First measurement of projected phase correlations and large-scale structure constraints

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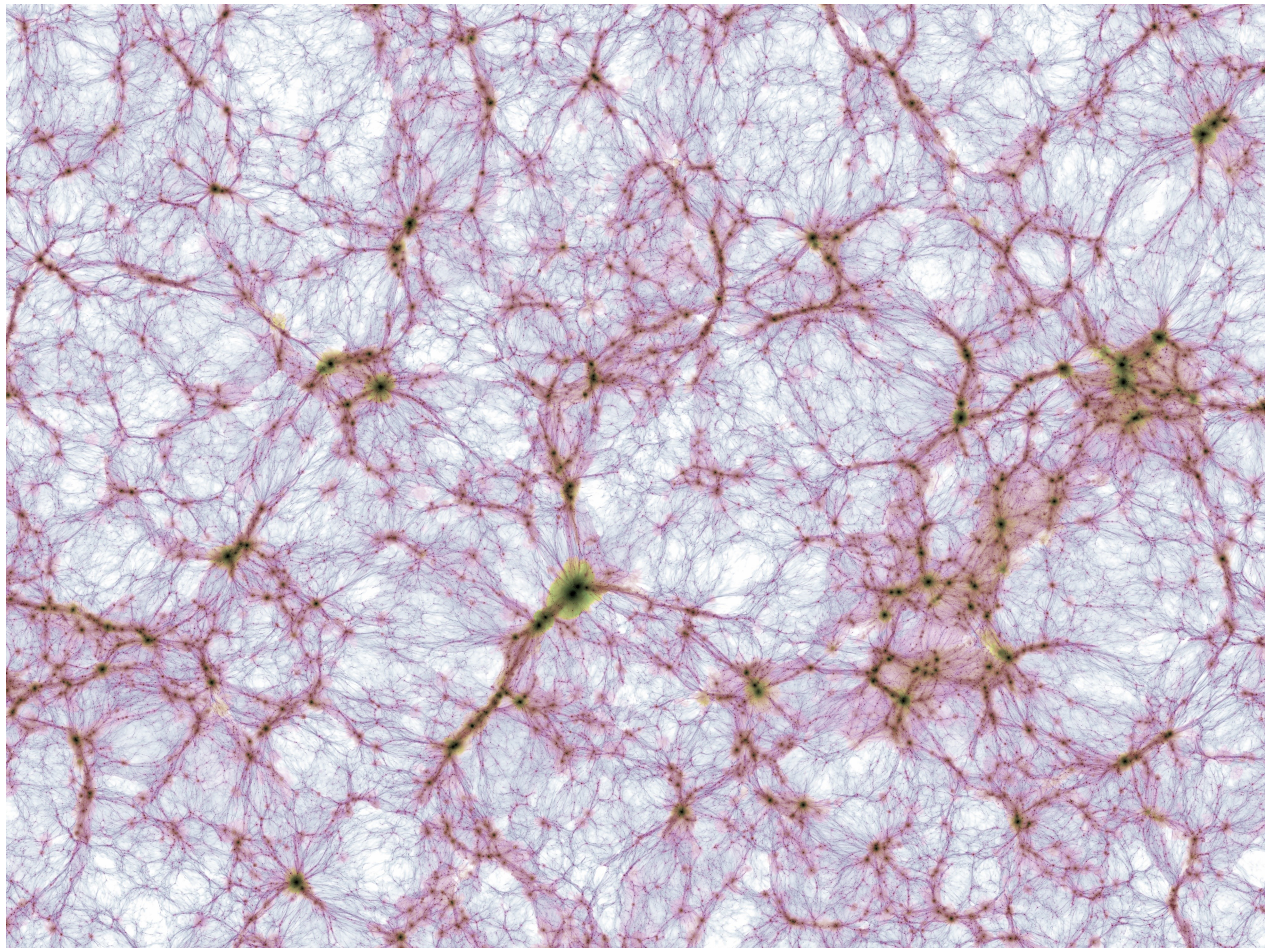
Motivation

- The Large Scale Structure (LSS)
- Distribution of matter in the late-time Universe: clusters, filaments, sheets, and voids ⟶ cosmic web
- Signatures of a strongly non-Gaussian field



Credit: "TNG Collaboration"

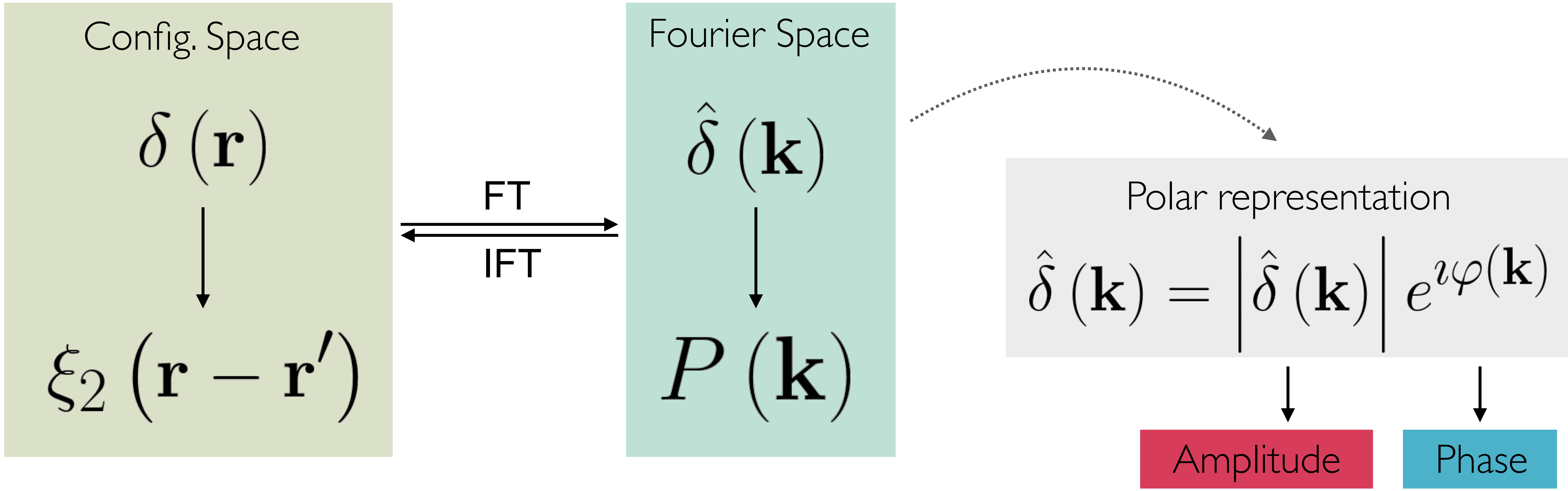
- Significant information regarding its origin and evolution

How to extract this information?

