Title: Searching for New Physics in the Late Universe With Millions of Galaxies in Millions of Dimensions - VIRTUAL ONLY

Speakers: Minh Nguyen

Series: Cosmology & Gravitation

Date: April 02, 2024 - 11:00 AM

URL: https://pirsa.org/24040073

Abstract: The growth of cosmic structures provides a bridge between observations and theories. In the first part of this talk, I will review the sigma8 tension between early- and late-time measurements of cosmic structure growth, and its physical implications. Are we seeing a chink in the standard cosmological model's armor? To unveil the origin of this tension (and possibly new physics in the late Universe), galaxy clustering and spectroscopic surveys will play an indispensable role. In the second part of the talk, I will introduce a novel framework to extract cosmological information from millions of galaxies in spectroscopic surveys, directly at the field level--i.e. the three-dimensional map level with millions of grid points. The goal is to achieve a percent-level constraint on sigma8 and growth of structure with stage-IV surveys like DESI. I will further discuss recent progress towards this goal, highlighting latest breakthroughs, results in a community data challenge, and remaining challenges.

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Zoom link

Searching for New Physics in the Late Universe

with millions of galaxies in millions of dimensions

Minh Nguyen - Leinweber Center for Theoretical Physics

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Perimeter Institute Cosmology Seminar — Arpril 2, 2024

UNIVERSITY OF MICHIGAN

About me

MPI für Astrophysik

Physical Cosmology

LCTP, U-M LSA Physics

Theoretical Cosmology

Kavli IPMU, Tokyo

Cosmology

Saigon, Vietnam

Birth —> College

Growth of Structure - σ_8 tension

Hints of new physics?

(arXiv: 2302.01331)

Growth of Structures and Density Fluctuations

Jessie Muir

Growth - Simulation

z = 15.00, Dark matter surface density

1000 Mpc

100 Mpc

FLAMINGO
Virgo Consortium
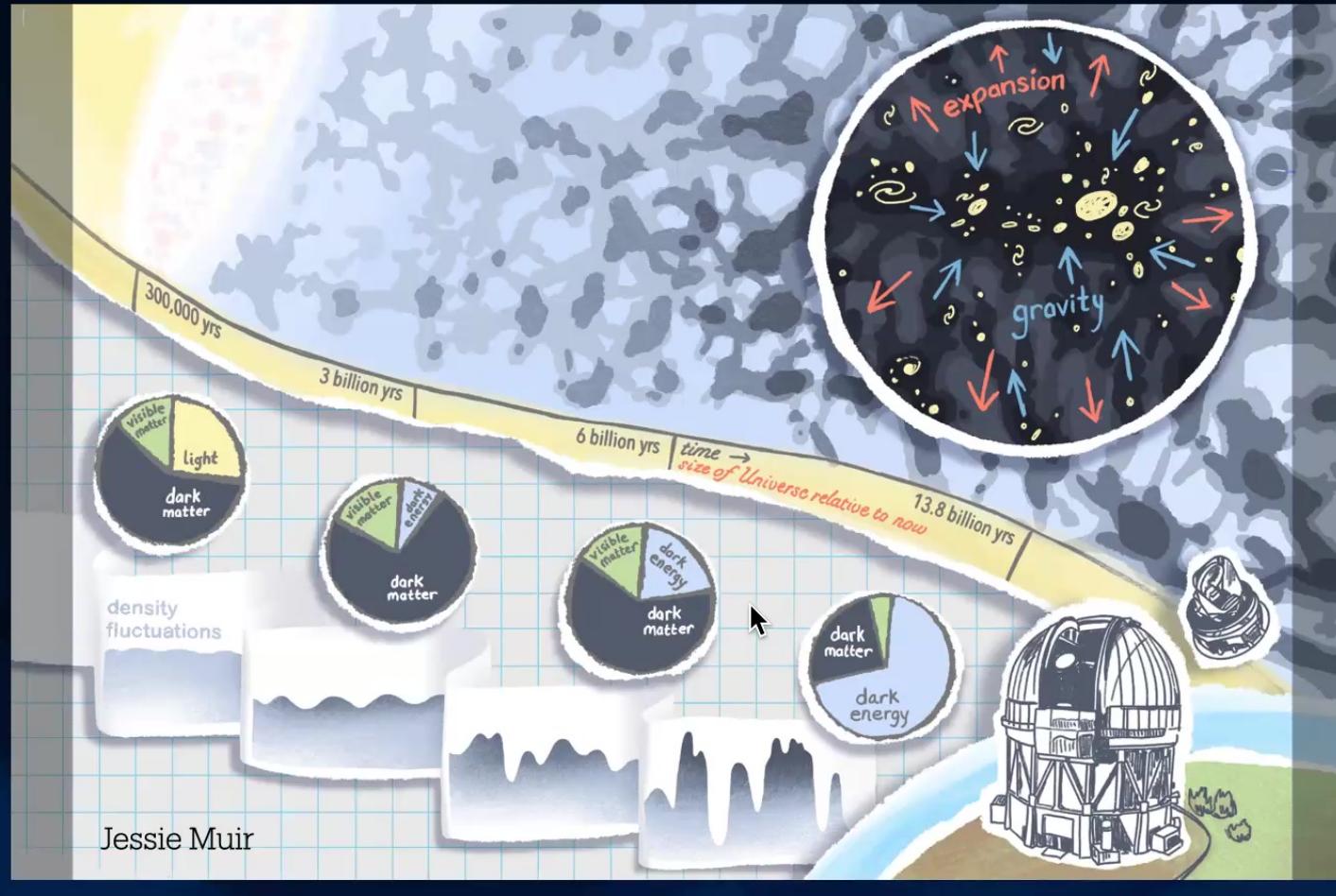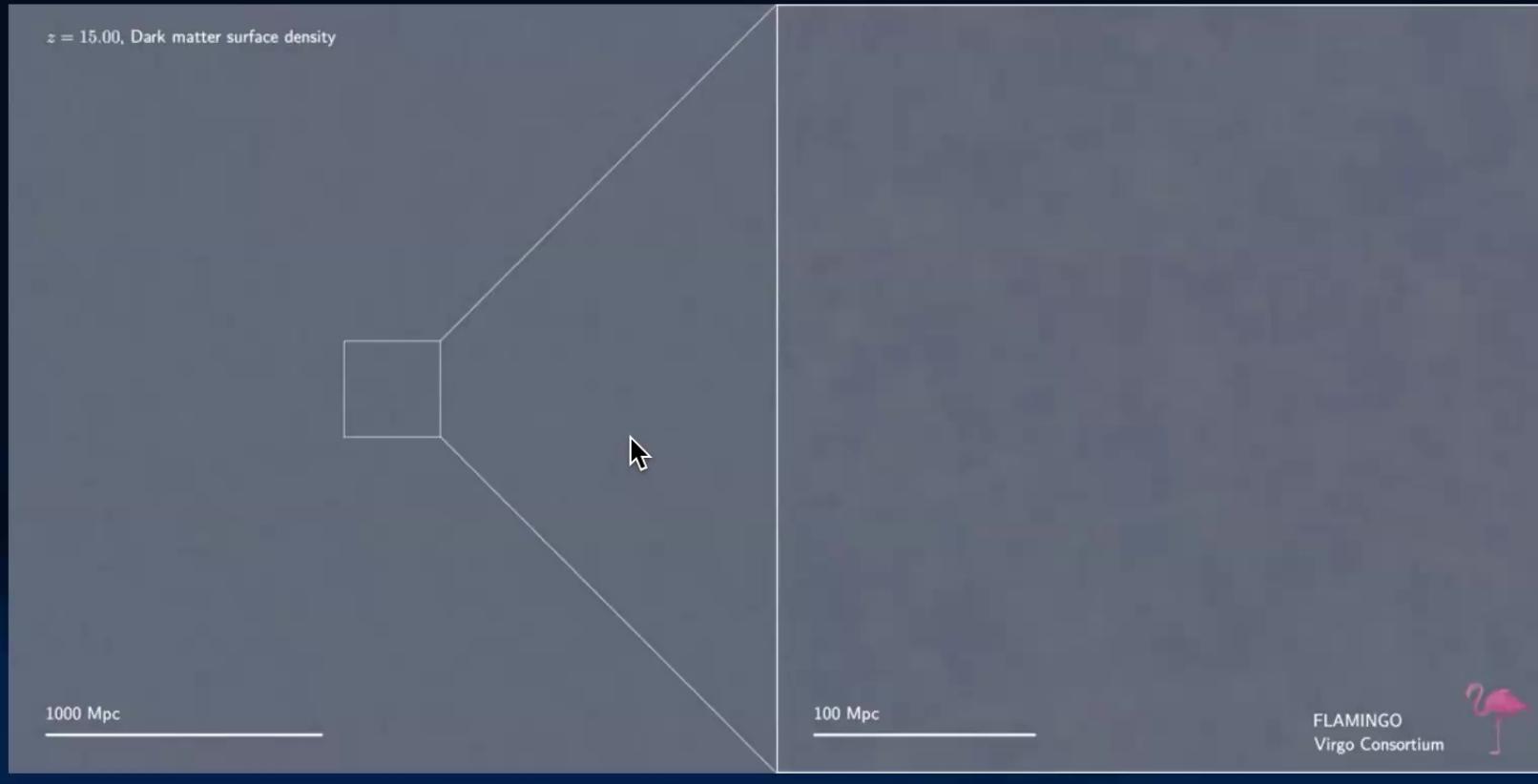
Growth - Linear Theory

Linear fluctuations $\delta(\mathbf{k}, z) \sim \mathcal{N}\left(0, \mathbf{C} = \mathrm{diag}\left[P_L(k, z)\right]\right)$


$z = 0.87$, Dark matter surface density

$$\delta(\mathbf{x}, z) = \frac{\rho(\mathbf{x}, z) - \langle\rho(\mathbf{x}, z)\rangle_{\mathbf{x}}}{\langle\rho(\mathbf{x}, z)\rangle_{\mathbf{x}}}$$

1000 Mpc
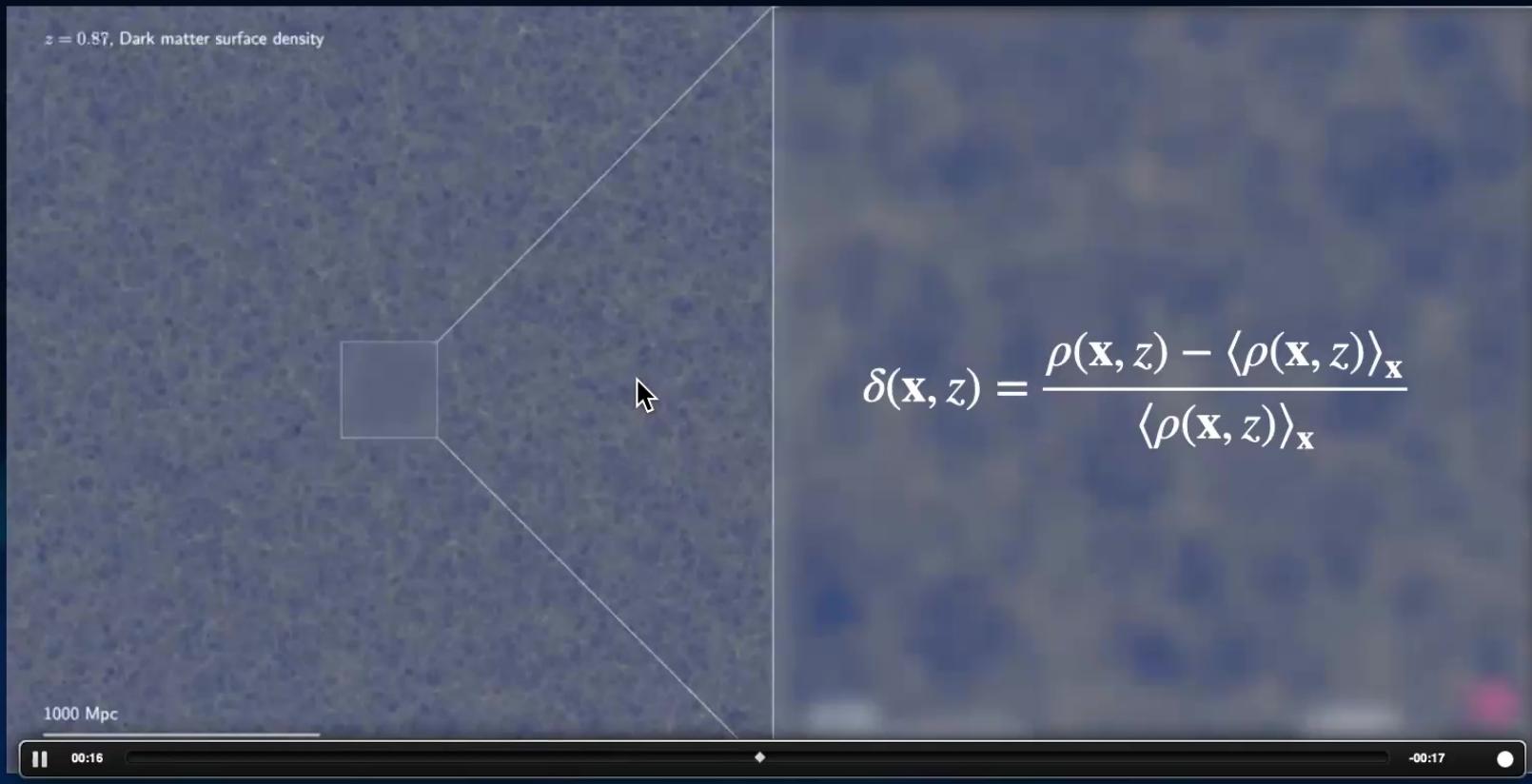
Growth - Extrapolation

Proxy for **today** growth

$$\sigma_8^2 = \frac{1}{2\pi^2} \int dk k^2 \, P_L(k, z=0) \, W_{R=8h^{-1}\mathrm{Mpc}}^2(k)$$

extrapolated

from

snapshots of large-scale structure
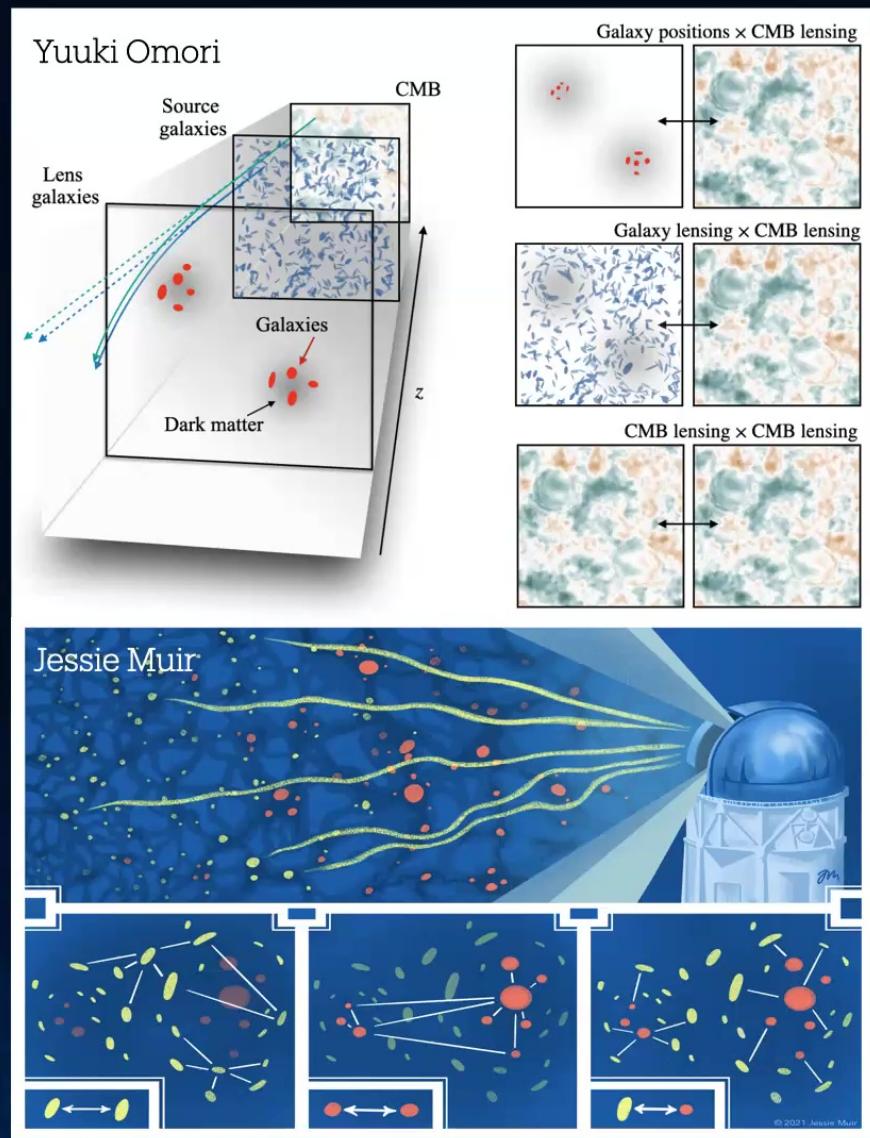
Early Universe

