Constraining the mass of *Planck* protocluster candidates with *ACT* DR6 CMB lensing maps

PhD thesis : Modeling galaxy protoclusters from cosmic dawn to cosmic noon and comparison with data from *JWST* , *Euclid* and *NIKA2*

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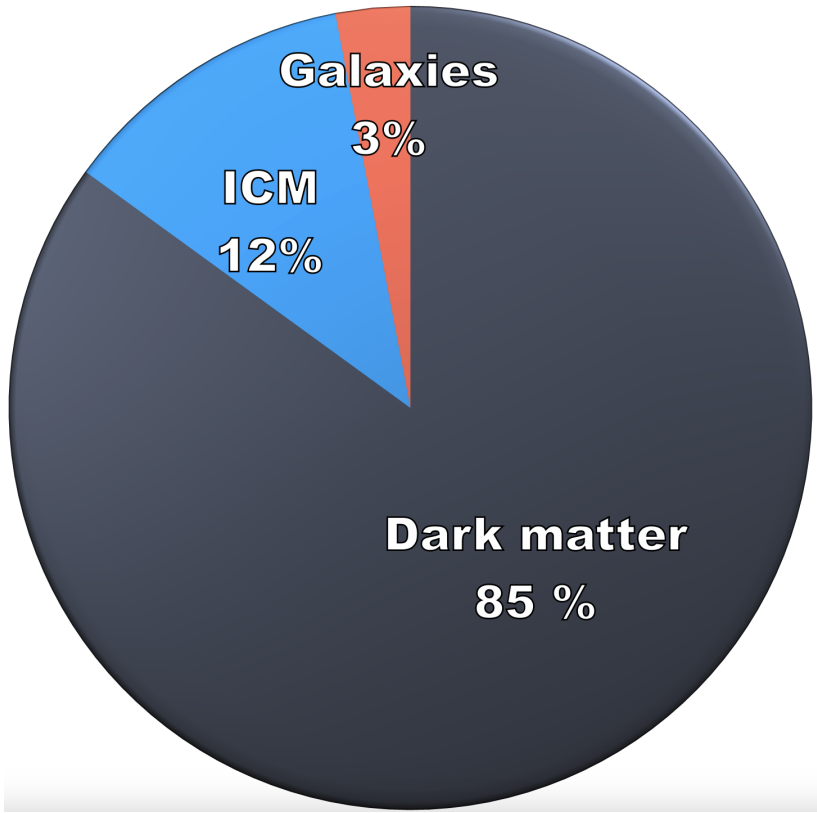
14 October 2025

1 - Protoclusters: What are they ?

- Clusters : largest gravitationally bound structures
- Protoclusters are clusters being formed !



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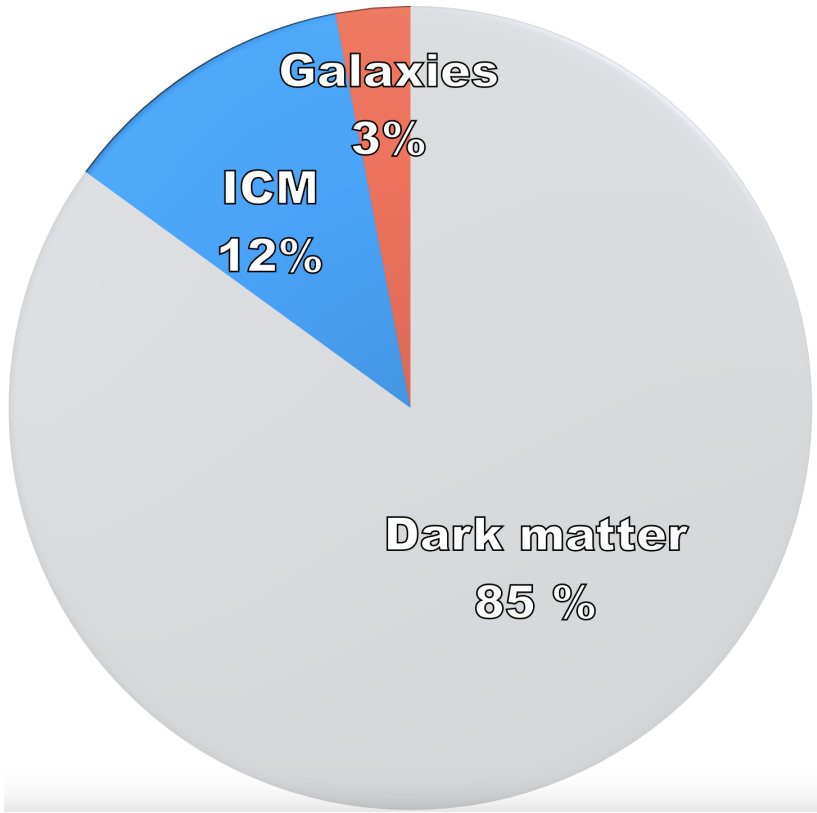

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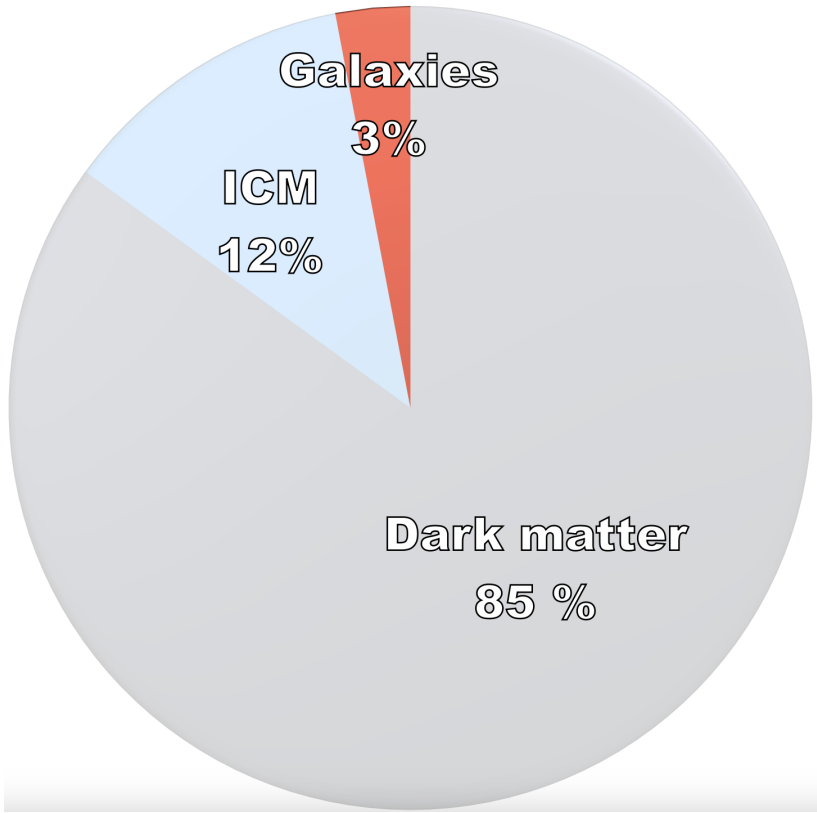

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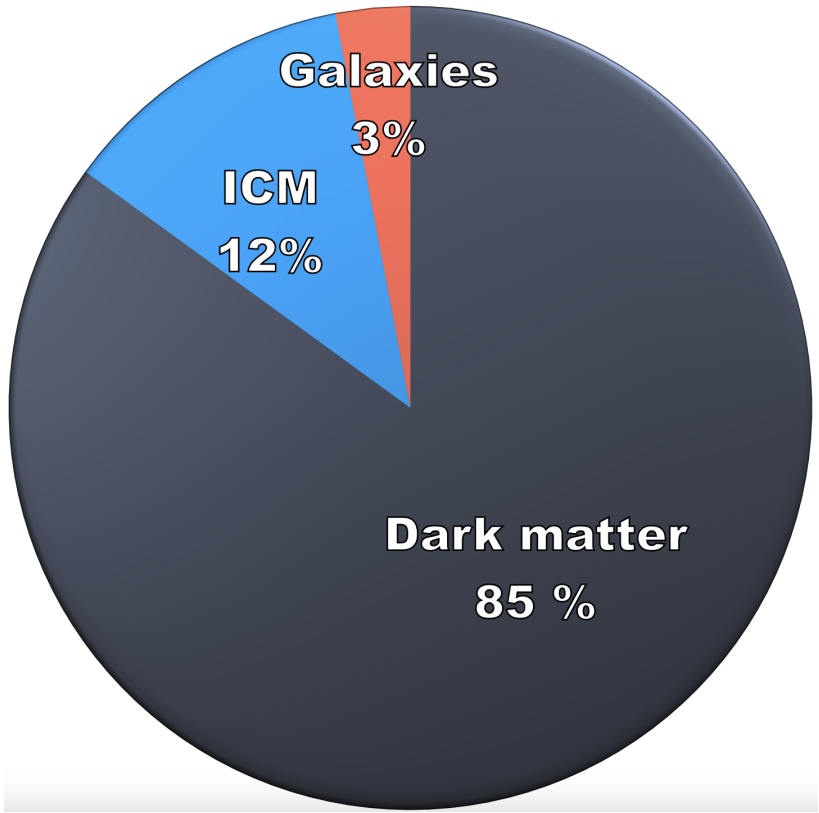
- **CMB acts as a background source for lensing !**



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1 - Protoclusters: The *Planck* candidates

Planck intermediate results. XXXIX. The Planck list of high-redshift source candidates

