Non-Gaussianity with the CMB bispectrum

What is the bispectrum and why study it?

- Harmonic equivalent of the three point function:

$$\langle a_{\ell_1,m_1} a_{\ell_2,m_2} a_{\ell_3,m_3} \rangle = \mathcal{G}^{m_1,m_2,m_3}_{\ell_1,\ell_2,\ell_3} b_{\ell_1,\ell_2,\ell_3}$$

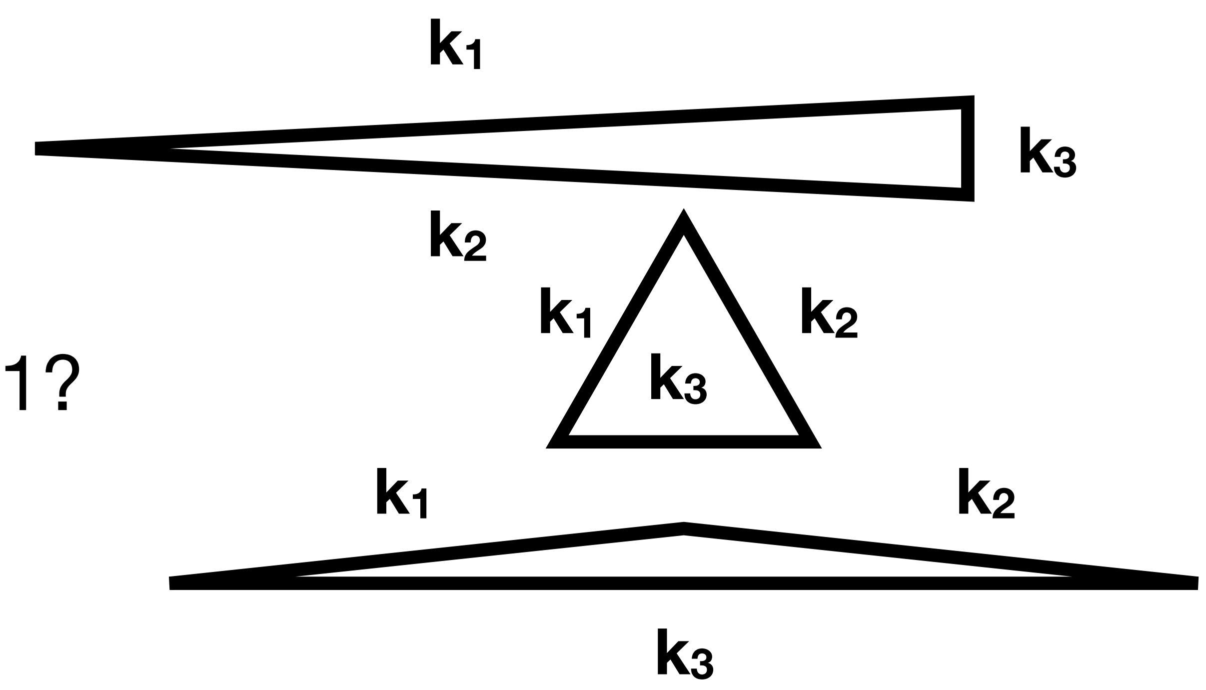
- Primordial non-Gaussianity:
  - Are the initial conditions Gaussian? What is the physics of inflation?
- Intrinsic CMB bispectrum:
  - non-Gaussianity induced by non-linear evolution of perturbations.
- To study CMB secondaries
- To study the galactic emissions

What can we learn from primordial non-Gaussianity?

- Unique window into physics of early universe
    - Highly complementary to B mode searches
- Theoretical models of inflation give us predictions

$$\langle \zeta(k_1)\zeta(k_2)\zeta(k_3) \rangle \propto \; shape \times f_{NL}$$

- Three commonly studied shapes:
    - Local - Multi-field inflation?
    - Orthogonal / Equilateral - $c_s \neq 1$?
    - Folded - Non-bunch Davies initial conditions?



