Forward Modeling Cosmic Large-Scale Structure

Model Choice in Bayesian Inference, Center for Advanced Studies, LMU, 24.03.2026

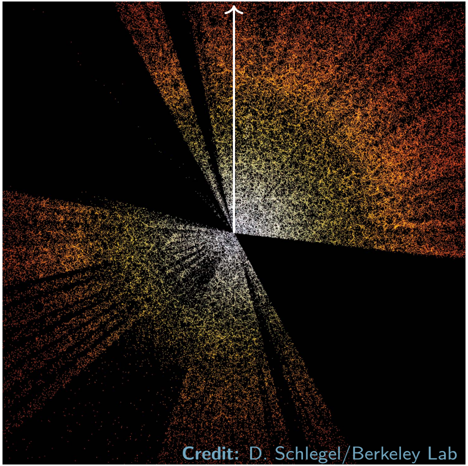
Julia Stadler, Ludwig-Maximilians-Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

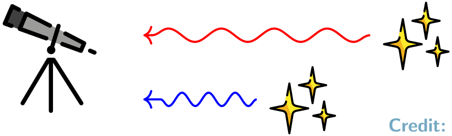
LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Galaxy Surveys

$$z + 1 = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{emit}}$$



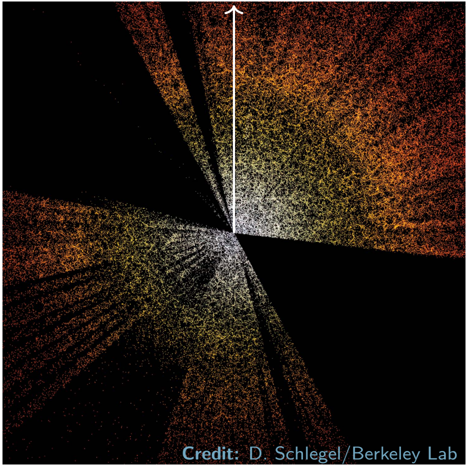
Credit: D. Schlegel/Berkeley Lab



Credit: OpenMoji

Galaxy Surveys

$$z + 1 = \lambda_{\text{obs}}/\lambda_{\text{emit}}$$

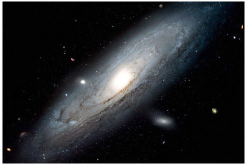


10 billion light years

Proxima Centauri,
4 light years

Galactic Center,
26 000 light years

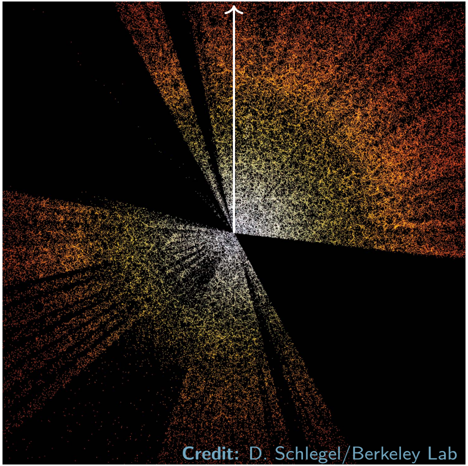
Andromeda Galaxy,
2.5 million light years



Credit: ESA/Hubble & NASA, ESO/S. Brunier, Luc Viatour

Galaxy Surveys

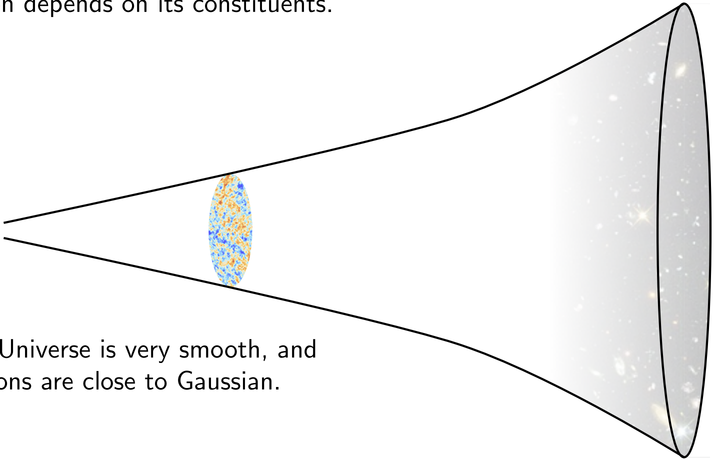
$$z + 1 = \lambda_{\text{obs}}/\lambda_{\text{emit}}$$



- ▷ How did the Universe begin?
- ▷ How is the Universe expanding?
- ▷ What contributes to the energy density?

