Searching for New Physics in the Late Universe

with millions of galaxies in millions of dimensions

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UNIVERSITY OF MICHIGAN

CCAPP CosmoLunch — March 20, 2024

About me

MPI für Astrophysik
Physical Cosmology
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Theoretical Cosmology
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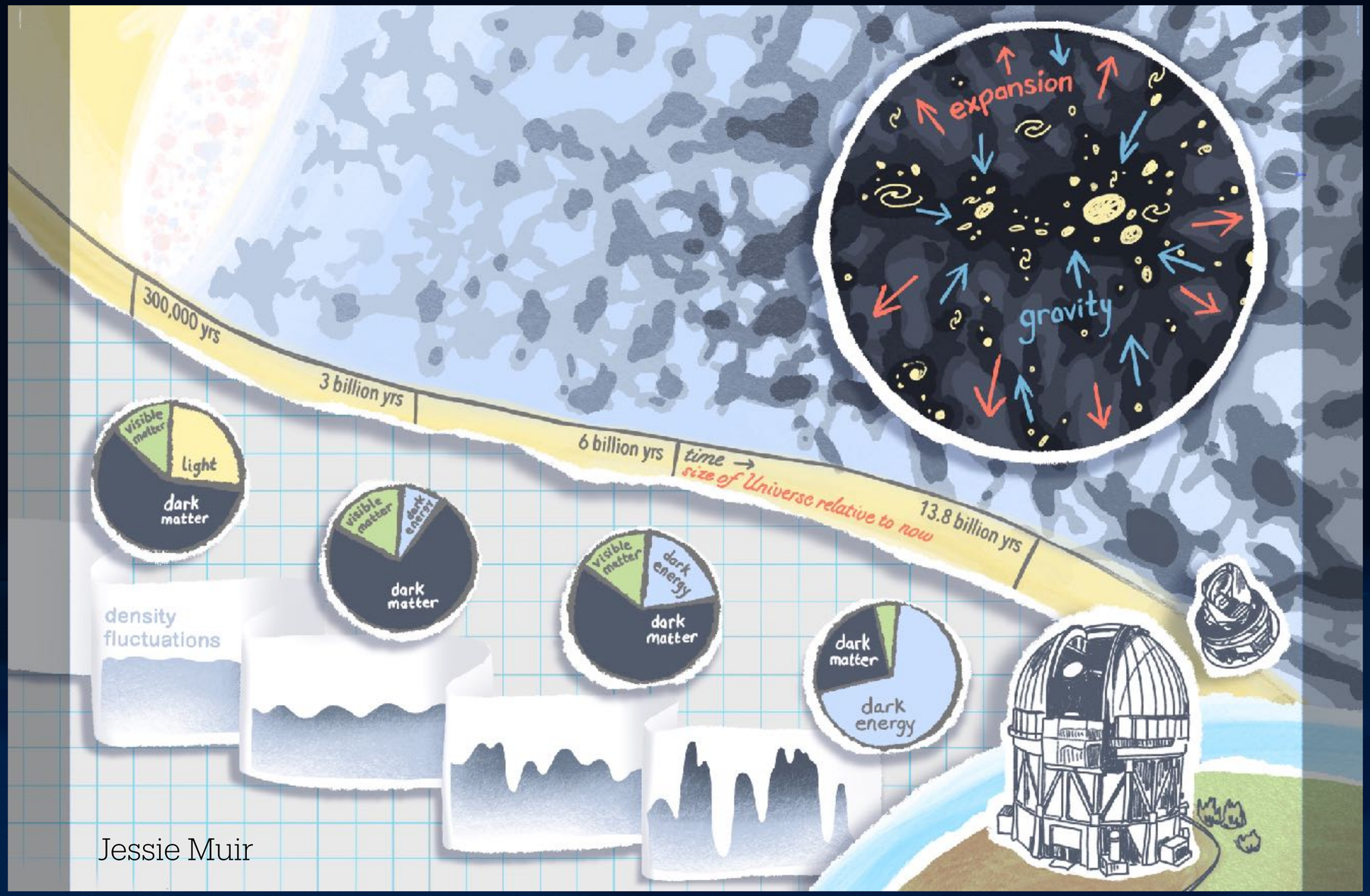
Cosmology
Saigon, Vietnam
Birth —> College

Growth of Structure - σ_8 tension

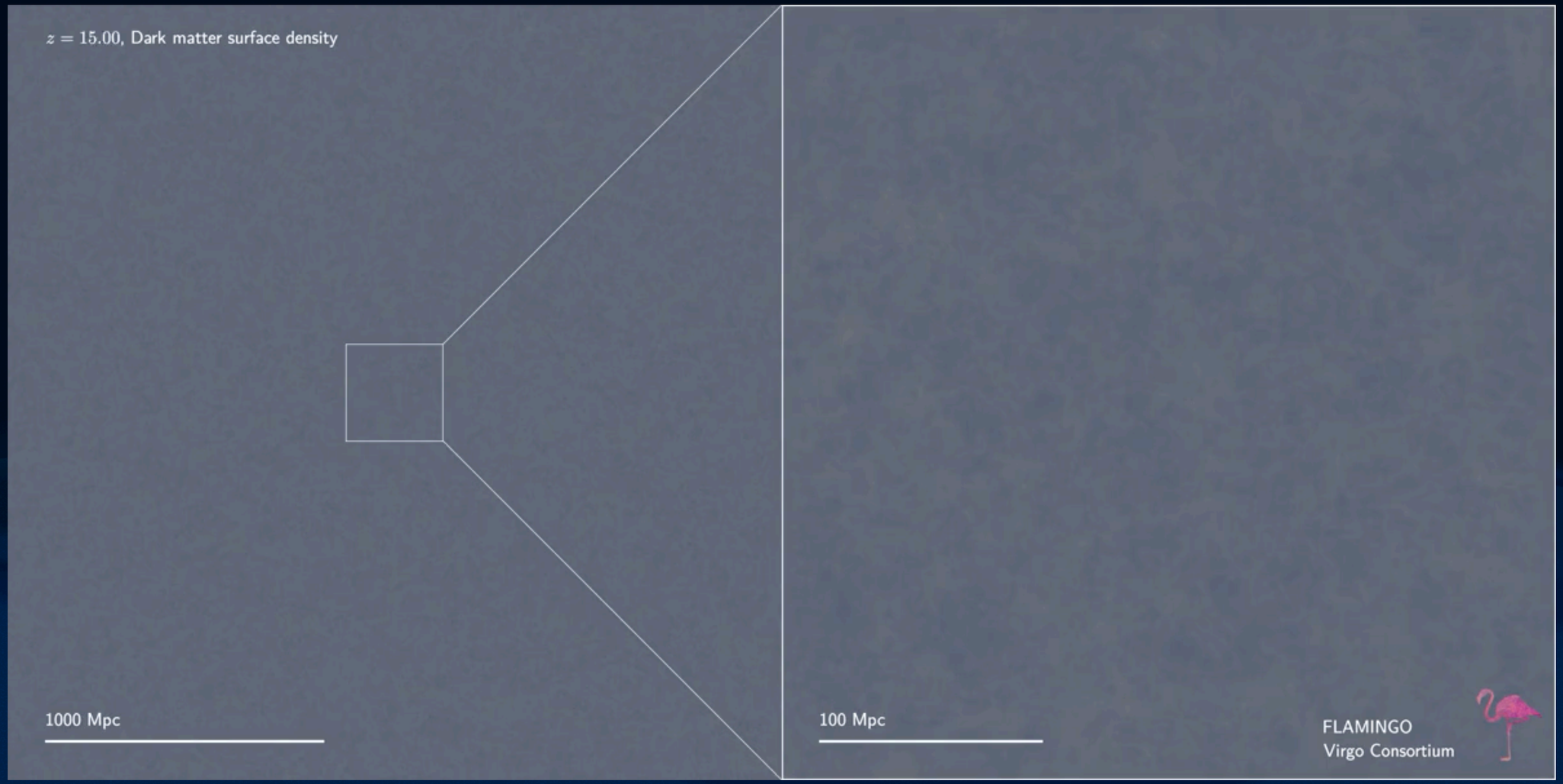
Hints of new physics?

Growth of Structures and Density Fluctuations



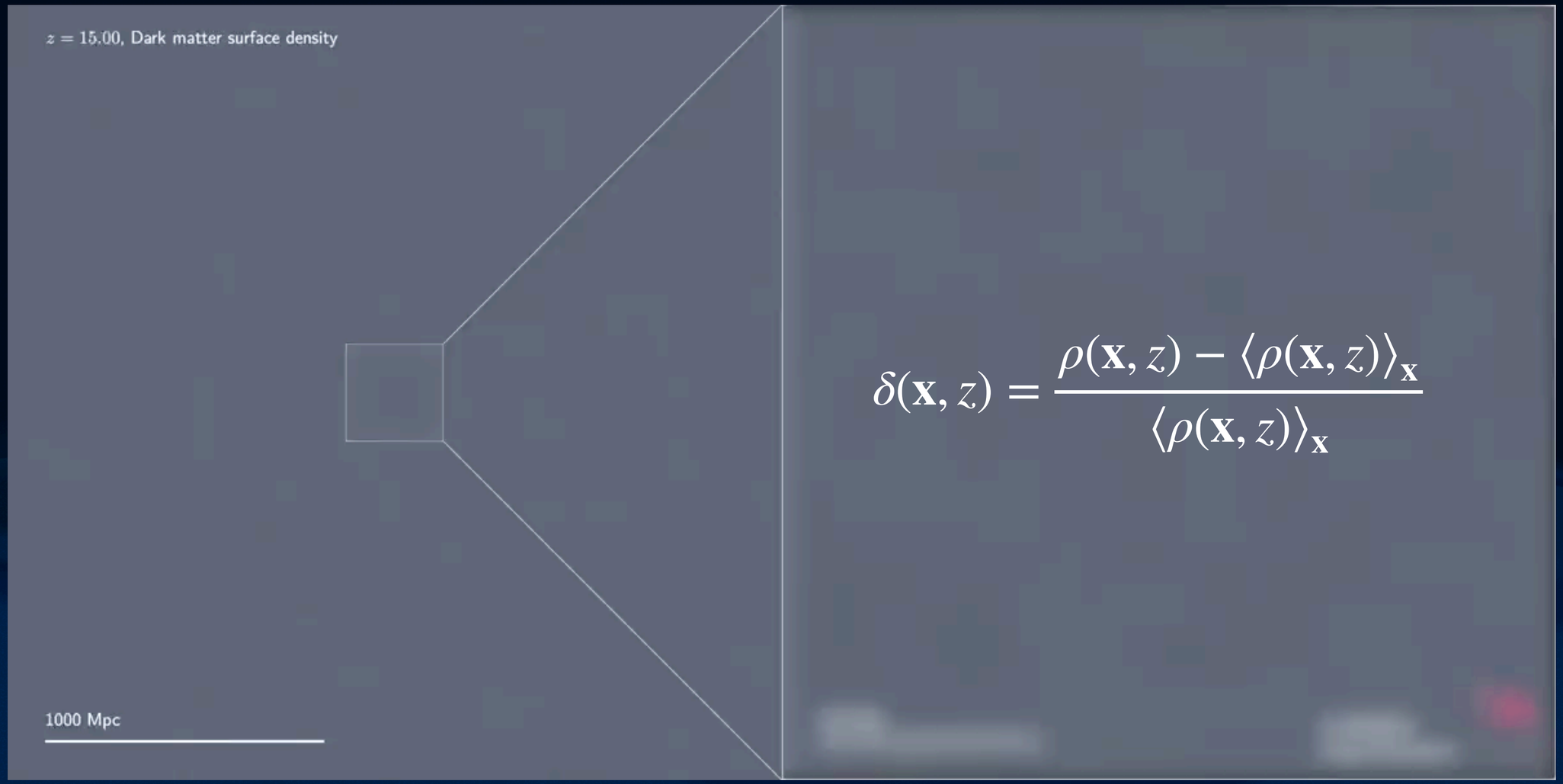
Jessie Muir

Growth - Simulation



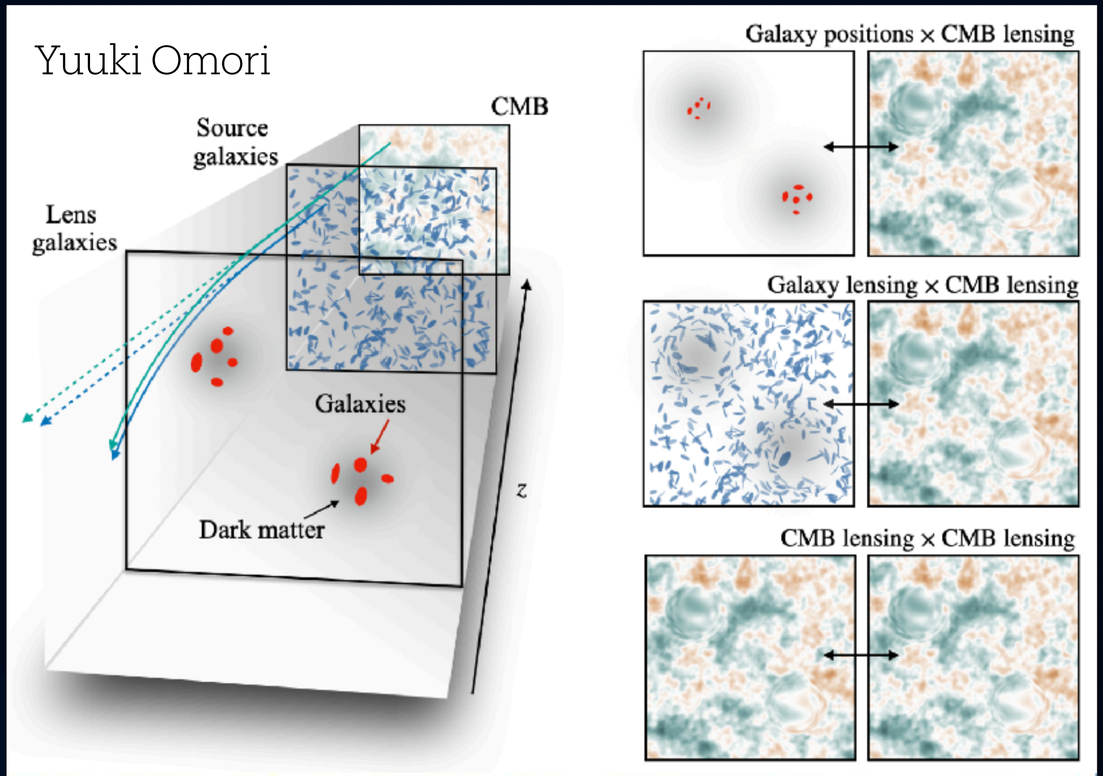
Growth - Linear Theory

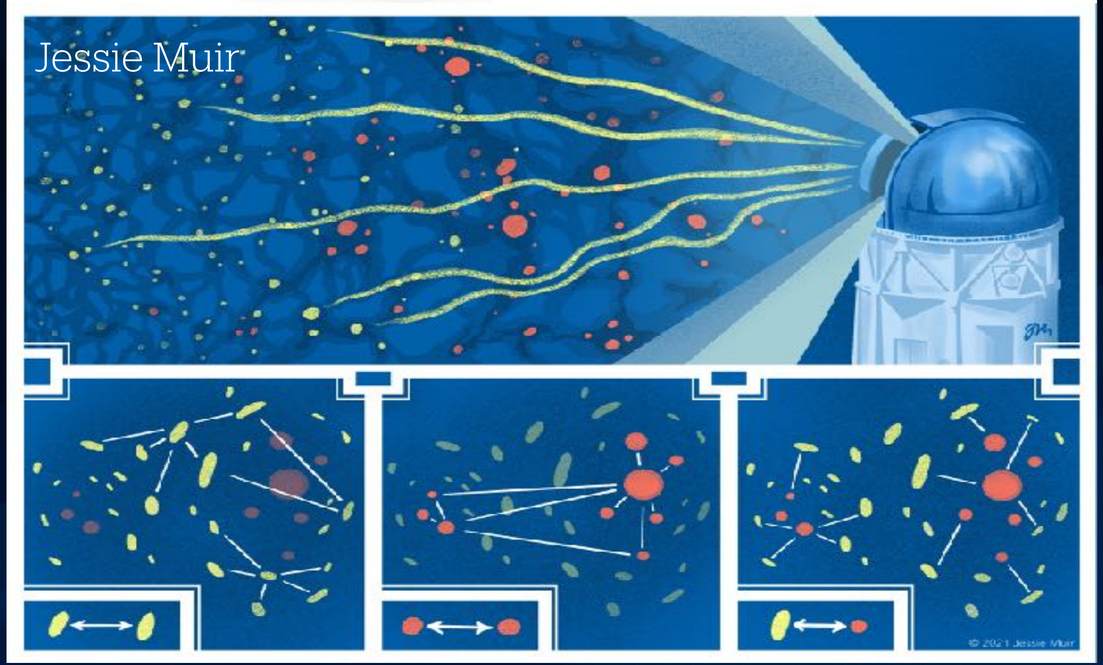
Linear fluctuations $\delta(\mathbf{k}, z) \sim \mathcal{N}\left(0, \mathsf{C} = \mathrm{diag}\left[P_L(k, z)\right]\right)$



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

Growth - Observation





Growth - Extrapolation

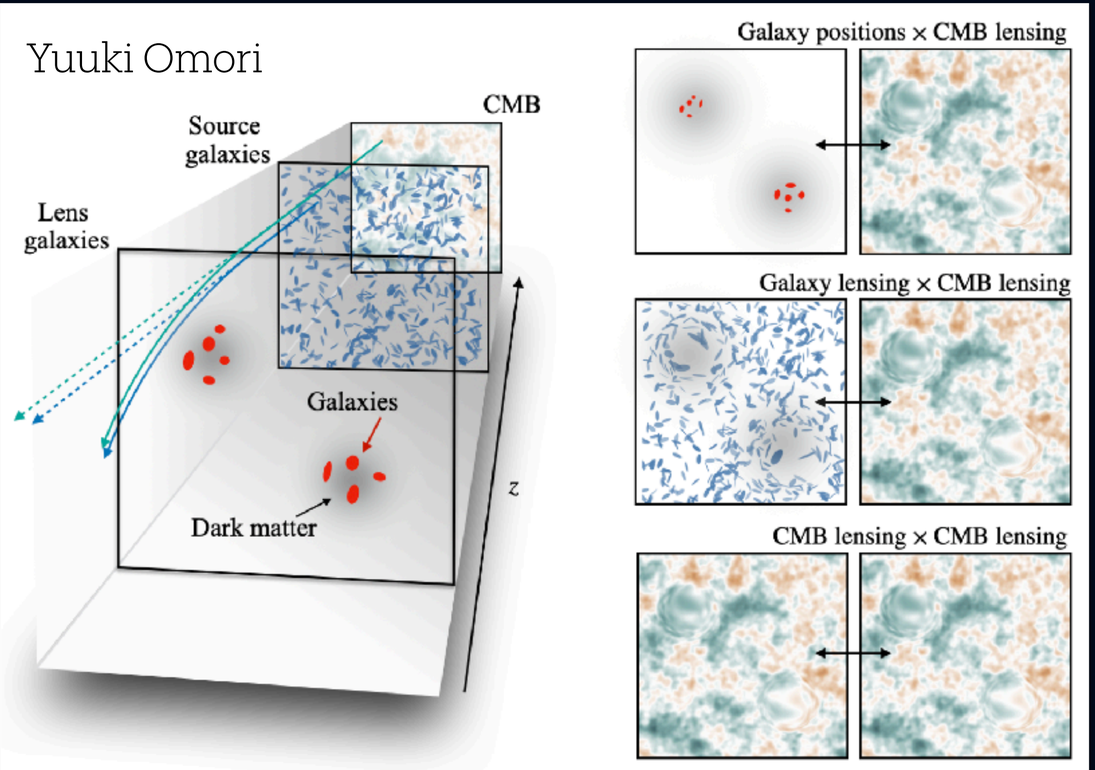
Proxy for **today** growth

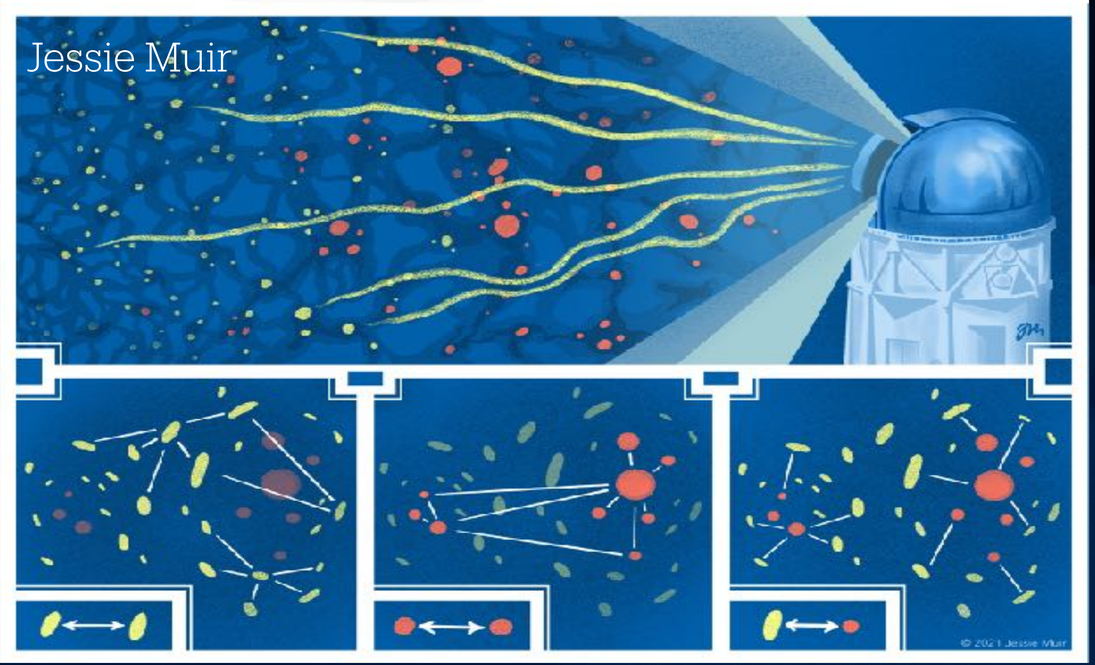
$$\sigma_8^2 = \frac{1}{2\pi^2} \int dk k^2 \, P_L(k, z=0) \, W^2_{R=8h^{-1}\mathrm{Mpc}}(k)$$

