UNIVERSITÀ DEGLI STUDI DI PADOVA

Testing Inflation with Cosmological Observations

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In collaboration with: Gabriel Jung, Dionysis Karagiannis, Marco Baldi, William Coulton, Benjamin Wandelt, Francisco Villaescusa Navarro, Licia Verde

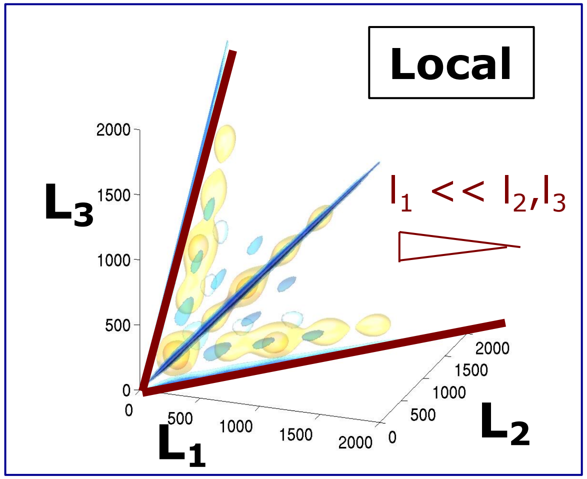
ArXiv:

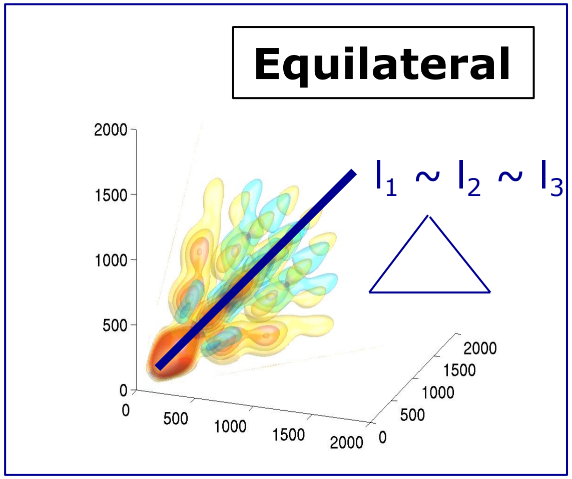
Jung et al. 2022 (2206.01624)

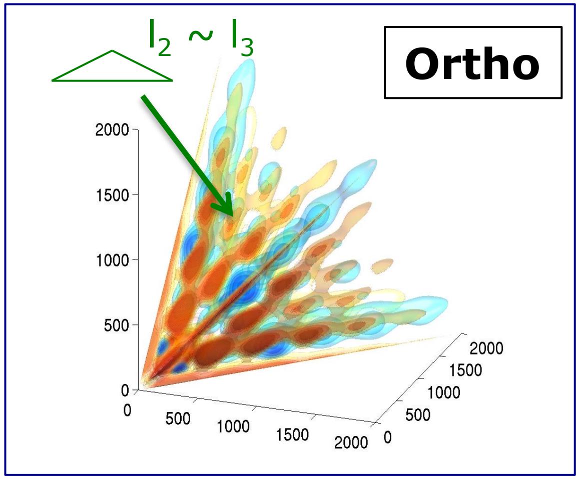
Coulton et al. 2022 (2206.01619, 2206.15450)

Beyond power spectra: non-Gaussianity

Primordial non-Gaussianity. Measures interactions. Many inflationary scenarios (notably, multi-field Inflation) predict small, model-dependent deviations from Gaussianity. **Additional information in 3-point (bispectrum) and 4-point (trispectrum) functions.**







- Multi-field
- Curvaton
- Ekpyrotic/cyclic

- Non-canonical kinetic terms (K-inflation, DBI)
- Higher derivative terms (Ghost Inflation)
- EFT

- Variants of non canonical
- Kinetic terms and higher derivatives
- EFT

Planck LEO constraints

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
`SMICA` (T)		
Local	6.7 ± 5.6	**−0.5 ± 5.6**
Equilateral	4.0 ± 67	**4.7 ± 67**
Orthogonal	−38 ± 37	**−15 ± 37**
`SMICA` (T+E)		
Local	4.1 ± 5.1	**−0.9 ± 5.1**
Equilateral	−25 ± 47	**−26 ± 47**
Orthogonal	−47 ± 24	**−38 ± 24**

Planck 2018 results. IX, arXiv:1905.05697

Future goals

- It is generally accepted that the next sensitivity target should be $f_{NL} \sim 1$
- Local shape: $f_{NL} > 1$ would rule out single-field inflation. $f_{NL} < 1$ would rule out a large class of multi-field models (“spectator fields”)
- Equilateral, Orthogonal: the $f_{NL} \sim 1$ threshold allows discriminating between the single-field slow-roll and non-slow-roll regimes.