The Cosmological Standard Model

General Relativity predicts that the Universe expands (or collapses).
The evolution depends on its constituents.

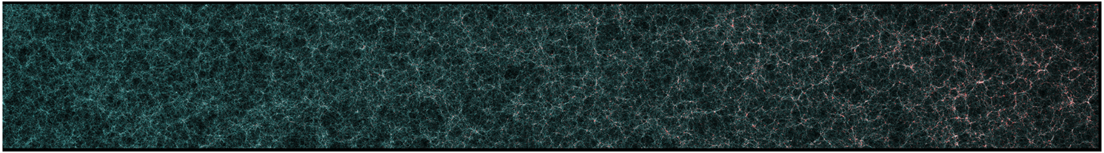


The early Universe is very smooth, and perturbations are close to Gaussian.

$$\left.\begin{array}{r}\text{most matter is dark}\\ \text{accelerated expansion} \rightarrow \text{dark energy}\end{array}\right\} \Lambda\mathrm{CDM}$$

Cosmic Structure Formation

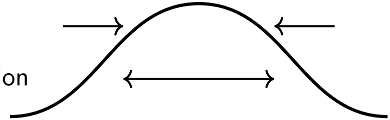
$\longleftarrow$ ~ 10 billion years ago today $\longrightarrow$



Credit: Carretero, Tallada, Serrano & the Euclid Consortium Cosmological Simulations SWG

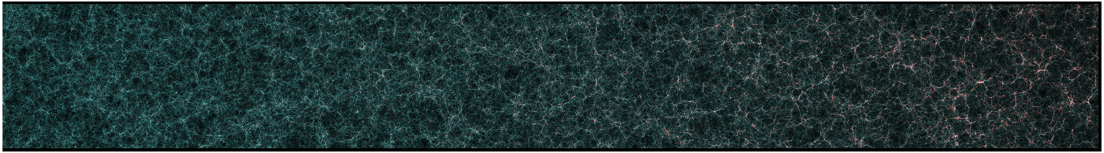
gravity

cosmic expansion



Cosmic Structure Formation

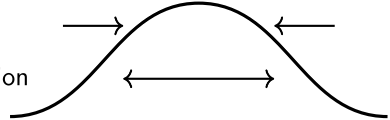
⟵ ~ 10 billion years ago | today ⟶



Credit: Carretero, Tallada, Serrano & the Euclid Consortium Cosmological Simulations SWG

gravity

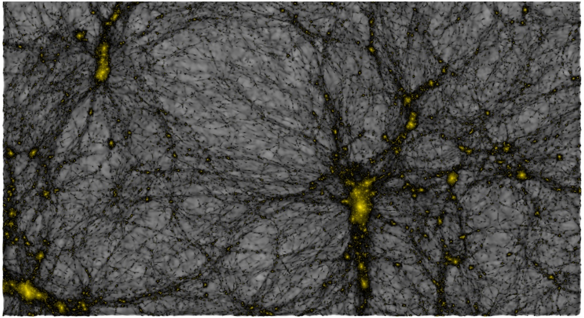
cosmic expansion



- ▷ How is the Universe expanding?
- ▷ Is gravity consistent with General Relativity?
- ▷ What are the initial conditions?
- ▷ Does LSS agree w/ other observations?

