Prospects and challenges for future CMB primordial non-Gaussianity measurements

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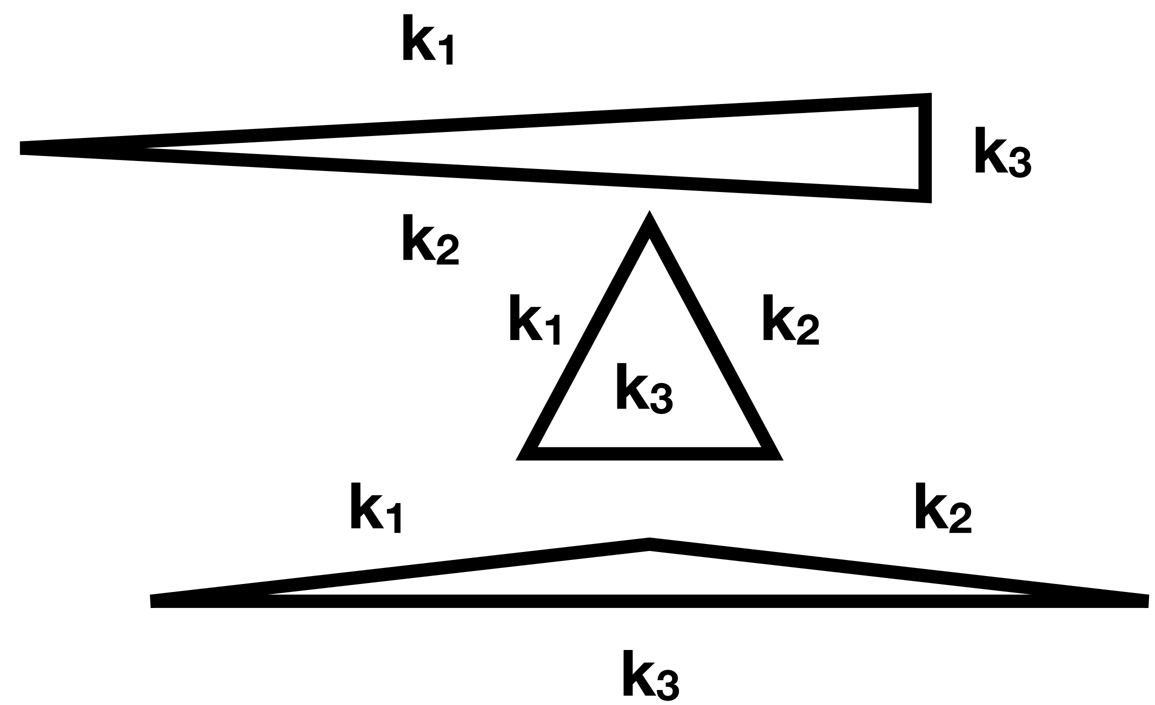
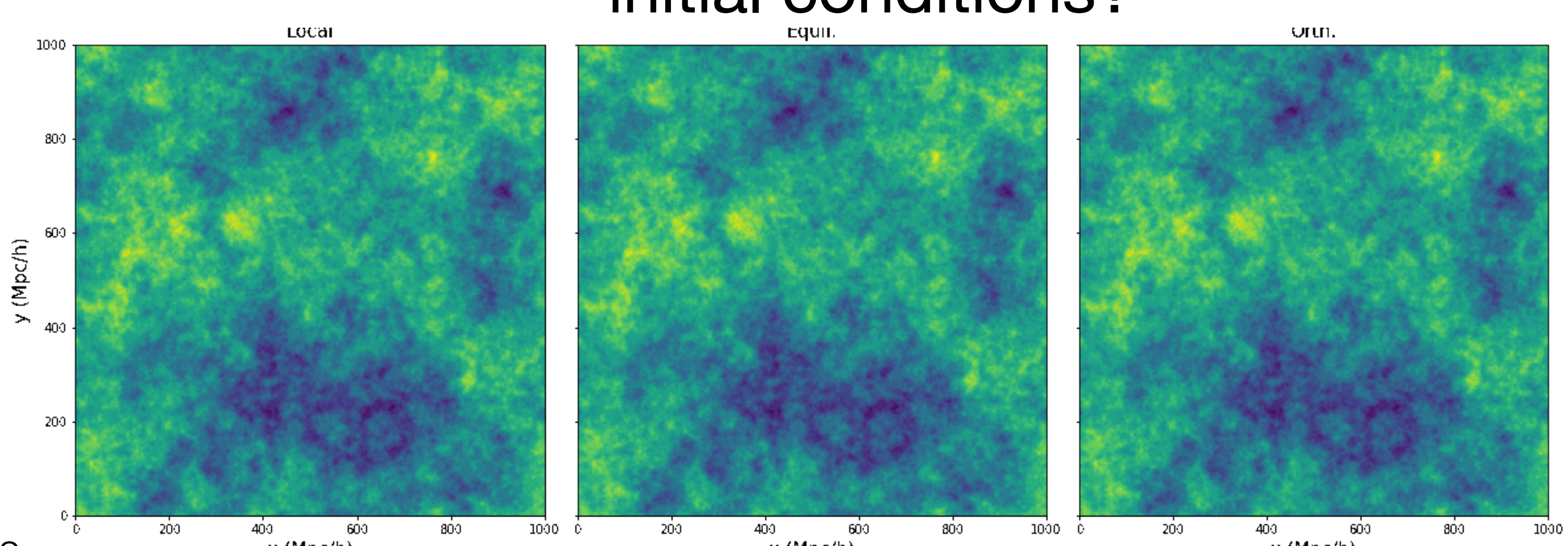
What can we learn from primordial non-Gaussianity?

- Unique window into physics of early universe
  - Highly complementary to B mode and N_{eff} searches
- 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

Parameterization of the non-Gaussianity

- The bispectrum is, often, the leading source of non-Gaussianity

$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3) f_{\rm NL} B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

- More generically we have

$$\langle \zeta(\mathbf{k}_1)\ldots\zeta(\mathbf{k}_N)\rangle_c = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+..\mathbf{k}_N) g^N_{\rm NL} F(\mathbf{k}_1..\mathbf{k}_N)$$

- Two interesting trispectra (4pnt correlators)
  - g_{NL}:
    $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle_c \propto P_\zeta(k_1)P_\zeta(k_2)P_\zeta(k_3) + ..$
  - τ_{NL}:
    $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle_c \propto P_\zeta(k_1)P_\zeta(k_2)P_\zeta(|\mathbf{k}_1+\mathbf{k}_2|) + ..$

How to measure non-Gaussianity?

- The CMB is well suited to studying primordial non-Gaussianity as

  $a_{\ell m} \propto \zeta(\mathbf{k})$ (where $\Delta T(\mathbf{n}) = \sum Y_{\ell m}(\mathbf{n})\, a_{\ell m}$)

- Ideally measure every configuration

  $$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle \propto \langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3) \rangle$$

- Computational prohibitive and signal is weak

- Two broad solutions:

  - Compress the data: e.g. Binned bispectrum
    This averages over 'nearby' configurations

  - Compress the information: e.g. KSW or Modal estimators
    These compress the data to a set of template amplitudes.
    Crudely:

    $$\hat{f}_{\mathrm{NL}} \propto \sum b^{\mathrm{theory}}_{\ell_1 \ell_2 \ell_3} a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3}$$

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

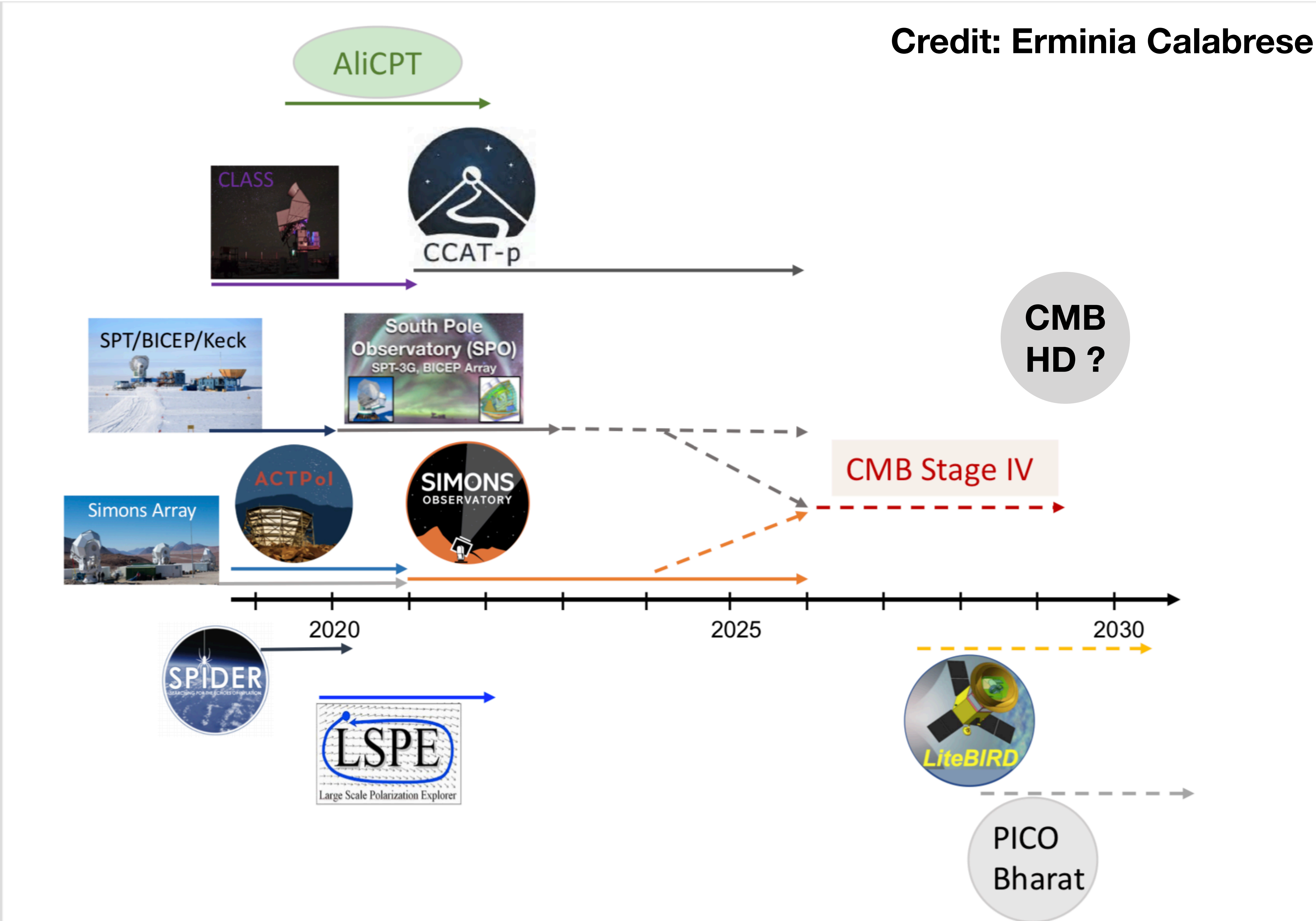
Current Constraints

	Shape	Constraint
Bispectra	Local	-.9± 5.1
	Equilateral	-26± 47
	Orthogonal	-38 ± 23
Trispectra	g_{NL}^{local}	$(-5.8 \pm 6.5) \times 10^4$
	$g_{NL}^{\sigma^4}$	$(-0.8 \pm 1.59 \times 10^4$
	$g_{NL}^{(\partial\sigma)^4}$	$(-3.9 \pm 3.9) \times 10^6$
	τ_{NL}	36 ± 283

See Wuhyun's talk on Friday for extended shapes

Planck Collaboration XI (2019)
Marzouk et al (2022)

