The parity-odd intrinsic CMB -bispectrum

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

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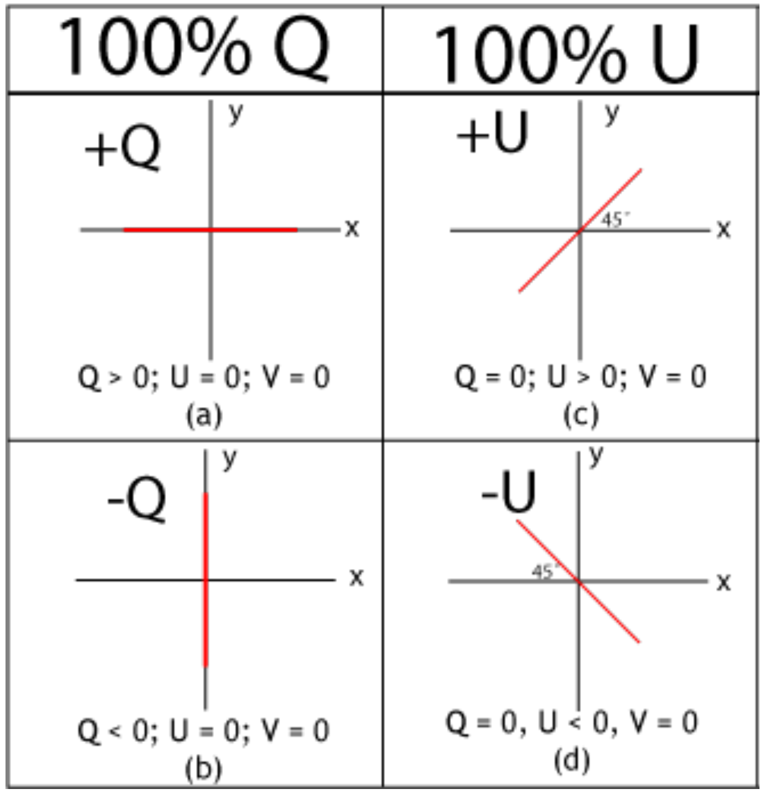
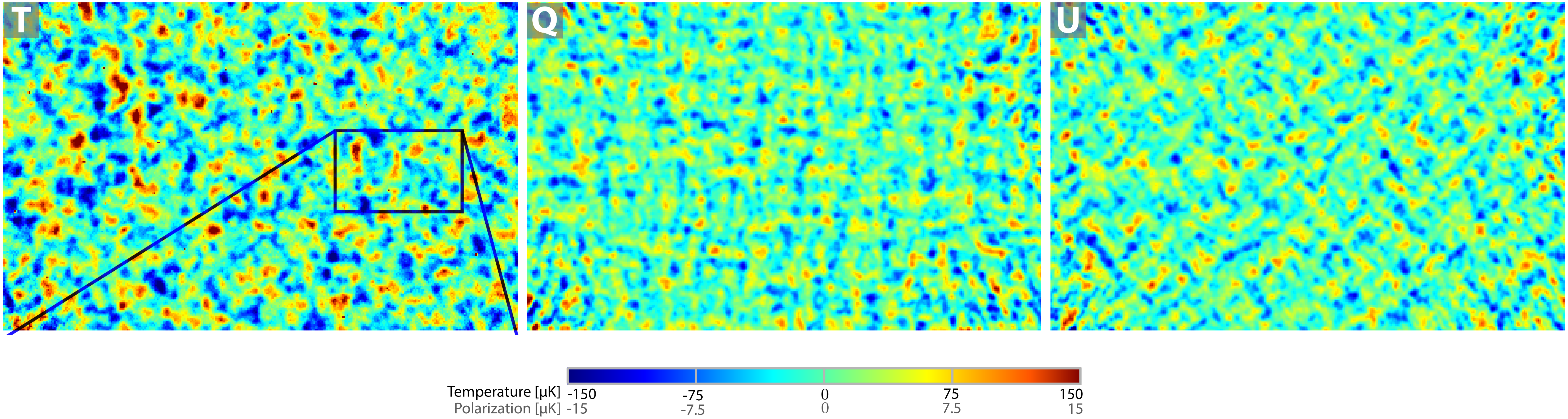
(2103.08614)

