First Constraints on Small-Scale Non-Gaussianity from UV Galaxy Luminosity Functions

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Goal

The most accepted paradigm to explain the current observed features of the Universe is that it went through an inflationary period at early times. This framework is, however, quite broad in terms of determining which fundamental mechanism was actually operating. A key feature of many inflationary models is a deviation in the distribution of primordial matter fluctuations from the simplest Gaussian prediction, a feature known as *primordial non-Gaussianity* (PNG).

A departure from Gaussianity in the primordial fluctuations alters the abundance of dark matter halos, and thus the UV luminosity function (UV LF) measured by, for example, the Hubble Space Telescope (HST). Here we show that this makes the UV LF a powerful probe of PNG, enabling us to search for it at scales corresponding to wavenumbers $k \gtrsim 0.1\,\mathrm{Mpc}^{-1}$, which are difficult to access by cosmic microwave background (CMB) and large-scale structure (LSS) observations.

1. The UV Luminosity Function

In the early Universe, galaxies contain young stars that emit in the ultra-violet part of the spectrum. This radiation gets redshifted due to the expansion of the Universe and can be observed today with telescopes such as the HST. The abundance of galaxies in the early Universe can thus be indirectly tracked through their luminosity function, which describes the relation between the observed number density of galaxies and their magnitude. It is defined as:

$$\phi_{\rm UV} = \frac{\mathrm{d}n}{\mathrm{d}M_{\rm UV}} = \frac{\mathrm{d}n}{\mathrm{d}M_{\rm h}} \times \frac{\mathrm{d}M_{\rm h}}{\mathrm{d}M_{\rm UV}} \qquad (1)$$

Abundance of dark matter halos with mass $M_{\rm h}$

Connection between halo mass and UV magnitude

The LF consists of two parts: The first is the halo mass function, which describes how many halos of each mass there are, and is mainly influenced by cosmology. The second is the halo-galaxy connection, driven by astrophysical processes and which allows us to relate the halo mass to the observed emission.

2. Halo Mass Function

Massive, high-luminous galaxies tend to be hosted by heavy dark matter halos. While massive halos are more likely able to form such galaxies, they are more rarely found than lower mass halos. Here we follow an approach based on ellipsoidal gravitational collapse of dark matter halos (which results in a better agreement with numerical simulations than spherical-collapse models) and adapt the formalism developed by Sheth & Tormen.

3. Halo-Galaxy Connection

We follow a simple phenomenological approach to link host halos to the luminosity of galaxies that reside in them:

1. The efficiency at which galaxies will form stars depends on the mass of the host halo and is expected to exhibit a peak at halo masses $10^{11} - 10^{12}\,M_{\odot}$, similar to that of our own Milky Way. A simple analytic model that captures this behaviour relates the typical stellar mass M_* inside the halo to the mass of the host halo $M_{\rm h}$ via a double power-law:

$$\frac{M_*}{M_{\rm h}} = \frac{\epsilon_*}{\left(\frac{M_{\rm h}}{M_{\rm c}}\right)^{\alpha_*} + \left(\frac{M_{\rm h}}{M_{\rm c}}\right)^{\beta_*}}\,, \qquad (2)$$

   where ϵ_*, α_* and β_* are free parameters that we will fit for with data and $M_{\rm c}$ is a constant.

2. What we actually observe is the flux of the UV emission of massive, young stars in galaxies at some redshift. We can relate the stellar mass M_* to the star-formation rate, the latter which can be expressed in terms of the UV luminosity (or equivalently UV magnitude $M_{\rm UV}$). This then gives M_* as a function of $M_{\rm UV}$.

Now we are able to relate the host halo mass $M_{\rm h}$ to the UV magnitude $M_{\rm UV}$ of galaxies that reside in it. Eq. (1) is then used to express the UV LF in terms of $M_{\rm UV}$. We show the dependence of the UV LF on the free parameters of Eq. (2) in Figure 1.

