Galaxy clusters seen through every galaxy

eROSITA X-ray $\times$ Legacy Survey cross-correlations

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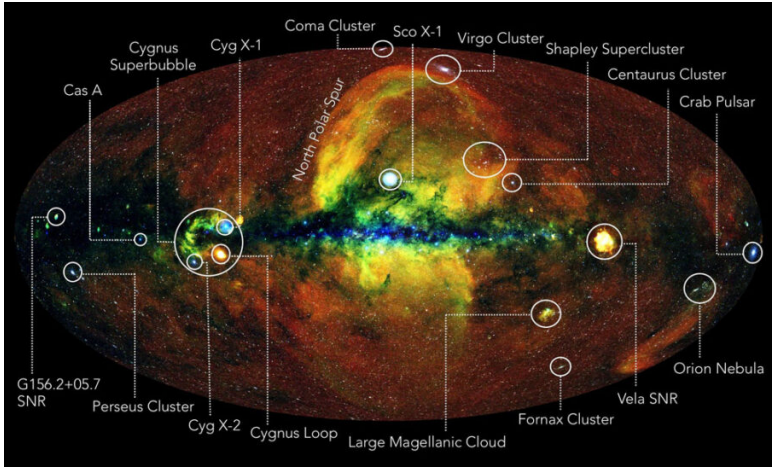
26 November 2026

Comparat, Merloni, Ponti et al. 2025, A&A 697, A173 · Comparat, Macías-Pérez, Combet et al. 2025, A&A 700, A271

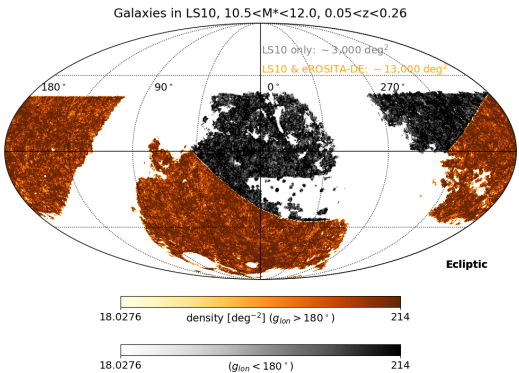
Two measurements

I. galaxies $\times$ the full 0.5–2 keV photon field
II. eRASS1 clusters $\times$ quiescent and star-forming galaxies



Predehl et al. 2021 · Merloni et al. 2024

The galaxy samples: DESI Legacy Imaging Surveys



- Stellar-mass-selected, volume-limited samples (photometric redshifts, LePhare stellar masses).
- **13.9 million** galaxies over **16 800 deg^2** at $z < 0.35$.
- $\log_{10}(M_\star/\mathrm{M}_\odot)$ thresholds from 10 to 11.5.
- Complete: no central/satellite classification, no masking.

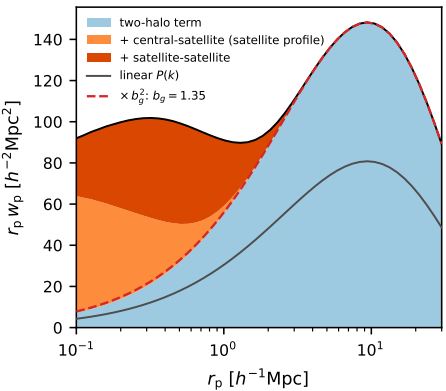
Dey et al. 2019 · Zhou et al. 2023

Correlation functions 101

- Excess probability, over random, of finding a pair separated by r:

$$\xi(r) = \langle \delta(\mathrm{x})\, \delta(\mathrm{x}+\mathrm{r}) \rangle, \qquad \delta = \frac{n}{\bar{n}} - 1.$$

- $\xi > 0$: more clustered than random. Fourier pair of $P(k)$.
- Cross-correlation of two fields A and B: $\xi_{\mathrm{AB}} = \langle \delta_{\mathrm{A}}\, \delta_{\mathrm{B}} \rangle$
  - A = galaxies, B = X-ray photons (Part I);
  - A = clusters, B = galaxies by type or colour (Part II).
- Halo model: **1-halo term** (pairs in the same halo, small r; central–satellite and satellite–satellite) + **2-halo term** (pairs in different haloes, large r).
- Photometric redshifts: projected $w_p(r_p)$ or angular $w(\theta)$.



halo model of w_p, LS10 $M_\star > 10^{10.5}\,\mathrm{M}_\odot$

Model: `ggah_mod` Documentation: `ggah-mod.readthedocs.io` Install: `pip install ggah-mod`

