Constraining local primordial non-Gaussianity using long-wavelength modulation of local small-scale statistics

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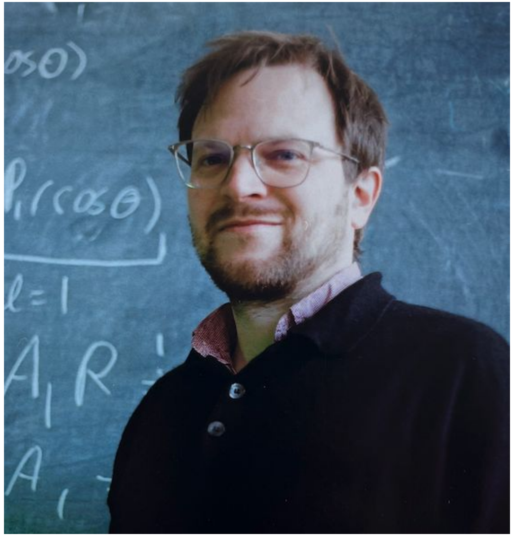
Work done in collaboration with



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Based on 2305.03070, 2205.12964

Introduction/Gist

I will present two simulation based approaches for tightening constraints on f_{NL}

1a. A non-perturbative approach sensitive to f_{NL} via higher *N*-point functions.

- A *neater* formulation+use of position-dependent power spectrum approach (**Chiang, Wagner, Schmidt, Komatsu 2014, Smith, Loverde, Zaldarriaga 2012, de putter 2018 and others**)
- Very *efficient* from computational and modelling point of view
- Allows us to tap into very non-linear scales, outperforms some recent forecasts.

1b. A machine learning enhanced version of the above formalism.

- In principle sensitive to f_{NL} information in soft limits of all higher *N*+1 point functions

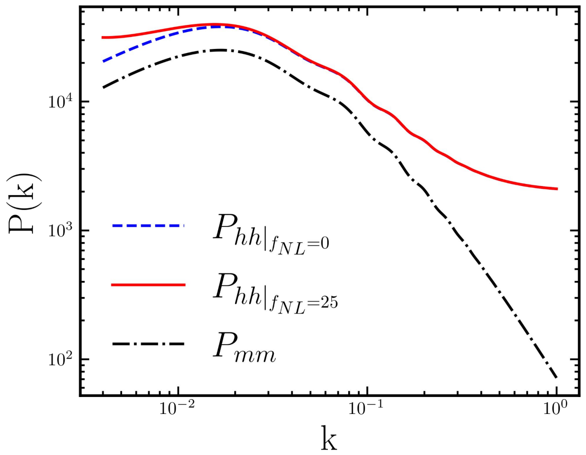
We harness large-small mode coupling feature of PNG universe + LSS consistency relation guarantees of Gaussian universe, to ***derive a large-scale field*** π^f ***composed out of very non-linear density field, which has a clean fNL/k^2 bias similar to halos***

f_{NL} from LSS: Current status and motivation

The most promising method has been via the

PNG induced scale-dependent bias

$$P_{hh}(k_L) = \left(b_G + \frac{b_{NG} f_{NL}}{k_L^2}\right)^2 P_{mm}(k_L)$$



Additionally, B_{hhh} contains term $\propto \frac{f_{NL}}{k_L^2}$

However, they are:

- Hard to model analytically beyond k ~ 0.2 h/Mpc
- Simulation-based approaches are computationally very challenging

SOTA: Pk + Bk constraints: $\sigma(f_{NL}) = \mathcal{O}(20-30)$ **[Cabass et al. 22, D'Amico et al]**

Question: How much would a proper inclusion of higher N-point functions tighten constraints on f_{NL}? How to best do it in a manageable way? (!! Several recent studies report constraints saturating around k ~0.3!!)

Cabass, Ivanov, Philcox, Simonovic, Zaldarriaga (2022), D'Amico, Lewandowski, Senatore, and Zhang (2022) and others

A non-perturbative approach

Main idea: 1/k^2 will appear in any field sensitive to small scale power

(Covered nicely by Oliver Philcox and Sam Goldstein's talk earlier)

Define a field π^f which is a measure of local power/variance for observable f

$$\pi^f(\mathbf{x}) = \left(\int \frac{d^3\mathbf{k}}{(2\pi)^3} W(k) \rho_f(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}} \right)^2$$

$$W^i(\mathbf{k}) = \begin{cases} 1 & \text{if } k^i_{\min} < |\mathbf{k}| < k^i_{\max} \\ 0 & \text{elsewhere} \end{cases}$$

f could be late time matter field δ_m or a tracer like the halo number density n_h

$$P_{m\pi^m}(\mathbf{k}_L) = \left(b_\pi + 2\beta_\pi \frac{f_{NL}}{k^2} \right) P_{mm}(\mathbf{k}_L)$$

$$P_{\pi^{m\prime}\pi^m}(\mathbf{k}_L) = \left(b_{\pi'} + 2\beta_{\pi'} \frac{f_{NL}}{k^2} \right) \left(b_\pi + 2\beta_\pi \frac{f_{NL}}{k^2} \right) P_{mm}(\mathbf{k}_L) + N_{\pi\pi'}$$

sensitive to **squeezed bispectrum** & **collapsed trispectrum**

Testing our conjectures using simulations.