Timeline of CMB experiments



Future Constraints

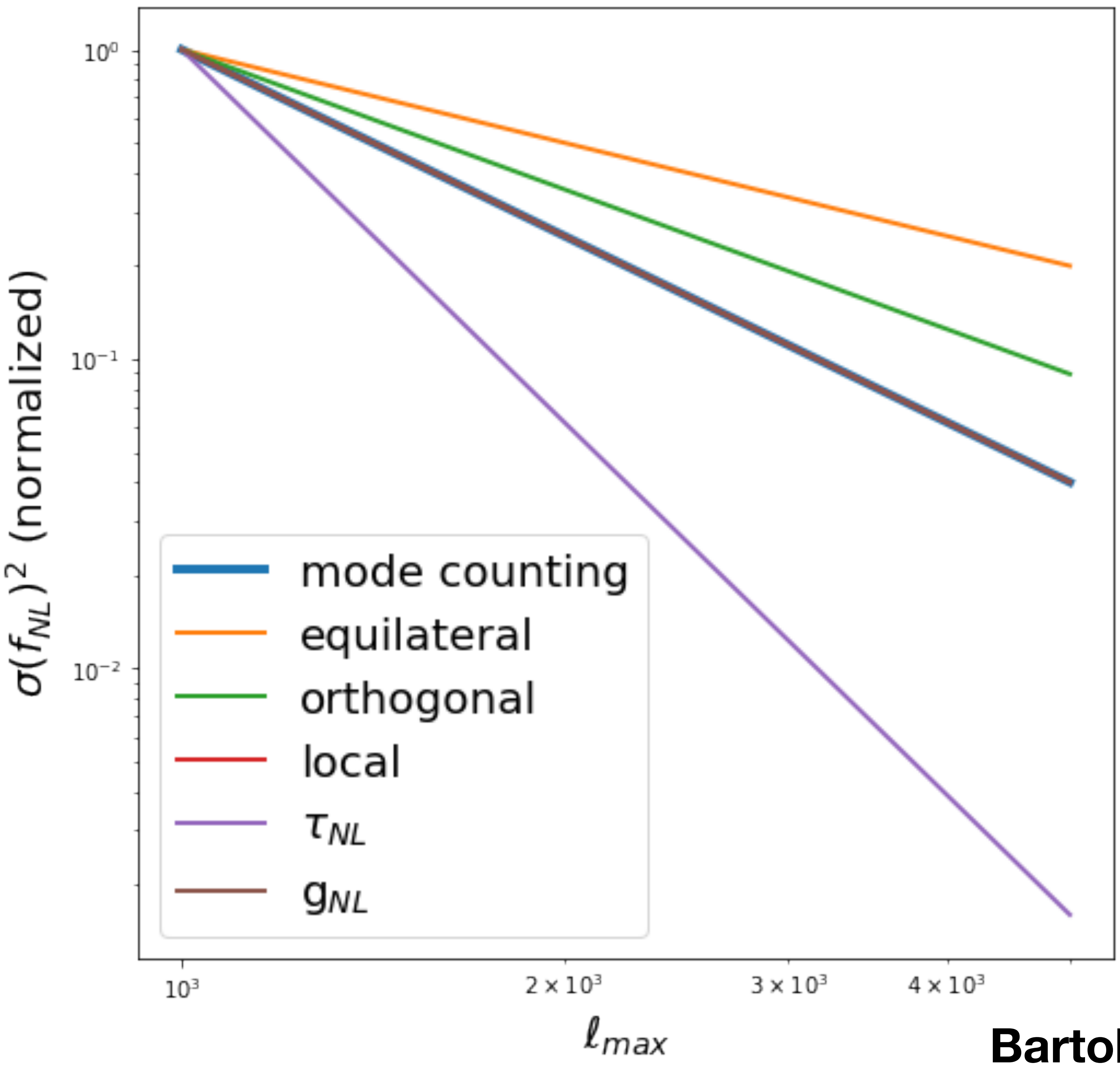
Shape ($\zeta\zeta\zeta$)	Current	SO constraint
Local	-0.9 ± 5.1	3
Equilateral	-26 ± 47	24
Orthogonal	-38 ± 23	13

Planck Collaboration (2019)

The Simons Observatory Collaboration XI (2018)

What can we learn from the CMB?

How can we understand (and exploit) this hierarchy of scalings?



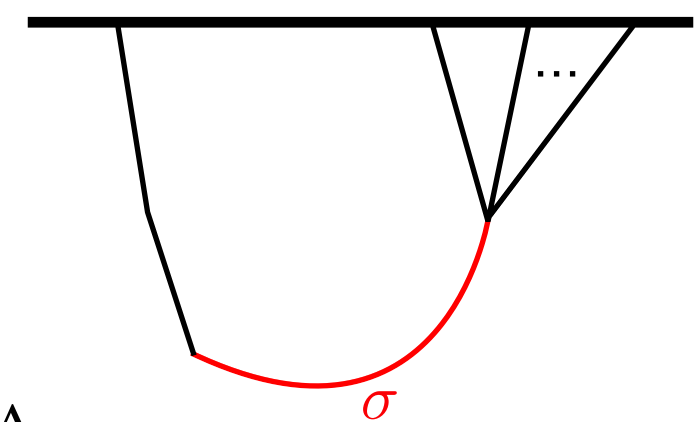
Bartolo and Riotto (2009)
Nogo and Komatsu (2006)

Interesting correlation regimes

- Correlations produced by inflation contact terms most important when (given de Sitter symmetries):

$$F(k_1 \sim k_2 \ldots k_N) \sim \frac{1}{k^{3(N-1)}}$$

- Correlations induced by mediators:

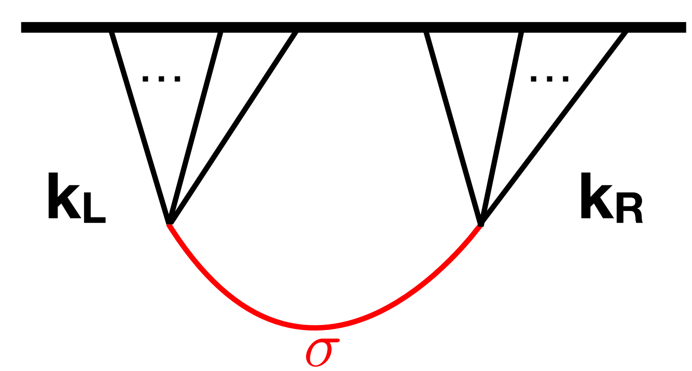


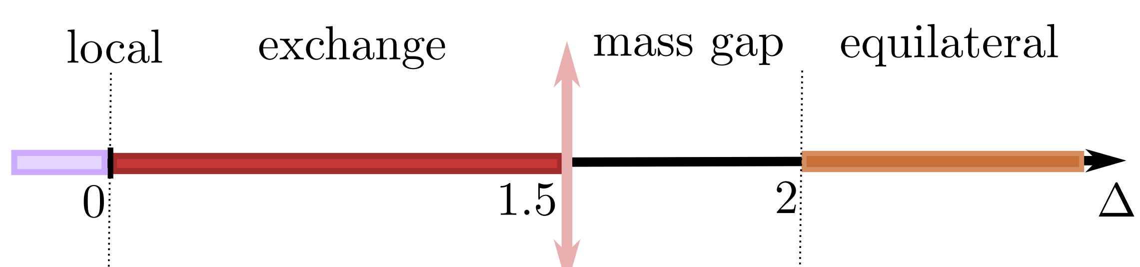
"Squeezed"

$$F(k_1 <<< k_2 \ldots k_N) \sim \frac{1}{k_1^3 k^{3(N-2)}} \left(\frac{k_1}{k}\right)^{\Delta_s}$$

"Collapsed"

$$F(k_I <<< k_L \; k_R) \sim \frac{1}{k_I^3 k_R^{3(M-2)} k_L^{3(N-M-1)}} \left(\frac{k_I^2}{k_R k_L}\right)^{\Delta_c}$$



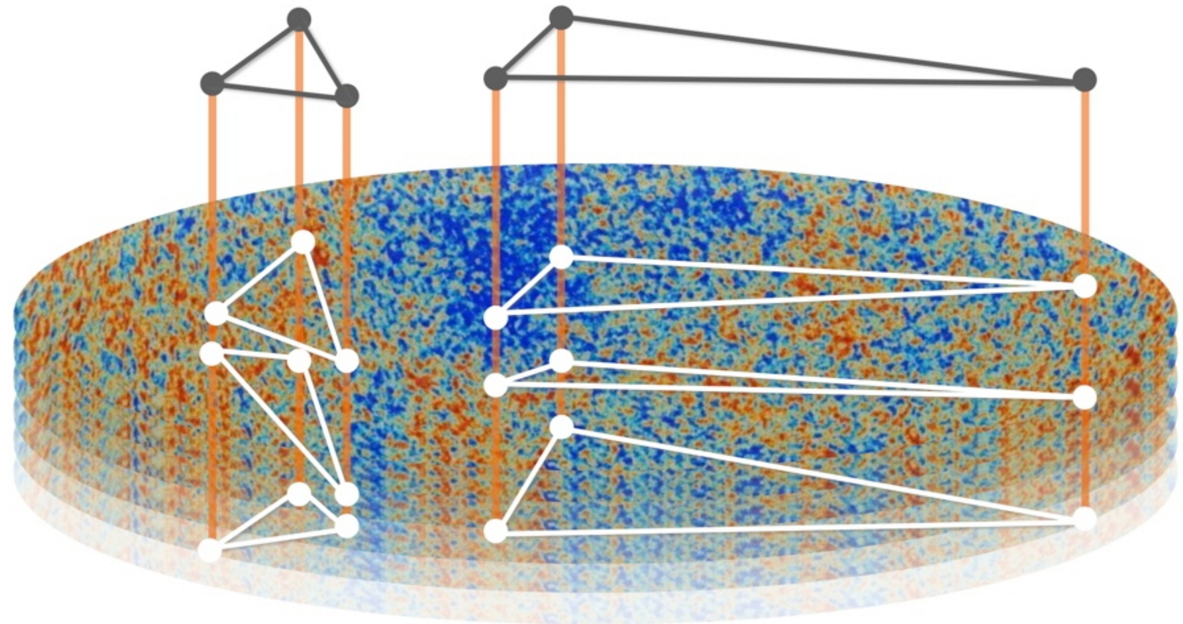


- Δ encodes interesting new physics!

Kalaja et al (2020)

Understanding expected scalings

- Two key processes:
  - damping and projection



	Undamped 2D	Damped 2D	3D
Contact	$\ell_{\max}^{2}$	$\ell_{\max}^{4-N}$	$k_{\max}^{3}$
Squeezed	$\ell_{\max}^{2}$	$\ell_{\max}^{5-N-2\Delta_S}$	$k_{\max}^{3}$
Collapsed	$\ell_{\max}^{4-8\Delta_C/3}$	$\ell_{\max}^{8-N-4\Delta_C}$	$k_{\max}^{6-4\Delta_C}$

- For the damped CMB higher N-point functions saturate!
  - e.g no further information beyond N=4 for contact terms
- Squeezed and collapsed configurations can mitigate damping effects

Kalaja et al (2020)

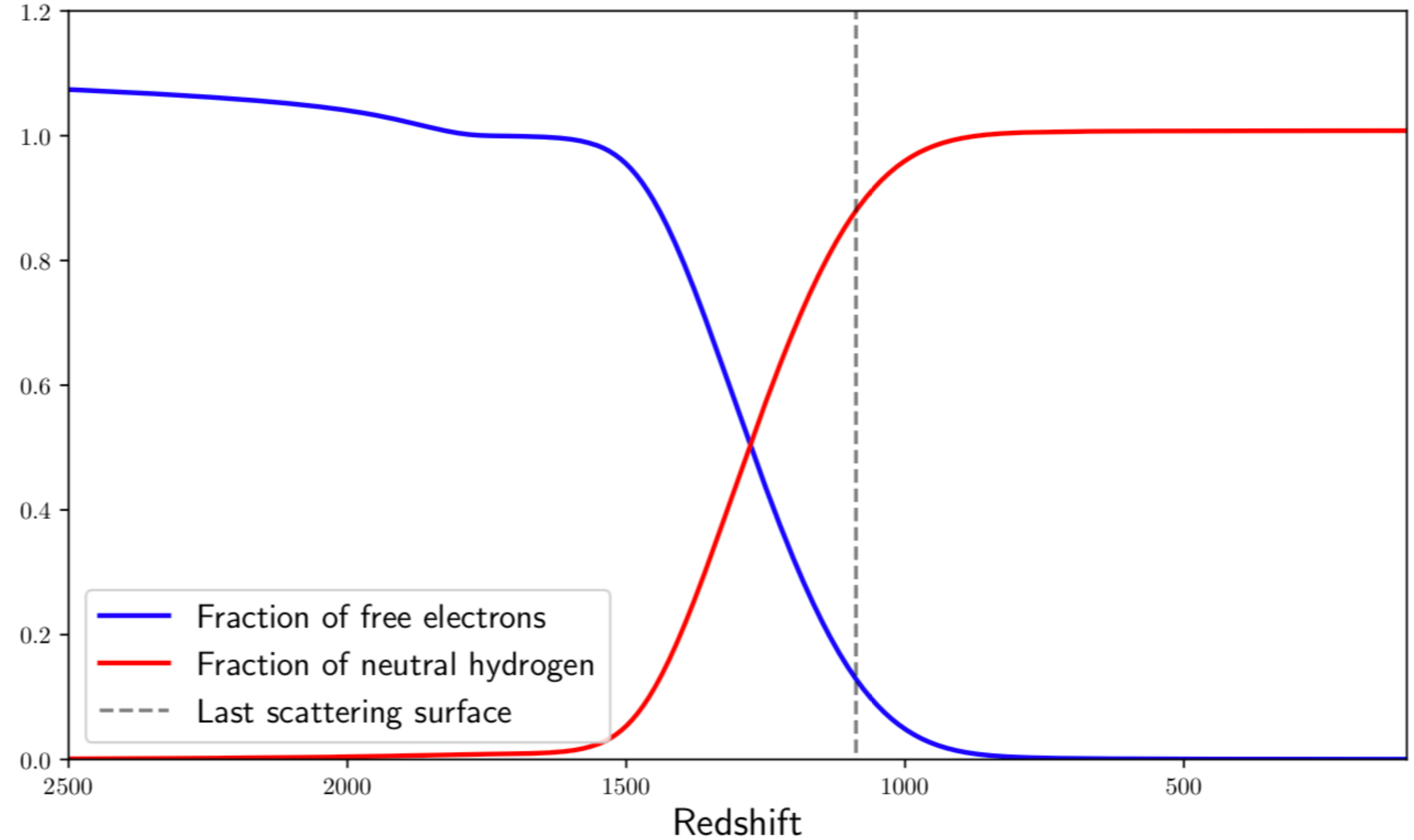
Rayleigh Scattering

- Usual Thomson scattering is the frequency independent of photons off charged particles

- Rayleigh scattering is the scattering of light from particles whose size is much smaller than the wavelength

