Cross-correlations between the Legacy Survey and the CMB

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Background *The evolution of the universe since the Big Bang can be mainly probed at two key era: the early time of recombination, through the Cosmic Microwave Background (CMB), and relatively 'recent' times, through galaxy surveys. The near-by galaxy fields encodes valuable information which corresponds to the early history of the universe.*

Cosmic Microwave Background (CMB)

A few hundred thousand years after the Big Bang ($z\sim1000$), the universe has expanded and cooled such that the photons decoupled with matter. The photons were then able to propagate freely to us today, with their wavelengths redshifted in the microwave band.

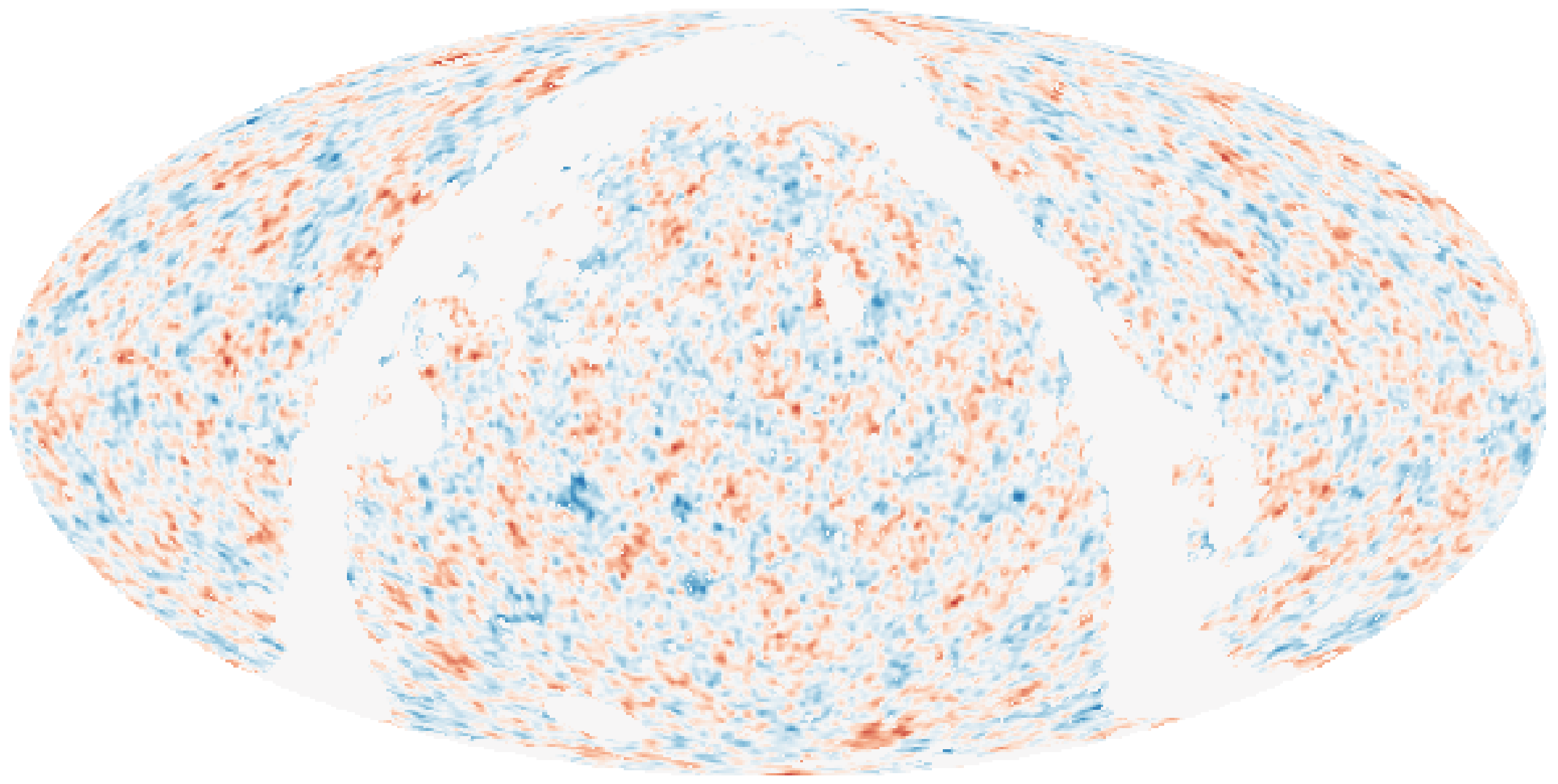


Fig.1 The CMB temperature map

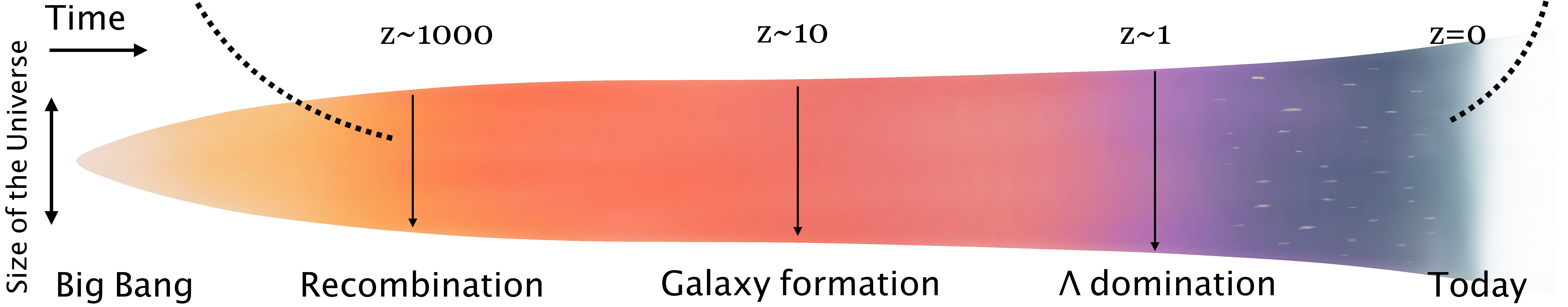
This form a very uniform background radiation from all directions in the sky. It is the earliest era we could probe in the comic history. The CMB maps we use are the 2018 version measured by the **Planck** Satellite. We also adopt our fiducial cosmological parameters from their 2018 papers.

The Legacy Survey

