How much Information can be extracted from Galaxy Clustering at the Field Level?

arXiv: 2403.03220

Fabian Schmidt

Beatriz Tucci

Minh Nguyen (Nguyễn Nhật Minh)

LCTP Fellow, University of Michigan

nguyenmn@umich.edu

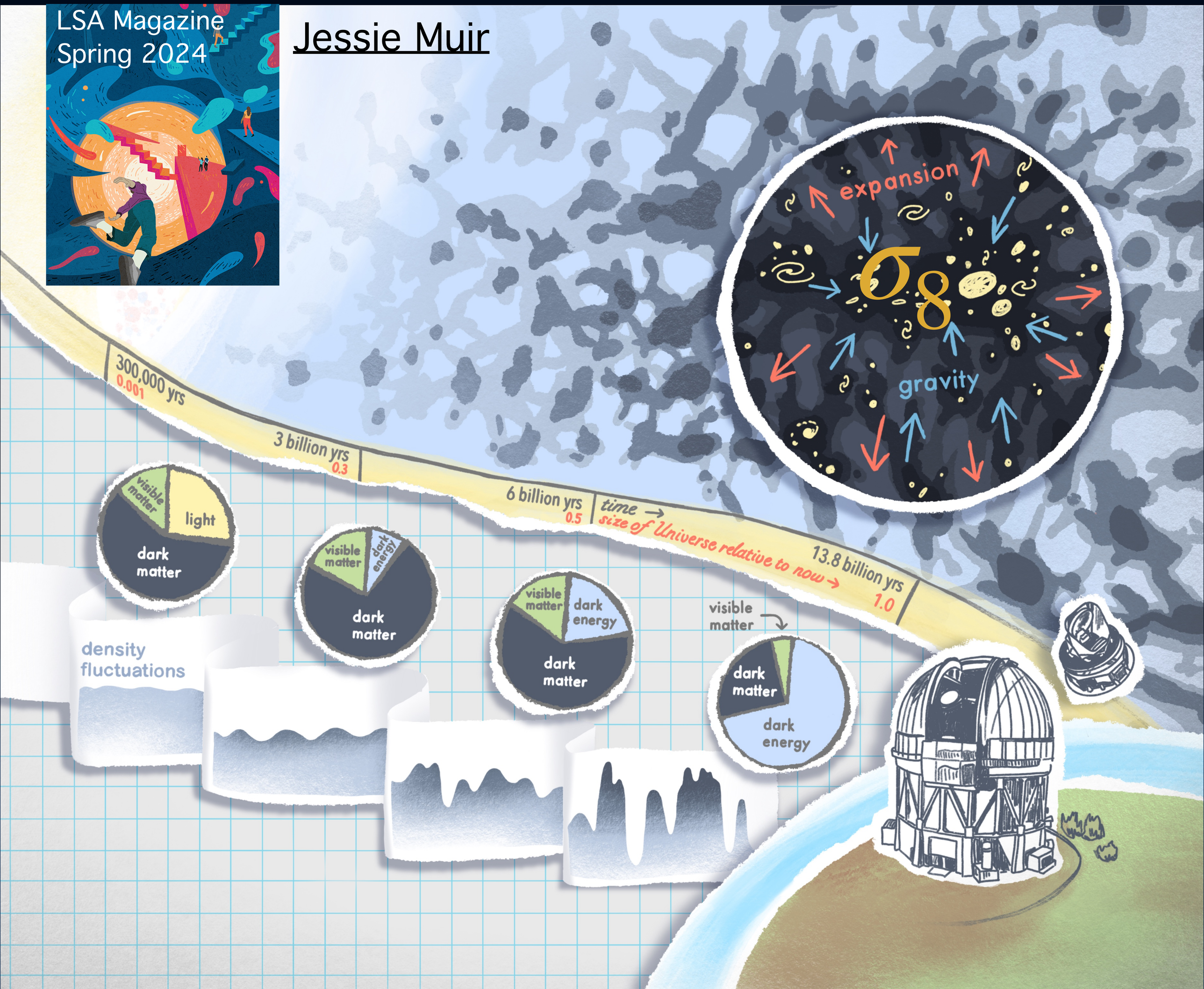
UNIVERSITY OF MICHIGAN

New Physics from Galaxy Clustering

Shedding light on dark matter and dark energy*

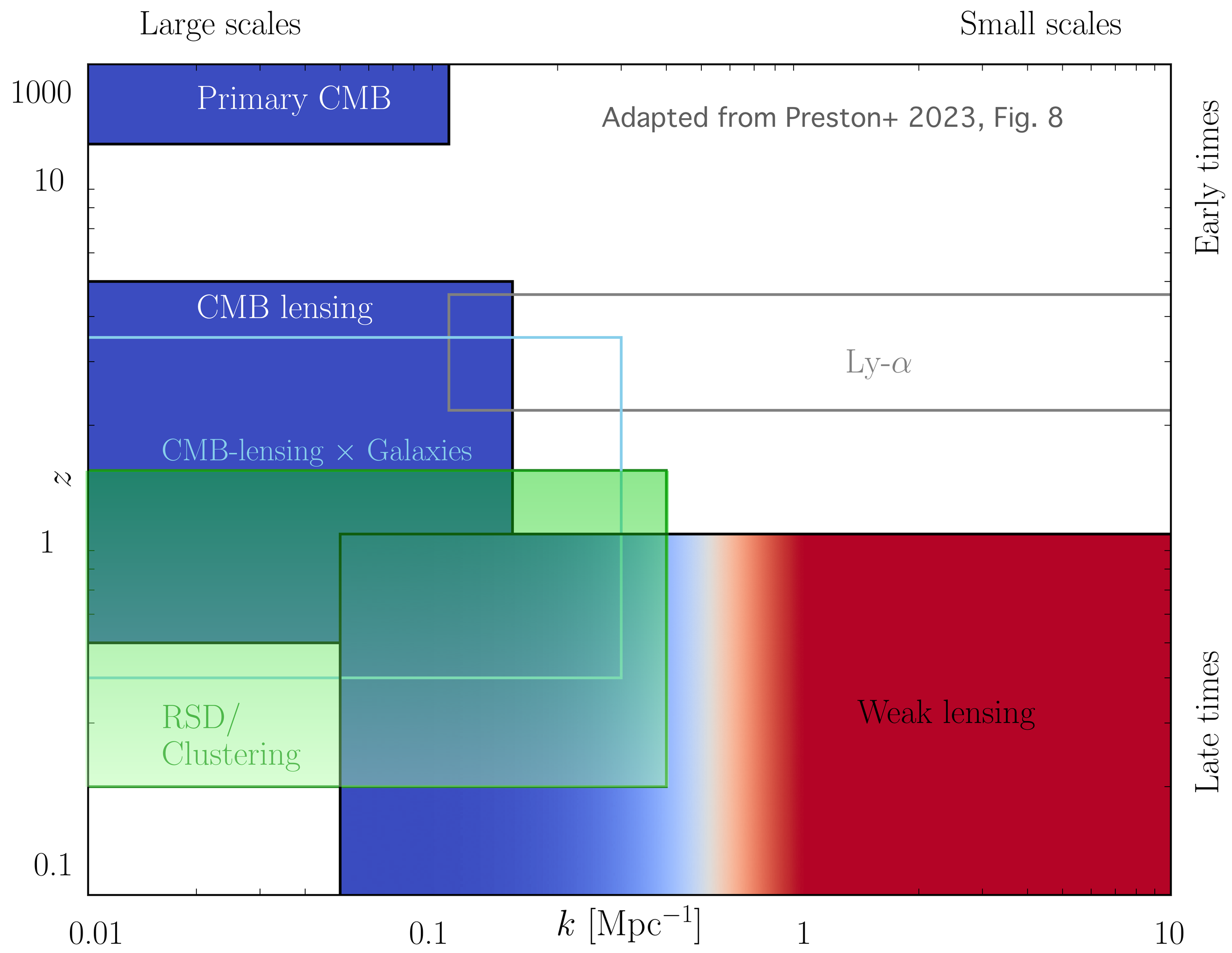
*Article on arXiv:2302.01331

Jessie Muir



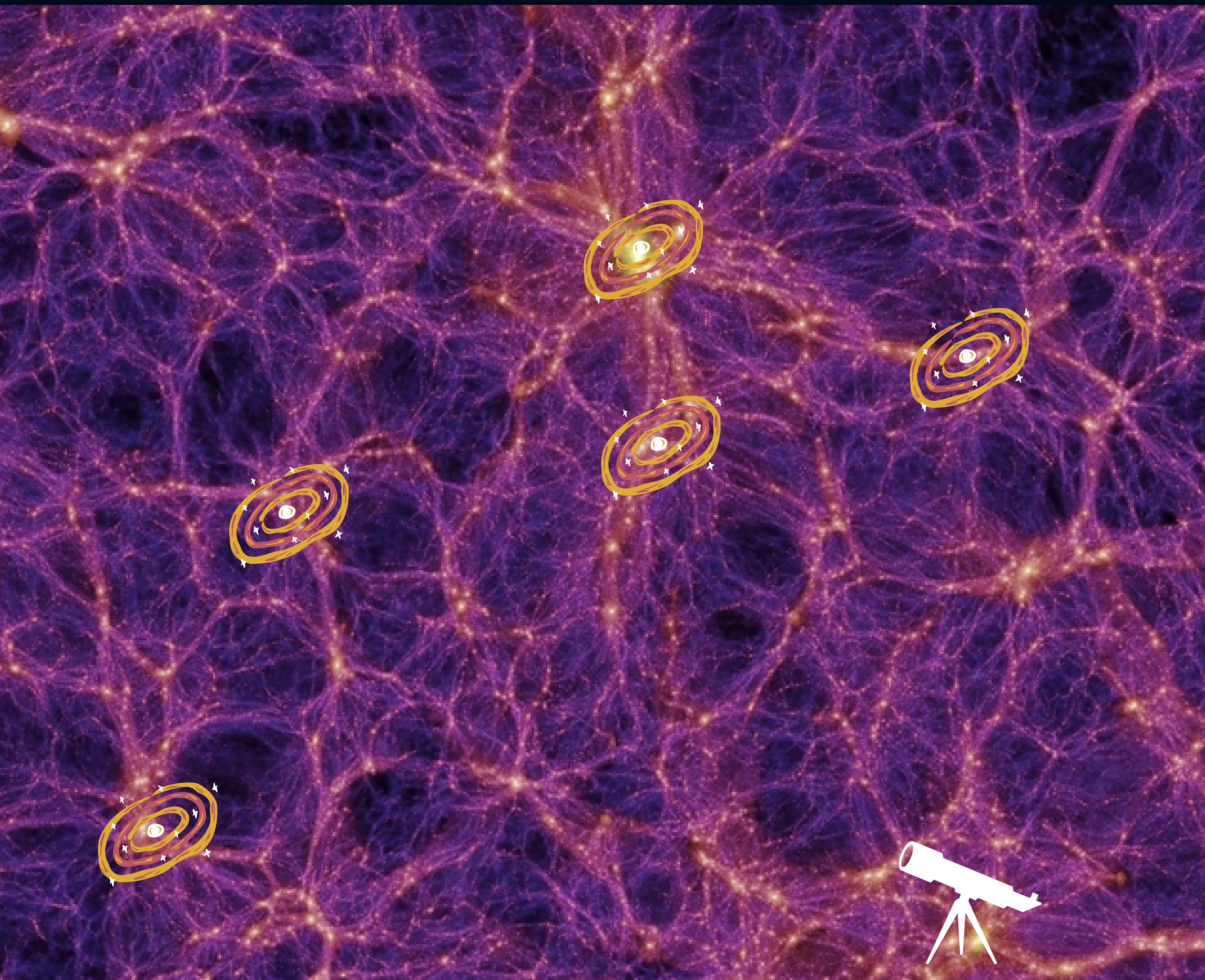
Where is the new physics?

S_8 tension: early- vs late-universe or large- vs small-scales?

