Simulation-based inference with the integrated 3PCF

David Gebauer

PhD Student with Cora Uhlemann

Funded by the European Union

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European Research Council

Established by the European Commission

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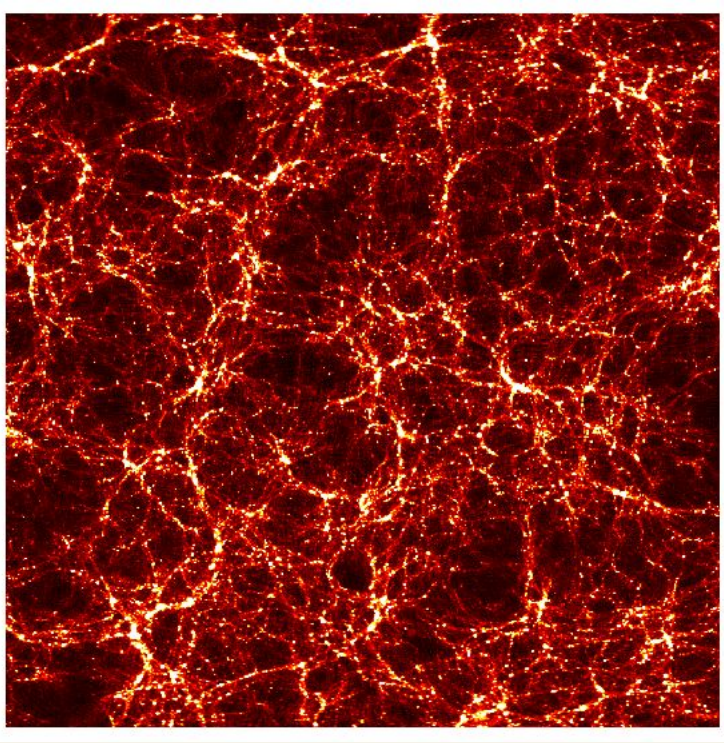
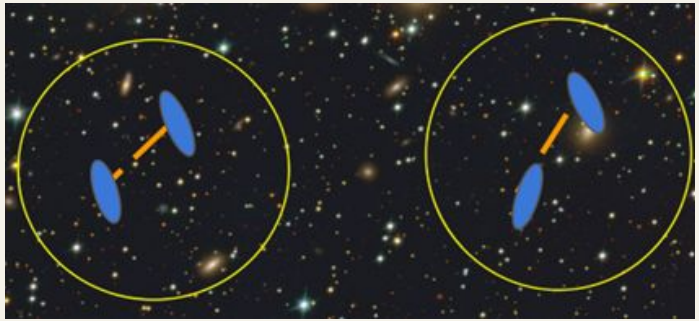
The Non-Gaussian Field



The Integrated 3 Point Correlation Function



From Halder et al. 23

⇒ Correlates local 2PCFs with Aperture Mass

$$\zeta_{\pm} = \langle M_A \xi_{\pm} \rangle$$

The Integrated 3 Point Correlation Function

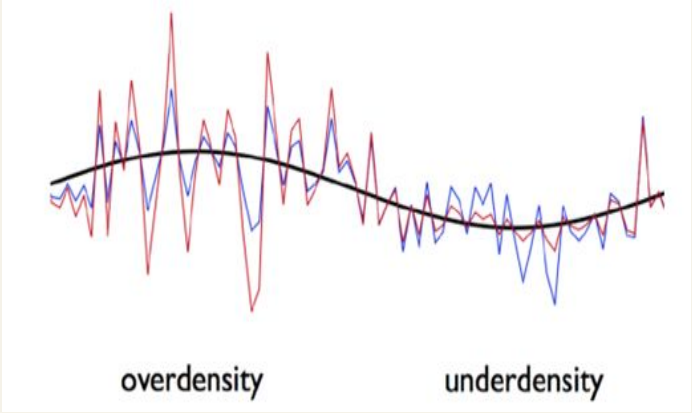


Image credit:
E. Komatsu

⇒ Correlates local 2PCFs with Aperture Mass

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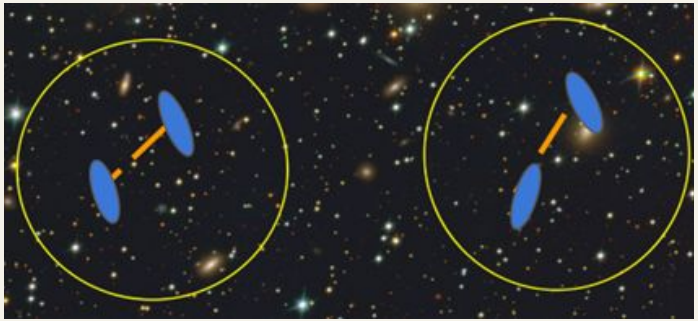
The Integrated 3 Point Correlation Function



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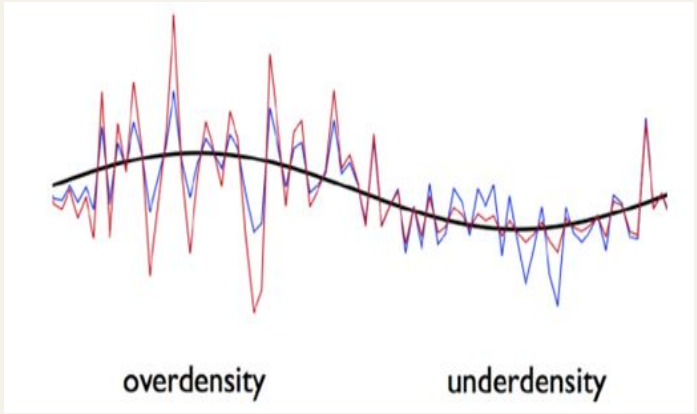

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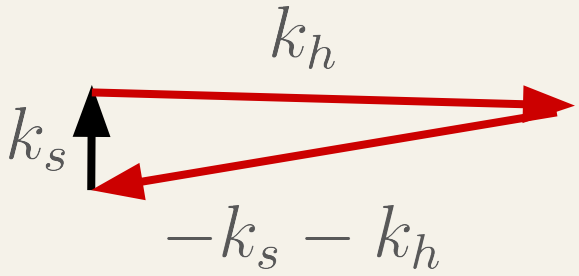
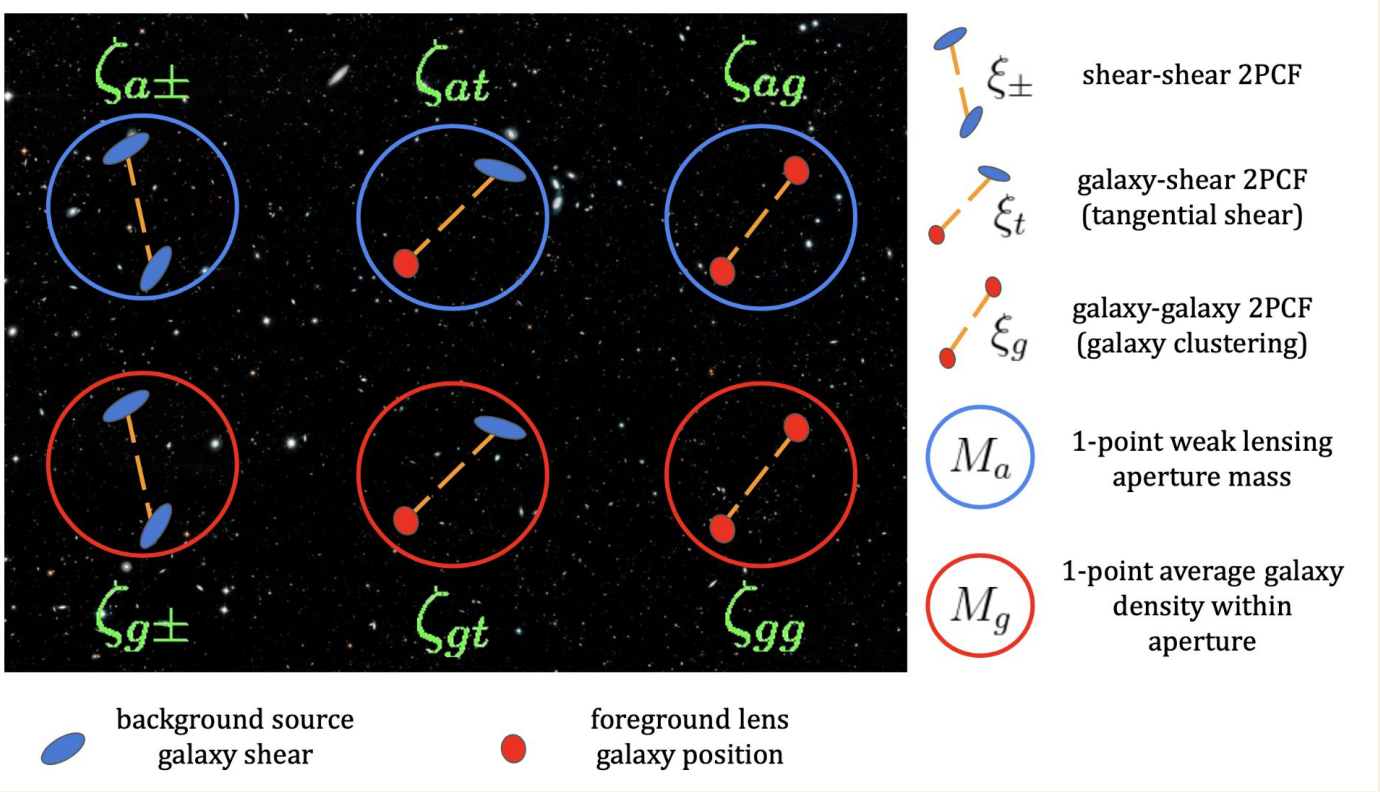


Squeezed Bispectrum

Cross-Correlations



Why not Likelihood Based Inference?

