Constraints on primordial non-Gaussianity from CMB lensing cross-correlations with DESI and Quaia

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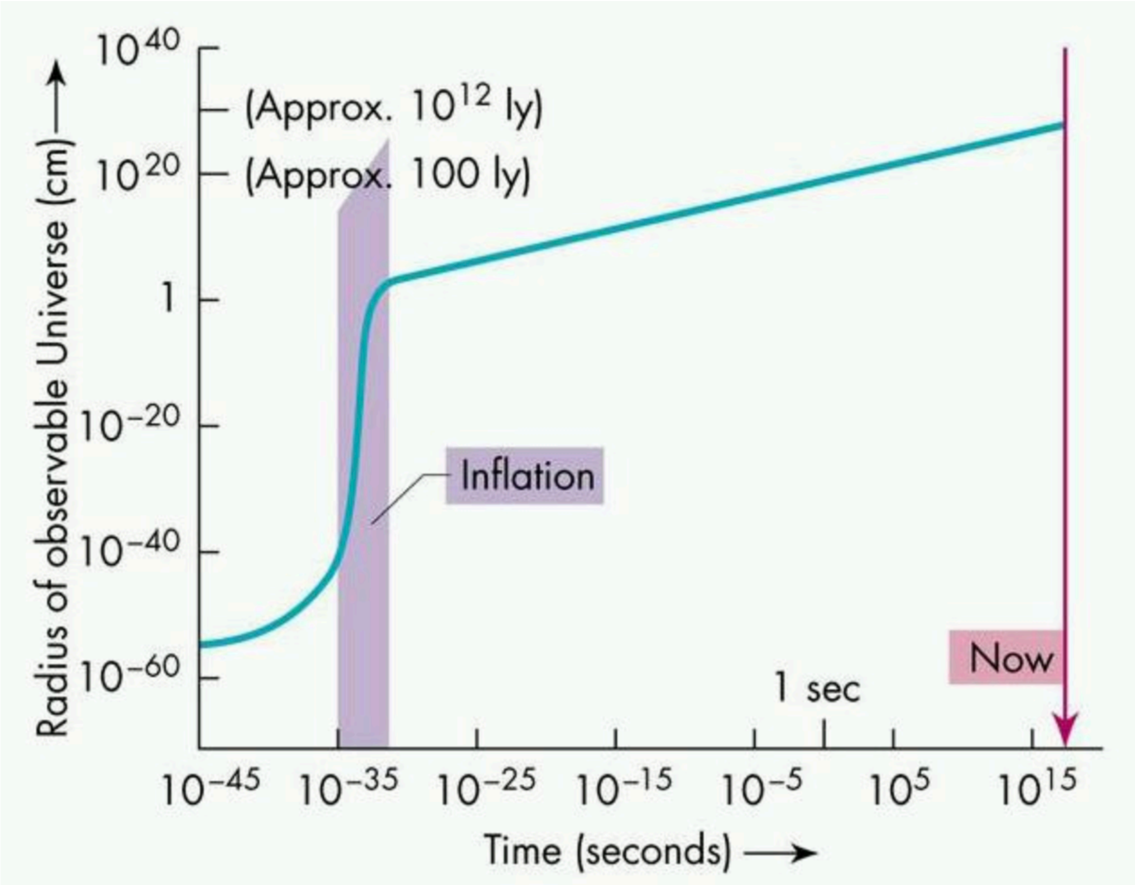
Outline

- Introduction to PNG
- PNG from DESI LRG x Planck lensing
- New methodologies for measuring PNG
- Application of new methodologies to Quaia data x Planck lensing

Introduction: inflationary physics

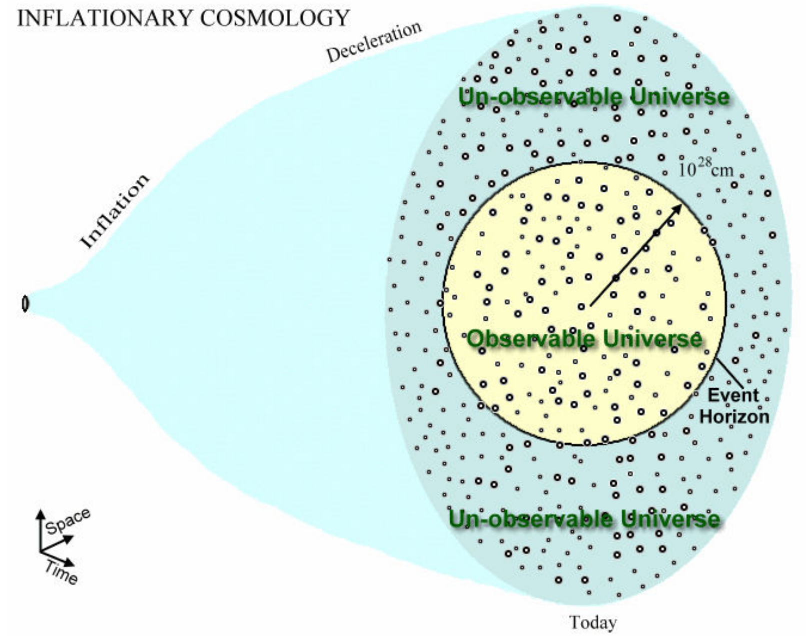
Cosmic inflation was introduced in the early 1980s (Guth 1981, Starobinsky 1980) **to solve the Big Bang model problems** (horizon, magnetic monopole, flatness…)

Beyond solving the Big Bang problems, it explains the formation of primordial density perturbations



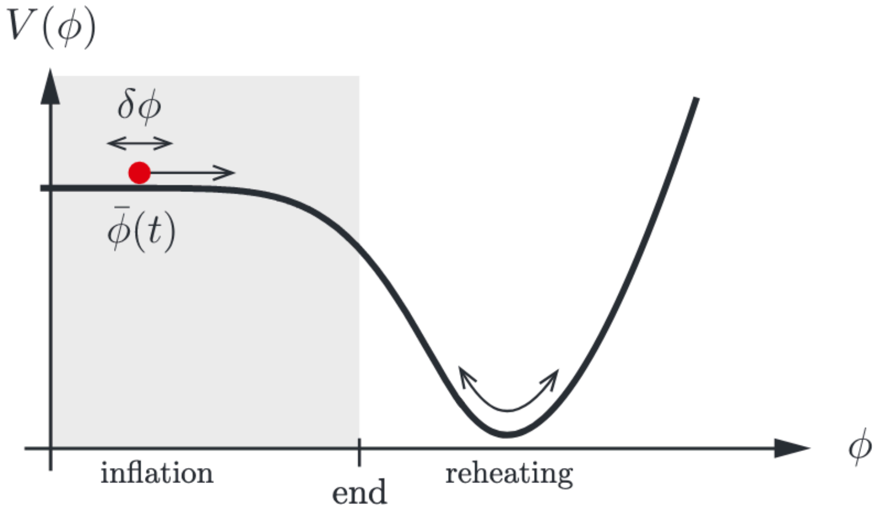
Introduction: inflationary physics

Inflation is defined as an early accelerated expansion phase driven by a scalar field ϕ. The form of the potential $V(\phi)$ defines the model.