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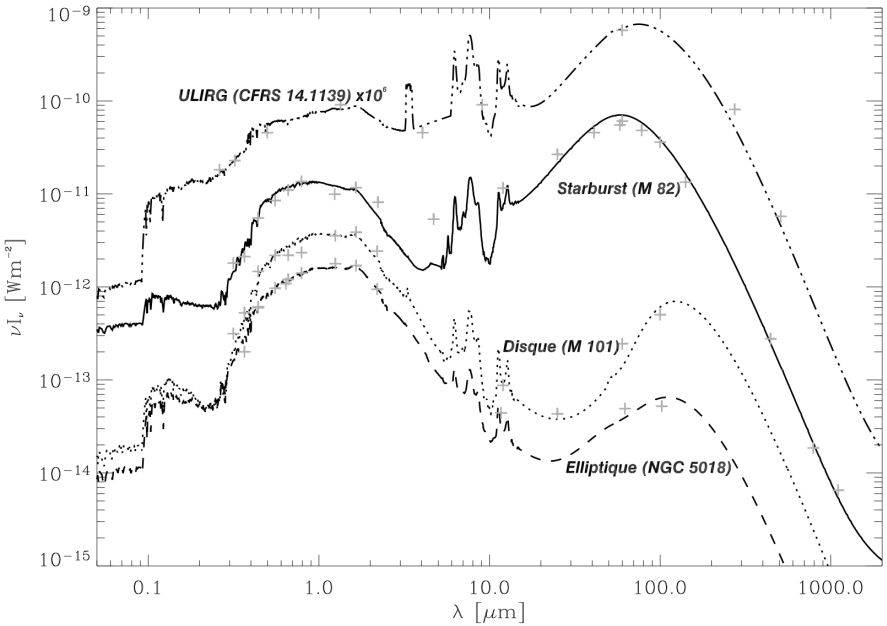

Figure: Spectra of galaxies exhibiting different stellar activities (S. Galliano 2004)

- Catalogue of CIB spots
- High redshift star forming sources

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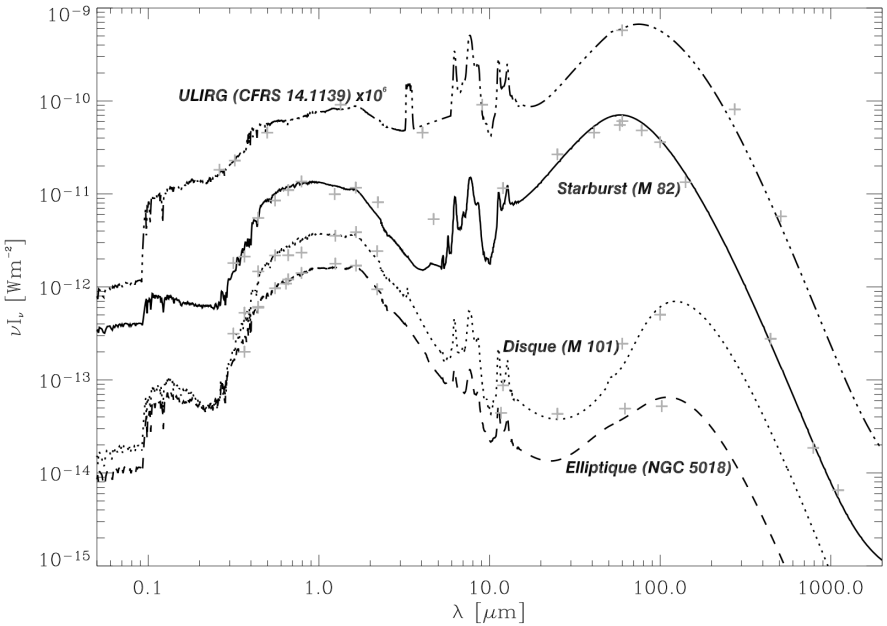

Figure: Spectra of galaxies exhibiting different stellar activities (S. Galliano 2004)

- Catalogue of CIB spots
- High redshift star forming sources
- At least 70% of them should be protoclusters (simulations from Gouin 2022)
- Follow-ups with *Herschel* and *Euclid*

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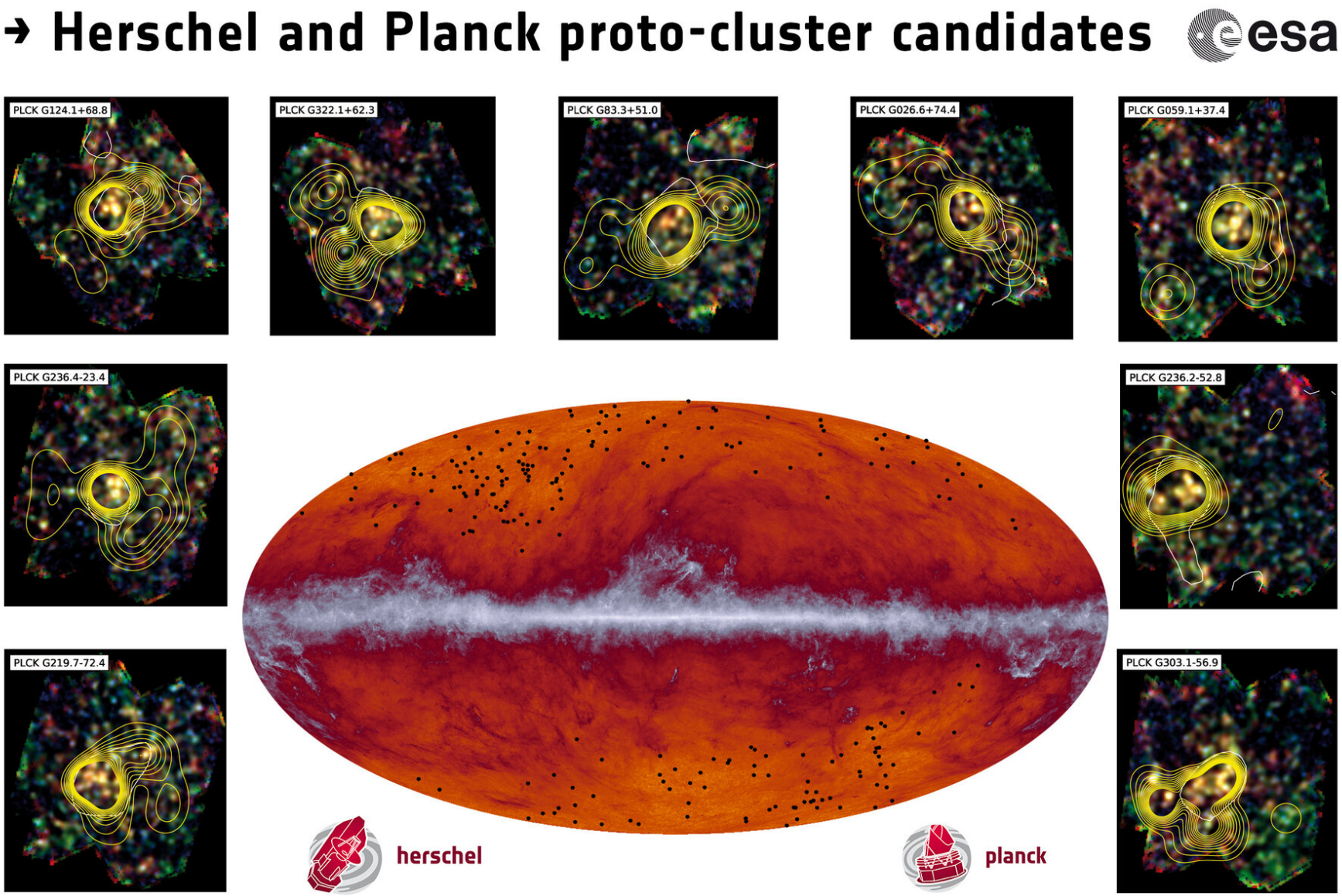
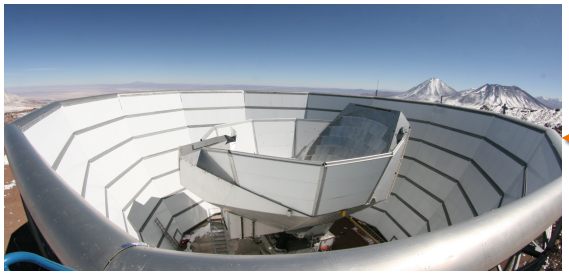
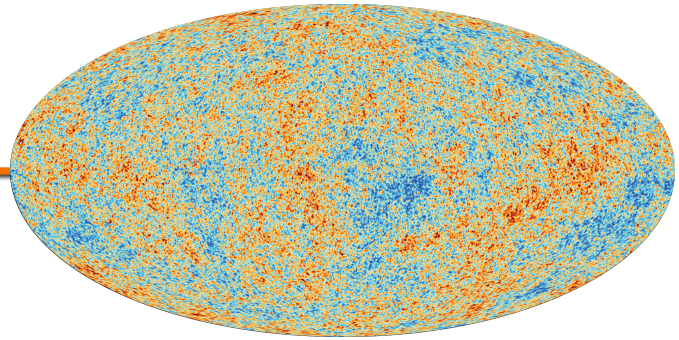


2 - CMB lensing: Main concepts





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- Correlations are induced between multipoles ℓ