$\Rightarrow$ Phrase as parameter measurement

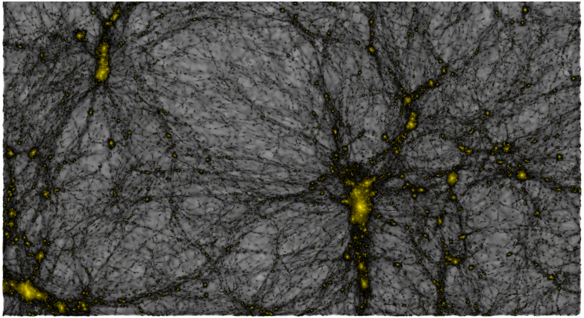
From Dark Matter to Galaxies



Credit: J. Stadel, Euclid-Flagship-Simulation

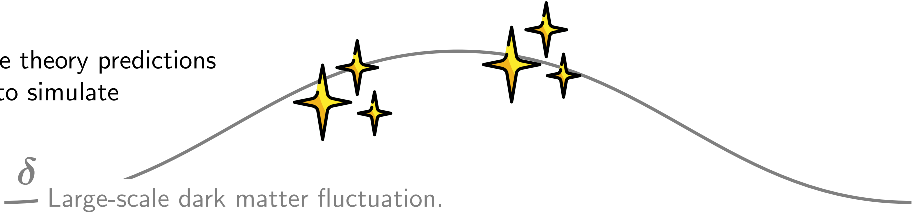
Dark Matter: precise theory predictions
Galaxies: very hard to simulate

From Dark Matter to Galaxies



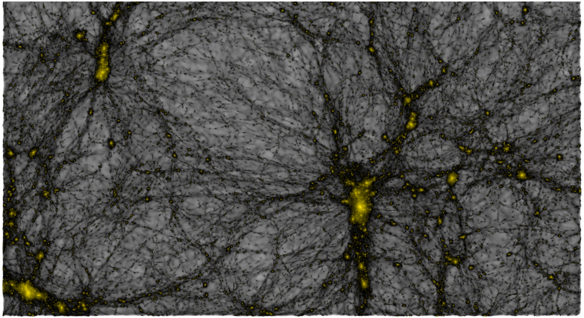
Credit: J. Stadel, Euclid-Flagship-Simulation

Dark Matter: precise theory predictions
Galaxies: very hard to simulate



Large-scale dark matter fluctuation.

From Dark Matter to Galaxies



Credit: J. Stadel, Euclid-Flagship-Simulation

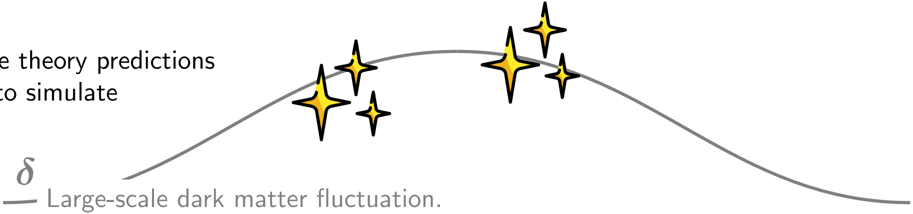
Bias expansion of the large-scale galaxy density:

$$\delta_{\rm g} = b_1 \delta + b_2 \delta^2 + c_{\rm s} \nabla^2 \delta + \ldots + \epsilon$$

- How many galaxies occupy a dark matter overdensity (mean and stochasticity)
- Functional form fixed, coefficients are free

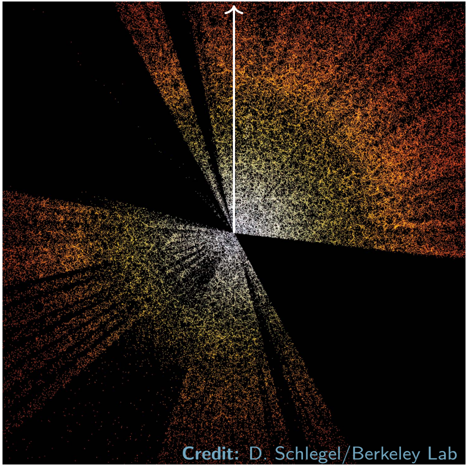
[Desjacques, Jeong & Schmidt 2018]

