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Primordial Trispectrum from kSZ Tomography*

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[Motivation] Inflation & PNG Basics

Primordial Potential: $\Phi = \underline{\underline{\phi}} + f_{\rm NL}\phi^2$

Inflaton (Gaussian)

- Primordial potential is non-Gaussian → non-zero 3-point correlation function

$$f_{NL} \propto \frac{1}{4} \lim_{k_1 \to 0} \xi^{(3)}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$$

- Planck 2018: $f_{\rm NL} = -0.9 \pm 5.1$ [1]
- Galaxy Clustering (BOSS): $f_{\rm NL} = -33 \pm 28$ [2]
- LSS + kSZ based forecast: Münchmeyer et al. [3]

[1] Y. Akrami et al. (2020) [1905.06697]; [2] G. Cabass et al. (2022) [2204.01781]; [3] Münchmeyer et al. (2018) [1810.13424]

[Motivation] Multifield Inflation:

Primordial Potential: $\Phi = \phi + \underline{\psi} + f_{\rm NL}(1+\underline{\Pi})^2[\psi^2 - \langle\psi^2\rangle]$[1]

Additional Gaussian Field (Curvaton)

$\Pi \equiv \frac{P_\phi}{P_\psi}$

- Non –zero 3- & 4- point correlation functions:

$$f_{NL} \propto \frac{1}{4}\lim_{k_1\to 0}\xi^{(3)}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) \qquad \left(\frac{5}{6}\right)^2 \underline{\tau_{NL}} \propto \frac{1}{8}\lim_{k_{12}\to 0}\xi^{(4)}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3,\boldsymbol{k}_4)$$

$$\tau_{NL} \equiv \left(\frac{6}{5}f_{\rm NL}\right)^2(1+\Pi)$$

- Planck 2018: $\tau_{\rm NL} = (-5.8 \pm 6.5)\times 10^4$[2]
- LSS based (multi-tracer) forecast: Ferraro & Smith[3]

[1] Tseliakhovich et al. (2010) [1004.3302]; [2] Y. Akrami et al. (2020) [1905.06697]; [3] Ferraro & Smith (2014) [1408.3126]

[Motivation] Larger Picture

Primordial Potential: $\Phi = \phi + \psi + f_{\rm NL}(1+\Pi)^2[\psi^2 - \langle\psi^2\rangle]$ [1]

$$\tau_{NL} \equiv \left(\frac{6}{5} f_{\rm NL}\right)^2 (1+\Pi)$$

Model Distinguishability:

⇢ Larger allowed non-Gaussianity: $f_{\rm NL} \gtrsim 1$ or enhanced $\tau_{\rm NL}$ [1, 2]

⇢ Multi-field parameter:

$$r_{\rm NL} = (5/6)^2 \tau_{\rm NL} - f_{\rm NL}^2$$

[1] Tseliakhovich et al. (2010) [1004.3302]; [2] Lyth et al. (2002) [astro-ph/0208055]

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[Measurement] Basic Methodology

$$\delta_m(\boldsymbol{k}, z) = \alpha(k, z)\Phi(\boldsymbol{k}) \quad \text{where} \quad \alpha(k,z) = \frac{2k^2T(k)G(z)}{3\Omega_m H_0^2}$$

δ_m → Matter Overdensity Field

1. Method 1: Measure bispectrum/ trispectrum of $\delta_m(\boldsymbol{k}, z)$
   ⇢ Convoluted by gravity-induced non-linearities
   ⇢ Is there a way to rely only on power spectrum measurements?

2. Method 2: Scale Dependent Bias Measurement![1]
   ⇢ Halos are a biased tracer of matter → PNG causes bias relation depend on *k*
   ⇢ Only measure power spectra of halo and matter distributions!

[1] N. Dalal et al. (2008) [0710.4560]

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[Measurement] Scale Dependent Bias

Gaussian Φ: $\delta_h(\boldsymbol{k}, z) = b_h(z)\delta_m(\boldsymbol{k}, z) \Rightarrow P_{hh}(k, z) = b_h^2(z) P_{mm}(k, z)$

Non-Gaussian Φ: $P_{hh}(k, z) = b_1(k, z) P_{mm}(k, z)$

Bias relation parametrized by $\{f_{\rm NL}, \tau_{\rm NL}\}$

Note the scale dependence

Method 2: Scale Dependent Bias Measurement (Galaxy Data)

⇢ Use galaxy survey data to obtain $P_{hh}(k)$ & fit to bias parametrization

⇢ Signal most dominant on large scales   Sample Variance Limited!

Method 2.5: Scale Dependent Bias (Multi-Tracer) Measurement [2, 1]

⇢ Galaxy Data + kSZ Tomography

[1] Ferraro & Smith (2014) [1408.3126] ; [2] U. Seljak (2008) [0807.1770]

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[Measurement] kSZ Tomography

What is kSZ Tomography?

- kSZ Effect: Scattering of CMB photons off bulk motion of free e^-
- As a function of z : Cross-correlate CMB map with Galaxy density field[1]
- Allows for large scale reconstruction of radial velocity field [1]

$$v_r(\boldsymbol{k}, z) = \mu \frac{faH}{k} \delta_m(\boldsymbol{k}, z)$$

- Noise in reconstructed matter over-density field [2]

$$N_{mm}^{\text{rec}} \propto \mu^{-2} \left(\frac{k}{faH} \right)^2 \qquad \text{as } k \to 0$$

[1] Deutsch et al. (2018) [1707.08129] ; [2] K. Smith et al. (2018) [1810.13423]

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[Measurement] Scale Dependent Bias

Method 2.5: Scale Dependent Bias Measurement (Galaxy Data + kSZ Tomography)

- Galaxy Survey Data: $P_{hh}(k)$
- kSZ Tomography data: $P_{vv}(k)$ ⟶ $P_{vv}(k) = \left(\frac{faH}{k}\right)^2 P_{mm}(k)$
- Two independent tracers of matter

$$P_{hh}(k) = \underline{\underline{b_1}}(k) P_{mm}(k) \qquad P_{vh}(k) = \left(\frac{faH}{k}\right) \underline{\underline{b_2}}(k) P_{mm}(k)$$

Both biases parametrized in terms of $\{f_{\rm NL}, \tau_{\rm NL}\}$

Sample Variance Cancellation!

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[Forecast] Bias & Noise Models

Signal:

$$P_{hh}(k) = \left[{b_h}^2 + 2 b_h \beta_f \frac{f_{\rm NL}}{\alpha(k)} + \beta_f^2 \frac{\left(\frac{5}{6}\right)^2 \tau_{\rm NL}}{\alpha^2(k)} \right] P_{mm}(k)$$

$$P_{vh}(k) = \frac{b_v f a H}{k} \left[b_h + \beta_f \frac{f_{\rm NL}}{\alpha(k)} \right] P_{mm}(k) \quad \text{where}$$

$$\alpha(k, z) = \frac{2k^2 T(k) G(z)}{3\Omega_m H_0^2}$$

$$\beta_f = 2\delta_c (b_h - 1)^*$$

Noise: ⇢ N_{hh}: Shot noise + photo-z errors

⇢ N_{vv}: Based on bispectrum model in Smith et al.[1]

Includes photo-z errors

[*] May need a different approach, see A. Barreira (2022) [2205.05673]; [2] K. Smith et al. (2018) [1810.13423]

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[Forecast] Experiment Specifications

- Assumed Redshift (z) = 1.0
- Photo-z errors only included for DESI
- Parameter values chosen to match Münchmeyer et al. [1]

		LSST + CMB S4	DESI + SO
survey volume	V	100 Gpc^3	100 Gpc^3
halo bias	b_h	1.6	1.6
galaxy density	n_{gal}	10^{-2} Mpc^{-3}	2×10^{-4} Mpc^{-3}
photo-z error	σ_z	0.06	-

[1] M. Münchmeyer et al. (2018)