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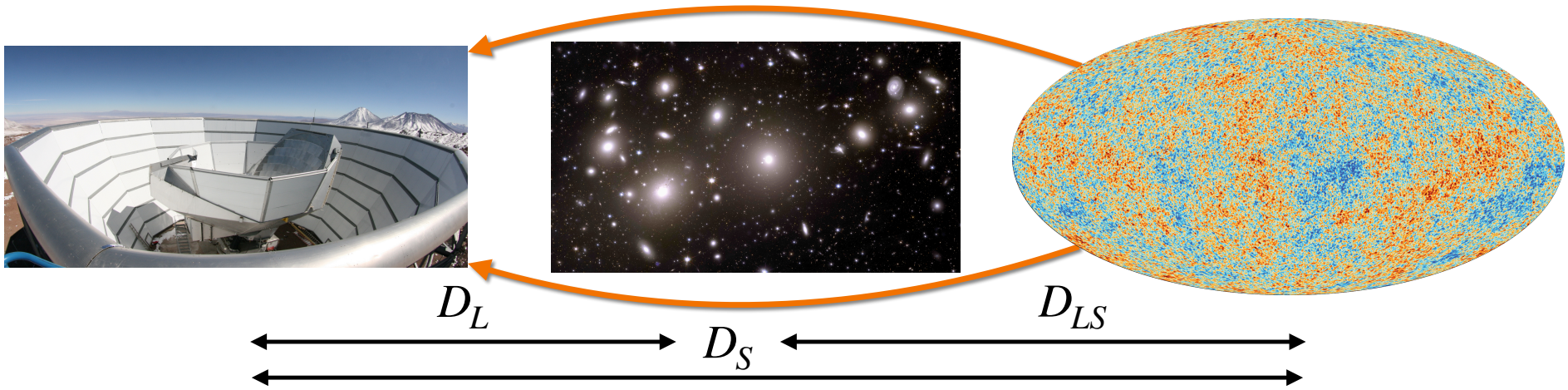

- In a homogeneous Universe, light goes straight
- However, mass repartition deviates CMB photons
- Correlations are induced between multipoles ℓ

Convergence for a thin lens

$$\kappa = \Sigma(\theta)/\Sigma_c$$

Critical surface density

$$\Sigma_c = \frac{c^2}{4\pi G}\frac{D_S}{D_{LS}D_L}$$

2 - CMB lensing: *ACT* DR6 data

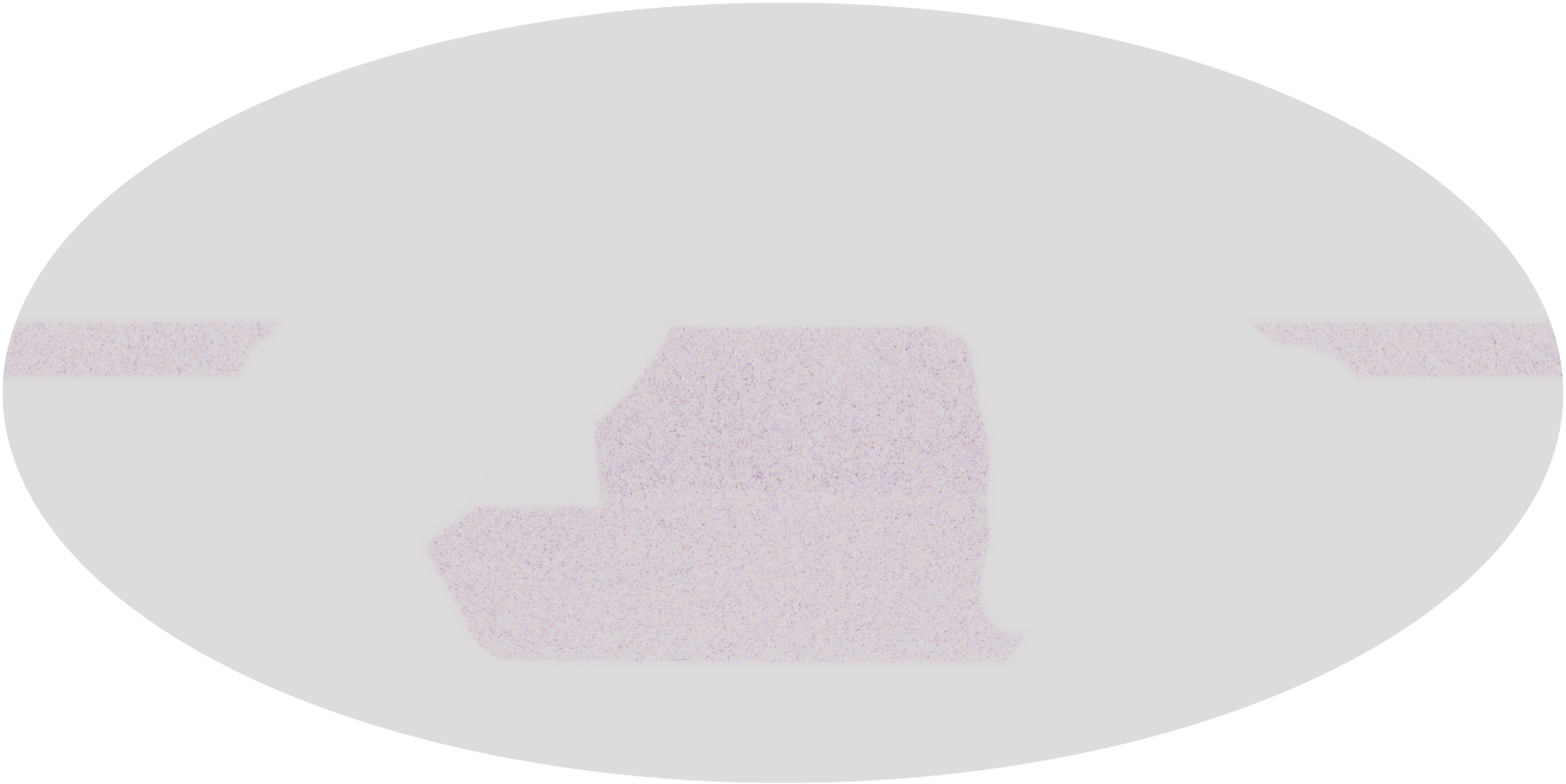

Figure: CMB lensing convergence map recreated from the spherical harmonics amplitudes $\kappa_{\ell m}$ corresponding to multipoles $2 < \ell < 3000$, determined using *ACT* data (Madhavacheril et al. 2024)

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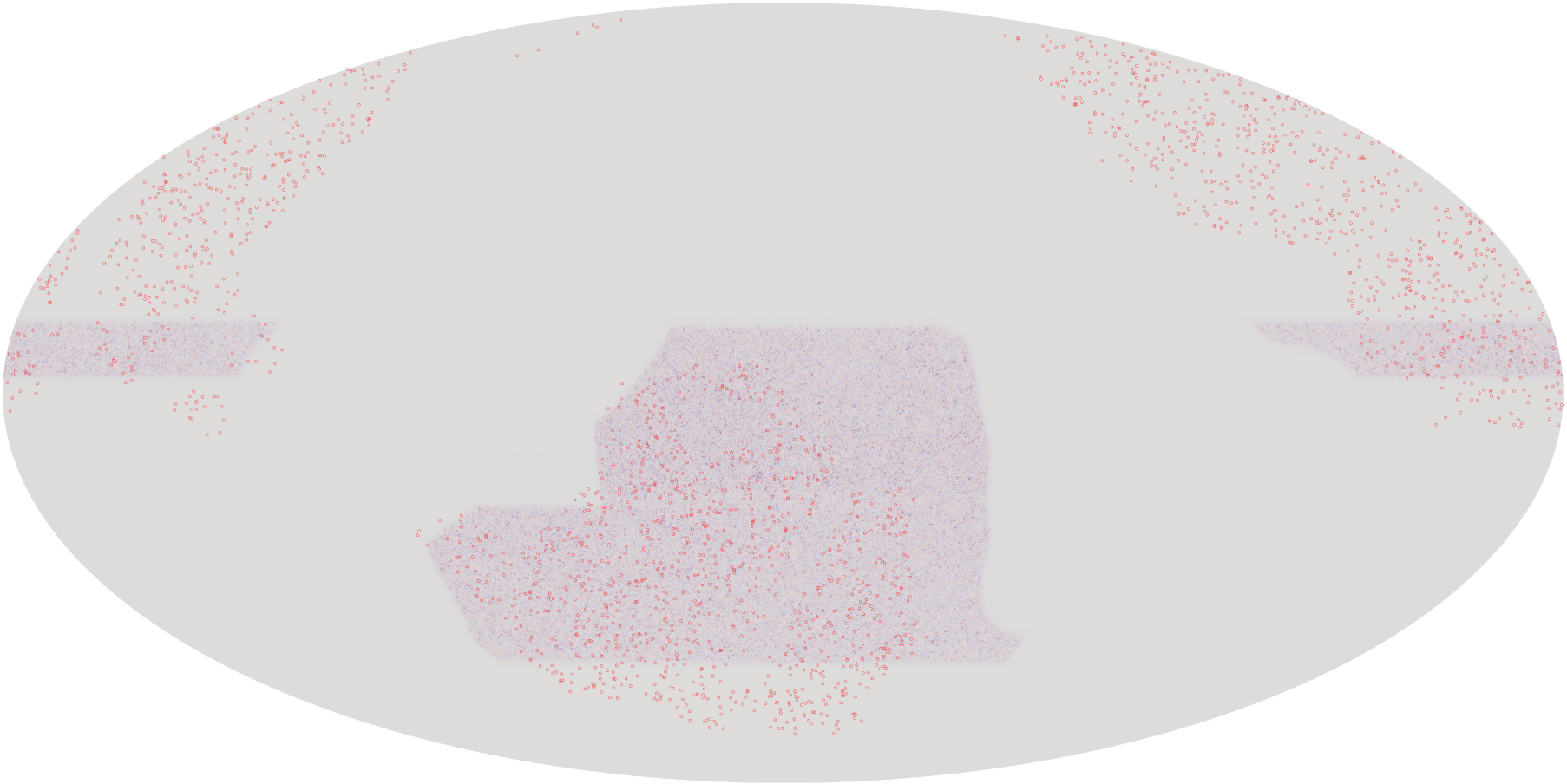

Figure: CMB lensing convergence map recreated from the spherical harmonics amplitudes $\kappa_{\ell m}$ corresponding to multipoles $2 < \ell < 3000$, determined using *ACT* data (Madhavacheril et al. 2024). *Red points:* *Planck* protocluster candidates.