Motivation

- This can be challenging:
  - No optimal summary statistics exists for generic non-Gaussian fields in terms of data compression
  - The number of independent elements grow geometrically for high-order correlations
  - Lack of general analytical solutions → often it is not possible to derive theoretical predictions

Phase Correlations



- Gaussian random field:
  - statistical properties are completely contained in the power spectrum

$$P(\mathbf{k}) \sim \left\langle \left|\hat{\delta}(\mathbf{k})\right|^2 \right\rangle \longrightarrow \text{amplitude information}$$

  - phases are uniformly distributed

Phase Correlations

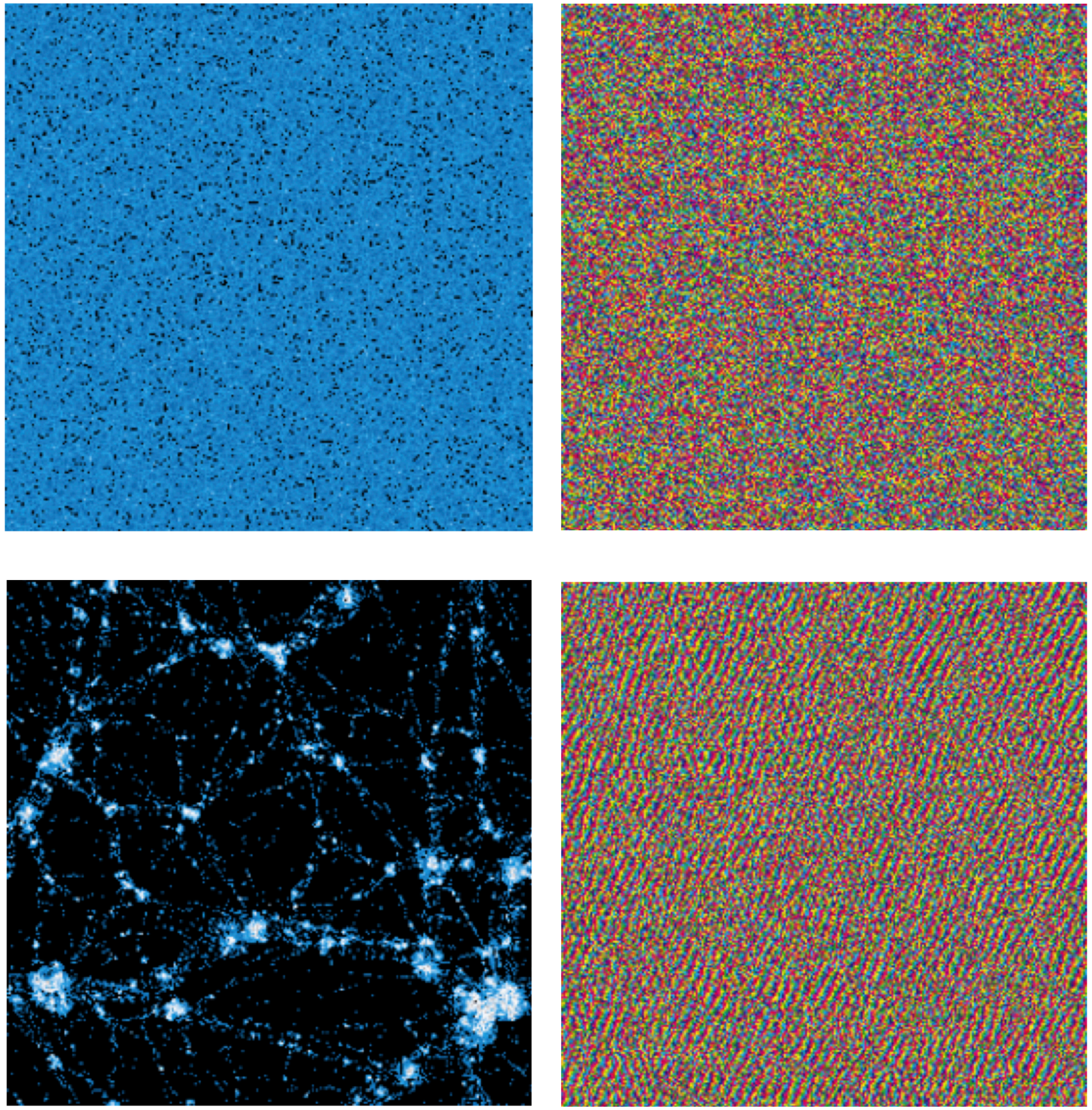
- Non-Gaussianities ⟶ introduce phase couplings
- Phase correlations

$$\langle \varepsilon\left(\mathbf{r}_1\right) \ldots \varepsilon\left(\mathbf{r}_N\right) \rangle$$

- Phase factors

$$\varepsilon\left(\mathbf{r}\right) \equiv \mathrm{IFT}\left[\varepsilon\left(\mathbf{k}\right)\right]$$

