EMU simulations for a cosmic magnification test of GR

By Albany Asher
PhD candidate, WSU / CSIRO

Primary supervisor: Dr Luke Barnes
Co-supervisors: Professor Ray Norris, Professor David Parkinson, Professor Miroslav Filipović & Dr Nithyanandan Thyagarajan

The Evolutionary Map of the Universe (EMU) Survey

- The EMU survey (Norris et al. 2011) is a wide-field radio continuum galaxy survey currently being conducted by the Australian Square Kilometre Array Pathfinder (ASKAP) radio telescope.
- ASKAP consists of 36 x 12m antennas, with baselines up to 6km, and has an instantaneous field of view (31 deg^2).
- The EMU survey covers the entire Southern Sky, extending North to +30 degrees in declination, in the 800 - 1100 MHz frequency range.
- The survey began in late 2022 and will detect ~40 million radio galaxies by 2027.

Image credit: CSIRO (Norris et al. 2011)

ASKAP-EMU goal: Testing Einstein's gravity on cosmological scales

- Testing GR on cosmological scales is a key science goal of the ASKAP-EMU cosmology project.

- Theoretical community recommends a large-scale radio continuum galaxy survey for this type of test.

- Cross-correlate radio galaxies ($z>1$) with optical galaxies ($z<1$) and measure weak gravitational lensing effects (i.e. cosmic magnification).

- Distortion of light is small, hence tens of millions of galaxies are required to generate a statistically-significant cross-correlation signal.

Image credit: CSIRO

Cosmic magnification

- Occurs due to distortions induced by large-scale structures along the line of sight to high-z galaxies.

- Background galaxy light will:

  - Magnify when subjected to weak gravitational lensing by an over-dense region (such as galaxy clusters).
  - Demagnify when lensed by under-dense regions (such as voids).

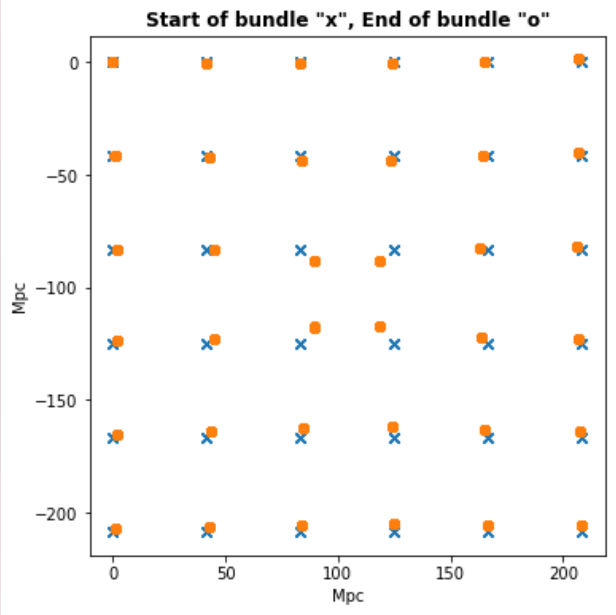
- Cosmic magnification is represented by the formula: $\mu = \frac{image\ area}{source\ area}$

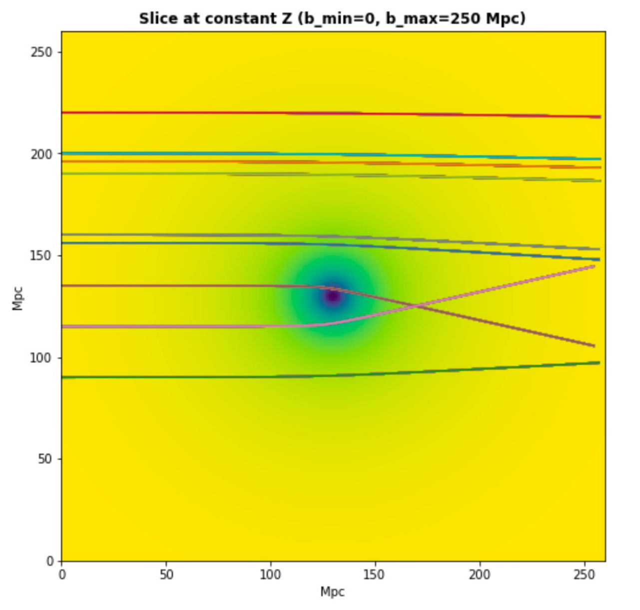
- When testing GR, our concern will be changes in the brightness distribution.

- Galaxies will be treated as point sources.

EMU simulations: overall objective

- **Part 1:** Create a simulation and analysis pipeline.
  - Make predictions of weak lensing effects.
  - Run auto/cross-correlations and measure angular correlation function w(θ).
  - Conduct cosmological analyses.
- **Part 2:** Measure w(θ) with and without a predicted lensing effect using the ray-tracing algorithm Developed during my MRes degree.





Galaxy clustering statistics: $w(\theta)$ and C_ℓ

- A weak lensing study entails the measurement of two important galaxy clustering statistics: the **angular correlation function (ACF)**, represented by **$w(\theta)$.**

- The ACF tells us the excess probability of finding a galaxy (or number of galaxies) at some angular separation from another galaxy. The formalism is (Landy-Szalay version):

$$\omega(\theta) = \frac{\overline{DD}(\theta) - 2\overline{DR}(\theta) + \overline{RR}(\theta)}{\overline{RR}(\theta)}$$

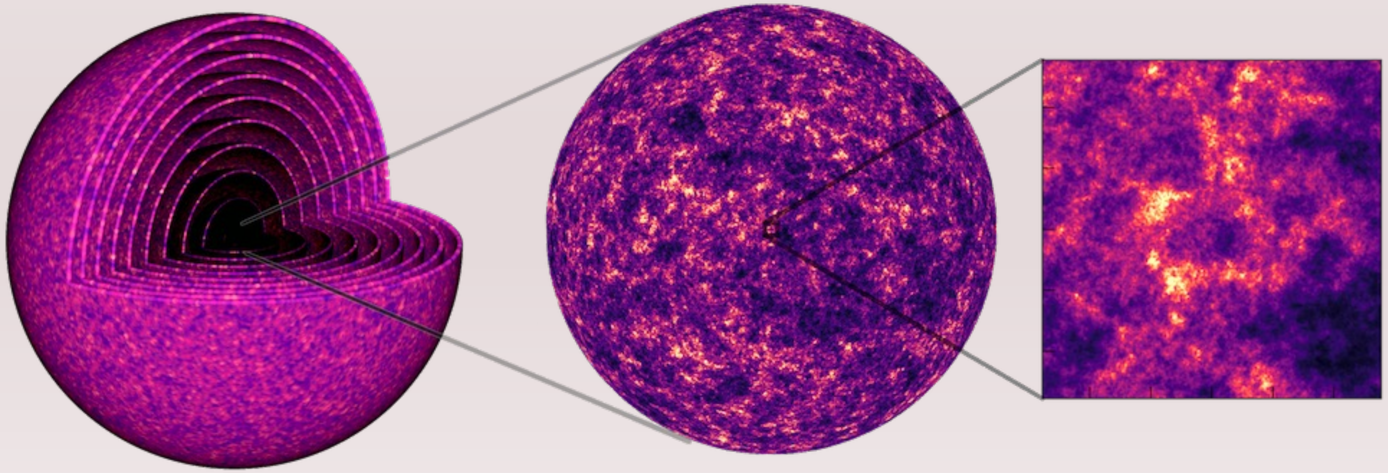
- The second is the **angular power spectrum (APS)**, which measures the contribution to the statistical distribution of galaxies on the sky from different angular scales.

