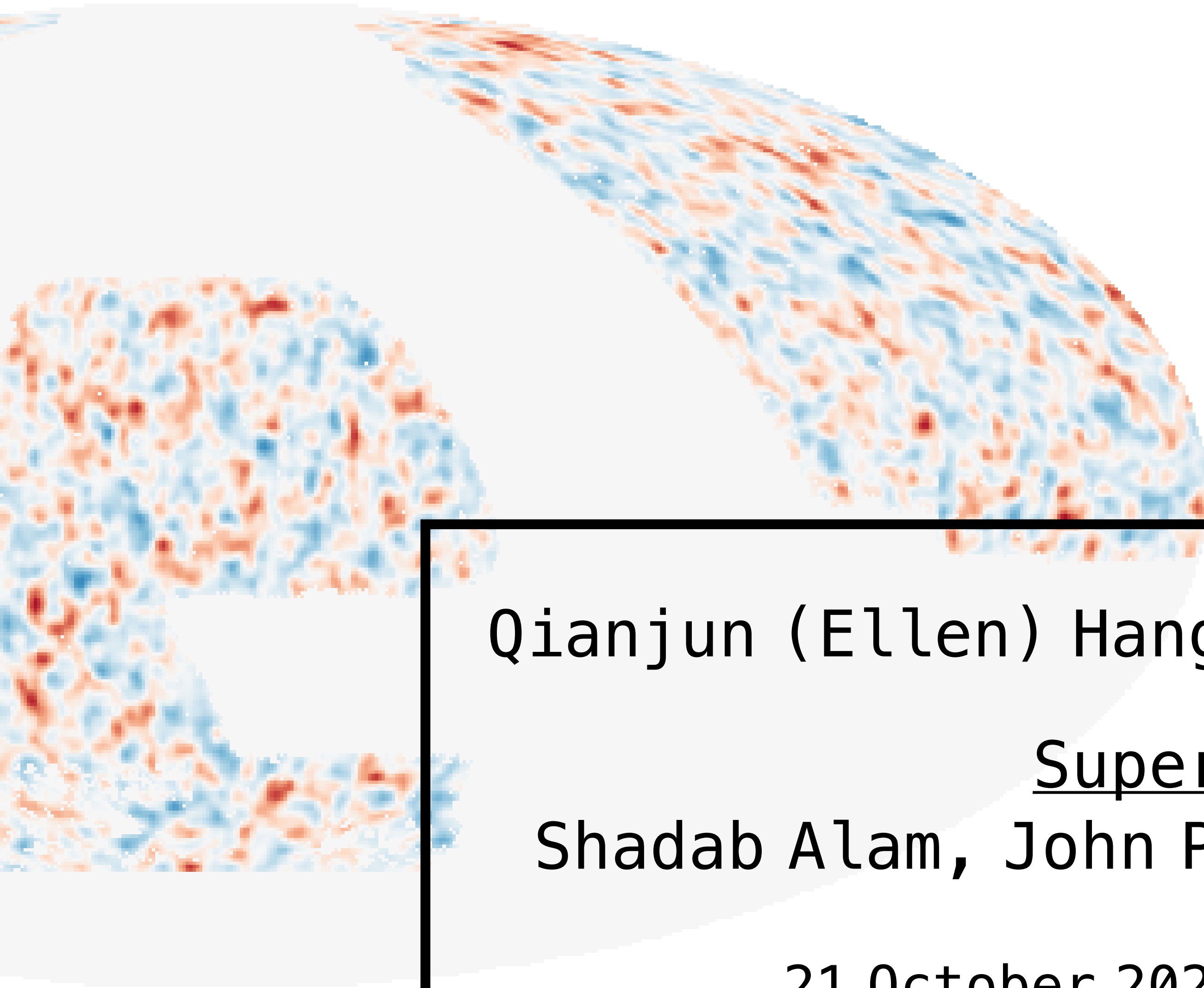
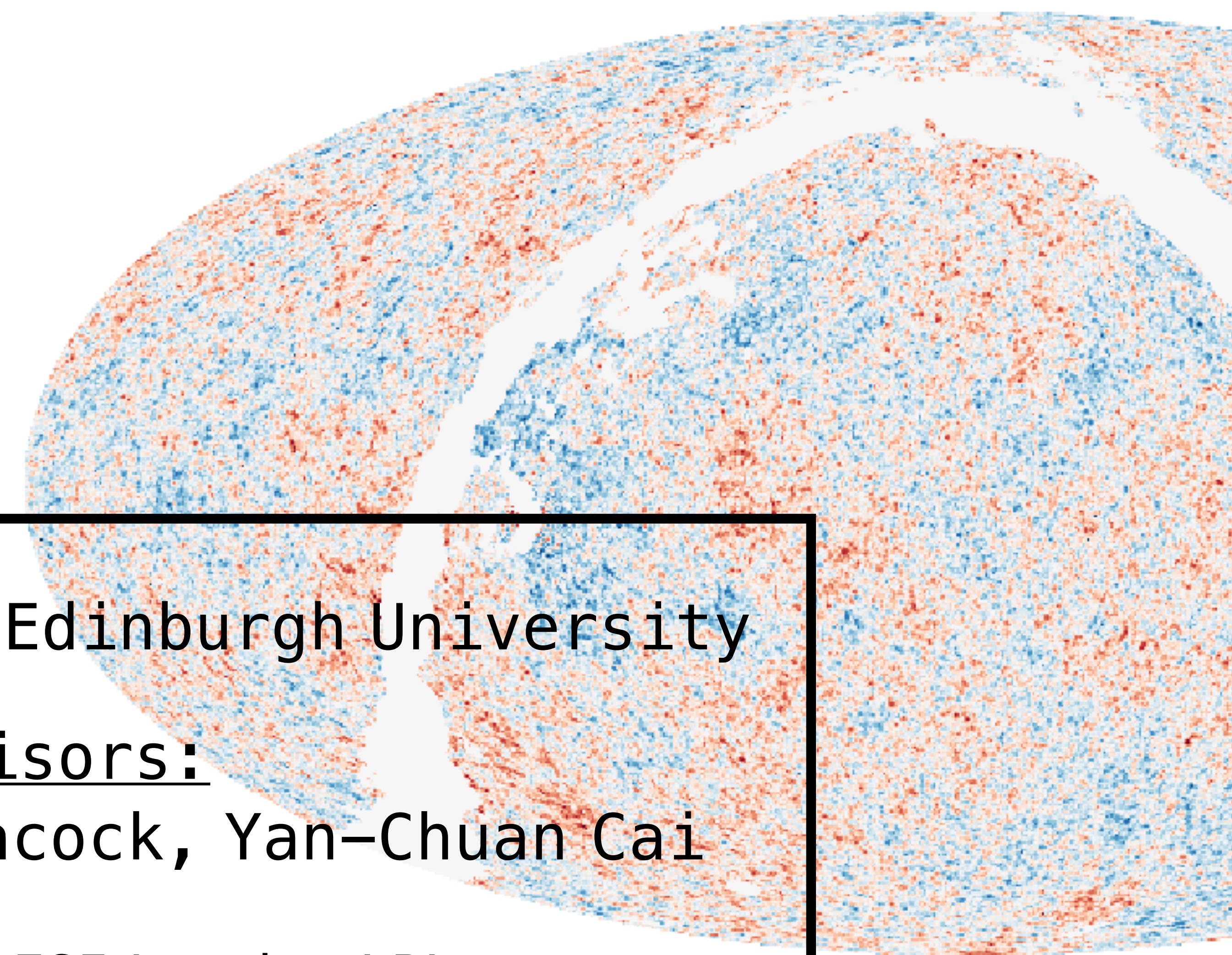
Galaxy clustering in the Legacy Survey and its imprint on the CMB





Qianjun (Ellen) Hang, Edinburgh University

Supervisors:
Shadab Alam, John Peacock, Yan-Chuan Cai

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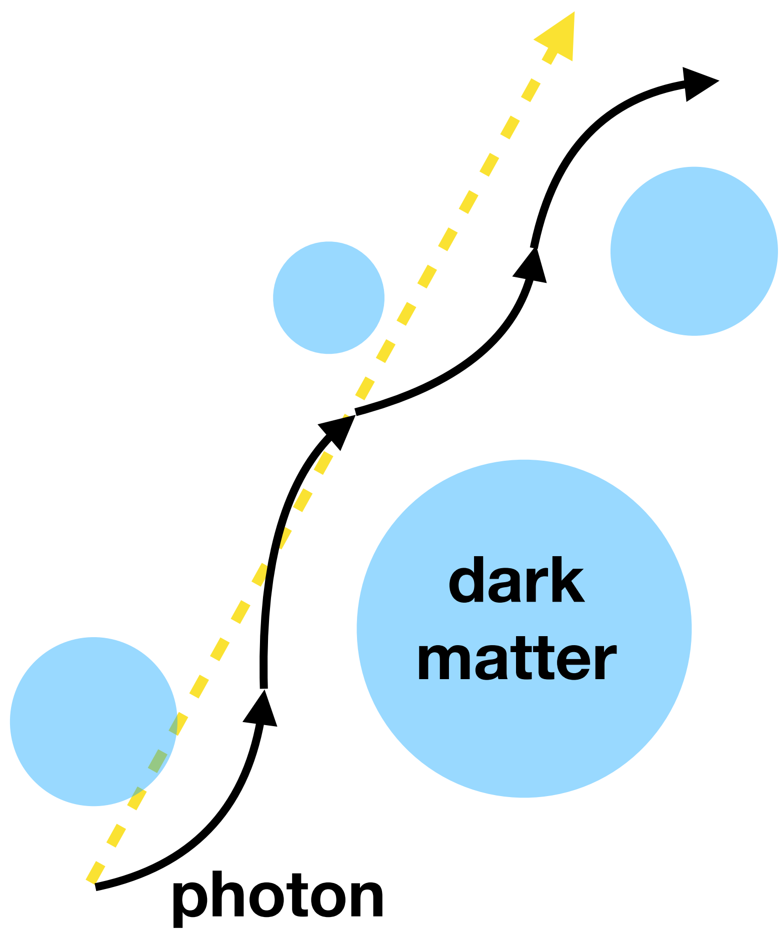
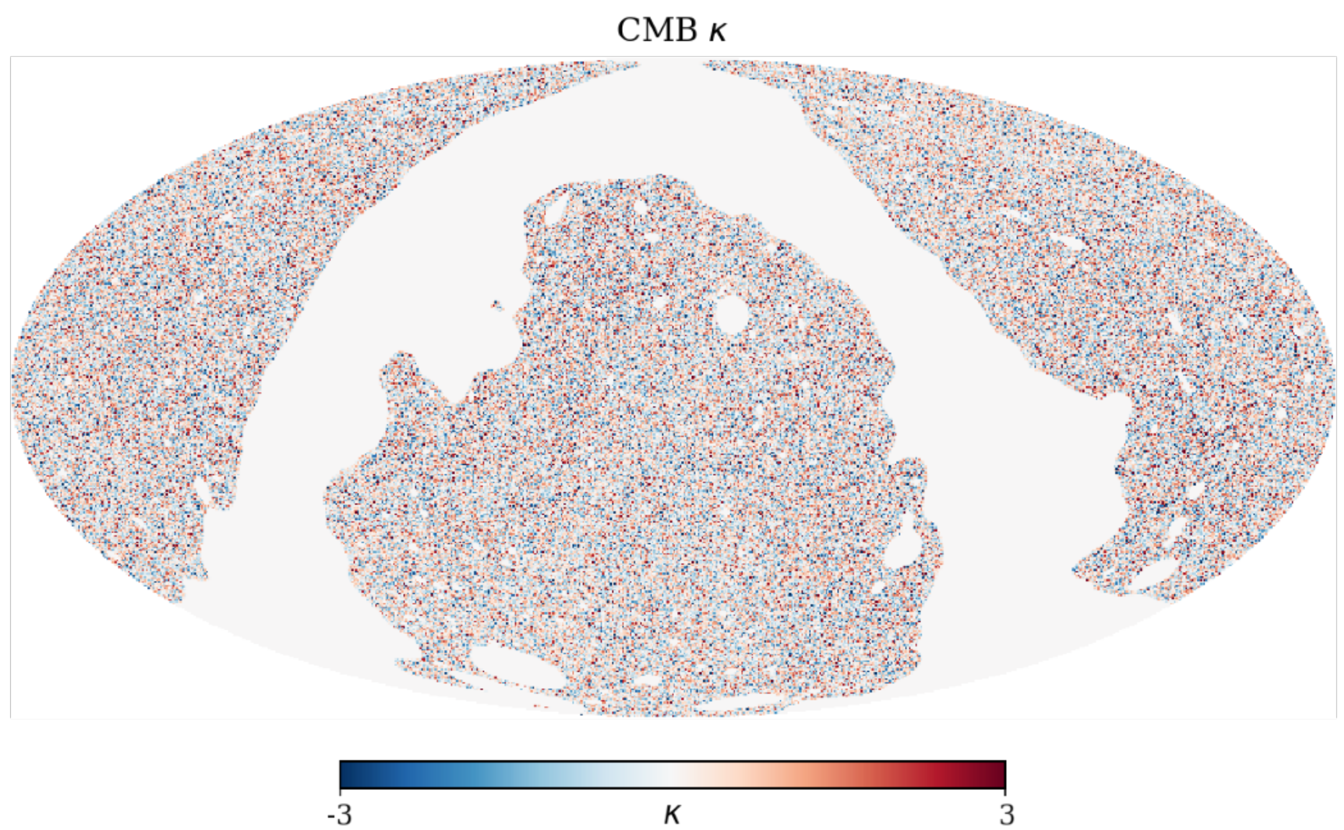
Q. Hang et al 2020, arXiv: 2010.00466