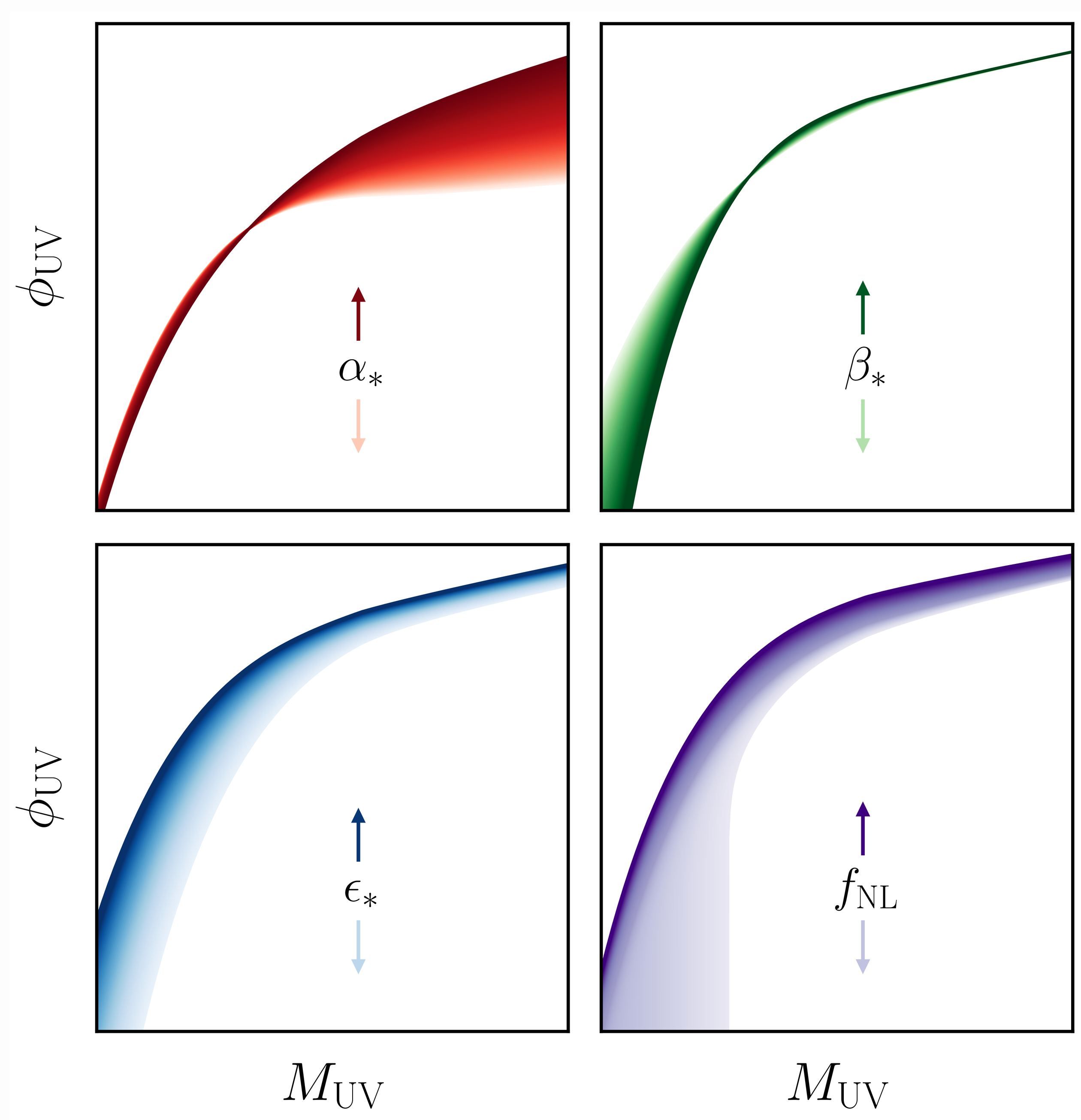

Figure 1. An illustration of the dependence of the UV luminosity function on the fitting parameters in Eq. (2) and the amplitude $f_{\rm NL}$ of the small-scale PNG.