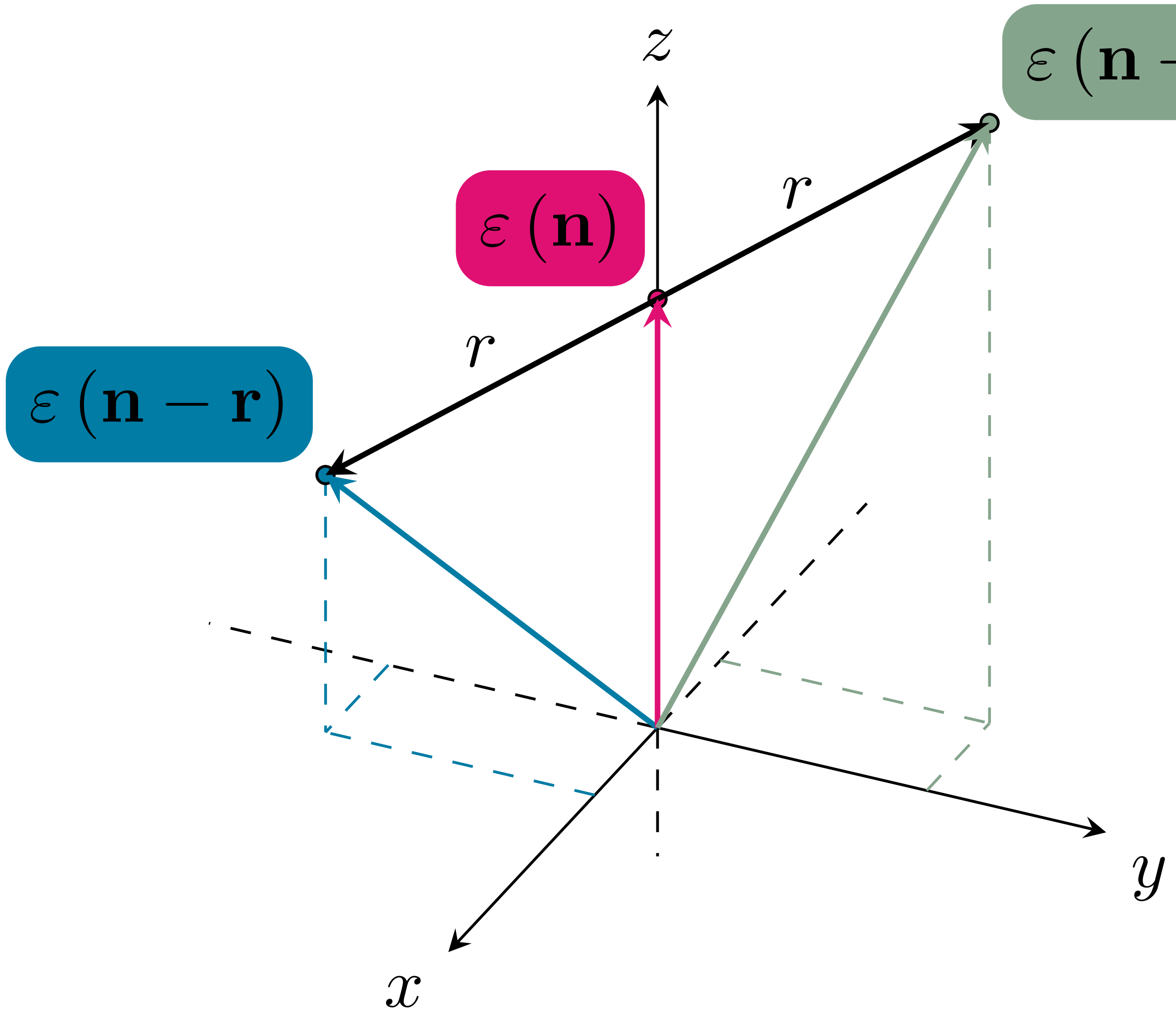
$$\varepsilon\left(\mathbf{k}\right) \equiv \frac{\hat{\delta}\left(\mathbf{k}\right)}{\left|\hat{\delta}\left(\mathbf{k}\right)\right|} = e^{\imath\varphi\left(\mathbf{k}\right)}$$



Peter Coles & Lung-Yih Chiang (2000)

Line-Correlation Function

- Line-Correlation Function is a specific three-point phase correlation



- It can break the degeneracy between the measurement of the growth rate of structure f and the amplitude of perturbations σ_8
- Redshift-space distortions
- Modified theories of gravity

LCF is sensitive to filamentary structures

Observational Motivation

- In the future, photometric galaxy surveys will probe the late-time structures and play a significant role in our current understanding of the Universe

- Projected maps of the matter and galaxy distributions still preserve much of the underlying non-Gaussian structure

