Forward-modelling galaxy surveys:
A forward model for non-local stochastic galaxy bias

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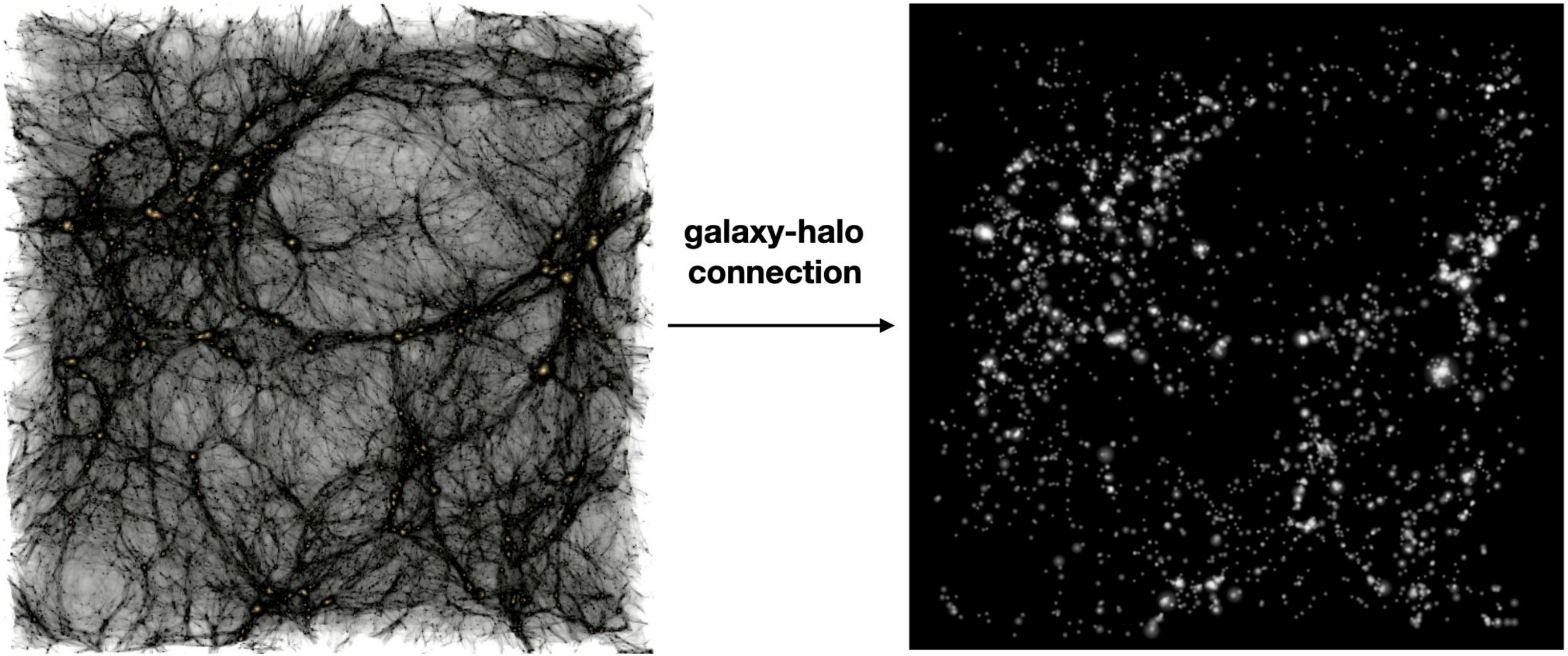
A multi-scale and multi-tracer view of the cosmic web, NAM 2025 — 8th July 2025

In collaboration with Nicolas Tessore, Qianjun Hang, Niall Jeffrey, Benjamin Joachimi

Euclid consortium · UK Space Agency · UKRI · Institute for Computational Cosmology · Durham Centre for Extragalactic Astronomy · Durham University

Galaxy-Halo Connection/Galaxy Bias



Wechsler & Tinker 2018

Galaxy Bias: Theory

Matter density contrast:

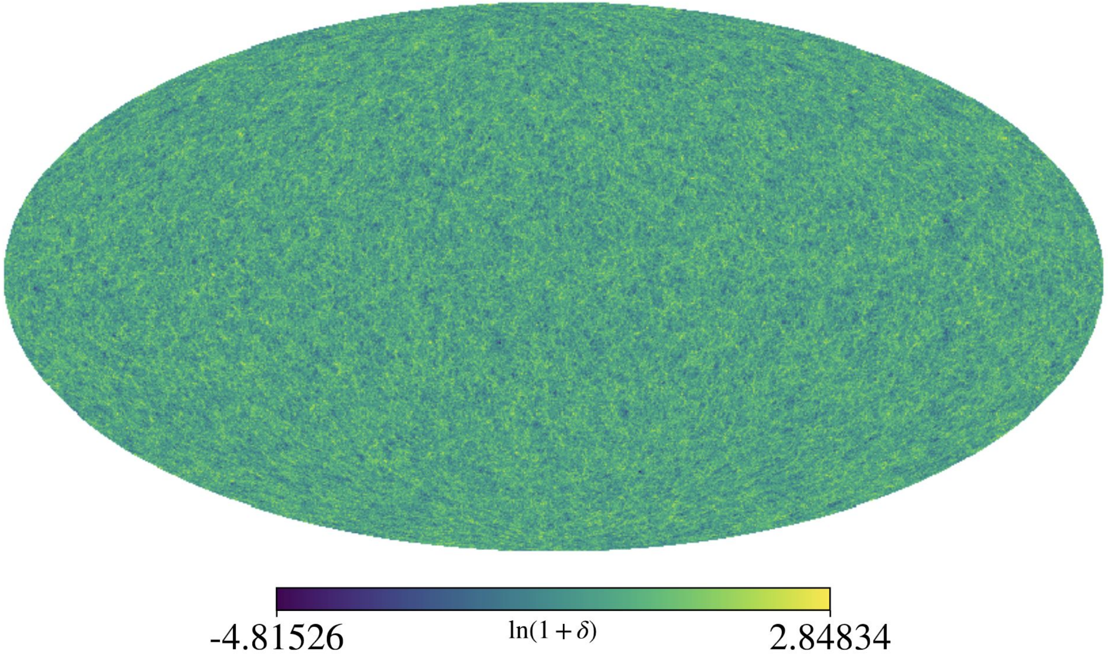
$$\delta(x,\tau) = \frac{\rho(x,\tau) - \bar{\rho}(\tau)}{\bar{\rho}(\tau)}$$

Galaxy count contrast:

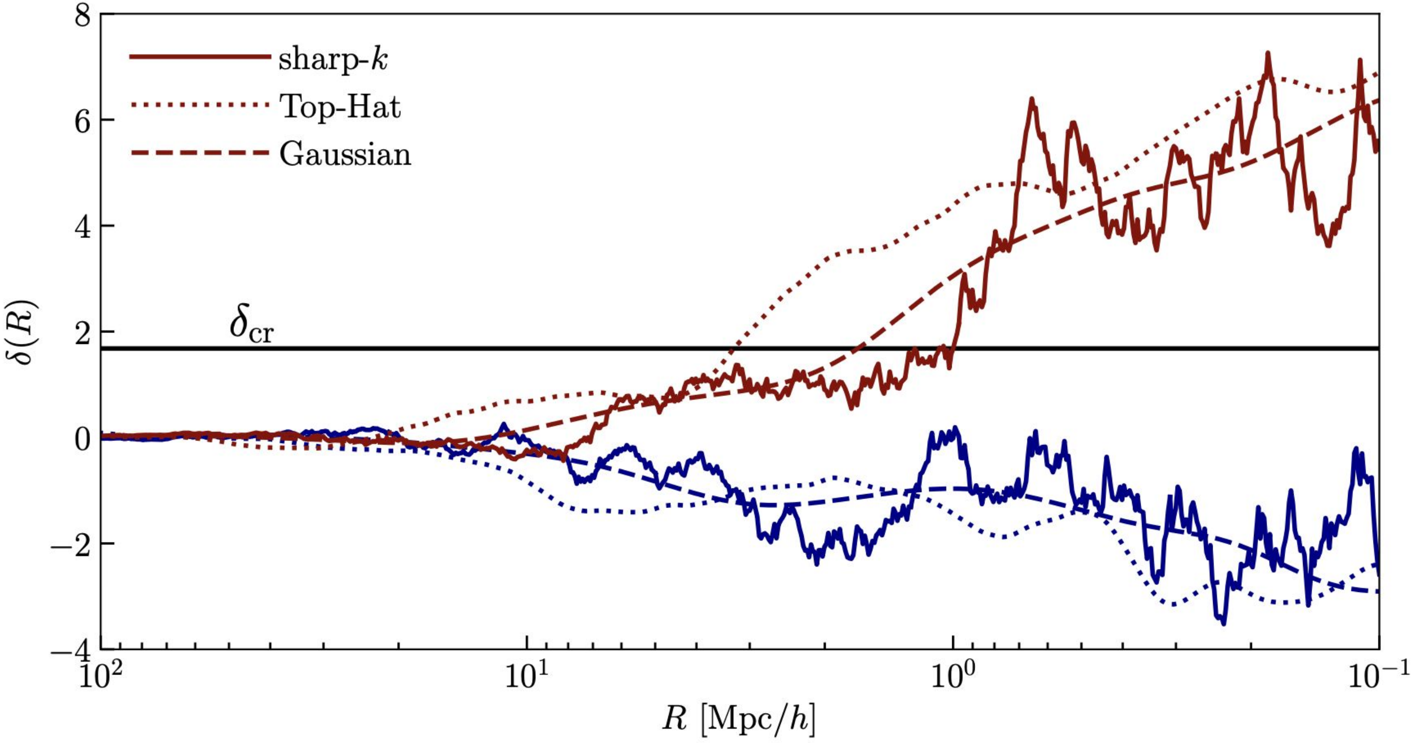
$$\delta^g(x,\tau) = \frac{N(x,\tau) - \bar{N}(\tau)}{\bar{N}(\tau)}$$