Primordial non-Gaussianity (**PNG**) encodes important information about inflation. Primordial potential with a local PNG:

$$\Phi = \phi + f_{NL}(\phi^2 - \langle\phi\rangle^2)$$

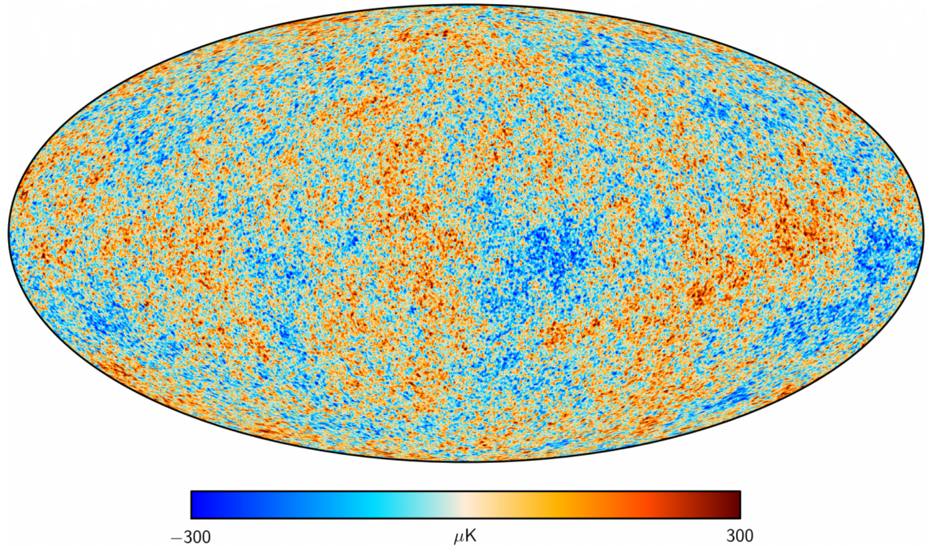


f_{NL} is a parameter that can **rule out or confirm inflationary models**, corresponding $f_{NL} = 0$ to Gaussian initial conditions

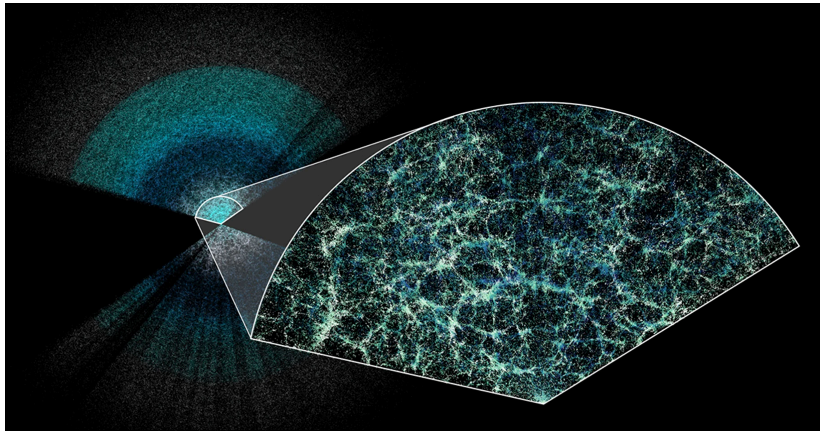
Introduction: inflationary physics

Two cosmic windows to PNG:

CMB: prefers Gaussianity: $f_{NL} = -0.9 \pm 5.1$ (Planck collaboration 2020).



LSS: many upcoming measurements in the next years. Current sensitivity already <10, e.g.: $f_{NL} = -3.6^{+9.1}_{-9.0}$ (Chaussidon et al. 2025 with DESI DR1 data)



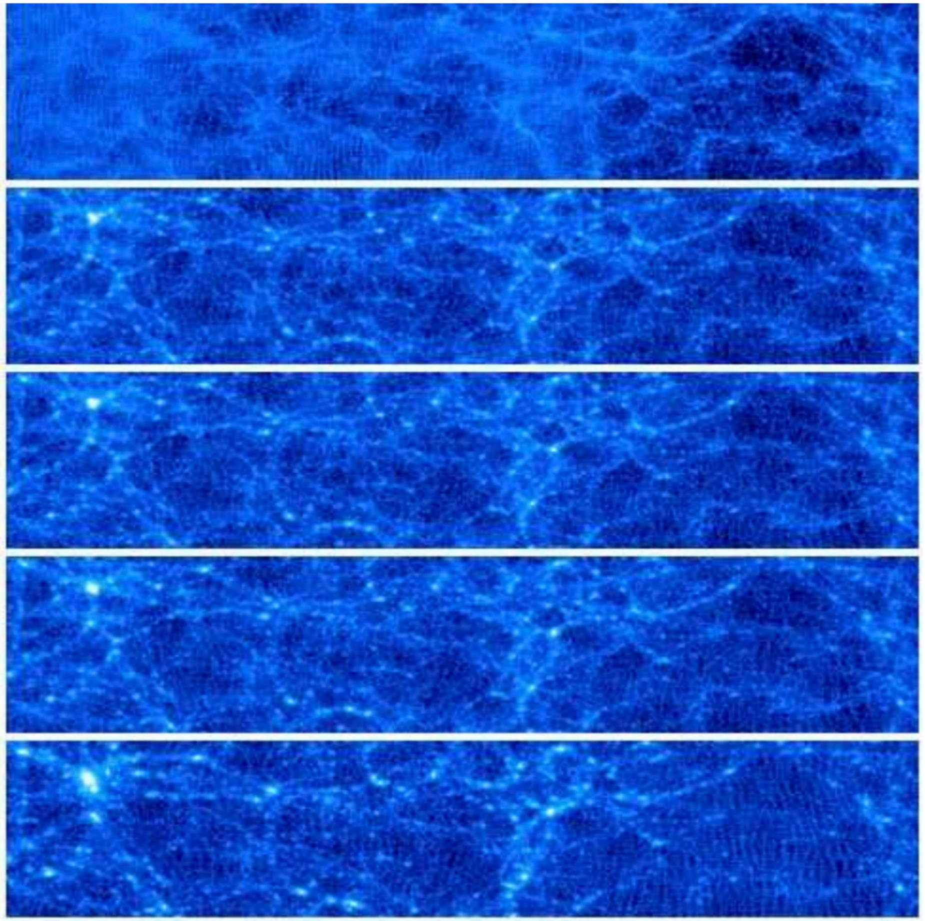
Introduction: non-Gaussianity from LSS

A local f_{NL} leaves its imprint in the LSS tracers as a contribution to the **galaxy bias**, i.e. the ratio of total (dark+baryons) to visible matter:

$$\Delta b(k,z) = 2(b_g - p) f_{NL} \frac{\delta_{crit}}{\alpha(k)} \qquad p \simeq 1$$

$$\alpha(k) = \frac{2k^2 T(k) D(z)}{3\Omega_m} \frac{c^2}{H_0^2} \frac{g(0)}{g(\infty)}$$

Large Scale Structure surveys are **a window to constrain inflation and fundamental physics**