extrapolated

from

snapshots of large-scale structure

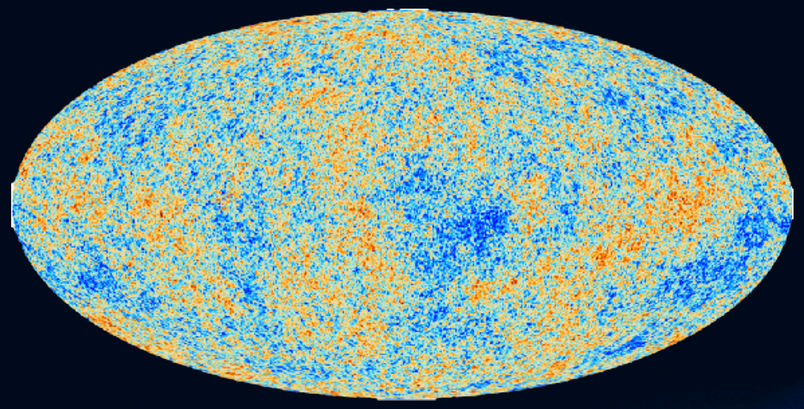




Early Universe

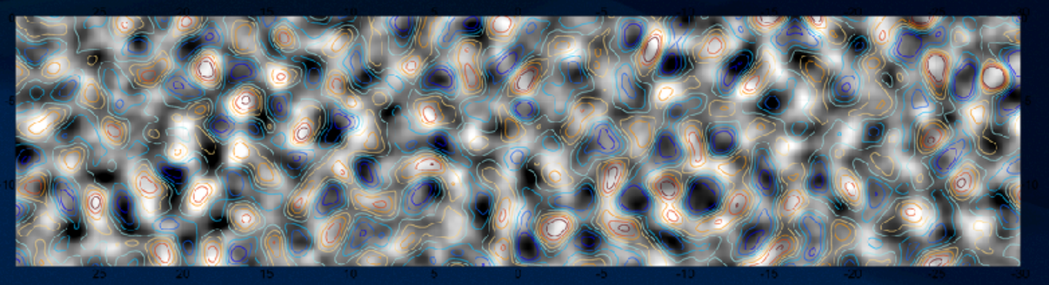
Early-time probes of growth

Cosmic Microwave Background

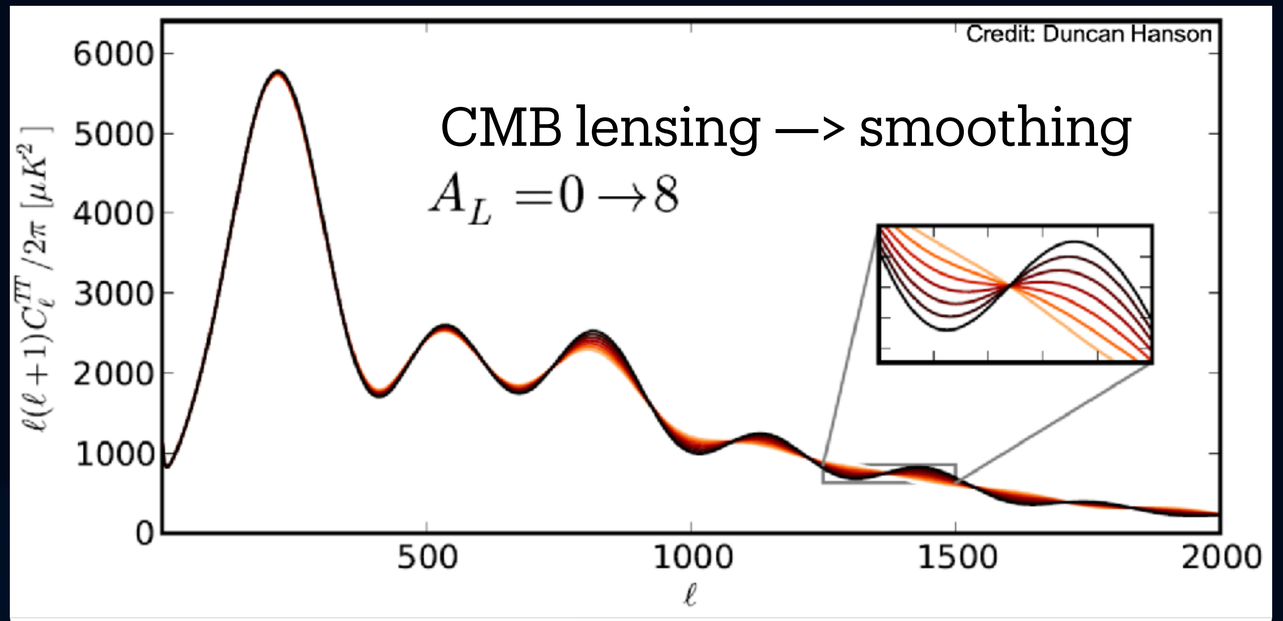


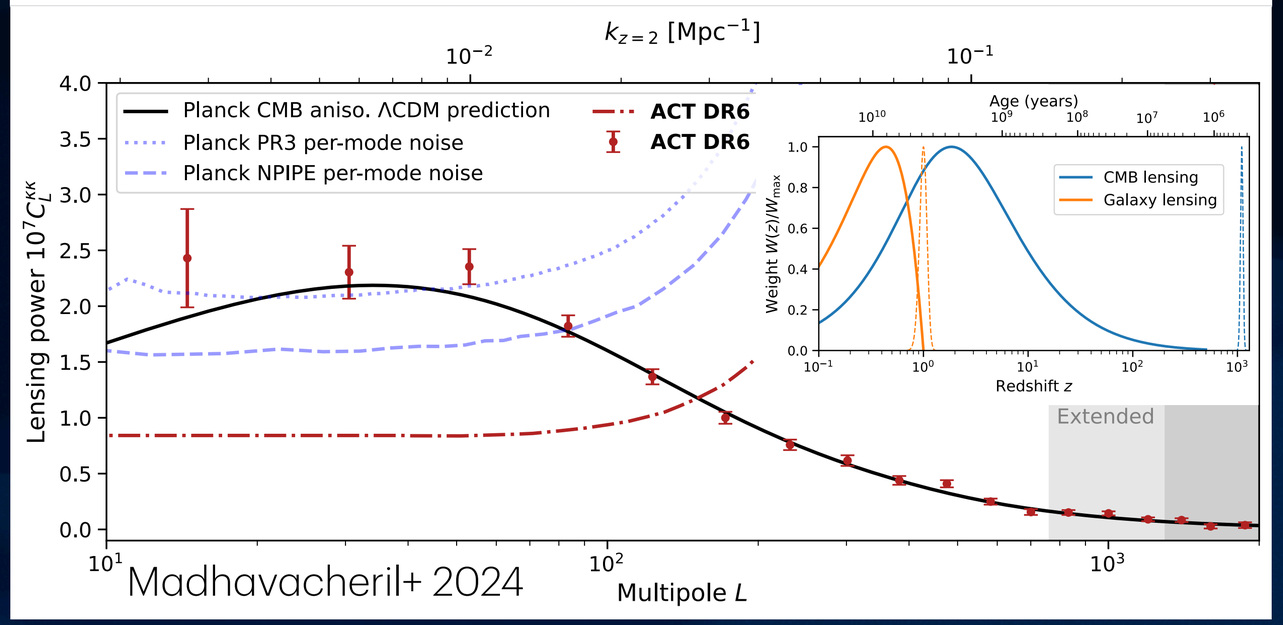
Planck PR3 temperature map

CMB weak gravitational lensing



ACT DR6 CMB lensing mass map

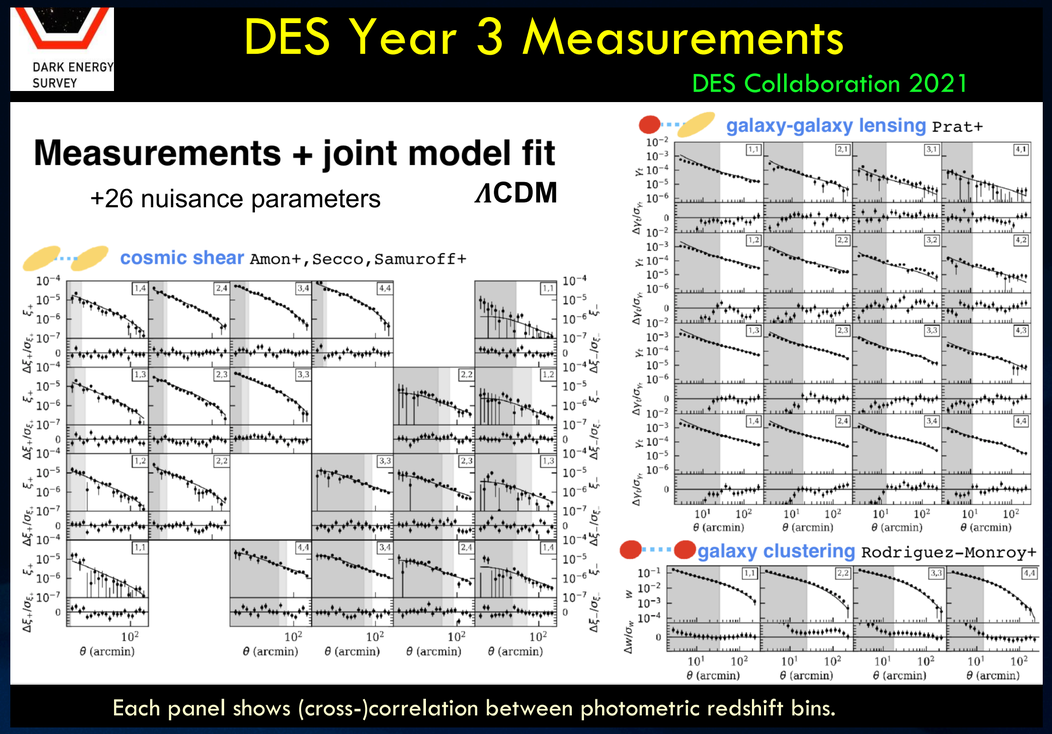




Madhavacheril+ 2024

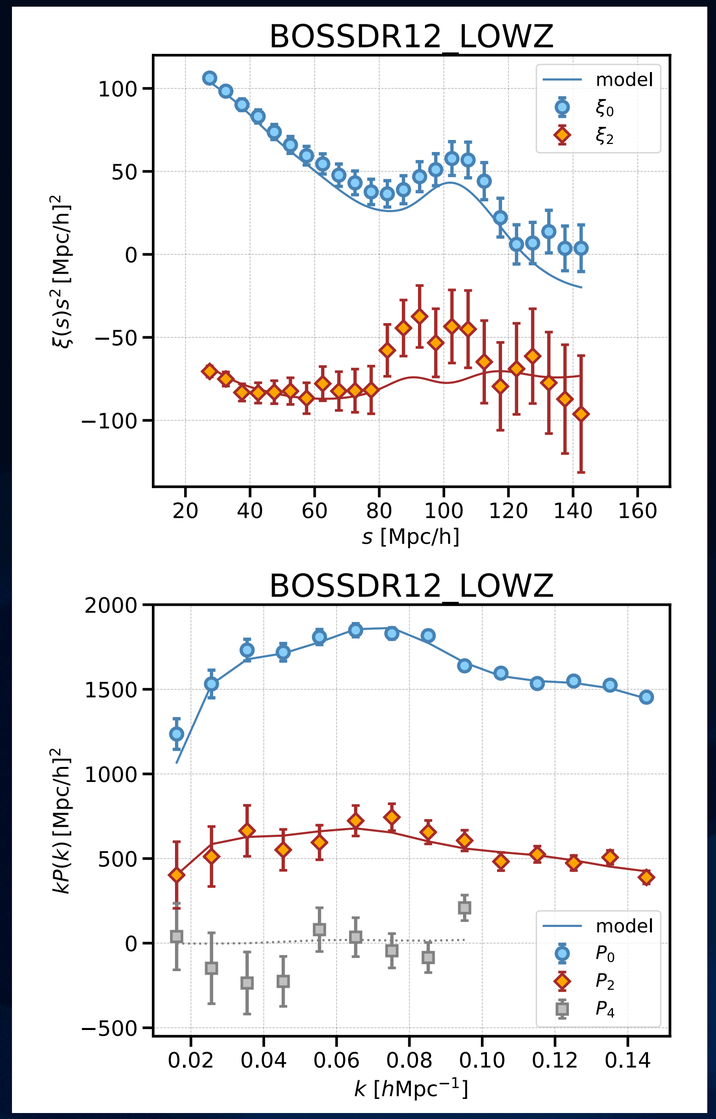
Late Universe

Late-time probes of growth

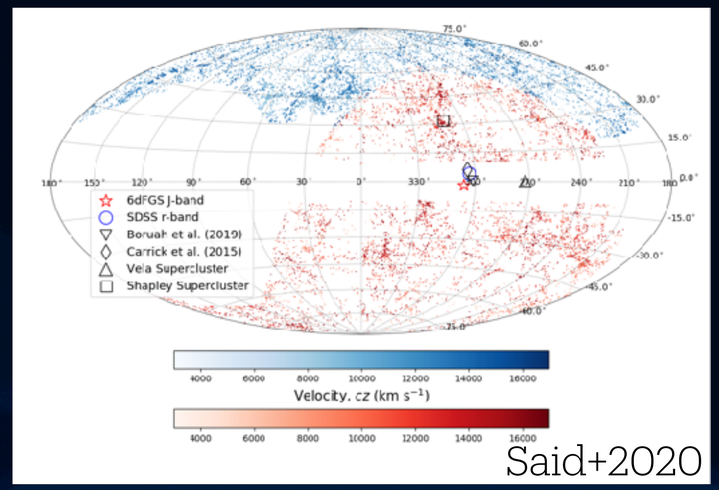


Galaxy photometric 3x2-point correlation (intermediate-late Universe)

Galaxy clustering (late Universe)

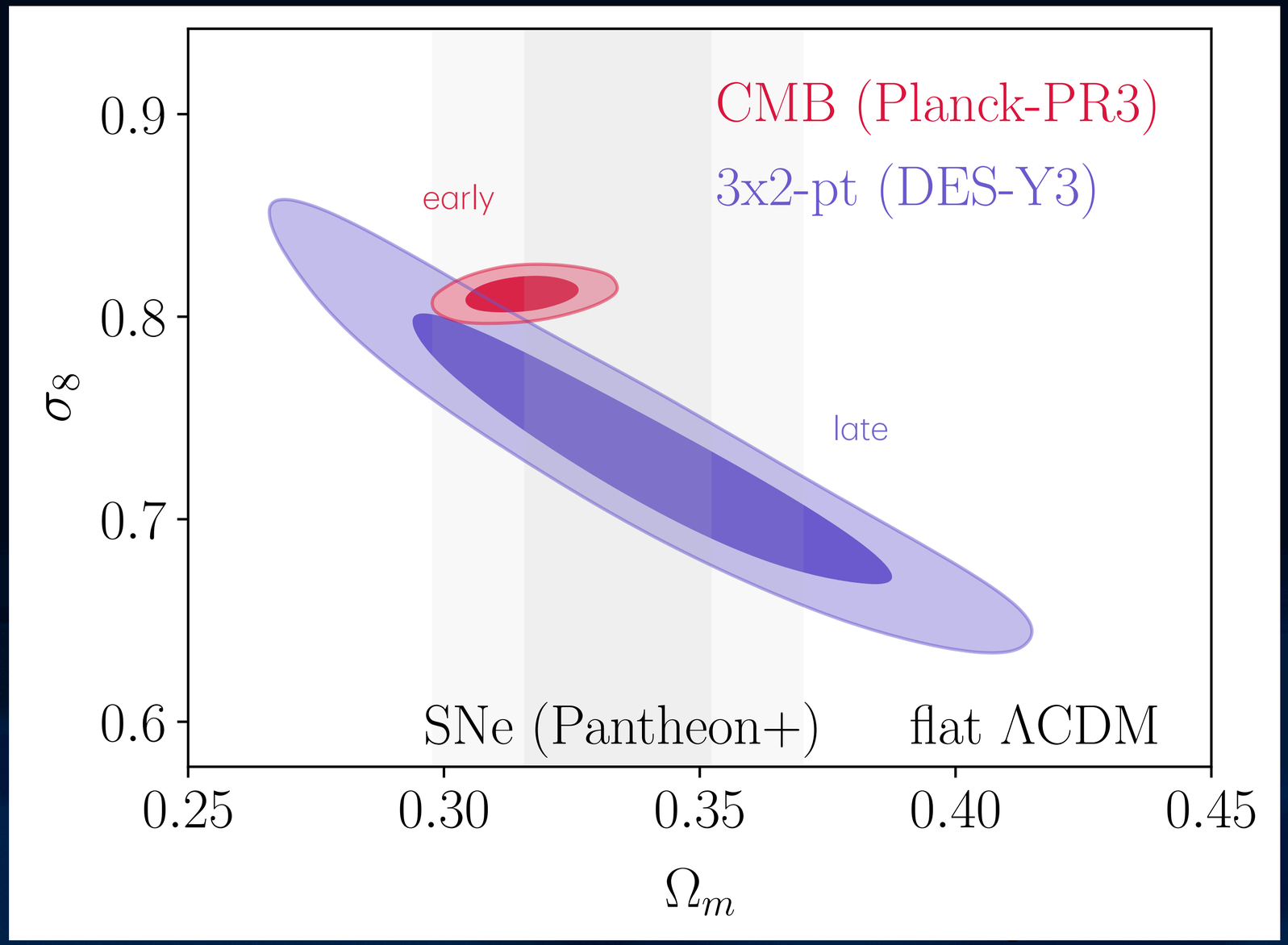


BOSS collaboration (MNRAS 470, 2617; 2017)
(plot by Jiamin Hou, MPE)



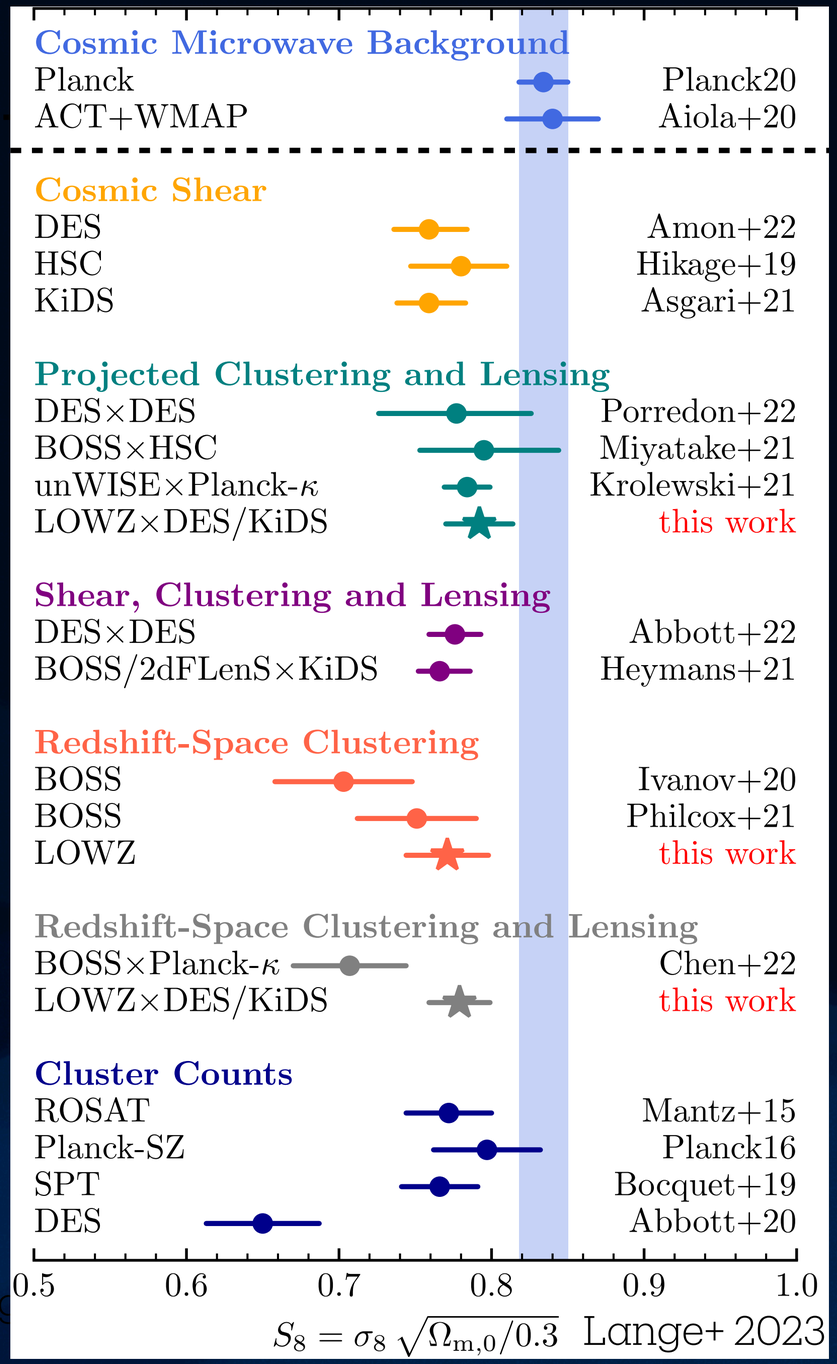
Galaxy peculiar velocity (very late Universe)

A growing tension



Early- vs Late-time tension?

Discrepancy between early- and late-time measurements?



Early- vs Late-time tension?

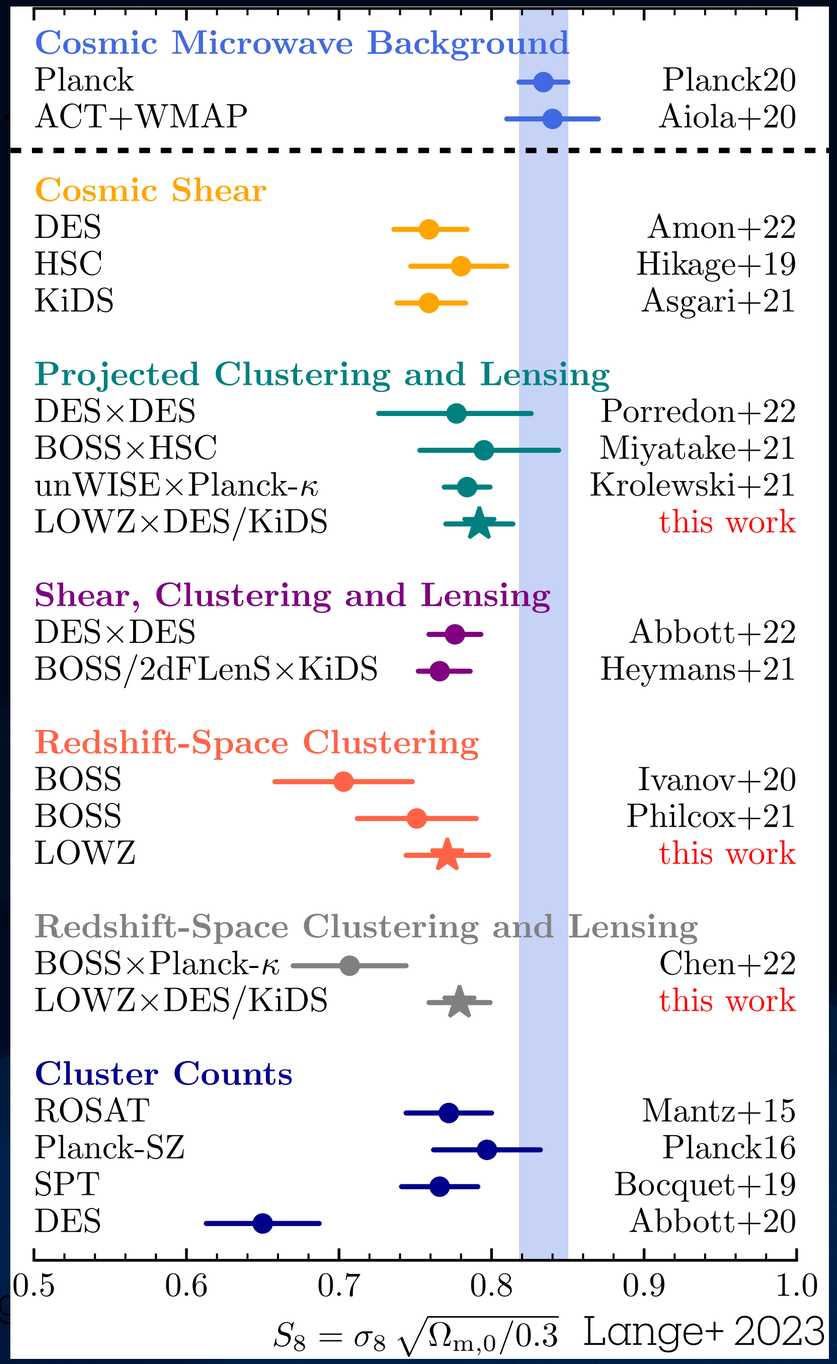
Discrepancy between

early- and late-time

~~measurements?~~

extrapolations

within ΛCDM.



Late-time new physics?

Separating Growth and Expansion histories

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

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

Late-time growth suppression?

