Simulation-Based Inference Analysis of KiDS-1000 Cosmic Shear

[arXiv:2404.15402]

M. von Wietersheim-Kramsta,[1,2*] K. Lin,[1] N. Tessore,[1] B. Joachimi,[1]
A. Loureiro,[3] R. Reischke,[4,5] A.H. Wright[5]

[1]University College London, [2]Durham University, [3]Stockholm University, [4]Argelander-Institut für Astronomie, [5]Ruhr University Bochum

*maximilian.von-wietersheim-kramsta@durham.ac.uk

Introduction

Cosmic shear, the weak gravitational lensing effect on distant galaxies due to matter in the foreground, is a powerful tool to study the distribution of matter, to probe its large-scale structure, and infer the cosmological model of the Universe. Standard analyses are typically based on the assumption of a Gaussian likelihood with a parameter-independent covariance, but these assumptions may not hold for all observables, scales and/or all systematics. Simulation-based inference (SBI) addresses this by evaluating an effective likelihood from forward-simulations which map parameters to data vectors. This has the following advantages:

- Full Bayesian uncertainty modelling from data to parameters.
- Arbitrary levels of complexity can be incorporated the uncertainty model.
- Likelihood can take any form and the noise can be parameter-dependent.
- Amortised inference: model evaluations are only necessary once to characterise the likelihood. When the data or the priors change, the posteriors can be trivially re-evaluated.

We apply SBI to two-point shear statistics using a forward model which captures many physical and observational systematics which are typically not considered in weak lensing analyses. With this, we aim to give more insight into the robustness against systematics of standard weak lensing analyses to better understand the σ_8-tension.

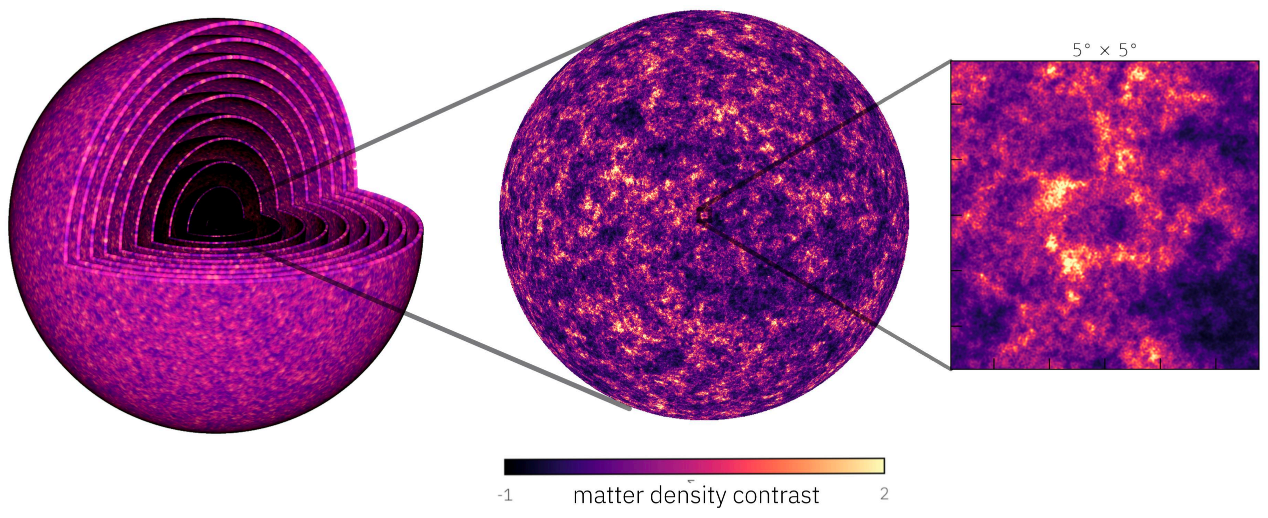

Figure 1: Rendering of the geometry of log-normal random matter fields simulated with the Generator for Large-Scale Structure (GLASS; [6]). The left shows a simulated light-cone made of up concentric discrete shells with the observer at the centre. For a given shell, the matter field is simulated as a projected two-dimensional overdensity field. Figure from [6].

1 KiDS-1000 Data and the Forward Model

The Kilo-Degree Survey (KiDS) is a large public photometric galaxy survey conducted by the European Southern Observatory using the OmegaCAM CCD mosaic camera [7] which is attached to the 2.6 m VLT Survey Telescope (VST). The fourth data release (KiDS-1000) covers approximately 1,000 deg^2, and measures positions, shapes and photometric redshifts of $\sim 10^7$ galaxies split across 5 tomographic bins.