	$f_{\rm NL}^{\rm loc} \lesssim 1$	$f_{\rm NL}^{\rm loc} \gtrsim 1$
$f_{\rm NL}^{\rm eq,\, orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{\rm NL}^{\rm eq,\, orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

(from Alvarez et al., arXiv:1412.4671)

- This talk is mostly focused on LEO shapes, but keep in mind that there are many interesting additional shapes (e.g. oscillatory features)

LEO shapes: forecasts

	LiteCOrE-120	COrE+	Planck 2015	LiteBird	ideal
T local	3.7	3.4	5.7	9.4	2.7
T equil.	59	56	70	92	46
T ortho.	25	25	33	58	20
E local	4.5	3.9	32	11	2.4
E equil.	46	43	141	76	31
E ortho.	21	19	72	42	13
T+E local	2.2	**1.9**	**5.0**	5.6	1.4
T+E equil.	22	**20**	**43**	40	15
T+E ortho.	10	**9.1**	**21**	23	6.7

- A cosmic variance dominated E-mode reconstruction up to l_{max} ~ 3000 (PRISM, CMBpol) allows an improvement in f_{NL} error bars by a factor ~2 for *all shapes* c

PNG from LSS

- Future LSS galaxy clustering data have the potential to improve over CMB bounds: 3D LSS density field vs 2D CMB anisotropies field => **more modes**

- **Power spectrum**. Biased tracers of the dark matter field. Specific NG scale-depedent feature in the bias. For local shape:

$$\Delta b(k) = 2(b-1) f_{\mathrm{NL}} \delta_c \frac{3\Omega_m}{2a\, g(a) r_H^2 k^2}$$

- **Bispectrum**. Major challenge: if we want to increase S/N we need to include Fourier modes that are in the non-linear regime of structure formation.
  Late time NG ~ 1000 x primordial NG !

  Needs **very precise** modeling of non-linearities

  - Resort on analytical perturbative approach. Hard to go beyond k ~ 0.2 h/Mpc
  - **Resort on numerical, simulation-based approaches (implicit likelihood inference)**

