Local Primordial Non-Gaussianity from Large-Scale Galaxy Surveys

Charuhas Shiveshwarkar[1]

September 25, 2024

[1]Work in collaboration with Marilena Loverde, Thejs Brinckmann, Drew Jamieson, and Matt McQuinn

ΛCDM Cosmology

- On the largest scales, the expanding universe is *spatially flat* as well as *homogeneous* and *isotropic* on the largest scales.

- Expansion driven primarily by Cosmological Constant (70%) and Cold Dark Matter (25%)

$$\left(\frac{\dot{a}}{a}\right) \propto (\bar{\rho}_{\Lambda} + \bar{\rho}_{cdm} + \bar{\rho}_{b} + \bar{\rho}_{rad}) \quad , \quad H = \left(\frac{\dot{a}}{a}\right) \approx 70 \text{ km/s/Mpc}$$

- How did departures from large-scale homogeneity (aka *structure*) come about ?? (Cosmic Inflation)

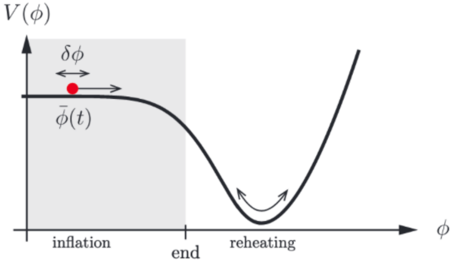
Cosmic Inflation

- Early phase of accelerated, near-exponential expansion – $a(t) \sim \exp Ht$ – explains large-scale homogeneity
- Quantum fluctuations in inflationary era $\rightarrow$ primordial density/curvature fluctuations (ζ) $\rightarrow$ *structure* at late times.
- Nearly Gaussian, nearly scale-invariant fluctuations

$$\langle |\zeta_k|^2 \rangle \propto \frac{1}{k^3} \left(\frac{k}{k_p} \right)^{n_s - 1} \quad ; \quad n_s \sim 0.96 \quad ; \quad \frac{\langle \zeta^n \rangle}{\langle \zeta^2 \rangle^{n/2}} \ll 1 \; (n \geq 3)$$

What do we know/don't know about the Inflationary Universe?

- Current observations favour *single-field*, *slow-roll* picture :



Credit: arXiv:0907.5424

- No meaningful insight into any possible, additional contents of the universe or their interactions.

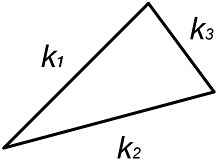
- Need *model-dependent* observables – like Primordial Non-Gaussianity (PnG).

Primordial Non-Gaussianity (PnG)

- Higher-point correlation functions of ζ can probe the microphysics of inflation

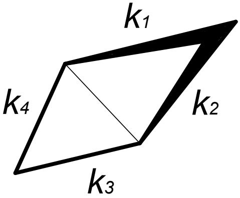
- Bispectrum :

$$\langle \zeta(\vec{k_1})\zeta(\vec{k_2})\zeta(\vec{k_3})\rangle' = B_\zeta(k_1, k_2, k_3) \equiv$$



- Trispectrum :

$$\langle \zeta(\vec{k_1})\zeta(\vec{k_2})\zeta(\vec{k_3})\zeta(\vec{k_4})\rangle' = T_\zeta(\vec{k_1}, \vec{k_2}, \vec{k_3}, \vec{k_4}) \equiv$$

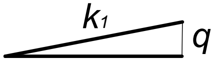


- Different shapes of B_ζ, T_ζ map on to different features of inflationary models and can be probes using cosmological surveys

Local Primordial Non-Gaussianity (LPnG)

- Non-trivial soft limits of correlation functions parametrised by $f_{NL}, \ g_{NL}$, etc.