I will talk about…

1. Motivation and theory
2. Legacy Survey and selection
3. Calibration of the photometric redshifts
4. Cross-correlation Results and errors
5. Conclusion: a lower-density universe

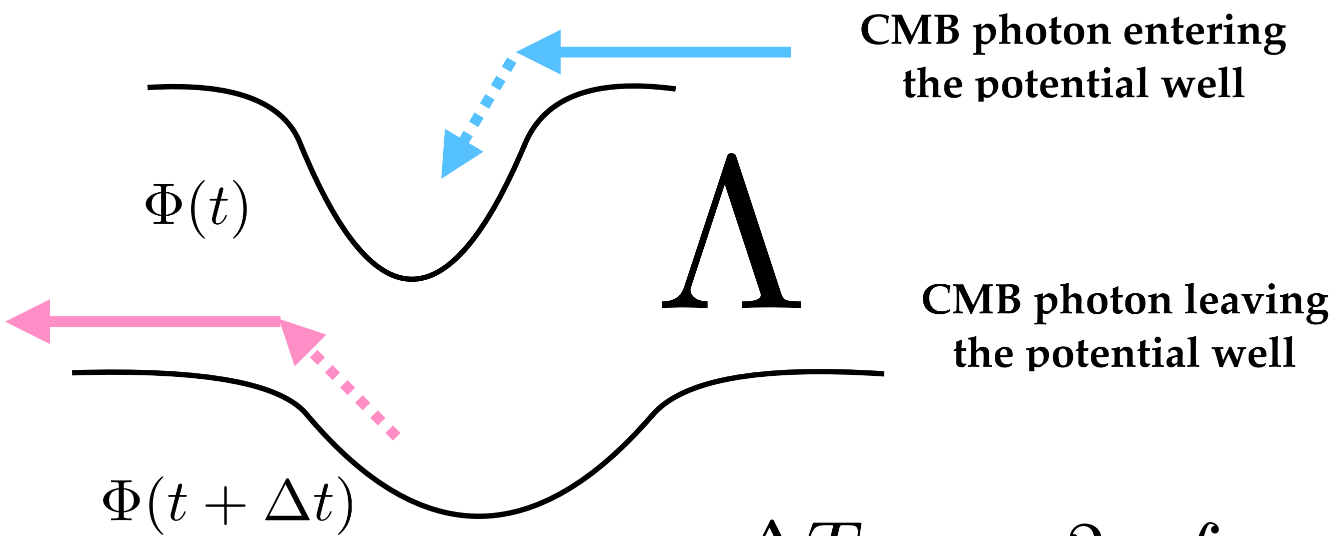
Imprints on the CMB lensing map



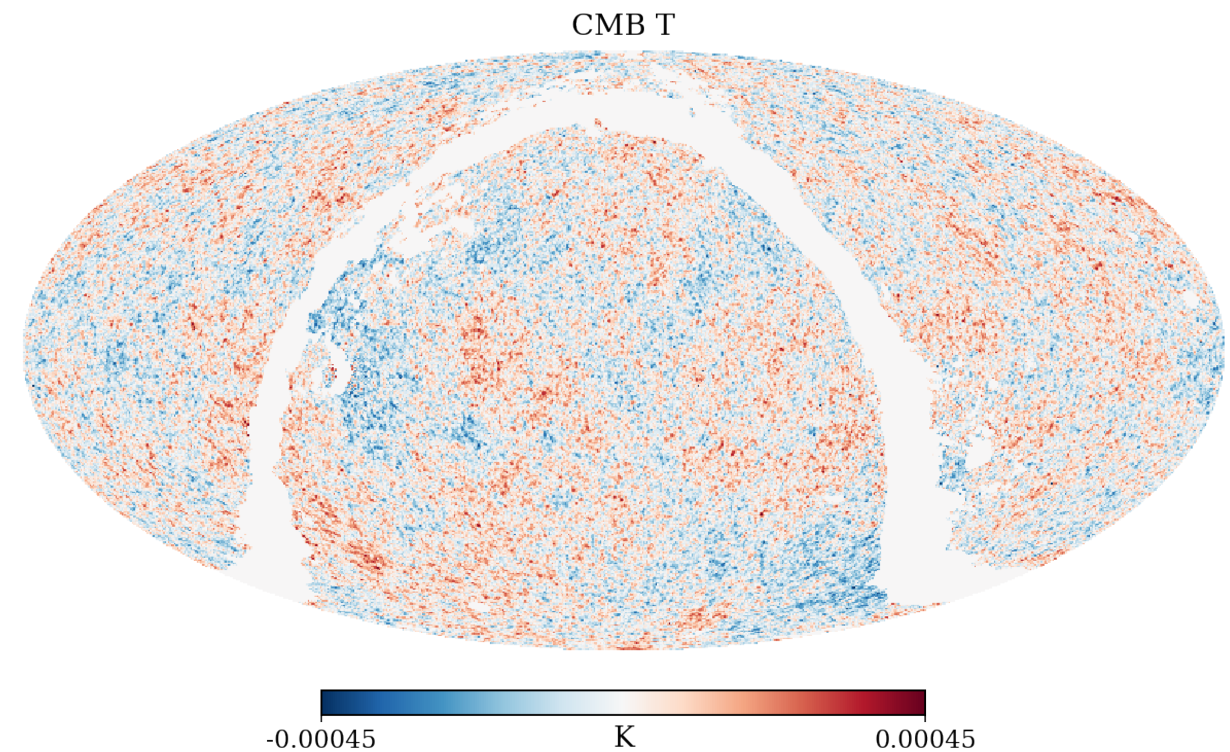


- Weak gravitational lensing -> deflect CMB photon trajectory by LSS
- Distortion on the CMB -> κ map
- Matter density projected along the line of sight from the CMB to us.

Imprints on the CMB temperature map



$$\frac{\Delta T}{T} = -\frac{2}{c^2}\int \dot{\Phi}\, dt$$



- Integrated Sachs-Wolfe (ISW) -> energy shifts in the CMB photons due to LSS
- Only present with the late time dark energy domination -> time-varying potential.
- Modifies the peaks and troughs in the CMB temperature fluctuations. Power mostly on large scales.

Aim: measure this signal *tomographically* by cross-correlating with galaxies in redshift bins

galaxy-galaxy auto/cross-correlations between redshift slices

$$\boxed{b}$$

- Galaxies are biased tracers of matter, $\delta_g = b\delta_m$
- Constraint by galaxy auto-correlations
- (Data)/(Theory with dark matter)=b^2.

$$\boxed{p(z)}$$

- Photometric redshift distribution is uncertain
- Constraint by galaxy cross-correlations
- Bias independent correlation coefficient:

$$r = \frac{C_\ell^{AB}}{\sqrt{C_\ell^{AA} C_\ell^{BB}}}$$

Methods

- Measurement: Healpy (Healpix) -> pixellated map -> spherical harmonics, a_{lm} -> Angular power spectrum C_l

- Maps: Planck 2018 lensing convergence and temperature maps with masks.

- Theory: non-linear matter power spectrum from CAMB (halofit for the non-linear part)

- Fiducial Cosmology: Planck 2018 best-fit parameters

$$\boxed{\Omega_m = 0.315 \quad \sigma_8 = 0.811} \quad h = 0.674$$

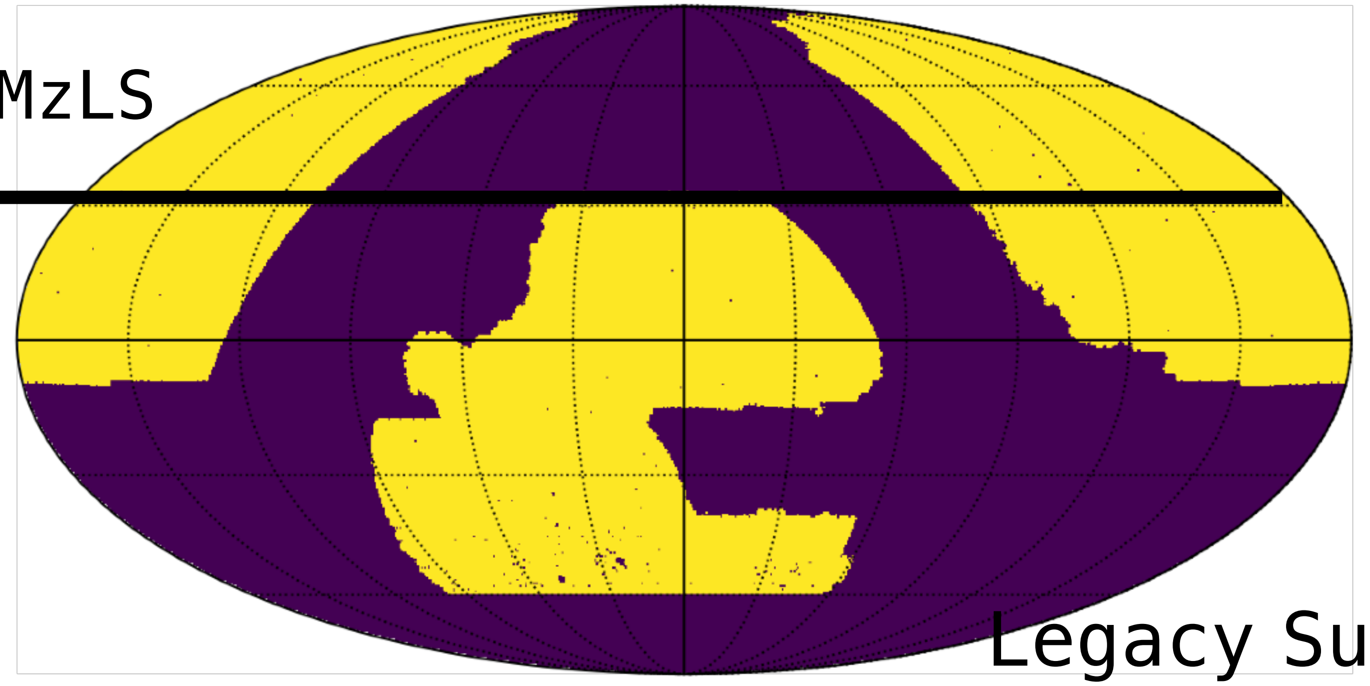
$$n_s = 0.965 \quad \Omega_b = 0.0493$$

2.Legacy Survey and selection

- The DESI Legacy Imaging Survey (DR7) covers an area of 14,000 deg^2, about 1/3 of the whole sky, with ~O(10^8) galaxies. It's a combination of 3 telescopes: DECaLs in the south and BASS+MzLS in the north.

- The photometric bands available are: g, r, z (optical wavelength), and three WISE bands: W1, W2, W3 (infrared wavelength).

- It is really amazing that DESI made this great dataset public for the world community!



Legacy Survey footprint

2. Legacy Survey and selection

- Exclude PSF types (stars, quasars etc.);
- Require measurements in g, r, z, and w1 bands;
- Apply galactic extinction correction;
- Magnitude cuts: g<24, r<22, w1<19.5 for uniform depth;
- Completeness map from Bitmask: pixels >0.86 -> weights; pixels <0.86 -> masked.
- Normalize North and South separately;
- We correct for stellar density from the ALLWISE total density map (very large scales near galactic plane) more;
- Selection based on 3D colour (see next slide).

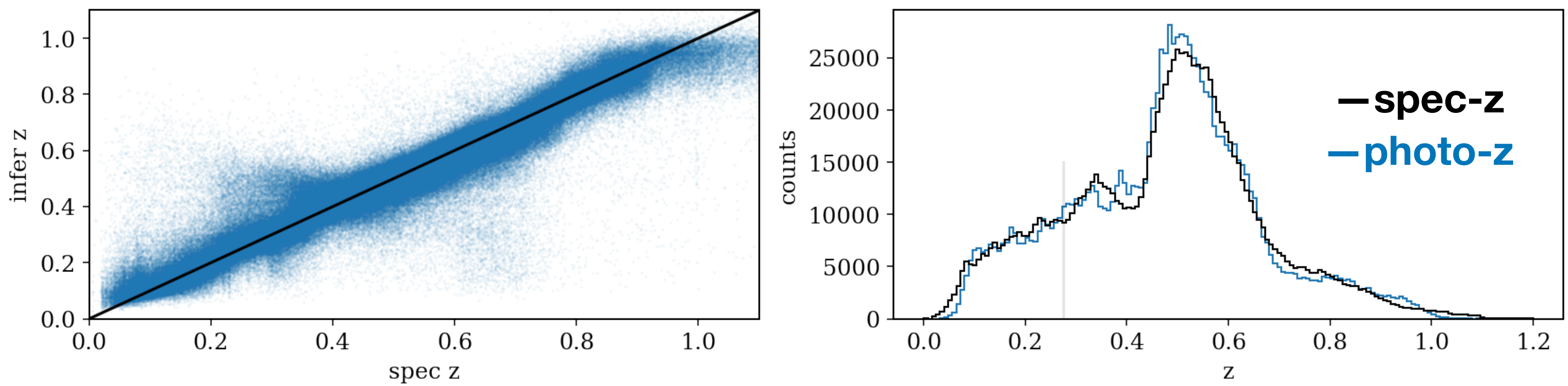
~4.5×10^7 galaxies selected

3.Calibration of the photometric redshifts

- Spectroscopic surveys are used to calibrate the redshift of Legacy Survey galaxies (GAMA, BOSS, eBOSS, VIPERS, DEEP2, COSMOS, DESY1A1 redMaGiC). These galaxies are matched in the Legacy Survey sample using their sky positions.