- I calculate the quantity known as **C_ℓ**, which measures fluctuations in the galaxy density on angular scales θ ~180 degrees / ℓ. We can calculate the APS from the 3D power spectrum $P(k)$ using the following equation:

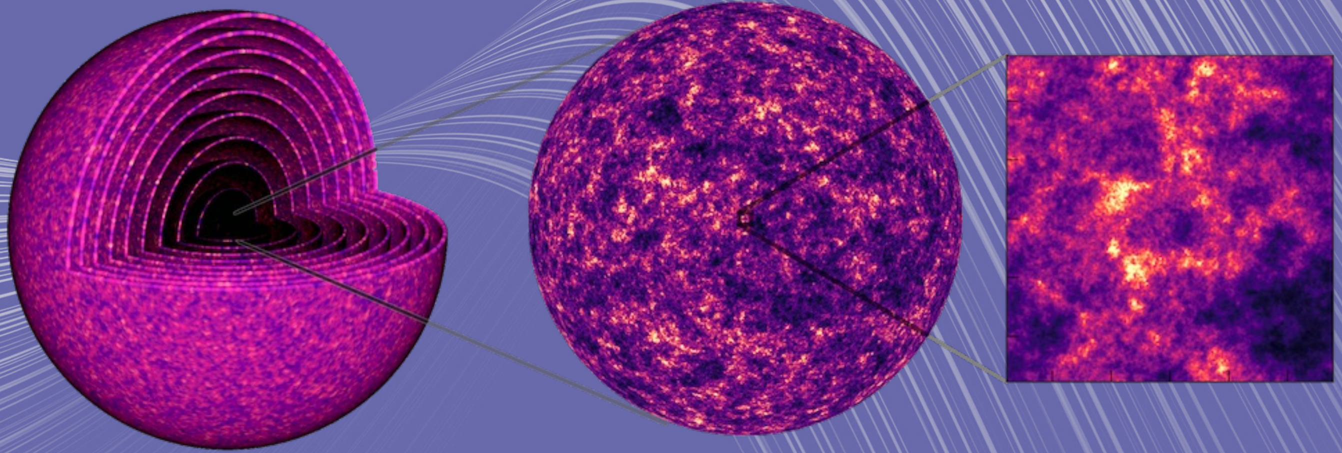
$$C_l = \frac{2}{\pi} \int dk k^2 P(k) [W_l(k)]^2$$

EMU SIMULATION & ANALYSIS PIPELINE

- **Step 1:** **Generate mock galaxy catalogues**
- **Step 2:** **Make theoretical predictions of correlation statistics**
- **Step 3:** **Compute auto/cross-correlations**
- **Step 4:** Bootstrap resampling
- **Step 5:** **Generate covariance / correlation matrices**
- **Step 6:** Chi-squared estimator
- **Step 7:** **Log-likelihood grid**
- **Step 8:** MCMC analysis
- **Step 9:** **Lensed / unlensed cross-correlations**



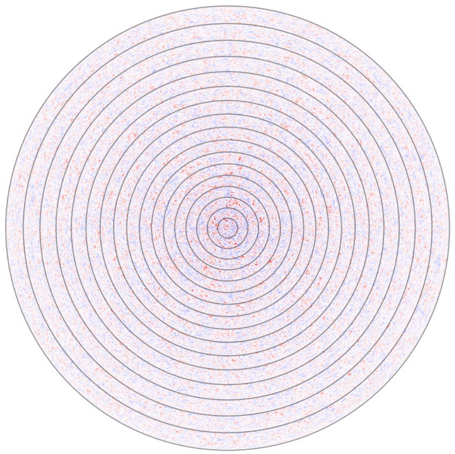
EMU SIMULATIONS PIPELINE



STEP 1: GLASS - GENERATOR FOR LARGE SCALE STRUCTURE

Tessore et al. (2023)