See e.g. Chen (2010) for a review

Beyond scalar non-Gaussianity

- Scalar non-Gaussianity

$$\langle \delta(k_1)\delta(k_2)\delta(k_3)\rangle \propto Shape \times f_{NL}$$

- Tensor-scalar non-Gaussianity

$$\langle \delta(k_1)\delta(k_2)h(k_3)\rangle \propto Shape \times f'_{NL}$$

$$\langle \delta(k_1)h(k_2)h(k_3)\rangle \propto Shape \times f''_{NL}$$

- Tensor non-Gaussianity

$$\langle h(k_1)h(k_2)h(k_3)\rangle \propto Shape \times f'''_{NL}$$

- Probe h modes through CMB B mode polarisation

Beyond scalar non-Gaussianity

- In most inflationary models these types of non-Gaussianity are vanishingly small
- However can be large in a range of interesting models.
    - Partially massive fields
    - When tensor modes are not sourced from vacuum fluctuations eg. Axion-gauge inflation models
    - Models with violations of spatial isometries
- Generically: Means to test origin measurement of r!

Agrawal et al (2019) Akhshik (2018)
Baumann et al (2018) Maldacena (2003) Bordin et al (2017)

S4 Constraints

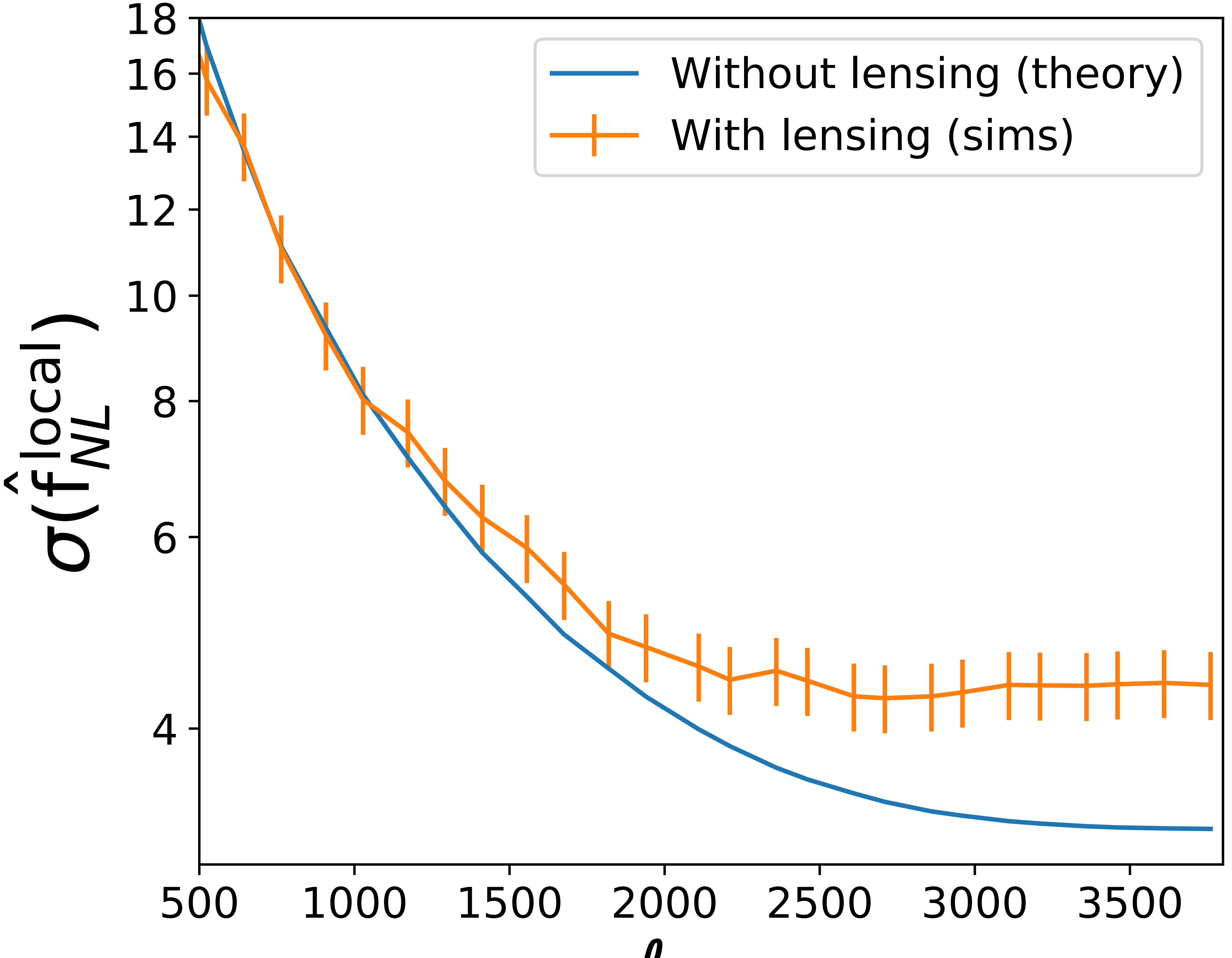
Shape ($\zeta\zeta\zeta$)	Current	S4 constraint
Local	-0.9 ± 5.1	1.9
Equilateral	-26 ± 47	22.1
Orthogonal	-38 ± 23	9
Shape ($\zeta\zeta h$)	Constraint	
Local	-48 ± 28	0.79
Equilateral	-	16
Orthogonal	-	4.4