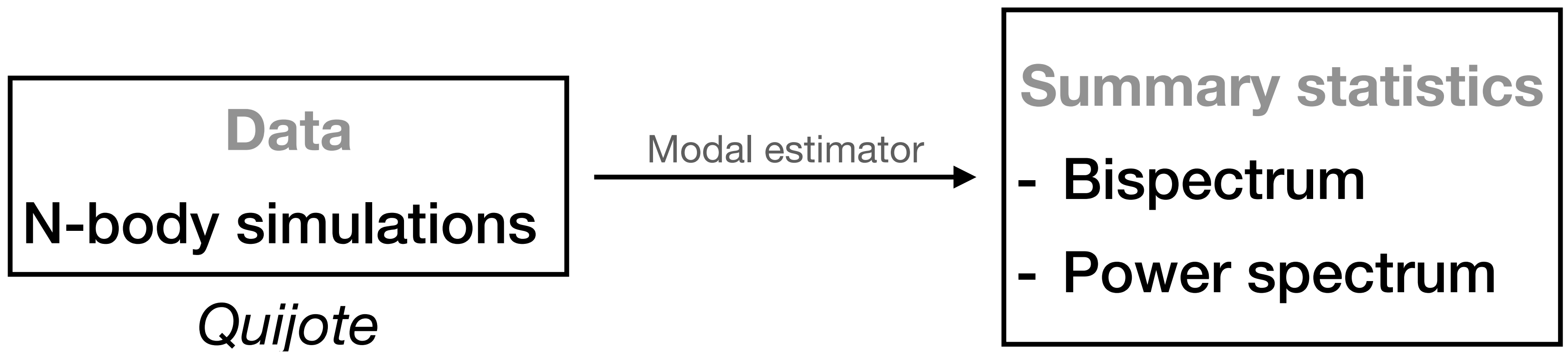
Pipeline

Data

N-body simulations

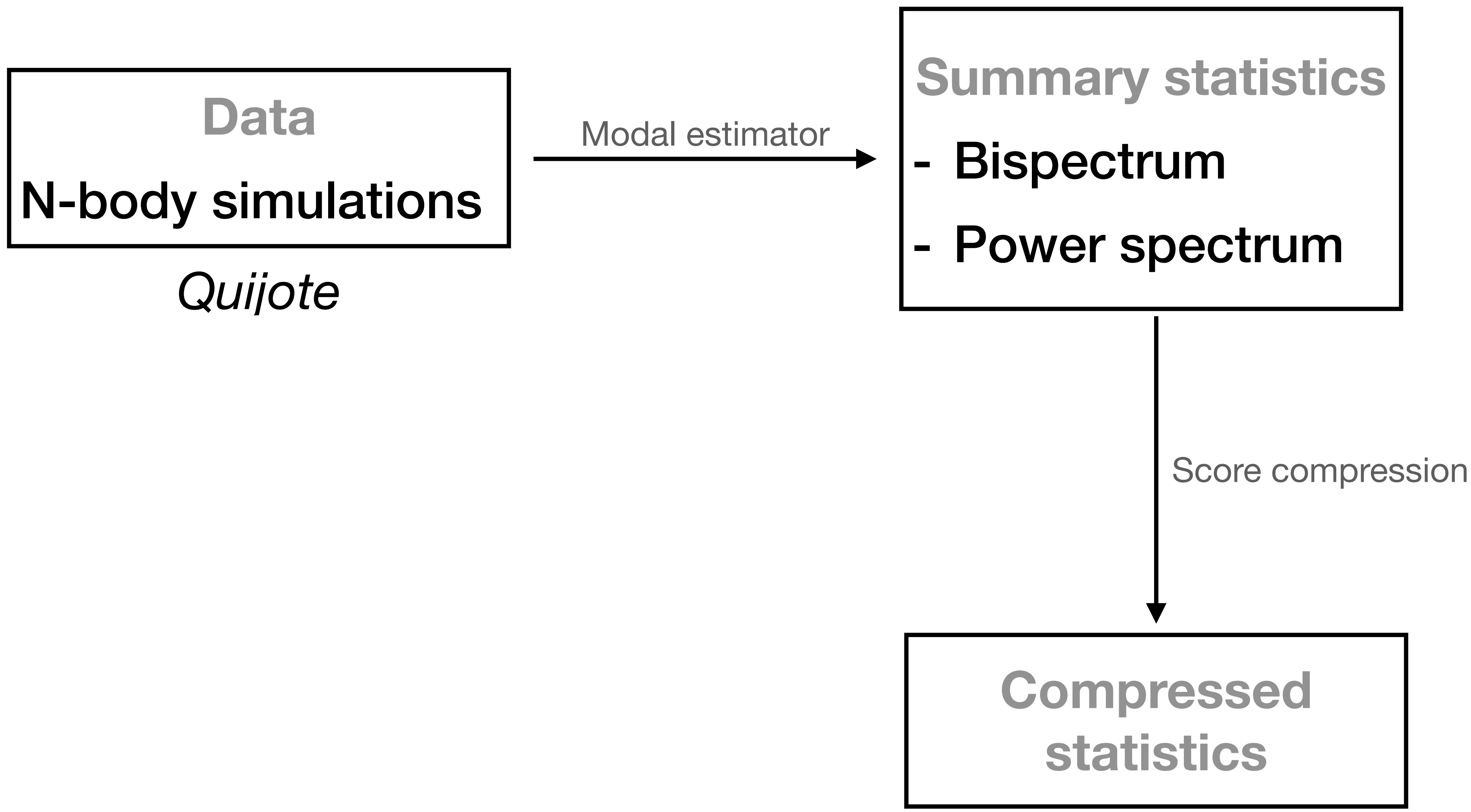
Quijote

Pipeline



Data
N-body simulations
Quijote
Modal estimator
Summary statistics
- Bispectrum
- Power spectrum

Pipeline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Score compression
Compressed statistics

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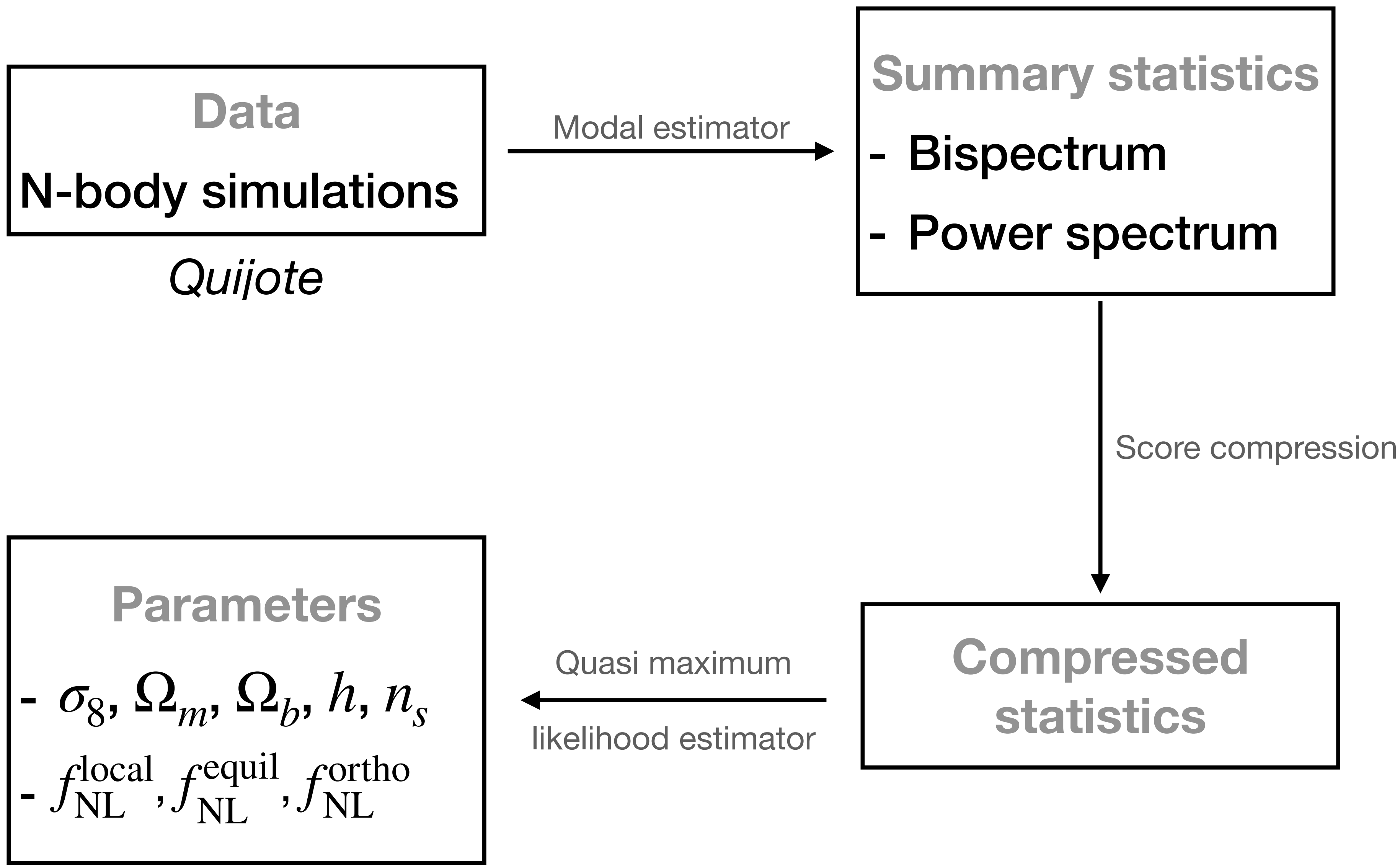

