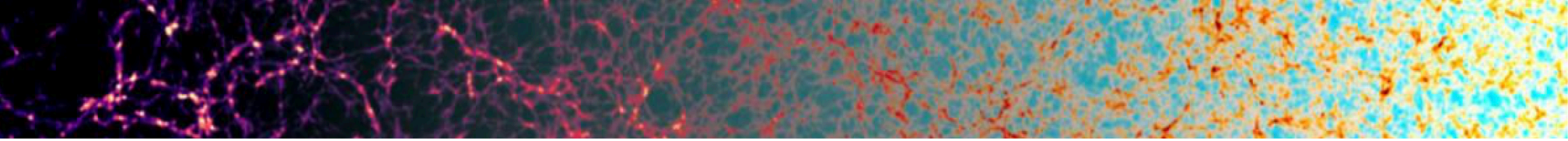


Bayesian Inference of Initial Conditions from Non-Linear Cosmic Structures using Field-Level Emulators

Ludvig Doeser, Drew Jamieson, Stephen Stopyra, Guilhem Lavaux, Florent Leclercq, Jens Jasche

arXiv: 2312.09271

New Strategies for Extracting Cosmology from Galaxy Surveys II – July 5, 2024
SEXTEN CENTER FOR ASTROPHYSICS RICCARDO GIACCONI

Oskar Klein centre

UNIVERSITET STOCKHOLMS

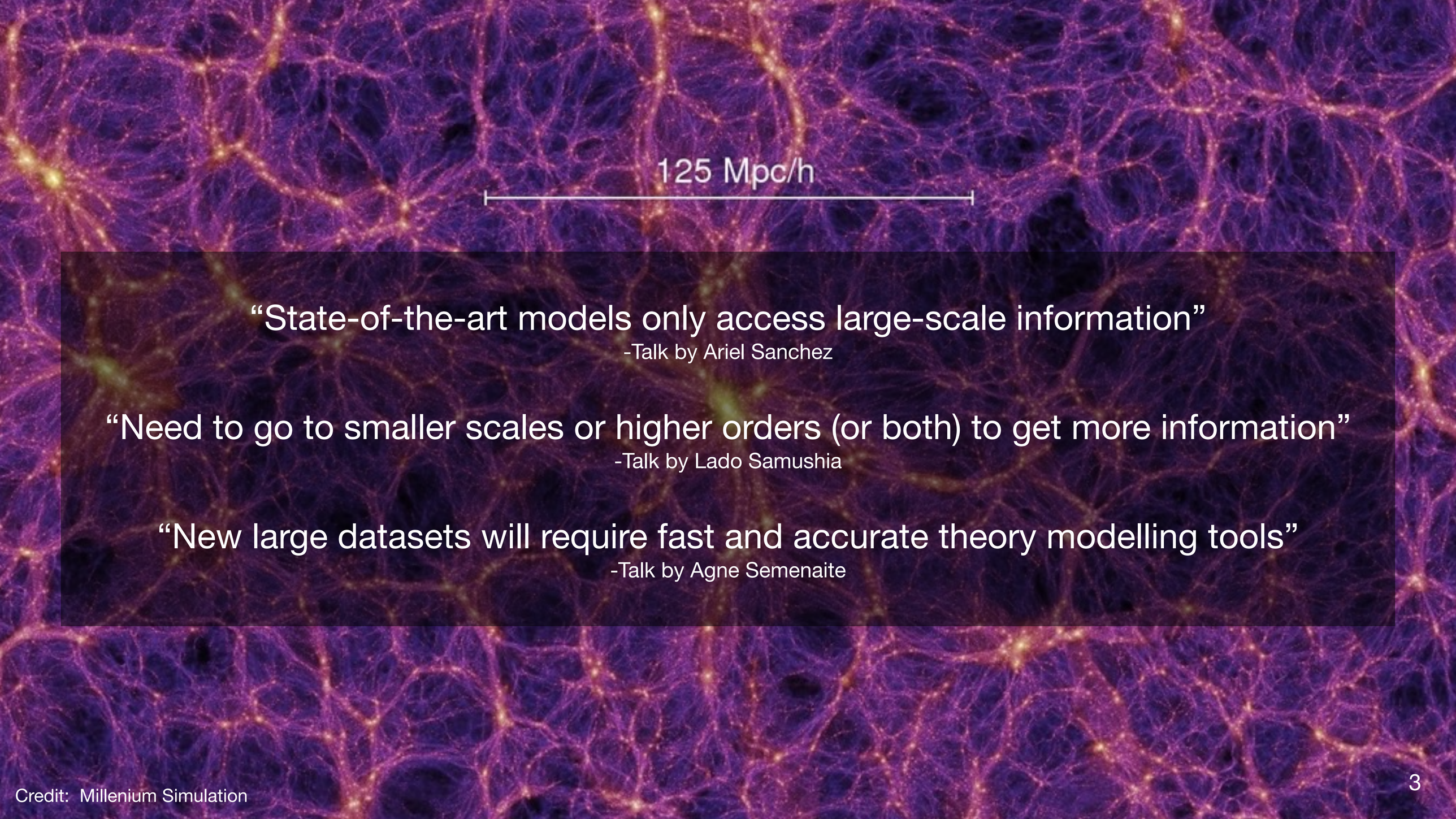
Swedish Research Council

Aquila

SF
SIMONS FOUNDATION

Bayesian Inference of Initial Conditions **from Non-Linear Cosmic Structures** using Field-Level Emulators

1. Why are we interested in non-linear cosmic structures?



“State-of-the-art models only access large-scale information”

-Talk by Ariel Sanchez

“Need to go to smaller scales or higher orders (or both) to get more information”

-Talk by Lado Samushia

“New large datasets will require fast and accurate theory modelling tools”

-Talk by Agne Semenaite

Credit: Millenium Simulation

“State-of-the-art models only access large-scale information”

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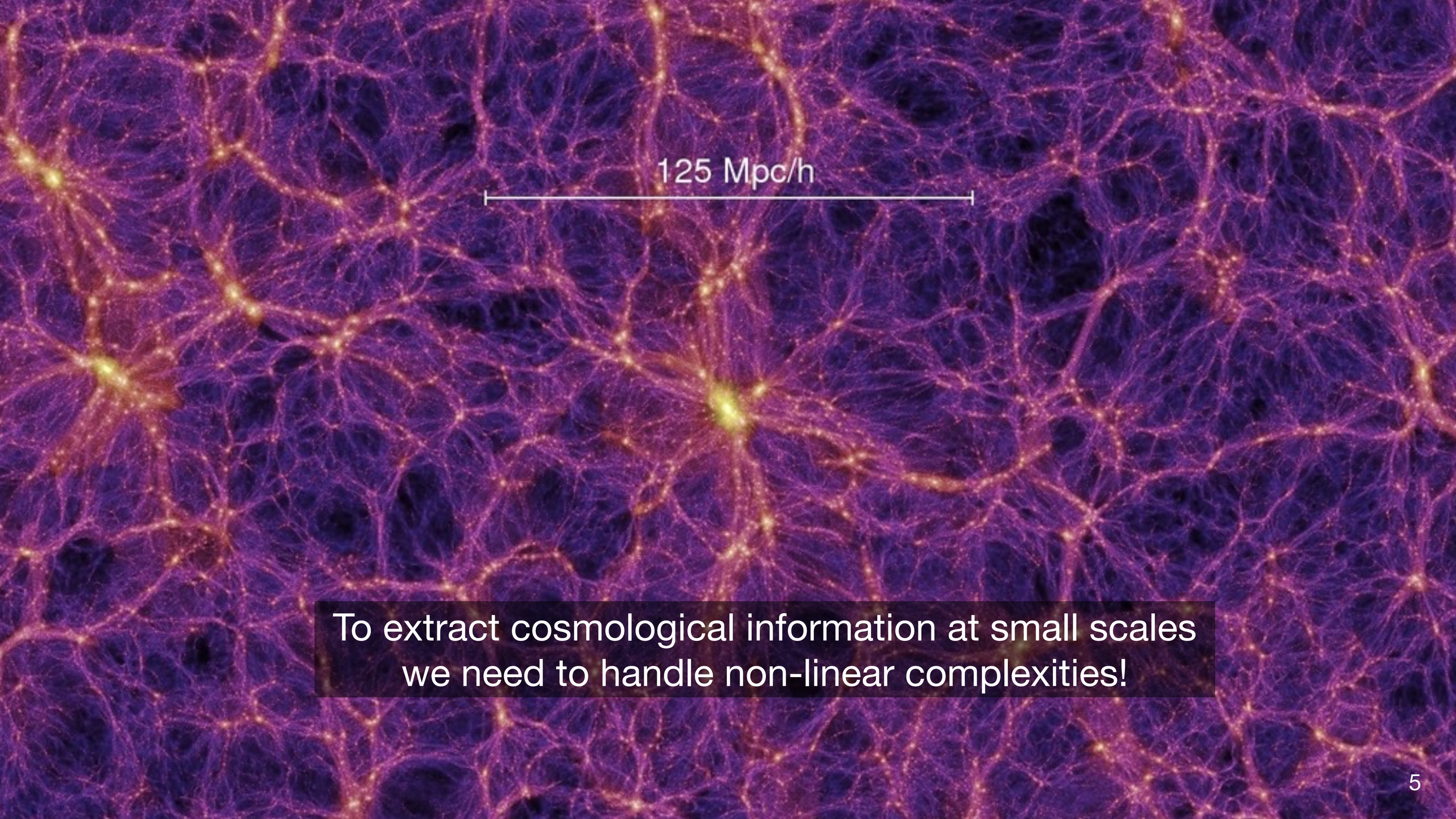
-Talk by Agne Semenaite

Visualisation inspired by Ben Wandelt



To extract cosmological information at small scales
we need to handle non-linear complexities!

Bayesian Inference of Initial Conditions from Non-Linear Cosmic Structures using Field-Level Emulators

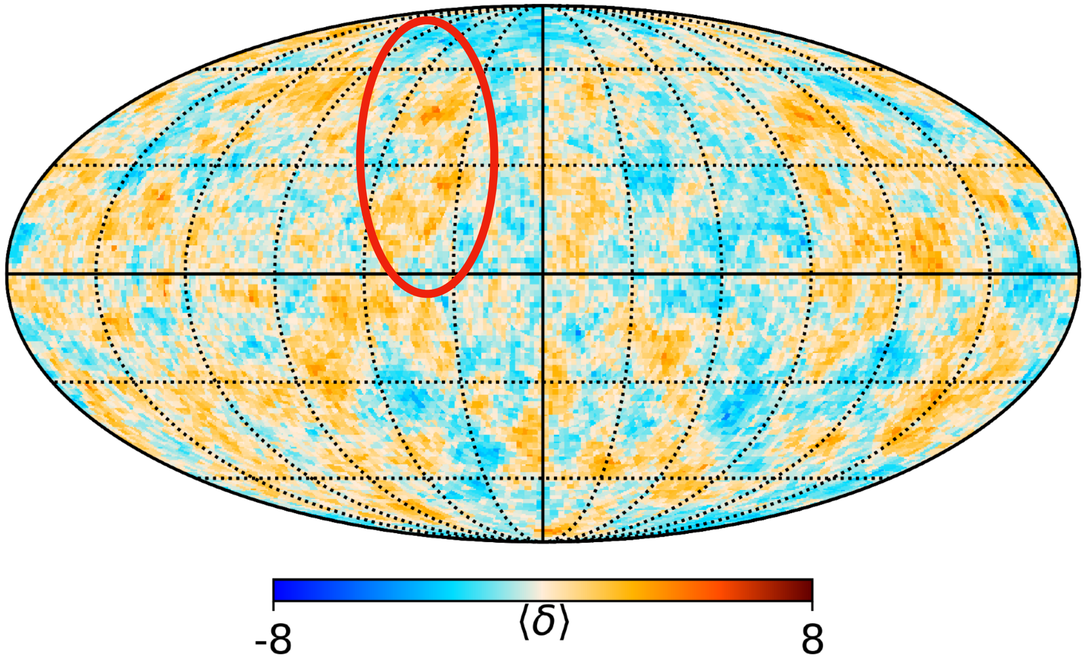
2. Why Bayesian Inference of Initial Conditions?