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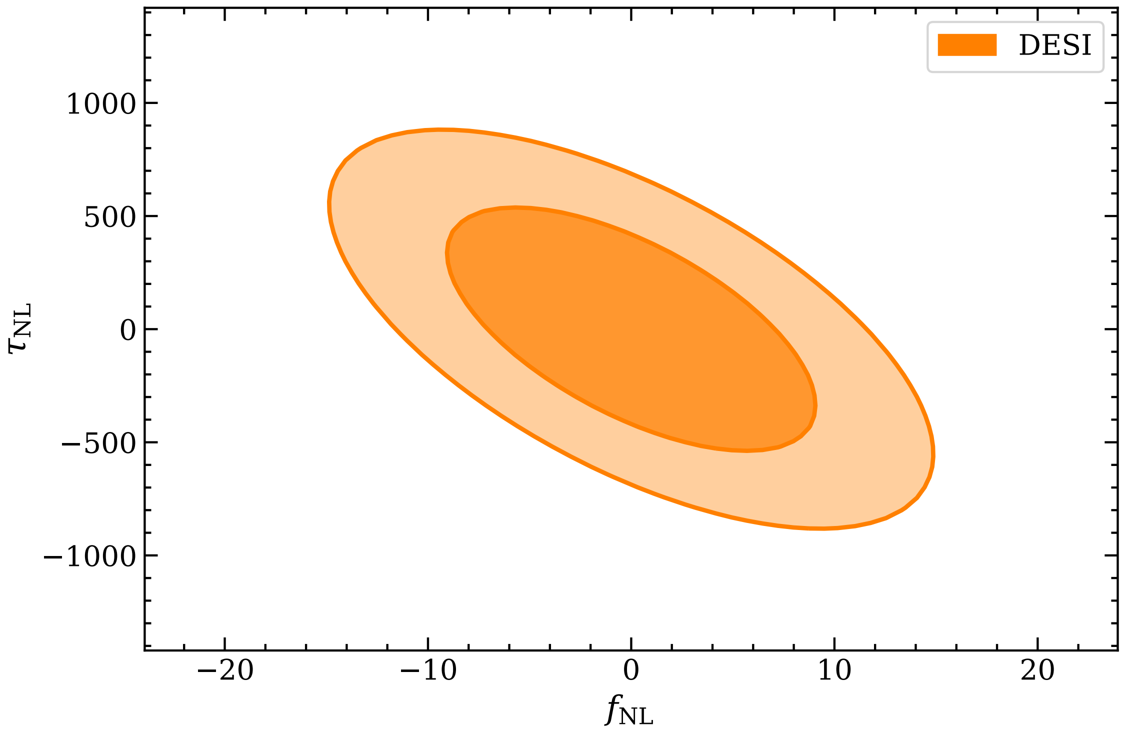
[Forecast] Results

DESI + SO

Galaxy

$$\sigma_{f_{\rm NL}} \approx 6.0$$

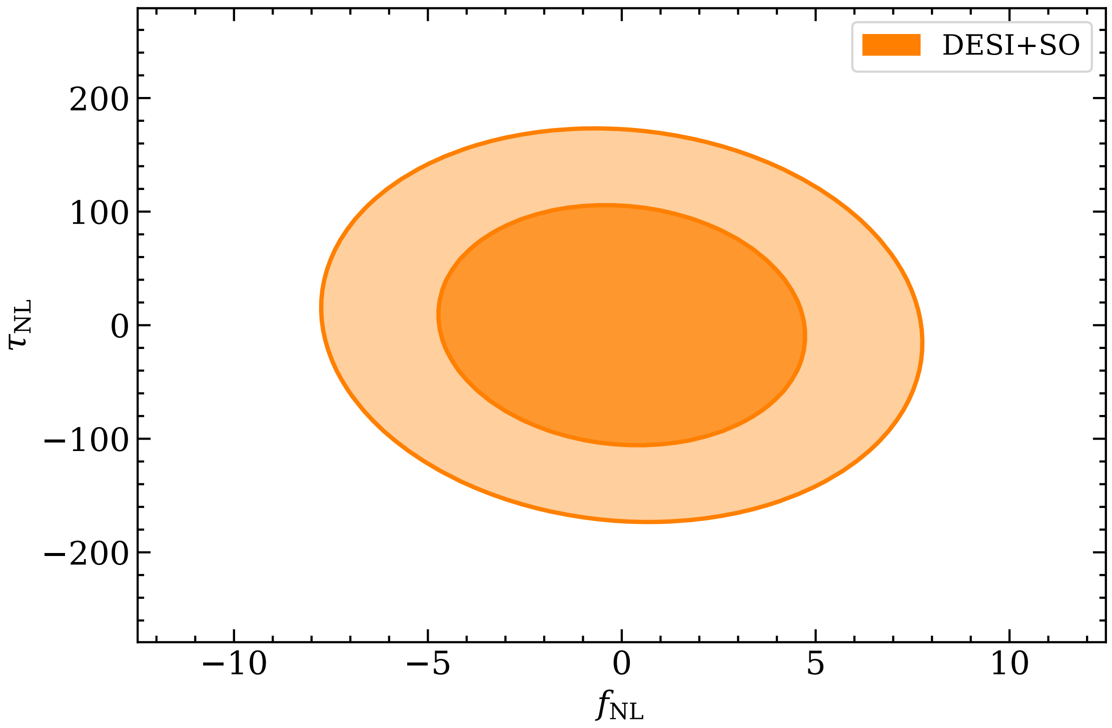
$$\sigma_{\tau_{\rm NL}} \approx 3.6 \times 10^2$$