$3.7\sigma - 4.2\sigma$ evidence

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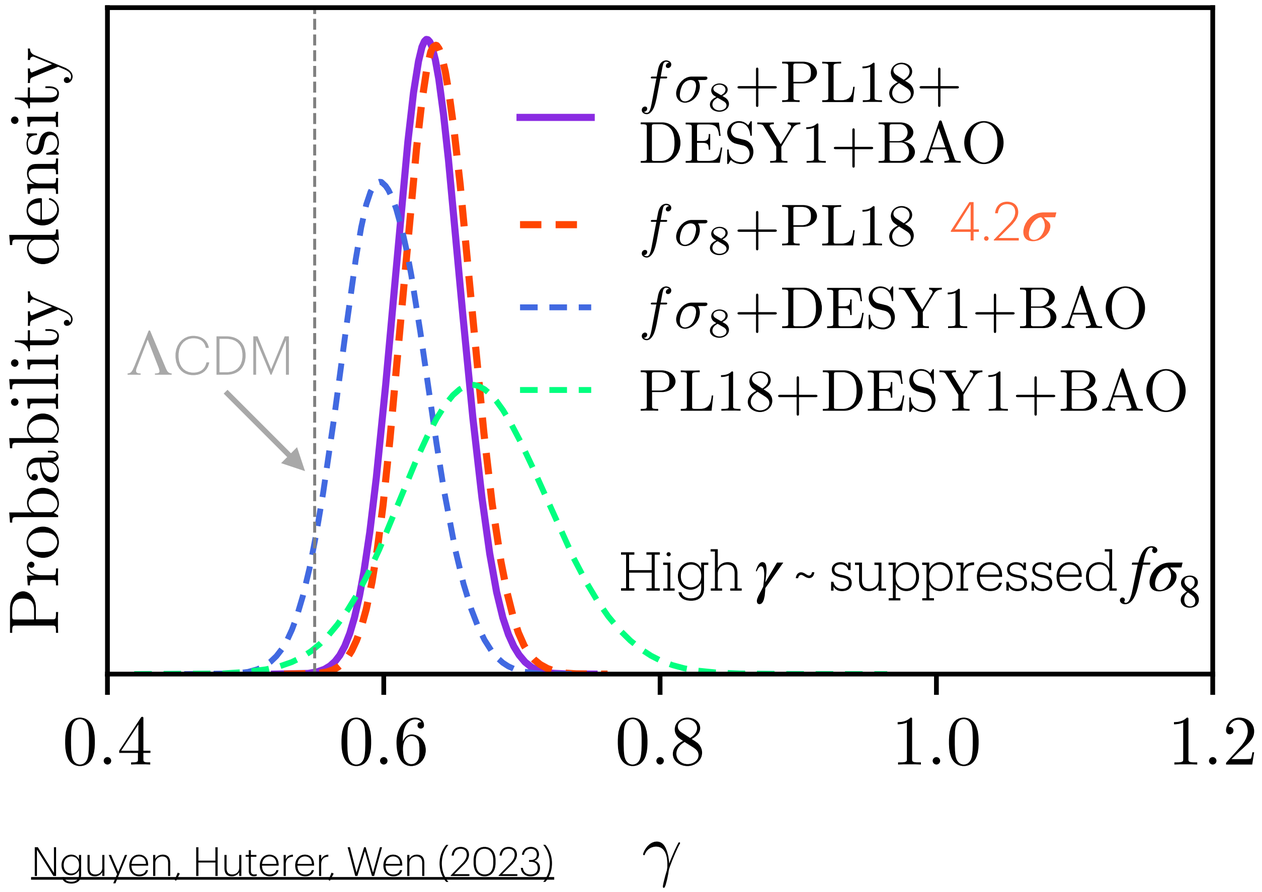
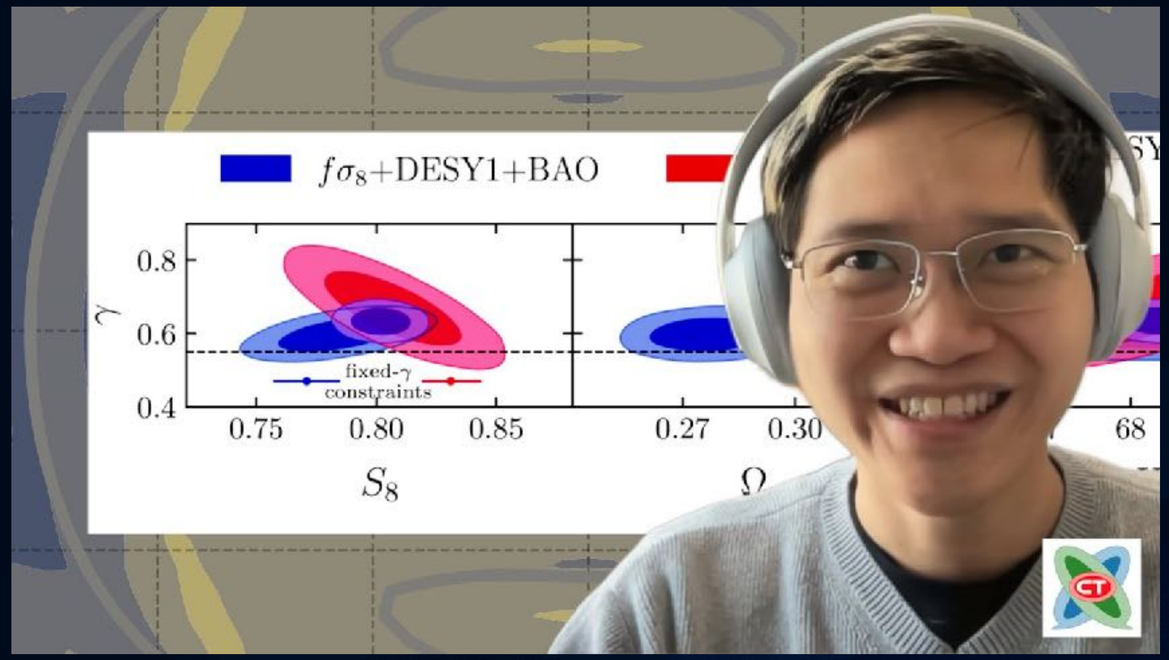


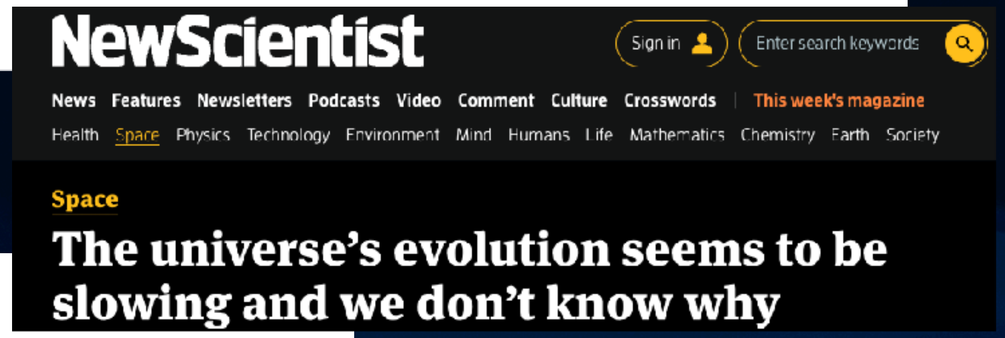
Nguyen, Huterer, Wen (2023)

Reception - Public vs Expert

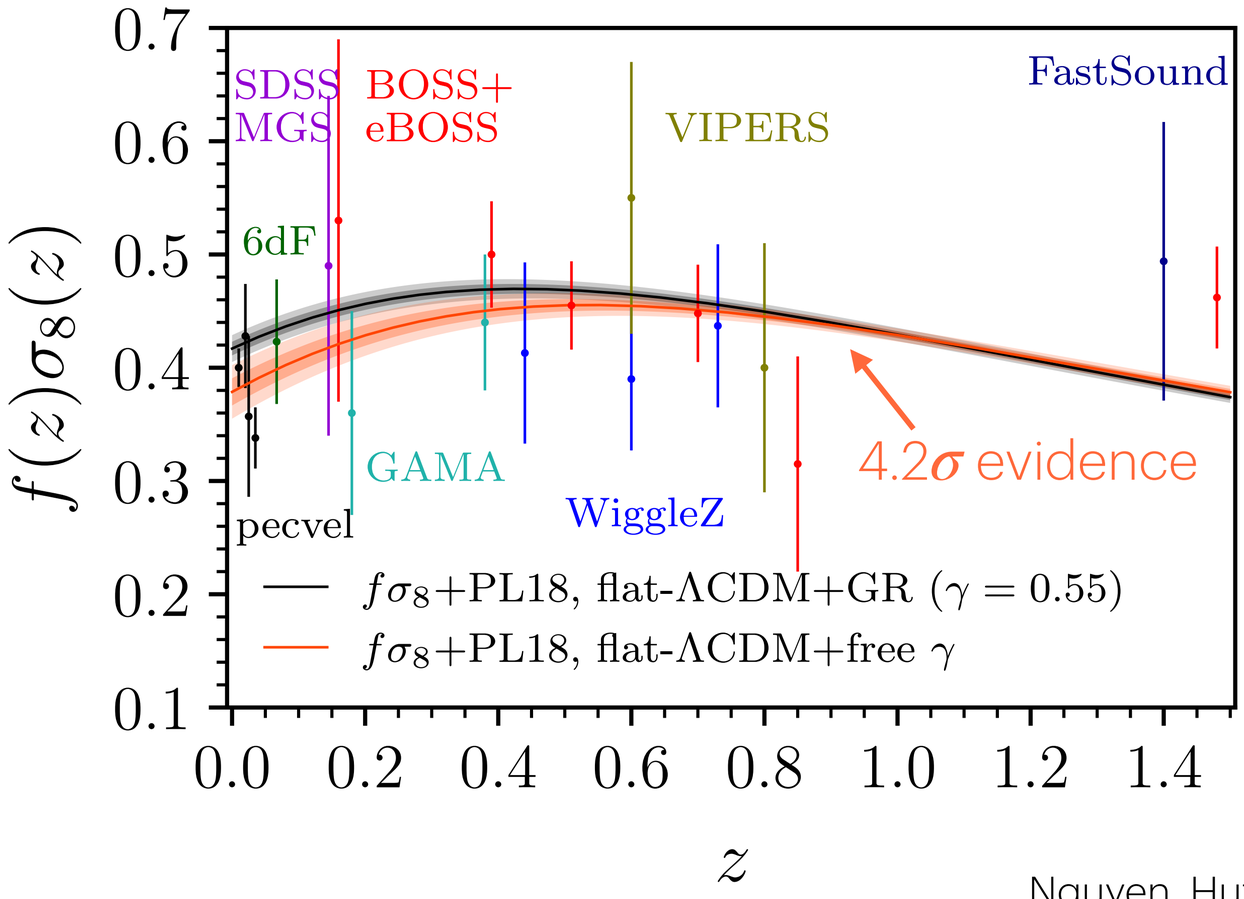


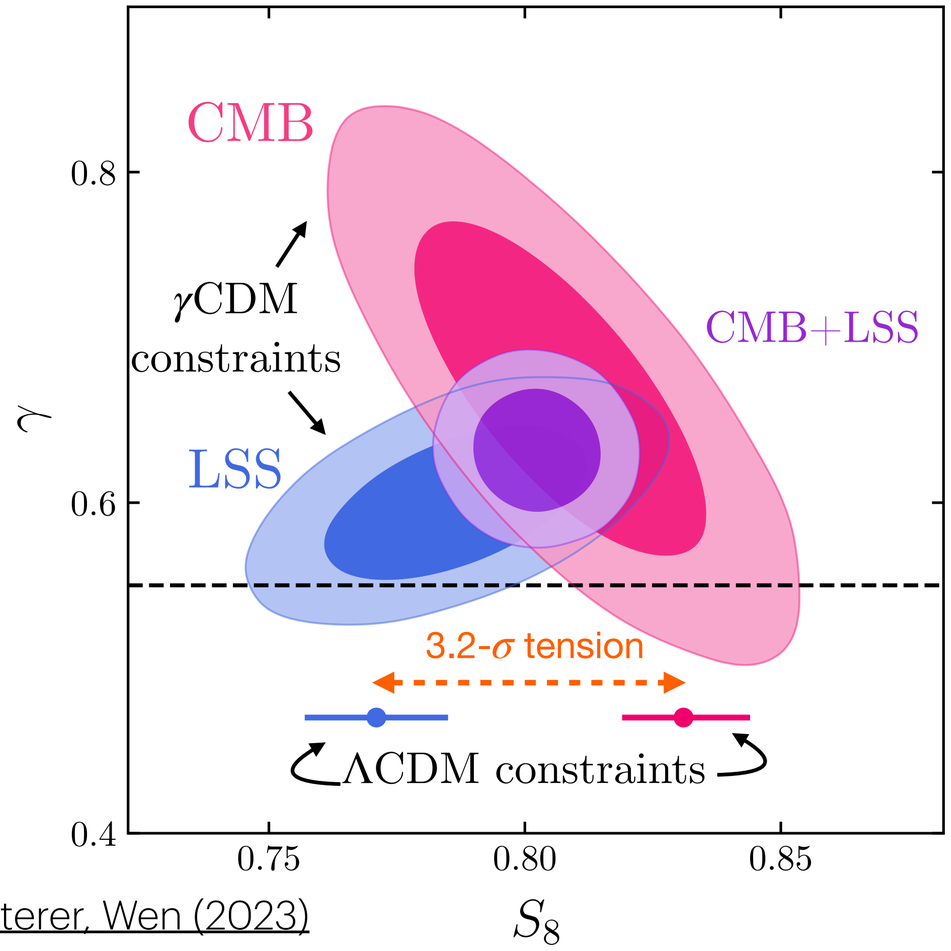
"I'm not sure I would have published this paper."

David Spergel



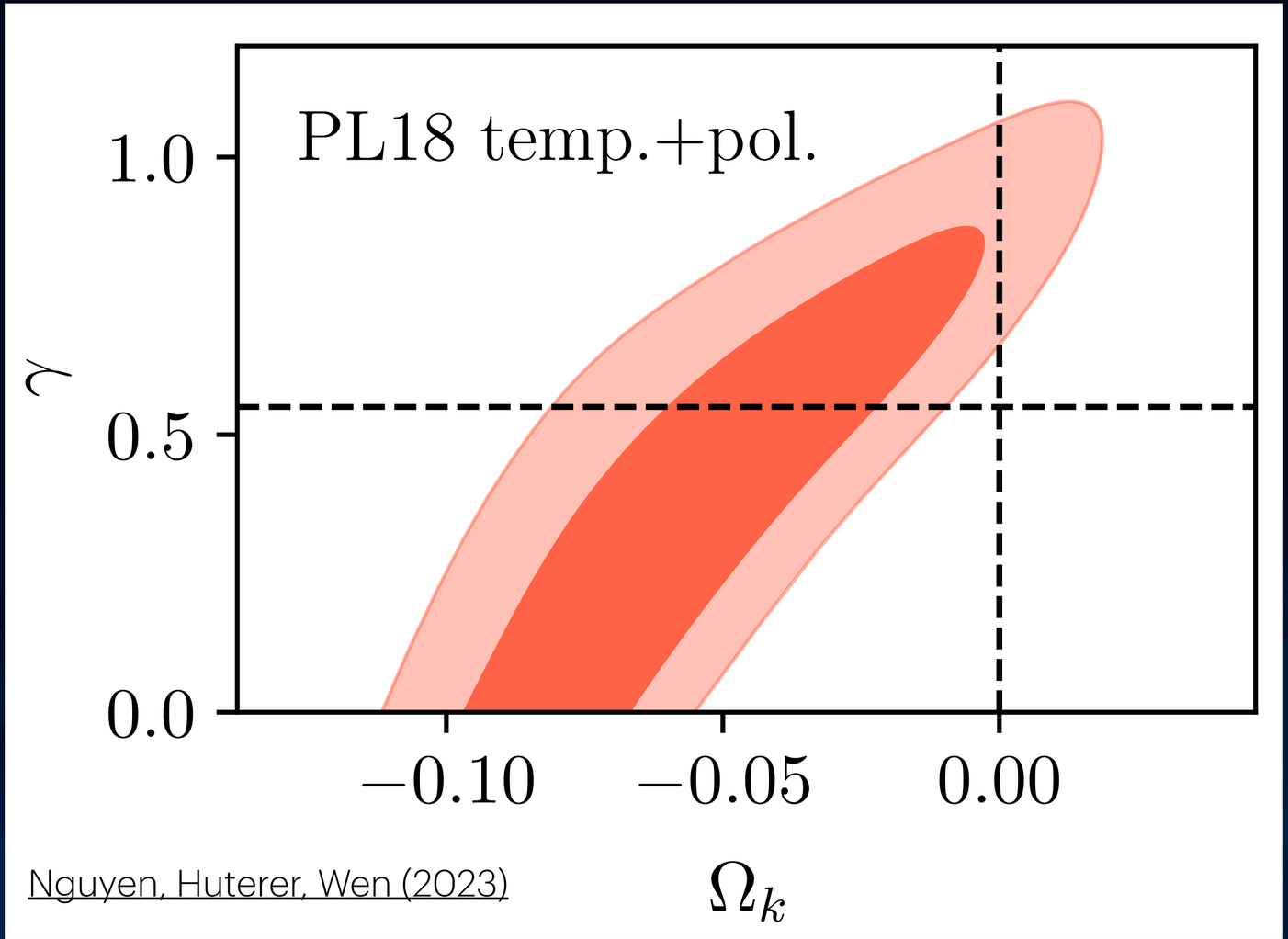
S_8 tension - a manifestation?





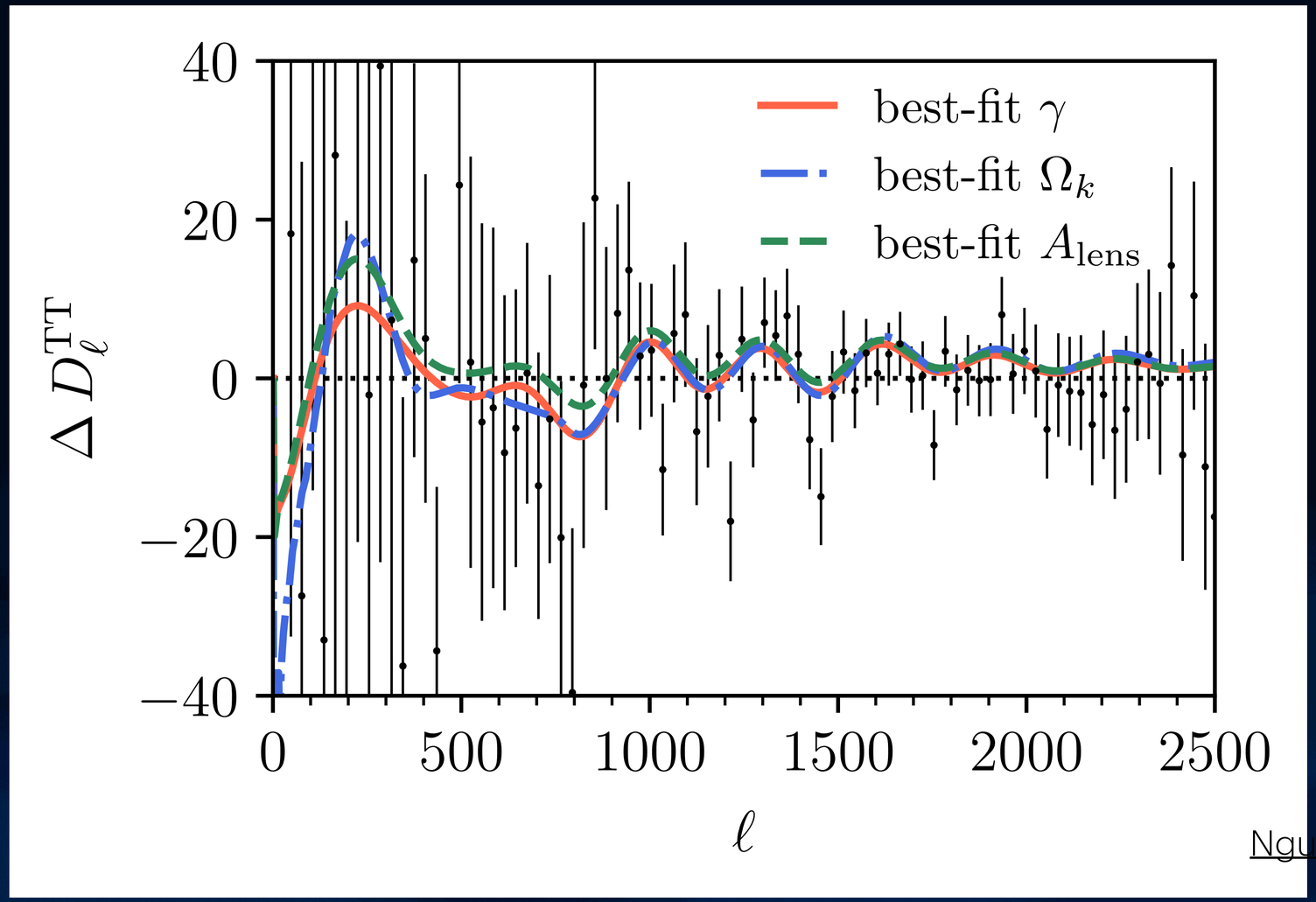
Nguyen, Huterer, Wen (2023)

Planck Ω_k preference - another manifestation?



Nguyen, Huterer, Wen (2023)

New physics or systematics?



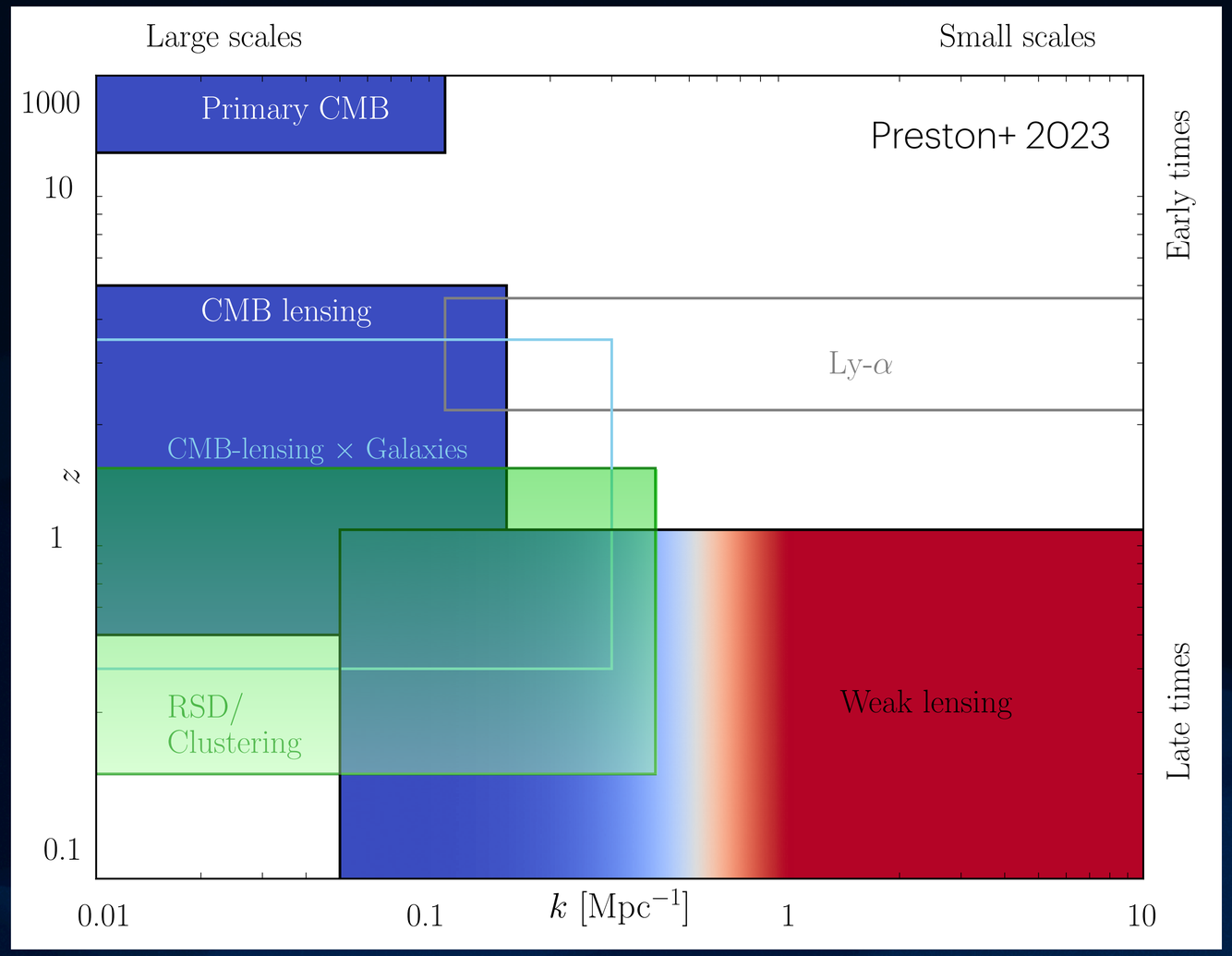
Nguyen, Huterer, Wen (2023)

Nguyen, Huterer, Wen (2023)

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?