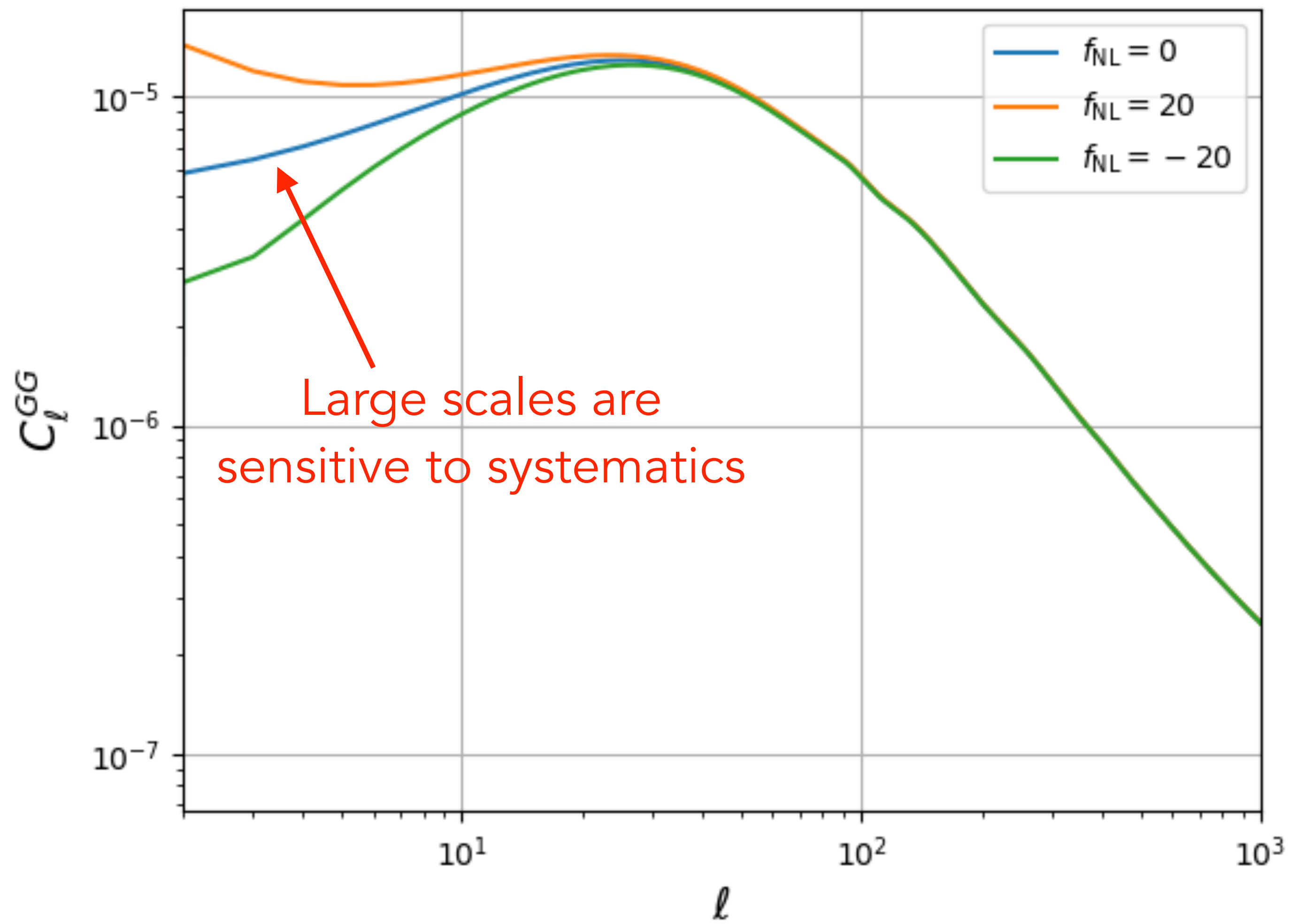


Simulated slices at z=0 for various f_{NL} values.
Dalal et al. (2008)

Introduction: non-Gaussianity from LSS

The most challenging issue for performing a good PNG measurement from LSS are **observational systematics**: extinction, star density, changes in observing conditions …

These systematics induce "fake" clustering signal at large scales, where the PNG signal arises



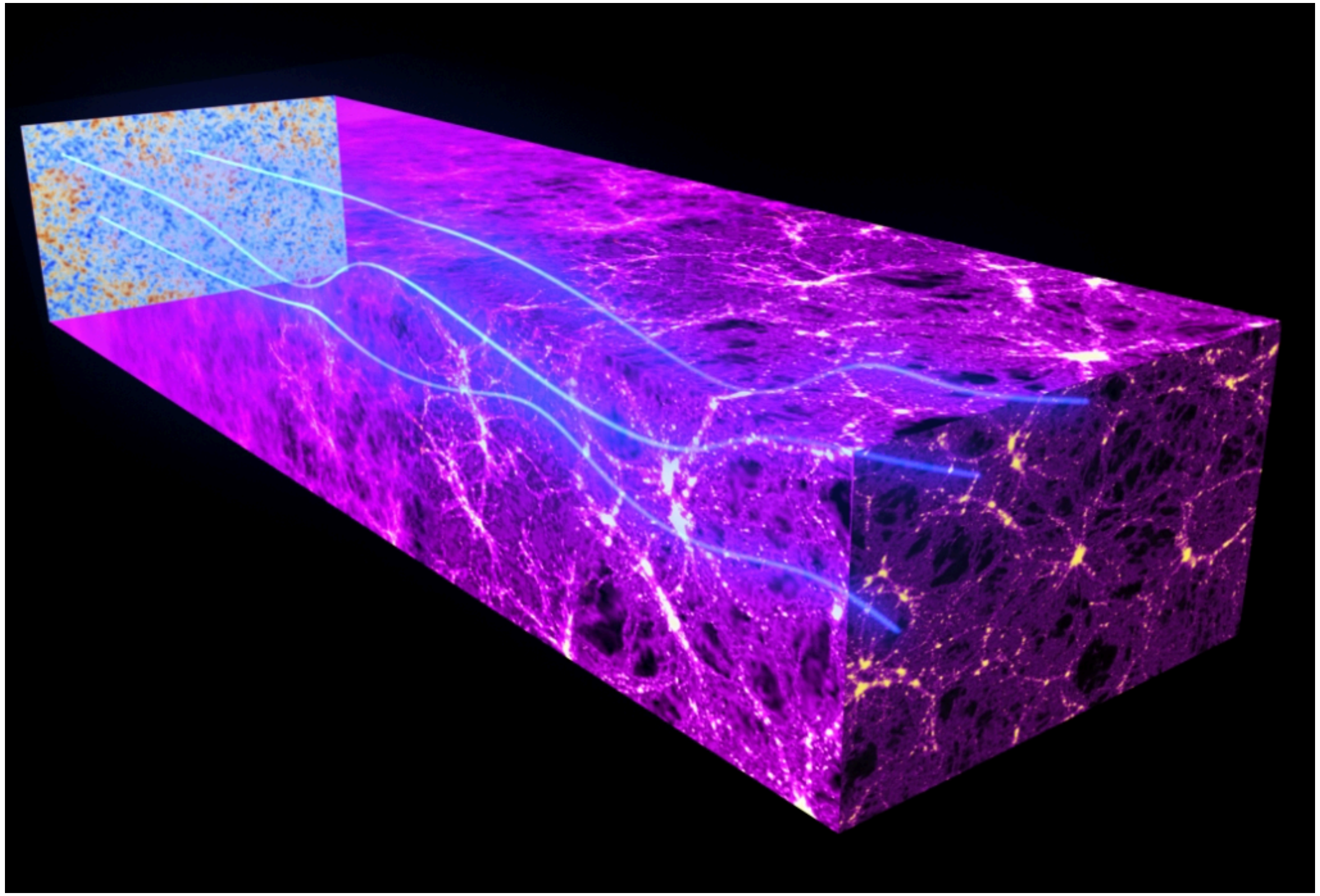
Galaxy angular power spectra for different f_{NL} values

Introduction: non-Gaussianity from LSS

Theoretical predictions (e.g. Bermejo-Climent et al. 2021) show also **cross-correlations between the CMB and LSS** can be helpful to measure $f_{\rm NL}$ through the scale-dependent bias effect

Most significant: **CMB lensing x LSS**

Cross-correlations usually drop out most of the systematics



CMB lensing effect (Image credits: ESA)

PNG from DESI x *Planck* lensing

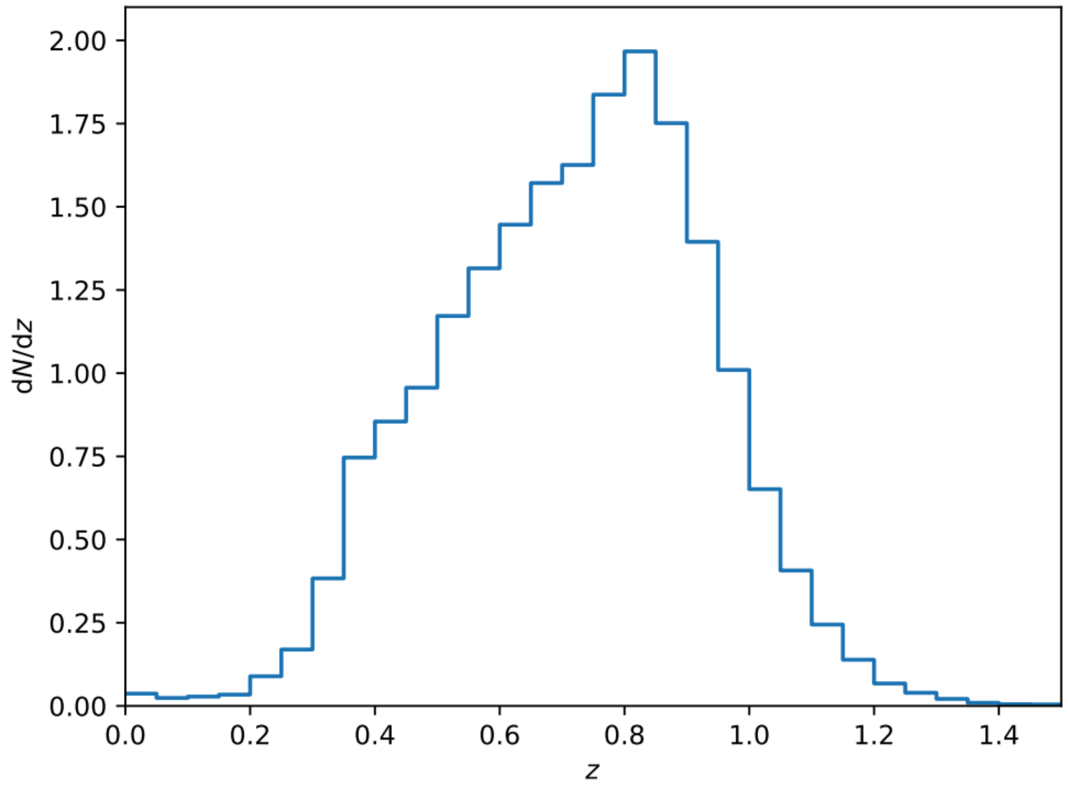
Aim: to perform a $f_{\rm NL}$ measurement using cross-correlations of DESI data with the CMB lensing

Data:

Luminous Red Galaxies (**LRG**) from the **DESI DR9** imaging **Legacy Survey**: a targeting survey already completed. ~9 million galaxies covering ~16k deg2

CMB lensing maps from ***Planck***.