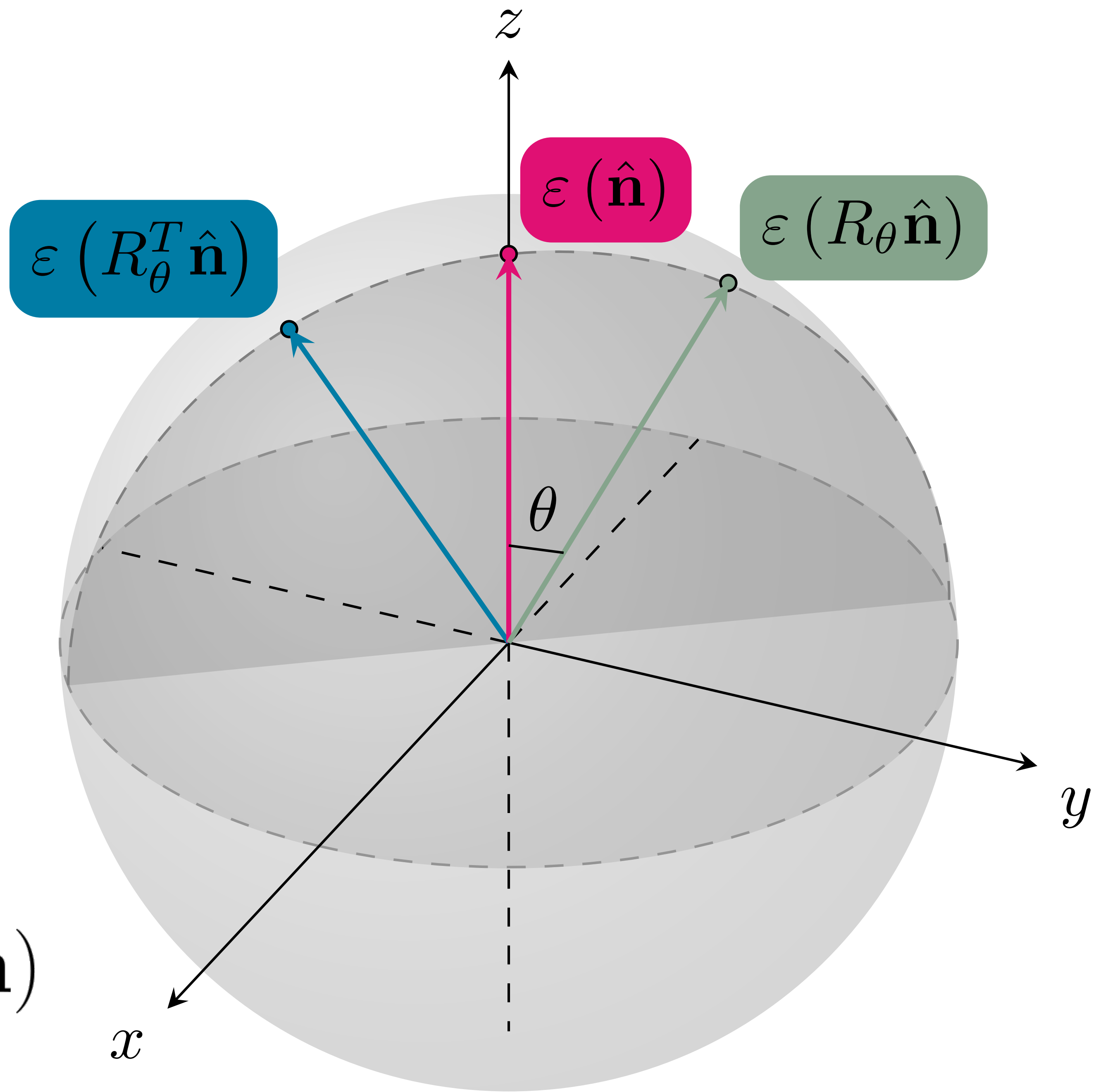
↓

the study of phase correlations on the sphere

The projected line correlation function

- LCF is defined as the correlation between the harmonic-space phases at three equi-distant points lying on a great circle

$$L(\theta) \equiv \left\langle \varepsilon\left(R_\theta^T \hat{\mathbf{n}}\right) \varepsilon(\hat{\mathbf{n}}) \varepsilon(R_\theta \hat{\mathbf{n}}) \right\rangle$$



- Spherical Harmonic Transform:

$$\varepsilon(\hat{\mathbf{n}}) \equiv \sum_{\ell,m} Y_{\ell m}(\hat{\mathbf{n}})\, \varepsilon_{\ell m}$$

$$\varepsilon_{\ell m} \equiv \frac{\delta_{\ell m}}{|\delta_{\ell m}|} \qquad \delta_{\ell m} \equiv \int d^2\hat{\mathbf{n}}\, Y_{\ell m}^\dagger(\hat{\mathbf{n}})\, \delta(\hat{\mathbf{n}})$$

Data

The 2MASS Photometric Redshift catalog (2MPZ)

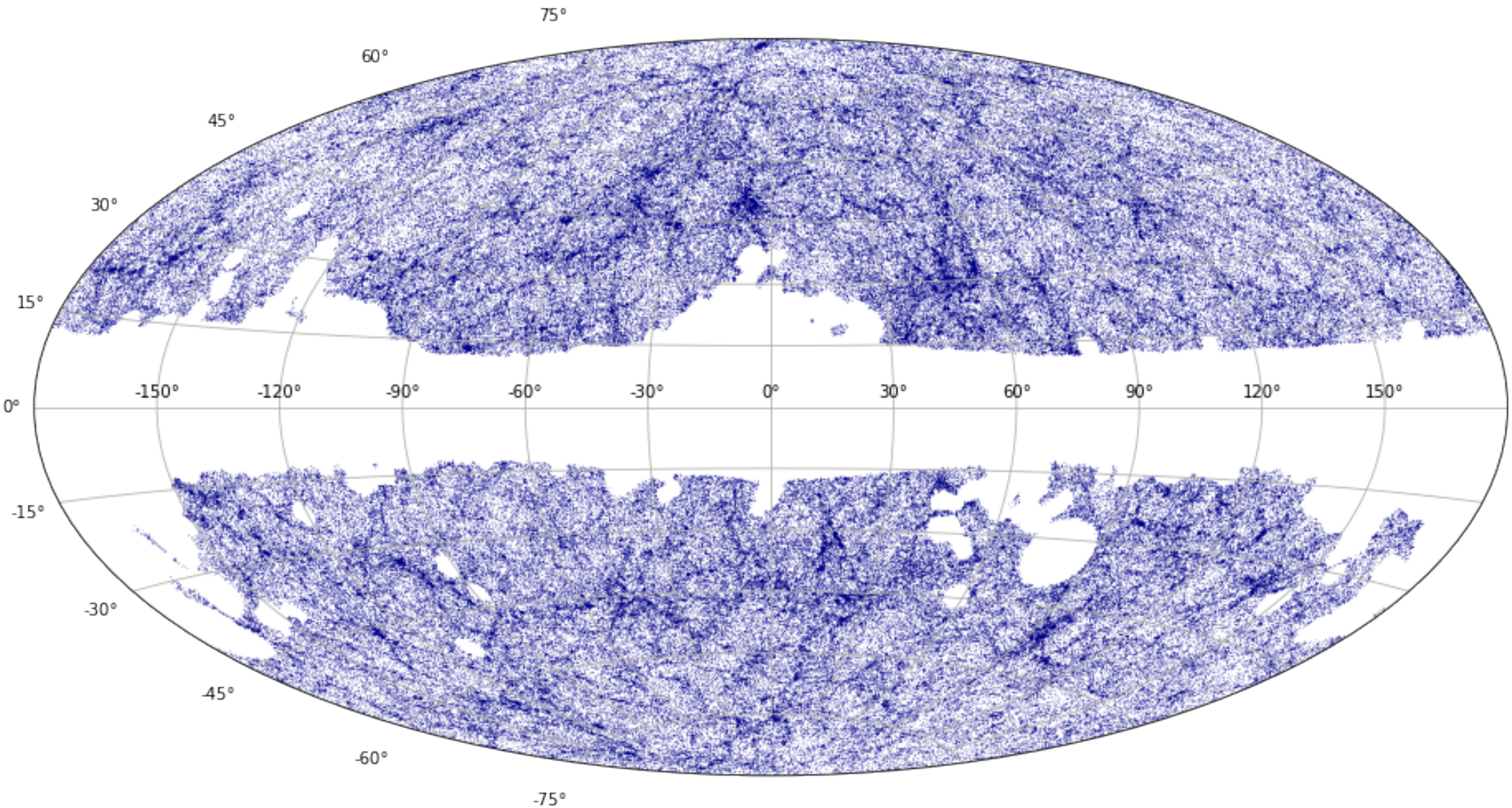
Two Micron All-Sky Survey Extended Source Catalogue (2MASS)

