Towards a precise determination of primordial non-Gaussianity with LSS surveys

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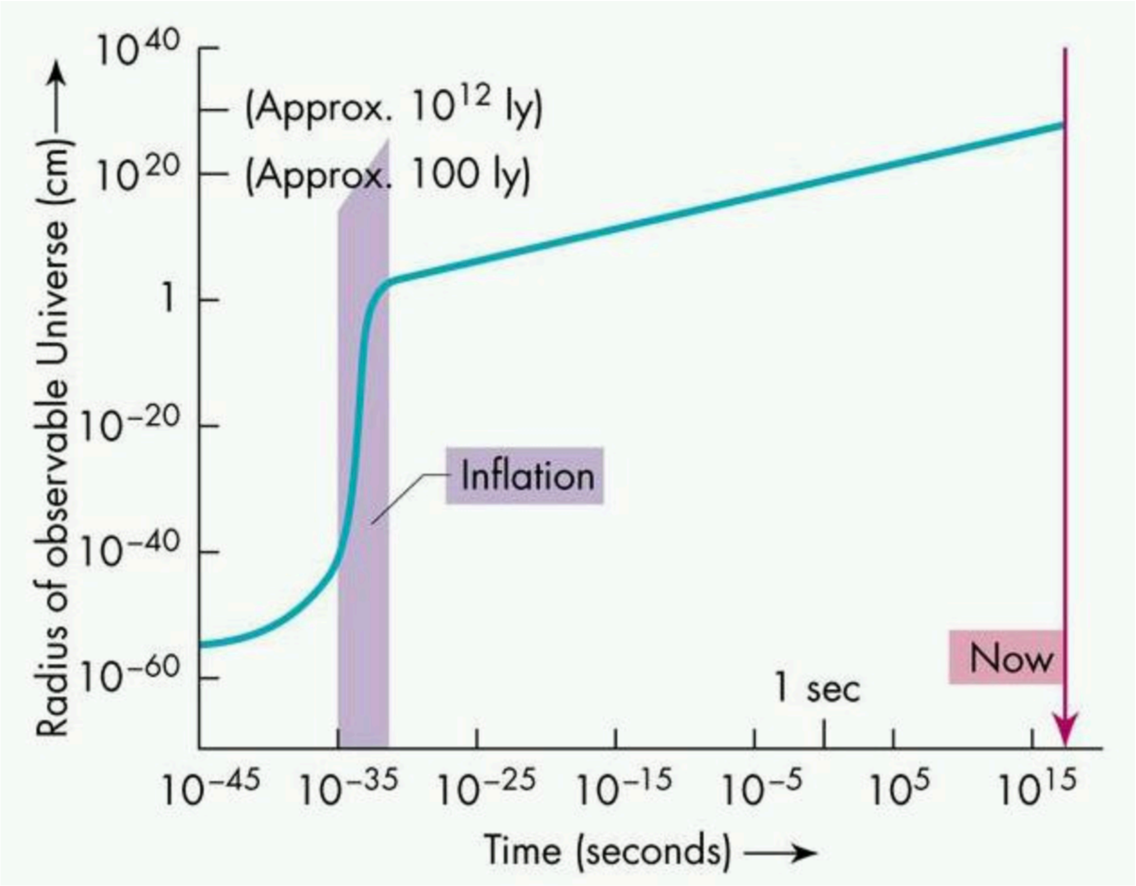
Introduction: inflationary physics

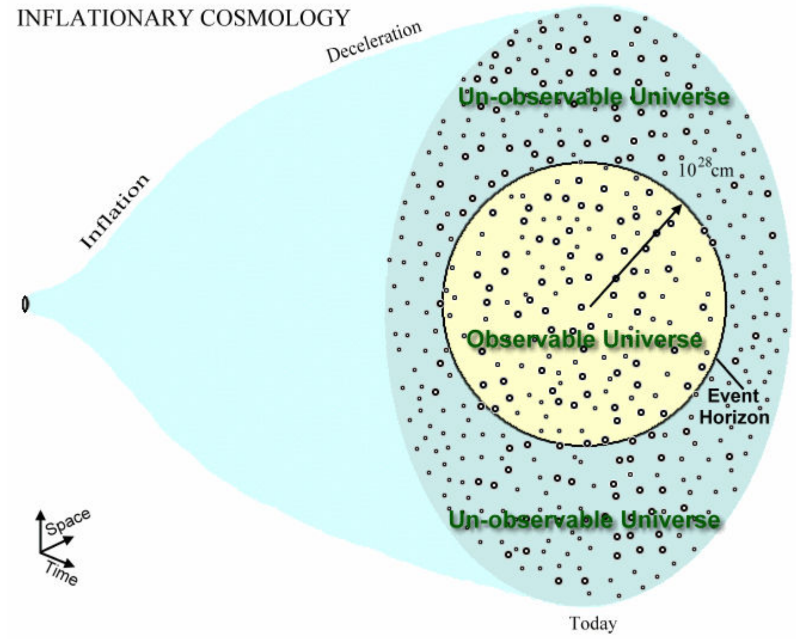
Cosmic inflation was introduced in the early 1980s (Guth 1981, Starobinsky 1980) **to solve the Big Bang model problems** (horizon, magnetic monopole, flatness…)

