Cosmology with Bayesian hierarchical models of cosmic shear data

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with Alan Heavens, Daniel Mortlock & Guilhem Lavaux
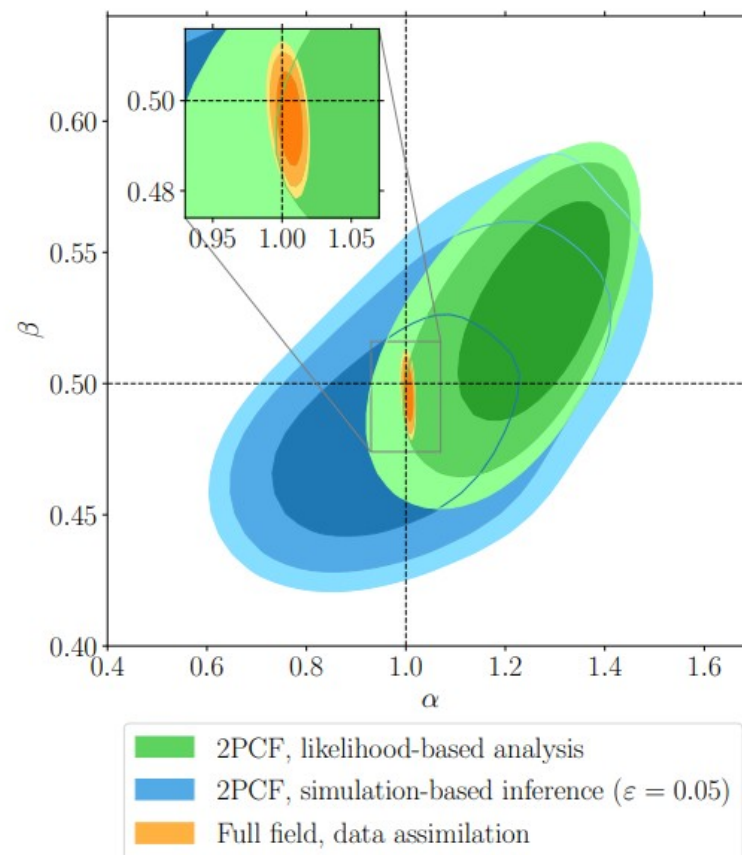
Cosmology from Home – July 2021

Why Bayesian hierarchical models?

More accurate and precise results

- Uses every point in the shear fields.

- Avoids the problem of the covariance matrix of summary statistics, which is very difficult to compute accurately.

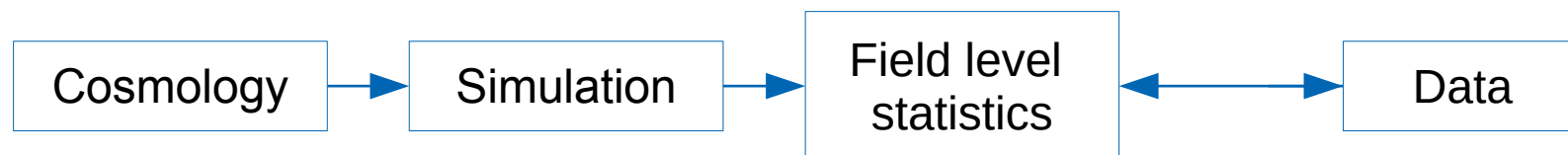- Deals correctly with the non-Gaussianity of the cosmic shear field.

- 2PCF: inaccurate, can be imprecise

- LFI (2PCF-based): accurate, imprecise

- Field-based: accurate and more precise

For a log-normal field:

2PCF, likelihood-based analysis
2PCF, simulation-based inference ($\varepsilon = 0.05$)
Full field, data assimilation

Leclercq & Heavens 2103.04158

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What physics do we include in the model?