Aim: Cosmological inference with the large-scale structure (LSS)

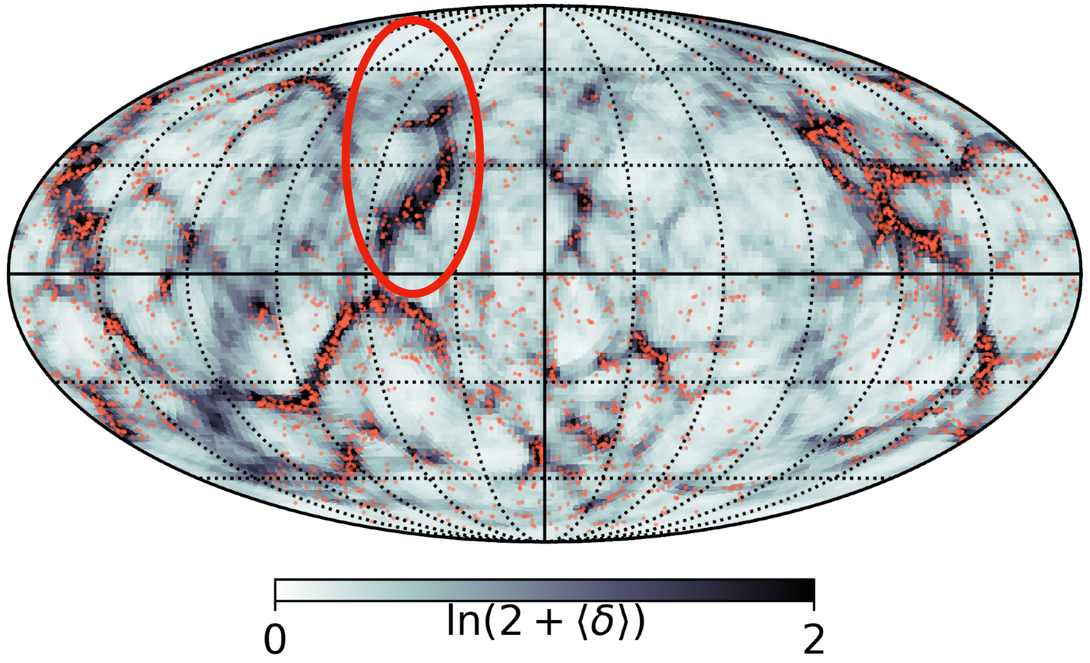
- **Optimal information extraction*:** Field-level analysis

* e.g. Leclercq & Heavens 2021 (arXiv: 2103.04158), Ngyuen 2024 (arXiv: 2403.03220)

- Model the entire 3D LSS to capture all significant physics information, e.g. Jasche & Lavaux 2019 (arXiv: 1806.11117):

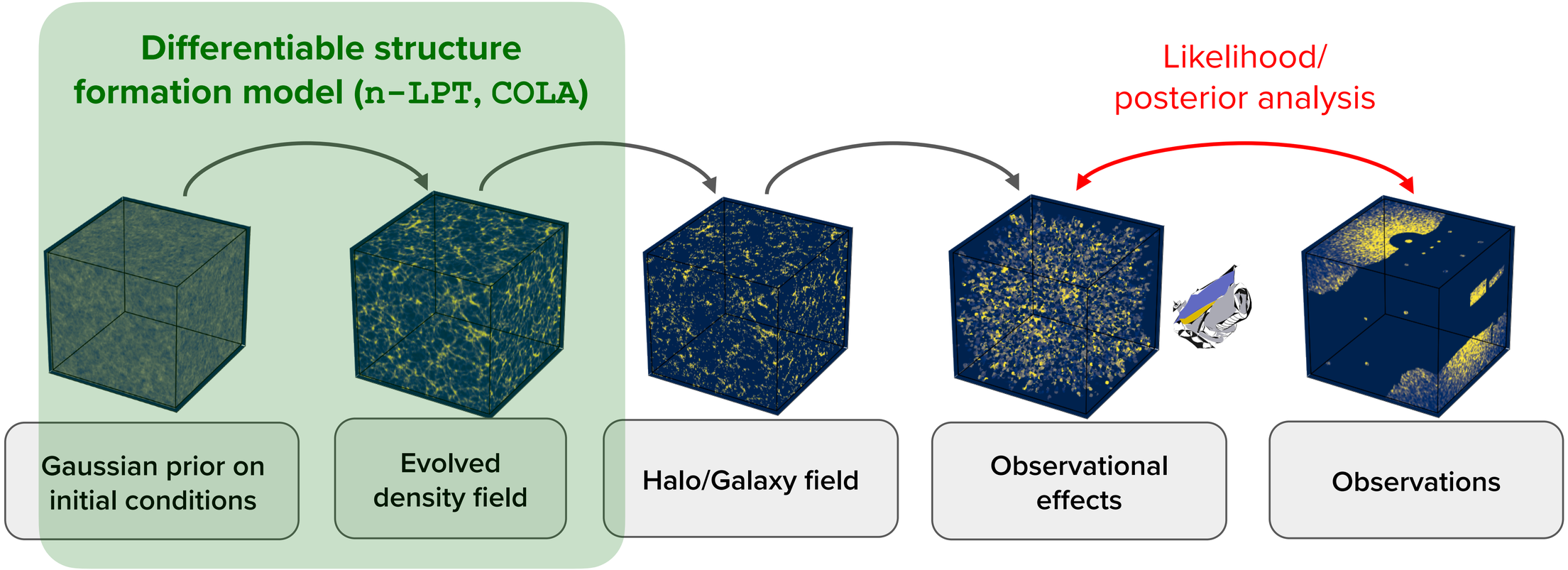


Inferred primordial density field



Inferred evolved density field + observed galaxies

Field-level inference with **BORG**: full posterior of initial conditions



[Jasche & Wandelt 2013 (arXiv: 1203.3639),](#)
[Jasche, Leclercq, & Wandelt 2015 (arXiv: 1409.6308),](#)
[Jasche & Lavaux 2019 (arXiv: 1806.11117)](#)

Bayesian Origin Reconstruction from Galaxies
https://www.aquila-consortium.org/

Bayesian Inference of Initial Conditions from Non-Linear Cosmic Structures **using Field-Level Emulators**

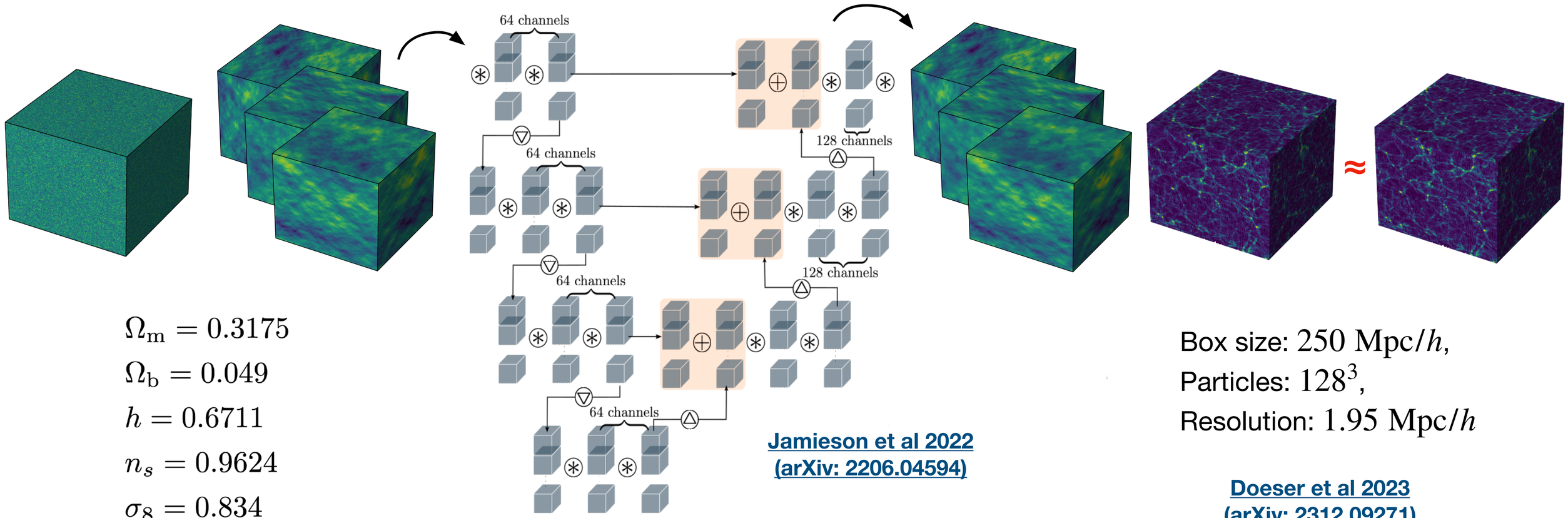
3. Why use field-level emulators?

BORG-EM: V-Net model for accurate and fast non-linear modelling

1LPT
(~0.1s)

Emulator
(~1s)

N-body
(~600s)



$\Omega_{\rm m} = 0.3175$

$\Omega_{\rm b} = 0.049$

$h = 0.6711$

$n_s = 0.9624$

$\sigma_8 = 0.834$

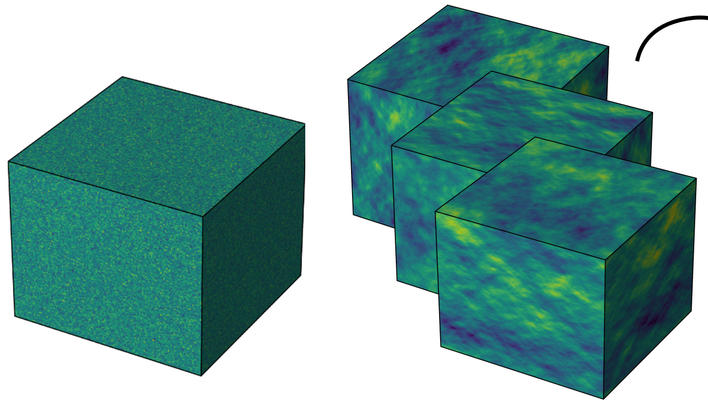
[Jamieson et al 2022 (arXiv: 2206.04594)]

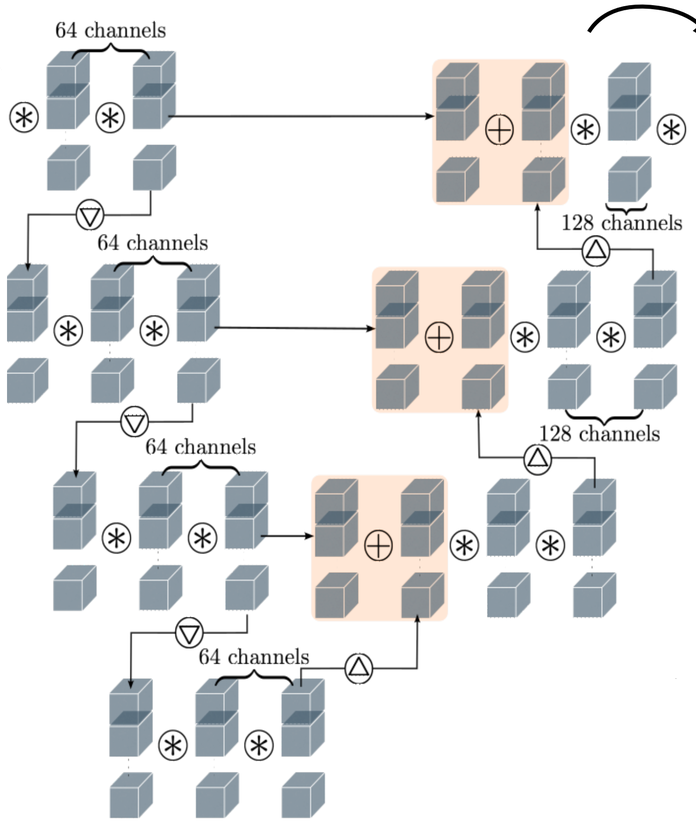
Box size: $250\ \mathrm{Mpc}/h$,
Particles: 128^3,
Resolution: $1.95\ \mathrm{Mpc}/h$