- Mean spec-z in 3D colour grids: g-r, r-z, z-W1, with pixel width of ~0.03mag.

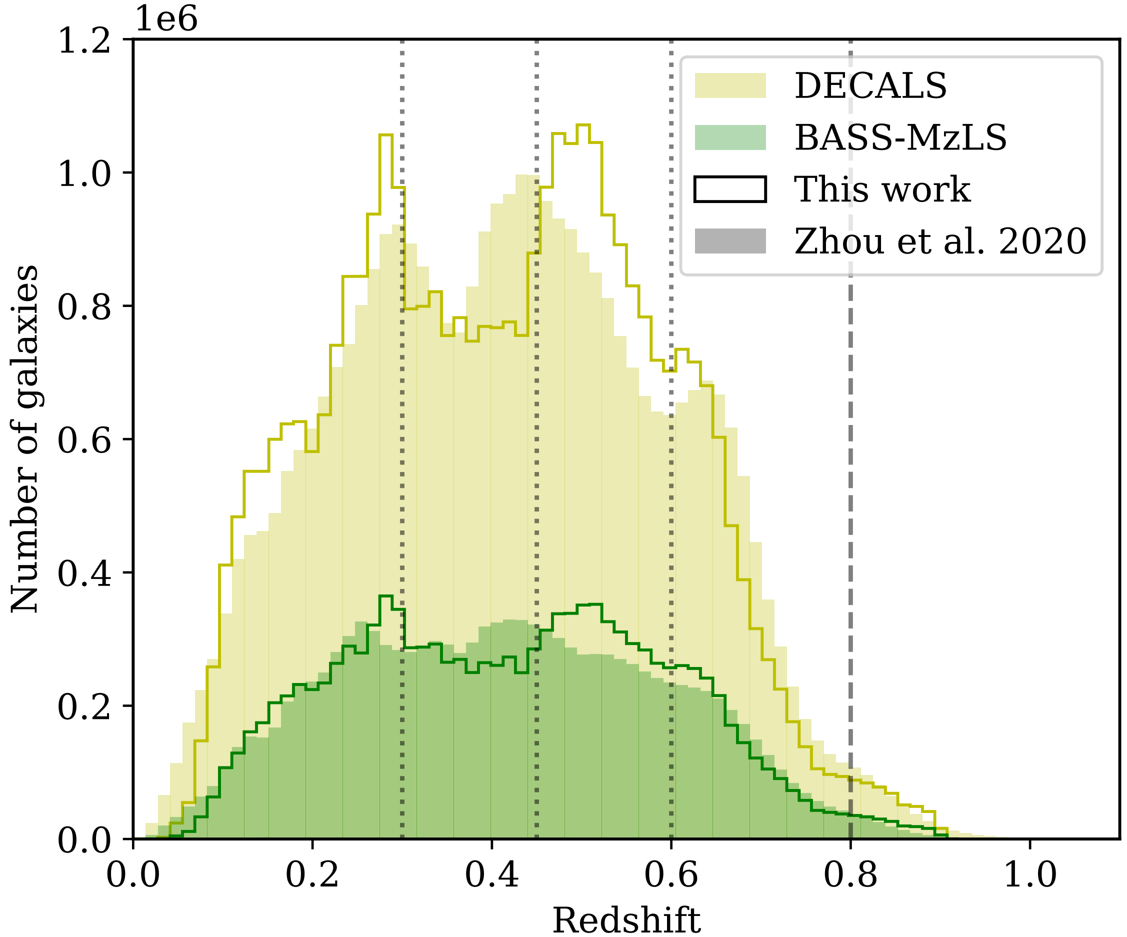
Calibration sample



- We assign the mean redshifts in these grids to the Legacy Survey galaxies. Galaxies falling outside the grid covered by the calibration sample are excluded.

- 78.6% of the selected Legacy Survey galaxies get assigned a photometric redshift.

3.Calibration of the photometric redshifts



- We also compare with the Zhou et al. (2020) machine-learning photometric redshift catalogue -> select galaxies with $|\Delta z|<0.05$.
- We split the sample into 4 tomographic bins in the redshift range $0<z<0.8$.

Photo-z error

The raw redshift distribution is convolved with L(x) to obtain the final redshift distribution.

Normalization such that the integral is 1

$$L(x) = \frac{N}{(1+((x-x_0)/\sigma)^2/2a)^a}$$

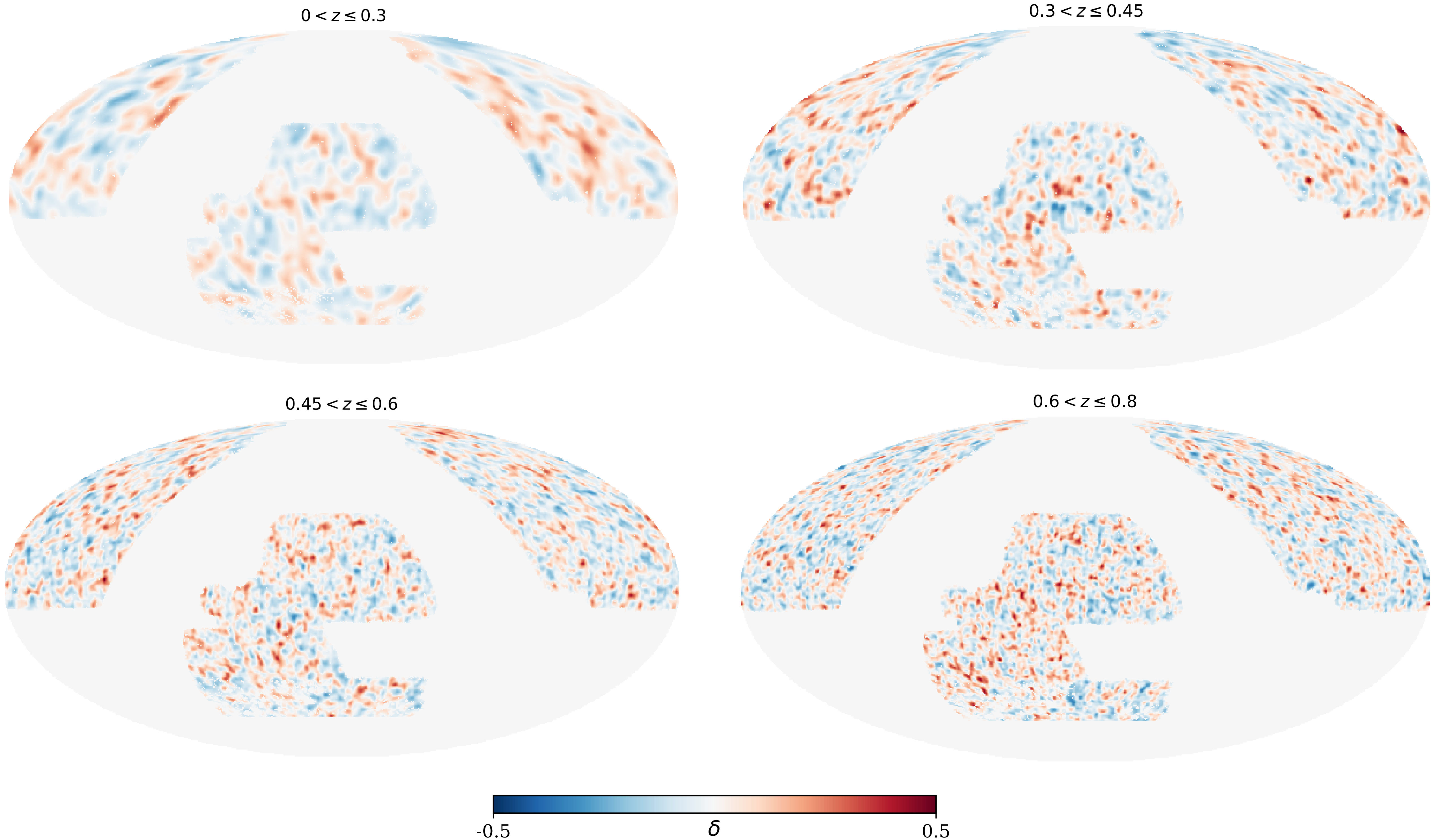
mean, free with constraint that sum of four bins is zero

width, fixed by fitting the spectroscopic sample in each z bin

Tail, free to account for faint galaxies

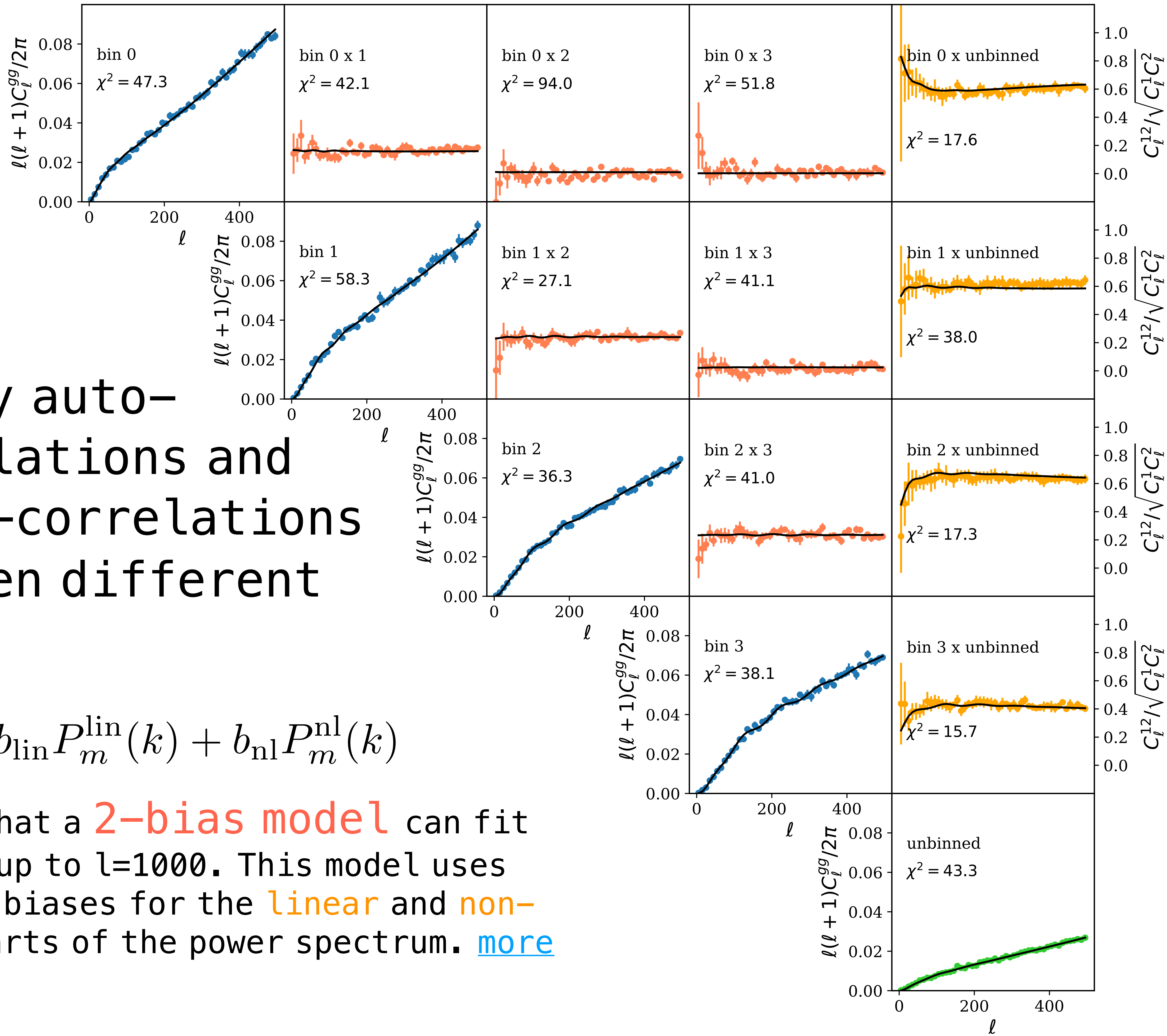
Galaxy density maps

∗These density maps are smoothed with Gaussian kernel of width σ=20Mpc/h.