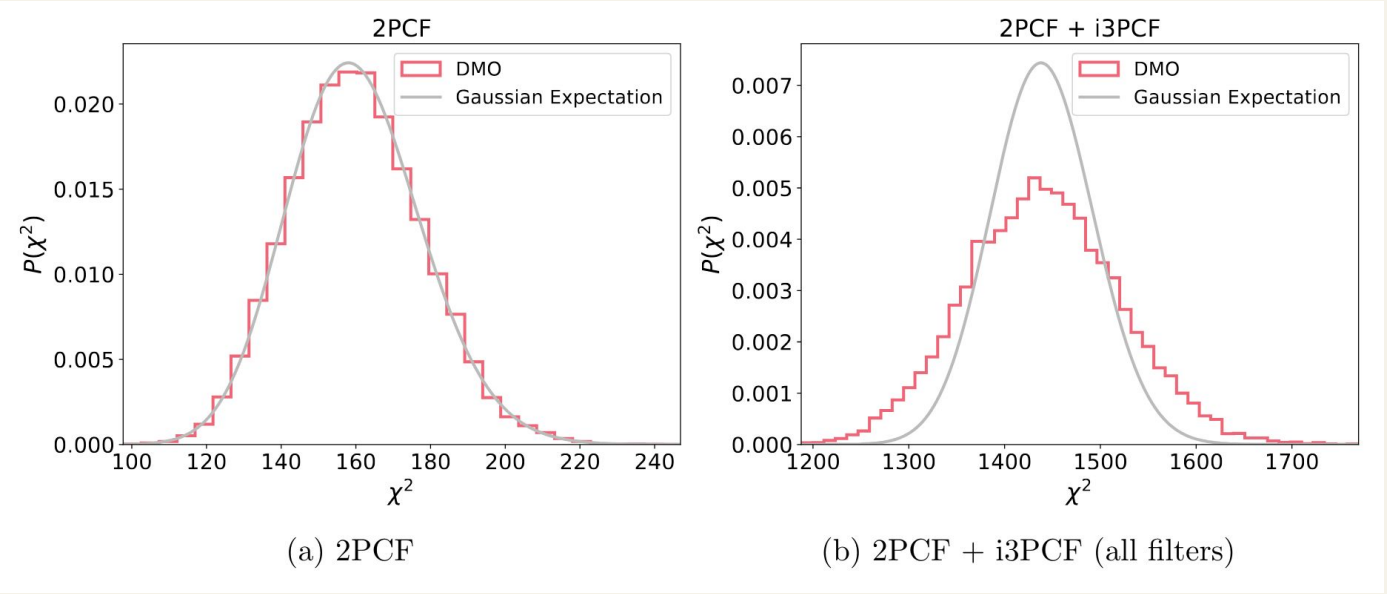
Correction	Reference	Percentage of sample variance		
		$\ell = 10$	$\ell = 100$	$\ell = 1000$
Source-lens clustering	Yu et al. (2015)	N/A	6.0	57.2
Reduced shear + magnification bias	Deshpande et al. (2020a)	0.4	1.8	15.3
Post-Limber reduced shear	Deshpande & Kitching (2020)	0.2	0.6	1.9
Non-linear ellipticity-shear relation	Krause & Hirata (2010)	0.2	0.6	1.9
Limber + fla	Kitching et al. (2017)	9.8	3.0	1.0
Local Unive	Hall (2020)	7.8	24.2	N/A
Higher-ord	& Hirata (2010)	$O(\phi^4)$	$O(\phi^4)$	$O(\phi^4)$
Time delay		$O(\phi^4)$	$O(\phi^4)$	$O(\phi^4)$
Deflection			$O(\phi^4)$	$O(\phi^4)$
Born appr				$O(\phi^4)$
Lensing l				$O(\phi^4)$
Second-order				<0.01
Temporal-Born approximati				<0.01
Finite-beam corrections				<0.01
Doppler-shift	Deshpande			<0.01
Unequal-time correlators	Kitching & Heavens (20			<0.01
Sachs-Wolfe effect	Cuesta-Lazaro et al. (2018)			<0.01
Integrated Sachs-Wolfe effect	Cuesta-Lazaro et al. (2018)	<0.01		<0.01
Flexion correction	Schneider & Er (2008)	N/A	N/A	N/A
Flat-geometry assumption	Taylor et al. (2018b)	−2.0	−6.0	−19.1
Source obscuration	Hartlap et al. (2011)	−2.0	−6.0	−19.1
Spatially-varying survey depth	Heydenreich et al. (2020)	−5.9	−18.1	−57.2

Too many effects for analytical modelling!

Euclid Collaboration et al. 2024

⇒ Stage IV Surveys much more sensitive to systematic effects

Why not Likelihood Based Inference?

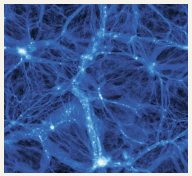


(a) 2PCF

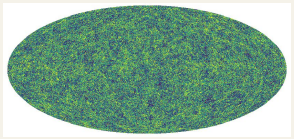
(b) 2PCF + i3PCF (all filters)

⇒ Gaussian likelihood assumption breaks down for many HOS

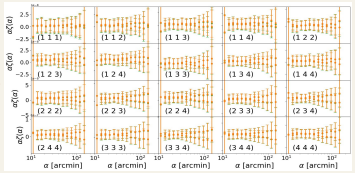
The SBi3PCF Framework



N-Body Simulations



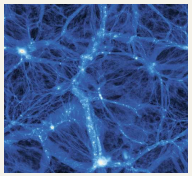
Weak Lensing Maps



Summary Statistics

Forward Model

The SBi3PCF Framework



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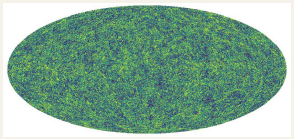

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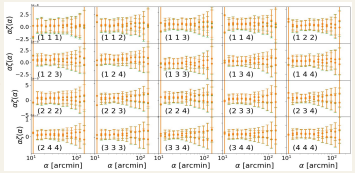

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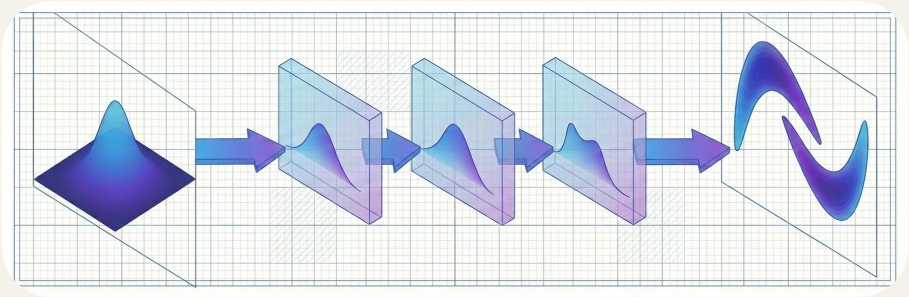
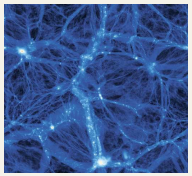
Forward Model



Normalizing Flow

The SBi3PCF Framework



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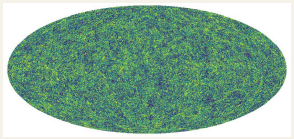

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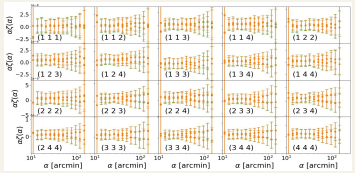
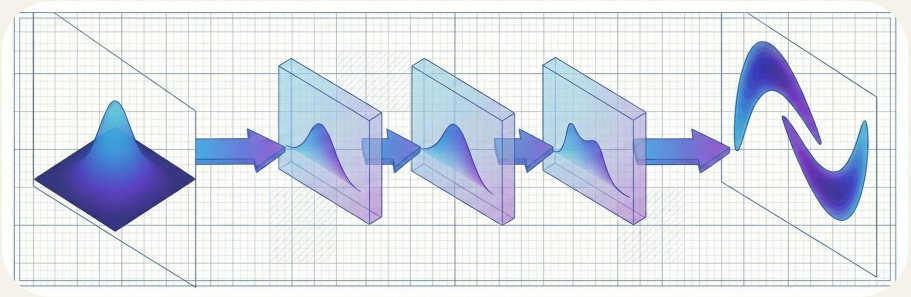
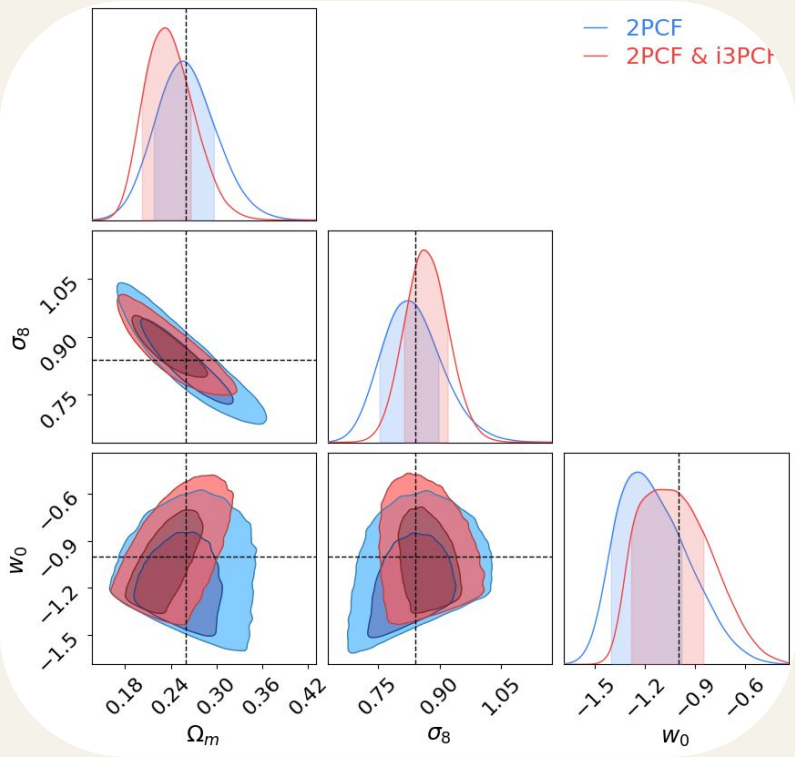