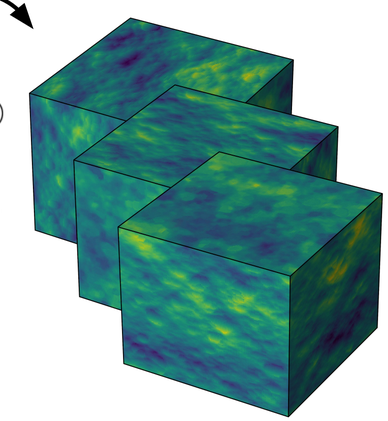
[Doeser et al 2023 (arXiv: 2312.09271)]

BORG-EM: Inferring the initial conditions of N-body

1LPT
(~0.1s)

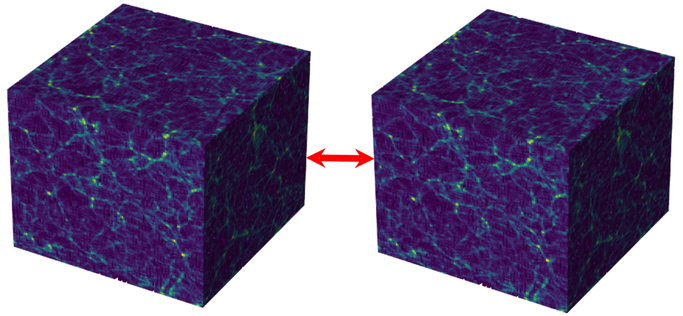






Emulator
(~1s)

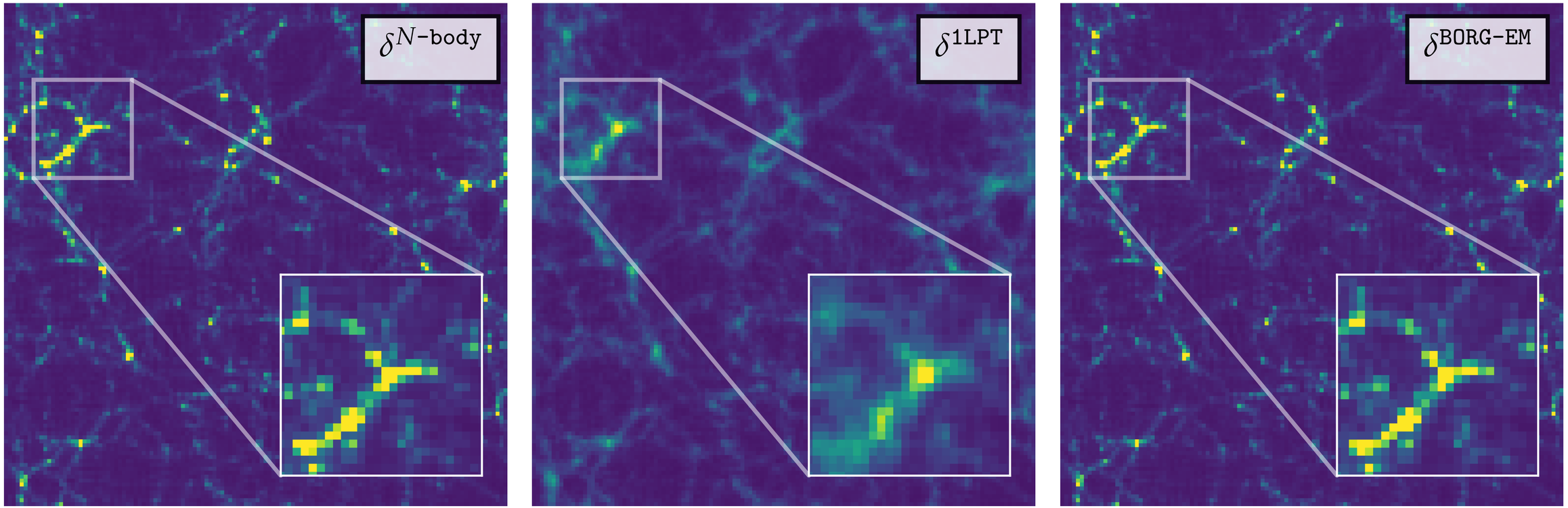
N-body
(~600s)
+ Gaussian noise



$128^3 \approx 10^6$ parameters
~100,000 mcmc-samples
~25 eval / mcmc-sample
~1 month (BORG-EM)
~40 yrs N-body

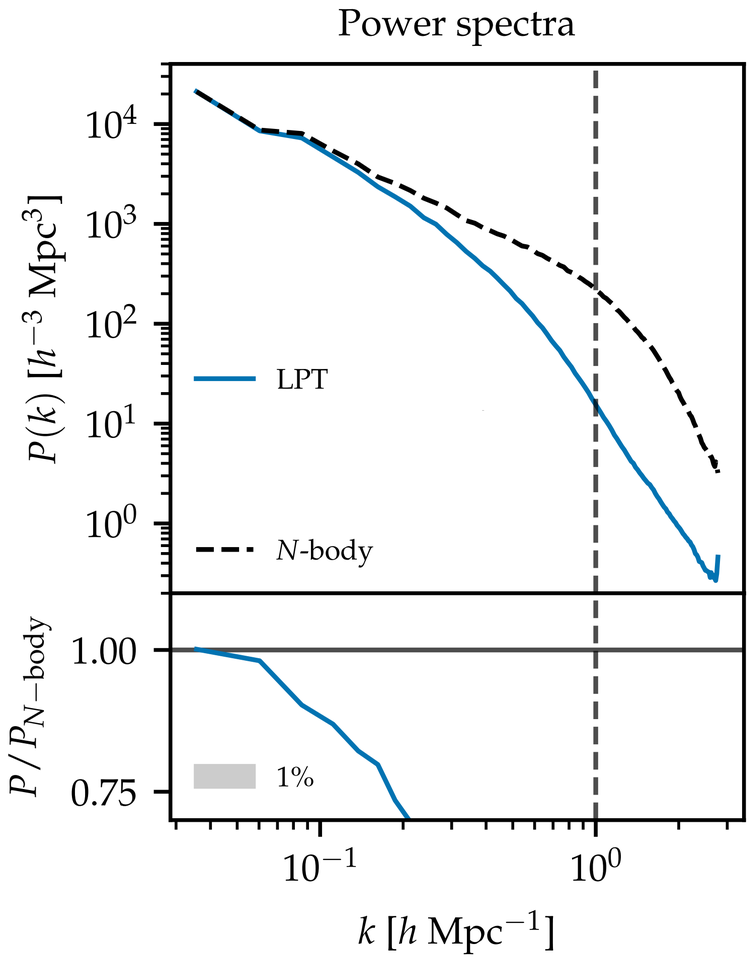
Gaussian Likelihood

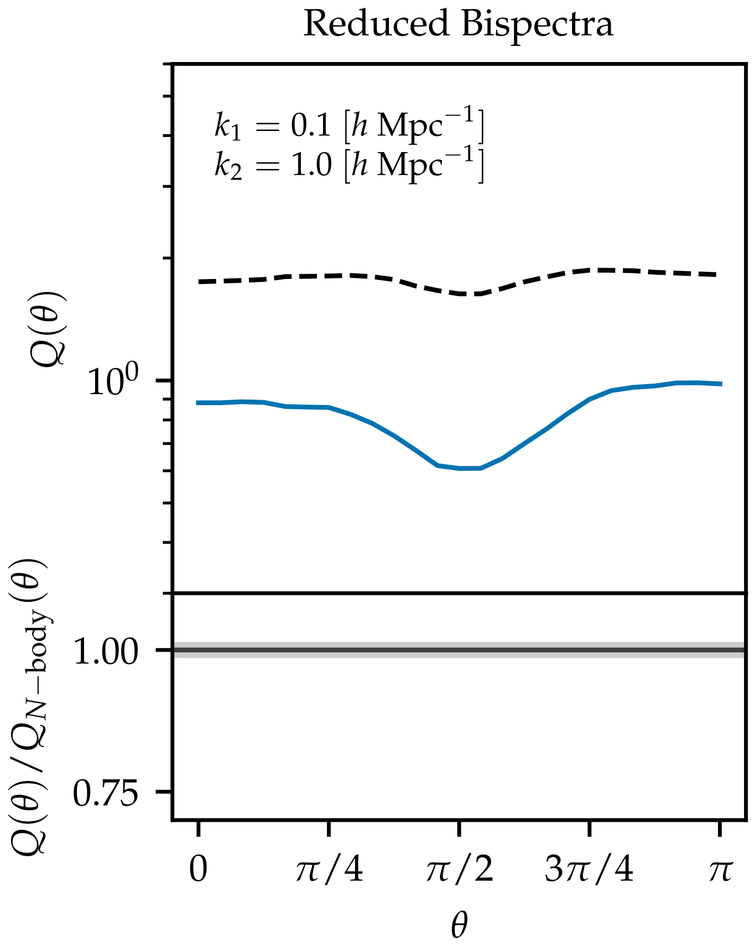
Accuracy: Model validation of forward simulation

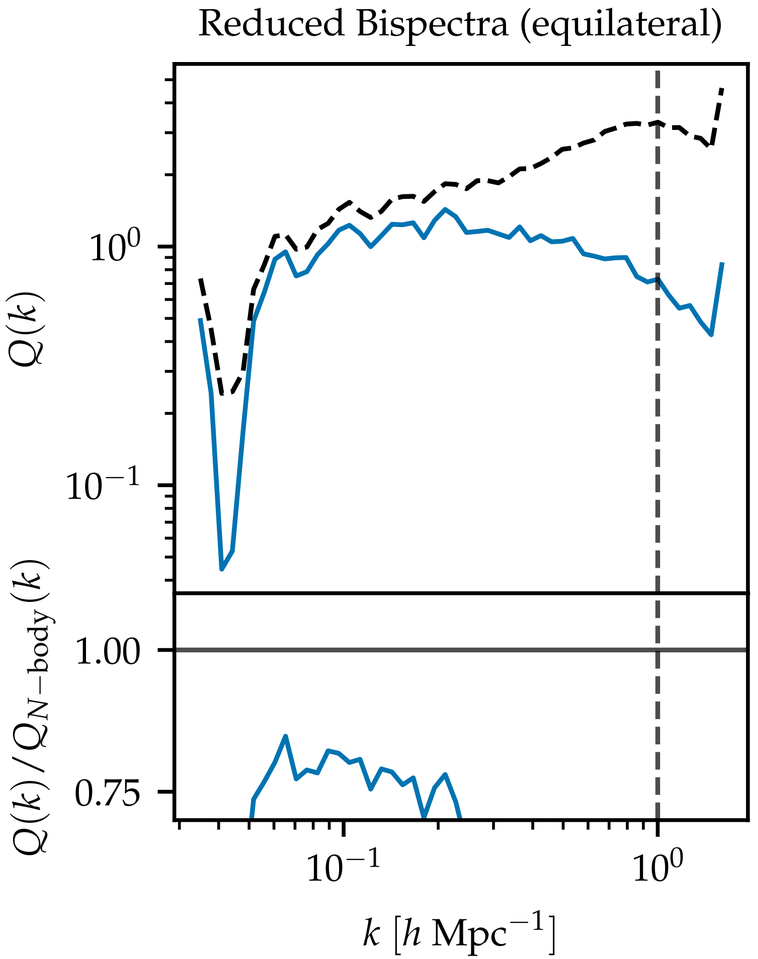


Doeser et al 2023
(arXiv: 2312.09271)