Cosmology from anisotropies

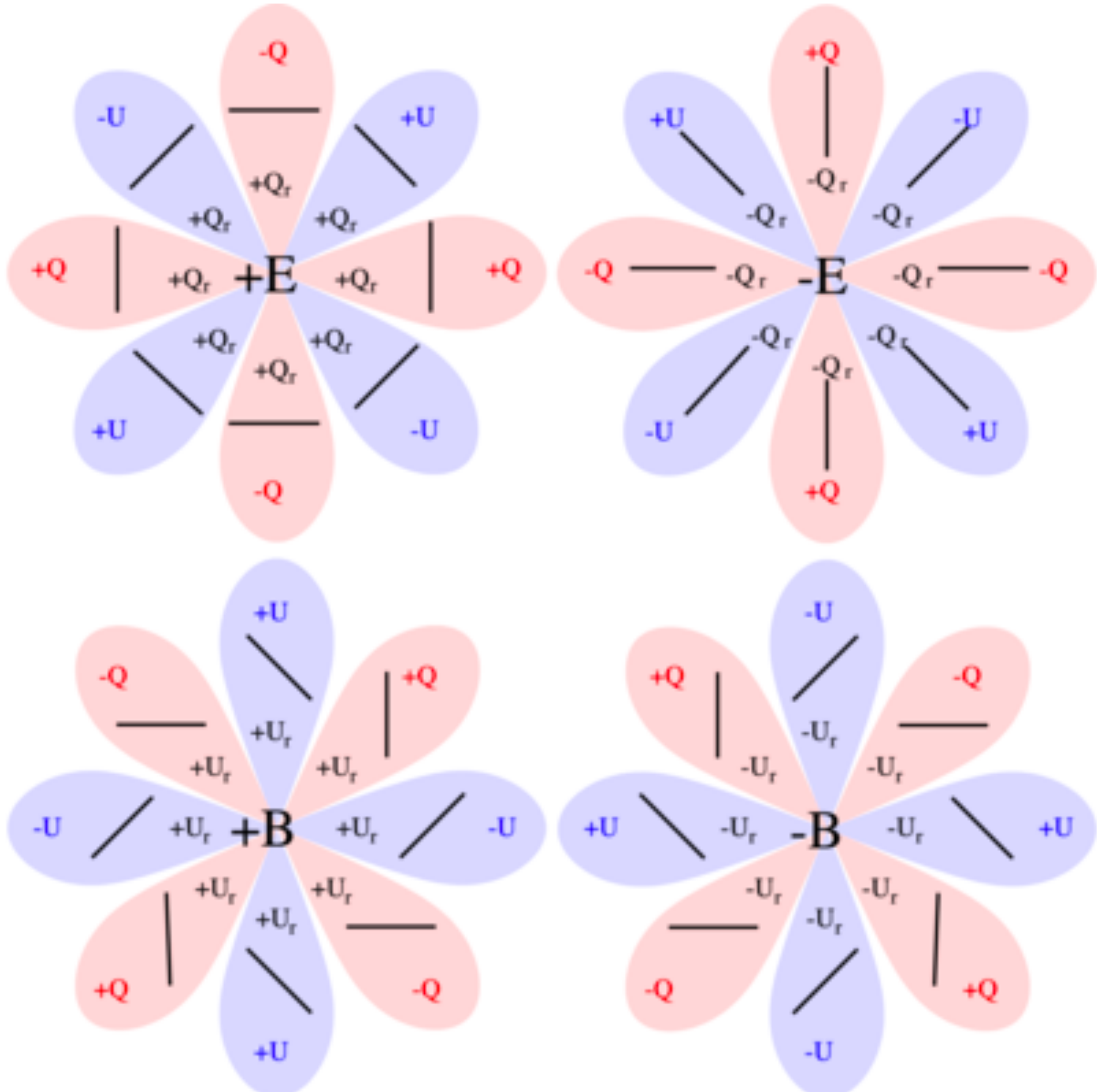


Source: Wikipedia

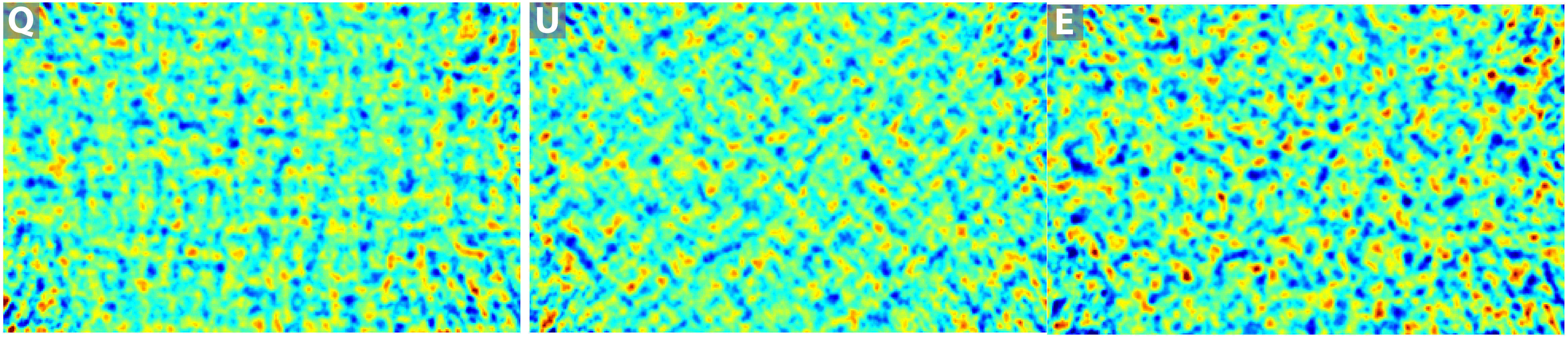


Naess et al (2014)

E modes and B modes



Credit: Sigurd Naess



What is 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:

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

- Vanishes for Gaussian fluctuations

Komatsu (2002)
Spergel and Goldberg (1999)

CMB anisotropies at a high level

- The evolution of primordial fluctuations to CMB anisotropies is described by the Boltzmann equations.

- The solution to the linearized Boltzmann equation can be written schematically

$$a_{\ell m}^{X} \sim \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3} T_\ell^X(k,\eta_0)\Phi(\mathbf{k}, t=0)$$

where $T_\ell^X(k,\eta_0)$ - transfer functions that encode physics of evolution
$\Phi(k, t=0)$ - primordial perturbation

- Linear relation: Gaussian initial conditions, Gaussian anisotropies

- No mode mixing: Primordial scalars can only source temperature and E mode polarization patterns - B modes must come from primordial tensors

Beyond leading order

- Given primordial fluctuations are small we expect the bispectrum will be the most powerful tool to probe these effects

- Heuristically $\delta T \sim \Phi^{(1)} + \Phi^{(1)}\Phi^{(1)}$ will lead to a bispectrum as:

$$< \delta T \delta T \delta T > \sim < \Phi^{(1)}\Phi^{(1)}\Phi^{(1)}\Phi^{(1)} >$$

- Then we can expect:

$$B^{\mathrm{2nd-order}}(k_1, k_2, k_3) \sim P_\Phi(k_1)P_\Phi(k_2) + \ldots$$

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

- At second order:

  - CMB non-Gaussianity can arise from Gaussian initial conditions

- Do we have the sensitivity to probe this?

