Bayesian field-level inference using DESI and ZTF SN Ia

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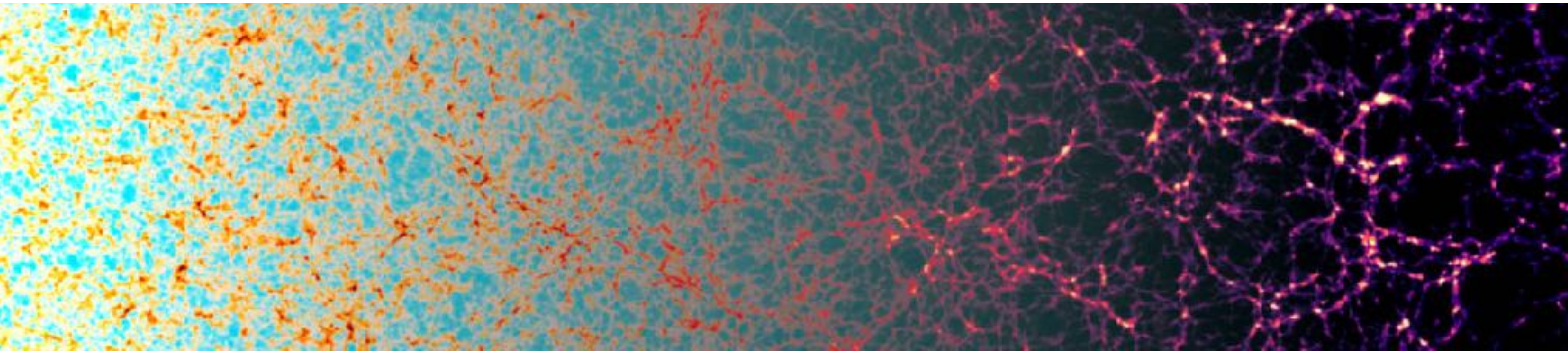
ADE, November 5th 2025

How to extract cosmological information?

Sensitivity to cosmology

Inflation and primordial features — Dark matter and neutrinos — Dark energy and gravity

Redshift



Initial Gaussian and linear density field — *Today non-Gaussian and non-linear density field*

← more robust — more optimal →

Two-point statistics (2pt)
Most mature and robust technique
Analytical model available up to quasi-linear scales (k_{max}=0.2 h/Mpc)
Computationally cheap
Only Gaussian and linear information

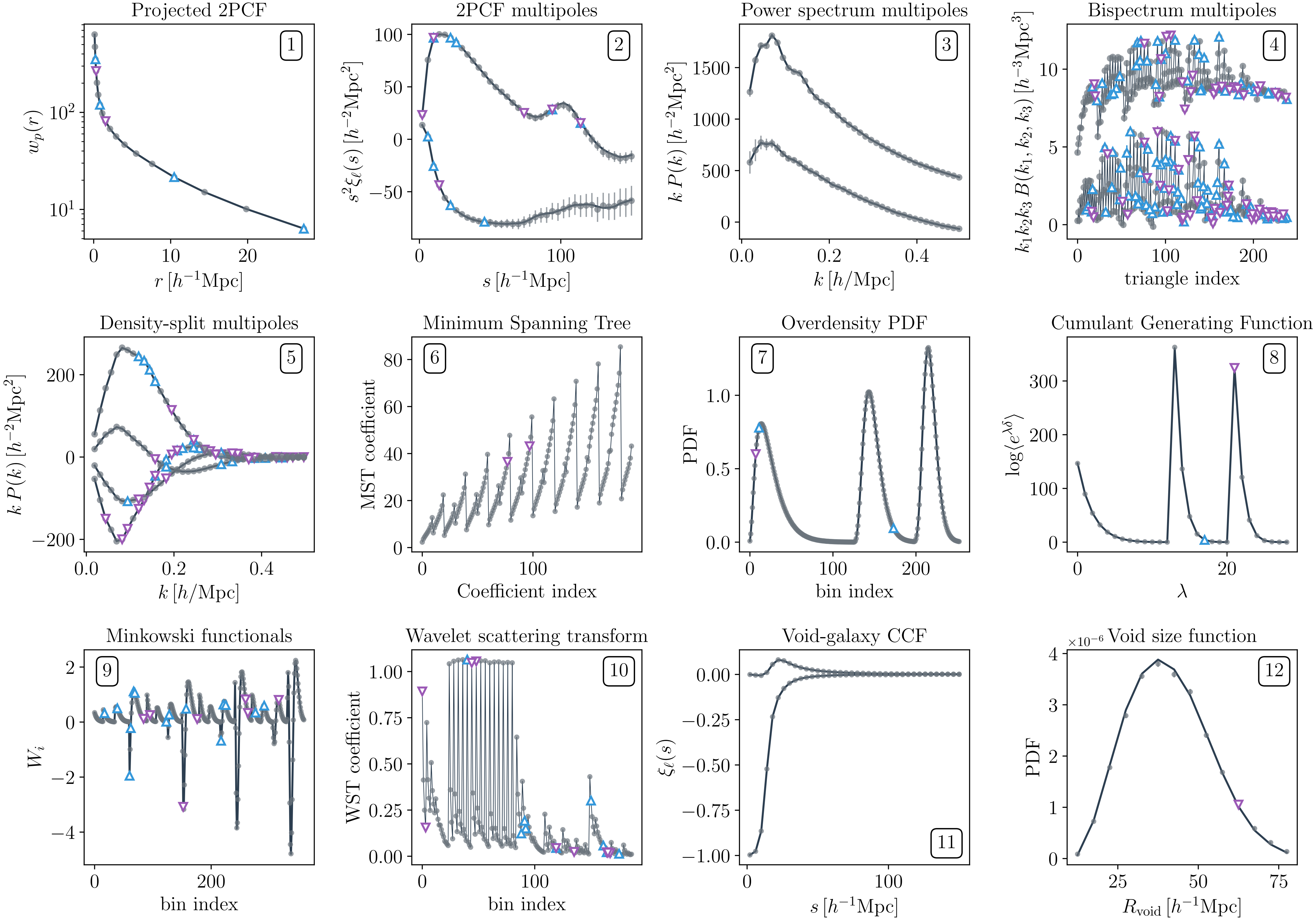
Higher-order statistics (HOS)
Capture some non-Gaussian information
Simulation-based model up to k_{max}=0.8 h/Mpc
Computationally cheaper than FLI but still requires hundreds of cosmological simulations
Factor 2 improvement wrt 2pt*

Field-level inference (FLI)
Retrieve the maximal information & deliver constrained simulations
Grid resolution up to k_{max}=0.8 h/Mpc
Computationally expensive
Factor 2-5 improvement wrt HOS**

*Euclid collaboration V 2023

** Nguyen et al. 2025, Porqueres et al. 2023

HOS or Alternative Clustering Methods

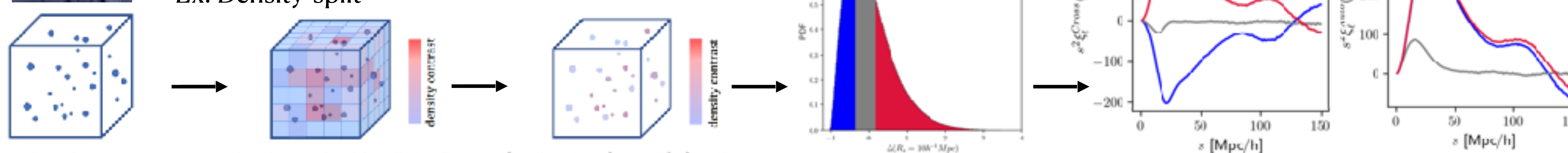


ACM pipeline (Paillas and the DESI ACM group, in prep)