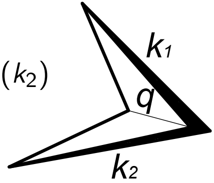
$$B_\zeta(q \to 0, k_1, k_2) \propto f_{NL} P_\zeta(k_1) P_\zeta(q)$$



- Distinguishing feature of at least one additional light (m≪H) field during inflation. (Meerburg et al. 2019; Achúcarro et al. 2022)

- Boosted collapsed limit(s) :

$$\lim_{q \to 0} \frac{T_\zeta(\vec{k_1}, \vec{q} - \vec{k_1}, -\vec{q} + \vec{k_2}, -\vec{k_2})}{P_\zeta(q)} \propto \tau_{NL} P_\zeta(k_1) P_\zeta(k_2)$$



- $f_{NL} \sim 1$ is an important theoretical target for observations.

Measuring LPnG

- CMB constraints from Planck (Aghanim et al. 2020)

  $$f_{NL} = -0.9 \pm 5.1 \;\; ; \;\; g_{NL} = (-5.8 \pm 6.5) \times 10^4 \;\; ; \;\; \tau_{NL} < 2800 \; (95\%)$$

  Not tight enough to constrain $f_{NL} \sim 1$; improvement limited by cosmic-variance.

- Large Scale Structure (LSS) constraints are, as yet, systematics dominated.

  BOSS (Cabass et al. 2022) $\rightarrow$ $f_{NL} = -33 \pm 28$

- Significantly higher potential for improvement – with improved systematic control in large-scale, high-redshift galaxy surveys.

Galaxy Surveys

- Measure statistical properties of galaxy clustering
- Power Spectrum :

$$\langle \delta_g(k_1)\delta_g(k_2)\rangle' = P_g(k_1)$$

- Bispectrum :

$$\langle \delta_g(k_1)\delta_g(k_2)\delta_g(k_3)\rangle' = B_g(k_1, k_2, k_3)$$

- Model observables using galaxy bias expansion :

$$\delta_g(k, z) = b_g(k, z)\delta_m(k, z) + ...$$

LPnG and Scale dependent bias

- Signature of LPnG on galaxy bias (Dalal et al. 2008) :

$$\Delta b_{NG} \propto \beta_f \frac{f_{NL}}{k^2}$$

  Can only have a primordial origin.

- Observable signal dominates at largest scales – more constraining than the bispectrum

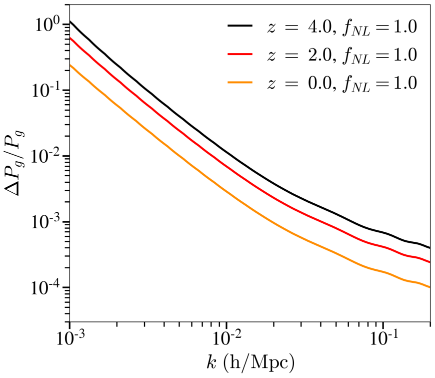
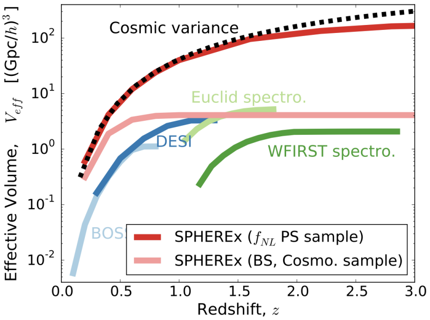


Figure: Fractional change in the galaxy power spectrum due to local $f_{NL} = 1$.

LPnG from Galaxy surveys



Credit: Doré et al. 2014

Figure: Effective volume probed by SPHEREx

- Large-scale, high-redshift surveys with improved systematic control could detect $f_{NL} \sim 1$
- Forecast constraints : $\sigma(f_{NL}) \approx 0.9$ (PS), $\sigma(f_{NL}) \approx 0.5$ (PS+BS)
- $\sim$ 90% constraining power from *linear* scales, i.e. $k \lesssim 0.02$ h/Mpc

Modelling Challenges/Theoretical Systematics

With improved control over observational systematics, LPnG constraints will be limited by modelling challenges and theoretical uncertainties :

- Post-inflationary, horizon-scale effects :
  - Effect of free-streaming light relics
  - Effect of ionising radiation fluctuations.
- Degeneracy w.r.t. higher-order LPnG parameters (like g_{NL}, τ_{NL}, etc.)