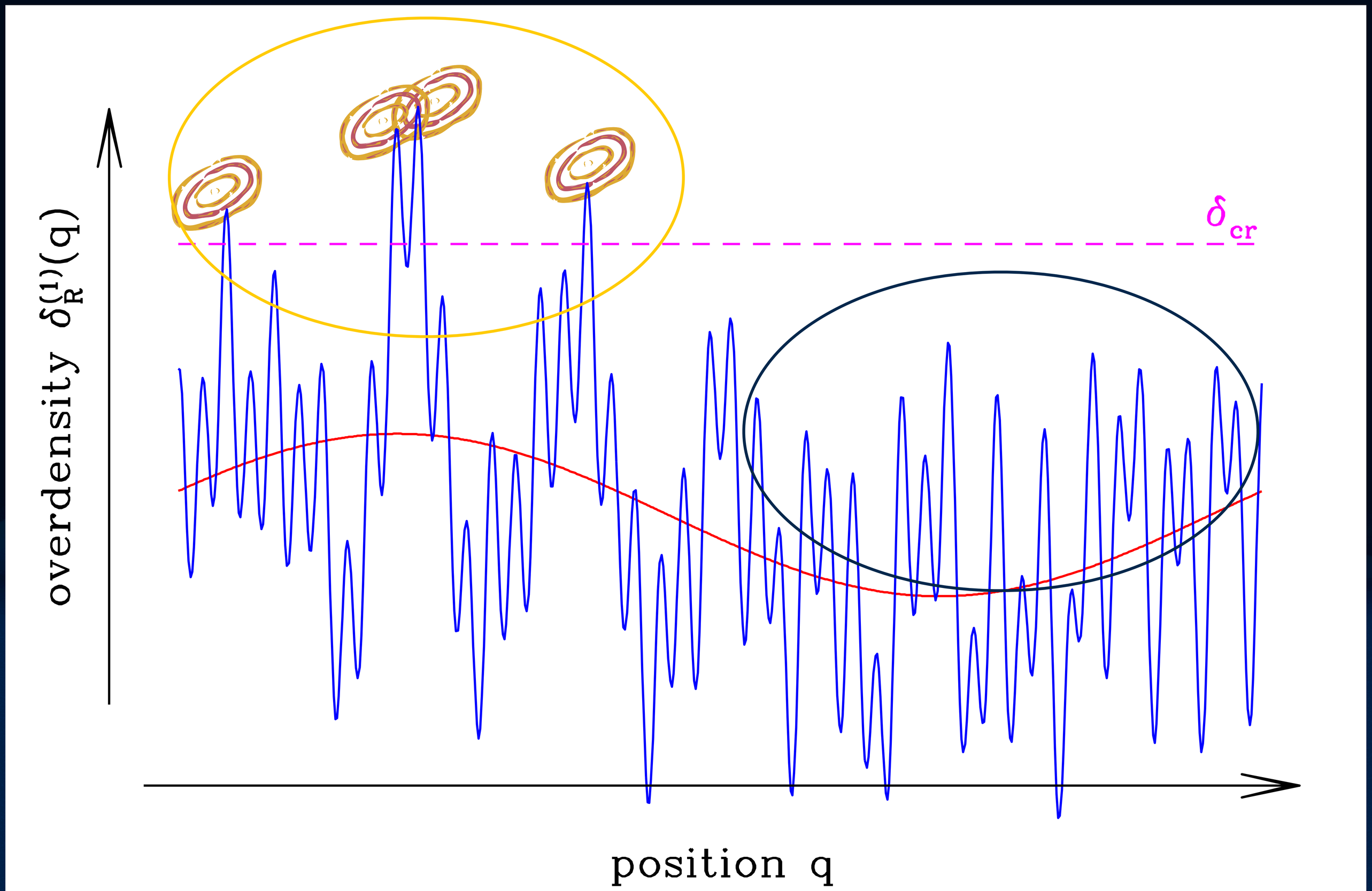


Galaxy Clustering observation

Galaxies as test particles for growth of structure



Galaxies are biased test particles

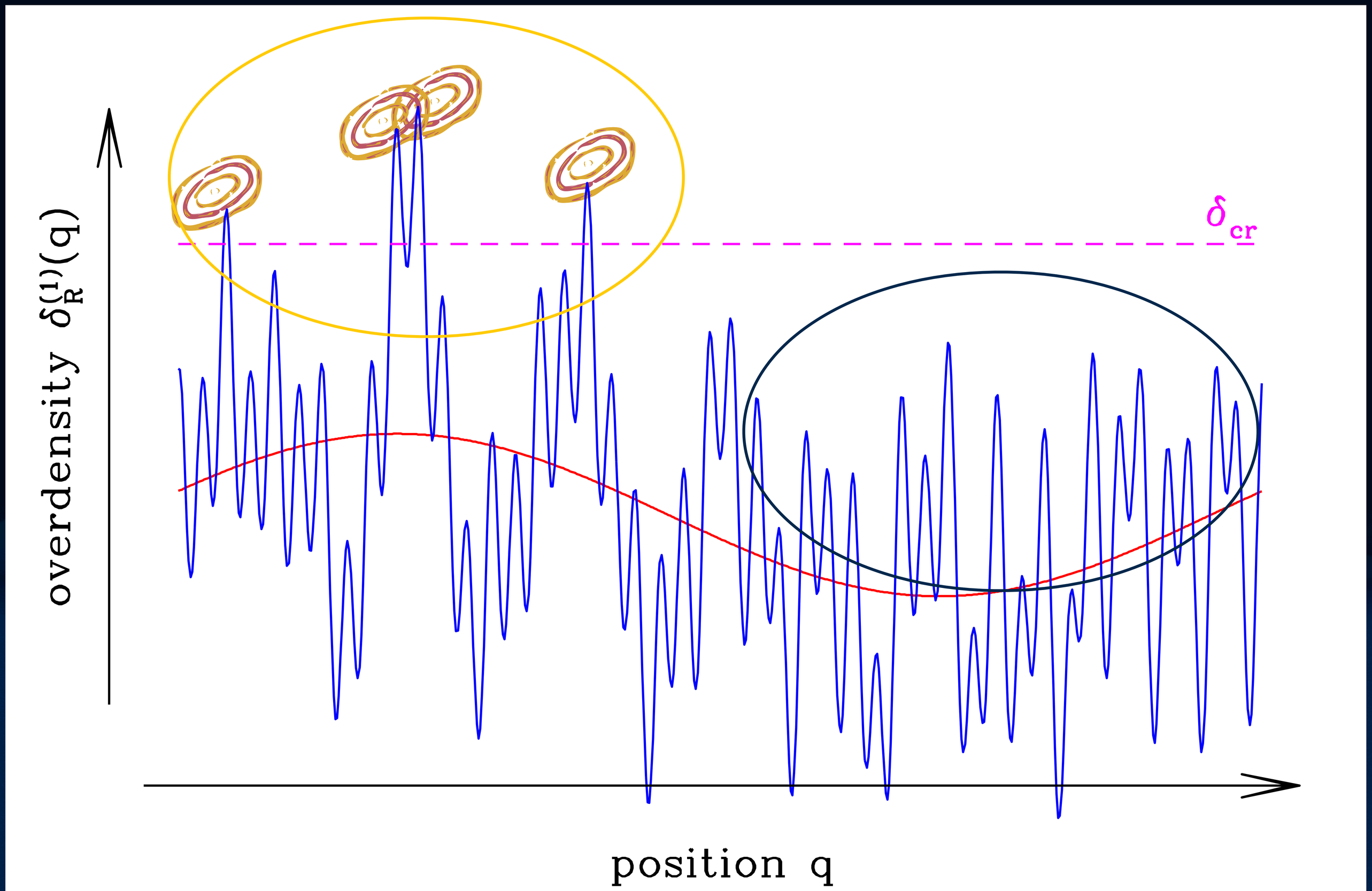


Galaxies are biased test particles

Breaking bias-σ_8 degeneracy requires either

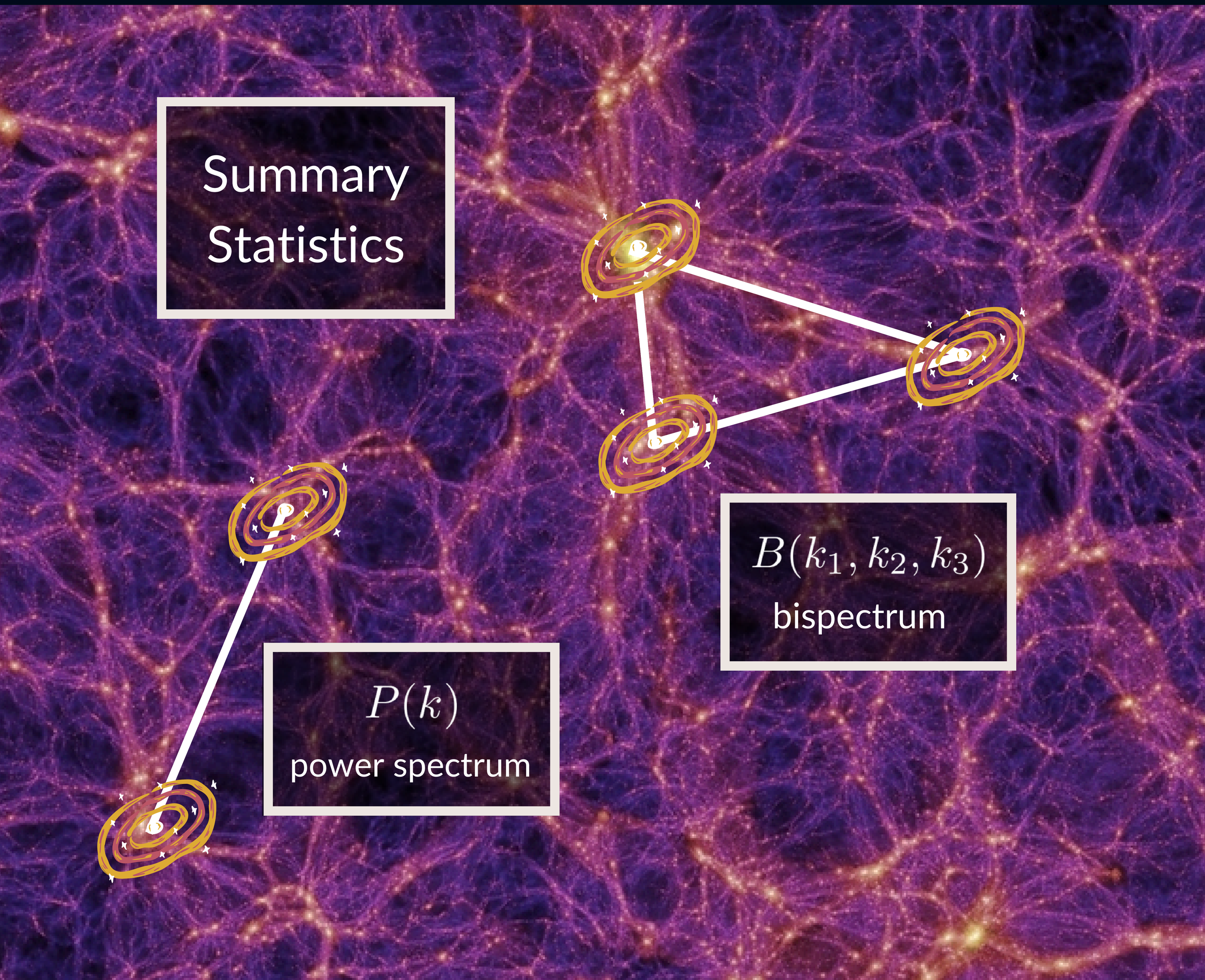
Redshift-space distortion (not the focus)

Nonlinear clustering (the focus of this talk)