Shiraishi et al (2018)
Planck Collaboration (2019)

DSR (2019)

Impact of lensing on PNG searches

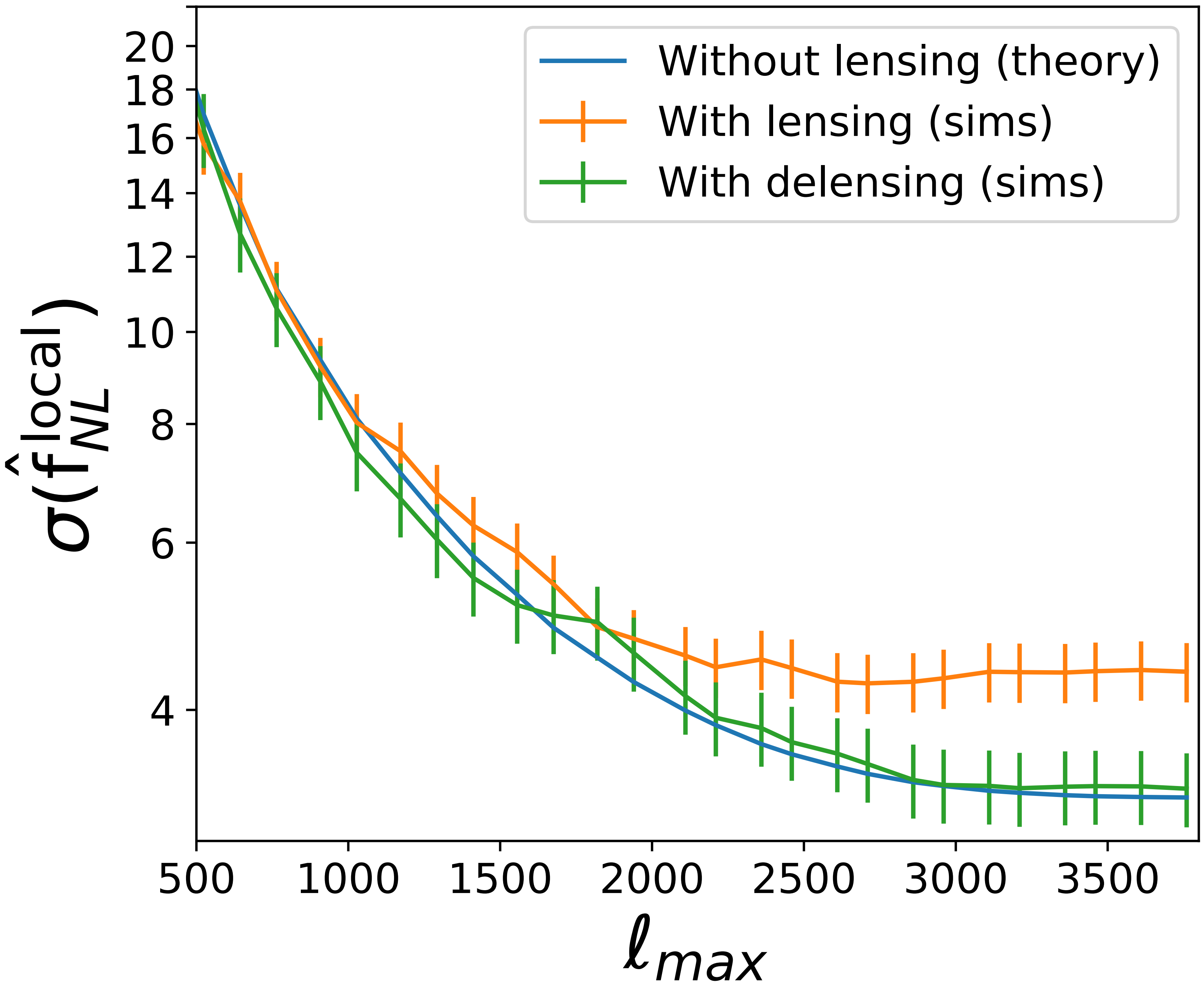
Local non-Gaussianity SNR for measurements with ~8uk’ noise