Effect of free-streaming light relics

- Scale-dependent galaxy bias due to free-streaming light relics :

$$\frac{b_g(k)}{b_g(k_{\rm max})} \rightarrow \text{const.} < 1.; \;\; k \rightarrow 0$$

- Can *negatively* bias f_{NL}
- For realistic neutrino masses, $|\Delta f_{NL}| \lesssim 0.2$

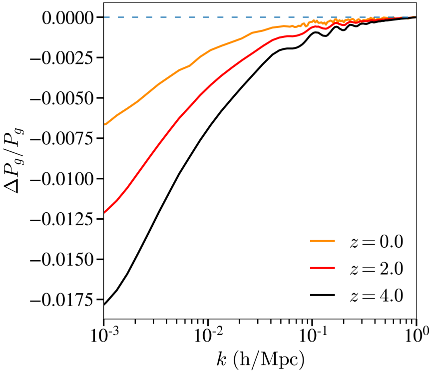


Figure: Fractional change in the galaxy power spectrum due to neutrino free-streaming. $M_\nu = 3 \times 0.02$ eV

Effect of Ionising Radiation Fluctuations

$$\delta_g = b_g \delta_m - b_J \delta_J$$

$$P_g = P_{mm} \left(b_g - b_J \frac{P_{mJ}}{P_{mm}} \right)^2 + b_J^2 P_{Jshot}$$

- $b_J \lesssim 0.1$ and P_{Jshot} is negligible for reasonable quasar lifetimes. (Sanderbeck et al. 2019)
- More important at higher redshifts

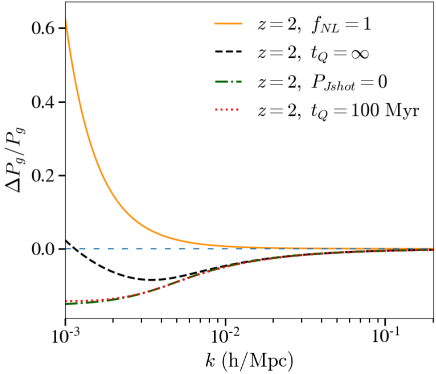
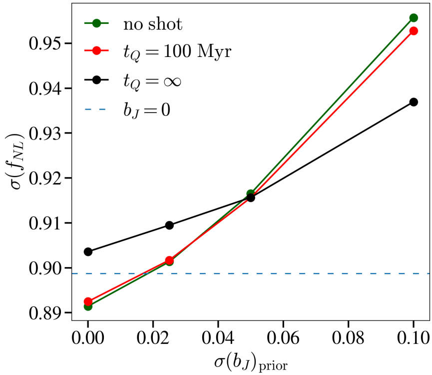
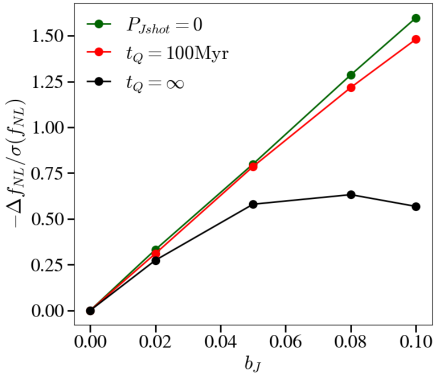


Figure: Effect of $b_J = 0.05$ in comparison to the effect of $f_{NL} = 1$ at $z = 2$

Effect of ionising radiation fluctuations on f_{NL} constraints





With appropriate priors,
$\Delta\sigma(f_{NL}) \approx 0$

$\Delta f_{NL} \approx -0.8\sigma$ for $b_J = 0.05$ and realistic quasar lifetime.