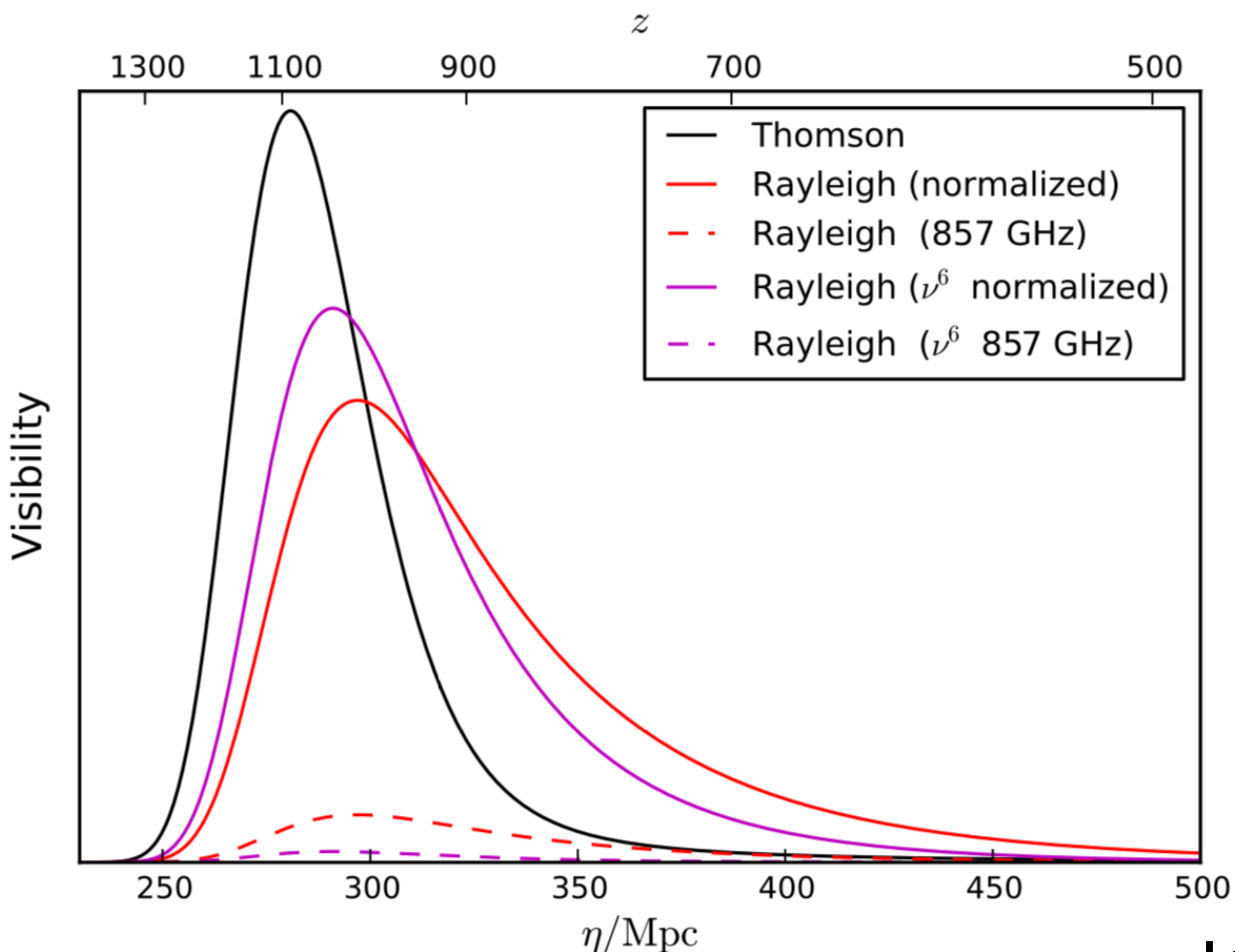
- For CMB scattering will be from neutral hydrogen (and a little helium).

- Frequency dependent!



$$\sigma_R(\nu) = \sigma_T \left[\left(\frac{\nu}{\nu_0}\right)^4 + \frac{638}{243}\left(\frac{\nu}{\nu_0}\right)^6 + \frac{1299667}{236196}\left(\frac{\nu}{\nu_0}\right)^8 + \ldots \right]$$

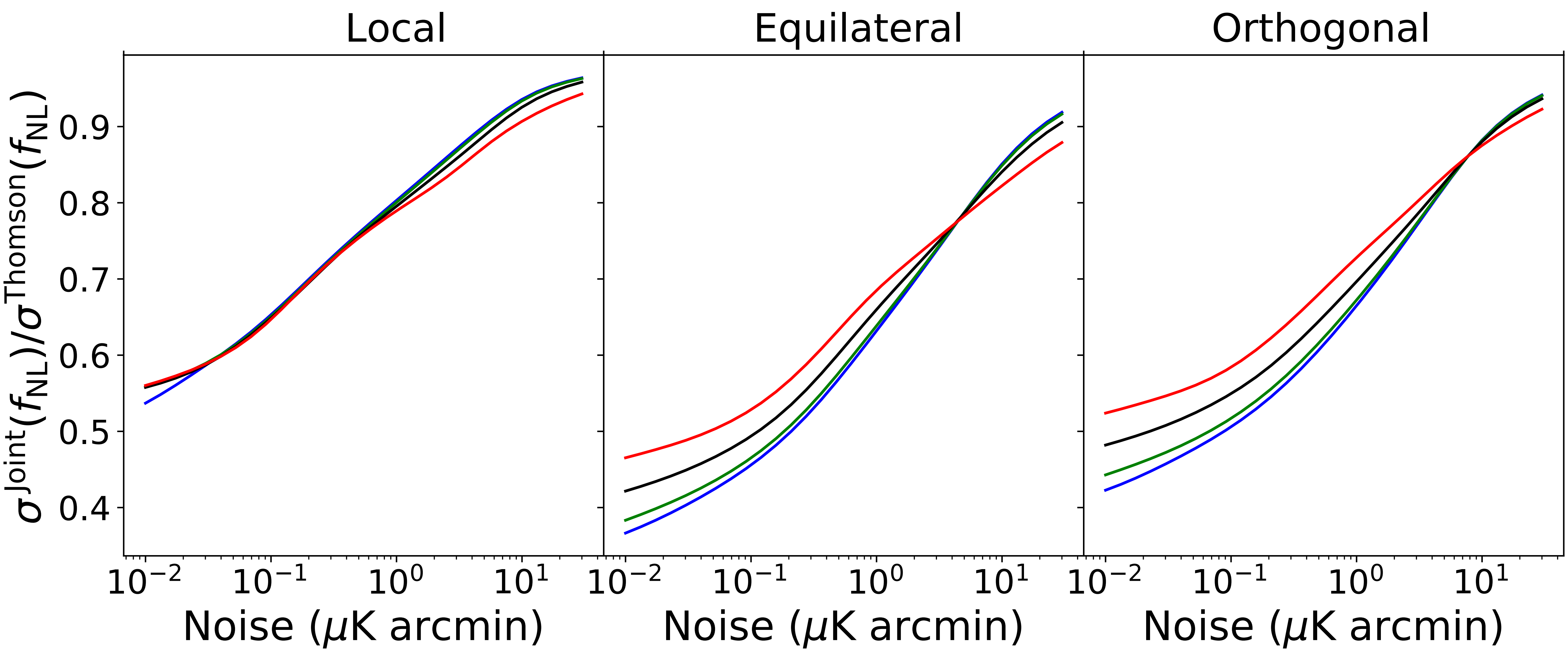
Rayleigh Scattering Probability



Lewis (2014)

Rayleigh scattering can undo damping

Comparison of PNG constraints using standard CMB anisotropies (Thomson) to a joint analysis of Thomson and Rayleigh scattering



Coulton et al (2020)

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

See Giorgio's talk!

Constraints with Upcoming Experiments

Shape ($\zeta\zeta h$)	Constraint	
Local	-48 ± 28	1
Equilateral	-	8
Orthogonal	-	3

Shiraishi et al (2018)

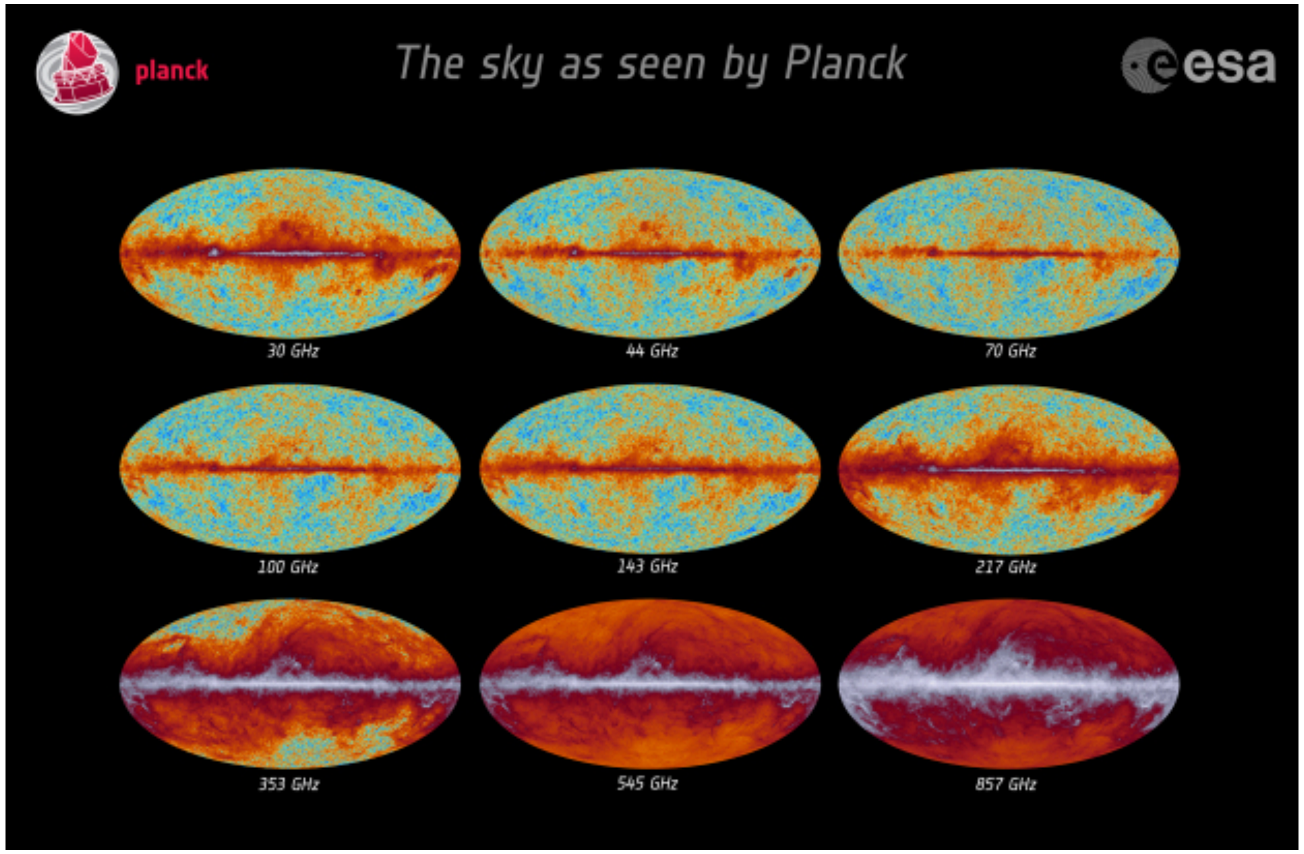
Planck Collaboration XI (2019)

The Simons Observatory Collaboration XI (2018)

Challenges from foregrounds

- Biases from Galactic foregrounds

Jung et al (2018)
Coulton and Spergel (2018)



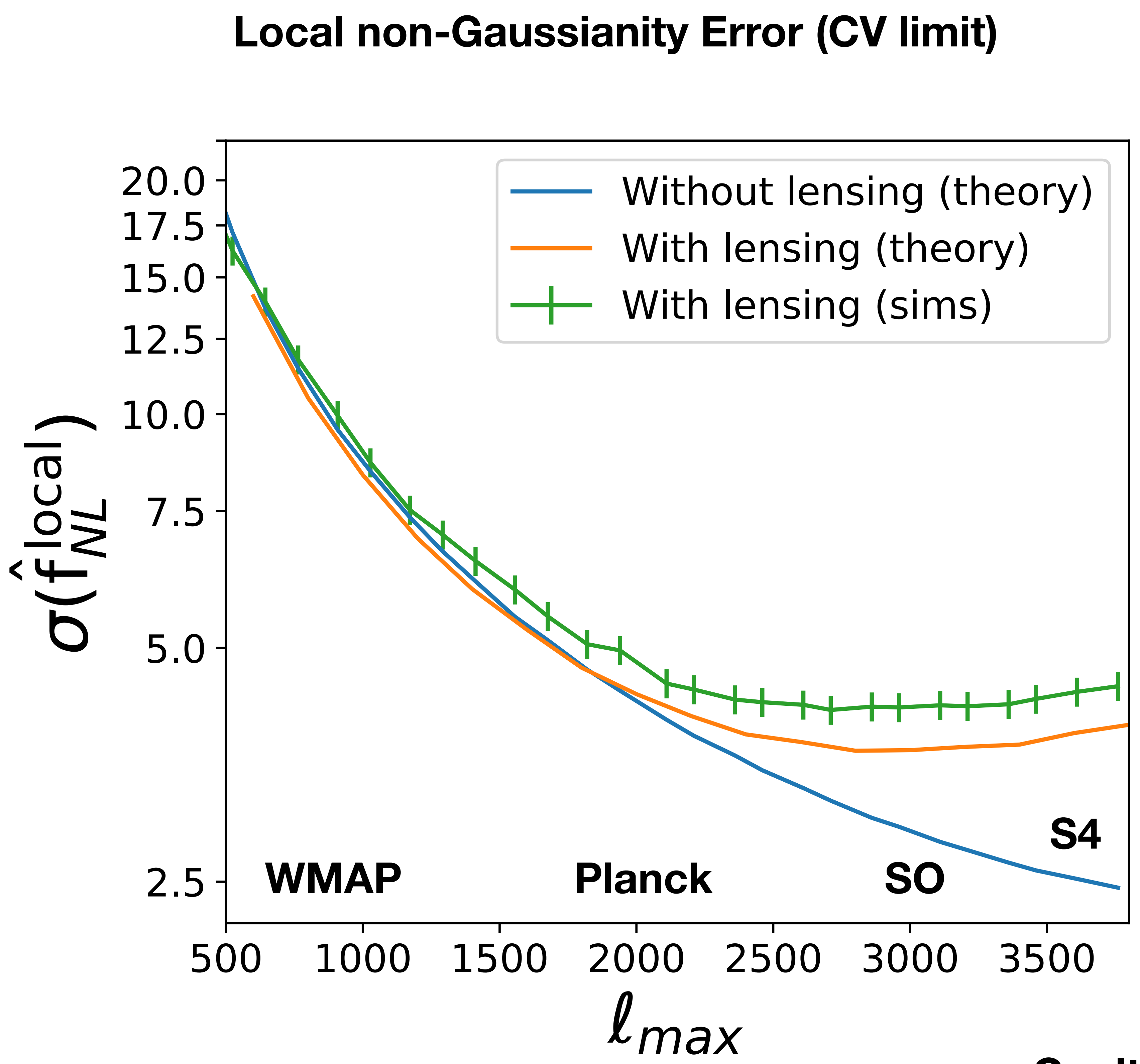
- Lensing induced noise

Coulton et al (2019)

- Biases from extra-Galactic sources - CMB secondary anisotropies

Curto (2015)
Hill (2018)
Coulton et al (2022)

Diminishing returns?