3 - Obtaining the mass map: Convergence signal at the location of *Planck* protoclusters

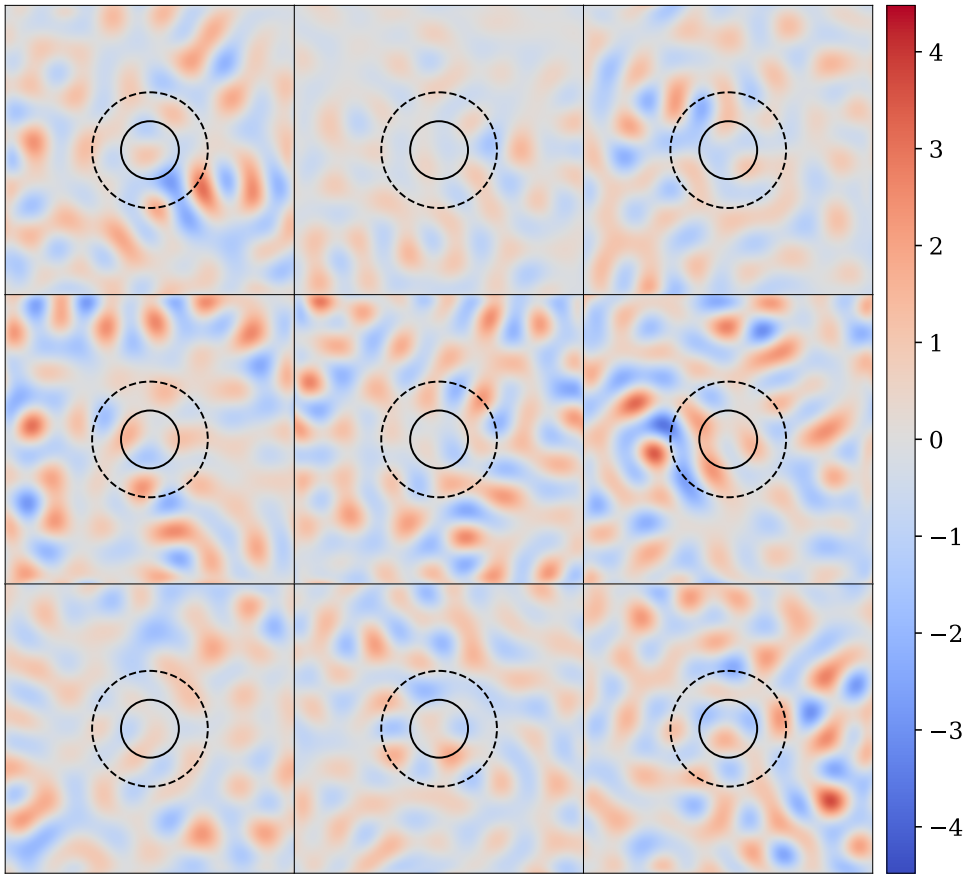

Figure: Convergence maps around nine protoclusters. *Circles radii:* 5' (full) and 10' (dotted)

- 1012 out of 2151 *Planck* protoclusters in *ACT* footprint

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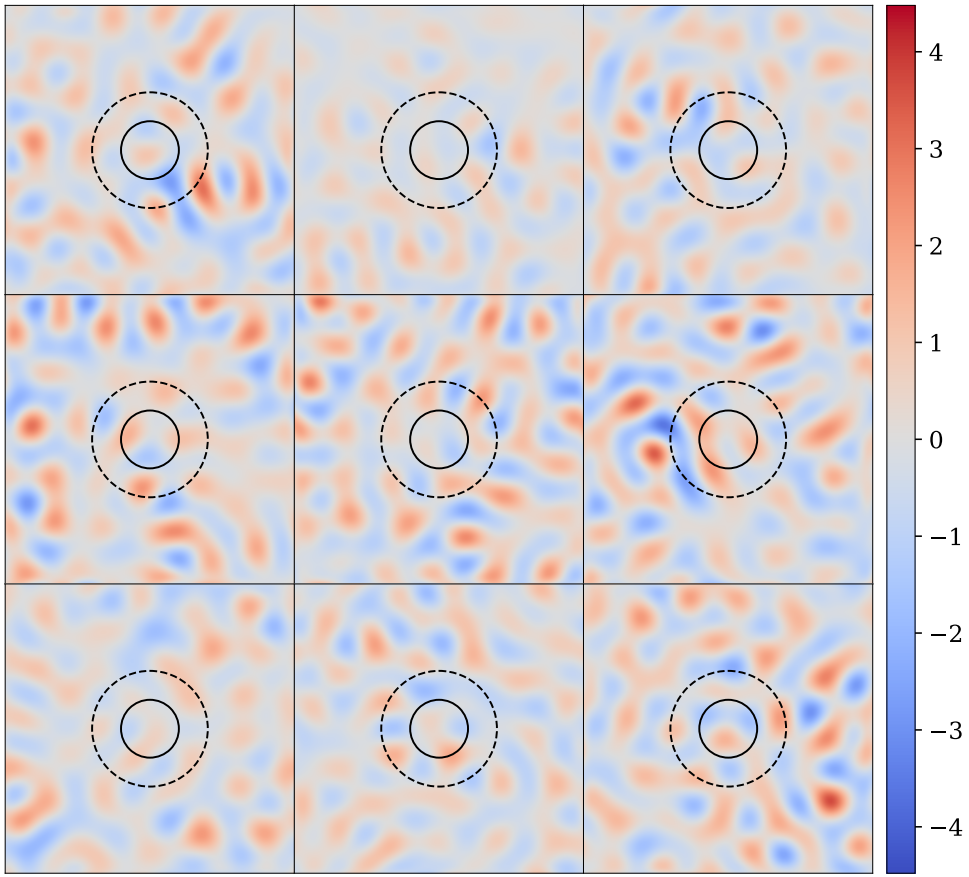

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- 1012 out of 2151 *Planck* protoclusters in *ACT* footprint
- Entirely dominated by noise...
- $|\kappa| > 0.5$ but no strong lensing ??

3 - Obtaining the mass map: Stacking *Planck* protoclusters

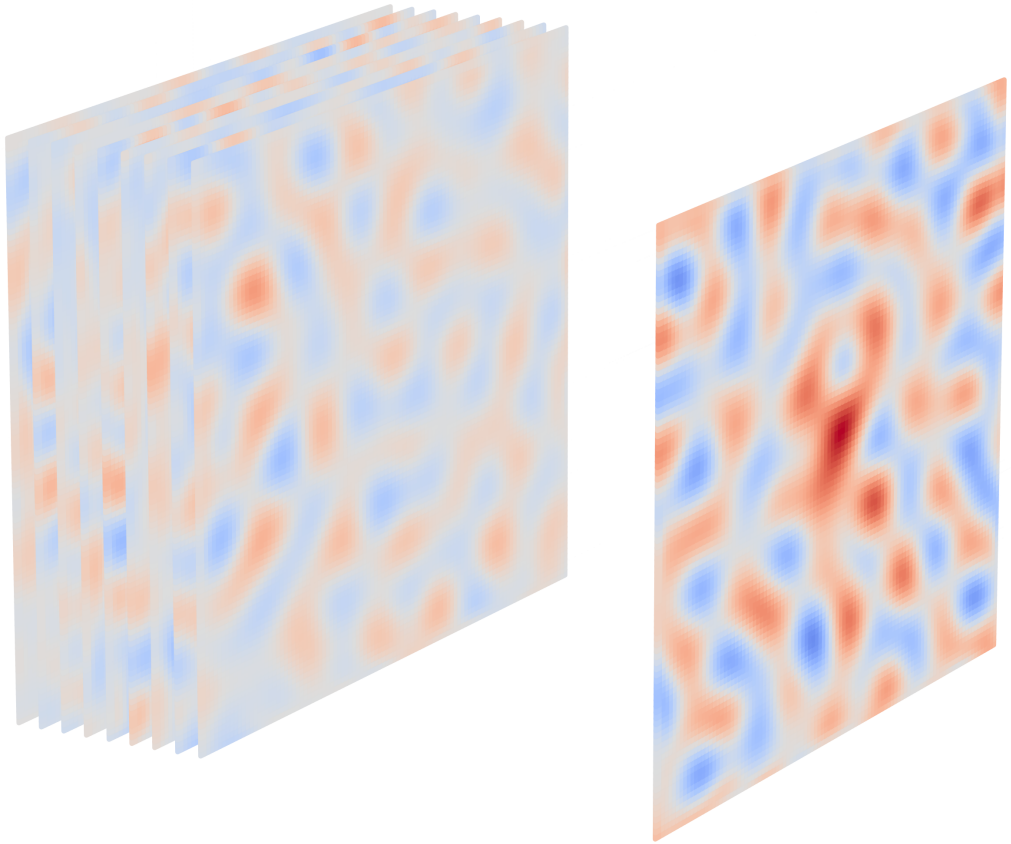

Figure: We study the mean signal from the 1012 tangential projections of the CMB convergence around each *Planck* protocluster.

