Signatures of Primordial Non-Gaussianity in the non-linear density field

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arXiv: 2206.01619, 2206.01624, 2206.15450, 2211.07565 & 2305.10597

In collaboration with the **Quijote-PNG** team (*W. Coulton, F. Villaescusa-Navarro, D. Karagiannis, D. Jamieson, M. Liguori, M. Baldi, L. Verde & B. Wandelt*)

Primordial non-Gaussianity (PNG)

Probing the early universe physics

Primordial non-Gaussianity: tiny deviations from Gaussianity of **primordial fluctuations**

➡ Predicted in different **shapes** (e.g. local, equilateral, orthogonal) and **amplitudes** $f_{\rm NL}$ by different models of inflation

➡ Best current constraints from **Planck CMB bispectrum** measurements (1905.05697)

$$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1, \; f_{\rm NL}^{\rm equil} = -26 \pm 47, \; f_{\rm NL}^{\rm ortho} = -38 \pm 24$$

➡ **Upcoming LSS surveys** (e.g. Euclid) should be able to improve these constraints

Growth of structure by gravitational instability is non-linear

➡ Very non-Gaussian matter distribution at low redshift ⇒ can we see the small PNG contributions?

➡ Theoretical predictions are difficult ⇒ what is the impact of PNG on small scales?

Solution: **simulation-based approach**

The Quijote-PNG simulations

https://quijote-simulations.readthedocs.io/en/latest/png.html

Coulton, GJ, Villaescusa-Navarro, Karagiannis, Jamieson, Liguori, Baldi, Verde, Wandelt

Goal: produce enough N-body simulations to measure the impact of PNG on the distribution of matter

Quijote-PNG

Coulton, Villaescusa-Navarro, Jamieson, Baldi, GJ, Karagiannis, Liguori, Verde, Wandelt (2206.01619)

➡ N-body simulations fully compatible with Quijote having PNG in their initial conditions

➡ Sets of **500 simulations** with $f_{\mathrm{NL}} = \pm 100$ (**local**, **equilateral** and **orthogonal** PNG)

➡ Codes: **2LPTPNG** (https://github.com/dsjamieson/2LPTPNG) and **Gadget-3**

Quijote https://quijote-simulations.readthedocs.io

Villaescusa-Navarro et al. (1909.05273)

➡ **15000 simulations** for a fiducial Planck cosmology

$$\{\sigma_8 = 0.834,\ \Omega_m = 0.3175,\ \Omega_b = 0.049,\ h = 0.6711,\ n_s = 0.9624,\ f_{\mathrm{NL}} = 0\}$$

➡ Sets of **500 simulations** varying one cosmological parameter

➡ Each simulation contains 512^3 dark matter particles and has a size of 1 Gpc/h

Modal Bispectrum of Quijote-PNG simulations

Modal estimator

Fergusson, Liguori & Shellard (0912.3411, CMB)
Schmittfull, Regan & Shellard (1207.5678, LSS)
Hung, Fergusson & Shellard (1902.01830, LSS)
Byun, Oddo, Porciani & Sefusatti (2010.09579, LSS)