GLASS code

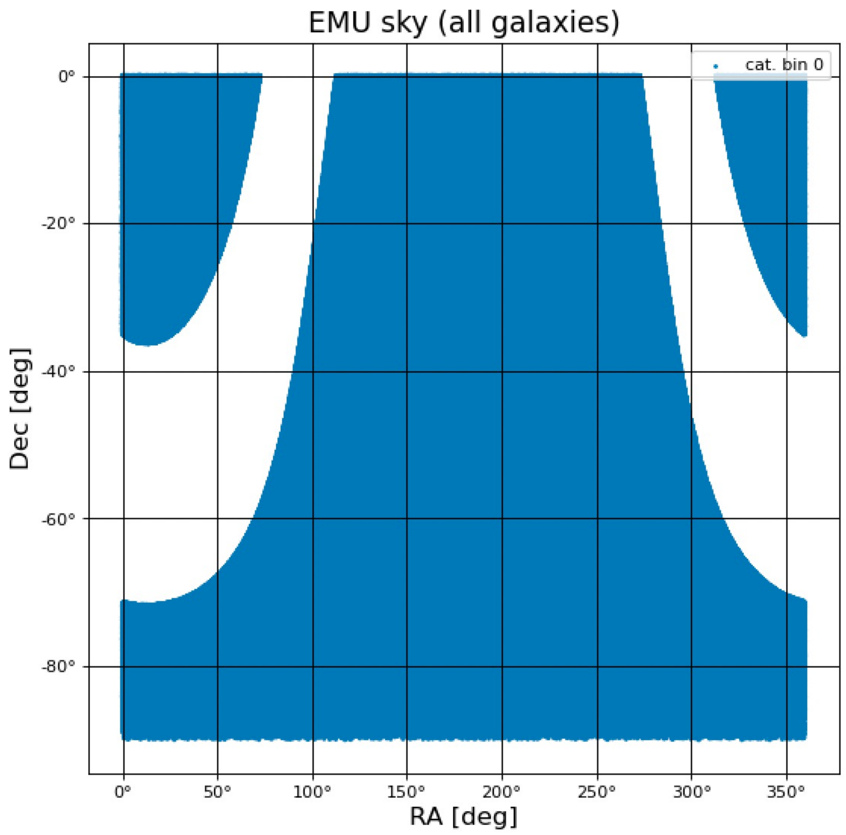


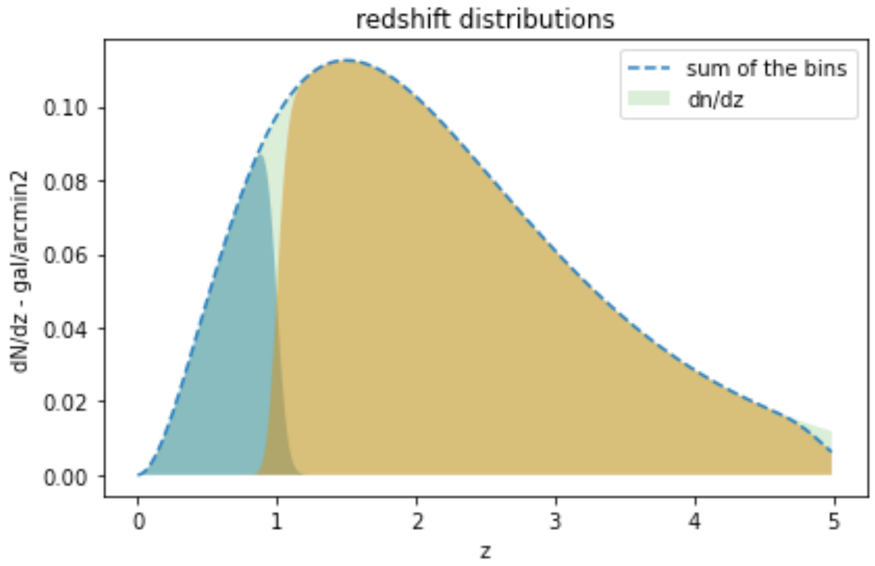
- Simulates galaxy surveys to conduct tests with percent level accurate two-point statistics of galaxy clustering and weak lensing.

- GLASS builds lightcone through a sequence of nested shells.

- Simulates the evolution of the comoving Universe in concentric spherical layers to z=5.

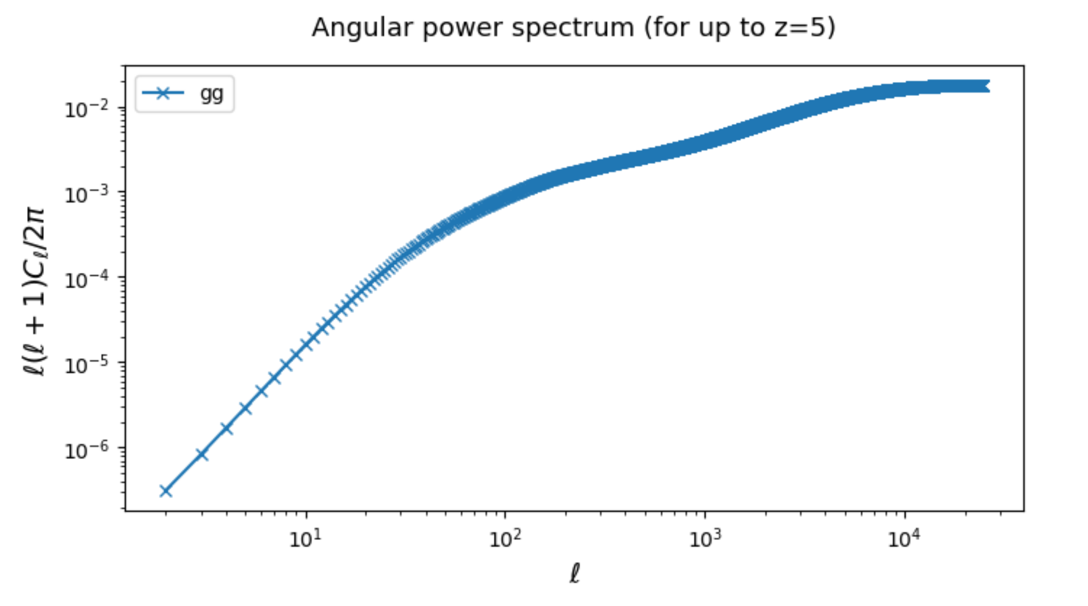
- Outputs a mock galaxy catalogue of RAs, DECs, Zs etc. for the section of sky being studied.

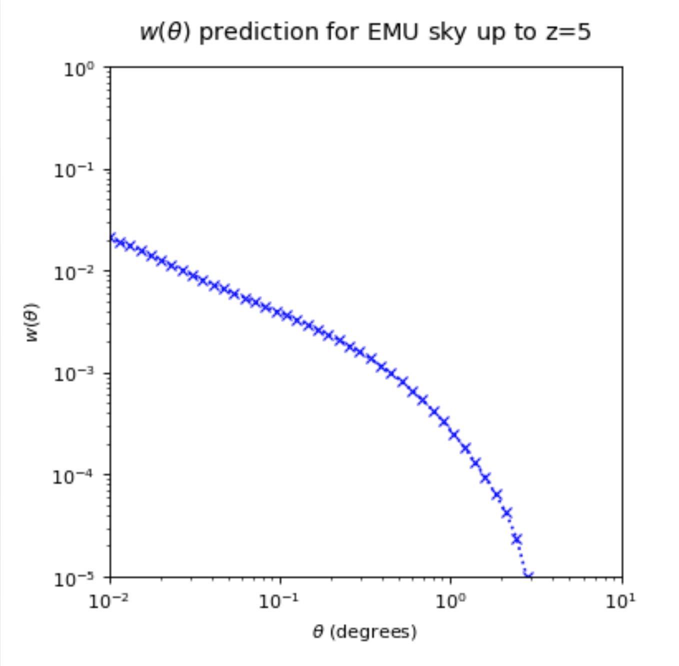




pyccl code – APS and ACF outputs

- State-of-the-art cosmology code to make theoretical predictions for large scale galaxy surveys.
- pyccl projects the 3D spectrum into the 2D $C\ell$ (output below left).
- pyccl legendre transforms the new $C\ell$ to get our prediction of w(Θ)- see 2D output on the right.





TreeCorr code

- **Step 1: auto/cross-correlate data from galaxy catalogues**

- **Step 2: generate randoms**

- Whilst testing the pipeline, we've been using the same amount of randoms as the data.