To learn the likelihood of the two-point shear statistics, we propose an efficient forward model based on log-normal random matter fields (see Figure 1) characterised by a three-dimensional matter power spectrum. The model incorporates baryonic feedback and intrinsic alignments, while also incorporating observational systematics when sampling galaxies: masking, photometric redshift uncertainties, shape calibration biases, shape and shot noise, and variable depth. From the simulated catalogues, we measure the shear-shear pseudo-angular power spectra, pseudo-Cls. The stochastic nature of this model allows us to compute a single cosmology evaluation within 20 minutes on a single core. Here, we distinguish between two models:

- Standard isotropic systematics: standard modelling assumption consistent with previous work (e.g. [2]), i.e. all systematics are isotropic for a given tomographic bin.
- Anistropic systematics: the model allows for anisotropies in the galaxy selection (variable depth, see Figure 2) as well as anisotropies in the shear bias due to PSF variations. The former correlates strongly with the photometric redshifts, galaxy densities and shapes.

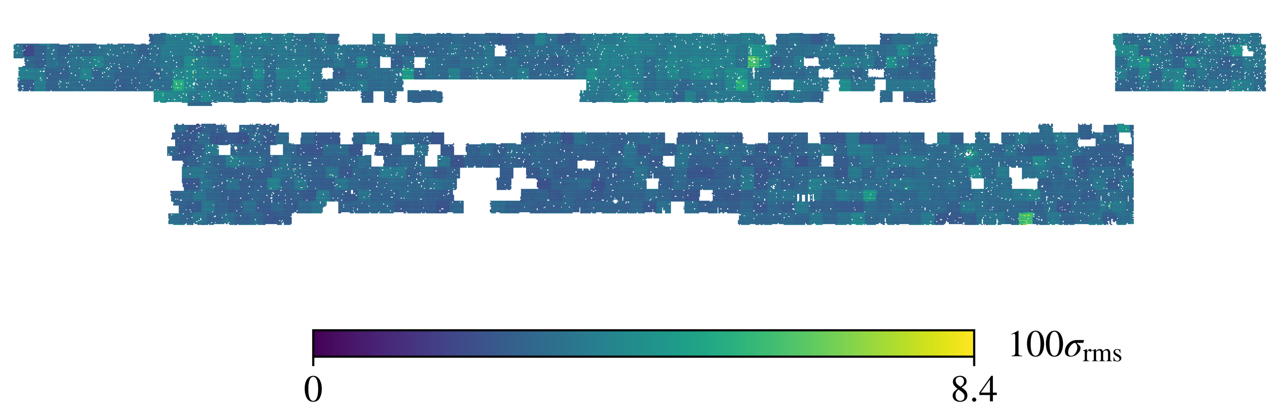

Figure 2: Cartesian spatial map ($N_{\rm side} = 1024$) of root-mean-square of the observed background noise, $\sigma_{\rm rms}$, throughout the KiDS-1000 North field in the upper panel and the KiDS-1000 South field in the lower panel.

