Lensing limitations on bispectrum constraints of primordial non-Gaussianity

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What is the bispectrum?

$$\frac{\Delta T(\vec{n})}{T} = \sum_{\ell,m} a_{\ell,m} Y_{\ell,m}(\vec{n})$$

- If CMB is purely Gaussian then the fluctuations can be fully described by the power-spectrum C_ℓ

- The bispectrum is the harmonic equivalent of the three point function

- For a homogeneous and isotropic universe it has the form:

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

Geometric factor

Reduced bispectrum - contains the physics

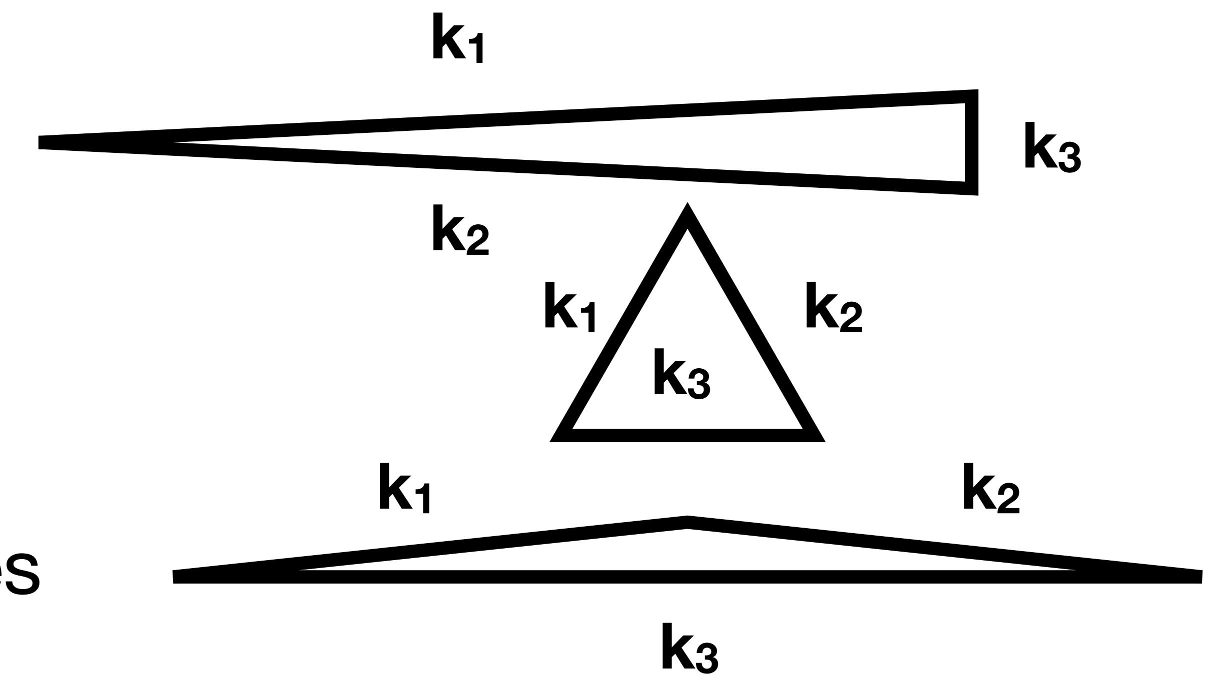
- Vanishes for Gaussian fluctuations

Why study 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?
    - Equilateral - $c_s \neq 1$?
    - Orthogonal - Non-bunch Davies initial conditions?



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

How to measure non-Gaussianity?

- Ideally measure every configuration

$$\langle a_{\ell_1,m_1} a_{\ell_2,m_2} a_{\ell_3,m_3} \rangle \propto \langle \zeta(k_1)\zeta(k_2)\zeta(k_3) \rangle$$

  - Computational prohibitive and signal is any triplet is expected to be small

- Two broad classes of estimators
  - Compress the information - KSW estimator
  - Compress the data - Modal and Binned estimator
- Regardless of estimator, to measure f_{NL} need

$$\hat{f}_{NL} \propto \sum_{\ell_i} b_{\ell_1,\ell_2,\ell_3} a_{\ell_1,m_1} a_{\ell_2,m_2} a_{\ell_3,m_3}$$

Komatsu, Spergel and Wandelt (2005)
Bucher et al (2013,2015)
Fergursson et al (2009)

Current Constraints

Shape ($\zeta\zeta\zeta$)	Constraint
Local	-0.9 ± 5.1
Equilateral	-26 ± 47
Orthogonal	-38 ± 23
Shape ($\zeta\zeta h$)	**Constraint**
Local	-48 ± 28
Shape (hhh)	**Constraint**
Equilateral	8 ± 11

For context, when $f_{NL} \sim 1$

$$\frac{\langle \zeta(k_1)\zeta(k_2)\zeta(k_3)\rangle}{\sqrt{P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3)}} \sim 10^{-5}$$