Linear bias:

$$\delta^{\mathrm{g}}(x) = b(x)\,\delta^{\mathrm{DM}}(x)$$

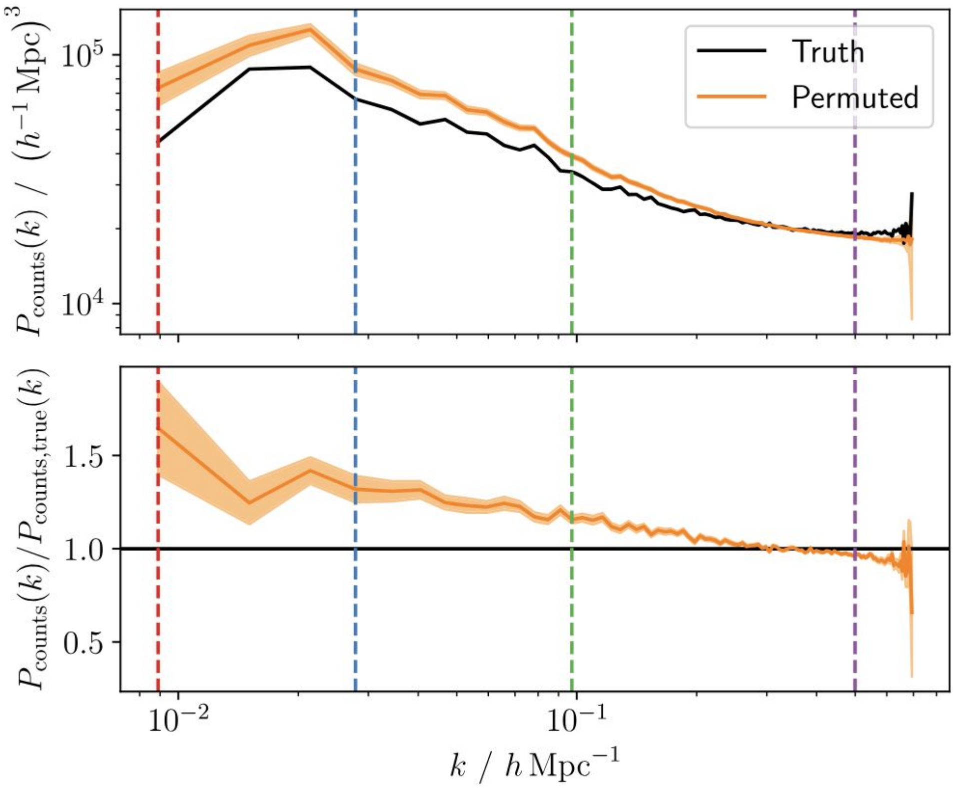


Stochasticity of Galaxy Bias



Desjacques, Jeong & Schmidt 2019

Non-Locality in Galaxy Bias



Bartlett, Ho & Wandelt 2024

See also Chan, Scoccimarro & Sheth 2012

Perturbative Modelling

Expand into bias terms:

$$\delta^g(x,\tau) = \sum_O b_O(\tau) O(x,\tau)$$

Operators of the matter field and gravitational potential: $\delta(x,\tau) \quad \Phi(x,\tau)$

Stochasticity: $$\delta^g(x,\tau) = \ldots + \epsilon(x,\tau) + \sum_O \epsilon_O(x,\tau) O(x,\tau)$$

Assumptions:

- Large, quasi-linear scales
- Gaussian and adiabatic initial conditions
- Statistical homogeneity and isotropy
- Locality of galaxy formation

etc.

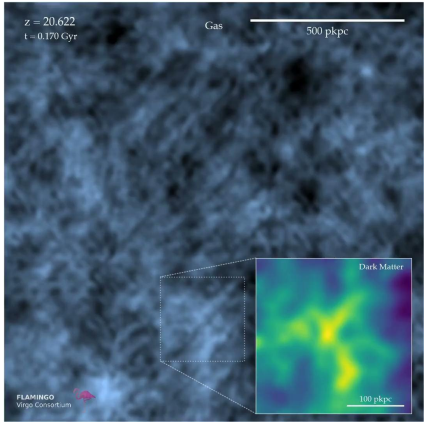
Forward Modelling Galaxy Bias

Approaches to modeling the galaxy-halo connection

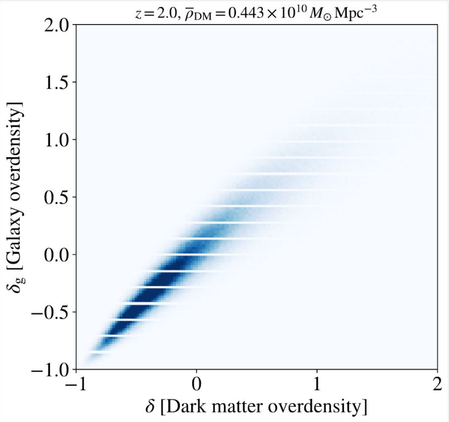
← physical models | empirical models →

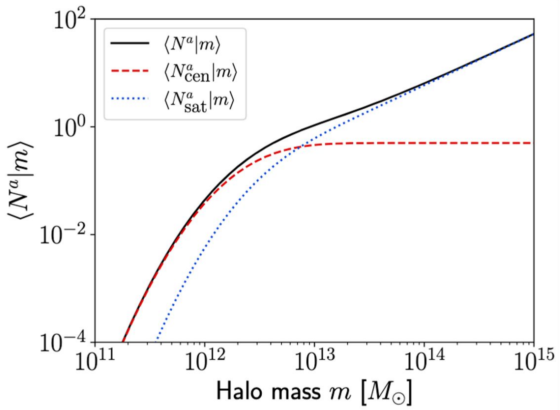
Hydrodynamical Simulations	Semi-analytic Models	Empirical Forward Modeling	Subhalo Abundance Modeling	Halo Occupation Models

Wechsler & Tinker 2018



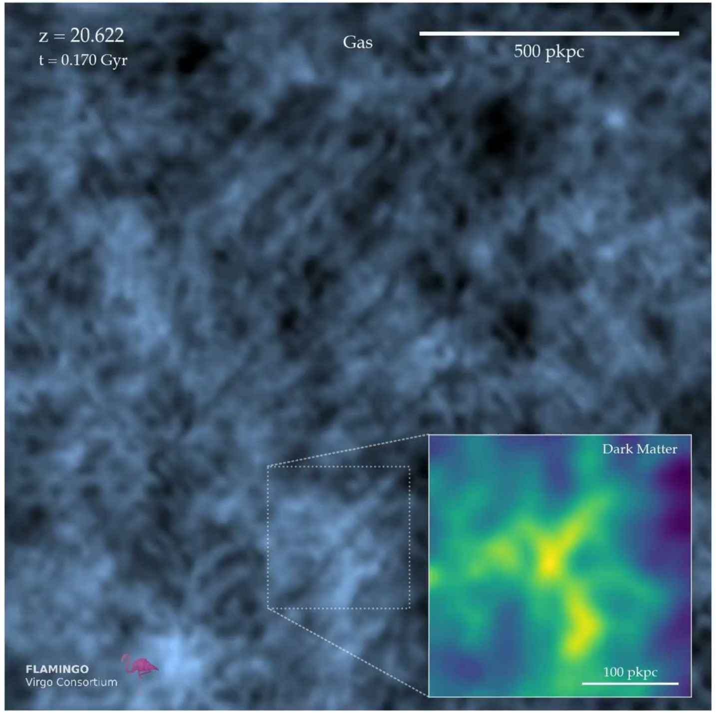
Schaye et al. 2023



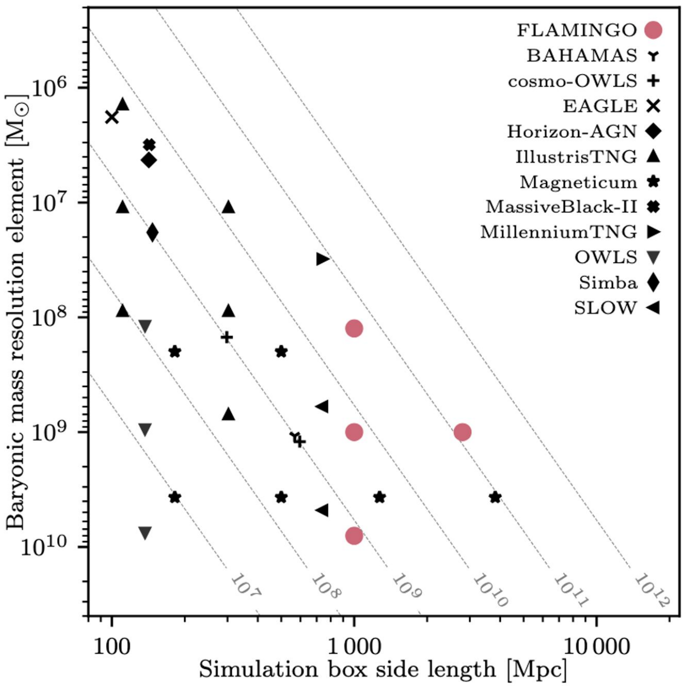


Linke et al. 2022

FLAMINGO Simulations

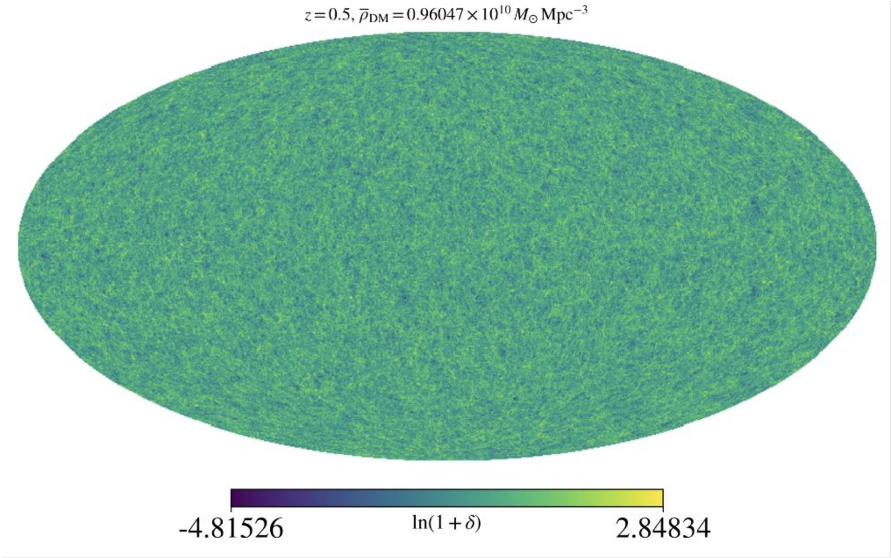


Schaye et al. 2023



- 1 Gpc & 2.8 Gpc boxes
- 4 cosmologies
- 8 feedback models
- 2 lightcones per realisation
- Dark matter only run for each simulation

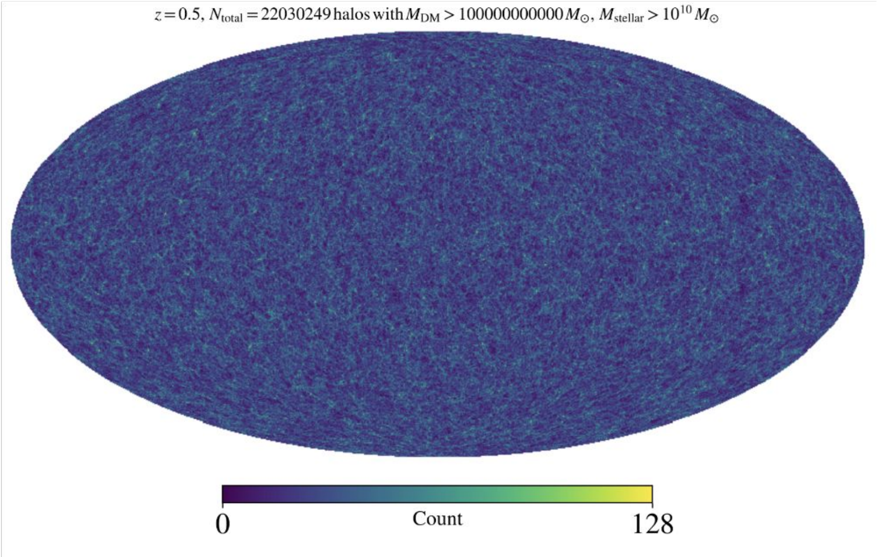
FLAMINGO Lightcones



Contains information on:

- Redshift
- Stellar mass
- Star formation rate
- Black hole mass
- Resolution

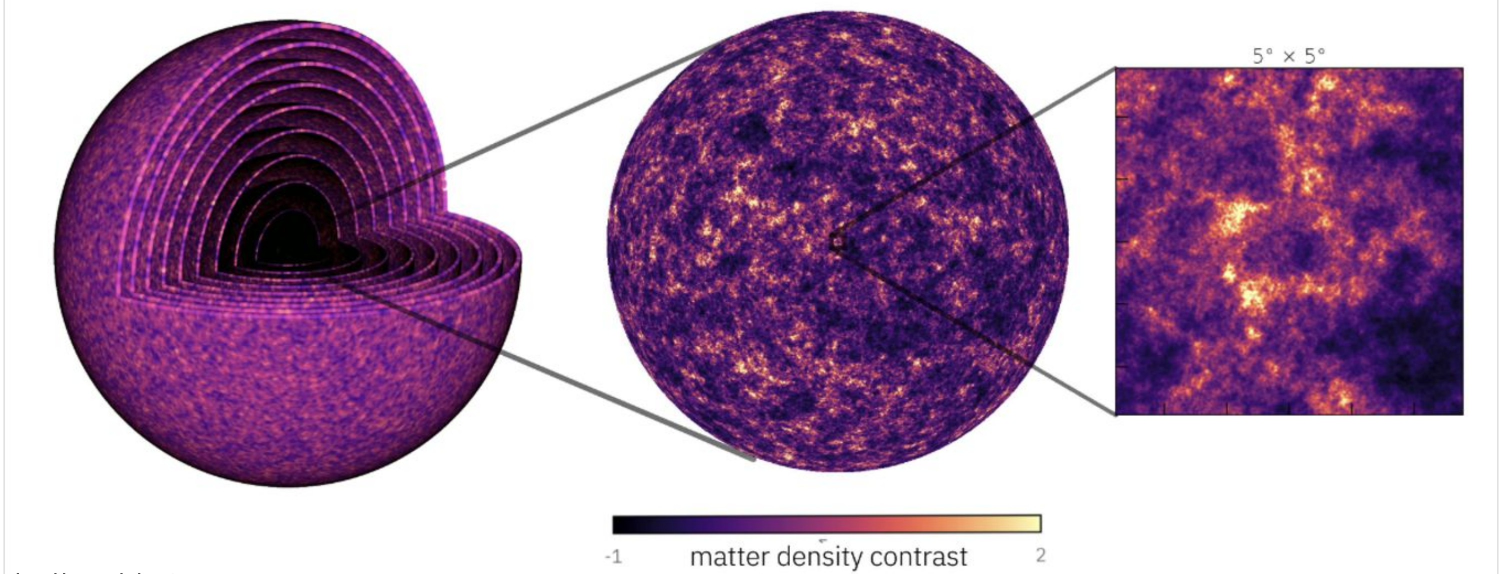
...



Forward Modelling Galaxy Bias

In projection along the line-of-sight:

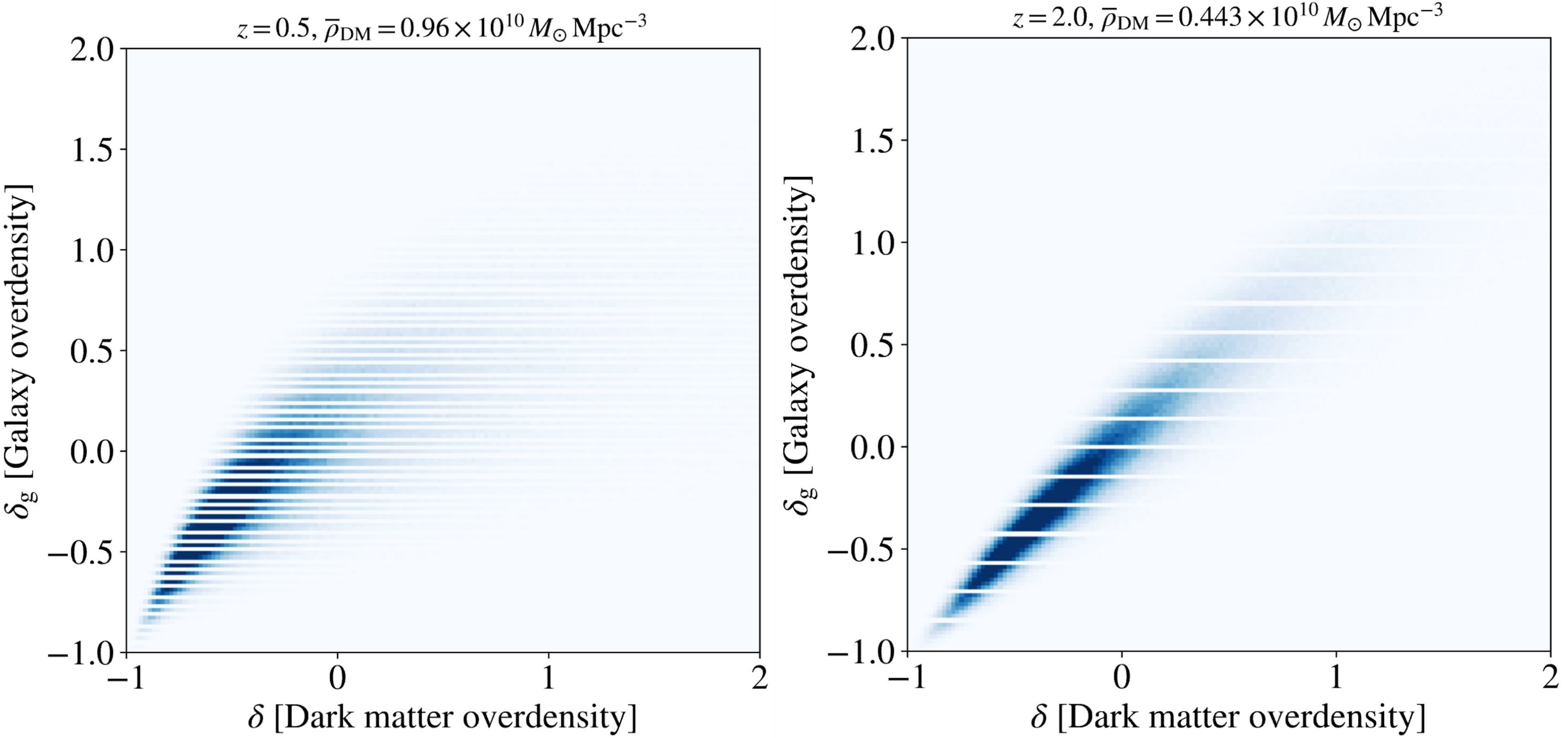
$$\delta(\theta) = \sum_{\ell m} \delta_{\ell m\,0} Y_{\ell m}(\theta) = \int \mathrm{d}z\, W(z)\, \delta(\theta, z); \;\; \delta(\theta, z) = \delta(x)$$



>70 shells with $\Delta z = 0.05$

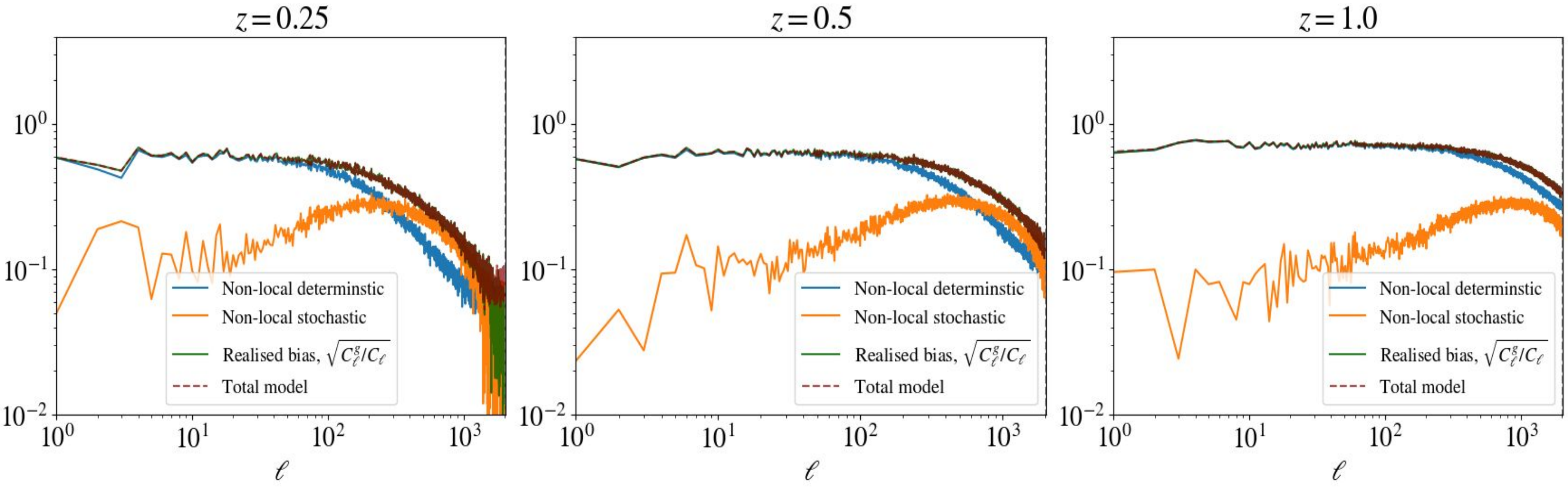
Tessore, et al. (2023)

Forward Modelling Galaxy Bias



von Wietersheim-Kramsta, et al. in prep.