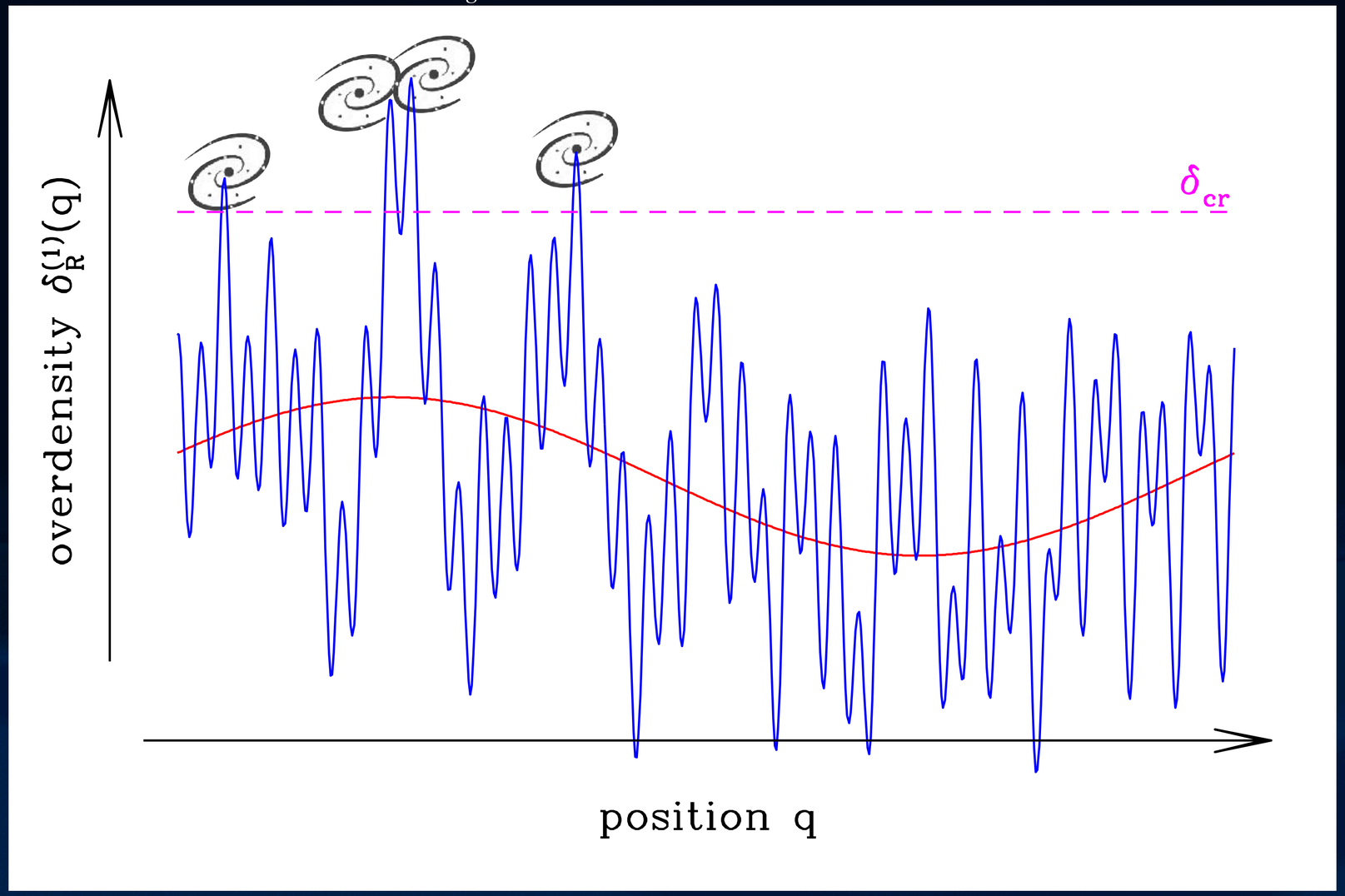
Lange+ 2023

Squeezing σ_8 from Galaxy Clustering

Field-level **B**ayesian **I**nference (FBI) in millions of dimensions

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

$$P_{\delta_g}(k,z) \sim b_\delta^2(z)\, P_L(k,z)$$



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

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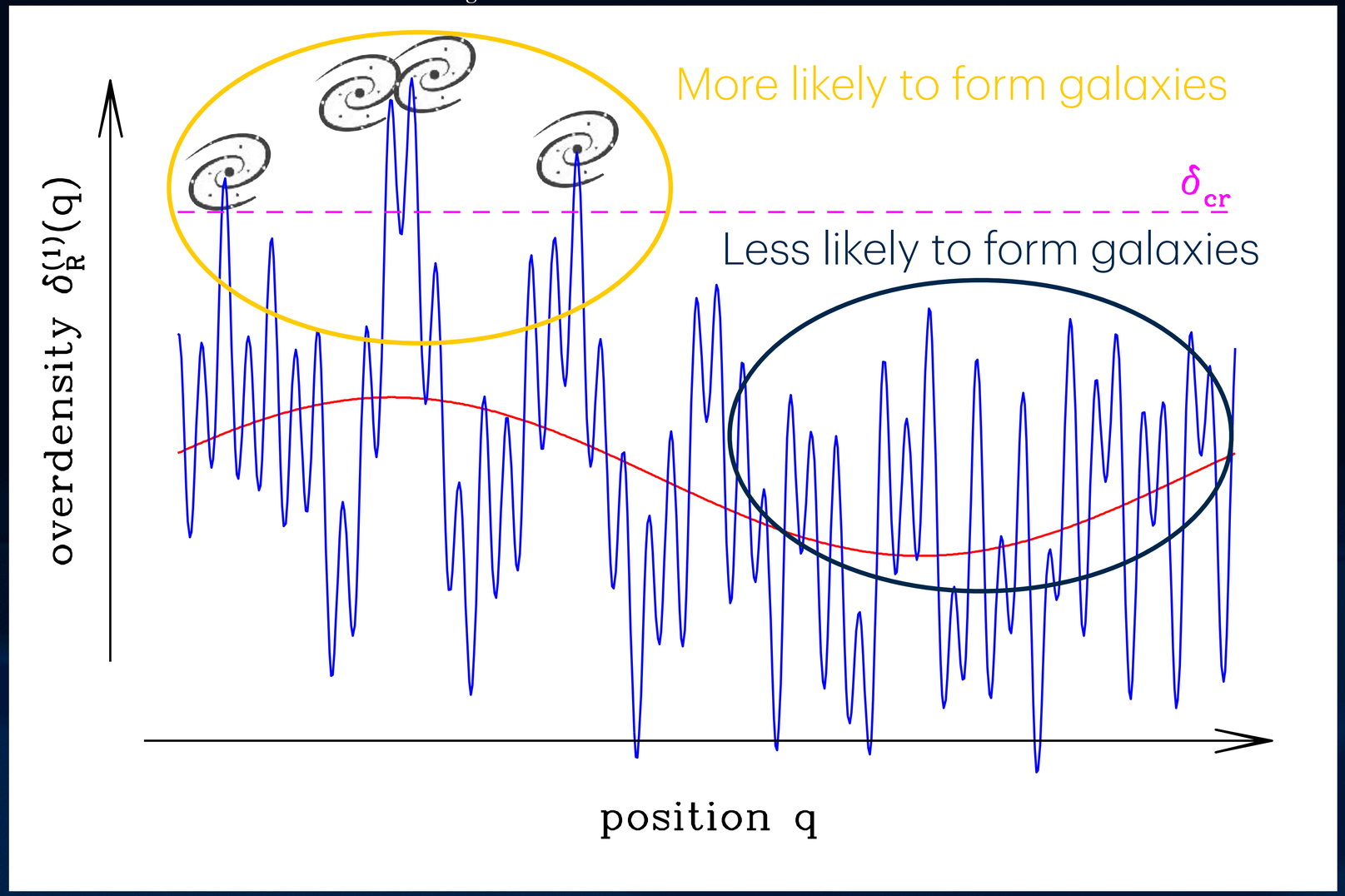
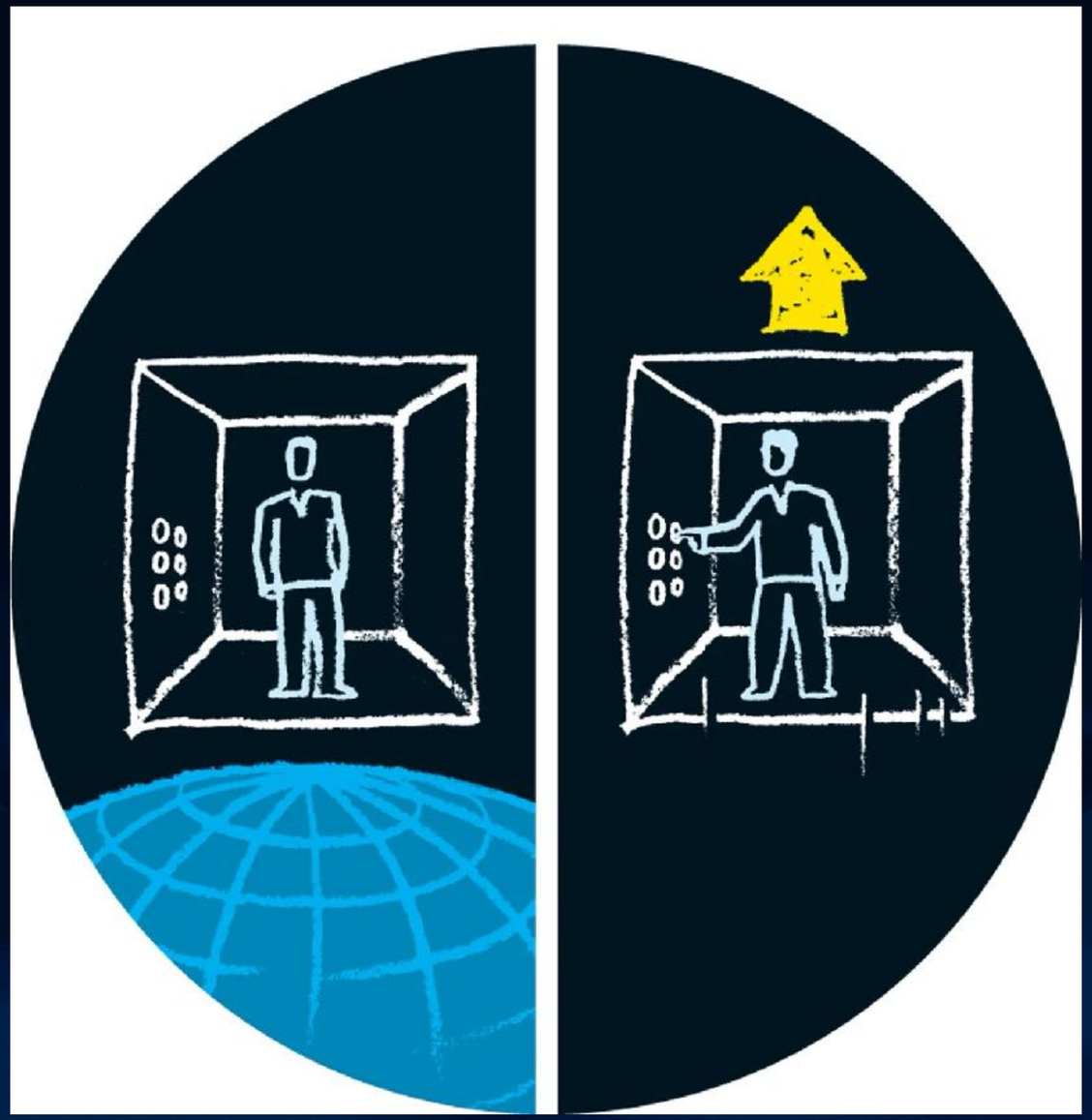


Breaking degeneracy with nonlinear clustering



Breaking degeneracy with nonlinear clustering

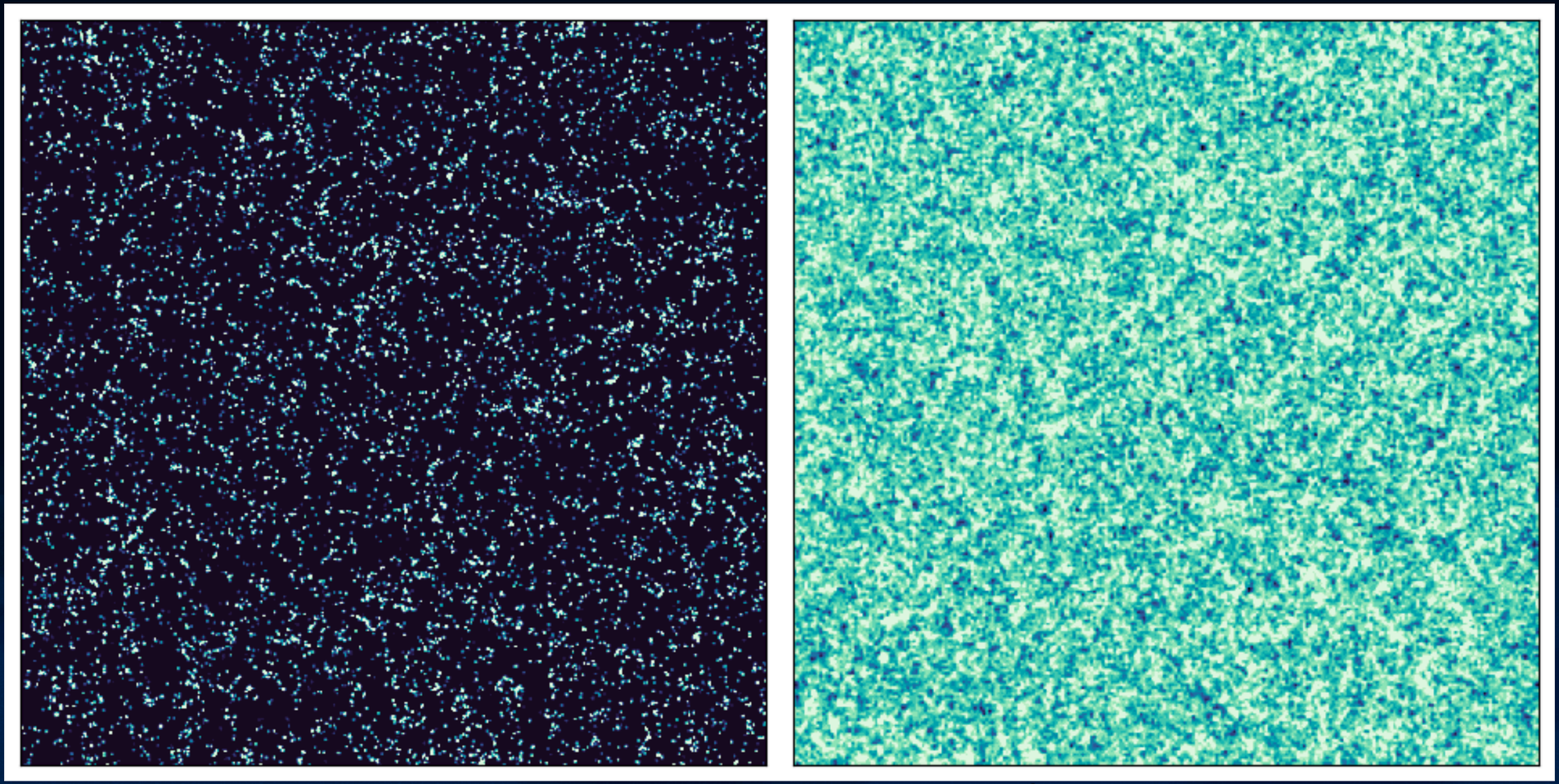
$$\delta_g = b_1 \delta^{(1)} \sim b_1 \sigma_8$$

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

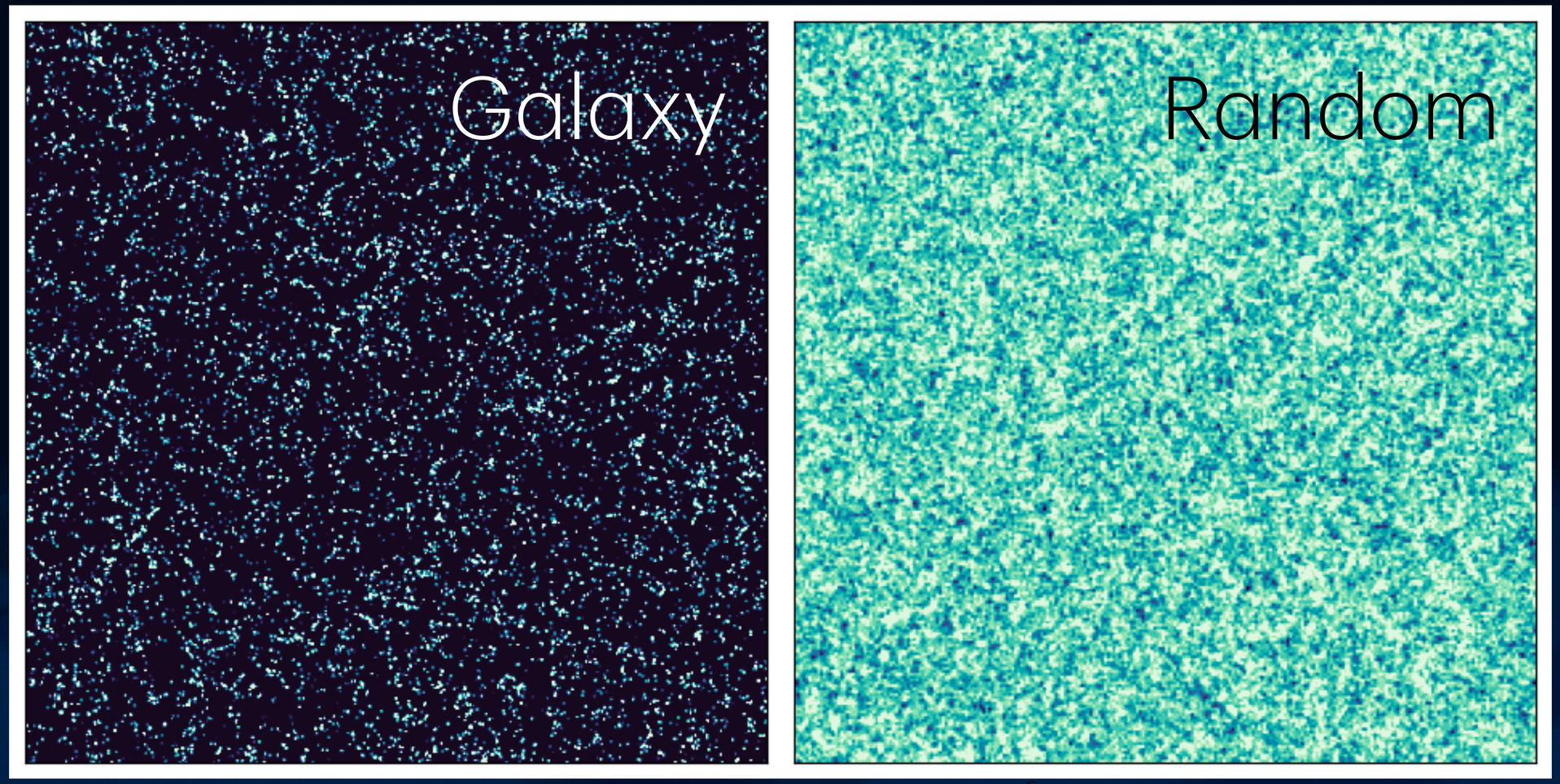
$$\delta^{(2)} = \frac{17}{21}\left[\delta^{(1)}\right]^2 + \frac{2}{7}\left[K_{ij}^{(1)}\right]^2 - s_{(1)}^i \partial_i \delta^{(1)}$$

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

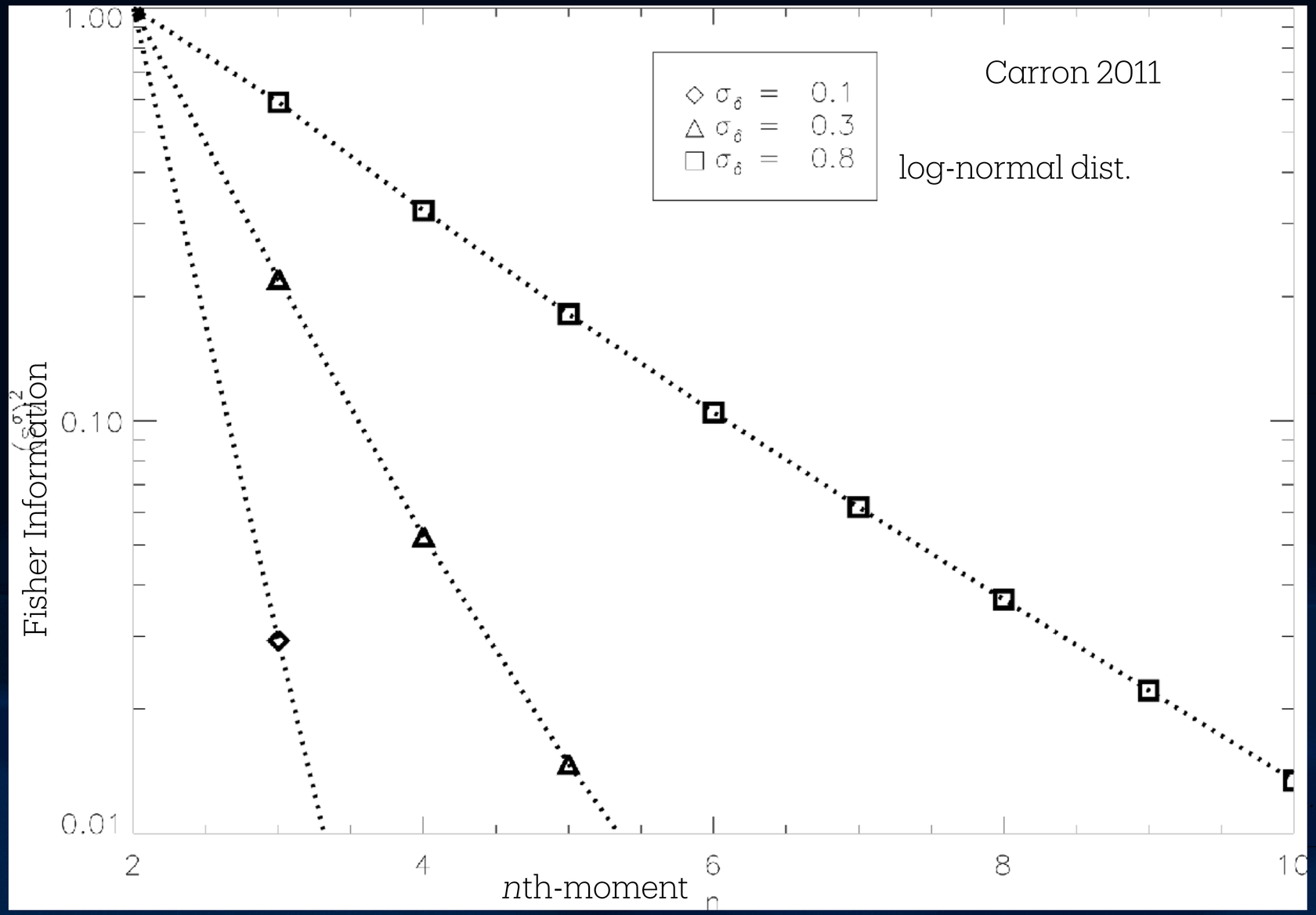
Nonlinear clustering beyond power spectrum



Nonlinear clustering beyond power spectrum



How much information exists beyond 2-point function?



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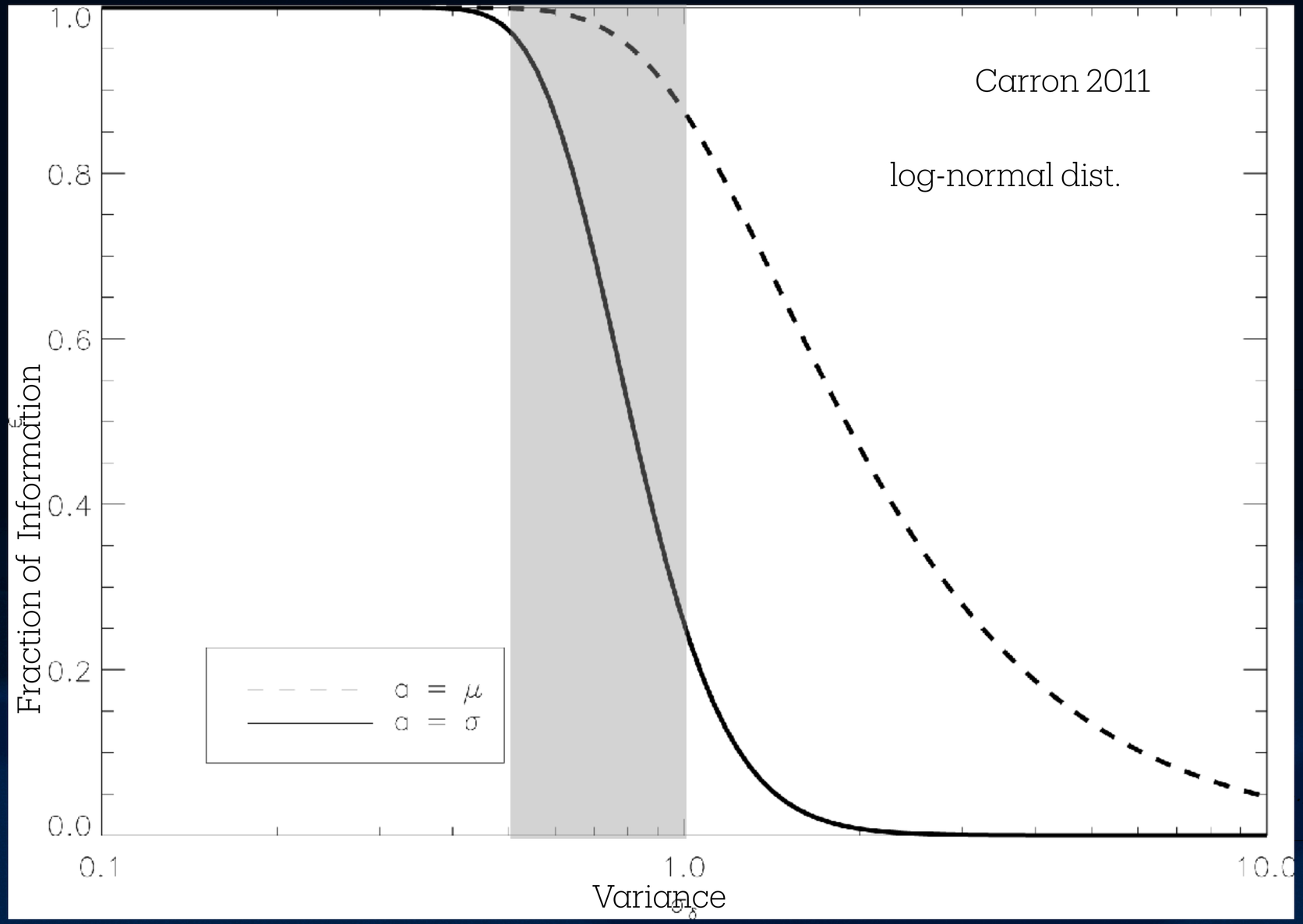
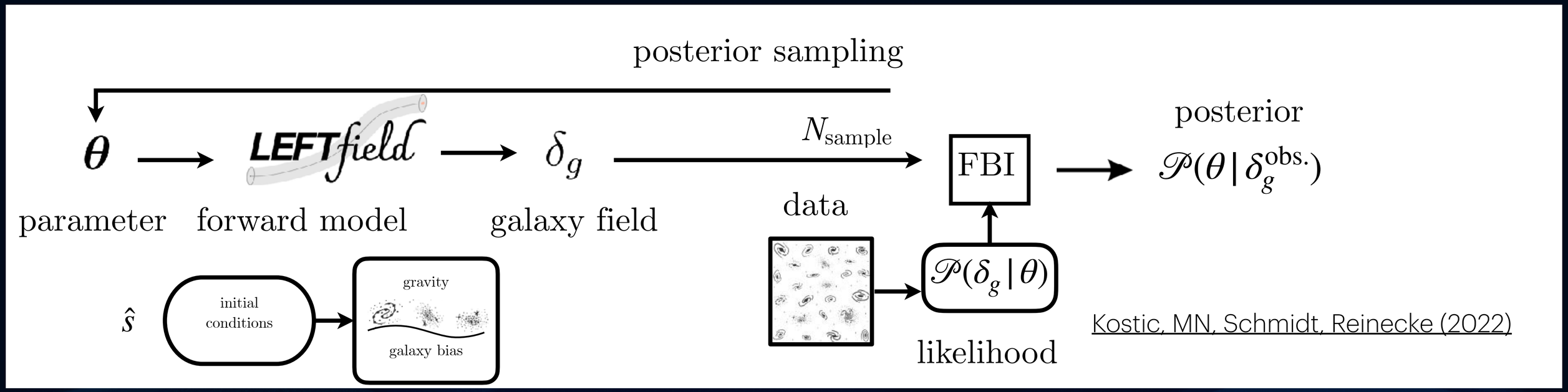


Field-level Bayesian Inference of galaxy clustering



Kostic, MN, Schmidt, Reinecke (2022)

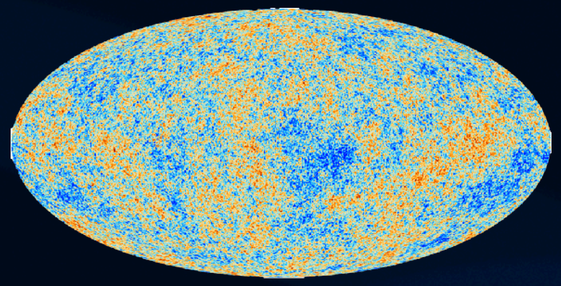
FBI — forward modeling

$$\mathscr{P}\left(\alpha \,|\, \delta_d\right) = \int_{\delta_g} \mathscr{P}\left(\delta_d \,|\, \alpha, \delta_g\right) \boxed{\mathscr{P}\left(\alpha, \delta_g\right)}$$

No analytical expression!