- Solution : stack all of the protoclusters
- S/N of the resulting map should be higher
- We are therefore working with a "mean" protocluster

4 - Mass of the stacked protocluster: Convergence signal

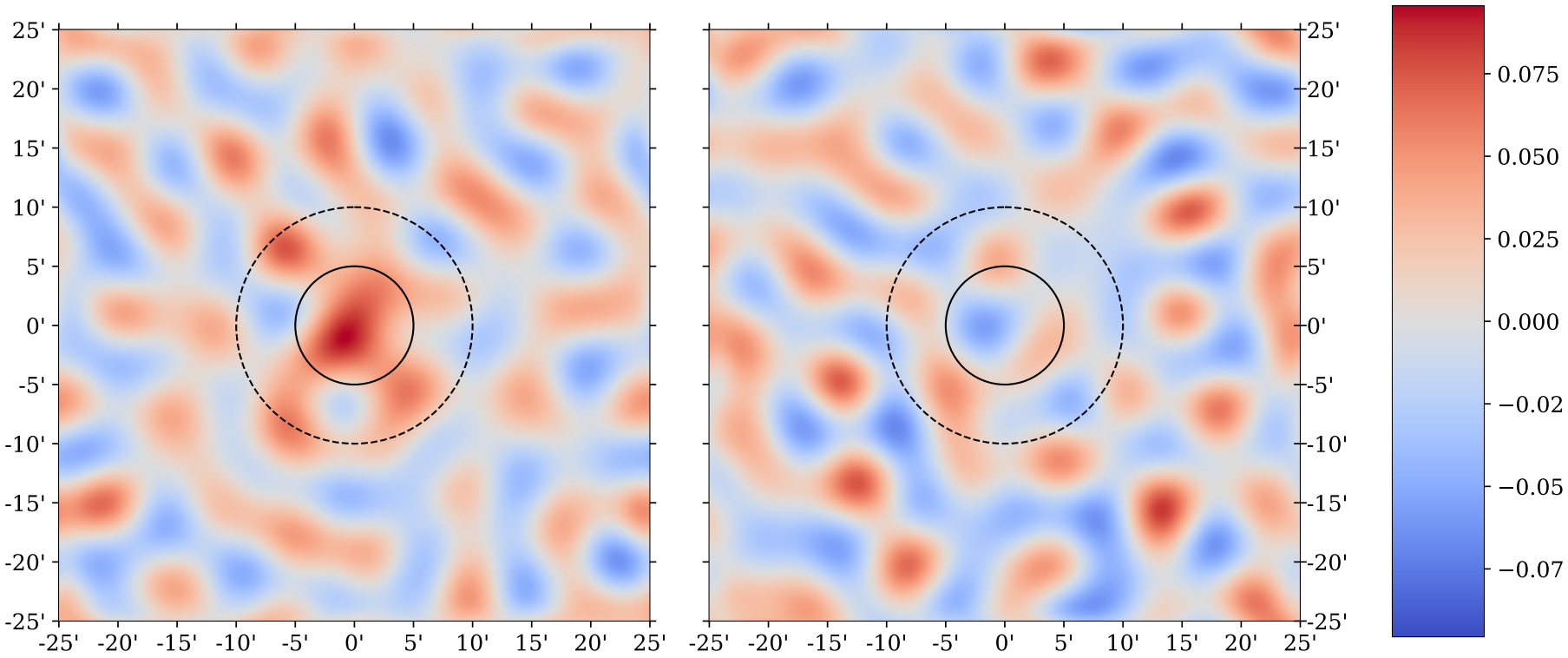

Figure: *Left:* Stacked convergence signal over the 1012 *Planck* protoclusters with *ACT* . *Right:* Null image, stacking of 1012 random fields. *Circles radii:* 5' (full) and 10' (dotted)

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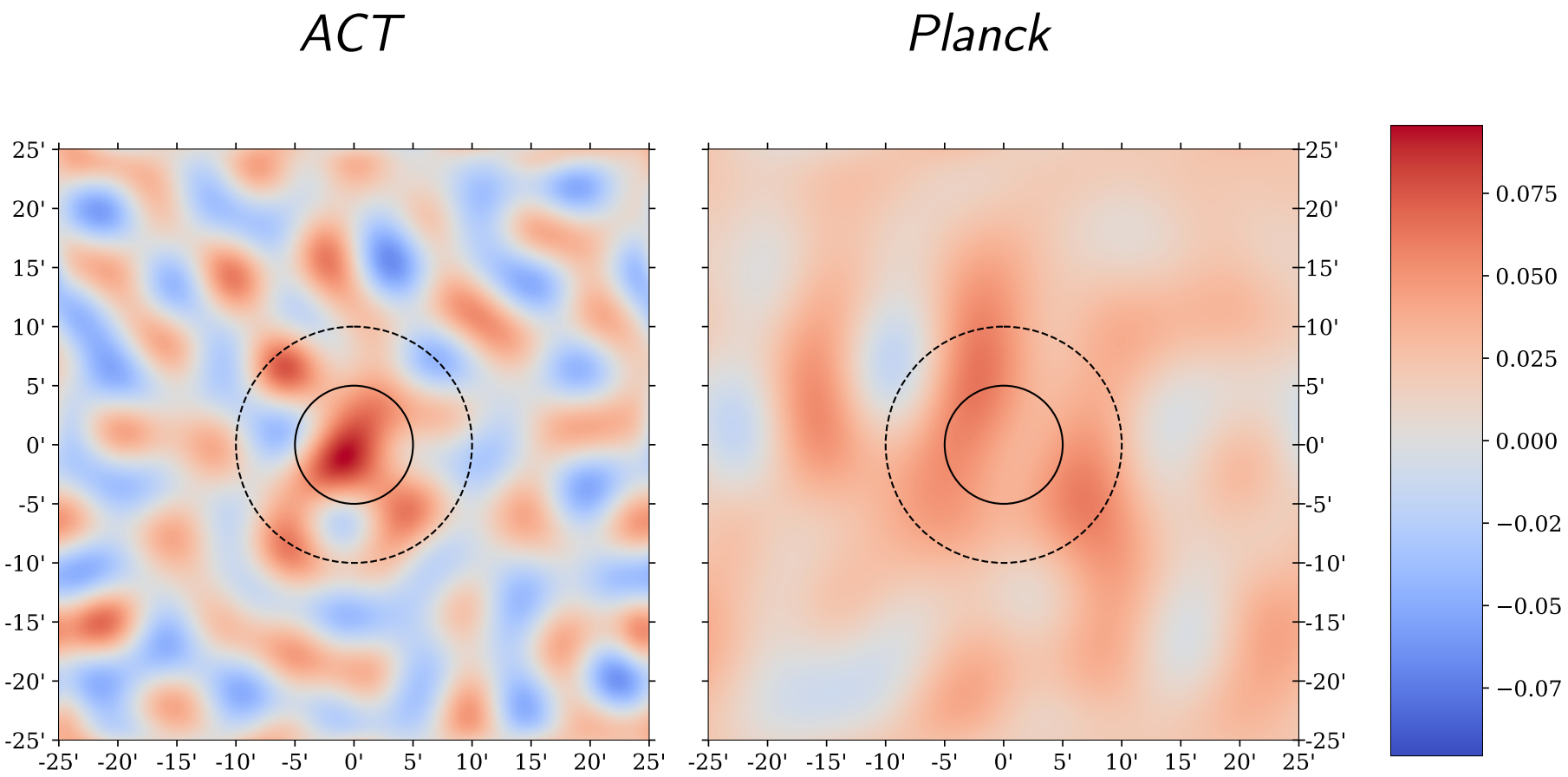

Figure: *Left:* Stacked convergence signal over 1012 protoclusters (*ACT*). *Right:* Stacked convergence signal over 2151 protoclusters (*Planck*). *Circles radii:* 5' (full) and 10' (dotted)

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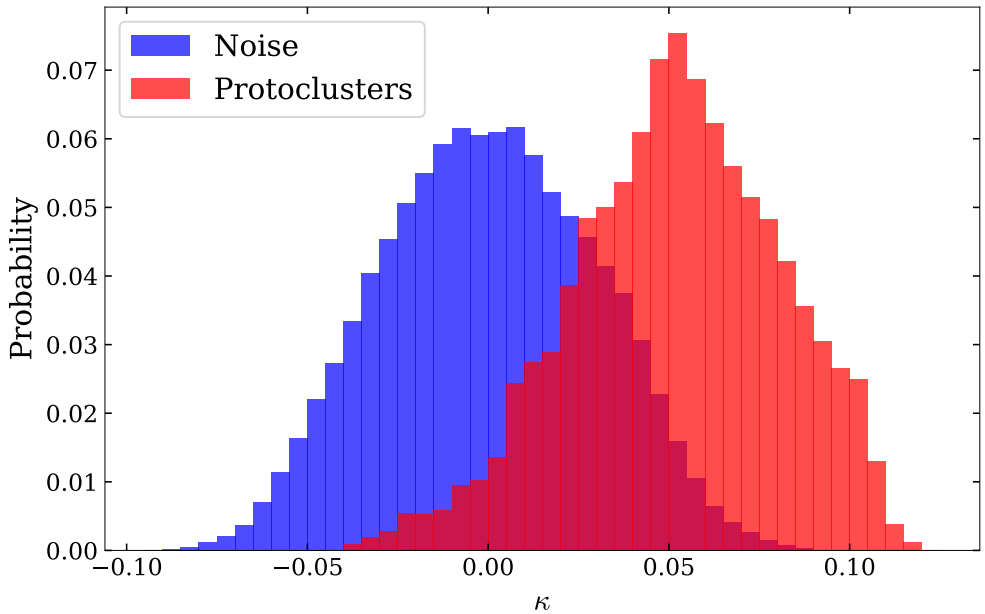

Figure: Distribution of convergence values inside the *Planck* beam (*Red*) and more than 10' away from the target (*Blue*).