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┌──────────┐      ┌──────────┐      ┌──────────┐      ┌──────────┐
│ Cosmology│ ───► │Simulation│ ───► │Field level│ ◄──► │   Data   │
│          │      │          │      │ statistics│      │          │
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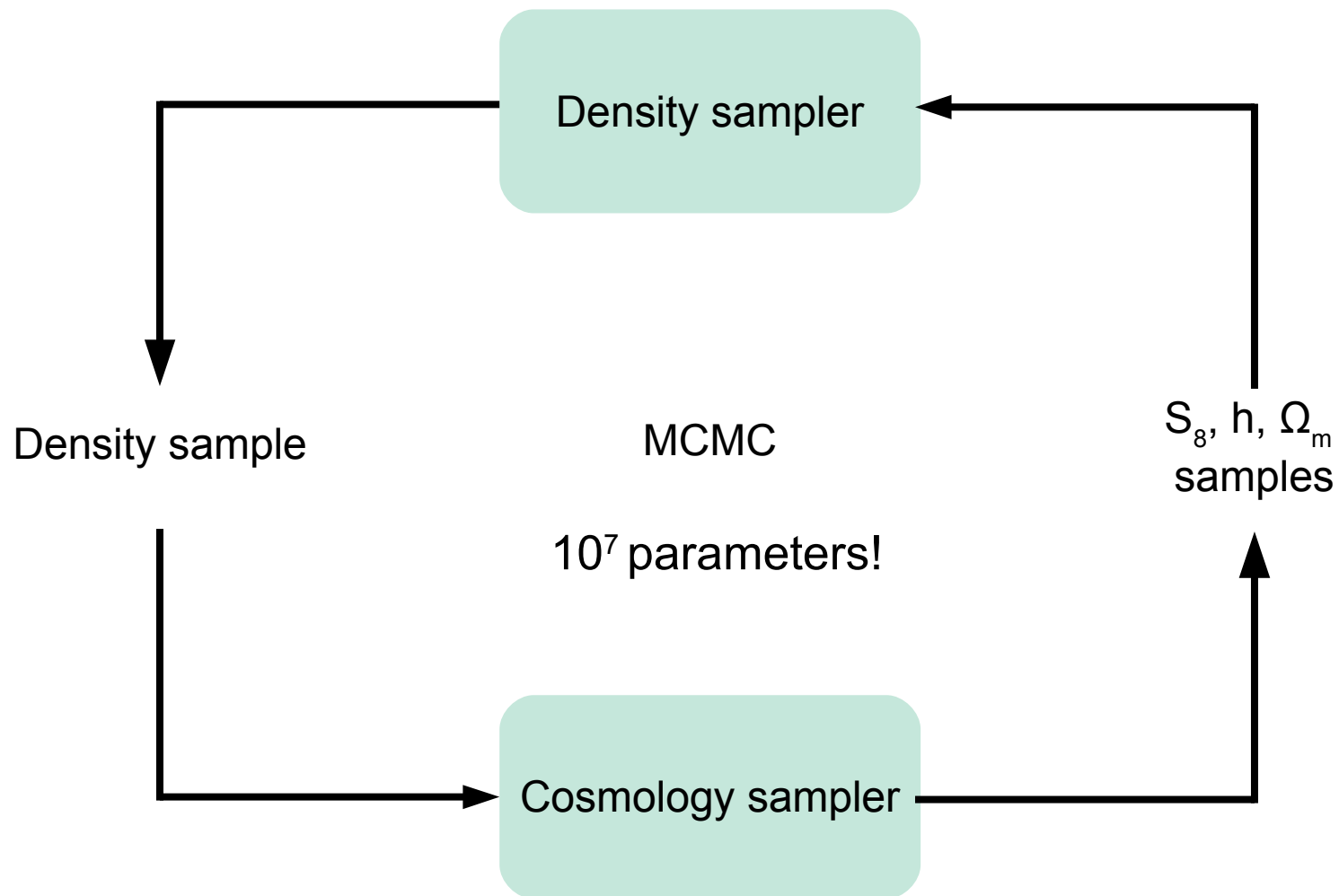
- An option: Gaussian/lognormal prior for shear/density field,

  but we know more about the matter distribution.