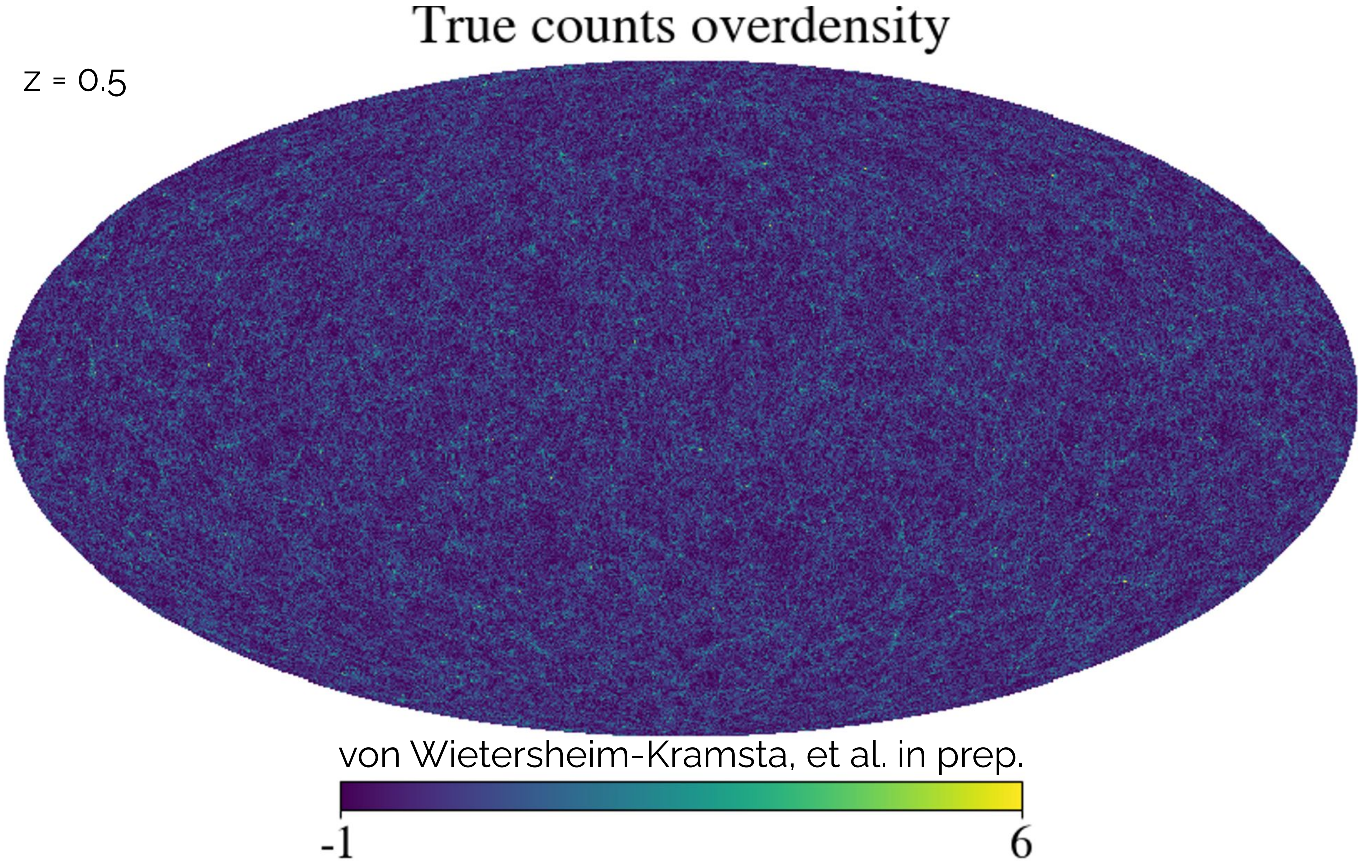
Forward Modelling Galaxy Bias



von Wietersheim-Kramsta, et al. in prep.

Forward Modelling Galaxy Bias

z = 0.5



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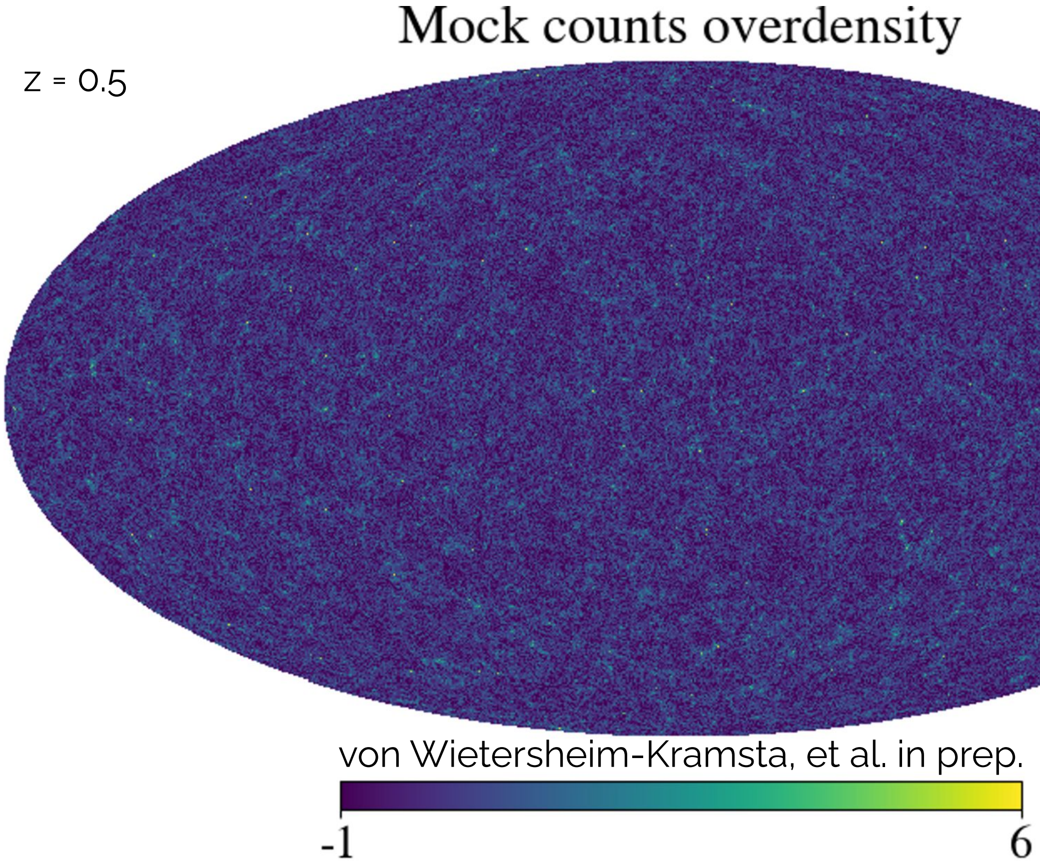

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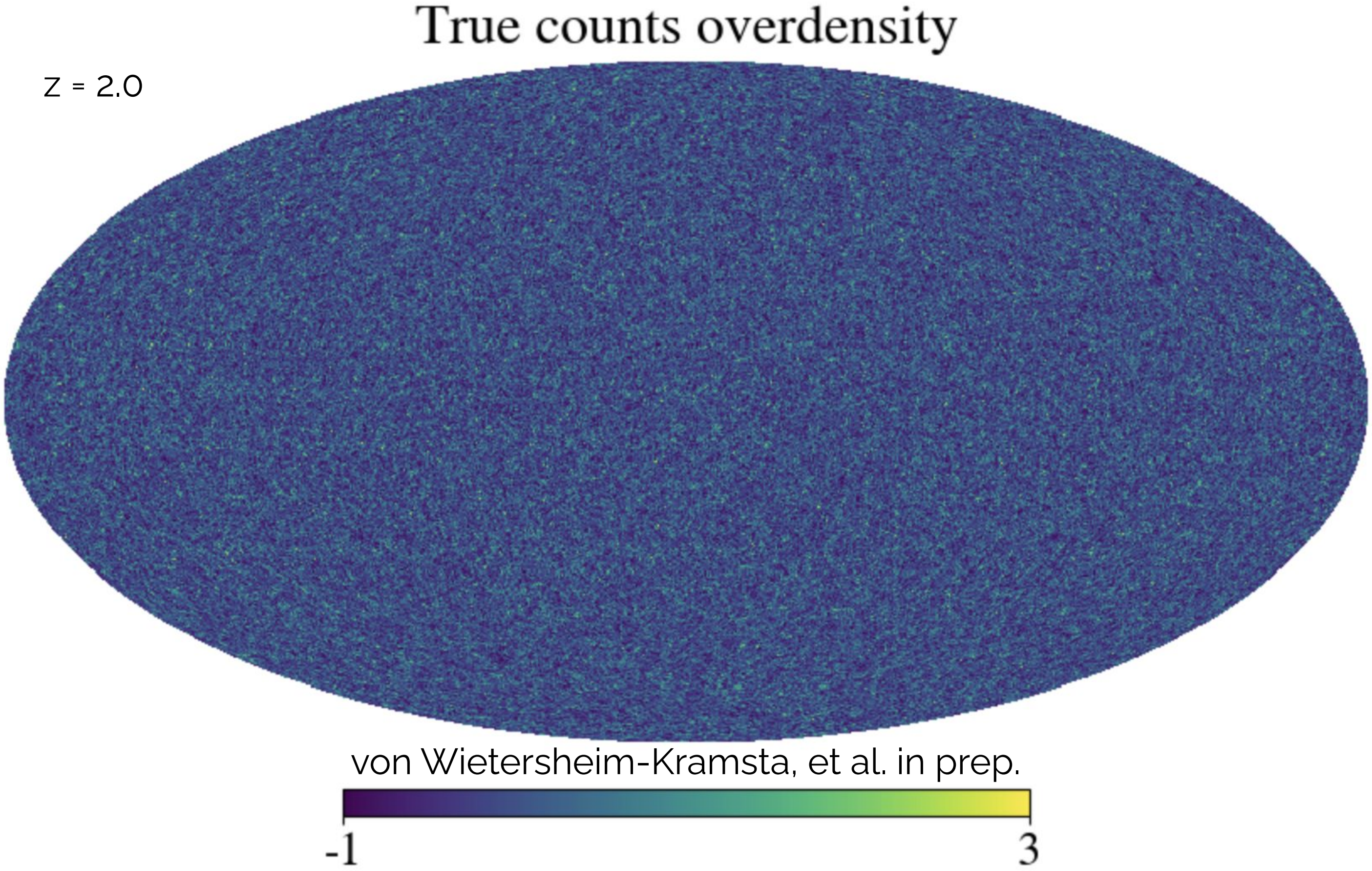
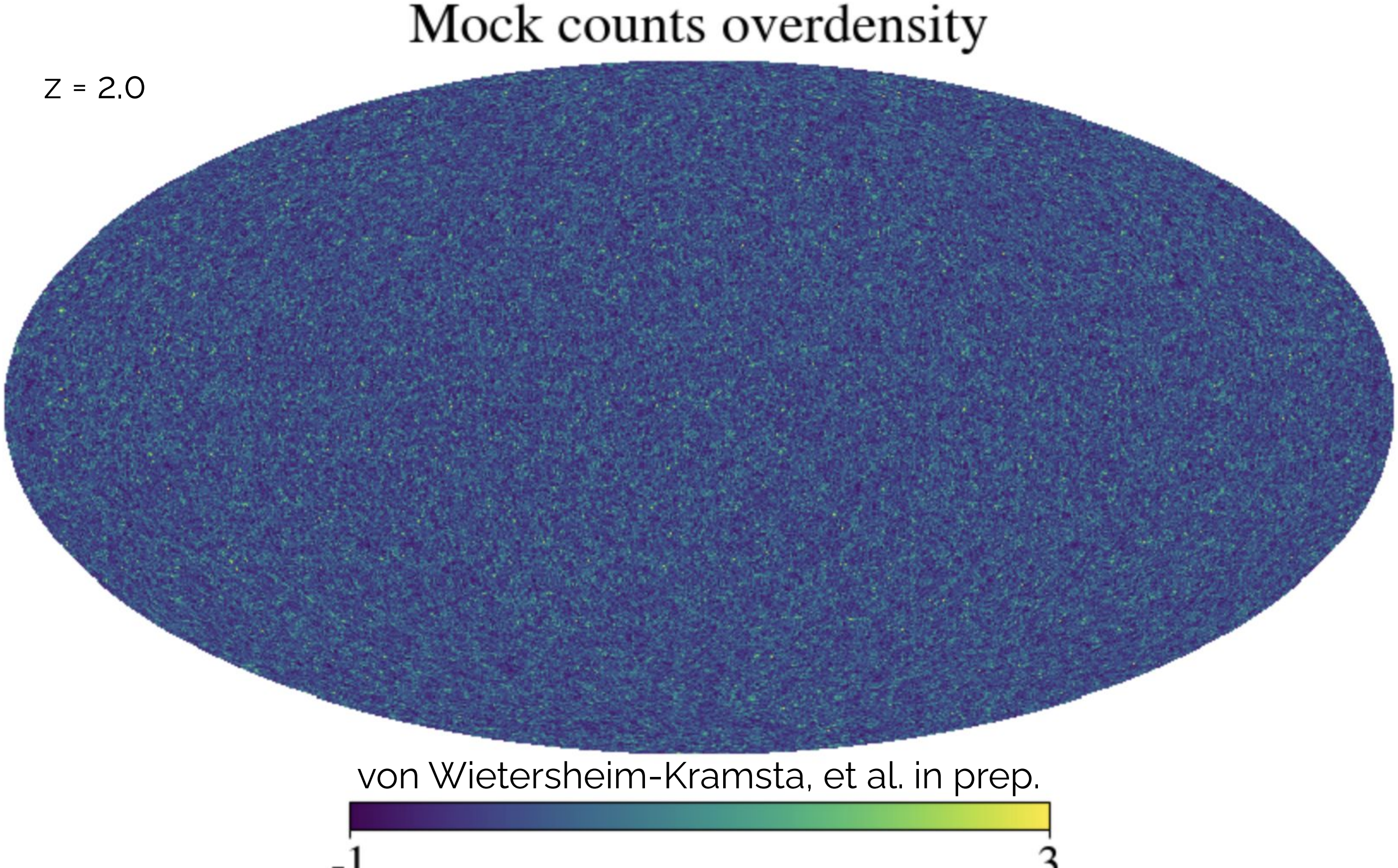
Forward Modelling Galaxy Bias



von Wietersheim-Kramsta, et al. in prep.