Coulton et al (2019)

Lensing contributions

- The effect of CMB lensing is to couple CMB modes:

$$\langle a_{\ell,m} a_{\ell',m'} \rangle = \sum f_{\ell,\ell',L} \phi_{L,M}$$

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

Adds to the bispectrum: $\hat{f}_{NL} \propto \sum_{\ell_1 \ell_2 \ell_3} b_{\ell_1 \ell_2 \ell_3} a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \propto \sum_{\ell_1 \ell_2 \ell_3} b_{\ell_1 \ell_2 \ell_3} a_{\ell_1 m_1} \hat{\phi}_{LM}$

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

$$\langle f_{NL}^{local^2} \rangle \propto \langle f_{NL}^{local^2} \rangle_{gaus} + \sum_{\{\ell_i\}} b^{local}_{\ell_1,\ell_2,\ell_3} C_{\ell_1} C_L^{\phi\phi} b^{local}_{\ell_1,\ell_2,\ell_3}$$

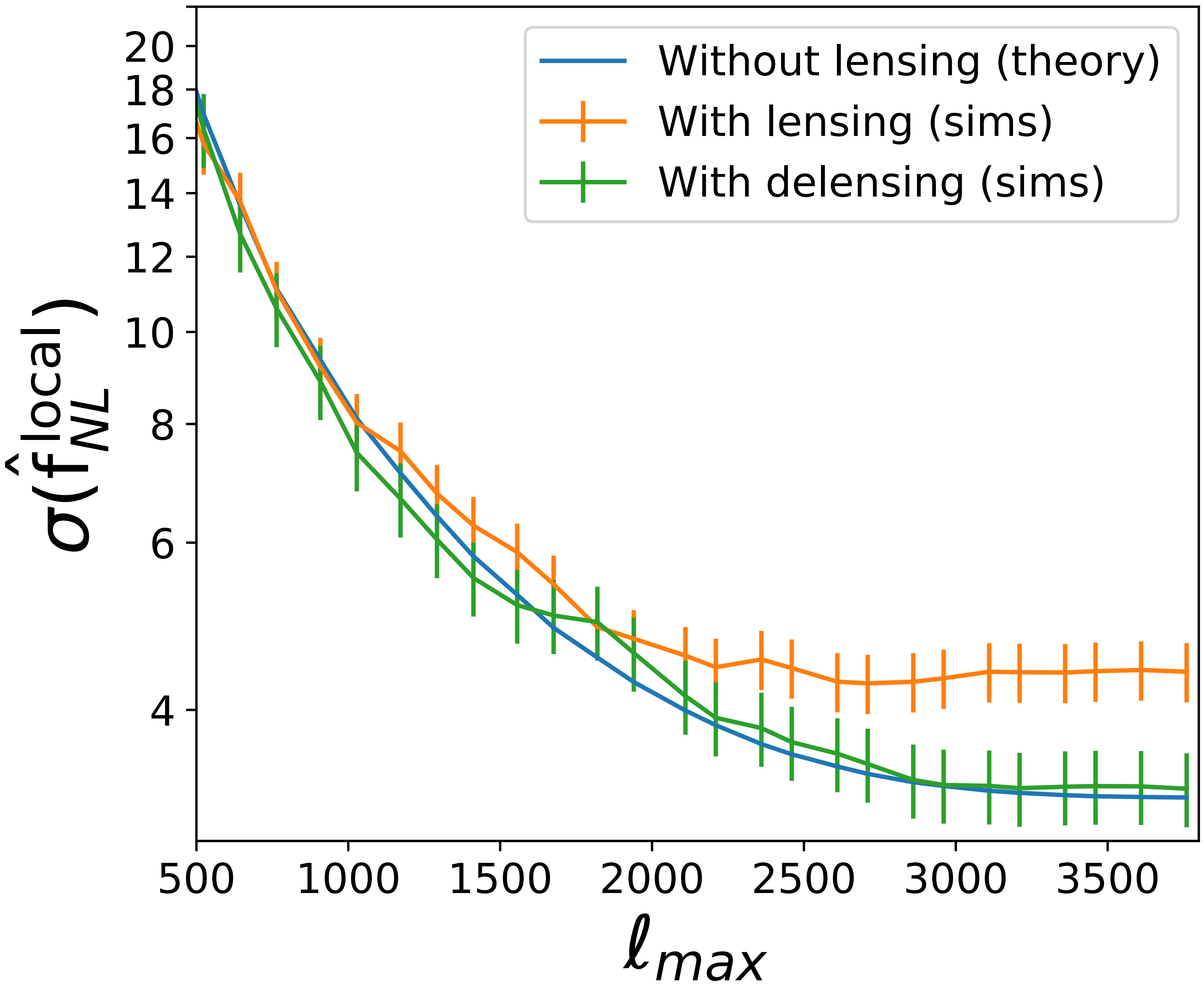
- Local primordial non-Gaussianity
    - Modulation of small scale power by large wavelength mode
- CMB Lensing:
    - Modulation of small scale power by intervening degree scale lens

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: $\hat{\tilde{T}}(\vec{n}) \approx T(\vec{n} - \nabla\hat{\phi})$
- Reconstruct the lensing potential via quadratic estimator (Hu and Okamoto 2003)
- Potential biases from correlations between reconstruction noise and estimator maps

Delensing for an SO-like experiment

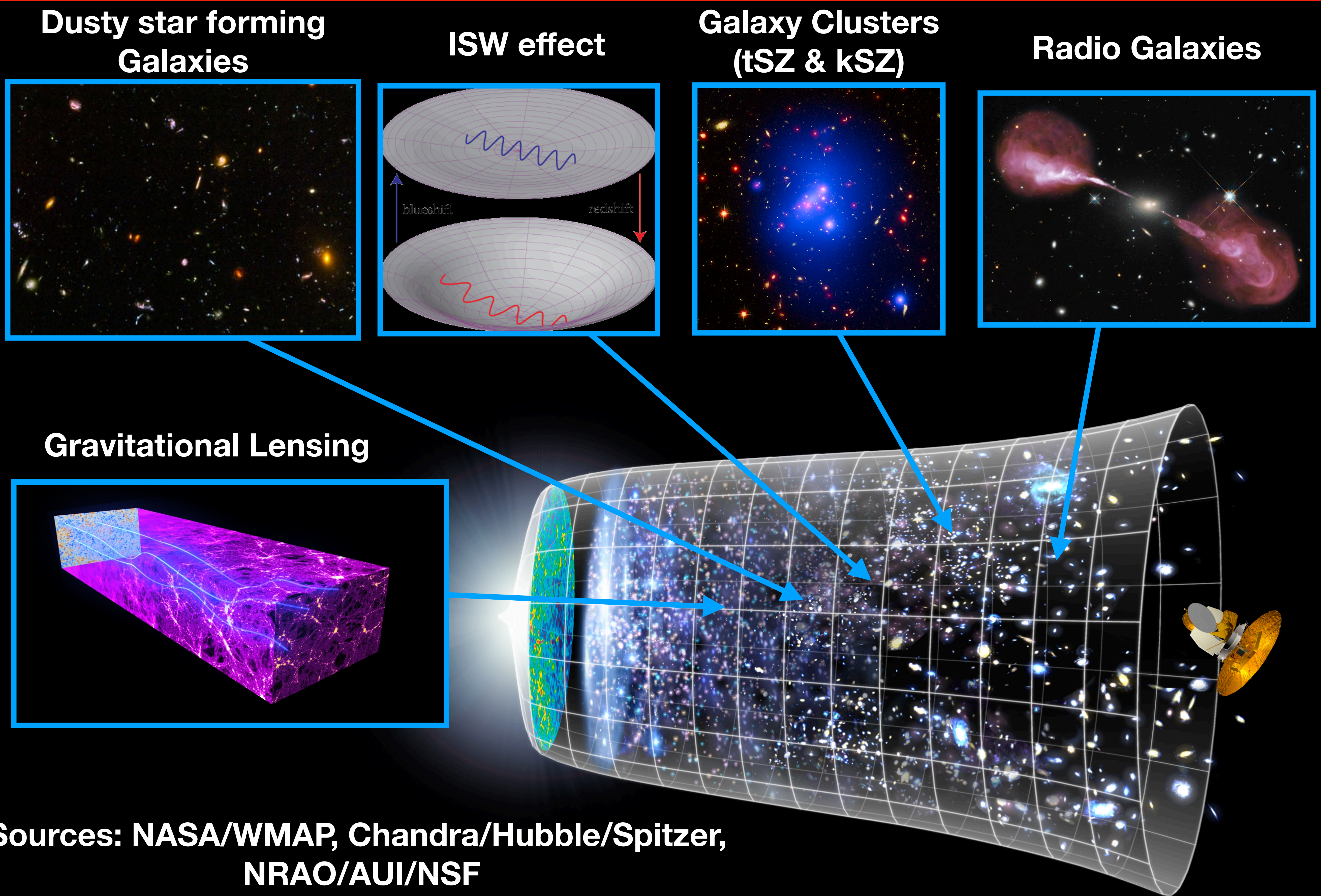
Local non-Gaussianity SNR for measurements with SO levels of noise with delensing!



Nearly optimal!
With no biases

Coulton et al (2019)

What are secondary anisotropies?

