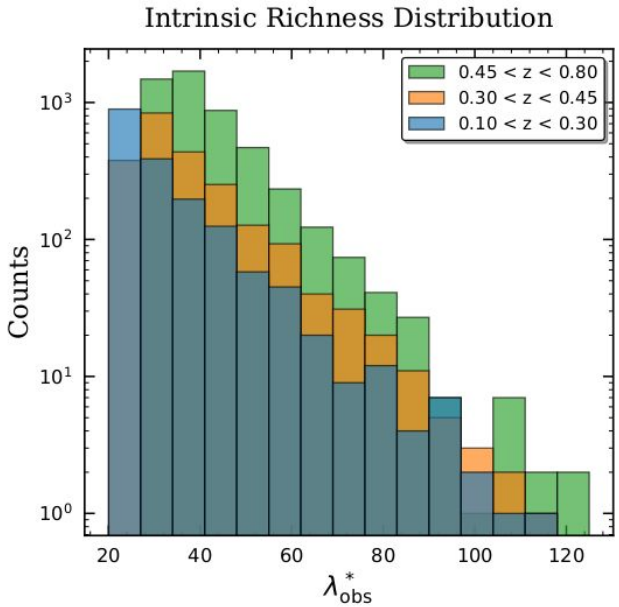
KiDS-1000: Richness selection and tomographic strategy

Three photometric redshift bins:

$\lambda^*_{obs} \geq 20, \quad z \in (0.10, 0.30]$ — 1767 clusters +
$\lambda^*_{obs} \geq 25, \quad z \in (0.30, 0.45]$ — 2240 clusters +
$\lambda^*_{obs} \geq 30, \quad z \in (0.45, 0.80]$ — 5042 clusters =

9049 clusters





Redshift calibration (Maturi+25) using KiDS cluster member galaxies with spectroscopic counterpart in the GAMA survey.

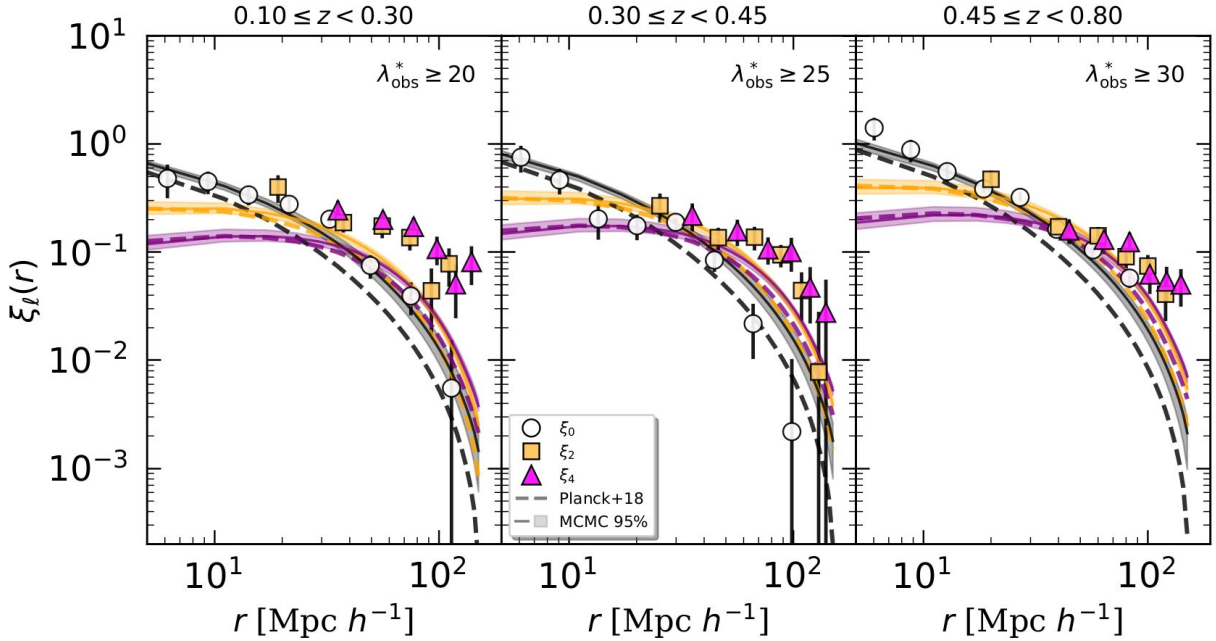
KiDS-1000: the two-point correlation function

Landy-Szalay estimator:

$$\hat{\xi}(r) = \frac{DD(r) + RR(r) - 2DR(r)}{RR(r)}$$

Multipoles measured over a variable range of scales, with $r \in [5, 150]$ Mpc h^{-1}.