Data
N-body simulations
Quijote
Modal estimator
Summary statistics
- Bispectrum
- Power spectrum
Score compression
Compressed statistics
Quasi maximum likelihood estimator
Parameters
- $\sigma_8, \Omega_m, \Omega_b, h, n_s$
- $f_{\rm NL}^{\rm local}, f_{\rm NL}^{\rm equil}, f_{\rm NL}^{\rm ortho}$

Modal bispectrum estimator

Data ⇒ Summary statistics

- **Weighted expansion of the bispectrum:**

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

- **Separable modal basis:** $Q_n(k_1, k_2, k_3) = q_r(k_1)q_s(k_2)q_t(k_3) + \text{perms}$, with $n \equiv \{r, s, t\}$

- Method originally developed for CMB
  - *Fergusson, Liguori & Shellard* (0912.3411)
  - Planck NG (1905.05697)

- Later implemented in the LSS context
  - *Schmittfull, Regan & Shellard* (1207.5678)
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⇒ **Only ~100 well chosen modes to describe the bispectrum up to** $k_{\rm max} = 0.5h/\text{Mpc}$

Optimal compression

Summary statistics $\Rightarrow$ Compressed statistics

- **Compression to the score function:** 1712.00012 (*J. Alsing, B. Wandelt)*

$$\beta_n \longrightarrow \tilde{\beta}_\theta$$

~100 modal coefficients β_n

1 per parameter θ ($f_{\mathrm{NL}}^{\mathrm{local}}, f_{\mathrm{NL}}^{\mathrm{equil}} \ldots$)

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- **Assuming a Gaussian likelihood for the summary statistics:**

compression equivalent to MOPED, astro-ph/9911102 (*A. Heavens, R. Jimenez & O. Lahav*)

$$\tilde{\beta}_\theta = \frac{\partial \beta_i}{\partial \theta} \mathrm{C}_{ij}^{-1} (\beta_j - \bar{\beta}_j)$$

Derivative

Inverse covariance of β

Mean of β

Data to compress

$$\frac{\partial \beta}{\partial \theta} = \frac{\beta(\theta_* + \Delta\theta) - \beta(\theta_* - \Delta\theta)}{2\Delta\theta}$$

⇒ Computed from simulations where θ is a step $\Delta\theta$ away from fiducial θ_*

⇒ Computed from simulations at fiducial cosmology θ_*

N-body simulations

Data

- **Quijote simulations** ($f_{\rm NL} = 0$)

  https://quijote-simulations.readthedocs.io (F. Villaescusa-Navarro)

  Large suite (~44000) of N-body simulations with 512^3 particles and a size of 1 Gpc/h

  ⇒ 8000 simulations at fiducial cosmology to estimate covariances

  ⇒ Sets of 500 simulations for numerical derivatives (σ_8, Ω_m, Ω_b, h, n_s)

- **Non-Gaussian Quijote-like (** $f_{\rm NL} = \pm 100$ **)**

  ⇒ Sets of 500 simulations for three primordial shapes: local, equilateral and orthogonal

  ⇒ Numerical derivatives ($f_{\rm NL}^{\rm local}, f_{\rm NL}^{\rm equil}, f_{\rm NL}^{\rm ortho}$)

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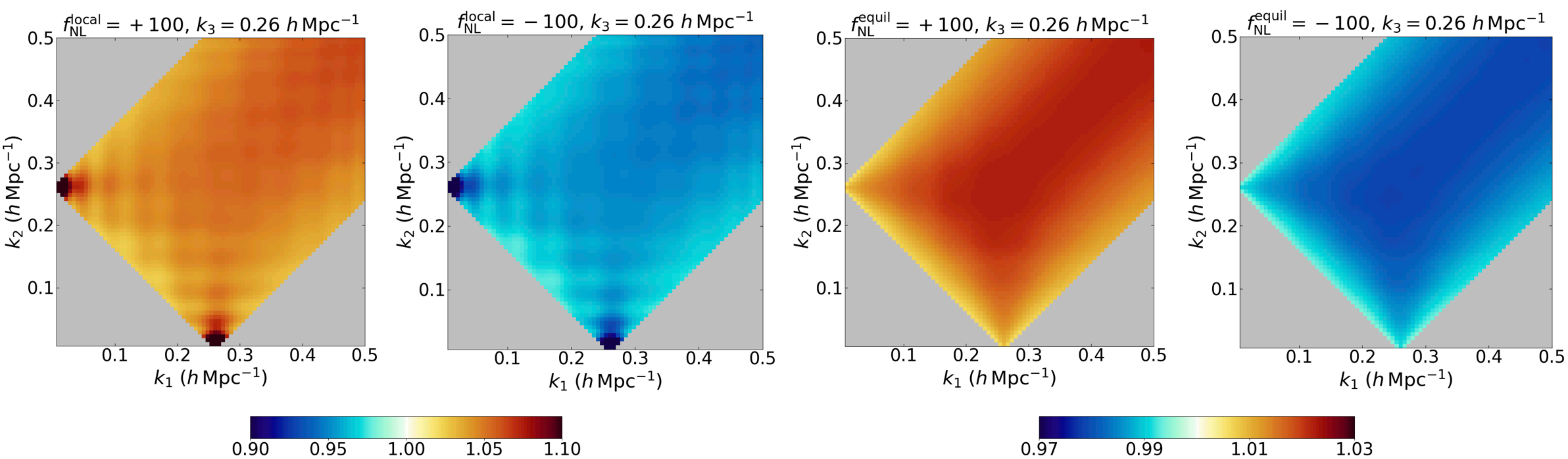