I. Galaxies $\times$ the eROSITA photon field

Comparat, Merloni & Ponti et al. 2025, A&A 697, A173

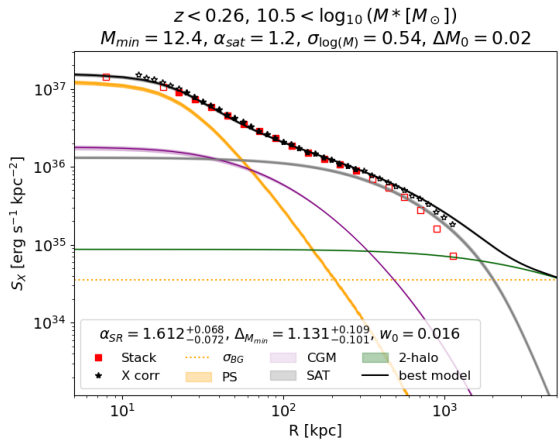
A&A 10.1051/0004-6361/202554208 DO 10.5281/zenodo.15111974

The measurement

- Every 0.5–2 keV photon over **13 000 deg^2** ($\sim 3 \times 10^8$ events).
- No source masking: AGN, X-ray binaries, gas and clusters all contribute.
- Angular cross-correlation $w_{\rm gX}(r_p)$ from 10 kpc to 1 Mpc.
- Statistical uncertainties **below one per cent**.

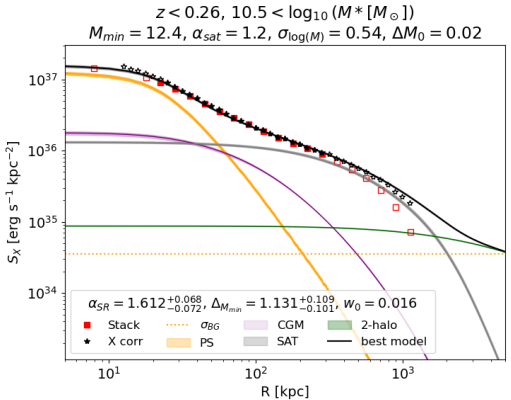
Halo-model extension

$w_{\rm gX}$ = point sources (AGN + XRB) + hot CGM + satellites in larger haloes + 2-halo term

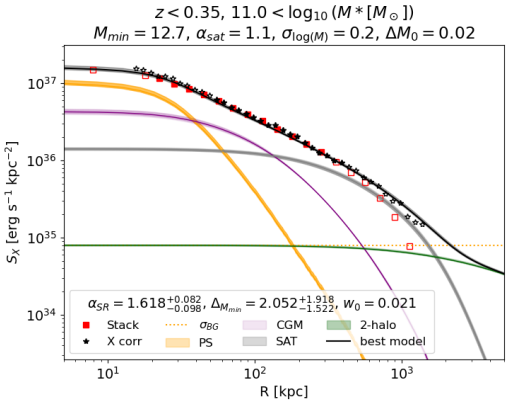


Comparat, Merloni & Ponti et al. 2025, A&A 697, A173

Trend with mass threshold



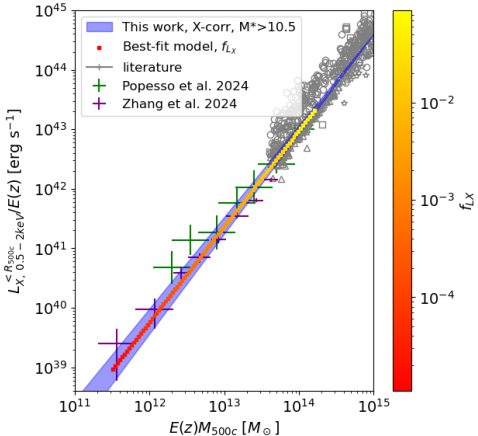
$M_\star > 10^{10.5}\,\mathrm{M}_\odot$



$M_\star > 10^{11}\,\mathrm{M}_\odot$

Comparat, Merloni & Ponti et al. 2025, A&A 697, A173

The M_{500c}–L_X relation over three decades in mass



- The model ties hot-gas luminosity to halo mass with a single power law.
- Slope 1.63 ± 0.09: a 5 per cent measurement.
- Valid from Milky Way-mass haloes to clusters.
- Consistent with stacking and cluster samples.