➡ **Expansion** of the data **bispectrum** on a basis of **separable functions**

$$B(k_1, k_2, k_3) = \sum_n \beta_n Q_n(k_1, k_2, k_3)$$

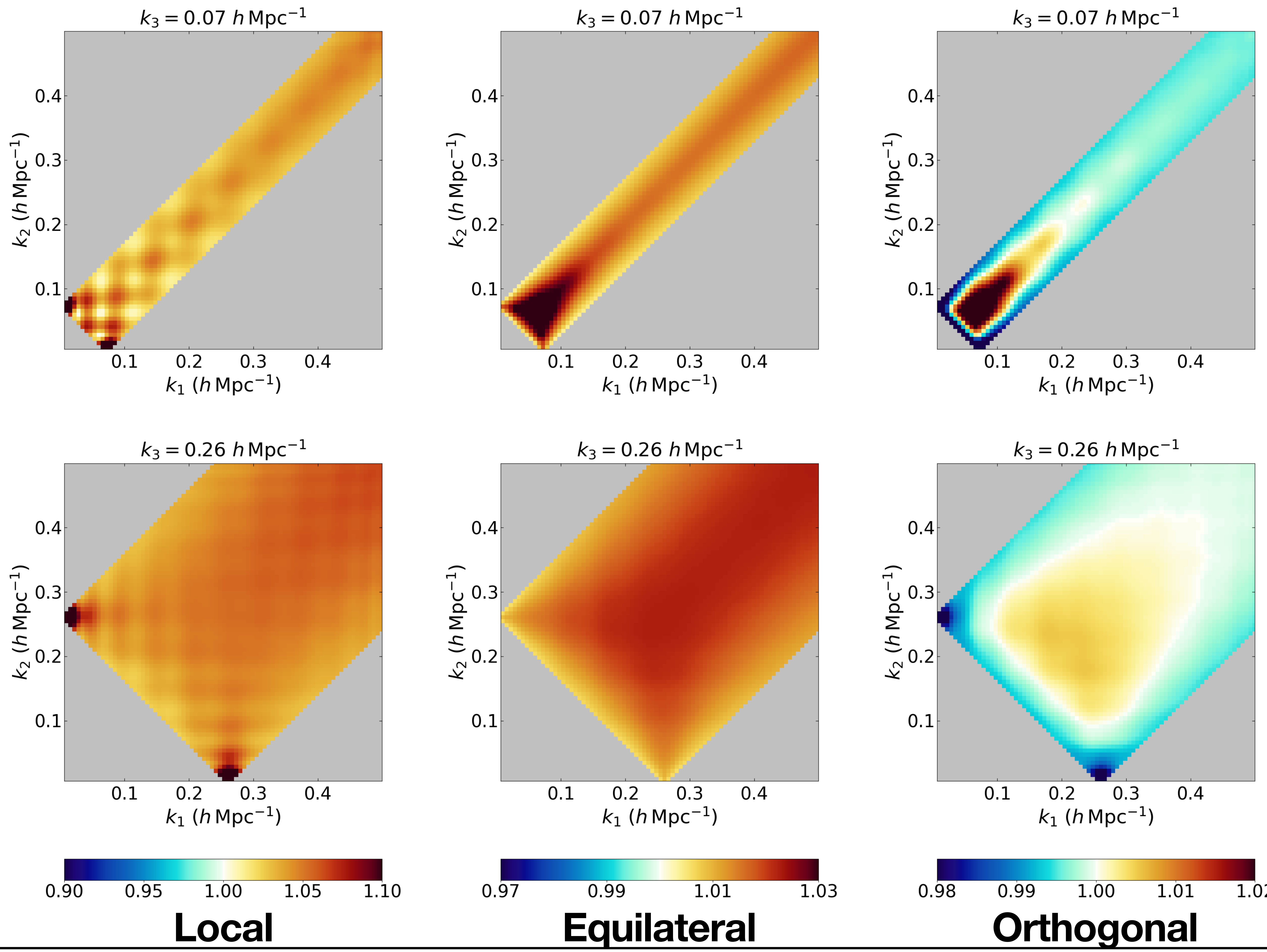
with

$$Q_{n\equiv\{r,s,t\}}(k_1, k_2, k_3) = q_r(k_1)q_s(k_2)q_t(k_3) + \text{perms}$$

➡ **Choice of modal basis**

- Step functions ⇒ **binned** estimator
  Thousands of bin-triplets $\beta_{\Delta k_1 \Delta k_2 \Delta k_3}$
- **Polynomials** ⇒ efficient compression, only ~100 β_n to describe the full bispectrum of the Quijote simulations!

Bispectrum ratio $f_{\rm NL} = 100$ to $f_{\rm NL} = 0$ simulations



Information content on parameters

"Standard" Fisher matrix

➡ **Parameters** $\{\theta_a\}$: $\{\sigma_8, \Omega_m, \Omega_b, h, n_s\}$
Observables S: bispectrum, etc.