Coulton et al (2020)

Impact of lensing on PNG searches

Local non-Gaussianity SNR for measurements with ~8uk' noise with delensing!



Nearly optimal!
With no biases

Coulton et al (2020)

Revisiting the intrinsic bispectrum

“Non-primordial-, non scalar- non-Gaussianity”

Coulton (on arXiv later this week)

Beyond leading order

- Usually only consider first order perturbation theory
  - Gaussian initial conditions lead to Gaussian anisotropies
  - Scalars, tensor and vectors do not mix.
- Second order effects breaks these properties!
- Heuristically we can expect:

$$B^{non-linear}(k_1, k_2, k_3) \sim P_\Phi(k_1)P_\Phi(k_2) + \ldots$$

- This could be similar size to $f_{NL} \sim 1$

Parity odd intrinsic bispectrum

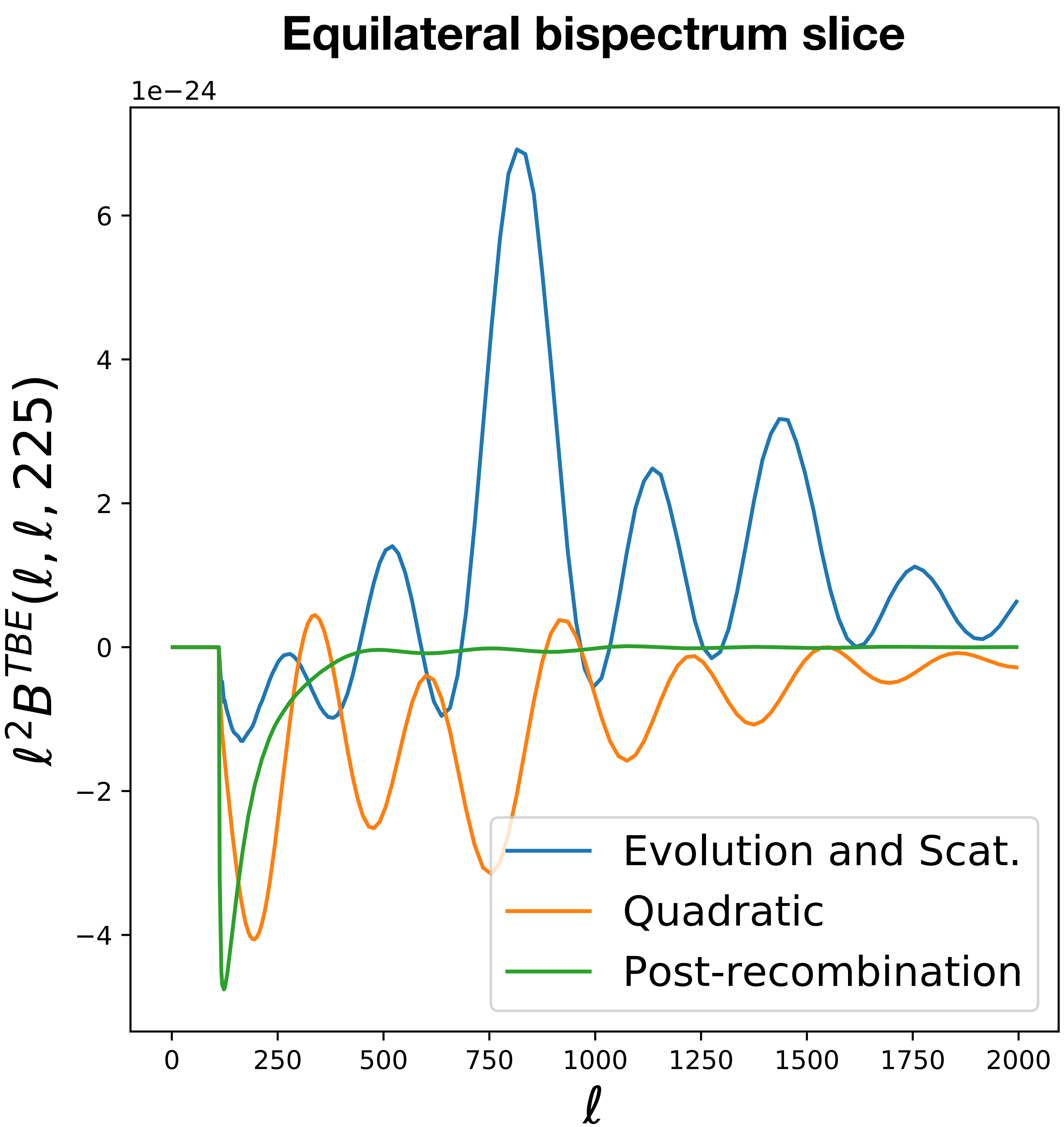
- Bispectrum between induced, second order B modes and T/E modes

$$\langle BTT \rangle, \langle BET \rangle, \langle BEE \rangle \neq 0$$

- Bispectrum has odd parity:
  - Non zero for $\ell_1 + \ell_2 + \ell_3 =$ odd
- B modes are only sourced by vectors and tensors!
- SNR will increase as lensing B modes are removed! (allows SNR larger that $\langle TTT \rangle, \langle TEE \rangle, \langle TTE \rangle, \langle EEE \rangle$)
- Numerically solve the 2nd order Boltzmann eqs. using SONG

Benke et al (2010,2011) Fidler et al (2015) Pettinari (2013),Pettinari et al (2013,2016)