Summary Statistics

Forward Model



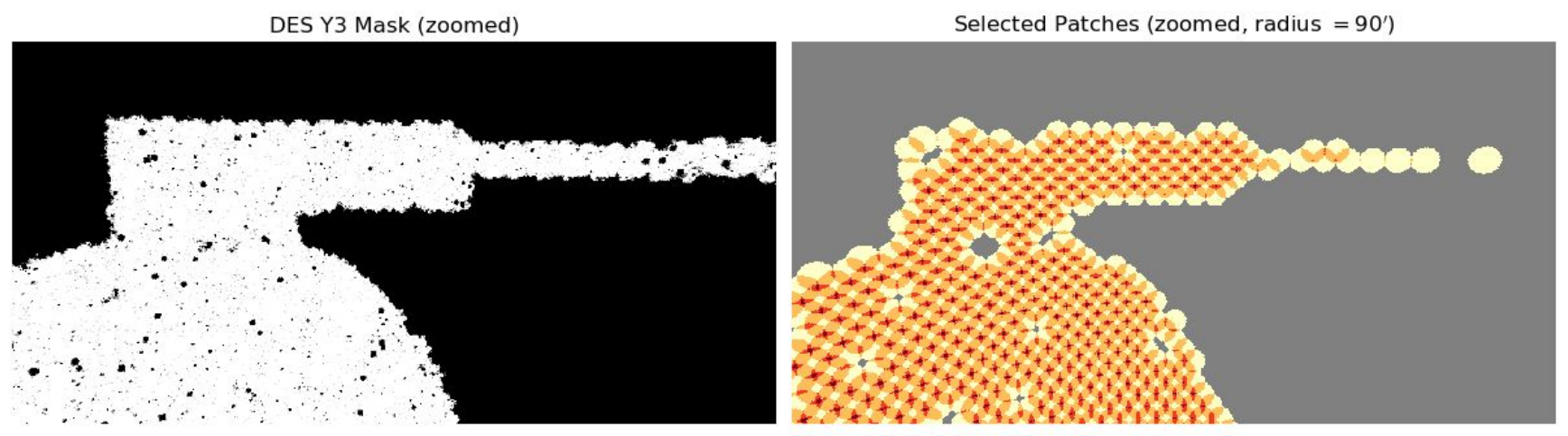
Normalizing Flow



CosmoFuse

Precompute pairs for local 2PCFs

⇒ Correlation function measurement reduced to matrix multiplication

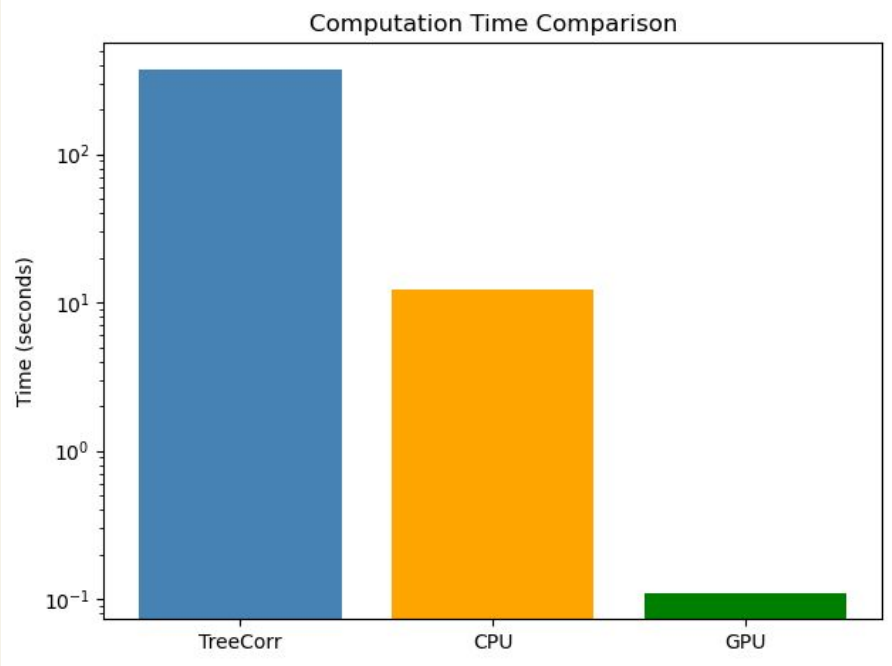


CosmoFuse

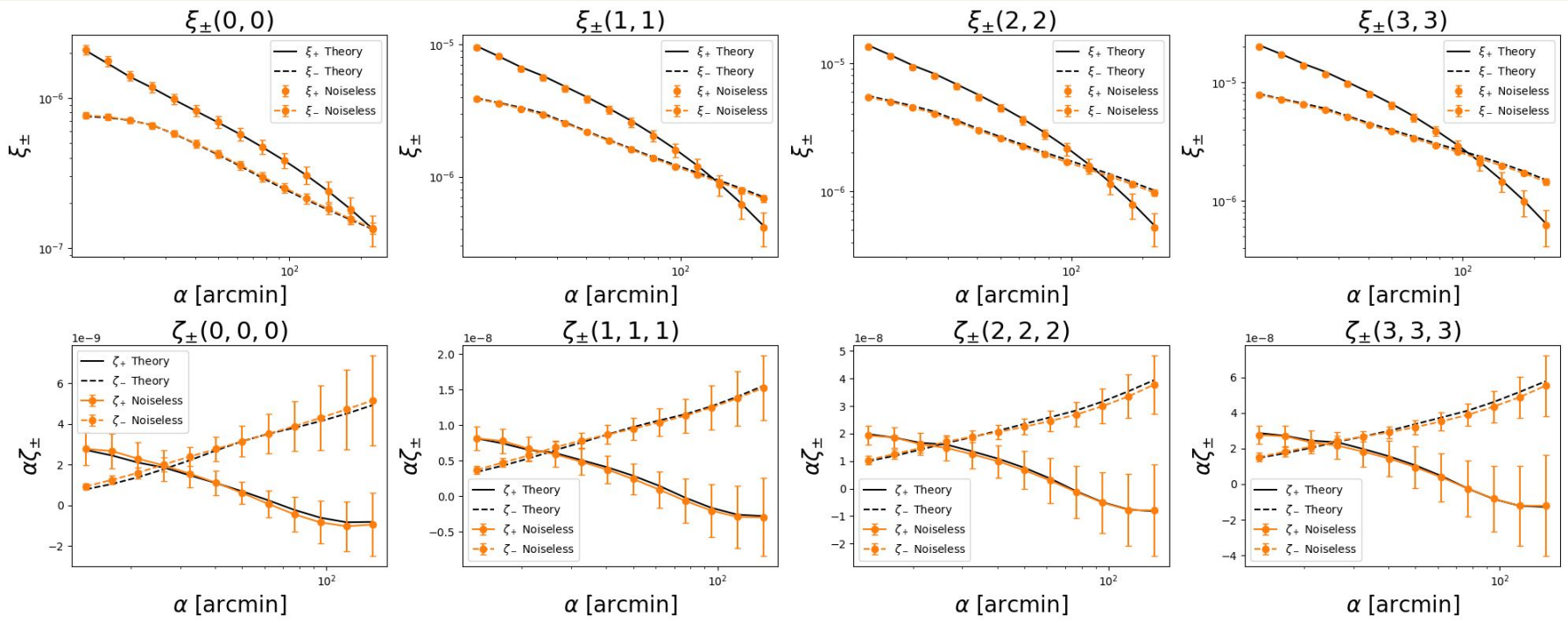
Move onto GPUs for maximum efficiency gains:

Method	Time Needed
TreeCorr	6 minutes
CosmoFuse (CPU)	12 seconds
CosmoFuse (GPU)	110 milliseconds

NSIDE 512, 1000 90’ patches, 4 tomographic bins
Full WL, GGL & GC tomographic analysis
On 160 CPU cores and 1x A100 80GB GPU