HOS or Alternative Clustering Methods

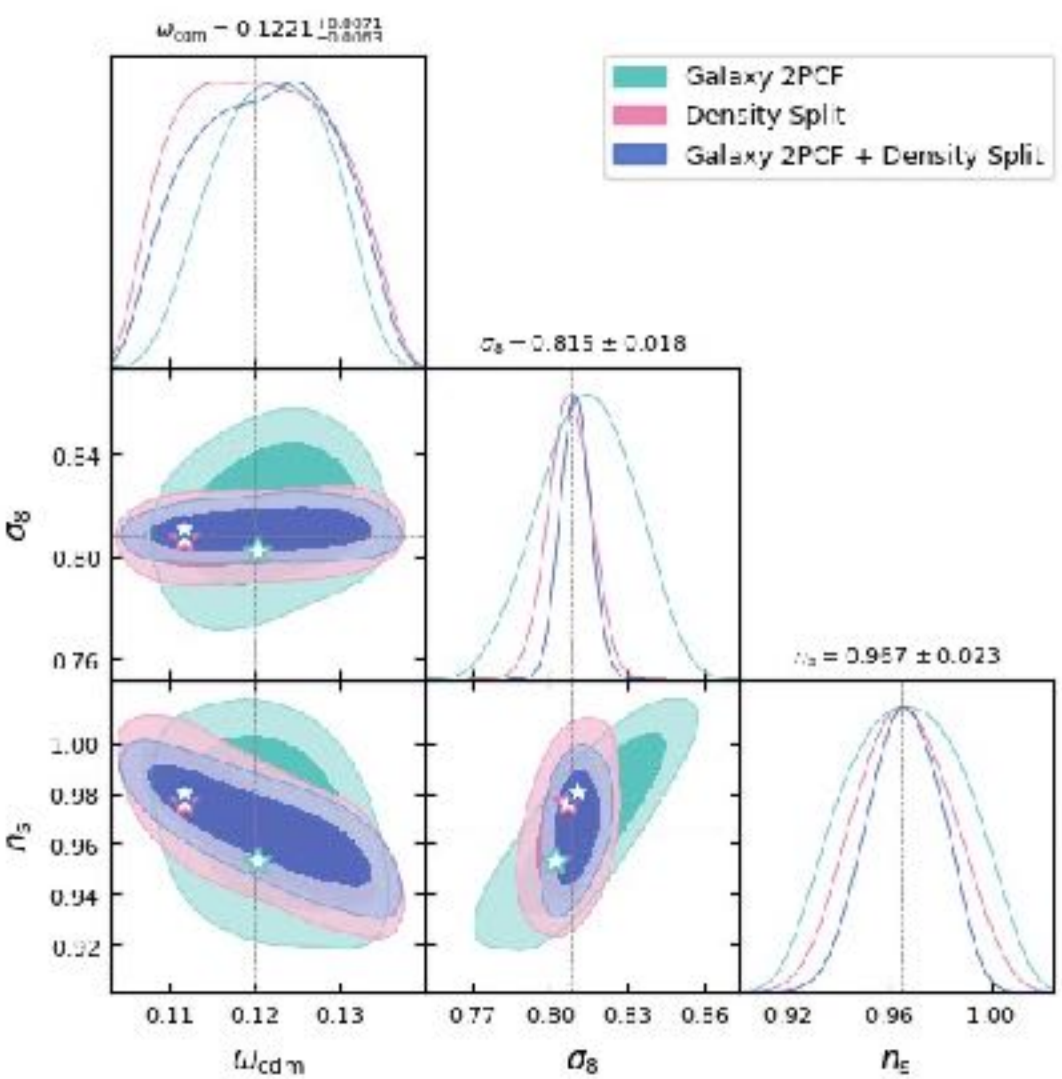
Optimal summary statistics for the DESI BGS
Simon Bouchard's PhD

Ex: Density-split



density histogram

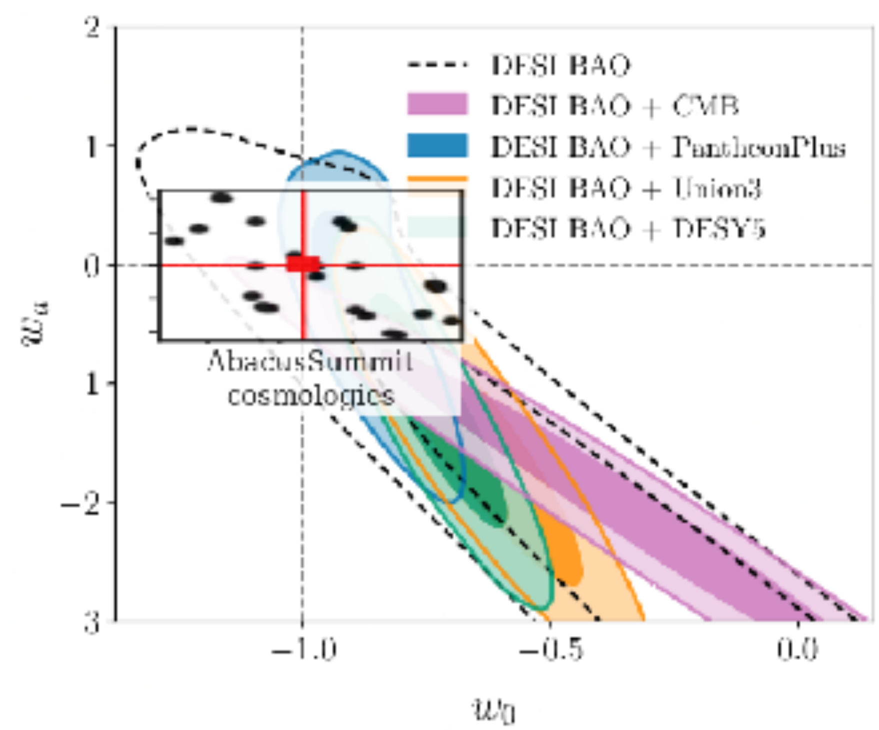
Correlation functions



Methodology

1) Start from a suite of N-body simulations (AbacusSummit)
2) Populate with HOD (AbacusHOD)
3) Compute the statistics of interest (2pt, DS, 3pt, WST,…)
4) Train a neural network model (SUNBIRD)
5) Perform simulation-based inference

BUT requires representative N-body simulations for both the cosmological and astrophysical spaces



Bayesian Field-level inference

Initial phases

World model

$$\pi(\boxed{x}, \boxed{\Omega}, \boxed{M} \,|\, d) = \pi(M \,|\, d)\pi(\Omega \,|\, d, M)\pi(x, d, M, \Omega)$$

Model parameters

Observed data

$\pi(M \,|\, d)$

Model evidence
(here ΛCDM)

$\pi(\Omega \,|\, d, M)$

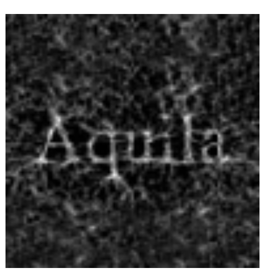
Parameter estimation
$\Omega_m, \sigma_8, n_s, h, \ldots$ + astro + nuisance