See e.g. Azadeh's talk

Planck Collaboration XI (2019)

Shiraishi et al (2018)

Future Constraints

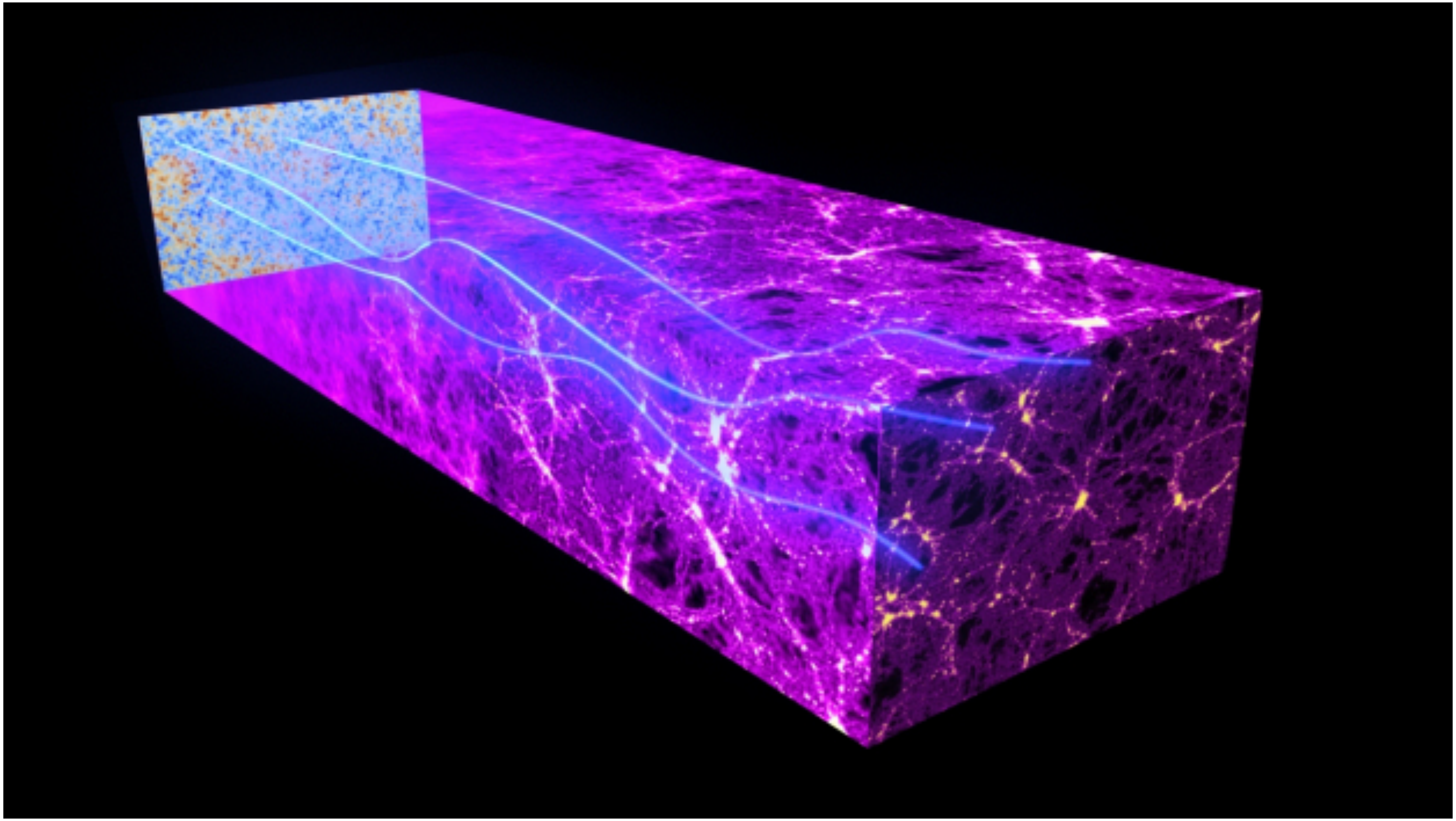
See e.g. David Alonso's talk yesterday for more information on the Simons Observatory (SO)

Shape ($\zeta\zeta\zeta$)	Current	SO constraint
Local	-0.9 ± 5.1	3
Equilateral	-26 ± 47	24
Orthogonal	-38 ± 23	13
Shape ($\zeta\zeta h$)	Constraint	
Local	-48 ± 28	1
Equilateral	-	8
Orthogonal	-	3

Planck Collaboration (2019)

The Simons Observatory Collaboration XI (2018)

Recap: CMB lensing



Planck Collaboration VIII (2019)

Lensing effects on the bispectrum

- CMB is non-Gaussian:
    - Planck detected CMB lensing at >40σ!
- Two consequences for bispectra analyses:

1. Signal contamination:
   Bias of CMB lensing on primordial non-Gaussianity
   This has been well studied e.g. Lewis et al (2011)

2. Extra source of noise:
   Degradation to the SNR of bispectrum estimators caused by lensing as first pointed out by Babich & Zaldarriaga (2004).