➡ **Optimal error bars:**

$$\sigma(\theta_a) \geq \sqrt{(F^{-1})_{aa}}$$

➡ **Fisher information:**

$$F_{ab} = \frac{\partial S_i}{\partial \theta_a} \mathrm{C}_{ij}^{-1} \frac{\partial S_j}{\partial \theta_b}$$

➡ Can be computed from simulations

- Inverse covariance of S (15000 simulations at fiducial cosmology)
- Derivatives (sets of 500 simulations with a displaced parameter)

➡ **Issue**: requires many simulations to avoid **superoptimal constraints**

"Compressed" Fisher matrix

Coulton & Wandelt (2305.08994)

➡ **Optimal data compression**: MOPED, score function

Heavens, Jimenez & Lahav (astro-ph/9911102)
Alsing & Wandelt (1712.00012)

$$\tilde{S}_\theta = \frac{\partial S_i}{\partial \theta} \mathrm{C}_{ij}^{-1} (S_j - \bar{S}_j)$$

- **Optimal**: no loss of statistical information about θ (if S is Gaussian)
- **Compression**: from N observables to n (number of parameters) statistics

➡ Compute the **Fisher information of compressed statistics**

- Noisy derivatives make the compression slightly suboptimal
- Derivatives of compressed statistics converge with much fewer simulations

$\Rightarrow$ **Conservative Fisher error bars**

➡ **"Combined" Fisher matrix**: mean of standard and compressed Fisher

Quasi-maximum likelihood estimator

$$\hat{\theta}_a = \hat{\theta}_a^* + (\mathrm{F}^{-1})_{ab}^* \tilde{S}_{\theta_b},$$ (*: evaluated at fiducial cosmology)

Results (matter density field)

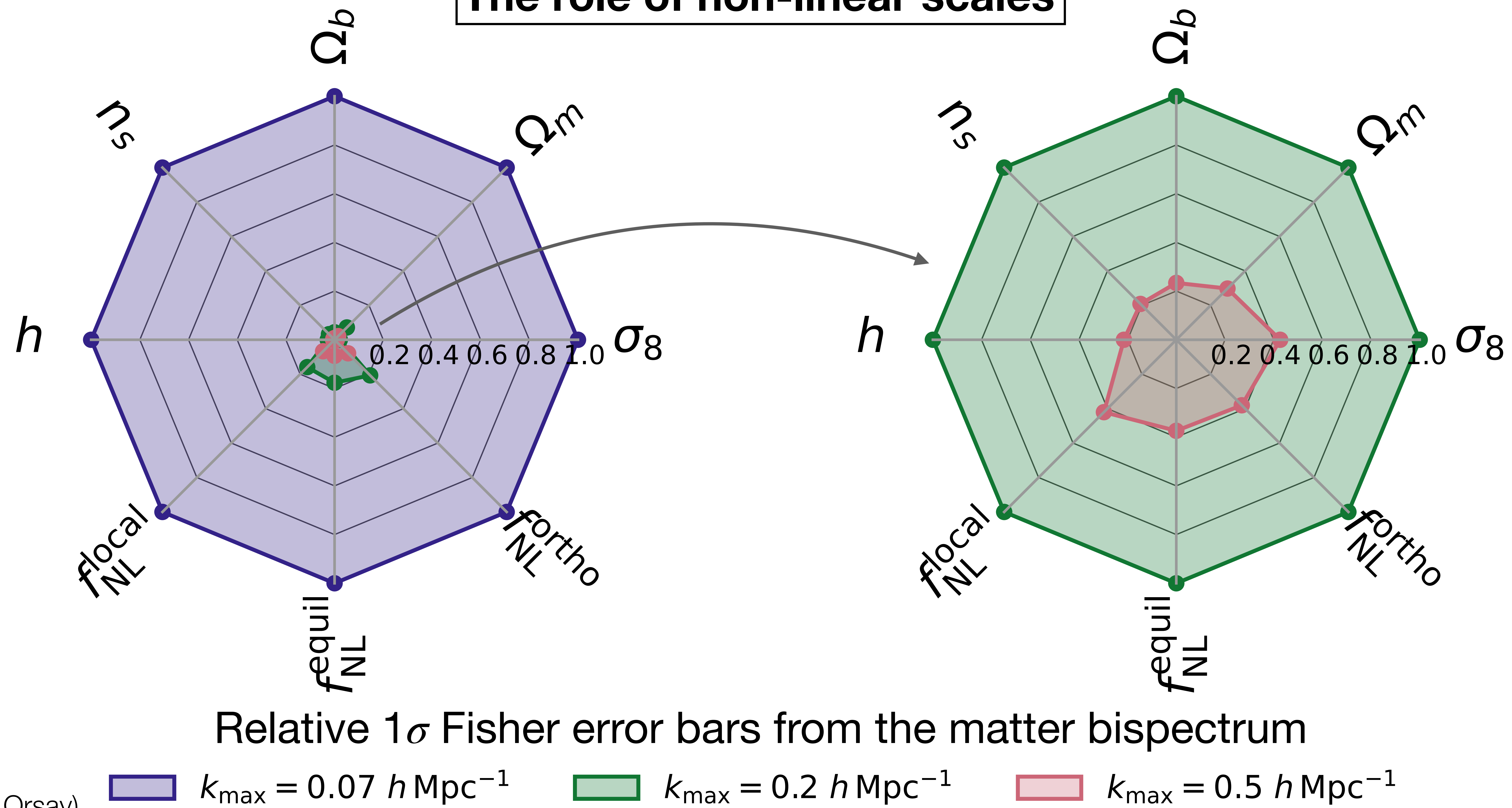
Joint Fisher analyses of ΛCDM cosmological parameters and PNG amplitudes $f_{\rm NL}$