4. Small-Scale Non-Gaussianity

The simplest model of primordial non-Gaussianity alters the initial gravitational perturbation Φ by a series expansion around a Gaussian field $\Phi_{\rm G}$, which to linear order reads:

$$\Phi(x) = \Phi_G(x) + f_{NL}\left(\Phi_G^2(x) - \langle\Phi_G^2\rangle\right) . \quad (3)$$

Now, the quantity of interest is the 3-point correlation function of Φ. This quantity is equal to 0 if Φ is Gaussian, but is proportional to f_{NL} in the presence of non-Gaussianity. We introduce a cut-off scale k_{cut}, below which this 3-point correlation function of Φ vanishes. This is done so, as to avoid constraints from CMB and LSS observations at large scales.

The deviation from Gaussianity is usually parametrised in terms of higher-order cumulants of the field Φ. We will work to first order in f_{NL}, where only the skewness, which we denote as κ_3, is relevant. This quantity can be thought of as the strength of non-Gaussianity as a function of halo mass. We show κ_3 as a function of halo mass in Figure 2 for different choices of the cut-off scale k_{cut}. Increasing k_{cut} produces an overall suppression of κ_3. The most striking effect is, however, the vanishing of κ_3 for halos much heavier than $M_{cut} = 4\pi\rho_m k_{cut}^{-3}/3$. For $k_{cut} = 0.1\,\mathrm{Mpc}^{-1}$ this corresponds to $M_{cut} \approx 2 \times 10^{14}\,M_\odot$, roughly the mass of galaxy clusters. This shows that the PNG models that we consider (with $k_{cut} = 0.1\,\mathrm{Mpc}^{-1}$) would leave no signature in usual searches (as κ_3 is $\sim$0 there), such as cluster abundance or CMB analyses, whereas they will affect the UV luminosity function.