SuperCOSMOS

Wide-field Infrared Survey Explorer (WISE)

- 2MPZ is an ideal sample:
  - photometric survey
  - low redshift and good photo-z accuracy
  - → filamentary structure of the cosmic web

Data



$\bar{z} = 0.08$ $\sigma_{\delta z} \sim 0.013$ $f_{\text{sky}} = 0.68$

Estimating LCF in the presence of a mask

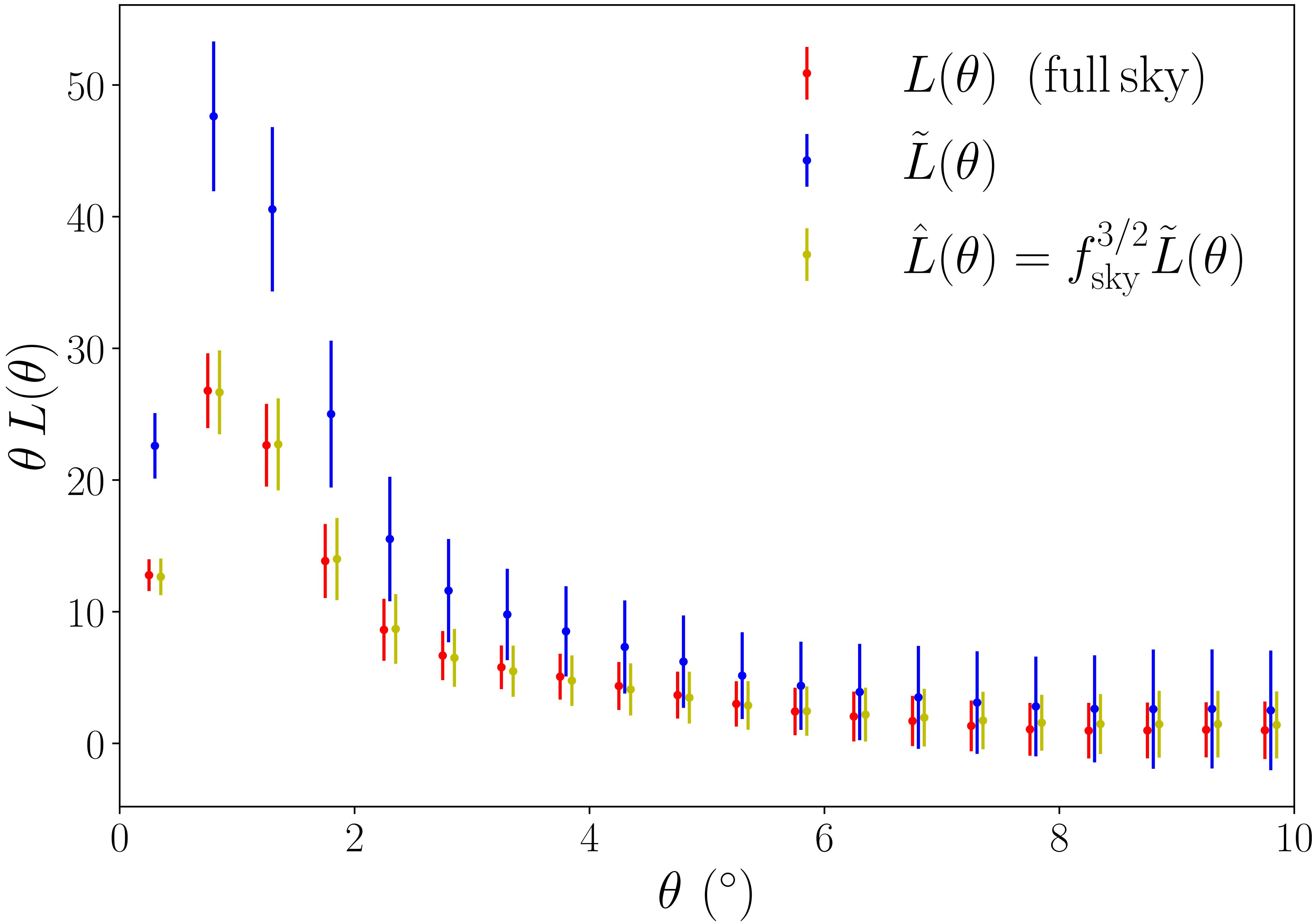
- What is the impact of an incomplete sky coverage on LCF?
- The mask leads to non-trivial statistical couplings between different modes that can affect the shape and normalisation of the resulting LCF
- Approximate estimator ➢ overall normalization

$$\hat{L}(\theta) = f_{\mathrm{sky}}^{3/2} \tilde{L}(\theta)$$

- We comput:

$$\tilde{L}(\theta) = \frac{\sum_{ij} \varepsilon_i \varepsilon_j \varepsilon_{ij} \Theta\left(\theta < \theta_{ij}/2 < \theta + \Delta\theta\right)}{\sum_{ij} \Theta\left(\theta < \theta_{ij}/2 < \theta + \Delta\theta\right)}$$