Early-time probes of growth

Cosmic Microwave Background
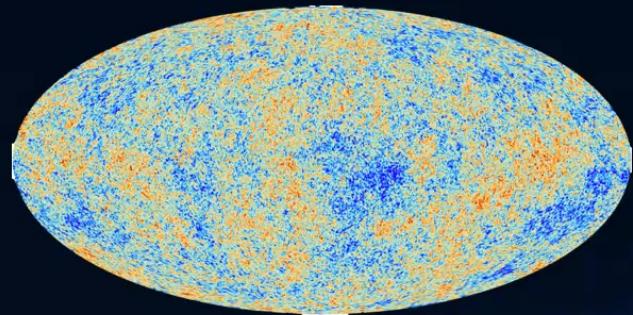
Planck PR3 temperature map

## CMB weak gravitational lensing
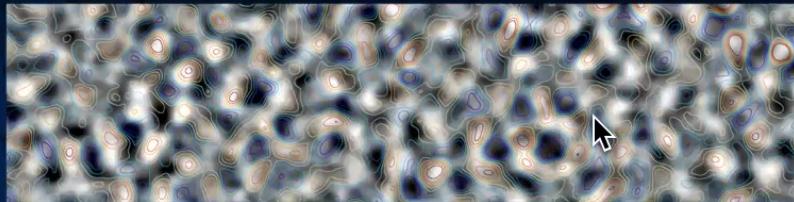
ACT DR6 CMB lensing mass map

CMB lensing —> smoothing
$A_L = 0 \rightarrow 8$

Credit: Duncan Hanson

Madhavacheril+ 2024
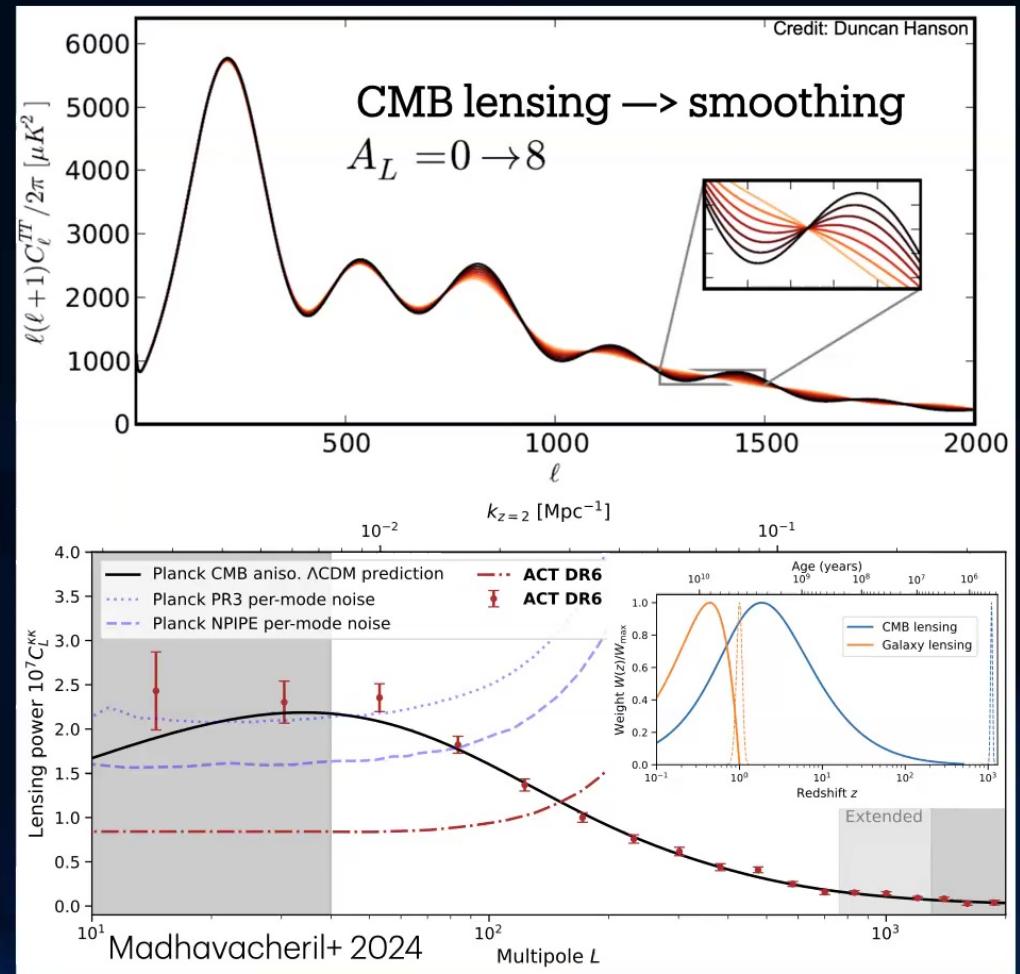
Late Universe

Late-time probes of growth
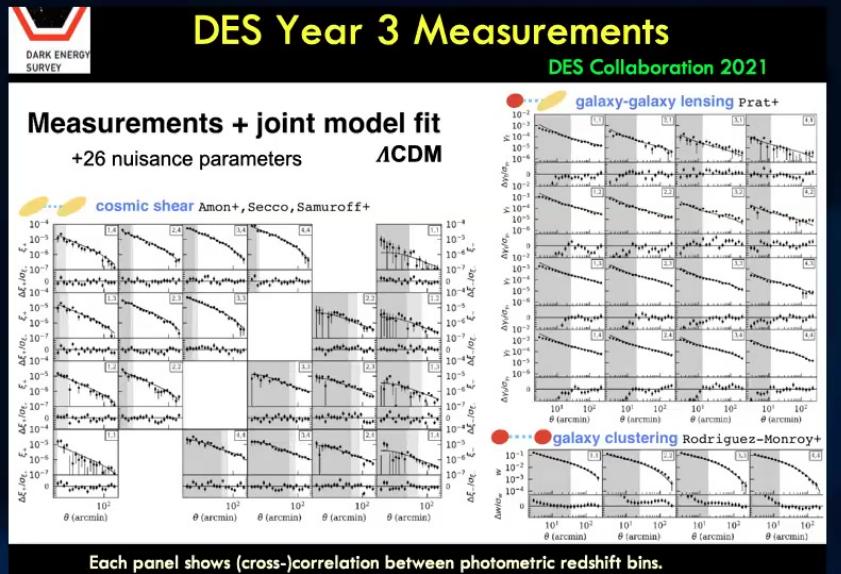
**Galaxy photometric 3x2-point correlation (intermediate-late Universe)**

Galaxy clustering (late Universe)
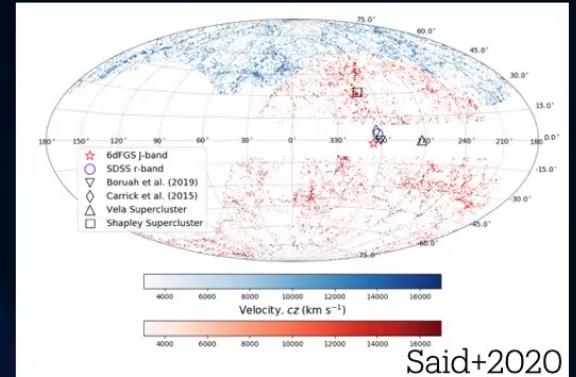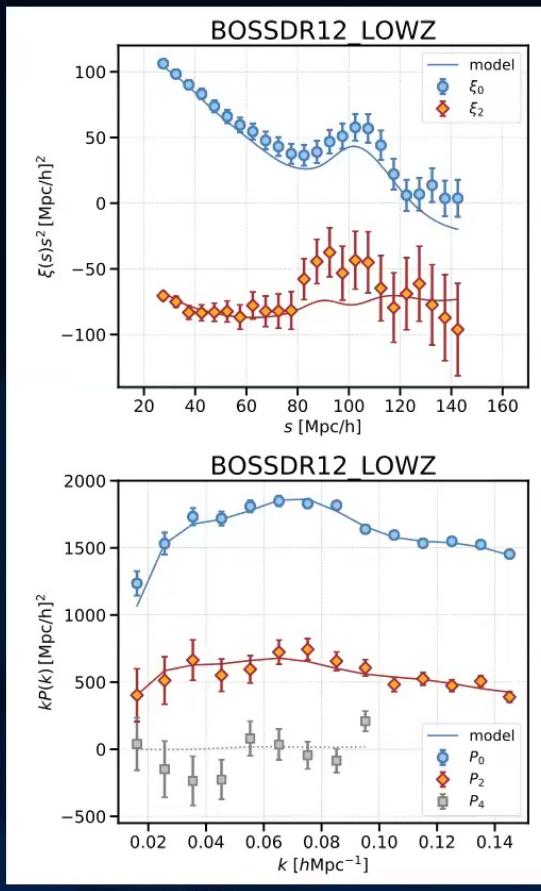
Galaxy peculiar velocity (very late Universe)

Said+2020

Early- vs Late-time tension?

Discrepancy between
early- and late-time
~~measurements?~~

extrapolations

within ΛCDM.

Lange+ 2023

$S_8 = \sigma_8 \sqrt{\Omega_{m,0}/0.3}$
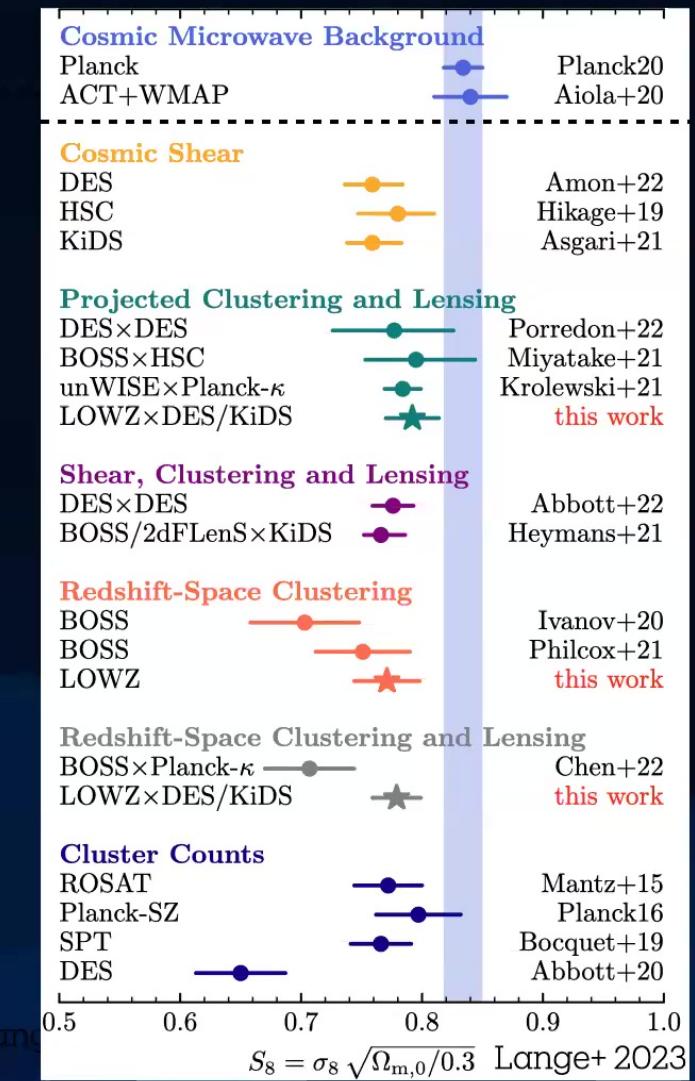
Late-time growth suppression?

$3.7\sigma - 4.2\sigma$ evidence

1. Parametrize growth rate to separate growth-expansion

$$f(a) \equiv \frac{dlnD}{dlna} = \Omega_m(a)^{\gamma}$$

2. Integrate to get growth factor

$$D(a) = \exp\left[\int_1^a d\ln a\, \Omega_m^{\gamma}(a)\right]$$

3. Rescale matter power spectrum

$$P_L(k, a) = P_{L,\text{today}}(k, a = 1)\, D^2(a)$$

Legend:
- $f\sigma_8$+PL18+DESY1+BAO (solid purple)
- $f\sigma_8$+PL18 4.2σ (red dashed)
- $f\sigma_8$+DESY1+BAO (blue dashed)
- PL18+DESY1+BAO (green dashed)

ΛCDM

High γ ~ suppressed $f\sigma_8$

Nguyen, Huterer, Wen (2023)

γ
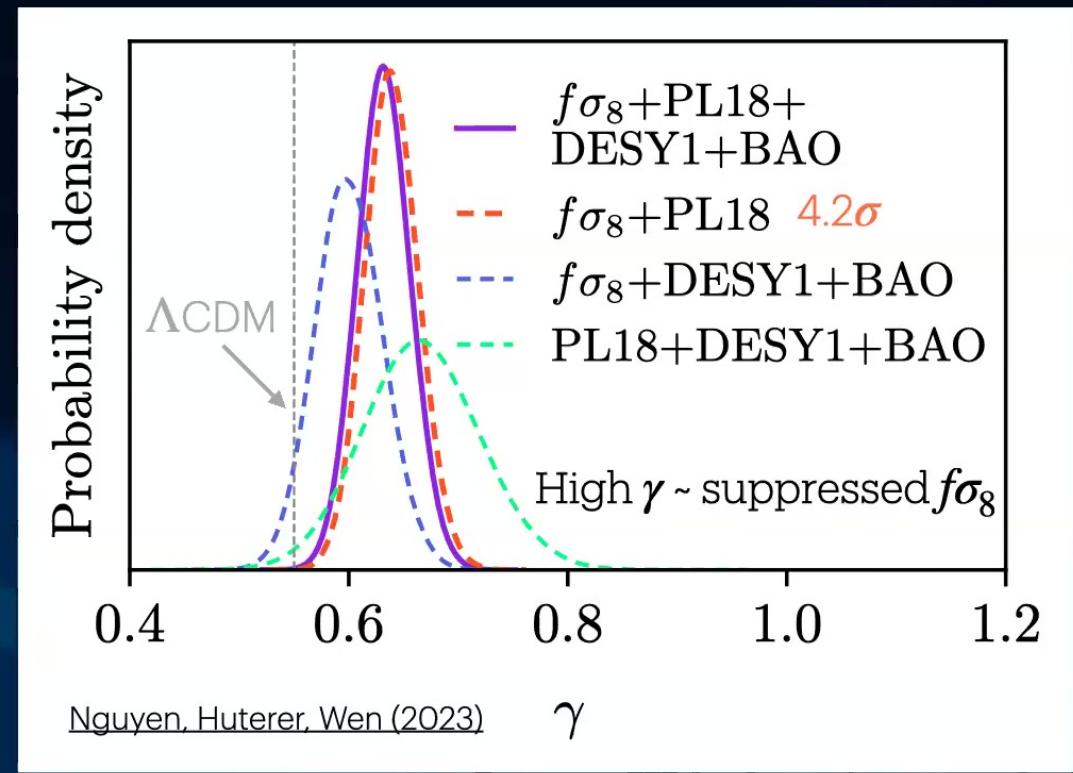
Reception - Public vs Expert

S_8 tension - a manifestation?