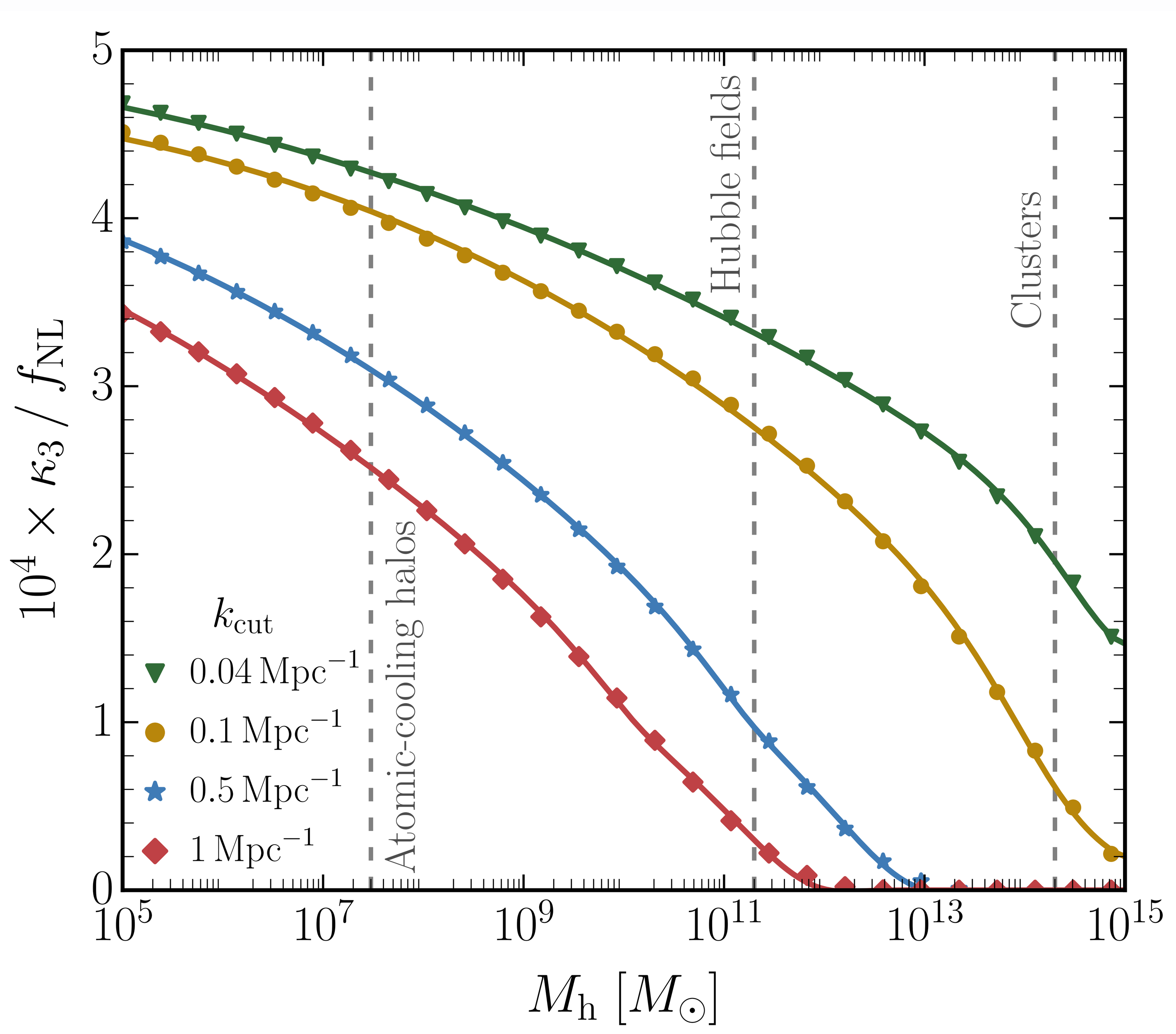

Figure 2. The skewness κ_3 as a function of halo mass in the presence of local-type non-Gaussianity for different cut-off scales k_{cut}. The dashed vertical lines roughly represent – from left to right – the mass of atomic cooling halos (relevant to the 21-cm signal from cosmic dawn), the heaviest halos probed in the Hubble Legacy/Frontier Fields and halos in which clusters reside.

The deviation from Gaussianity in the distribution of matter perturbations in the early Universe will become imprinted onto the abundance and distribution of galaxies. In principle, this means that the halo mass function in Eq. (1) changes as follows:

$$\frac{dn}{dM_h} \Longrightarrow \frac{dn}{dM_h} \times \mathcal{C}(M_h, f_{NL}) , \quad (4)$$

where $\mathcal{C}$ is a factor that encodes the impact of non-Gaussianity on the halo mass function. In a Gaussian cosmology, the distribution function (PDF) of matter density perturbations is given by $\rho = \left(2\pi\sigma^2\right)^{-1/2}\exp(-\delta^2/2\sigma^2)$. Now, in a non-Gaussian cosmology, the PDF can be written as a series in the higher-order cumulants of the distribution (κ_3 in our case). The factor $\mathcal{C}$ in Eq. (4) can be then obtained from such expansion.

Finally, together with the formalism in Section 3, Eq. (4) can be plugged in Eq. (1) to obtain the dependence of the UV LF on the astrophysical parameters α_*, β_* and ϵ_*, the UV magnitude M_{UV}, redshift z and the non-Gaussianity parameter f_{NL}.

5. Results

The high-redshift UV LF has been observed by the Hubble Space Telescope over a decades-long endeavour. This has resulted in two main data catalogs dubbed the Hubble Legacy Fields (HLF) and the Hubble Frontier Fields (HFF). The first consists of several deep-field surveys and has robustly probed the UV LF at the bright end (lower M_{UV}), while the latter consists of observations of six cluster lenses, where faint background galaxies are magnified enough to become observable. As can be readily seen in the lower right panel of Figure 1, the impact of primordial non-Gaussianities will be mainly visible at the bright end of the LF. Therefore, we perform our main analysis with the data obtained from the HLF. We show this data set in Figure 3, along with our best-fit model (in the absence of primordial non-Gaussianity).