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



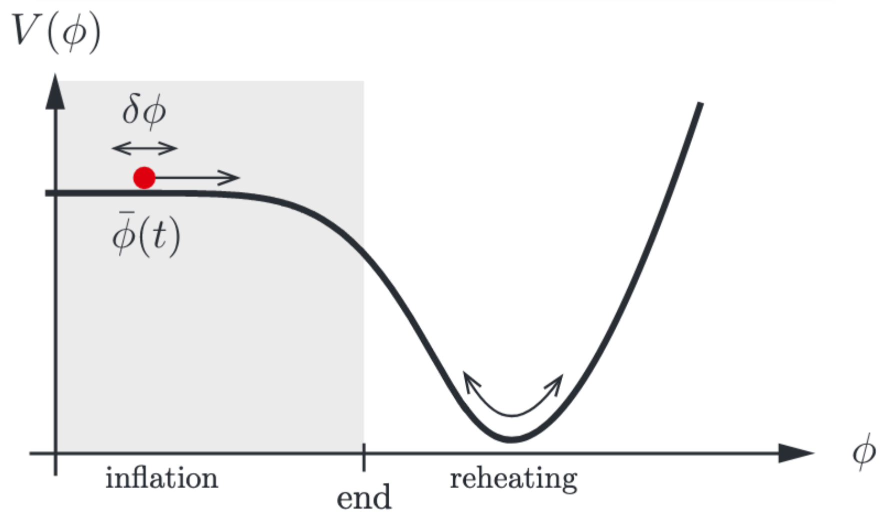
Introduction: inflationary physics

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:

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

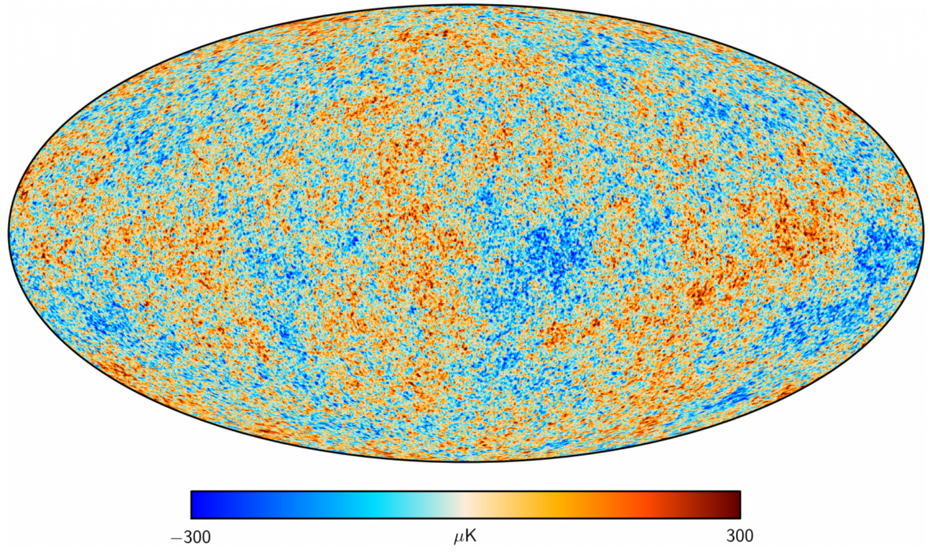


f_{NL} is a parameter that can **rule out or confirm inflationary models**, corresponding $f_{NL} = 0$ to Gaussian initial conditions

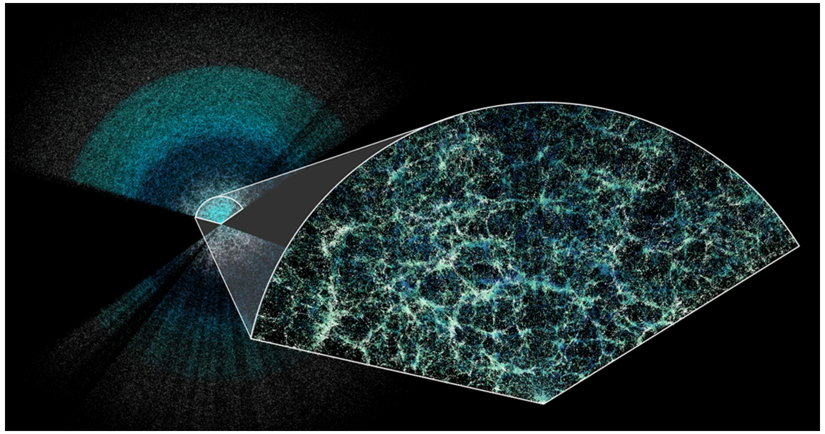
Introduction: inflationary physics

Two cosmic windows to PNG:

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



LSS: many upcoming measurements in the next years. Current sensitivity ~20, e.g.: $f_{\rm NL} = -12 \pm 21$ by Müller et al. 2022 using eBOSS quasars