Nguyen, Huterer, Wen (2023)
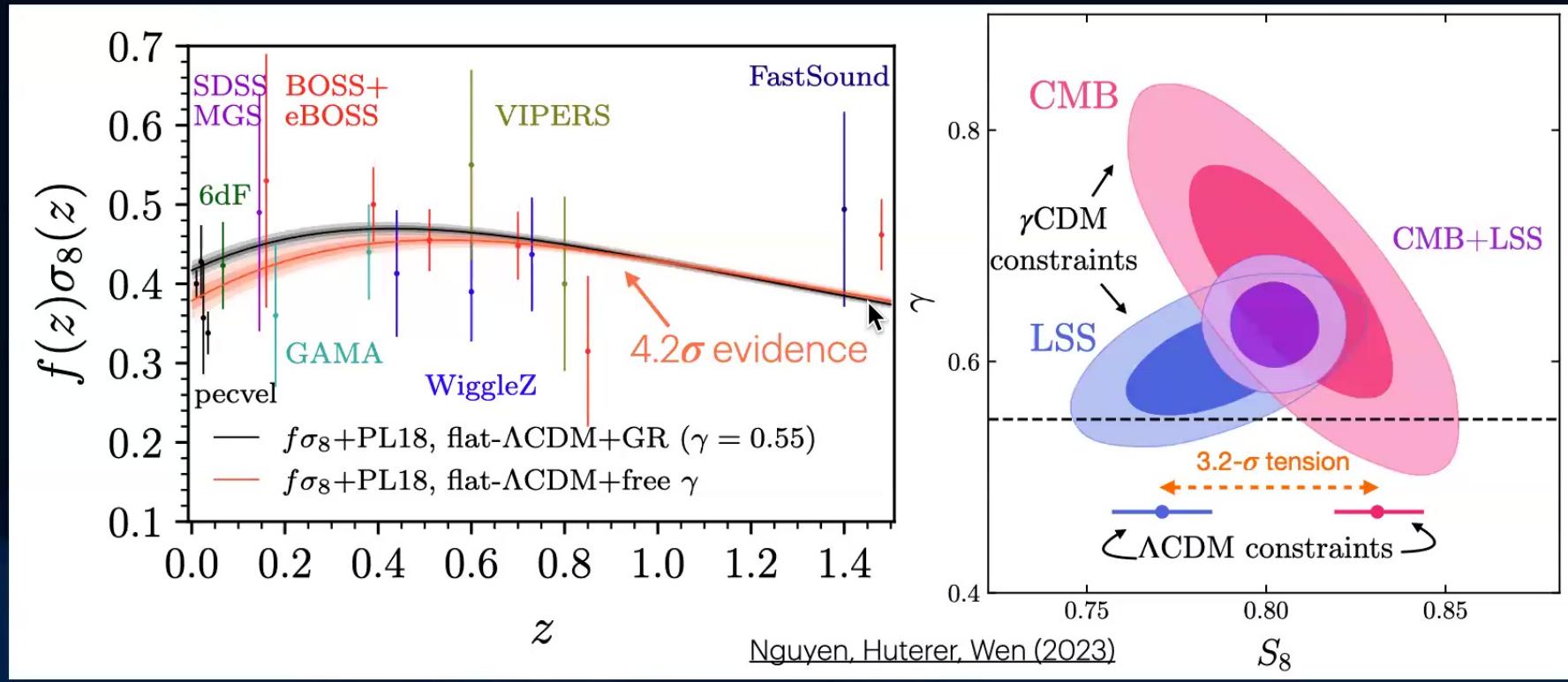
Planck Ω_k preference - another manifestation?

Nguyen, Huterer, Wen (2023)
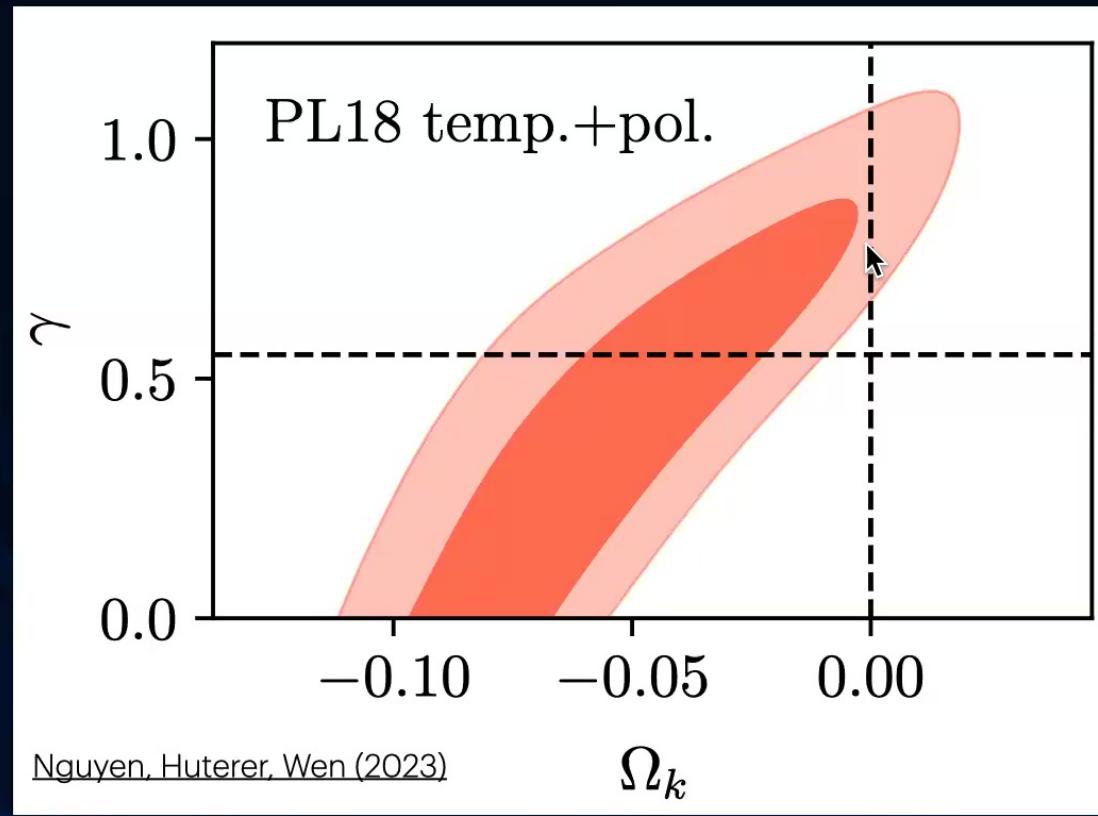
New physics or systematics?
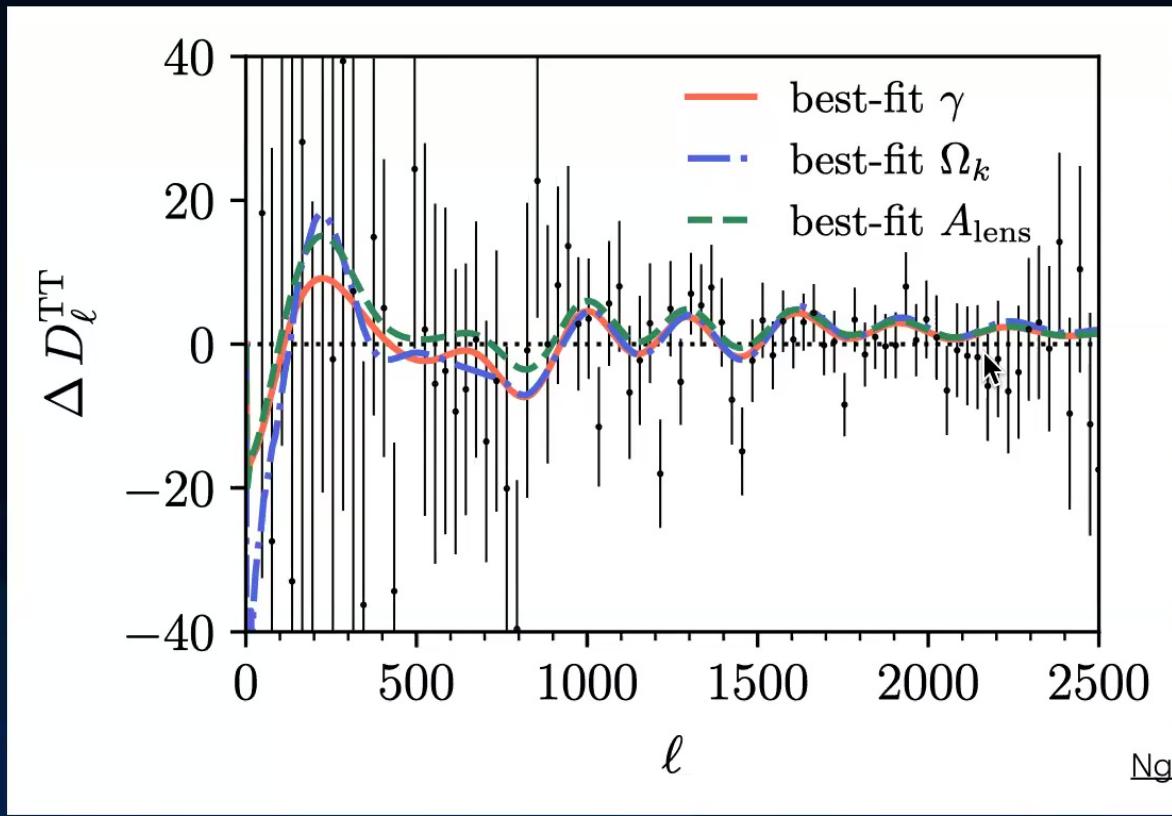
Early- vs Late-time or Large vs Small-scale?

Galaxy clustering to the rescue

1. New properties of DE, e.g. DM-DE
2. Modified gravity
3. Self-interacting/Decaying DM
4. Ultralight axions
5. Baryonic feedback?
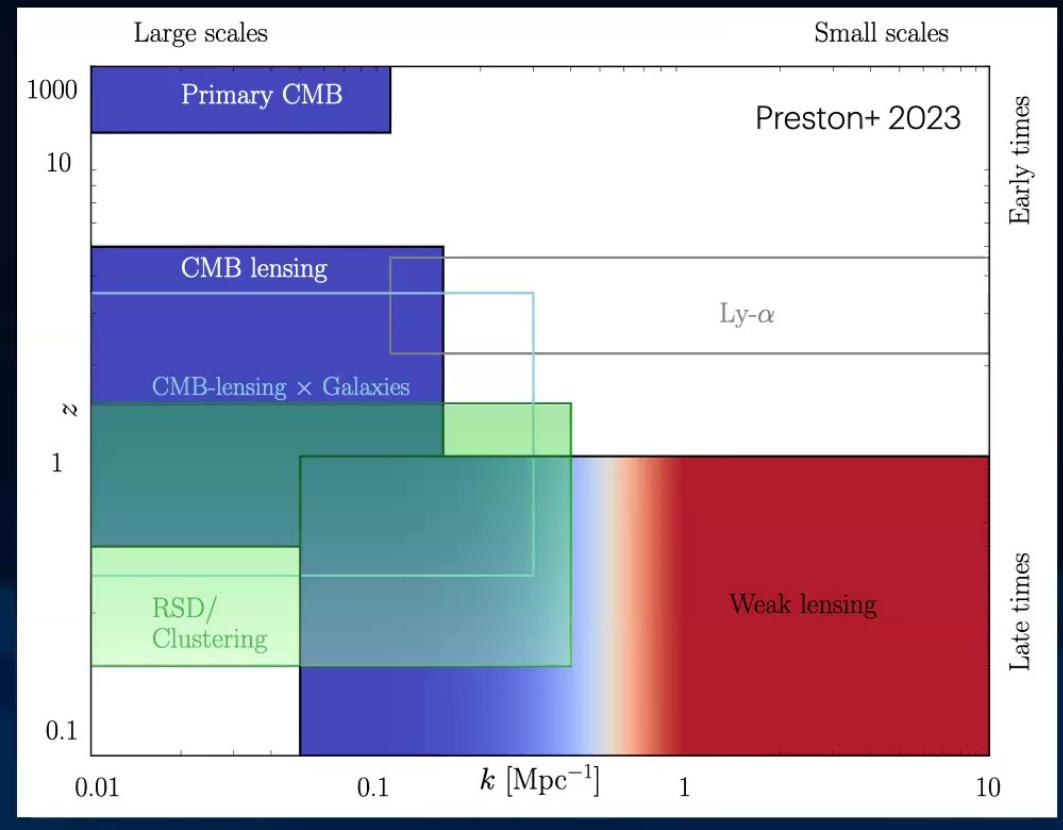
Squeezing σ_8 from Galaxy Clustering

Field-level Bayesian Inference (FBI) in millions of dimensions

(arXiv: 2403.03220)