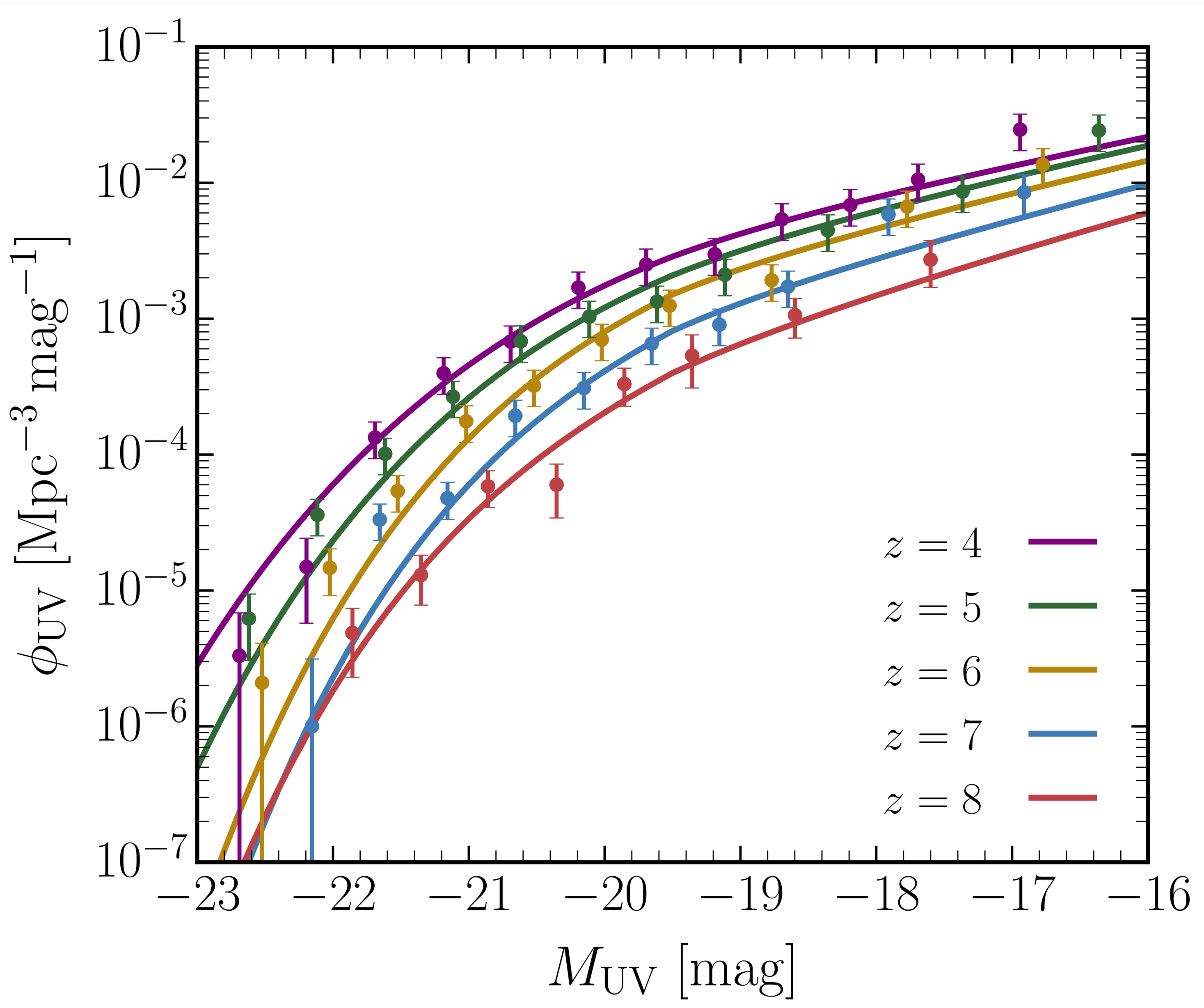

Figure 3. Global fits of our UV luminosity function model to the data from the HLF catalog in the absence of non-Gaussianity (i.e., fixing $f_{NL} = 0$).