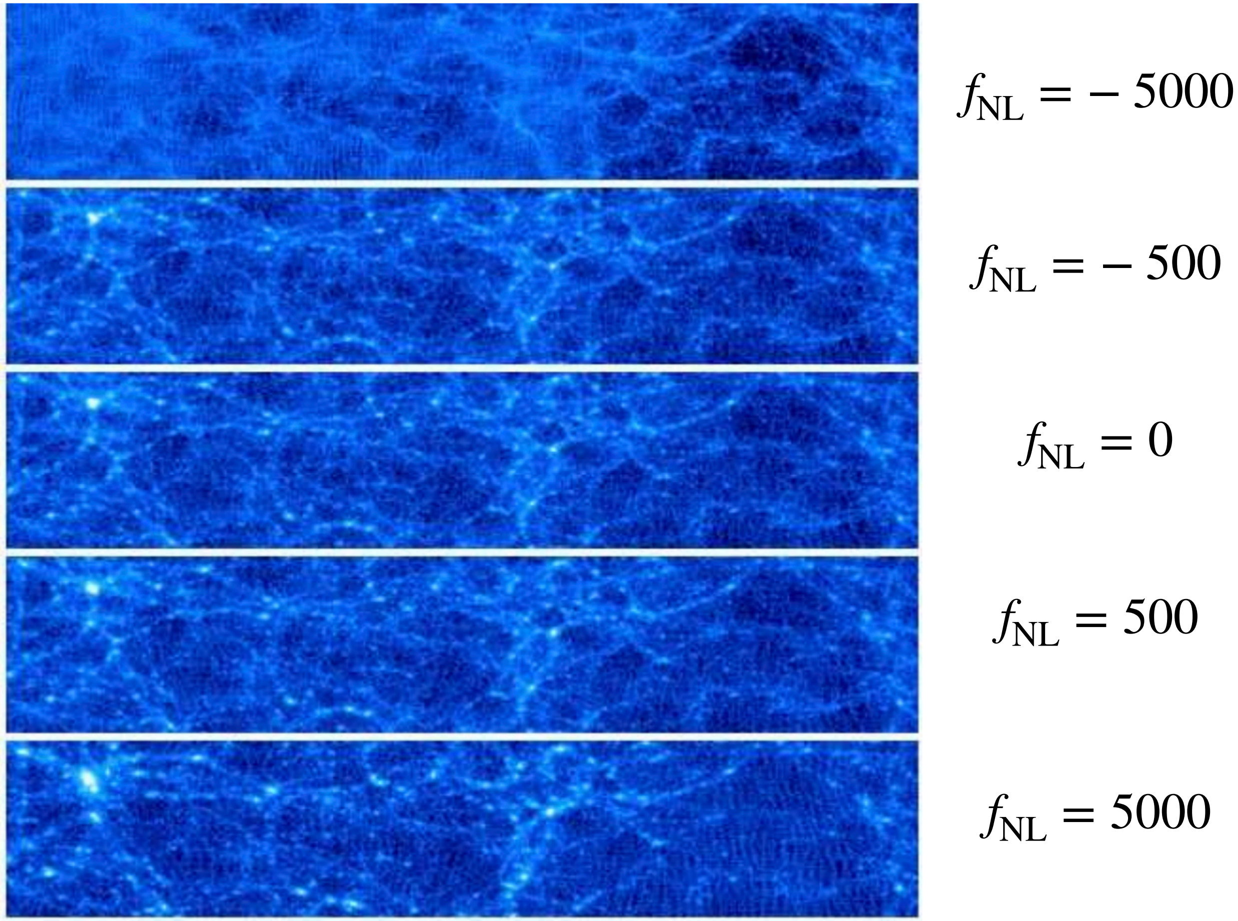
Introduction: non-Gaussianity from LSS

A local $f_{\rm NL}$ 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:

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

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

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

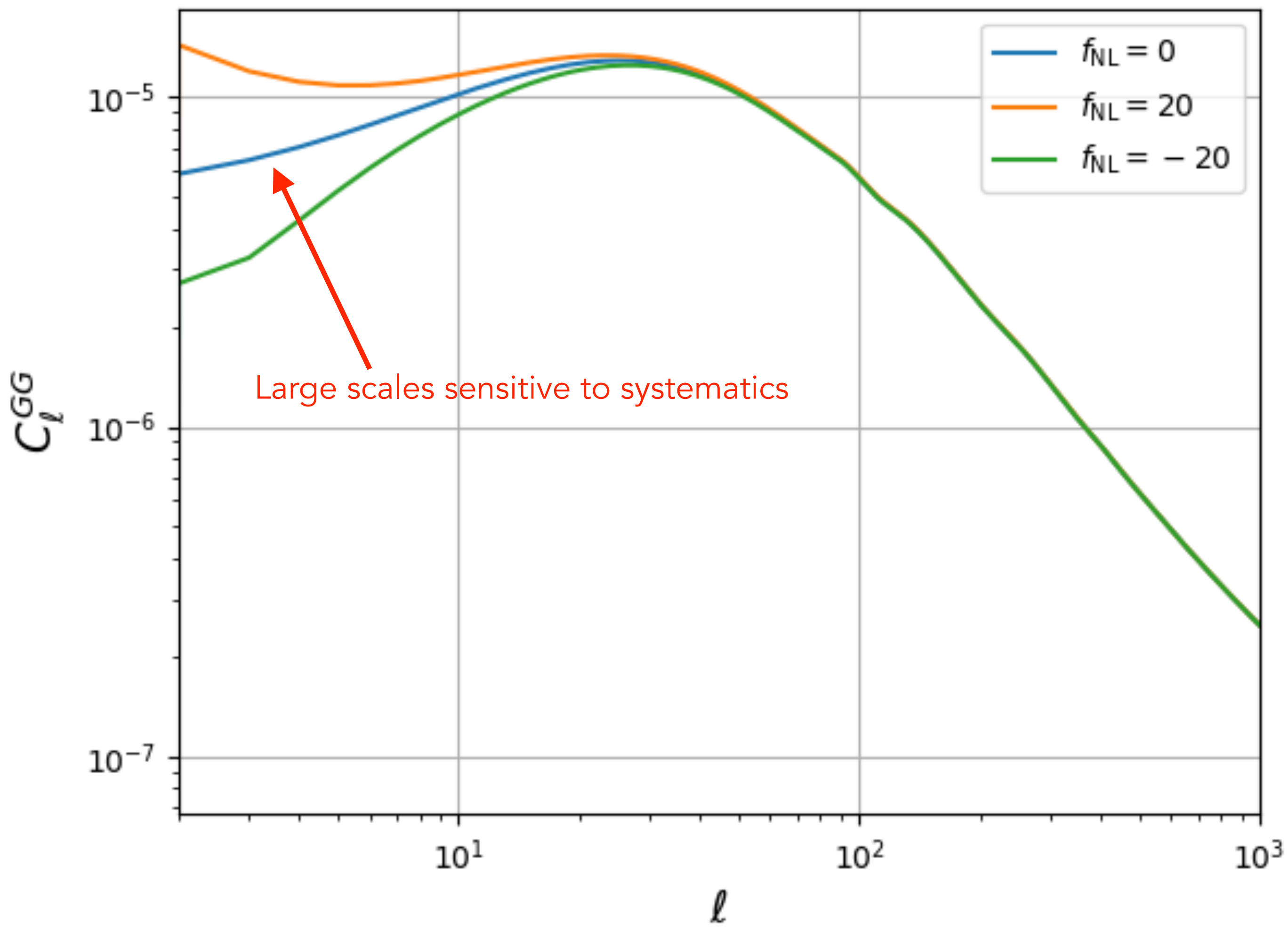


Simulated slices at z=0 for various $f_{\rm NL}$ values.
Dalal et al. (2008)

