

Cosmology on Ultralarge Scales with Intensity Mapping of the Neutral Hydrogen 21 cm Emission: Limits on Primordial Non-Gaussianity

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The large-scale structure of the Universe supplies crucial information about the physical processes at play at early times. Unresolved maps of the intensity of 21 cm emission from neutral hydrogen HI at redshifts $z \approx 1-5$ are the best hope of accessing the ultralarge-scale information, directly related to the early Universe. A purpose-built HI intensity experiment may be used to detect the large scale effects of primordial non-Gaussianity, placing stringent bounds on different models of inflation. We argue that it may be possible to place tight constraints on the non-Gaussianity parameter f_{NL} , with an error close to $\sigma_{f_{\text{NL}}} \sim 1$.

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The statistical properties of large-scale structures are a rich source of information about the physics of the early Universe, its subsequent evolution, and its current state (e.g., Ref. [1]). Constraints on the ultralarge-scale properties of density perturbations at redshifts $z \approx 1-5$ can improve our understanding of the primordial Universe; these scales are, in principle, uncontaminated by the non-linear growth of structure or the poorly understood effects of baryons. Yet, such scales are also extremely difficult to access with conventional redshift or peculiar velocity surveys, while best attempts at using the cosmic microwave background are hampered by poor sampling, namely, cosmic variance.

An alternative approach for probing the density field of the large-scale structure has recently been advocated [2–5]. It involves mapping out the combined emission of the 21 cm, or HI, line from unresolved galaxies. In doing so, the large-scale structure is detected in three dimensions—a process which is usually referred to as “intensity mapping.” If one foregoes identifying individual galaxies, one can greatly speed up the observation and detection of the large-scale structure. Intensity mapping experiments are sensitive to structures at a redshift range that is observationally difficult to span for ground-based optical surveys [6]. Moreover, first attempts at mapping HI have been promising [7,8].

In this Letter we explore this method for constraining one particular aspect of current models of structure formation: the non-Gaussianity of primordial fluctuations, which may lead to scale dependent biasing and a distinctive signature on large scales. Furthermore, this approach can also be useful for probing general relativistic effects on these scales [9–13]. Non-Gaussian initial fluctuations can arise in different models of inflation [14]. A particularly convenient (albeit not universal) way to parametrize non-Gaussianity consists of writing the gauge-invariant Bardeen

potential Φ —corresponding to the Newtonian potential in longitudinal gauge—as the sum of a Gaussian random field ϕ and a quadratic correction [15,16], $\Phi = \phi + f_{\text{NL}} * (\phi^2 - \langle \phi^2 \rangle)$, where $*$ denotes convolution between functions, and reduces to standard multiplication when f_{NL} is a constant. Canonical single field inflation models predict $|f_{\text{NL}}| \sim \mathcal{O}(10^{-2})$ [14], while evolution after inflation can generate an $f_{\text{NL}} \sim \mathcal{O}(1)$ [16–18]. The method of excellence for constraining f_{NL} has been to measure higher order correlation functions of the cosmic microwave background leading to $|f_{\text{NL}}| \lesssim 10^3$ with the MAXIMA data [19], $|f_{\text{NL}}| \lesssim 10^2$ with the WMAP data [20], and now $|f_{\text{NL}}| \lesssim 10$ with the Planck data [21].

The non-Gaussian properties of initial fluctuations will also induce a scale and redshift dependence to a biased tracer X of the underlying matter distribution [22,23]. The modification $\Delta b_X(z, k)$ to the Gaussian large-scale bias b_X^G is such that $\Delta b_X(z, k) = 3[b_X^G(z) - 1]\Omega_m H_0^2 \delta_c / [c^2 k^2 T(k) D_+(z)] f_{\text{NL}}$. Here, $\Omega_m = \Omega_b + \Omega_{\text{DM}}$ is the total (baryons plus dark matter) matter fraction, H_0 is the Hubble constant, $\delta_c \approx 1.686$ is the critical collapse density contrast of matter, $T(k)$ is the matter transfer function versus the physical wave number k , and $D_+(z)$ is the linear growth factor of density perturbations. Attempts at detecting this effect with redshift surveys have led to some constraints on f_{NL} [24].

To assess how we might improve constraints on f_{NL} using scale dependent bias, let us first restrict ourselves to a simple, cosmic variance limited survey. If we divide up the power spectrum in bins with constant logarithmic width, $\Delta k_\alpha = A k_\alpha$, the number of modes per bin is given by $N_\alpha / V_{\text{eff}} = A k_\alpha^3 / (2\pi^2)$, where V_{eff} is the effective volume of the survey and α spans the number of bins N_{bins} . Then $\sigma_{f_{\text{NL}}}^2 \approx [b_X^G T(k_\alpha) D_+(z) c^2]^2 / \{[6(b_X^G - 1)\Omega_m H_0^2 \delta_c]^2 (\sum_\alpha N_\alpha k_\alpha^{-4})\}$, where $T(k)$ is assumed constant on these large scales. Two obvious features immediately stand out: (i) better

constraints on f_{NL} will be obtained for larger N_α (that is for larger and deeper surveys), but also (ii) the further away the bias b_X^G is from unity, the better. For fiducial values of the cosmological parameters and bias evolution, we find that $\sigma_{f_{\text{NL}}} \sim 1$ may only be achievable if the survey depth is greater than $z \sim 3.5$. Intensity mapping surveys seem ideally suited for this goal (for proposals for doing so in the epoch of reionization, see Refs. [25–29]).