- Noise : seemingly gaussian, zero-centered
- Kolmogorov-Smirnov test between the two distributions yields $p << 10^{-2}$
- Noise variance : 25%
- Sample variance (bootstrap) : 12%

4 - Mass of the stacked protocluster: Towards a mass estimate

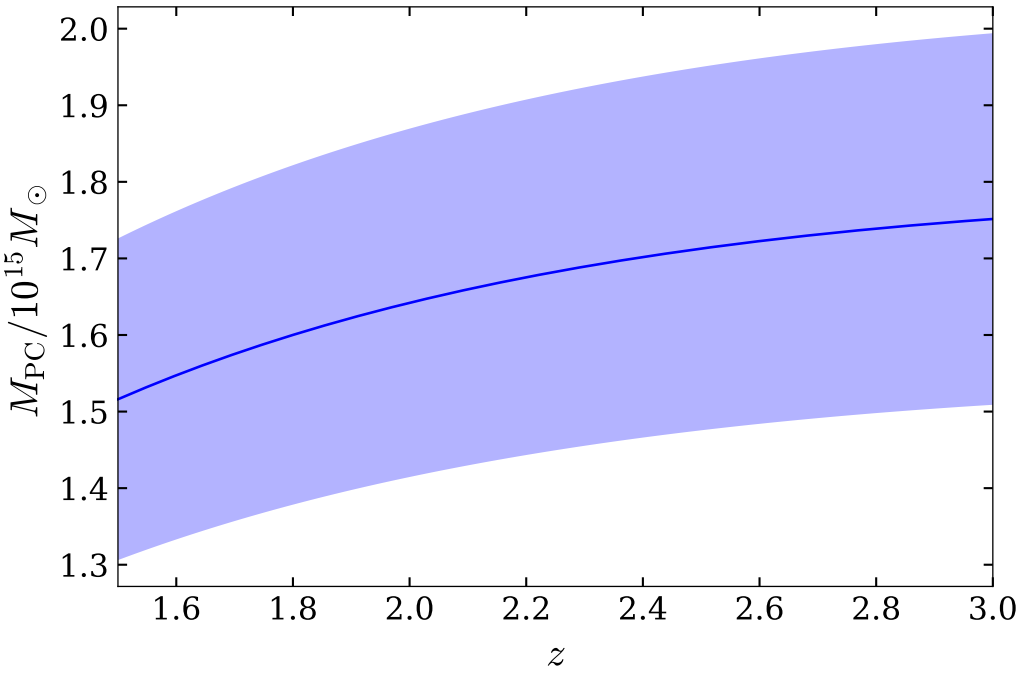

Figure: Direct derivation of the stacked protocluster mass from the convergence. Errors are estimated using the noise.

- Depends on the redshift of protoclusters (lensing critical density)
- **Too high according to former works and theory (factor $\geq$ 4)**

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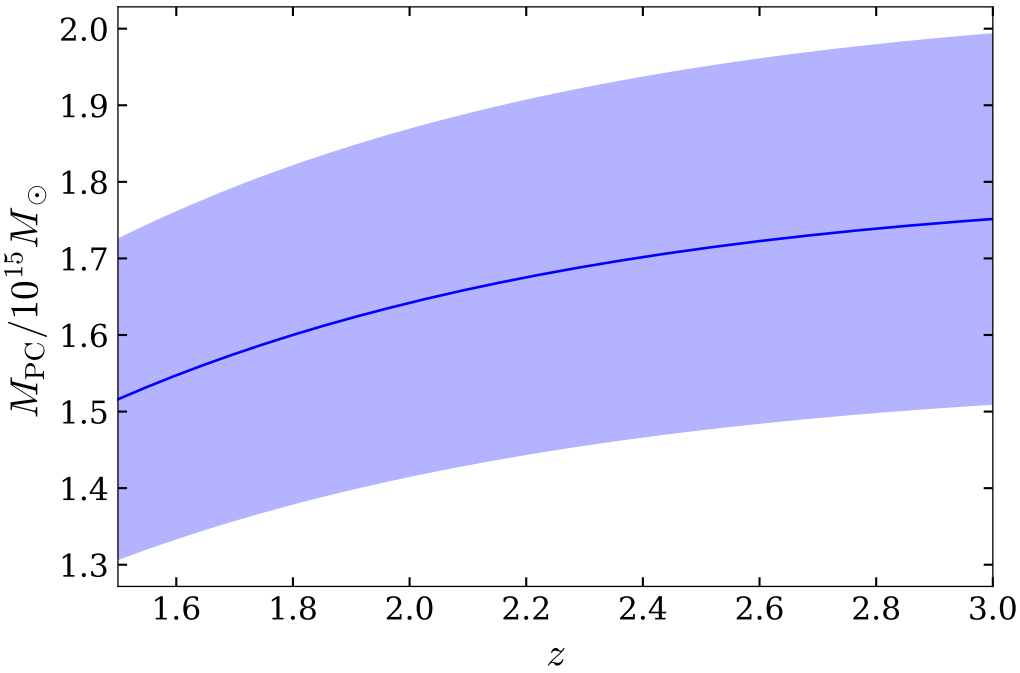

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- Depends on the redshift of protoclusters (lensing critical density)
- **Too high according to former works and theory (factor $\geq$ 4)**
- Mean field subtracted
- CIB deprojected (10% lower than baseline)

5 - Properties of protoclusters: Shape (the *Euclid* view)

Is there only **one** protocluster per field ?

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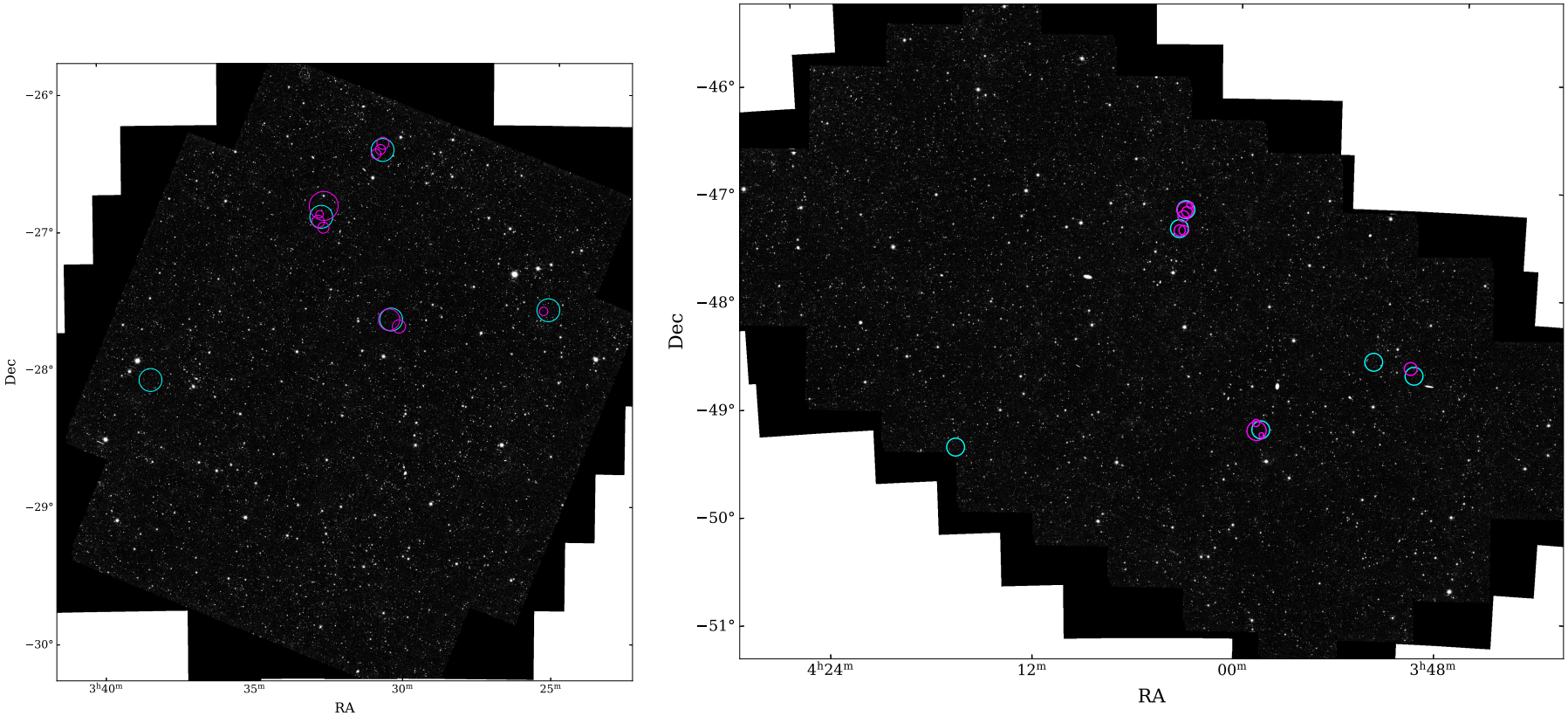

Figure: *Euclid* Deep Fields Fornax (*Left*) and South (*Right*) with *Planck* protoclusters in cyan and *Euclid* detected counterparts in magenta (Euclid collab, Dusserre et al. 2025)

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3D density profiles

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\frac{r}{R_S}(1+\frac{r}{R_S})^2}$$

$$\rho_{\rm Ein}(r) = \rho_0 \exp\left[-\left(\frac{r}{R_S}\right)^{1/n}\right]$$

Fit by MCMC with a gaussian likelihood

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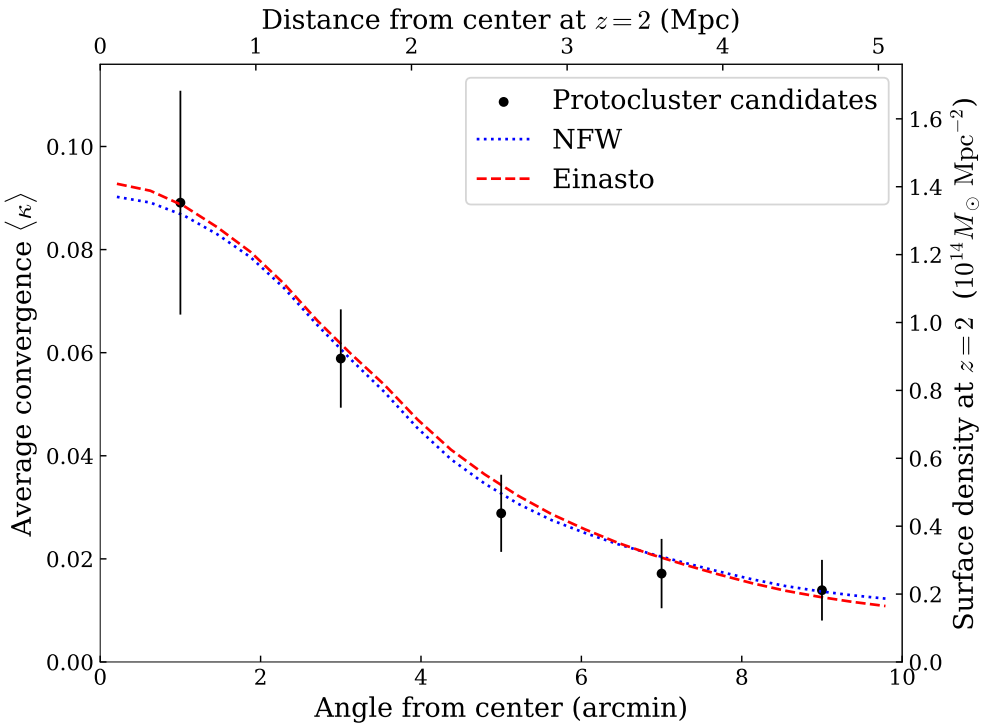

Figure: Surface density profiles for the stacked protocluster (averaged inside concentric rings) and the Einasto and NFW best fits.