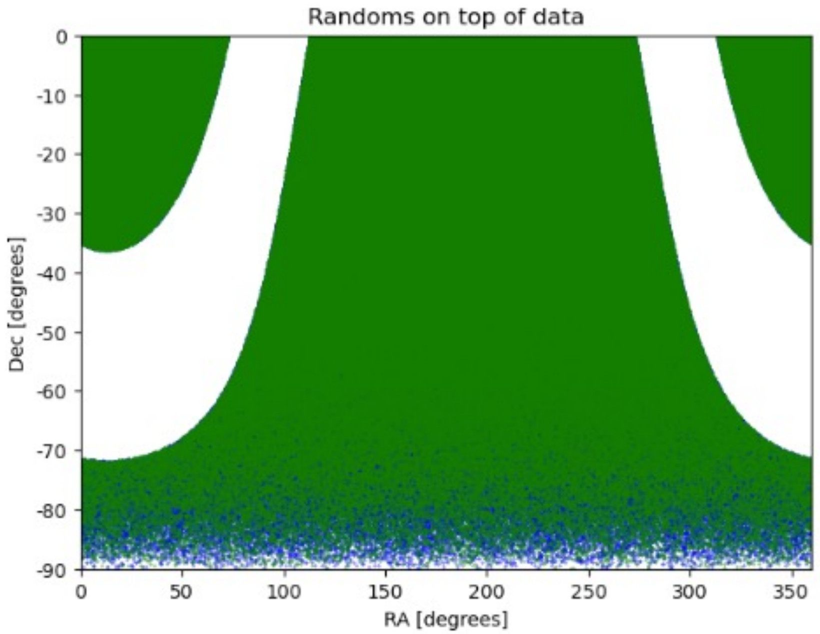
- **Step 3: masking**

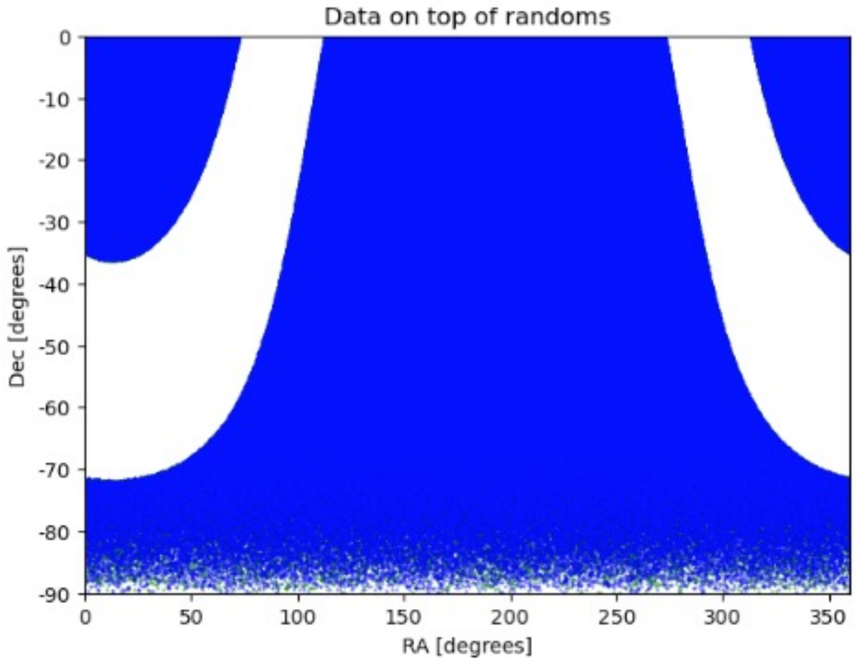
o i.e. if the catalogue data is masked, the randoms have to be masked too.

- **Step 4: auto/cross-correlate randoms**

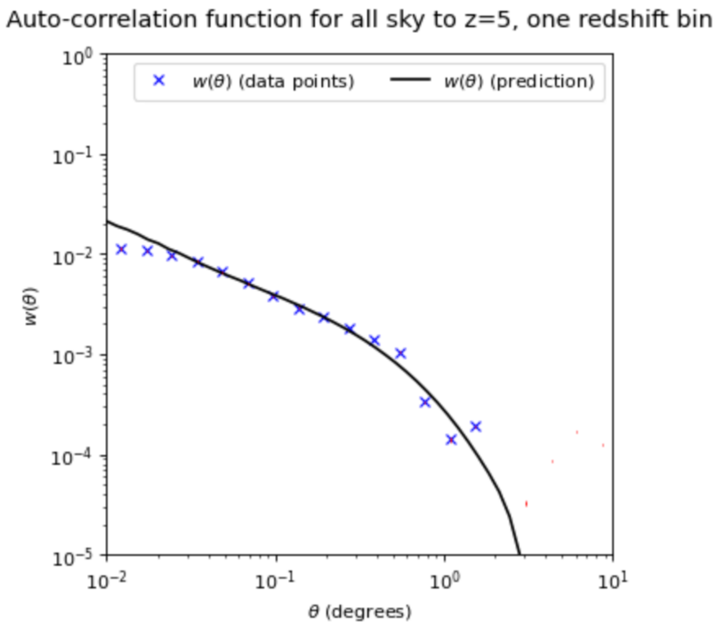
- **Step 5: cross-correlate data with randoms**

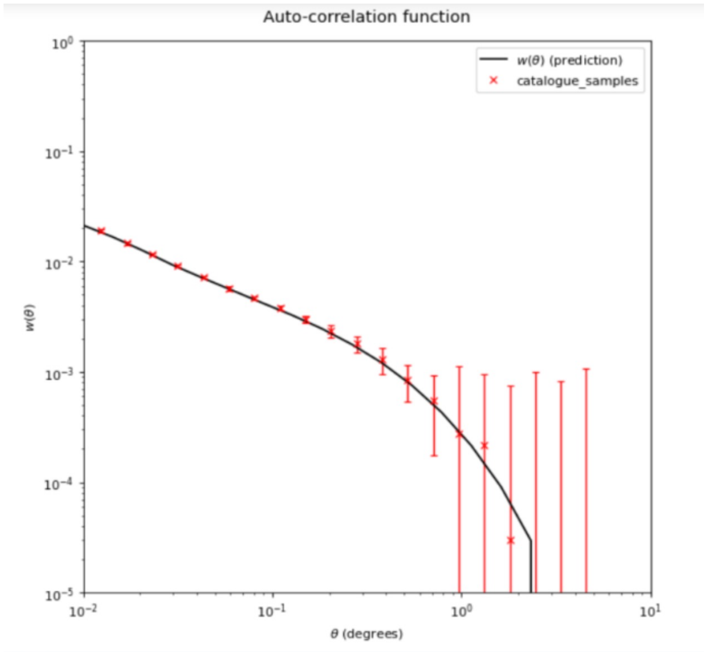
o Formalism (Landy-Szalay version): $\omega(\theta) = \frac{\overline{DD}(\theta) - 2\overline{DR}(\theta) + \overline{RR}(\theta)}{\overline{RR}(\theta)}$