In order to study degeneracies between the different parameters, we have performed an MCMC analysis and show the posteriors in Figure 4. Note that while at a single redshift the impact of f_{NL} and ϵ_* on the UV LF is highly degenerate (see lower panels in Figure 1), this degeneracy is lifted when combining data at different redshifts, as is clear in Figure 4. This is because different redshift slices have slightly different $f_{NL}-\epsilon_*$ degeneracy directions, making their combination break the degeneracy and yielding a nearly Gaussian posterior. The MCMC best fit at 2σ reads:

$$f_{NL} = 71^{+426}_{-237} . \quad (5)$$

While this error is significantly larger than the one obtained with CMB data (where $\sigma(f_{NL}) = 5.1$ for local-type PNG), it places a constraint on smaller scales, beyond where CMB data can naturally access, and is thus complementary to such bounds.

6. Future Data

We have also studied how well future data from the epochs of cosmic dawn and reionisation will be able to constrain small-scale PNG. We focused on two probes. The first is the upcoming James Webb Space Telescope (JWST), which will significantly improve upon the UV LFs of the HST. The second is 21-cm measurements during cosmic dawn, which have access to halos as small as $M_h \sim 10^7\,M_\odot$ and redshifts as high as $z \sim 25$, where the effects of small-scale PNG can be very dramatic.

A set of forecasts shows that such experiments would be able to further improve upon the current bound by a factor 3 – 4.