People: J. Bermejo-Climent, R. Demina, A. Krolewski, E. Chaussidon, M. Rezaie et al.

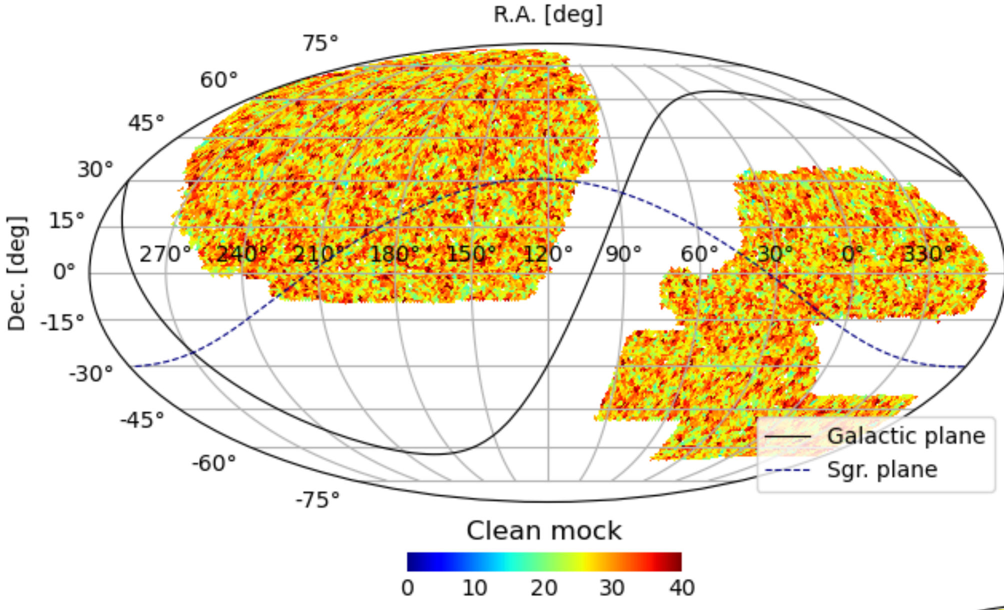


DESI LRG redshift distribution

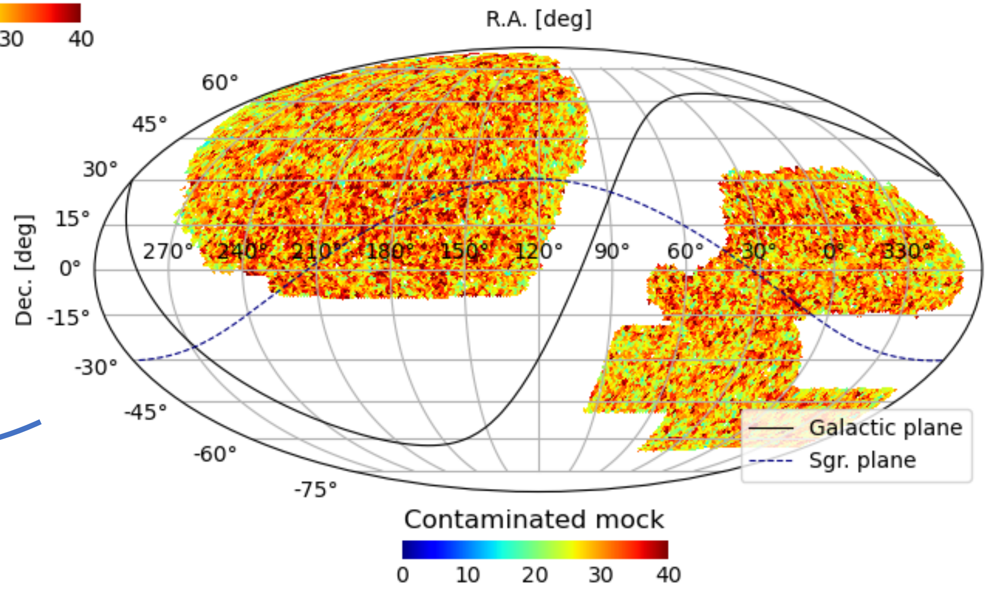
PNG from DESI x *Planck* lensing

The analysis required an extensive effort to understand observational systematics

We created 100 Gaussian LRG mock fields for f_{NL} = 0, 50, -50 and 100 correlated CMB mock fields using **synfast**



We contaminated the LRG mocks with **regressis** (by Edmond Chaussidon)

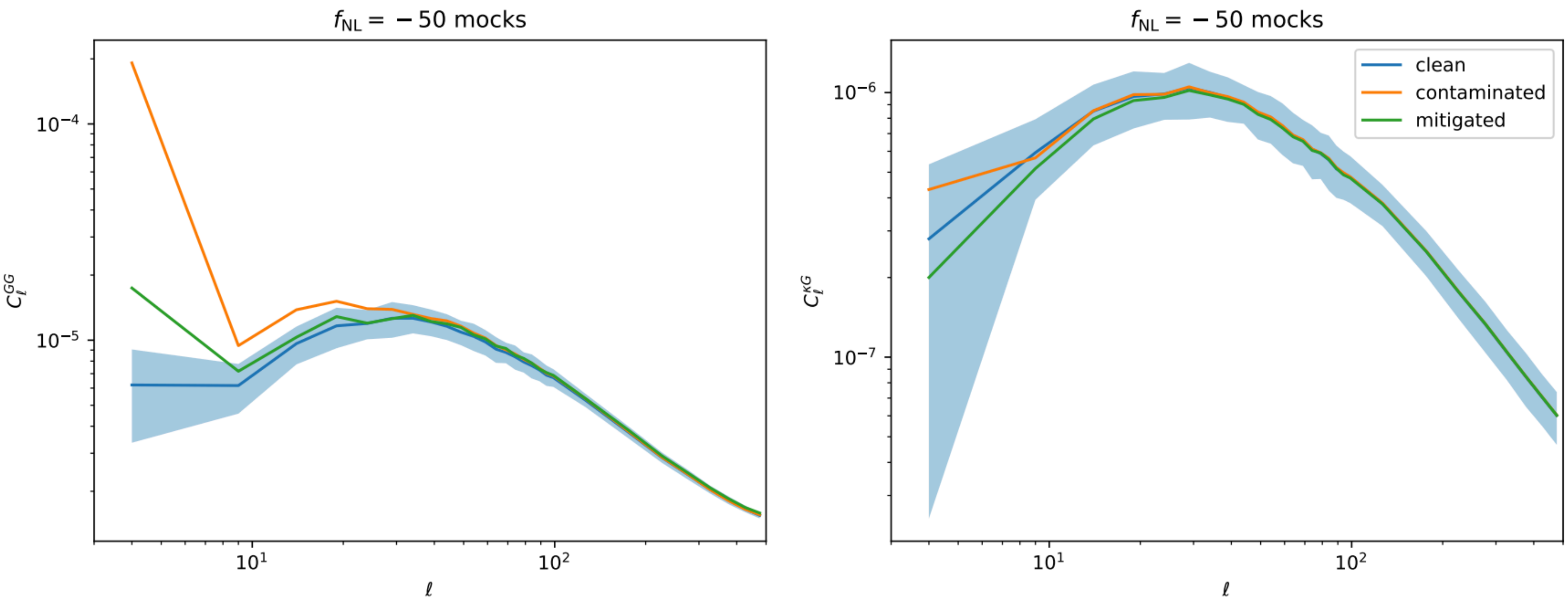


We applied **SYSnet** (by Mehdi Rezaie), a neural network code for systematics mitigation

PNG from DESI x *Planck* lensing

The analysis required an extensive effort to understand observational systematics

We finally compared the input and measured C_ℓ (after contamination and mitigation)