Larger effect for high-redshift surveys

Beyond f_{NL} : f_{NL} and g_{NL}

Scale-dependent bias is a combined measure of f_{NL}, g_{NL}, etc.

$$\Delta b_{NG} \propto \frac{f_{NL}\beta_f + g_{NL}\beta_g + ..}{k^2}$$

Degraded constraint (SPHEREx forecast)

$$\sigma(f_{NL}) \sim \sigma(10^{-4} g_{NL}) \sim 2.5$$

$\mathrm{Cov}(f_{NL}, g_{NL}) \sim -0.9.$

Need to model $\beta_f(z)$ and $\beta_g(z)$!

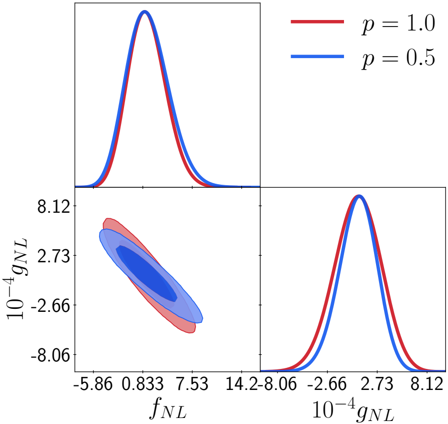
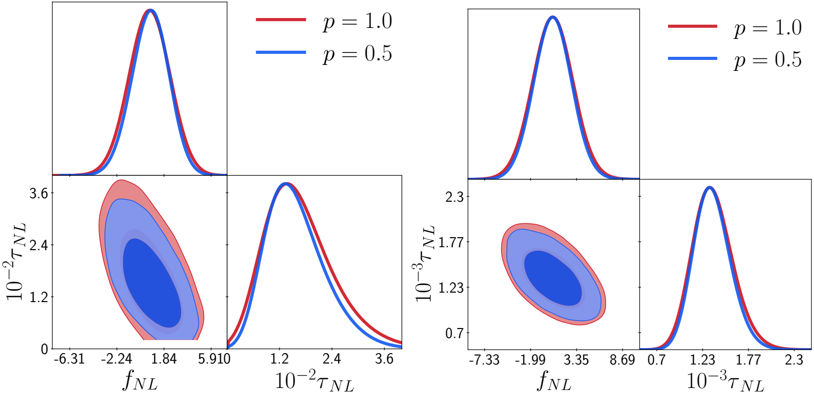


Figure: Joint SPHEREx power spectrum forecasts for two modelling choices $p = 1$ and $p = 0.5$.

Beyond f_{NL} : f_{NL} and τ_{NL}



(a) Fiducial $f_{NL} = 1.0$ and fiducial $\tau_{NL} = 1.3 \times 10^2$

(b) Fiducial $f_{NL} = 1.0$ and fiducial $\tau_{NL} = 1.3 \times 10^3$

p	$\sigma(f_{NL})$	$\sigma(\tau_{NL})$
1.0	1.79	0.78×10^2
0.5	1.64	0.67×10^2

(a) Fiducial $f_{NL} = 1.0$ and fiducial $\tau_{NL} = 1.3 \times 10^2$

p	$\sigma(f_{NL})$	$\sigma(\tau_{NL})$
1.0	2.42	0.24×10^3
0.5	2.22	0.21×10^3

(b) Fiducial $f_{NL} = 1.0$ and fiducial $\tau_{NL} = 1.3 \times 10^3$

Table: Joint MCMC forecast for f_{NL} and τ_{NL} obtained from the SPHEREx multitracer likelihood. For each fiducial value of τ_{NL}, we consider two example values of $p = 1$ and $p = 0.5$

Covariance between f_{NL} and τ_{NL} remains ~ -0.6 : less degenerate than f_{NL} and g_{NL}.

Can potentially constrain τ_{NL} tightly at the expense of f_{NL}.