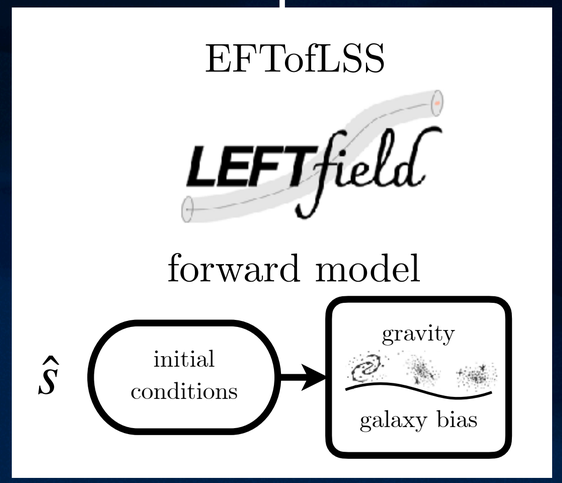
$$\mathscr{P}\left(\alpha \,|\, \delta_d\right) = \int_{\hat{s}} \mathscr{P}\left(\delta_d \,|\, \alpha, \delta_g(\alpha, \hat{s})\right) \mathscr{P}(\alpha) \boxed{\mathscr{P}\left(\hat{s}\right)}$$

Very close to Gaussian!



Planck PR3 temperature map

see also Planck 2018 results. VII

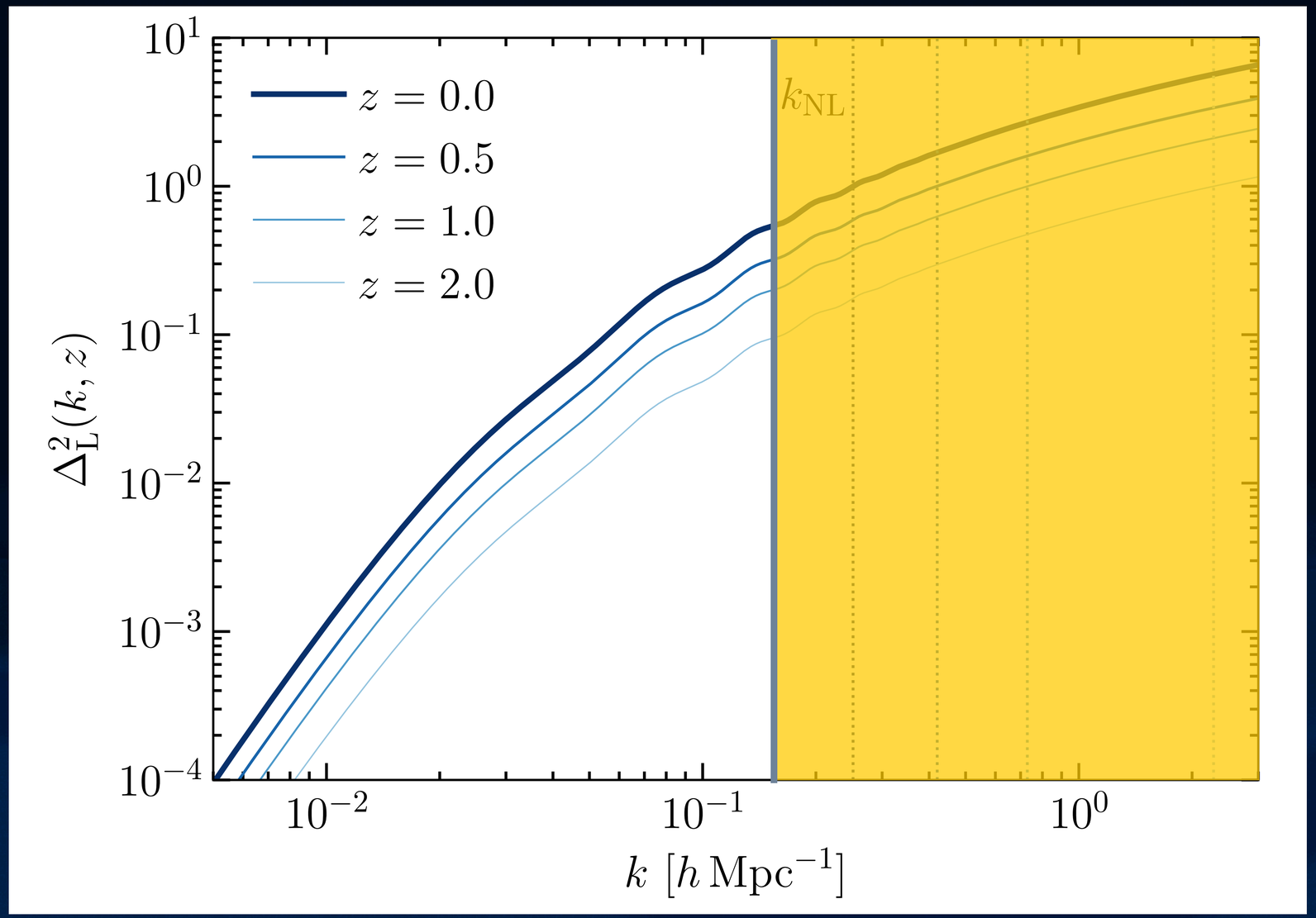


real-space mock

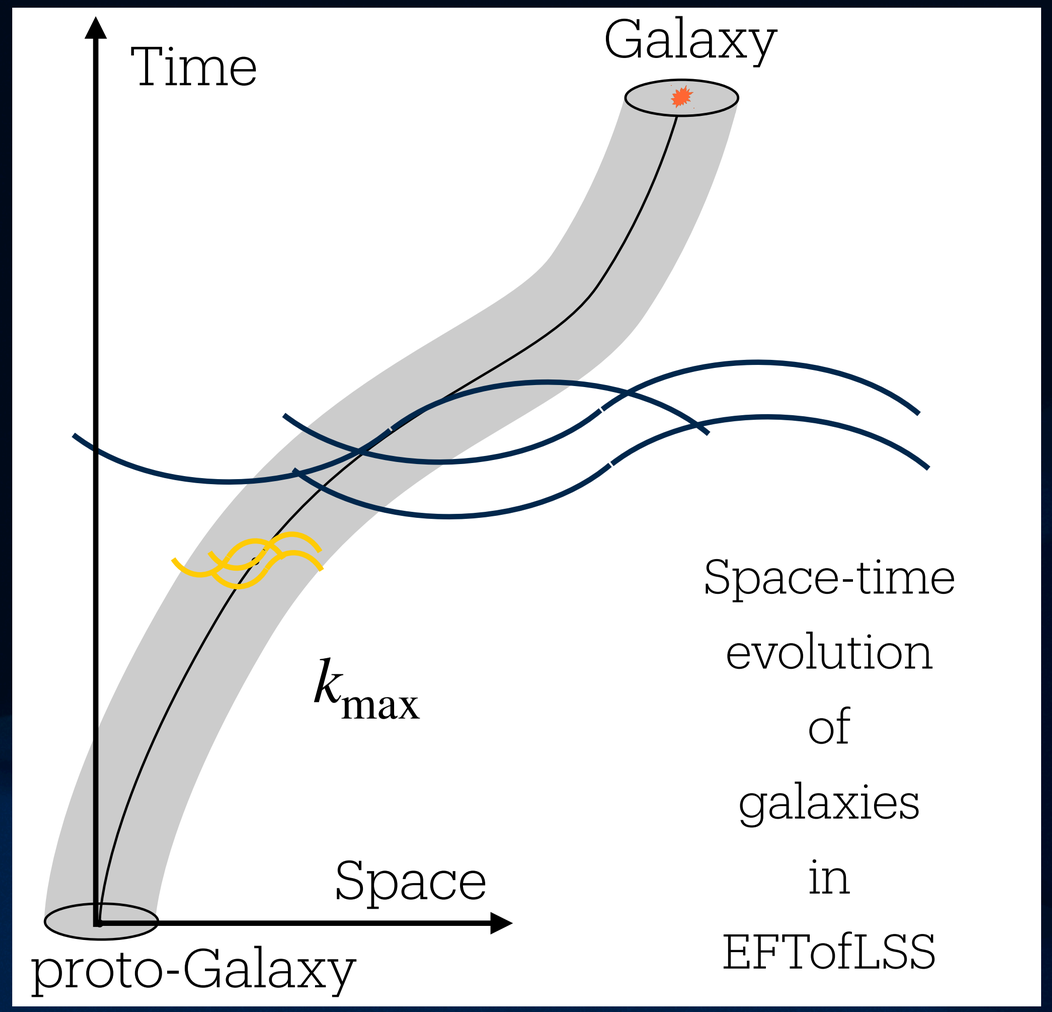
FBI — Effective Field Theory forward model

$\delta_{k_{\max}}$ $k_{\max}$ δ_s

Time



FBI — EFT galaxy bias and likelihood



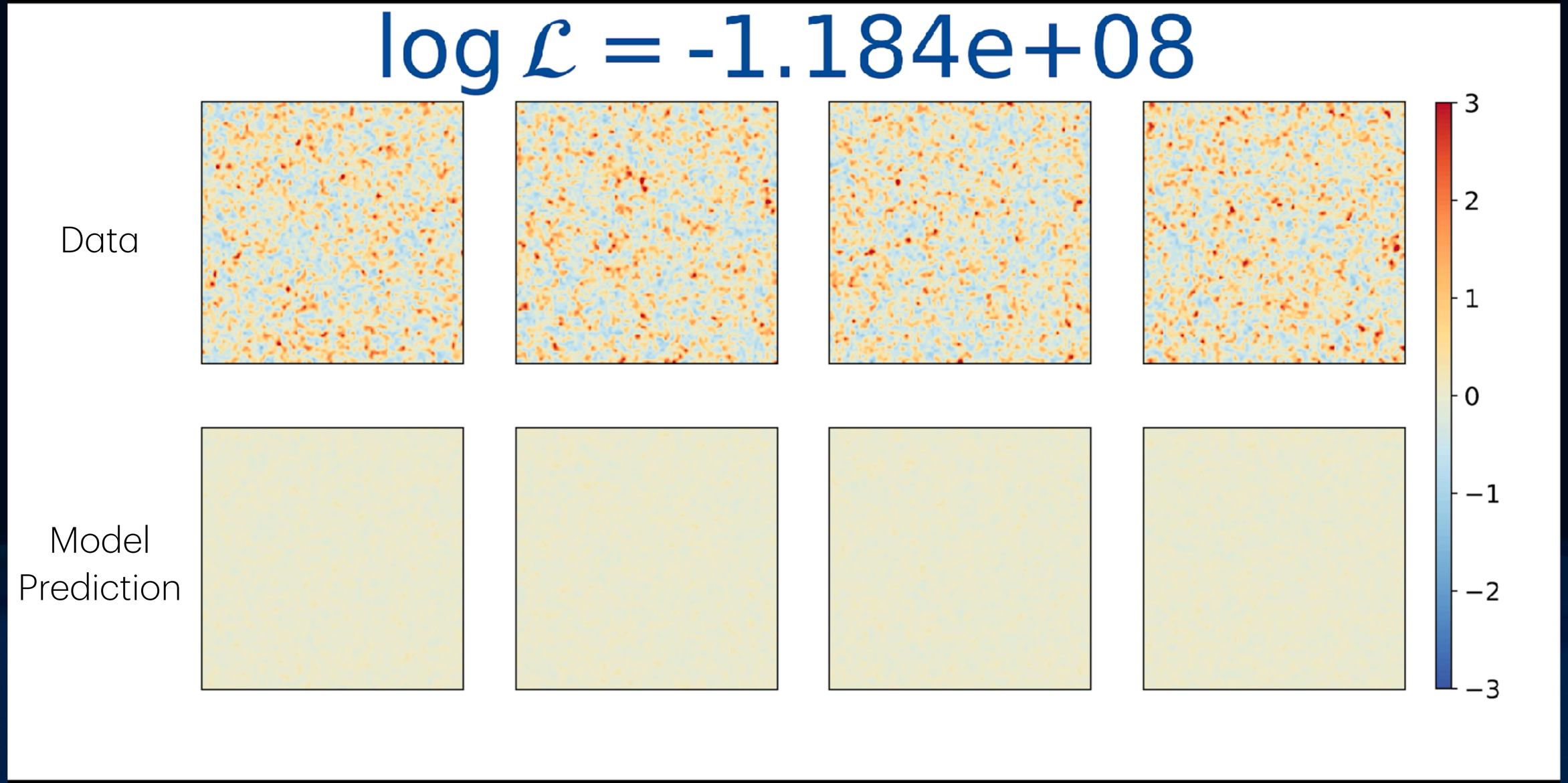
$$\delta_g(\mathbf{k}) = \sum_O b_O O\left(k\right) + \epsilon$$

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

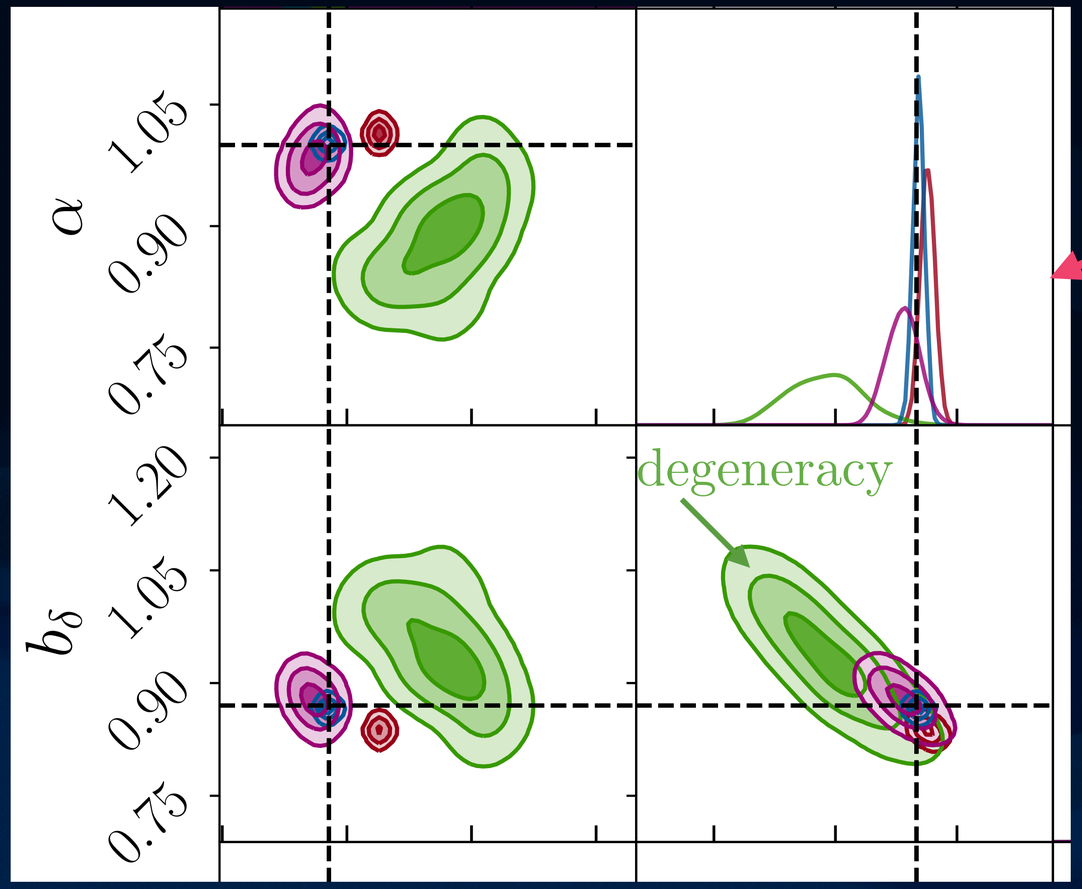
Constrain observed galaxy field in 3D

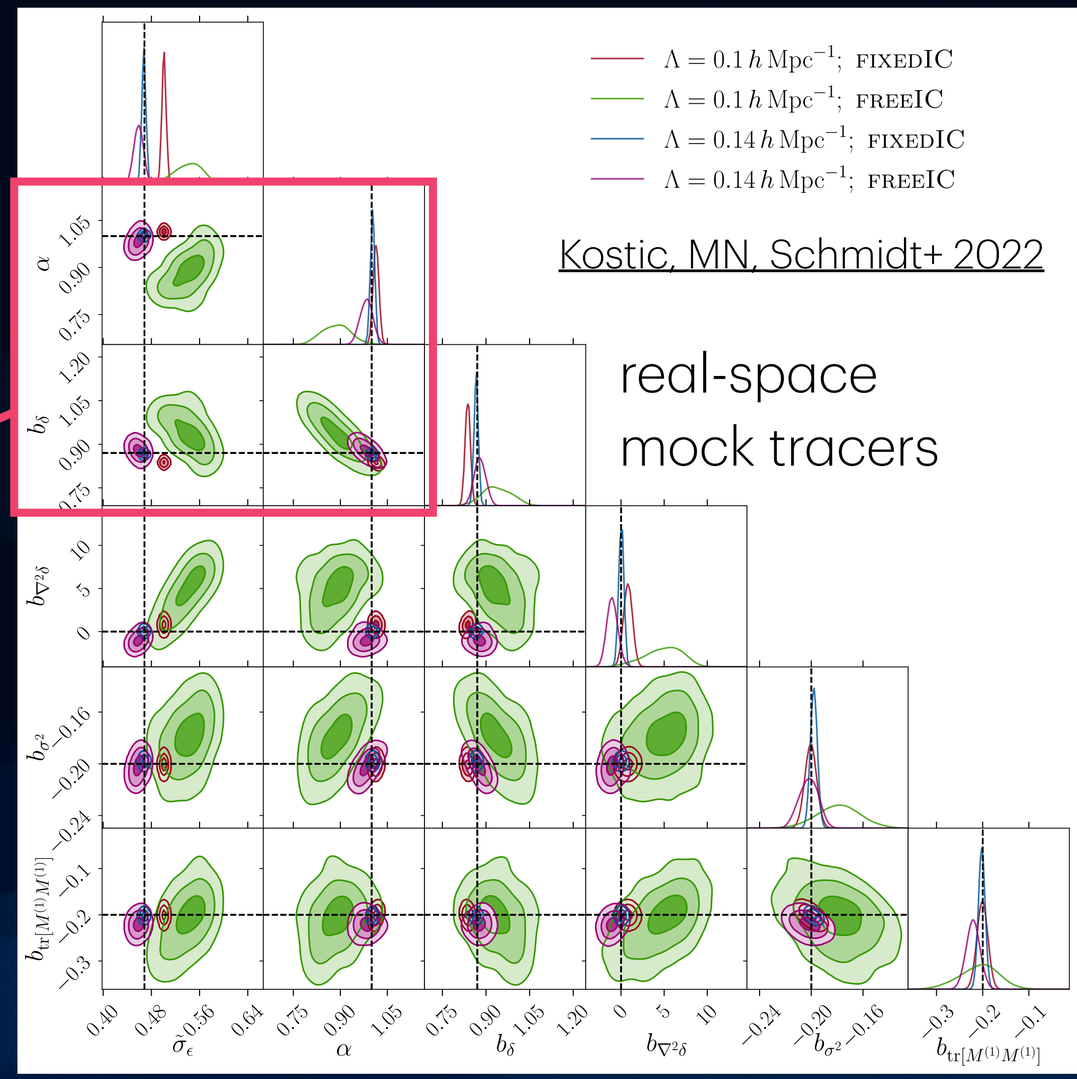


Constrain cosmology and galaxy bias

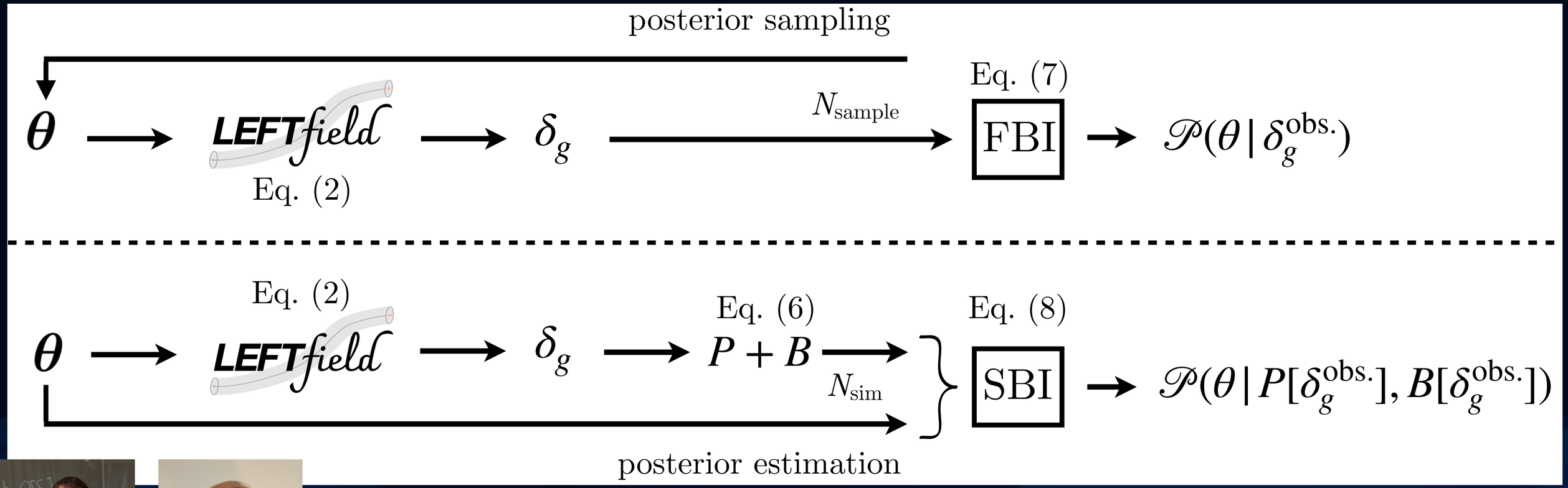
$$\alpha = \frac{\sigma_8}{\sigma_{8,\mathrm{true}}}$$