- Our approach: include model of non-linear clustering and structure growth,

  and sample from initial conditions.

  Gaussian prior for initial conditions + Gravity model
  (BORG framework)
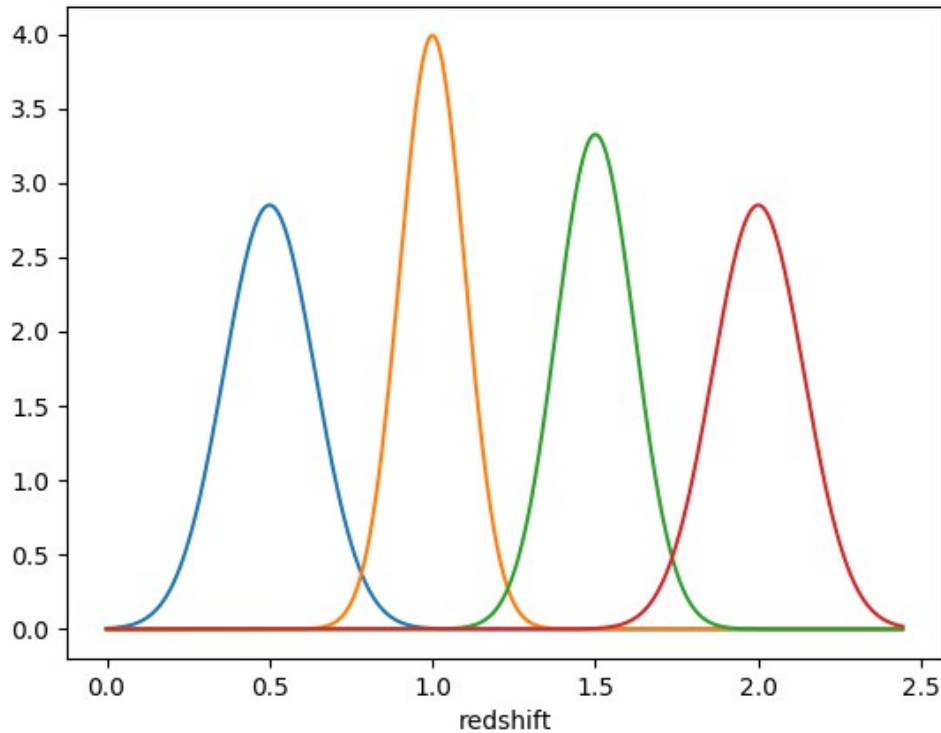
Bayesian hierarchical model of cosmic shear

$U(\Omega)$ — Uniform prior for cosmological parameters

Ω

$P(\delta^{\mathrm{IC}}|\Omega)$ — Gaussian prior for initial conditions

δ^{IC}

$M(\delta^{\mathrm{IC}})$ — Gravity model (+ lightcone) (LPT, PM)

z-distribution

$n^b(z)$

δ^{F}

$\gamma^b(\delta^{\mathrm{F}}, n^b(z))$ — Shear field (flat-sky)

Sensitivity to cosmology:
- Geometry
- Growth of structures
- Initial matter power spectrum

data

$\hat{\gamma}_1^{\,b},\ \hat{\gamma}_2^{\,b}$

$\gamma_1^{\,b},\ \gamma_2^{\,b}$

$P(\hat{\gamma}_1^{\,b},\ \hat{\gamma}_2^{\,b}\,|\,\gamma_1^{\,b},\ \gamma_2^{\,b})$

Assuming Gaussian noise:

$$-\log P(\hat{\gamma}_1, \hat{\gamma}_2|\gamma_1, \gamma_2) = \sum_b \sum_{mn} \frac{(\gamma_{1,mn}^b - \hat{\gamma}_{1,mn}^b)^2 + (\gamma_{2,mn}^b - \hat{\gamma}_{2,mn}^b)^2}{2\sigma_{mn}^2}$$

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Statistical modular framework

Density sampler

Density sample

MCMC

10^7 parameters!