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



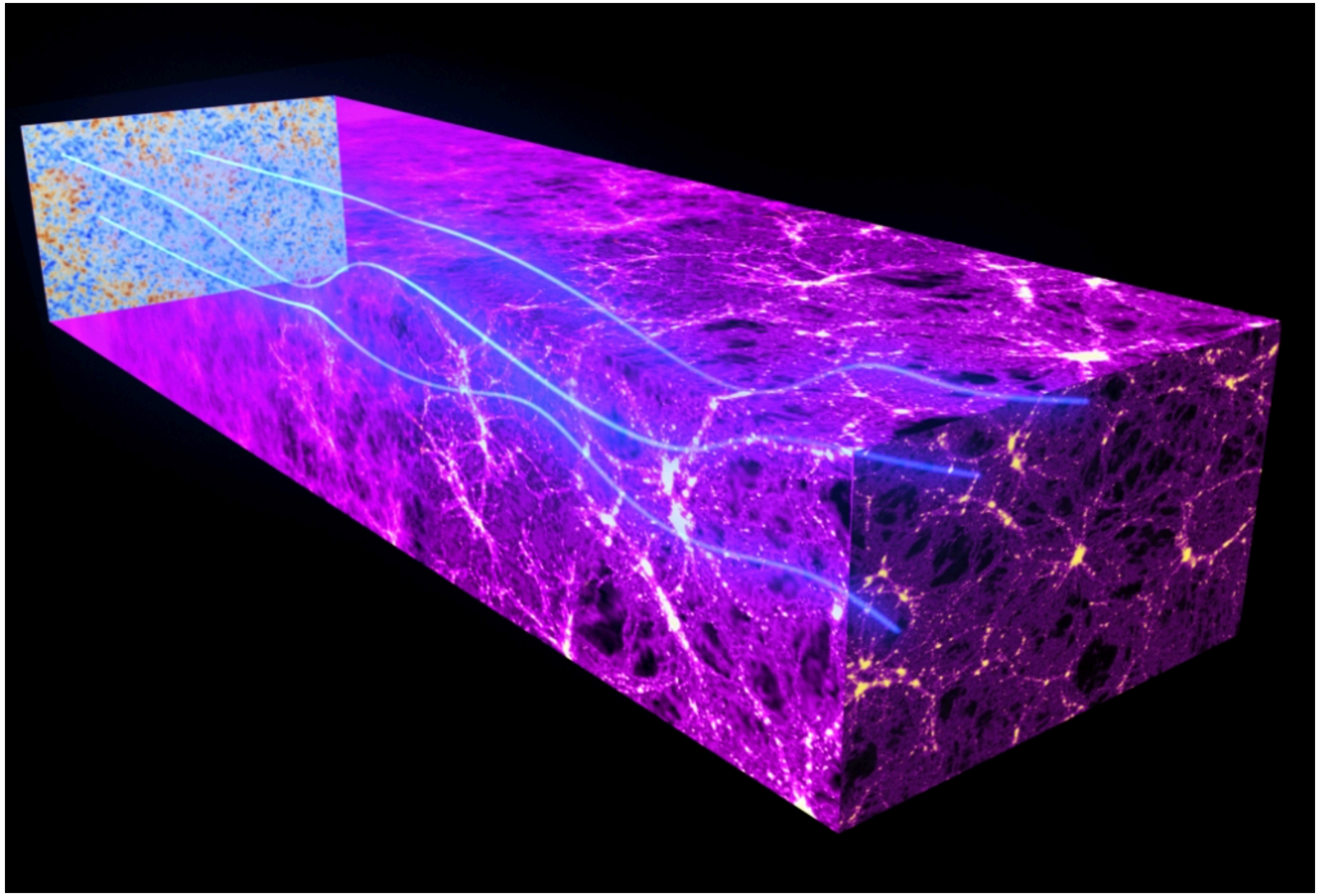
Galaxy angular power spectra for different f_{NL} values

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

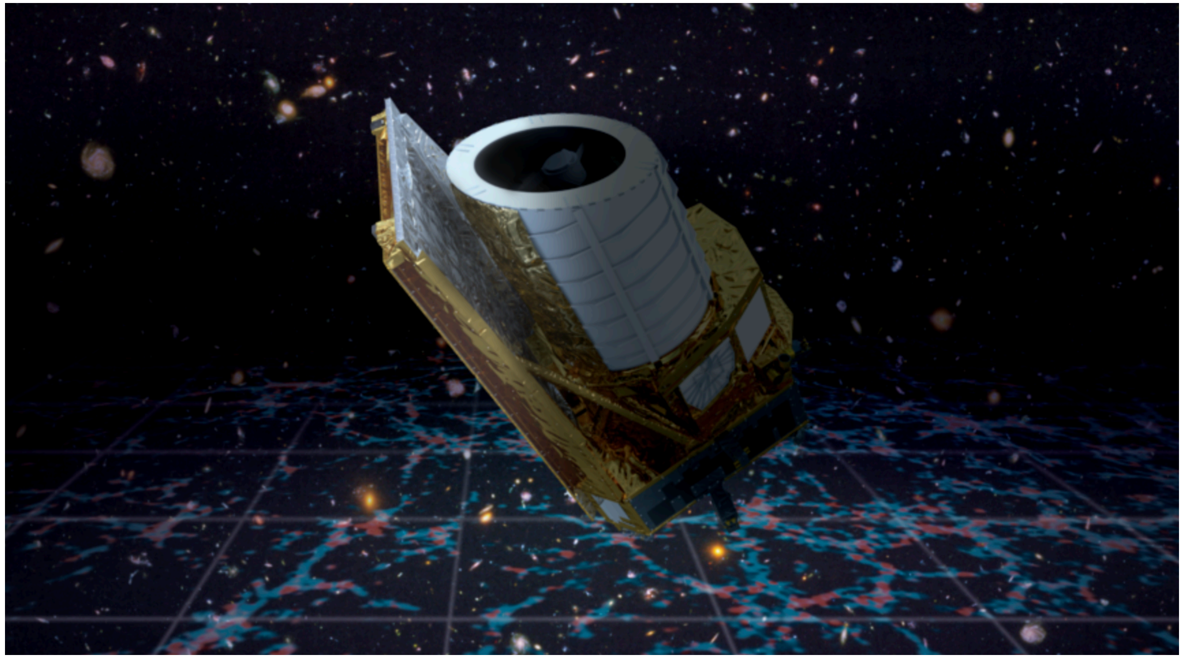
Most significant: **CMB lensing x LSS**

Cross-correlations usually drop out most of the systematics



CMB lensing effect (Image credits: ESA)