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





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

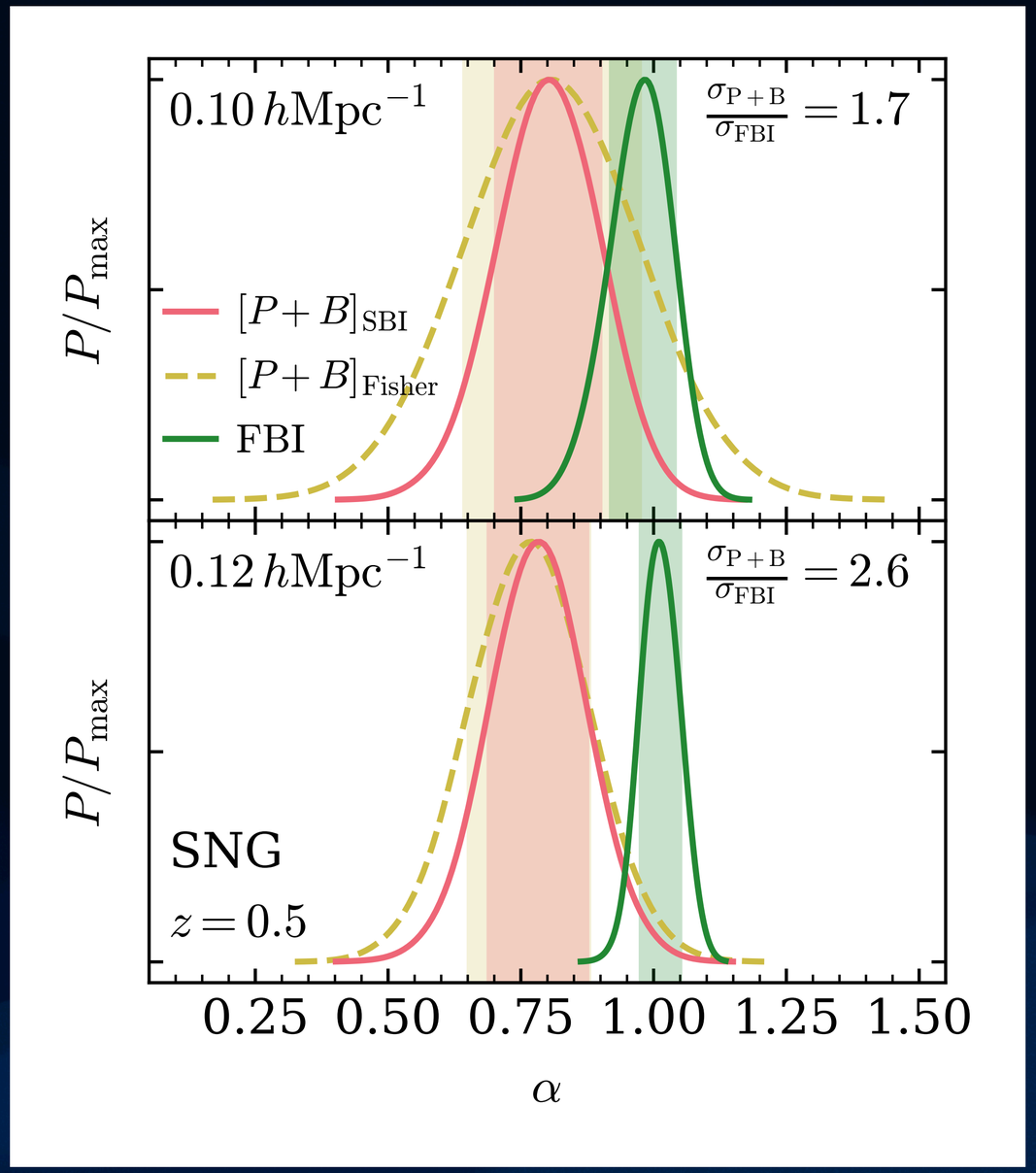
Dark-matter main halos

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

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

Improvement increases with scale cut

MN, Schmidt, Tucci+ 2024



Improvement generalizes across tracers

More apple-to-apple comparison

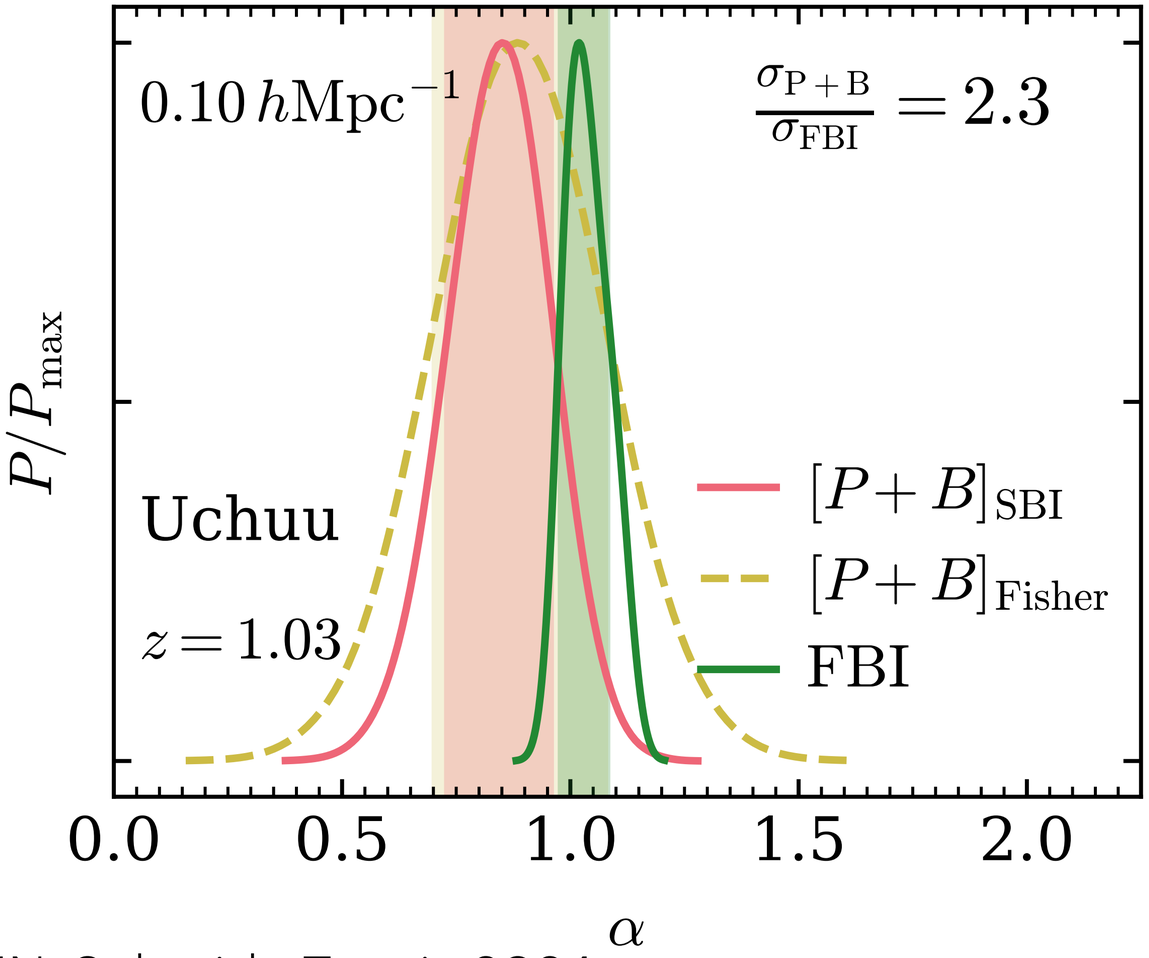
Uchuu simulations Ishiyama+ 2020

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

Evidence from (more) "realistic" galaxies

Apple-to-orange comparisons

First community exercise

7 international teams

HOD galaxies in different

frames

cosmologies

~~Blind~~ Parameter-masked challenge

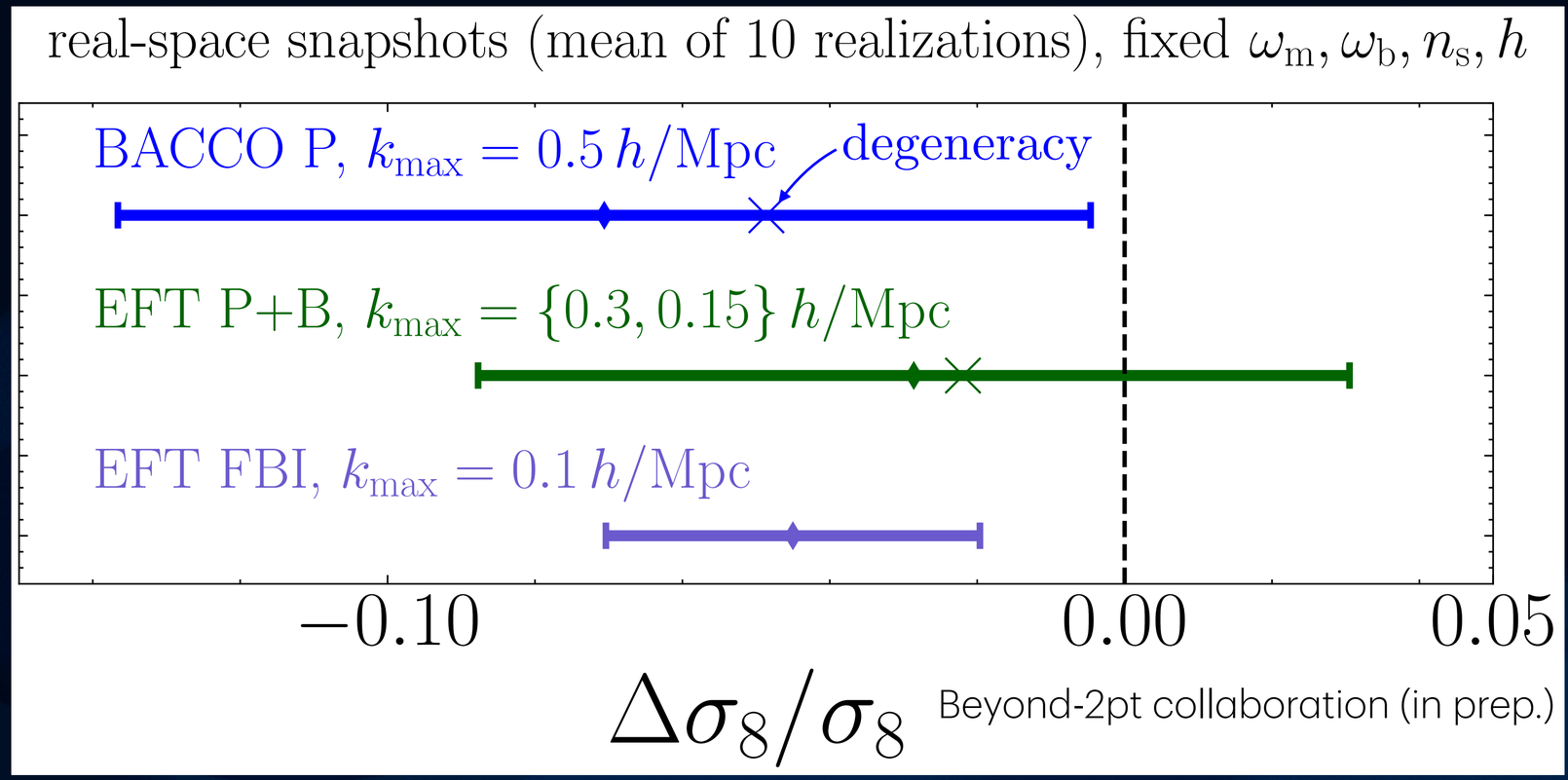
First field-level constraint

from "realistic" tracers

Beyond-2pt challenge

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

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



Beyond-2pt collaboration (in prep.)

EFT FBI team: MN and Schmidt

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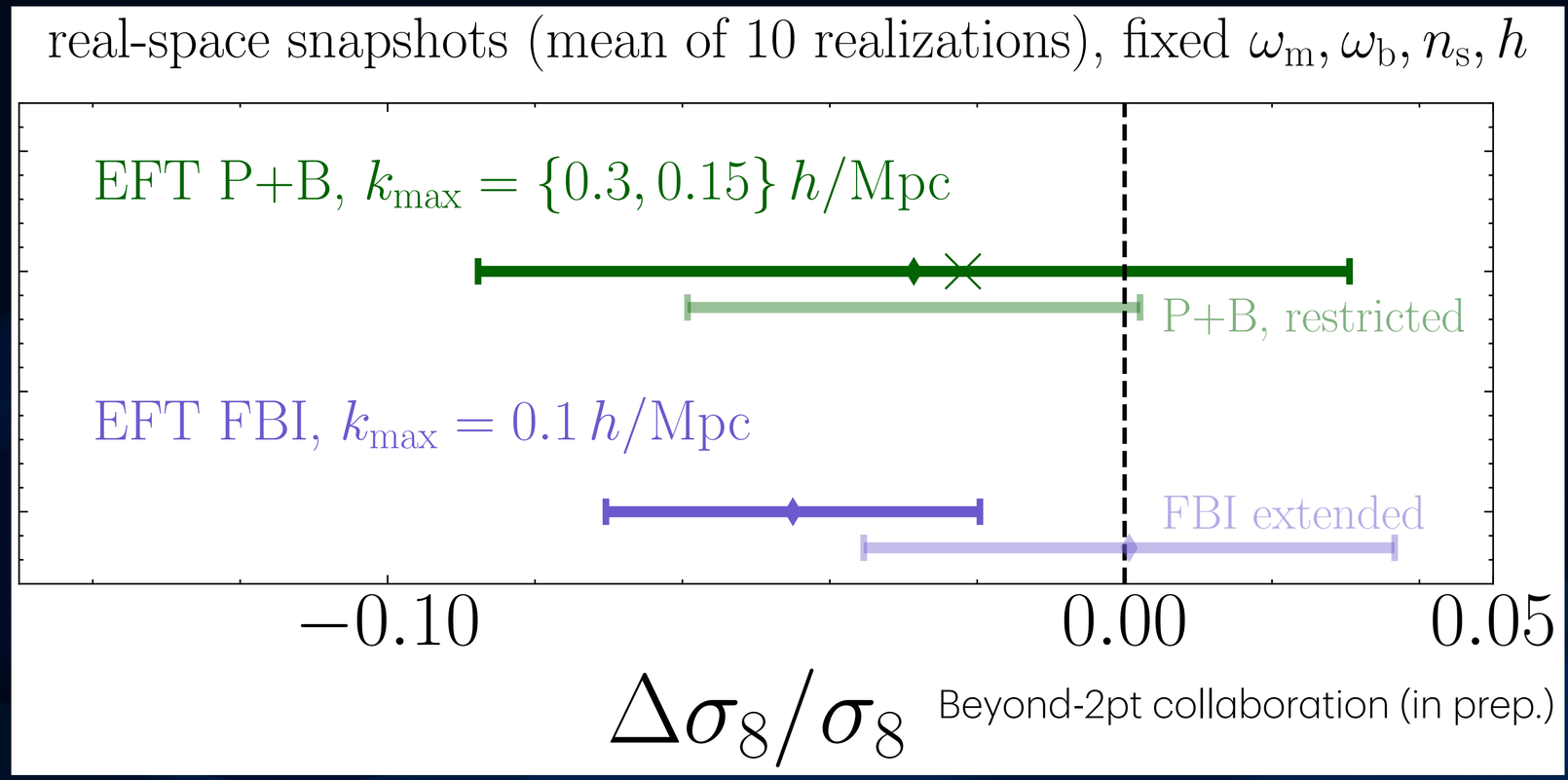


Beyond-2pt collaboration (in prep.)

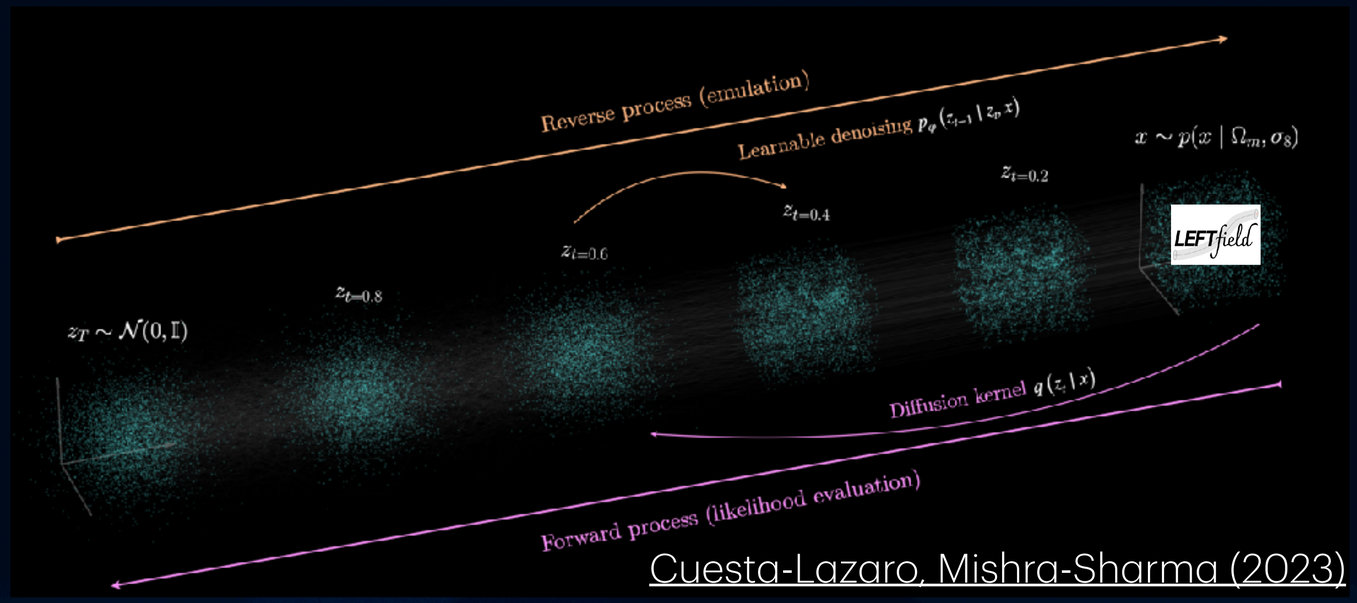
EFT FBI team: MN and Schmidt

Scaling up and Expanding FBI

New Physics from Galaxy Clustering and Beyond

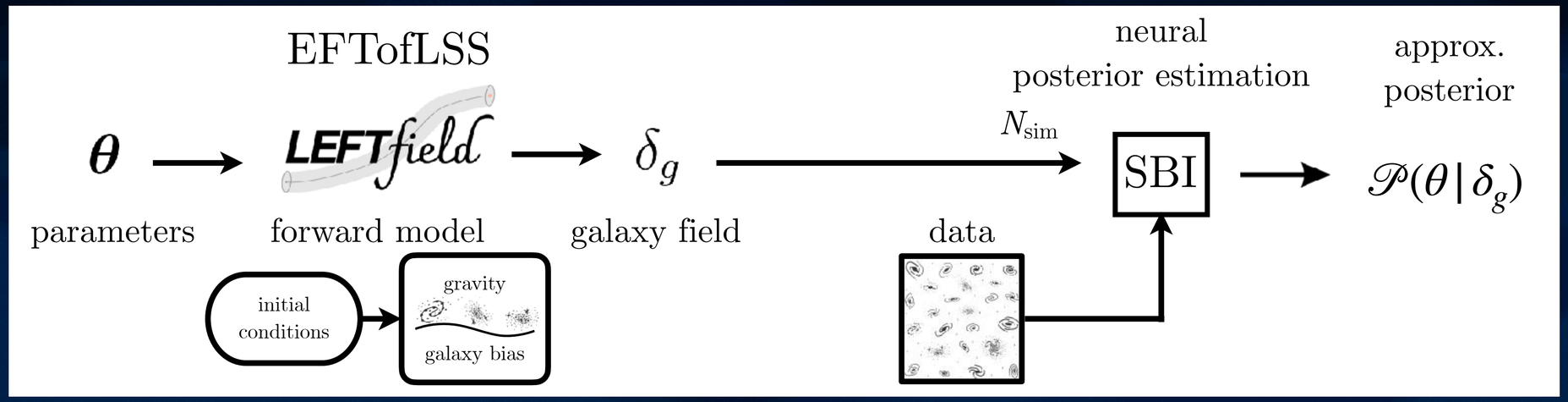
Towards SBI at field level

More flexible and efficient FBI with 3D Diffusion Models?



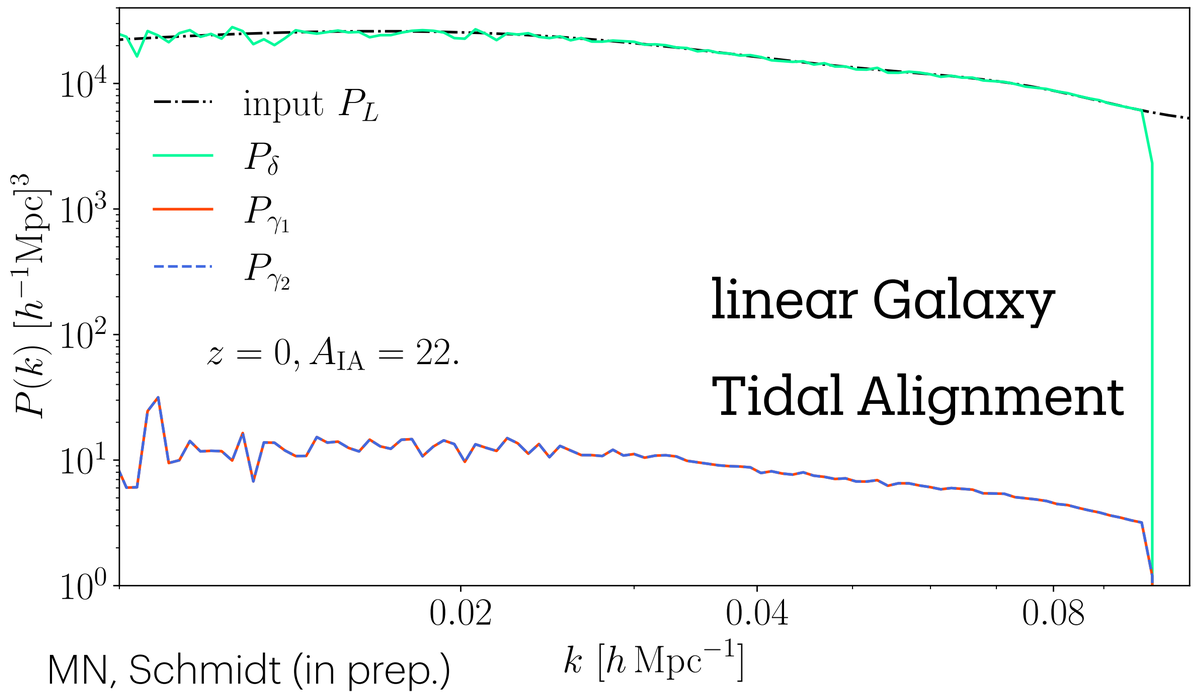
Cuesta-Lazaro, Mishra-Sharma (2023)

Sharrock+ (2022)
Legin+ (2023)
Mudur+ (2023)

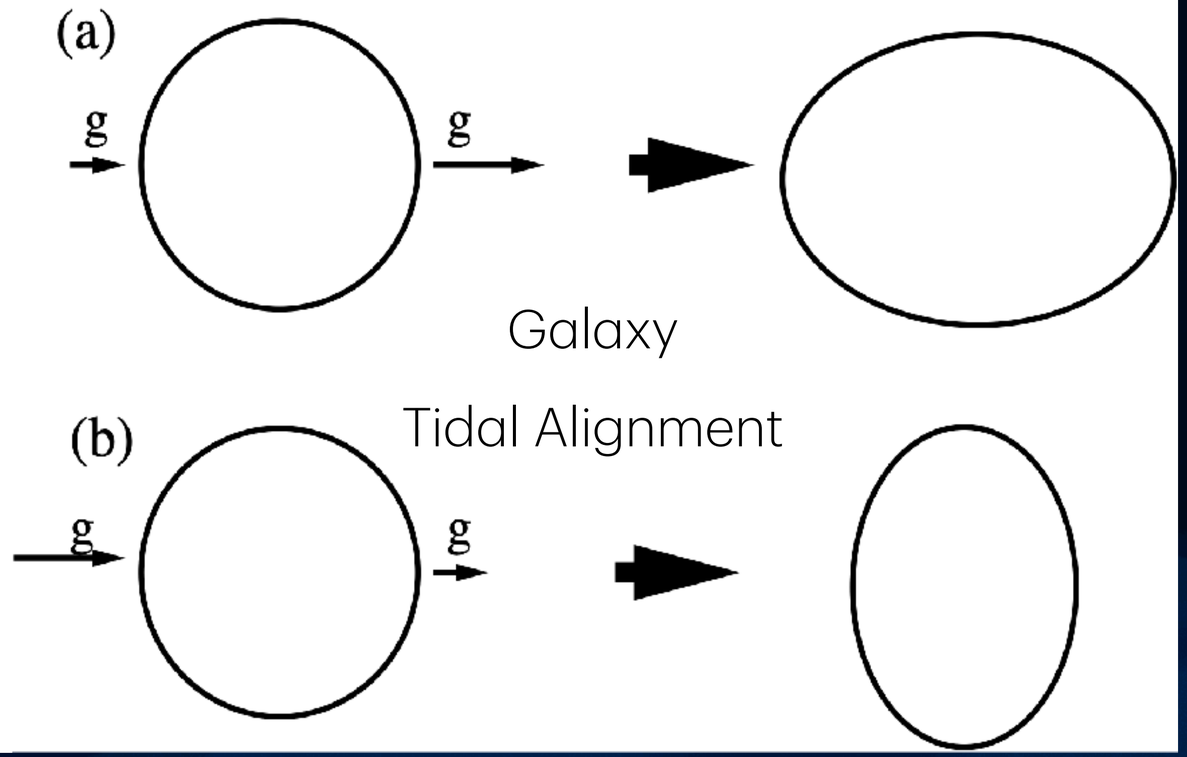


Towards galaxy position x shape

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

Differentiable
Boltzmann + hybrid-EFT

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

Nothing fundamentally prohibited!