Galaxy Clustering analysis

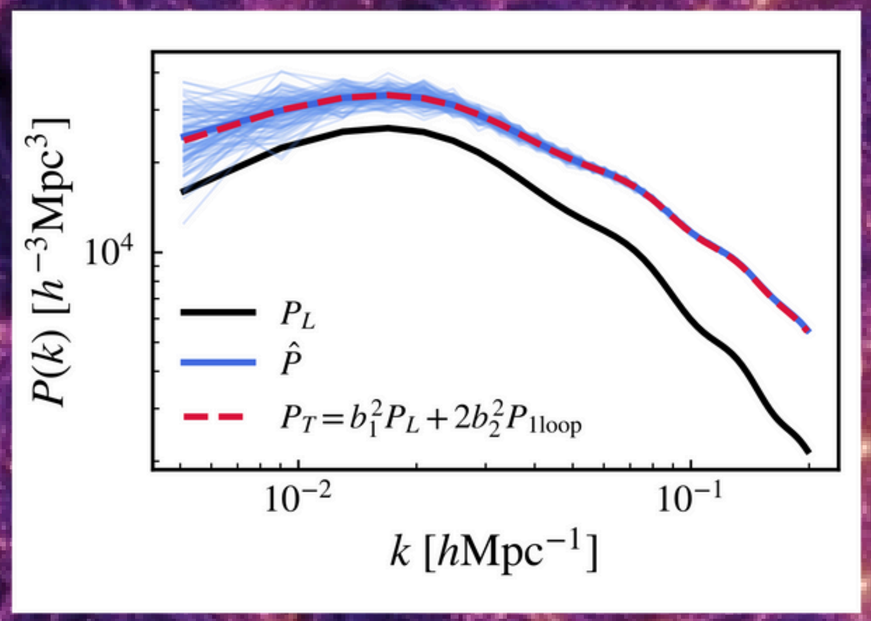
Summary statistics of galaxy clustering

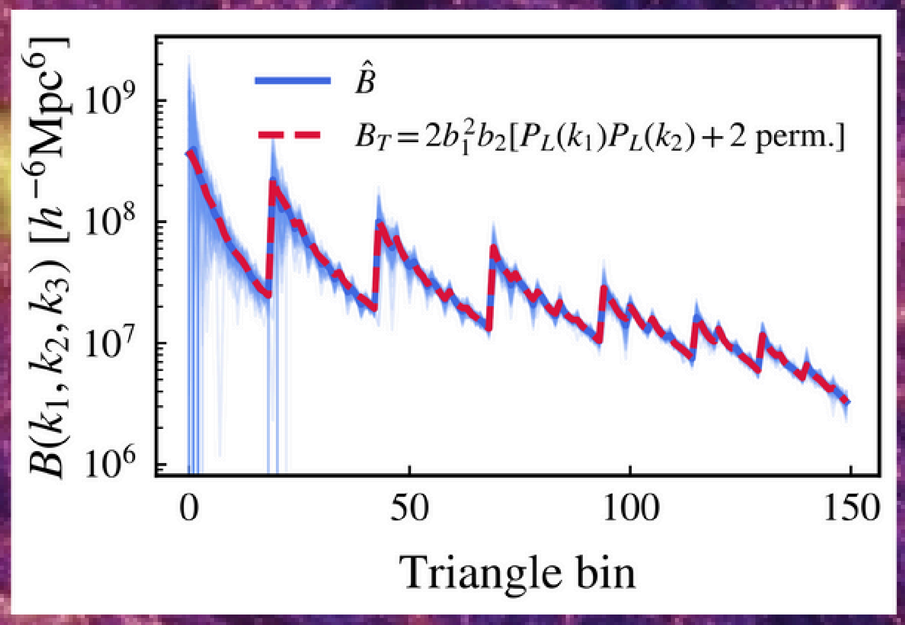


Galaxy Clustering analysis

Summary statistics of galaxy clustering

Summary Statistics





$B(k_1, k_2, k_3)$

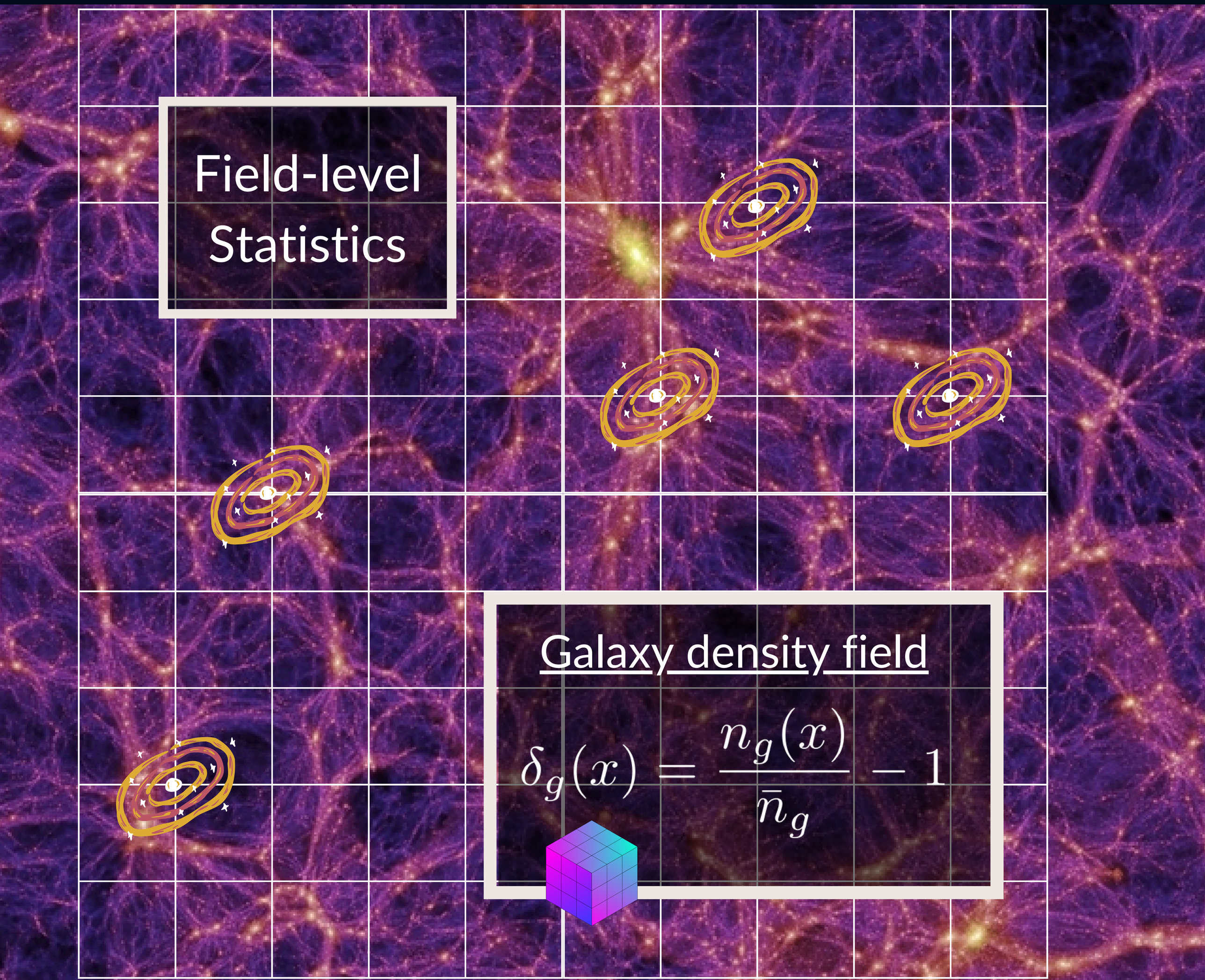
bispectrum

$P(k)$

power spectrum

Galaxy Clustering analysis

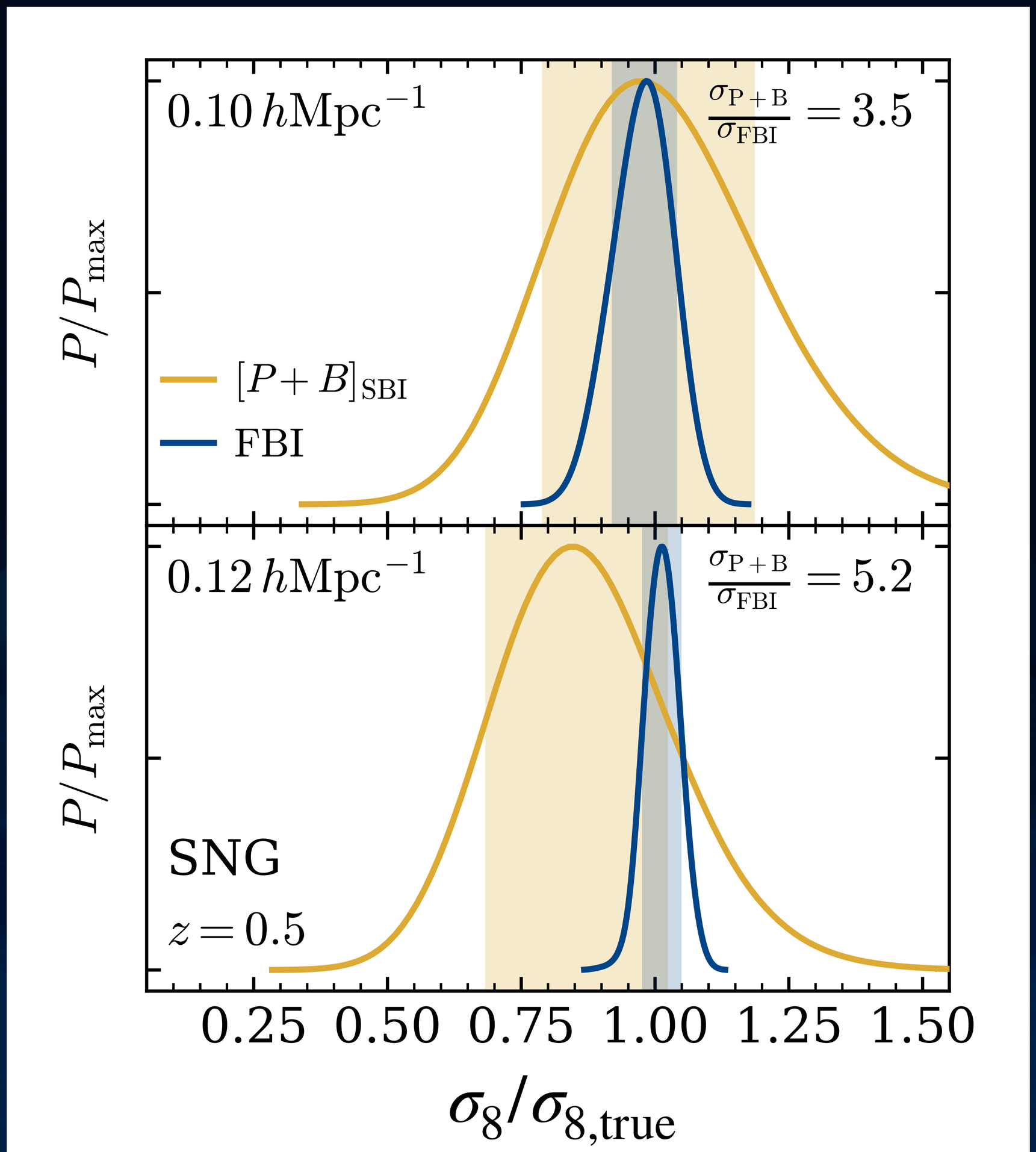
Field-level statistics of galaxy clustering



Maximize information from Galaxy Clustering

From summary (P+B) to field-level Bayesian inference (FBI)

Constraints on σ_8 obtained from FBI and P+B

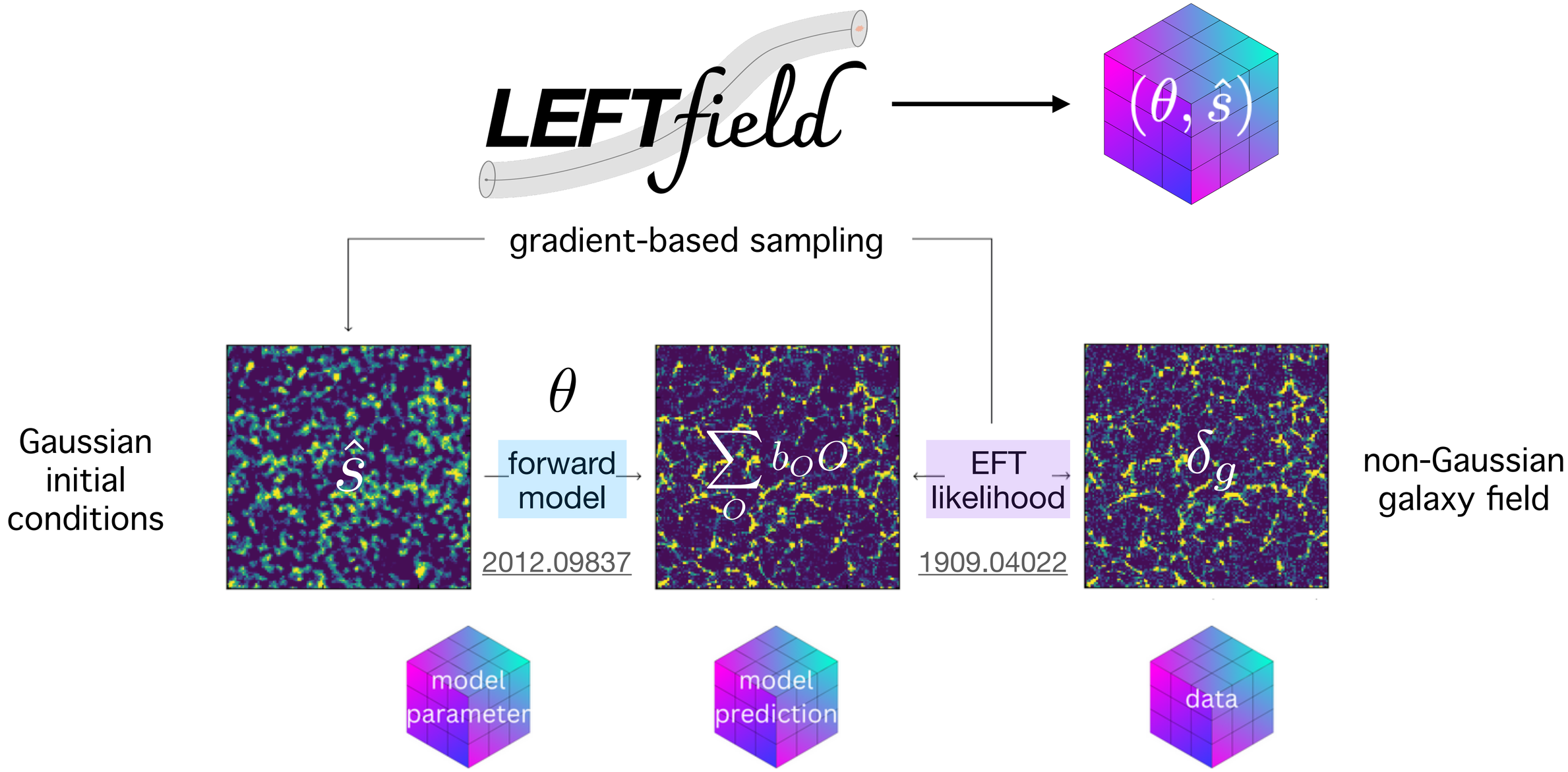


Field-level Bayesian Inference (FBI)

From Gaussian initial conditions to galaxy field (and back)

We build the LEFTfield framework for FBI from galaxy clustering

- Fast
- Efficient
- Differentiable

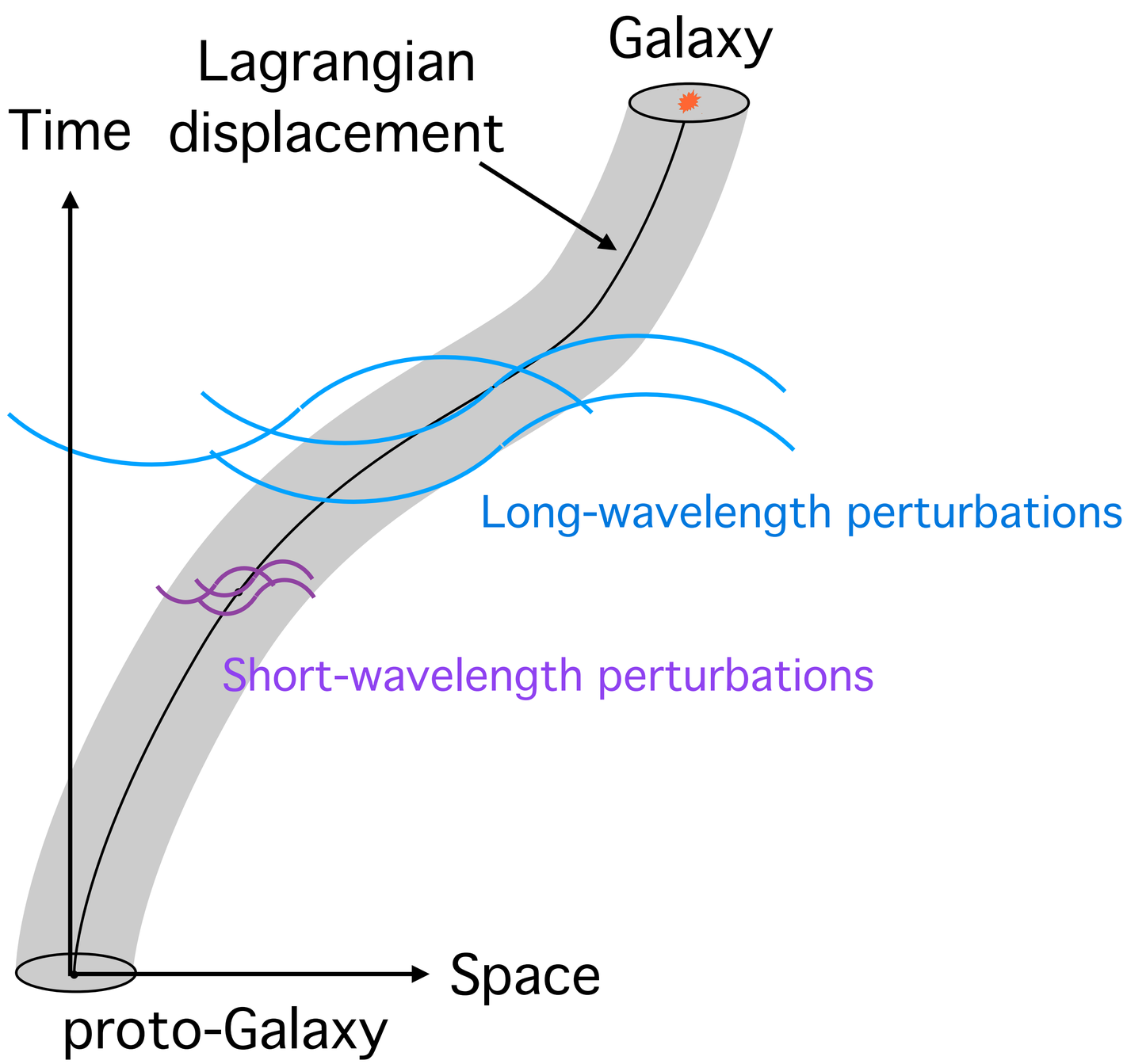


Adapted from Julia Stadler

LEFTfield forward model for FBI

Lagrangian, Effective Field Theory-based forward model for fields

An EFT description of galaxy field on large scales based on the nature of cold dark matter and structure formation