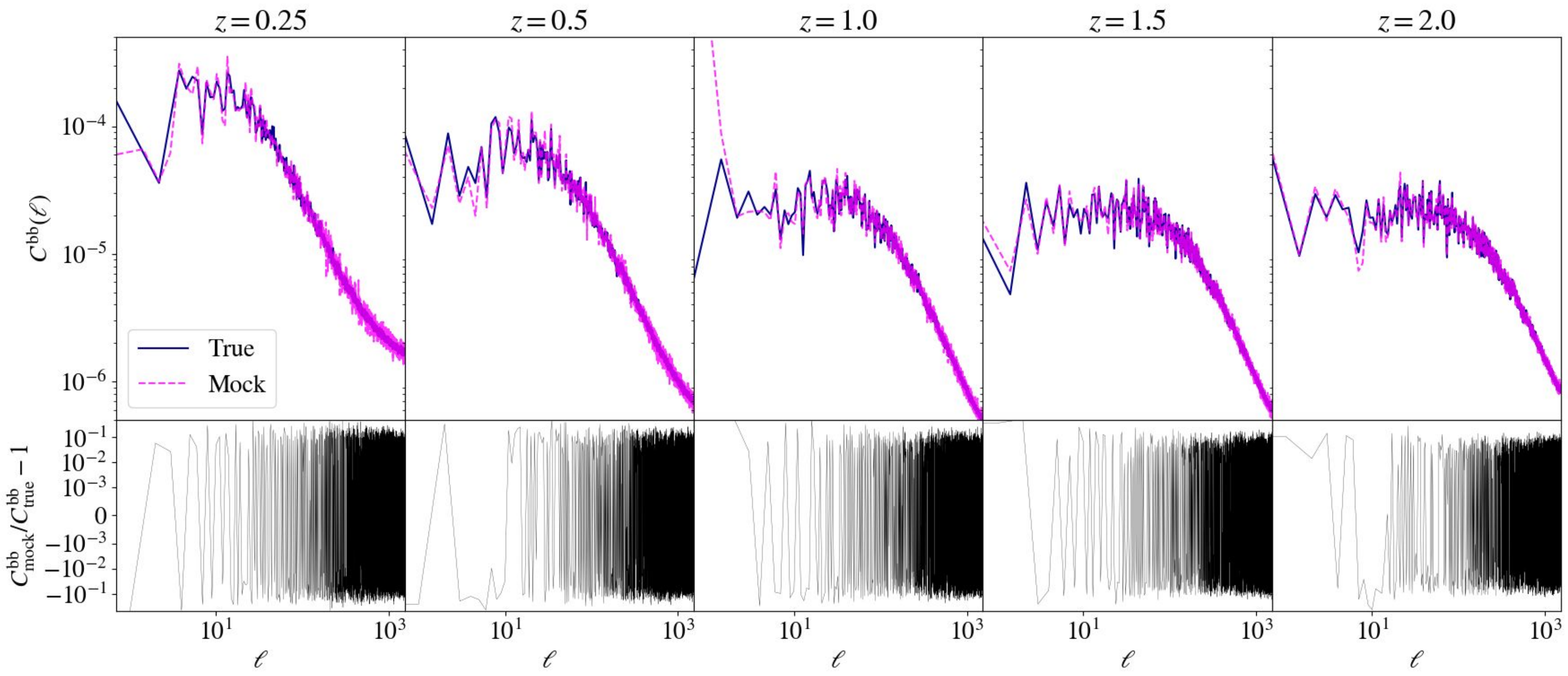
Forward Modelling Galaxy Bias

z = 2.0



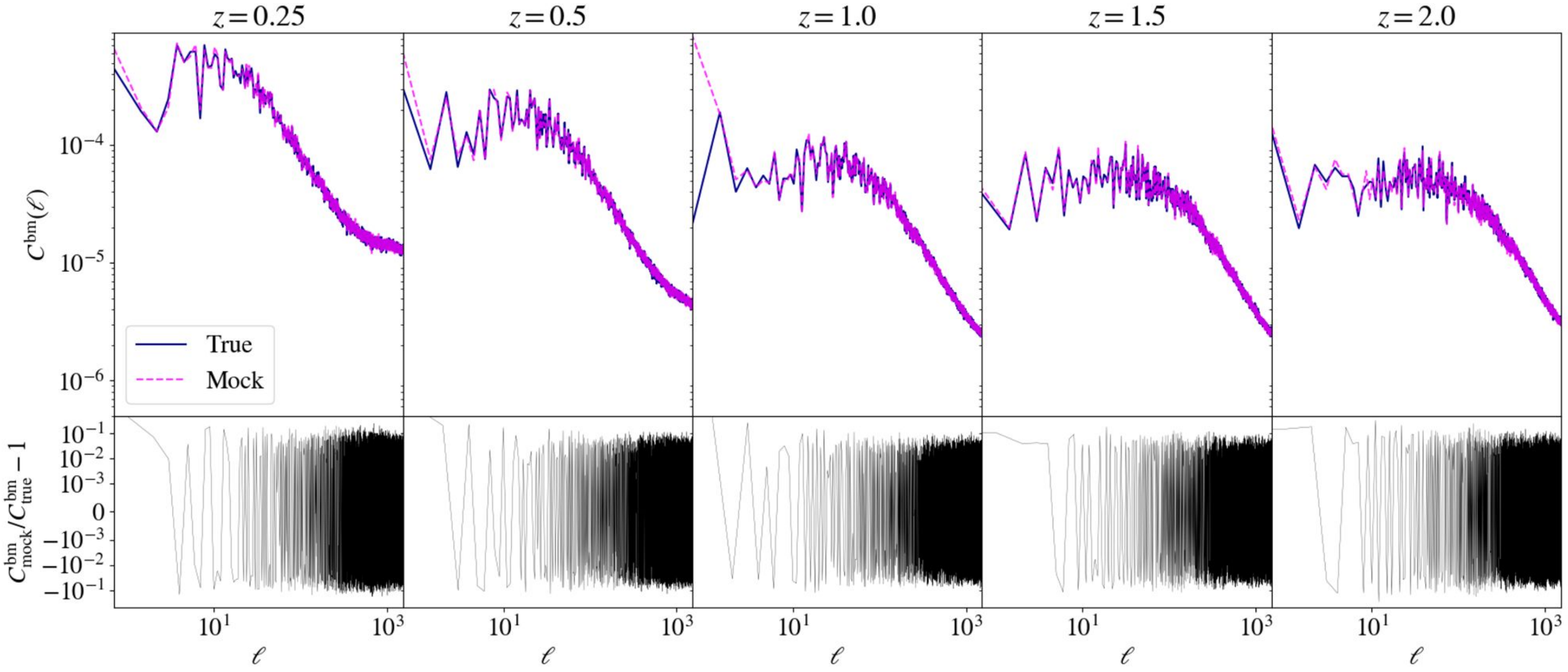
von Wietersheim-Kramsta, et al. in prep.

Accuracy at the 2pt Level



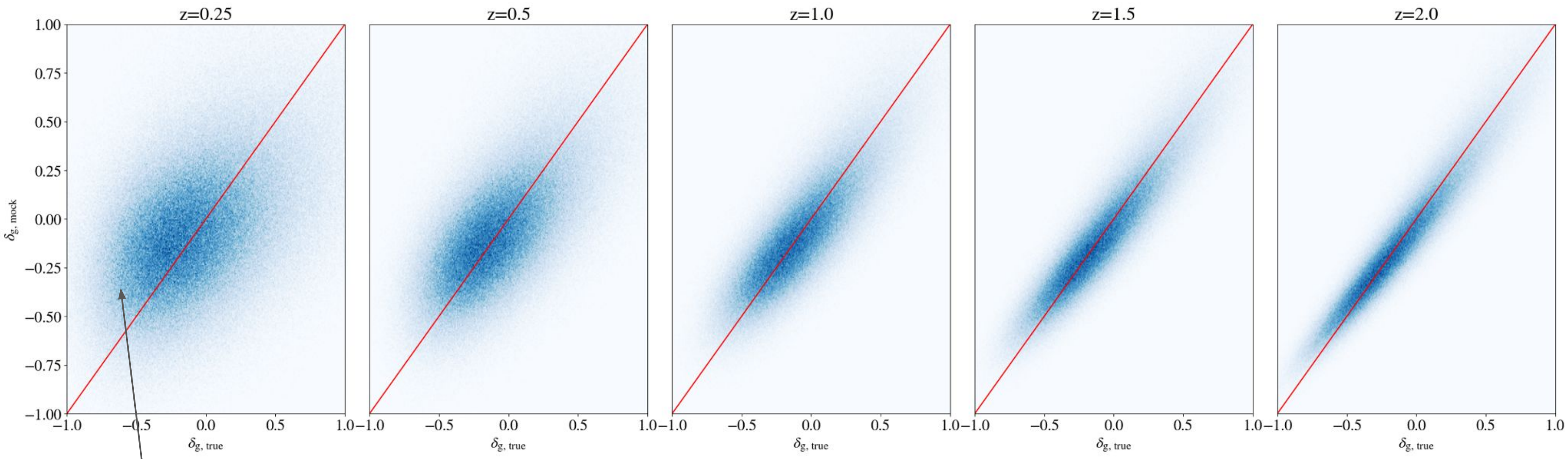
von Wietersheim-Kramsta, et al. in prep.

Accuracy at the 2pt Level



von Wietersheim-Kramsta, et al. in prep.

Overall Accuracy



Random sampling preferentially populates pixels

von Wietersheim-Kramsta, et al. in prep.

Accuracy for Higher-Order Statistics

Wavelets, $\{\psi_{j,\theta}\}_{j,\theta}$, for a given dilation and rotation (dilation j and rotation θ).