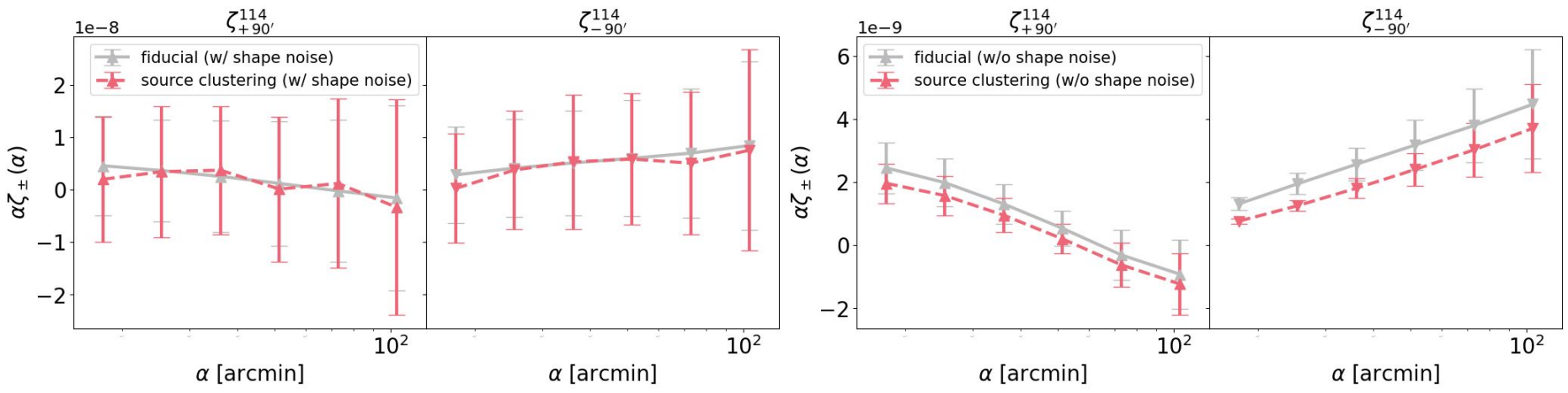


Validation



⇒ Excellent agreements of forward model with analytical

Validation - Source Clustering

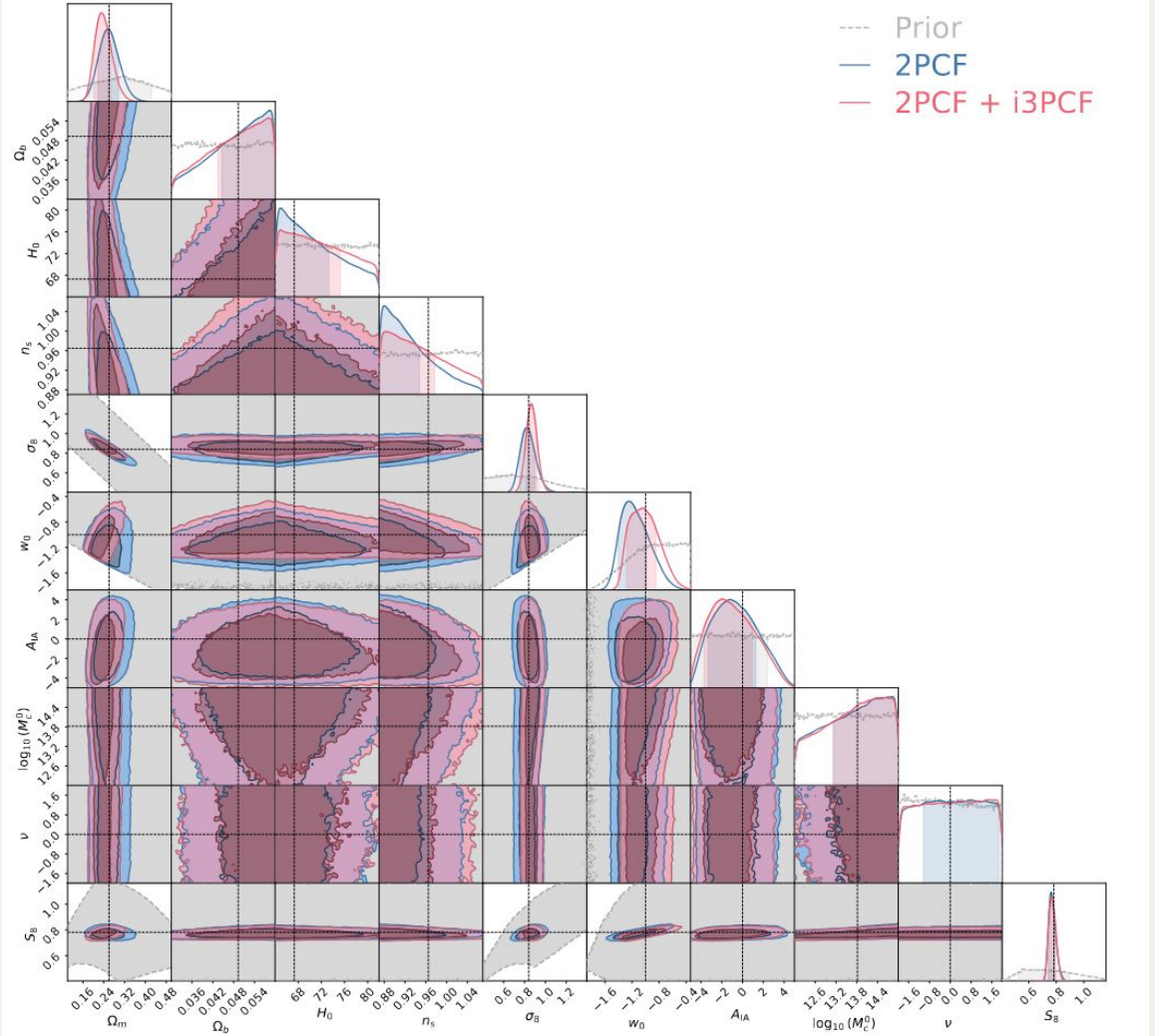


⇒ Minimal effect of source clustering

Fiducial Constraints

⇒ Chain for prior probability in grey

⇒ Most parameters unconstrained

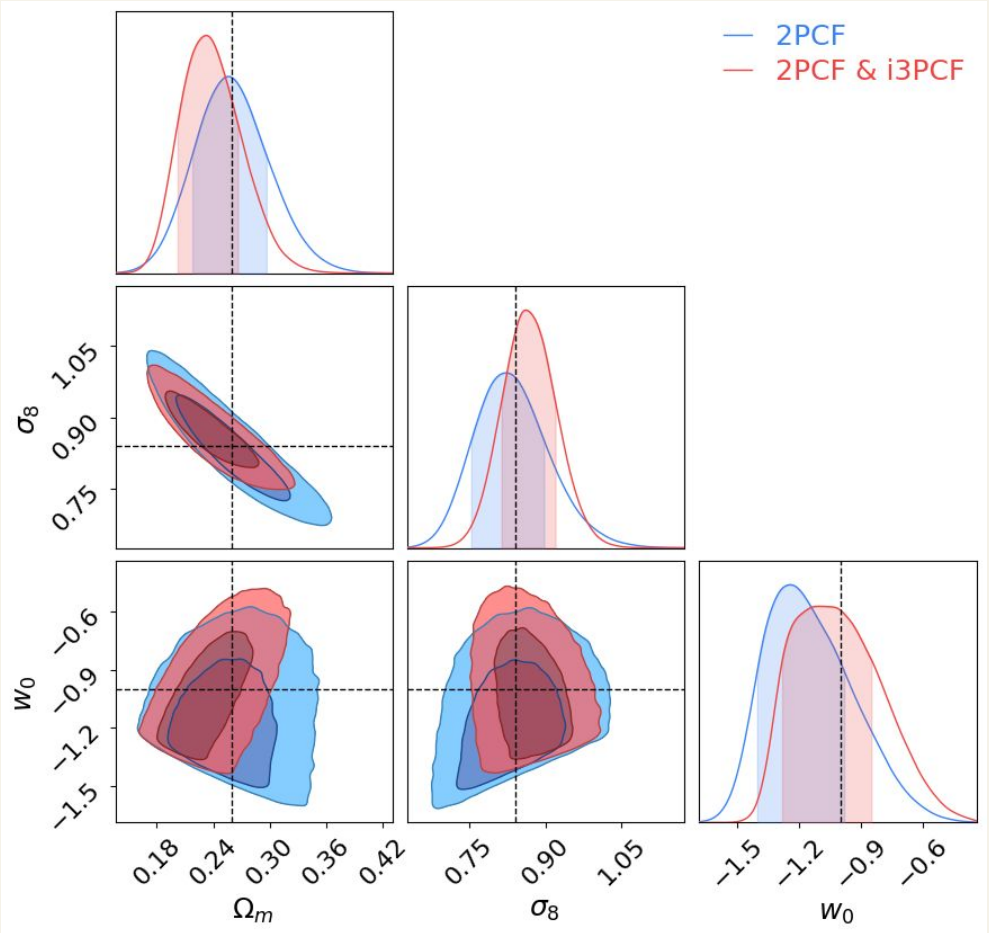


Fiducial Constraints

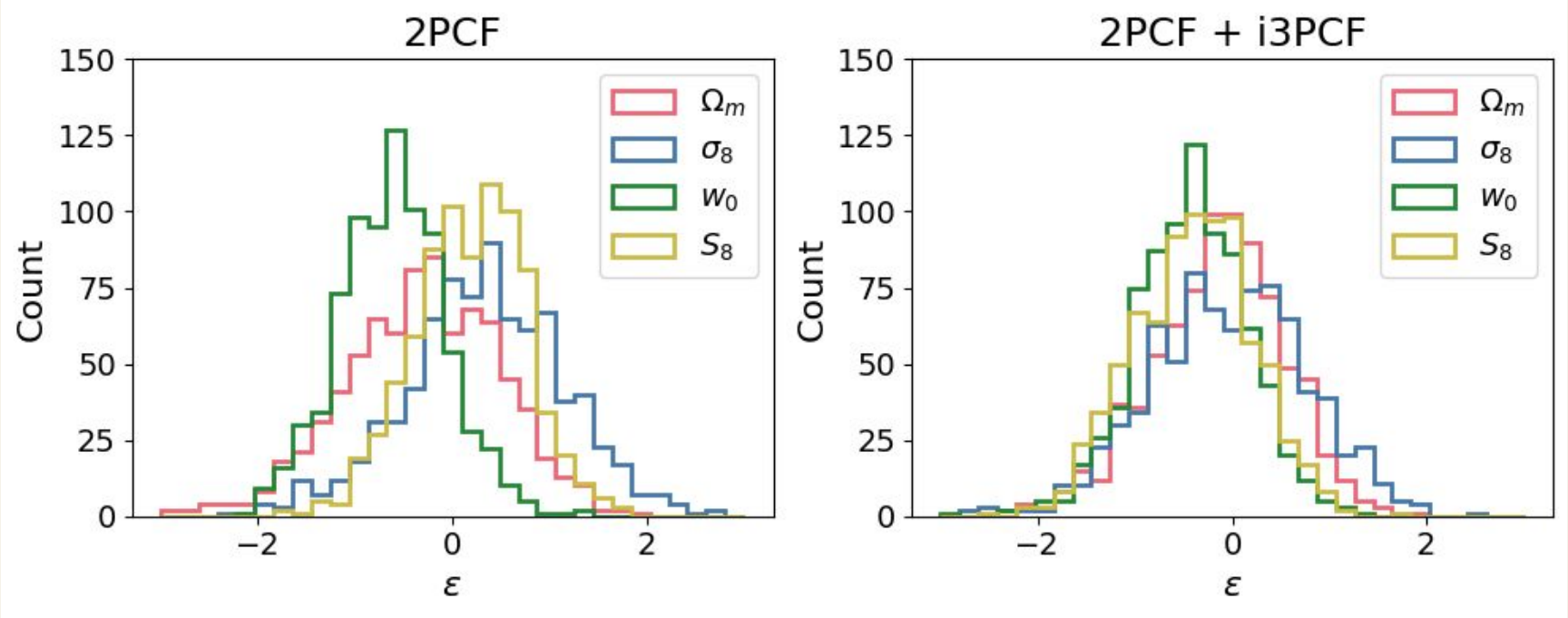
⇒ Chain for prior probability in grey

⇒ Most parameters unconstrained

⇒ True parameters recovered!

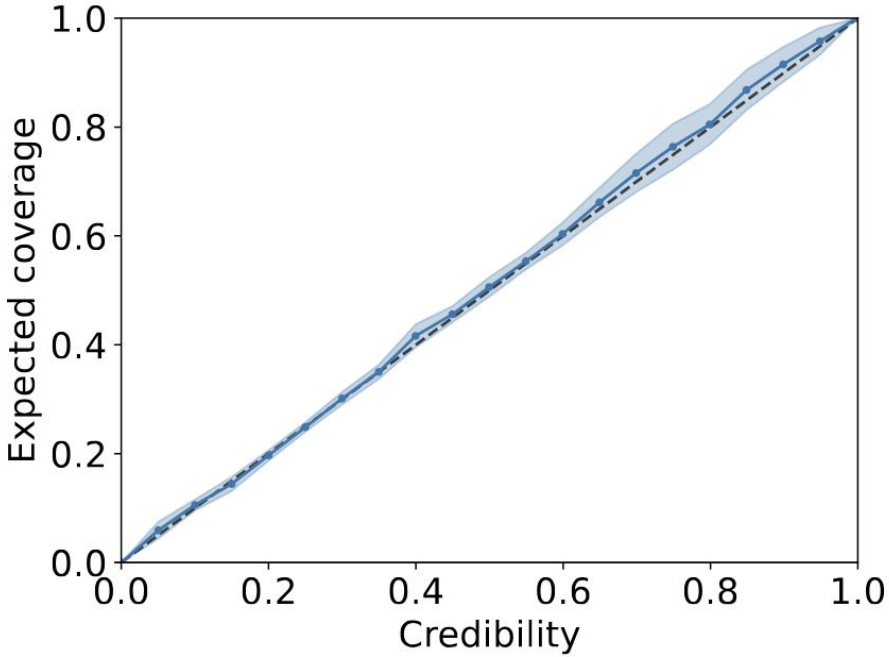


Bias

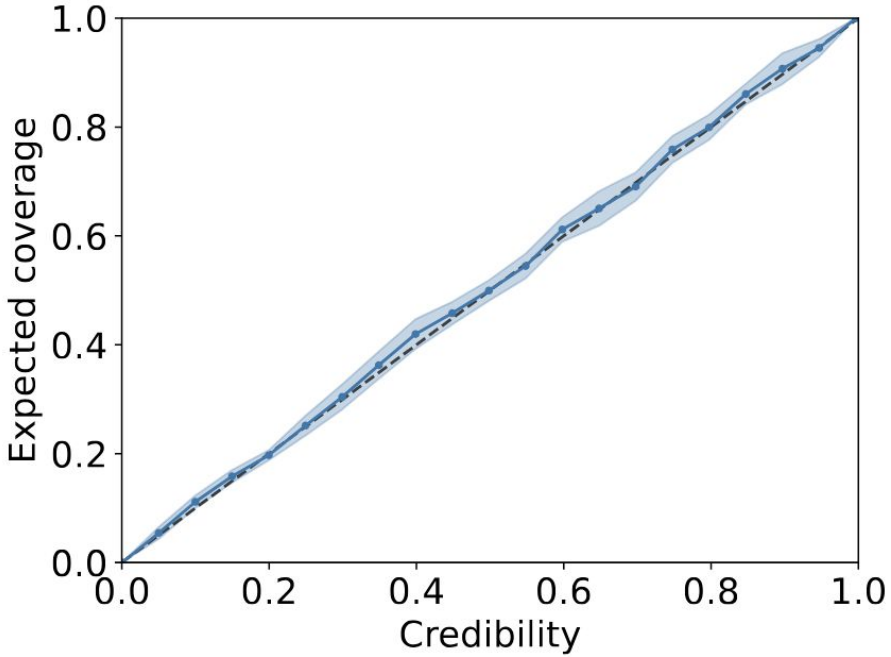


$$\varepsilon \equiv \frac{\theta_{\text{median}} - \theta_{\text{truth}}}{\frac{1}{2}\left|\theta_{84\%} - \theta_{16\%}\right|},$$

Coverage Test (Tarp)

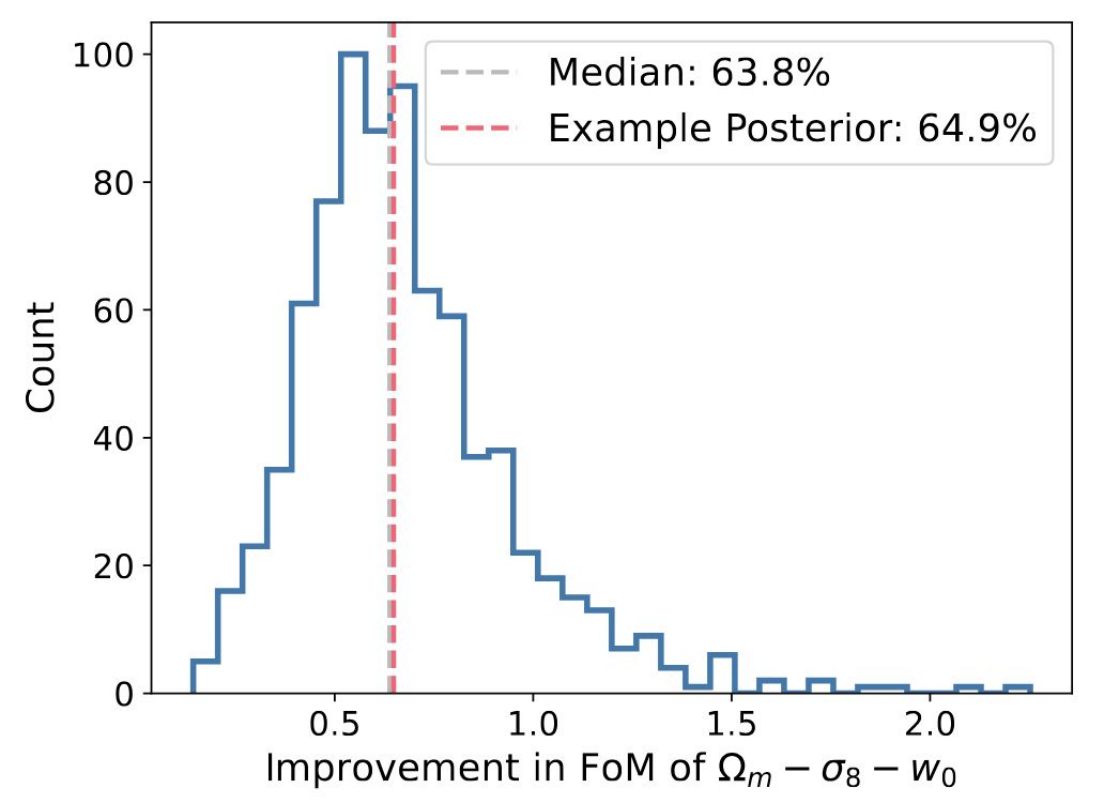


(a) Coverage using 2PCF data vector.