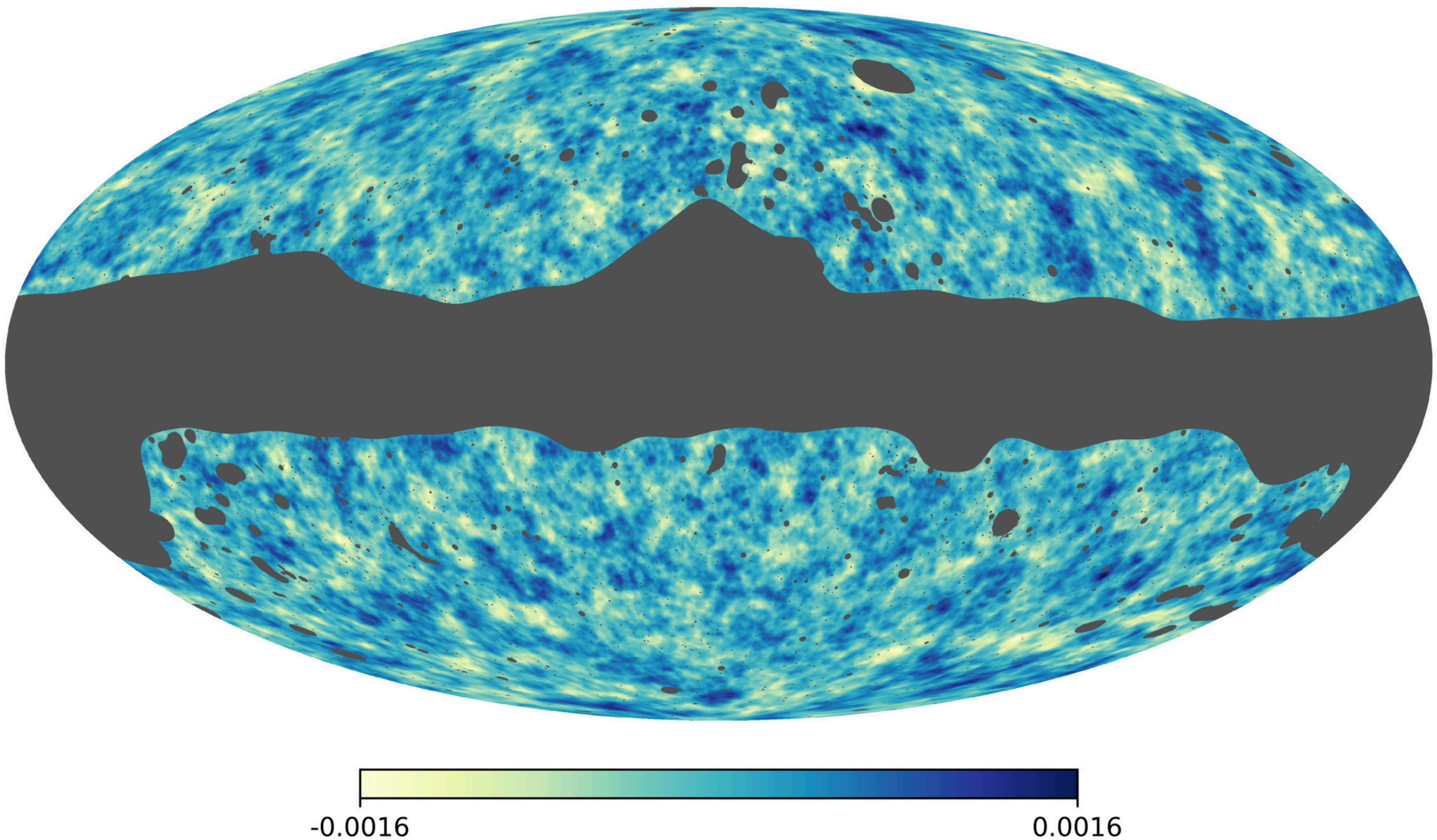
Second order effects: Lensing

- Gravitational lensing!

$$T(\mathbf{n}) = \tilde{T}(\mathbf{n} + \nabla\phi) \simeq \tilde{T}(\mathbf{n}) + \nabla\tilde{T}\cdot\nabla\phi$$