Bispectrum: ratio non-Gaussian/Gaussian

Constraints

Compressed statistics $\Rightarrow$ Parameters

- **Pseudo maximum-likelihood estimator:**

$$\hat{\theta} = \theta_* + F^{-1}\tilde{\beta}$$

where the Fisher information is $F = \mathrm{Cov}[\tilde{\beta}, \tilde{\beta}]$.

Constraints

Compressed statistics ⇒ Parameters

- **Pseudo maximum-likelihood estimator:**

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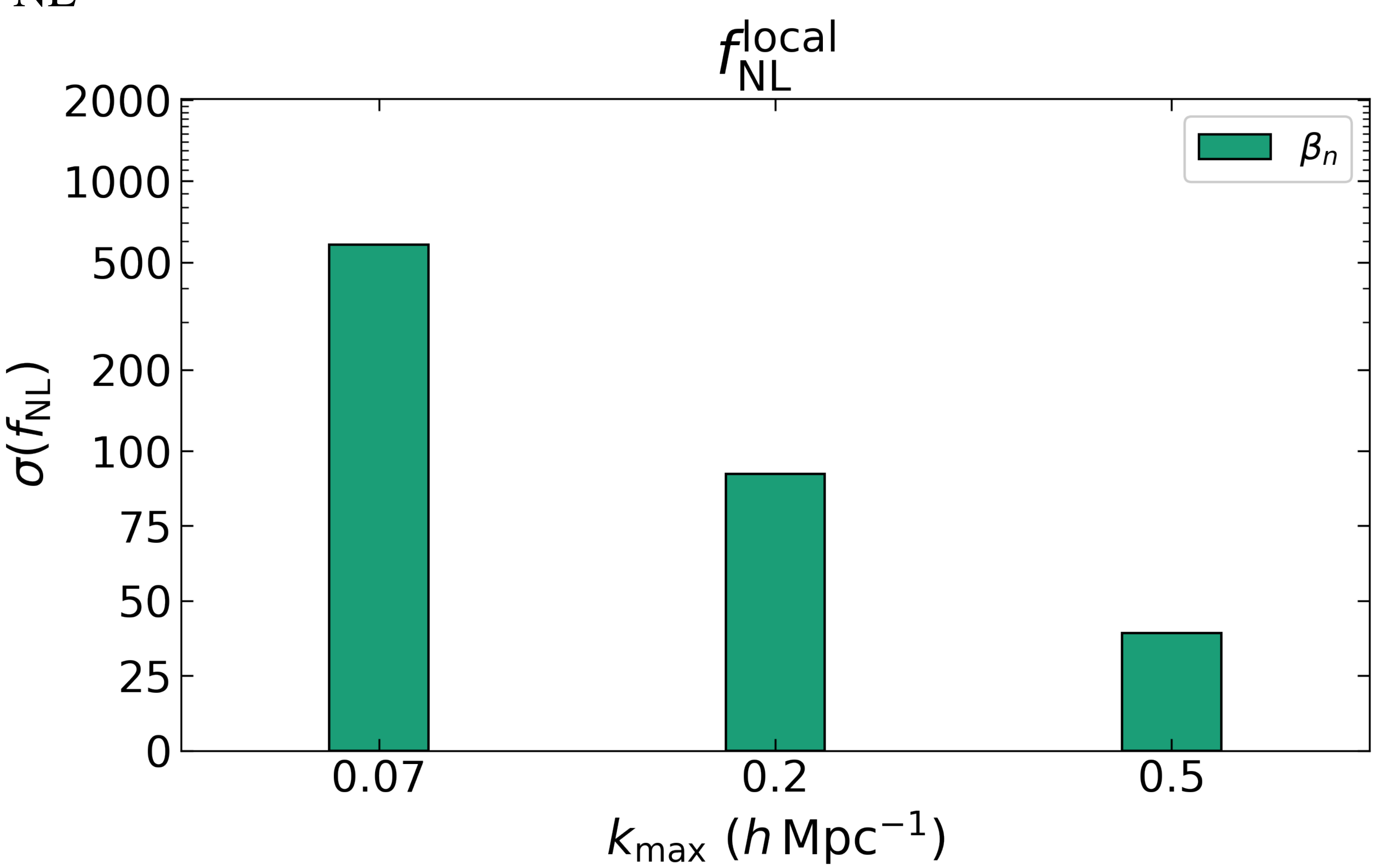
- **Constraints on $f_{\rm NL}^{\rm local}$:**