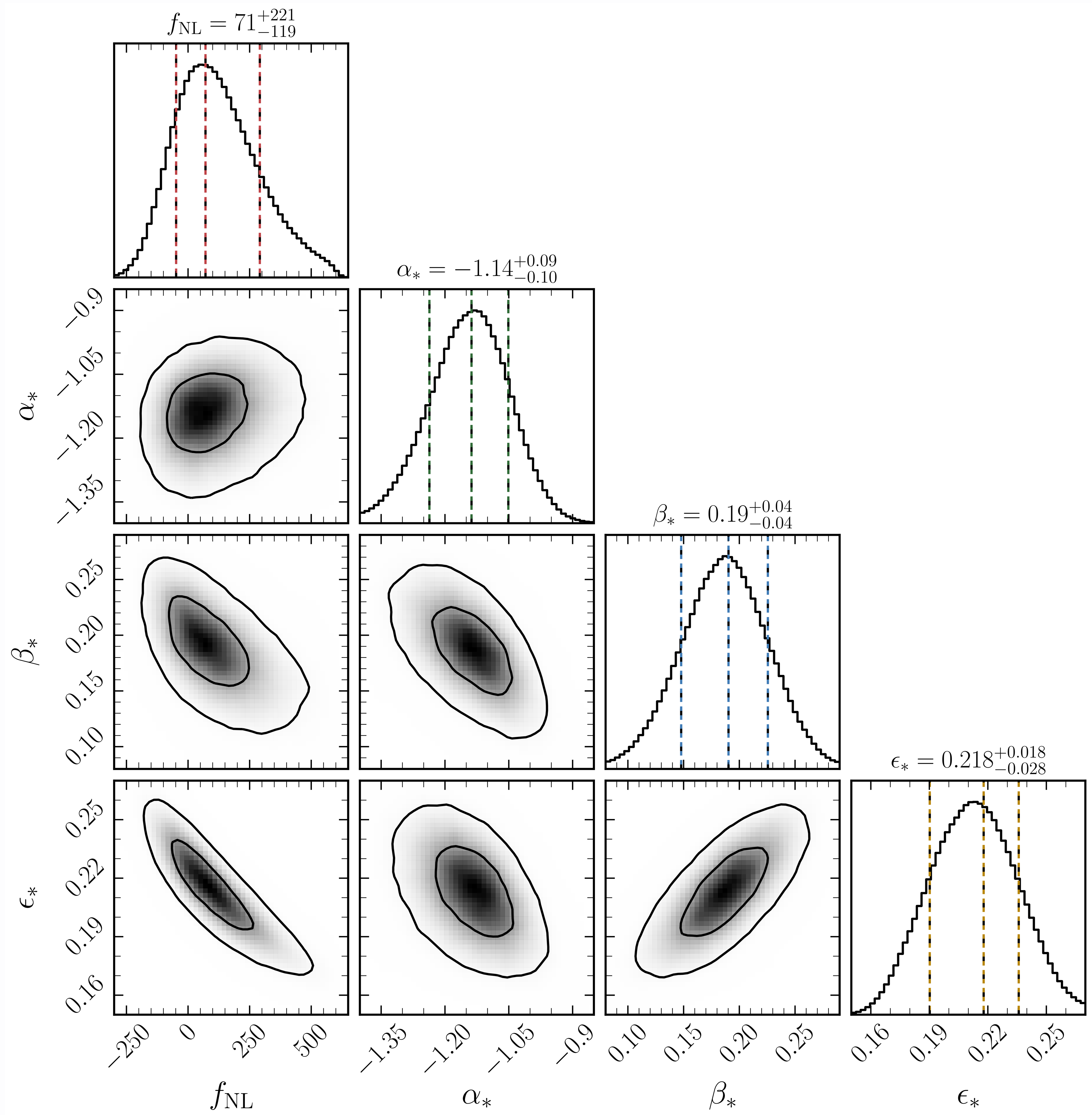

Figure 4. Posteriors for α_*, β_*, ϵ_* and $f_{\rm NL}$ using UV LF data from the HLF catalog and a cut-off scale in the 3-point correlation function of $k_{\rm cut} = 0.1\,{\rm Mpc}^{-1}$. The 2D contours depict the 1σ and 2σ confidence levels. The titles and vertical lines in the 1D posteriors represent the maximum-likelihood best fit (central line) and the $\pm1\sigma$ quantiles (outer lines).

7. Conclusions

In this work we have demonstrated the ability of UV luminosity functions to probe small-scale non-Gaussianity. This opens a window into the physics of the highest energies known, cosmic inflation.

We focused on non-Gaussianity manifested at scales smaller than those probed by the CMB and LSS, for which there are no other current bounds, cf. Figure 5. We have shown that constraints can already be obtained from HST observations. By using UV LF data from the Hubble Legacy Fields catalog, we have put bounds on the non-Gaussianity parameter $f_{\rm NL}$ and examined its robustness with regards to several assumptions in our analysis. We conclude that:

- Small-scale non-Gaussianity affects the UV luminosity function mostly at the bright end. While there are degeneracies between $f_{\rm NL}$ and some astrophysical parameters, these can be broken by combining data at different redshifts.
- Current observations of the UV luminosity function can provide robust bounds on small-scale non-Gaussianity. Our main analysis is performed by using UV LF data from the HLF catalog and assuming a cut-off scale in the 3-point correlation function of $0.1\,{\rm Mpc}^{-1}$. We obtain constraints on $f_{\rm NL}$ of 71^{+426}_{-237} at 2σ.
- The James Webb Space Telescope and cosmic-dawn 21-cm experiments can further improve upon these bounds by a factor $3-4$.

This work establishes the UV LF as a powerful probe of the fundamental processes that were at play in the early Universe. Upcoming cosmological surveys will offer an exciting possibility to unveil the origin of structures in our cosmos and in which process the UV LF will play a prominent role.