Galaxy + kSZ

$$\sigma_{f_{\rm NL}} \approx 3.1$$

$$\sigma_{\tau_{\rm NL}} \approx 6.9 \times 10^1$$



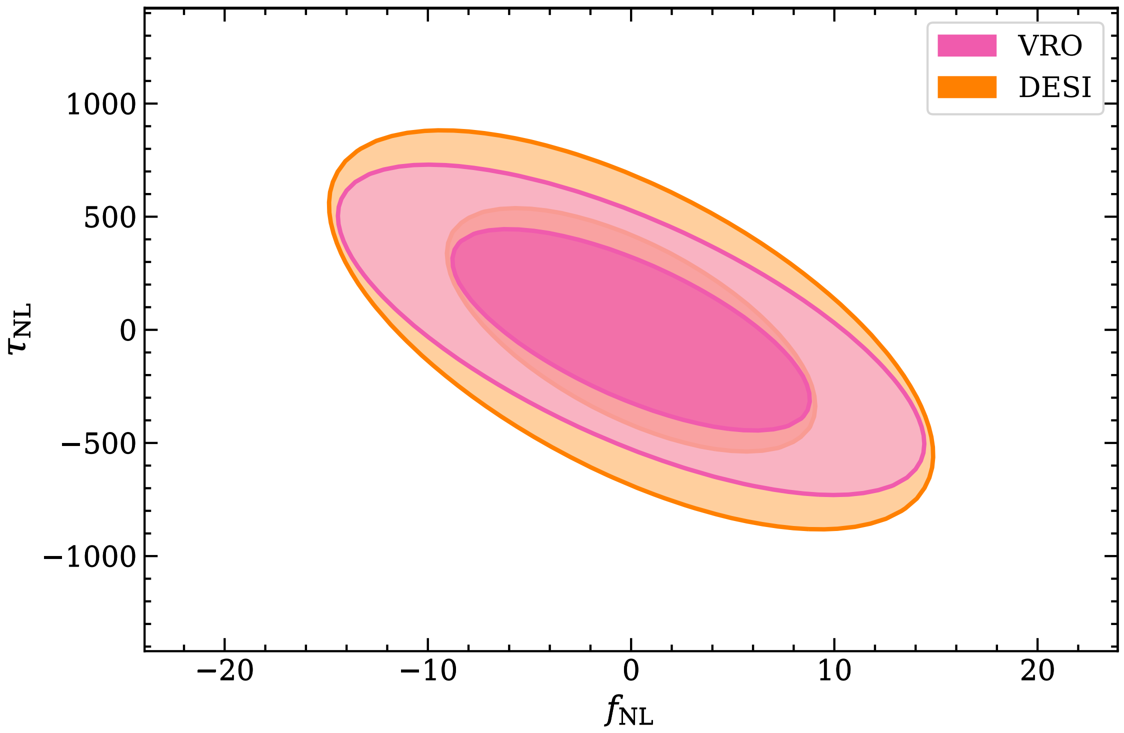
[Forecast] Results

LSST + CMB S4

Galaxy

$$\sigma_{f_{\rm NL}} \approx 5.8$$

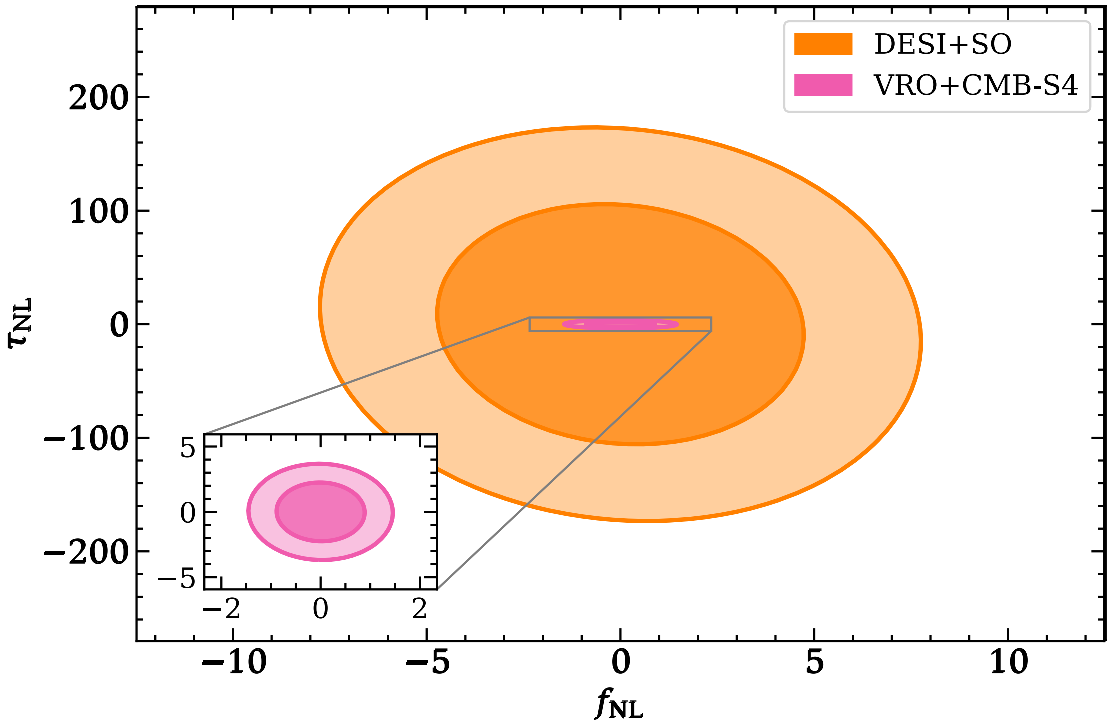
$$\sigma_{\tau_{\rm NL}} \approx 2.9 \times 10^2$$



Galaxy + kSZ

$$\sigma_{f_{\rm NL}} \approx 5.9 \times 10^{-1}$$

$$\sigma_{\tau_{\rm NL}} \approx 1.5$$



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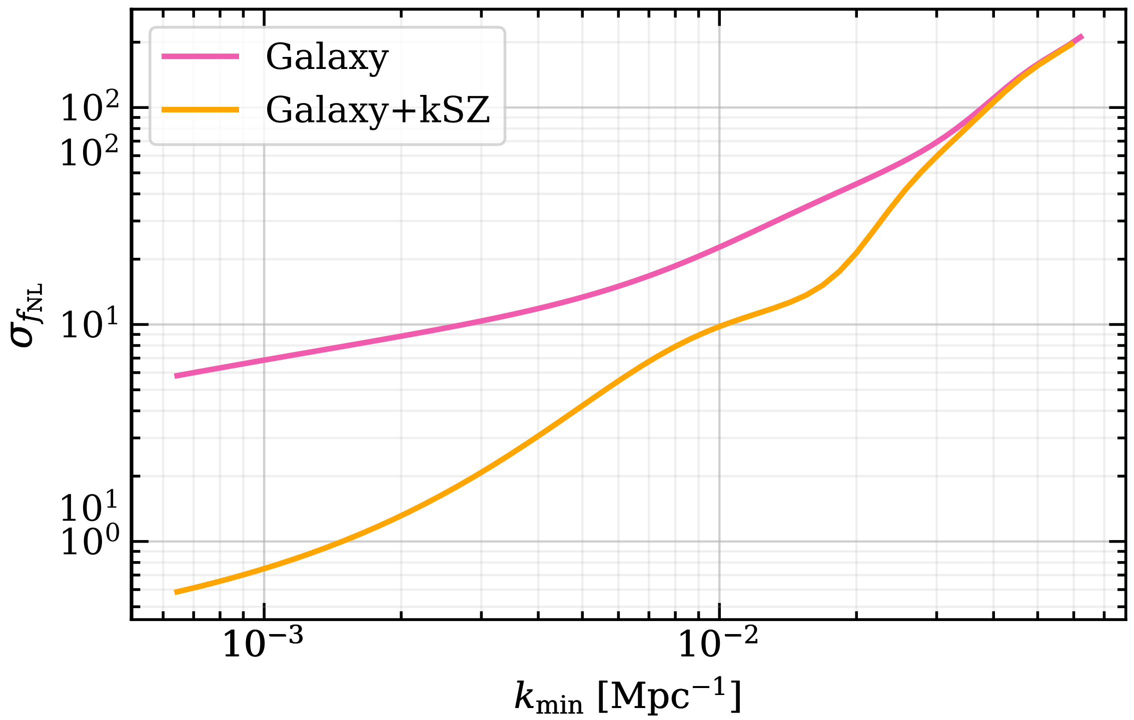
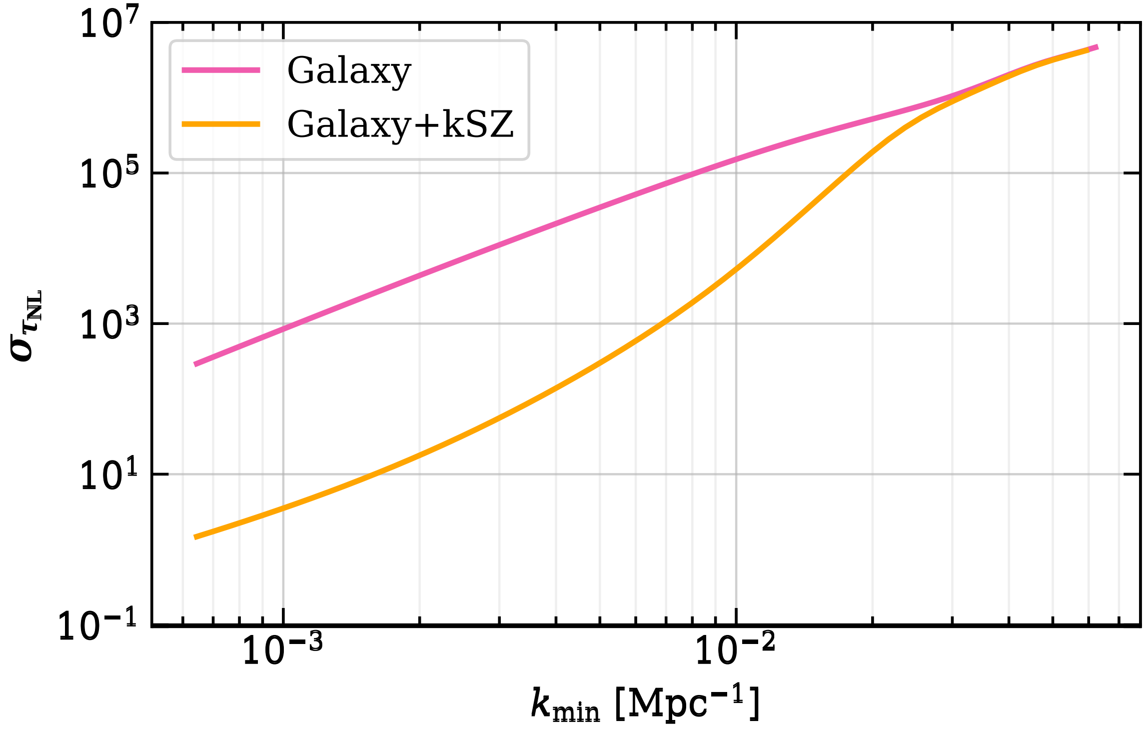
[Forecast] Results (LSST + CMB S4)