When line-of-sight scattering and self-absorption phenomena are neglected, the HI line radiation discussed above can be related to the differential number counts of halo objects (e.g., Ref. [10]), from which we can estimate the HI bias b_{HI} [30]. The mean HI temperature from galaxies, assuming that the signal is seen in emission, is then $\bar{T}_b^g(z) \approx 566h[H_0/H(z)][\Omega_{\text{HI}}(z)/0.003](1+z)^2 \mu\text{K}$, where $H(z)$ is the Hubble parameter, whose present-day value is $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{HI}}(z) \equiv \rho_{\text{HI}}(z)/\rho_c$ is the comoving neutral hydrogen energy density in units of ρ_c , the critical density today.

If we assume that, after reionization, the neutral hydrogen is mostly contained within galaxies, we calculate ρ_{HI} by integrating the Sheth and Tormen mass function [31], assuming the HI mass to be proportional to the halo mass. Setting the minimum and maximum mass in the integration by using a cutoff for the circular velocity [32], we can fix the constant of proportionality with the constraint on $\Omega_{\text{HI}}(z) \times b_{\text{HI}}(z)$ from Ref. [8]. Finally, we have that $b_{\text{HI}}(z)$ is the appropriately weighted halo bias [31]. Thus, the HI clustering power spectrum takes the form $P^{\text{HI}}(k, z) = [\bar{T}_b^g(z)b_{\text{HI}}(k, z)]^2 P^\delta(k, z)$, with $P^\delta(k, z)$ the total matter power spectrum. The goal is then to target $P^{\text{HI}}(k, z)$. In Fig. 1, we plot $P^\delta(k, z)$ and $b_{\text{HI}}^2(z)P^\delta(k, z)$ for $|f_{\text{NL}}| = 10$ (in synchronous gauge). We see that HI structures at low redshifts are underbiased with respect to dark matter, while at earlier times neutral hydrogen is highly biased. Moreover, the non-Gaussian effects we are looking for only come into play on extremely large scales.

To tackle the problem of forecasting $\sigma_{f_{\text{NL}}}$ more carefully, it is appropriate to work with the Fourier-Bessel transform on the sky and the HI angular power spectrum $C_\ell^{\text{HI}}(\nu_i, \nu_j)$,

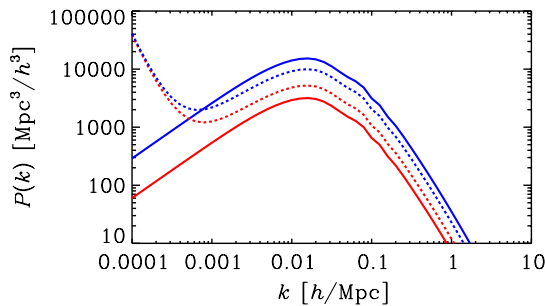


FIG. 1 (color online). $P^\delta(k, z)$ (solid lines) and $b_{\text{HI}}^2 P^\delta(k, z)$ (dashed lines) for $|f_{\text{NL}}| = 10$ at $z = 0.4$ (top blue pair) and $z = 2.5$ (bottom red pair).

where ν_i is the frequency of shell i . To calculate this quantity, we use the CAMB_sources code [10], and include the redshift space distortion but discard subdominant terms. Since, for an intensity mapping experiment, the frequency range can be (almost) arbitrarily small, the window function we adopt is thus a simple top-hat function. As a reference cosmology, we adopt a Λ CDM flat universe with cosmological parameters $\Omega_m = 0.28$, $\Omega_b = 0.045$, Hubble constant $h = 0.7$ in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, spectral index of the primordial power spectrum $n_s = 0.96$, normalization of the present-day power spectrum $\sigma_8 = 0.8$, and $f_{\text{NL}} = 0$.

With these definitions in hand, we can proceed to perform a Fisher matrix analysis [33,34]. Thus, the marginal error $\sigma_{f_{\text{NL}}}$ obeys

$$\frac{1}{\sigma_{f_{\text{NL}}}} = \sqrt{\sum_{\ell=\ell_{\text{min}}}^{\ell_{\text{max}}} (2\ell+1) f_{\text{sky}} \frac{\partial [C_\ell^{\text{HI}}]_{ij}}{\partial f_{\text{NL}}} [\Gamma_\ell^{\text{HI}}]_{ij, mn}^{-1} \frac{\partial [C_\ell^{\text{HI}}]_{mn}}{\partial f_{\text{NL}}}},$$