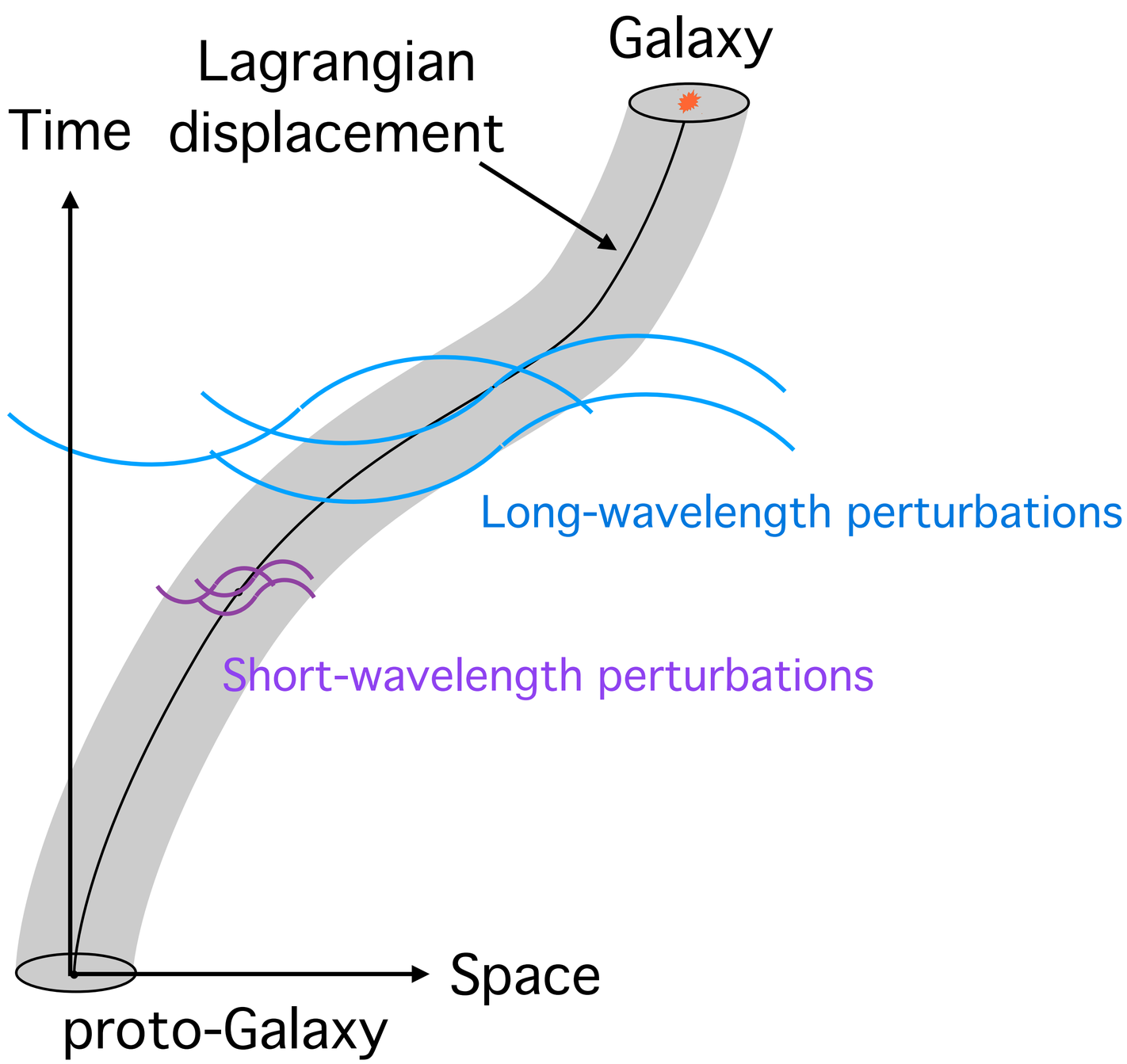
LEFTfield forward model for FBI

Lagrangian, Effective Field Theory-based forward model for fields

An EFT description of galaxy field on large scales based on

the nature of cold dark matter and structure formation

the symmetry of gravity (Einstein's equivalence principle)



Field-level EFT bias expansion

$$\delta_g(\theta, \hat{s}) = \sum_O b_O O(\theta, \hat{s}) + \epsilon$$

LEFTfield forward model for FBI

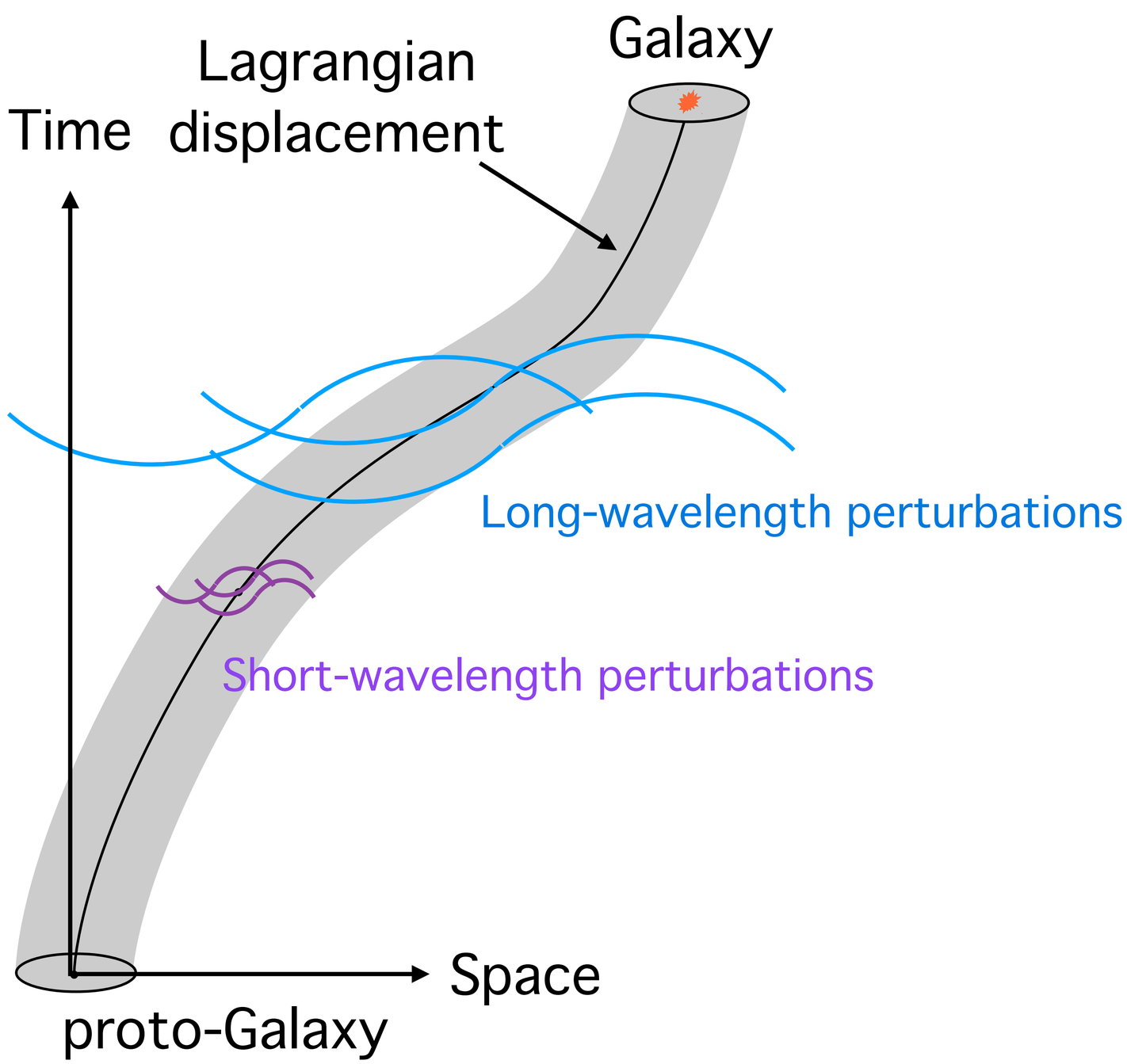
Lagrangian, Effective Field Theory-based forward model for fields

An EFT description of galaxy field on large scales based on

the nature of cold dark matter and structure formation

the symmetry of gravity (Einstein's equivalence principle)

A recursive relation for the Lagrangian displacement field



Field-level EFT bias expansion

$$\delta_g(\theta, \hat{s}) = \sum_O b_O O(\theta, \hat{s}) + \epsilon$$

+

n^{th}-order Lagrangian displacement field

=

LEFTfield forward model for FBI

Lagrangian, Effective Field Theory-based forward model for fields

An EFT description of galaxy field on large scales based on

the nature of cold dark matter and structure formation

the symmetry of gravity (Einstein's equivalence principle)

A recursive relation for the Lagrangian displacement field

$$\delta_\Lambda^{(1)}(\boldsymbol{k}, z) = W_\Lambda(k)\sqrt{\alpha^2 P_L(k, z)}\,\hat{s}(\boldsymbol{k})$$

$$\alpha \equiv \sigma_8/\sigma_8^{\rm fid}$$

$$\hat{s}(\boldsymbol{x}) \sim \mathcal{N}(0, 1)$$

$$1 + \delta(\boldsymbol{x}, \tau) = |\mathbf{1} + \boldsymbol{M}(\boldsymbol{q}, \tau)|^{-1}$$

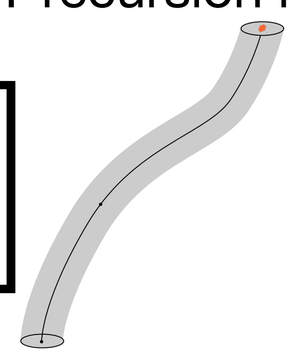
$$M_{ij} \equiv \partial_i s_j$$

$$\mathrm{tr}[\boldsymbol{M}_\Lambda^{(1)}] = -\delta_\Lambda^{(1)}$$

nLPT recursion relations

n^{th}-order **Lagrangian** displacement field

$$\boldsymbol{s}^{(n)}$$



2012.09837

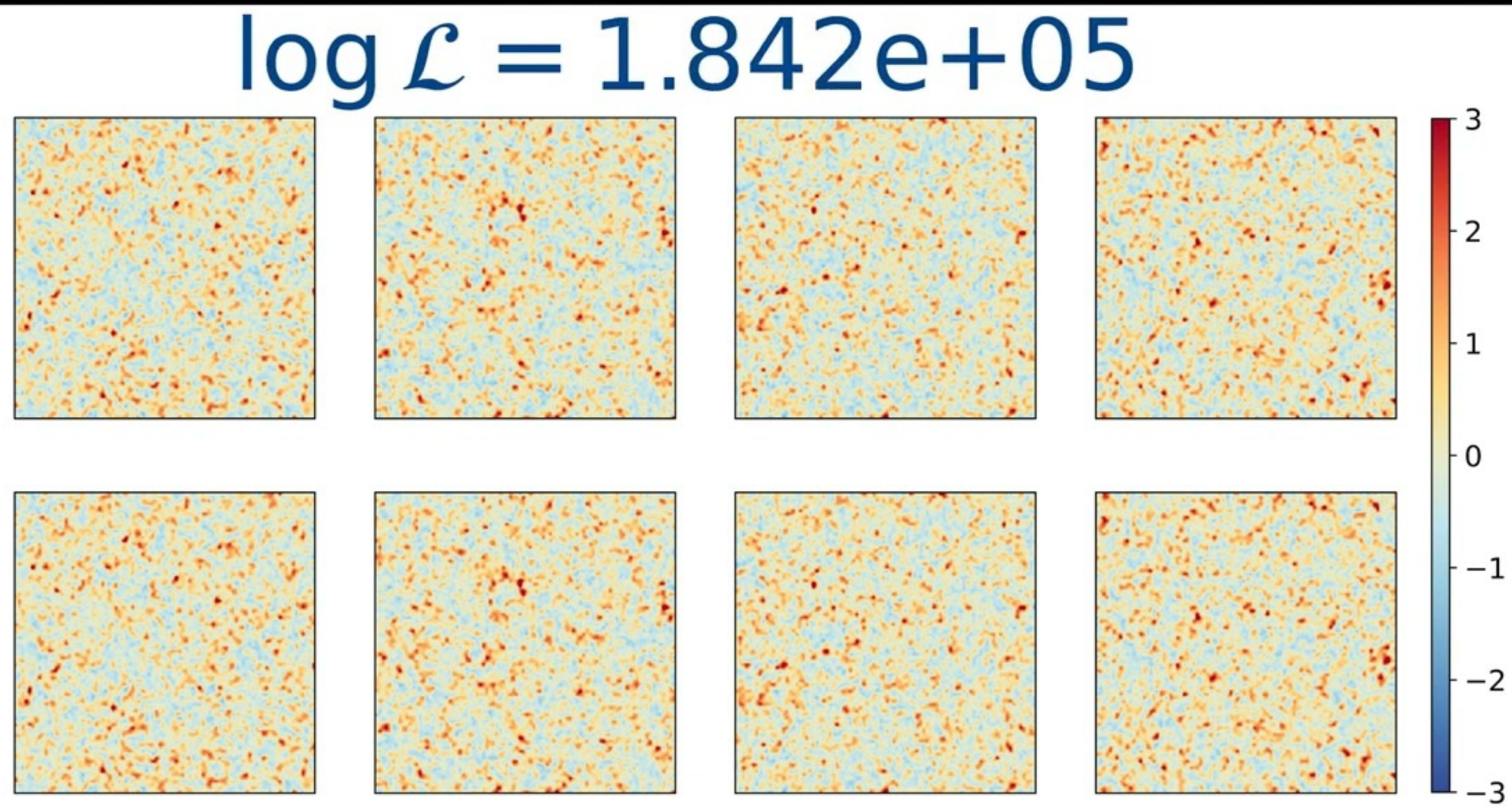
EFT field-level likelihood for FBI

FBI in action

$$\ln \mathscr{L} \sim -\frac{1}{2}\sum_{\mathbf{k}>0}^{\mathbf{k}_{\max}}\left[\ln 2\pi\sigma_\epsilon^2(k) + \frac{1}{\sigma_\epsilon^2(k)}\left|\delta_g(\mathbf{k}) - \delta_g[\sigma_8, \hat{s}](\mathbf{k})\right|^2\right]$$

$$\sigma_\epsilon(k) = \sigma_{\epsilon,0}\left[1 + \sigma_{\epsilon,k^2}k^2\right]$$