Performance evaluation – 2pt and 3pt







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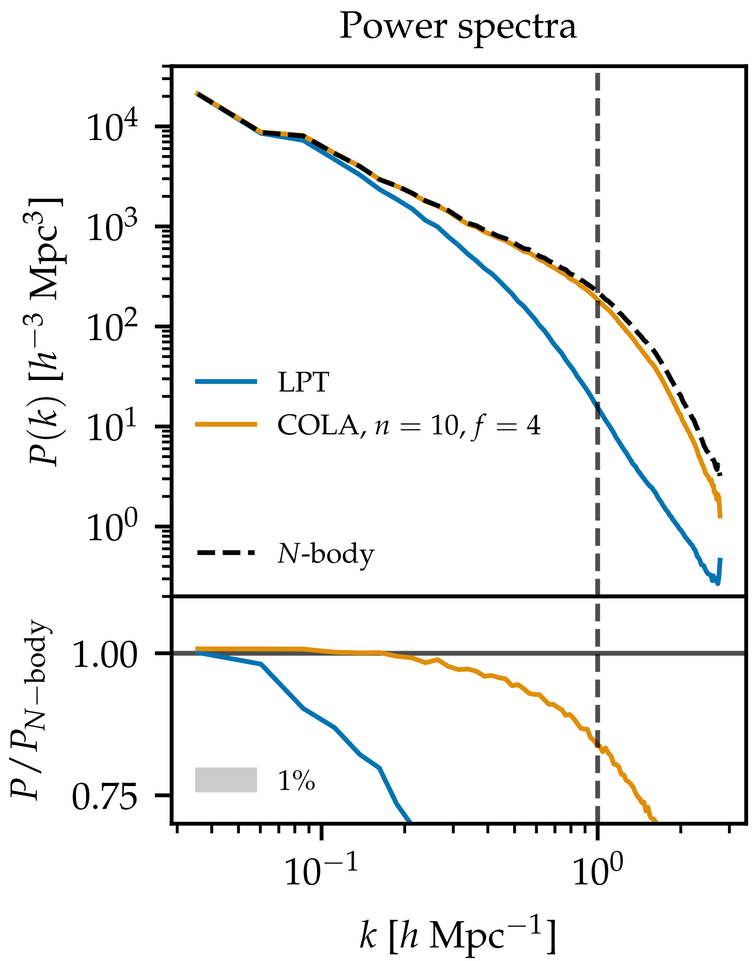

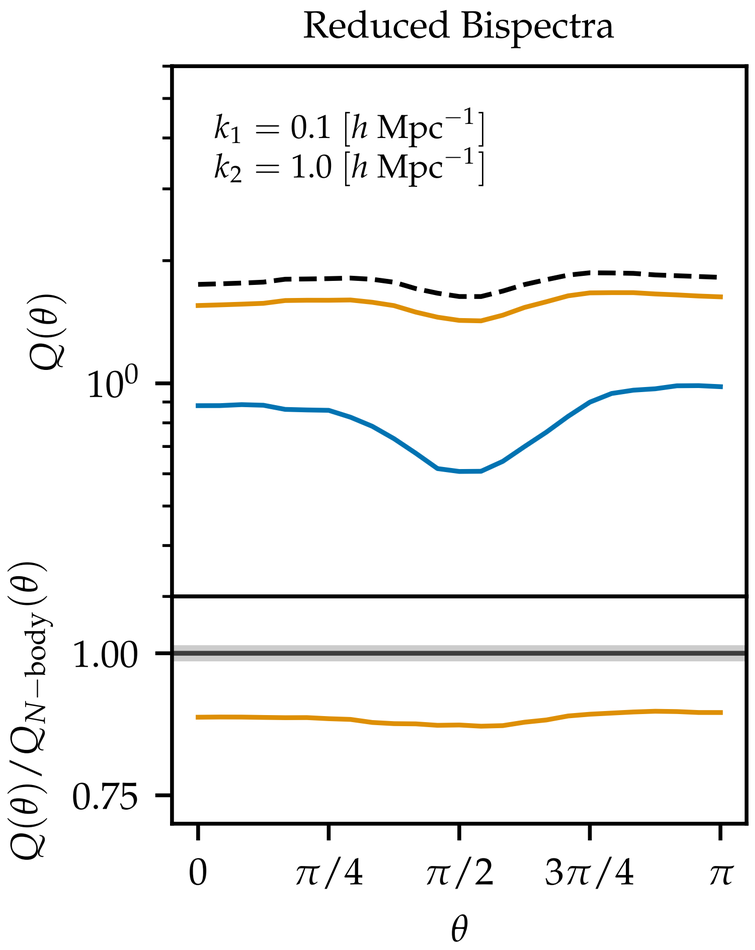

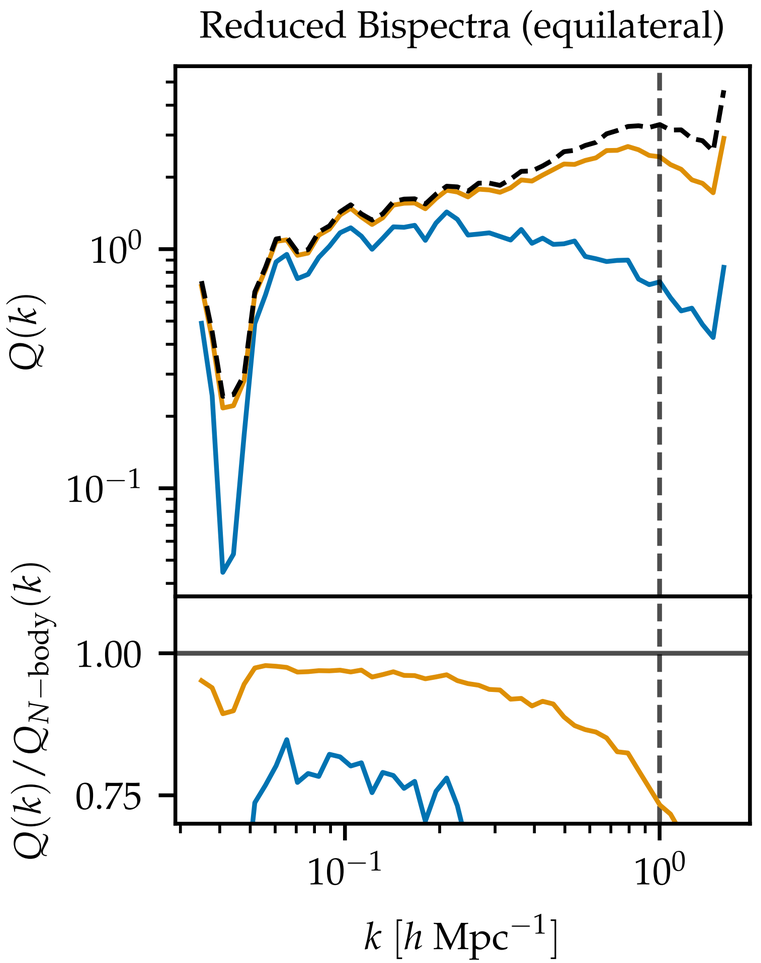

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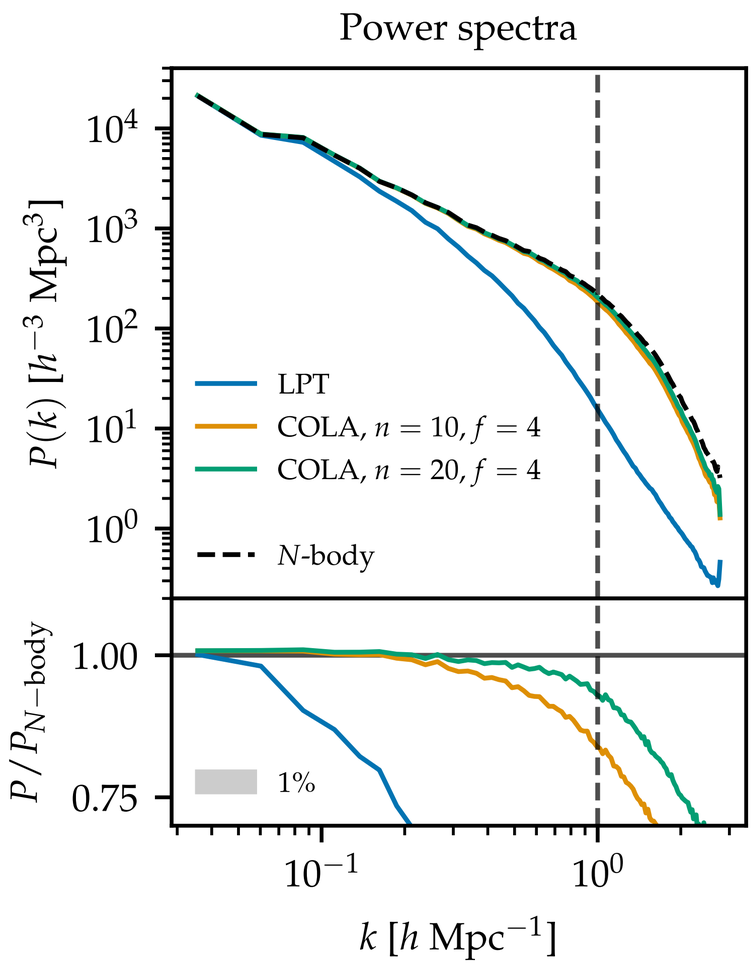

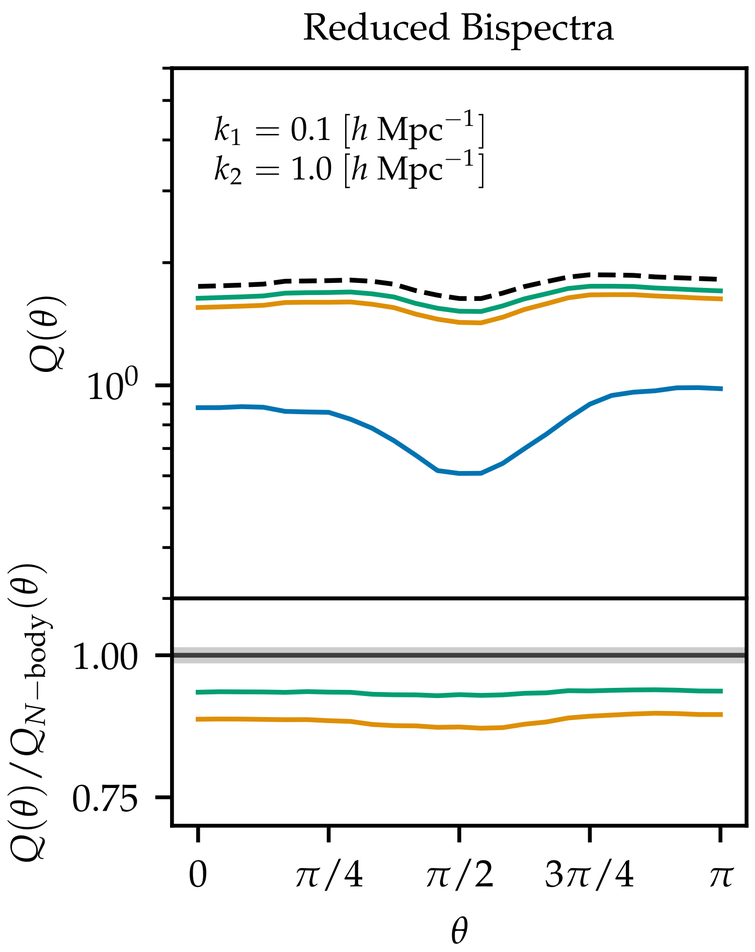

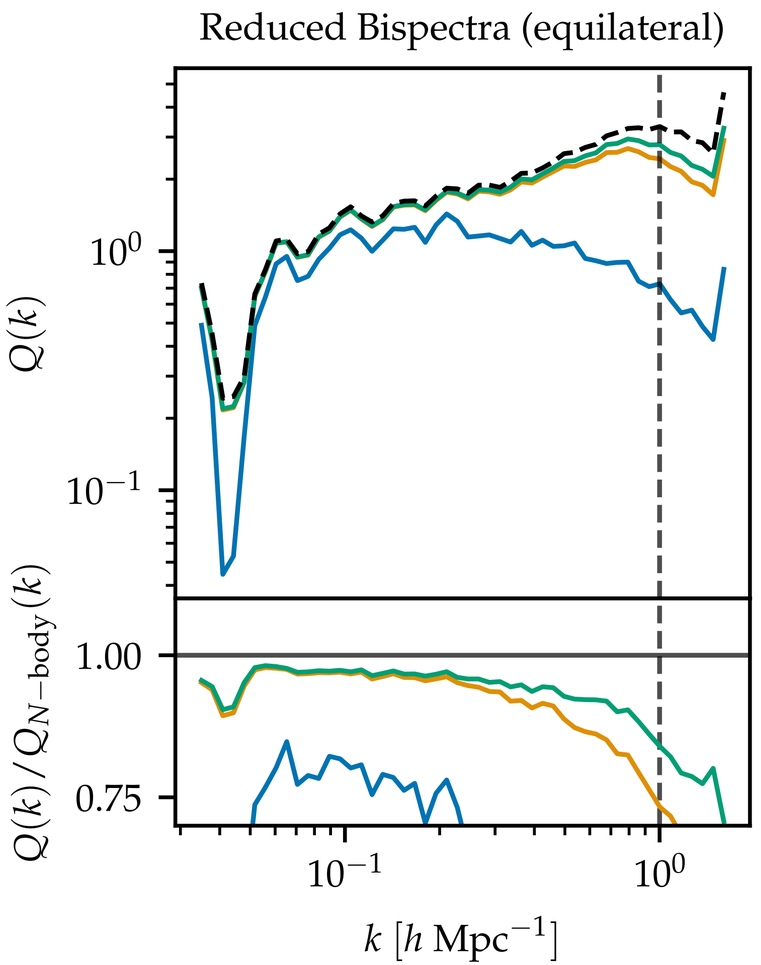

Doeser et al 2023 (arXiv: 2312.09271)