(b) Coverage using 2PCF + i3PCF data vector.

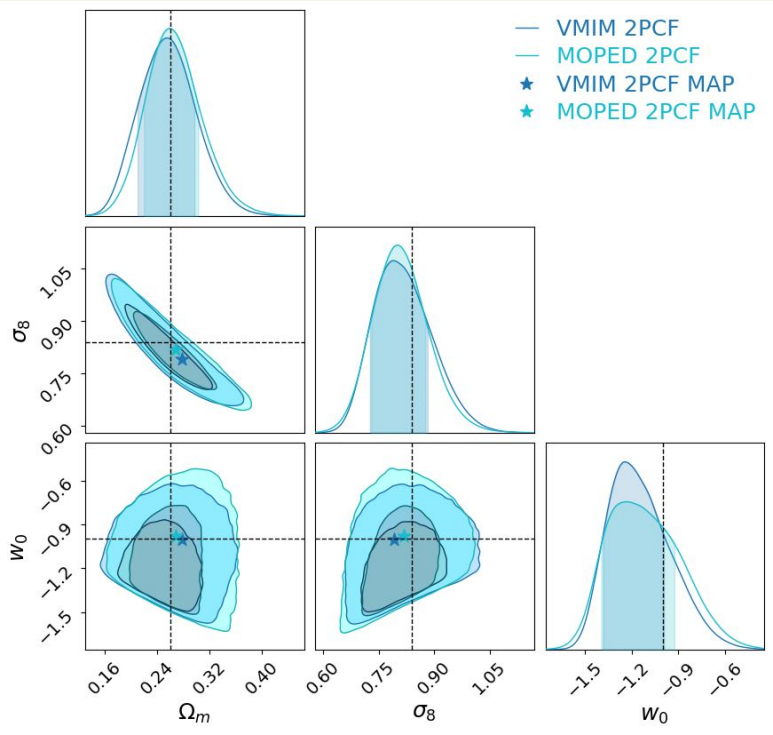
Improvements



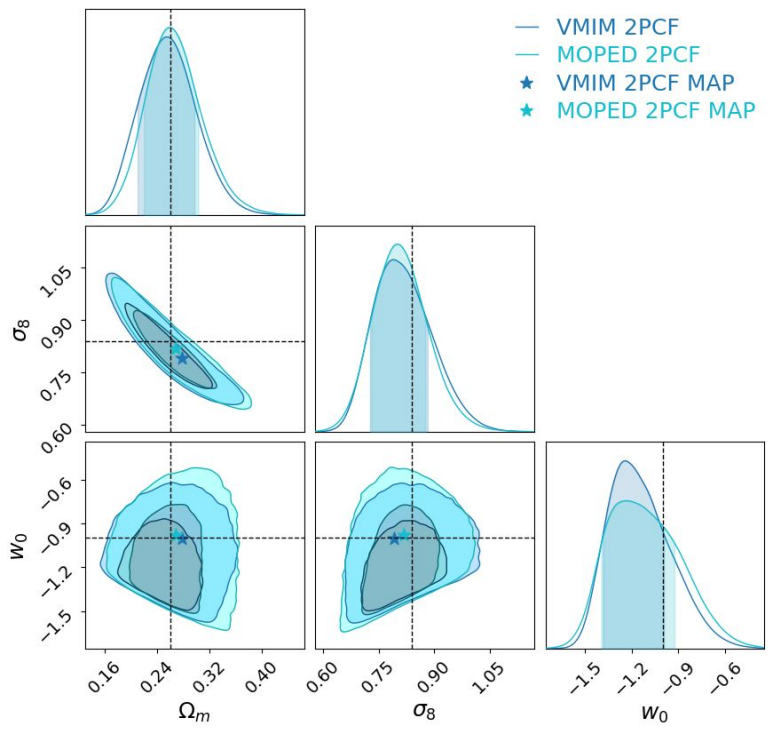
Work in Progress

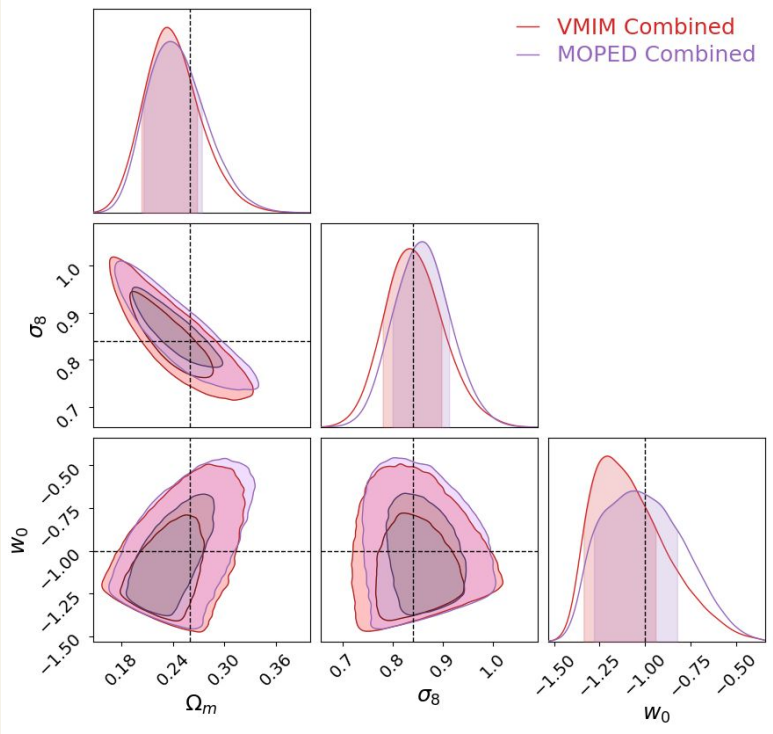
Application to DES Y3 Catalogue

VMIM vs MOPED

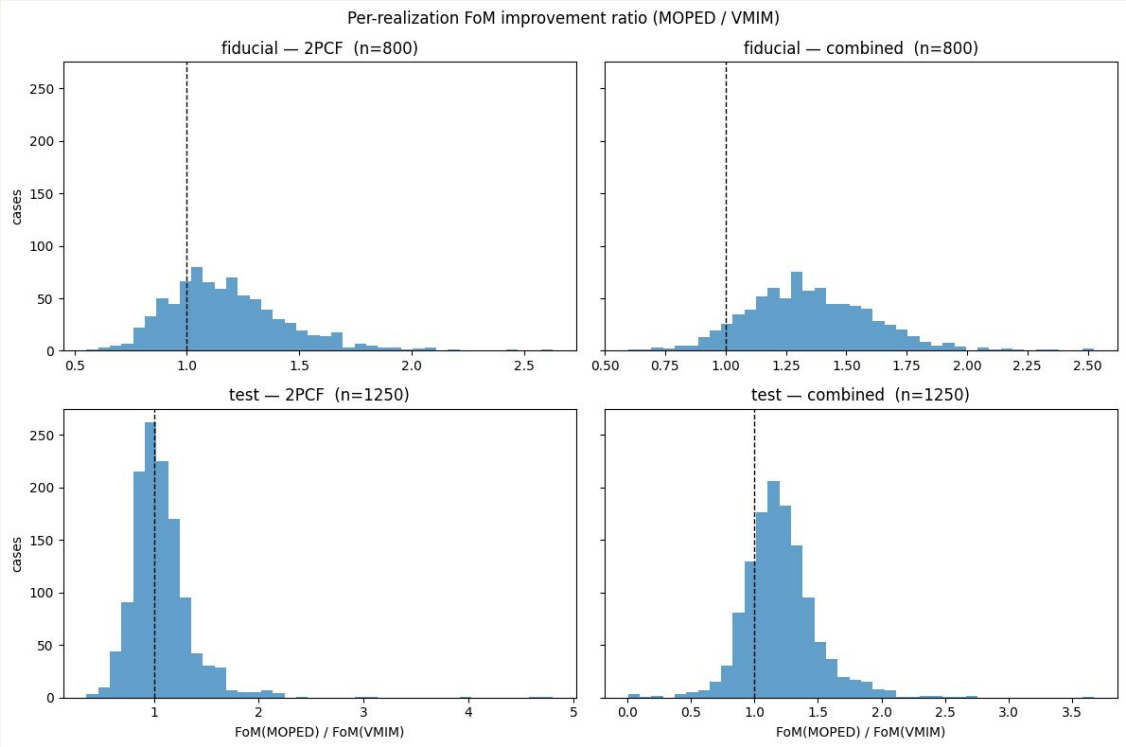


VMIM vs MOPED

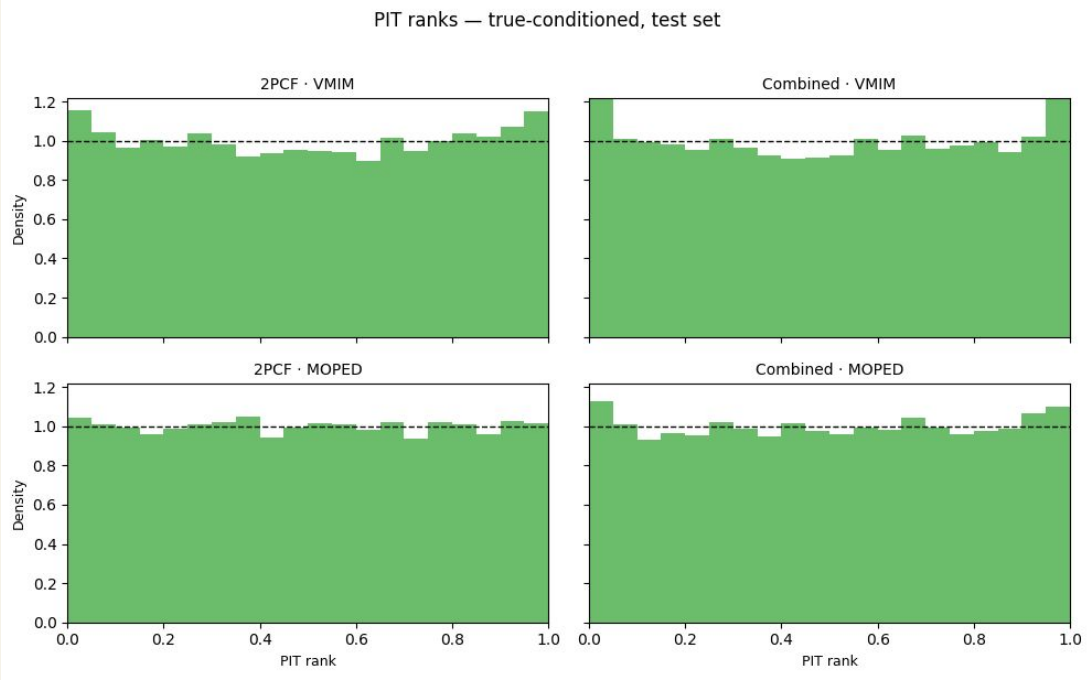




VMIM vs MOPED



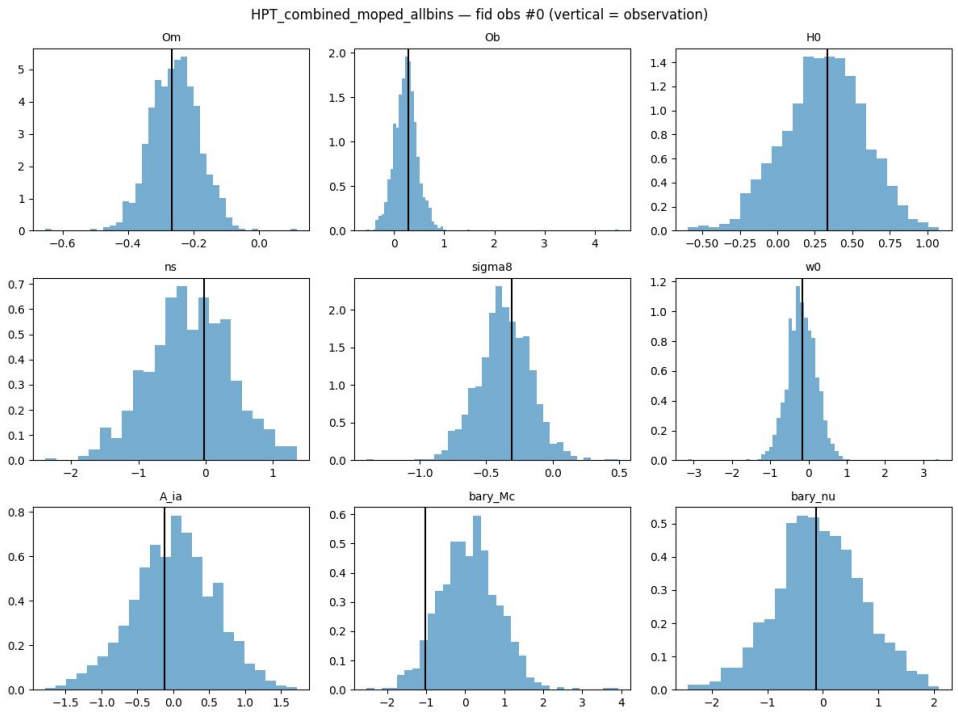
Testing the Likelihood