Dark Matter: precise theory predictions
Galaxies: very hard to simulate



Analysis of Galaxy Clustering

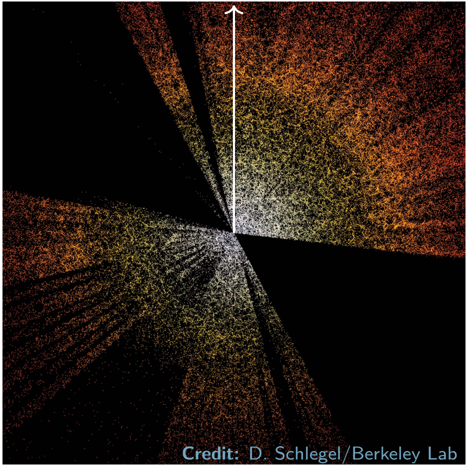
$$z + 1 = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{emit}}$$

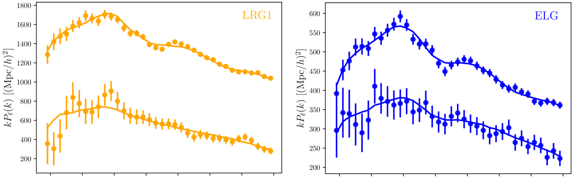


- Galaxies trace fluctuations in the dark matter.
- Initial fluctuations are small and Gaussian.
- Gravity growth, expansion dilutes fluctuations.
- Fluctuations are smaller on larger scales.

Analysis of Galaxy Clustering

$z + 1 = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{emit}}$

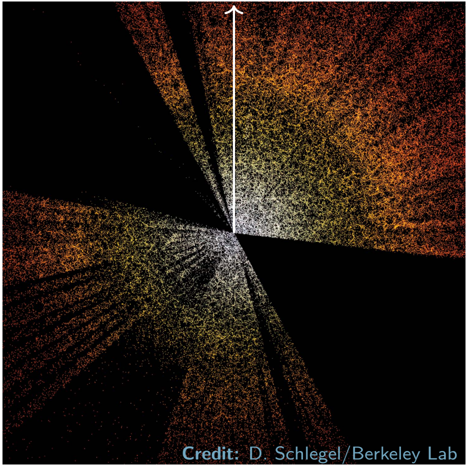




Power spectrum (2-point correlation) [DESI 2024]

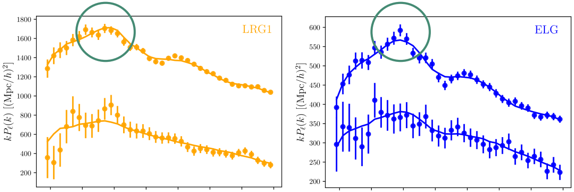
Analysis of Galaxy Clustering

$$z + 1 = \lambda_{\text{obs}}/\lambda_{\text{emit}}$$



Angle of the **BAO** peak w/ redshift

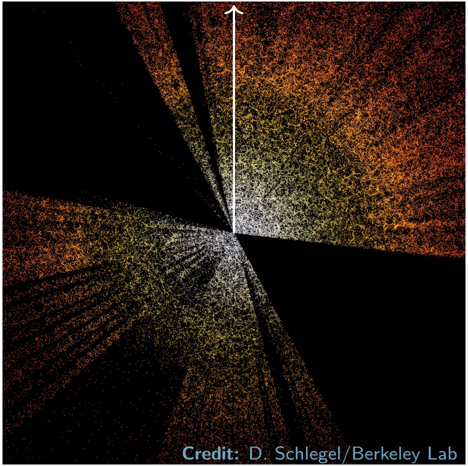
$\Rightarrow$Expansion of the Universe



Power spectrum (2-point correlation) [DESI 2024]