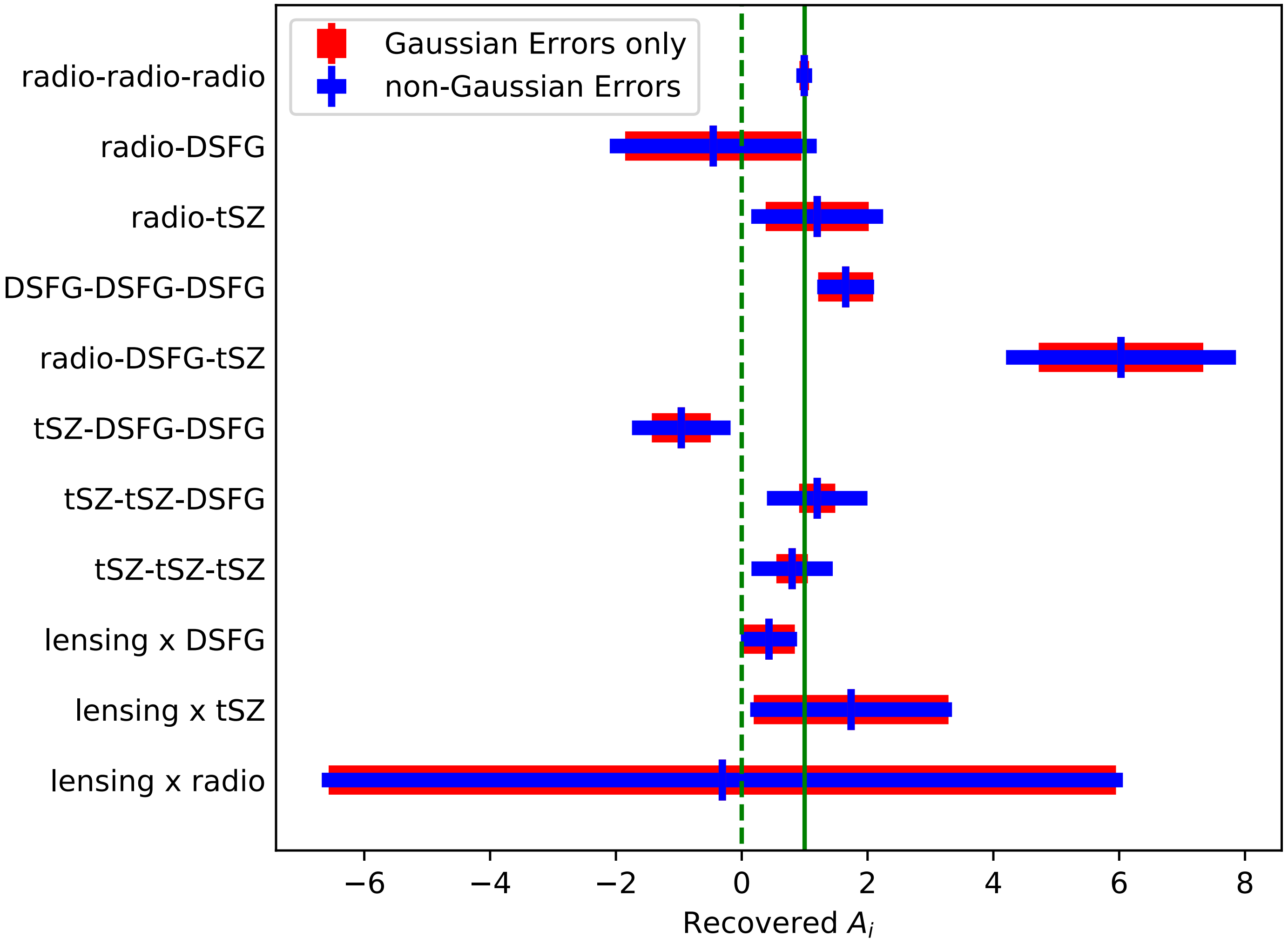


Sources: NASA/WMAP, Chandra/Hubble/Spitzer, NRAO/AUI/NSF

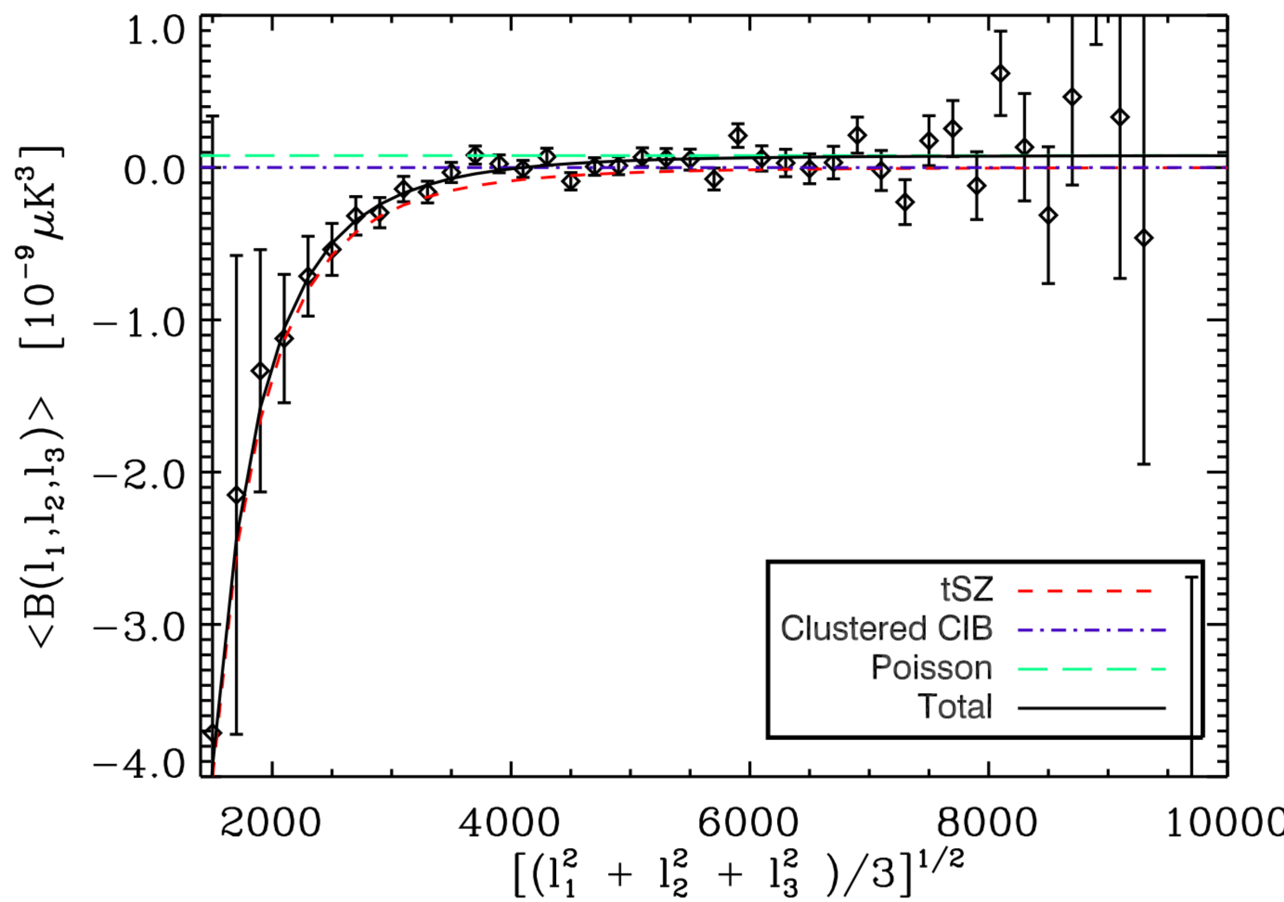
Why are they important?

Measurements of the bispectrum from CMB secondary anisotropies

ACTPol



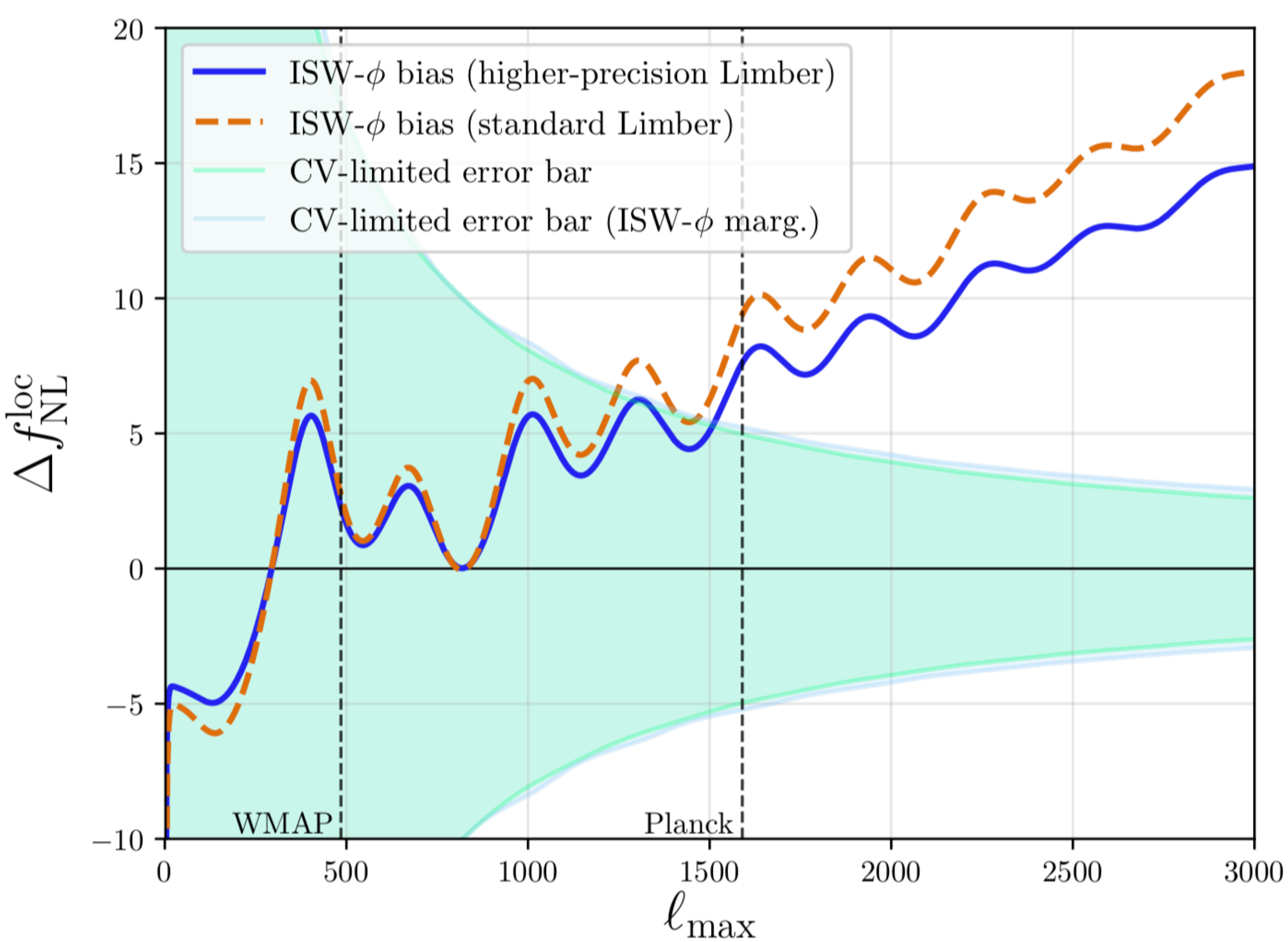
SPT



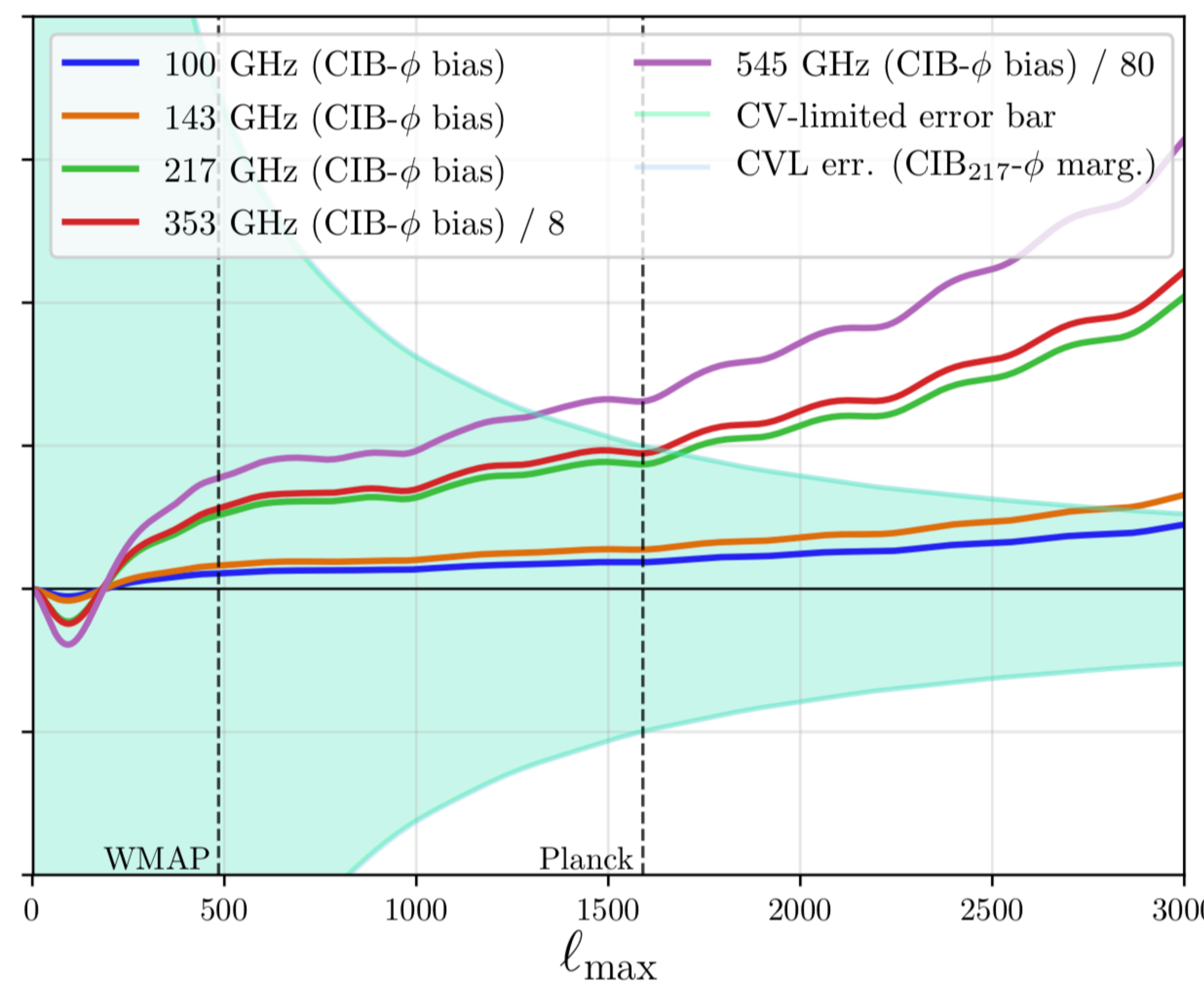
Crawford et al (2014)
Coulton et al (2018)

Biases to local non-Gaussianity measurements

ISW-lensing bispectrum bias



CIB - lensing bispectrum bias



From: Hill (2018)

Smith et al (2006), Lewis et al (2011)

Small scale non-Gaussianities

- Bispectra from CMB secondaries project on primordial templates. i.e.