4.Cross-correlation Results and errors

- l<10 modes are excluded from fitting.
- We use pseudo-power estimate $\hat{C}_\ell = C_\ell^{\mathrm{masked}} / f_{\mathrm{sky}}$
- Use Δl=10 power bins. Covariance matrix then accurately diagonal (based on lognormal simulations). more
- Tomographic slices not completely independent. Use un-binned data for combined result.



Galaxy auto-correlations and cross-correlations between different z bins

$$P_g(k) = b_{\rm lin} P_m^{\rm lin}(k) + b_{\rm nl} P_m^{\rm nl}(k)$$

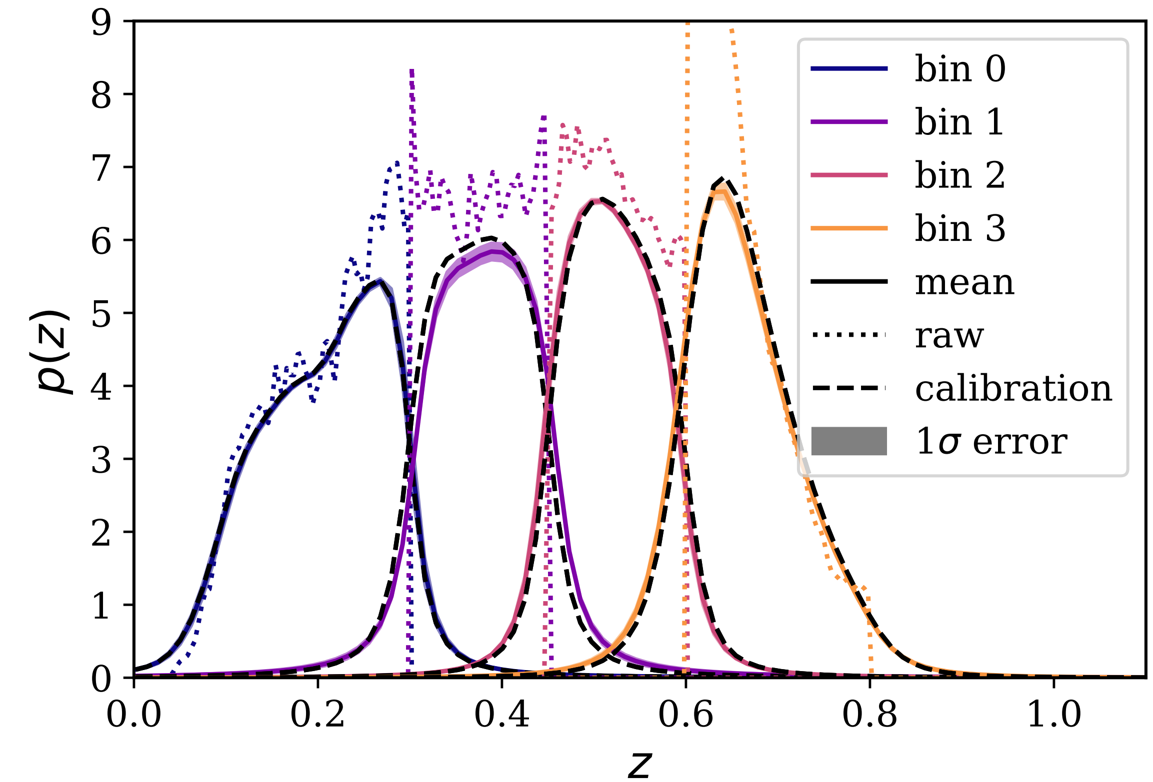
We find that a 2-bias model can fit the data up to l=1000. This model uses separate biases for the linear and non-linear parts of the power spectrum. more

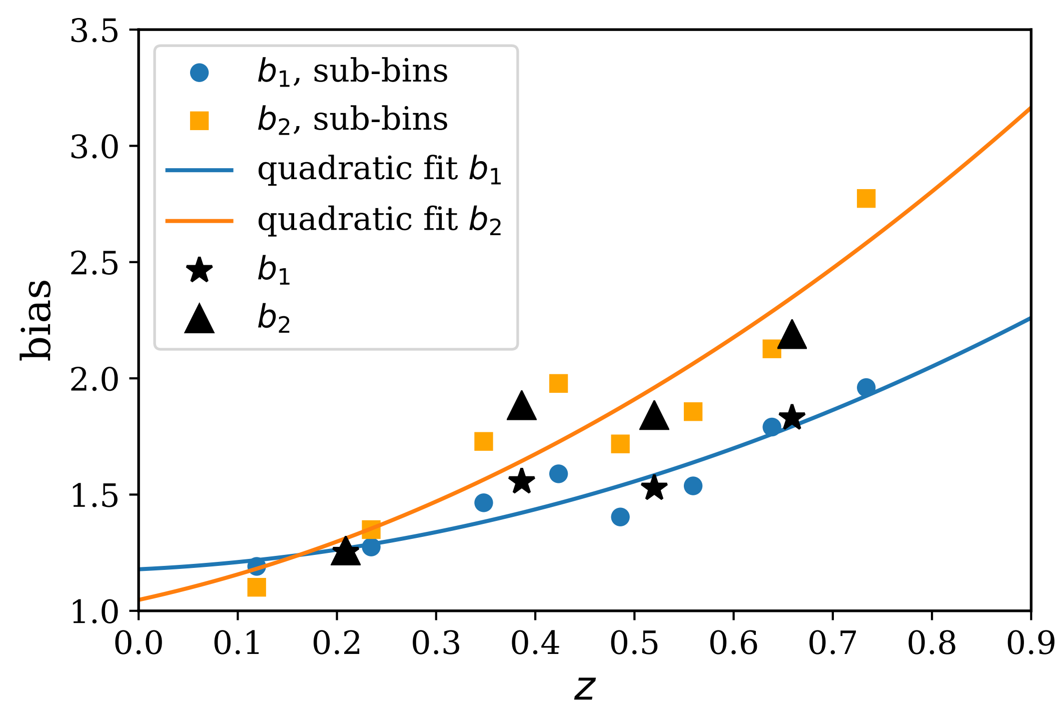
Galaxy auto-correlations and cross-correlations between different z bins

- We minimize the total chi square from the 10 galaxy correlations by varying photo-z parameters. For each set of parameters, we fix bias at the lowest chi square value.

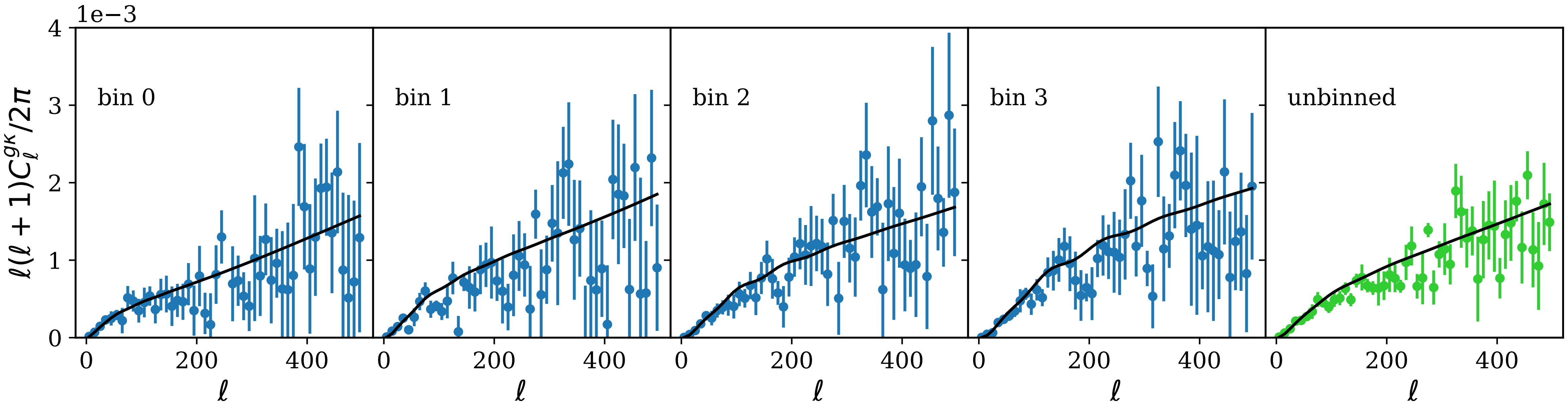
- For the combined bin case, we also further consider the bias redshift evolution, approximated via quadratic curve.

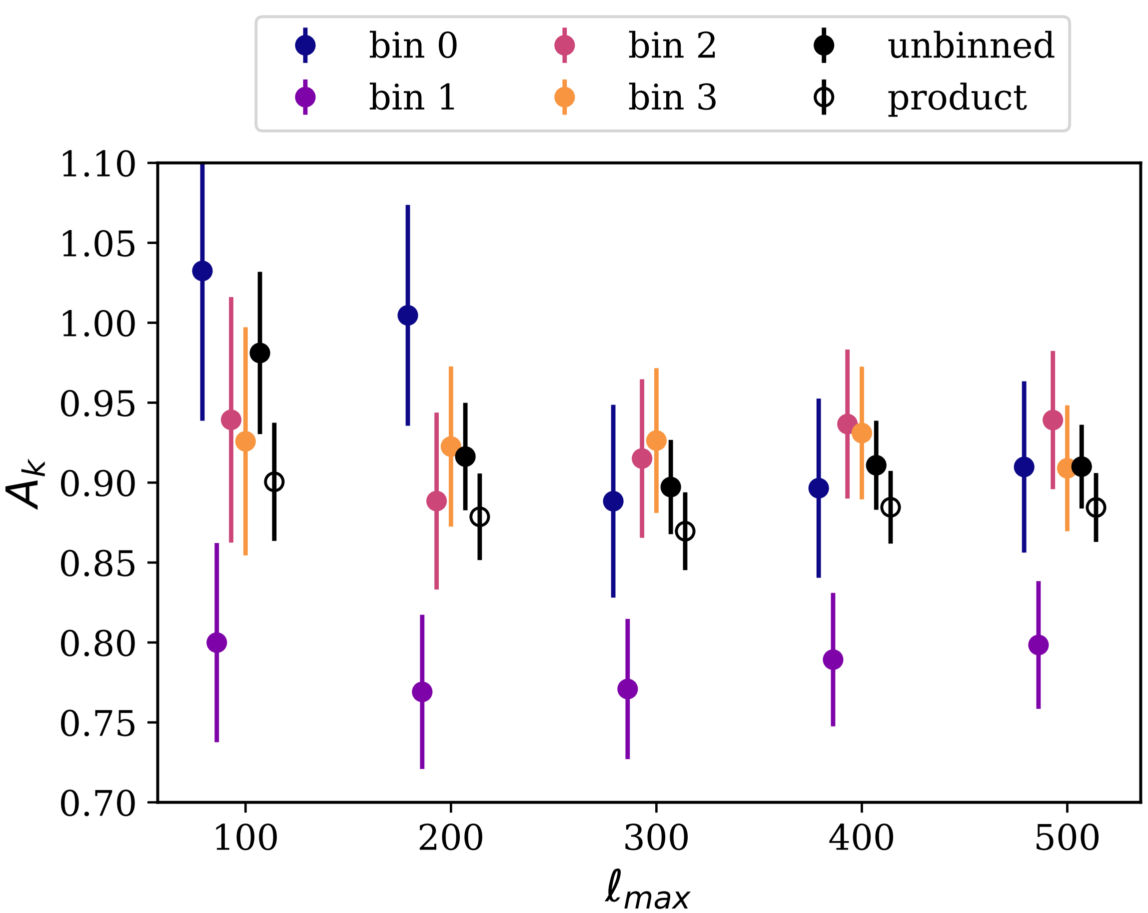
- The galaxy biases (and the evolution) are fixed for the CMB cross-correlation analysis.