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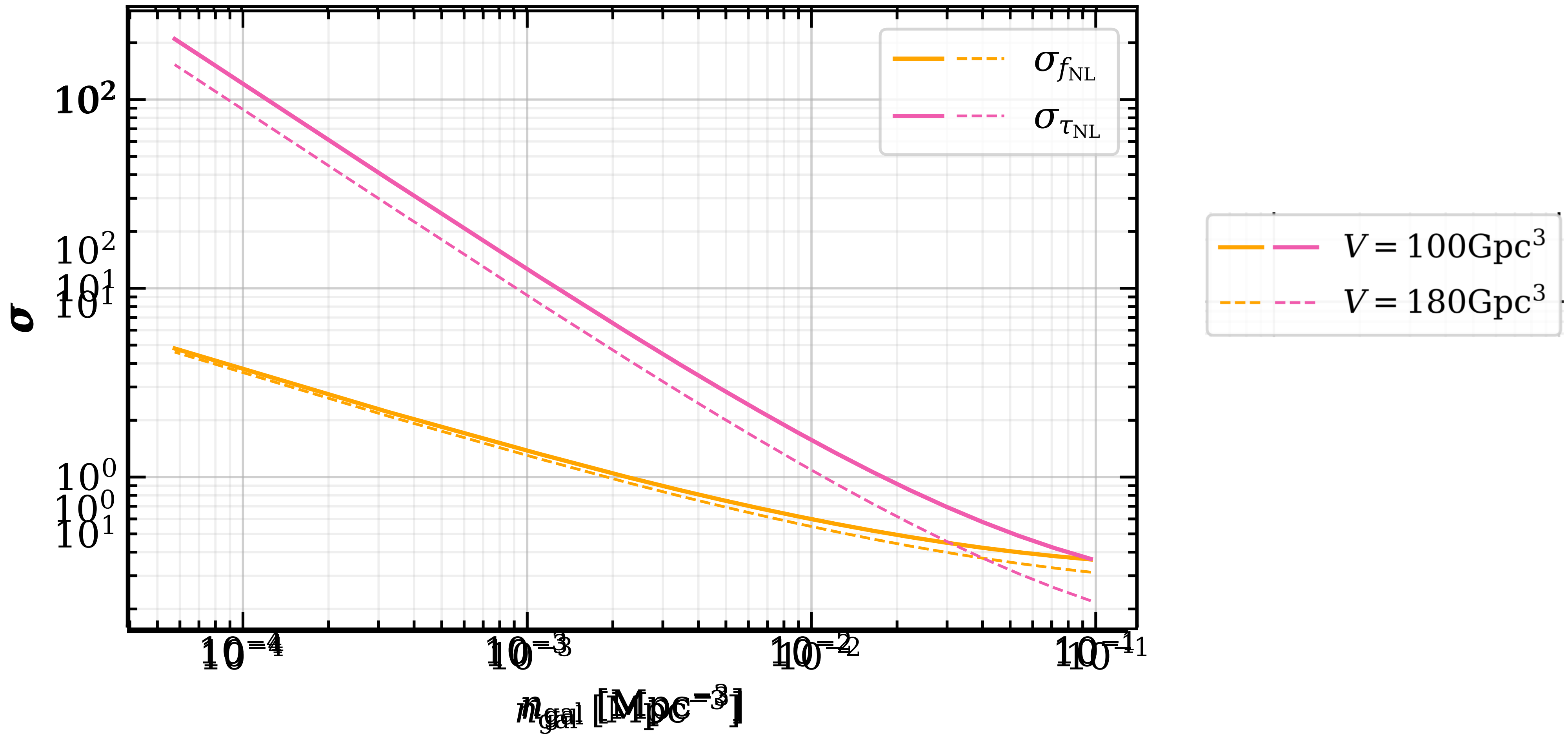
[Forecast] Results (LSST + CMB S4)

Galaxy + kSZ



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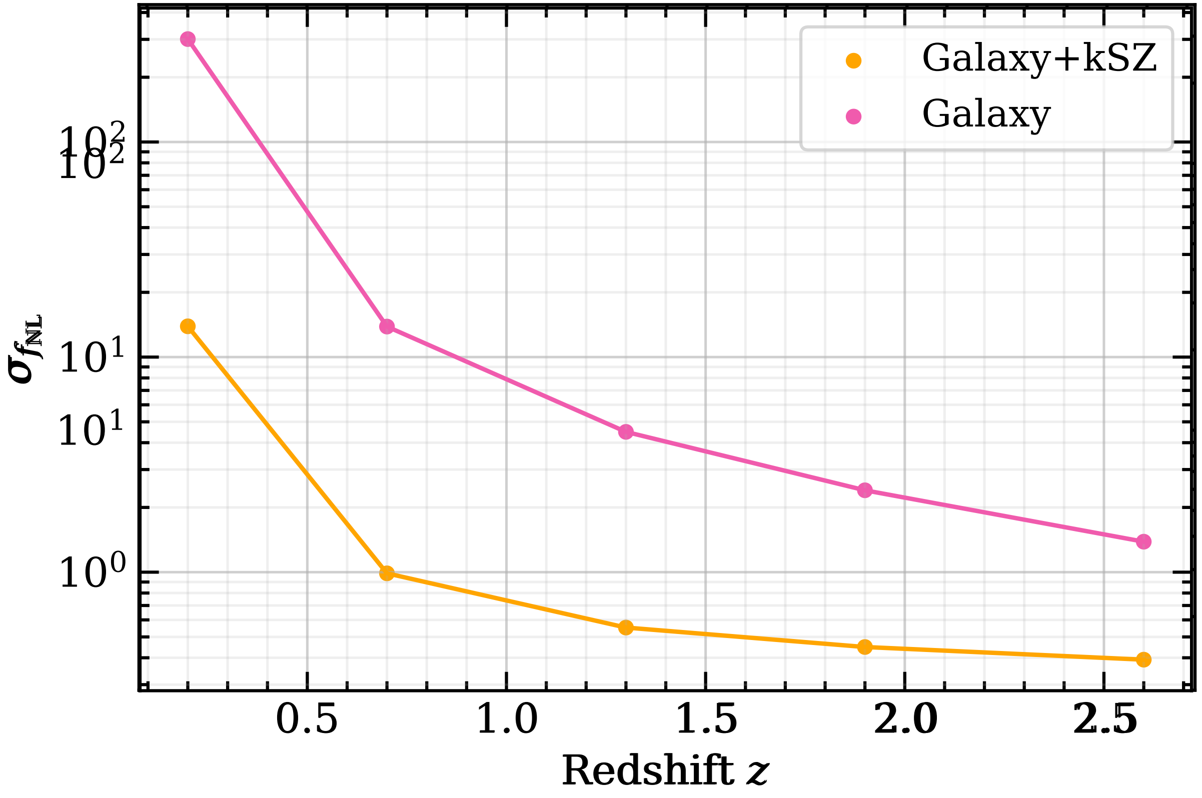
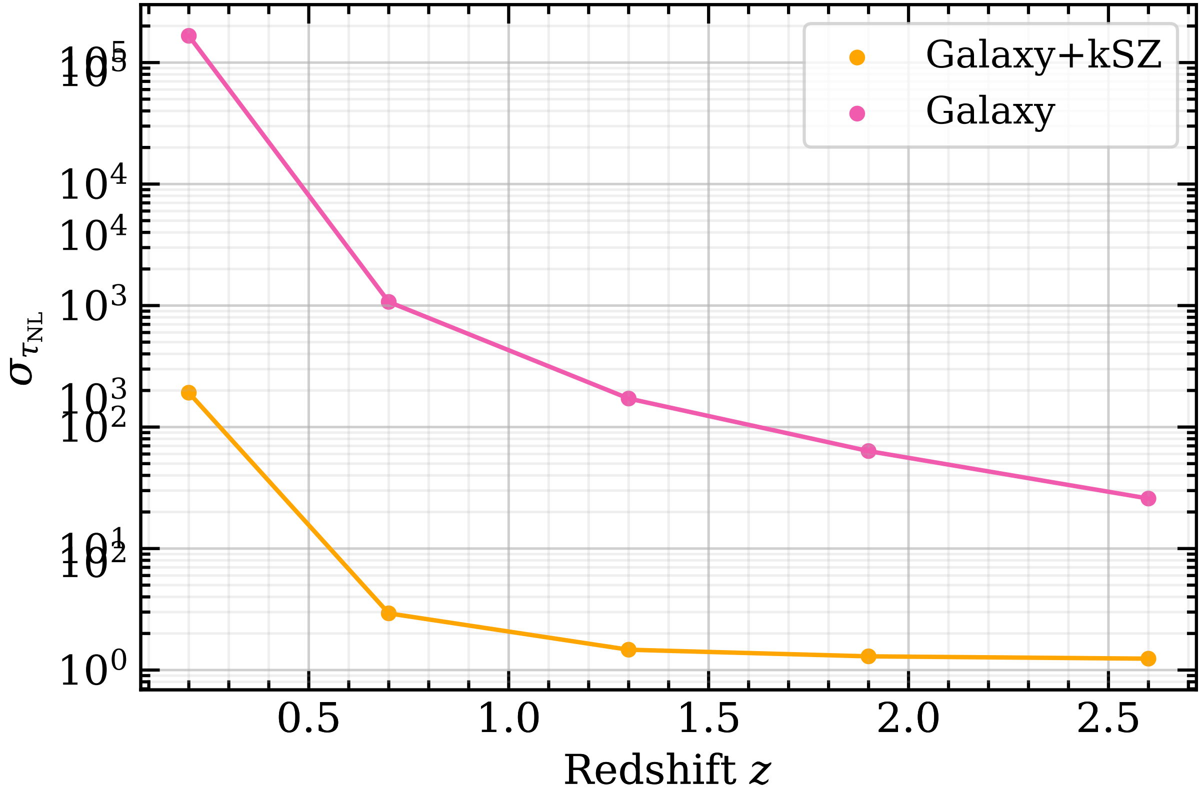
[Forecast] Results (LSST + CMB S4)