PIT rank plots

Goodness of fit test

Likelihood Sample



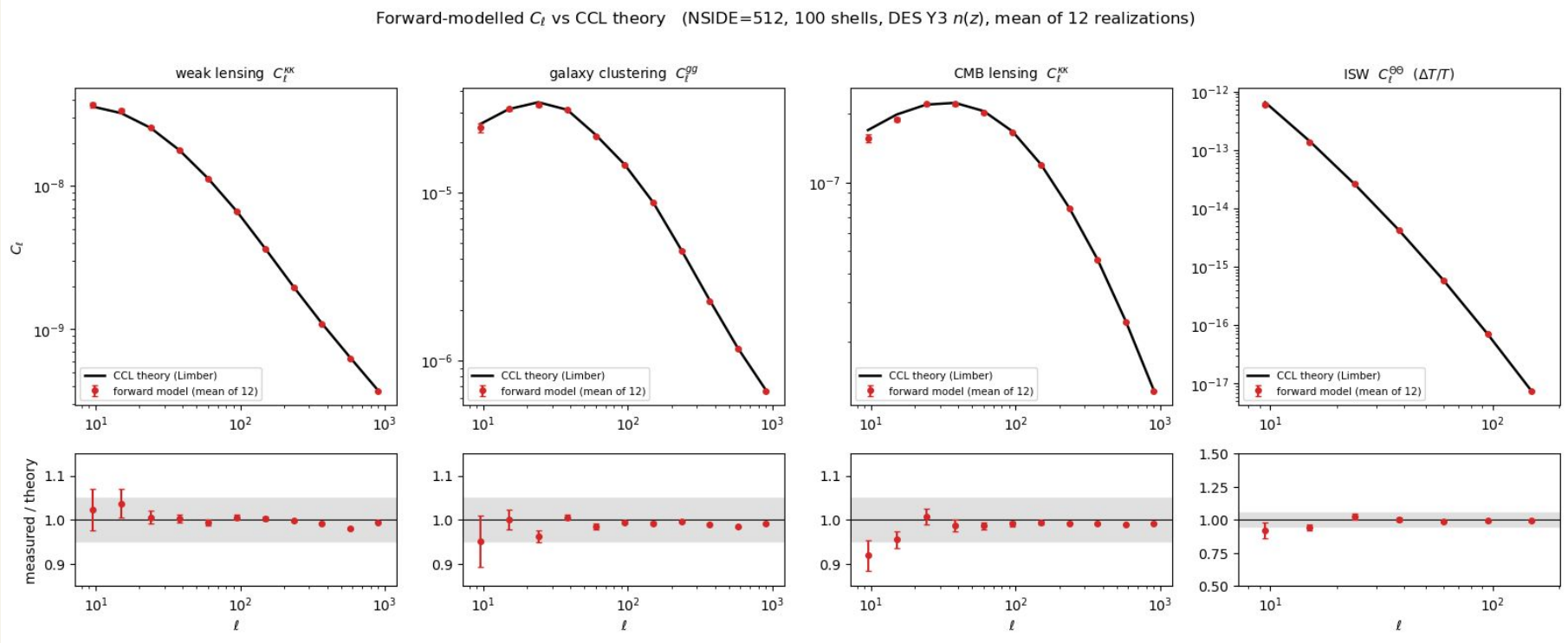
Samples from the likelihood $P(x|\theta_{\mathrm{MAP}})$

Shows 9 MOPED coefficients

Work in Progress

Extending the forward model

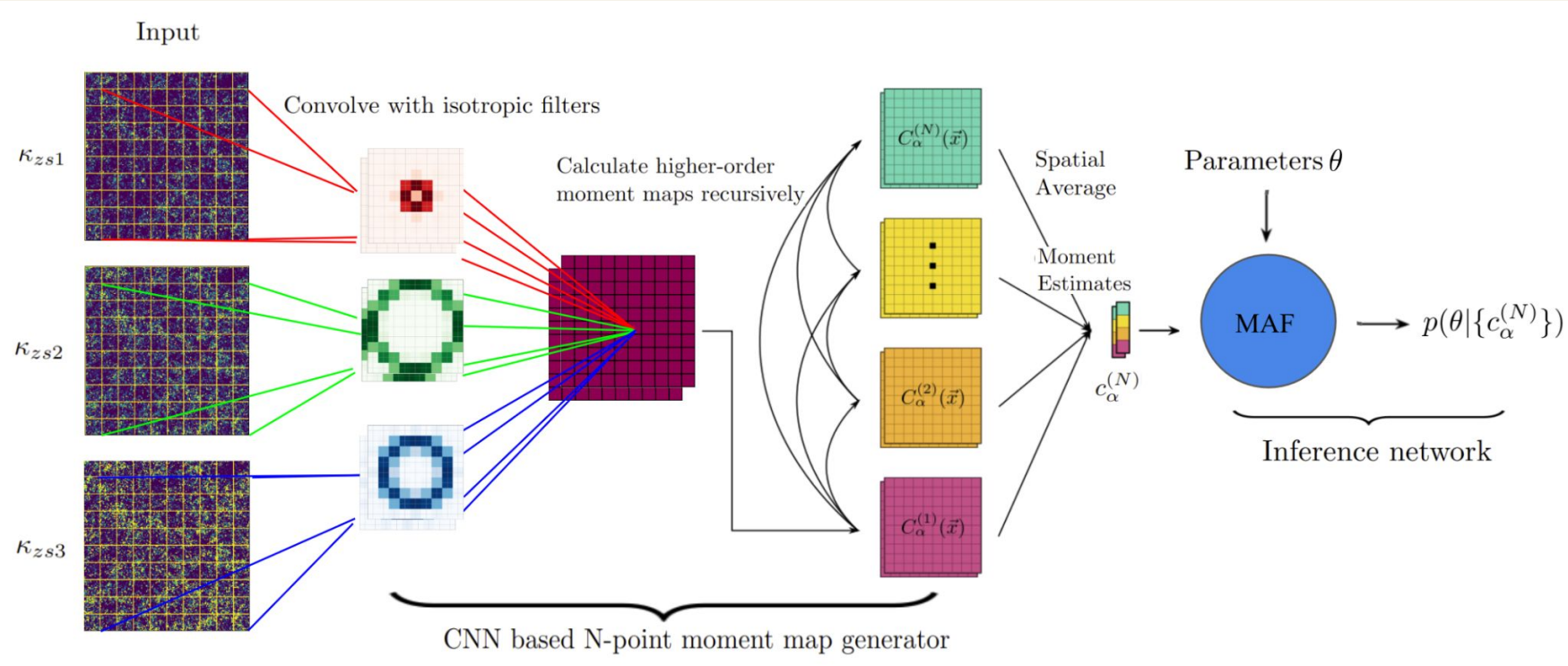
Extended Forward Model



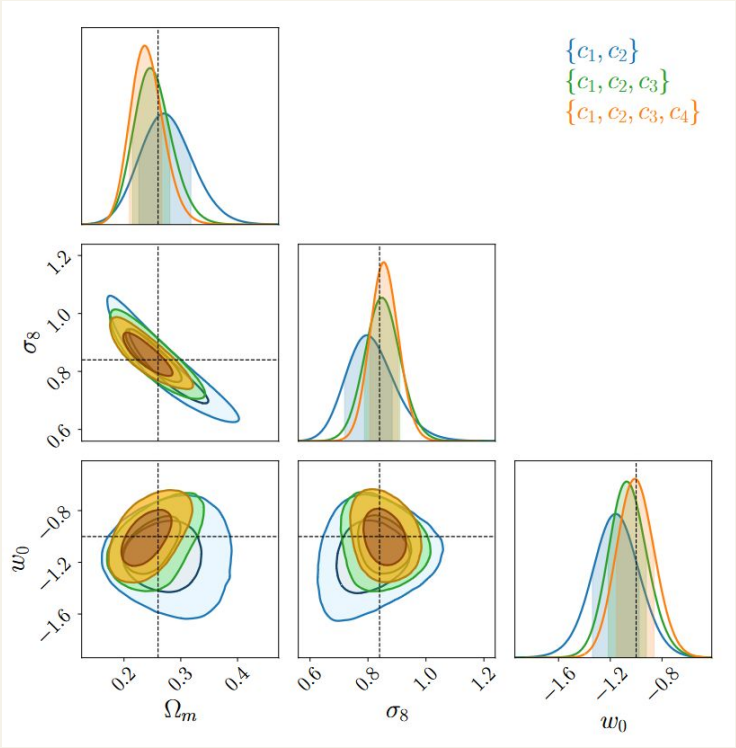
Bonus Project

Cosmological Correlator Convolutional Neural Network (C3NN)