Galaxy surveys map out the nearby galaxy fields. In this study, we use the publicly available Legacy Imaging Survey data, observed using a combination of three instruments: DeCALS, BASS, and MzLS. The survey covers about **40%** of the whole sky and contains order of 10^7 galaxies.

The sources have three optical bands: g, r, z, and three WISE bands: w_1, w_2, w_3. We select galaxies with the magnitude cuts: $g<24$, $r<22$, and $w_1<19.5$, and apply the survey mask (dark regions in Fig.2).

Fig.2 The Legacy Survey Galaxy map



Redshifts

We use redshift, z, as an indicator for **distance** to galaxies, as well as a **cosmic clock**. It is a challenge in the study is to determine the redshifts of the Legacy Survey galaxies through the limited photometry bands.

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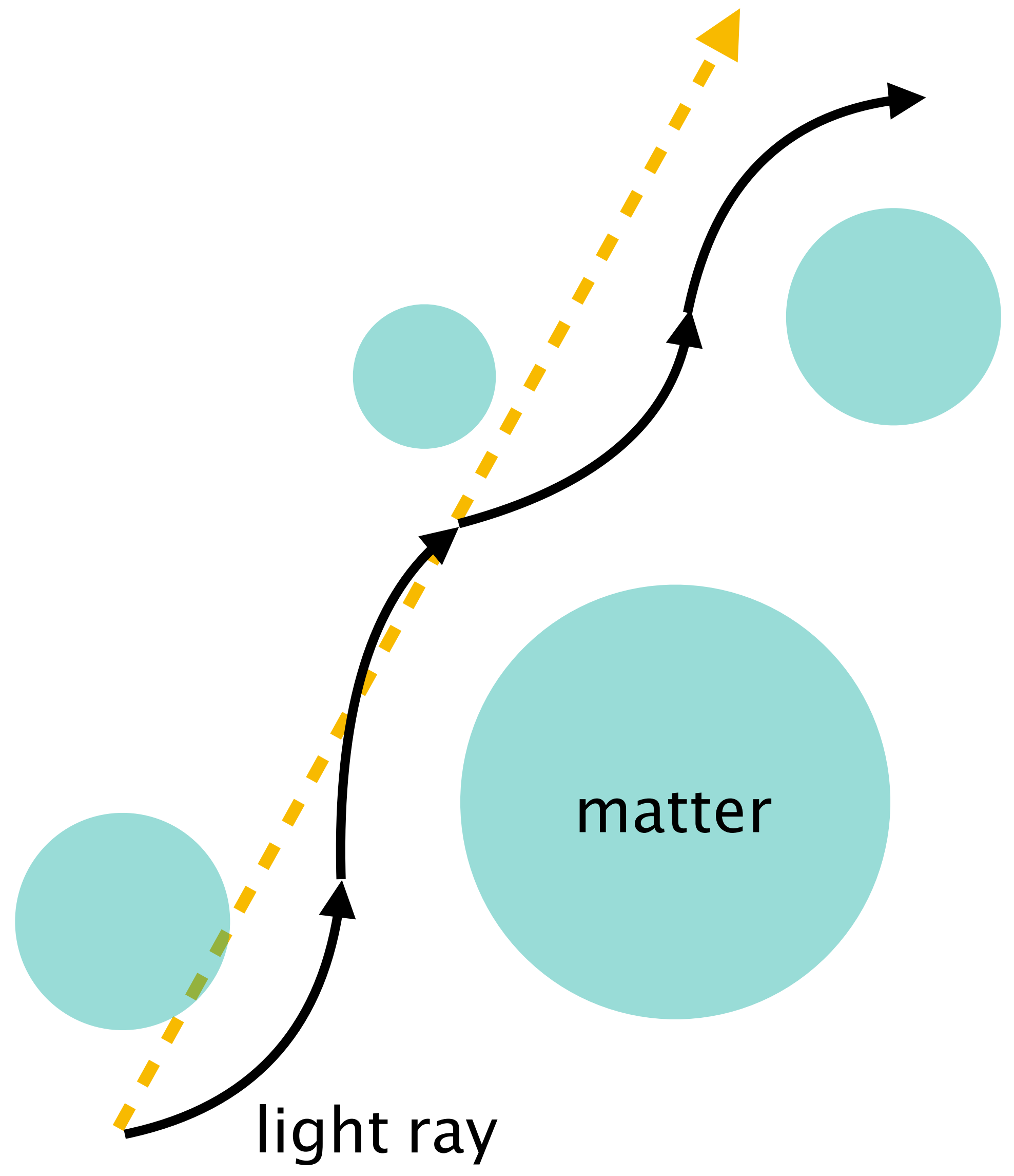
Theory *To exploit the connection between the early and late universe, one can look at angular cross-correlations,* C_l*, between the galaxy density maps and the CMB lensing and temperature map. Such correlation arises from the spatial and temporal perturbations to the CMB photon path by the evolving large scale structures of the universe.*