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

real-space mock

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

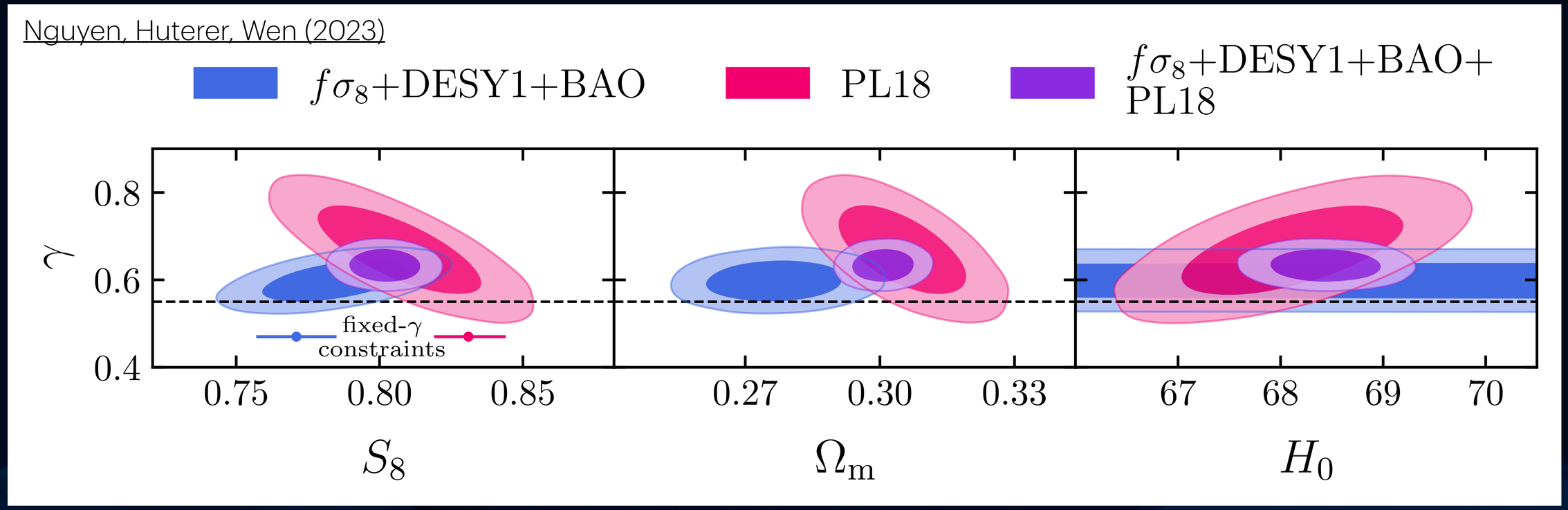
Field-level Bayesian Inference will improve σ_8 constraint from galaxy clustering

Some challenges ahead, mostly computational

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

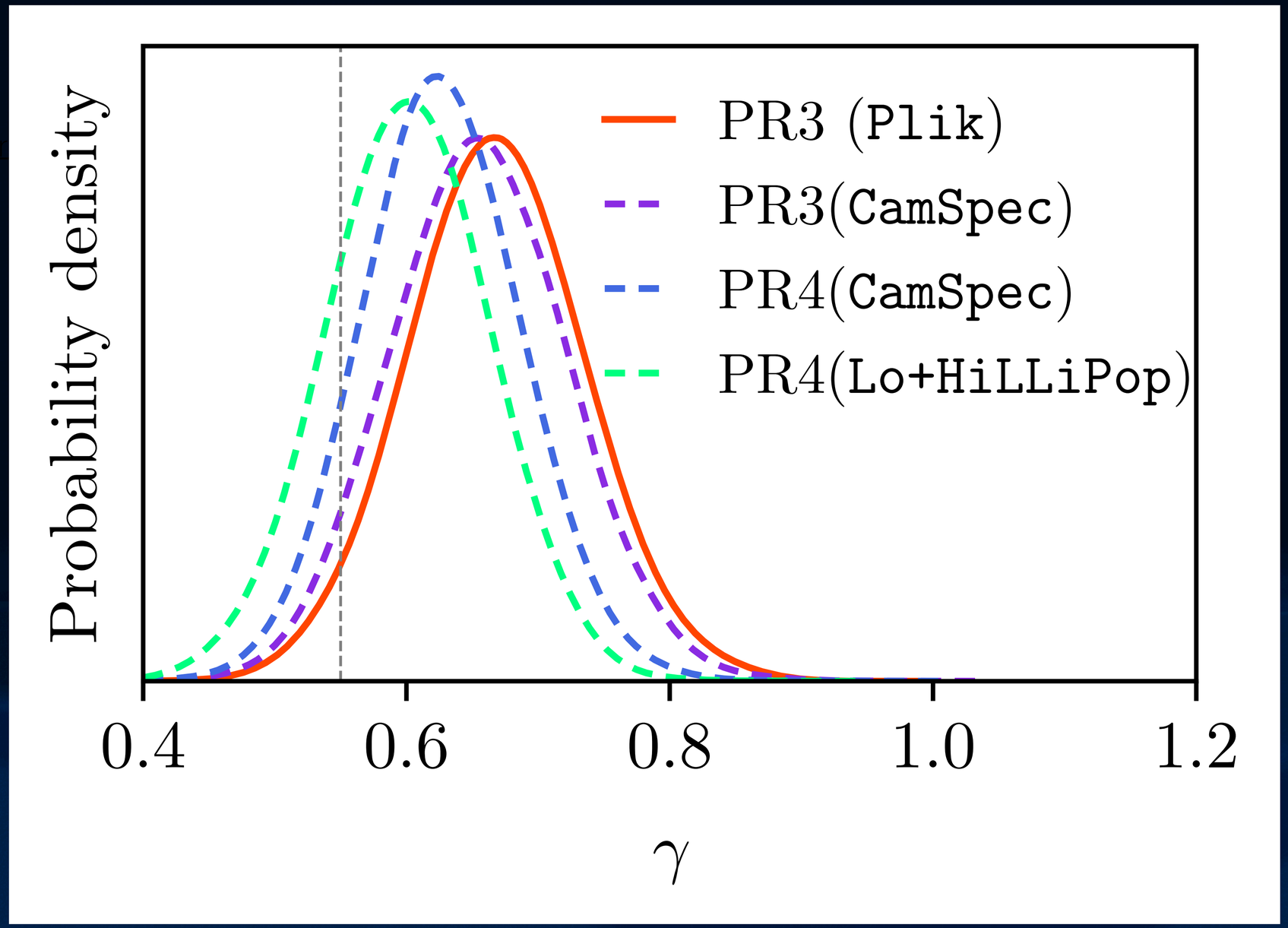
2302.01331 Details

Parameter constraints in γCDM



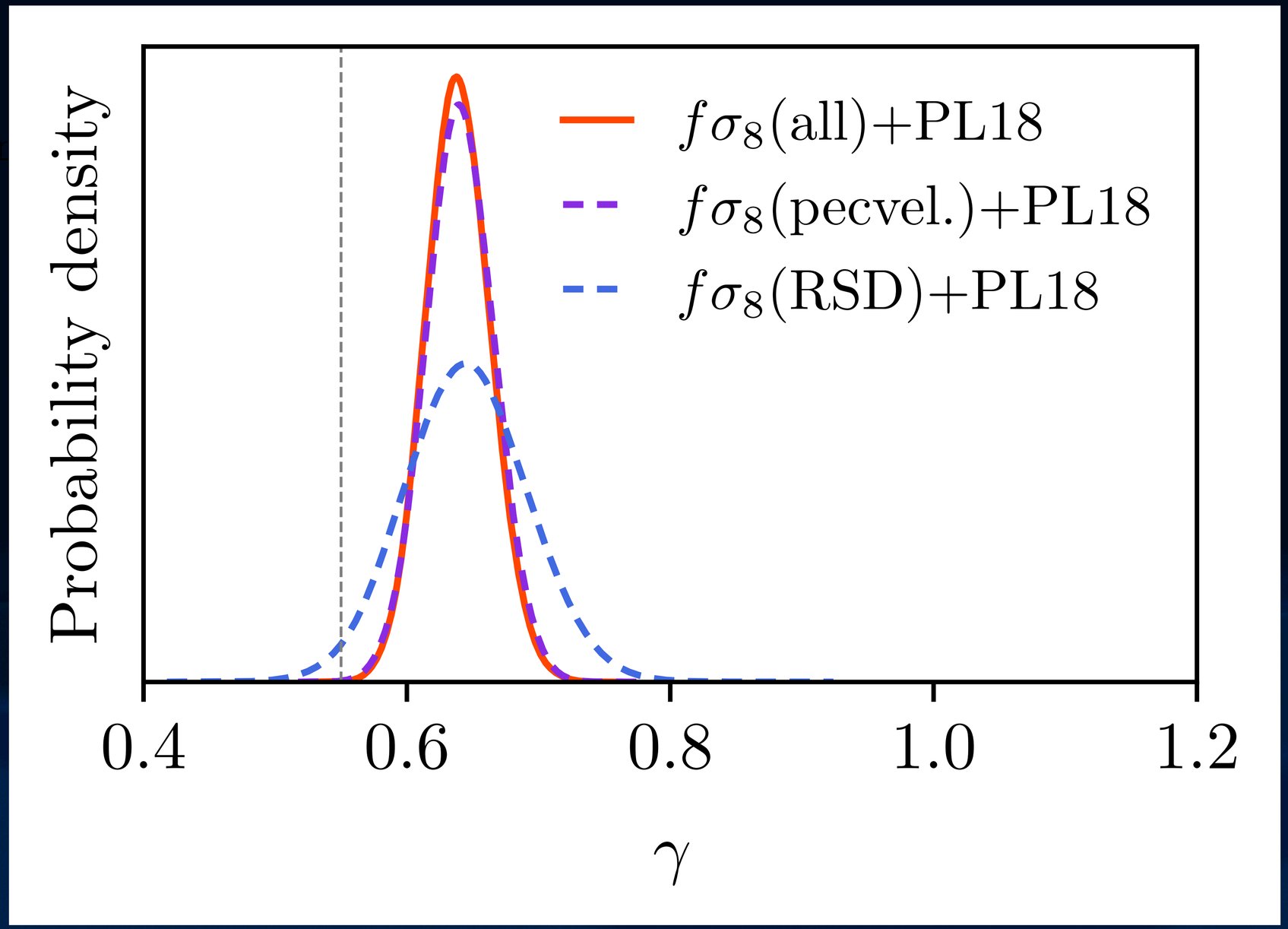
Robustness to Planck Likelihoods

Nguyen, Huter



Robustness to Peculiar Velocity and RSD

Nguyen, Huter



Robustness to Peculiar Velocity and RSD

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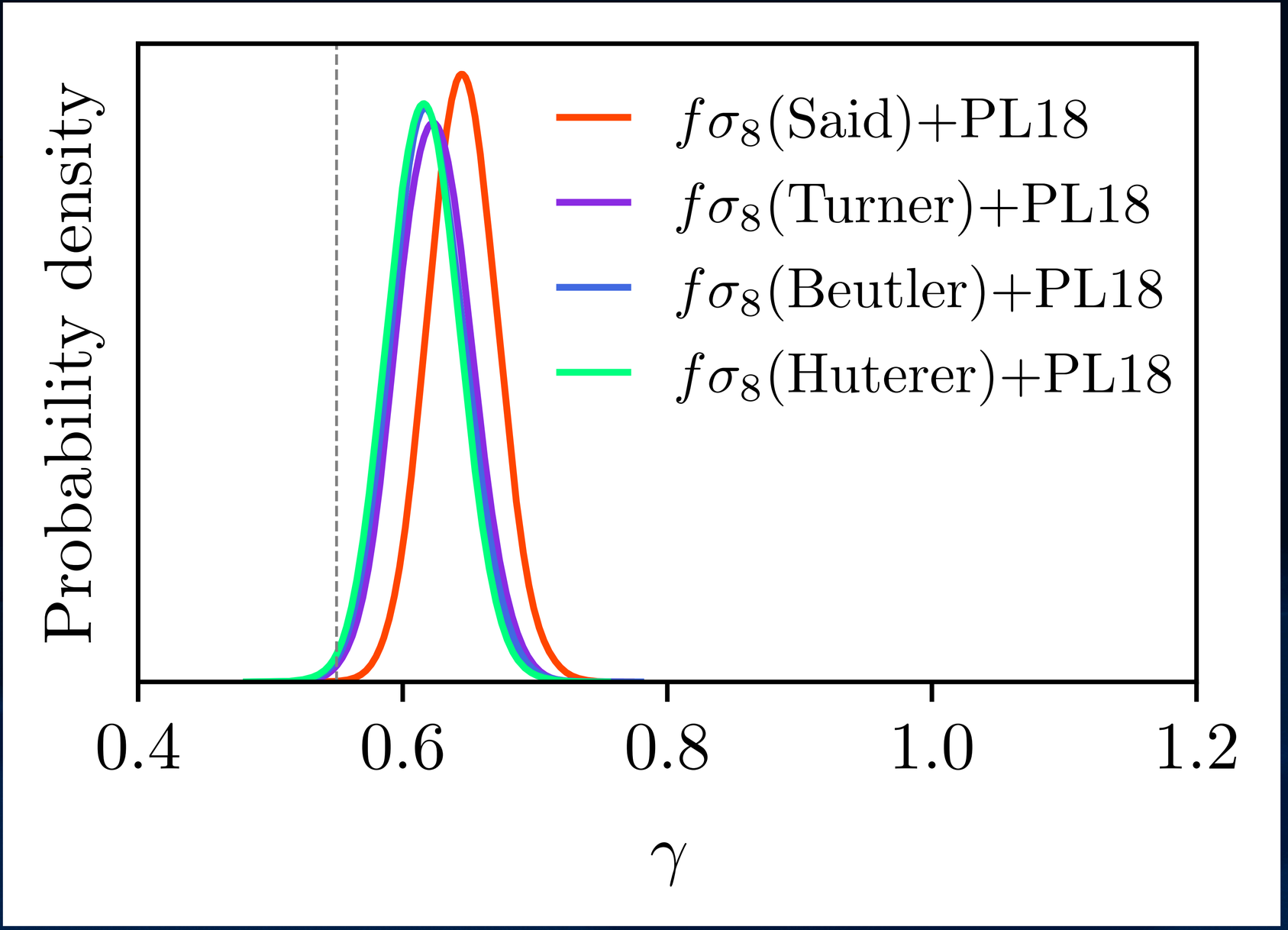
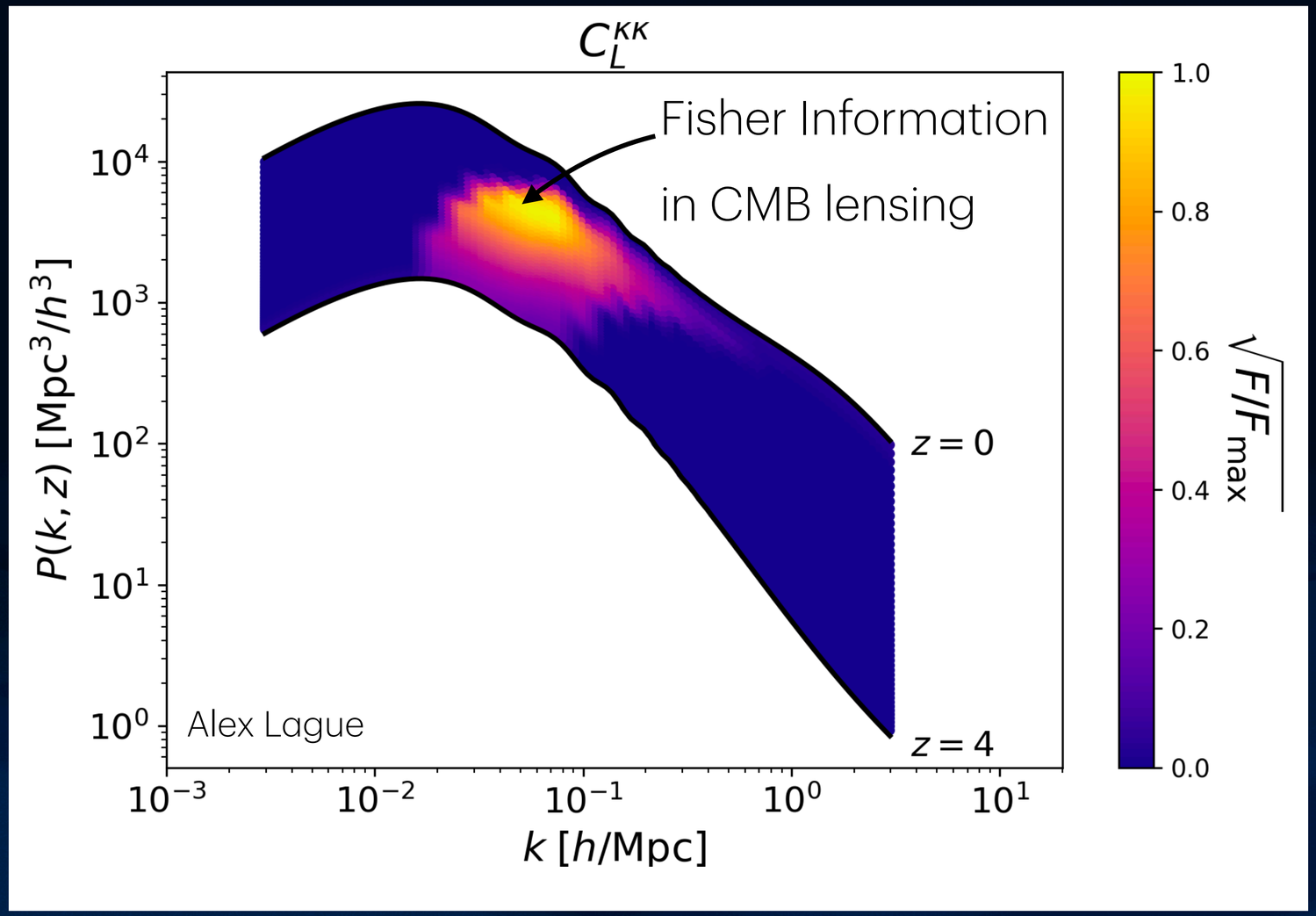