$\pi(x \,|\, d, M, \Omega)$

Specific realisation
Initial phases / modes

Ensemble view: laws and parameters, statistically consistent

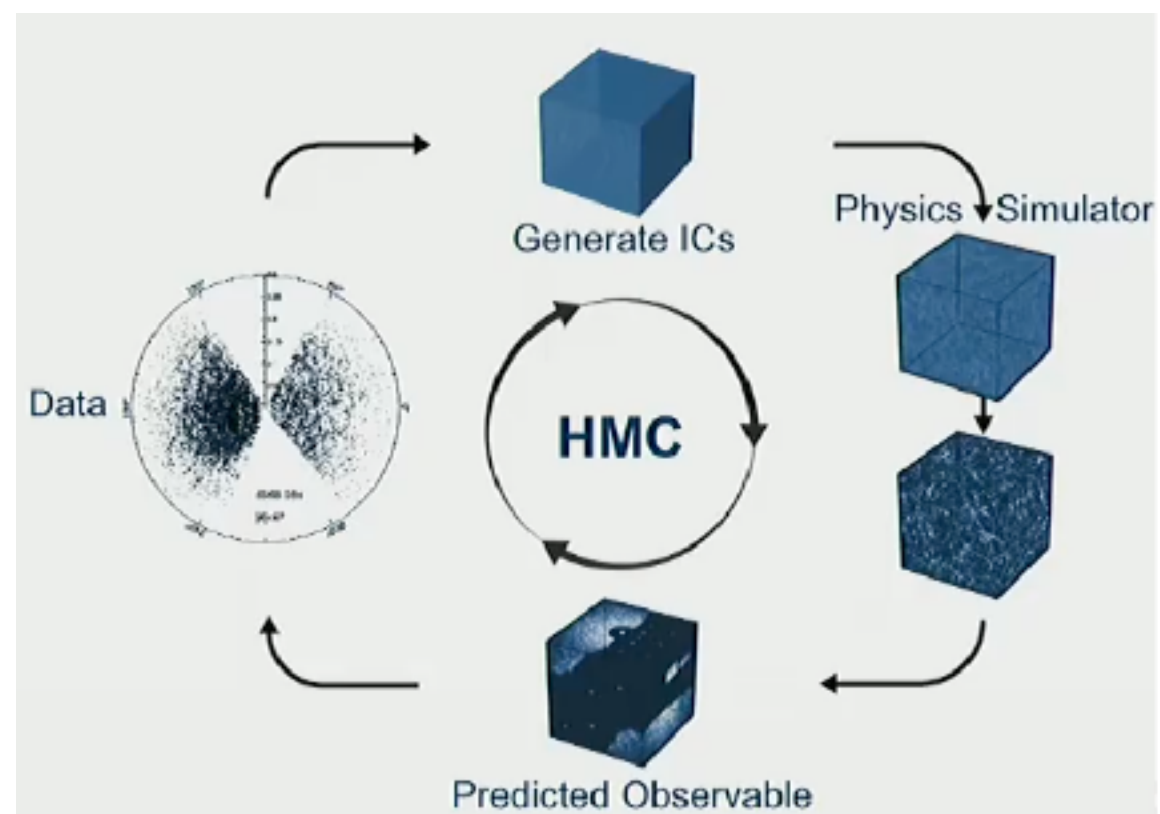
Realization view: our Universe



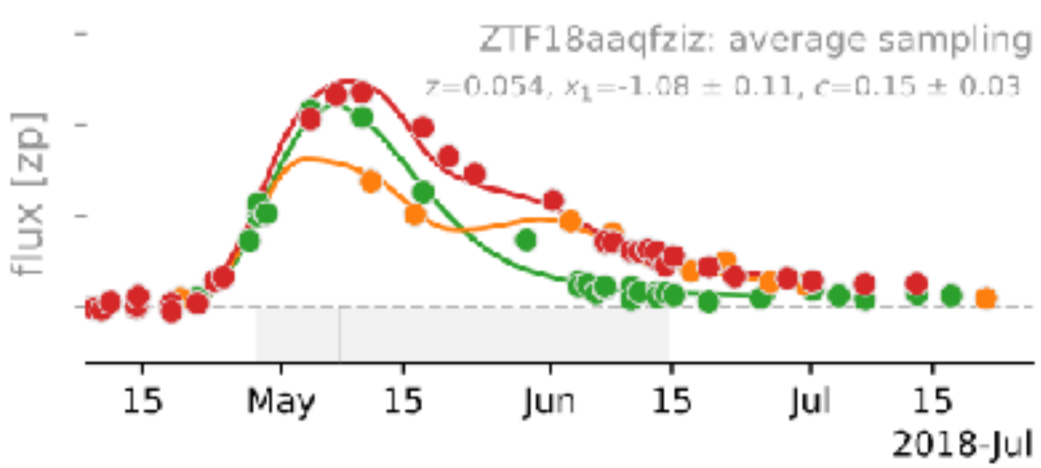
BORG: Bayesian Origin Reconstruction from Galaxies

Jasche & Wandelt (2013), Jasche et al. (2015), Jasche & Lavaux (2019)

- **differentiable model** of cosmic structure formation (using COLA)
- **Explicit likelihood** given initial conditions, cosmological and nuisance parameters
- HMC to explore IC parameter space + block sampling
- Handles survey geometry and systematics via forward modelling



BORG applied to ZTF SN Ia



NaCl
(Regnault, Osman et al. in prep)

↓

x0,x1, c
Cov

↓

EDRIS
(Khun, Betoule et al. in prep)

↓

μ

↓

Cosmologix
(Betoule et al. in prep)

↓

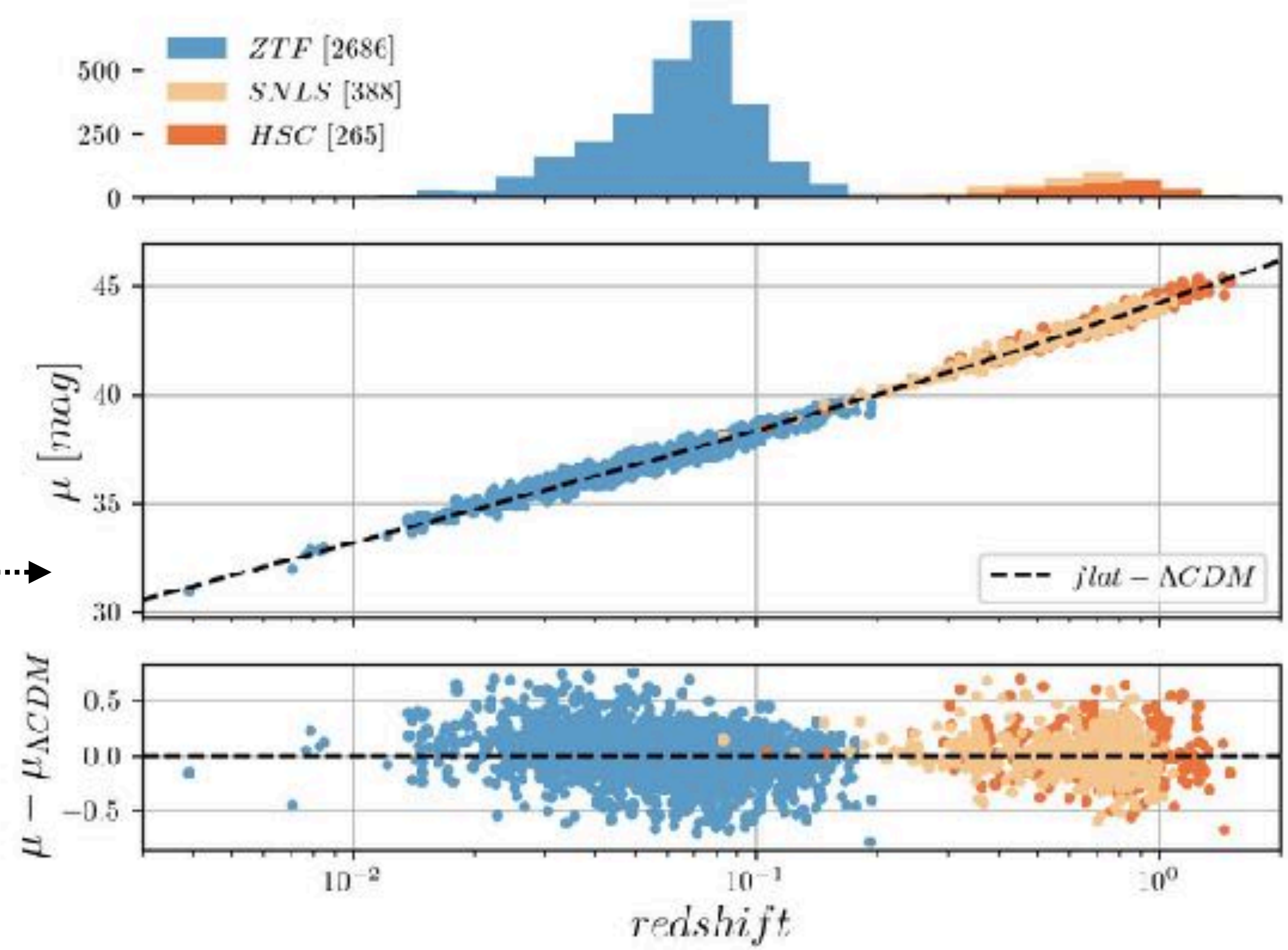
Ω_m , w_o , w_a

LEMAITRE pipeline

↓

PV

Mahmoud Osman's PhD:
New spectrophotometer model for SN Ia (NaCl)
Field-level inference of ZTF SN Ia data with BORG