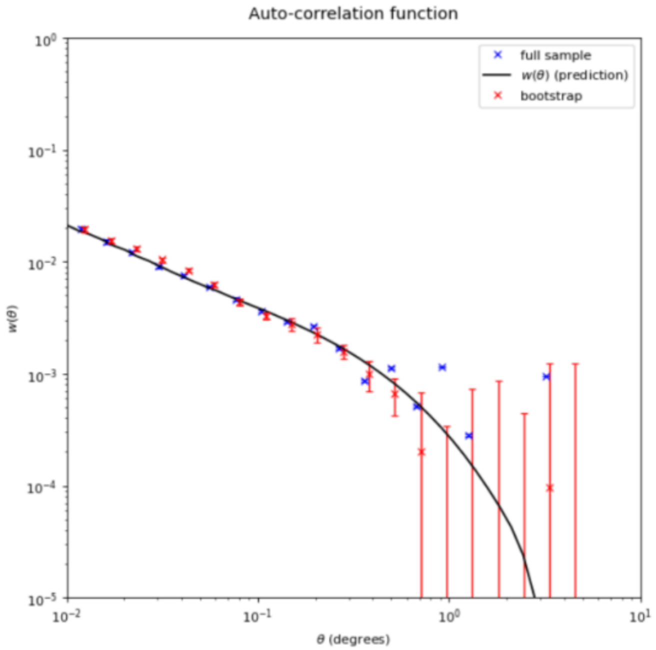




TreeCorr code – ACF outputs

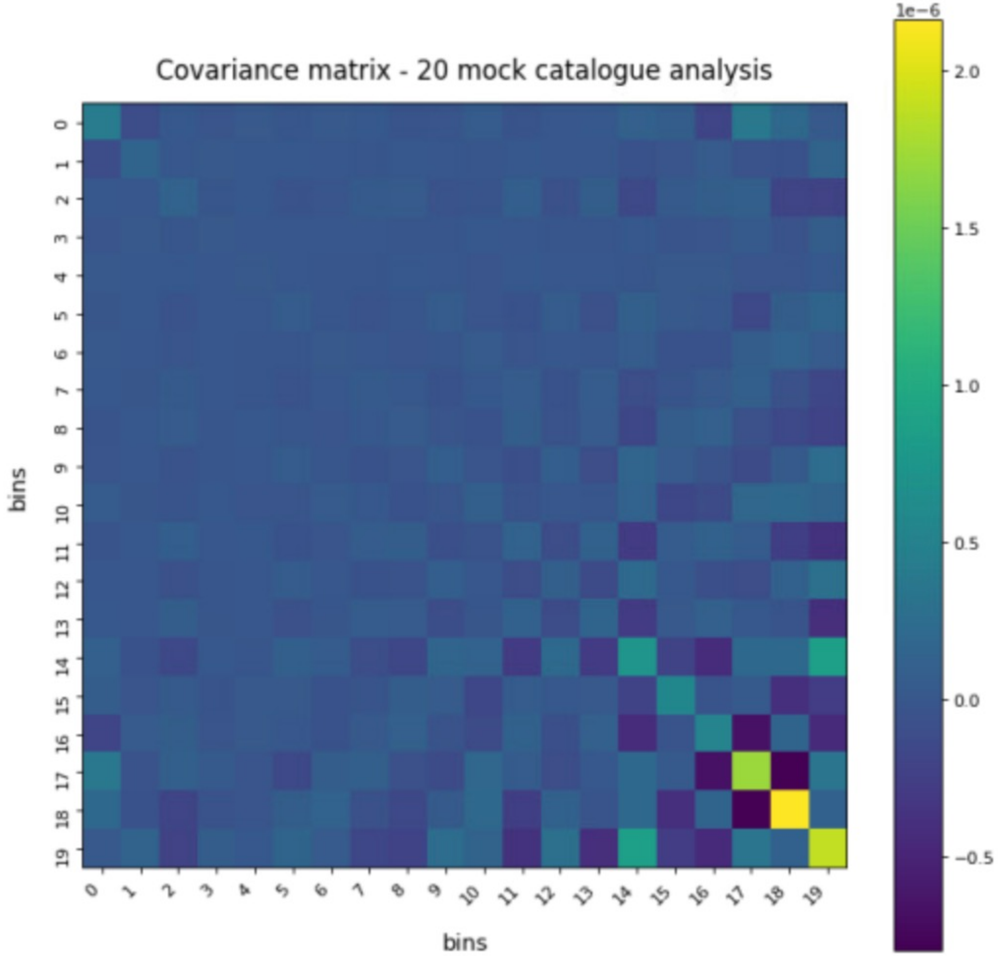


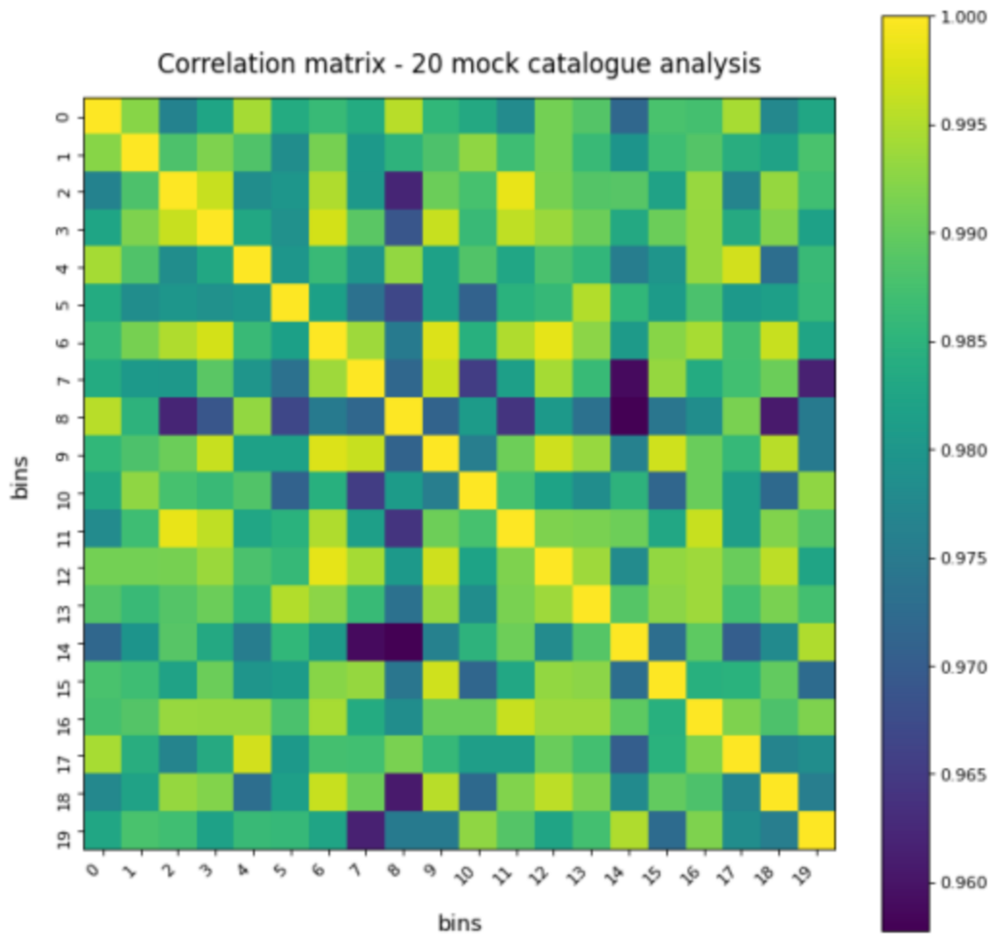




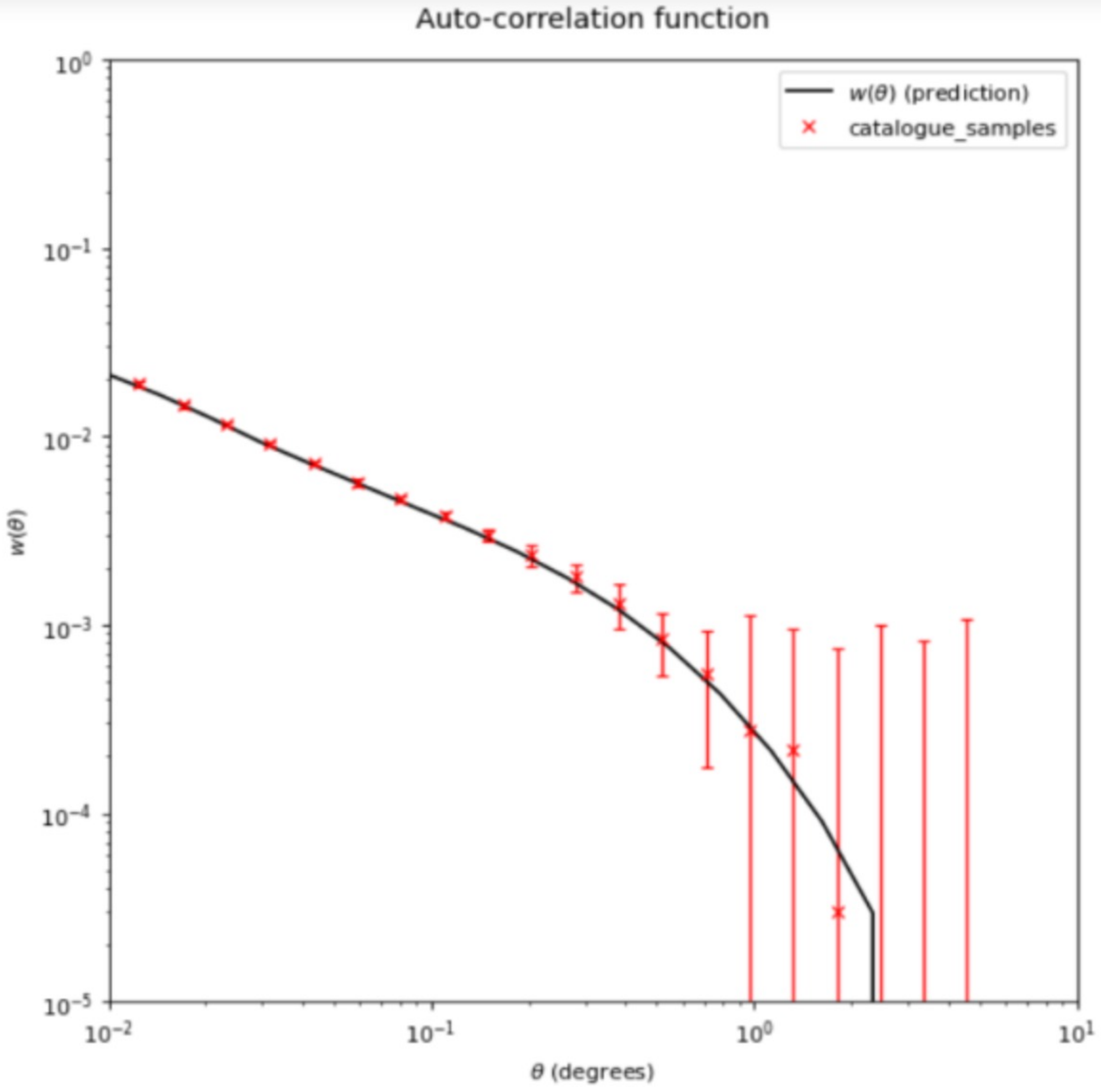
Covariance Matrix / Correlation Matrix