1909.04022



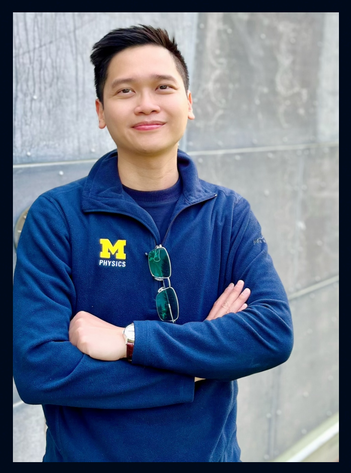
An apple-to-apple comparison of FBI vs P+B

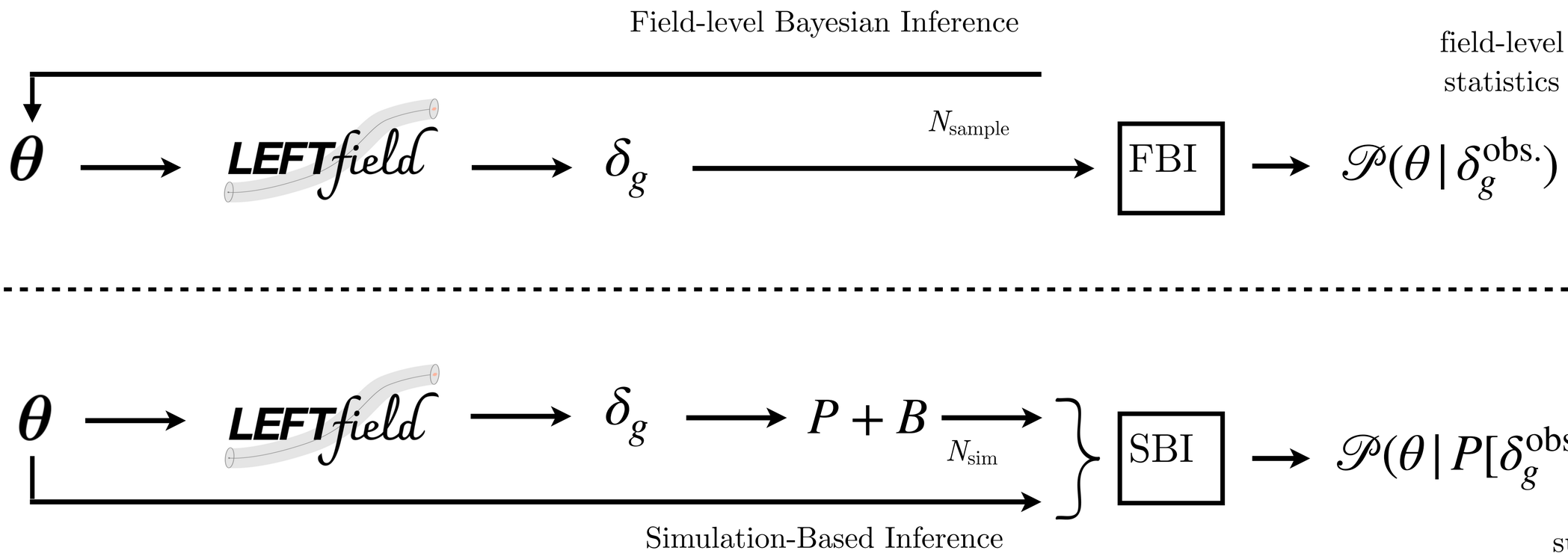
arXiv:2403.03220

Same data: exactly same δ_g Fourier modes

Same forward model: LEFTfield

$$\theta = [\sigma_8, \{b_O\}, \sigma_\epsilon]$$





MN+ 2024, Fig. 1

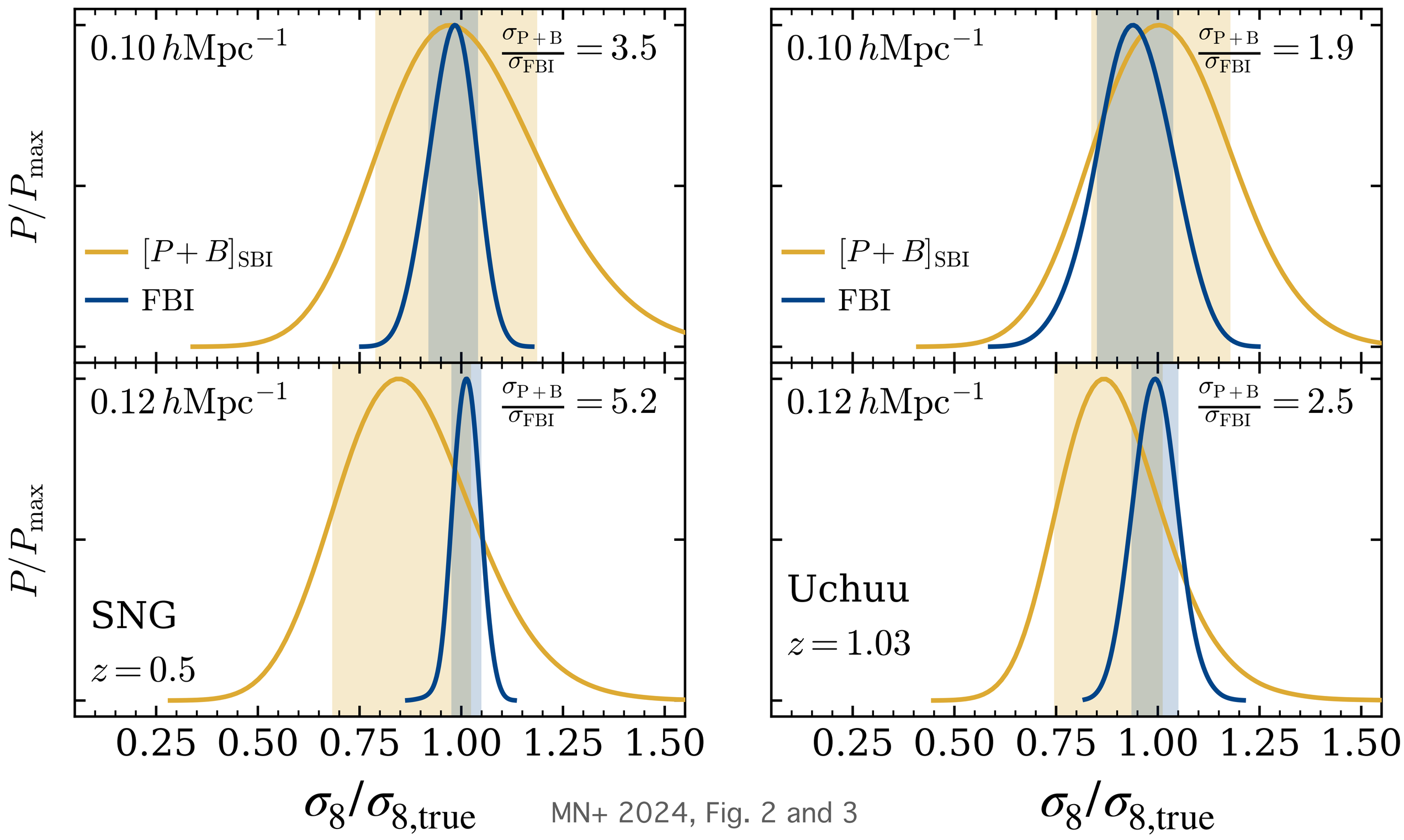
How much (robust) information can we gain?

σ_8 constraints from dark matter halos in rest frame (real space)

Results for

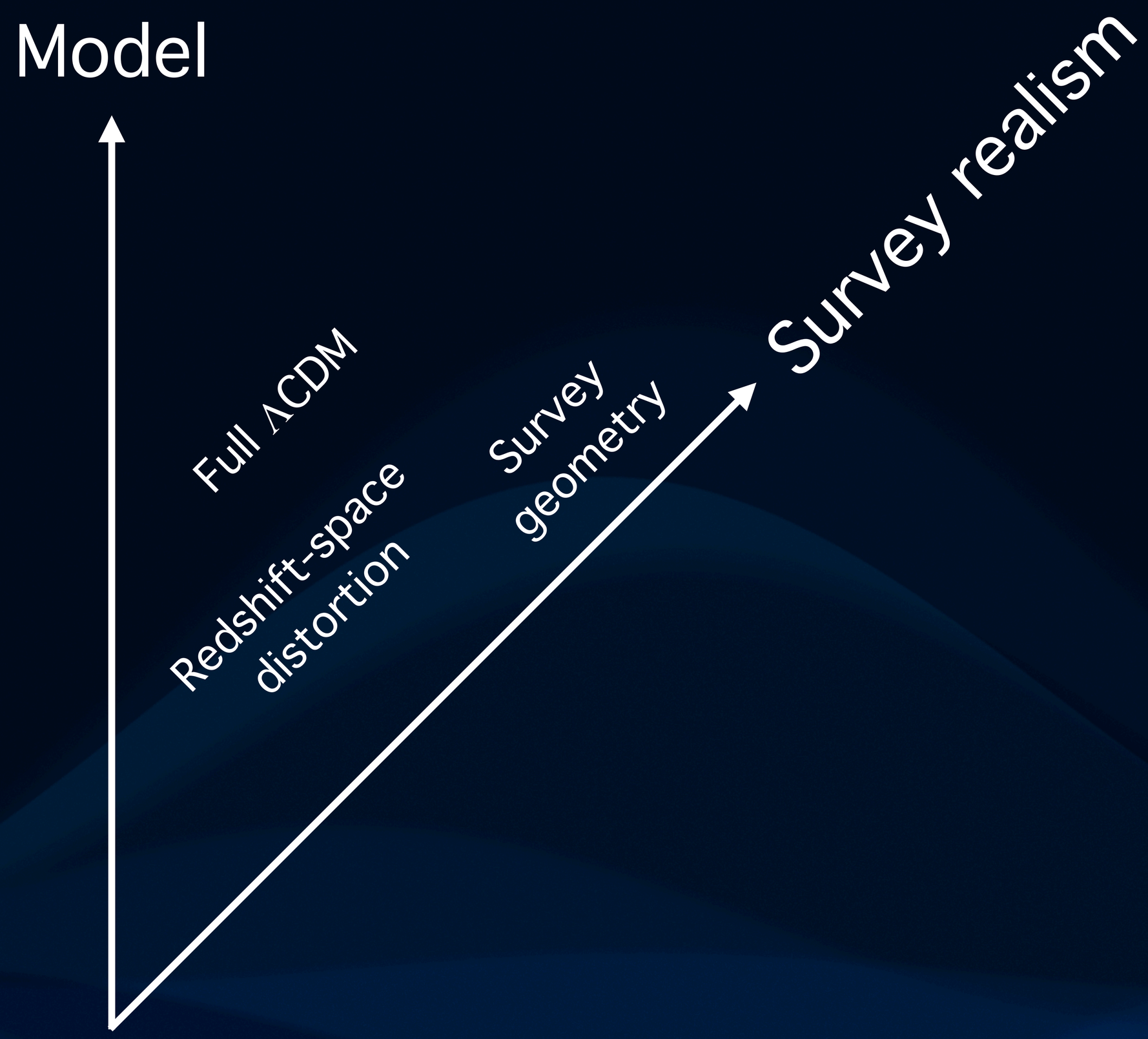
two different halo samples (cosmologies, redshifts, densities)

two different analysis cutoff scales ($k_{\rm max} = 0.1, 0.12\,h{\rm Mpc}^{-1}$)