Ongoing and future LSS surveys



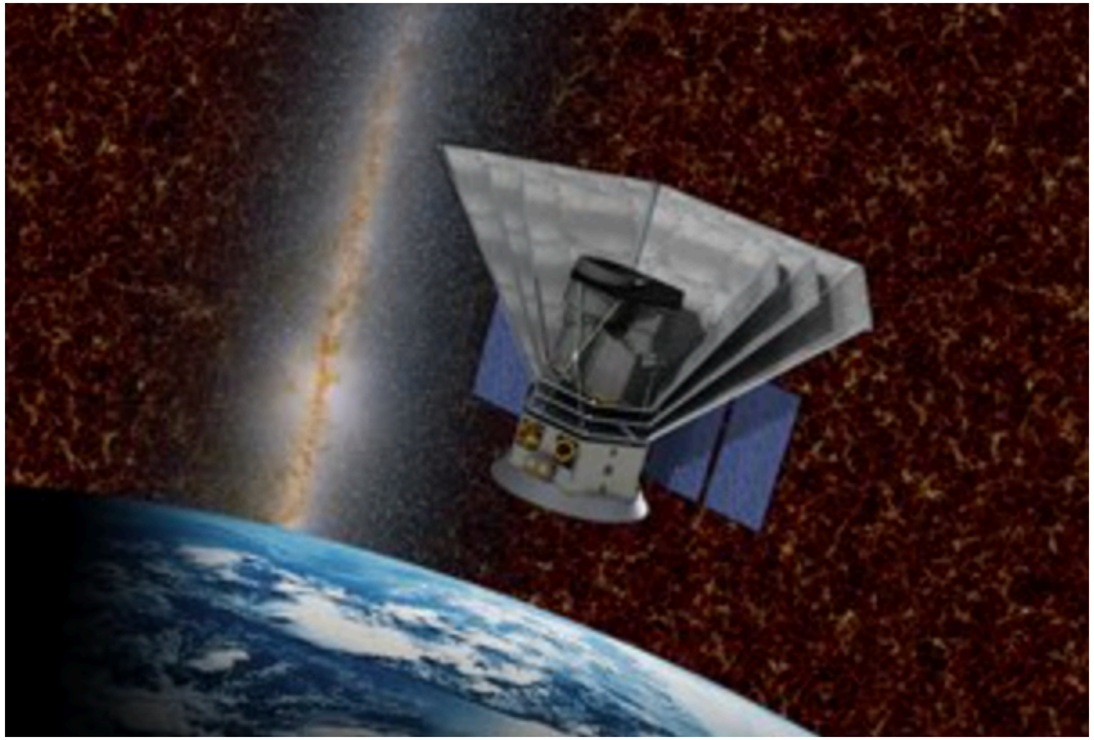
Dark Energy Spectroscopic Instrument (**DESI**) at Kitt Peak, Arizona: ~40 million objects spectroscopic survey across ~1/3 of the sky. Operations started 2021

Euclid: ESA satellite launched in 2023. Measures both spectra and imaging to produce the largest map of the Universe ever

Ongoing and future LSS surveys

Many other experiments coming will also be useful for measuring PNG

Legacy Survey of Space and Time (LSST)



SPHEREx

PNG from DESI x *Planck* lensing

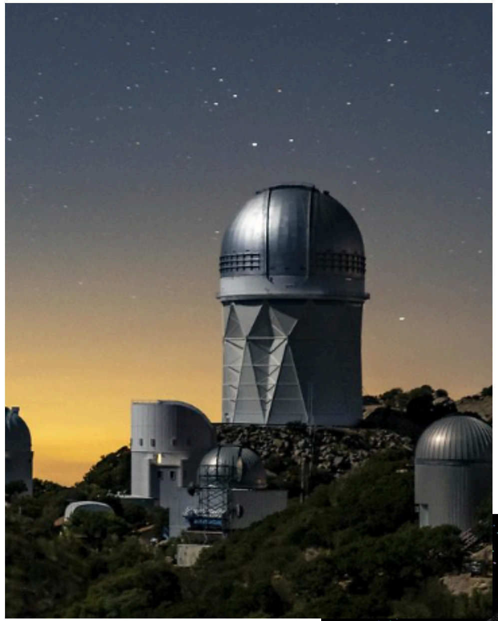
Aim: to perform a f_{NL} measurement using cross-correlations of DESI data with the CMB lensing

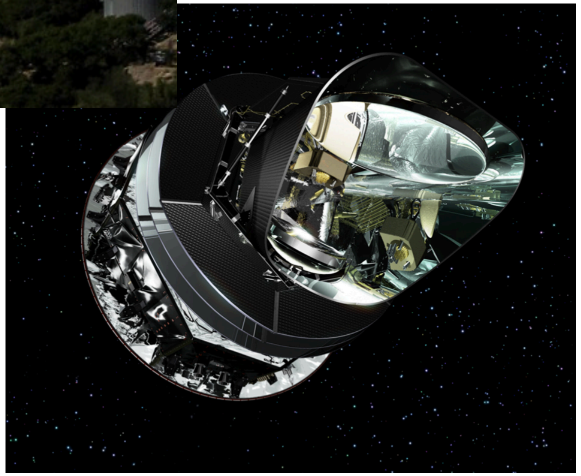
Data:

Luminous Red Galaxies (**LRG**) from the DESI 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.