S_8, h, Ω_m samples

Cosmology sampler
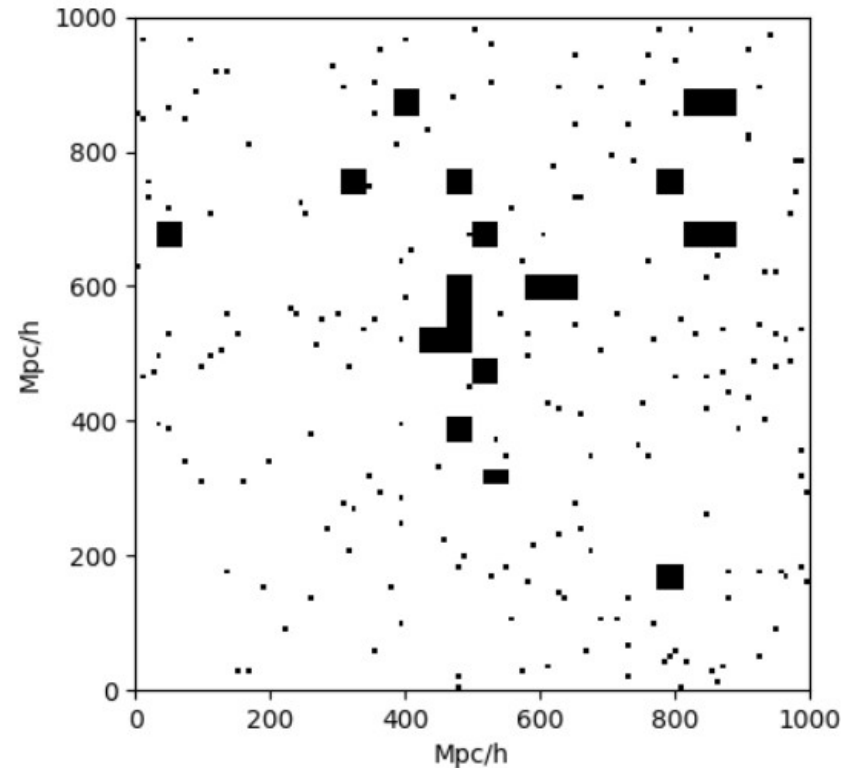