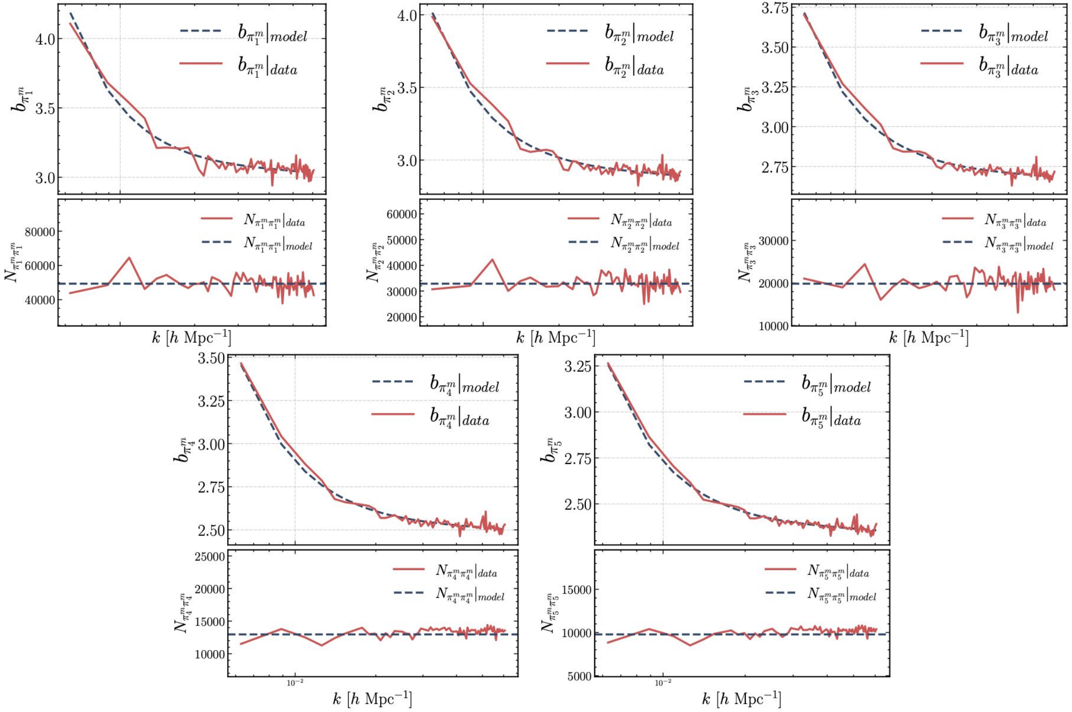
We use an ensemble of ***Quijote & Quijote-PNG*** (**Villaesuca-Navarro et al 2019, Coulton et al 2022 Jung et al 2022**) simulations

We generate π_i^m fields using disjoint top-hat filters $W^i(\mathbf{k})$

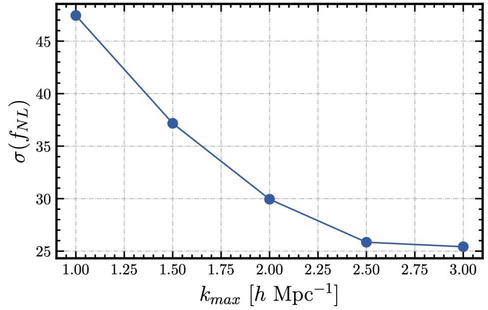
$k \in [(0.5, 1.0), (1.0, 1.5)...(2.5, 3.0)]$

We demonstrate that:

- The large-scale bias shows expected $1/k^2$ scaling.
- Noise is white as expected.