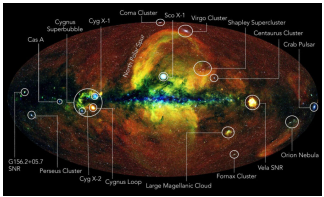
Comparat, Merloni & Ponti et al. 2025, A&A 697, A173

II. eRASS1 clusters × quiescent and star-forming galaxies

Comparat, Macías-Pérez, Combet et al. 2025, A&A 700, A271

A&A 10.1051/0004-6361/202555287 DO 10.5281/zenodo.15806800

The cluster samples: eRASS1

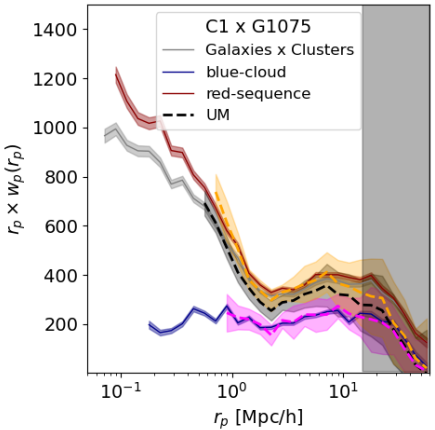


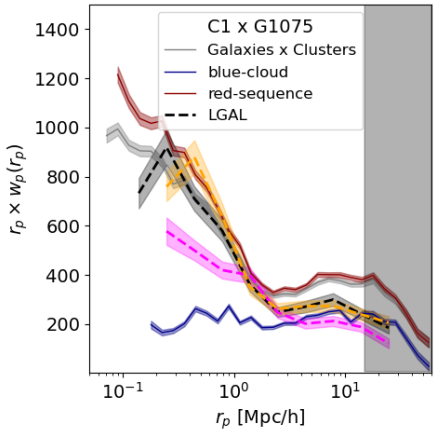
- Volume-limited X-ray-selected samples: up to **3 700 clusters** at $0.1 < z < 0.4$.
- Cross-correlated with the LS10 samples, split into quiescent and star-forming galaxies.

Label	Selection			$\langle z \rangle$	N	Volume [Gpc^3]	Density [10^{-7} Mpc^{-3}]	S/N
	$z_{\rm min}$	$z_{\rm max}$	$L_{\rm X,min}$ [erg s^{-1} cm^{-2}]					
S0	0.1	0.2	42.7	0.153	1650	0.68	24.44	29.9
S1	0.1	0.3	43.1	0.206	2993	2.33	12.85	39.4
S2	0.1	0.4	43.4	0.264	3732	5.22	7.15	41.1
S3	0.1	0.5	43.6	0.315	3670	9.49	3.87	35.4
S4	0.1	0.6	43.8	0.369	3333	15.16	2.19	29.7

Bulbul et al. 2024 · Seppi et al. 2024

Measurement vs. models

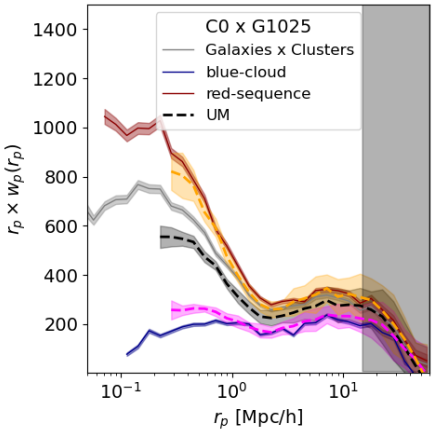


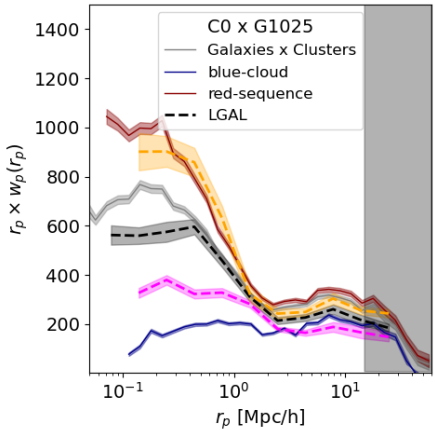


C1 $\times$ G10.75: $\log_{10}(M_\star/\mathrm{M}_\odot) > 10.75$; models: Uchuu+UniverseMachine (left), L-Galaxies (right)