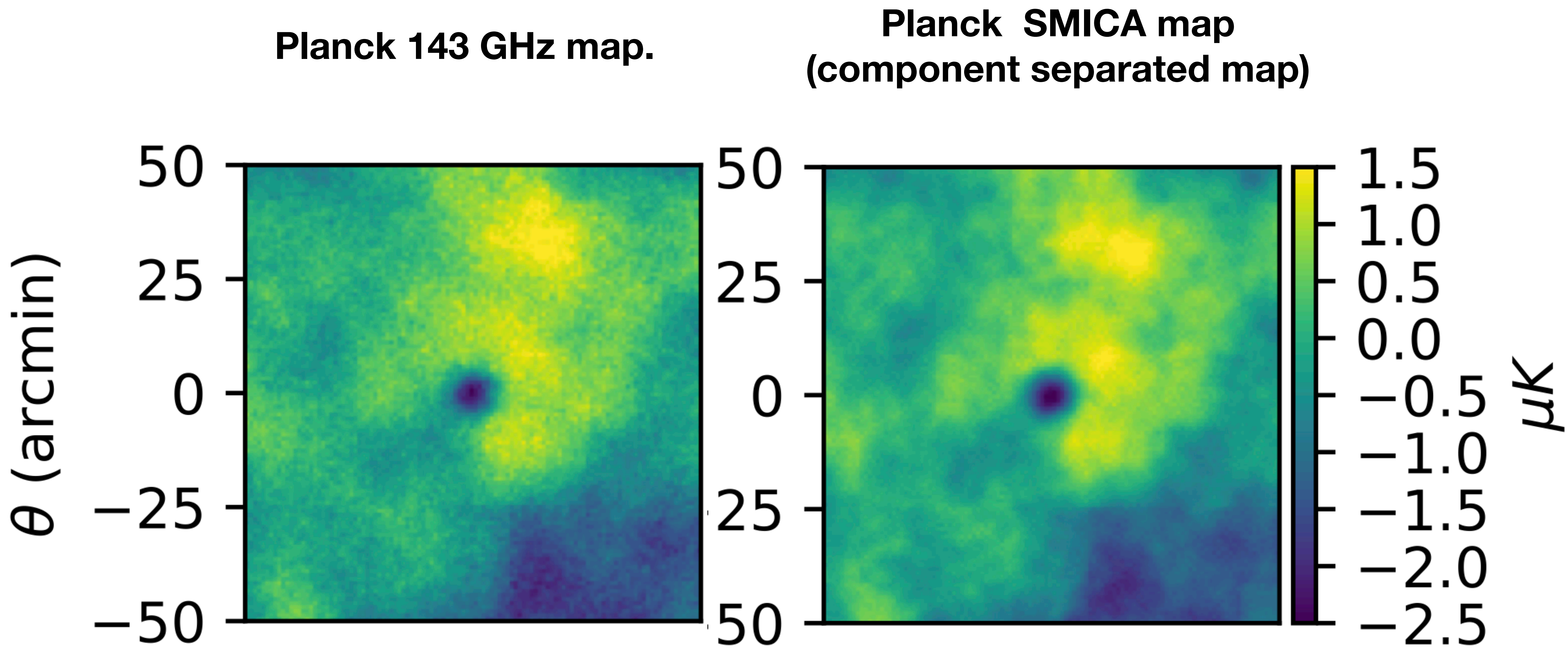
$$f_{NL} \propto \sum b_{\ell_1,\ell_2,\ell_3} \langle T_{\ell_1} T_{\ell_2} T_{\ell_3} \rangle$$

ISW		**ISW**		**ISW**
tSZ		**tSZ**		**tSZ**
kSZ		**kSZ**		**kSZ**
CIB	**x**	**CIB**	**x**	**CIB**
Radio		**Radio**		**Radio**
Lensing		**Lensing**		**Lensing**

Smith et al (2005) Hill (2018) Coulton et al (2022)

The challenge of removing foregrounds

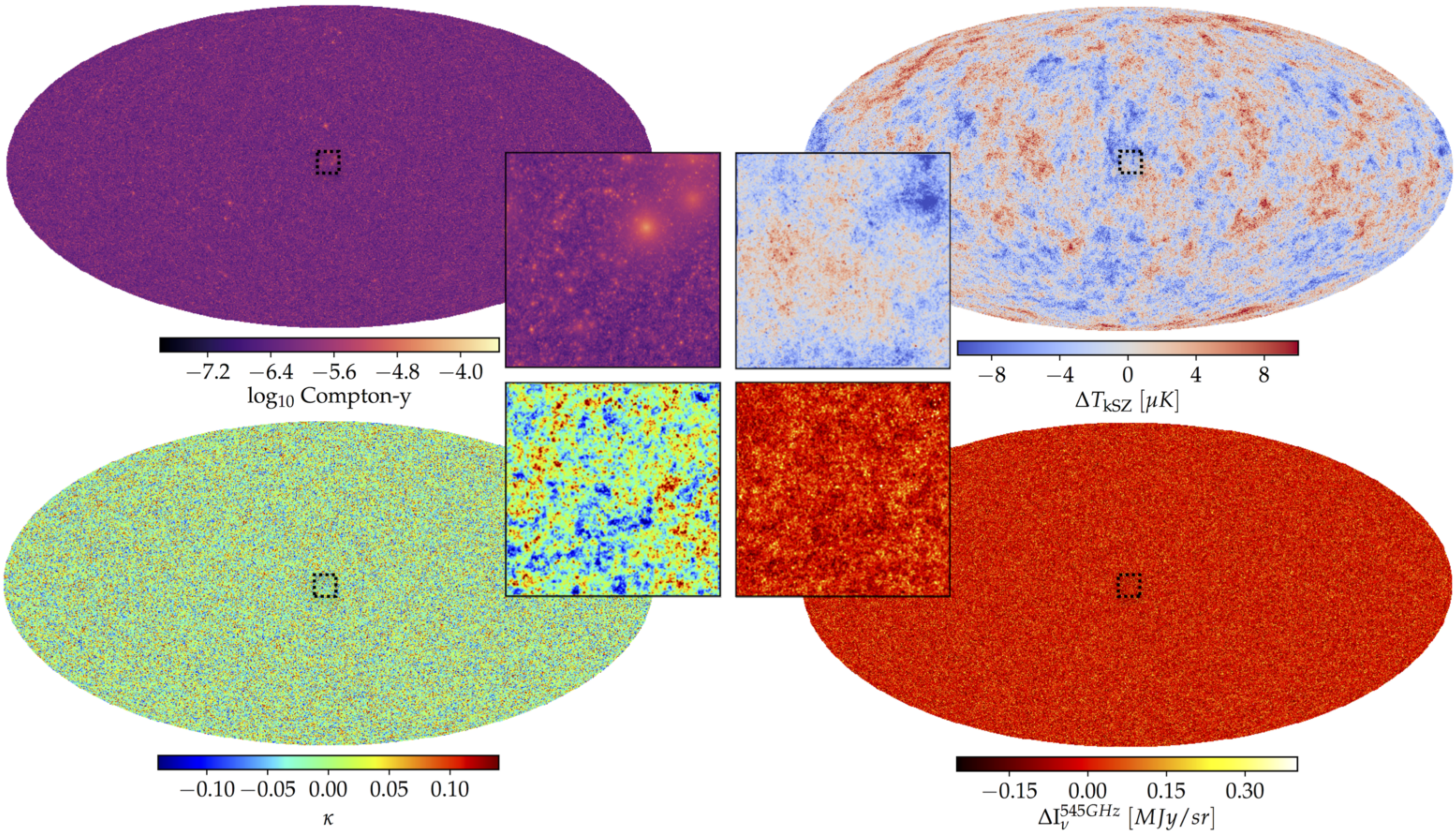
CMB maps stacked on the locations SDSS DR8 redMaPPer clusters



Madhavacheril and Hill (2018)

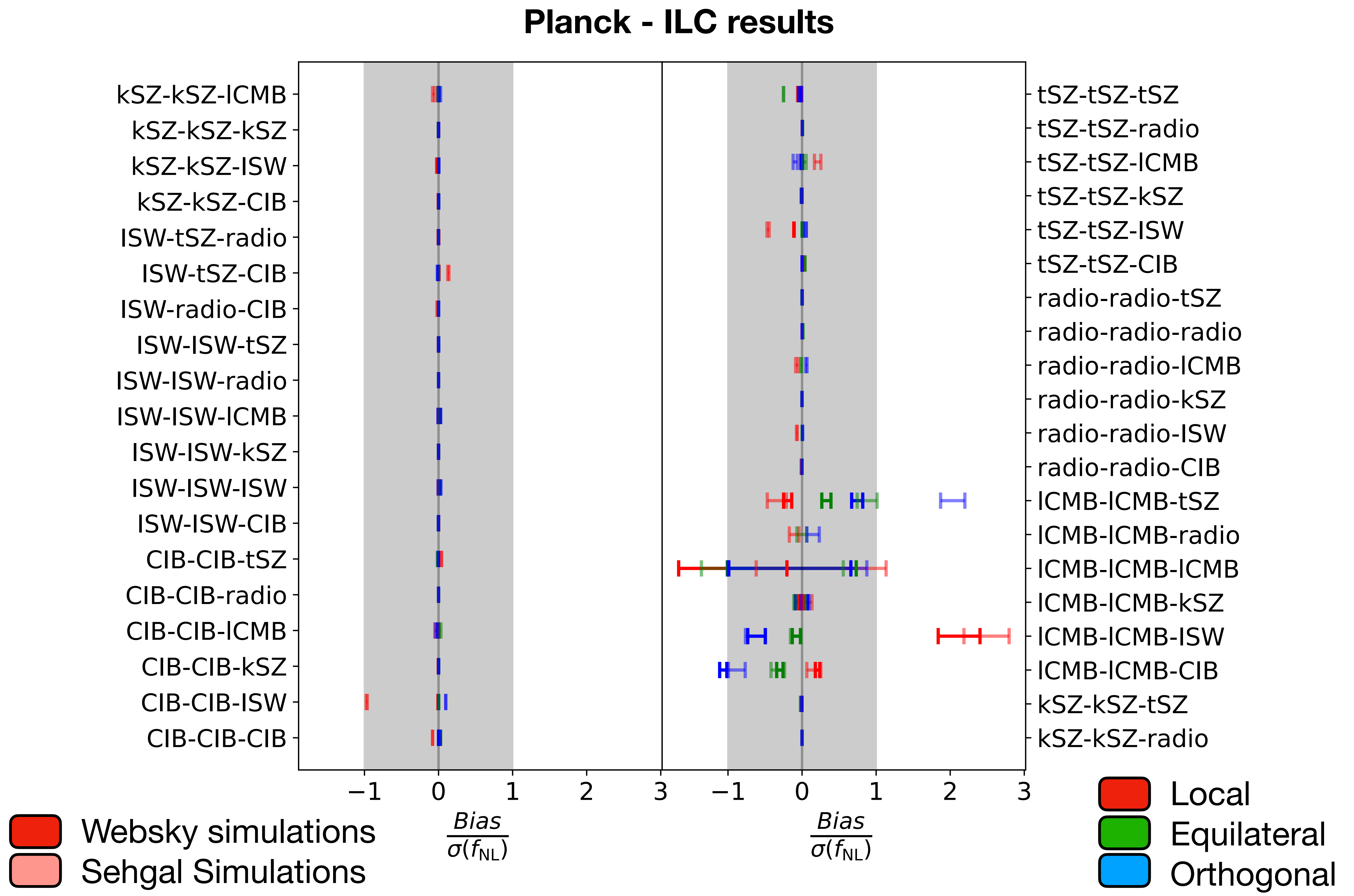
Exploration with simulations

WebSky simulation of extra-galactic foregrounds



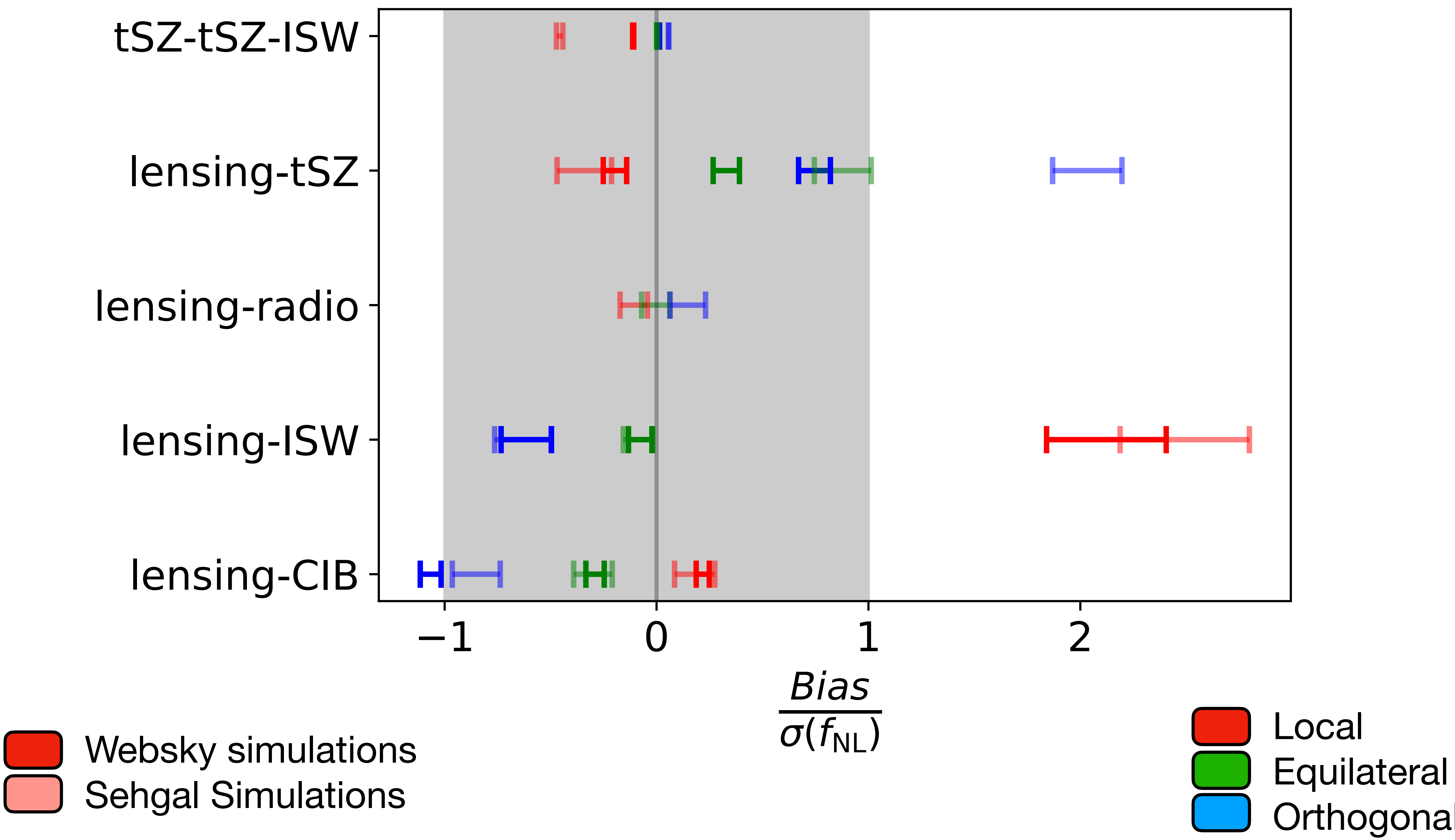
Stein el al (2019) Sehgal et al. (2010)

What biases could there be for Planck?