Weak gravitational lensing

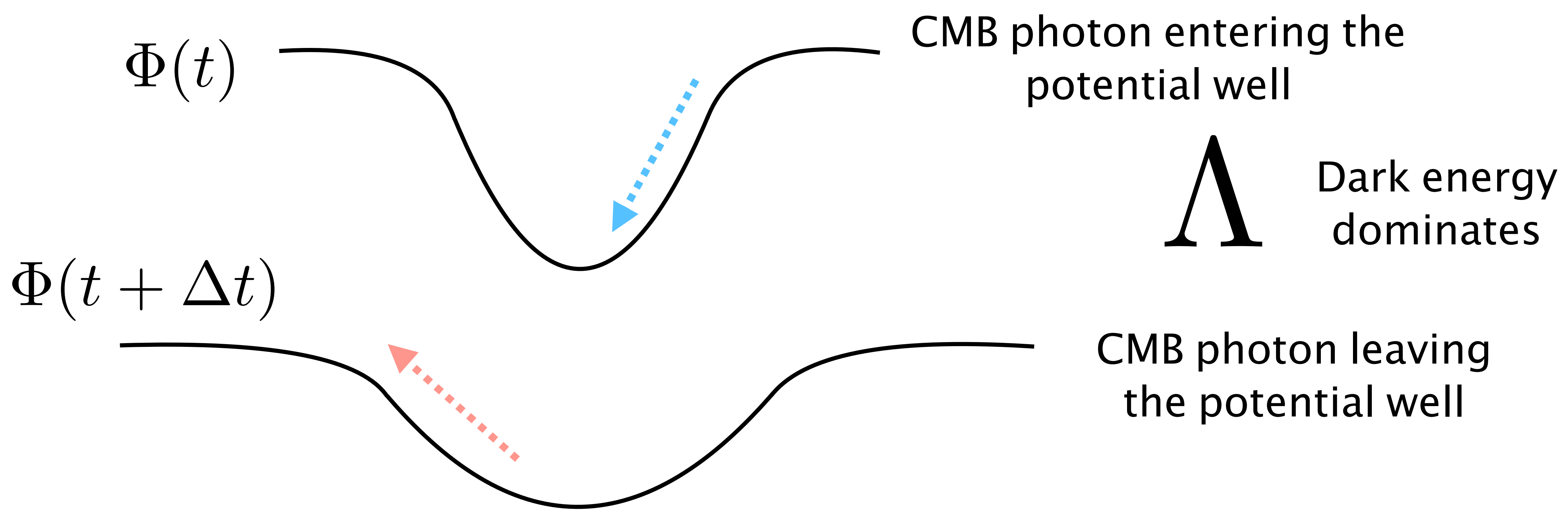


Weak gravitational lensing refers to the bending of light passing by small clumps of matter through their gravitational field. More specifically, it corresponds to the **spatial** perturbation to the photon trajectory by the fluctuating matter density field.

The CMB temperature maps are **distorted** due to this effect as the photons travel to us. By careful reconstruction, one can obtain the CMB **lensing convergence (κ) map**.

The lensing κ map directly measures the project total matter density, Ω_m, from the CMB to today.