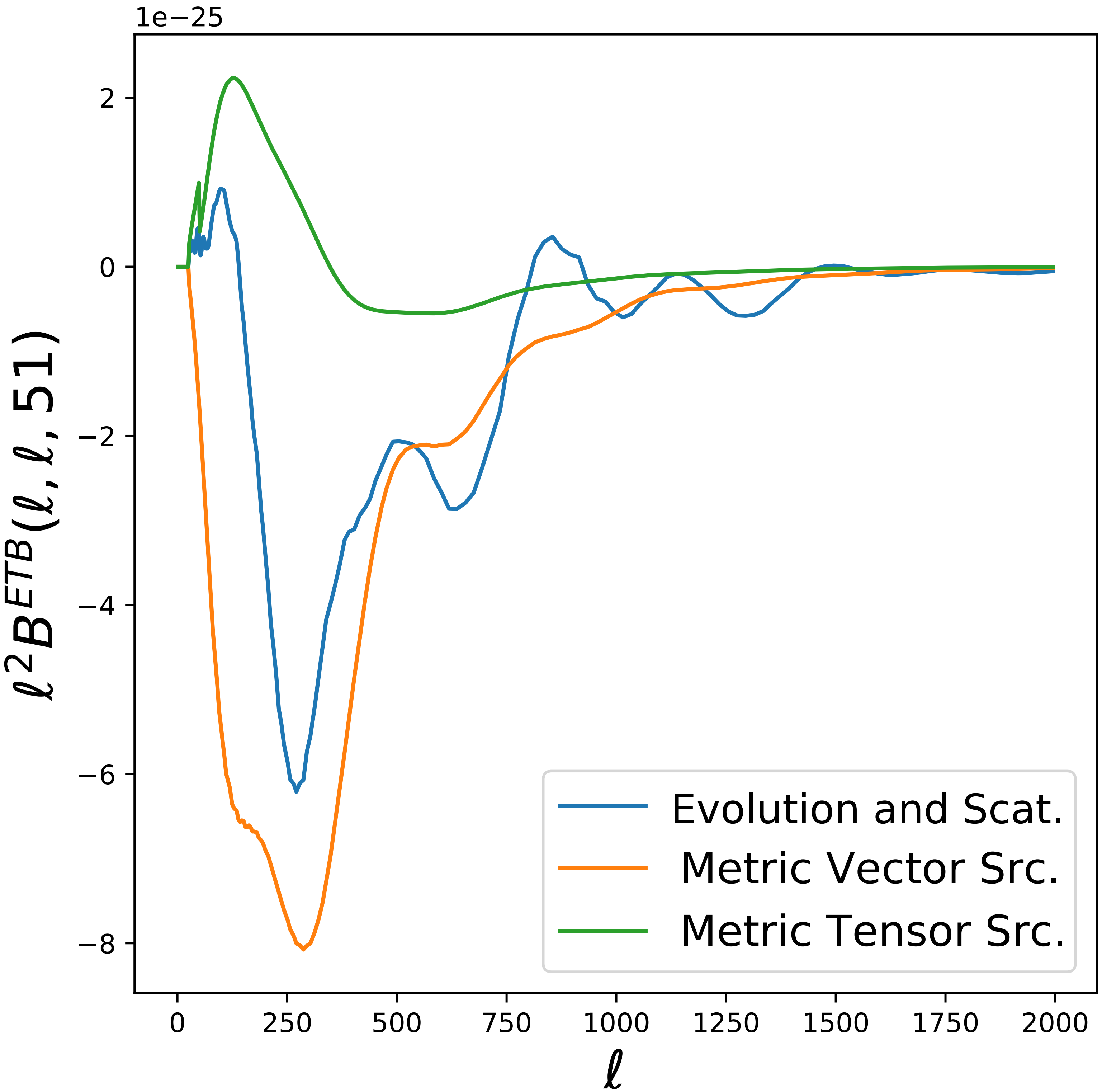
The parity-odd intrinsic bispectrum



- Evolution and Scattering:
  - Non-scalar modes from nonlinear evolution
  - Modulation of the scattering rate by bulk flows and large scale perturbations
- Quadratic term:
  - the non-linear relation of temperature at 2nd order
  - redshifting terms
- Post-recombination:
  - Propogation through inhomegenous universe