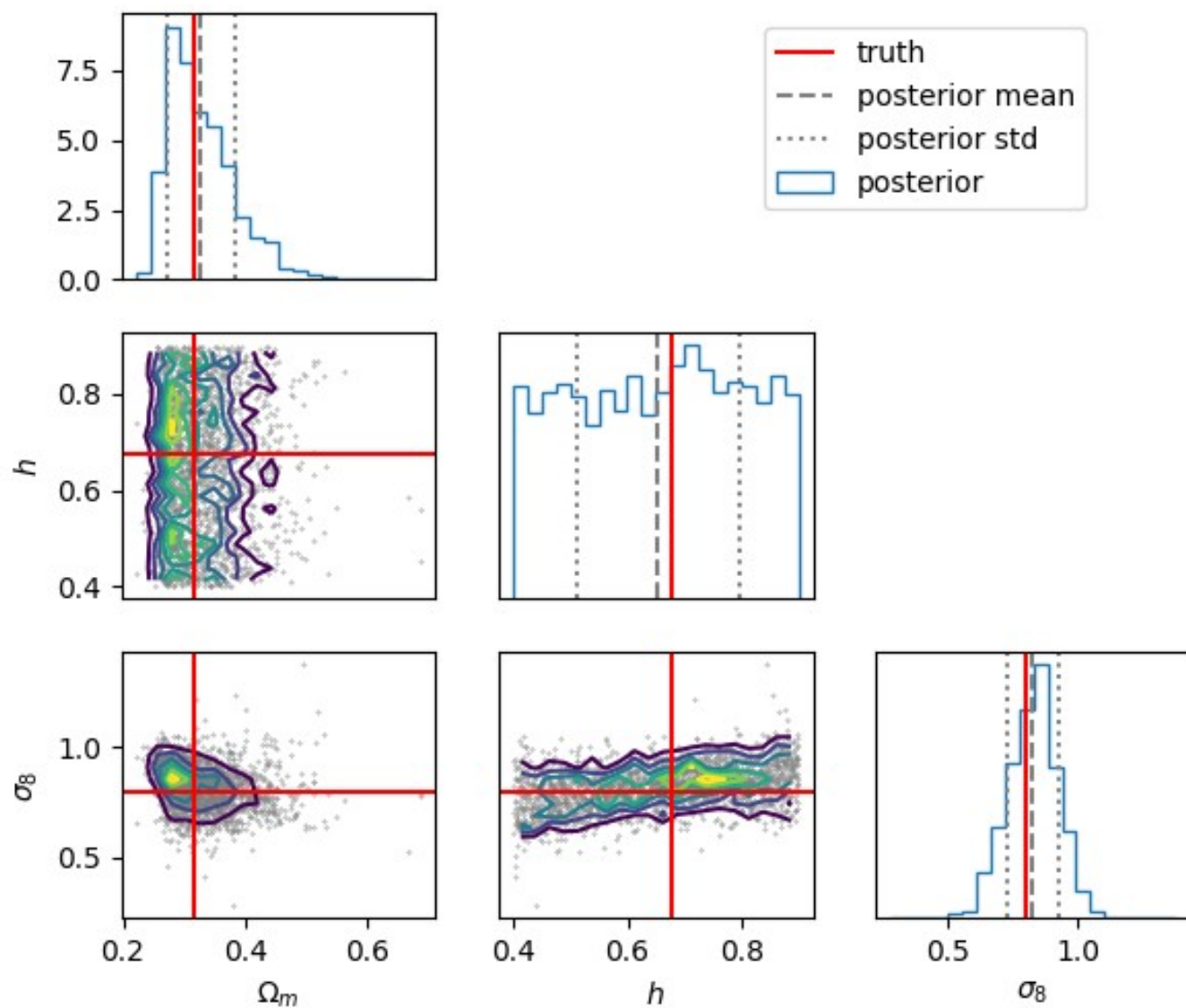
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Simulated data