Cross-correlations with the CMB maps – lensing results

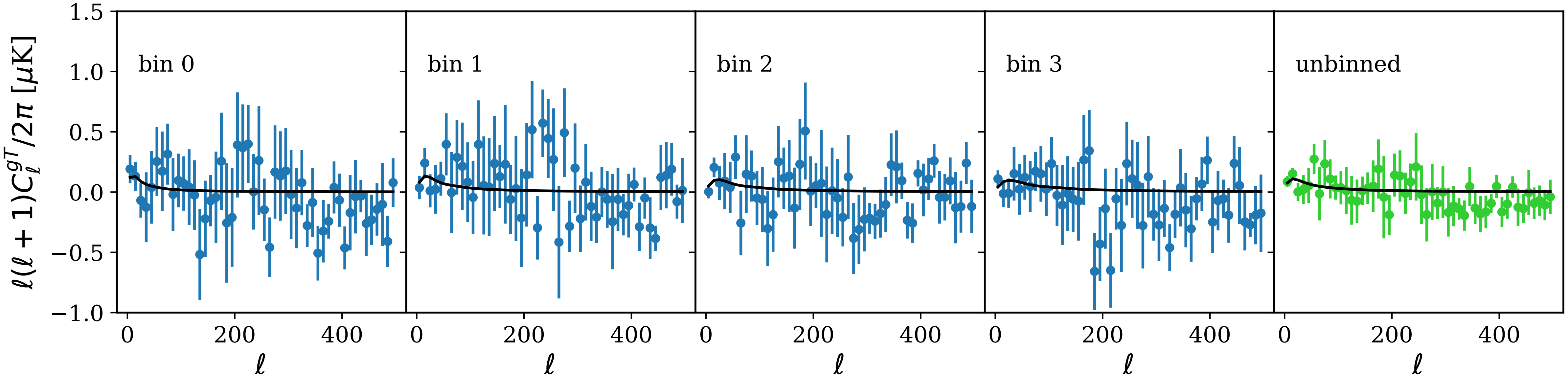


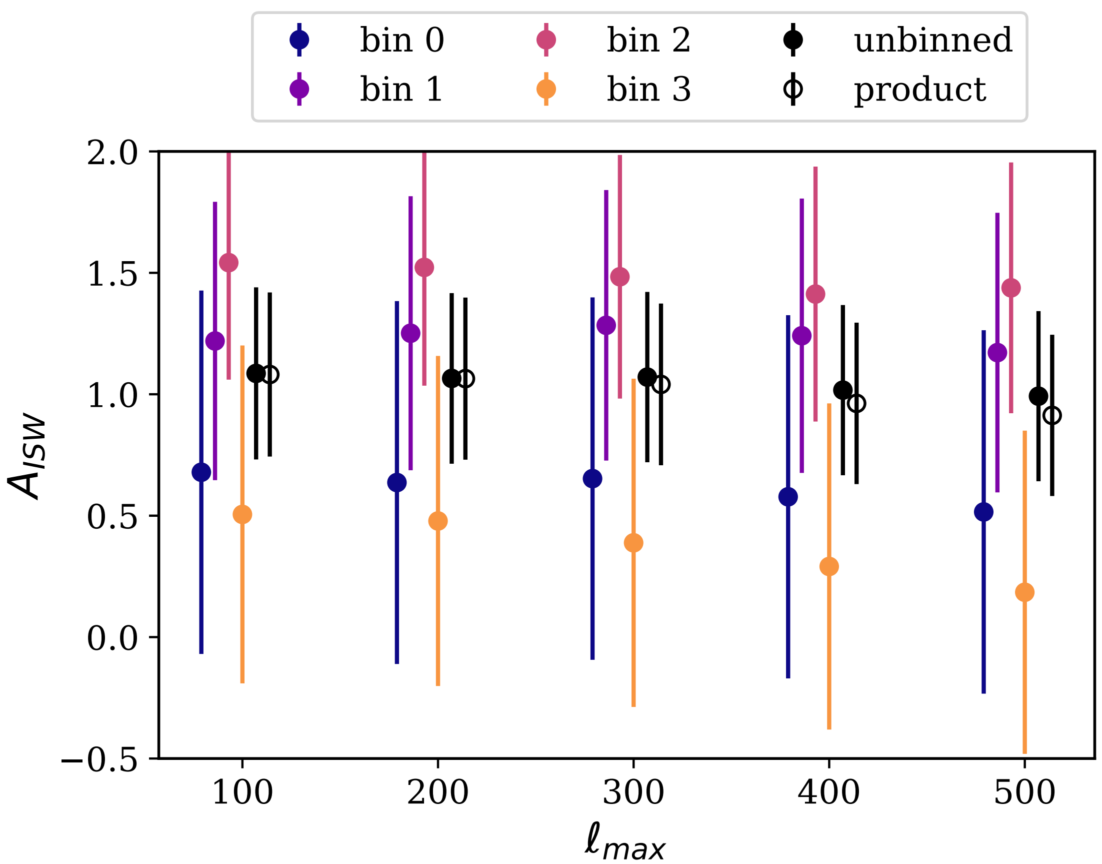


The black lines are not fits to the data. We use A=data/theory to quantify the consistency between the two. A=1 -> fiducial cosmology is preferred. The result of combining the four redshift bins and the un-binned case both lie below unity.

$$A_\kappa = 0.901 \pm 0.026$$

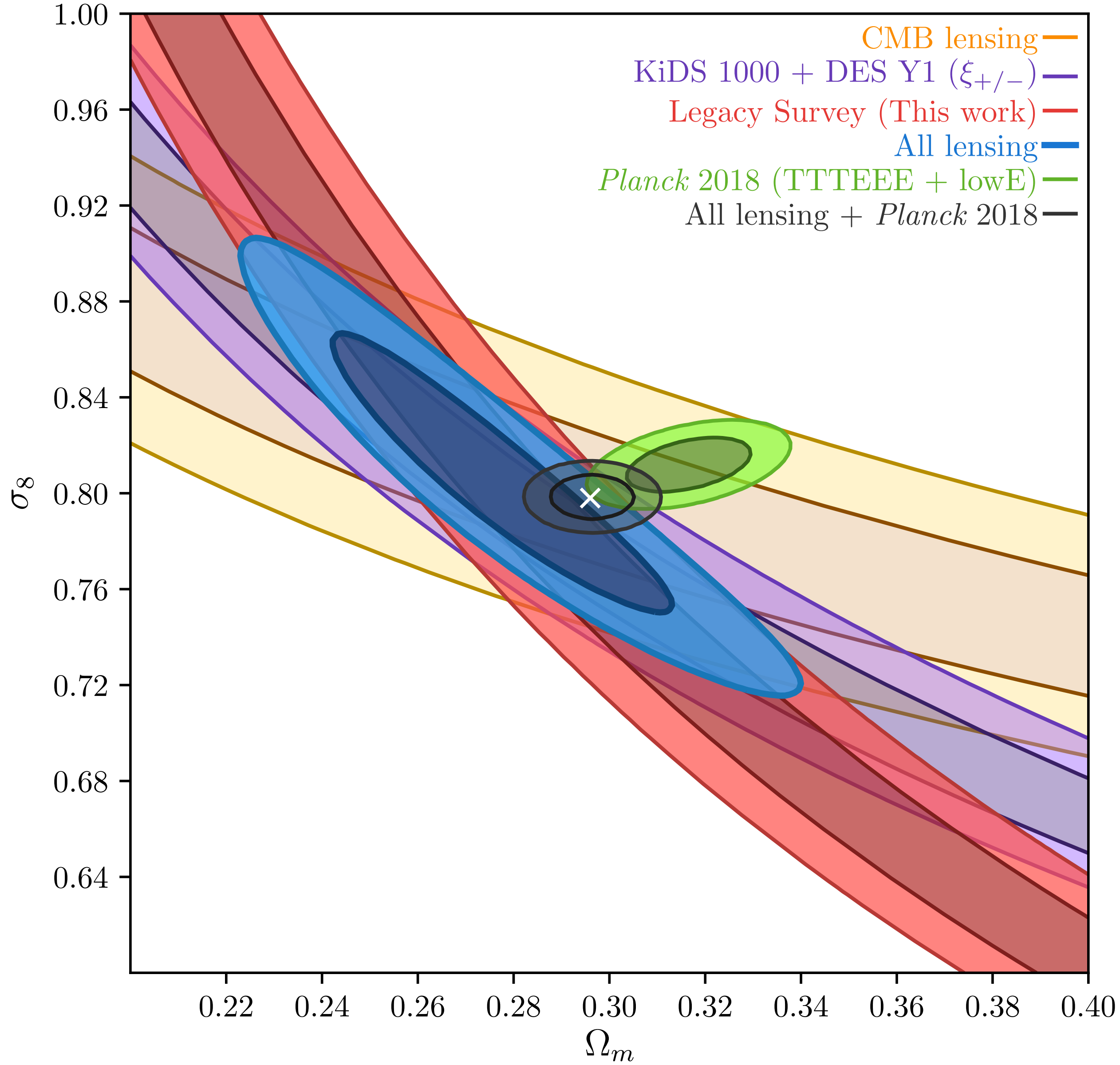
Cross-correlations with the CMB maps – ISW results





- The ISW signal is very noisy.
- We find that $A_{\rm ISW} = 0.98 \pm 0.35$
- It is fully consistent with the fiducial cosmology given the large error bar. This consistency helps us rule out the AvERA model – a model which predicts much higher ISW signal in order to explain the excess signal in the stacking results.

Cosmological implications of low A_κ



- Tomographic galaxy–CMB lensing measures $\sigma_8\Omega_m^{0.78}$. Our results put a constraint on the quantity: $\sigma_8\Omega_m^{0.78}=0.297\pm0.009$. Total CMB lensing measures $\sigma_8\Omega_m^{0.25}=0.589\pm0.020$. In combination, we have $\Omega_m=0.275\pm0.024$; $\sigma_8=0.814\pm0.042$.

- The other galaxy weak lensing experiments, KiDS-1000 (Asgari et al. 2020) and DES Y1 (Troxel et al. 2018) gives constraints which are consistent with ours, and in slight tension with Planck.

- Combination of all lensing results show $\Omega_m=0.274\pm0.024$; $\sigma_8=0.804\pm0.040$. It seems that this prefers a lower Ω_m than the Planck 2018 result.

- Everything combined: $\Omega_m=0.296\pm0.006$; $\sigma_8=0.798\pm0.006$. The value is touching the 95% contour of both sets.

Cosmological implications of low A_κ

- Bad luck in statistics?
- Unknown systematics in galaxy data, e.g., photo-z, contamination…
- CMB side?
- Massive neutrinos? – the effect is negligible at low redshift. At Planck side, it increases the tension.
- Modified gravity? – to suppress growth of structure to achieve A_κ=0.9, it needs substantial modification, which can be ruled out by other evidence such as RSD measurements.
- Modelling? [Kitanidis & White, 2020] found similar results with LRG using halofit, but not in perturbation theory.

Cosmological implications of low A_κ

There are also implications on the H_0 tension…

Since the acoustic scale mainly fixes $\Omega_m h^3$, a lower Ω_m needs higher h.

Our preferred Ω_m=0.27 would yield h=0.71, consistent with the local universe measurements from e.g., distance ladder.

Summary

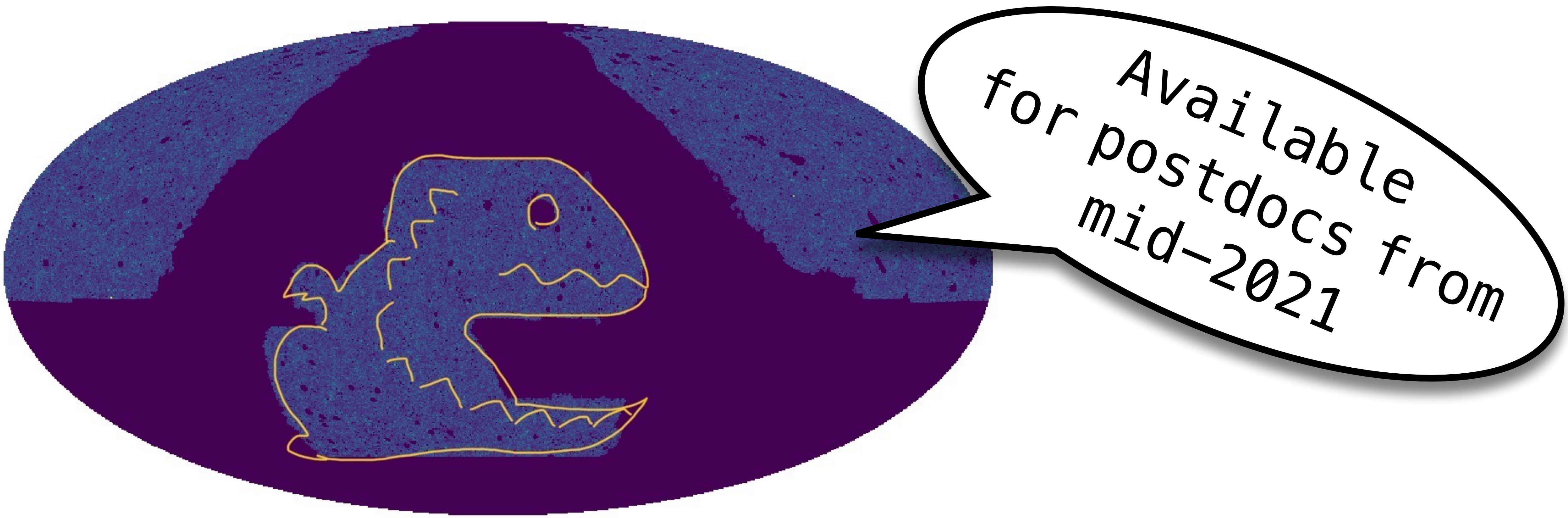
- We selected galaxies from the DESI Legacy Image Survey and obtained robust photometric redshifts using the available three colour bands.
- We constructed galaxy density maps for four tomographic bins between $0<z<0.8$.
- We measured the cross-correlation between these galaxy maps with the CMB lensing convergence and temperature maps.
- Compared with theoretical prediction based on Planck 2018 Cosmology, we find $A_\kappa=0.901\pm0.026$ and $A_{ISW}=0.98\pm0.35$.
- Our result translate to a strong evidence for lower Ω_m combined other lensing probes.
- Future surveys such as DESI will no doubt provide more insight into this issue!