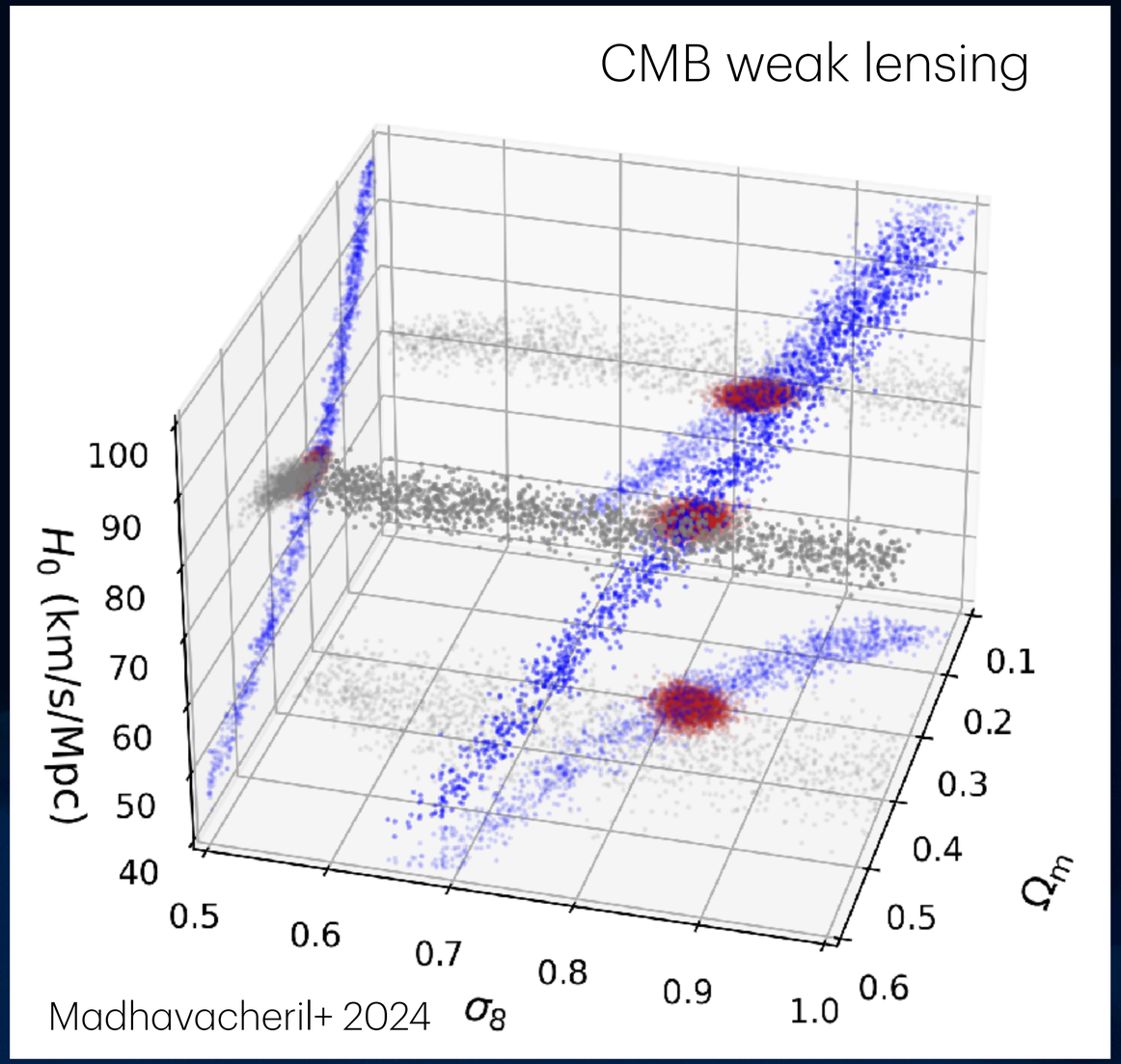
Scales probed by CMB lensing

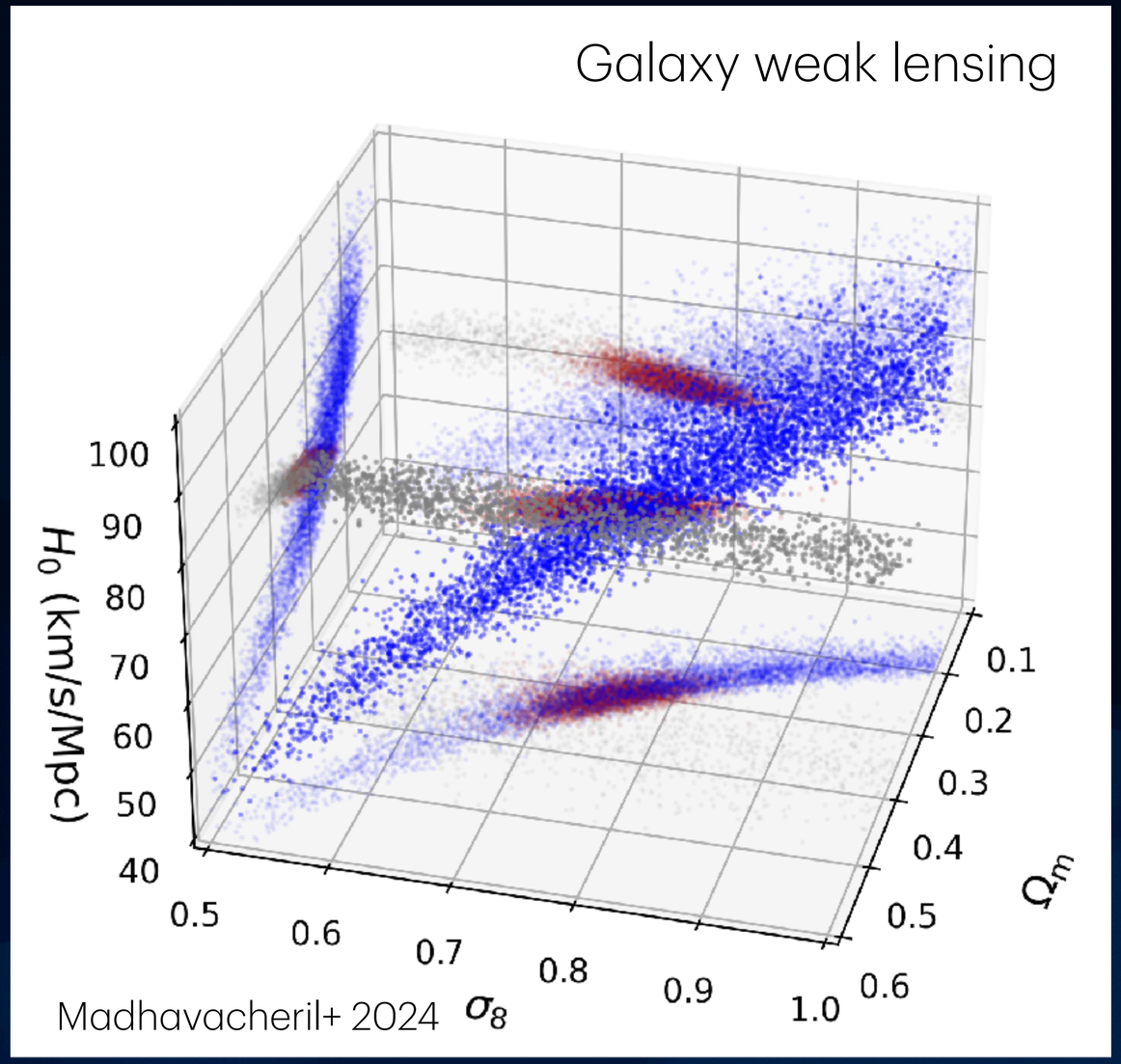
Fisher Information distribution



CMB lensing and Galaxy lensing + BAO

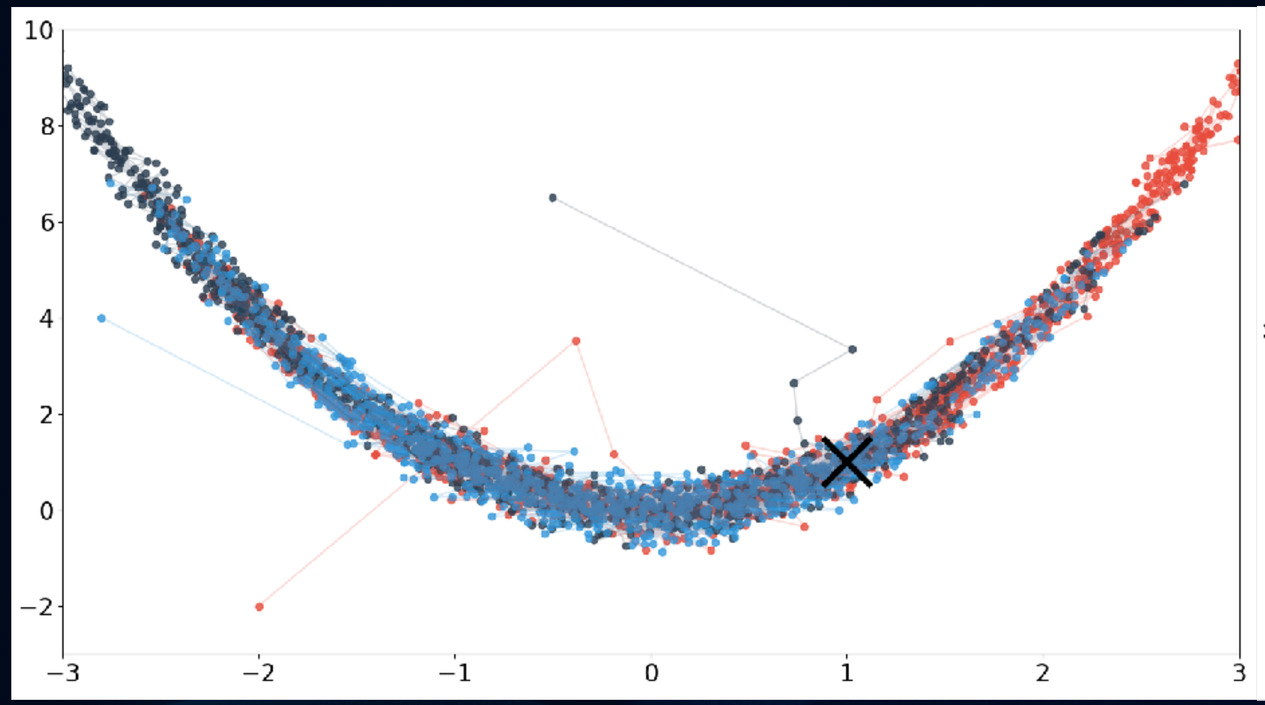
Parameter degeneracies



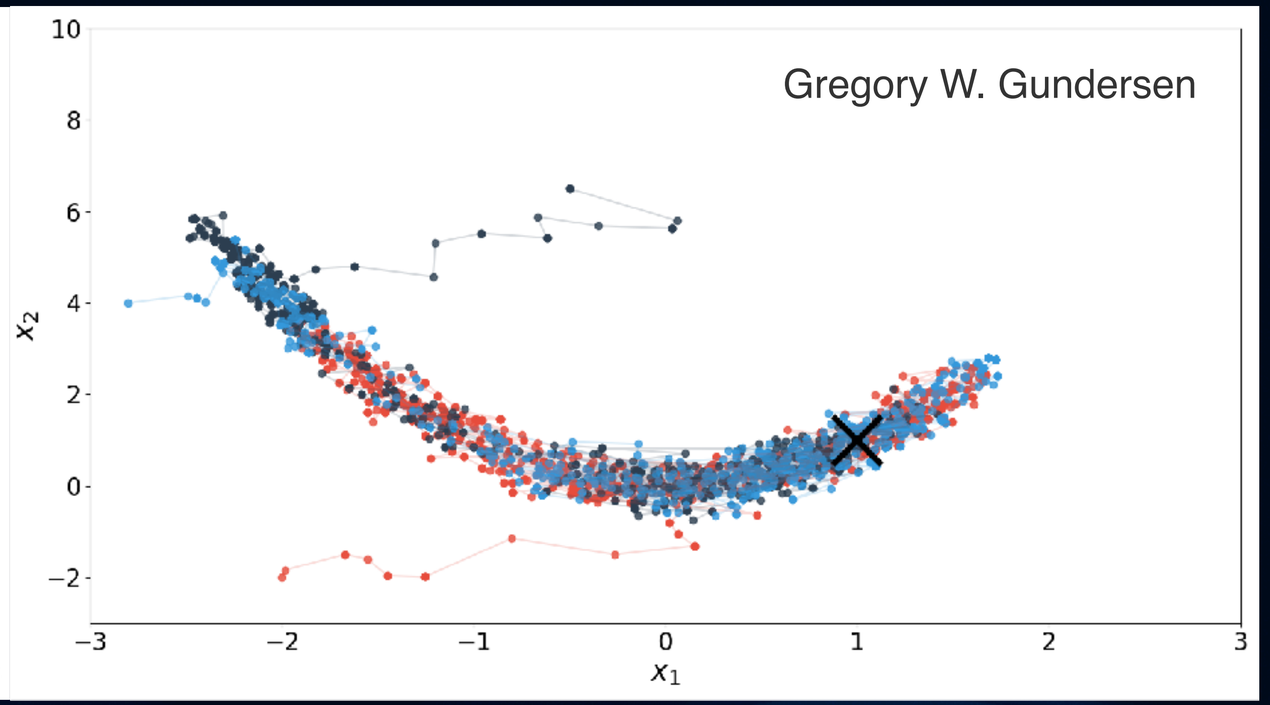


2403.03220 Details

Hamiltonian Monte Carlo for sampling the ICs



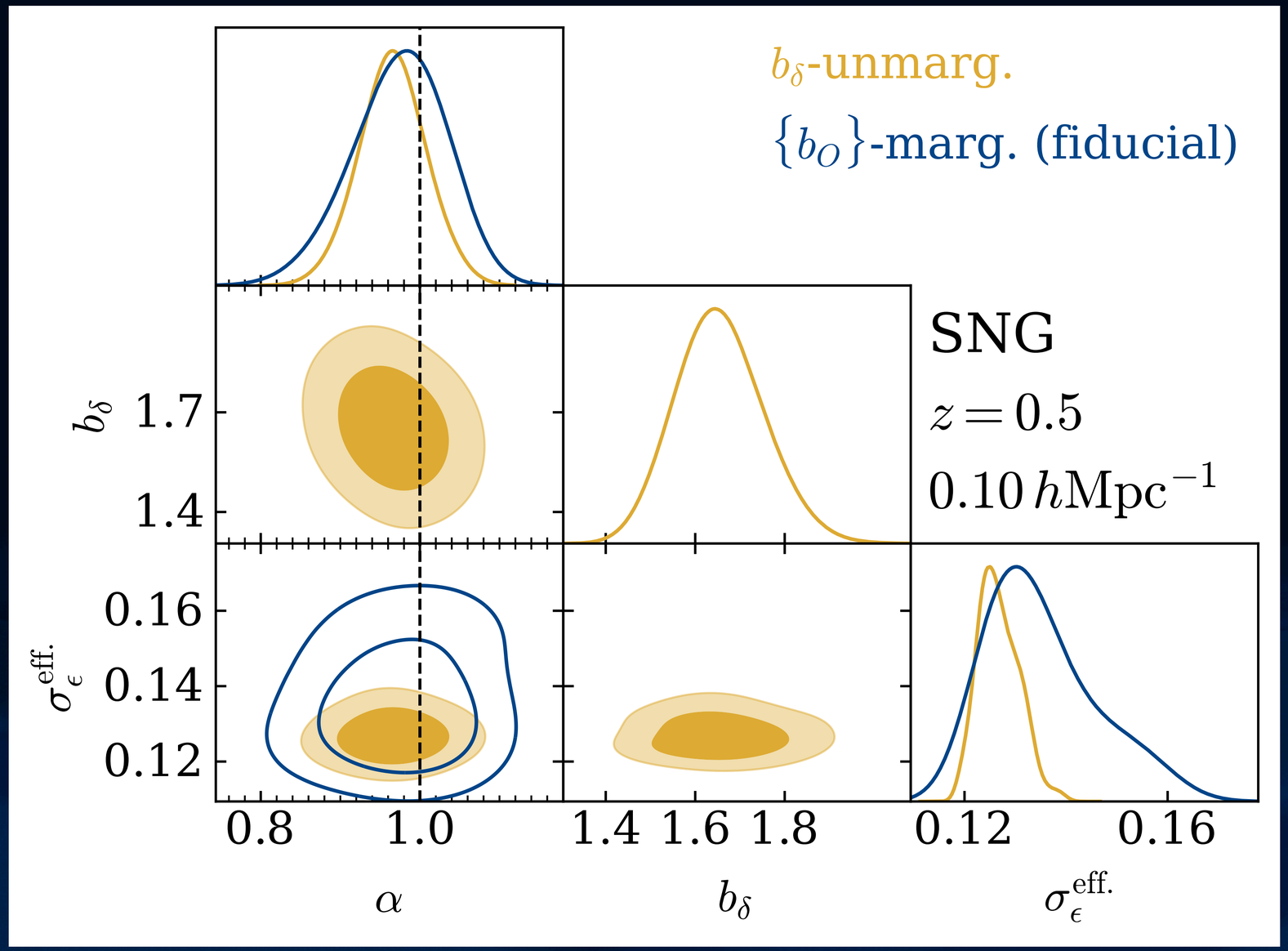
Hamiltonian Monte Carlo



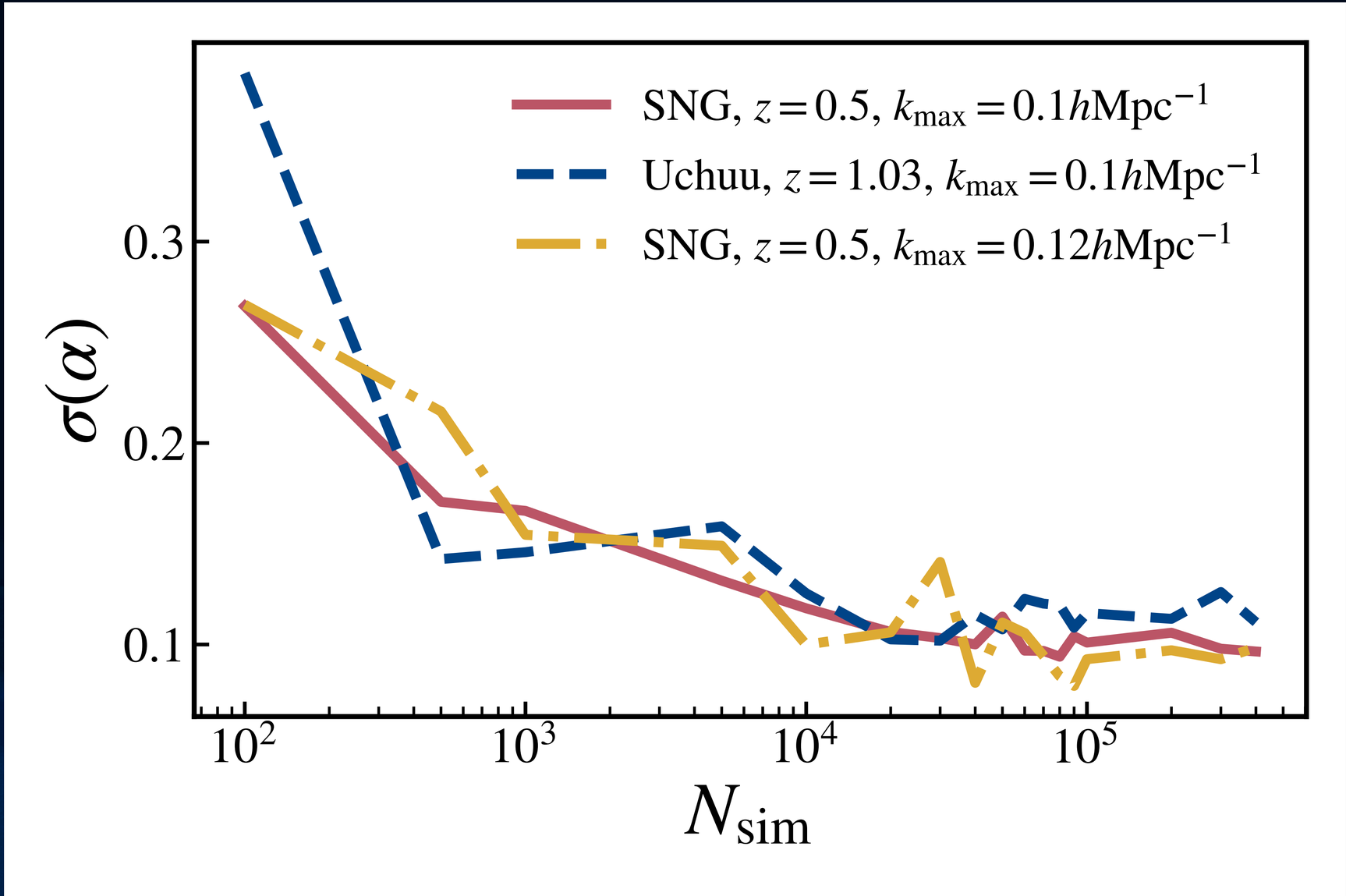
standard Metropolis-Hasting

Rosenbrock function

Marginalized- vs Unmarginalized-Likelihood

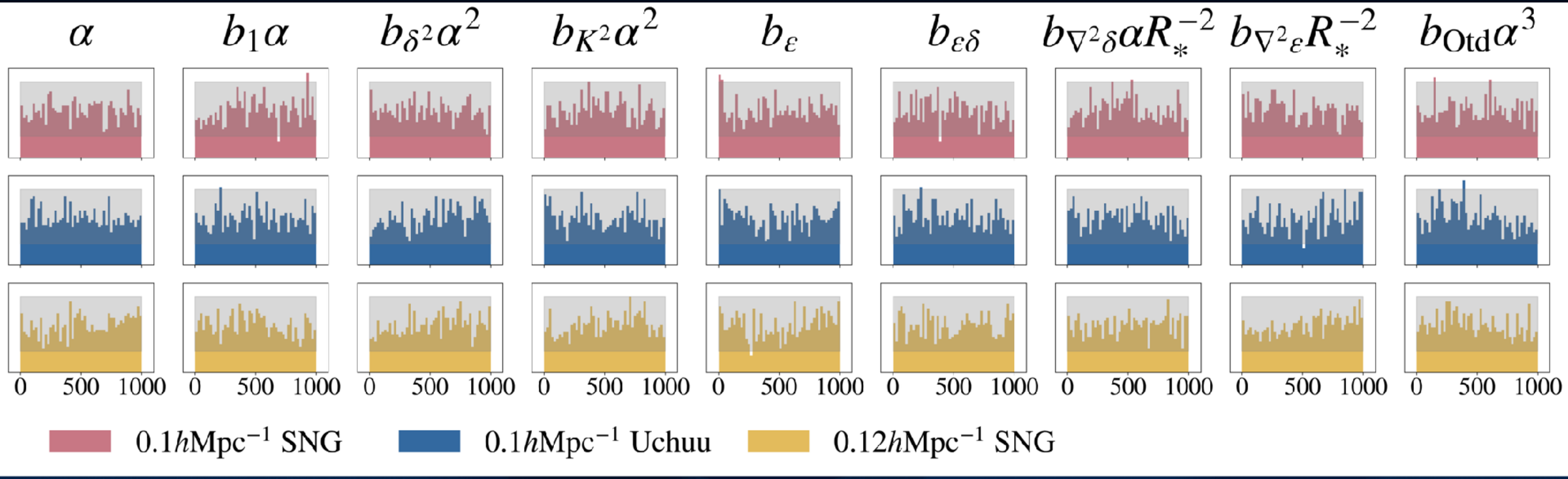


SBI P+B convergence

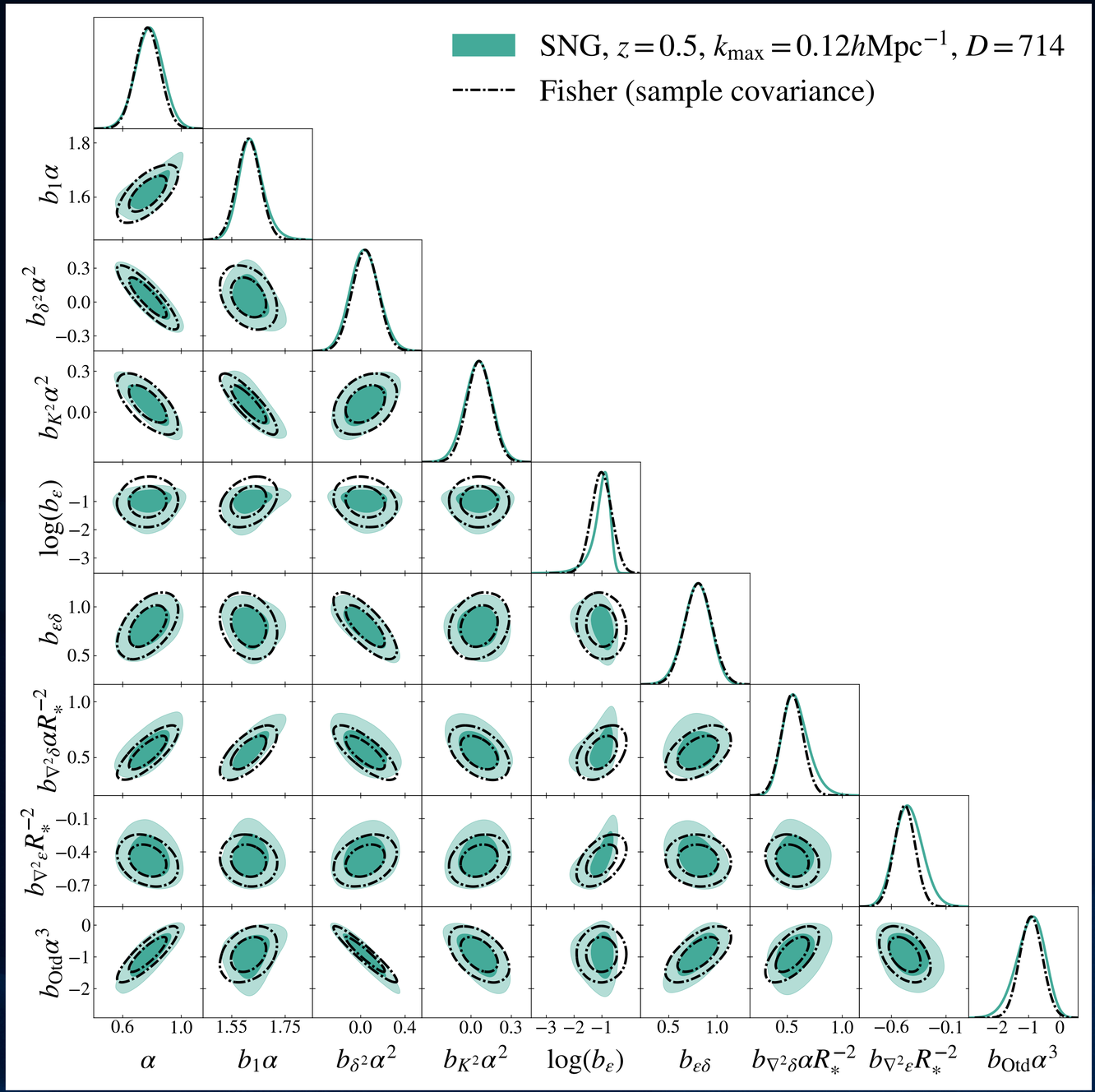


SBI P+B calibration test

All rank distributions are uniform

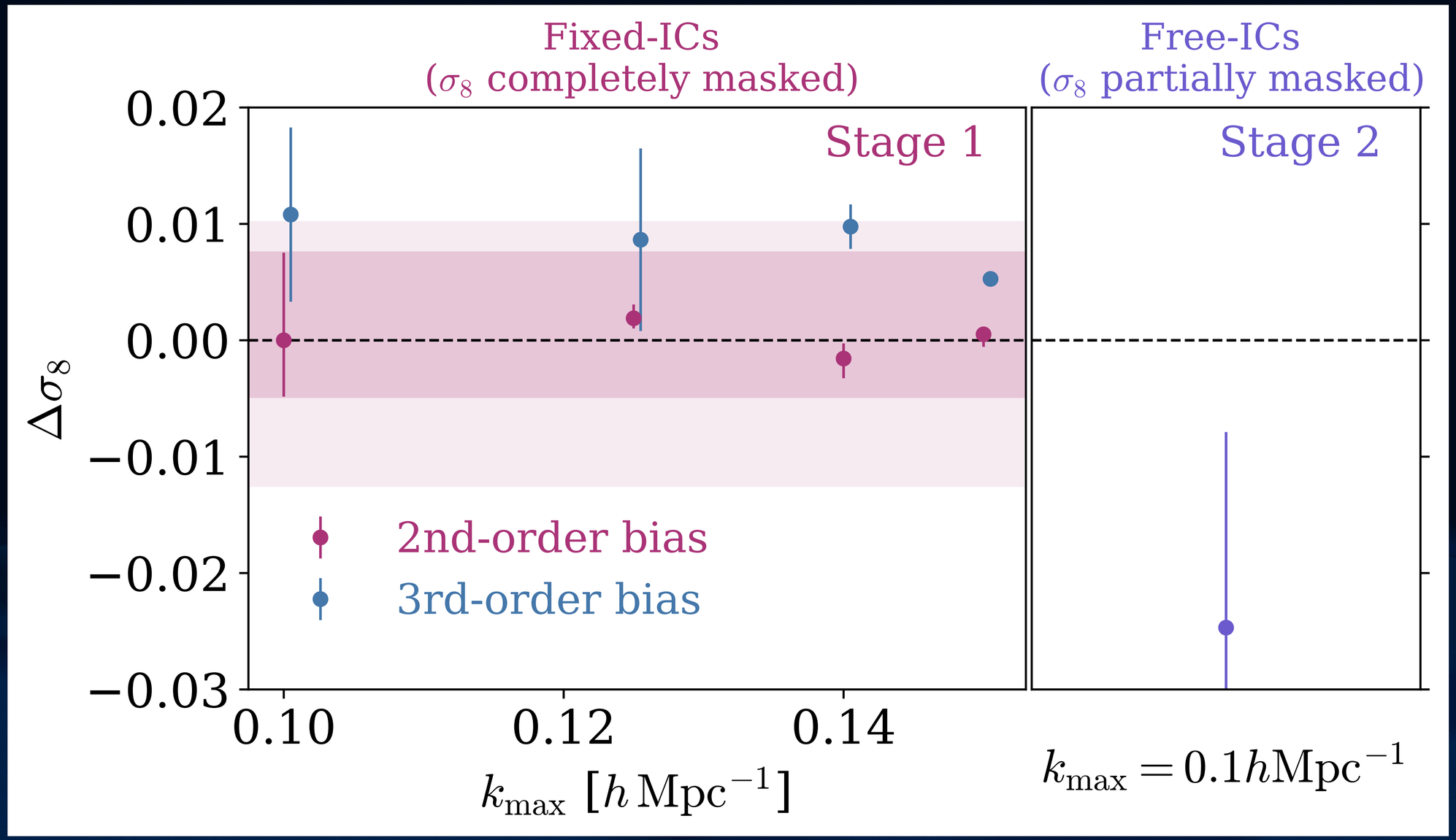
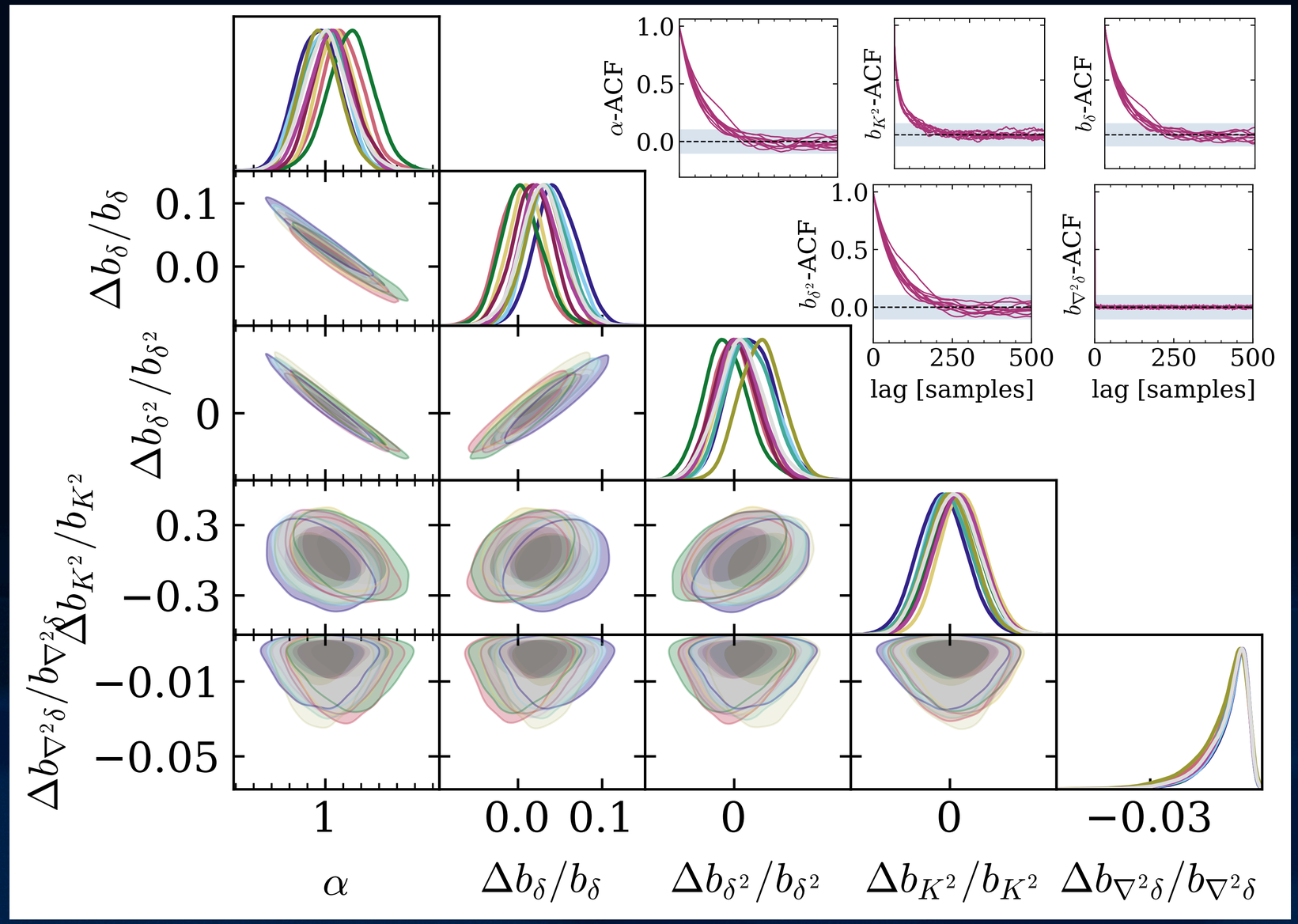


SBI P+B Fisher test



Beyond-2pt Challenge Details

Modeling Consistency & Convergence



Sampling Correlation & Convergence