$b_\delta - \sigma_8$ degeneracy in linear galaxy clustering

$$P_{\delta_g}(k, z) \sim b_\delta^2(z) \, P_L(k, z)$$
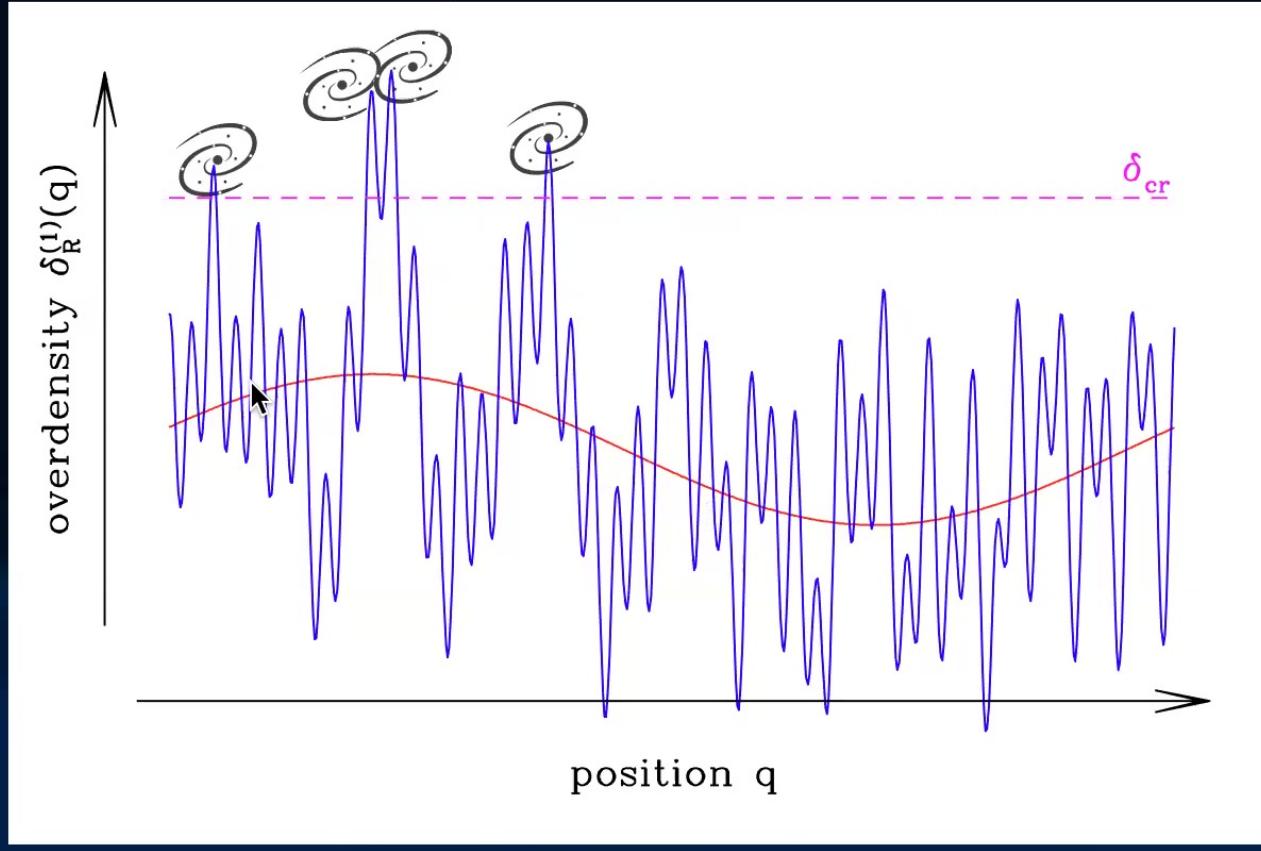
Breaking degeneracy with nonlinear clustering
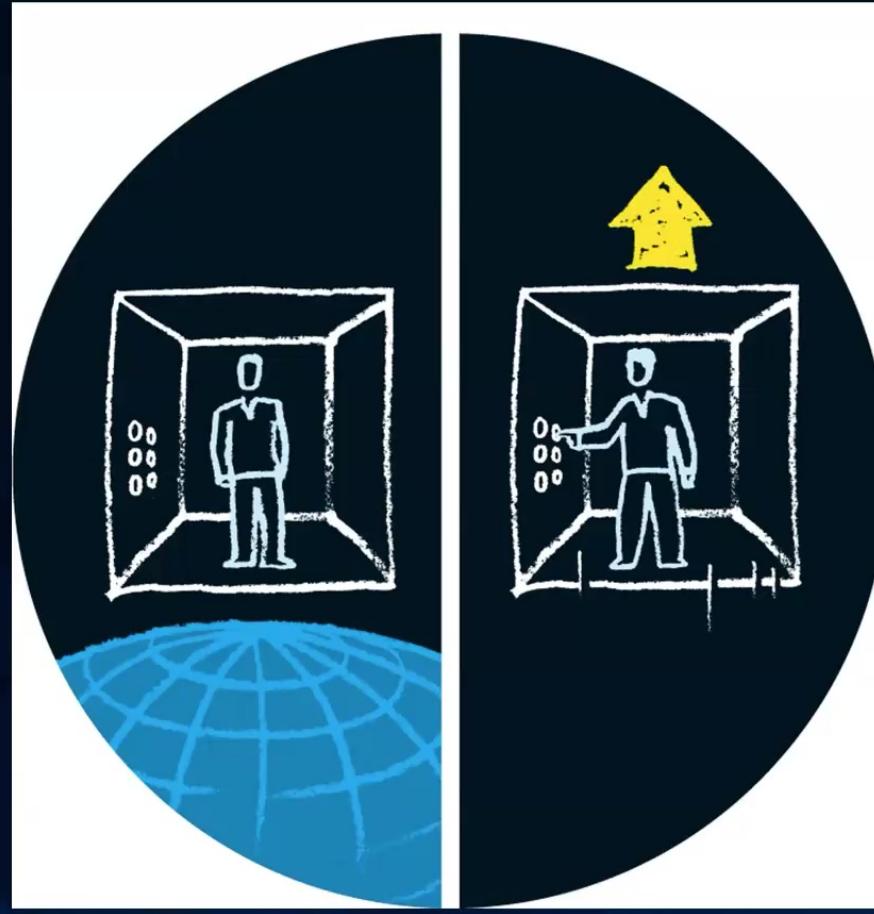
Breaking degeneracy with nonlinear clustering

$$\delta_g = b_1 \delta^{(1)} \sim b_1 \sigma_8$$

$$\delta^{(1)} \rightarrow \delta = \delta^{(1)} + \delta^{(2)} + \mathcal{O}\left(\delta^3\right)$$

$$\delta^{(2)} = \frac{17}{21}\left[\delta^{(1)}\right]^2 + \frac{2}{7}\left[K_{ij}^{(1)}\right]^2 - s_{(1)}^i \partial_i \delta^{(1)}$$

$$s_{(1)} = -\frac{\nabla}{\nabla^2}\delta^{(1)}$$

How much information exists beyond 2-point function?
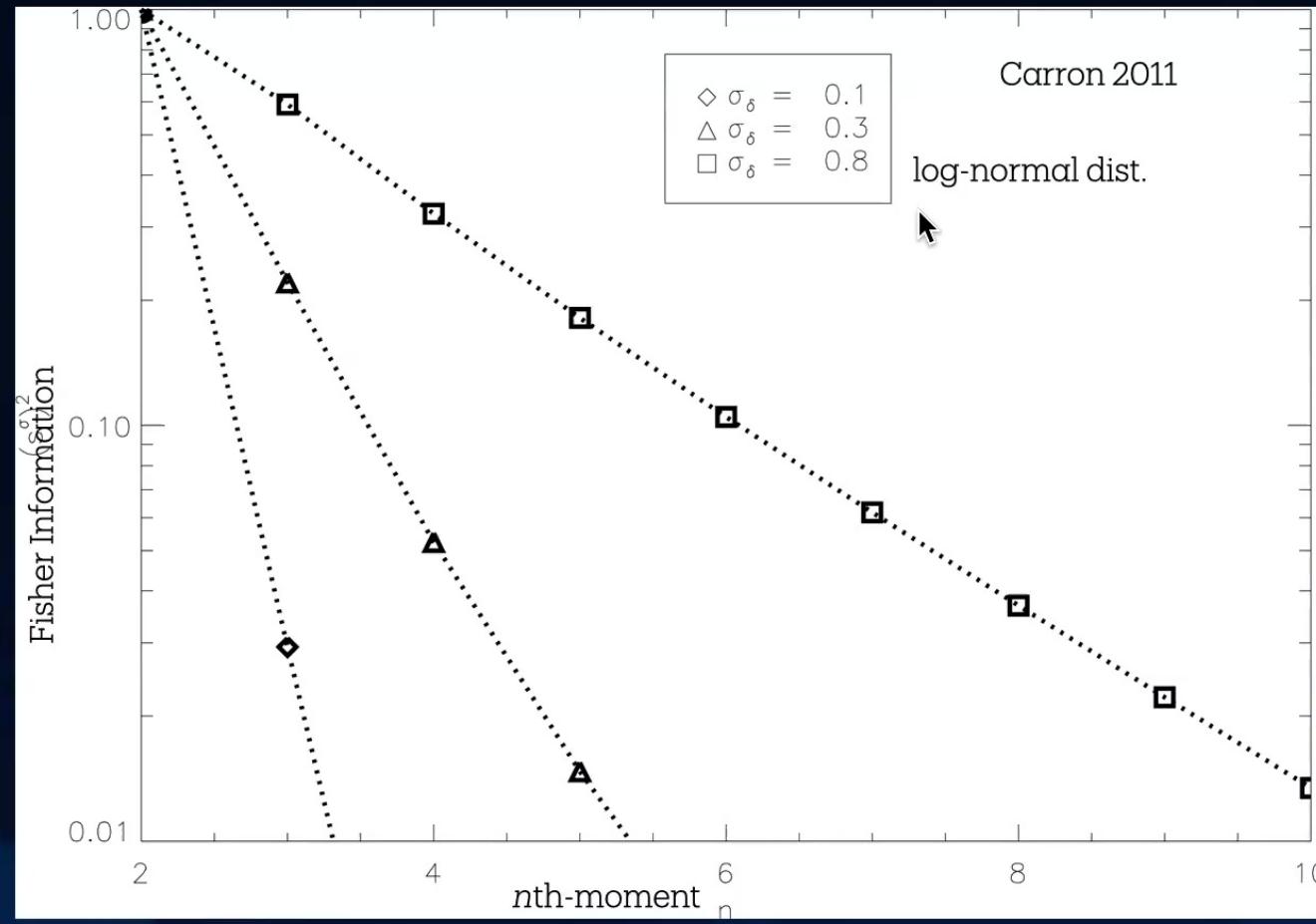
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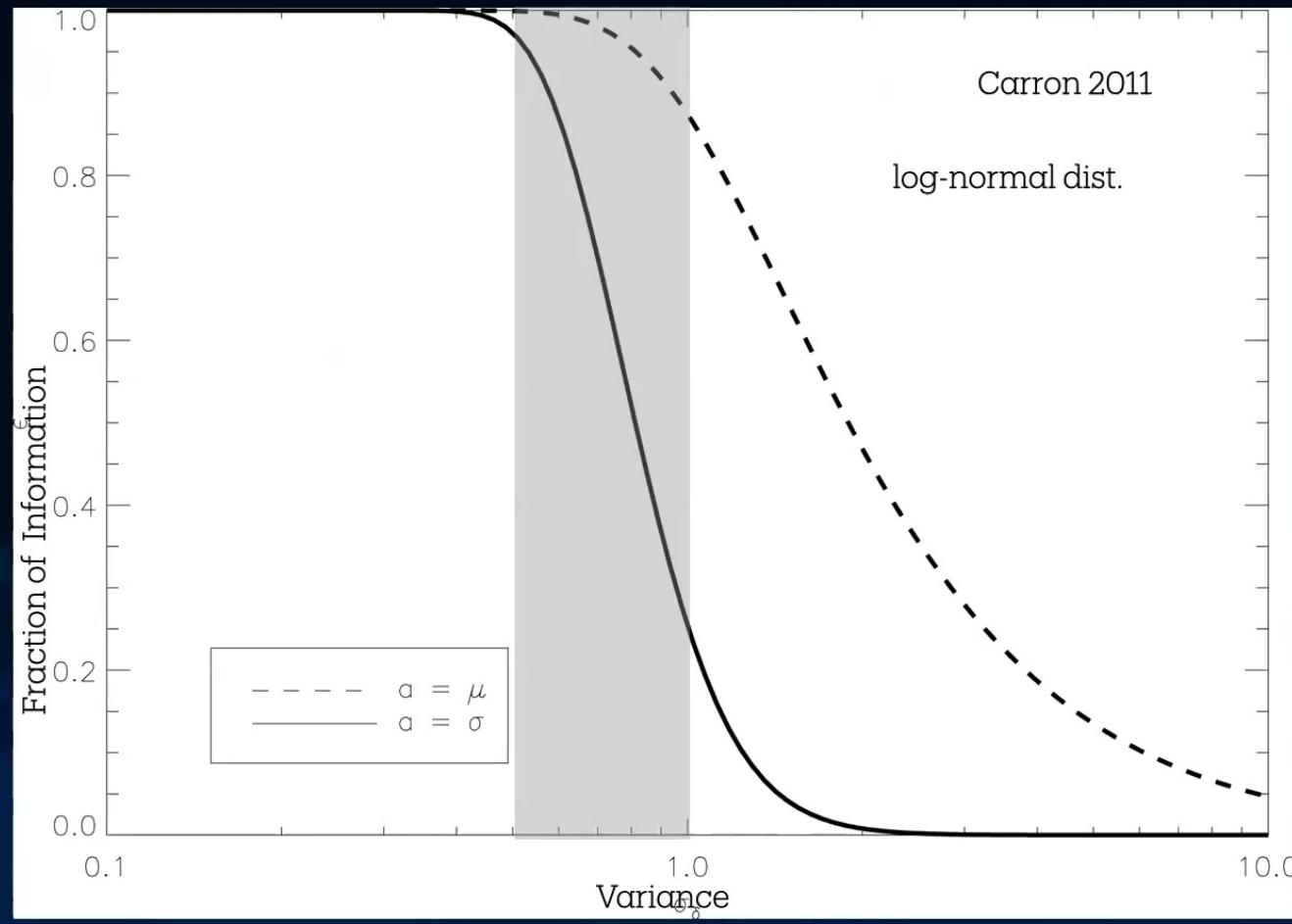
Field-level Bayesian Inference of galaxy clustering
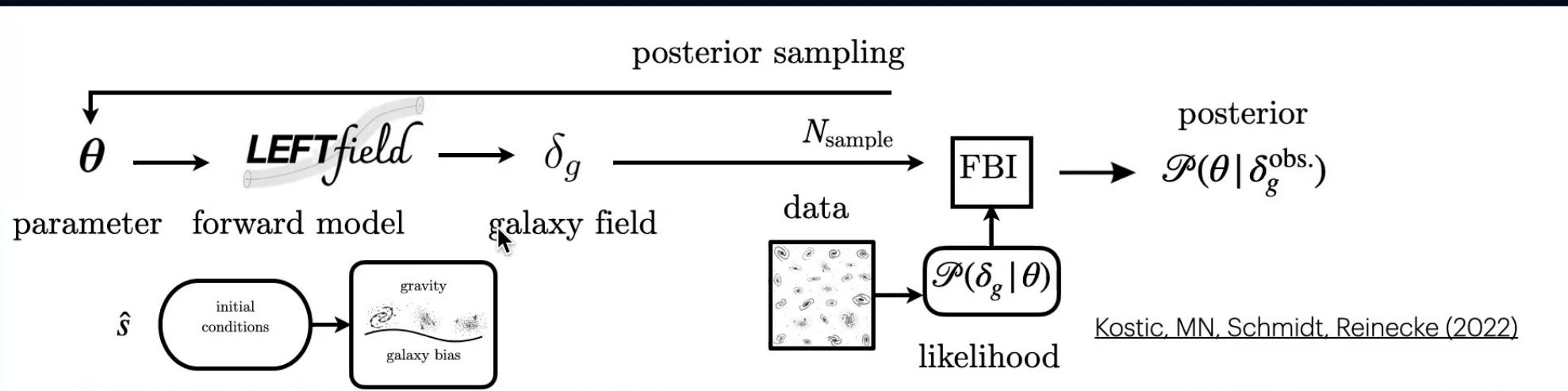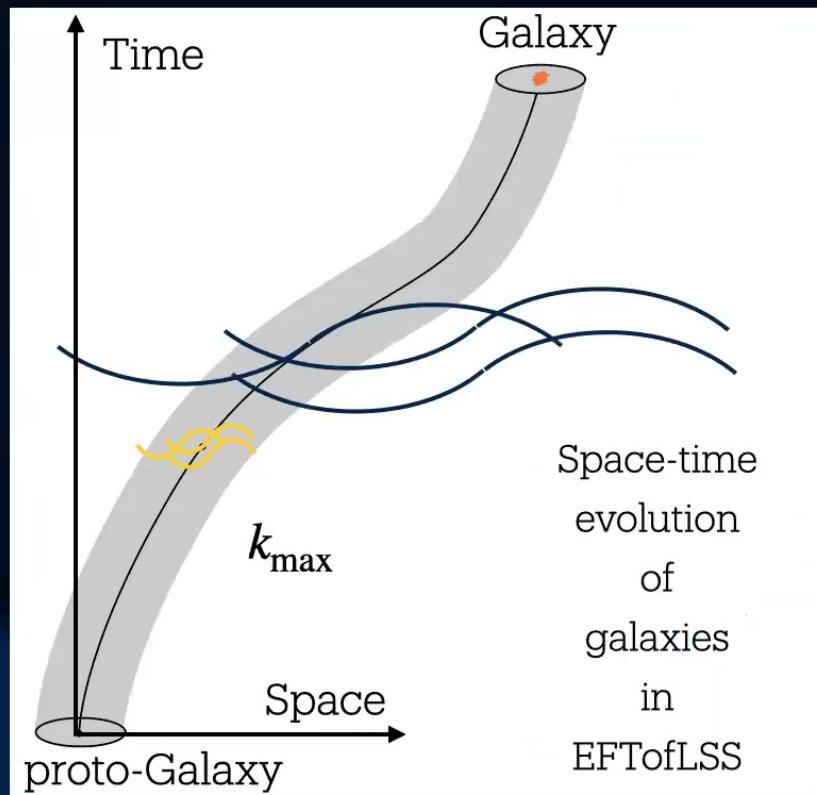
Kostic, MN, Schmidt, Reinecke (2022)