$$\sigma_z = \sigma_{z,0}(1+z) \qquad \sigma_{z,0} = 0.014$$

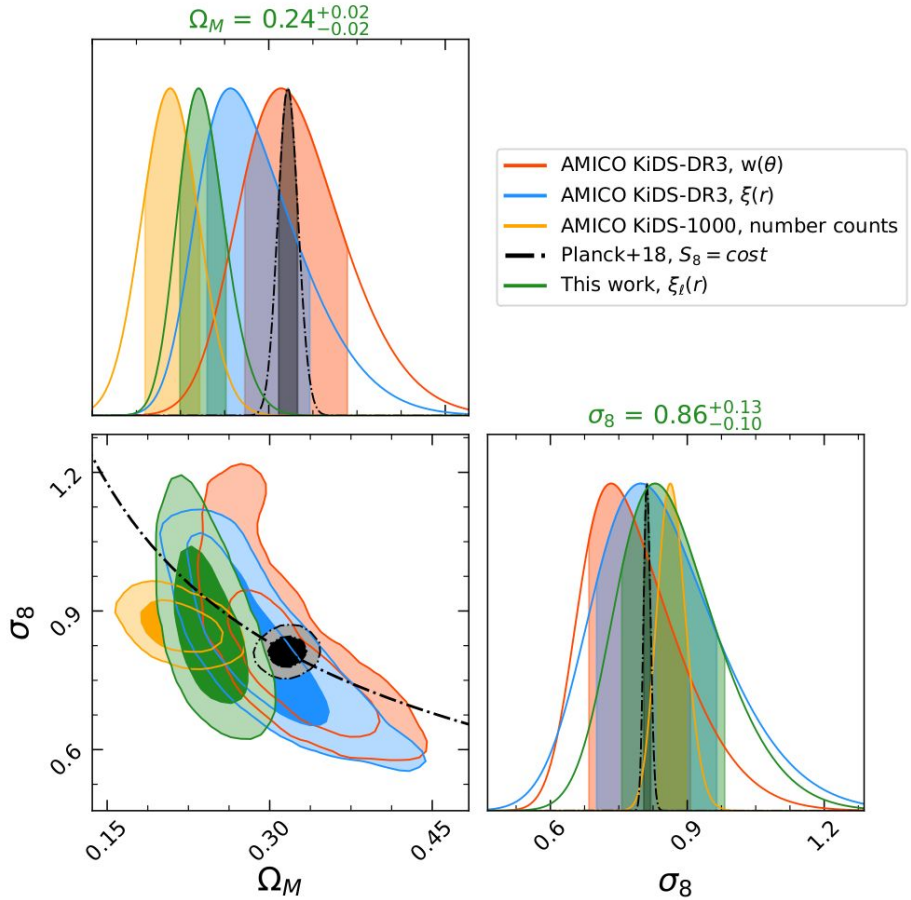


$$b_{\rm eff}(\Delta z_{\rm obs}) = \frac{\int_0^\infty {\rm d}z_{\rm tr} \frac{{\rm d}^2V}{{\rm d}z_{\rm tr}{\rm d}\Omega} \int_0^\infty {\rm d}M n(M, z_{\rm tr}) b(M, z_{\rm tr}) \mathcal{K}(M, z_{\rm tr})}{\int_0^\infty {\rm d}z_{\rm tr} \frac{{\rm d}^2V}{{\rm d}z_{\rm tr}{\rm d}\Omega} \int_0^\infty {\rm d}M n(M, z_{\rm tr}) \mathcal{K}(M, z_{\rm tr})}$$

Integration kernel (convolution with completeness, mass-richness scaling relation)

$P(\lambda^*_{\rm tr} \mid M, z_{\rm tr})$

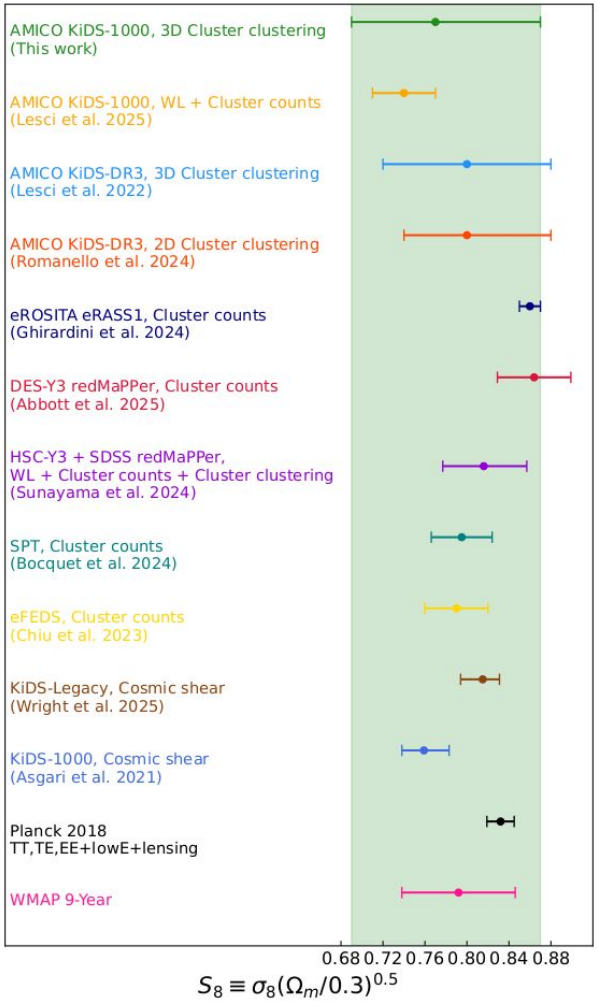
Cosmological constraints from AMICO KiDS-1000



$$\Omega_{\rm m} = 0.24^{+0.02}_{-0.02}$$

$$\sigma_8 = 0.86^{+0.13}_{-0.10}$$

- 1σ agreement with weak lensing and cluster number counts analyses in Lesci+22 and Lesci+25.
- For the parameter Ω_m, we find 2σ tension with Planck+18 and KiDS-DR3 angular correlation function.
- Figure of Merit (FoM) increased by a factor of 1.8.



Conclusions and future prospects

$$S_8 = 0.77^{+0.10}_{-0.08}$$

1σ agreement with early and late-time cosmological probes:

- KiDS-1000 combined weak-lensing and cluster number counts, KiDS-DR3 3D and angular cluster clustering;
- Cluster cosmology in X-ray, optical and millimetric bands;
- CMB (Planck+18, WMAP Y9);
- Cosmic shear (KiDS-1000 and KiDS-Legacy).

No improvement along the direction of degeneracy, with respect to DR3 clustering.

We expect independent and more competitive constraints from final KiDS-Legacy cluster catalogue.