LEMAITRE blinded Hubble diagram

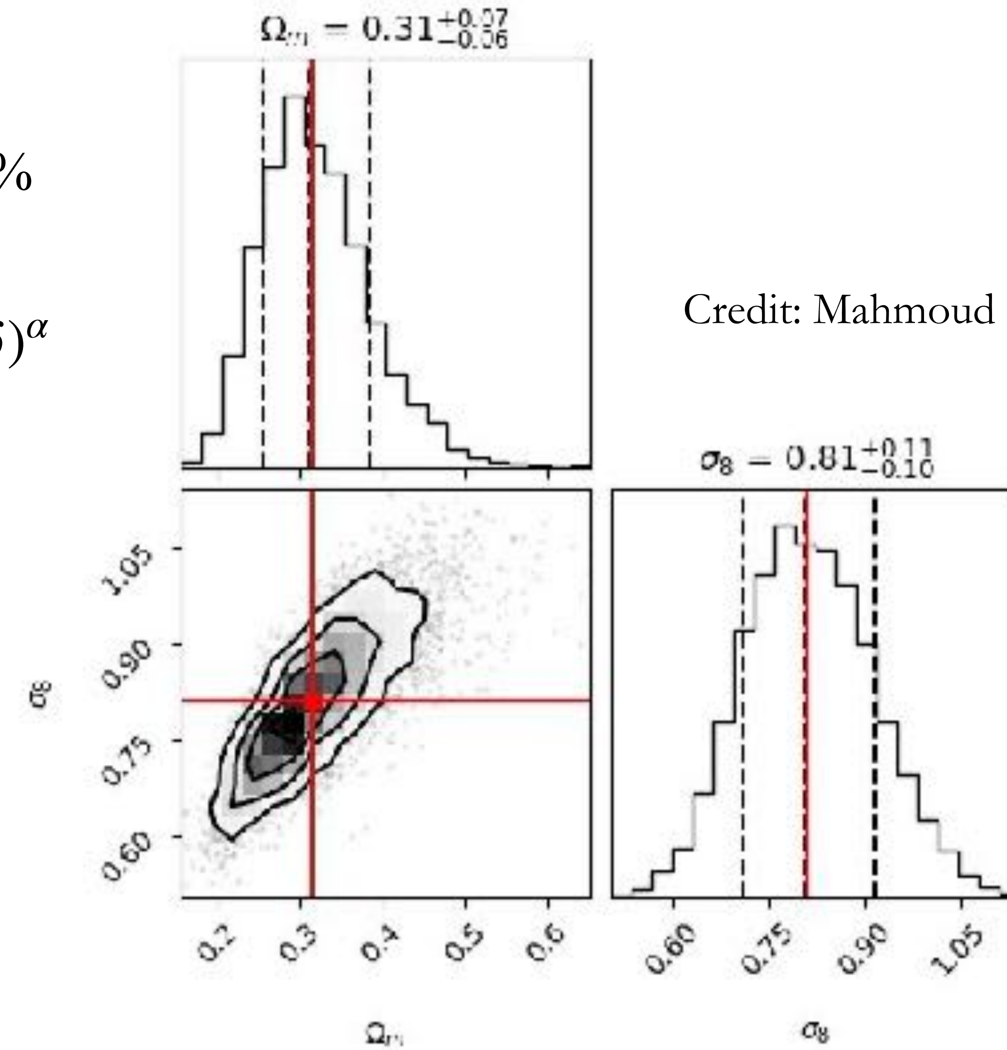
Methodology and first validation

Input data: SN positions and standardised distances with a 7% distance uncertainty from self-consistent mocks
Gravity solver: LPT
SN bias model: Poisson source distribution with mean $(1+\delta)^\alpha$
Selection function: no selection function*
Likelihood: Gaussian
Parameters: IC, bulk flow, σ_v (150 km/s), α (2.3), Ω_m, σ_8

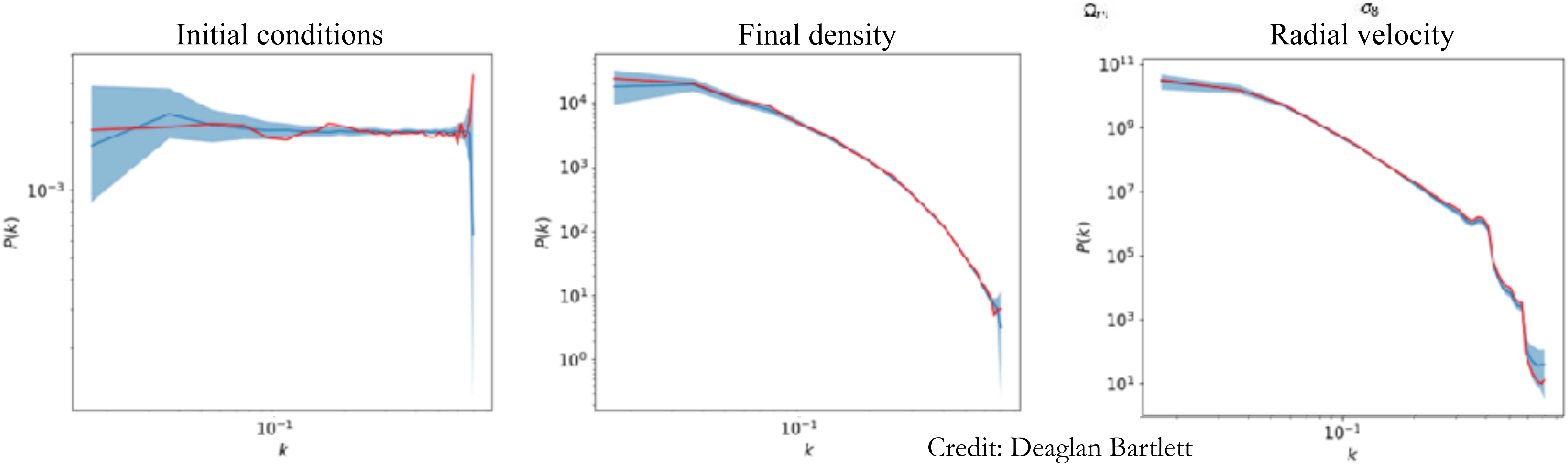
$$\pi(x, \Omega \,|\, M, d)$$

—> Using our collaborator's code Deaglan Bartlett (Fellow at Oxford University)

* selection function can be handled now (see Stiskalek et al 2025b)