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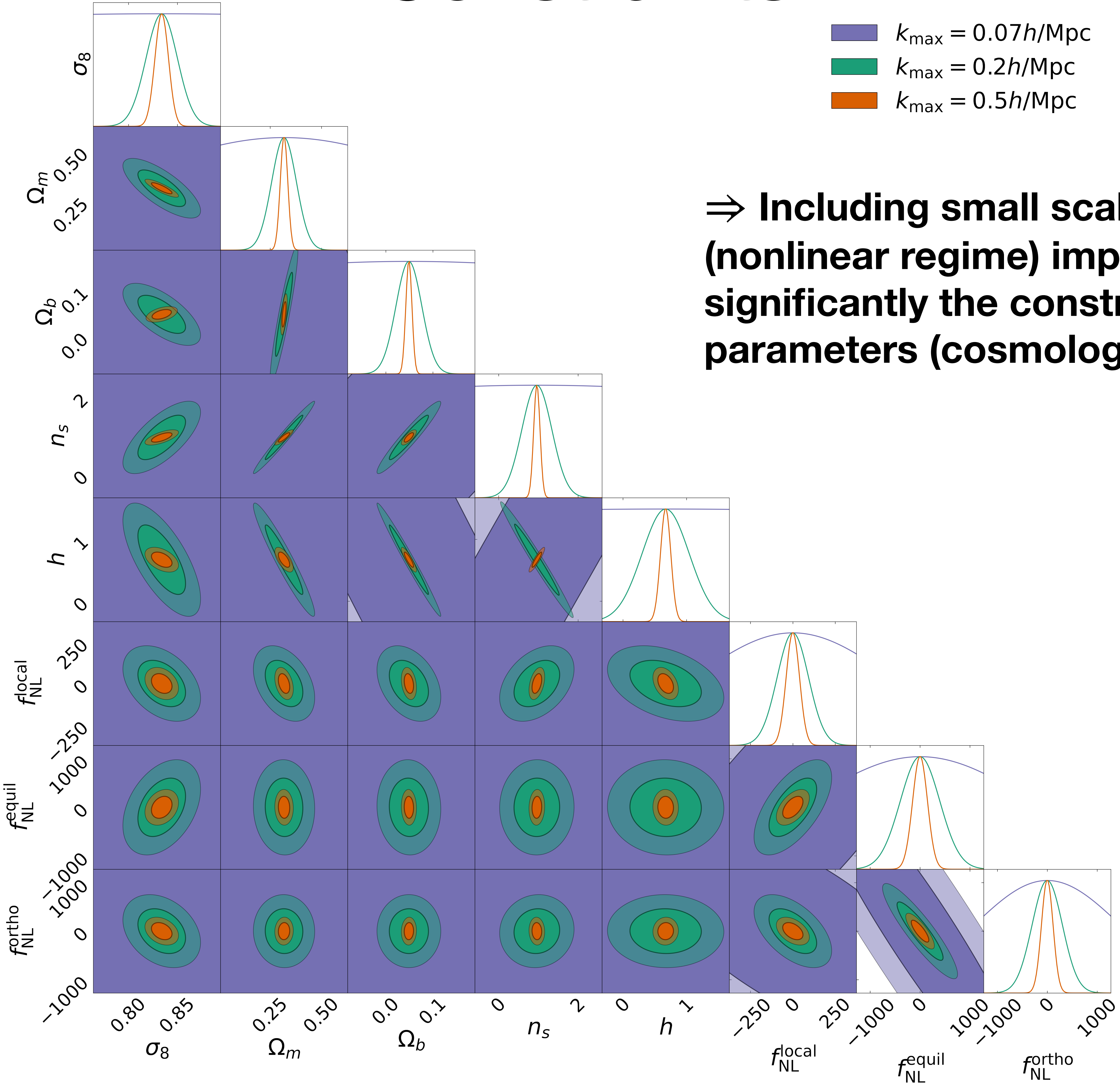
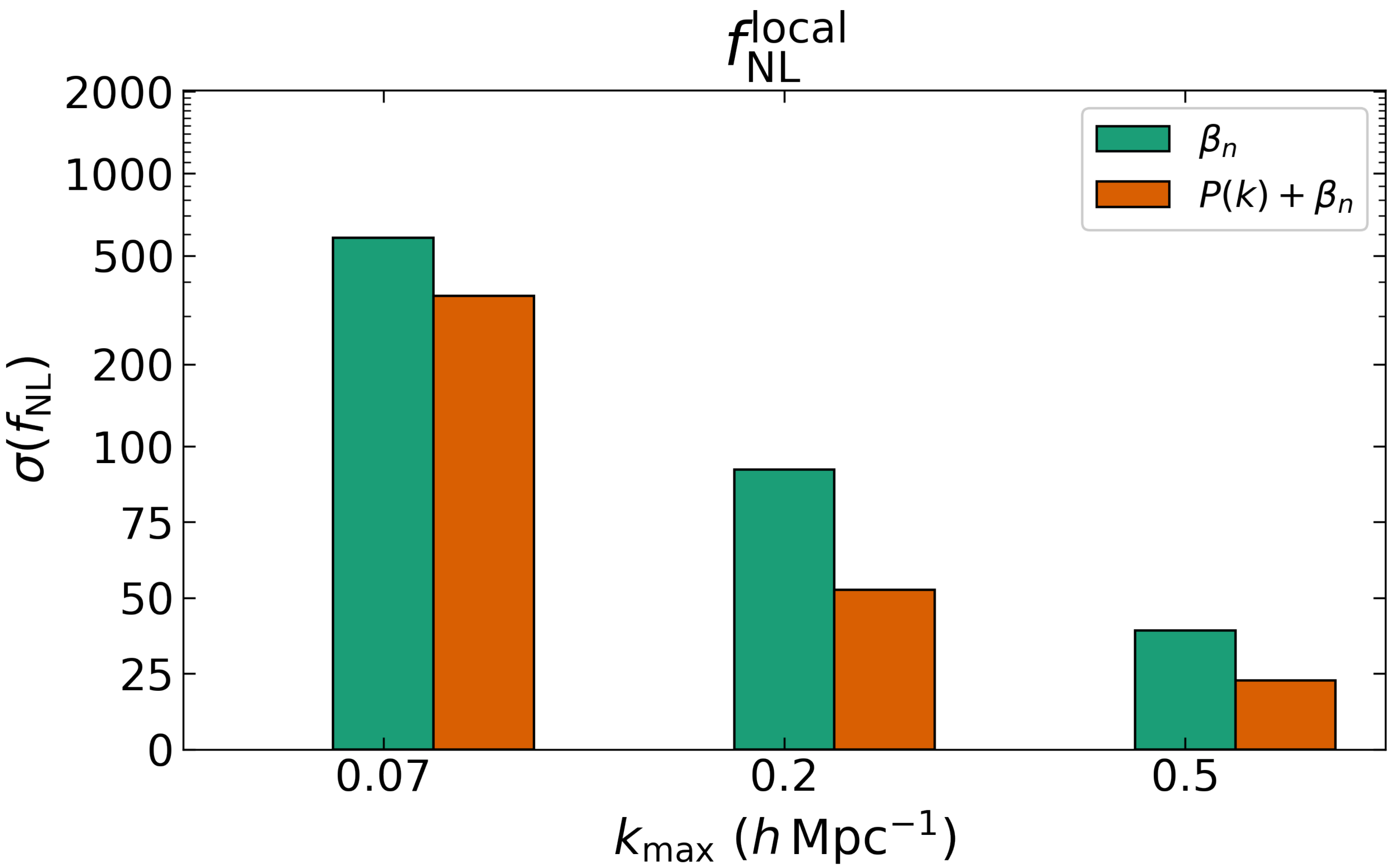