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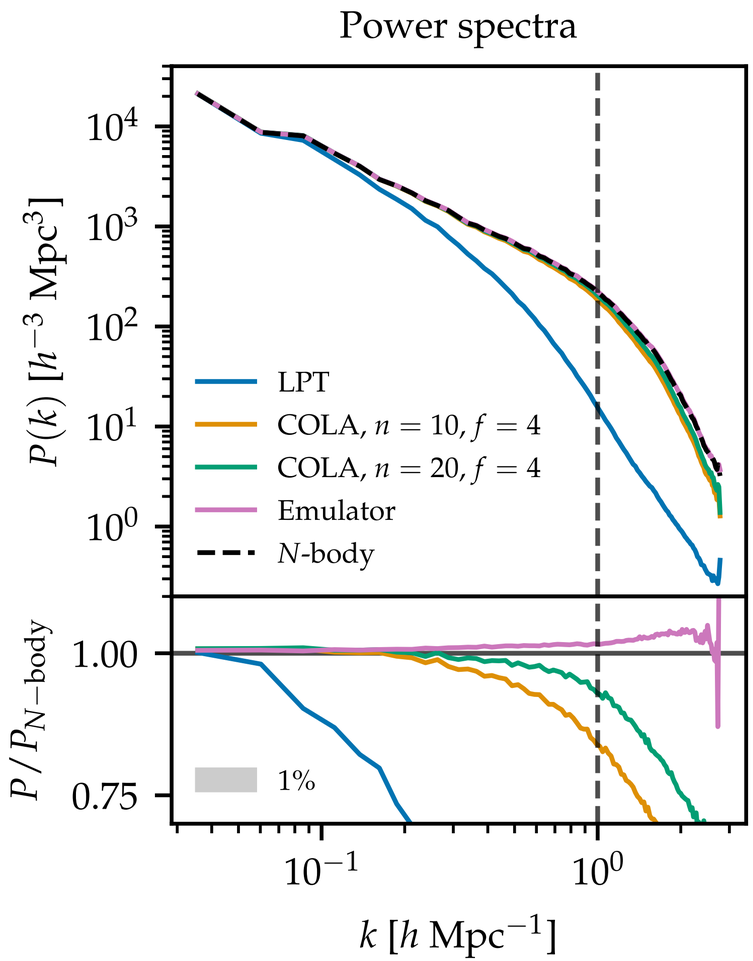
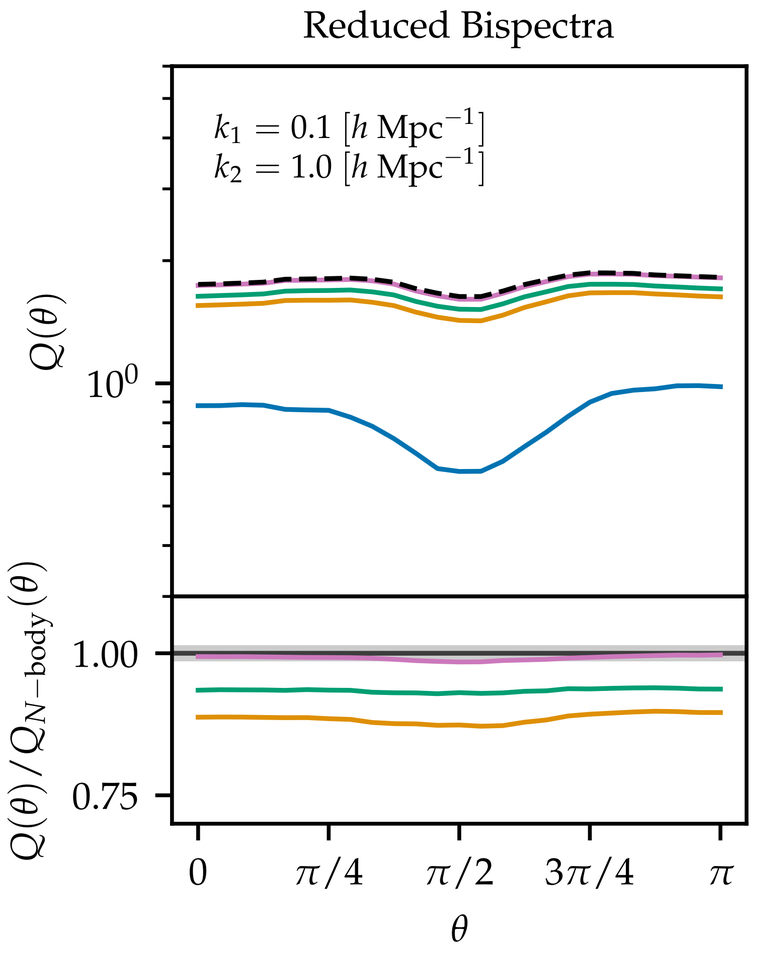
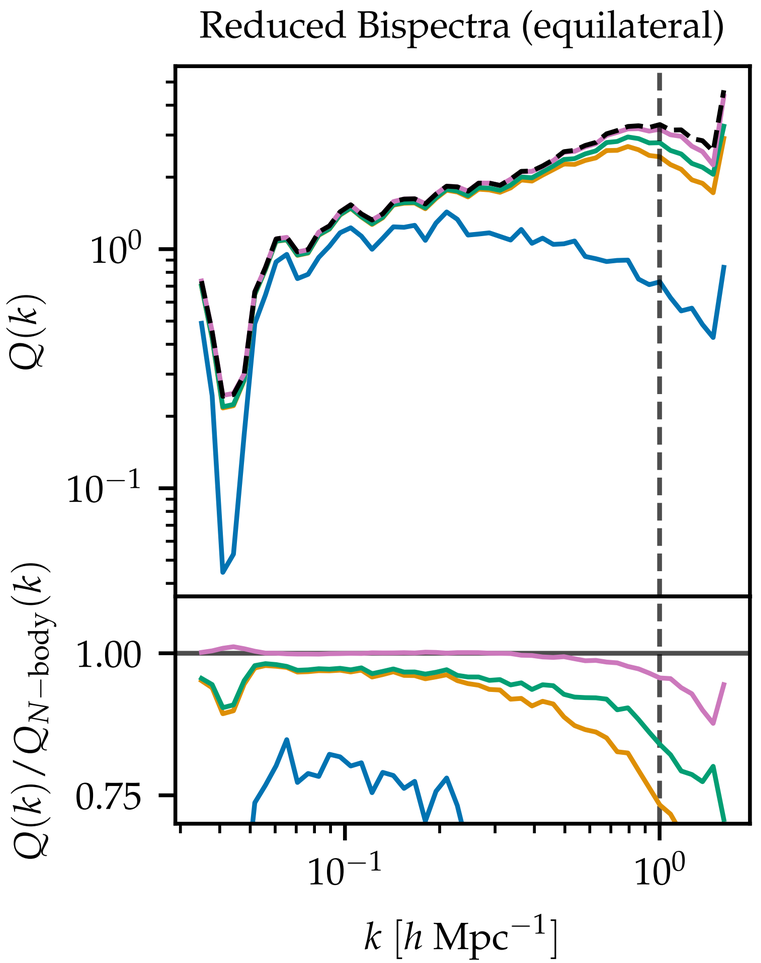




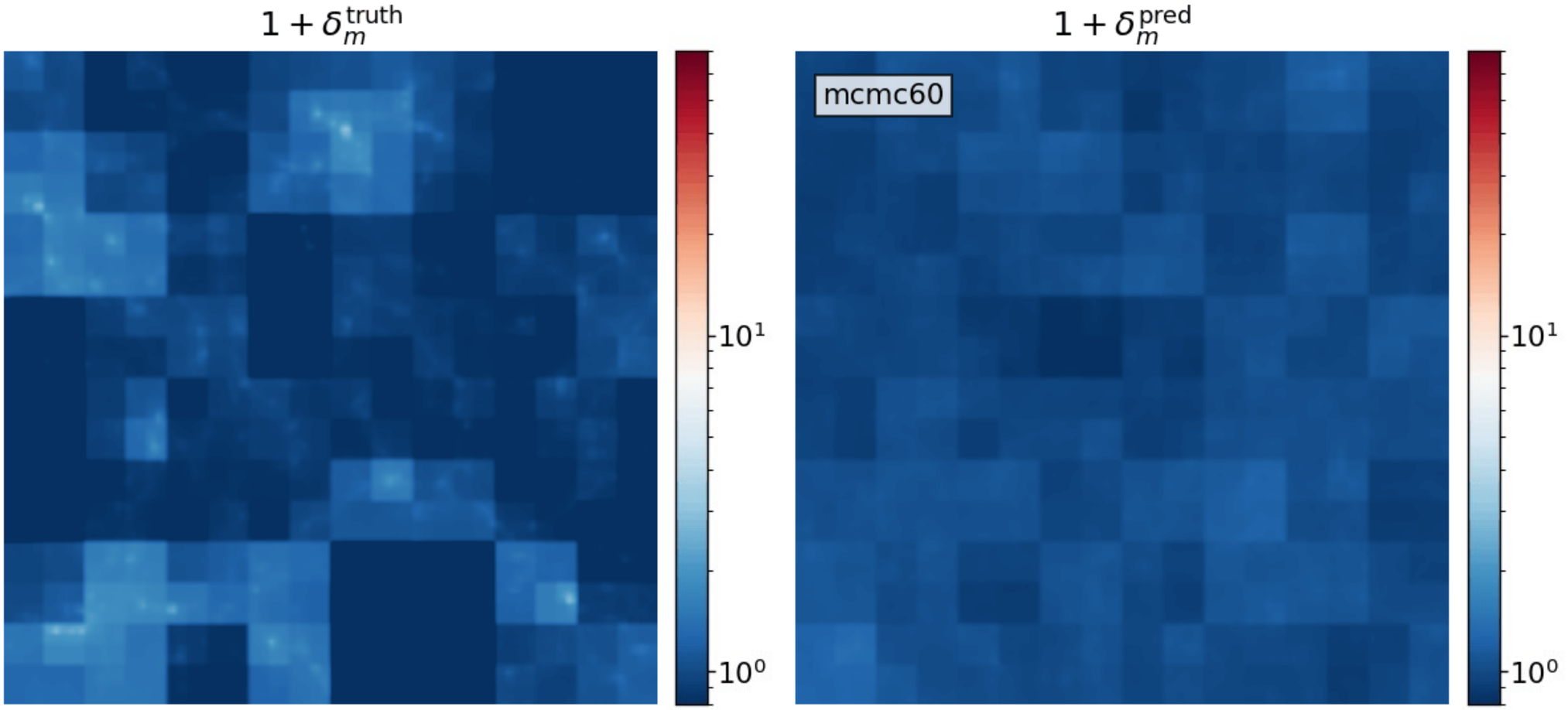


Doeser et al 2023 (arXiv: 2312.09271)