For more info: Q. Hang et al 2020, arXiv: 2010.00466

My other ongoing works:

Stacking of super structures in the Legacy Survey with CMB [Q. Hang et al. in prep.]

RSD from group-galaxy cross-correlation using GAMA [Q. Hang et al. in prep.]



Modelling the signal

$$\frac{\ell(\ell+1)}{2\pi} C_\ell^{gX} = \frac{\pi}{\ell} \int b\, \Delta^2(k=\ell/r, z)\, p(z) K^X(z) r\, dz$$

galaxy bias

matter power spectrum

redshift distribution

<u>X=Lensing</u> $$K^\kappa = \frac{3H_0^2\Omega_m}{2c^2 a} \frac{r(r_{\rm LS}-r)}{r_{\rm LS}}$$

<u>X=ISW</u> Assume linear theory, $\Phi = \dfrac{3H_0^2\Omega_m}{2ak^2}\delta$

growth rate

$$K^T = \frac{2T_{\rm CMB}}{c^3} \frac{3H_0^2\Omega_m}{2k^2} H(z)\,(1-f_g(z))$$

Theory: galaxy-galaxy auto/cross-correlations

Galaxy bias and redshift distribution can be constrained from the galaxy-galaxy correlations, given fixed cosmology.

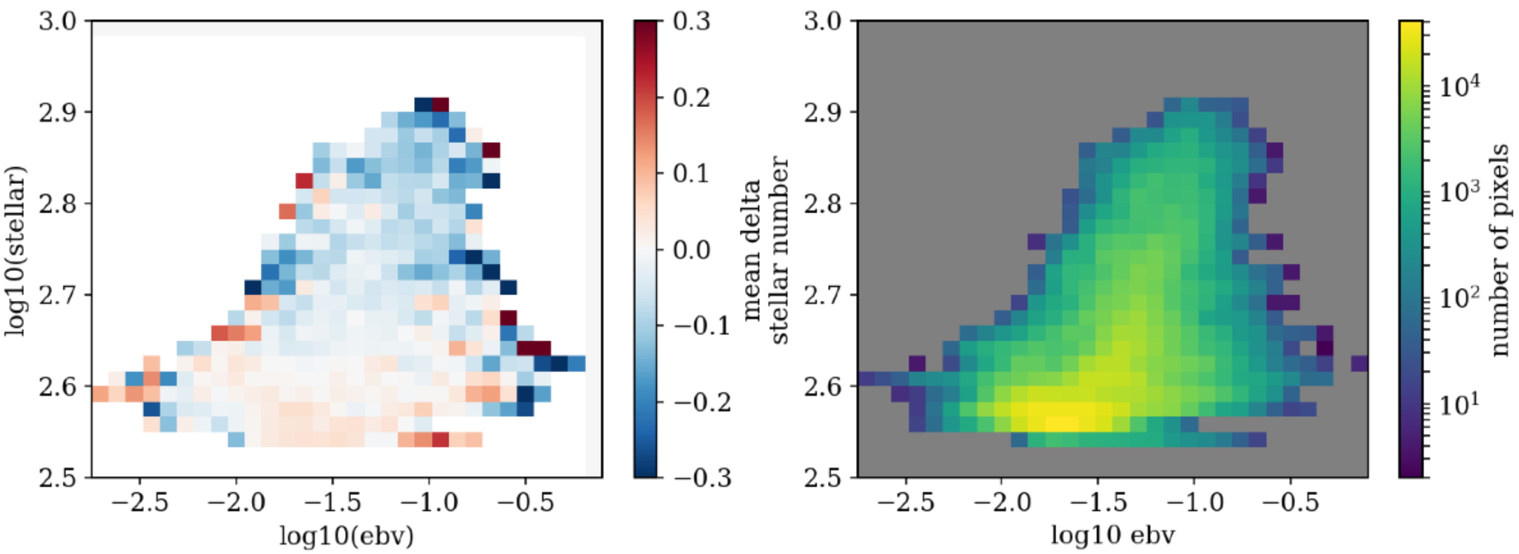
$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{gg} = \frac{\pi}{\ell}\int b_1 b_2\,\Delta^2(k=\ell/r,z)\,p_1(z)p_2(z)\frac{H(z)r}{c}dz$$

In principle, the galaxy bias can have redshift and scale dependence.

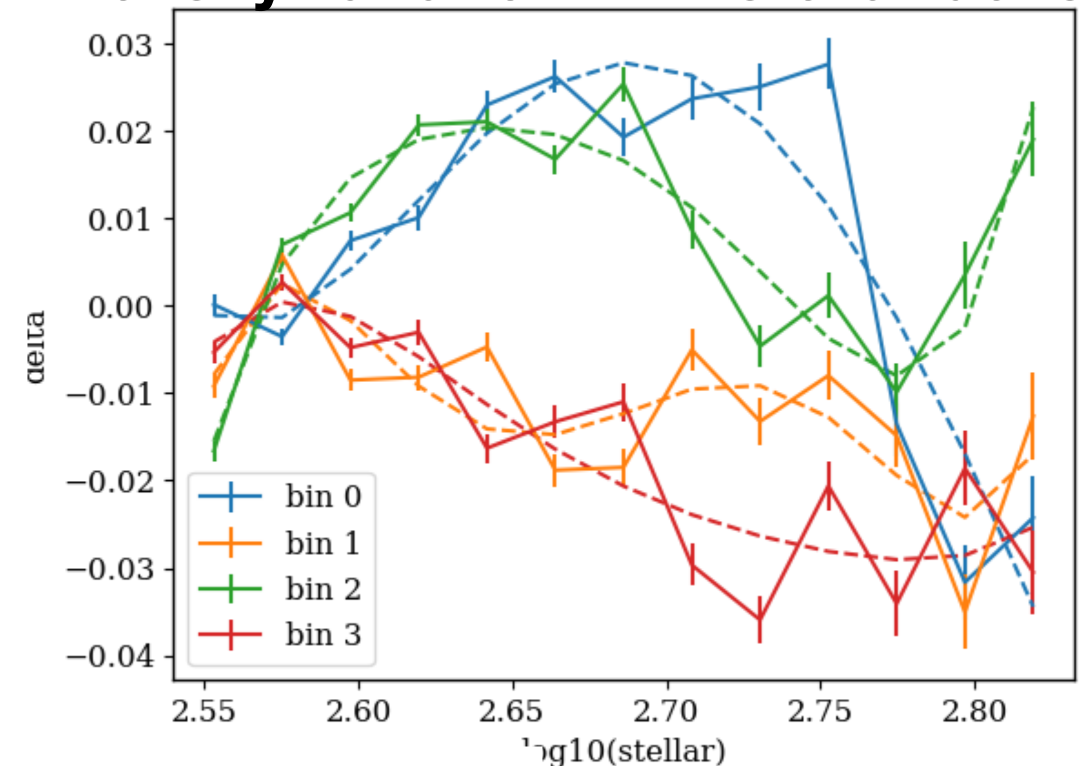
p1=p2 -> auto-correlation,
p1≠p2 -> cross-correlation between different redshift slices.

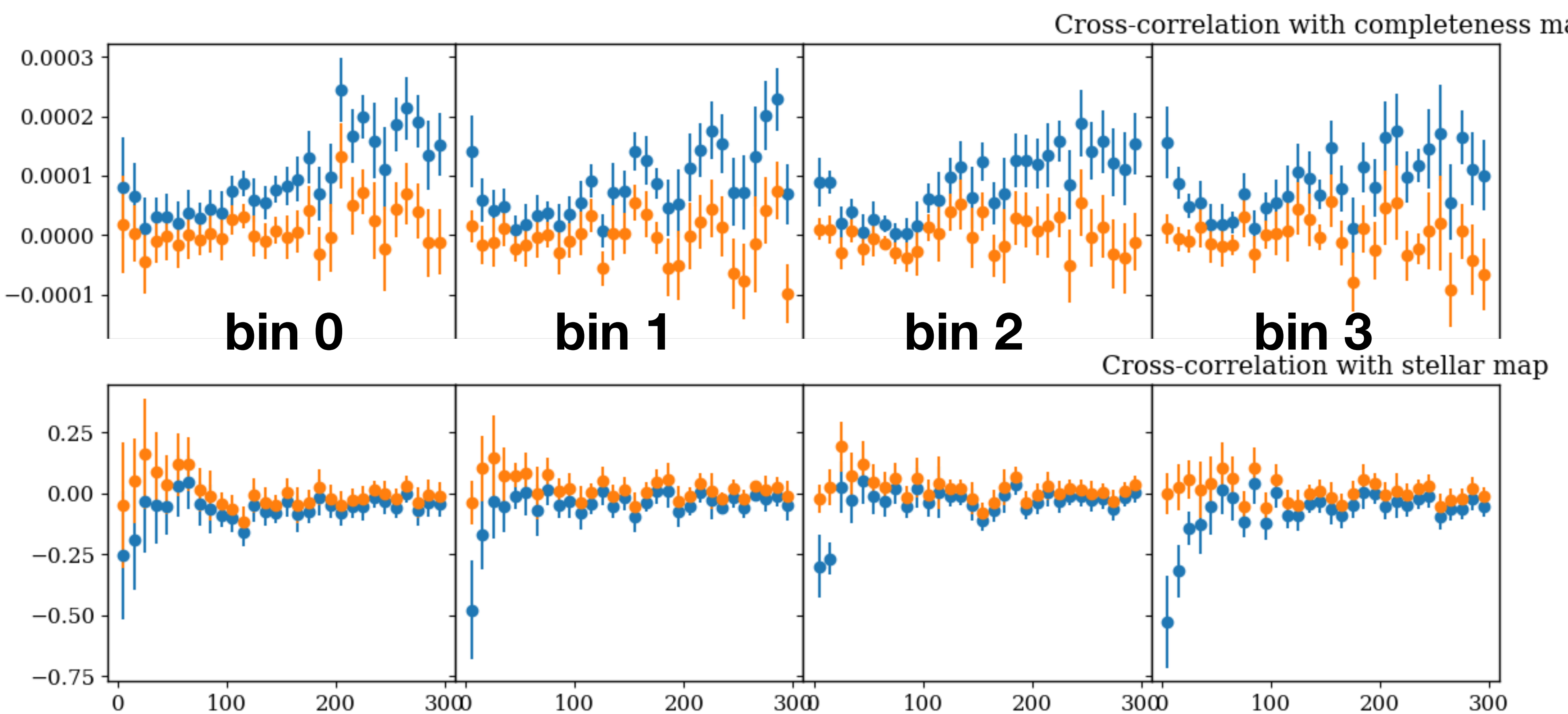
Density map systematic correction

Mean density split in bins of stellar number and E(B-V)