Redshift Binning Specifications taken from Table II of M. Münchmeyer et al. (2018)

Future Direction

1. Key Takeaway: Addition of kSZ data hugely improves constraints on some primordial physics parameters

⇢ Maybe we can attempt to constrain other characteristics : Uncorrelated CIP ?

2. Implications of having an independent tracer of $\delta_m(k,z)$

⇢ Estimator construction via mode-by-mode comparison → CIP!

⇢ Not cosmic variance limited → only limited by measurement errors [1]

$$\widehat{A} = b_{\rm cip}^2 \sigma_{\widehat{A}}^2 \sum_{\vec{k}} \frac{\left|\widehat{\delta_{g,\vec{k}}} - b_g \widehat{\delta_{m,\vec{k}}}\right|^2 / F(k)}{2\left[P_{\Delta\Delta}^N(\vec{k})/F(k)\right]^2}$$

[1] **Anil Kumar et al.** (2022) [2208.02829]

Appendices

* arXiv: 2205.03423

[Forecast] Bias Models

What happens when we eliminate the assumption $\beta_f = 2\delta_c(b_h - 1)$?

Signal:

$$\boldsymbol{P_{hh}(k)} = \left[b_h^2 + 2 b_h \frac{\beta_f \times f_{\rm NL}}{\alpha(k)} + \left(\frac{5}{6}\right)^2 \frac{\beta_f^2 \tau_{\rm NL}}{\alpha^2(k)} \right] P_{mm}(k)$$

$$\boldsymbol{P_{vh}(k)} = \frac{b_v f a H}{k} \left[b_h + \frac{\beta_f \times f_{\rm NL}}{\alpha(k)} \right] P_{mm}(k) \quad \text{where} \quad \alpha(k, z) = \frac{2k^2 T(k) G(z)}{3\Omega_m H_0^2}$$

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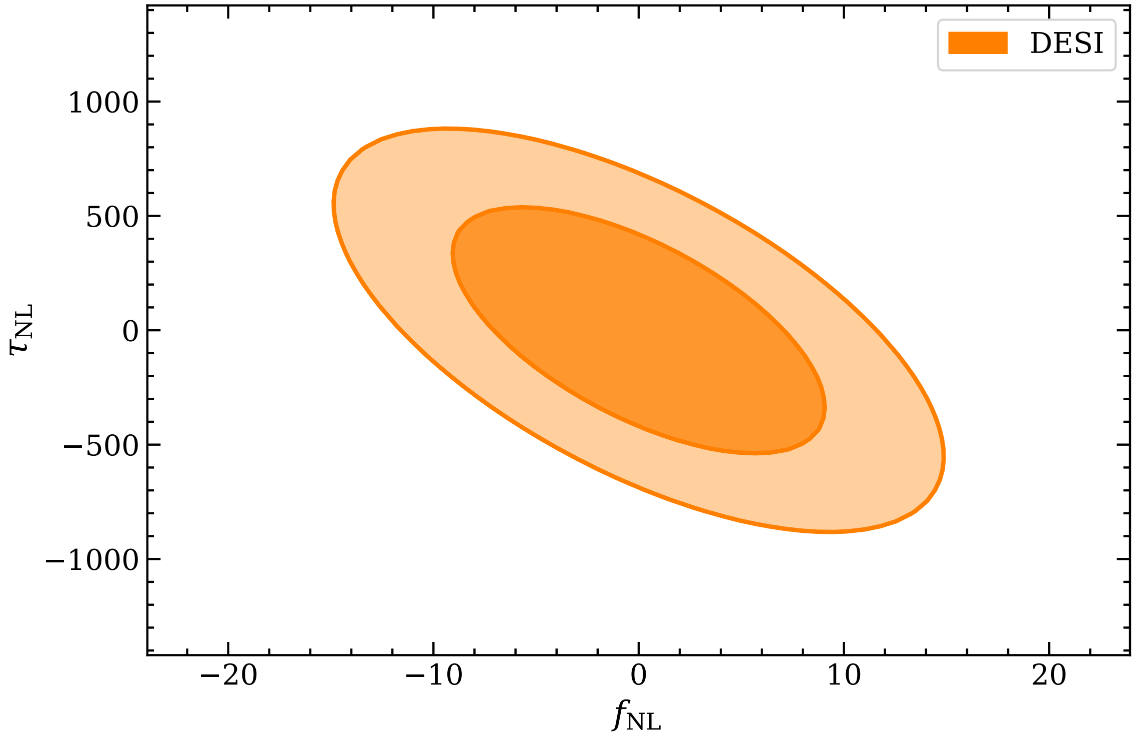
[Forecast] Results

DESI + SO

Galaxy

$$\sigma_{\beta_f \times f_{\rm NL}} \approx 12$$

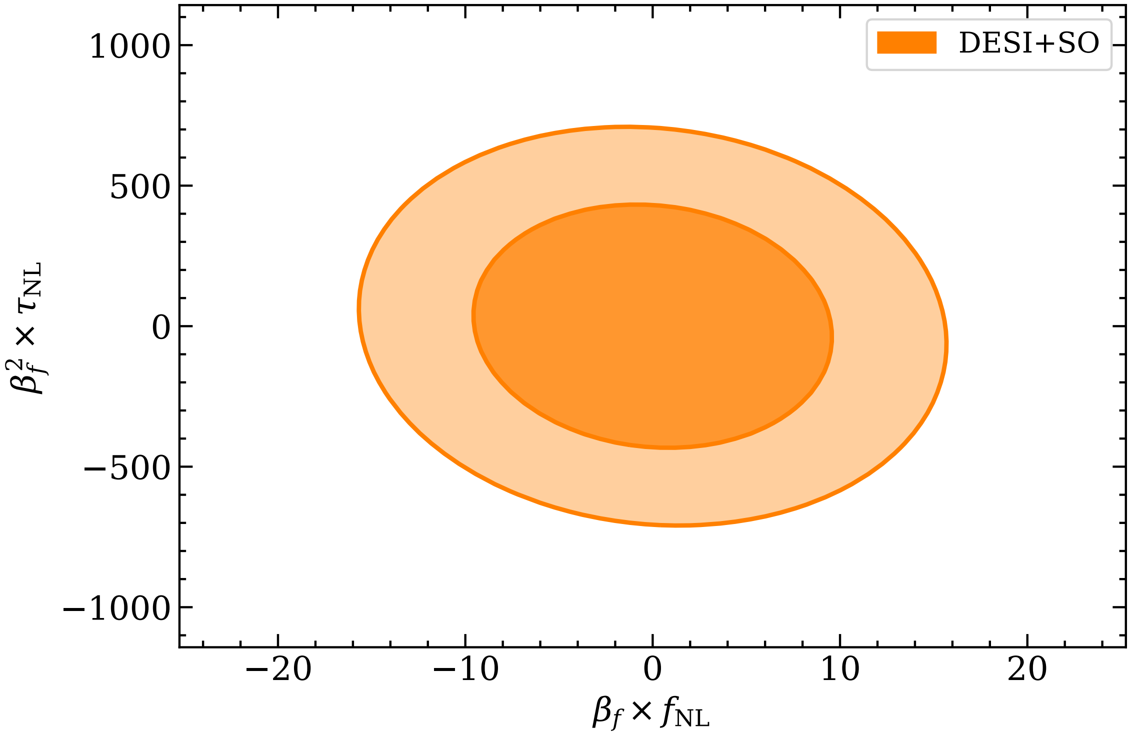
$$\sigma_{\beta_f^2 \times \tau_{\rm NL}} \approx 1500$$