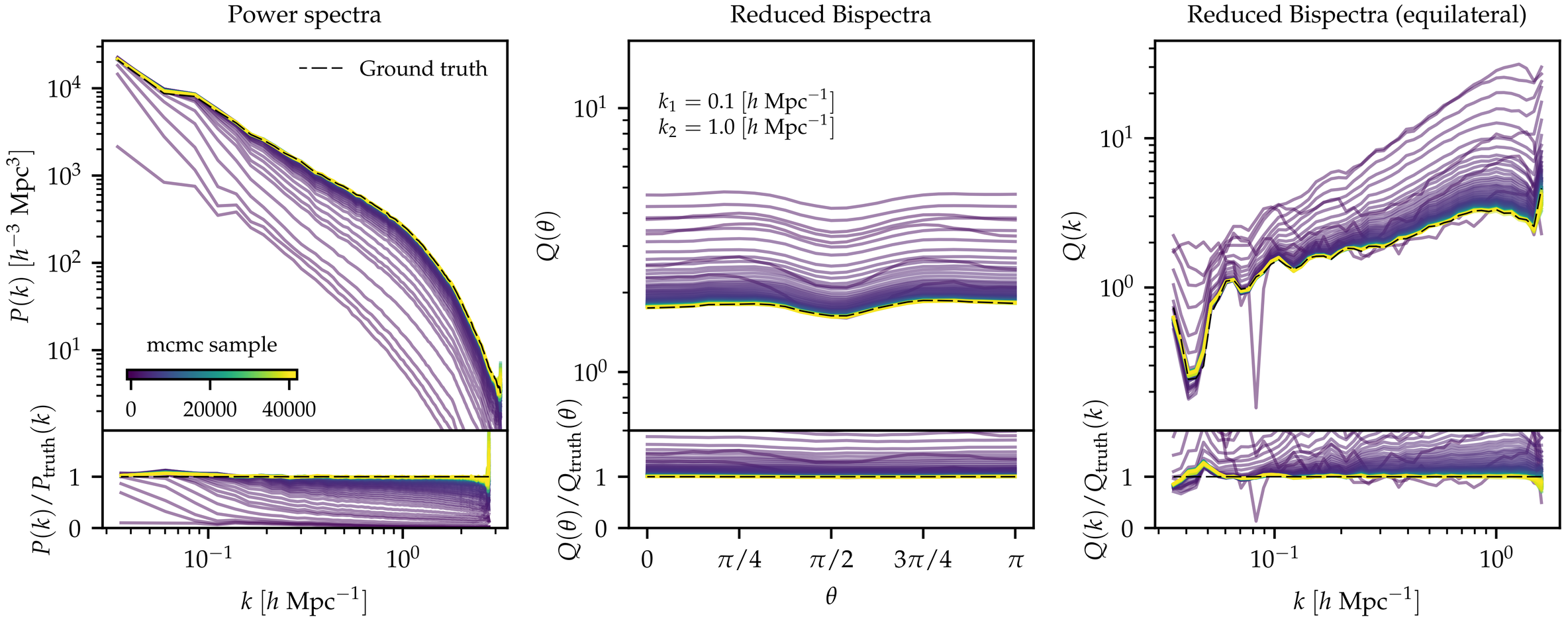
Bayesian Inference of Initial Conditions from Non-Linear Cosmic Structures using Field-Level Emulators

4. Inferring the initial conditions

Inference with BORG-EM: Sequential updates at z=0



Approaching ground truth from remote initial guess

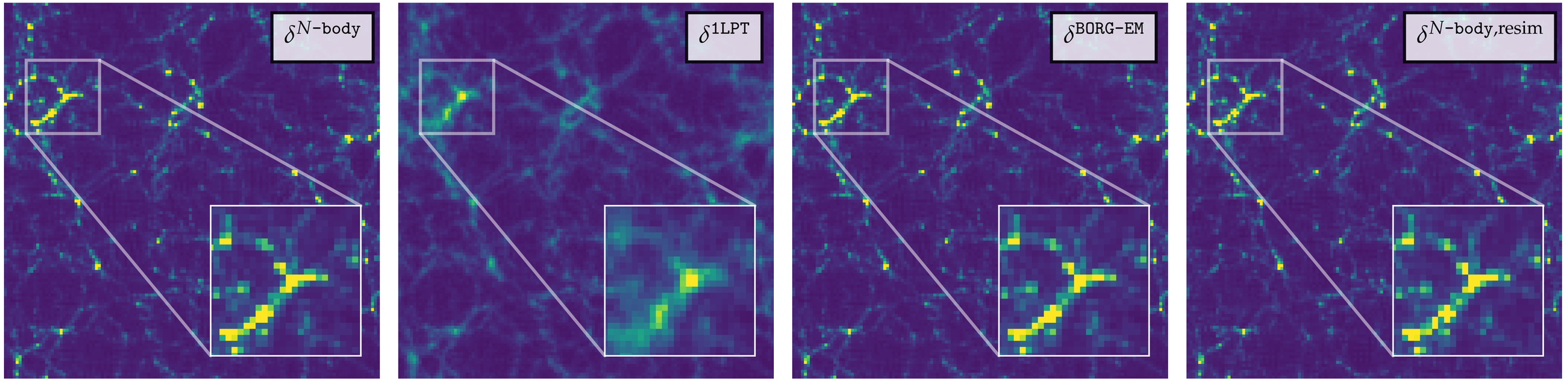


Doeser et al 2023 (arXiv: 2312.09271)

Bayesian Inference of Initial Conditions from Non-Linear Cosmic Structures using Field-Level Emulators

5. Using the inferred initial conditions in posterior resimulations

Posterior Resimulations: initial conditions in N-body

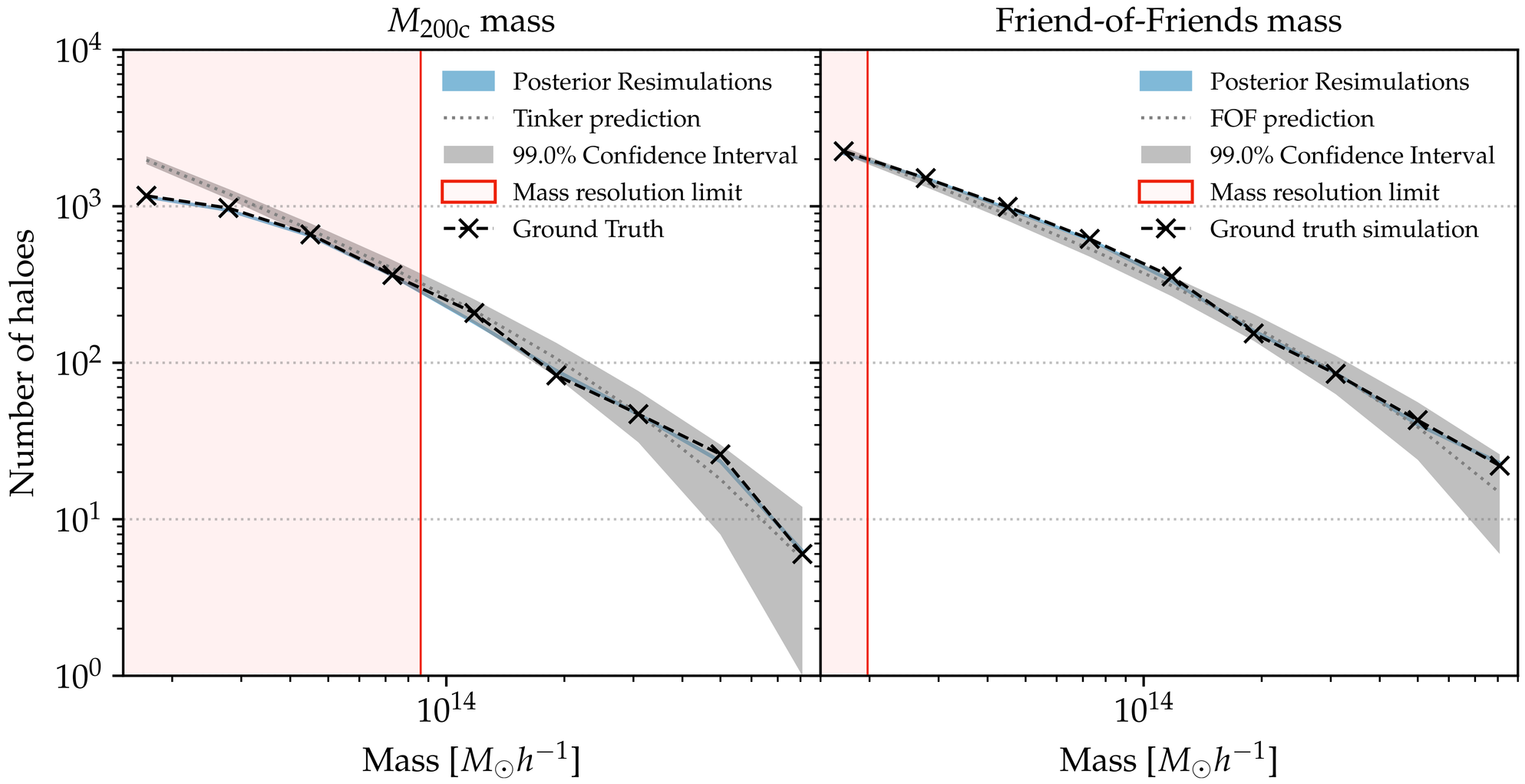


Ground truth initial conditions (ICs)

Inferred ICs

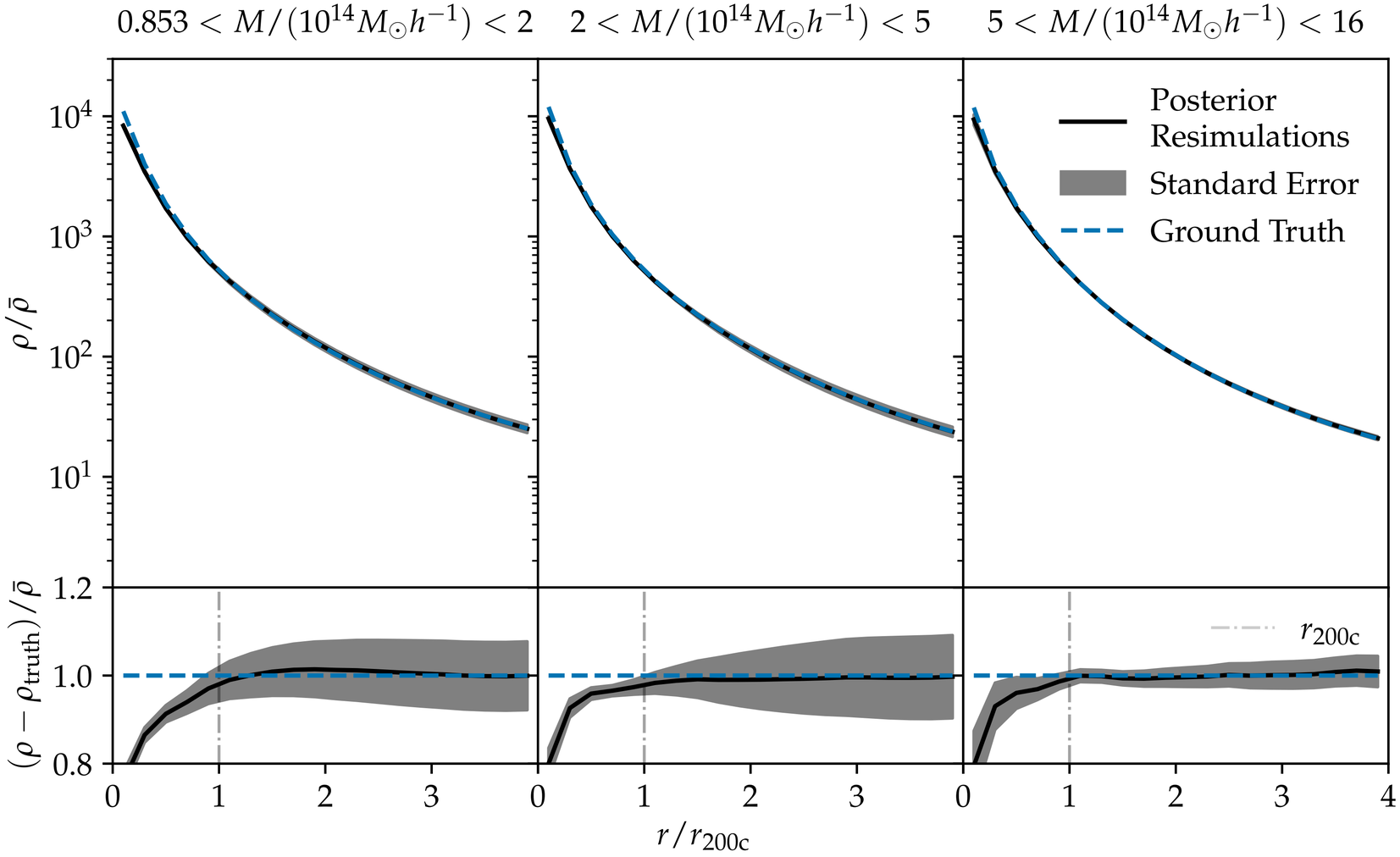
Doeser et al 2023
(arXiv: 2312.09271)