WPH moments of field X:

$$C_{\lambda,p,\lambda',p'}(\tau) = \mathrm{Cov}\left([X * \psi_\lambda(\mathbf{r})]^p, [X * \psi_{\lambda'}(\mathbf{r}+\tau)]^{p'}\right)$$

Coefficients:

$$S^{(1,1)} : \lambda = \lambda', p = p' = 1, \tau = \tau_{n,\alpha}$$

Weighted averages of the power spectrum over the bandpass of ψ_λ

$$S^{(0,1)} : \lambda = \lambda', p = 0, p' = 1, \tau = 0;$$

Couplings between the scales included in the same bandpass

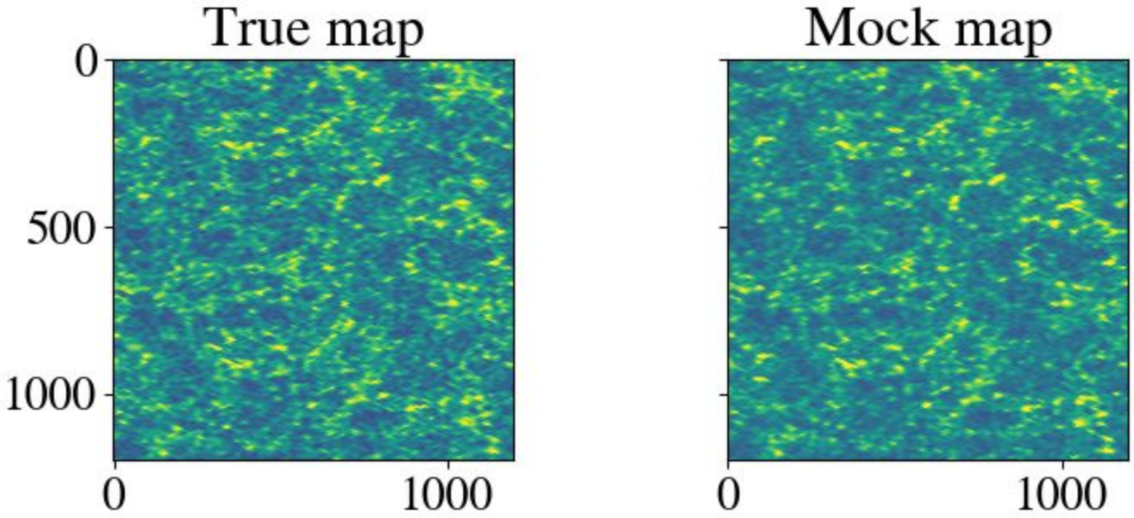
$$C^{(0,1)} : p = 0, p' = 1, \ldots$$

Correlation between local levels of oscillation for the scales in the bandpasses associated with ψ_λ and ψ_λ.

Regaldo-Saint Blancard et al. 2021

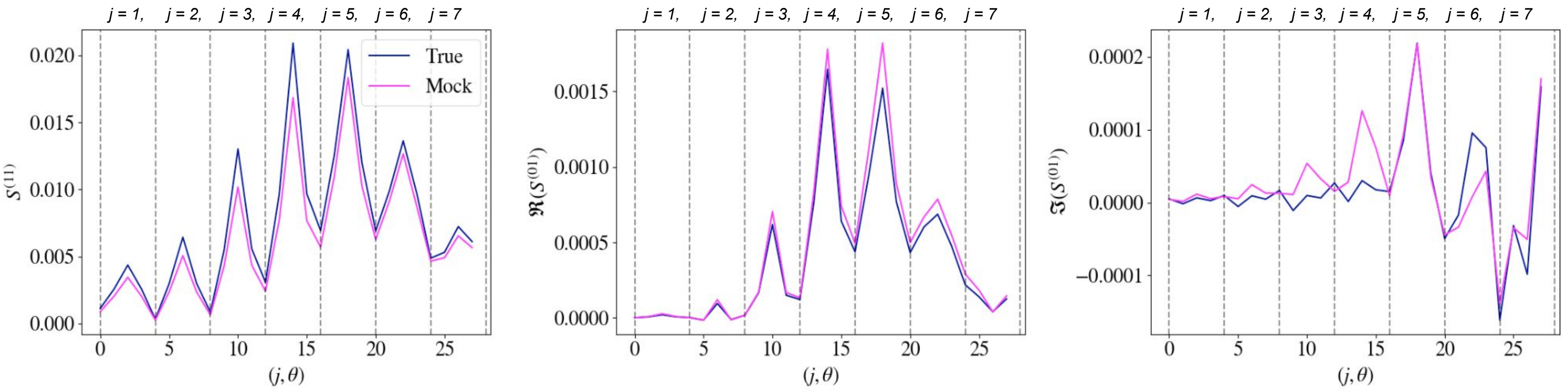
Accuracy for Higher-Order Statistics

10 deg x 10 deg
Cartesian
projection



von Wietersheim-Kramsta, et al. in prep.

Accuracy for Higher-Order Statistics



Weighted averages of the power spectrum over the bandpass of ψ_λ

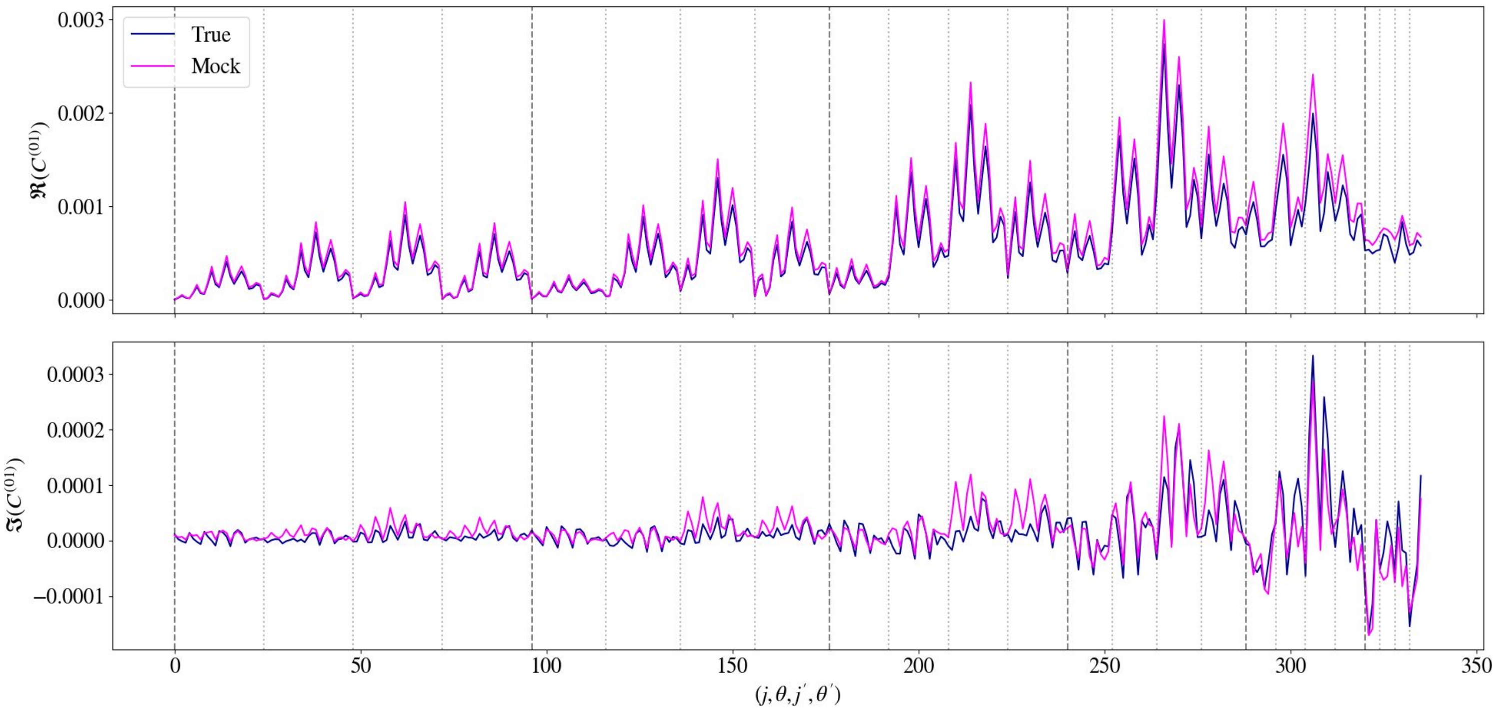
Couplings between the scales included in the same bandpass

von Wietersheim-Kramsta, et al. in prep.

Accuracy for Higher-Order Statistics

-- Lines of constant (j, θ)

Correlation between local levels of oscillation for the scales in the bandpasses associated with ψ_λ and $\psi_{\lambda'}$.