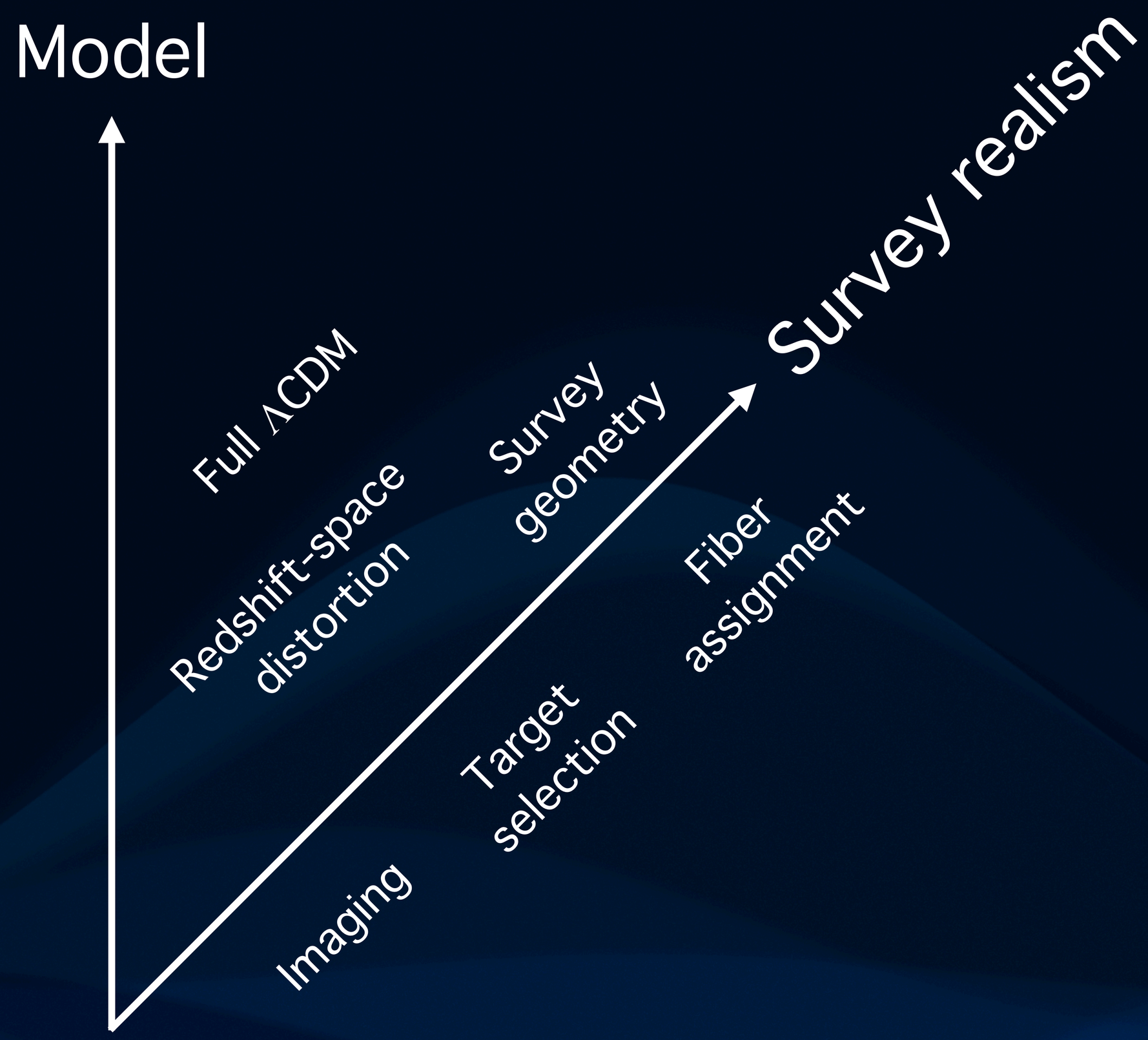


MN+ 2024, Fig. 2 and 3

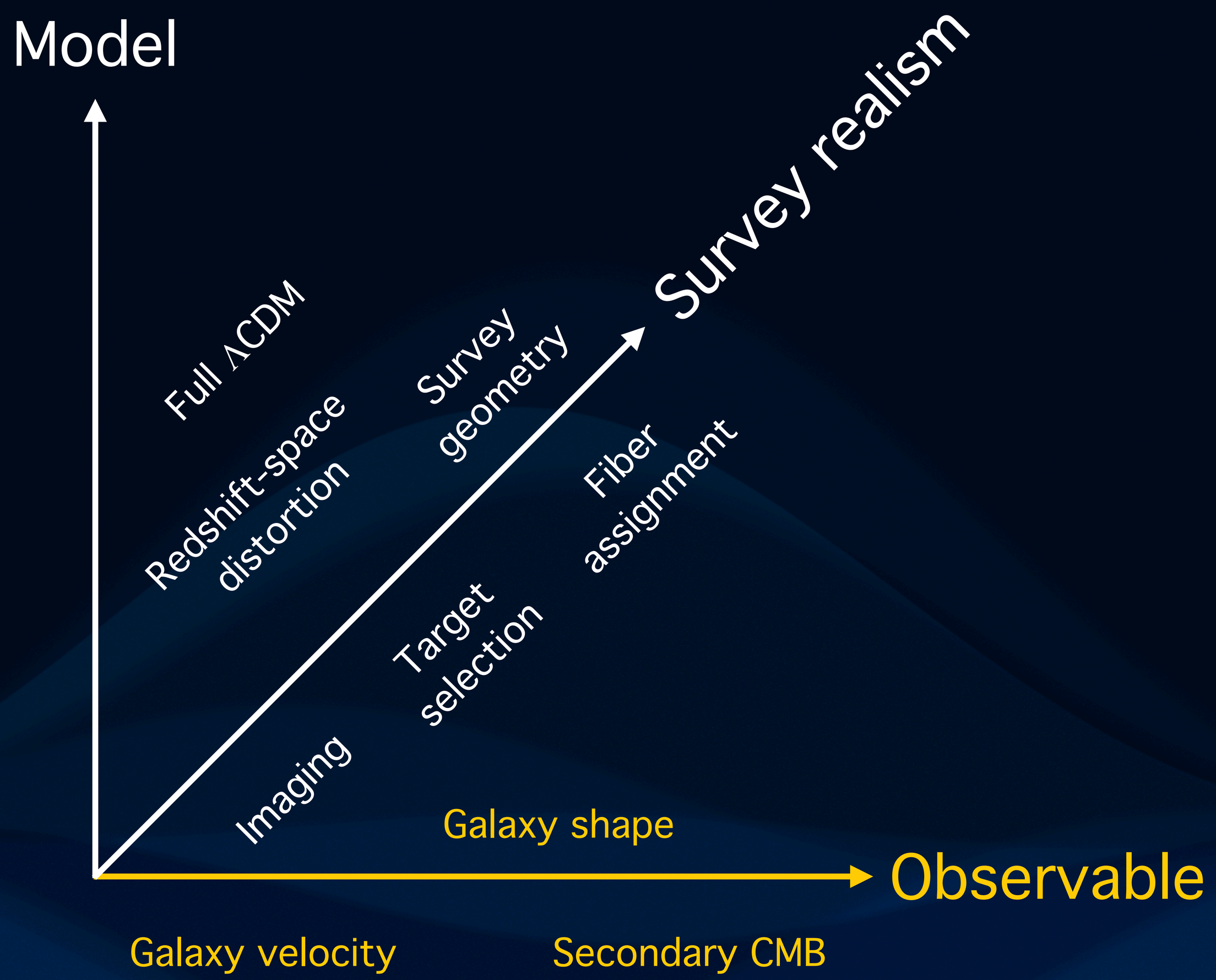
Outlook - Model



Outlook - Survey Realism



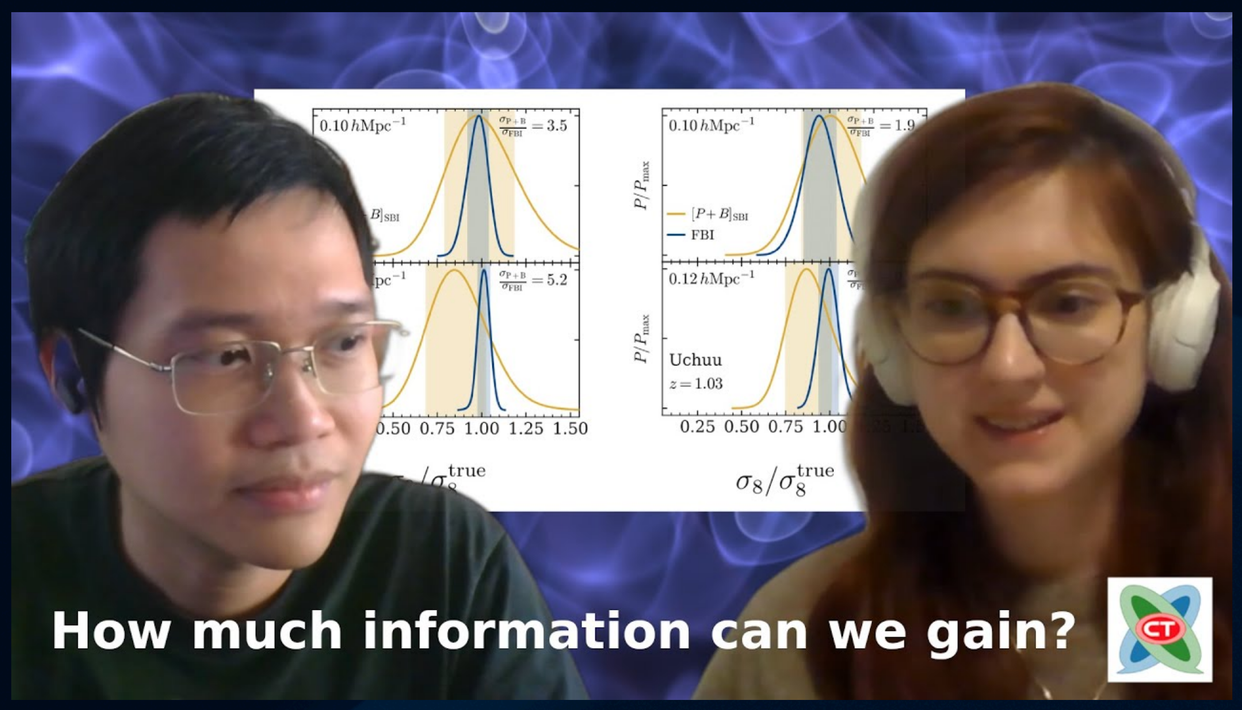
Outlook - Observable

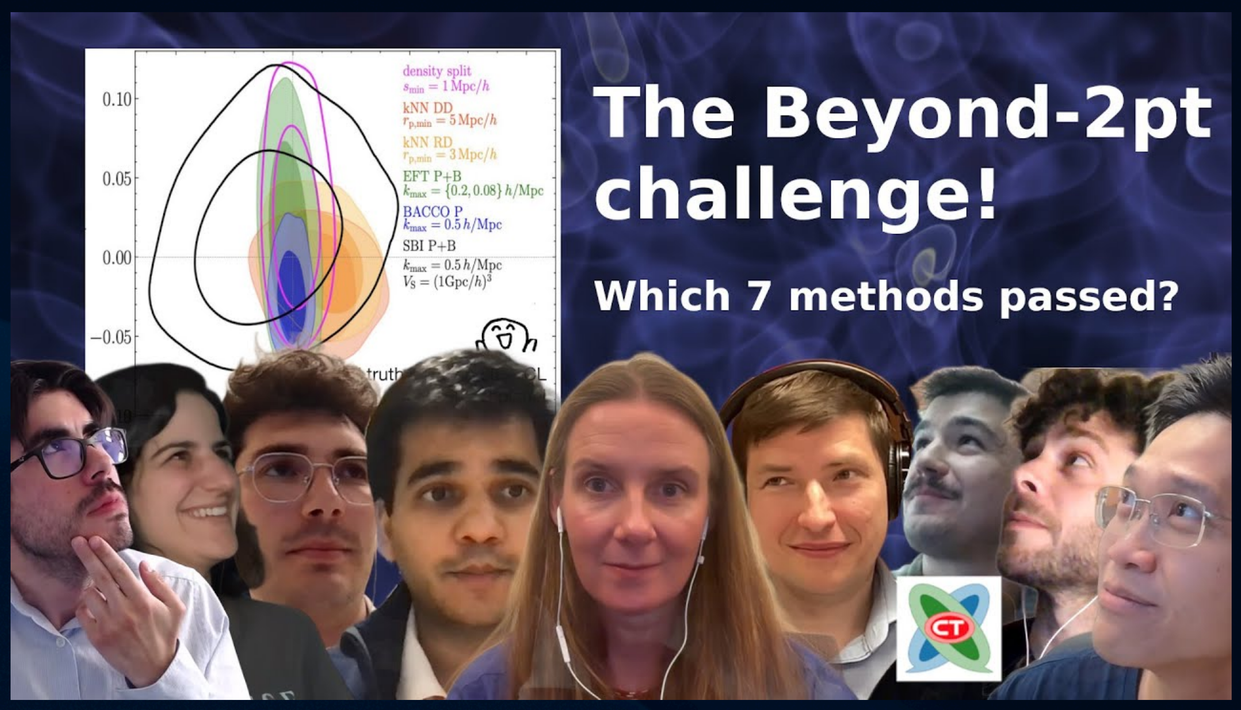


More info on Cosmology Talks

Thank you! Cảm ơn!

Please check out these Cosmology Talks interviews!





arXiv: 2403.03220

arXiv: 2405.02252

Questions?

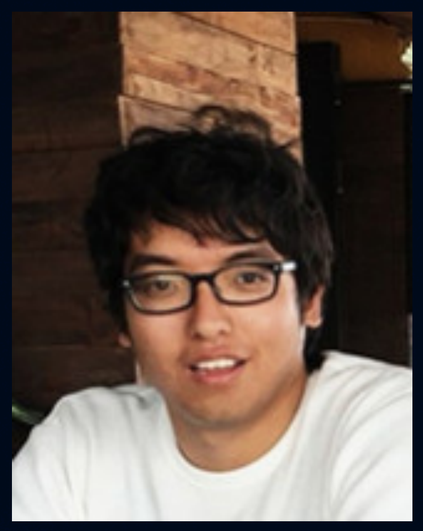
nguyenmn@umich.edu

UNIVERSITY OF MICHIGAN

A few more details...