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No significant difference between profiles...

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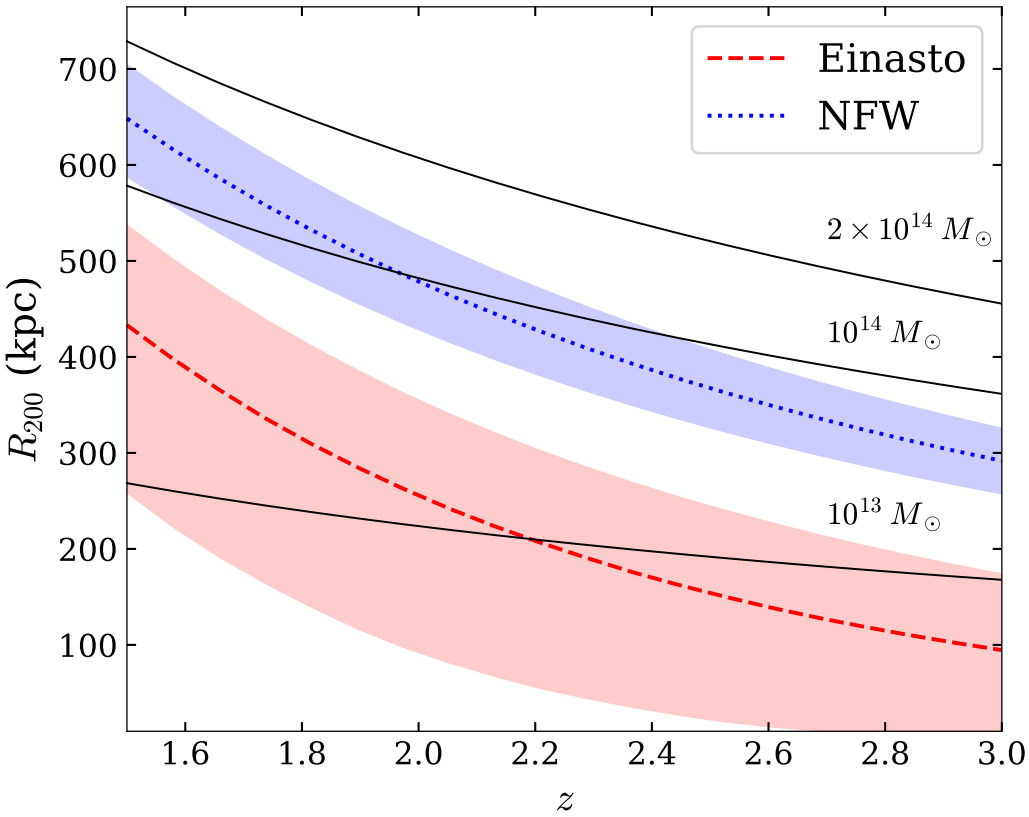

Definition of R_{200}

$$\langle \rho(r) \rangle_{r<R_{200}} = 200 \rho_{\rm crit}(z)$$

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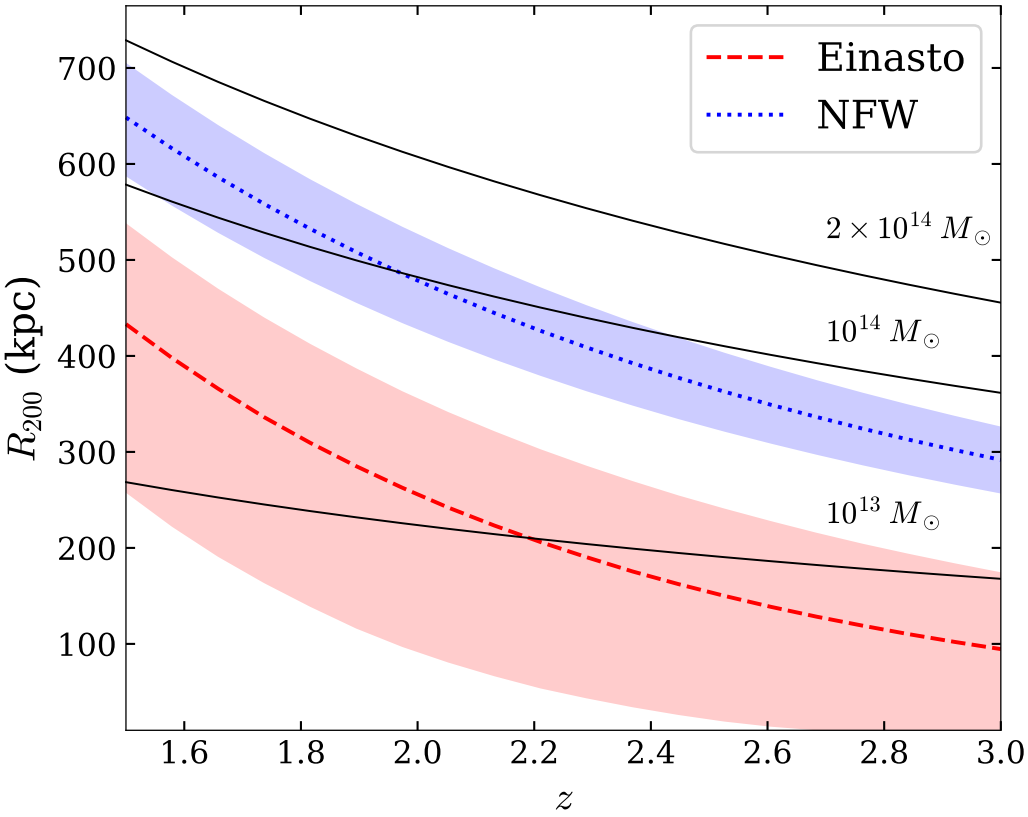

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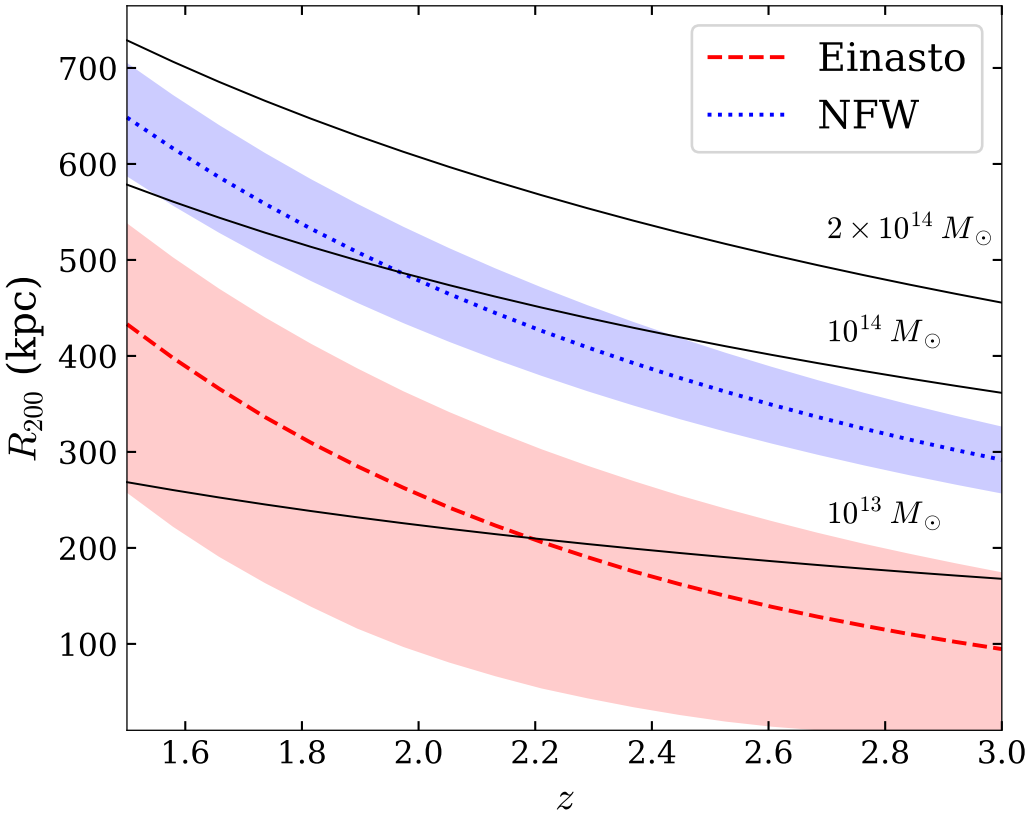

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- **We are reaching the limits of the data**

6 - Conclusion:

Successes

- We detect a convergence signal from the stacked *Planck* CIB spots.
- We finally observe the full mass distribution of protoclusters !