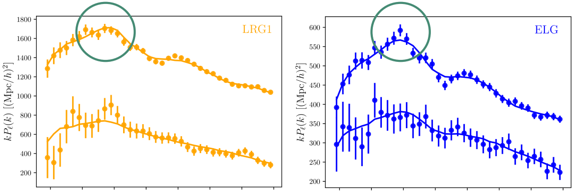
Analysis of Galaxy Clustering

$$z + 1 = \lambda_{\rm obs}/\lambda_{\rm emit}$$



Angle of the **BAO** peak w/ redshift

⇒Expansion of the Universe

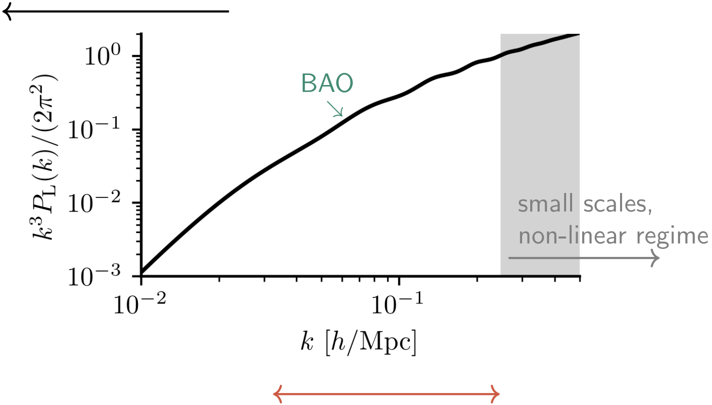


Power spectrum (2-point correlation) [DESI 2024]

⇒Expansion, growth and initial conditions

Non-Linear Information

Large scales are close to Gaussian, and the power spectrum is optimal.



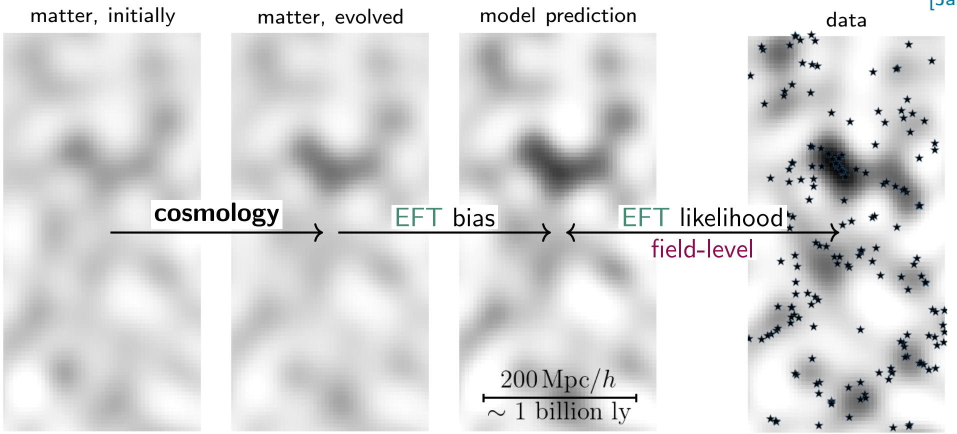
Non-Gaussianity from gravity & galaxy bias on quasi-linear scales

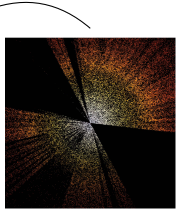
✔ Statistics of the initial conditions ✗ Statistics at late times

✗ Realization of the initial conditions ✔ Time-evolution

Field-Level Analysis

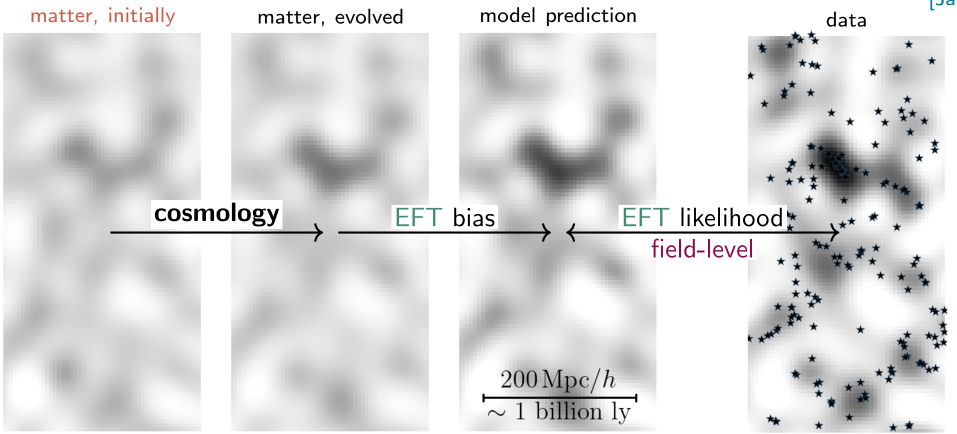
[Jasche & Wandelt 2012]
[Schmidt et al. 2019]
[Elsner et al. 2020]