Using ~25000 simulations (Quijote) at $z = 1$, up to $k_{\rm max} = 0.5\,h/{\rm Mpc}$, volume: $1\,({\rm Gpc}/h)^3$

2206.01619

(Quijote-PNG team)

The role of non-linear scales



Relative 1σ Fisher error bars from the matter bispectrum

Results (matter density field)

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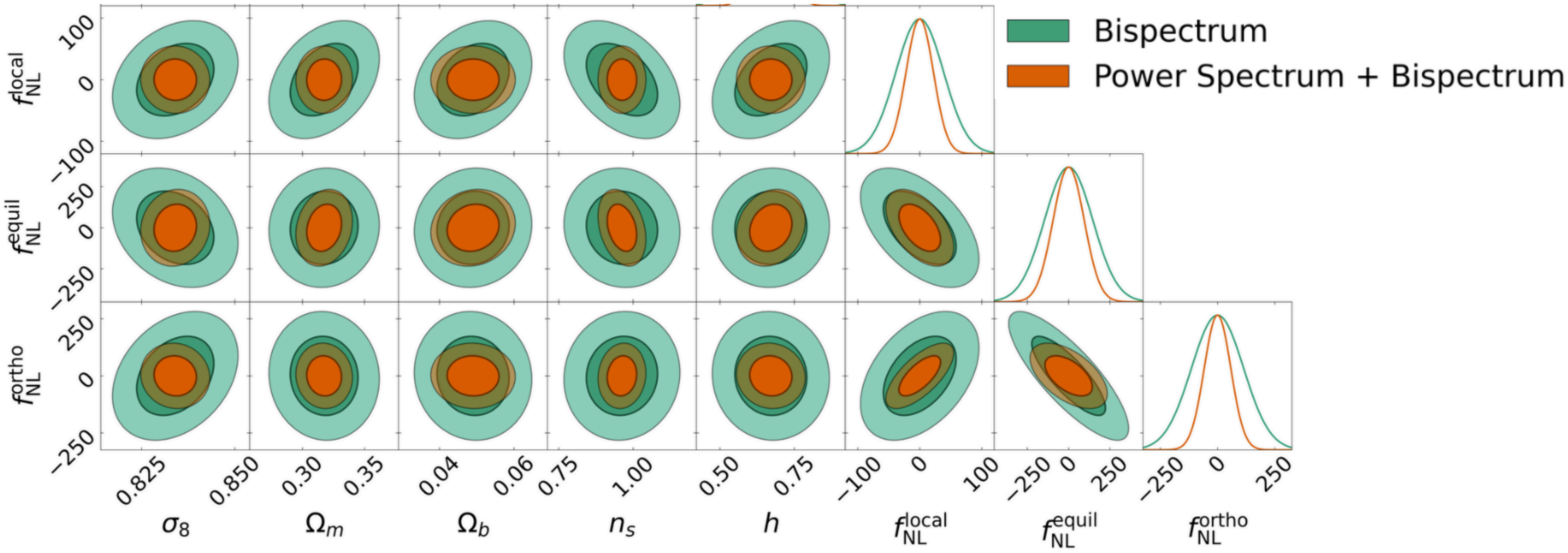
2206.01619
(Quijote-PNG team)

Power spectrum + Bispectrum analysis



Results (halo density field)