Tomographic bins

Mask

Simulation: 1 Gpc/h across the sky and 4 Gpc/h in radial direction

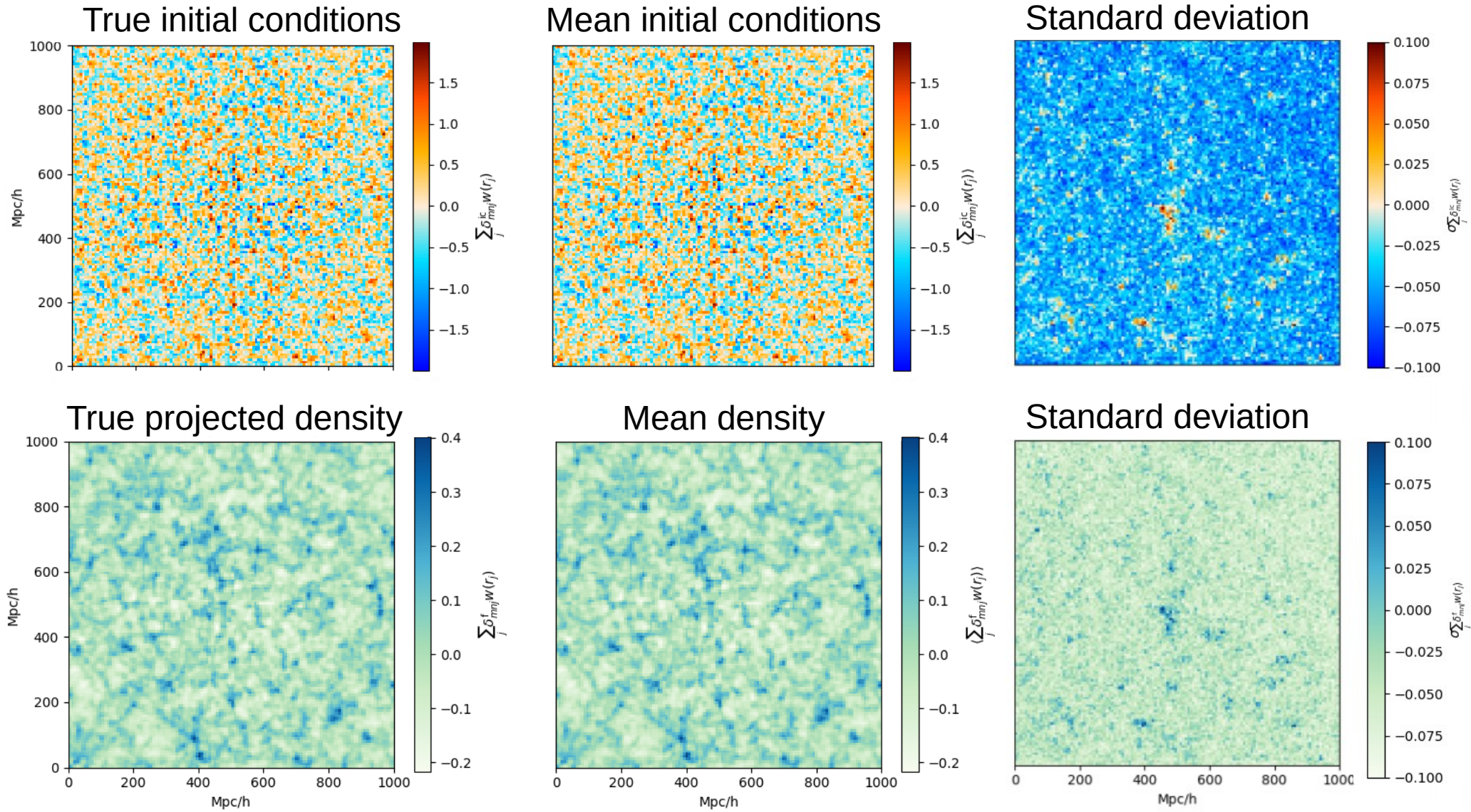Gaussian pixel-noise corresponding to 30 sources per arcmin^2