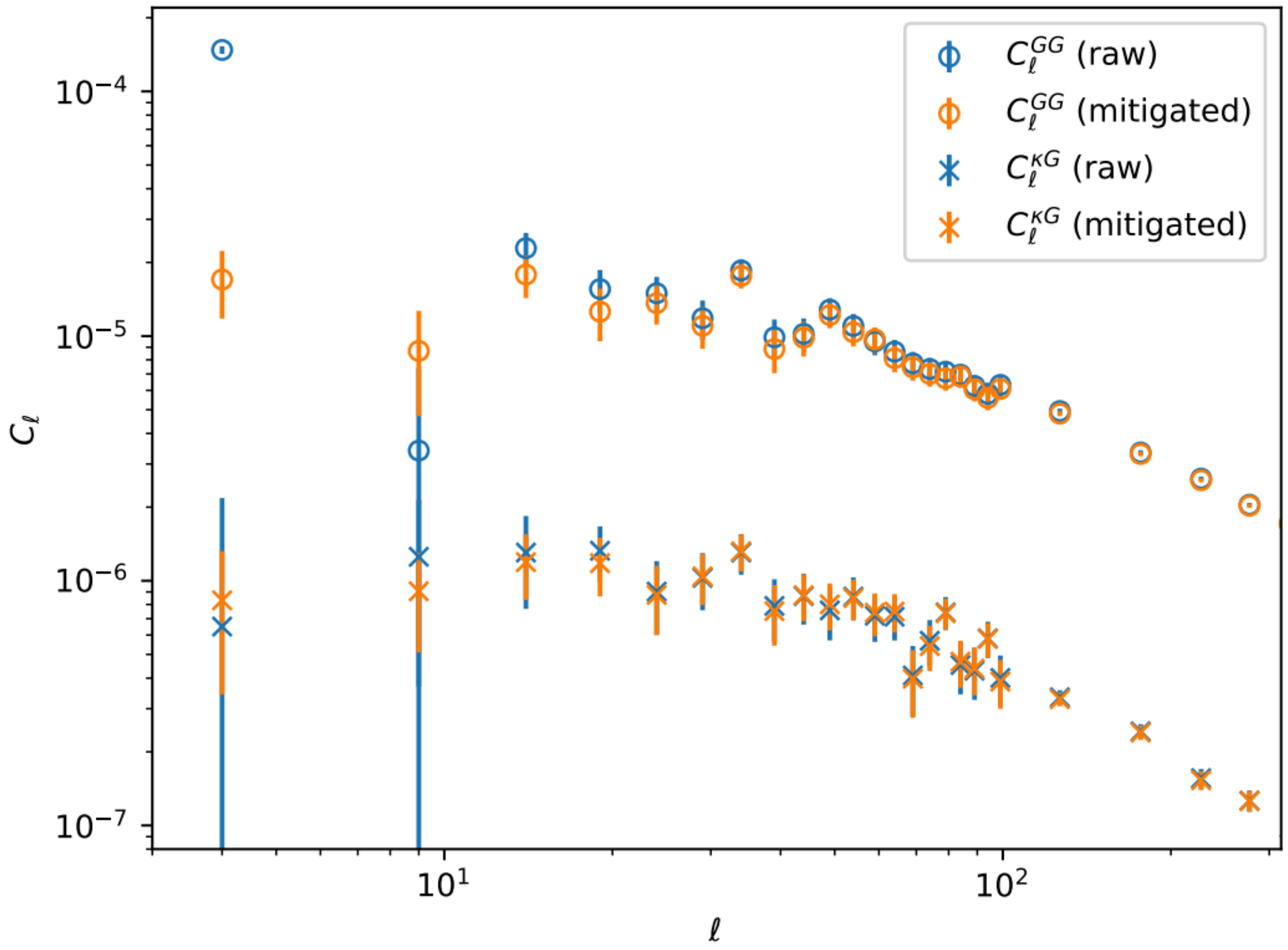


PNG from DESI x *Planck* lensing

The analysis required an extensive effort to understand observational systematics

- C_ℓ^{GG} data: we applied a $\ell_{\min} = 7$ scale cut basing on tests on mocks

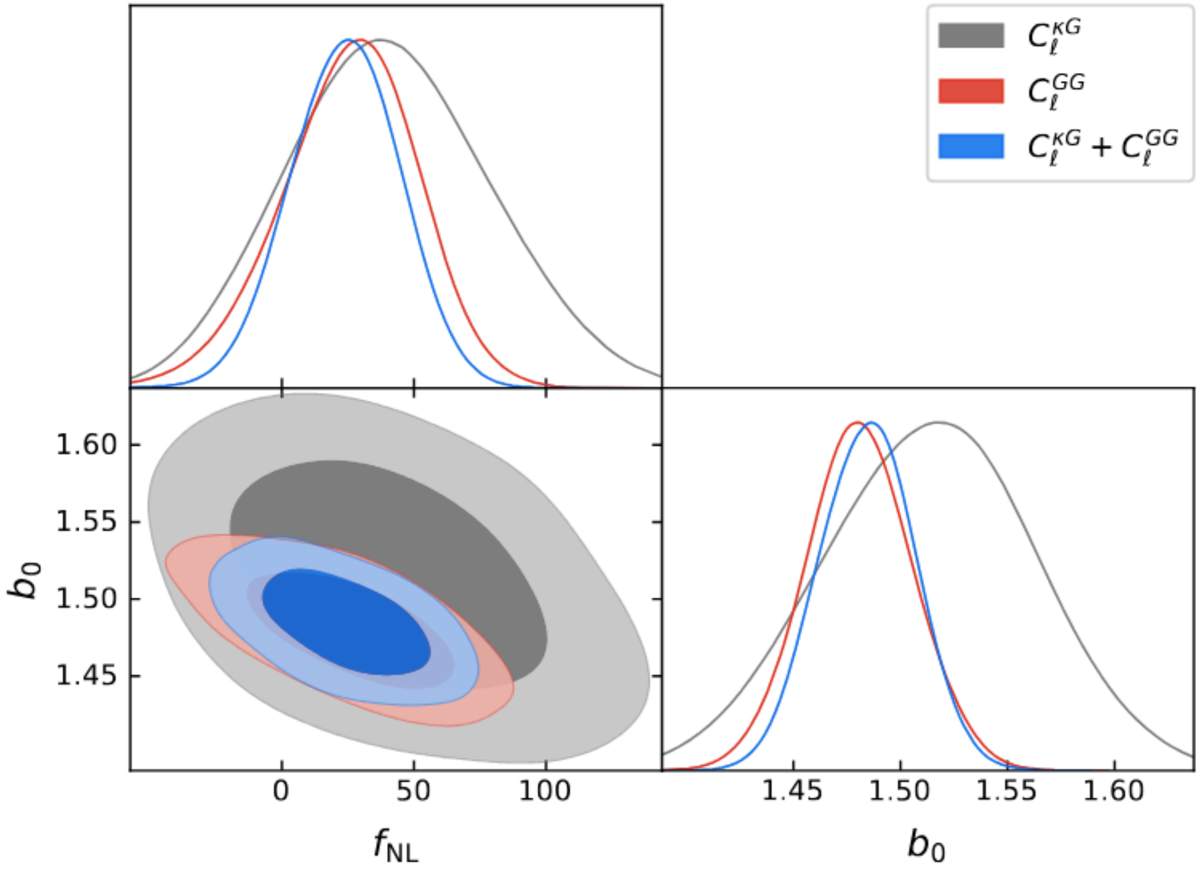
- $C_\ell^{\kappa G}$ data: more stable, but performing an accurate systematics mitigation is crucial for the covariance (larger measured C_ℓ^{GG} => larger errors)



PNG from DESI x *Planck* lensing

Constraints on $f_{\rm NL}$:

- Results from DESI alone limited by systematics to $\sigma(f_{\rm NL}) \sim 25$
- Adding CMB lensing improves the constraints by ~20%, getting $\sigma(f_{\rm NL}) \sim 20$



$f_{\rm NL} = 39^{+40}_{-38}$
$f_{\rm NL} = 28^{+24}_{-27}$
$f_{\rm NL} = 24^{+20}_{-21}$

Bermejo-Climent et al. 2025
(A&A 698, A177 [arXiv:2412.10279])

PNG from LSS: what’s next?

How can we improve current PNG measurements from LSS?