Density variation with stellar density



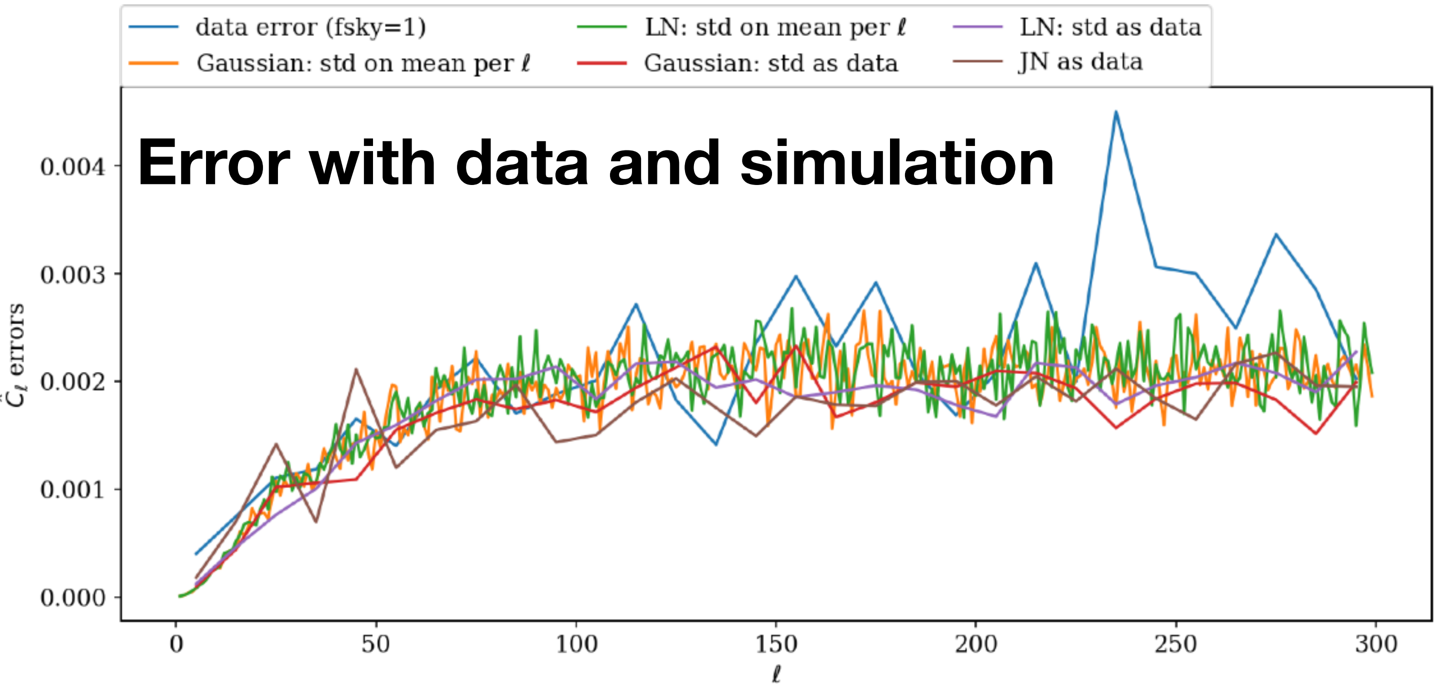


— Before weighting and stellar correction

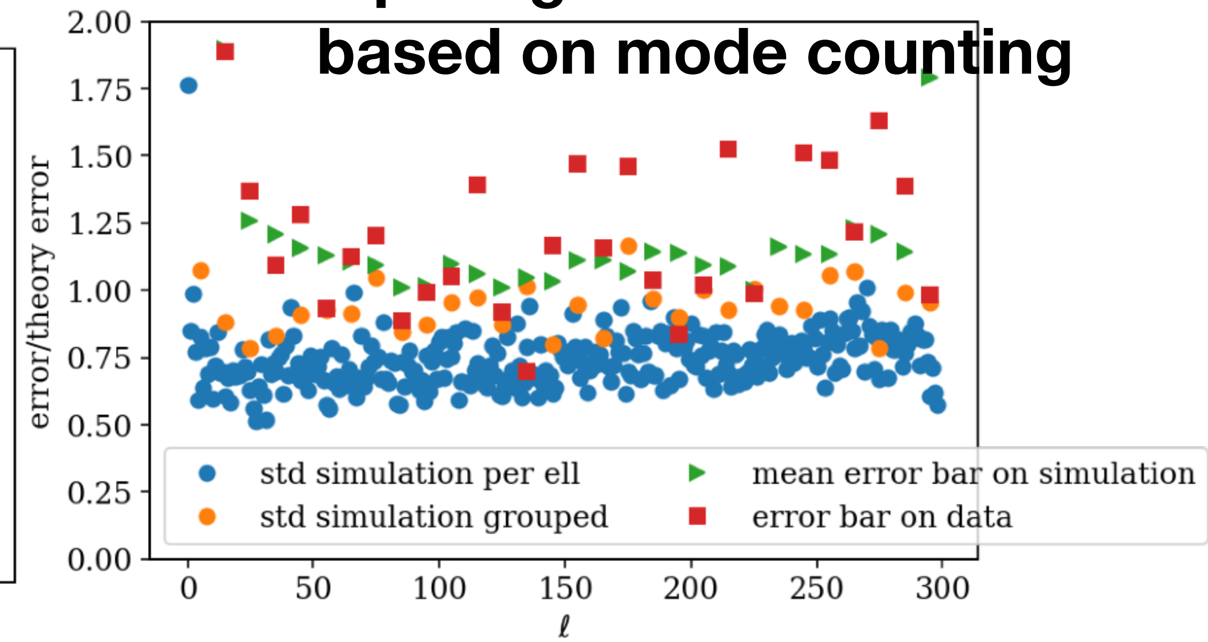
— Weighted by completeness and corrected by stellar density

Mask, shotnoise, errorbars

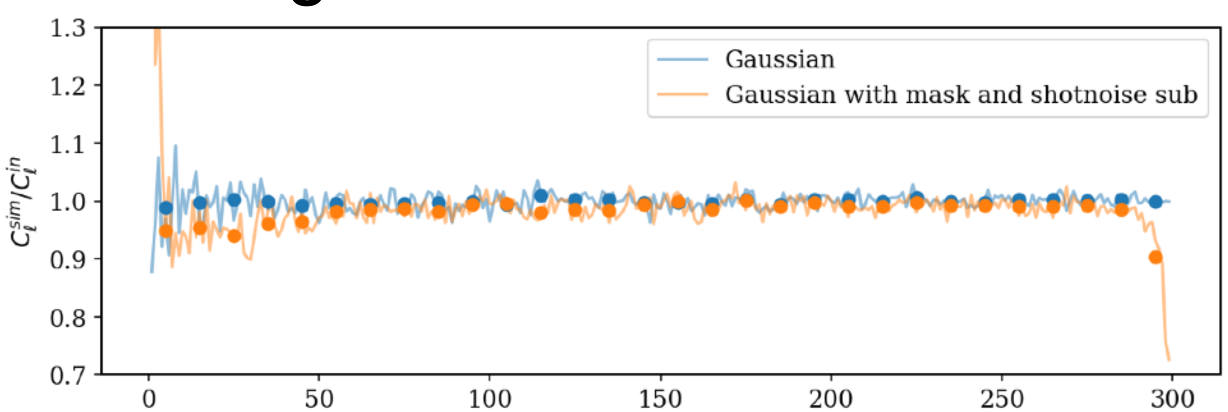
Error with data and simulation

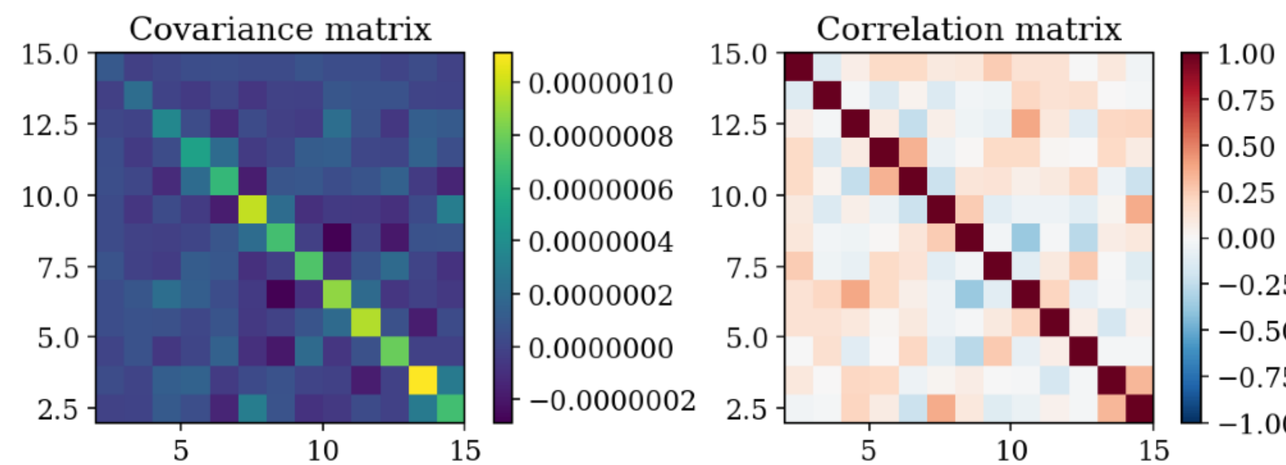


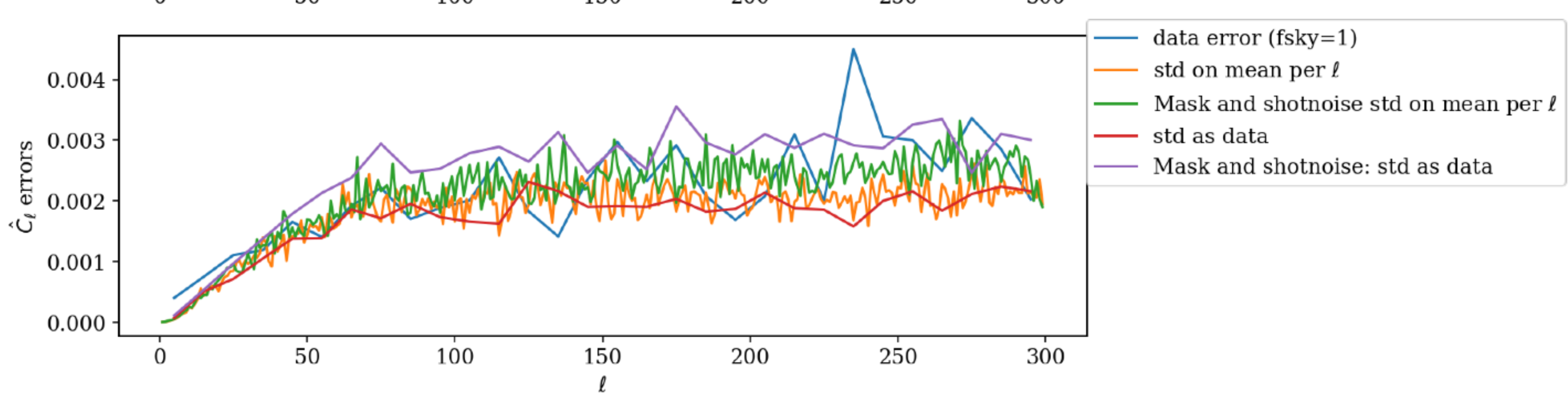
Comparing to theoretical error based on mode counting