Biased tracers of the matter density field

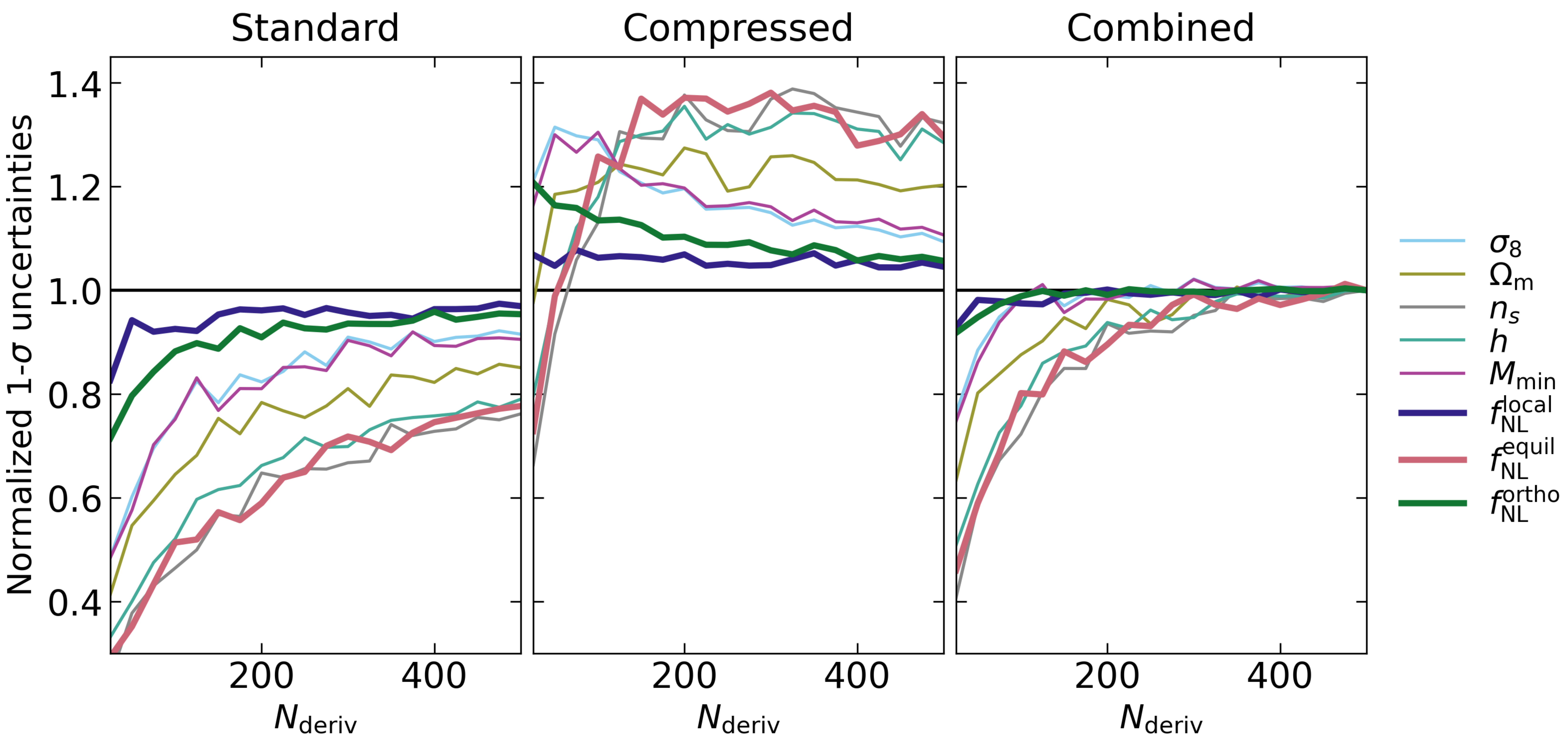
➡ **Halos** identified in Quijote simulations using **Friends-of-Friends** algorithm

➡ Only halos more massive than $M_{\rm min} = 3.2 \times 10^{13}\, M_\odot/h$ are considered

➡ Much lower number of halos than dark matter particles ⇒ large **shot noise**

2206.15450
2211.06565
(Quijote-PNG team)