Galaxy + kSZ

$$\sigma_{\beta_f \times f_{\rm NL}} \approx 6.3$$

$$\sigma_{\beta_f^2 \times \tau_{\rm NL}} \approx 290$$



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[Forecast] Results

LSST + CMB S4

Galaxy

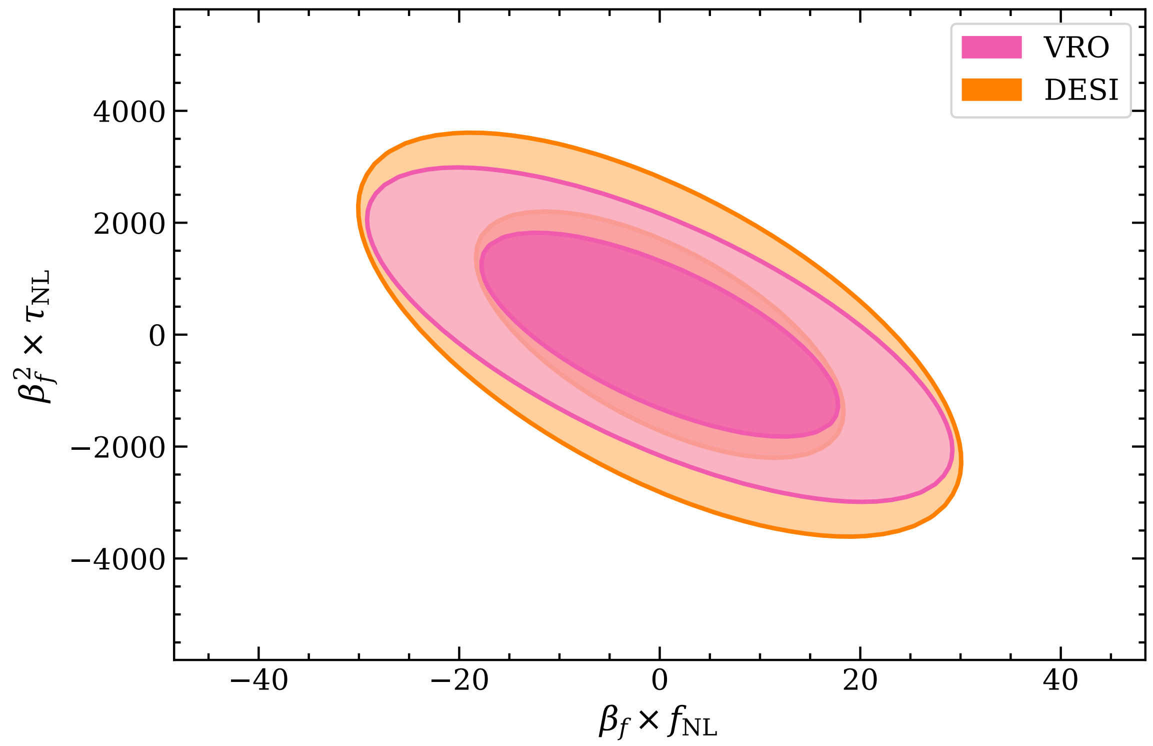
$$\sigma_{\beta_f \times f_{\rm NL}} \approx 11$$

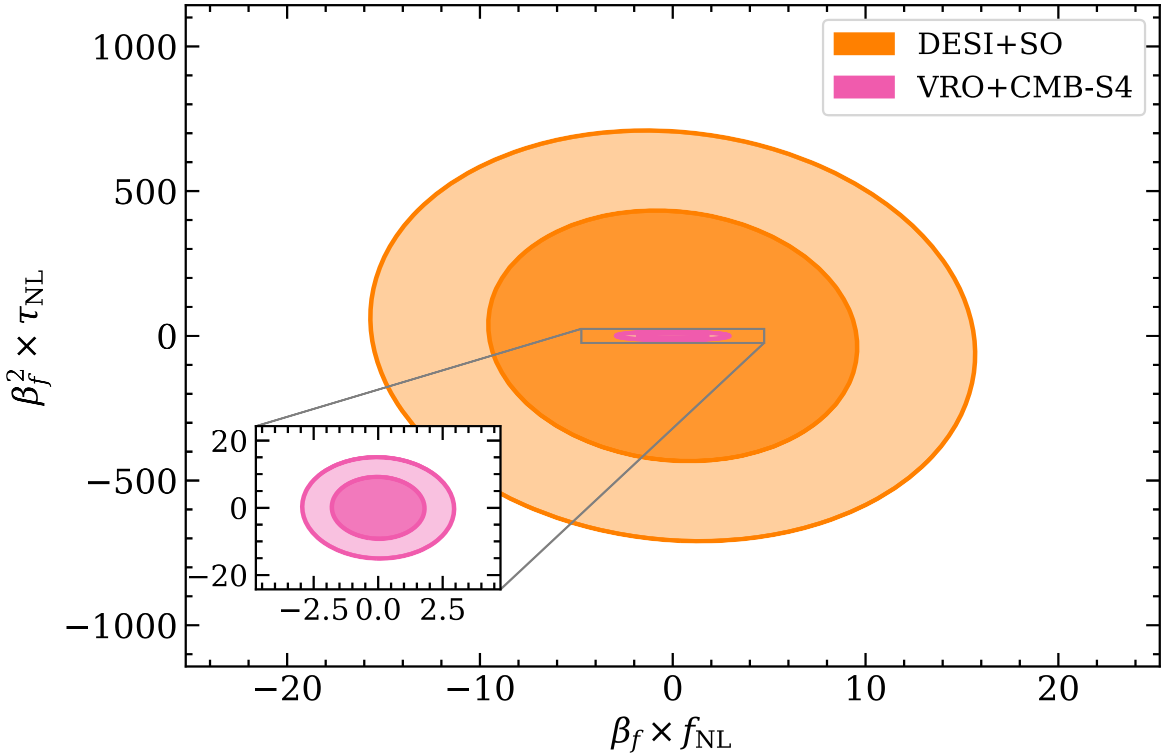
$$\sigma_{\beta_f^2 \times \tau_{\rm NL}} \approx 1200$$

Galaxy + kSZ

$$\sigma_{\beta_f \times f_{\rm NL}} \approx 1.2$$

$$\sigma_{\beta_f^2 \times \tau_{\rm NL}} \approx 6.1$$





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[Forecast] Experiment Specifications

		LSST + CMB S4	DESI + SO
redshift	z	1.0	1.0
survey volume	V	100 Gpc^3	100 Gpc^3
halo bias	b_h	1.6	1.6
galaxy density	$n_{\rm gal}$	10^{-2} Mpc^{-3}	2×10^{-4} Mpc^{-3}
photo-z error	σ_z	0.06	-
CMB resolution	$\theta_{\rm FWHM}$	1.5 arcmin	1.5 arcmin
CMB sensitivity	s	1 μK - arcmin	5 μK - arcmin

Parameter values chosen to match Münchmeyer et al. [1]

[1] M. Münchmeyer et al. (2018)

* arXiv: 2205.03423

[Forecast] Forecast Results

		LSST + CMB S4	DESI + SO
$f_{\rm NL}$ error	$\sigma^{\rm gal}_{f_{\rm NL}}$	5.8	6.0
	$\sigma^{\rm gal+kSZ}_{f_{\rm NL}}$	5.9×10^{-1}	3.1
$\tau_{\rm NL}$ error	$\sigma^{\rm gal}_{\tau_{\rm NL}}$	$2.9\times10^{+2}$	$3.6\times10^{+2}$
	$\sigma^{\rm gal+kSZ}_{\tau_{\rm NL}}$	1.5	$6.9\times10^{+1}$
$r_{\rm NL}$ error	$\sigma^{\rm gal}_{r_{\rm NL}}$	$2.0\times10^{+2}$	$2.5\times10^{+2}$
	$\sigma^{\rm gal+kSZ}_{r_{\rm NL}}$	1.0	$4.8\times10^{+1}$