Including mask and shot noise

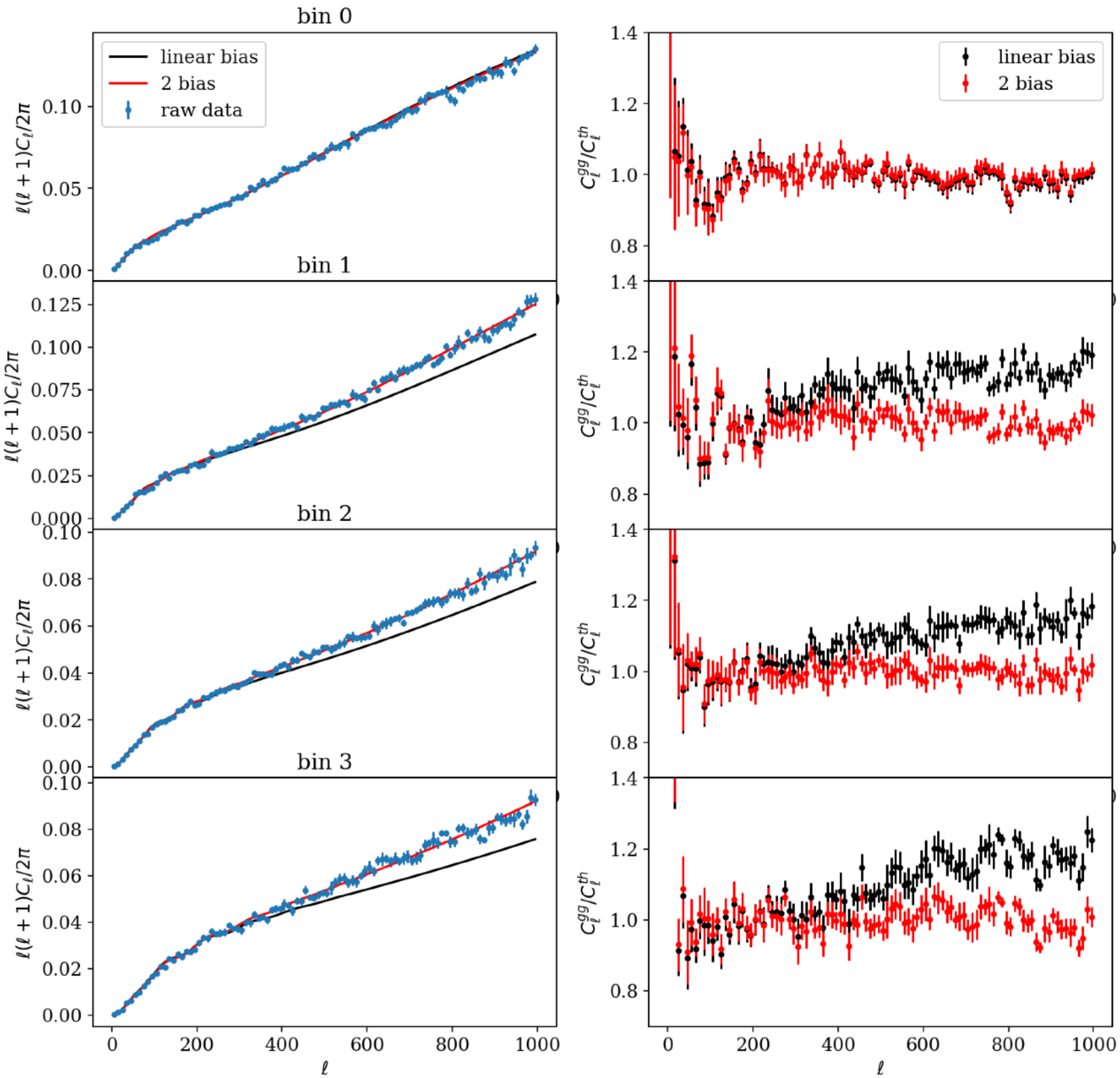






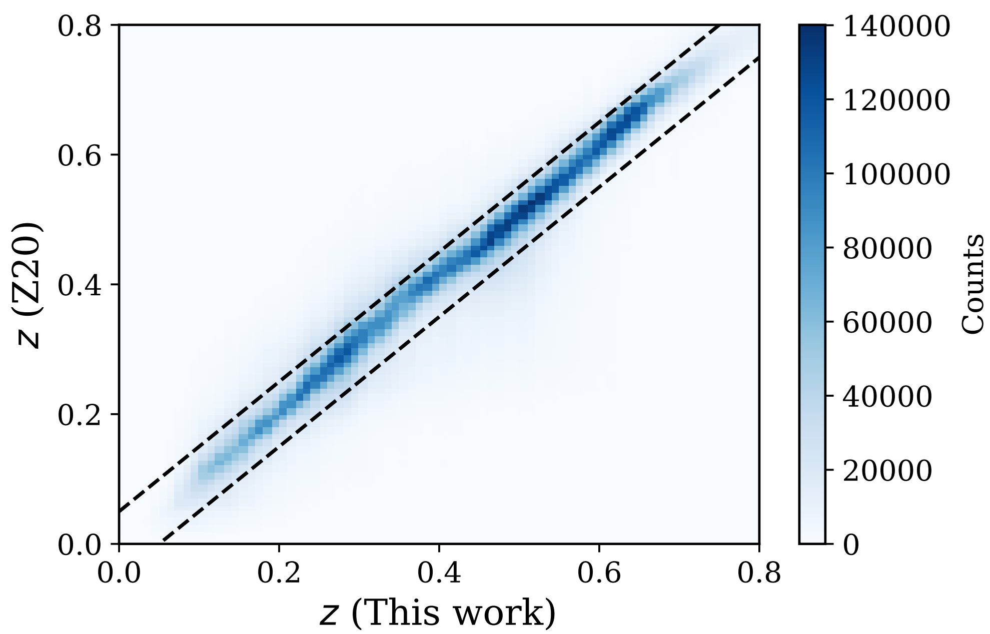
Covariance from 50 simulations for modes between 10<l<150, with mask and shot noise.

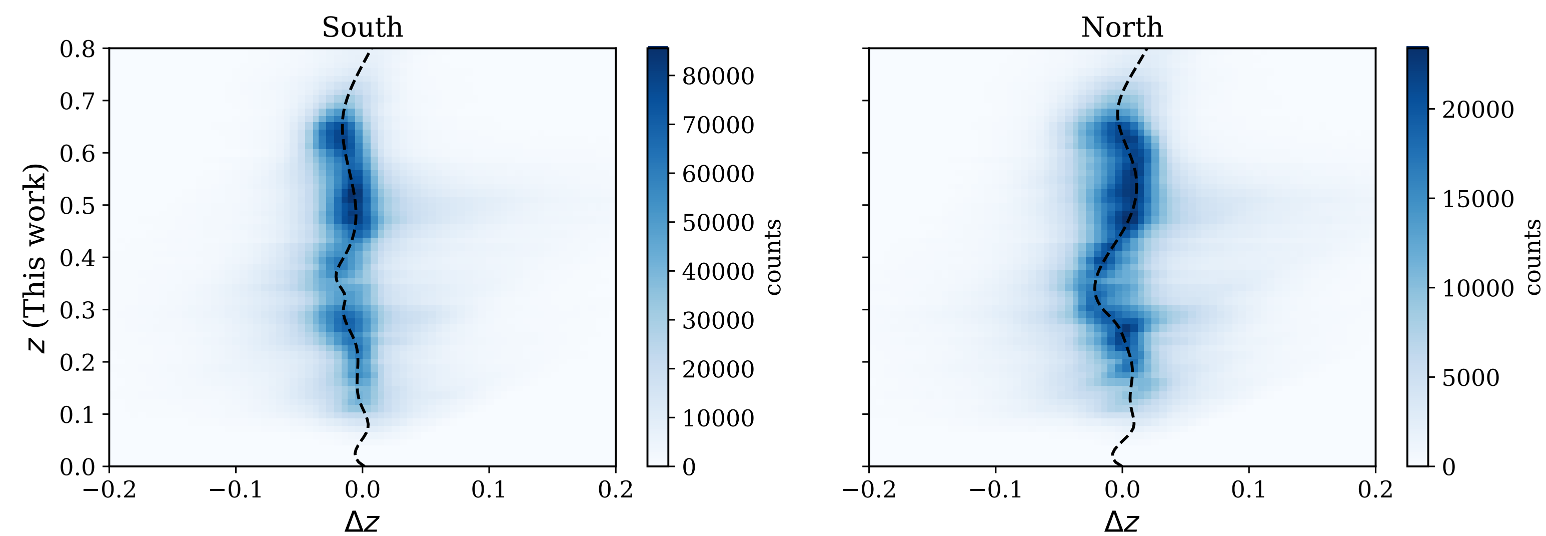
2-bias model

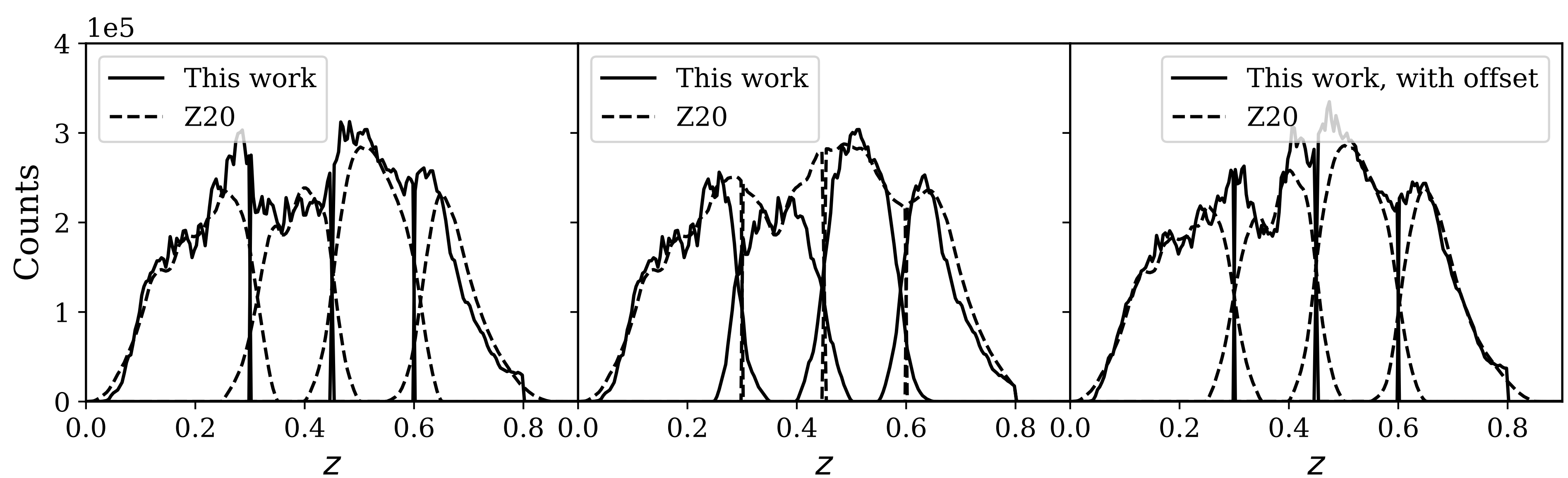


The ratio between data and model with a constant bias show a change at transition between linear and non-linear scales. The ratio on either end of the scales seem flat.

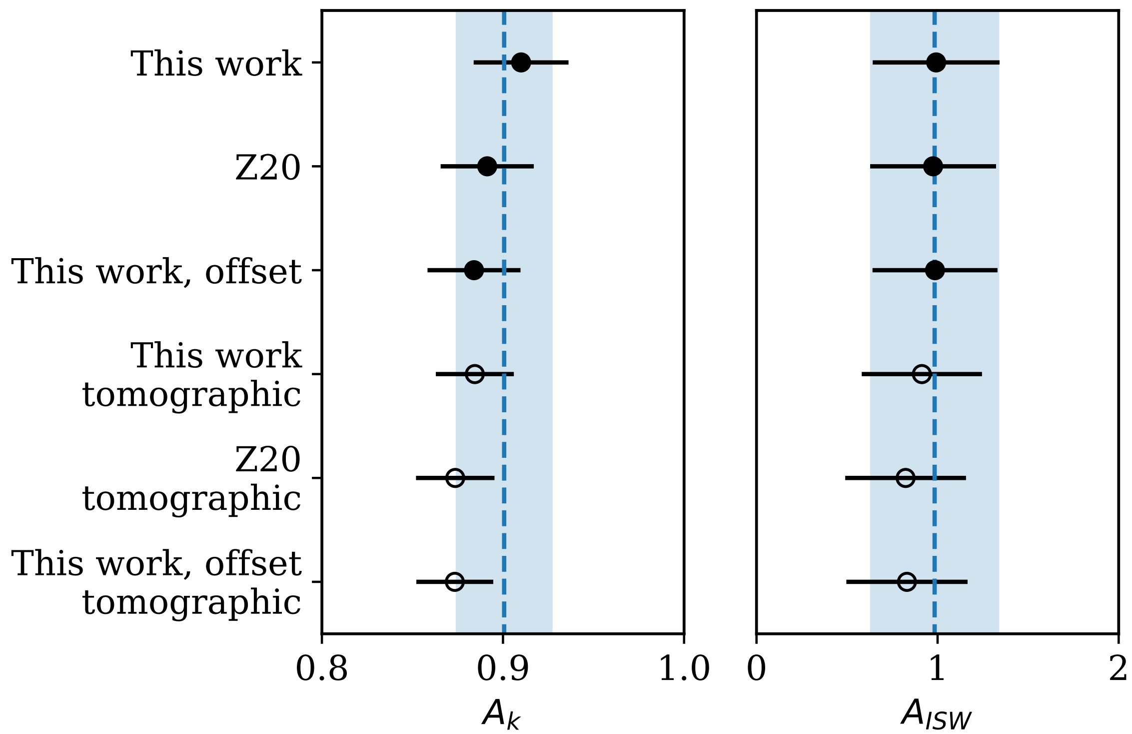
Comparison between our photo-z and [Zhou et. al. 2020]







Systematic tests



Parameters	bin0	bin1	bin2	bin3	combined	Un-binned
Redshift	$0 < z \leq 0.3$	$0.3 < z \leq 0.45$	$0.45 < z \leq 0.6$	$0.6 < z \leq 0.8$	-	$0 < z \leq 0.8$
Marginalized over $p(z)$						
b_1	1.25 ± 0.01	1.53 ± 0.02	1.54 ± 0.01	1.86 ± 0.02	-	-
b_2	1.27 ± 0.01	1.85 ± 0.03	1.82 ± 0.01	2.23 ± 0.02	-	-
A_k	0.91 ± 0.05	0.82 ± 0.04	0.94 ± 0.04	0.90 ± 0.04	0.89 ± 0.02	-
$A_{\rm ISW}$	0.52 ± 0.78	1.20 ± 0.63	1.48 ± 0.61	0.18 ± 0.67	0.91 ± 0.33	-
Best-fit $p(z)$						
b_1	1.25	1.56	1.53	1.83	-	1.43
b_2	1.26	1.88	1.84	2.19	-	1.59
A_k	0.91 ± 0.05	0.80 ± 0.04	0.94 ± 0.04	0.91 ± 0.04	0.88 ± 0.02	0.91 ± 0.03
$A_{\rm ISW}$	0.52 ± 0.75	1.17 ± 0.58	1.44 ± 0.52	0.18 ± 0.67	0.91 ± 0.33	0.99 ± 0.35
Zhou et. al.						
b_1	1.25	1.54	1.55	1.90	-	1.44
b_2	1.26	1.87	1.90	2.21	-	1.62
A_k	0.91 ± 0.06	0.81 ± 0.04	0.93 ± 0.04	0.87 ± 0.04	0.87 ± 0.02	0.89 ± 0.03
$A_{\rm ISW}$	0.50 ± 0.79	1.03 ± 0.59	1.37 ± 0.55	0.20 ± 0.63	0.82 ± 0.33	0.98 ± 0.35
Offset						
b_1	1.28	1.52	1.54	1.89	-	1.45
b_2	1.30	1.86	1.87	2.20	-	1.64
A_k	0.89 ± 0.05	0.81 ± 0.04	0.93 ± 0.04	0.89 ± 0.04	0.87 ± 0.02	0.88 ± 0.03
$A_{\rm ISW}$	0.45 ± 0.81	1.05 ± 0.58	1.32 ± 0.56	0.25 ± 0.46	0.83 ± 0.33	0.99 ± 0.35
AvERA model						
b_1	1.16	1.34	1.25	1.46	-	1.23
b_2	1.11	1.50	1.45	1.75	-	1.33
A_k	0.97 ± 0.06	0.80 ± 0.04	0.91 ± 0.04	0.85 ± 0.04	0.87 ± 0.02	0.91 ± 0.03
$A_{\rm ISW}$	0.24 ± 0.35	0.48 ± 0.25	0.55 ± 0.23	0.07 ± 0.24	0.35 ± 0.13	0.39 ± 0.14