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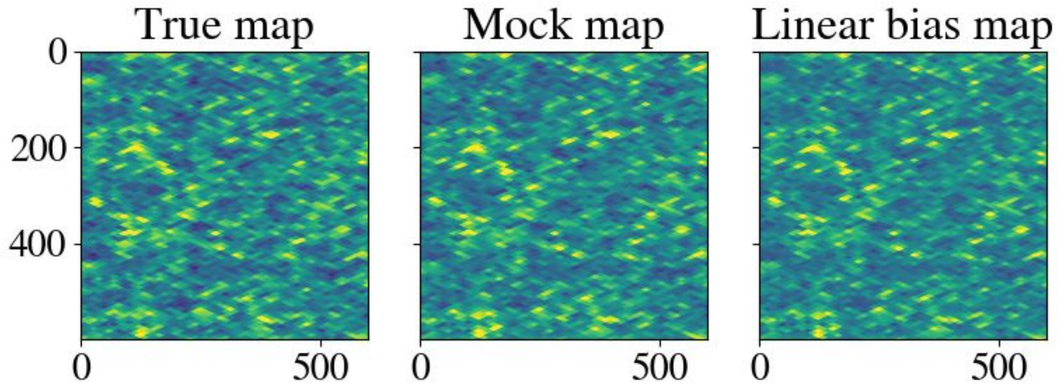
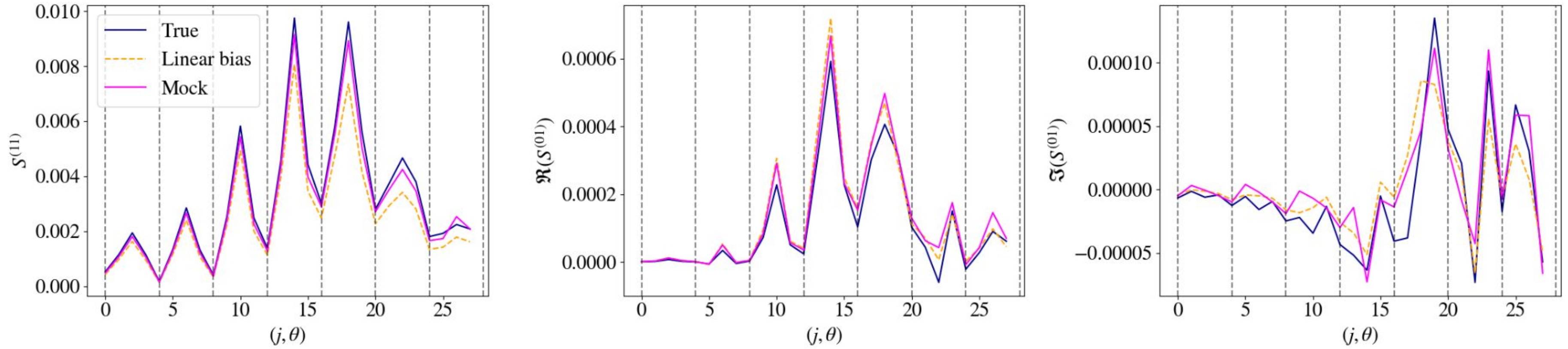
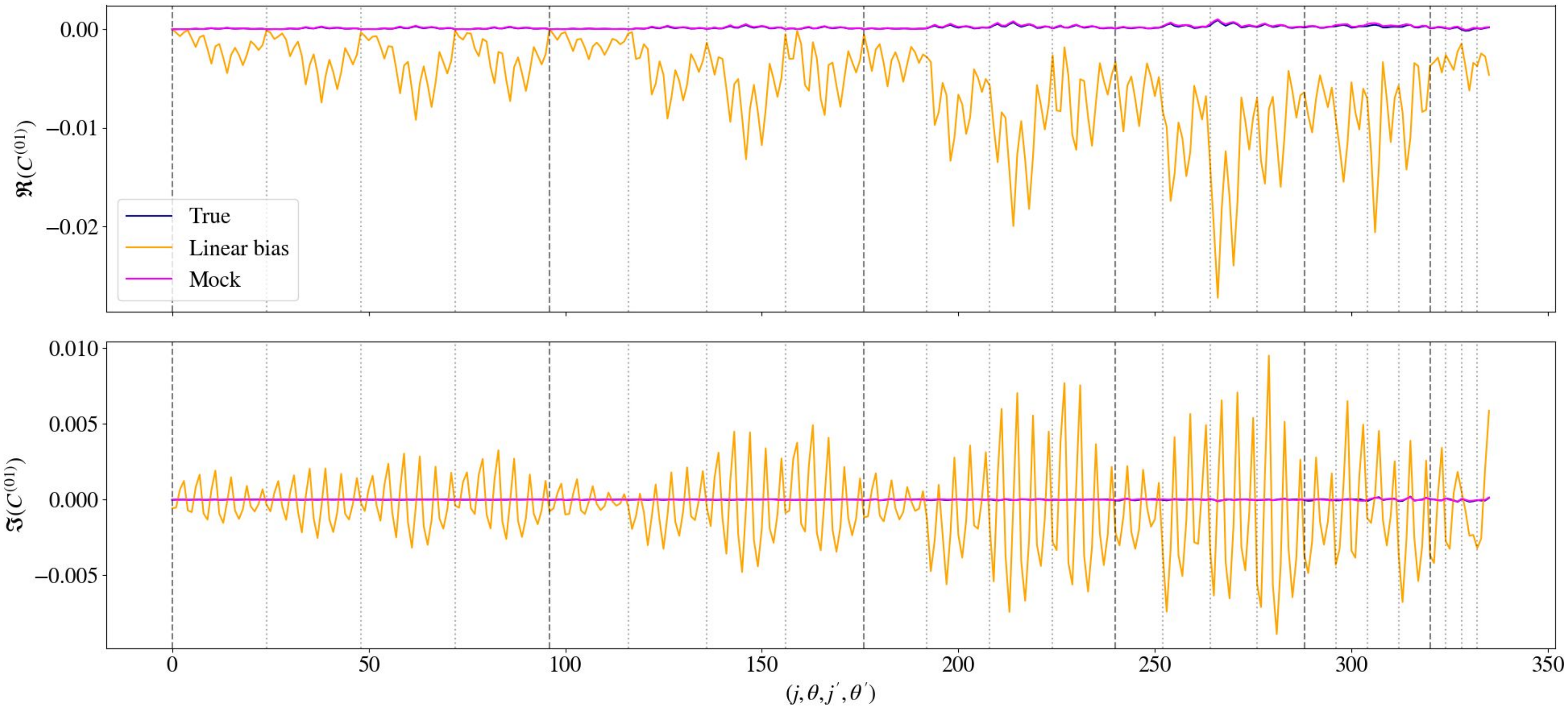
Accuracy for Higher-Order Statistics





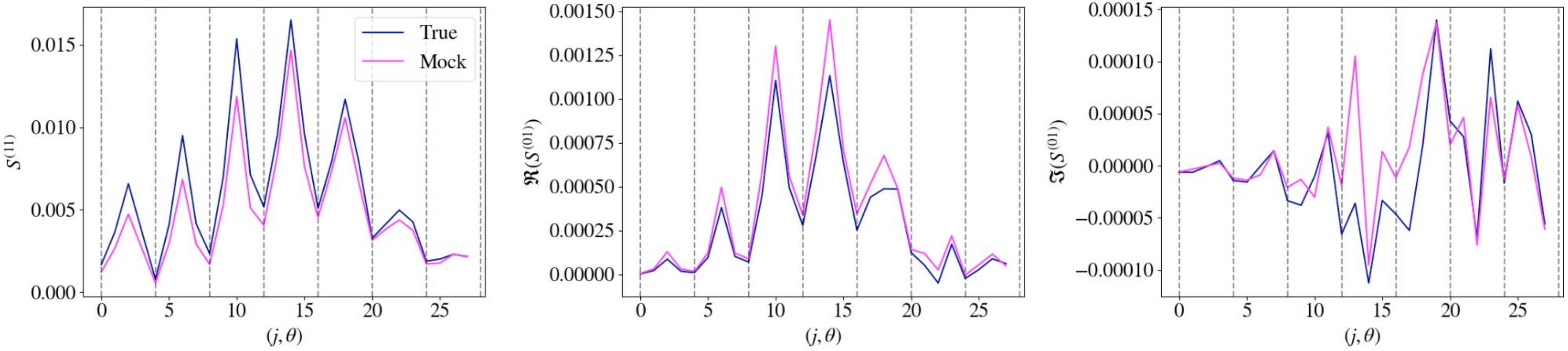
von Wietersheim-Kramsta, et al. in prep.

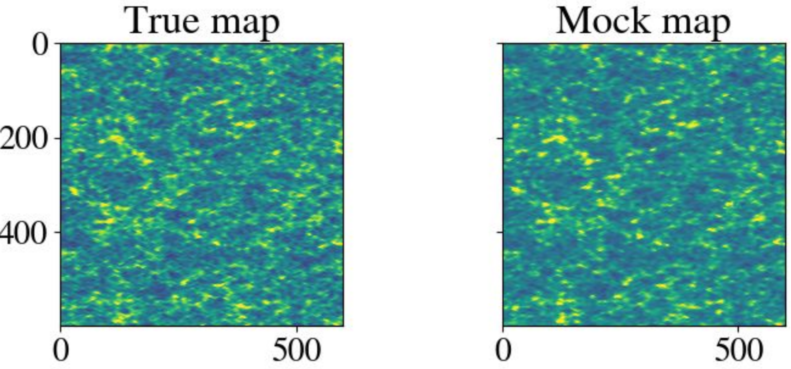
Accuracy for Higher-Order Statistics

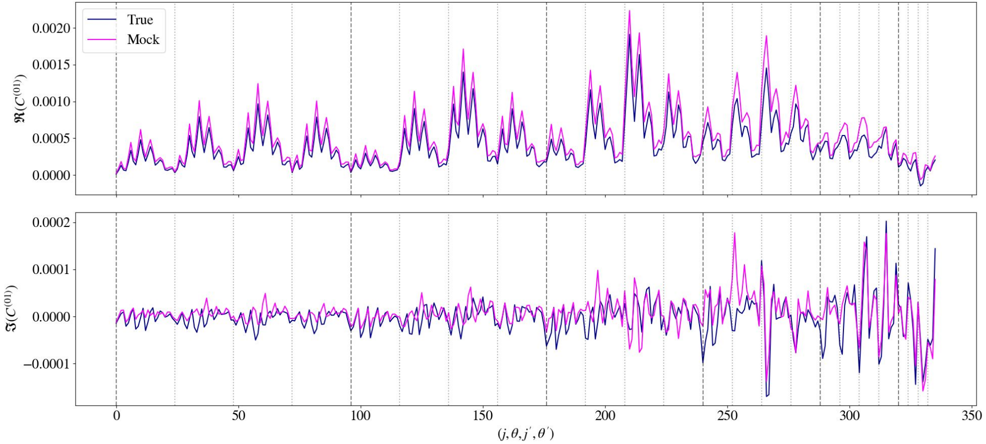


von Wietersheim-Kramsta, et al. in prep.

Accuracy for Higher-Order Statistics: z = 1.5







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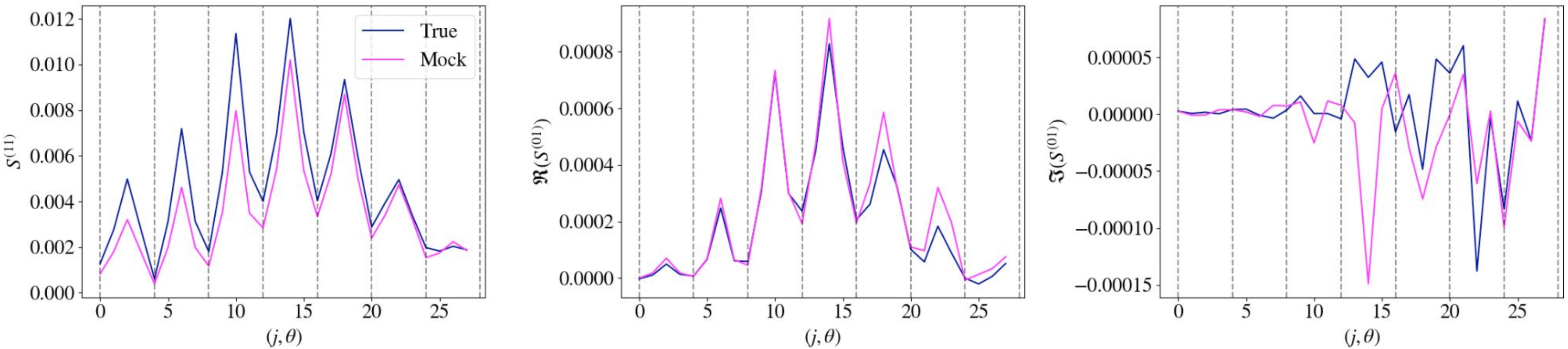
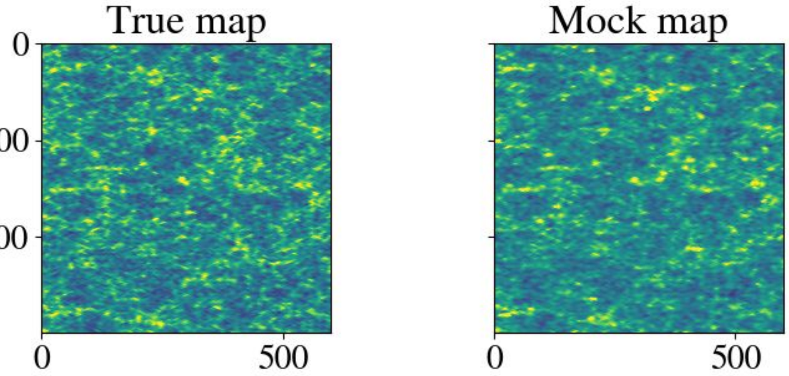
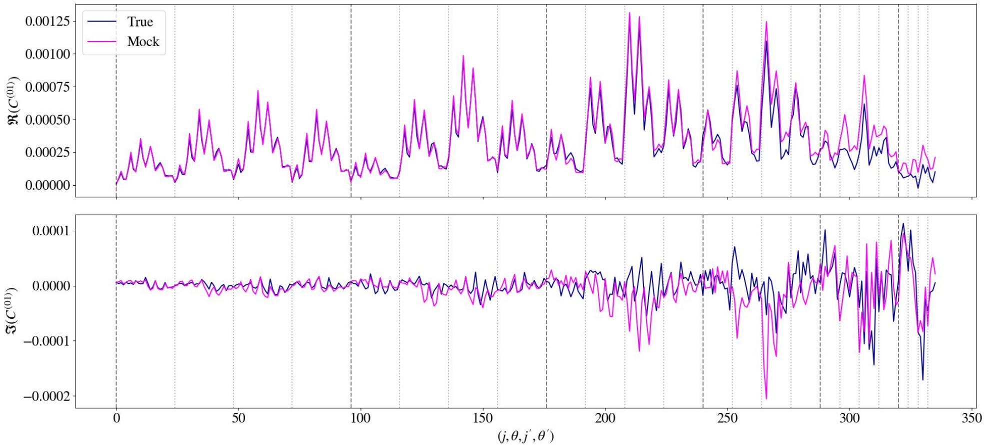
Accuracy for Higher-Order Statistics: z = 1.0