Meeting accuracy requirements: Halo mass function



Doeser et al 2023 (arXiv: 2312.09271)

Meeting accuracy requirements: Halo density profiles



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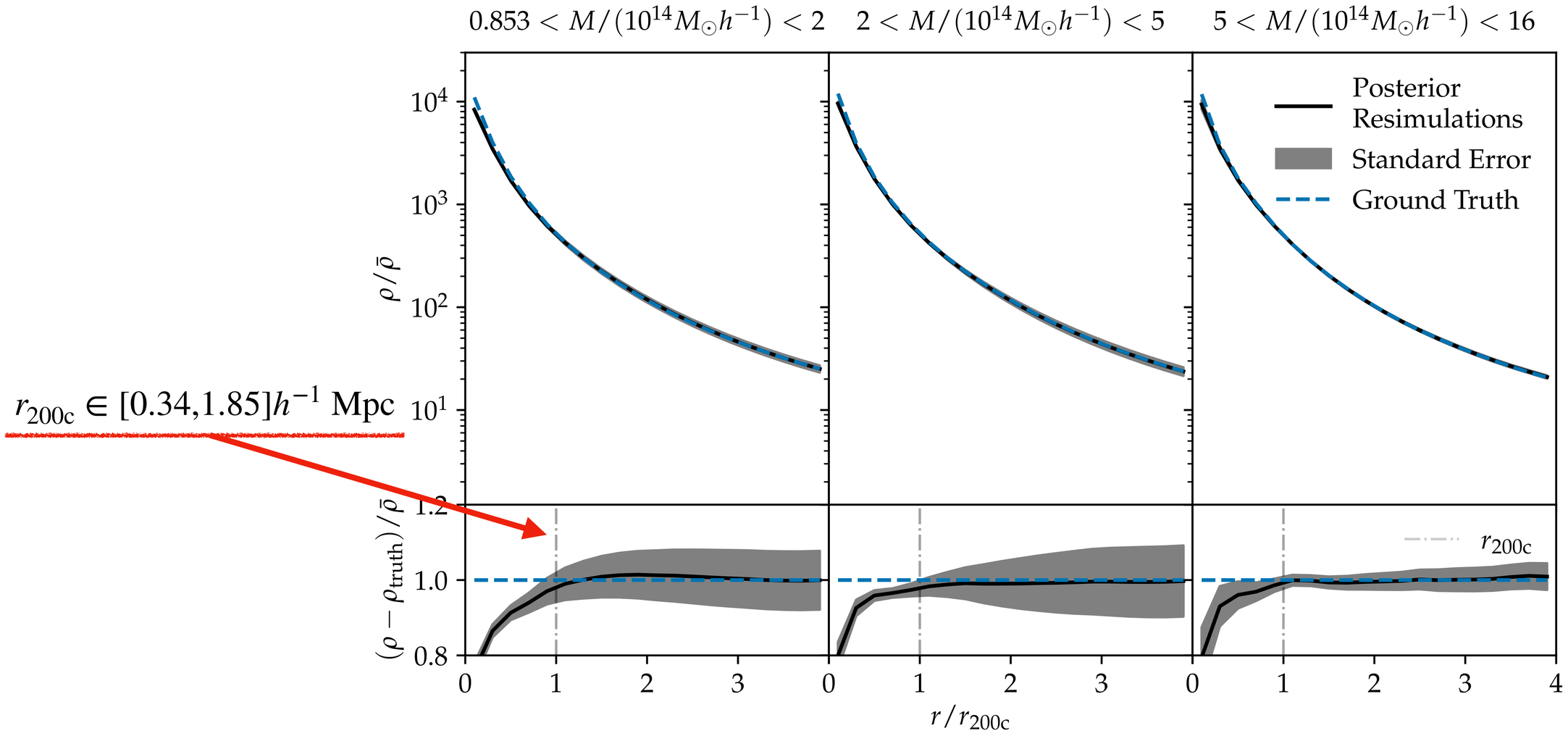
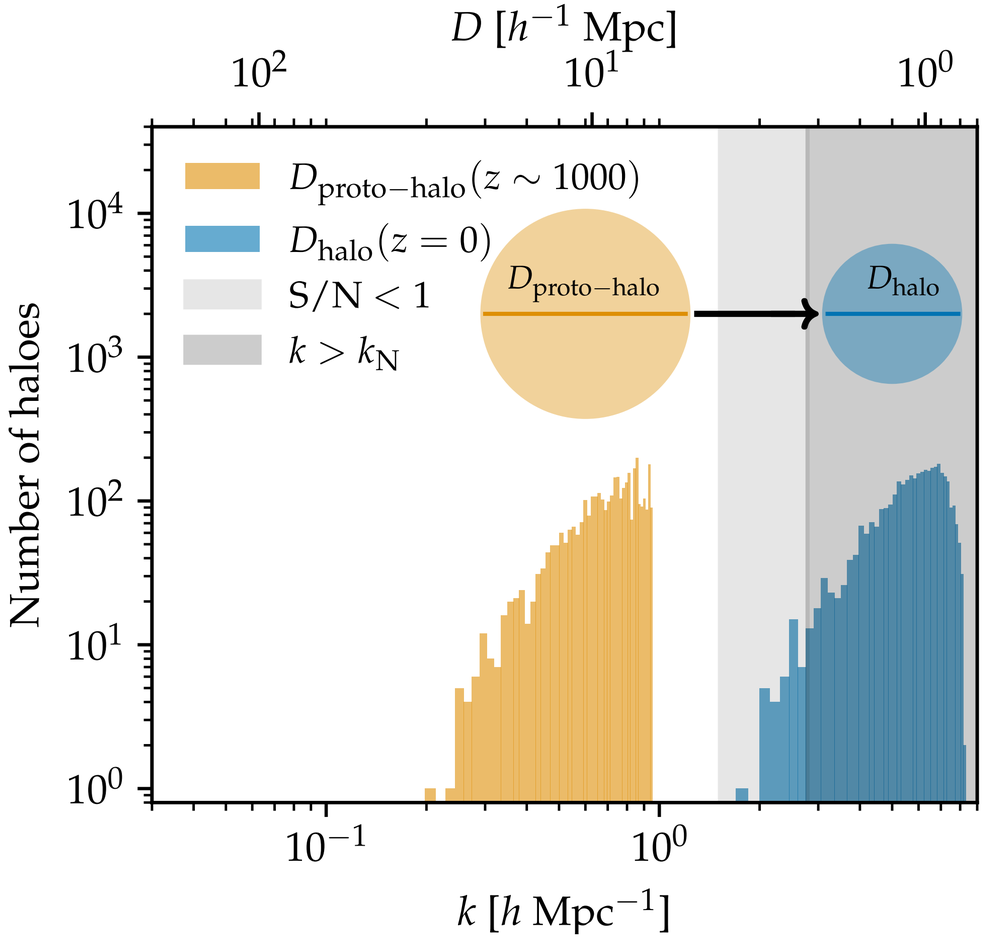
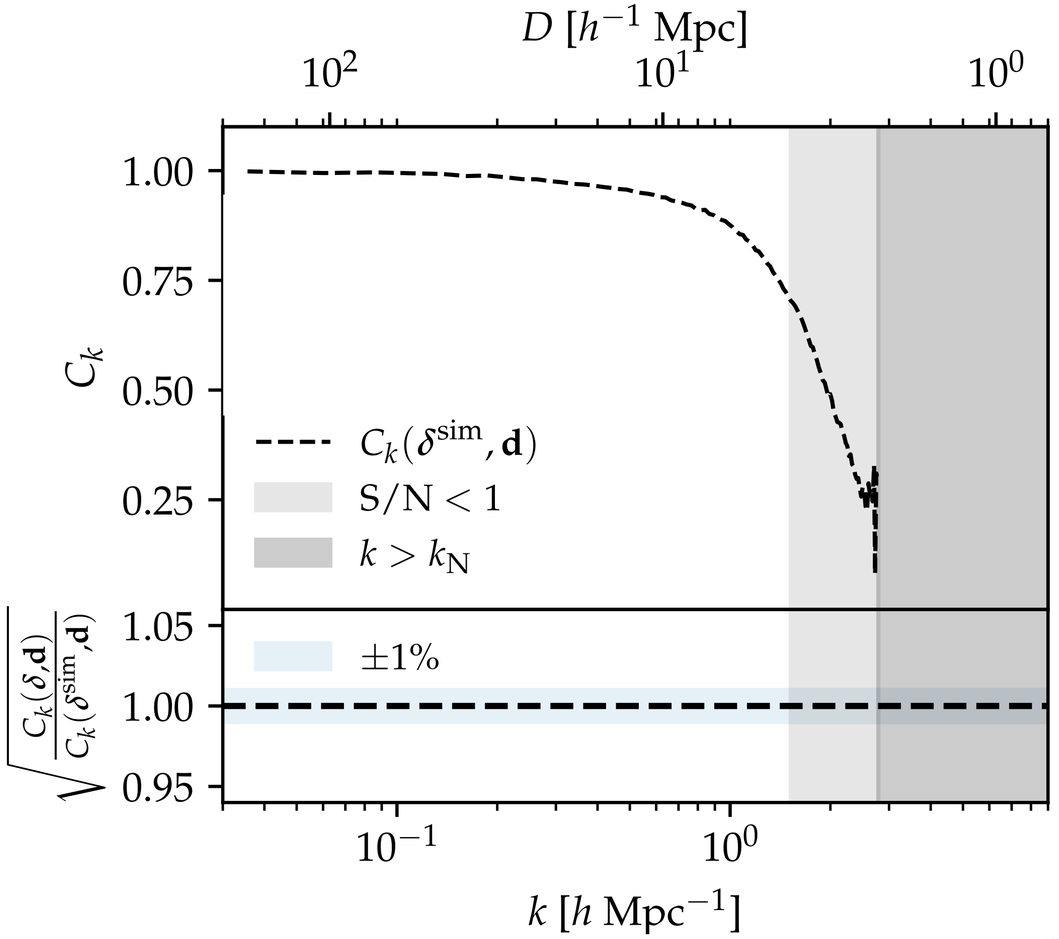


Doeser et al 2023 (arXiv: 2312.09271)

Small-scales today constrain larger scales in the early Universe

Linear scales in the early Universe contain information about small-scale structures of today