Comparat, Macías-Pérez, Combet et al. 2025, A&A 700, A271

Measurement vs. models

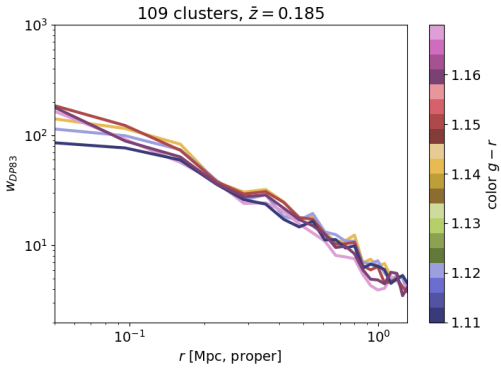




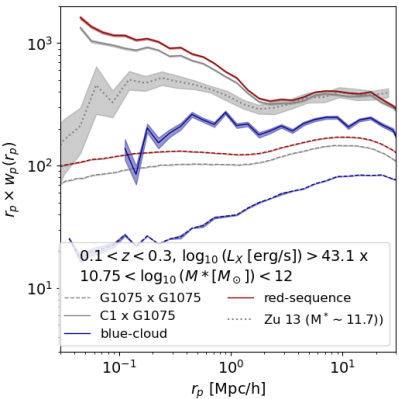
C0 $\times$ G10.25: $\log_{10}(M_\star/\mathrm{M}_\odot) > 10.25$; models: Uchuu+UniverseMachine (left), L-Galaxies (right)

Comparat, Macías-Pérez, Combet et al. 2025, A&A 700, A271

Cluster (redshift) × galaxies (colour): the method



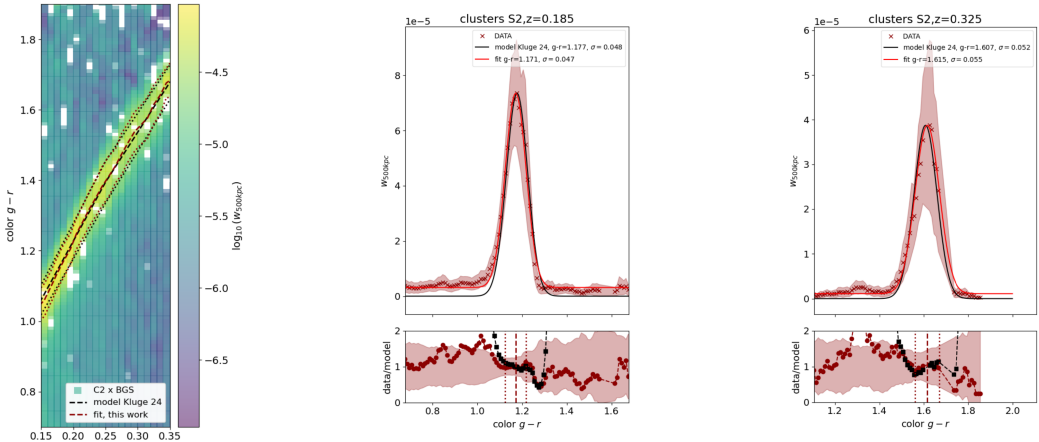
cross-correlation in narrow $g - r$ bins, integrated within **500 kpc** (1-halo term)



the 1-halo term is dominated by red-sequence galaxies

Comparat, Macías-Pérez, Combet et al. 2025, A&A 700, A271

The red sequence without calibration



Colour and scatter (**$\sim$0.05 mag** in $g-r$) agree with the eRASS1 red-sequence calibration, with neither spectroscopic redshifts nor galaxy classification.

Comparat, Macías-Pérez, Combet et al. 2025, A&A 700, A271 · Kluge et al. 2024

Summary

Galaxies × photons

- Full photon field, no masking, < 1 per cent errors.
- Point sources, hot CGM, satellites and 2-halo term separated.
- 80 kpc–2 Mpc: cluster-mass haloes hosting satellites.
- M_{500c}–L_X slope 1.63 ± 0.09 from Milky Way to clusters.

Clusters × galaxies

- Infall and quenching, split by quiescent and star-forming galaxies.
- $\sim$90 per cent quiescent in cores; models low at intermediate mass.
- Red-sequence colour and scatter ($\sim$0.05 mag) without spectra.

Use

Benchmarks for hydrodynamical simulations and semi-analytic models; a calibration route for the optical cluster finders of Euclid and LSST.

Perspective: Euclid $\times$ XMM in the Fornax Deep Field

- Euclid Deep Field Fornax: deep near-infrared and optical imaging, accurate photometric redshifts and stellar masses to $z \sim 1$ and beyond.
- XMM-Newton 40ks coverage of the same field.
- Same two measurements, pushed to higher redshift and lower mass:
  - galaxies $\times$ X-ray photons: hot gas and AGN versus halo mass and redshift;
  - X-ray groups and clusters $\times$ galaxies: quenching and the red sequence at the epoch of its build-up.
- A test bench for the Euclid cluster finders against X-ray selection.