Bispectrum Variance

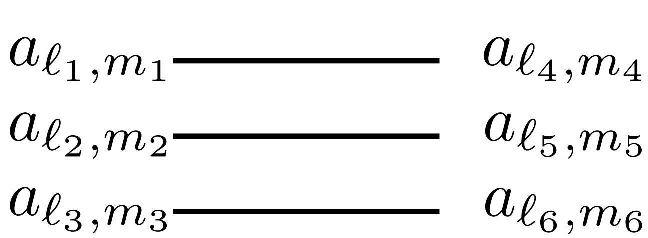
- Schematic variance of the primordial non-Gaussianity estimator

$$\langle {f_{NL}^{local}}^2 \rangle \propto \sum_{\{\ell_i\}} b_{\ell_1,\ell_2,\ell_3} \langle a_{\ell_1,m_1} a_{\ell_2,m_2} a_{\ell_3,m_3} a_{\ell_4,m_4} a_{\ell_5,m_5} a_{\ell_6,m_6} \rangle b_{\ell_4,\ell_5,\ell_6}$$

- For a Gaussian CMB, this simplifies!

$$\langle {f_{NL}^{local}}^2 \rangle \propto \sum_{\{\ell_i\}} b_{\ell_1,\ell_2,\ell_3} C_{\ell_1} C_{\ell_2} C_{\ell_3} b_{\ell_1,\ell_2,\ell_3}$$

- Diagrammatically (one perm. only)



Lensing contributions

- As Kimmy and Toshiya described yesterday

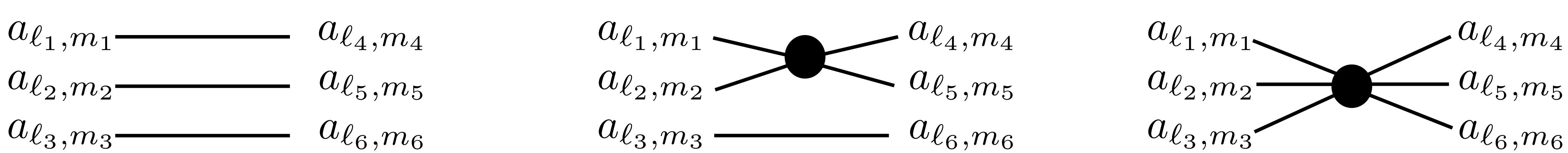
$$\langle a_{\ell,m} a_{\ell',m'} \rangle_{CMB} = \sum_{\ell_i, m_i} f_{\ell,\ell',L}\, \phi_{L,M}$$

where f is the lensing coupling kernel (Hu & Okamoto, 2002).

- This induces a connected four point function for the bispectrum variance

$$\langle {f_{NL}^{local}}^2 \rangle \propto \langle {f_{NL}^{local}}^2 \rangle_{gaus} + \sum_{\{\ell_i\}} b_{\ell_1,\ell_2,\ell_3} C_{\ell_1} T_{\ell_2,\ell_3,\ell_5,\ell_6} b_{\ell_1,\ell_5,\ell_6}$$