The Integrated Sachs-Wolfe (ISW) Effect



The ISW effect refers to the **temporal** (frequency) perturbation of the photon trajectory. The effect is only present when the dark energy, Λ , is in domination.

The CMB photon gains energy when entering a gravitational potential well generated by matter, and loses energy when climbing out of the well. When Λ dominates, the potential well flattens with time, making the photon gain extra energy as it passes through, i.e., **blue**-shifted. Similarly, the photon becomes **red**-shifted when it passes voids.

More formally… Given the galaxy redshift probability distribution function *p(z)*, galaxy bias, *b*, and the dimensionless matter power spectrum Δ^2, the cross-correlation power of the two effects can be computed by

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{g\kappa} = \frac{\pi}{\ell}\int b\Delta^2(k=\ell/r,z)\,p(z)K(r)\,r\,dz \quad \text{where} \quad K(r) = \frac{3H_0^2\Omega_m}{2c^2a}\frac{r(r_{\rm LS}-r)}{r_{\rm LS}}$$

for weak gravitational lensing, and

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{gT} = T_{\rm CMB}\,\frac{2\pi}{c^3}\int b\,\Delta^2_{\delta\dot{\Phi}}(k=\ell/r,z)/k\,p(z)\,a\,dz \quad \text{where} \quad \Delta^2_{\delta\dot{\Phi}}(k,z) = \frac{3H_0^2\Omega_m}{2k^2}\frac{H(z)\,(1-f_g(z))}{a}\Delta^2(k,z)$$

for the ISW effect.

Photometric Redshifts *One challenge in the study is to obtain the redshift distribution of the Legacy Survey galaxies from the limited photometric bands. We use the 3D colour space information calibrated by spectroscopic samples to infer their redshifts. Galaxies are split into four tomographic redshift slices to reveal evolution of the correlation signal.*

Redshift calibration for Legacy Survey

The Legacy Survey has limited photometric bands, which makes it hard to determine redshifts alone. Luckily, there are many existing spectroscopic galaxy surveys which gives accurate redshifts. We use the following samples to calibrate our photometric redshifts: GAMA, eBOSS (LRG, ELG), LOWZ, CMASS, DESY1 (LRG), VIPERS, DEEP2, COSMOS. After matching the sources based on their sky positions, we bin the calibration samples in **3D colour grids** in $g-r$, $r-z$, and $z-w_1$, and compute the mean redshifts in each grid. We then assign the mean redshifts to the Legacy Survey galaxies according to their colours.