Estimating LCF in the presence of a mask



- Validation: 100 fast mock realisations making use of `CoLoRe`

Simulation-based Emulator

- Theoretical model: N-body simulations from AbacusSummit
- Generate simulated galaxy catalogs for 100 different halo occupation distribution (HOD) models

Minimum halo mass required to host a central galaxy

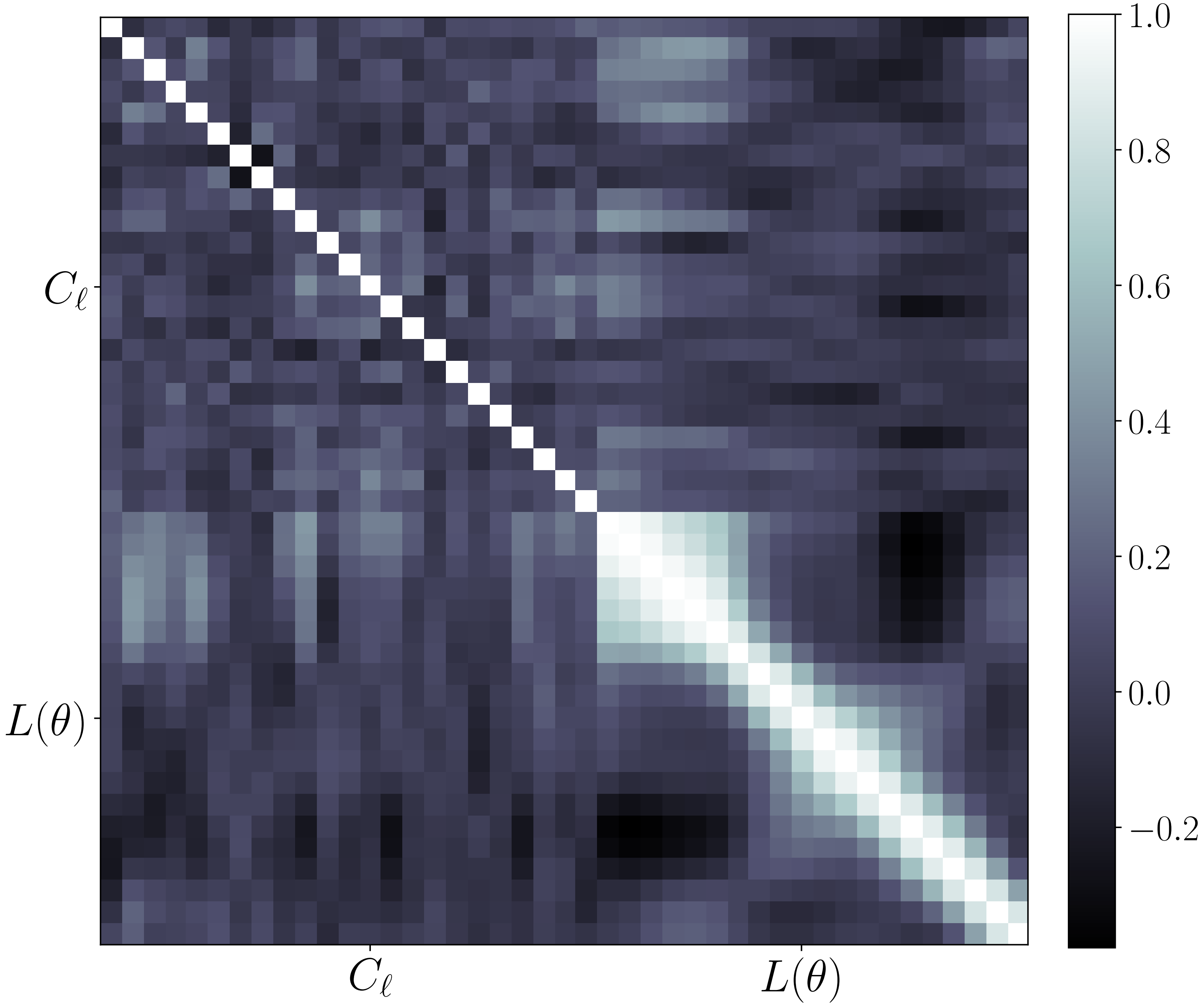
$$\log_{10}\left(M_{\rm min}/M_{\odot}h^{-1}\right) \in (10.7, 12.2)$$

Mass of halos that contain, on average, one satellite galaxy

$$\log_{10}\left(M_{1}/M_{\odot}h^{-1}\right) \in (11.5, 14.0)$$

Covariance Matrix

- Jackknife resampling method



- The LCF covariance has large off-diagonal element
- Non-negligible covariance between both measurements