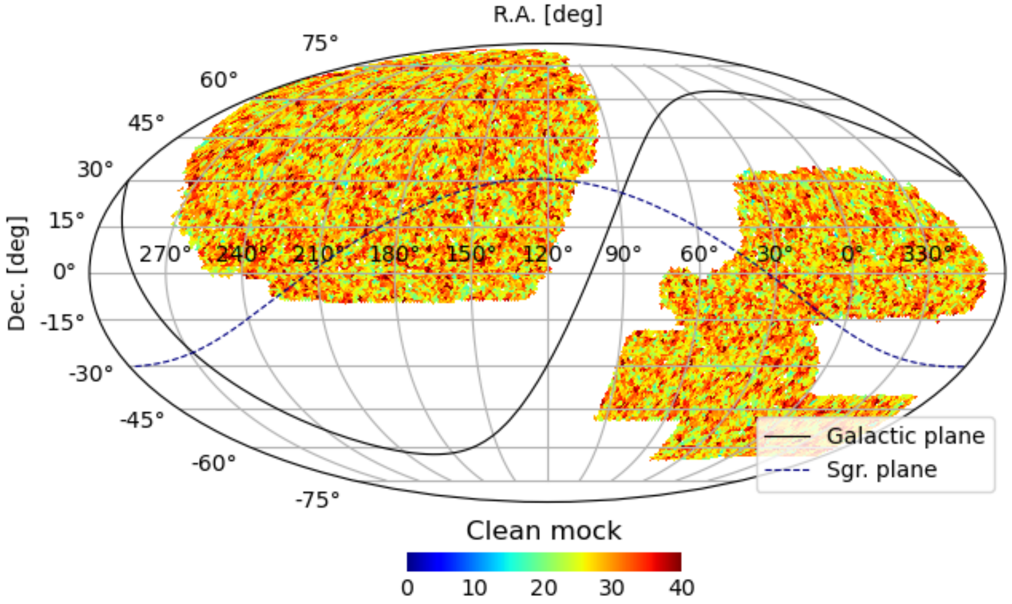




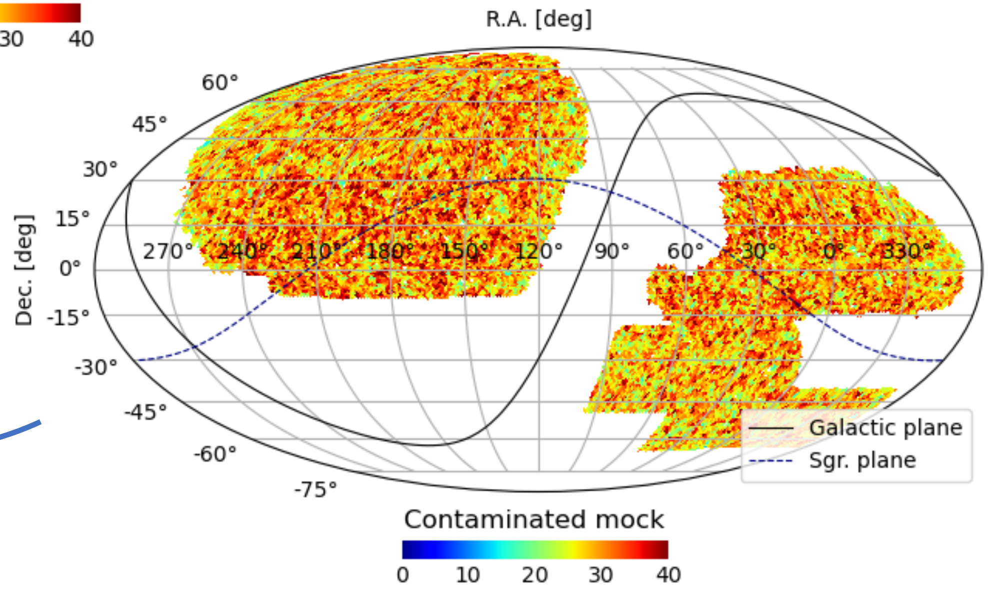
PNG from DESI x *Planck* lensing

The analysis required an extensive effort to understand observational systematics