where $[C_\ell^{\text{HI}}]_{ij}$ is a shorthand notation for $C_\ell^{\text{HI}}(\nu_i, \nu_j)$, and $[\Gamma_\ell^{\text{HI}}]_{ij, mn} = [C_\ell^{\text{HI}} + \mathcal{N}_\ell^{\text{HI}}]_{im} [C_\ell^{\text{HI}} + \mathcal{N}_\ell^{\text{HI}}]_{jn} + [C_\ell^{\text{HI}} + \mathcal{N}_\ell^{\text{HI}}]_{in} [C_\ell^{\text{HI}} + \mathcal{N}_\ell^{\text{HI}}]_{jm}$ is the covariance of the signal, given $\mathcal{N}_\ell^{\text{HI}}$ the angular power spectrum of experimental noise (shot noise is assumed to be negligible). In this analysis we are focusing on f_{NL} as the single parameter, a valid approximation on ultralarge scales.

Again, let us first focus on a zero-noise experiment. In the top panel of Fig. 2, we show how $\sigma_{f_{\text{NL}}}$ changes with frequency range, for $\ell_{\text{max}} = 60$ (red diamonds) and 300 (blue squares). Each point in the panel refers to the central redshift of a 200 MHz band with bin width $\Delta\nu = 10 \text{ MHz}$. As we saw before, it is essential for the bias to move away from 1 (usually at $z \sim 1$) in order to obtain strong constraints. Moreover, it is the volume of the survey that

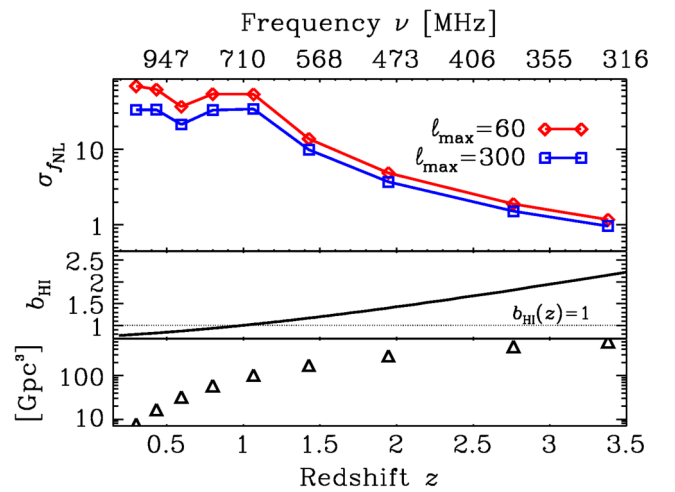


FIG. 2 (color online). Top panel: Forecasted 68.3% error on f_{NL} as a function of the mean redshift (or frequency) with a frequency interval of $\Delta\nu = 200 \text{ MHz}$. Middle panel: Redshift dependence of the bias. Bottom panel: Effective volume of the survey.

probe frequencies between 50 and 1420 MHz, but with only 30 dishes and a system temperature above 100 K, it will make it hard to go into the cosmic variance dominated regime. In terms of designing a new system from scratch, something like 10 000 small dishes between 2 and 4 m diameter, working at ~ 400 MHz, would be a good (and cheap) possibility to target the $f_{\text{NL}} \sim 1$ region (note that we are not requiring cross correlations between the dishes, thus making the system much simpler). This would provide an efficient experiment to probe the dark matter power spectrum out to $z \sim 4$ on ultralarge scales.

For interferometric surveys, none of the planned telescopes above are compact enough to deliver the required sensitivity on large scales. This means we would need in principle to wait for SKA phase 2, with the proposed “aperture array” system working below 1 GHz. Although the design is not set yet, it should be possible to achieve FOV ~ 1000 deg², thus reaching the $\sigma_{f_{\text{NL}}} \lesssim 1$ limit. However, SKA phase 2 is designed to achieve much higher angular resolution than what is needed for our purposes, and a smaller array with 80 m or less in diameter would be an interesting, near term, alternative, capable of reaching $\sigma_{f_{\text{NL}}} \sim 1$.

While we have outlined a simple forecasting procedure, there are two effects which must be taken into consideration if we were to lay out the specific experimental design and survey strategy. The signature we seek kicks in on scales where general relativistic and gauge effects become non-negligible. Furthermore, we have assumed that we have efficiently subtracted the foreground (i.e., our Galaxy) from the data set. We acknowledge this is an open question but, in principle, should be achievable—the Galaxy contributes a slowly varying frequency dependent signal along each line of sight, which can be accurately removed with enough radial bins to map out the small-scale structure. Indeed, foreground cleaning should be done using the largest available bandwidths (~ 1 GHz), while our signal analysis will be done using smaller bandwidths. We see in Fig. 2 that ~ 200 MHz can be enough as long as we are probing high redshifts. Nevertheless, a detailed and realistic analysis of how the foreground subtraction will affect our forecast must be undertaken.

We have shown the strength and weaknesses of HI surveys to efficiently constrain f_{NL} . More generally, our analysis gives us an idea of how effective HI surveys are at probing the ultralarge scales of the cosmos and, in doing so, telling us more about exotic aspects of our current cosmological models.

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