New projects

Collaboration welcome

Legacy surveys DR11 optical cluster catalogues

The code: `rema`

- Redesign of redMaPPer (Rykoff et al. 2014, 2016) written in JAX.
- Richness, redshift, centre and members; blind mode, or measured at given positions.
- Runs on CPU or GPU, exact derivatives of λ.
- DR11 griz red-sequence calibration built in.

The DR11 south catalogue

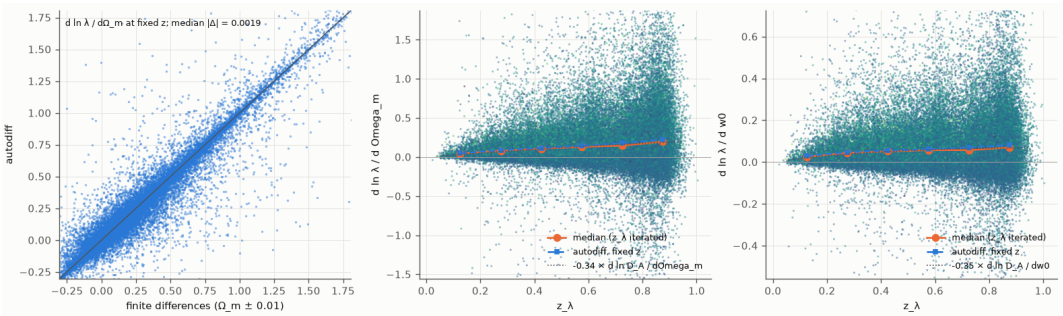
- $18\,500\,\mathrm{deg}^2$, $E(B-V) < 0.2$, $|b| \geq 15°$.
- 3.48 M clusters with $\lambda \geq 3$ (145 133 with $\lambda \geq 20$), 87.7 M members.
- z_λ scatter $0.0067(1+z)$ below $z = 0.6$.
- Recovers 93–95% of ACT and SPT clusters in the footprint.
- Scan at 1.64 M known clusters (ACT, SPT, PSZ2, MCXC, eRASS1, ...).

Cluster and member catalogues: DOI 10.5281/zenodo.24556115

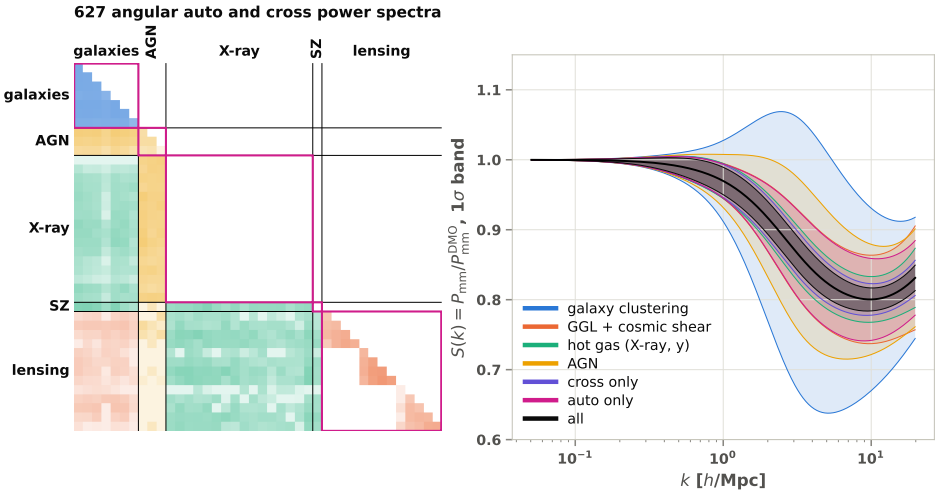
Documentation: `rema-jax.readthedocs.io` Install: `pip install rema-jax` DOI 10.5281/zenodo.24557263

Richness depends on cosmology: $\mathrm{d}\ln\lambda/\mathrm{d}\theta$

- The finder uses $D_A(z)$: the aperture, background and z_λ change with Ω_m and w_0.
- At $z \simeq 0.4$, a 5% change of Ω_m (± 0.015) changes λ by $\pm 0.24\%$ for $\lambda > 20$ ($\pm 0.29\%$ for $\lambda > 60$).
- A 5% change of w_0 (± 0.05) changes λ by $\pm 0.39\%$ for $\lambda > 20$ ($\pm 0.47\%$ for $\lambda > 60$).
- For comparison, the median σ_λ/λ is 9% for $\lambda > 20$ (5% for $\lambda > 60$).



Constraints on the power spectrum suppression



ggah_mod ggah-mod.readthedocs.io pip install ggah-mod DOI 10.5281/zenodo.24469941

Comparison with hydrodynamical simulations