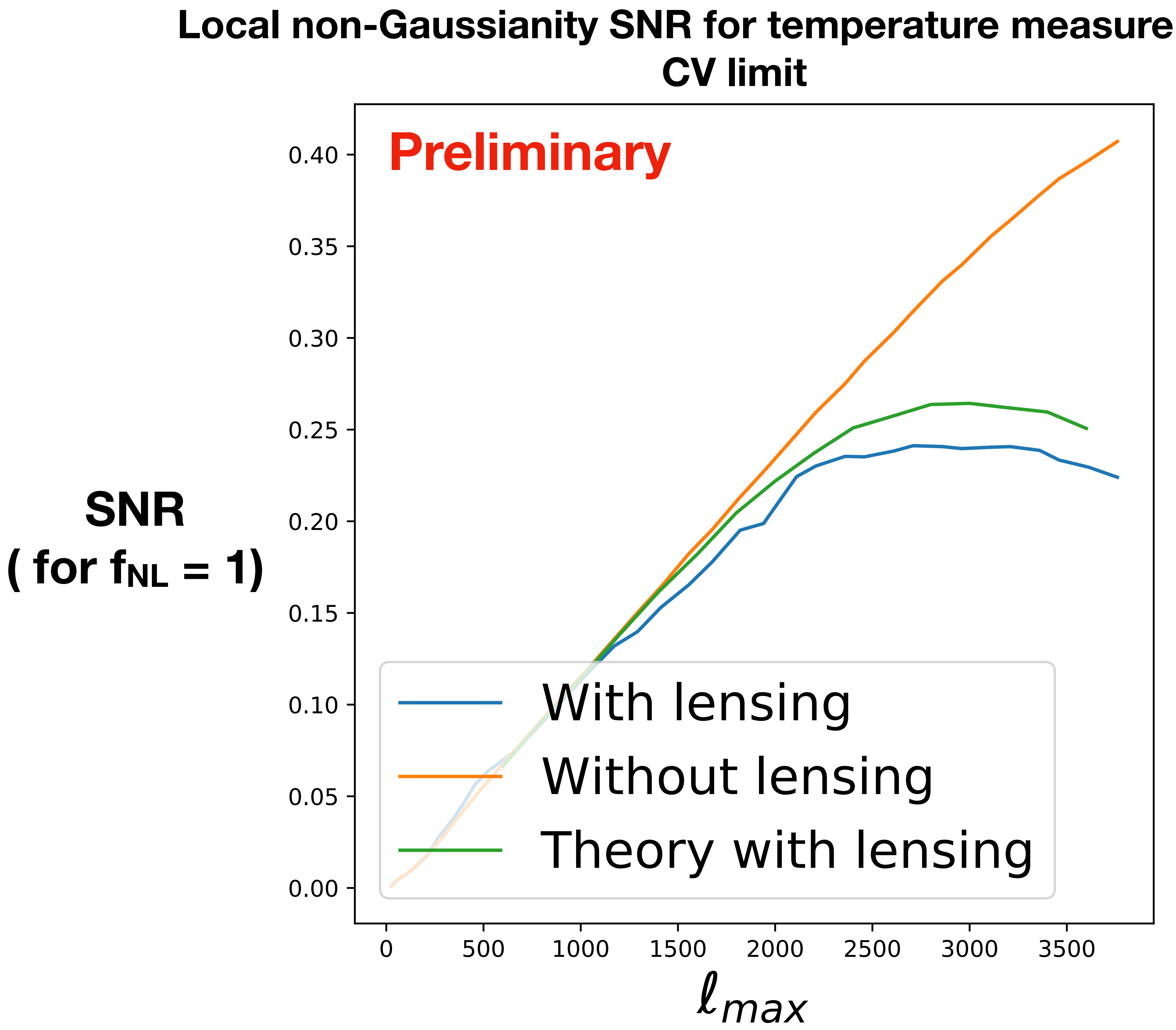
- Diagrammatically (one perm. only):



Gaussian/ Disconnected   Connected Four Point   Connected Six point (higher order term)

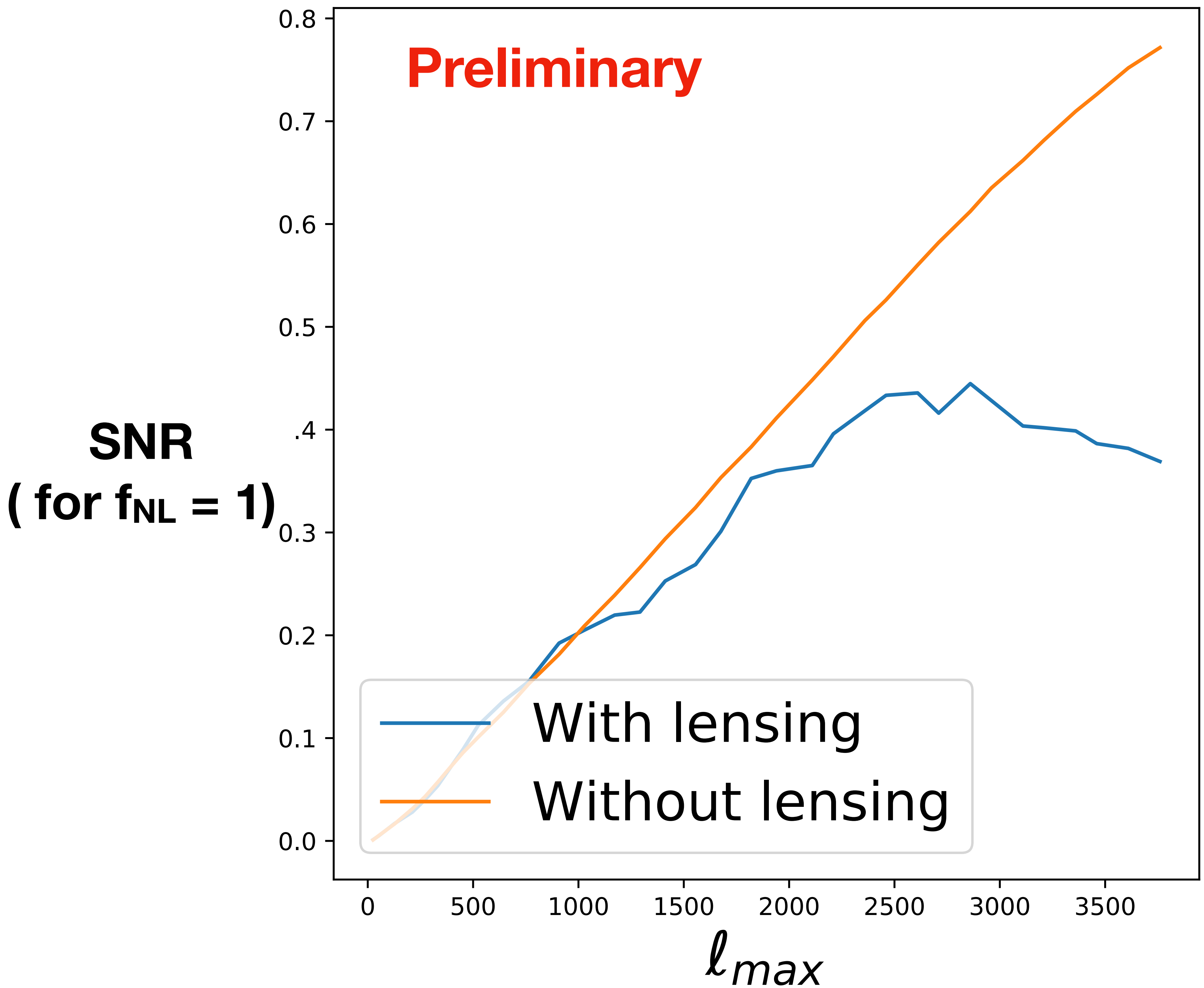
- Acts like extra noise to hinder bispectrum measurements!!