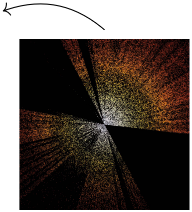




Field-Level Analysis

[Jasche & Wandelt 2012]
[Schmidt et al. 2019]
[Elsner et al. 2020]

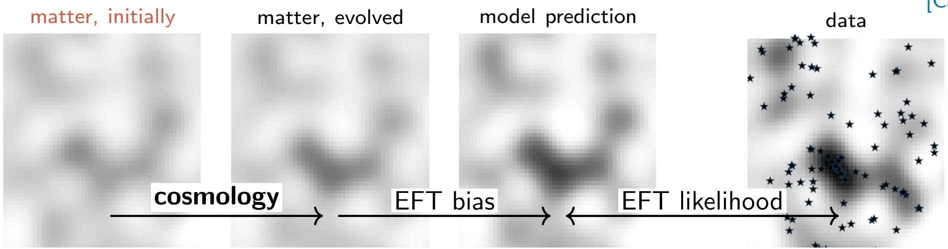




- Precise measurements by fully exploiting the data
- Robustness to theoretical uncertainties from EFT bias and likelihood
- Insights into evolution of local matter distribution and its evolution

Fully Bayesian Analysis of the Galaxy Density

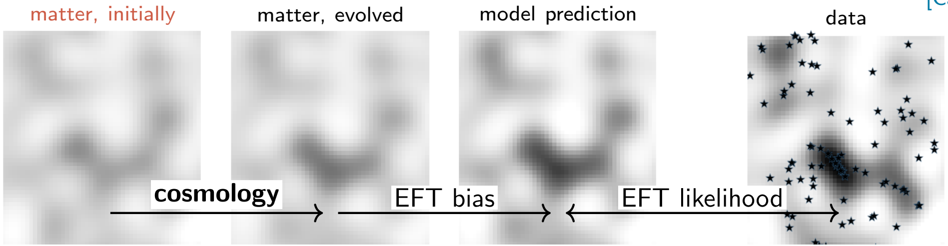
[Cabass & Schmidt 2020]
[Schmidt et al. 2019]
[Elsner et al. 2020]



$$\boxed{\underbrace{\mathcal{P}\left(\theta|\delta_{\rm g}\right) \propto \int db_{\mathcal{O}} \int \mathcal{D}\delta_{\rm ini}}_{\text{marginalization}} \; \underbrace{\mathcal{P}\left(\delta_{\rm g}|\theta, b_{\mathcal{O}}, \delta_{\rm ini}\right)}_{\text{likelihood}} \; \underbrace{\mathcal{P}\left(\delta_{\rm ini}|\theta\right) \mathcal{P}\left(\theta, b_{\mathcal{O}}\right)}_{\text{prior}}}$$

Fully Bayesian Analysis of the Galaxy Density

[Cabass & Schmidt 2020]
[Schmidt et al. 2019]
[Elsner et al. 2020]



$$\delta_{\rm fwd} = \sum_{\mathcal{O}} b_{\mathcal{O}}\, \mathcal{O}\left[\delta_{\rm ini}, \theta\right] \qquad \delta_{\rm g} = \delta_{\rm g,det} + \epsilon_{\rm g}$$