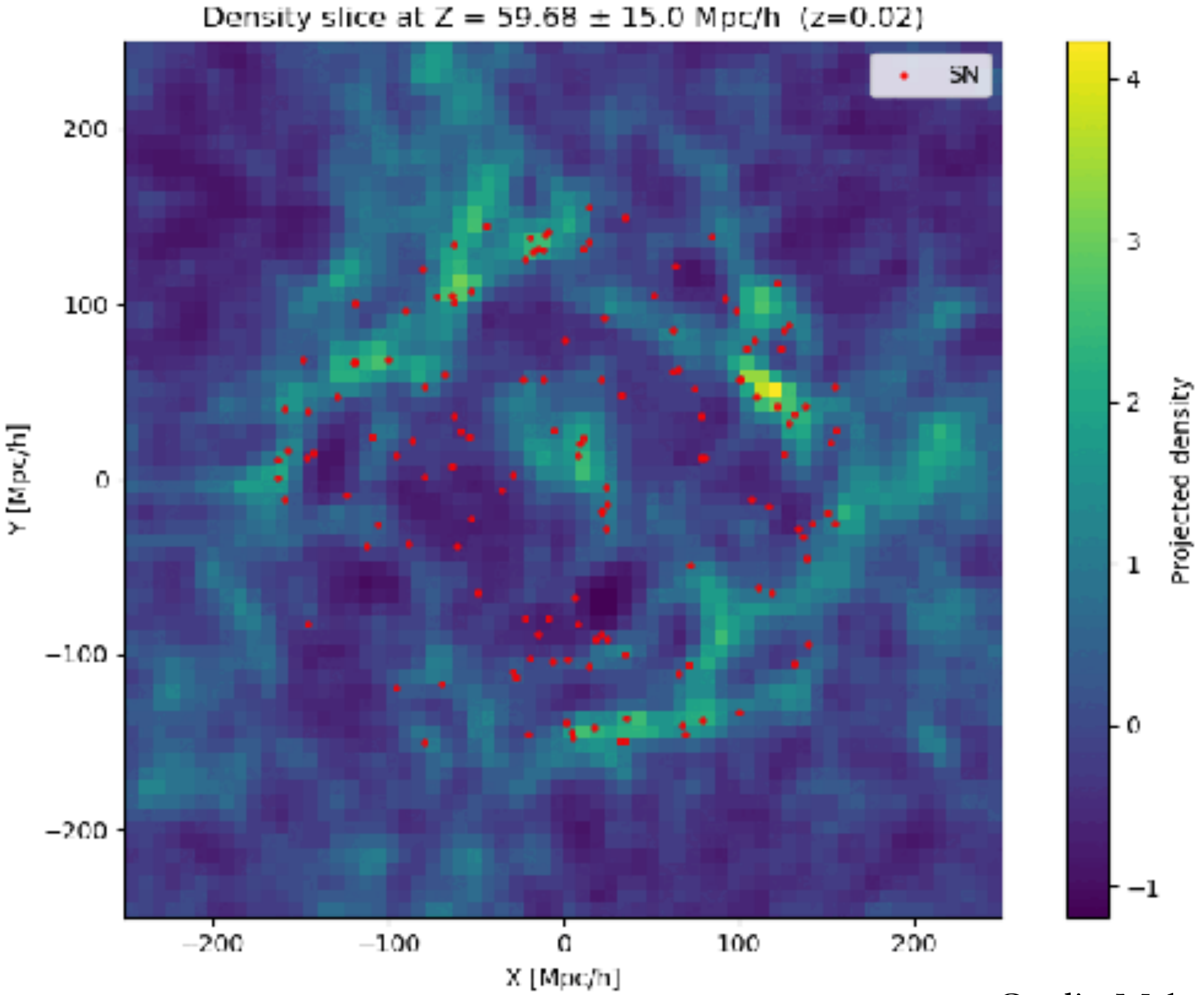
Credit: Mahmoud Osman

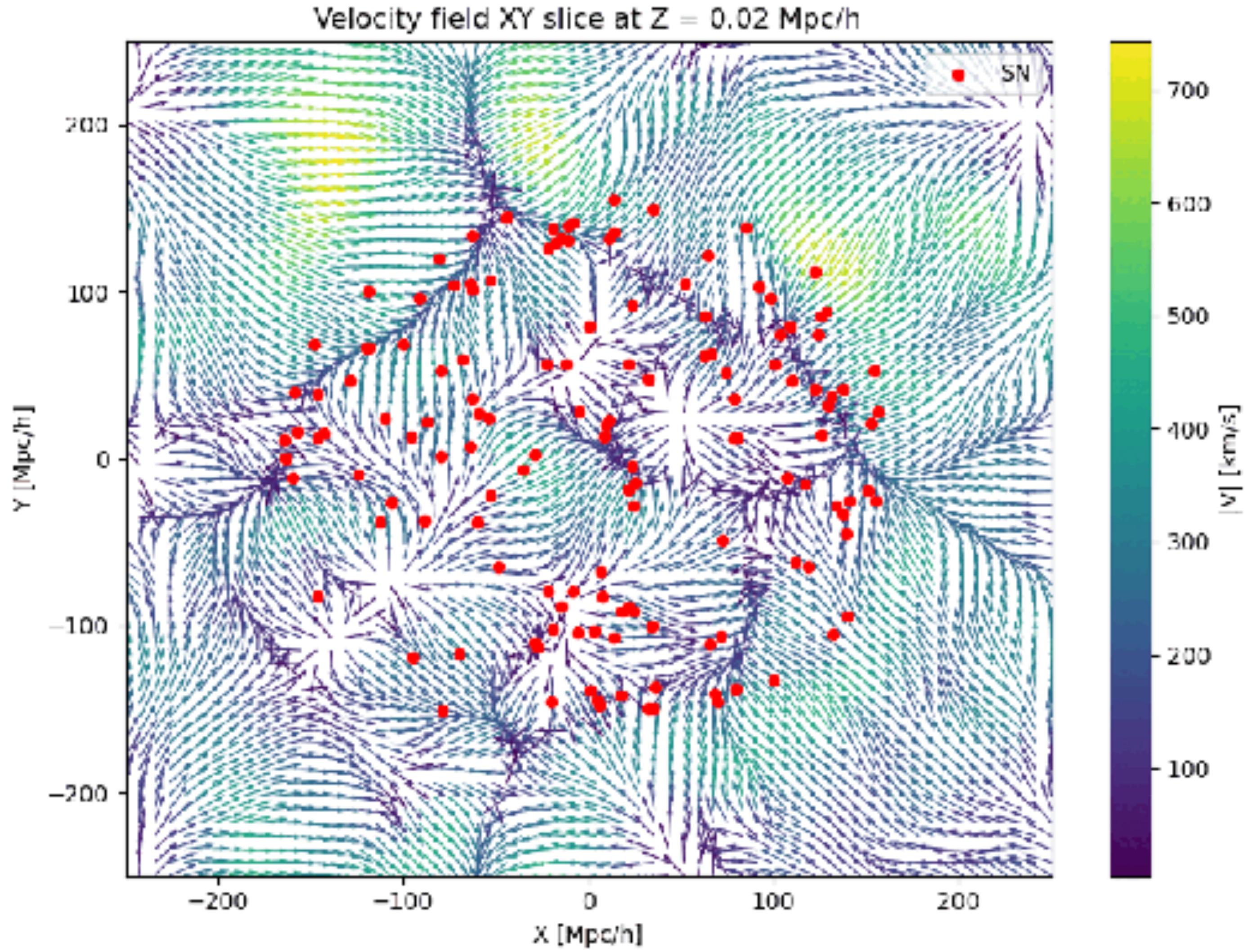


Credit: Deaglan Bartlett

Preliminary results

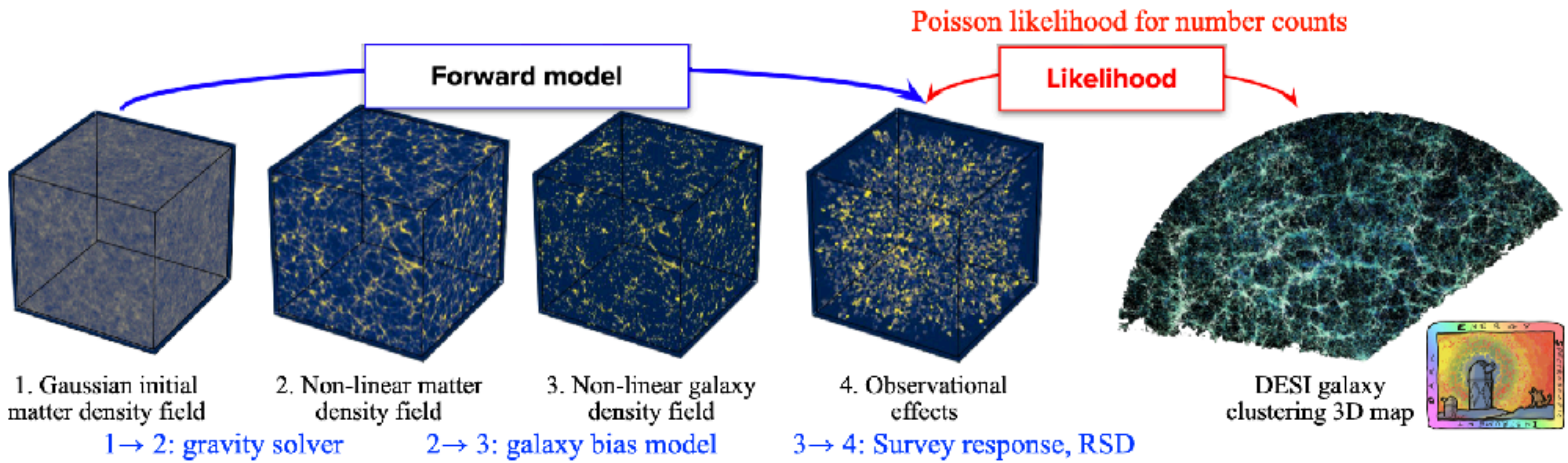
Input data: ZTF PV mock using Uchuu simulation (Ishiyama et al. 2021) from which we draw ZTF DR2 SN Ia using **skysurvey** (Rigault et al. in prep) —> see Rafael's talk
Gravity solver: COLA
SN bias model: Poisson source distribution with mean $(1+\delta)^{\alpha}$
Selection function: no selection function, magnitude/volume-limited sample instead with cut at z=0.06
Likelihood: Gaussian
Parameters: IC, bulk flow, σ_v, α, Ω_m, σ_8





Credit: Mahmoud Osman

BORG applied to DESI BGS



$$\pi(x, \Omega_{nuisance} \,|\, \Omega_{cosmo}, M, d)$$

—> At fixed cosmology for now

Input data: DESI BGS DR1 mock split by absolute magnitude (24 sub-catalogues in total)
Gravity solver: COLA, will also test field-level emulator (see Doeser et al. 2024)
Galaxy bias model: Sigmoid-Truncated Double Power-Law (see McAlpine et al. 2025)
Selection function: Angular completeness mask + radial selection based on Schechter luminosity function
Likelihood: Generalized Poisson likelihood (see McAlpine et al. 2025)