How important is this effect?



How important is this effect?

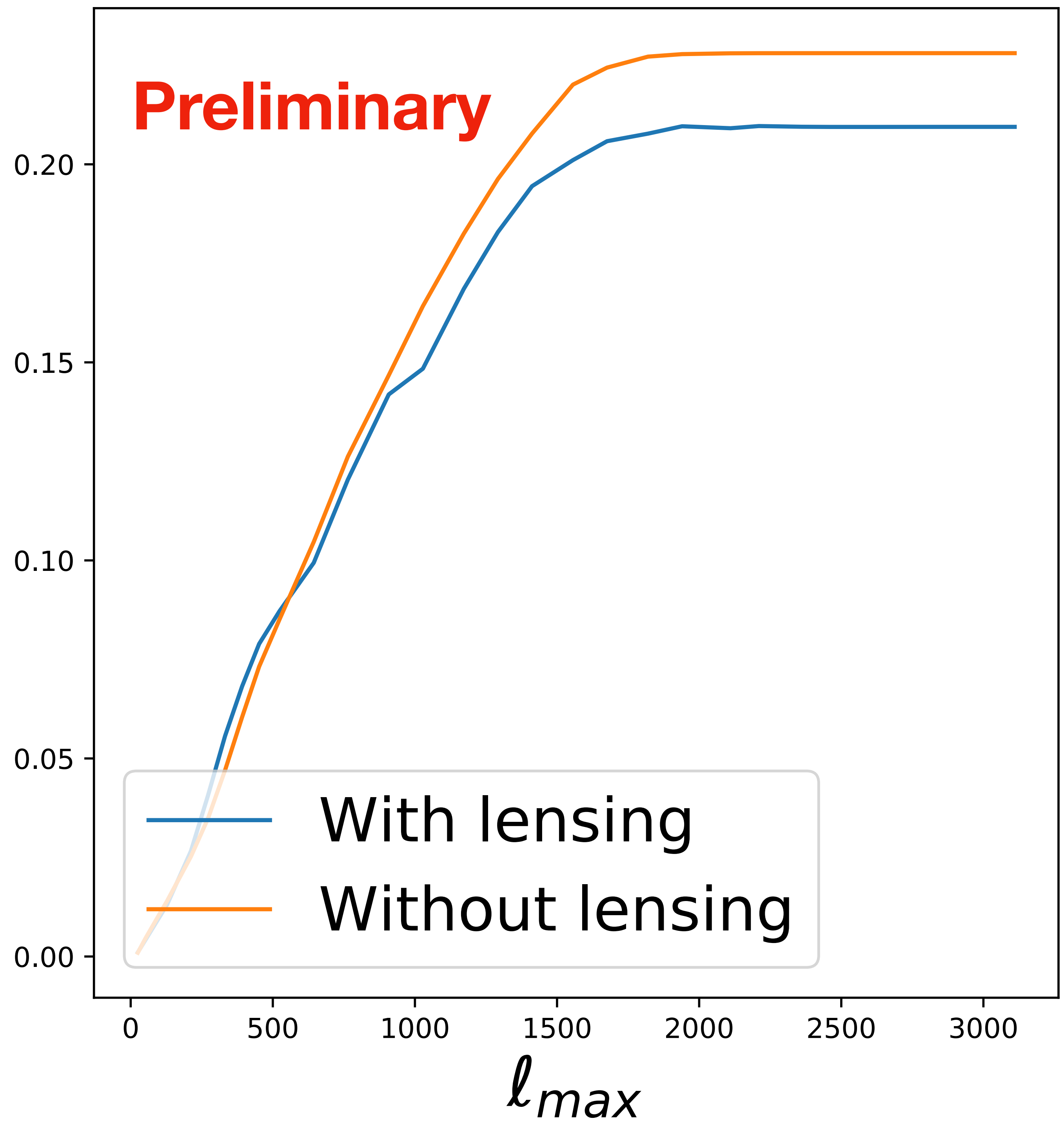
Local non-Gaussianity SNR for temperature and polarisation measurements
CV limit