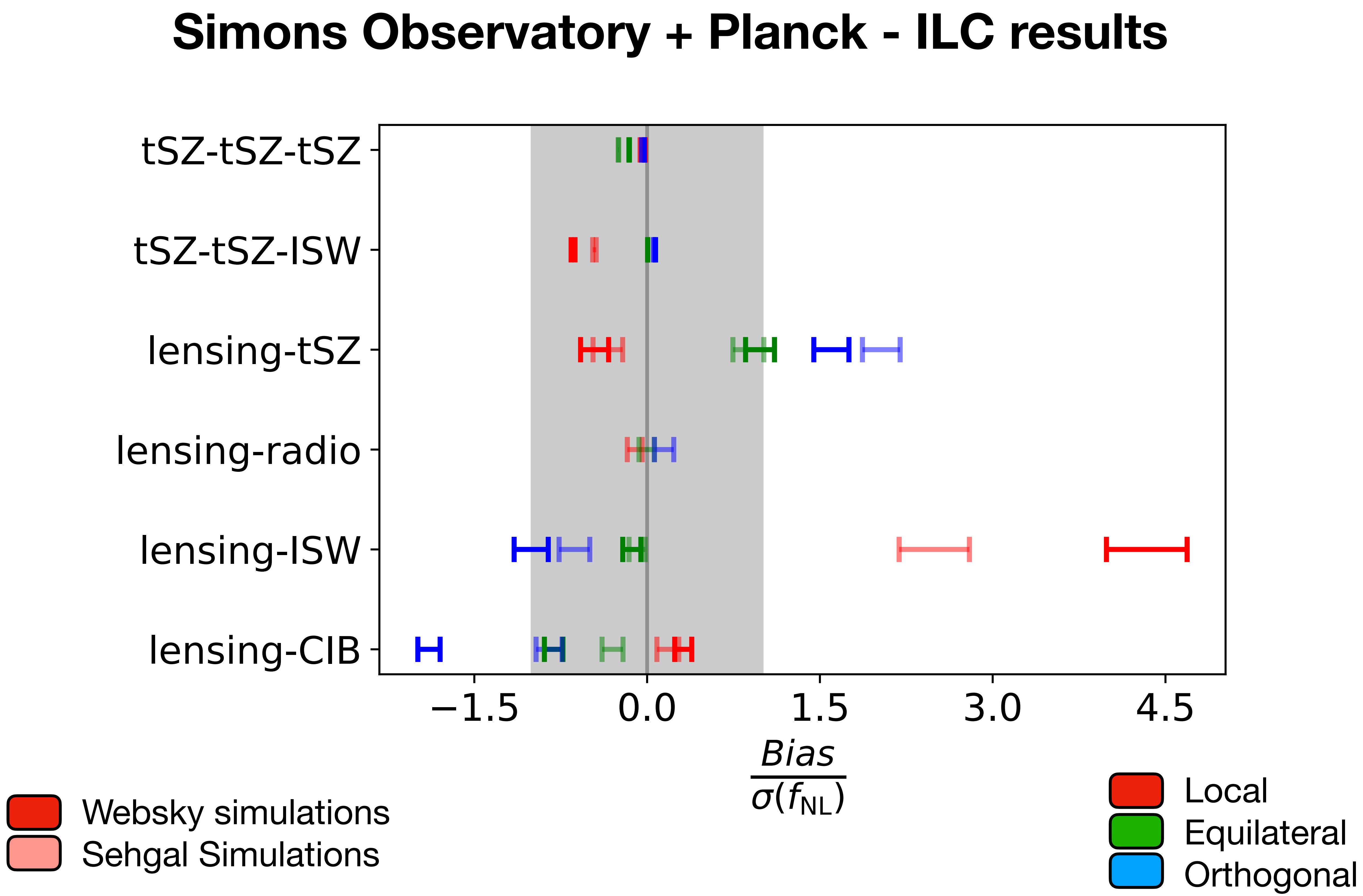


What biases could there be for Planck?

Planck - ILC results



Biases after foreground cleaning



With great sensitivity comes new opportunities

Revisiting the intrinsic bispectrum

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

Coulton (2021)

B mode Intrinsic Bispectrum

- Usually when we think of the CMB we think of linear perturbation theory:

$$T \propto \delta \quad \text{and} \quad B \propto h_{ij}$$

- However there are second order corrections:

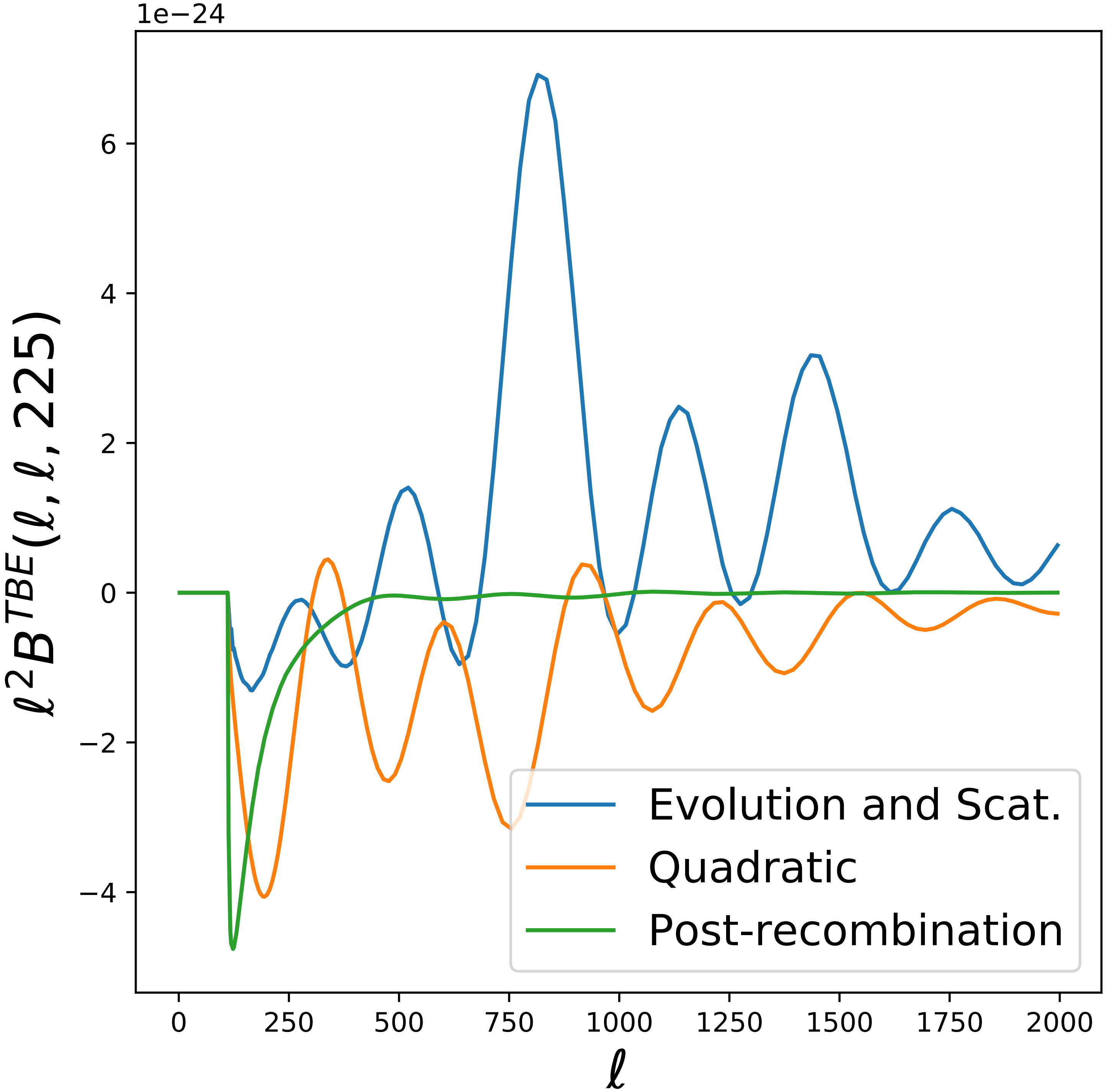
$$T \propto \delta + \delta^2 \qquad B \propto h_{ij} + \delta^2$$

- These second order modes will be correlated with the scalars. Ie:
  - $\langle TTT \rangle, \langle TTE \rangle, \langle TEE \rangle, \langle EEE \rangle \neq 0$
- These bispectra are hard to measure due to the large ‘noise’ from first order!
- Hence try: $\langle BTT \rangle, \langle BET \rangle, \langle BEE \rangle \neq 0$!

Benke et al (2010,2011) Fidler et al (2015)

The parity-odd intrinsic bispectrum

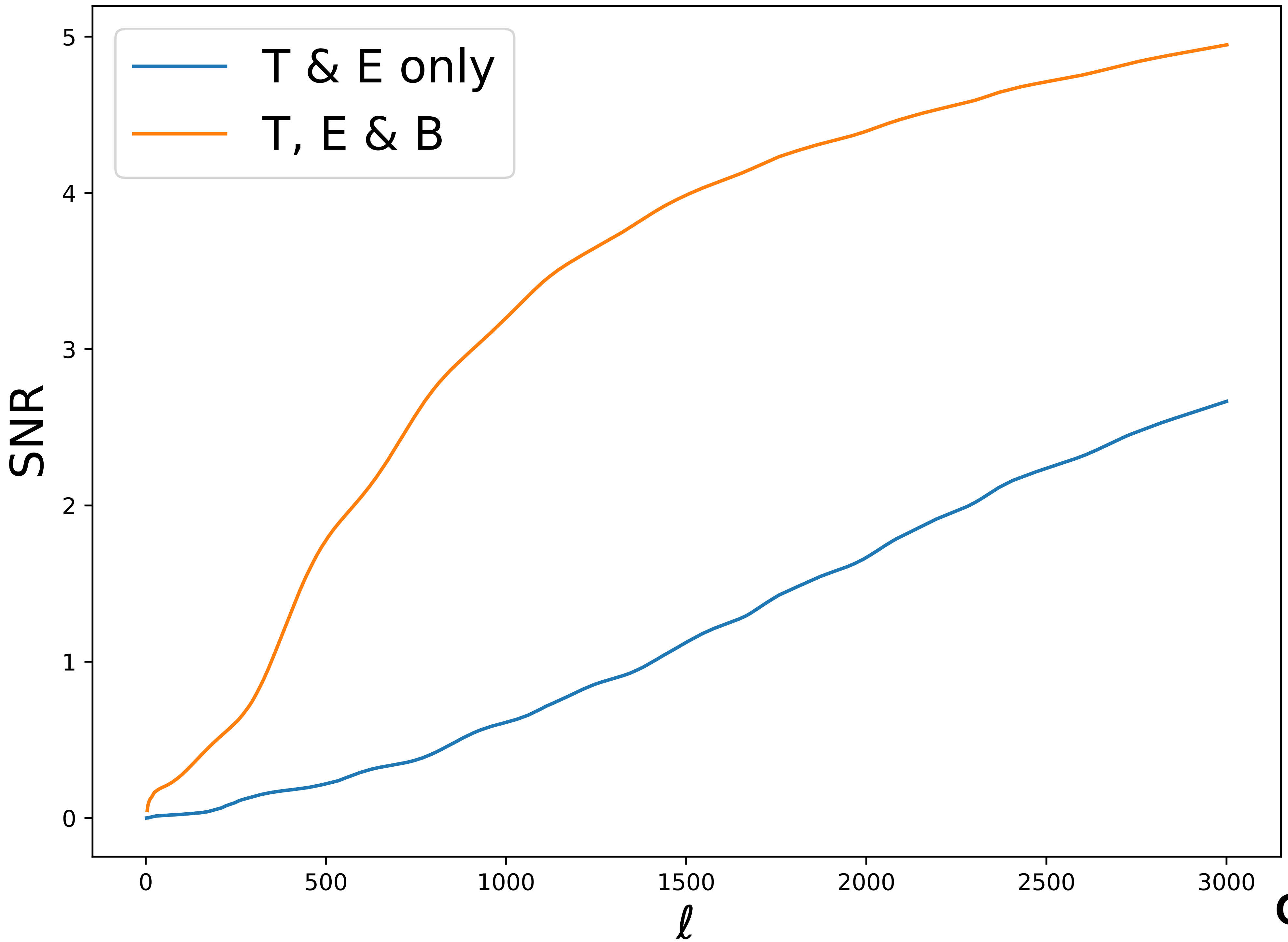
Semi-squeezed bispectrum slice



- 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 2^{nd} order
  - redshifting terms
- Post-recombination:
  - Propogation through inhomegenous universe

Is this detectable with CMB-S4?