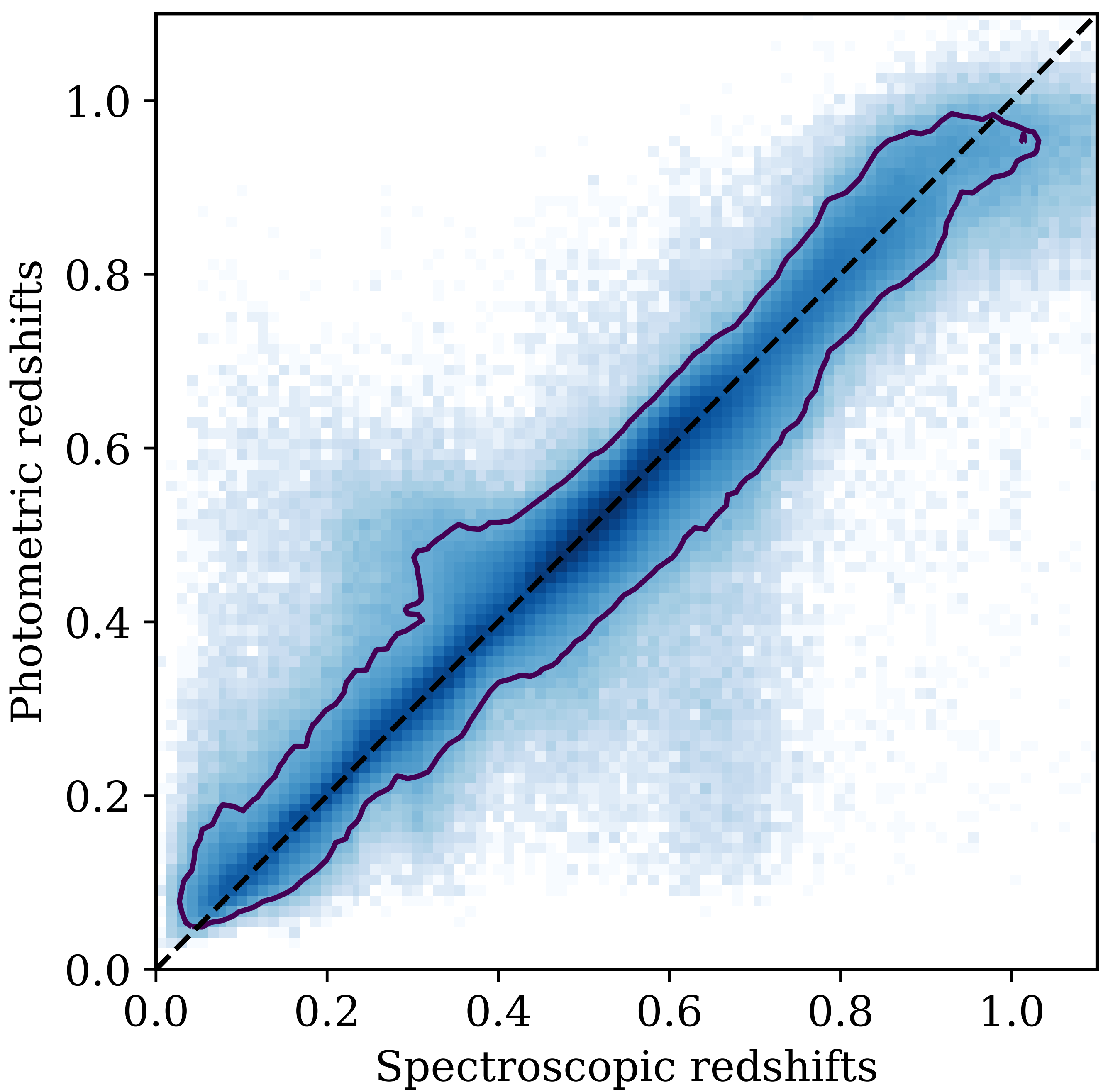


Fig.3 Calibration of the photo-z with spectroscopic samples.

Fig. 3 shows the inferred photometric redshifts versus the spectroscopic redshifts for the calibration samples. The contour encloses **95%** of all calibration objects. The errors in the photometric redshifts are well fitted by a modified Lorentzian function. Comparison with the official photo-z catalogue (**Zhou et al. 2020**) also shows good consistency.

Galaxies are separated into **4 tomographic slices**. We marginalize over the nuisance parameters in the error distribution according to the galaxy cross-correlation between different redshift slices.