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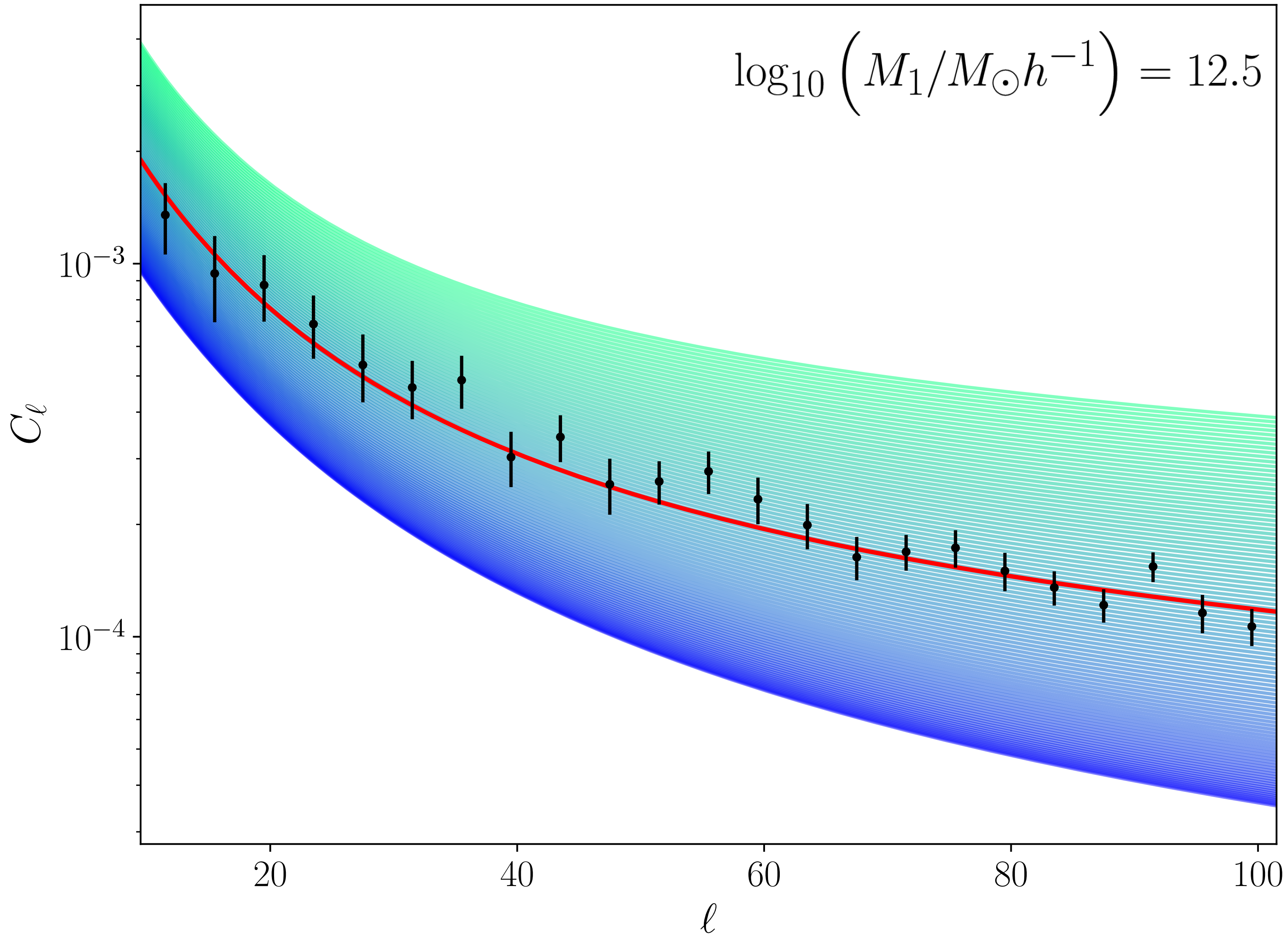
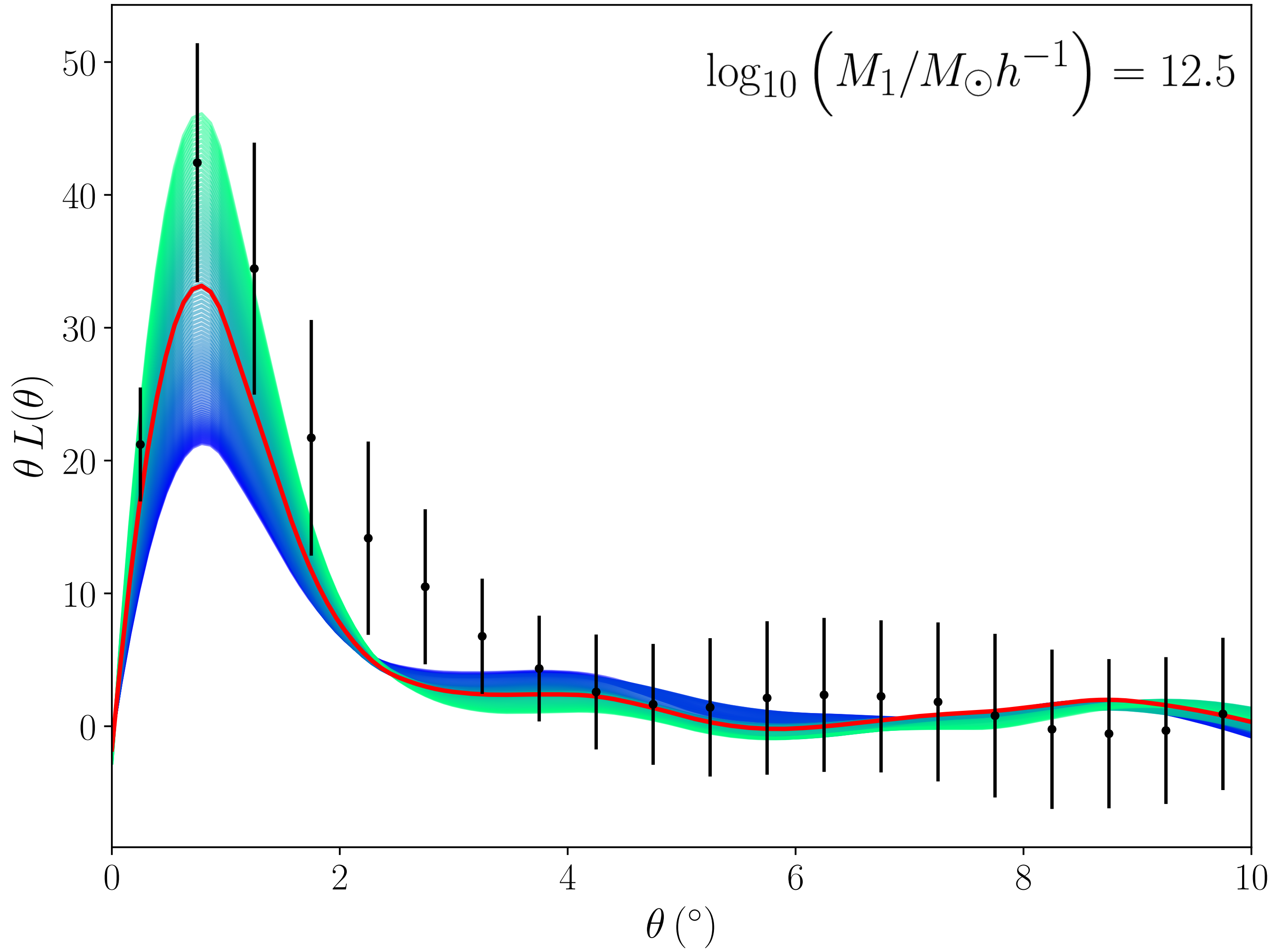
sourced by higher-order connected N-point correlators