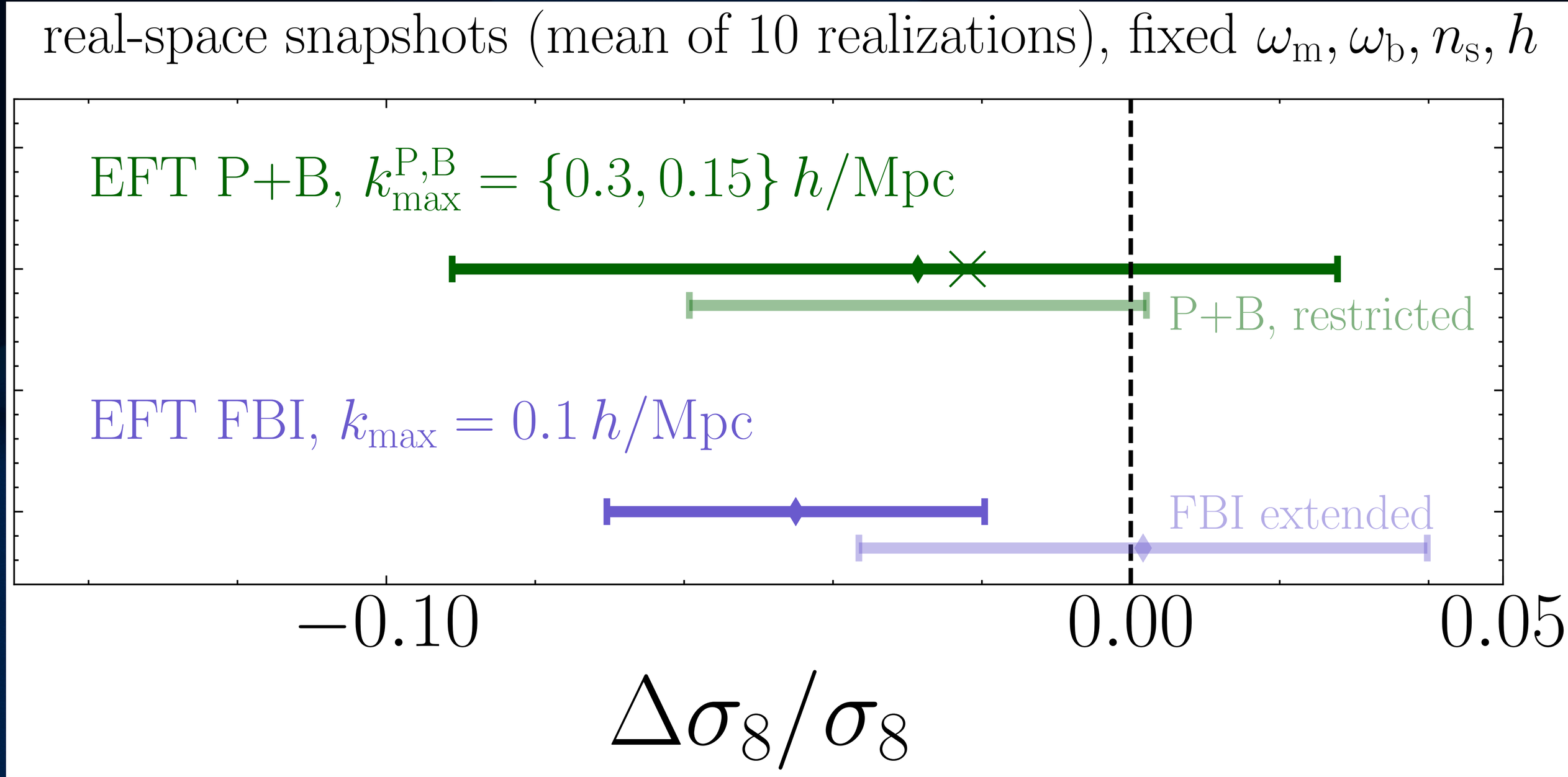
Beyond-2pt parameter-masked challenge

Blind challenge set up by



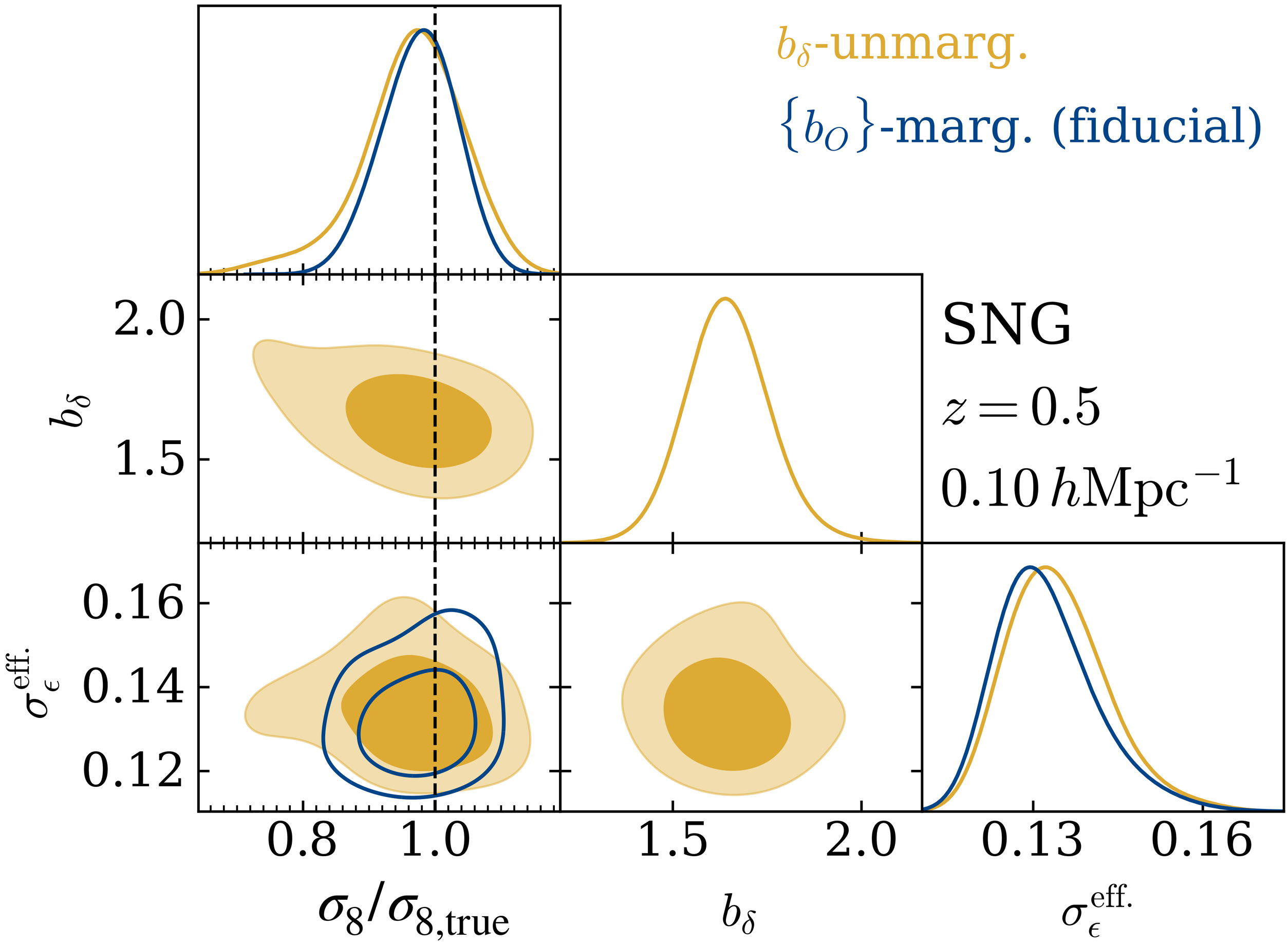
Yosuke Kobayashi Andrés N. Salcedo

FBI works on HOD galaxies and delivers competitive constraint



FBI - Breaking bias-σ_8 degeneracy

When left unmarginalized, linear bias b_δ is also well constrained

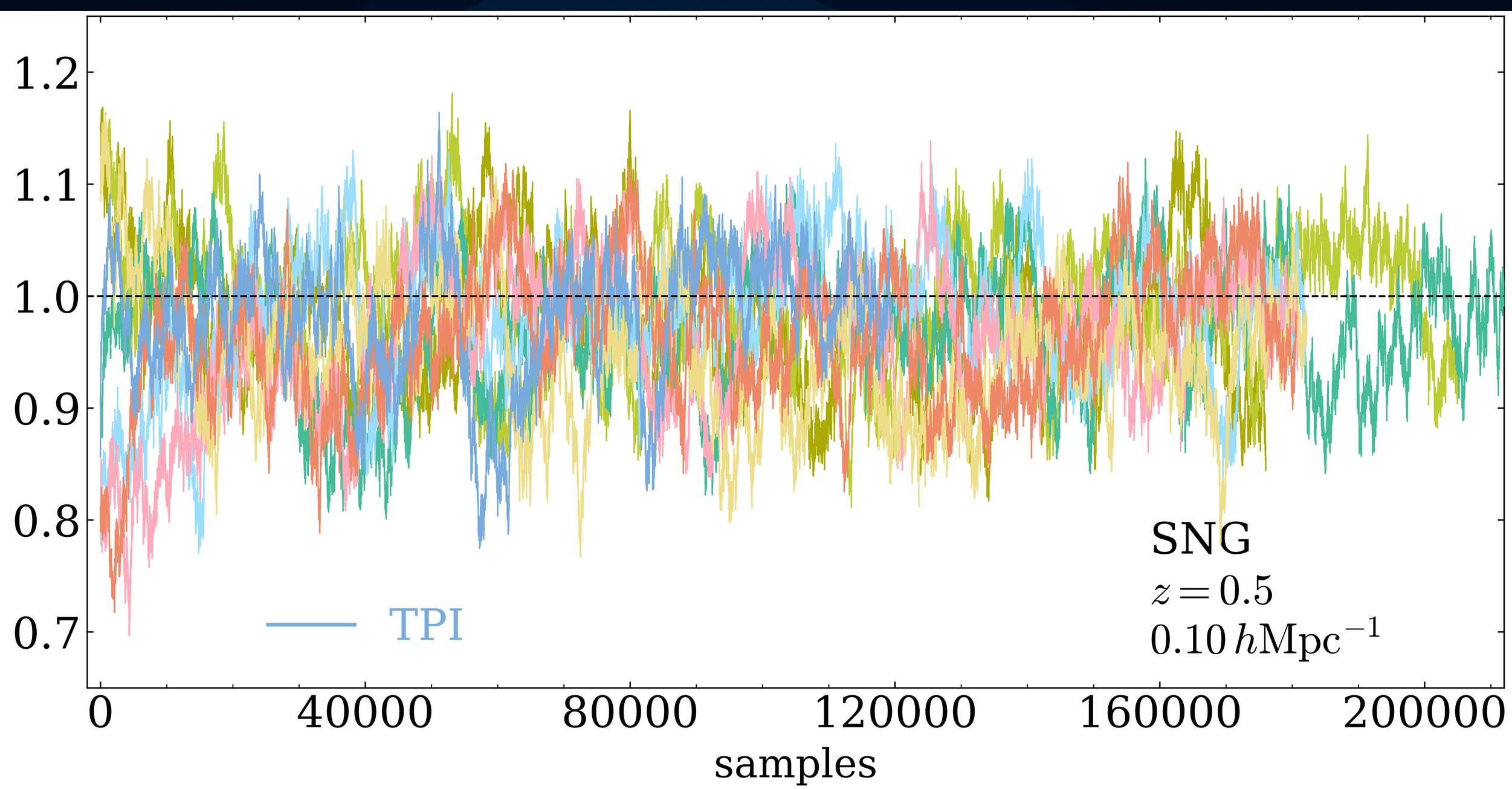


FBI - MCMC convergence

We run 4-10 MCMC chains for each FBI analyses

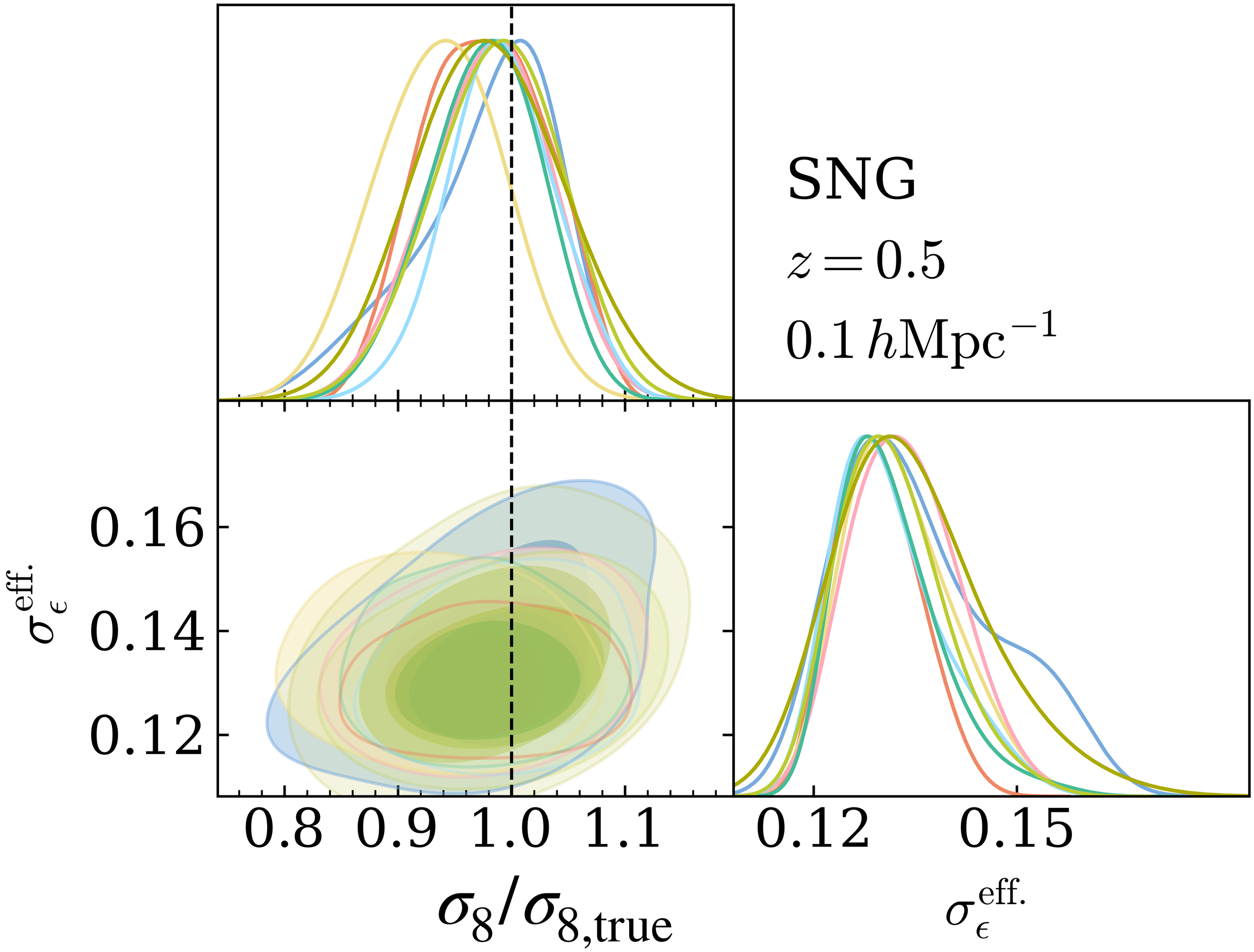
one start from the true initial conditions (TPI)