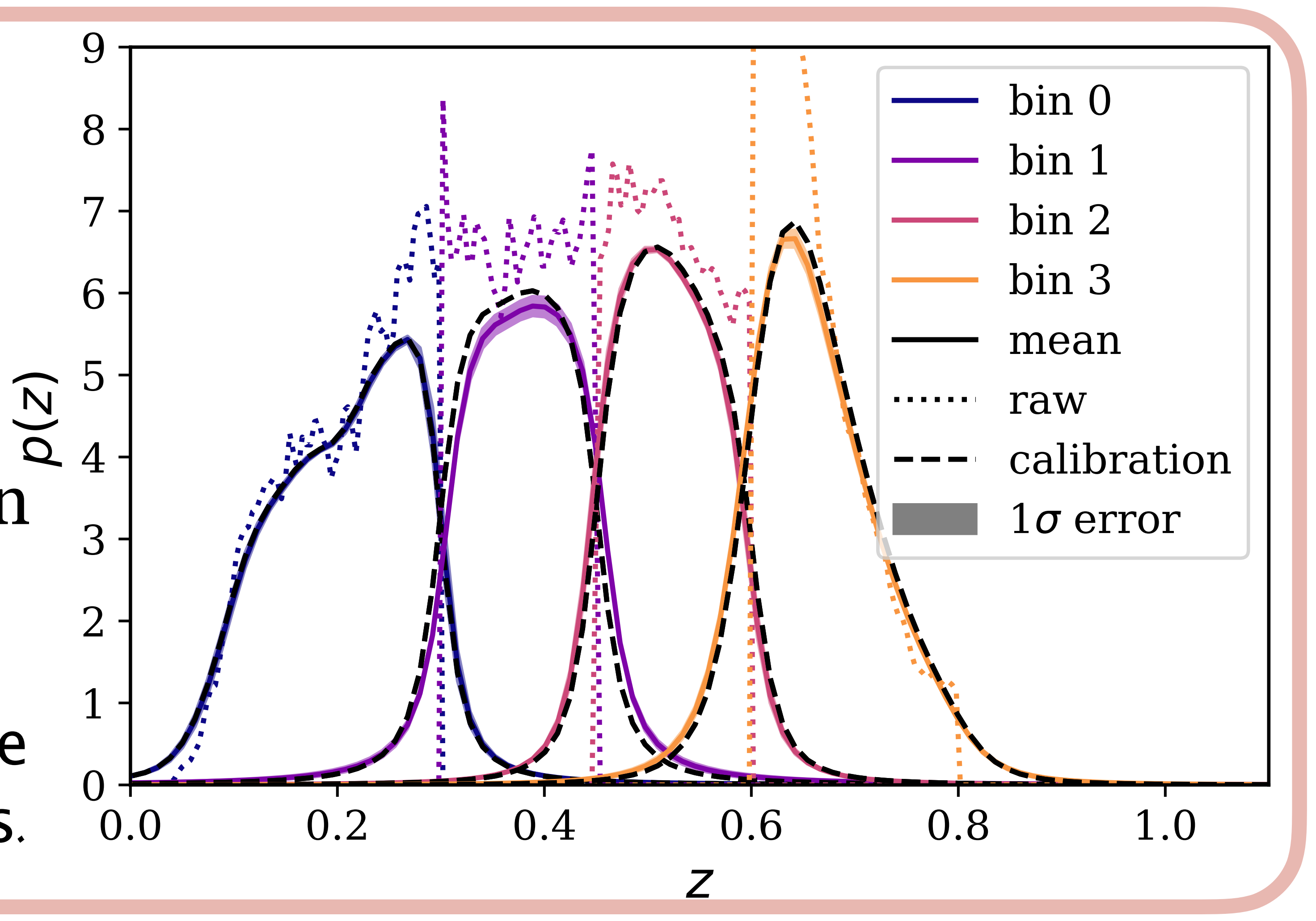


Fig.4 Photo-z distribution for the four tomographic bins.

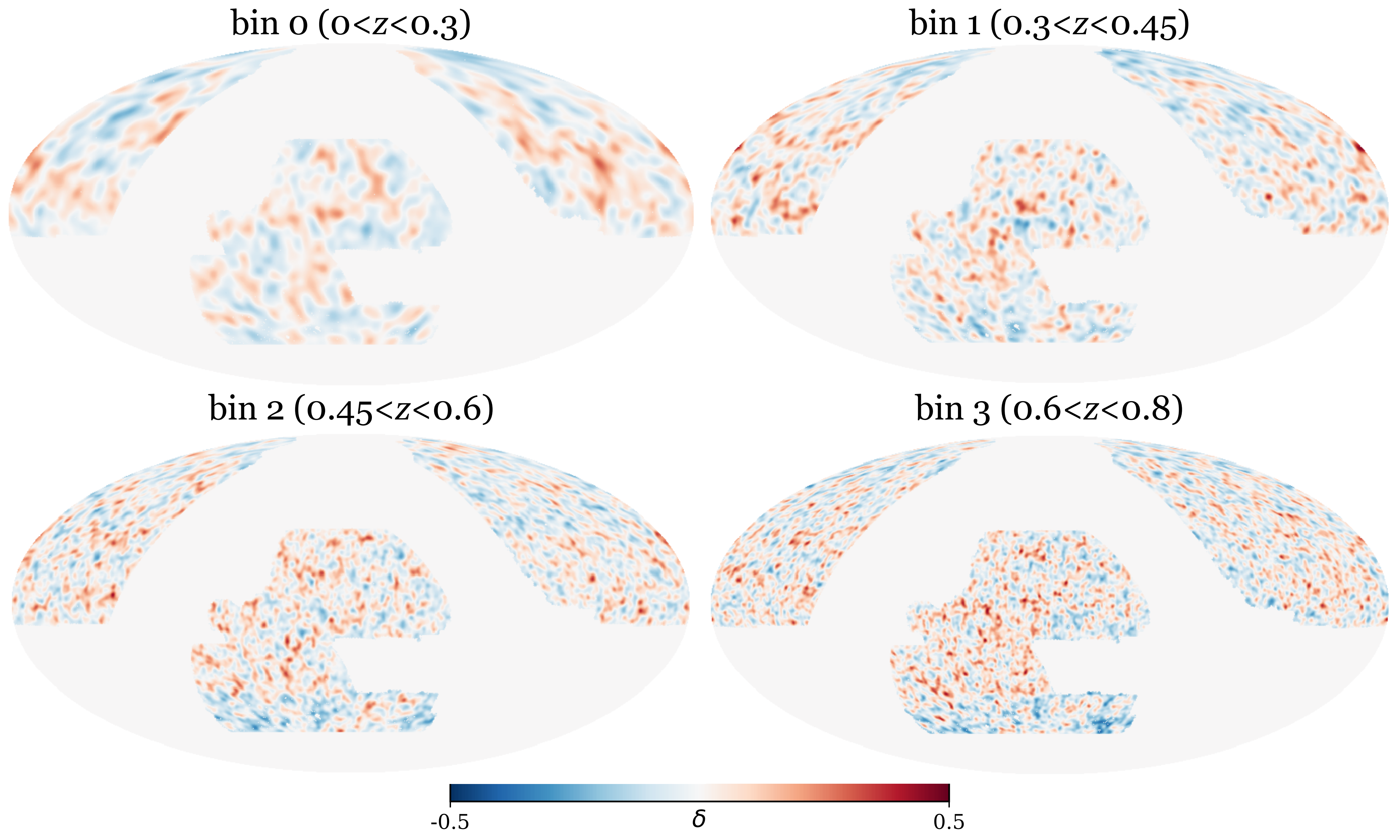


Fig.5 The galaxy density maps for the four tomographic slices smoothed on comoving scales of 20Mpc/h.