FBI — EFT galaxy bias and likelihood

Time

Galaxy

k_{max}

Space

proto-Galaxy

Space-time evolution of galaxies in EFTofLSS

$$\delta_g(\mathbf{k}) = \sum_O b_O O(k) + \epsilon$$

Only valid within the EFTofLSS framework

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

Comparing individual Fourier modes

Constrain observed galaxy field in 3D

$$\log \mathcal{L} = \text{-}1.184\text{e}{+}08$$
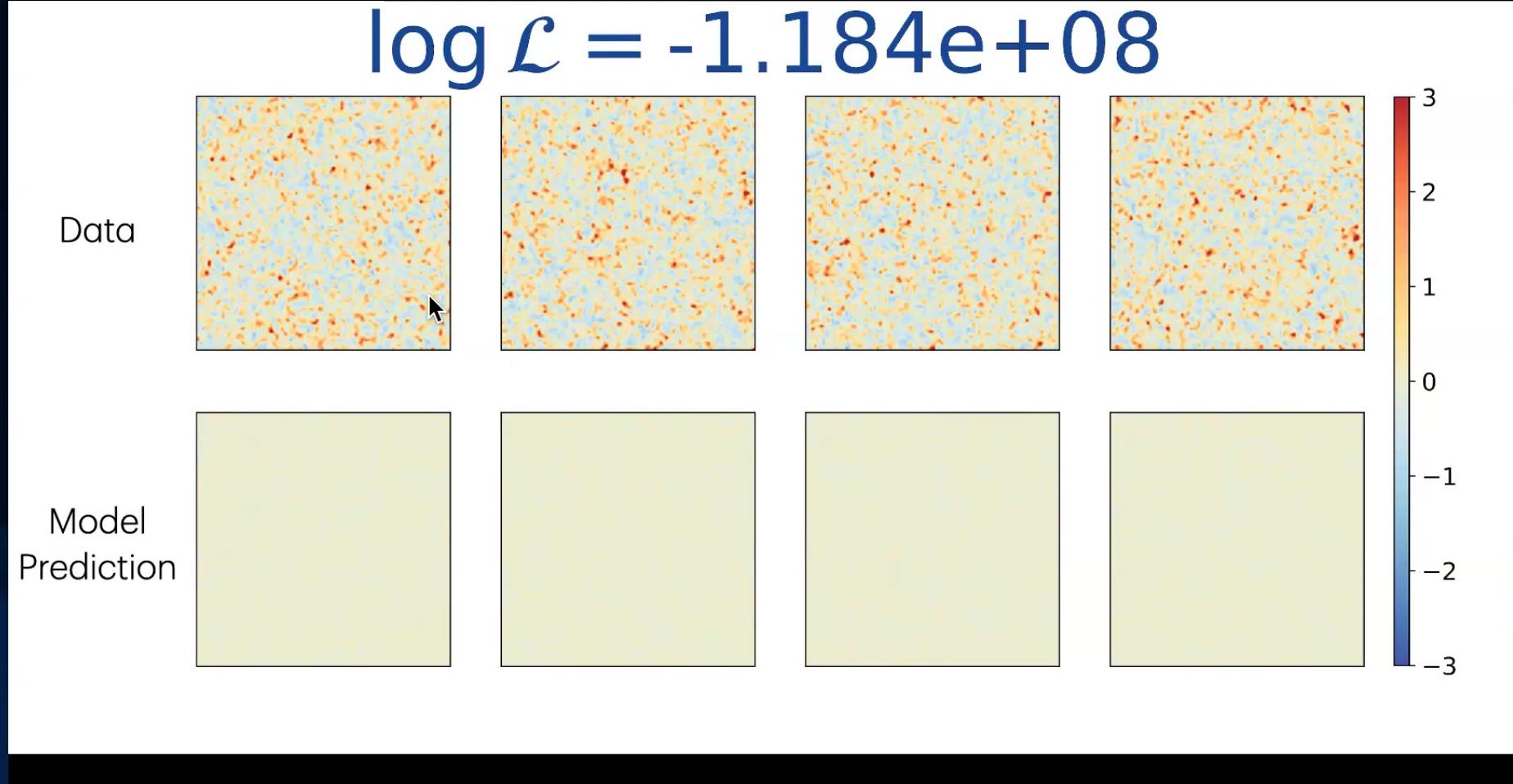
Constrain observed galaxy field in 3D

$$\log \mathcal{L} = -3.162\text{e}{+}05$$

Data
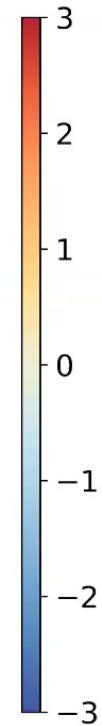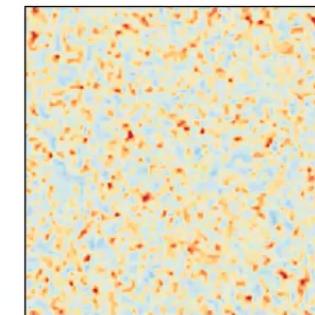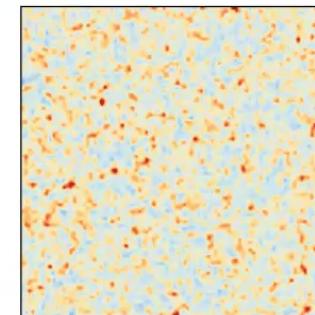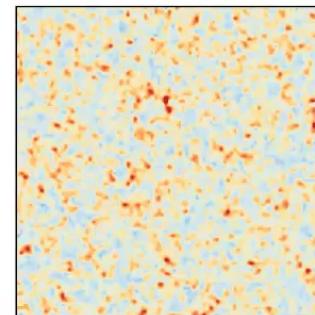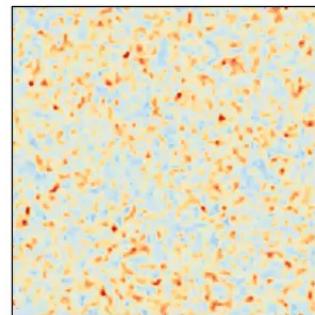
Model Prediction
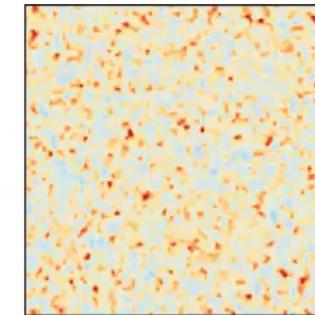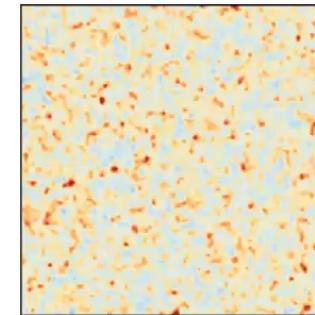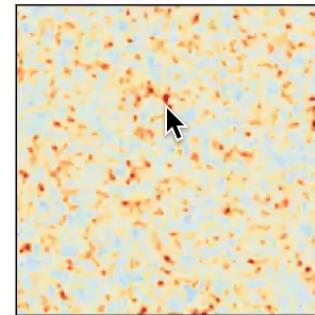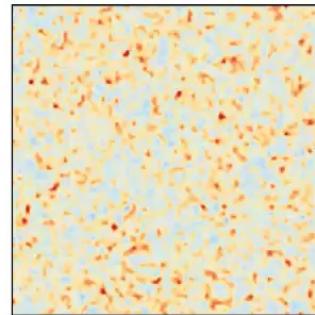
Constrain cosmology and galaxy bias

$$\alpha = \frac{\sigma_8}{\sigma_{8,\text{true}}}$$

Volume$=8(h^{-1}\text{Gpc})^3$

Kostic, MN, Schmidt+ 2022

real-space
mock tracers

degeneracy
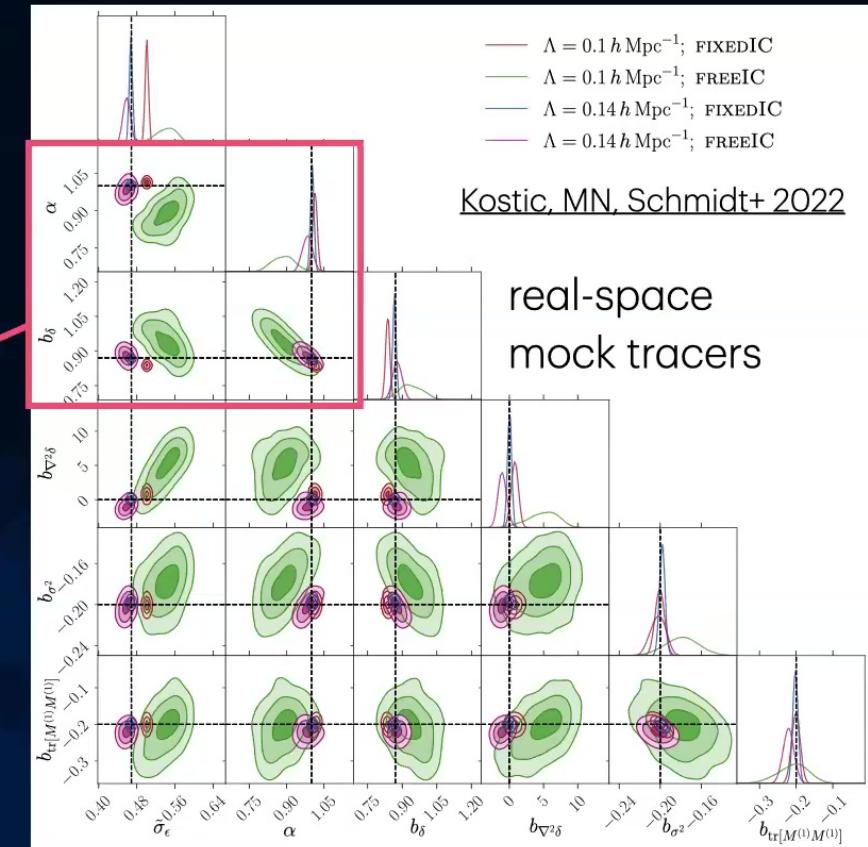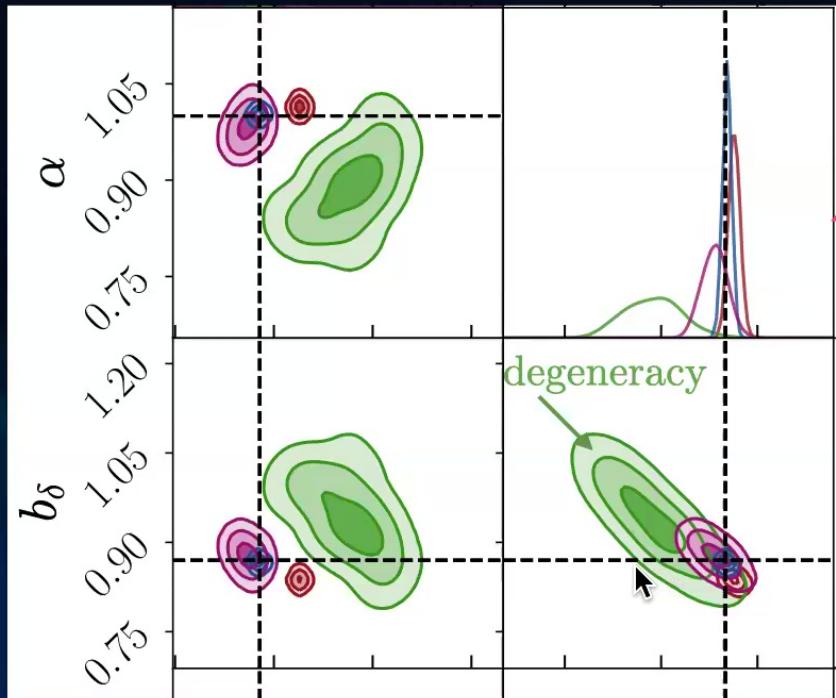
How much info beyond 2+3-pt? **FBI** vs SBI **P+B**
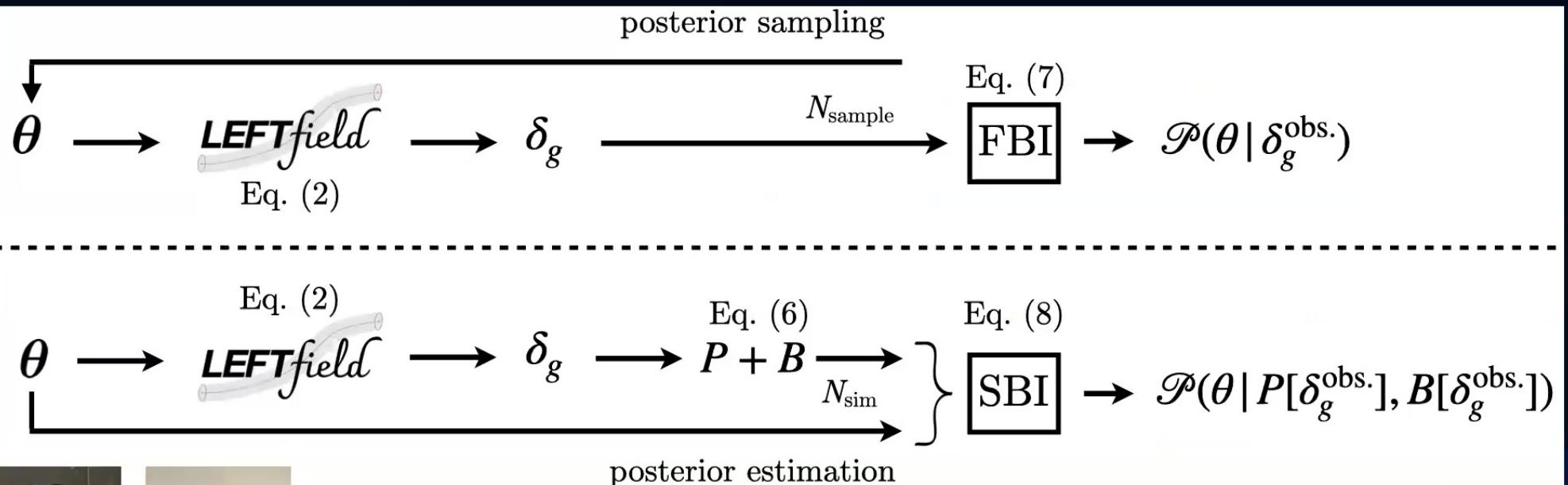
Kostic, MN, Schmidt, Reinecke (2022)