- **New data** (upcoming DESI and Euclid releases …)
- **New techniques:**
    - Adding more cosmological observables, such as Angular Redshift Fluctuations (**ARF**, Hernández-Monteagudo et al. 2020)
    - Multi-tracer approach using information from many surveys

PNG from LSS: new cosmological observables

In 2D analyses, we usually do cosmology with the ***density field*** and its cross-correlations (e. g. CMB lensing or cosmic shear)

$$\delta_g(\hat{n}) = \frac{\sum_{i \in \hat{n}} w_i}{\langle w_i \rangle} - 1$$

PNG from LSS: new cosmological observables

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$$\delta_g(\hat{\mathrm{n}}) = \frac{\sum_{i\in\hat{\mathrm{n}}} w_i}{\langle w_i \rangle} - 1$$

ARF: **A**ngular **R**edshift **F**luctuations

Redshift is introduced as a ***field***

$$\delta z(\hat{\mathrm{n}}) = \frac{\sum_{i\in\hat{\mathrm{n}}} w_i (z_i - \bar{z})}{\langle w_i \rangle}$$

ARFs measure the deviation of the average ***z*** in each direction of the sky with respect to the mean redshift of the full sample

PNG from LSS: new cosmological observables

First proposed as observable in Hernández-Monteagudo, Chaves-Montero & Angulo (2020)

ARFs are sensitive to the galaxy bias, density field and peculiar velocities

Ideally, if systematics are z-independent, ARFs should be insensitive to multiplicative and additive effects

Sensitive to the galaxy bias: useful for (but not limited to) measuring $f_{\rm NL}$

$$\bar{z} + \delta z(\hat{\mathbf{n}}) = \frac{\int dr\, r^2 \bar{n}(r)\left(1 + b_g \delta_{\rm m}(r, \hat{\mathbf{n}})\right)\left(z_H + z_{\rm vlos} + z_\phi\right) W(z_H + z_{\rm vlos} + z_\phi;\, \sigma_z)}{\int dr\, r^2 \bar{n}(r)\left(1 + b_g \delta_{\rm m}(r, \hat{\mathbf{n}})\right) W(z_H + z_{\rm vlos} + z_\phi;\, \sigma_z)}$$

$$\Delta b(k, z) = 2(b_g - p) f_{\rm NL} \frac{\delta_{\rm crit}}{\alpha(k)}$$

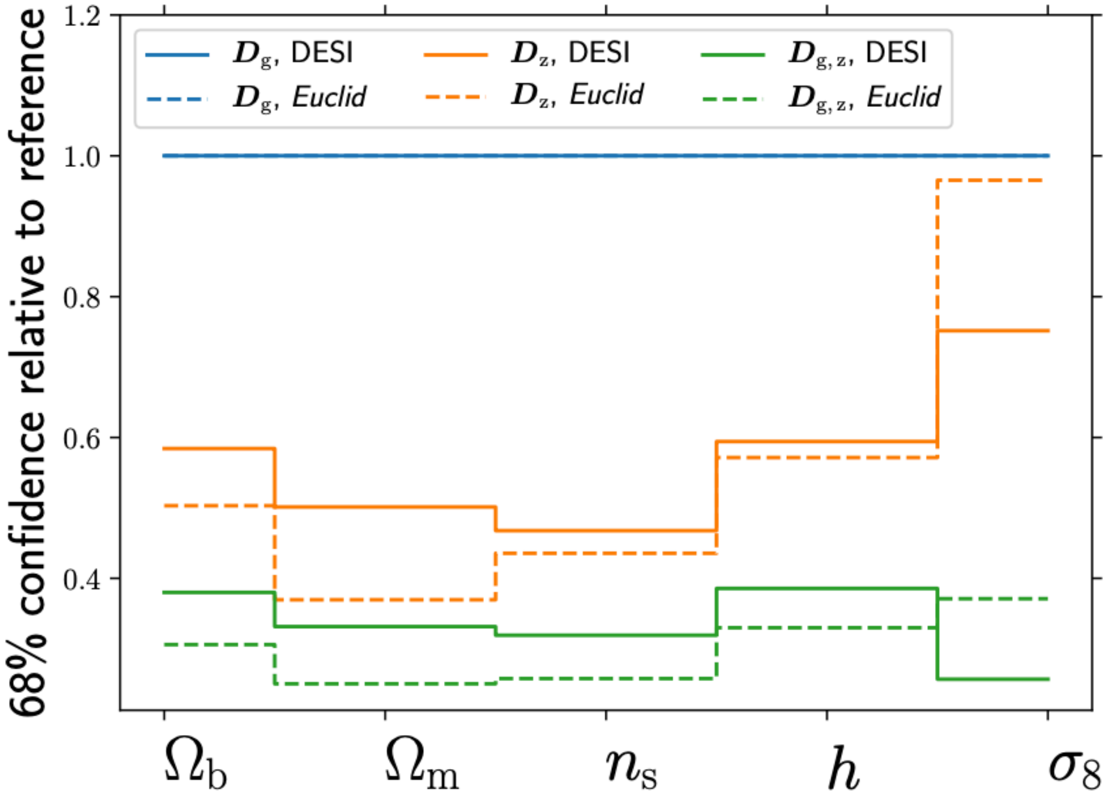
$$\alpha(k) = \frac{2k^2 T(k) D(z)}{3\Omega_{\rm m}} \frac{c^2}{H_0^2} \frac{g(0)}{g(\infty)}$$

PNG from LSS: new cosmological observables

Theoretical Fisher forecasts predict ARF can constrain cosmology and improve to the errors from 2D clustering on cosmological parameters

There are some reasons in favour of 2D tomographic analyses (see e.g. Asorey et al. 2012): it avoids model assumptions for converting to 3D or freezing redshift evolution inside a redshift bin

What about ARF with real data?



Forescasts for DESI-like and Euclid-like surveys (Legrand, Hernández-Monteagudo et al. 2021)

PNG from Quaia ARF: a new cosmological observable

Quaia (Storey-Fisher et al. 2024) is a spectrophotometric QSO catalog extracted from Gaia and unWISE data

Already used for measuring structure growth (Alonso et al. 2023) and $f_{\rm NL}$ (Fabbian et al. 2025)
Using 2D quasar density and CMB lensing, Fabbian et al. (2025) measured $f_{\rm NL} = -20^{+19}_{-18}$

Aim: quantify how much can we improve the measurement on $f_{\rm NL}$ by Fabbian et al. (2025) by adding ARF as extra observable (Fisher forecast predicted ~30%)

People: J. Bermejo-Climent, C. Hernández-Monteagudo, J. Camalich, A. Crespo-Perez, D. Alonso, G. Fabbian, K. Storey-Fisher …