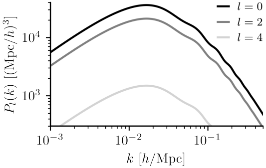
$$\text{likelihood} \propto \delta^{\rm D}\left(\delta_{\rm g,det} - \delta_{\rm fwd}\left[\delta_{\rm ini}, \theta, b_{\mathcal{O}}\right]\right) \times \exp\left(-\frac{1}{2}\int_{\boldsymbol{k}} \frac{\left|\delta_{\rm g}\left(\boldsymbol{k}\right) - \delta_{\rm g,det}\left(\boldsymbol{k}\right)\right|^2}{P_\epsilon(k)}\right)$$

$$\boxed{\underbrace{\mathcal{P}\left(\theta|\delta_{\rm g}\right) \propto \int db_{\mathcal{O}} \int \mathcal{D}\delta_{\rm ini}}_{\text{marginalization}}\ \underbrace{\mathcal{P}\left(\delta_{\rm g}|\theta, b_{\mathcal{O}}, \delta_{\rm ini}\right)}_{\text{likelihood}}\ \underbrace{\mathcal{P}\left(\delta_{\rm ini}|\theta\right)\mathcal{P}\left(\theta, b_{\mathcal{O}}\right)}_{\text{prior}}}$$

Posterior Exploration

~ 20 parameters (cosmology & bias)

$\sim 0.3\,\mathrm{s}$ per evaluation

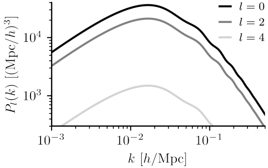


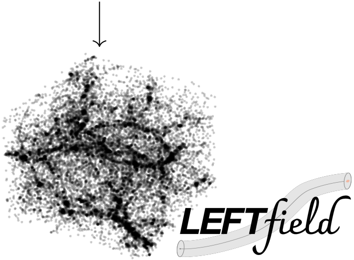
$\sim 10^5 – 10^6$ additional parameters

$\sim 2\,\mathrm{s}$ per evaluation

Posterior Exploration

~ 20 parameters (cosmology & bias)
$\sim 0.3\,\mathrm{s}$ per evaluation





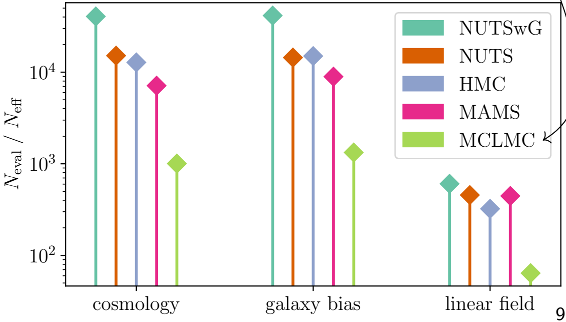
$\sim 10^5 – 10^6$ additional parameters
$\sim 2\,\mathrm{s}$ per evaluation

Sampling with Hamiltonian Monte Carlo [Neal, 1996]

▷ Exploit gradient information

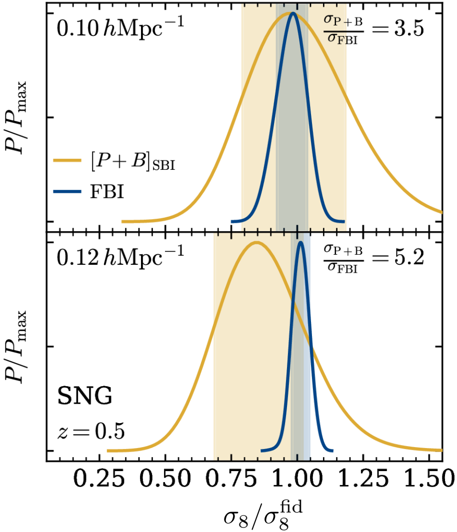
unadjusted, no guarantee to be unbiased

[Simon-Onfroy et al. 2025]



Field-Level vs. Power- & Bispectrum

[Nguyen, Tucci & Schmidt 2024]