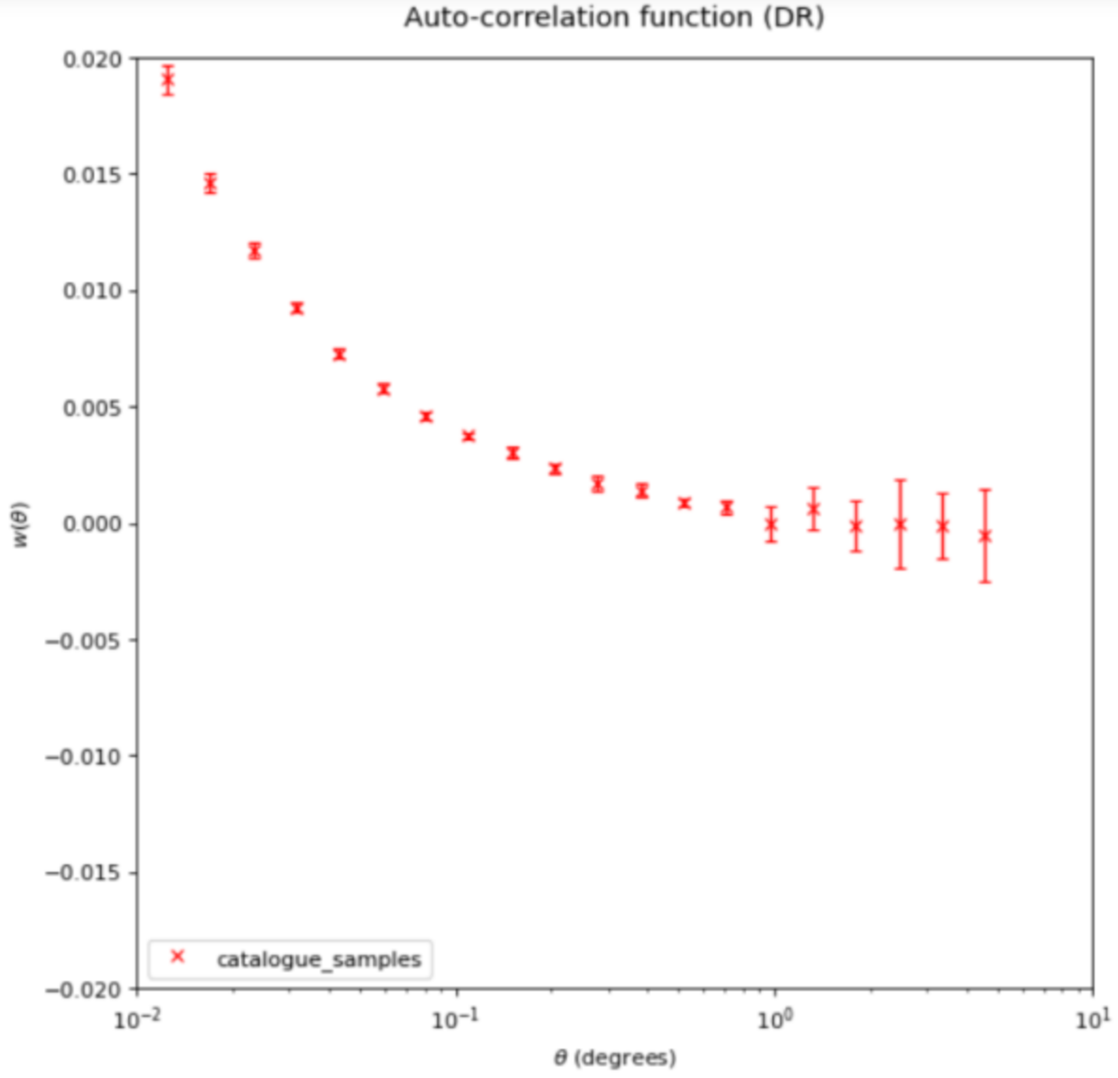
Covariance matrix	Correlation matrix





nside=8192 (logscale for both axes)	nside=8192 (linear y-axis, logscale x-axis)





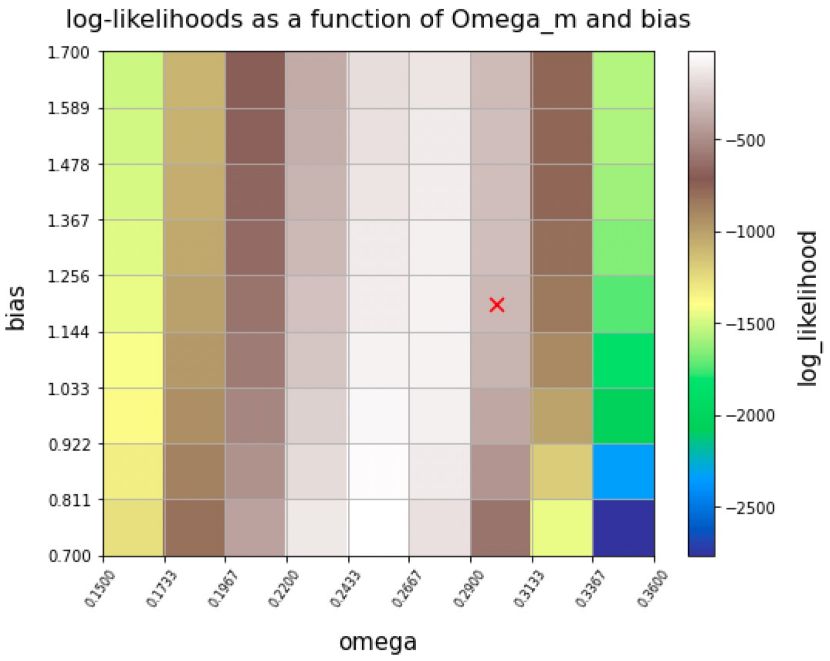
Exploring parameter space: Log-likelihood grid