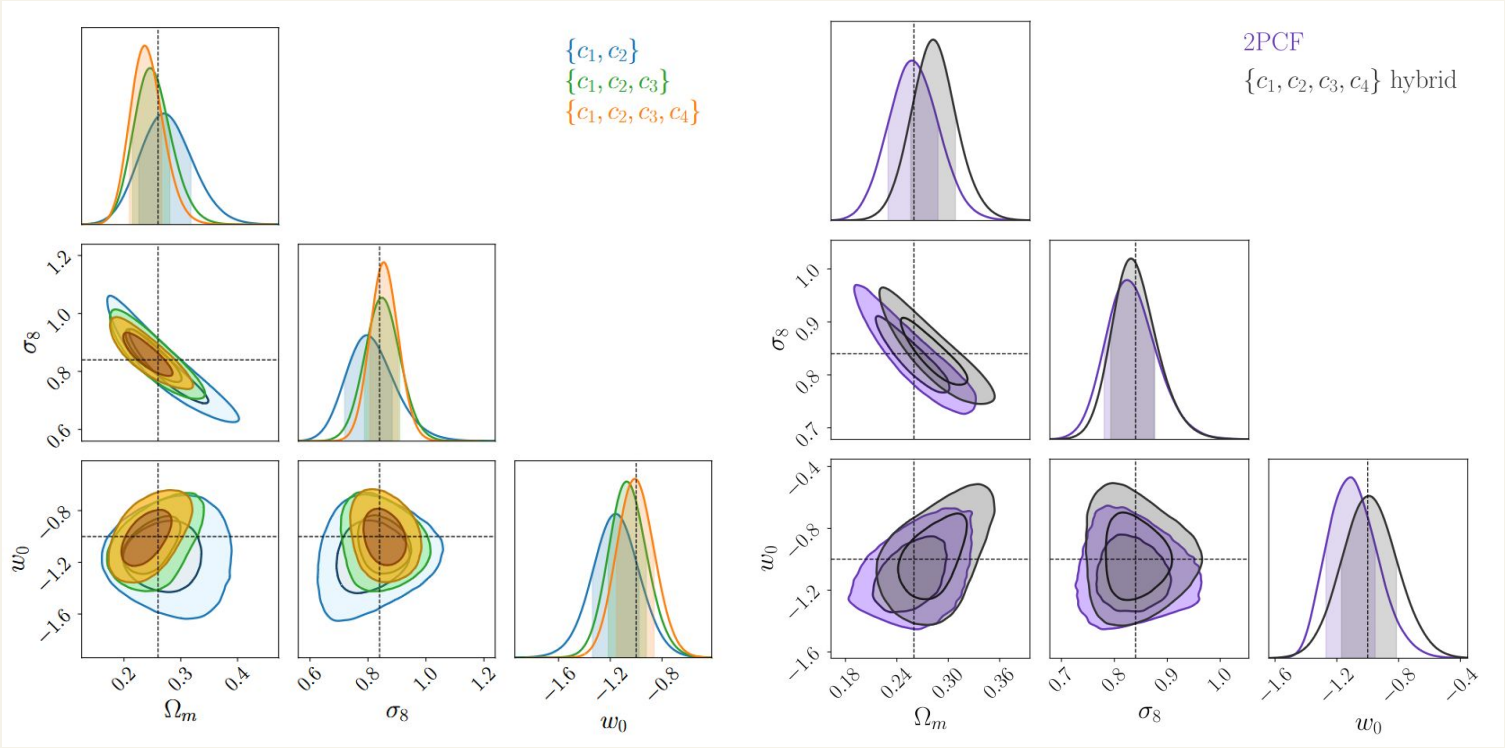
C3NN - ARCHITECTURE



C3NN - RESULTS

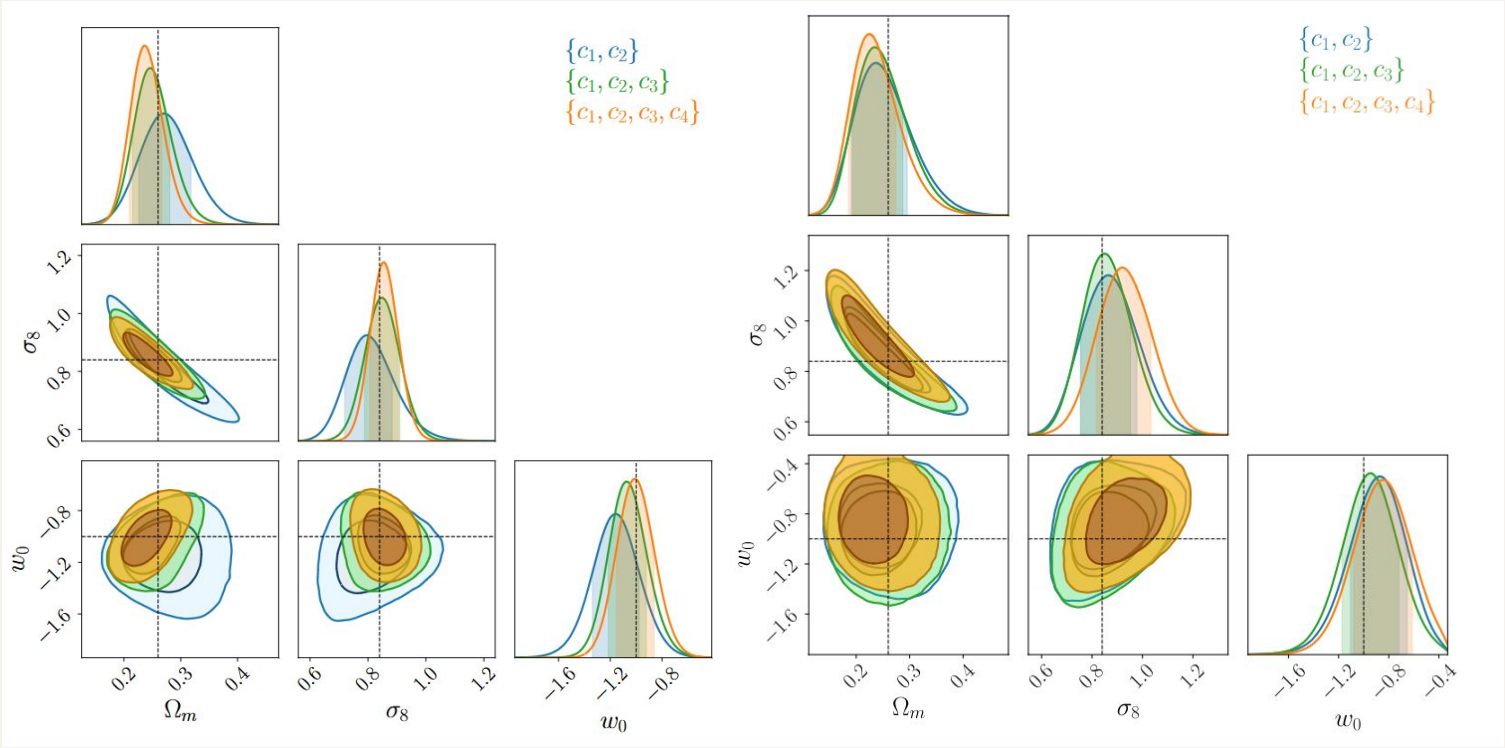


C3NN - RESULTS



C3NN - RESULTS

Randomized Phases:



Summary and Outlook

- ➔ The i3PCF efficiently captures non-Gaussian information
- ➔ Our forward model agrees with analytical predictions
- ➔ We can robustly infer cosmological parameters

My Website

⇒ **arxiv:*2510.13805 (DG, Halder, Seitz & Anbajagane)***

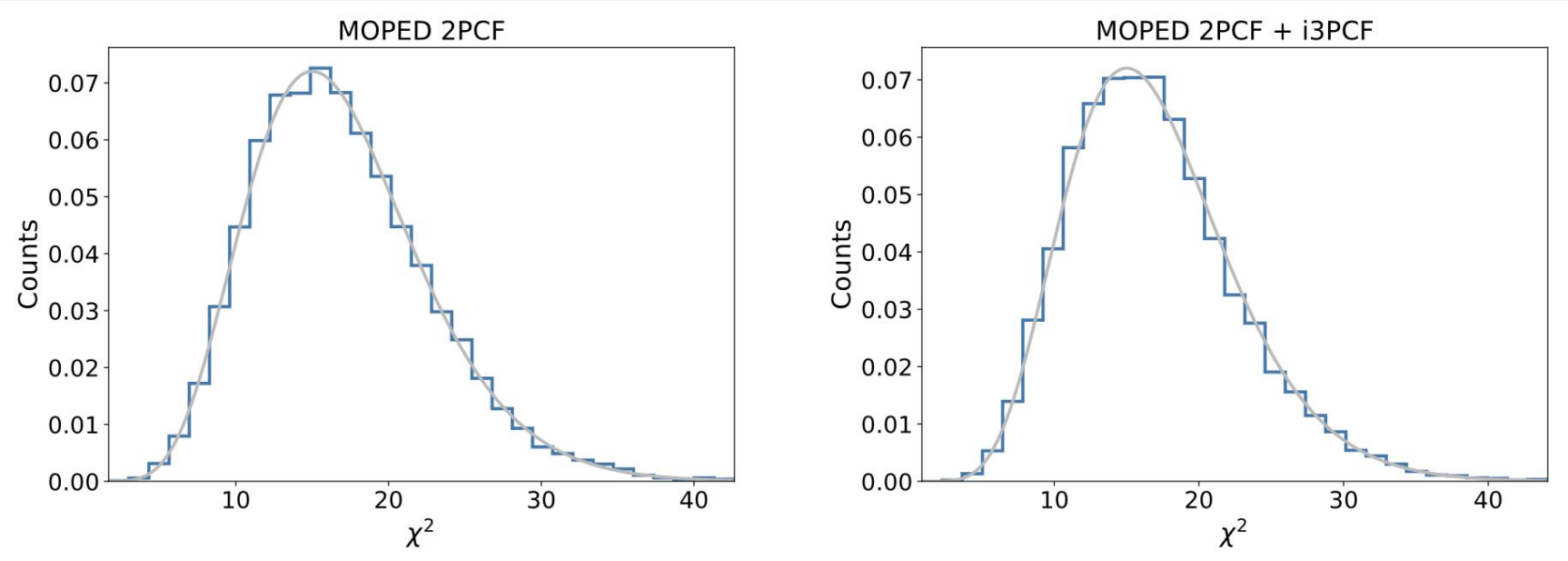
- ➔ Now apply this to DES Y3 source catalogue
- ➔ Include more statistics (e.g. 1-pt PDF)
- ➔ Extend to galaxy clustering, galaxy-galaxy lensing and CMB lensing

- ➔ C3NN: Interpretable NN architecture
- ➔ can efficiently extract information from N-point correlation functions