The intrinsic bispectrum components

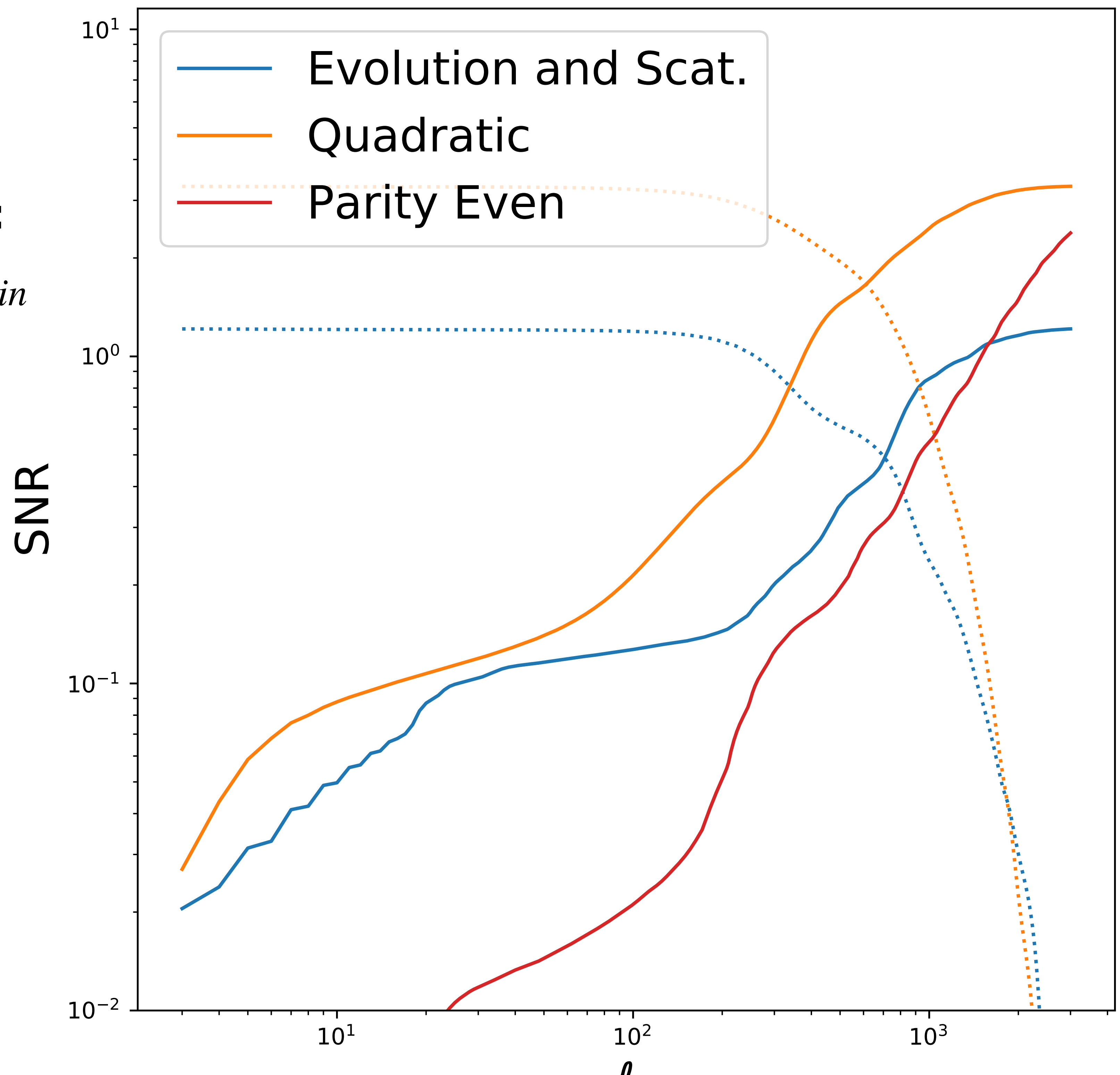
Contributions to the squeezed intrinsic bispectrum by mode type



Is this detectable with S4?

Parity odd SNR for S4
(assuming 80% of lensing B mode power removed)

Dotted Lines:
SNR wrt to ℓ_{min}



Solid Lines:
SNR wrt to ℓ_{max}

Conclusions

- S4 will extend beyond Planck's constraints on primordial non-Gaussianity:
    - Step towards $f_{NL} \sim 1$
    - Large improvements for tensor-scalar non-Gaussianity
    - Tool to test any detection of r
- S4 can find first hints of the intrinsic bispectrum!
    - With delensing ~3.5σ measurement
    - In the future, a probe of non-scalar perturbations!