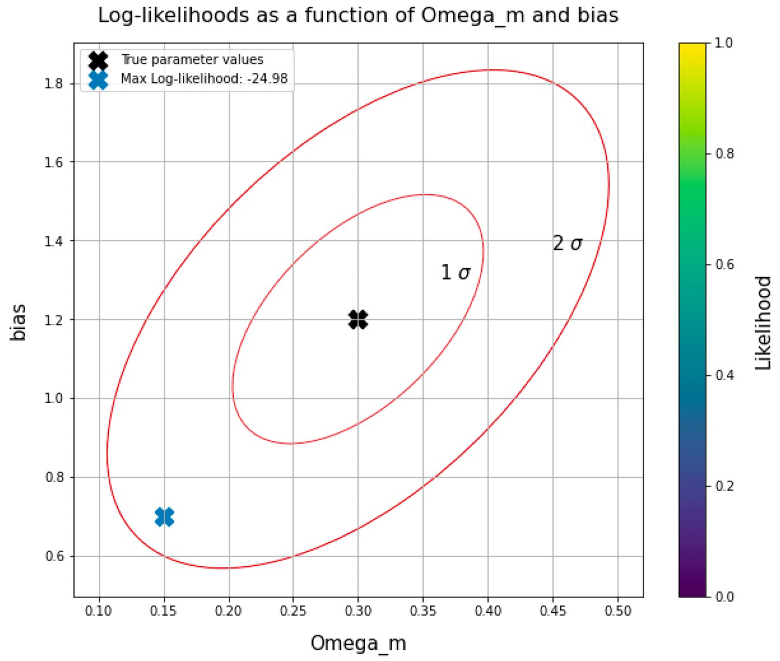
- A log-likelihood grid is a simple yet effective way to test whether our model fits the data for a minimal number of parameters (for numerous parameters, we use our Metropolis-Hastings MCMC code).