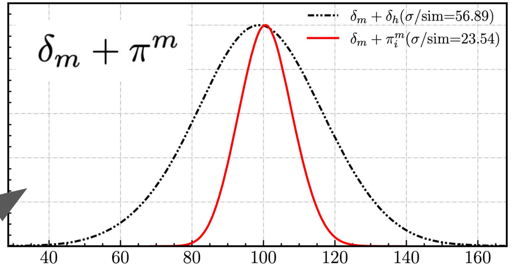


Constraining power



We perform likelihood analysis combining δ_m with π_i^m derived using disjoint tophat k-space filters in the range $k \in [(0.5, 1.0), (1.0, 1.5)...(2.5, 3.0)]$

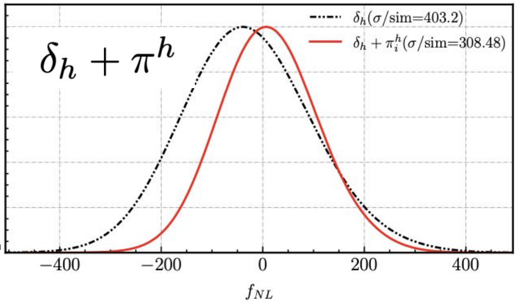
Relative improvement in $\sigma(f_{NL})$



We fix b_{NG_i} and marginalize over b_{G_i} and $N_{\pi_i \pi_j}$

$\delta_m + \pi^m$ constraints are **2.2x** times that of $\delta_m + \delta_h$

Constraints improve until very non-linear scales!!



$\delta_h + \pi^h$ gives modest improvements over a halo only analysis.

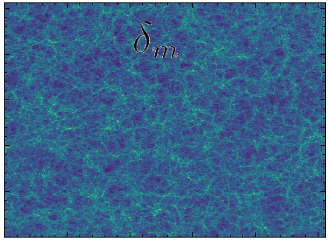
At M_{min} **of** $\sim 10^{13} M_\odot$**, our non-perturbative analysis only improves by 20%**

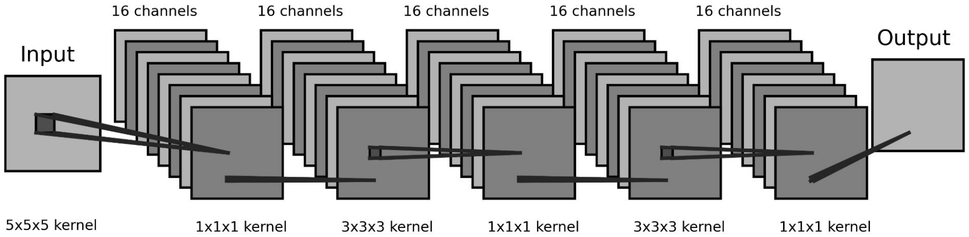
Part II: A Neural Network enhanced approach:

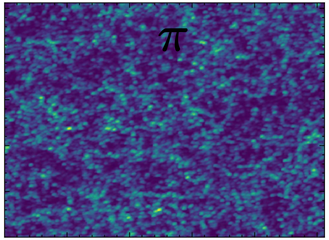
- Neural Networks (NNs) give very strong constraints on parameters like σ_8 and can potentially tap into the higher order information encoded in the density field.
- π^f modulation is not optimal, information has leaked into higher-order moments

We design a NN with small receptive field to learn π^{NN} field which locally estimates σ_8

$$\mathcal{L} = \left[\left(\frac{1}{N_{\text{voxels}}} \sum_{\text{voxels } \mathbf{x}} \pi(\mathbf{x}) \right) - \sigma_{\mathbf{8}}^{\text{true}} \right]^{\mathbf{2}}$$



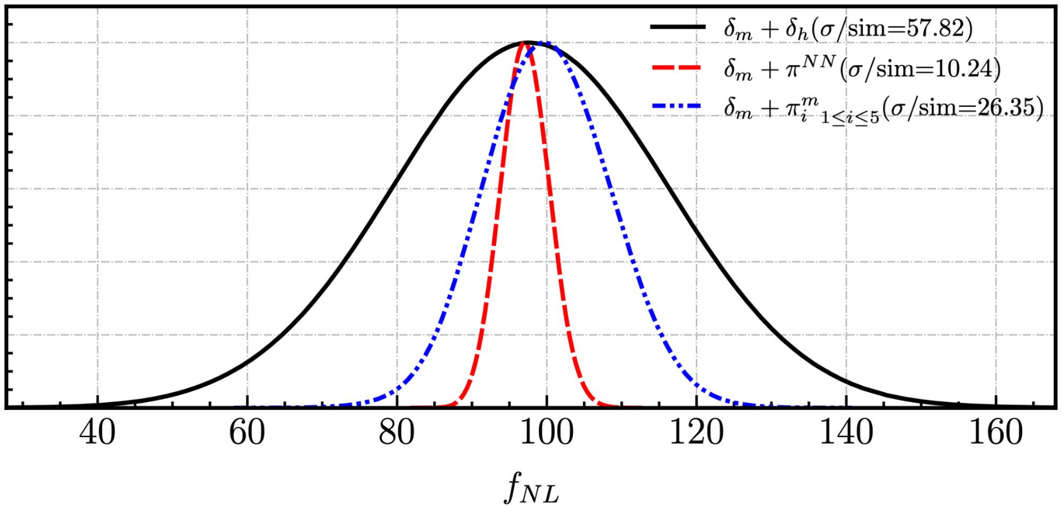




We use Quijote simulations with fixed cosmology but with varying σ_8 for training.