2 Methodology

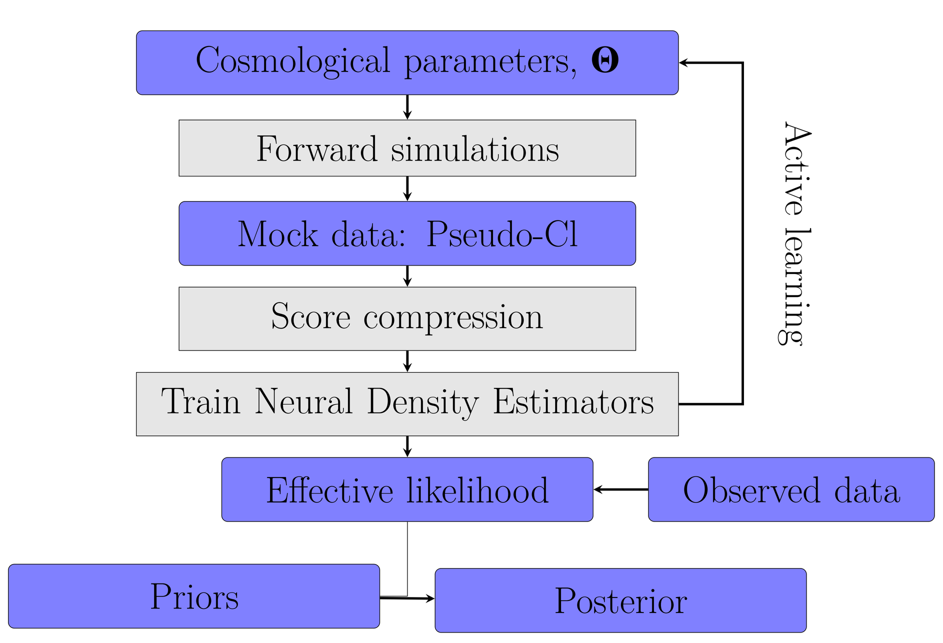

Figure 3: Flowchart describing the structure of the simulation-based inference pipeline.

The SBI is based on neural density estimation of the likelihood with active learning to infer the posterior distribution of spatially-flat ΛCDM cosmological parameters from 18,000 realisations from each model [3]. We choose to make use of Density Estimation Likelihood-Free Inference (DELFI, [1]) based on an ensemble of six independent conditional Masked Autoregressive Flows (MAFs; [4]) which are trained on score compressed data. We find that the learned posteriors are well covered, robust and unbiased.

3 Discussion and Conclusions

From the mock analyses, we find that the Gaussian likelihood assumption holds well for a fixed cosmology. However, when allowing the noise to vary with the model parameters, we find that the 1σ interval on $S_8 \equiv \sigma_8(\Omega_{\rm m}/0.3)^{0.5}$ increases by $\sim 30\%$. We find this effect is driven by the cosmology-dependence in the modelled cosmic variance as shown in Figure 4.