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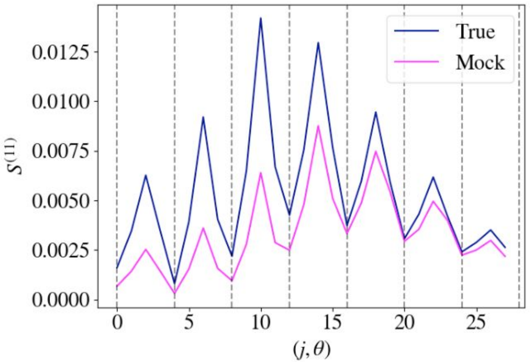
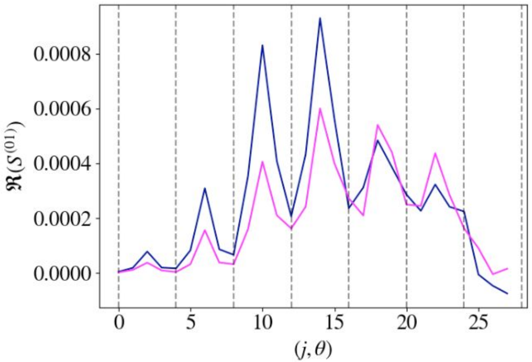
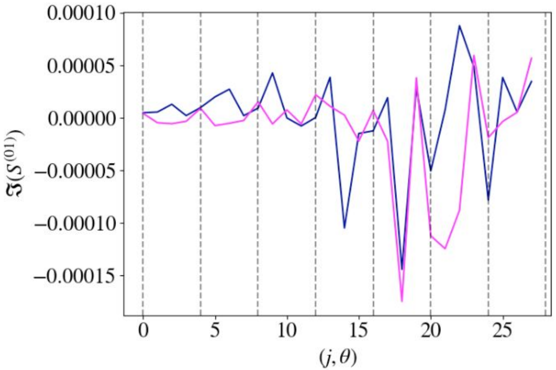
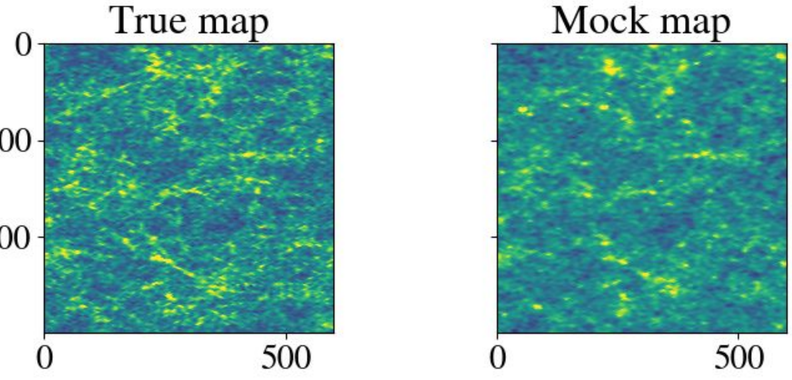
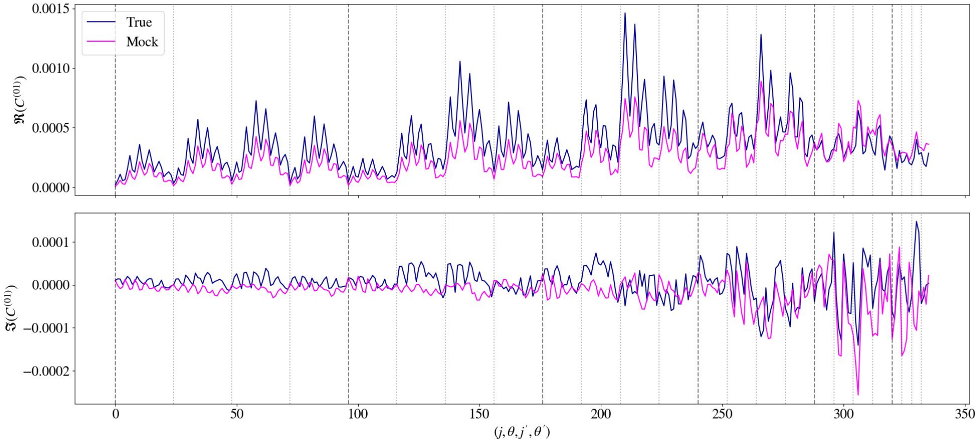
Accuracy for Higher-Order Statistics: z = 0.5











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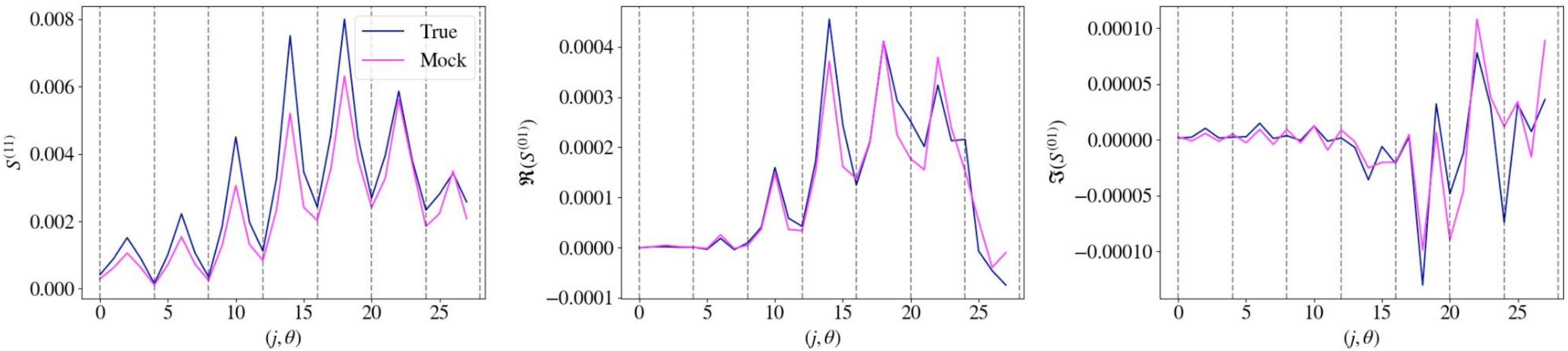
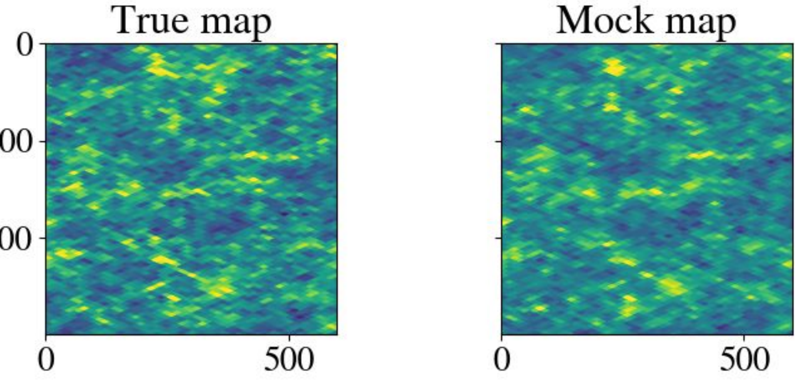
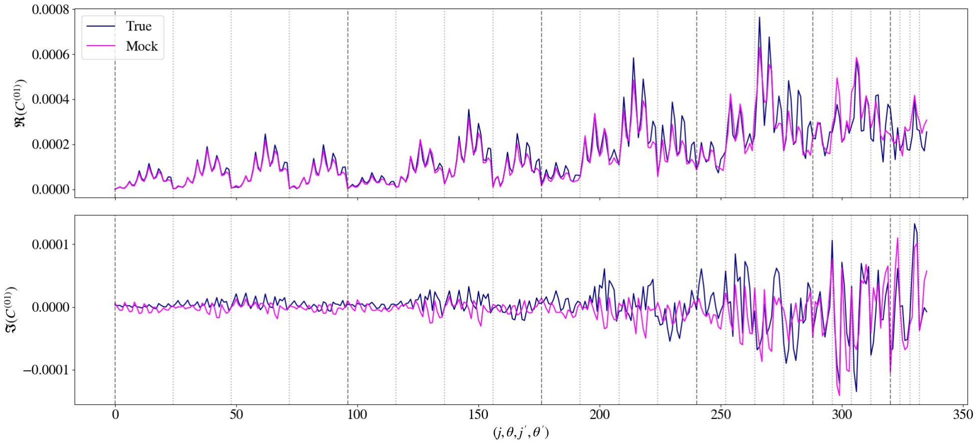
Accuracy for Higher-Order Statistics: Resolution







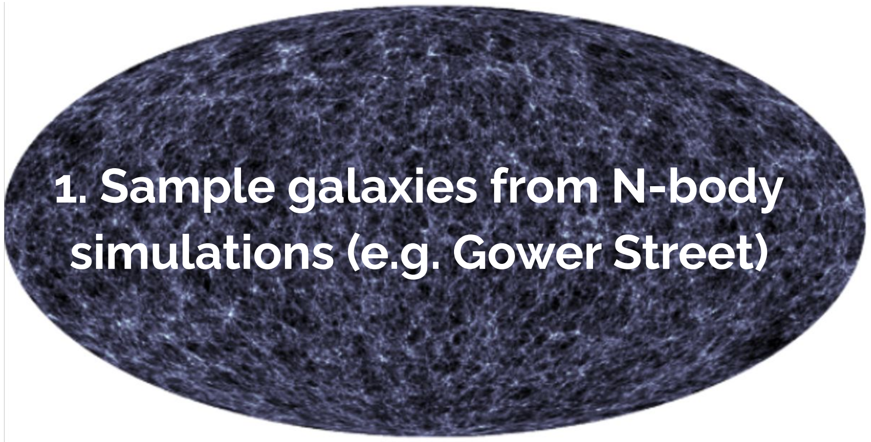
von Wietersheim-Kramsta, et al. in prep.

Outlooks

Further testing:

- On independent FLAMINGO lightcones
- On equivalent Dark Matter Only simulations

Applications to forward modelling & SBI:



2. Sample galaxies from GLASS lognormal simulations