the rest start from random initial conditions



FBI - posterior consistency

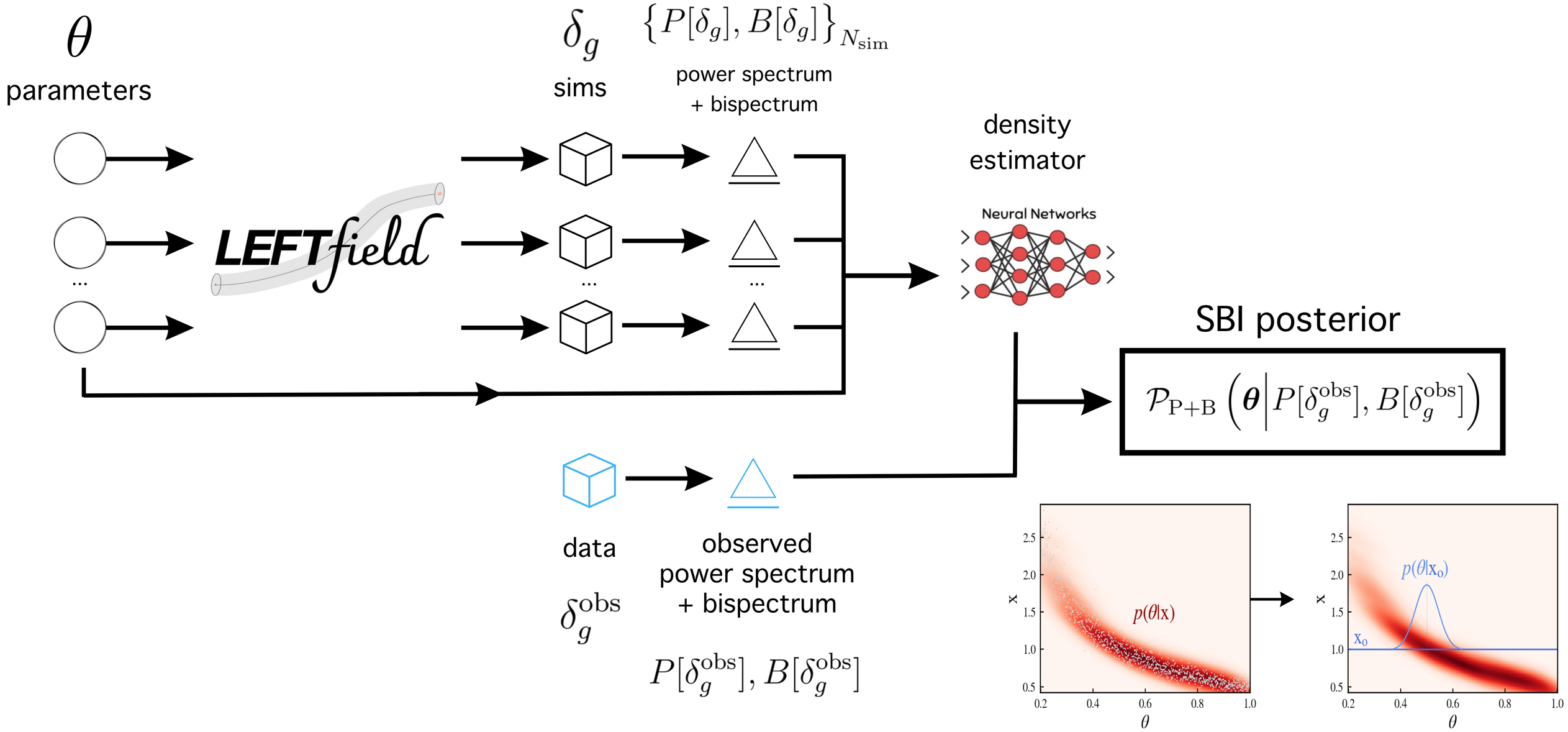
We check consistency between each chain before combining



Simulation-based Inference (SBI) P+B

We use SBI to estimate the posterior $P\left(\theta | P + B\right)$

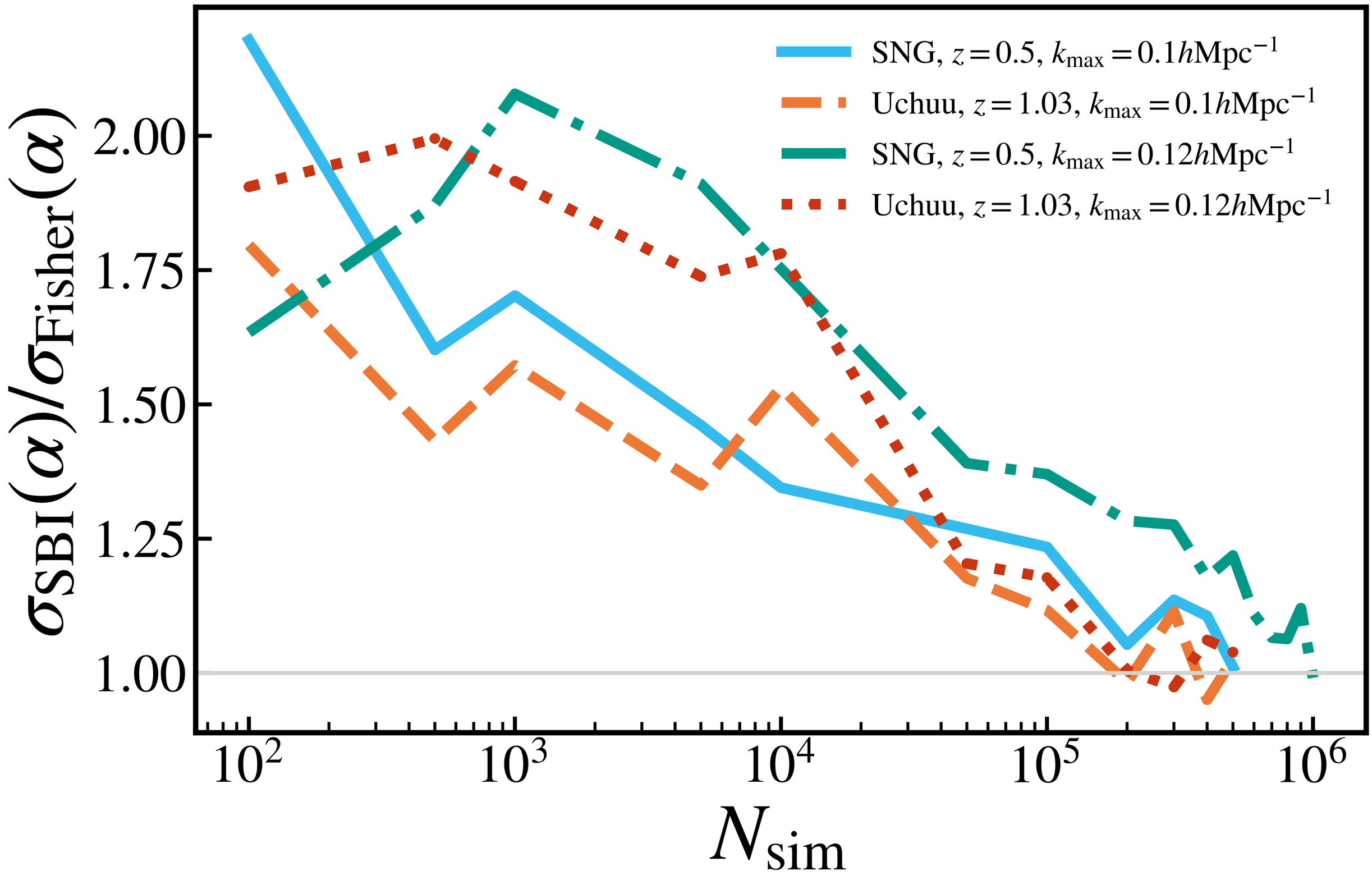
- LEFTfield to simulate data for training
- Normalizing flows to estimate the conditional density



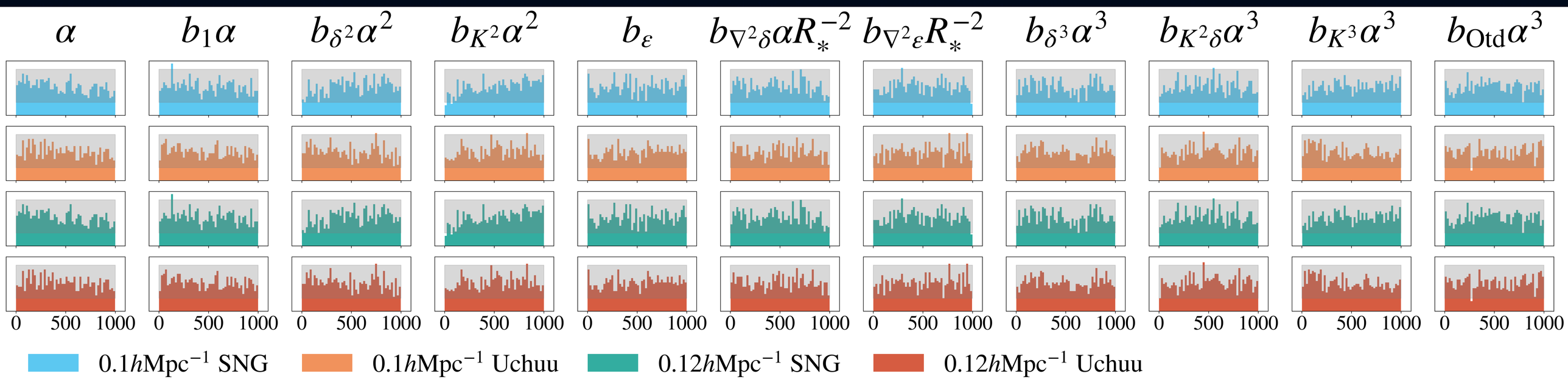
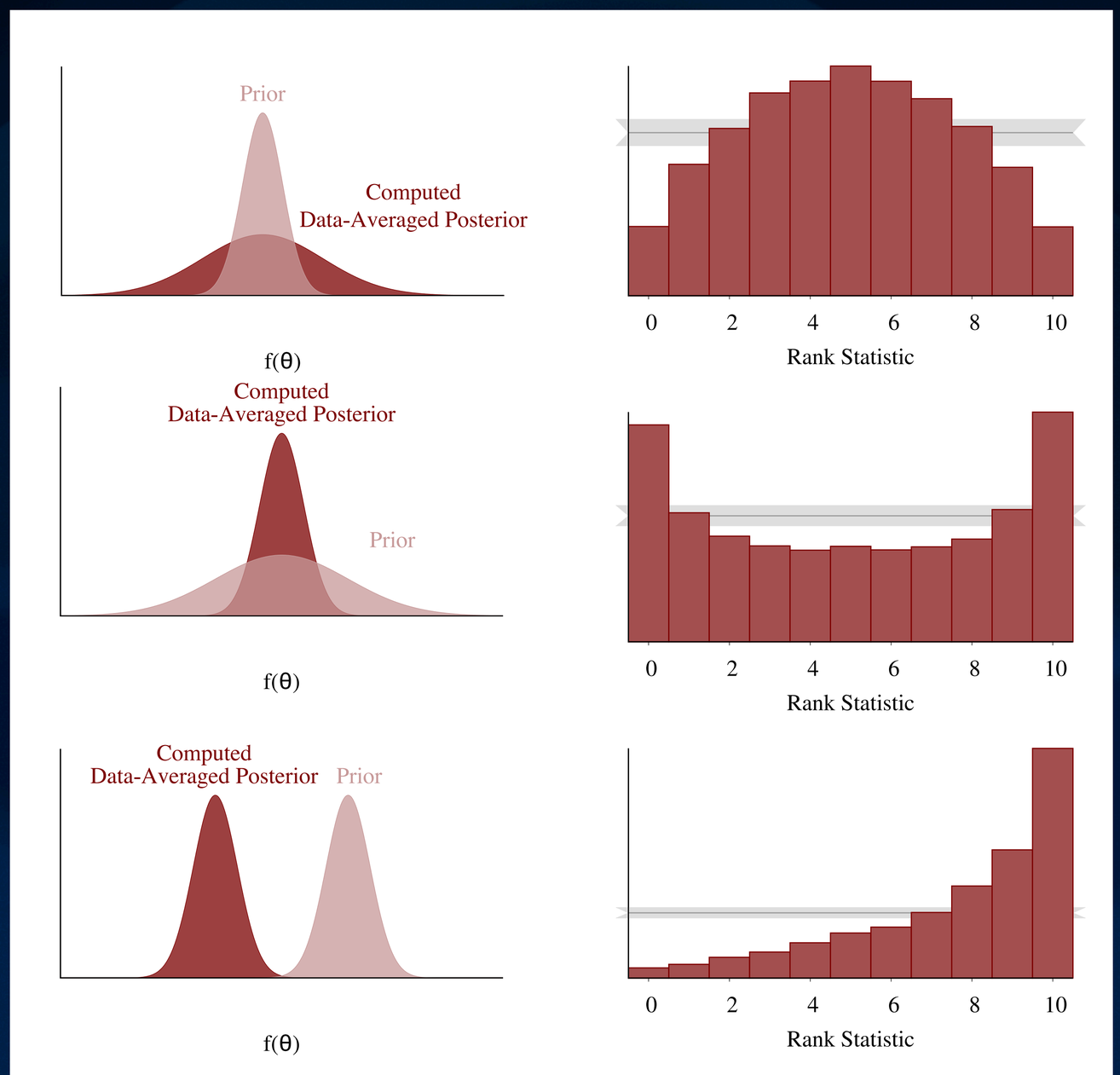
SBI P+B - Posterior convergence with $N_{\rm sim}$

All SBI posteriors converge to Fisher at the MAP

We check SBI errors vs Fisher (at the MAP) errors



SBI P+B - Posterior coverage test

Zero sign of posterior over- or under-estimation

$$\alpha = \sigma_8/\sigma_{8,\mathrm{true}}$$