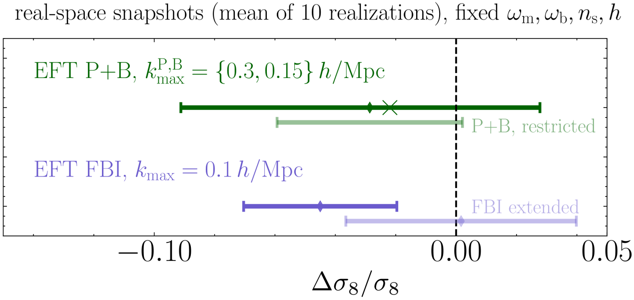
Power- & Bispectrum

Simulation Based Inference (SBI) w/ LEFTfield

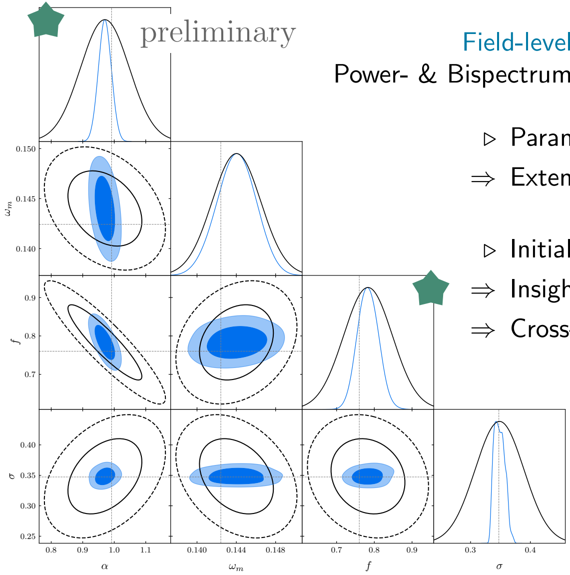
Field-level

simultaneous cosmology & initial condition inference

[The Beyond-2pt Collaboration, Krause et al. 2024]



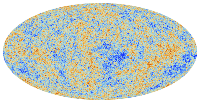
Field-Level vs. Power- & Bispectrum



Field-level
Power- & Bispectrum

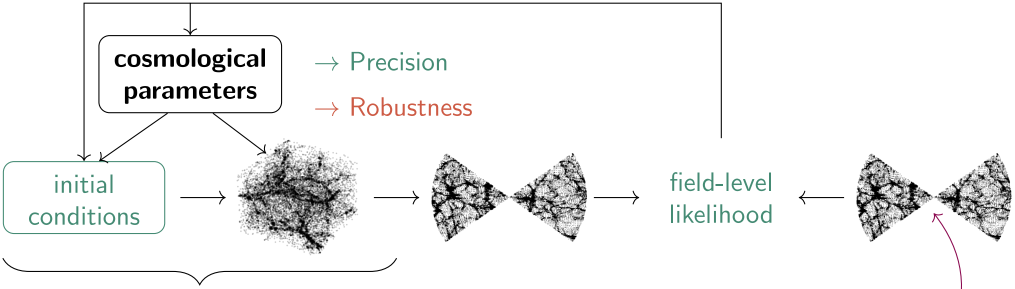
- ▷ Parameters w/ linear degeneracies improve most
- ⇒ Extended model test & consistency checks

- ▷ Initial conditions reconstruction
- ⇒ Insights into DM structures
- ⇒ Cross-correlation w/ other observables



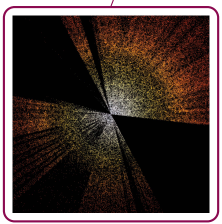

Credit: ESA and the Planck Collaboration
Credit: Dark Energy Survey

Field-Level Analysis for Galaxy Surveys



Effective model of gravity & galaxy bias

ΛCDM cosmology is also an effective model

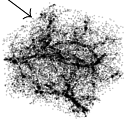
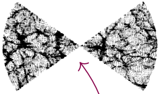


Field-Level Analysis for Galaxy Surveys

cosmological parameters

→ Precision

→ Robustness

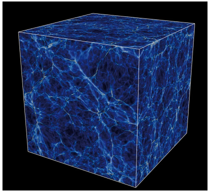
initial conditions →  →  → field-level likelihood ← 

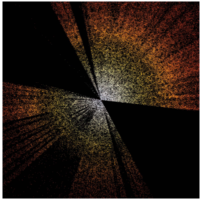
Effective model of gravity & galaxy bias

ΛCDM cosmology is also an effective model

Observational & systematics effects

state-of-the-art





Credit: D. Schlegel/Berkeley Lab
Credit: J. Oñorbe / MPIA