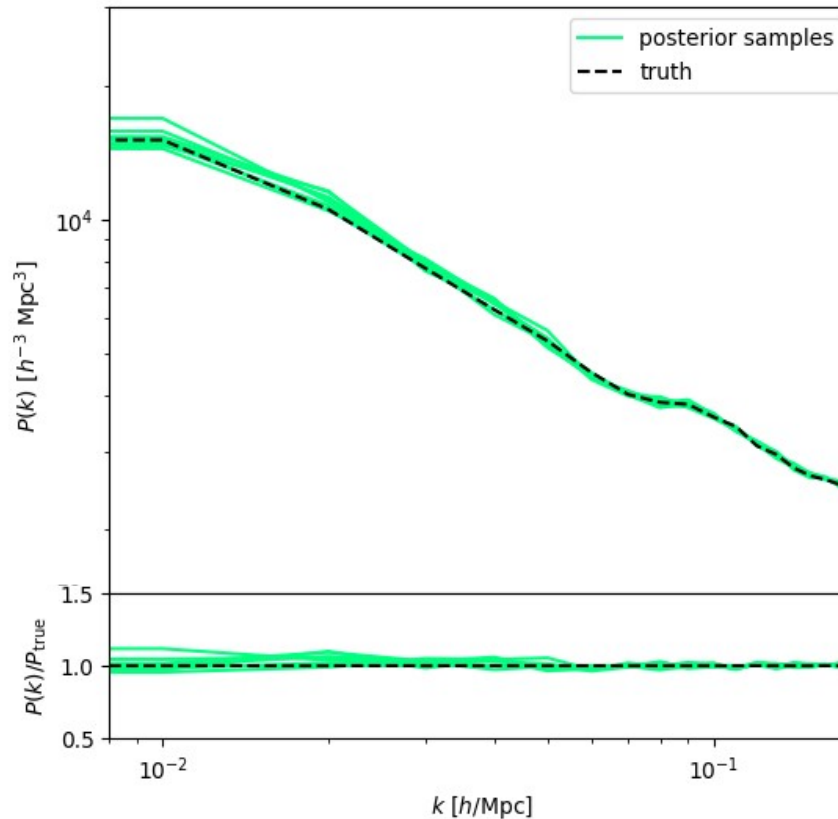Natalia Porqueres
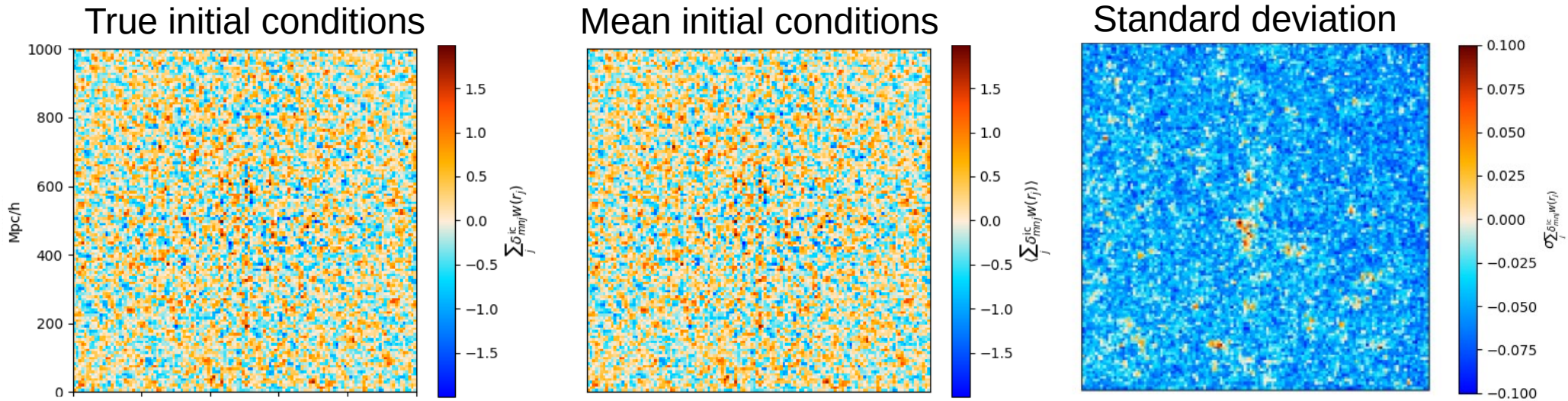
Posteriors on cosmological parameters

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Inferred projected density fields

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Inferred projected density fields

True initial conditions

Mean initial conditions

Standard deviation

Initial matter power spectrum (3D)