How important was this effect for Planck?

Local non-Gaussianity SNR for measurements with Planck levels of noise

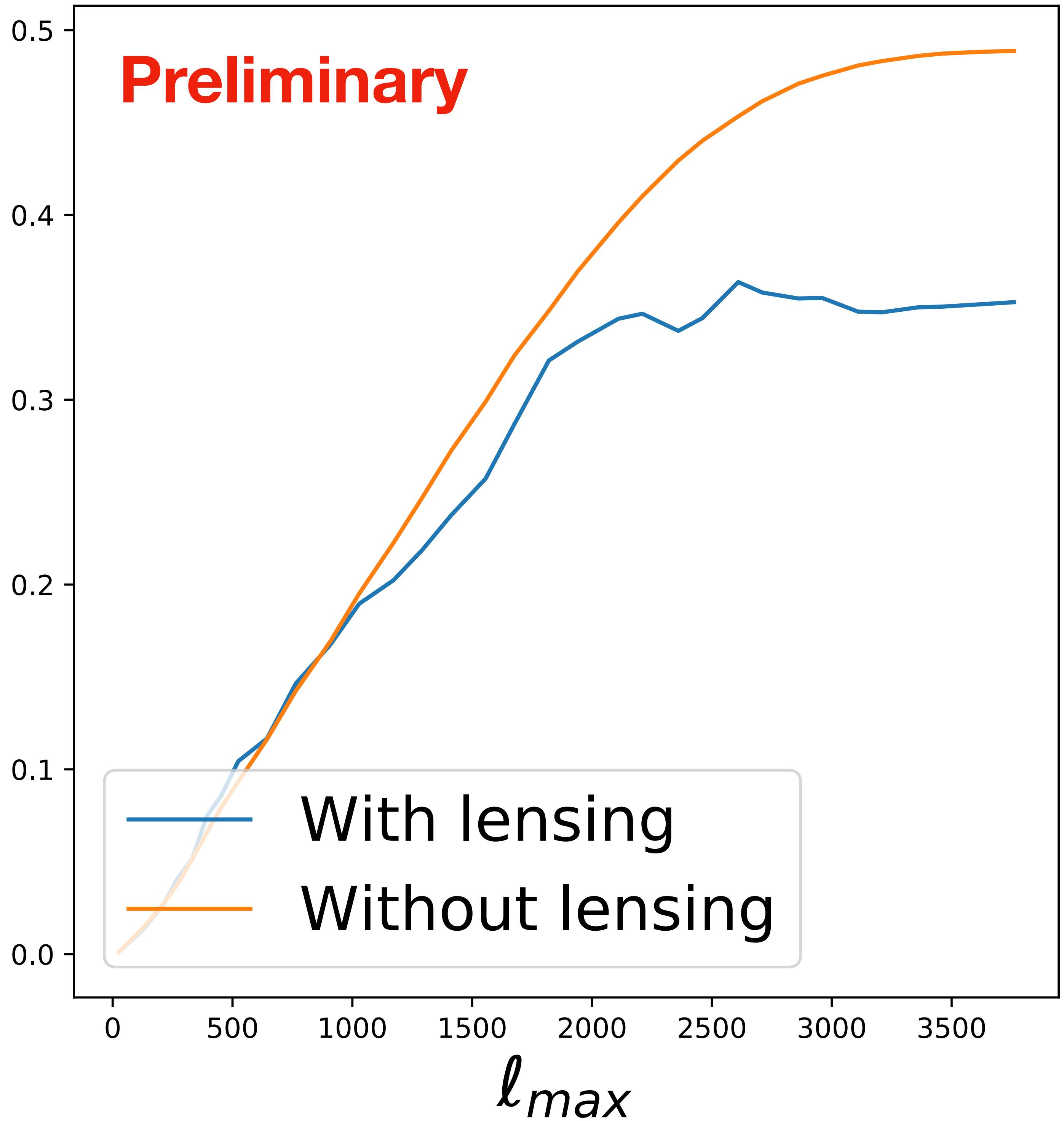
SNR
(for f_{NL} = 1)



How important is this effect for SO?