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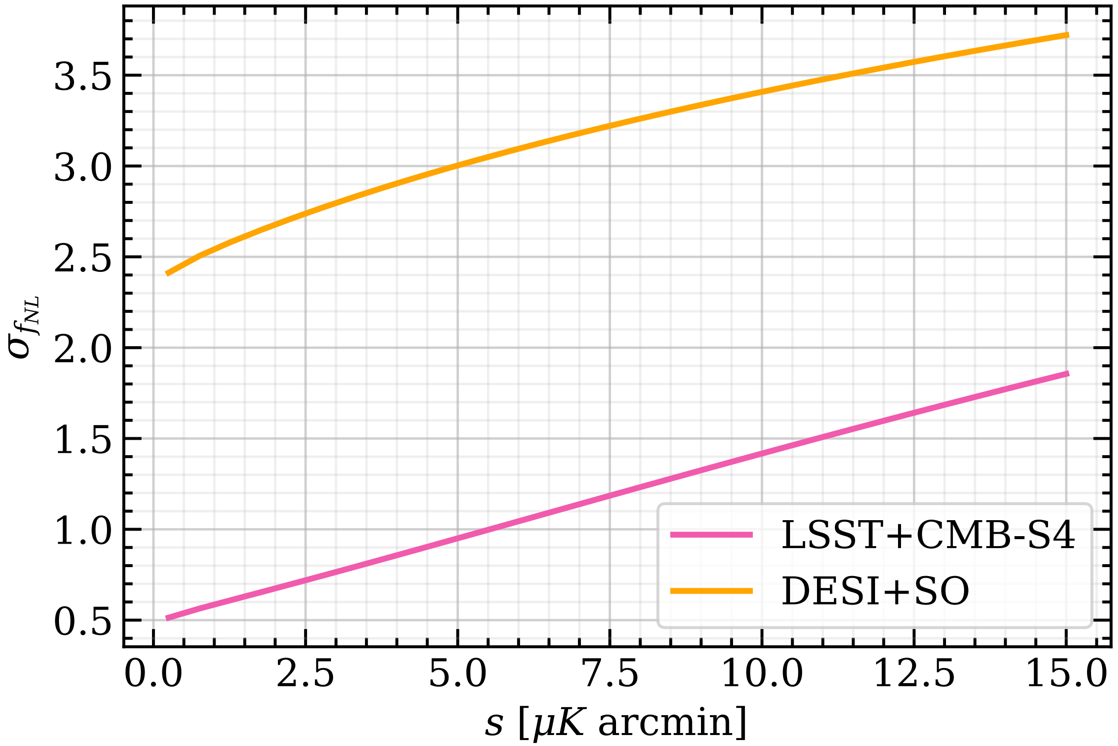
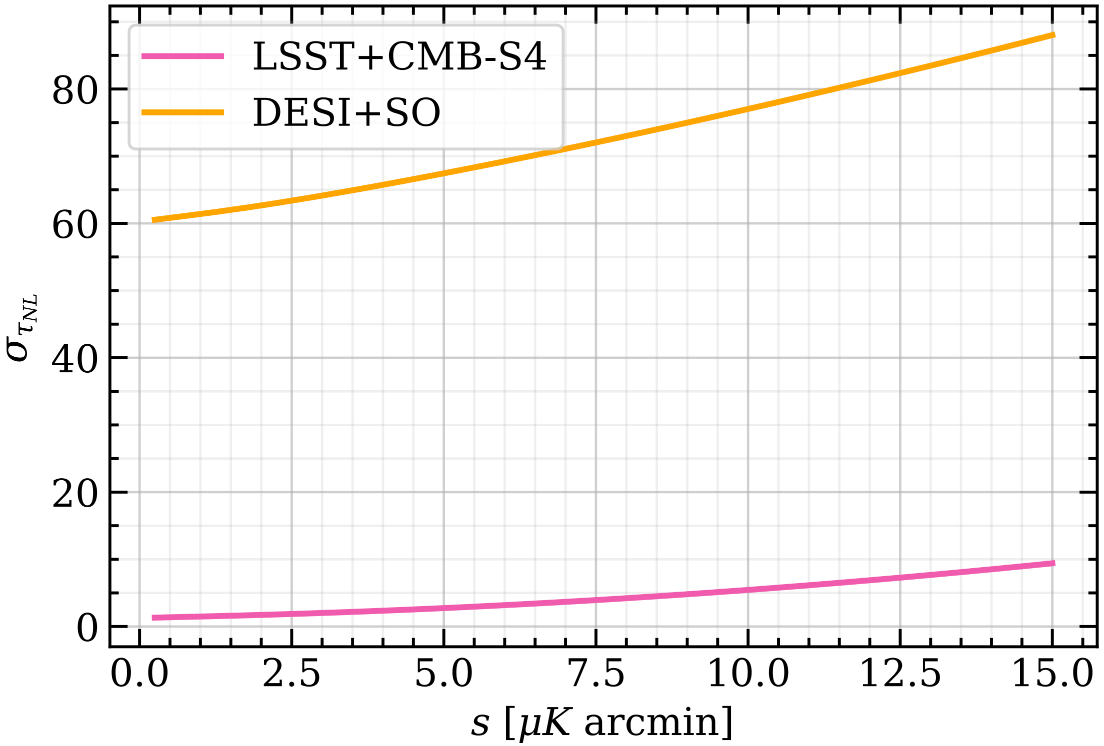
[Forecast] Results (CMB Sensitivity)





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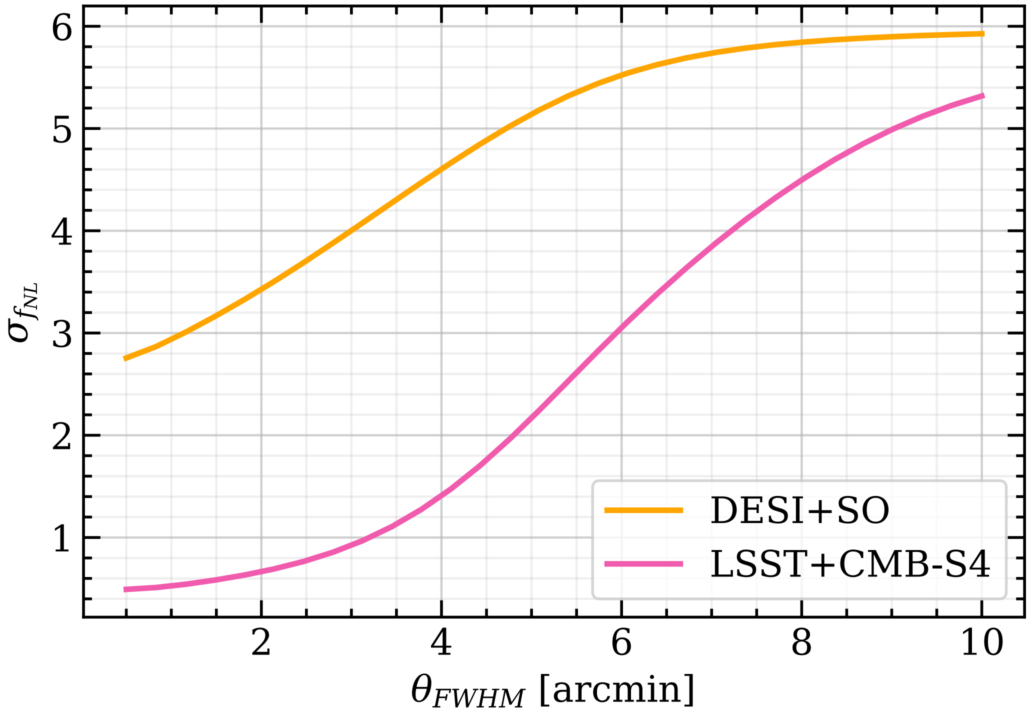
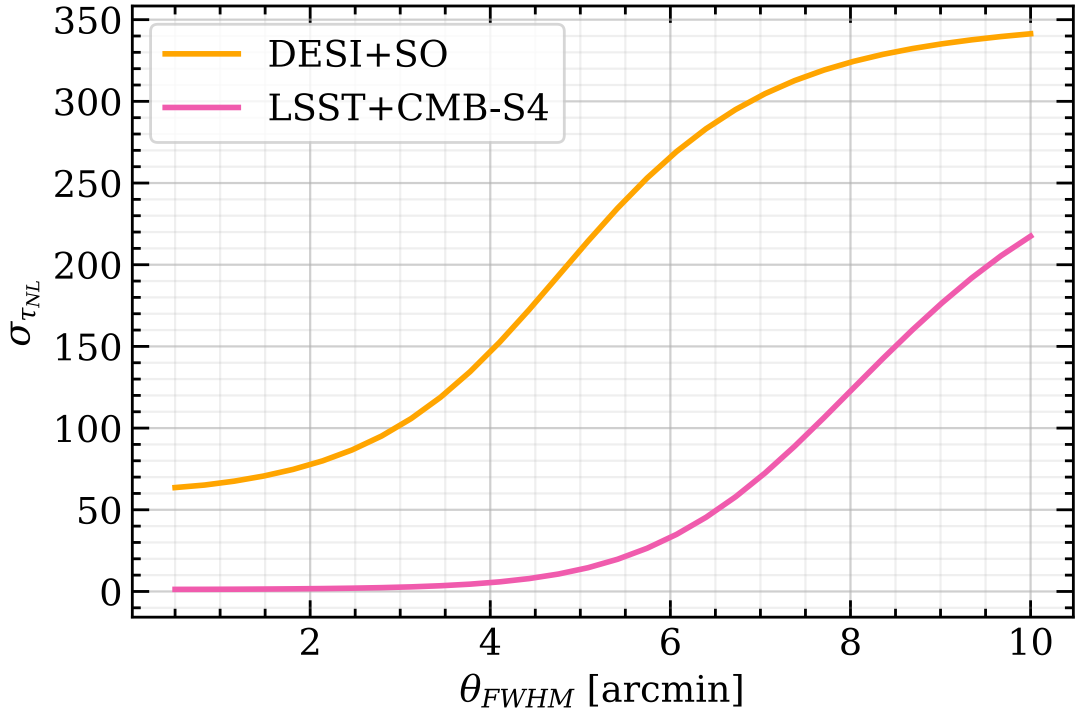
[Forecast] Results (CMB Resolution)