Convergence of Fisher error bars with the number of simulations

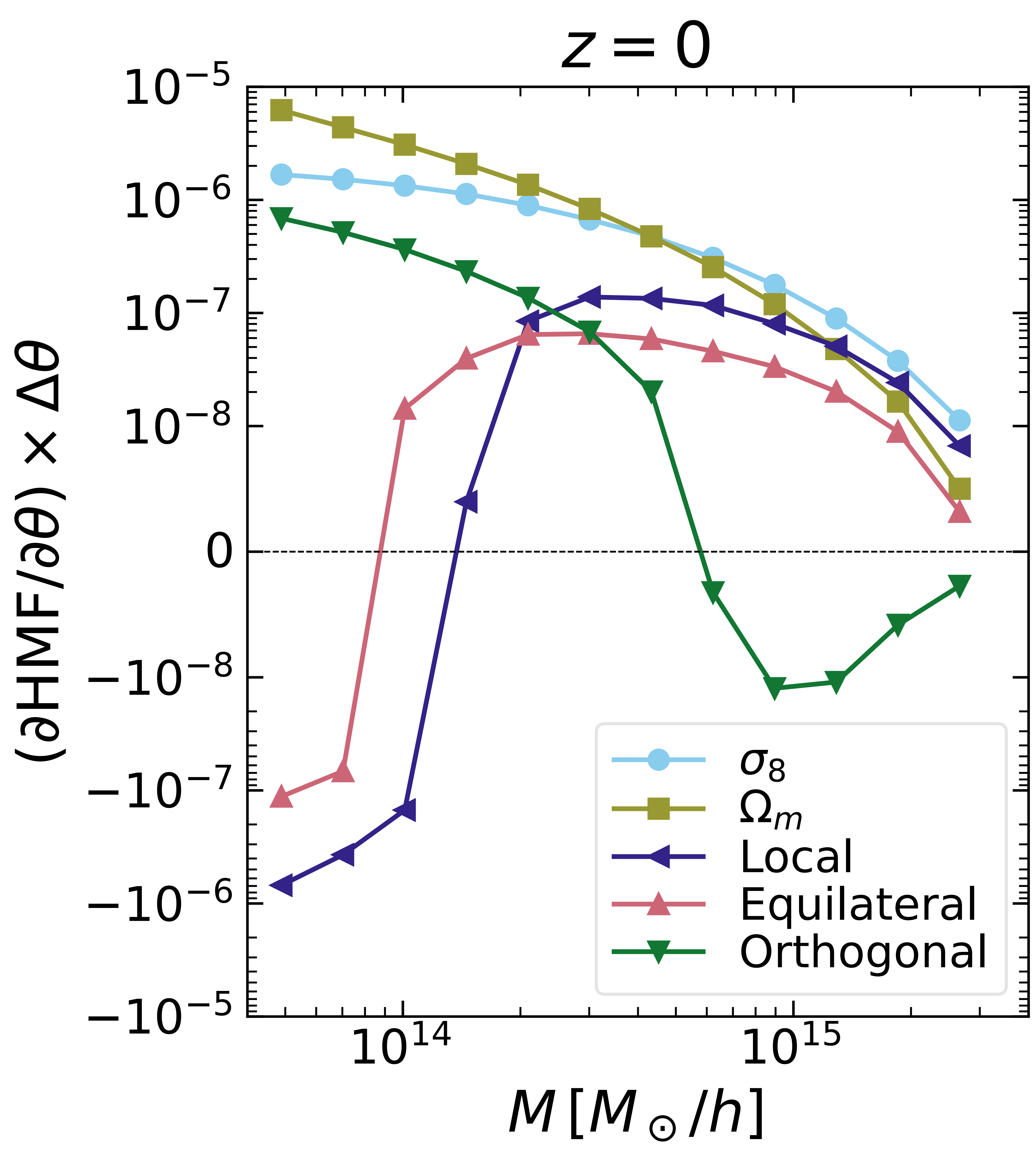


Beyond the bispectrum

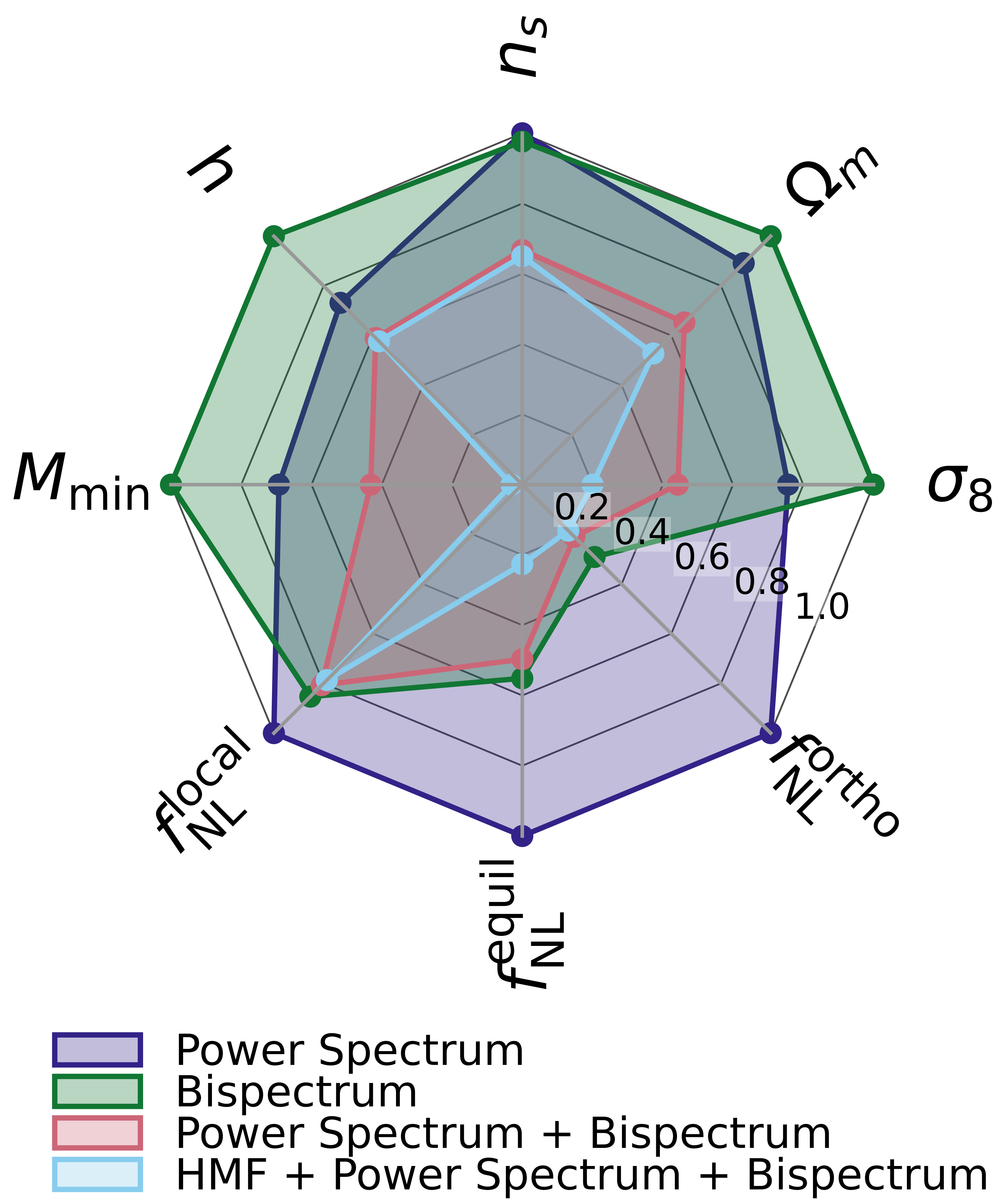
With the Halo Mass Function (HMF)

2305.10597 *(GJ, Ravenni, Baldi, Coulton, Jamieson, Karagiannis, Liguori, Shao, Verde, Villaescusa-Navarro, Wandelt)*

Impact of PNG on the HMF



Joint Fisher analysis HMF/Power Spectrum/Bispectrum



Summary of the talk

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Quijote-PNG simulations

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➡ 4000 publicly available N-body simulations with PNG (local, equilateral and orthogonal)

Analyses of the non-linear matter and halo density fields

➡ Measurements of power spectra and bispectra up to $k_{\rm max} = 0.5\, h/{\rm Mpc}$

➡ Fisher analyses highlighting the role of scales with $k > 0.2\, h/{\rm Mpc}$

➡ Several simulation-based Fisher methods to confirm the numerical stability of the results

➡ Quasi-maximum likelihood estimator of PNG parameters confirming Fisher forecasts

➡ Beyond the bispectrum: example of the halo mass function

Thanks!