Detection Significance for the intrinsic bispectrum with CMB-S4



Coulton (2021)

Probes beyond from the primary anisotropies

Scale Dependent Bias from CMB secondaries

- CMB secondaries are anisotropies imprinted upon CMB as light propagates through the universe to us.

- PNG can generate scale dependent bias on large scales
  $$b(k) \simeq b_1 + f_{NL} b^{NG}(k)$$

- Measuring large scale bias is limited by sample variance

- Heuristically, we can avoid sample variance by measuring $P^{g\delta}(k)/P^{\delta\delta}(k) \propto b_1 + f_{NL} b^{NG}(k)$

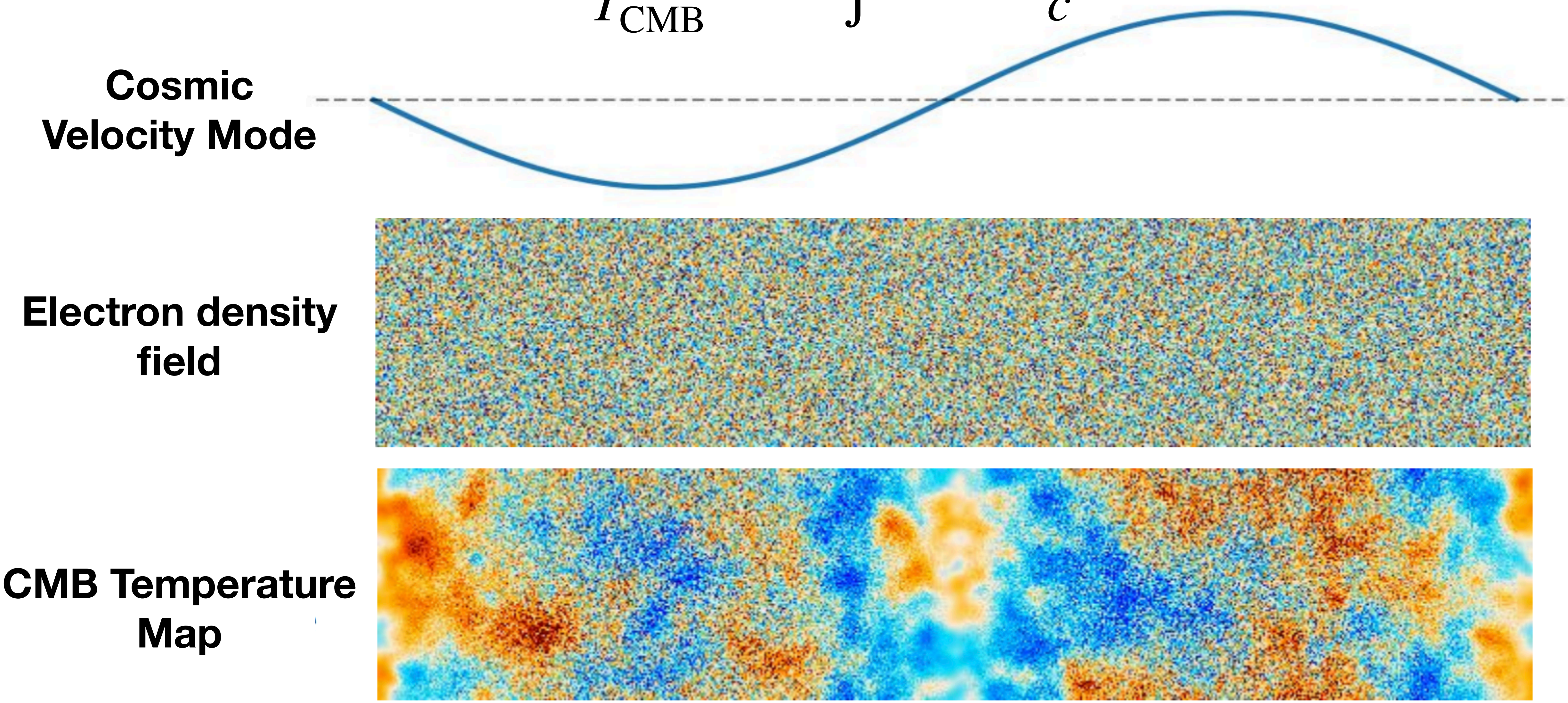
For probing trispectrum with kSZ see Anil Neta's talk!

- CMB secondaries can help via two ways:
  - Measuring $\delta(k)$ e..g via CMB lensing
  - Measuring a biased tracer, e.g. the CIB.
  - e.g. From Planck lensing and CIB we have $\sigma(f_{NL}^{local}) \sim 17$

Dalal et al (2008)
Seljack (2009)
McCarthy et al (in prep)

kSZ velocity reconstruction

$$\frac{\Delta T(\mathbf{n})}{T_{\mathrm{CMB}}} \propto -\int \mathrm{d}\chi \delta_e \mathbf{n} \cdot \frac{\mathbf{v}}{c}$$



Can reconstruct the velocity by

$$\hat{v}_r \propto \langle \delta_g T_{kSZ} \rangle_{\text{small scales}} \propto P_{ge} v_r$$

Madhavacheril (2019)
Smith (2019) ++

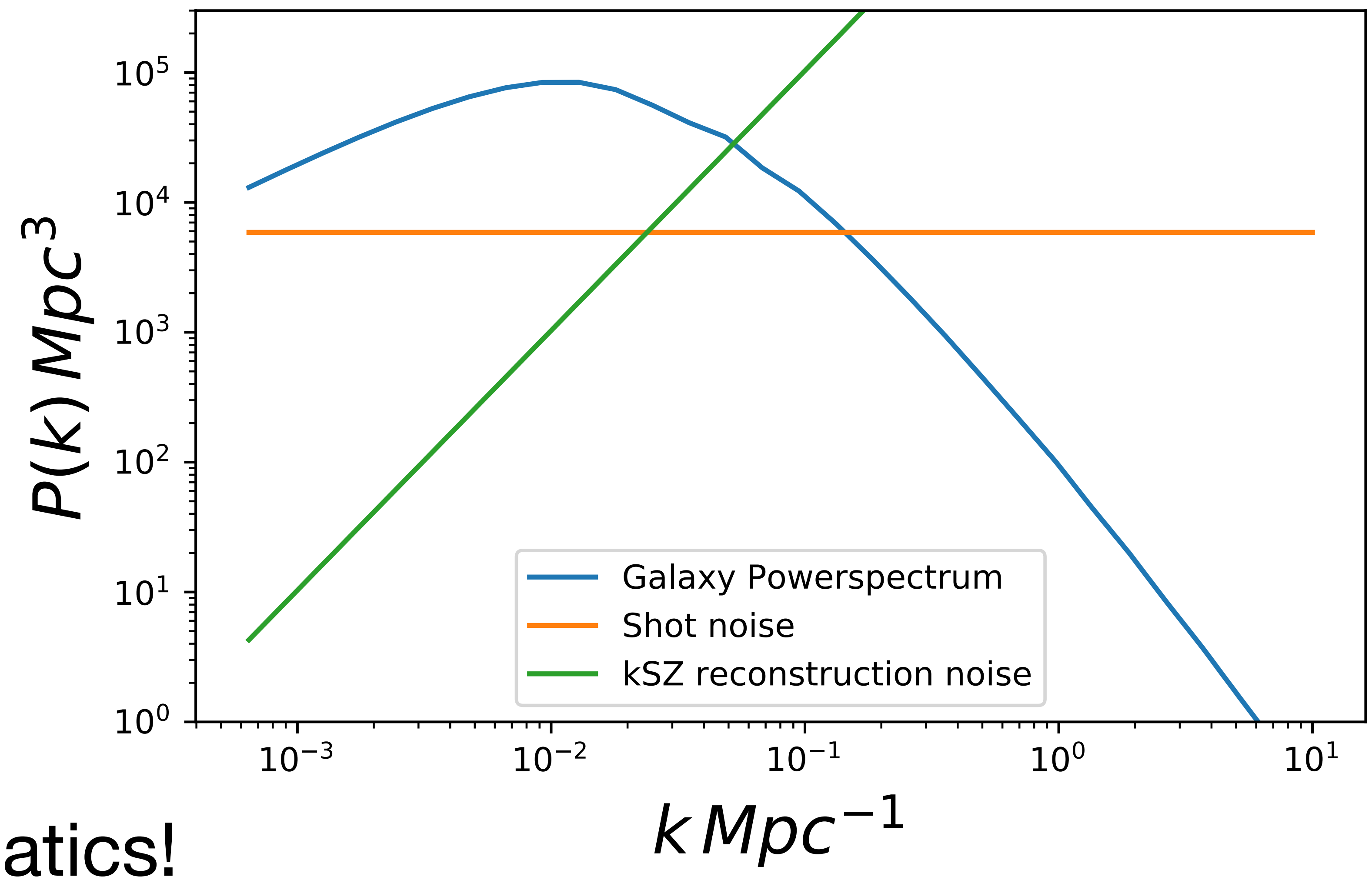
kSZ Velocity Reconstruction

- From cosmological perturbation theory:

$$v_r(k) = i\hat{k}_r \frac{aHf}{k} \delta(k)$$

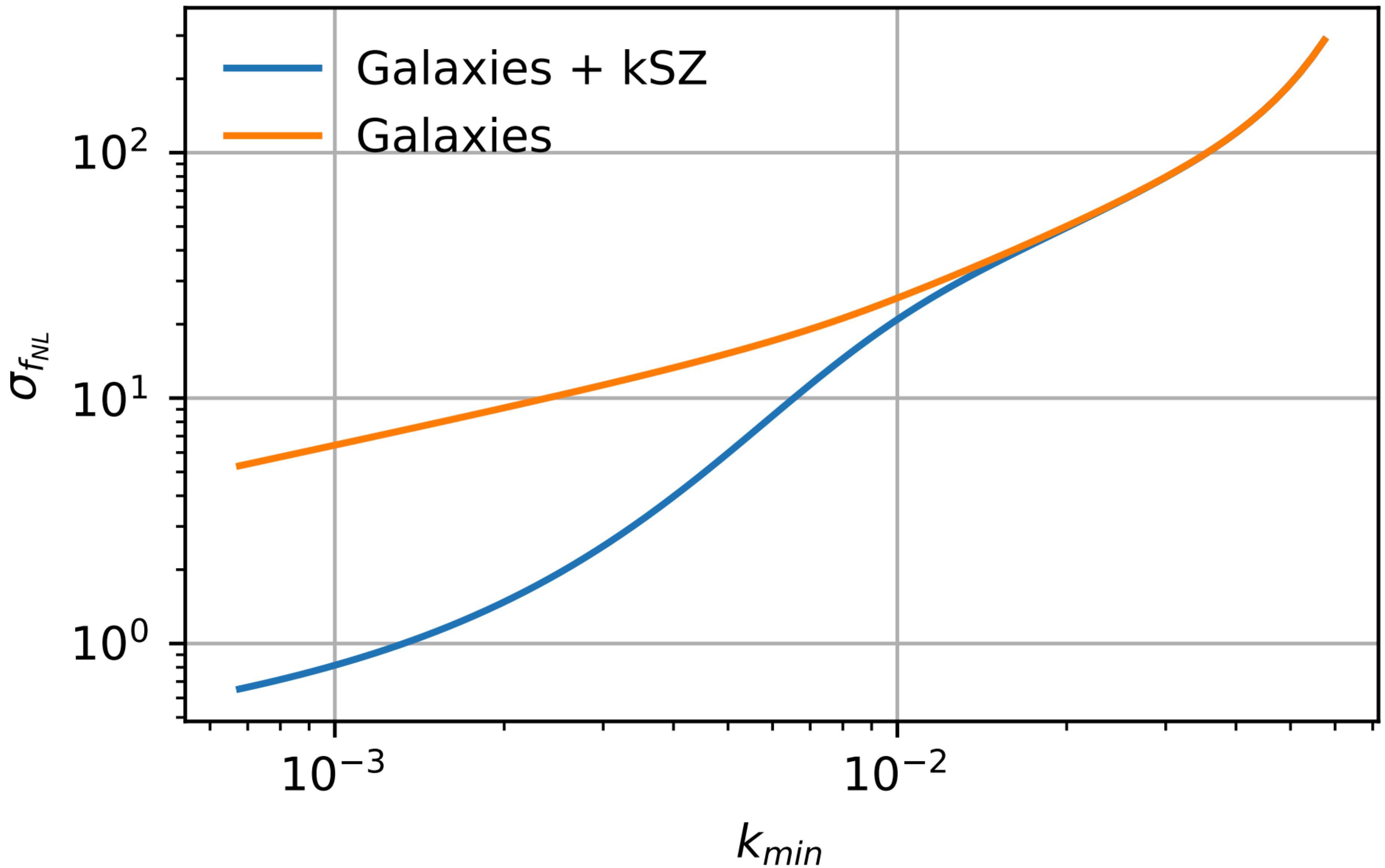
- Very low noise on large scale modes

- As a reconstructed mode it has very distinct systematics!



kSZ forecast constraints

Forecast of how well kSZ from CMB-S4 can aid LSST constraints on f_{NL}



See José Luis Bernal's talk for kSZ+ line intensity

Munchmyer et al (2018)

Conclusions

- Upcoming CMB experiments will significantly improve our understanding of the early universe through PNG constraints
- New signals to search for and methods to probe them:
    - Primordial correlations between tensors and scalars
    - Rayleigh scattering
    - Spectral distortions
    - Intrinsic bispectra
- Understanding and mitigating foregrounds is an important challenge!

Thanks!