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



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



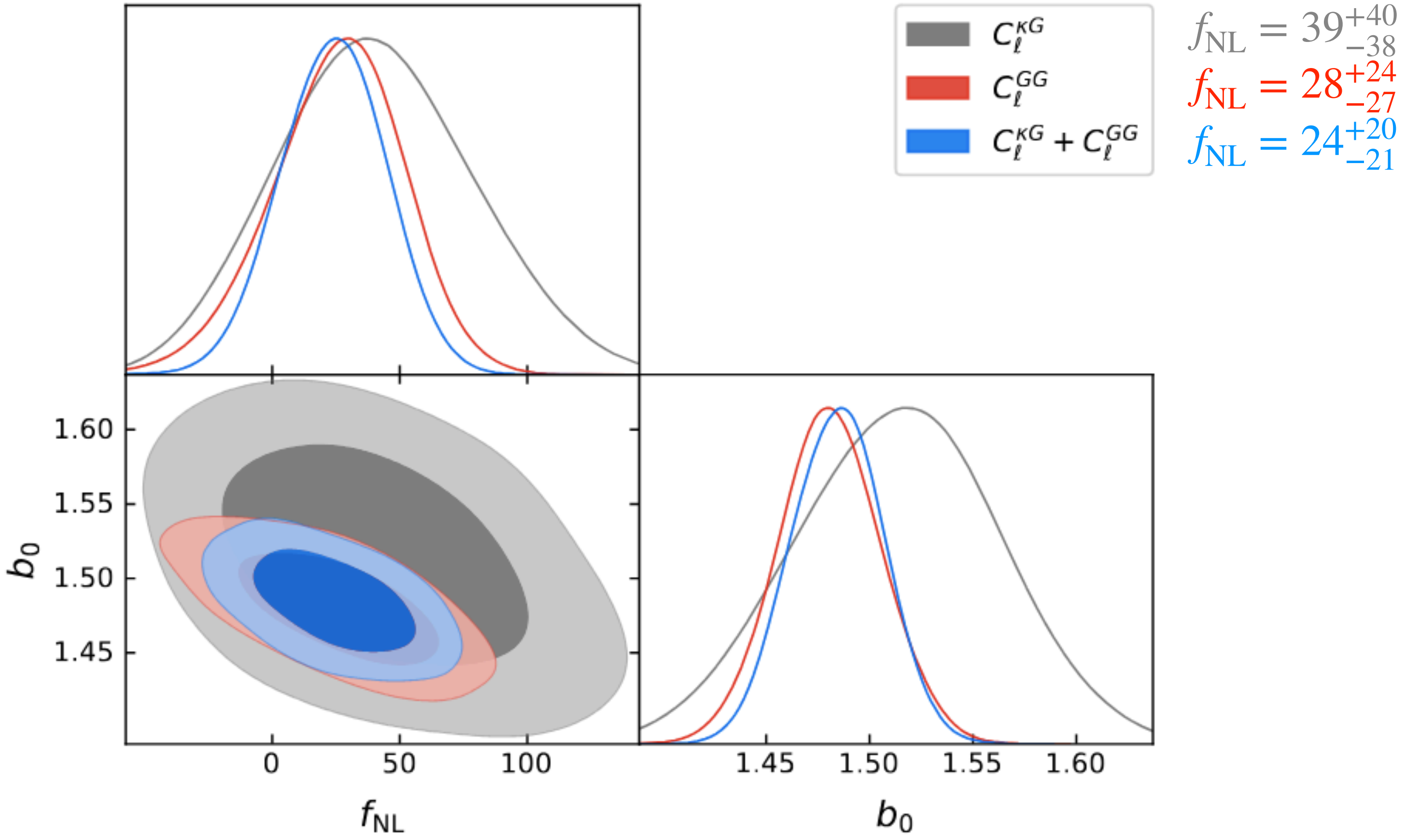
We applied **SYSnet** (by Mehdi Rezaie), a neural network code for systematics mitigation

PNG from DESI x *Planck* lensing

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 $\sigma(f_{\rm NL}) \sim 20$



Bermejo-Climent et al. 2024 (submitted to DESI internal review, to appear in arXiv soon)

PNG from LSS: what's next?

We are still limited to $\sigma(f_{\rm NL}) \sim 20$ from LSS. How can we improve this?

- **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 various 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)

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

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 Quaia ARFs: a new cosmological observable

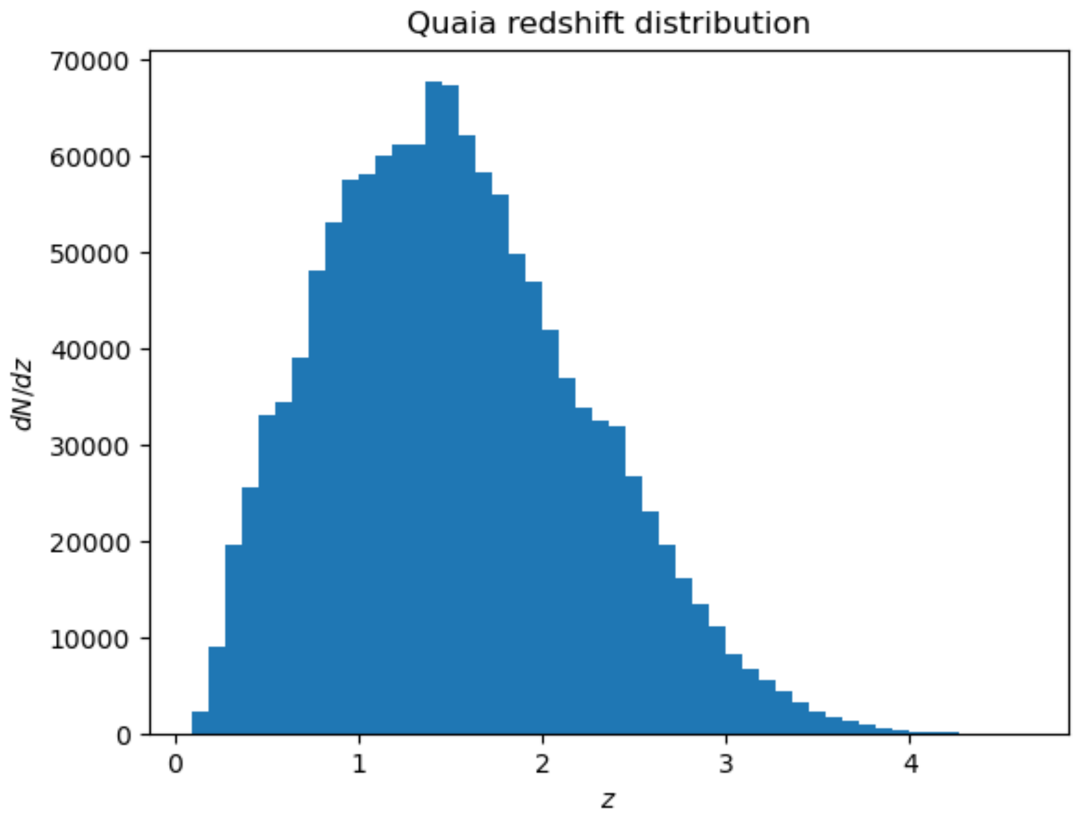
Quaia (Storey-Fisher et al. 2023): a spectrophotometric quasar sample from Gaia