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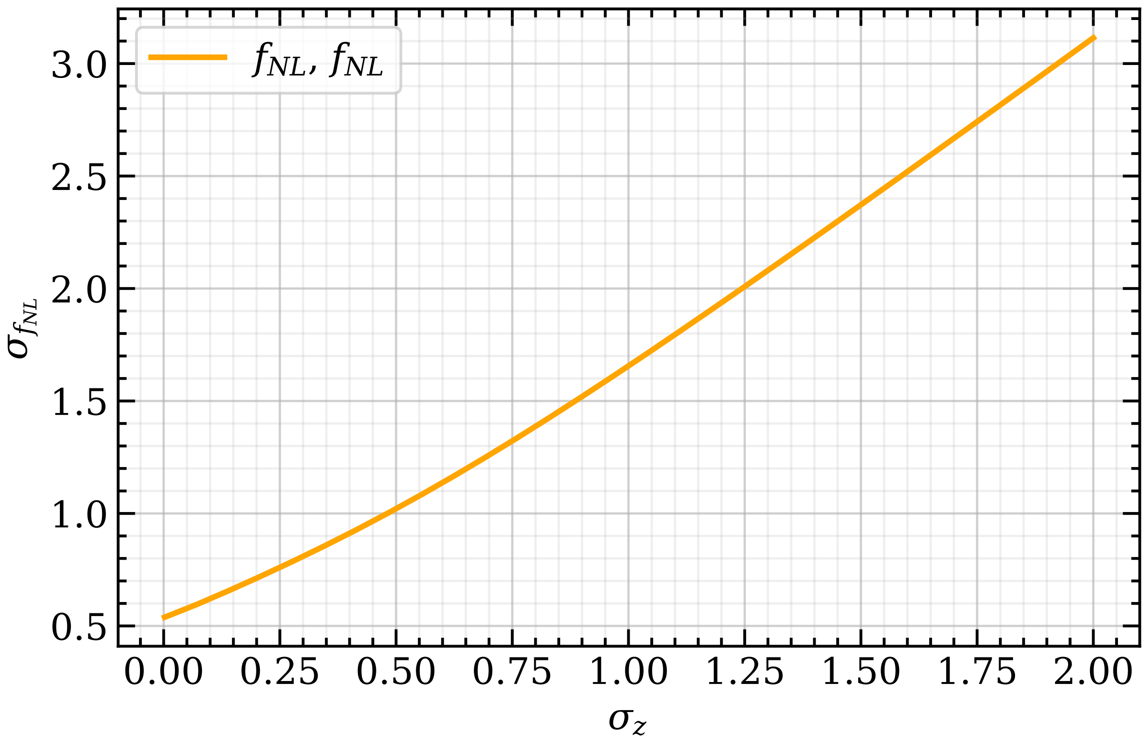
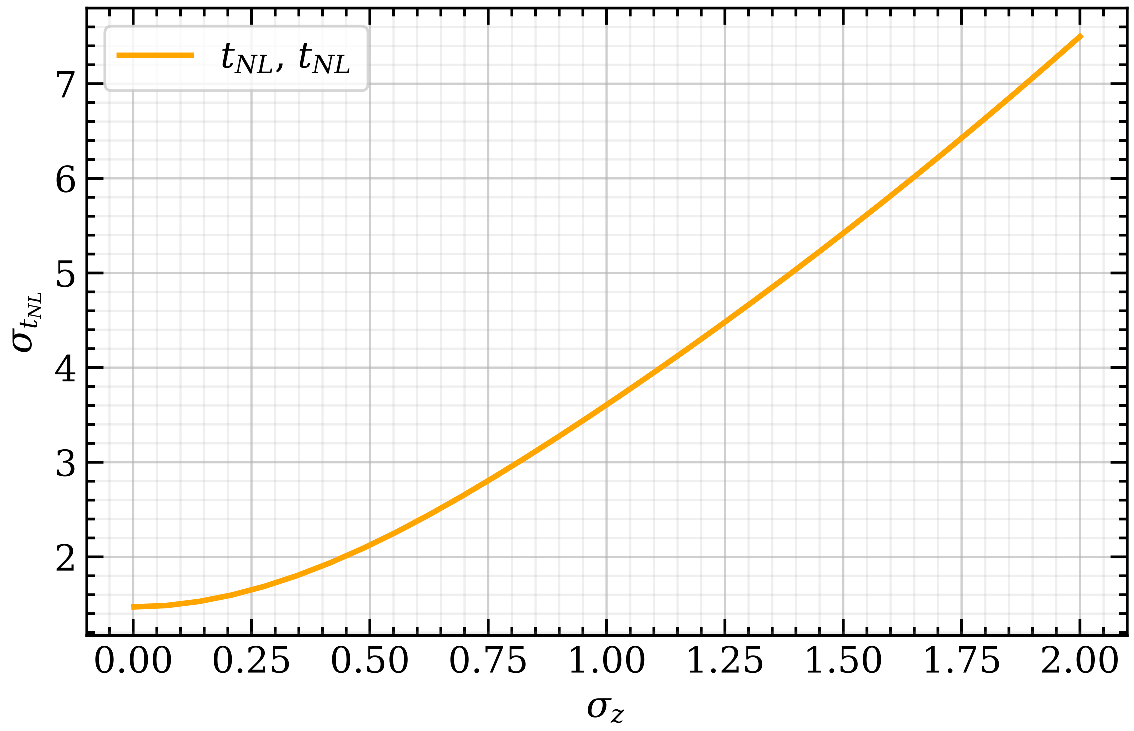
[Forecast] Results (Photo-z Error)





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[Forecast] Results (LSST + CMB S4)

Galaxy + kSZ

$$P_{vh}(k) = \frac{b_v f a H}{k}\left[b_h + \beta_f \frac{f_{\rm NL}}{\alpha(k)}\right] P_{mm}(k)$$

$$P_{hh}(k) = \left[{b_h}^2 + 2 b_h \beta_f \frac{f_{\rm NL}}{\alpha(k)} + \beta_f^2 \frac{\left(\frac{5}{6}\right)^2 \tau_{\rm NL}}{\alpha^2(k)}\right] P_{mm}(k)$$

with $\alpha(k,z) = \dfrac{2k^2 T(k) G(z)}{3\Omega_m H_0^2}$