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Results *We measure the angular cross-correlation for each redshift slice, and compute the theoretical prediction using p(z) assuming a fiducial cosmology. The ratio between data and theory is captured by the amplitudes A_κ and A_{ISW}. Our results show that the lensing amplitude A_κ is noticeably lower than the fiducial value, which may have interesting implications.*

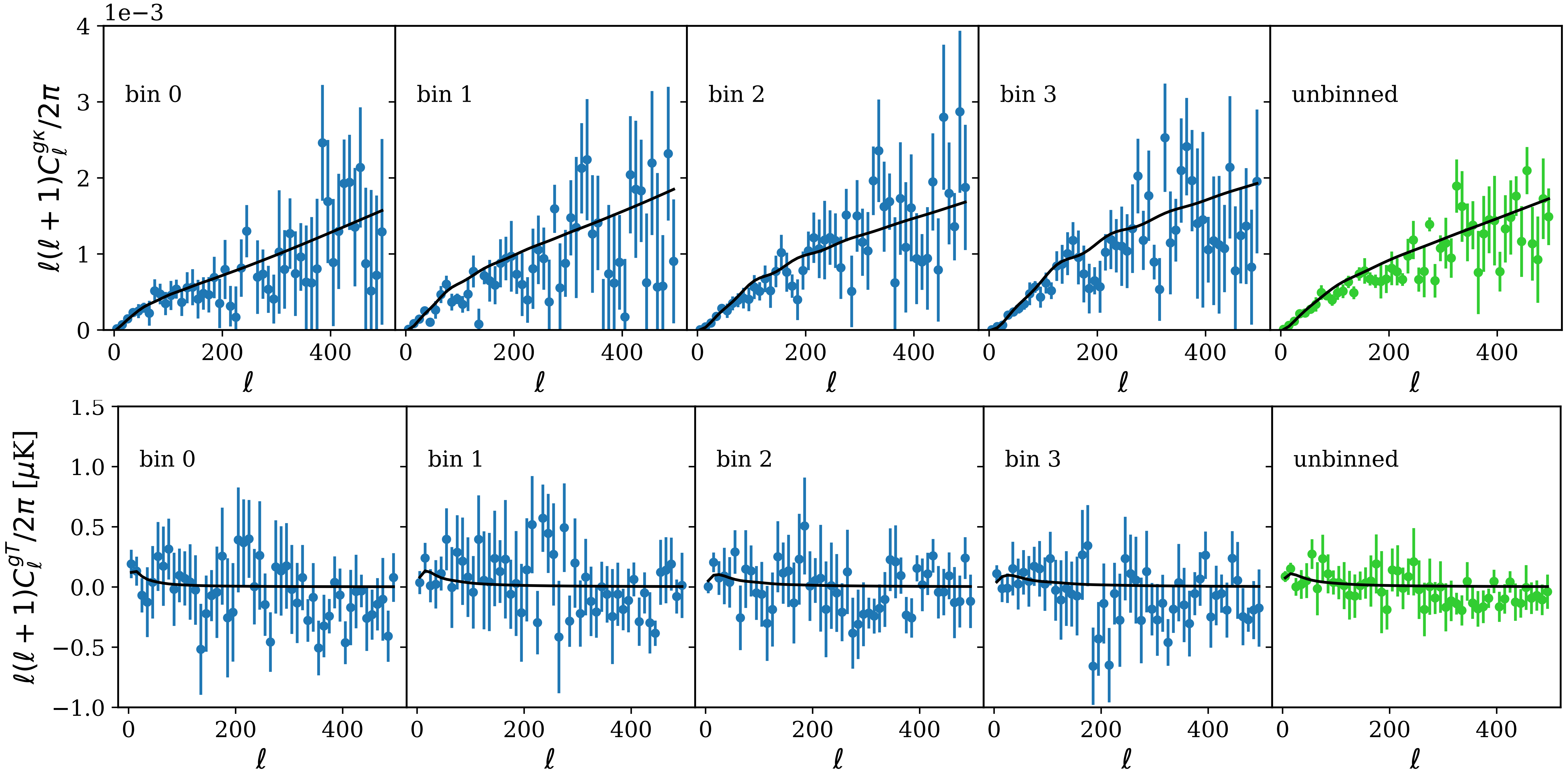

Fig.6 The cross-correlation of the galaxy density maps with the κ map (upper) and with the temperature map (lower) for the four tomographic bins and the combined case.