~1.3 million quasars up to z~4, full sky

We measure both **density** and **ARF**

+ *Planck* PR4 CMB lensing maps

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

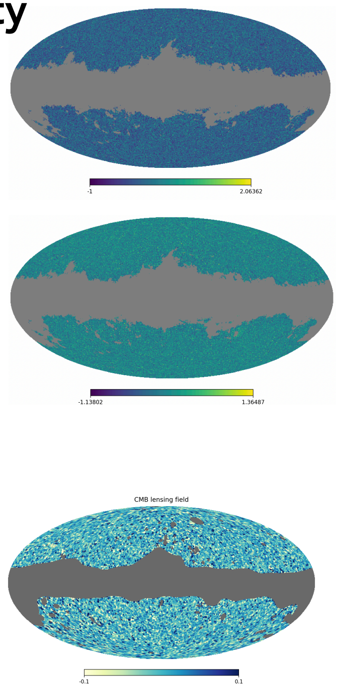


PNG from Quaia ARFs: a new cosmological observable

LSS catalog (Quaia)

Density

ARF



CMB lensing map *(Planck)*

Data: density, ARF and CMB lensing maps

Simulations of the density, ARF and CMB lensing fields

Theoretical model for observables: *ARFCAMB* code

Covariance matrices

Observables (angular power spectra)

Likelihood code
$\theta \equiv \{f_{\rm NL}, b_0\}$

We have already developed a pipeline to include ARFs in the analysis

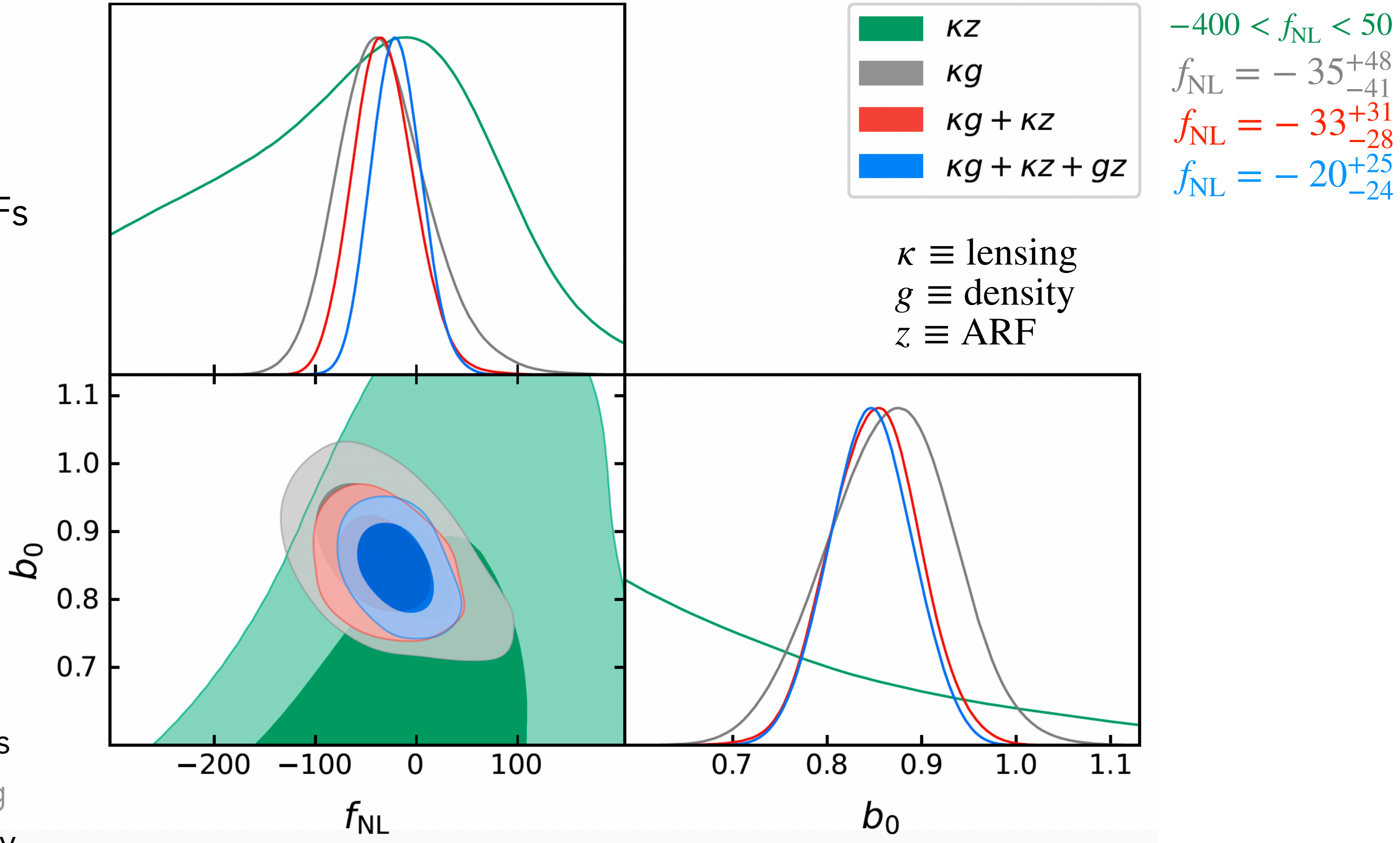
PNG from Quaia ARFs: a new cosmological observable

PRELIMINARY

Using cross-correlations only, we improve the f_{NL} errorbars by ~40-50% after adding ARFs

We might include autocorrelations once systematics are better understood

ARF x lensing breaks the density x lensing contours degeneracy



Bermejo-Climent et al. (2025 in prep.) using Quaia and Planck lensing

Future plans

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

- Longer term goal: combination of multiple 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_{NL}
- Although current measurements on f_{NL} from LSS are limited to $\sigma(f_{\mathrm{NL}}) \sim 20$ due to observational systematics, upcoming datasets will allow us to go beyond this limit
- ARF are a new cosmological observable and we have found they are a powerful tool for improving constraints on f_{NL}