Results:

The $\delta_m + \pi^{NN}$ based analysis gives a **factor of 5.5** better constraint than $\delta_m + \delta_h$



Conclusion:

- We have presented a neat method for extracting information from soft limits of density fields, in particular f_{NL} information from squeezed bispectrum and collapsed trispectrum.
- We find significant f_{NL} sensitivity on *very* non-linear scales*.
- Future surveys with ***large area + low shot-noise*** can exploit higher N-point functions in combination with power spectrum to further tighten constraints on f_{NL}
- Several interesting applications!

Interpretation and Validation

The bias model for π similar to that of δ_h

$$\pi^{NN}(\mathbf{k}_L) = b_\pi(\mathbf{k}_L)\delta_m(\mathbf{k}_L) + \epsilon$$

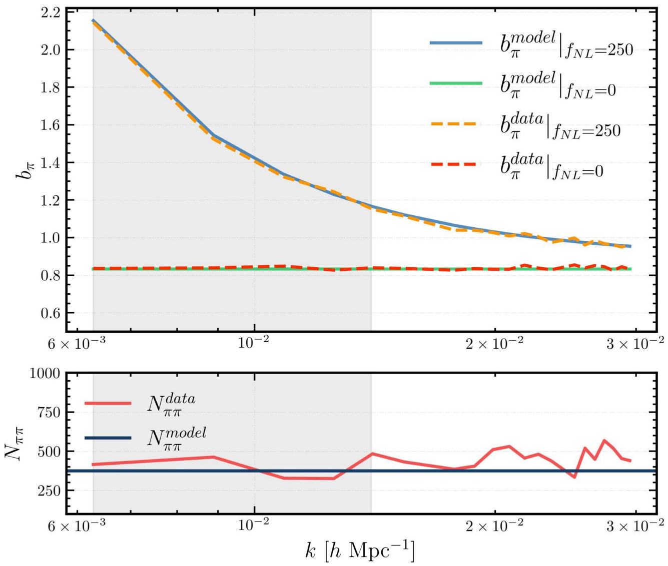
With

$$b_\pi(k) = b_\pi^G + b_\pi^{NG}\frac{f_{NL}}{\alpha(k,z)}$$

We evaluate this on **“unseen, non-gaussian”** sims

- Recover $1/k^2$ scaling, constant noise for $k \to 0$
- Find ~100% correlation with matter field

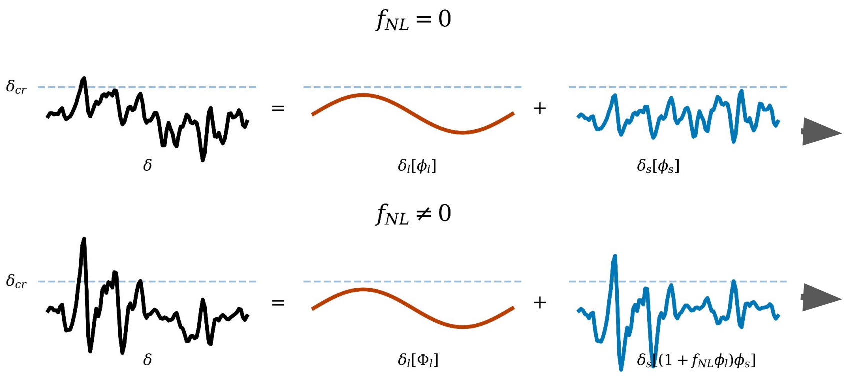
Robust $1/k^2$ scale dependence, can’t be faked!



This is not a "black box" approach and is physics informed. We can do several field level null-tests; cross-correlate with noise maps. Also with other cosmological fields.

Origin of scale-dependent bias in halos

To motivate our formalism, we first look at origin of scale-dependent halo bias



Large-scale behaviour of $n_h(\mathbf{x})$

$n_h(\mathbf{x}) = F[\delta_m(\mathbf{x})^n]$ modulated only by δ_l

$n_h(\mathbf{x}) = F[\delta_m(\mathbf{x}), \phi(\mathbf{x})]$

modulated by δ_l & $\phi_l(= \frac{\delta_l}{k^2})$

$$\delta_h(\mathbf{k}_L) = b_h(\mathbf{k}_L)\delta_m(\mathbf{k}_L) \quad ; \quad b(\mathbf{k}_L) = \frac{1}{\bar{n}_h}\frac{\partial n_h(\mathbf{x}|f_l)}{\partial f_{\mathbf{k}_l}} = b_\pi + 2\beta\frac{f_{NL}}{k^2}$$

Main idea: Similar modulation will appear in any field sensitive to small scale power