BORG's newest version: Manticore

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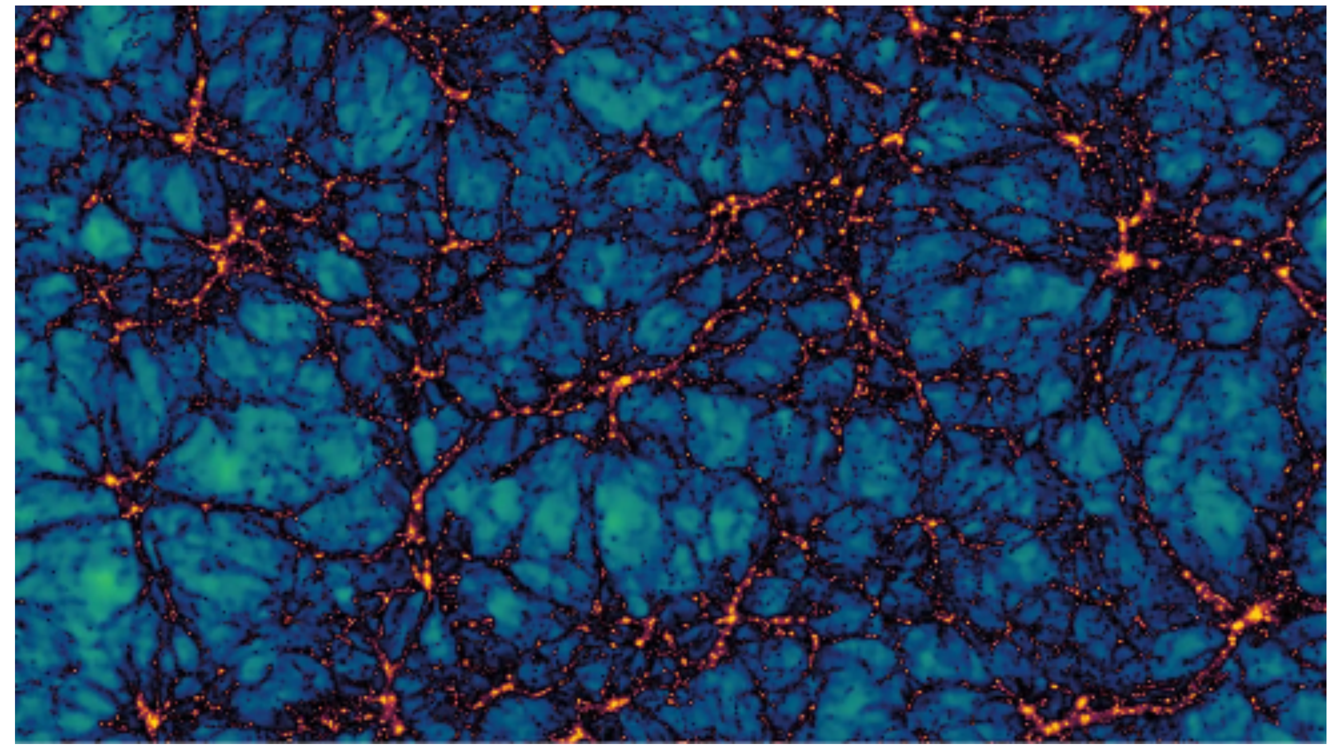
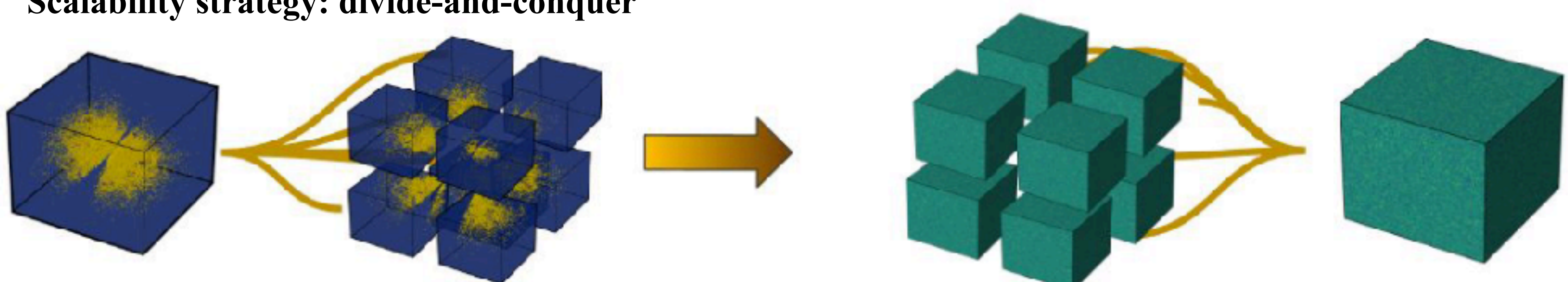
Manticore
- more flexible galaxy bias model
- Generalised Poisson likelihood
- Physics-informed priors: Gaussianity, isotropy, ΛCDM moments to constrain mean, variance, skewness and kurtosis to guarantee IC = white noise field

Already successfully applied to 2M++ (~69,000 galaxies at $z < 0.06$ corresponding to 300 Mpc)
256^3 grid, 80 posterior samples
HMF and P(k) consistent with ΛCDM
Manticore-local (McAlpine et al. 2025) → Set of evolved cosmic-variance-aligned digital twins