Fig. 6 shows the measurements of the cross-correlations. We fix the galaxy biases at their best-fit values from the galaxy auto-correlations. The theoretical prediction, shown in **black**, assumes 2018 *Planck* Cosmology, with key parameters Ω_m=0.315 and σ_8=0.811.

The amplitudes **A_κ** and **A_{ISW}** are used to indicate the consistency between the fiducial theory and the measurements, as shown in **Fig.7**. We find that while the ISW effect is **consistent with 1**, the weak lensing signal is **below unity** with statistical significance. This result is interesting in light with the recently published KiDS-1000 lensing measurements (**Asgari et al. 2020**), which shows similar level of tension with the *Planck* cosmological parameters. It may suggest some unknown systematics, or modification to the fiducial model.

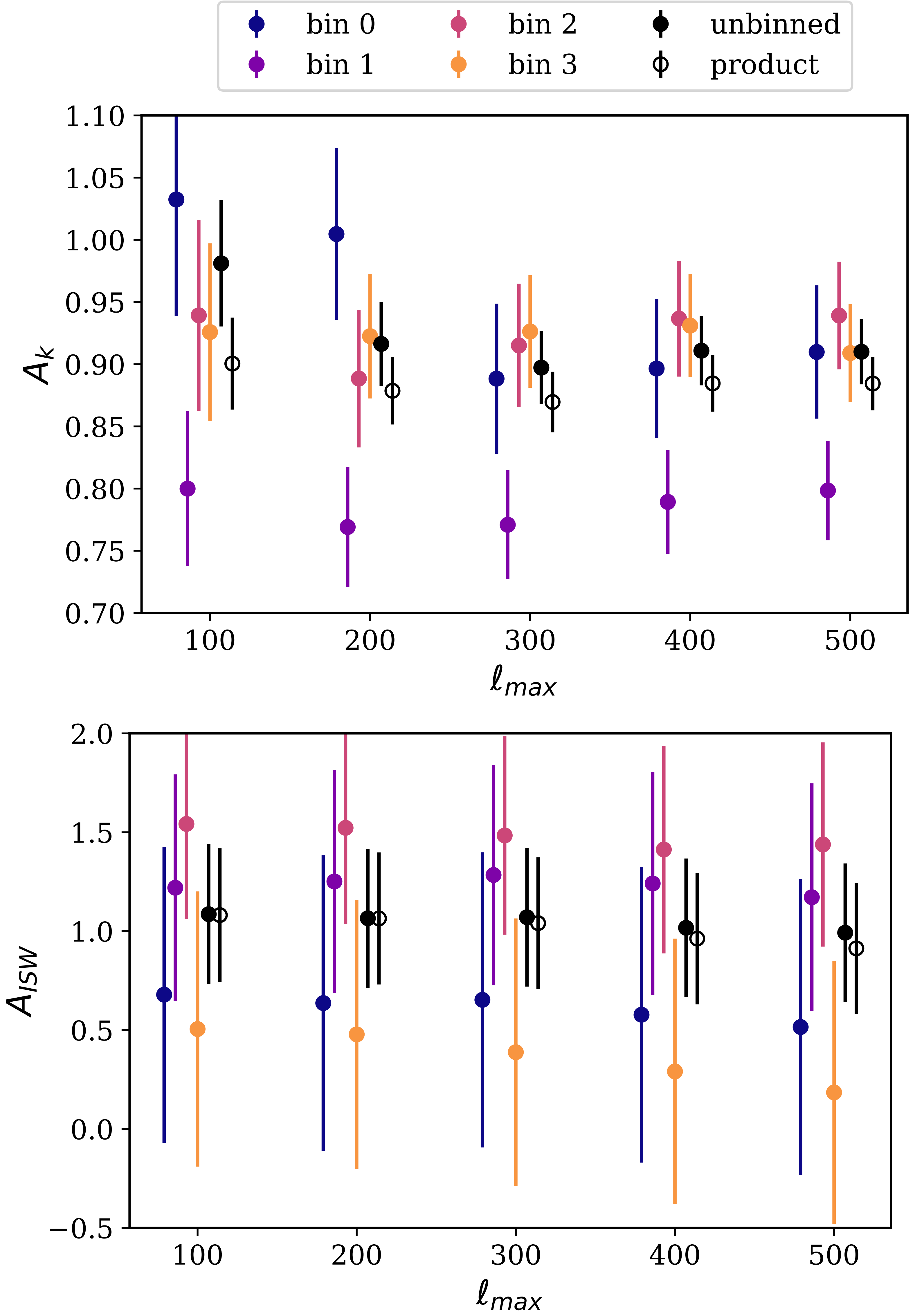

Fig.7 Constraints for the weak lensing and ISW amplitudes. The unbinned amplitudes at l_{max}=500 is A_κ = 0.91 ± 0.03 and A_{ISW} = 0.99 ± 0.35. While A_{ISW} is fully consistent with the fiducial model, A_κ is lower at 3σ level.