Local non-Gaussianity SNR for measurements with SO levels of noise

SNR (for f_{NL} = 1)



Why is this effect so large?

- Local primordial non-Gaussianity
  - Modulation of small scale power by large wavelength mode
- CMB Lensing:
  - Modulation of small scale power by intervening degree scale lens
- Small scale part of local bispectrum estimation like suboptimal lensing reconstruction! Thus it becomes sensitive to the lensing four point function.

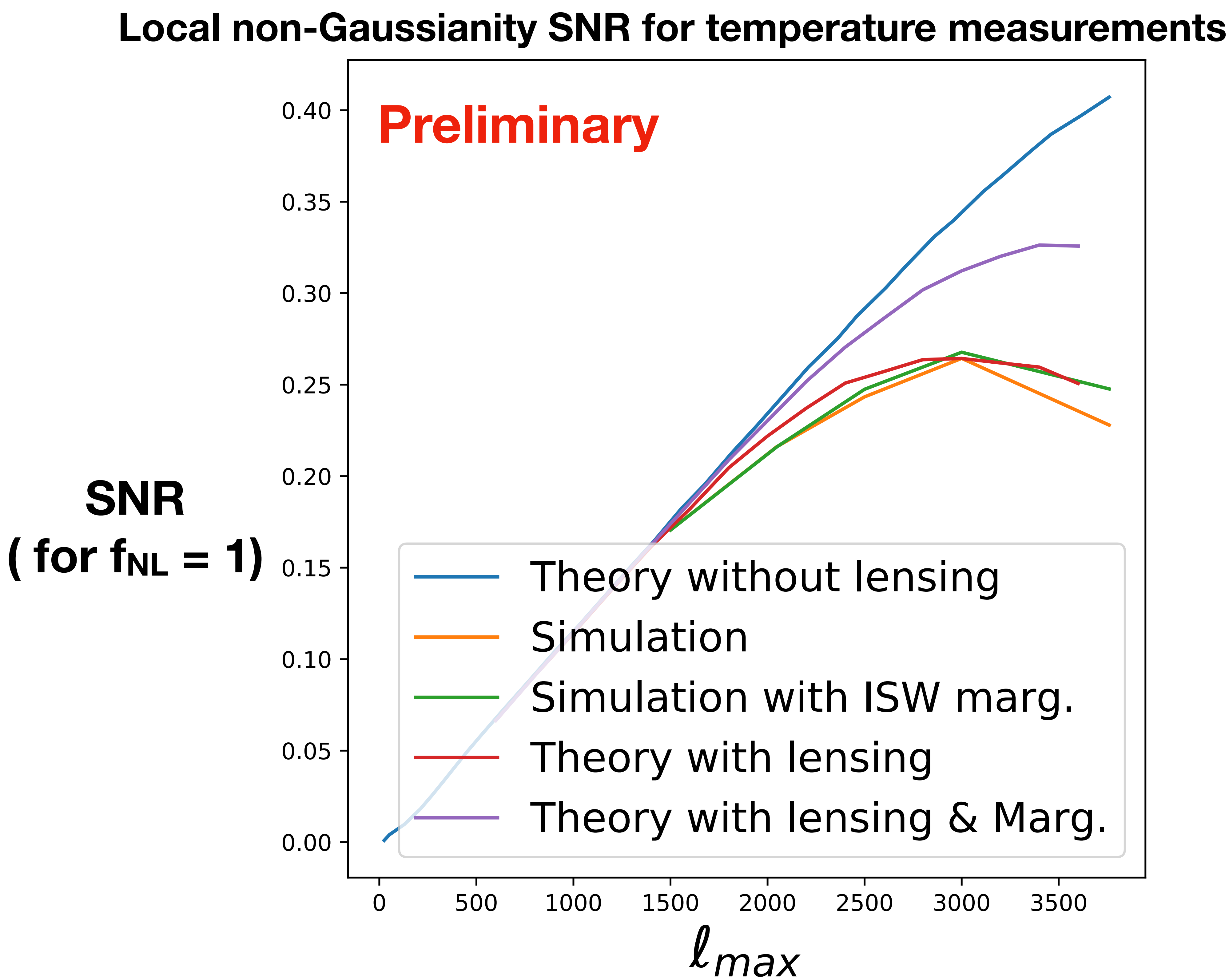
Is there a simple solution?

- Subtract from the estimator a similar term which explicitly picks up the lensing modes
    - i.e. deproject the lensing modes
- Schematically:

$$f^{\text{lensing-free}} = f^{local} - \sum_{\ell} W(\ell) a_{\ell,m} \hat{\phi}$$

- where $\hat{\phi}$ is the quadratically reconstructed lensing field
- ISW-lensing marginalisation does this!

Only to first order!