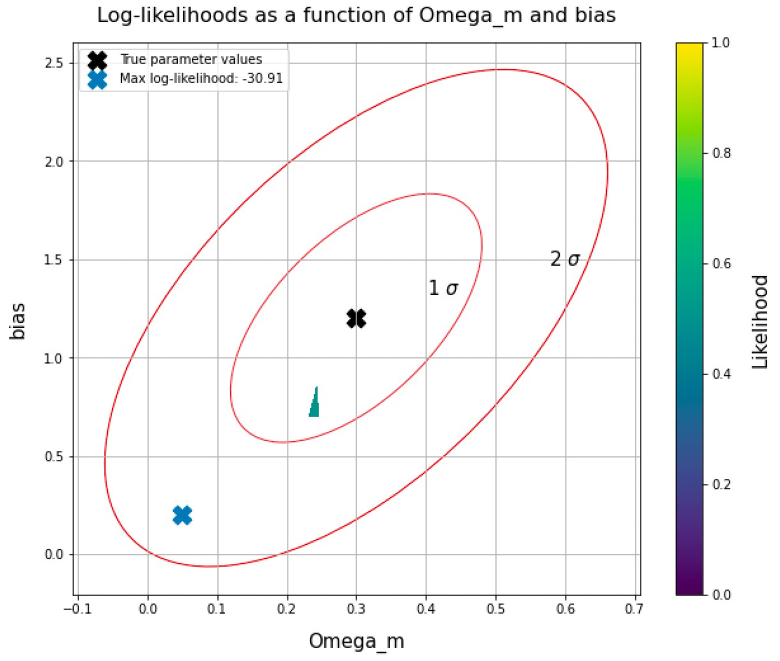
- A grid allows us to see some results swiftly, using 100 or 1000 samples.

- I tested log-likelihoods as a function of Ω_m and galaxy bias, with the latest test in the ranges of: **$0.15 < \Omega_m < 0.36$**, and **$0.7 <$ bias < 1.7**.

- For 20 data points, we expect a chi-squared value of ~20 and max log-likelihood of **~ -20**. For a mere 100 samples, the max log-likelihood is **-24.98** (indicated by the blue marker in plot 2).



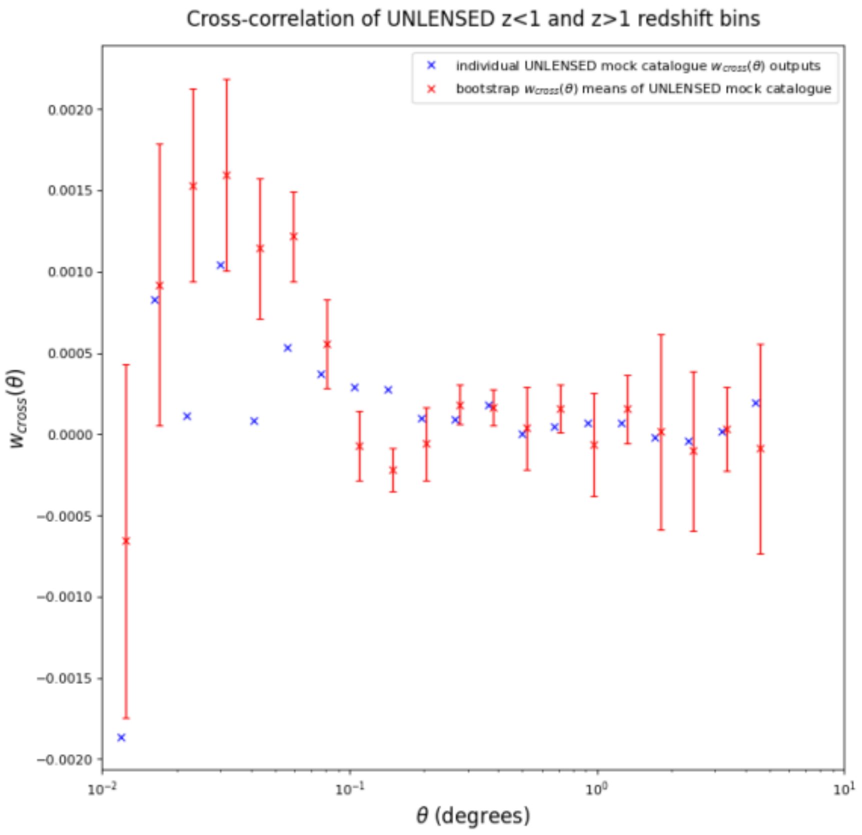


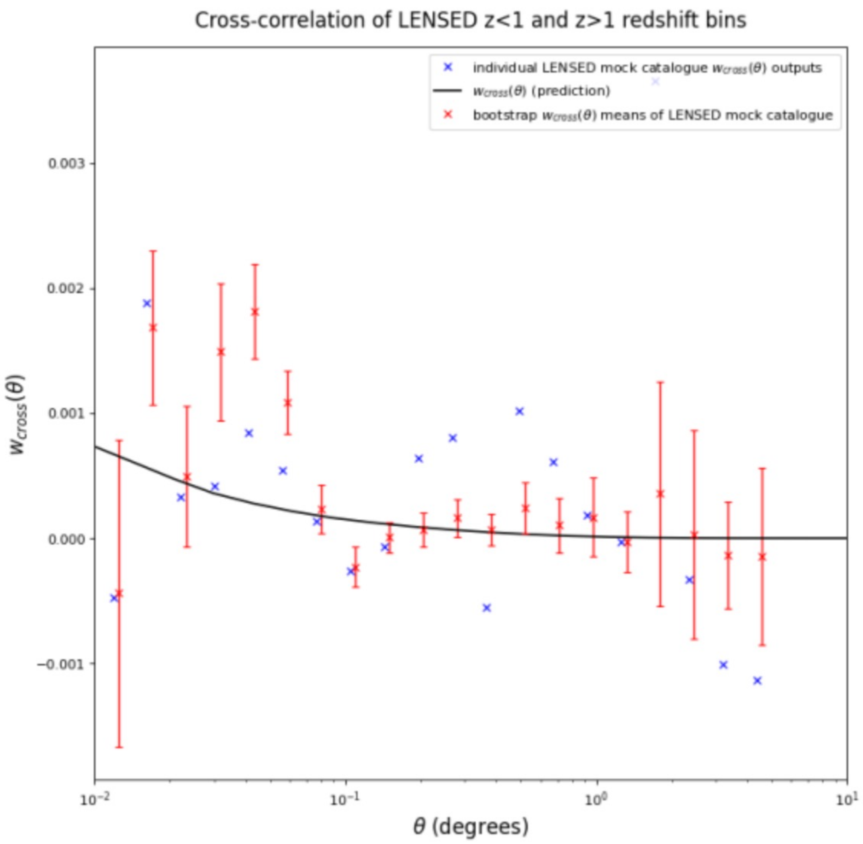


UNLENSED vs LENSED CROSS-CORRELATIONS

- Cross-correlate two redshift bins in TreeCorr WITHOUT and then WITH lensing effects.
- The expectation is that the results will align around the zero region (more so for the unlensed cross-correlation).

UNLENSED	LENSED





What's next?

Complete quality fitting for the log-likelihood grid AND complete paper 1.

Ray-tracing: simulate the real EMU sky. Measure $w(\theta)$ with/without predicted lensing effects.

Using RACS/Legacy survey data, measure the cross-correlation due to the cosmic magnification effect.

In 2025, conduct a preliminary test of GR on cosmological scales.

THANK YOU