Direct evidence for info beyond 2+3-point

Apple-to-apple comparisons

N-body gravity-only sims

Dark-matter main halos

$\log_{10} M_h = 12.5 - 14.0 h^{-1} M_\odot$

Volume=$8(h^{-1}\text{Gpc})^3$

Improvement increases with scale cut

MN, Schmidt, Tucci+ 2024
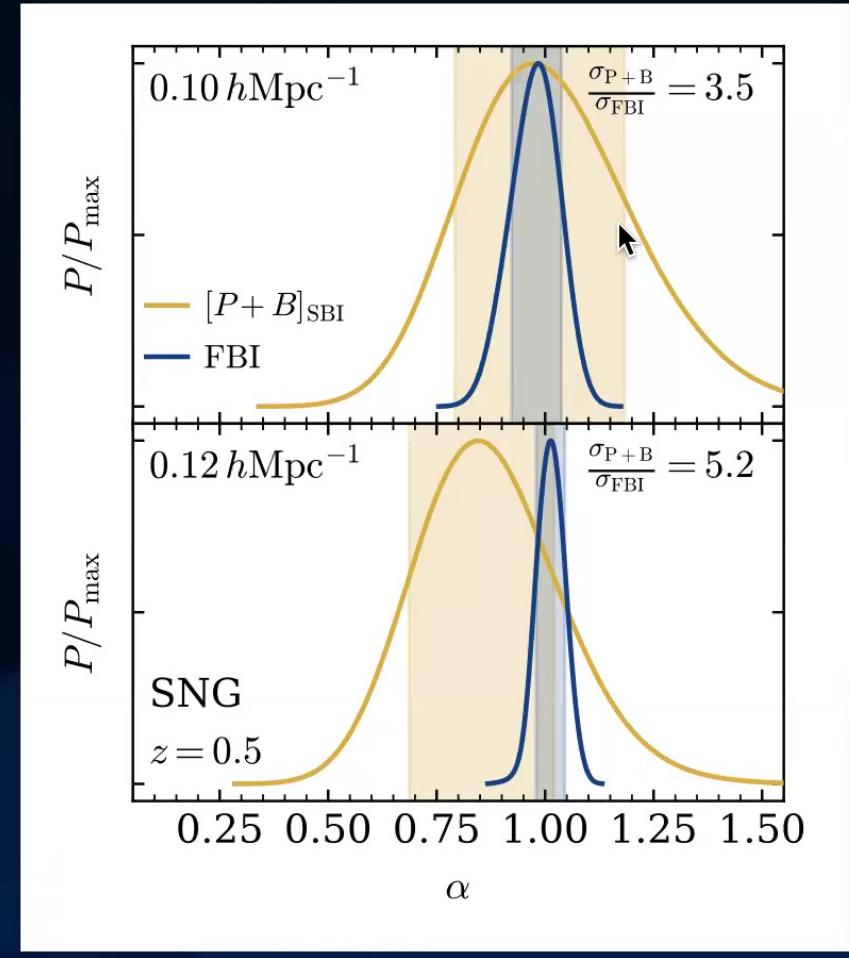
Improvement generalizes across tracers

More apple-to-apple comparison

Uchuu simulations [Ishiyama+ 2020](#)

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Improvement increases with scale cut

and number density

[MN, Schmidt, Tucci+ 2024](#)
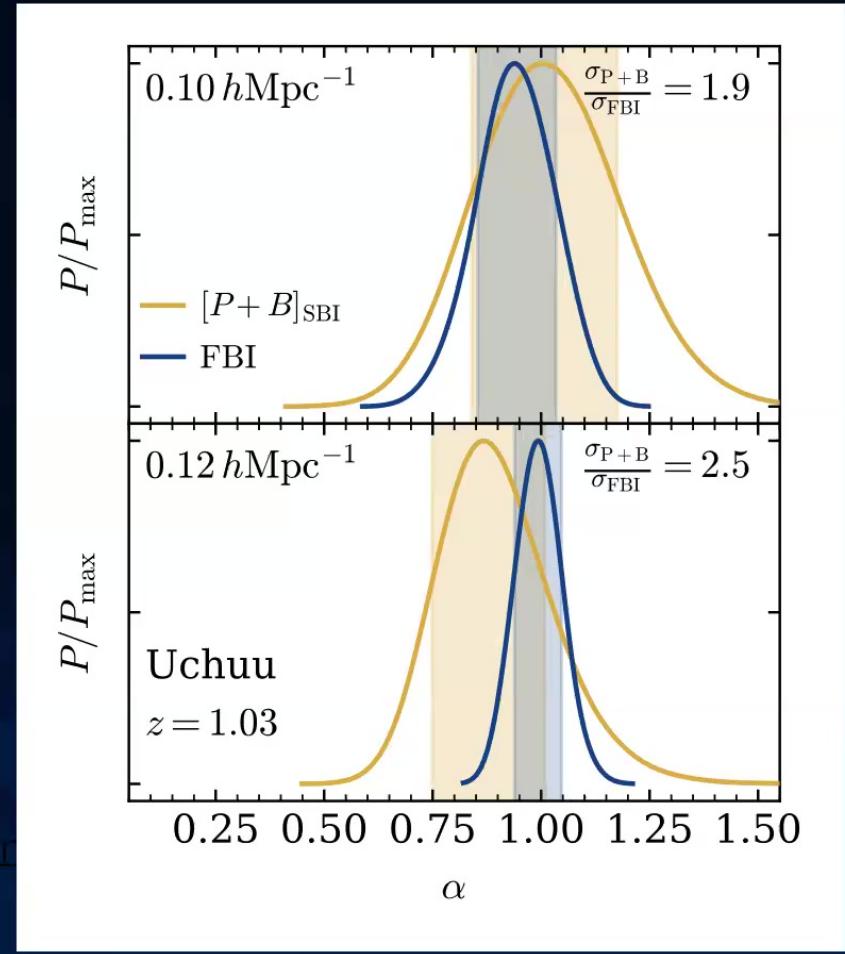
Evidence from (more) "realistic" galaxies

Apple-to-orange comparisons

First community exercise

7 international teams

HOD galaxies in different

    setups

    cosmologies

~~Blind~~ Parameter-masked challenge

First field-level constraint

    from "realistic" tracers

Beyond-2pt challenge (arXiv this month)   Volume=$8(h^{-1}\text{Gpc})^3$

led by Yosuke Kobayashi, Andres Salcedo and Elisabeth Krause (UofArizona)

real-space snapshots (mean of 10 realizations), fixed $\omega_{\text{m}}, \omega_{\text{b}}, n_{\text{s}}, h$

BACCO P, $k_{\text{max}} = 0.5\,h/\text{Mpc}$ degeneracy

EFT P+B, $k_{\text{max}} = \{0.3, 0.15\}\,h/\text{Mpc}$

EFT FBI, $k_{\text{max}} = 0.1\,h/\text{Mpc}$

-0.10 0.00 0.05

$\Delta\sigma_8/\sigma_8$ Beyond-2pt collaboration (in prep.)

EFT FBI team: MN and Schmidt

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合格！ わーい！

Scaling up and Expanding FBI
New Physics from Galaxy Clustering and Beyond

Towards SBI at field level

More flexible and efficient FBI with 3D Diffusion Models?
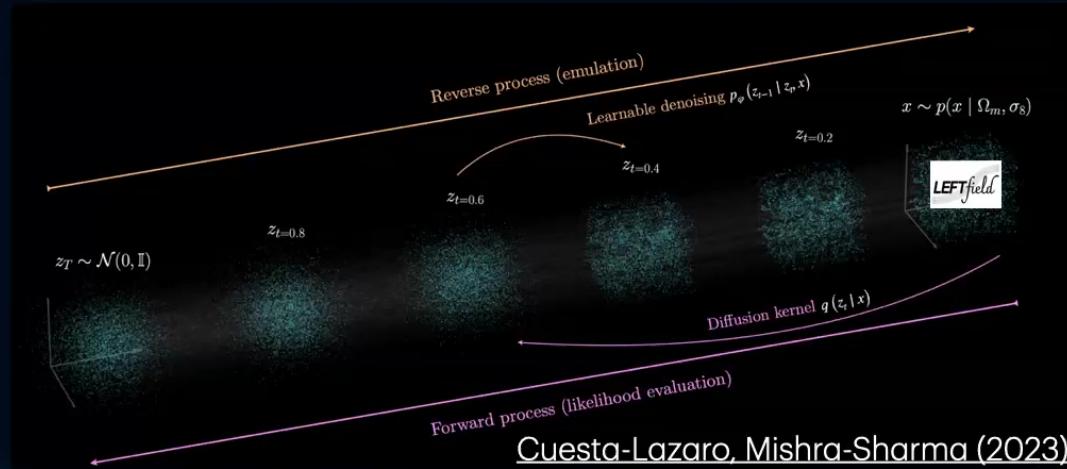
Sharrock+ (2022)
Legin+ (2023)
Mudur+ (2023)

Cuesta-Lazaro, Mishra-Sharma (2023)
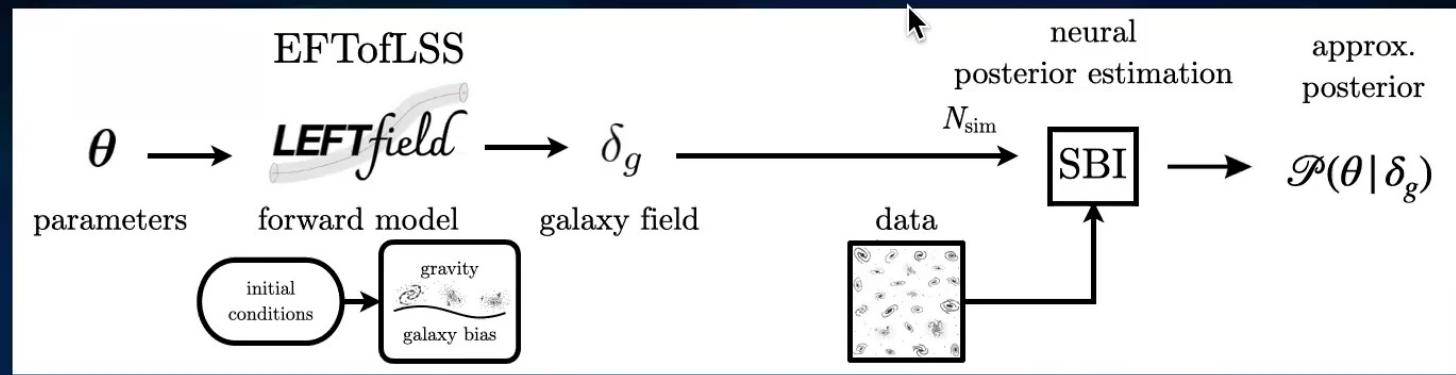
Towards galaxy position x shape

Additional cosmological information from non-scalar fields?

MN, Schmidt (in prep.)
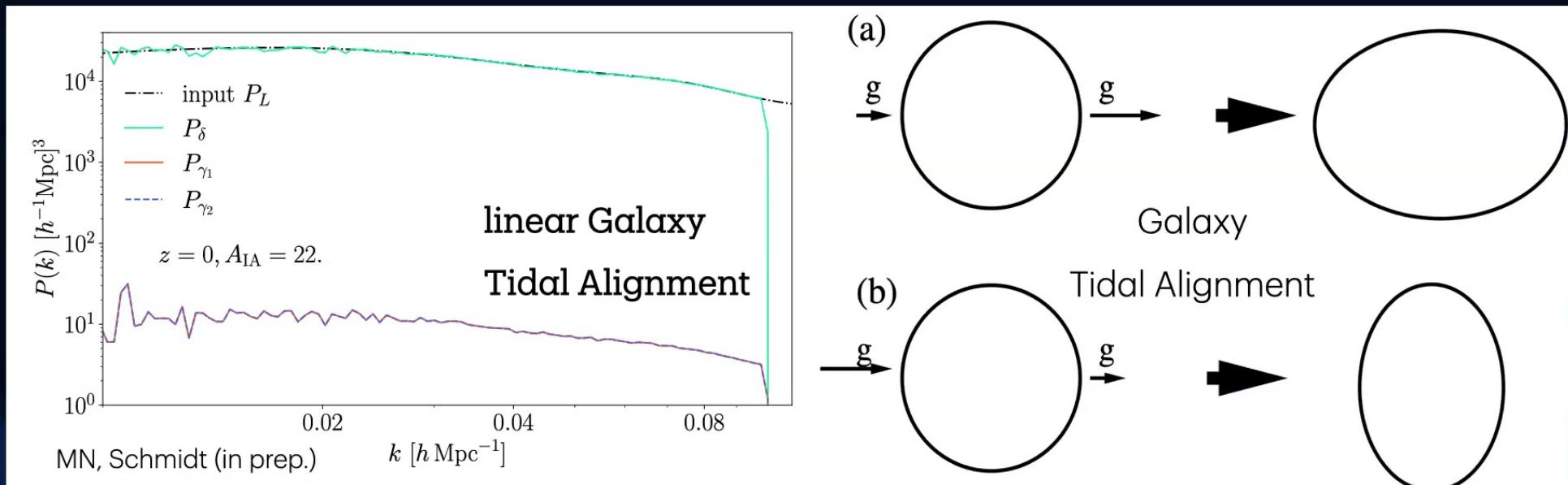
Growth of Structure from LSSxCMB surveys

Beyond the standard model and standard EFT

Can we

incorporate new physics in the forward model?

extend the forward model beyond quasi-linear regime?

improve modeling efficiency

Nothing fundamentally prohibited!