⇒ Including small scales (nonlinear regime) improves significantly the constraints on all parameters (cosmological + PNG)

Constraints

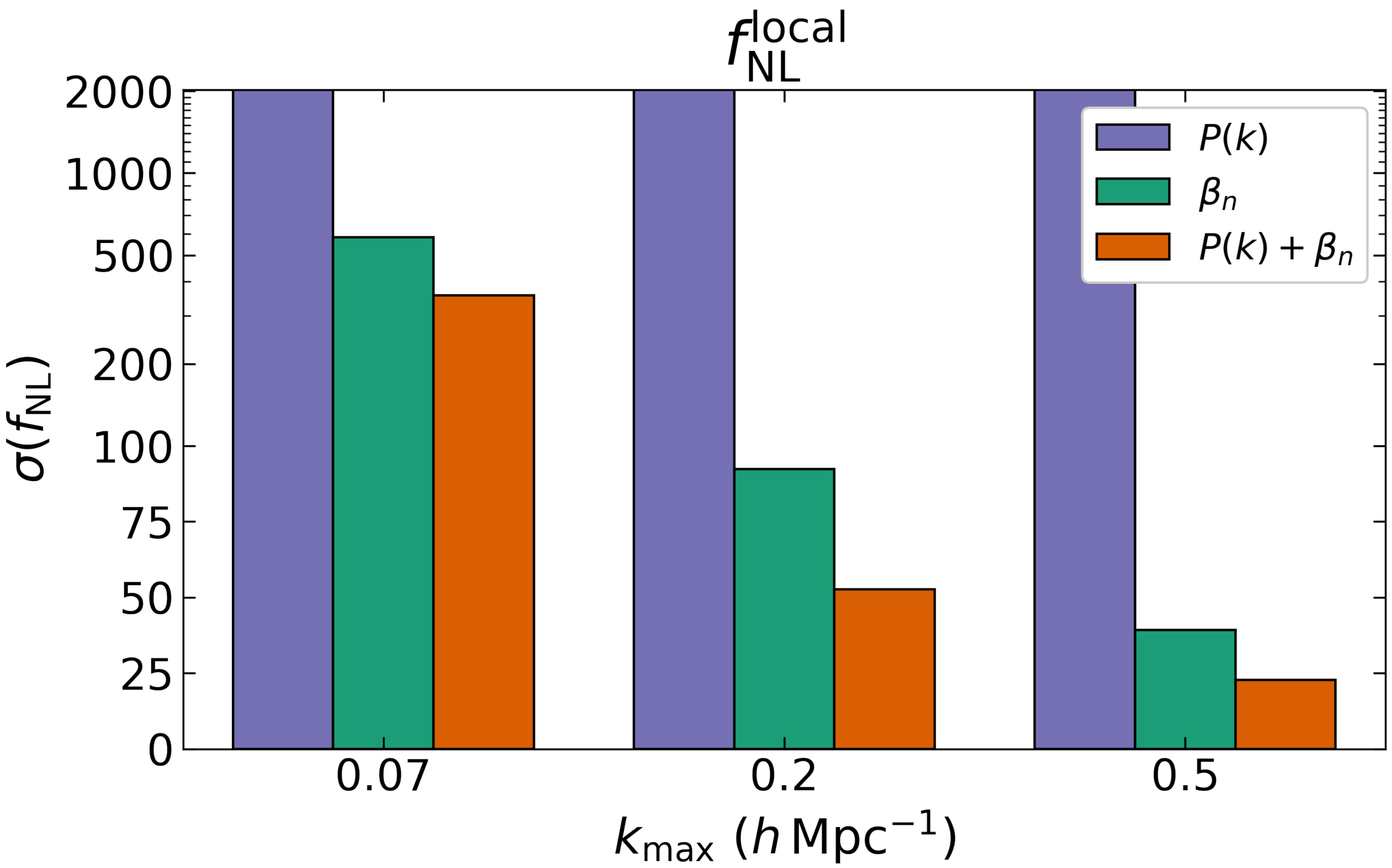
- **Constraints on $f_{\rm NL}^{\rm local}$:**