Measurements

Angular power spectrum



LCF



Detection of phase correlations in 2MPZ: $S/N = 6.5\,\sigma$

Constraining power

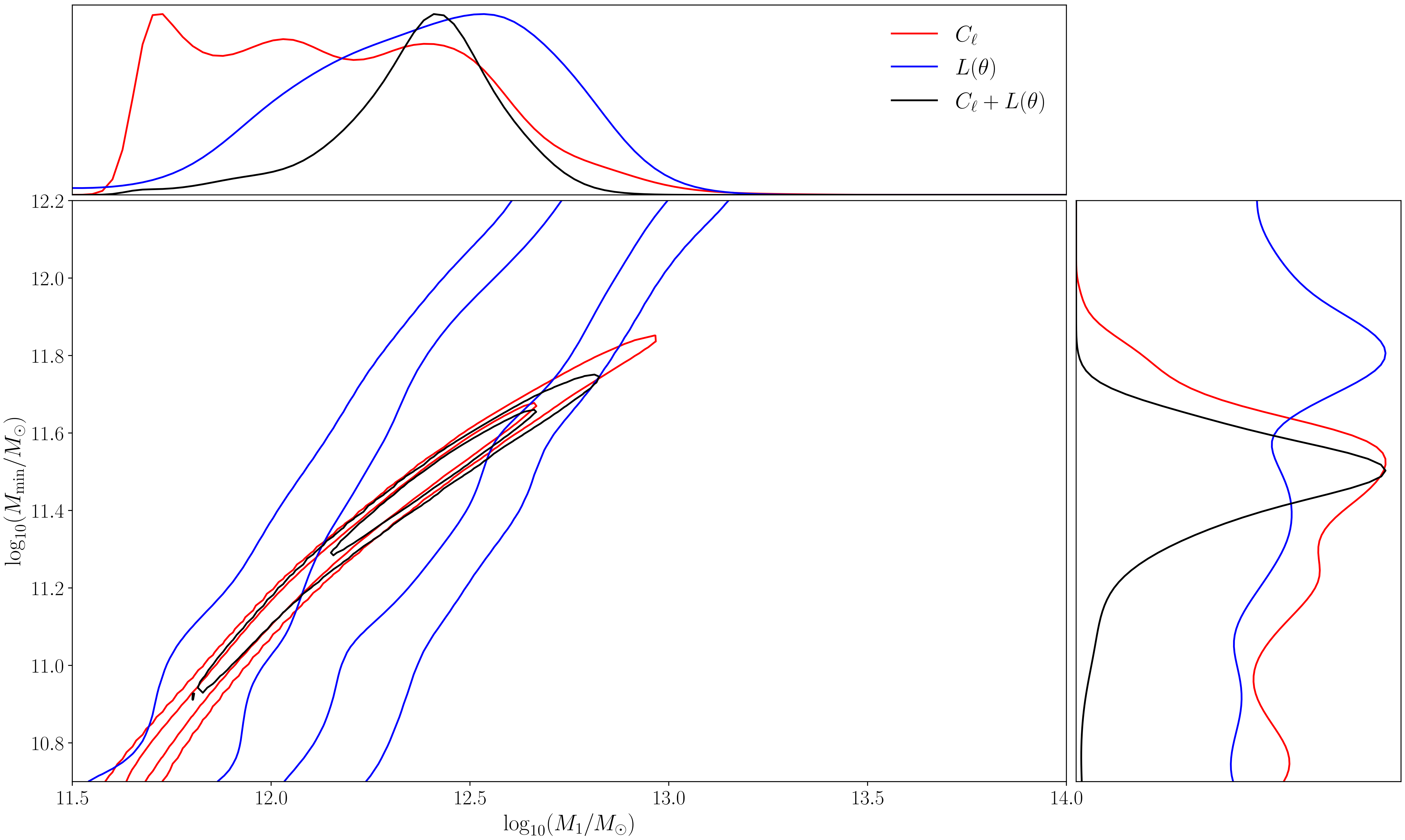
- We constructed a Gaussian likelihood of the form

$$-2\log p(\mathbf{d}|\mathbf{q}) = (\mathbf{d}-\mathbf{m}(\mathbf{q}))^T\,\mathsf{C}^{-1}(\mathbf{d}-\mathbf{m}(\mathbf{q}))$$

$\mathbf{d}$	data
C_ℓ	
$L(\theta)$	
$C_\ell + L(\theta)$	

$\mathbf{q}$	free model parameters
$\mathbf{m}$	the theoretical model provided by the emulator
C	the jackknife covariance matrix

Constraining power



$$\log_{10}\left(M_{\rm min}/M_\odot h^{-1}\right) = 11.45 \pm 0.17$$

$$\log_{10}\left(M_1/M_\odot h^{-1}\right) = 12.37 \pm 0.20$$

Conclusions and Future Perspectives

- The first measurement to date of phase correlations on real data
- The addition of the LCF is able to significantly improve the parameter constraints
- This advocates the use of phase correlations in cosmological data analysis
- Application for three-dimensional datasets
- Other phase correlation configurations may contain valuable cosmological information

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Thank you

- arXiv: 2206.11005

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