Differentiable
Boltzmann + hybrid-EFT

`DISCO-DJ` Hahn+ 2024
+
`pmwd` Li+ 2022
+
`NUFFT` Shih+ 2021

Summary

Part I

σ_8 tension —> late-time growth suppression —> new properties of DE, gravity or DM

Galaxy clustering can provide crucial insights into σ_8 tension

Part II

Beyond-2pt statistics contain significant cosmological information in galaxy clustering

Field-level Bayesian Inference will improve σ_8 constraint from galaxy clustering

FBI ~ a natural framework to analyze galaxy clustering, plus galaxy shapes, peculiar velocities

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More apple-to-apple comparison

Uchuu simulations   Ishiyama+ 2020

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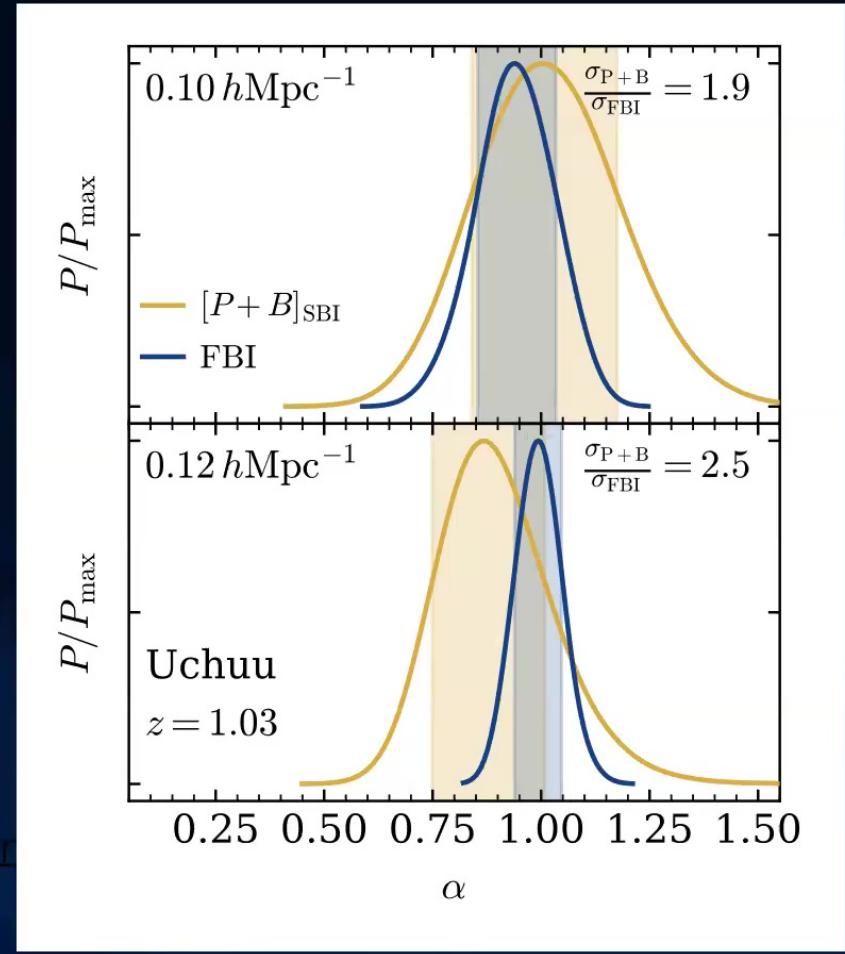
SBI P+B convergence
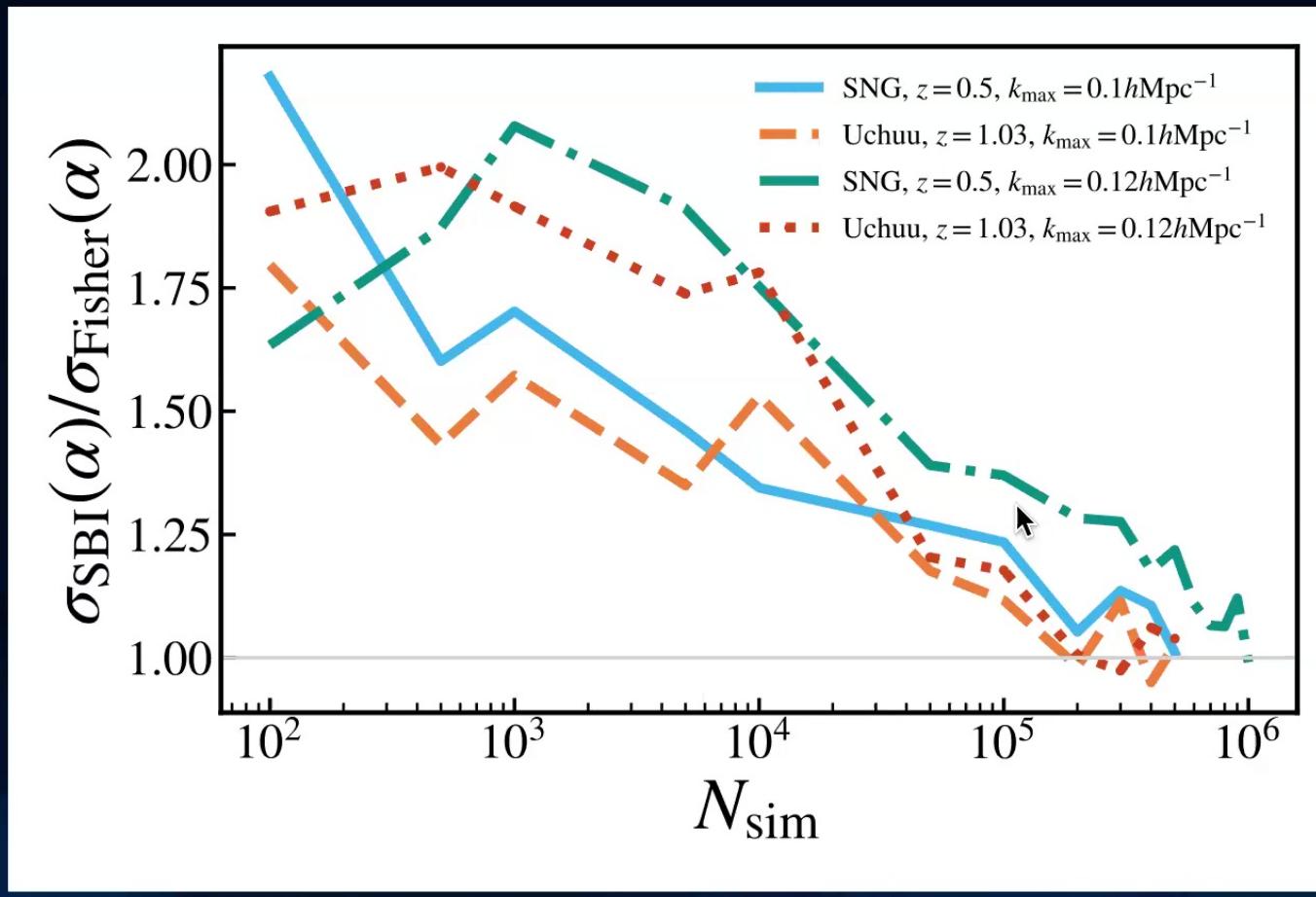
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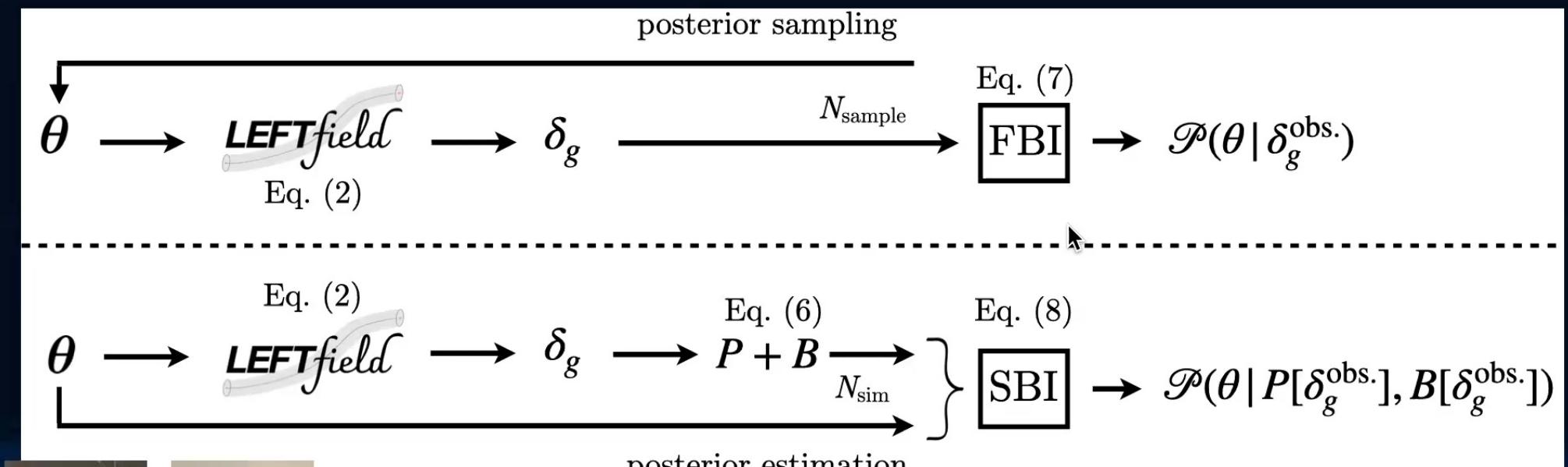
posterior sampling

$$\theta \longrightarrow \textbf{\textit{LEFTfield}} \longrightarrow \delta_g \xrightarrow{\quad N_{\text{sample}} \quad} \boxed{\text{FBI}}^{\text{Eq. (7)}} \longrightarrow \mathscr{P}(\theta \,|\, \delta_g^{\text{obs.}})$$

Eq. (2)

$$\theta \longrightarrow \textbf{\textit{LEFTfield}}^{\text{Eq. (2)}} \longrightarrow \delta_g \xrightarrow{\text{Eq. (6)}} P+B \xrightarrow{\quad N_{\text{sim}} \quad} \Big\} \boxed{\text{SBI}}^{\text{Eq. (8)}} \longrightarrow \mathscr{P}(\theta \,|\, P[\delta_g^{\text{obs.}}], B[\delta_g^{\text{obs.}}])$$

posterior estimation

Kostic, MN, Schmidt, Reinecke (2022)

FBI — EFT galaxy bias and likelihood

Space-time evolution of galaxies in EFTofLSS
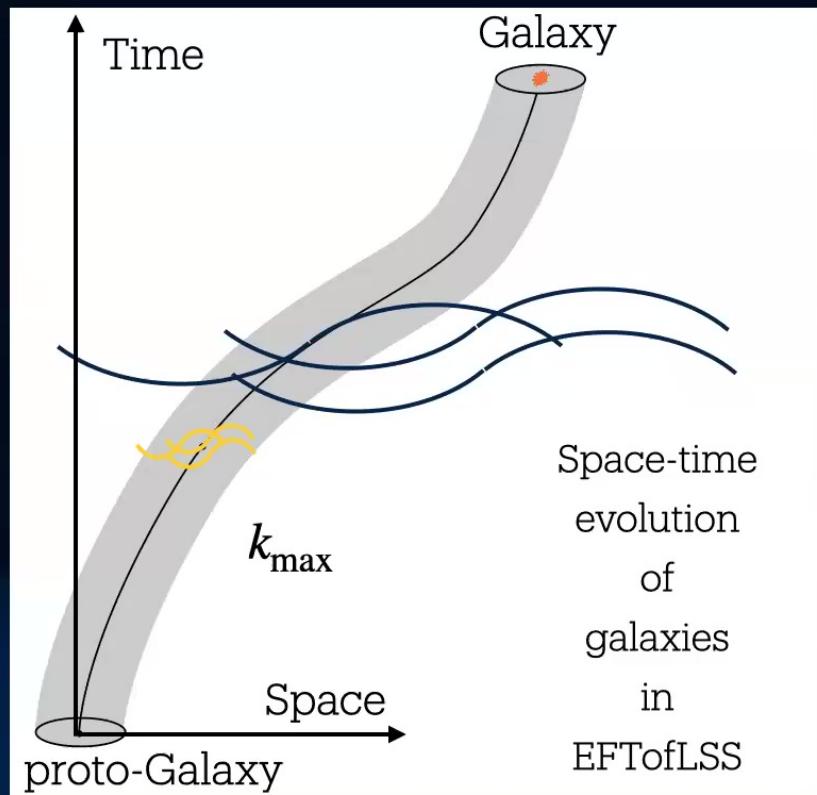
$$\delta_g(\mathbf{k}) = \sum_O b_O O(k) + \epsilon$$

Only valid within the EFTofLSS framework

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

Comparing individual Fourier modes

Evidence from (more) "realistic" galaxies

Mandarin-to-orange comparison

First community exercise

7 international teams

HOD galaxies in different

      setups

      cosmologies

~~Blind~~ Parameter-masked challenge

First field-level constraint

      from "realistic" tracers

合格! わ〜い!

<u>Beyond-2pt challenge</u> (arXiv this month)   Volume=$8(h^{-1}\text{Gpc})^3$

led by Yosuke Kobayashi, Andres Salcedo and Elisabeth Krause (UofArizona)

real-space snapshots (mean of 10 realizations), fixed $\omega_{\mathrm{m}}, \omega_{\mathrm{b}}, n_{\mathrm{s}}, h$

EFT P+B, $k_{\max} = \{0.3, 0.15\}\, h/\text{Mpc}$

P+B, restricted

EFT FBI, $k_{\max} = 0.1\, h/\text{Mpc}$

FBI extended

-0.10 0.00 0.05

$\Delta\sigma_8/\sigma_8$ Beyond-2pt collaboration (in prep.)
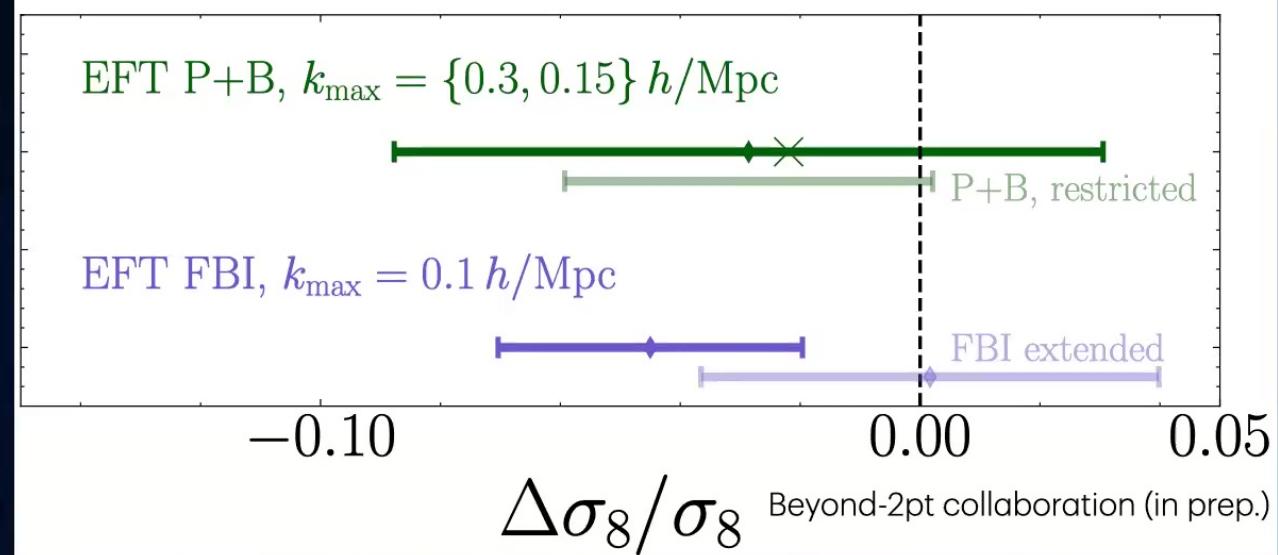
EFT FBI team: MN and Schmidt