PNG from Quaia ARF: a new cosmological observable

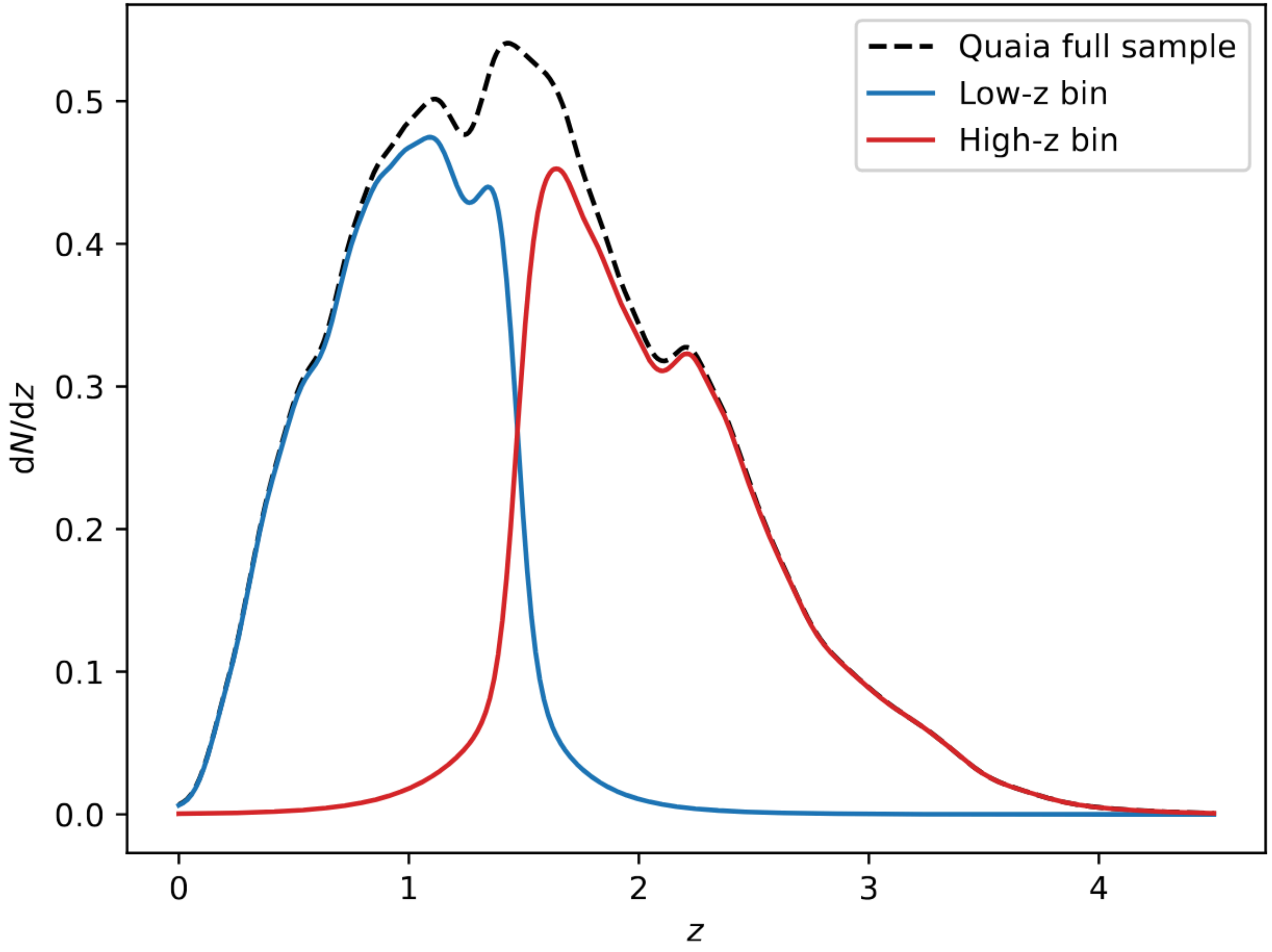
Quaia G < 20.5 magnitude sample:

~1.3 million quasars up to z~4, full sky.
The largest QSO volume ever sampled

We measure both 2D **density** and **ARF**

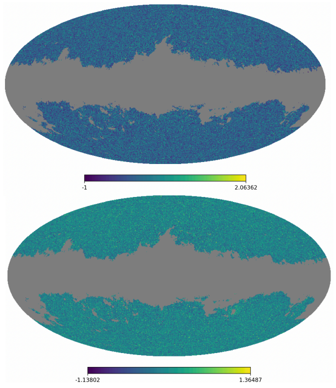
+ *Planck* PR4 CMB lensing maps for cross-correlations

Sample divided in **two redshift bins**

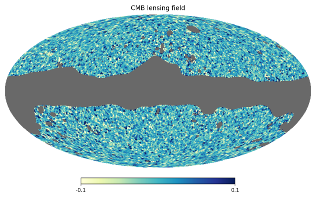


PNG from Quaia ARF: a new cosmological observable

Quaia catalog



Density and ARF maps from Quaia spectrophotometric catalog



Planck PR4 lensing maps

Theoretical model: CAMB modified version (by C. Herández-Monteagudo) including ARF

synfast

1000 **correlated mocks** in 2D for the density, CMB lensing and ARF fields

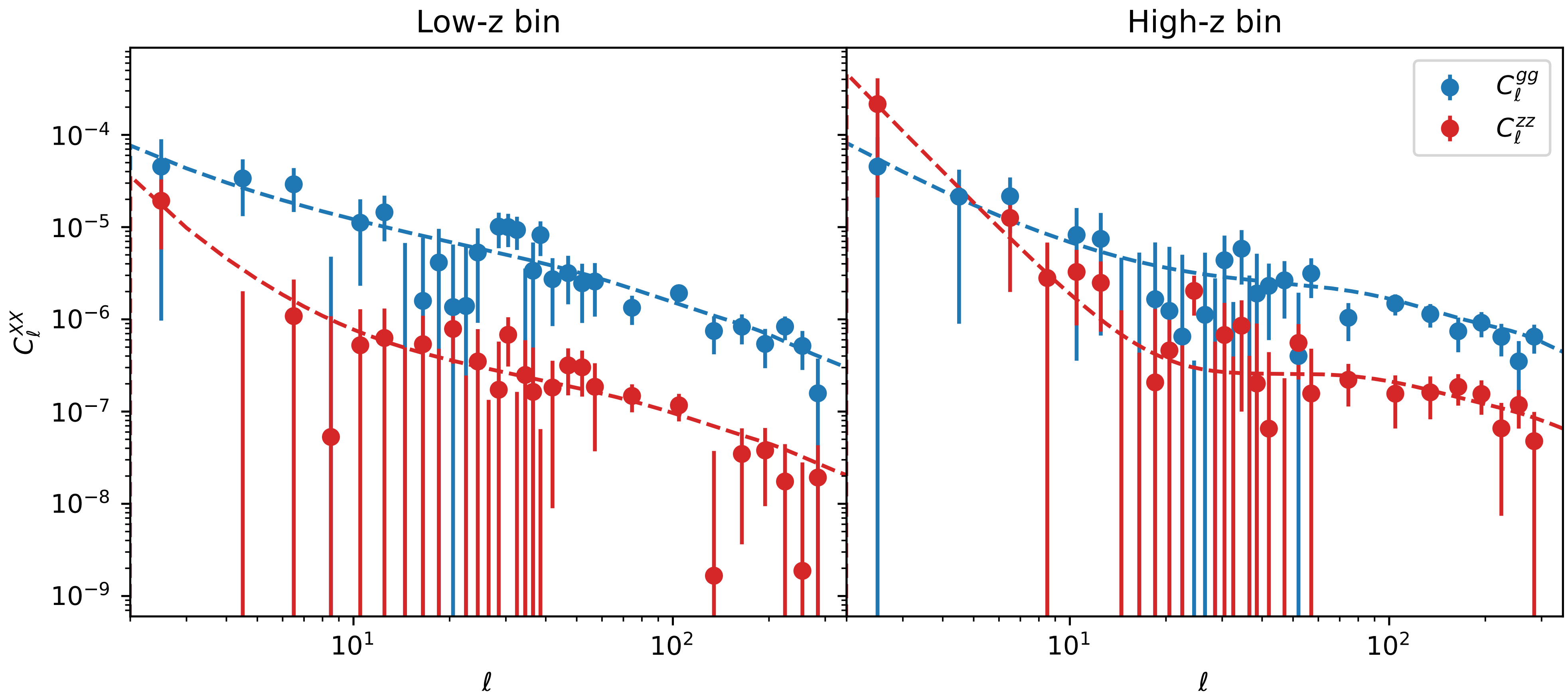
Covariance matrices

NaMaster (angular power spectra)