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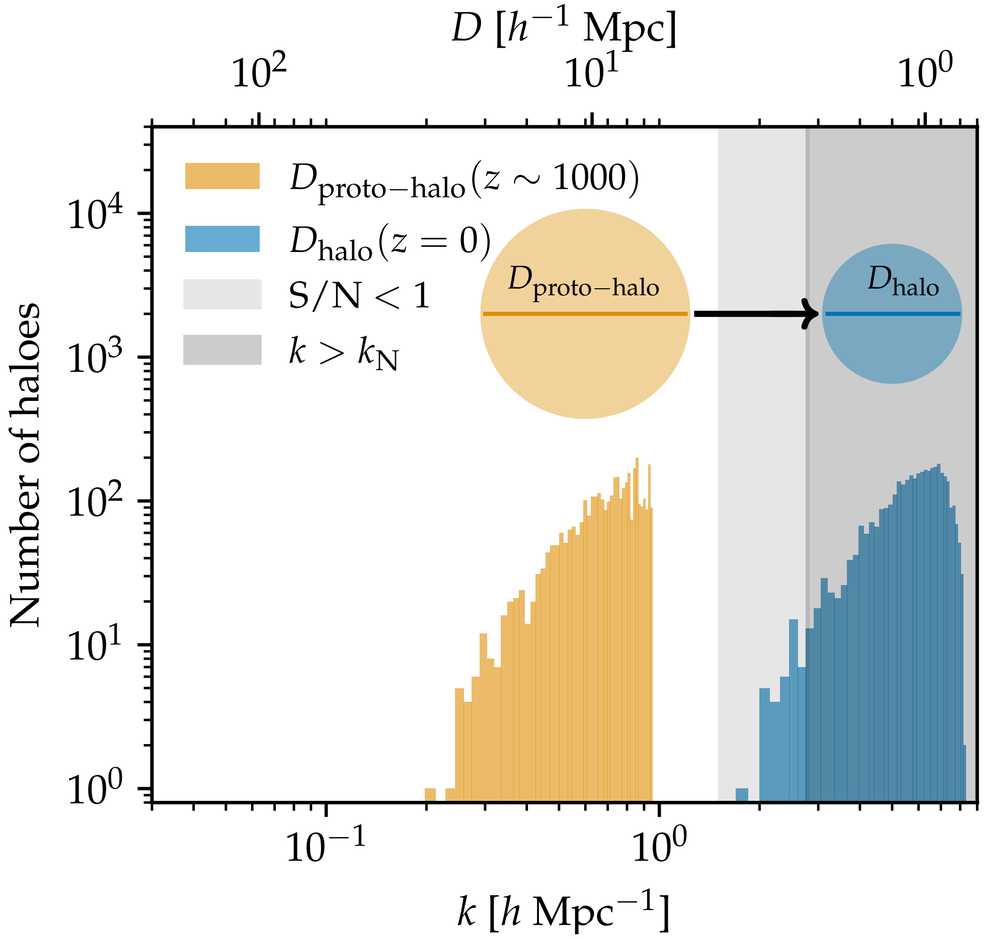

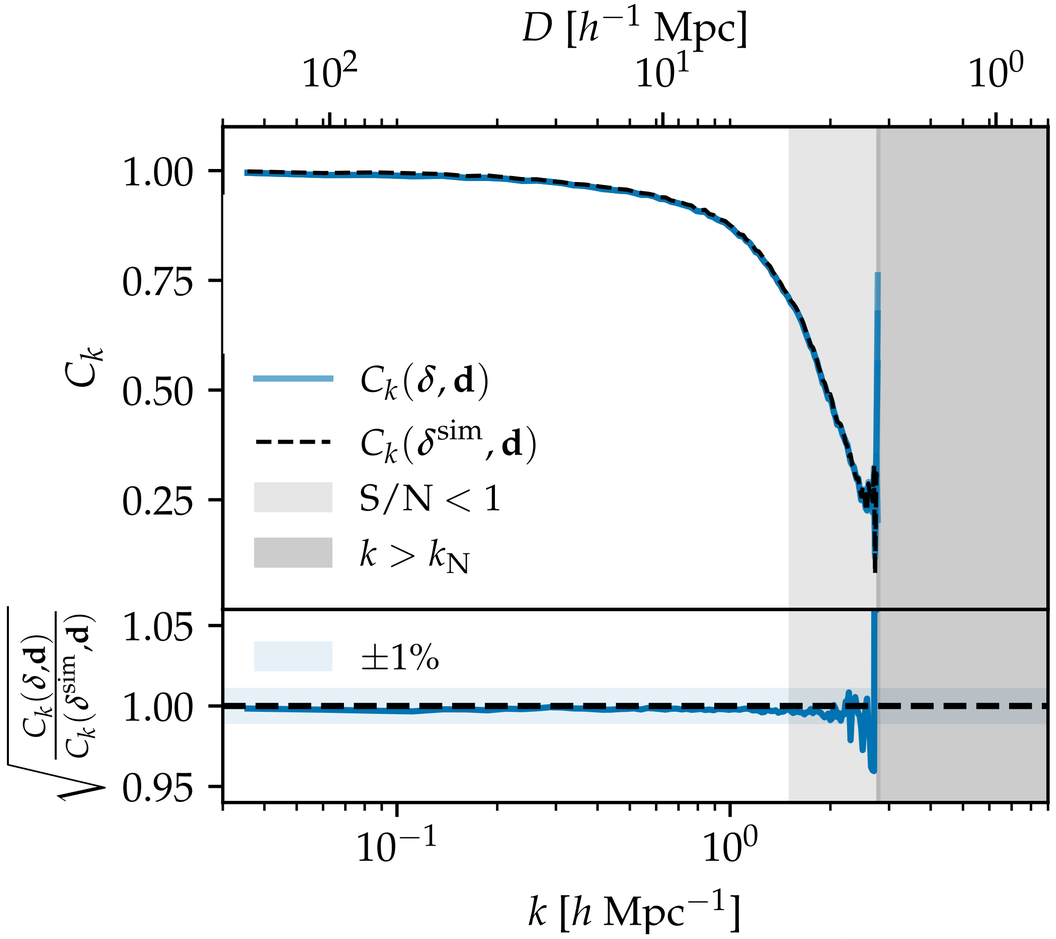

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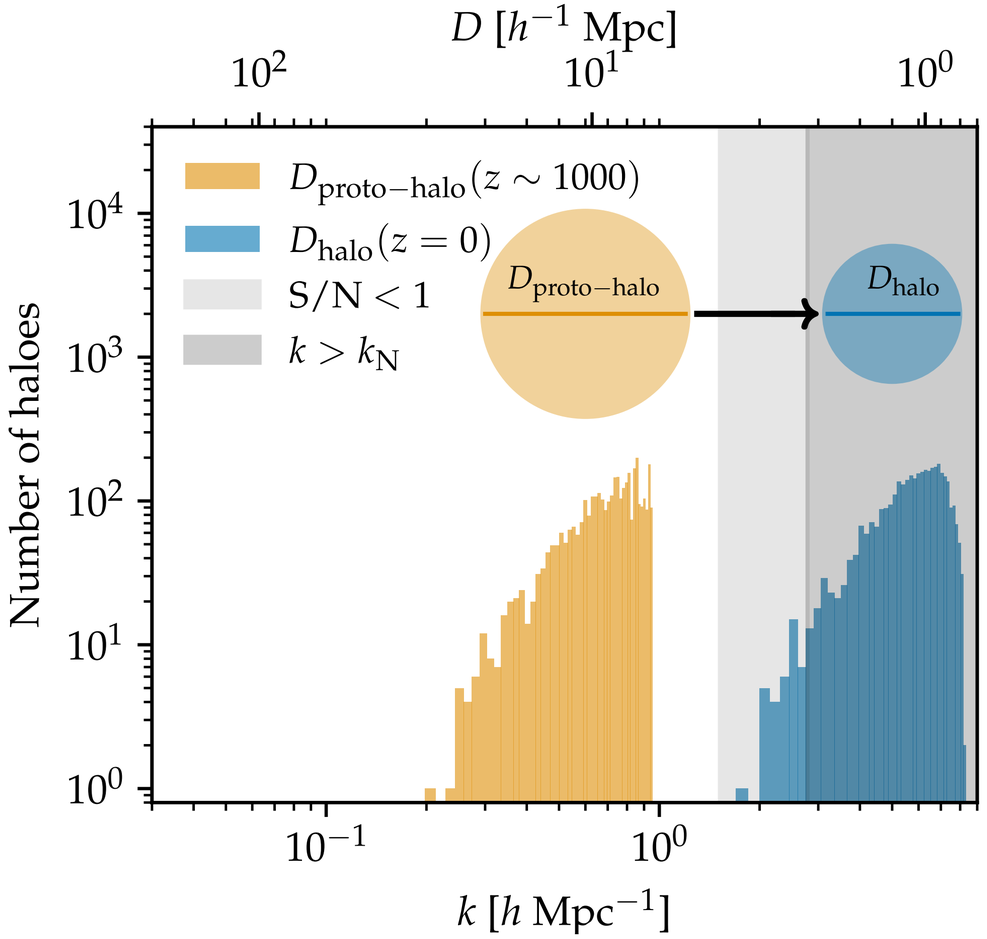

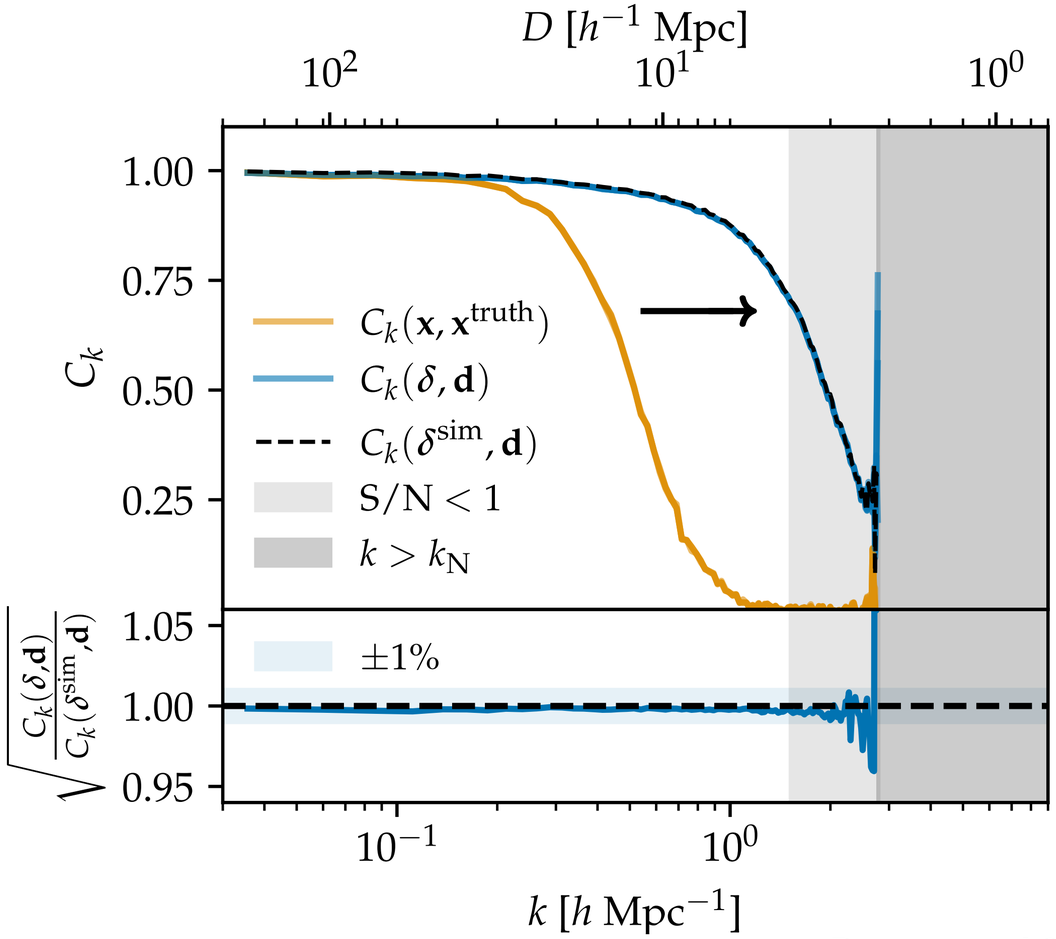

[Doeser et al 2023 (arXiv: 2312.09271)]

Summary & Conclusions

Unprecedented amount of cosmological data incoming

- Our capability to analyse data will limit knowledge gains
- Information reside at non-linear/small scales

Inference technology

- Field-level Inference offers information optimality and posterior dist
- Complete characterisation of cosmic structure (no compression)

Data modeling aided by Deep Learning

- Successful integration of fast, accurate, and differentiable field-level emulator
- Fully extracting all cross-correlation information from the data
- Accurate recovery of non-linear cosmic structures including halo statistics

Promising path forward towards analyzing next-generation galaxy surveys at non-linear scales

arXiv: 2312.09271

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