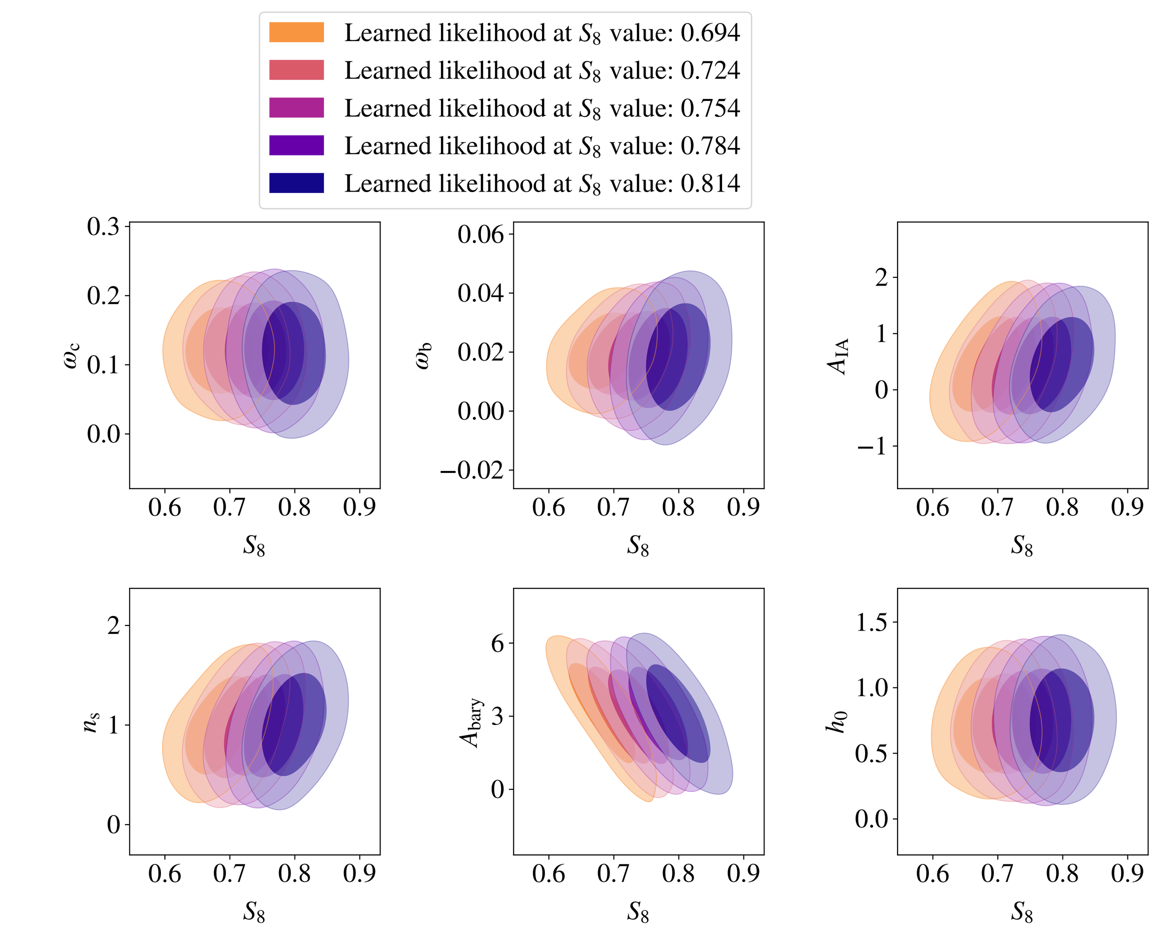

Figure 4: Likelihood marginals in the compressed data space for five different sets of cosmological parameters given the anisotropic systematics model within KiDS-SBI over the full prior space. The compressed data values are labelled according to the cosmological parameter with which they are most correlated. All other cosmological parameters are not varied between contours.