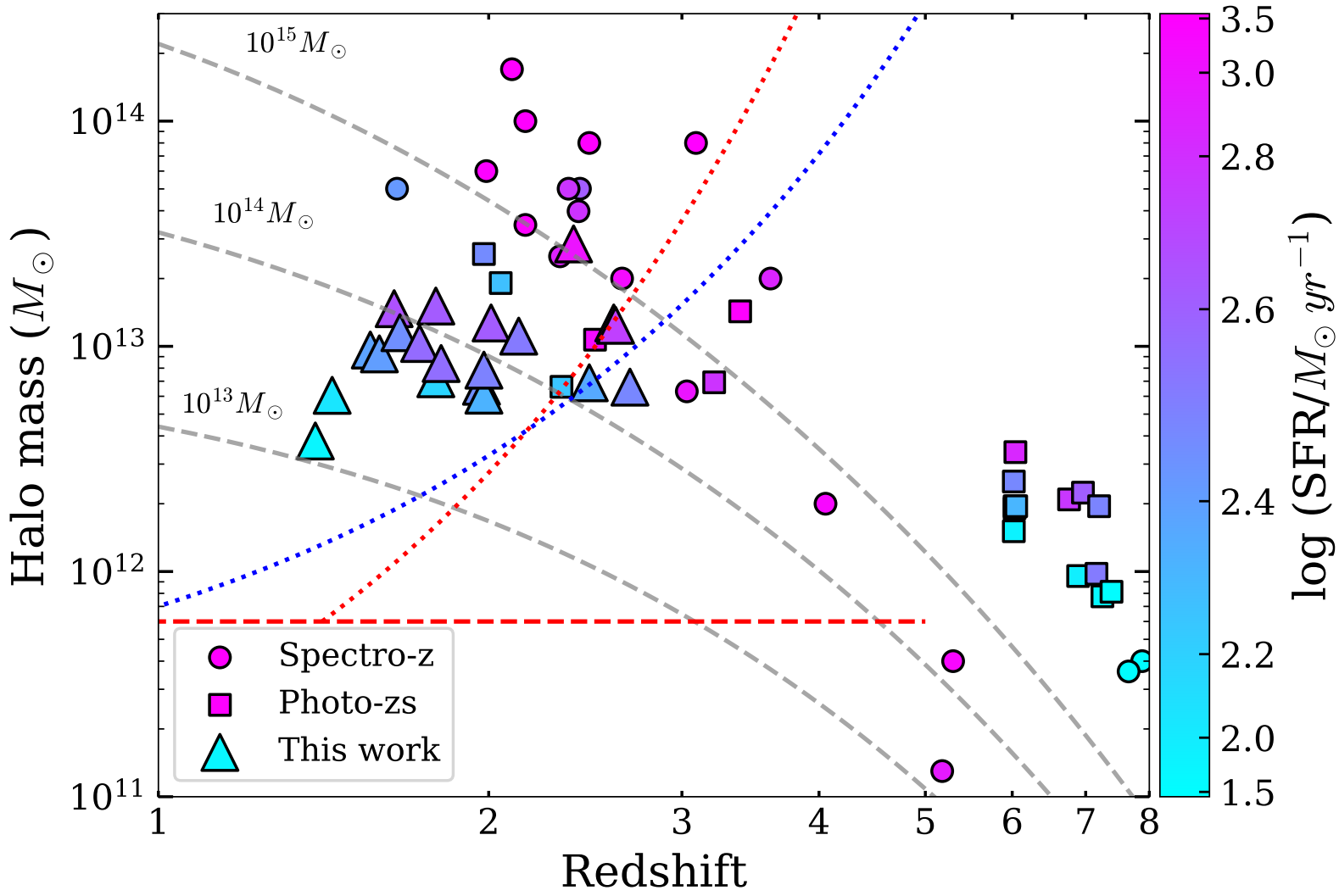
Limits of this work

- The direct computed mass is too high compared to the literature, although main systematics have been taken into account.
- Different mass density profiles cannot be compared with this data.

What to do now ?

- New theoretical models for the mass distribution inside protoclusters must be developed.
- Work with CMB lensing, visible and infrared observations as a whole.

Planck protoclusters seen in *Euclid* Q1



Euclid collab, Dusserre et al., 2025, in prep.

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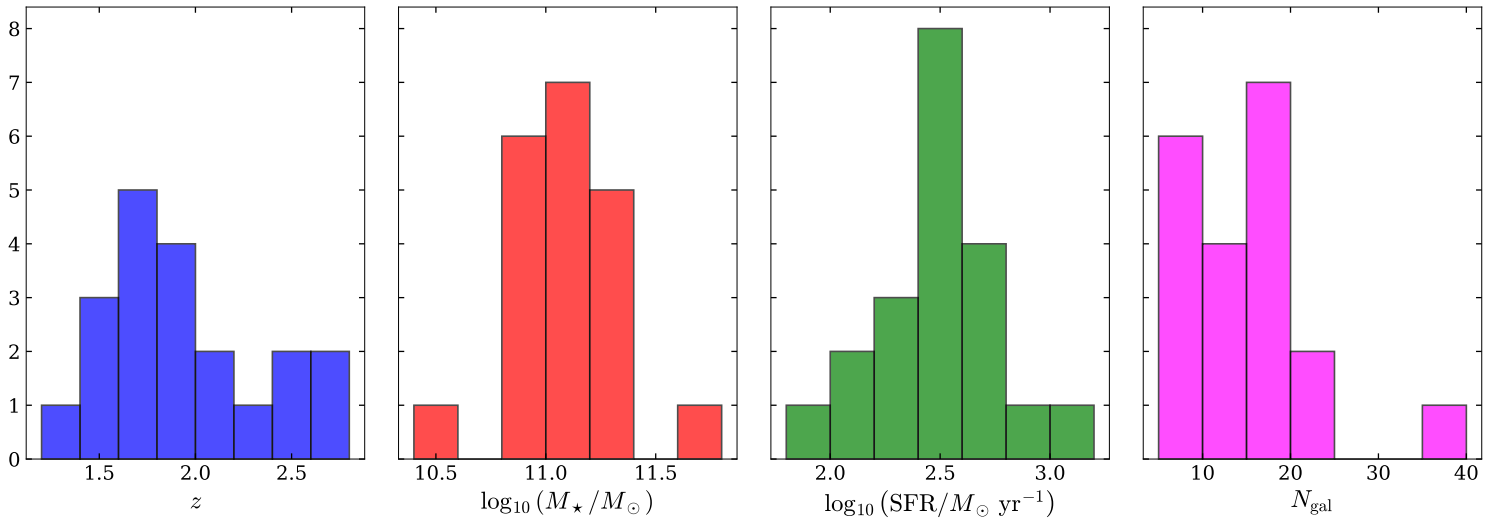

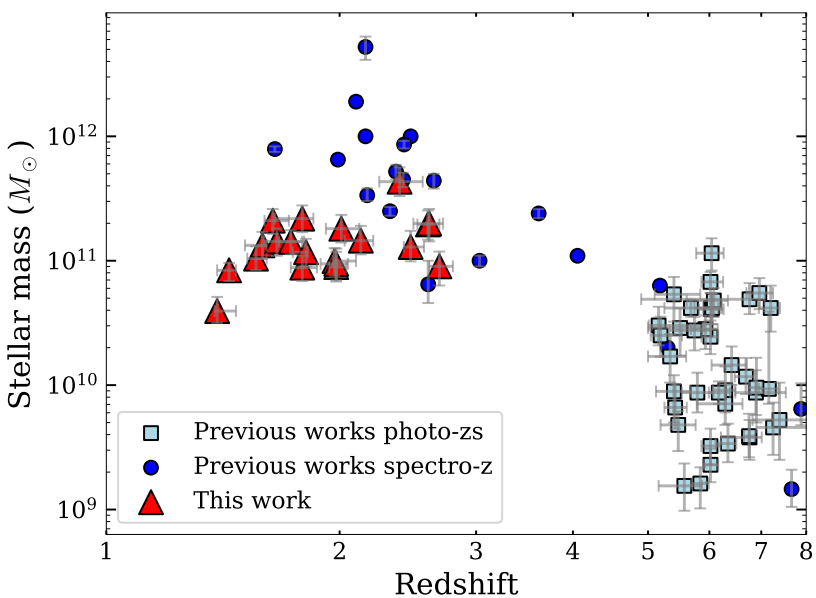

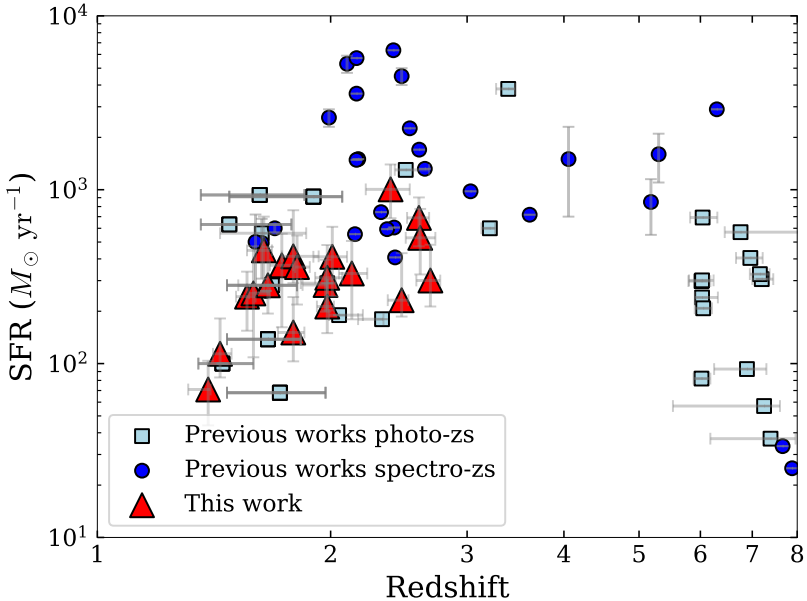

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Stacked *Planck* protoclusters in *Planck* CMB lensing