MCMC likelihood code

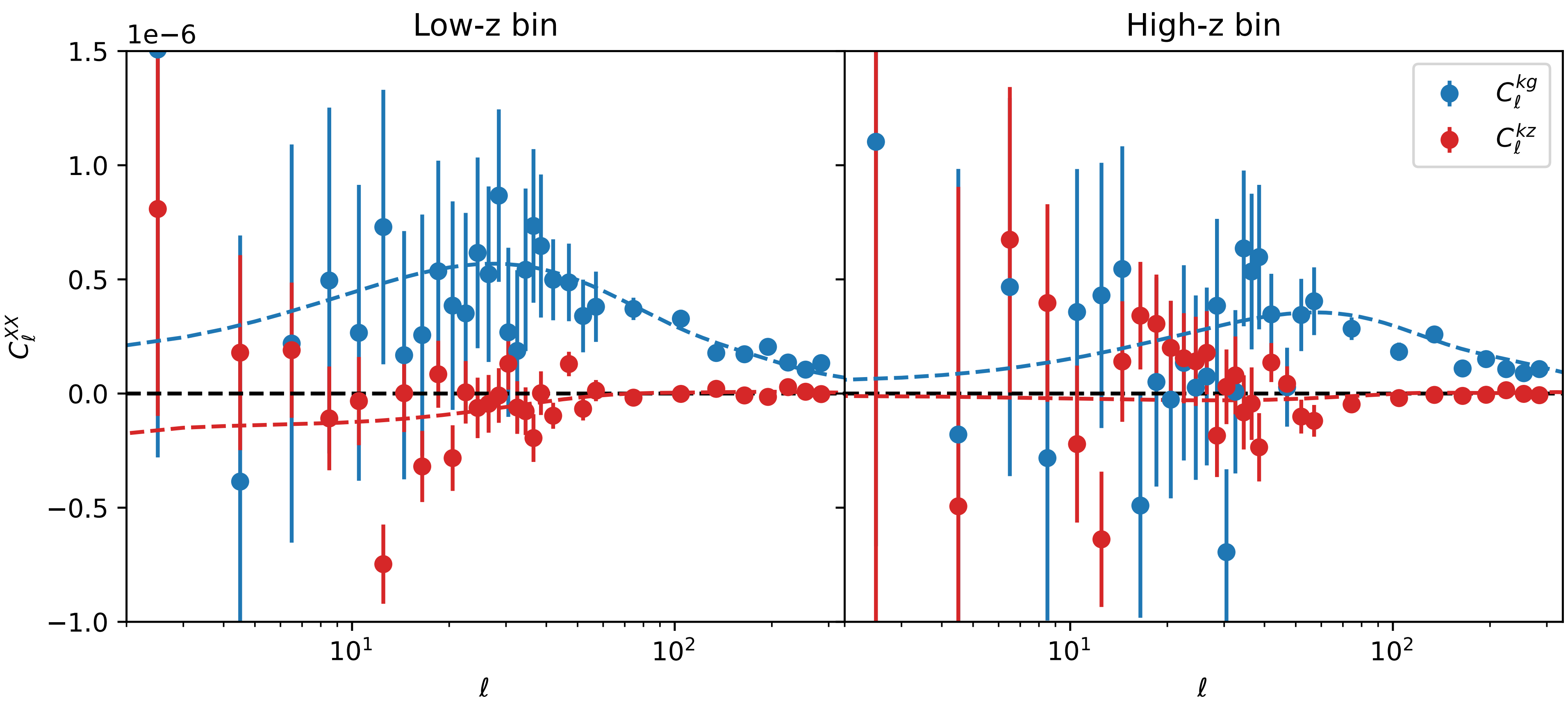
$\theta \equiv \{f_{\rm NL}, b_0, \alpha\}$

PNG from Quaia ARF: a new cosmological observable



Quaia autocorrelations for density and ARF: hints of systematics at $\ell \lesssim 10-15$. We apply scale cuts.
We fit a model to the data to generate mocks and obtain a realistic covariance matrix

PNG from Quaia ARF: a new cosmological observable



Quaia density and ARF cross-correlations with Planck PR4 lensing

consistent with theoretical model (no hints of correlated systematics)

PNG from Quaia ARF: a new cosmological observable

To appear in arXiv soon

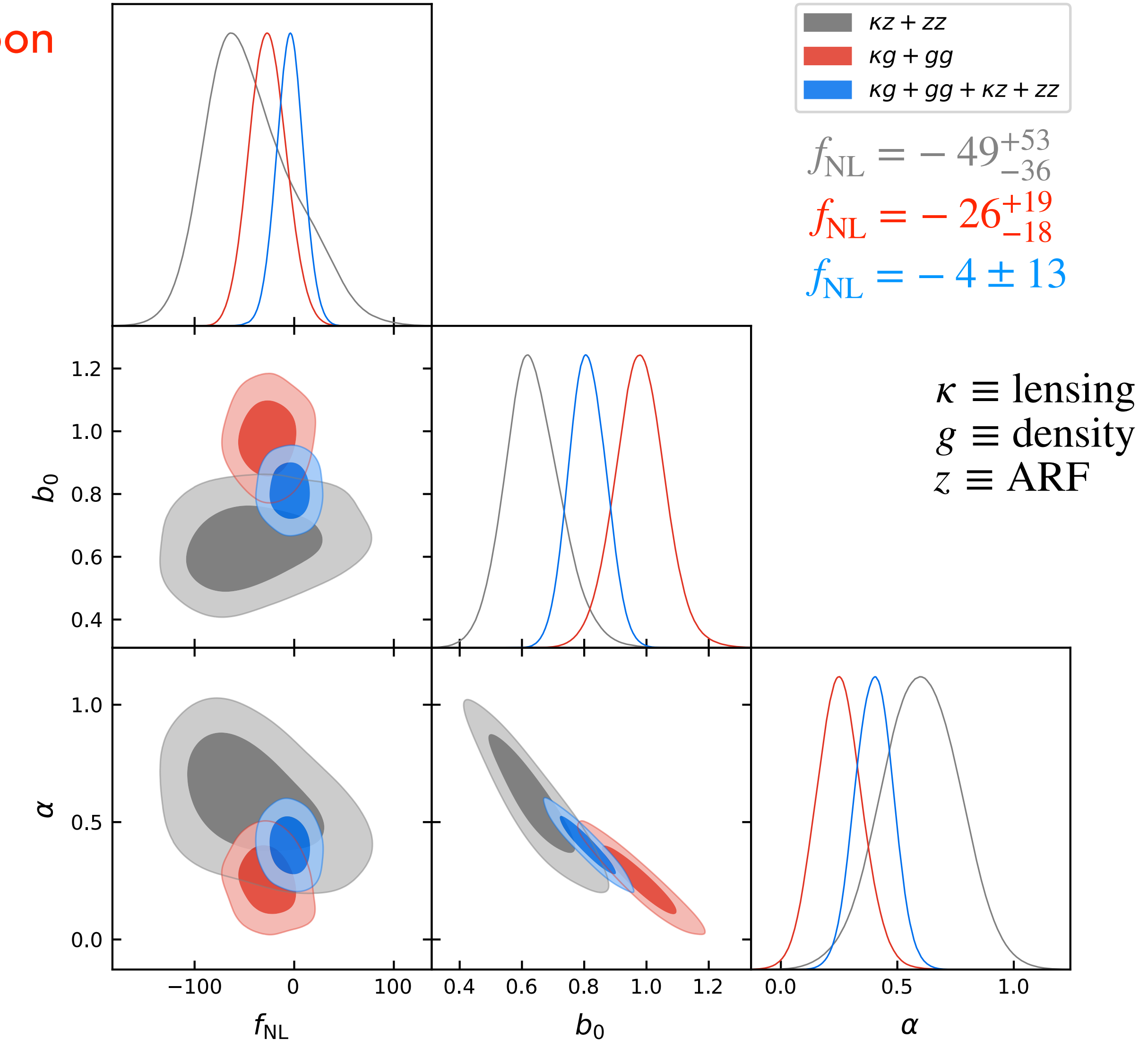
Bias evolution model:

$$b(z) = \frac{b_0}{D(z)}(1+z)^{\alpha}$$

3 free parameters in the analysis $(f_{\rm NL}, b_0, \alpha)$

Adding ARF and ARF x lensing improves the density + density x lensing constraints by ~30%, getting $\sigma(f_{\rm NL}) \sim 13$

This the second best constraint on $f_{\rm NL}$ from LSS (after DESI DR1) and the best achieved using projected 2D summary statistics



Future plans

- Projects on ARF already ongoing in **DESI** and **Euclid**: application and improvement of our existing pipeline for Quaia to DESI DR1 and Euclid DR1 releases to measure $f_{\rm NL}$ from lensing, galaxy clustering and ARFs.

- Longer term goal: combination of multiple tracers from various surveys (**multi-tracer**) approach. Explored from the theoretical perspective (forecasts) but not applied to real datasets yet. This will require to understand the correlation between systematics of different tracers.

Take-home messages

- LSS observations are a window to constrain inflation and fundamental physics by measuring $f_{\rm NL}$
- Although current measurements on $f_{\rm NL}$ from LSS are limited to $\sigma(f_{\rm NL}) \lesssim 10$ due to observational systematics, new datasets and techniques will allow to go beyond this limit
- CMB-LSS cross-correlations are a complementary and useful tool for measuring $f_{\rm NL}$. Using the DESI Legacy Survey LRG and Planck lensing we got $f_{\rm NL} = 24^{+20}_{-21}$ (Bermejo-Climent et al. 2025)
- ARF are a new cosmological observable and we have found they are a powerful tool for improving constraints on $f_{\rm NL}$. In particular, using Quaia data we have improved previous constraints by ~30% and measured $f_{\rm NL} = -4 \pm 13$ (2nd tightest constraint from LSS to date)