- **Nonlinear regime ($k_{\rm max} = 0.5h/{\rm Mpc}$ here) improves the constraints significantly**
- **Combining power spectrum and bispectrum also improves the constraints by a factor ~2**

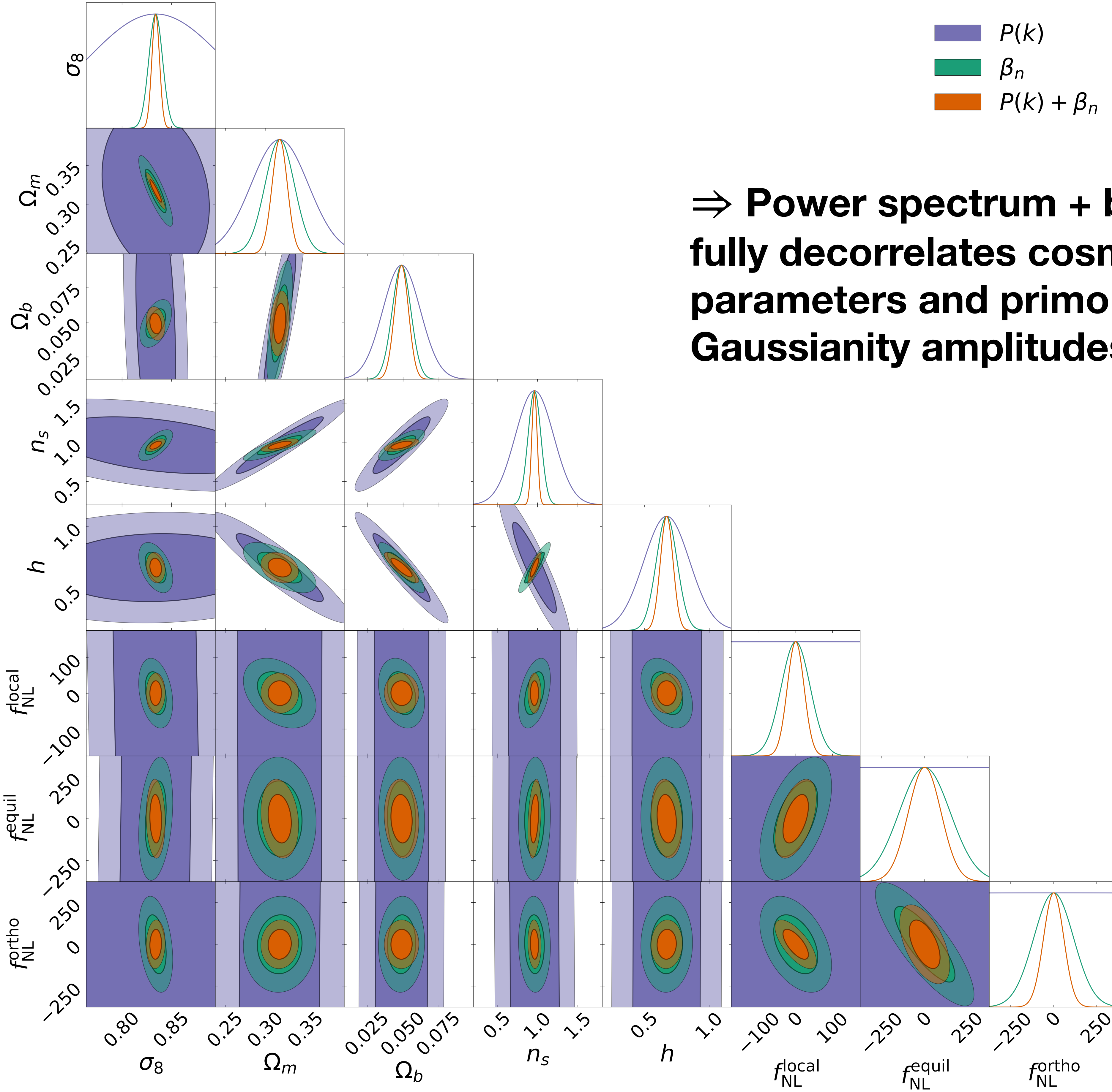
Constraints

- **Constraints on $f_{\rm NL}^{\rm local}$:**



- **Nonlinear regime ($k_{\rm max} = 0.5h/{\rm Mpc}$ here) improves the constraints significantly**
- **Combining power spectrum and bispectrum also improves the constraints by a factor ~2, even if the power spectrum constraining power is very small**

Constraints



⇒ Power spectrum + bispectrum fully decorrelates cosmological parameters and primordial non-Gaussianity amplitudes!

Summary of the talk

Conclusions

- Nonlinear scales → (a lot of) extra information about cosmology and primordial NG
- Combining power spectrum + bispectrum, constraints on primordial NG comes for free
- Pipeline (first version) combining forward simulations, modal bispectrum estimator and data compression

Future

- Extending the pipeline to halos and galaxies
- Find better summary statistics to study primordial NG