Robustness to Peculiar Velocity and RSD
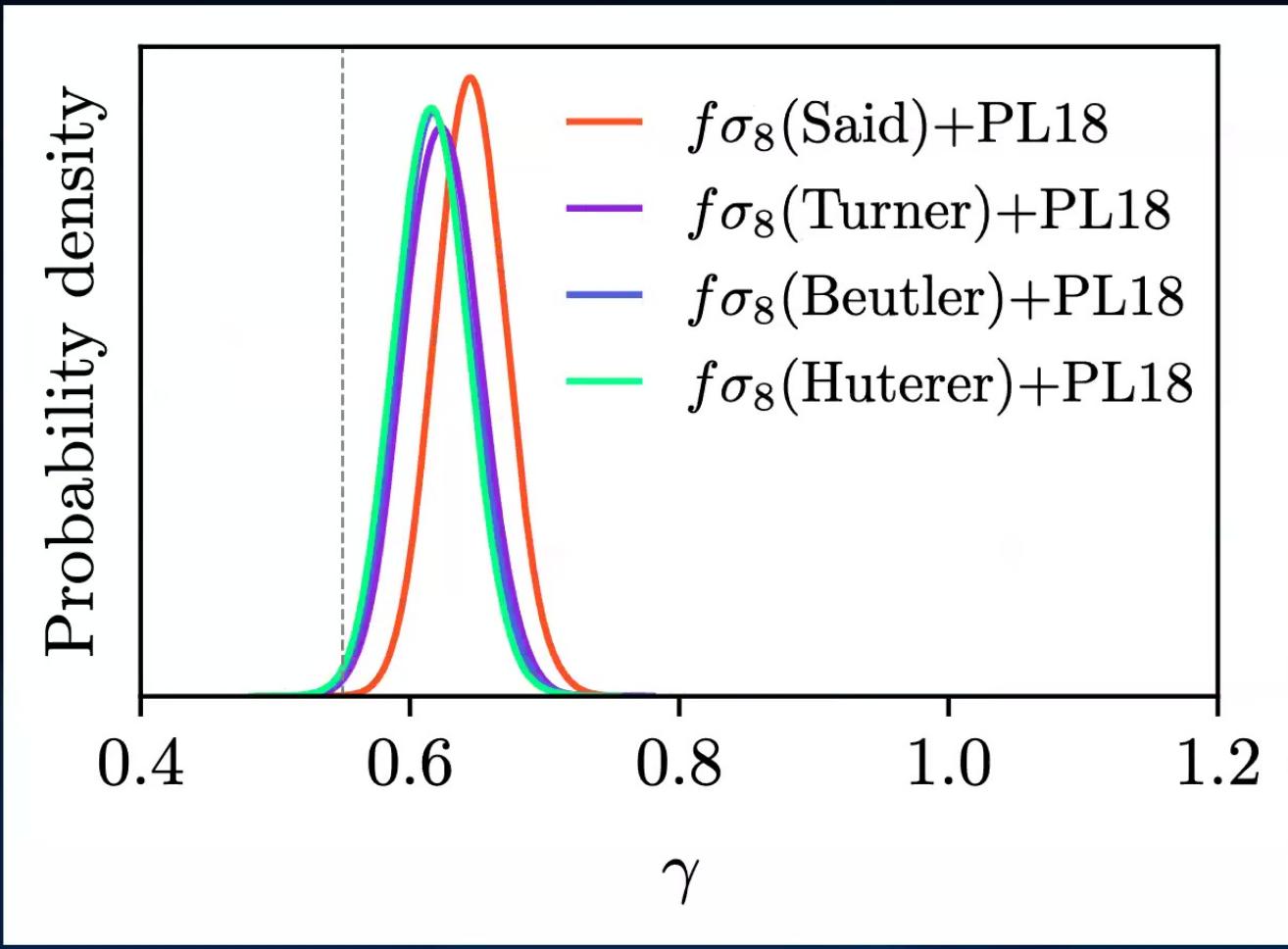
# CMB lensing and Galaxy lensing + BAO

Parameter degeneracies
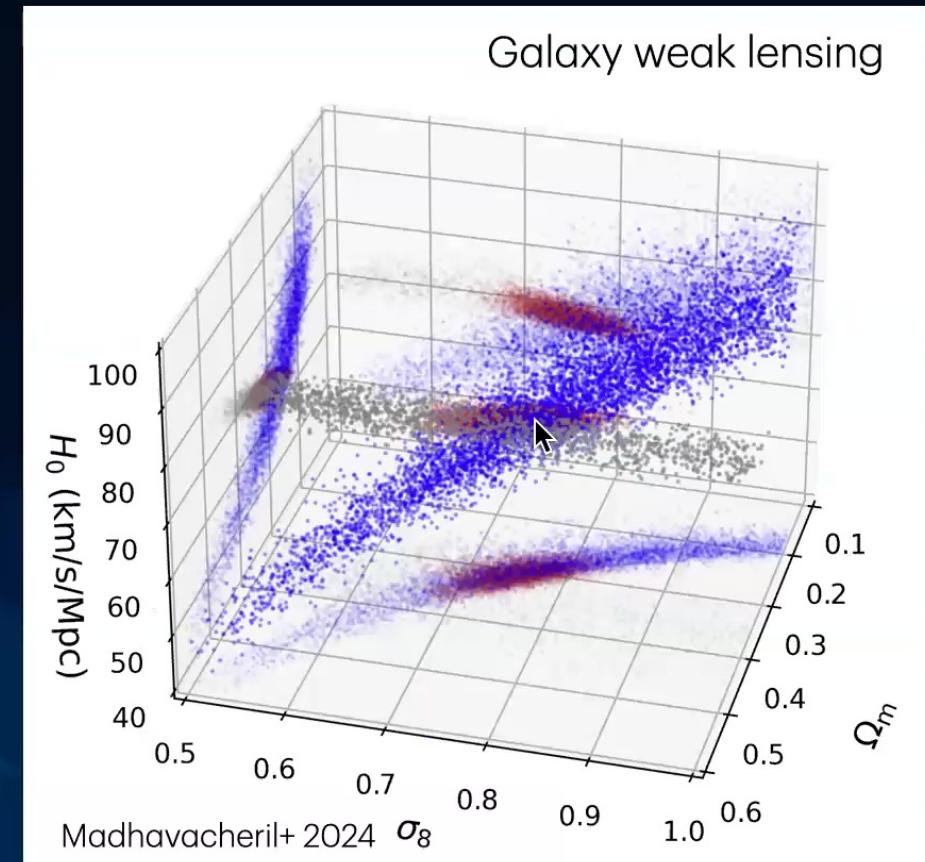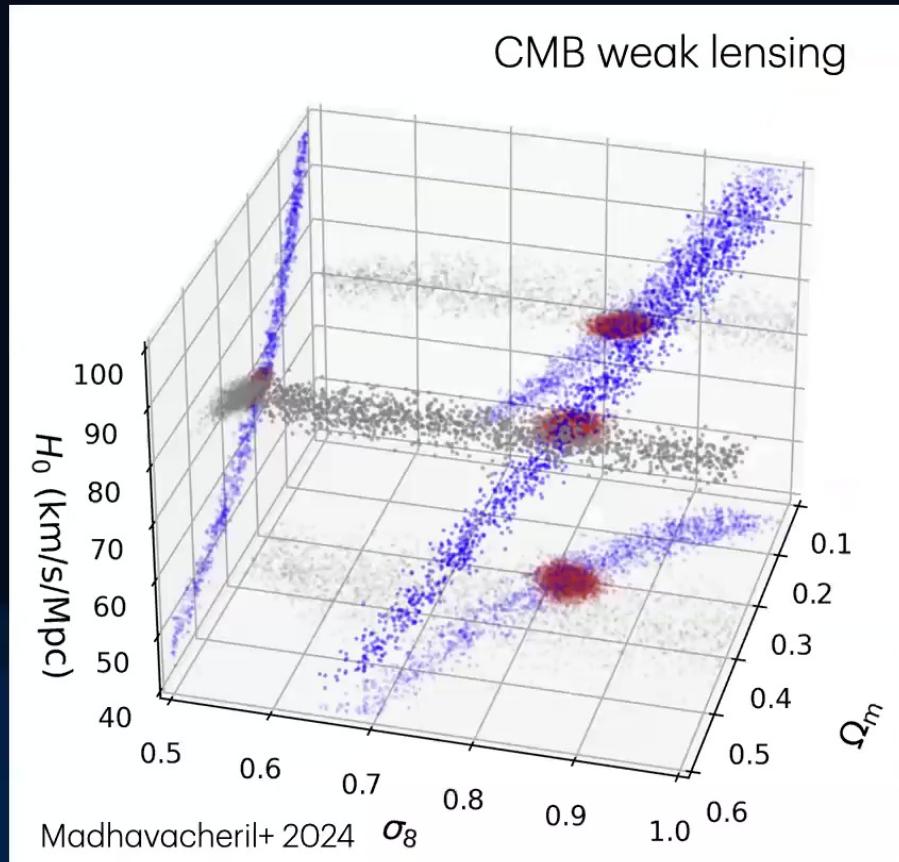
FBI convergence - MCMC trace
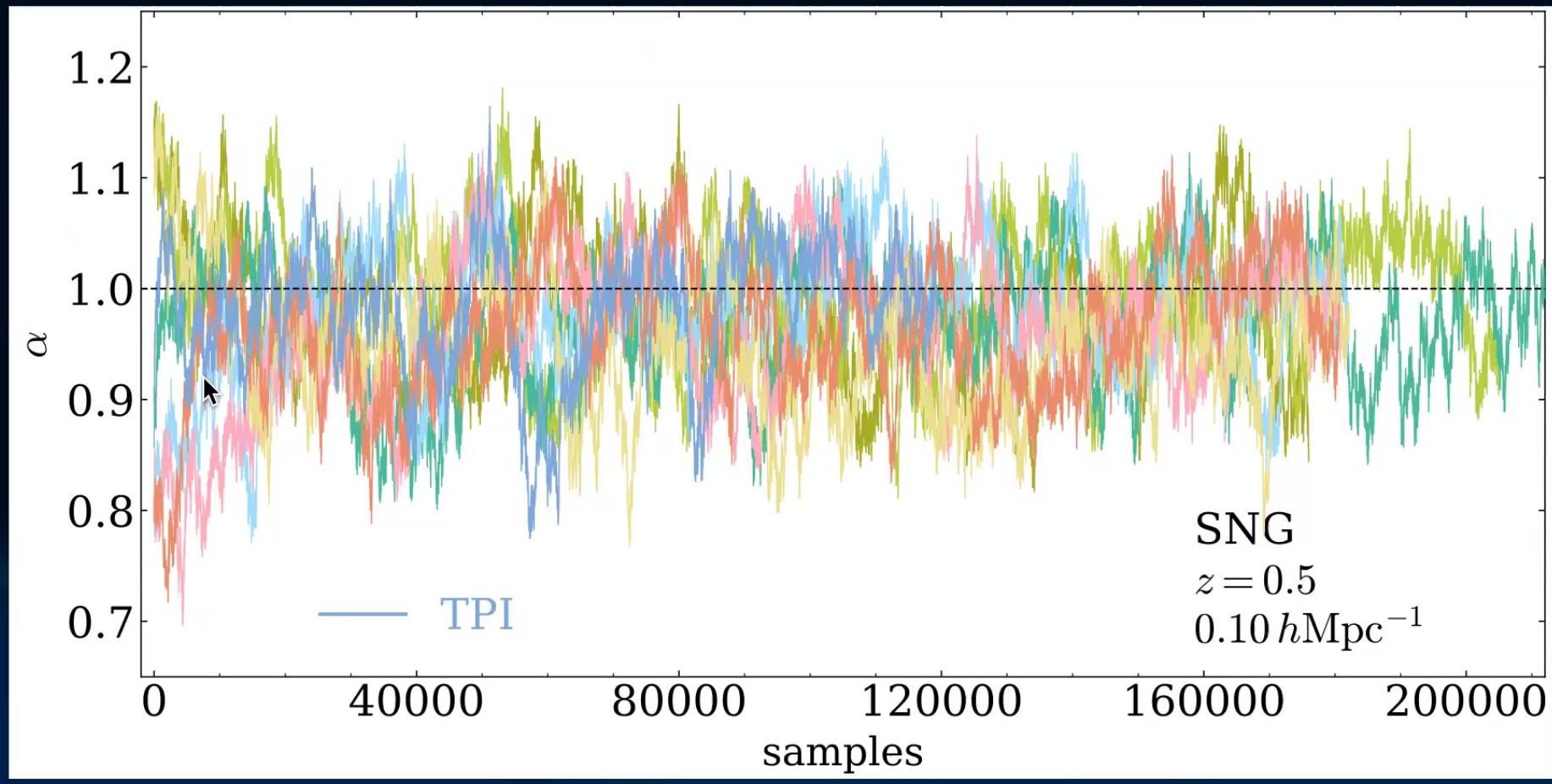
FBI convergence - Posterior

SNG
$z = 0.5$
$0.1\,h\mathrm{Mpc}^{-1}$
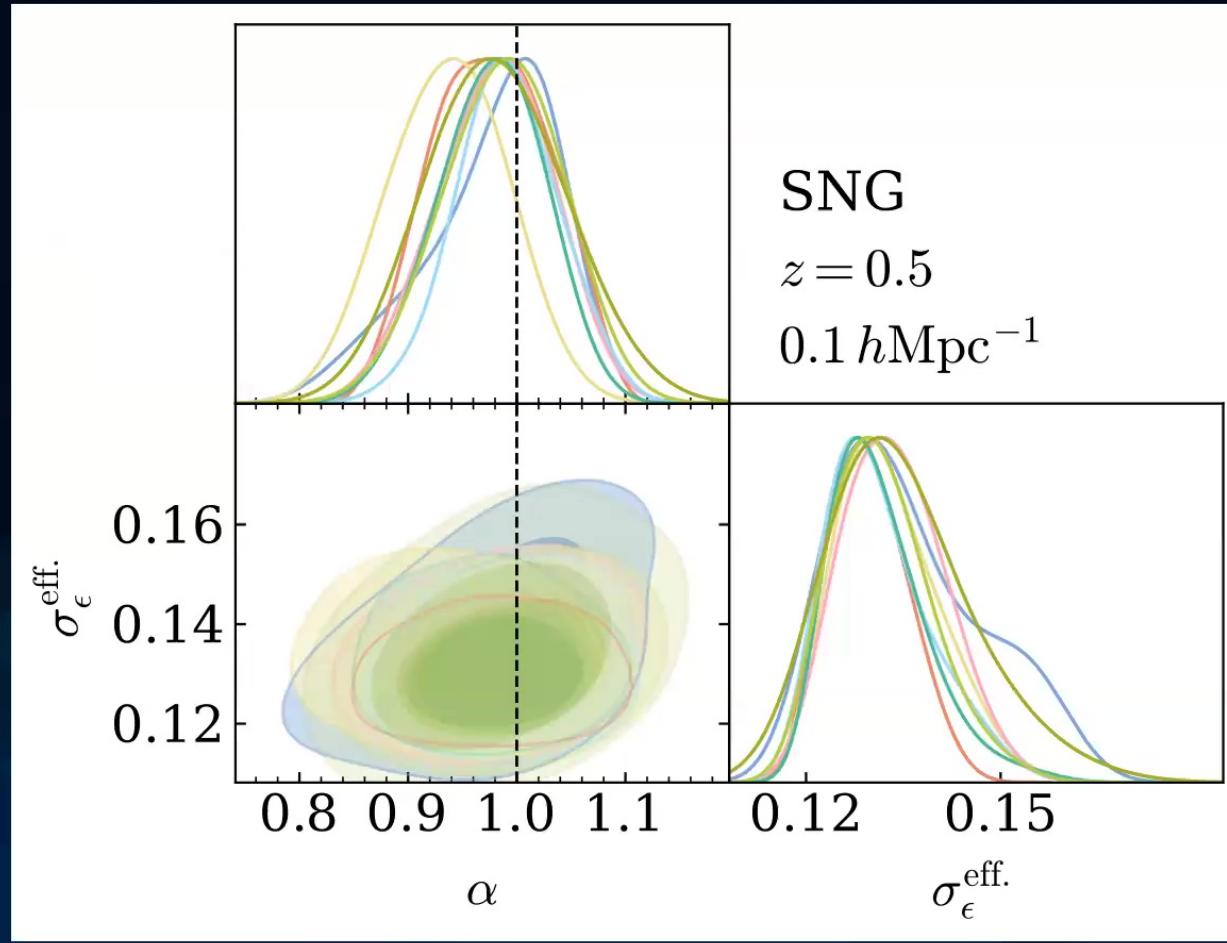
FBI convergence - MCMC trace

Improvement generalizes across tracers

More apple-to-apple comparison

Uchuu simulations   Ishiyama+ 2020

Dark-matter main halos

$\log_{10} M_h = 12.0 - 13.5 h^{-1} M_\odot$

Volume=$8(h^{-1}\mathrm{Gpc})^3$

Improvement increases with scale cut

and number density

MN, Schmidt, Tucci+ 2024