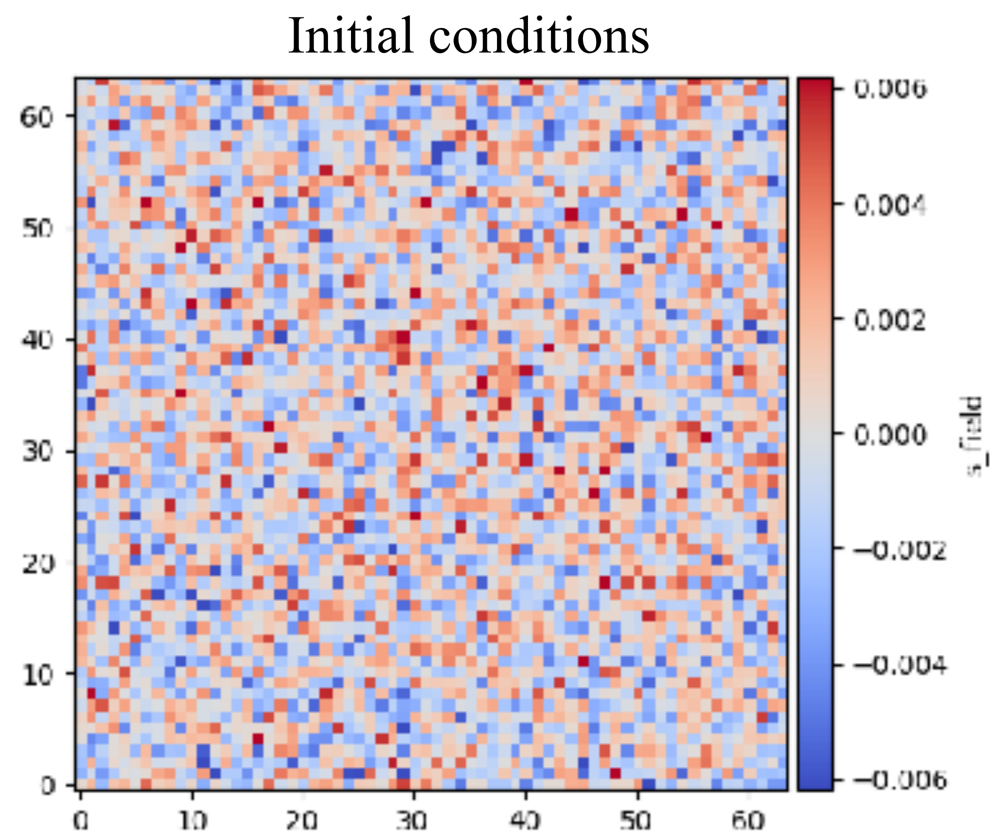


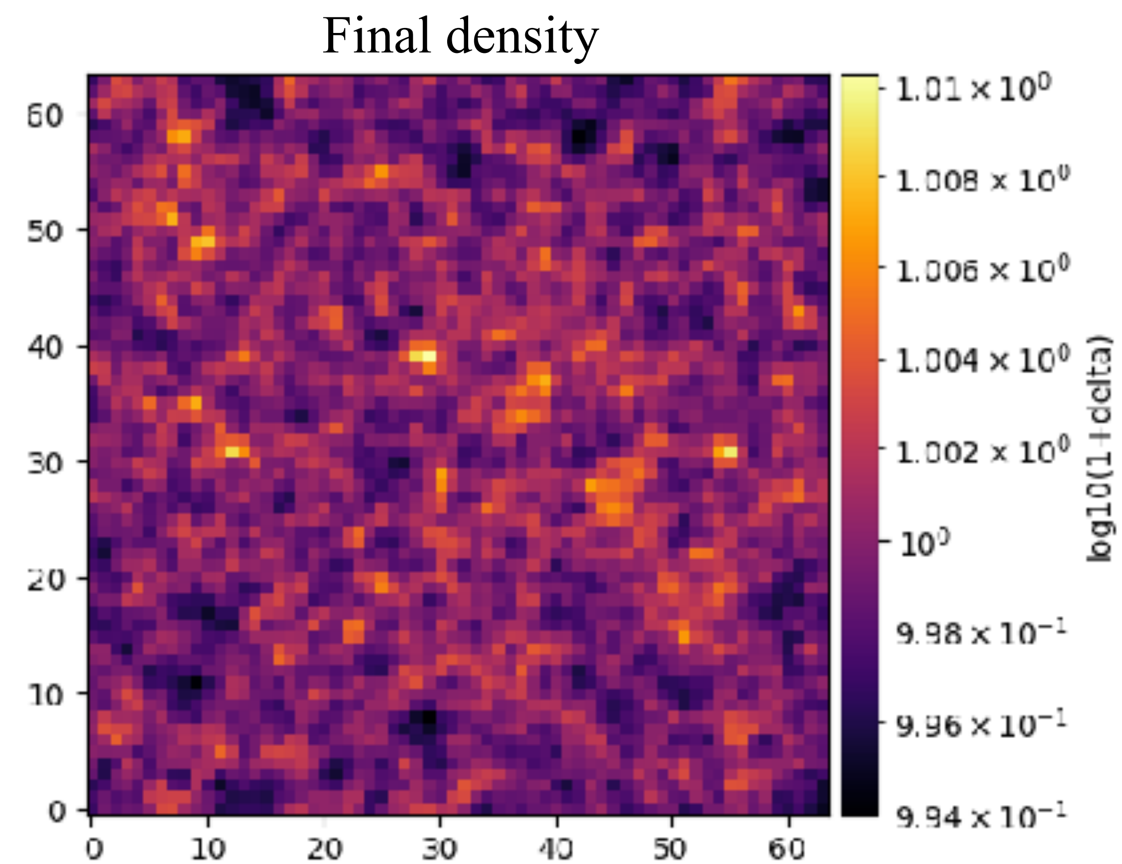
Scalability strategy: divide-and-conquer

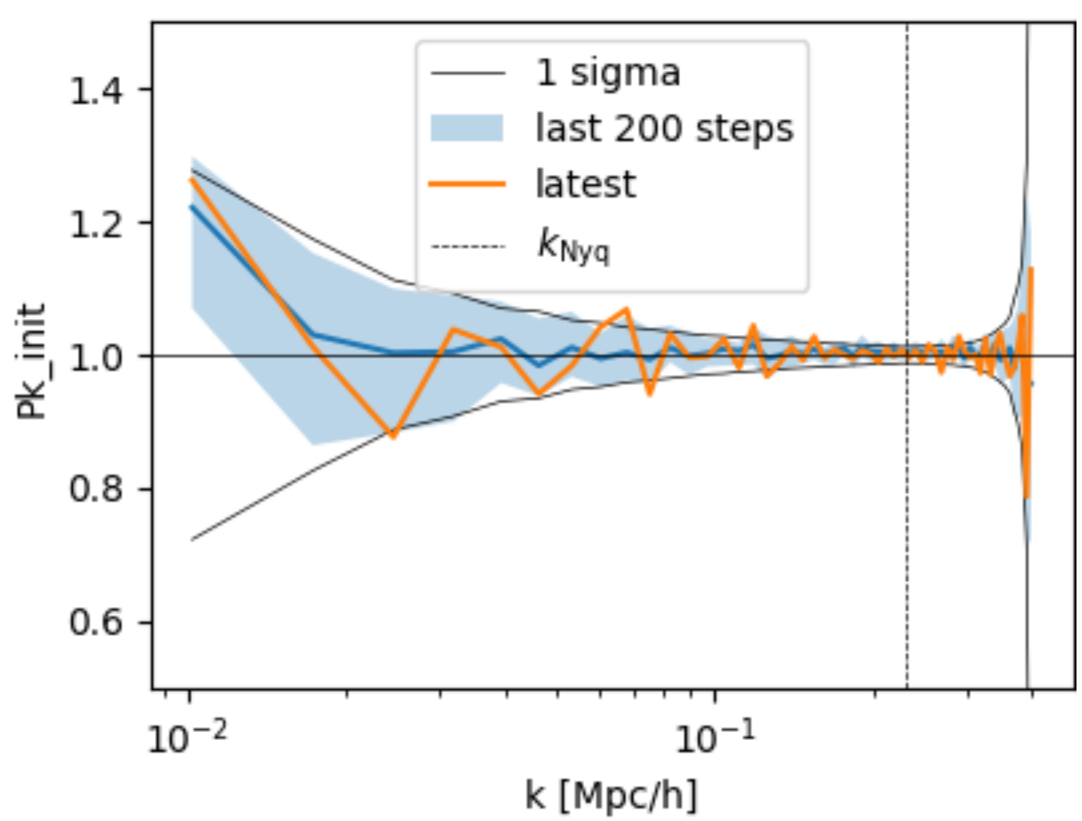


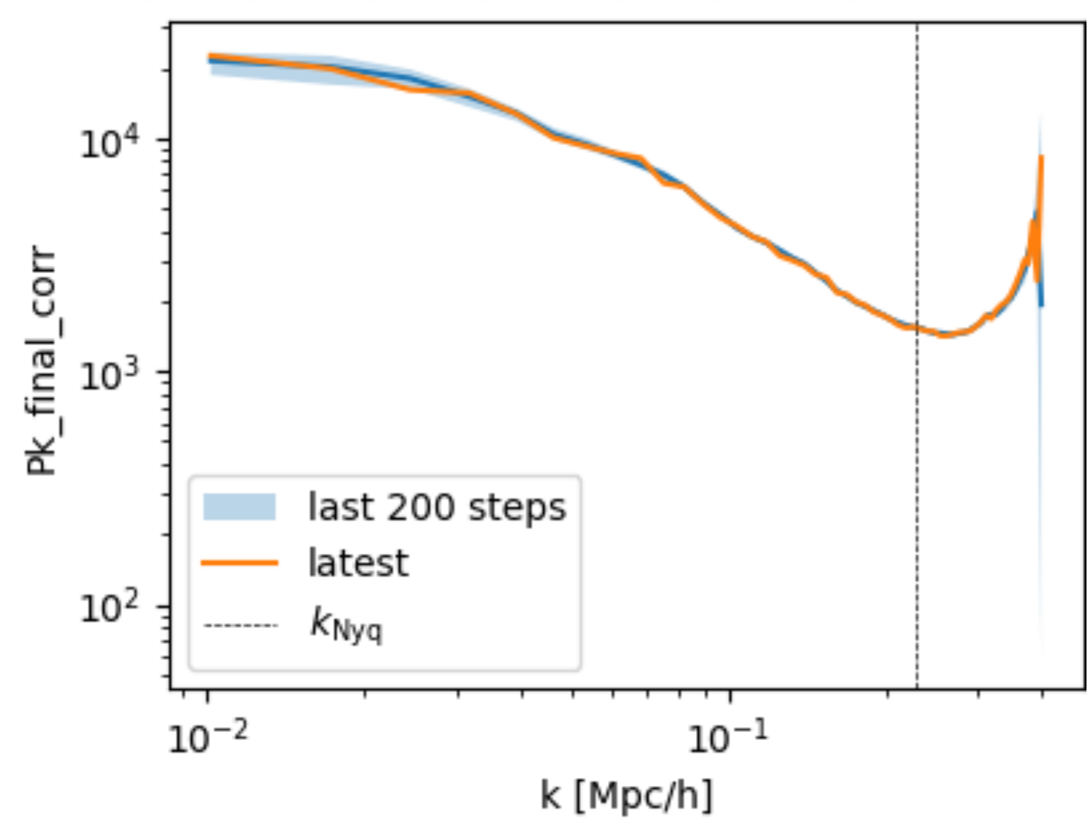
- Take data volume
- Split it into separate inverse problem
- Solve the problem in sub-boxes
- Recombine