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Can the inferred quantities explain the data?
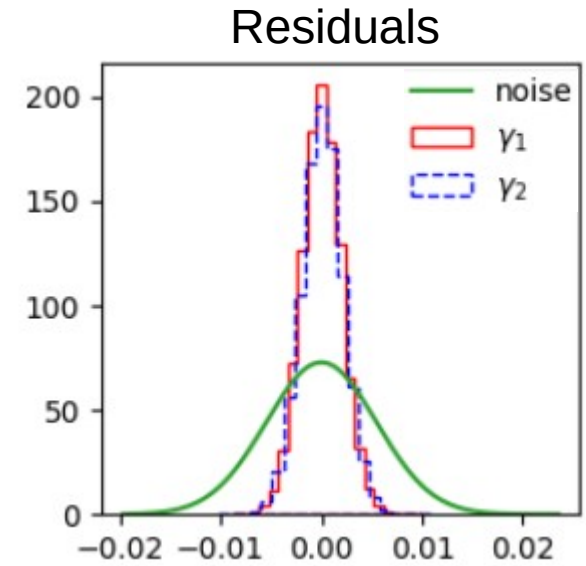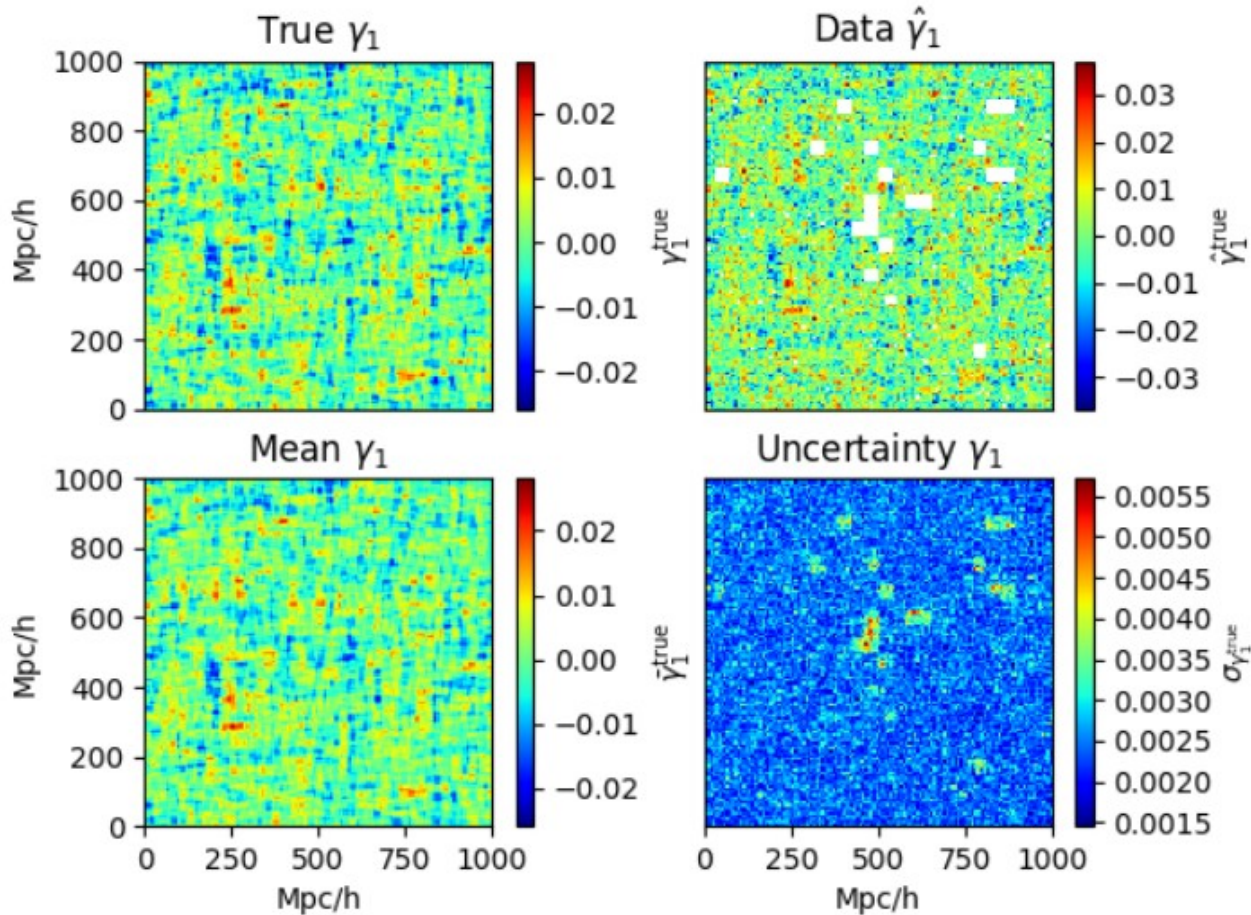
Inferred quantities
explain data to sub-noise
level

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Summary and outlook

- Bayesian analysis of weak lensing with non-linear models are **feasible**.

- Physical forward modelling bypasses summary statistics.

- **Joint constraints** of cosmological parameters and the matter distribution are possible.