⇒ **arxiv:2602.16768 *(Lehman, Gong, DG, Seitz & Weller)***

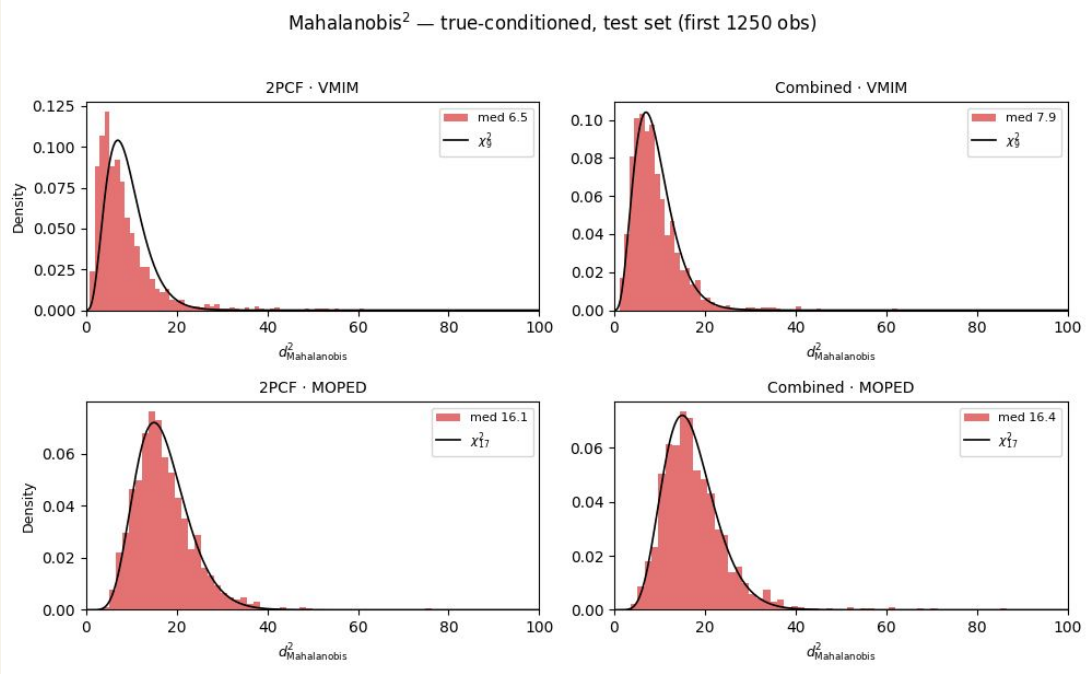
Backup Slides

Gaussianity Test



⇒ MOPED gaussianizes the likelihood

Testing the Learned Likelihood

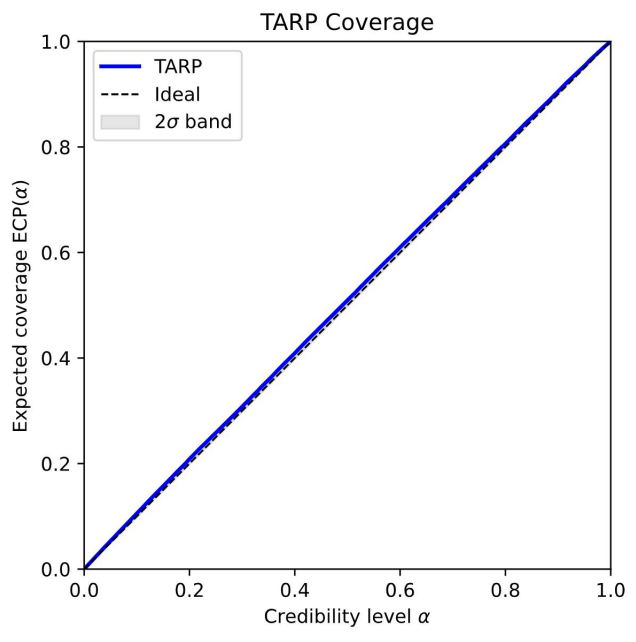


χ^2 test

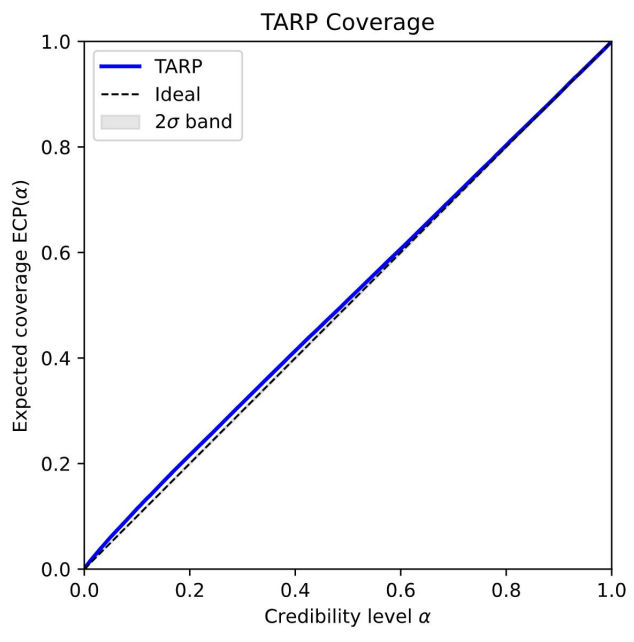
Where does “true” observation fall within sampled likelihood

⇒ All likelihoods slightly too wide (underconfident)
⇒ Mos extreme for VMIM 2PCF

2PCF Coverage - New Models

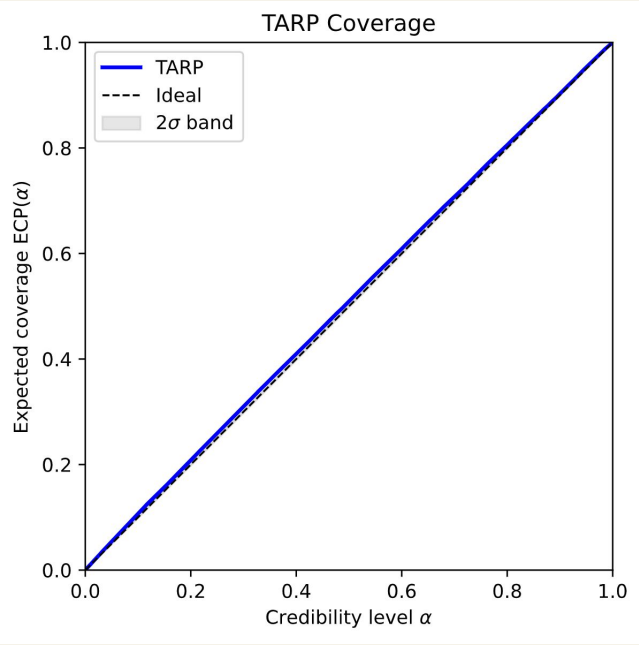


MOPED

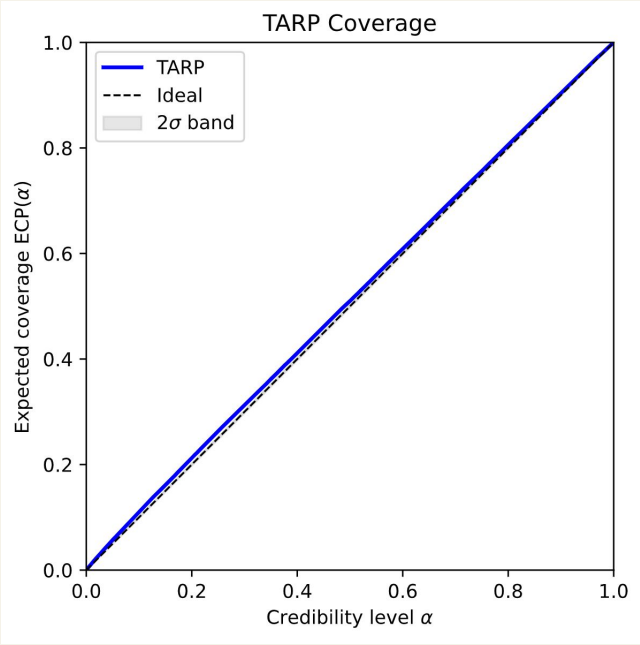


VMIM

Combined Coverage - New Models

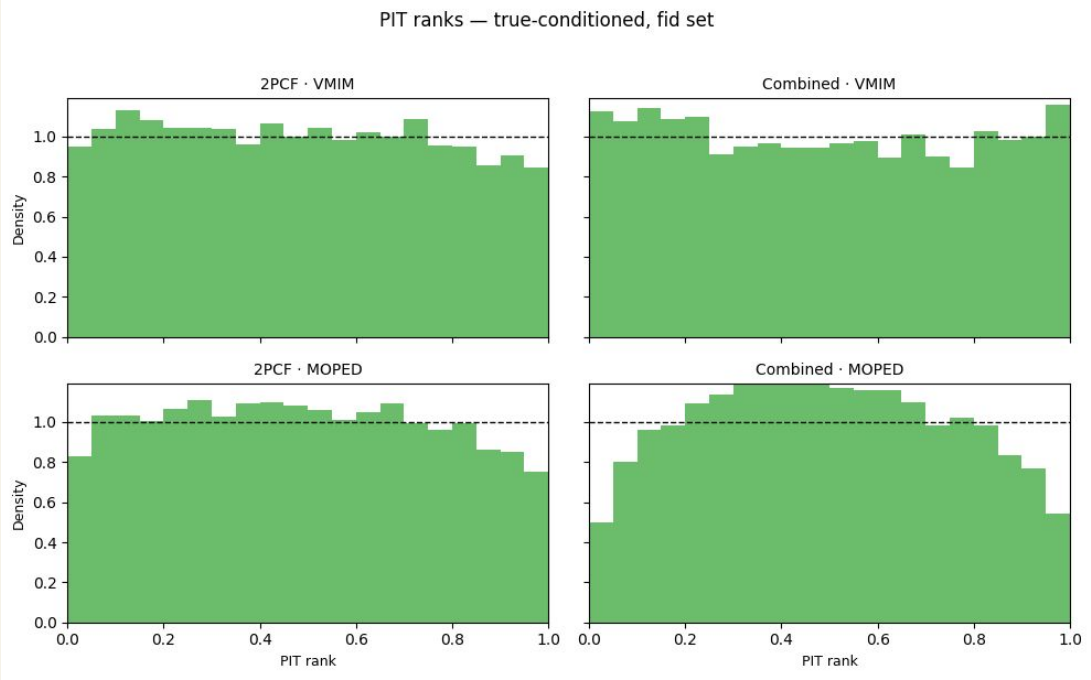


MOPED



VMIM

Testing the Likelihood

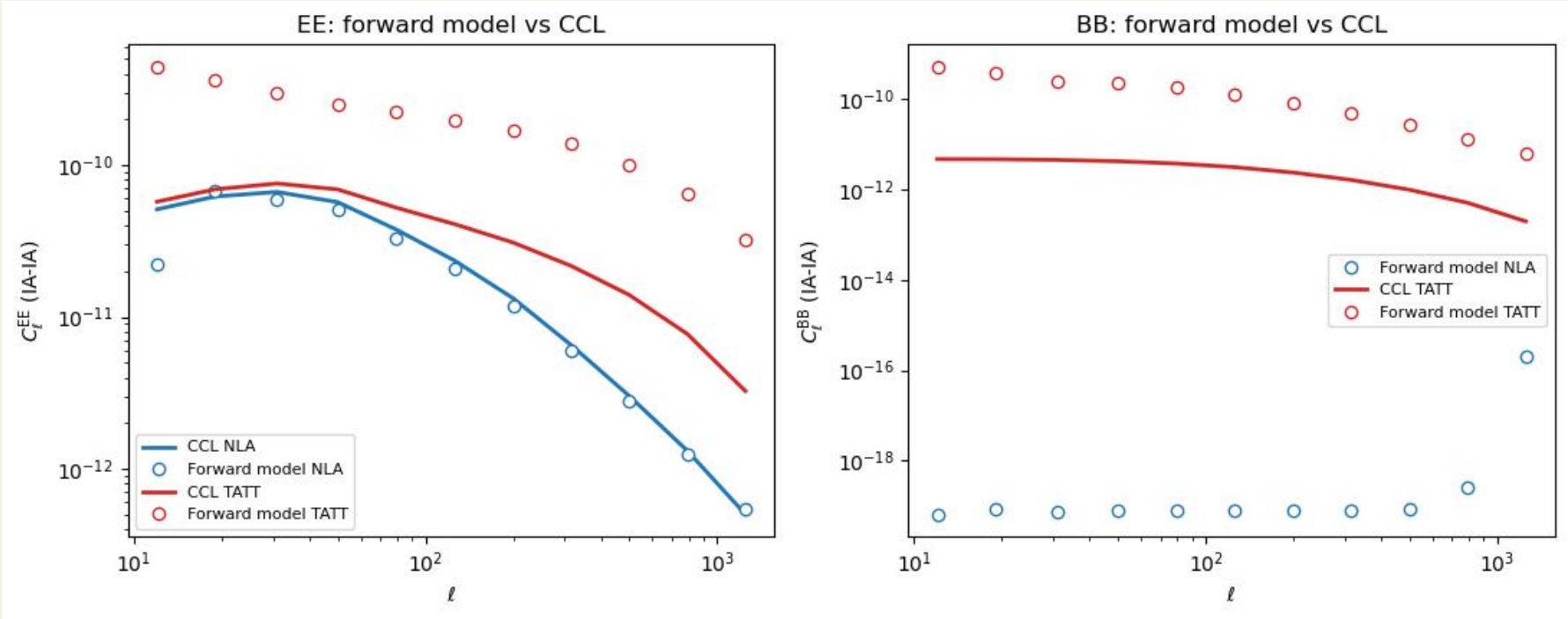


PIT rank plots

Goodness of fit test

Can also be done locally!

Intrinsic Alignment Issues



C3NN - RESULTS