Preliminary results using the DESI BGS



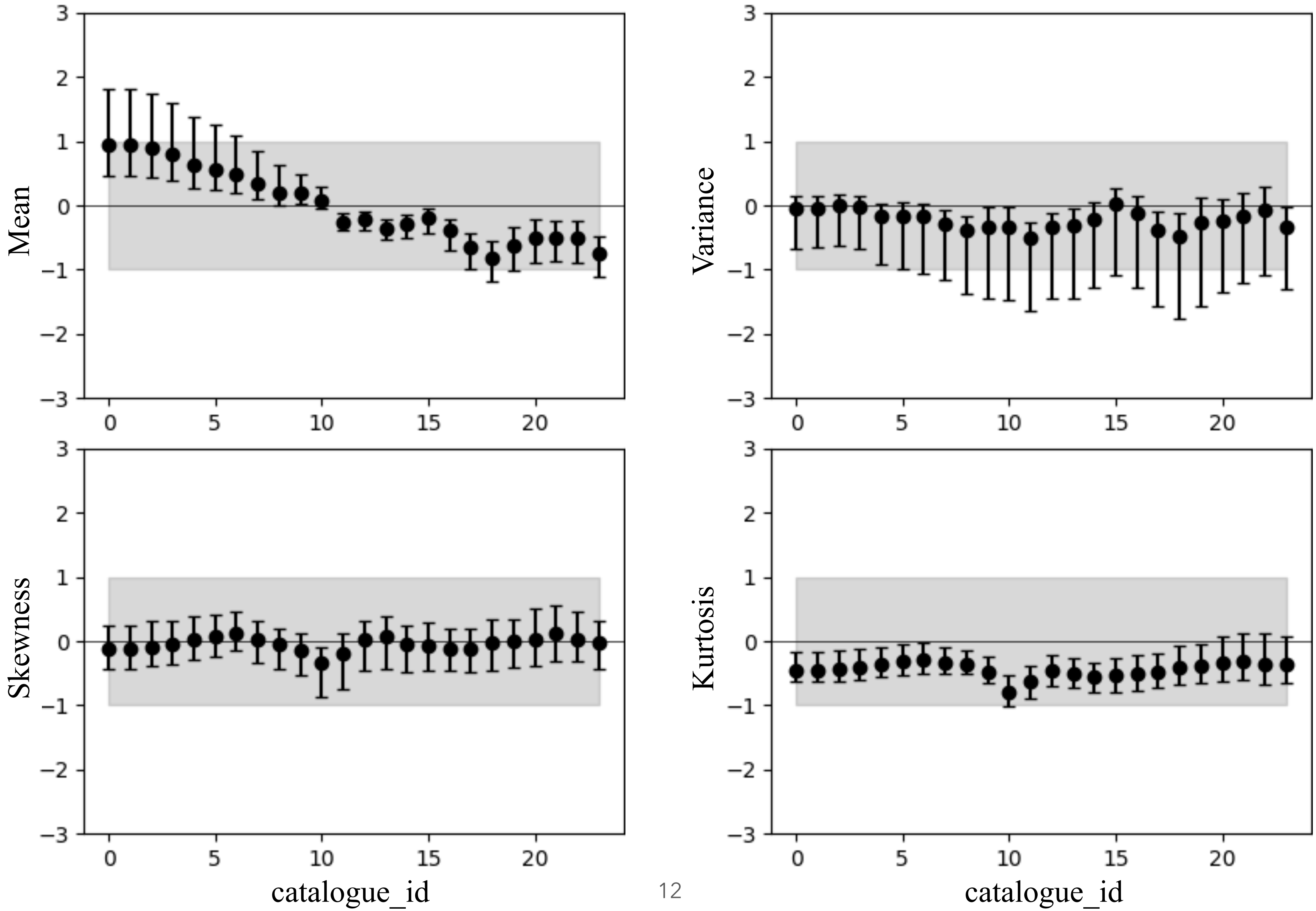




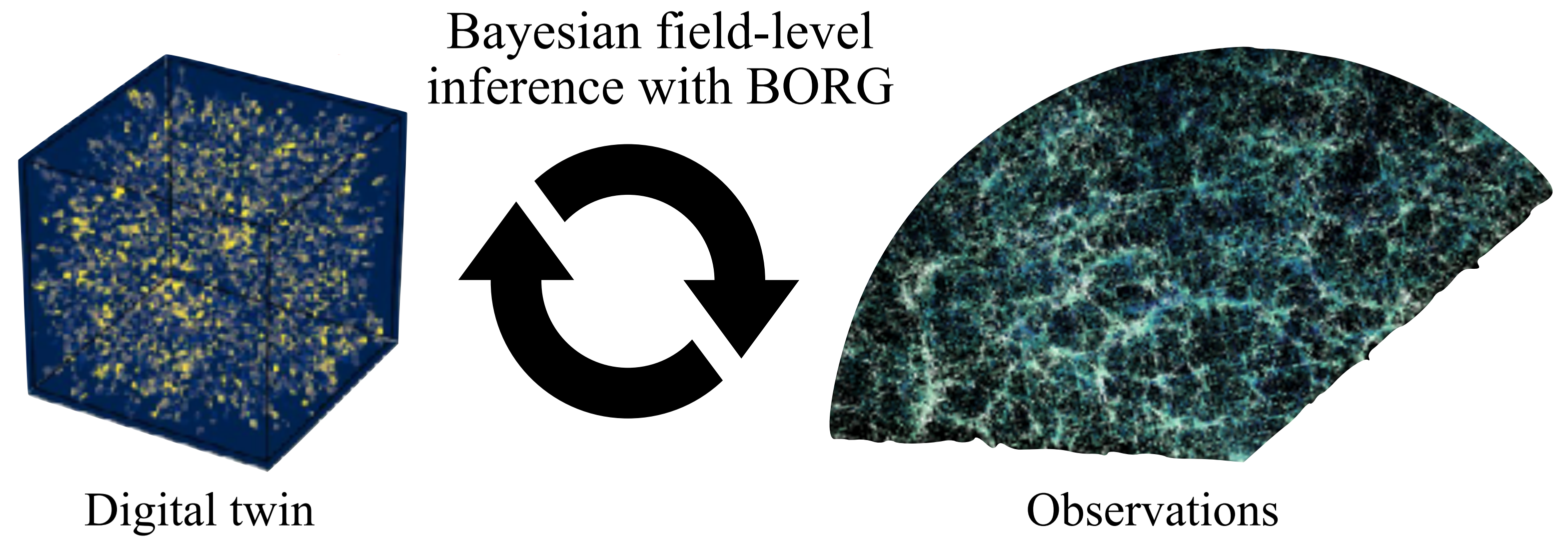


Preliminary results using the DESI BGS

Is the initial density field really a white noise field?



Conclusions



Field-level inference vs HOS

- the most optimal way of extracting all the information from the non-Gaussian cosmic fields
- Produce cosmic-variance-aligned digital twins
- Can tighten cosmological constraints by a factor 3-5 better than HOS
- But computationally more demanding

BORG

- most advanced end-to-end algorithm to infer the initial conditions and the cosmological parameters
- Successfully applied to previous generation data (galaxy clustering, weak lensing and SN Ia)
- Newest version: Manticore

<u>**This talk**</u>

1) **BORG applied to ZTF SN Ia** (with Mahmoud Osman, Deaglan Bartlett, Guilhem Lavaux)

   ✓ Using self-consistent mocks: reconstruction of IC, density and velocity and cosmological parameters

   Using ZTF PV mocks: bias on cosmological parameters, could be due to the SN bias model
   Next: include selection effects (up to z=0.12), infer standardisation parameters in the inference

2) **BORG/Manticore applied to DESI** (with Stuart McAlpine, Jens Jasche)

   ✓ Proof-of-concept using low resolution grid (256^3, 512^3)

   Test with target resolution (1024^3), field-level emulator, more refined galaxy bias model?