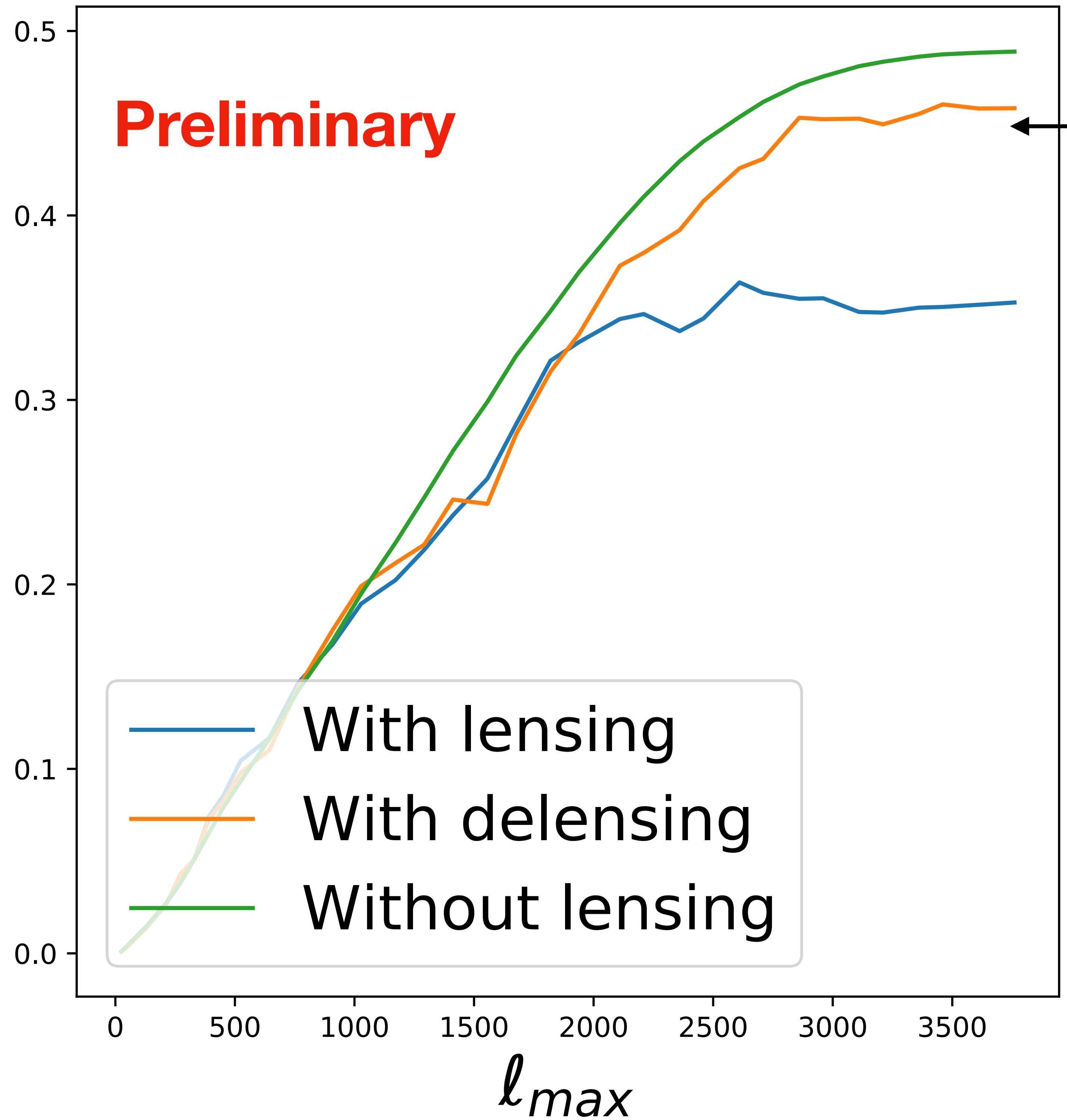


Delensing the CMB

- What is delensing?
    - Remap the pixels using an estimated lensing potential to reconstruct the fluctuations as seen at the LSS.
    - Lensing is: $T(\vec{n}) = \tilde{T}(\vec{n} + \nabla\phi)$
    - Delensing is: $\hat{\tilde{T}}(\vec{n}) \approx \tilde{T}(\vec{n} - \nabla\hat{\phi})$
- Potential biases from correlations between reconstruction noise and estimator maps

Delensing for an SO-like experiment

SNR
(for f_{NL} = 1)



Nearly optimal!
With no biases

Conclusions

- Simons Observatory will extend beyond Planck's constraints on primordial non-Gaussianity!
    - Step towards f_{NL} ~ 1
- Lensing of the CMB can act like noise for local (and orthogonal) primordial bispectrum estimators
- For next generation surveys delensing can remove this excess noise to achieve almost optimum performance
- Beside B mode delensing, most useful application of delensing!