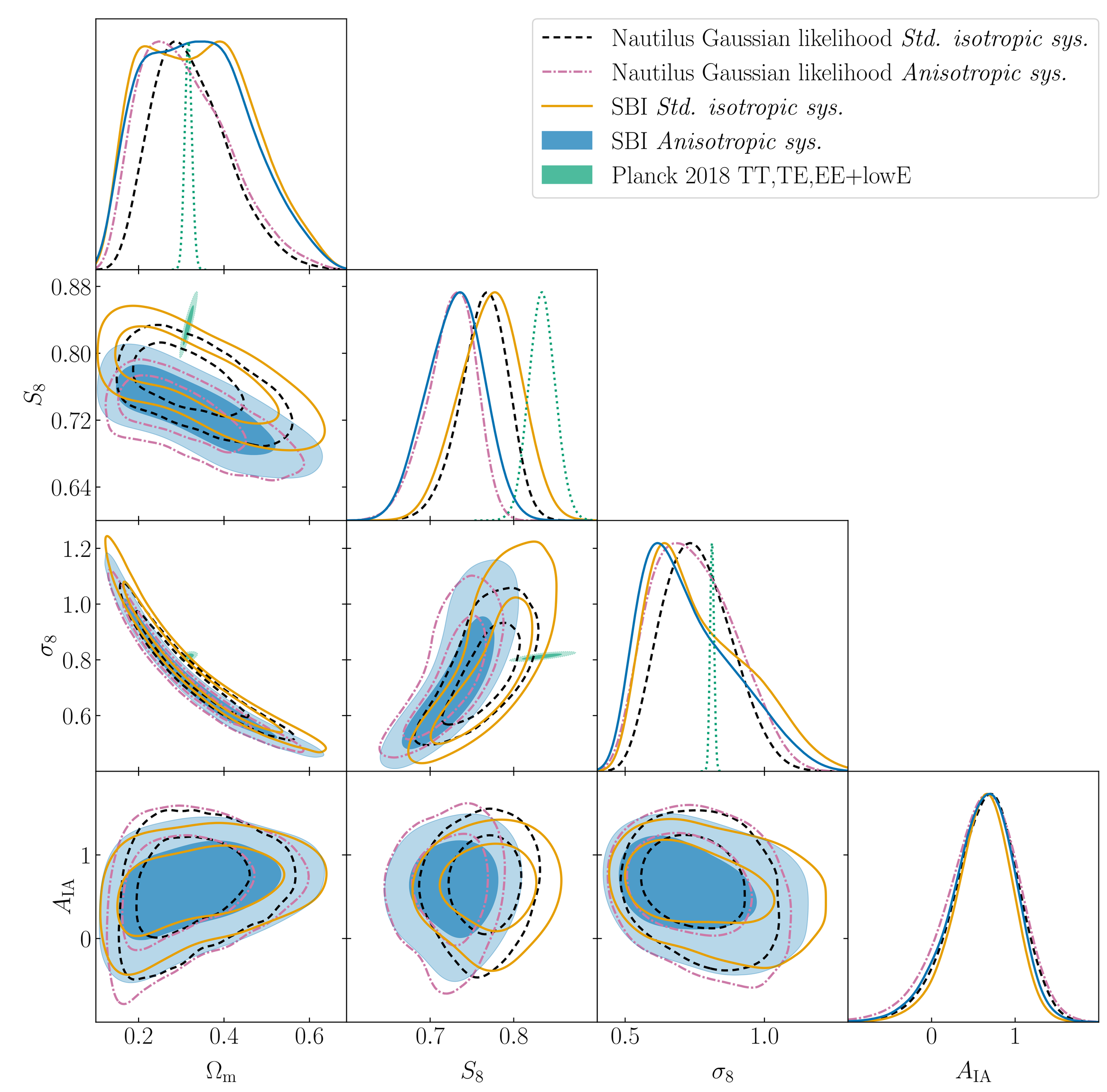

Figure 5: Posterior contours of the main constrained cosmological parameters from the KiDS-SBI analysis of the KiDS-1000 cosmic shear data assuming the anistropic systematics model (in blue), which incorporates additional systematics such as variable depth and shear biases, compared against posterior contours from other analyses. In pink, we show the contours for the equivalent standard analysis assuming a Gaussian likelihood. In orange, we show the posterior from the same data while assuming the standard isotropic systematics model, which considers the systematic effects which are typically modelled in standard cosmic shear analyses. In black, we show the posterior from a stardard analysis based on the standard isotropic systematics model. The green contour shows the posterior from the cosmic microwave background constraints [5].

Model	S_8	$\Omega_{\rm m}$	σ_8	ln(Z)	G.o.F. (PTE)
Anistropic sys.	0.731 ± 0.033	$0.337^{+0.097}_{-0.15}$	$0.73^{+0.10}_{-0.21}$	-14.18	0.84
Std. isotropic sys.	$0.772^{+0.038}_{-0.032}$	$0.333^{+0.093}_{-0.160}$	$0.78^{+0.12}_{-0.23}$	-15.07	0.86

Table 1: Mean marginals and 68% confidence intervals on the relevant cosmological parameters, the Bayesian evidence, Z, and the SBI goodness-of-fit as a probability-to-exceed (PTE) at the maximum-a-posteriori (MAP).

When applying the SBI based on both models to the KiDS-1000 weak lensing data, we obtain the posteriors shown in Figure 5. This shows that:

- We confirm the findings from Figure 4: the standard Gaussian likelihood analysis is consistently overconfident with respect to the SBI.
- When excluding the anistropic systematics in the data (variable depth and PSF variations), we find that this biases the inferred S_8 by 0.9σ or $\sim 5\%$.
- The latter also increases the relative uncertainty of S_8 by $\sim 6\%$.

Consequently, when considering the anistropic systematics model, we obtain a 2.9σ tension in S_8 with current constraints from the cosmic microwave background. Hence, Stage-IV weak lensing analyses, like Euclid, may have to drop the common assumption of a cosmology-independent uncertainty on shear two-point statistics, while also accounting for the impact of anisotropic systematics which can significantly bias the cosmological inference.

References

[1] Alsing et al. Fast likelihood-free cosmology with neural density estimators and active learning. MNRAS, 488(3):4440–4458, 2019.
[2] Asgari et al. KiDS-1000 cosmology: Cosmic shear constraints and comparison between two point statistics. A&A, 645:A104, January 2021.
[3] Lin et al. A simulation-based inference pipeline for cosmic shear with the Kilo-Degree Survey. MNRAS, 524(4):6167–6180, October 2023.
[4] Papamakarios et al. Masked autoregressive flow for density estimation. volume 30. Curran Associates, Inc., 2017.
[5] Planck Collaboration et al. Planck 2018 results. VI. Cosmological parameters. A&A, 2020.
[6] Tessore et al. GLASS: Generator for Large Scale Structure. The Open Journal of Astrophysics, 6:11, March 2023.
[7] Kuijken. OmegaCAM: ESO's Newest Imager. The Messenger, 146:8–11, December 2011.

Acknowledgements

MvWK thanks the Science and Technology Facilities Council for support. KL thanks the UCL Cosmoparticle Initiative. NT and BJ are supported by the ERC-selected UKRI Frontier Research Grant EP/Y03015X/1 and the UK Space Agency grants ST/W002574/1 and ST/X00208X/1. BJ is also supported by STFC Consolidated Grant ST/V000780/1. AL acknowledges support from the research project grant 'Understanding the Dynamic Universe' funded by the Knut and Alice Wallenberg Foundation under Dnr KAW 2018.0067. RR is supported by the European Research Council (Grant No. 770935). AHW is supported by the Deutsches Zentrum für Luft- und Raumfahrt (DLR), made possible by the Bundesministerium für Wirtschaft und Klimaschutz, and acknowledges funding from the German Science Foundation DFG, via the Collaborative Research Center SFB1491 "Cosmic Interacting Matters - From Source to Signal".