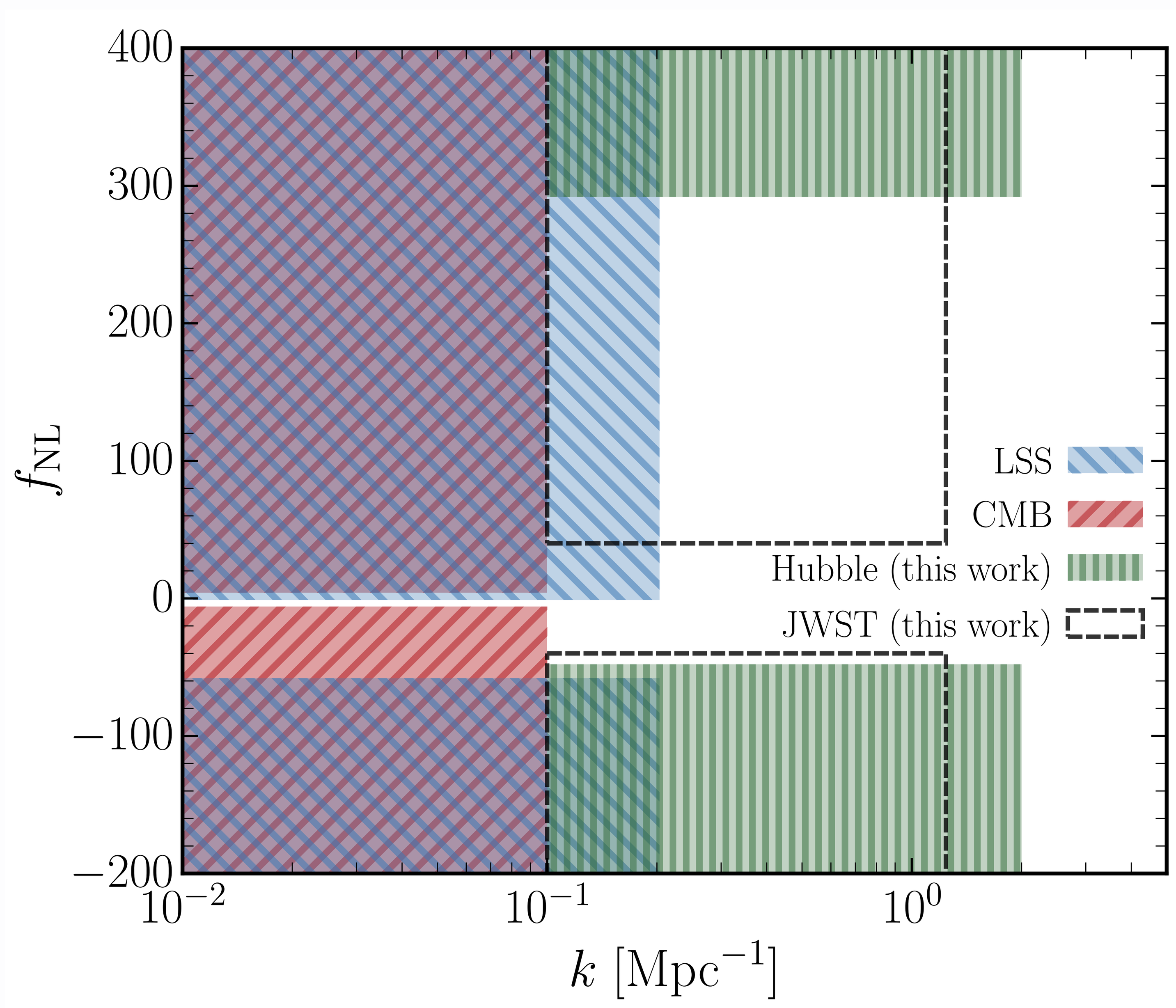

Figure 5. Illustration of the current 1σ constraints on $f_{\rm NL}$ as a function of comoving wavenumber k from LSS, CMB and LF observations, together with a forecast for JWST.