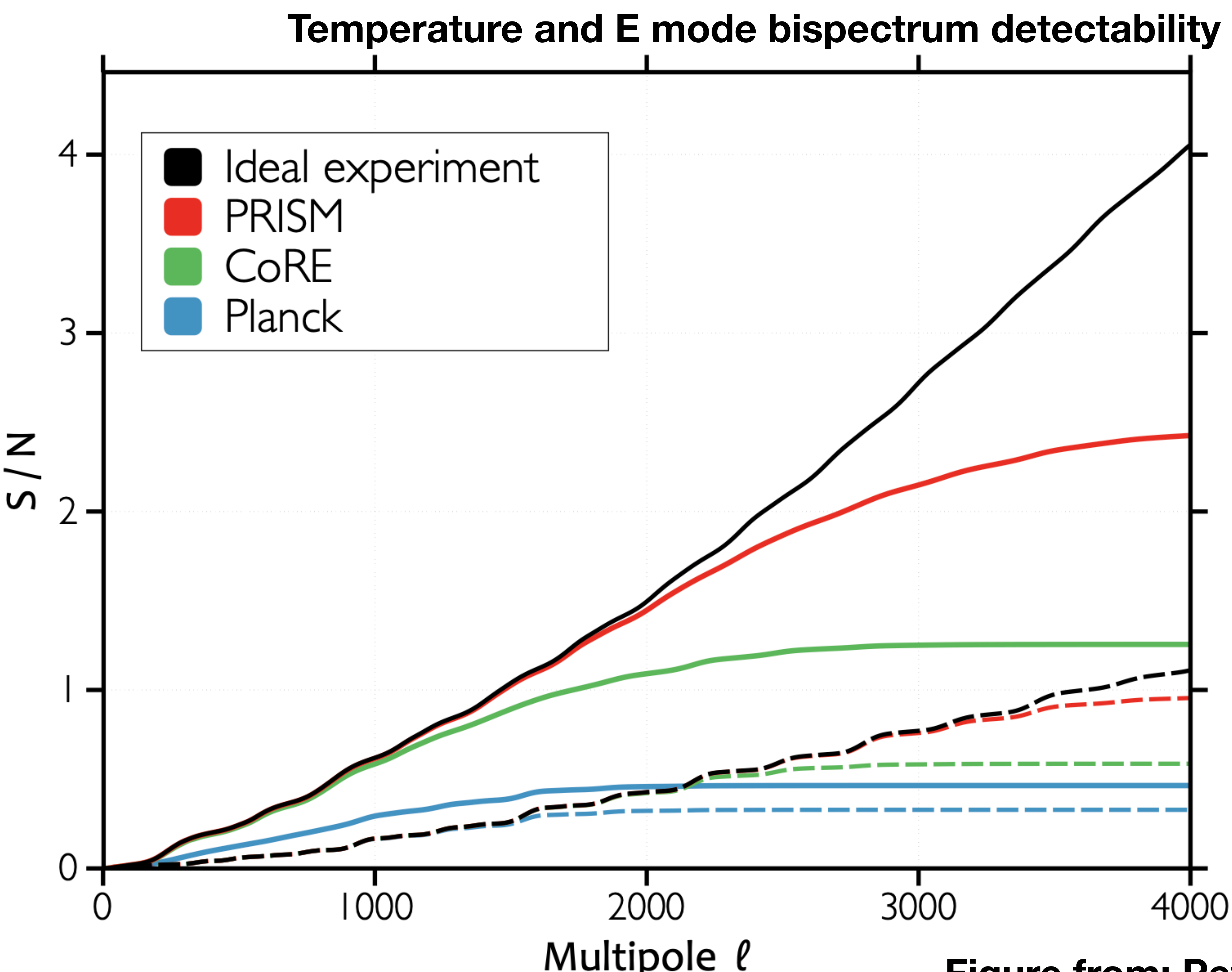
- Generates a non-zero trispectrum:

$$< TTTT > \propto \nabla\tilde{T}\cdot\nabla\phi\nabla\tilde{T}\cdot\nabla\phi\tilde{T}\tilde{T} \propto C^{\phi\phi}C^{TT}C^{TT}$$



Seljak 1995,Hu and Okamoto (2001), Planck 2018 VIII.

Intrinsic Bispectrum



Solid lines: T+E

Dotted lines: T

Figure from: Pettinari et al (2014)

Pettinari (2013) Pettinari et al (2014) Lewis (2013)

End of the story?

- All second order sources generates B modes!

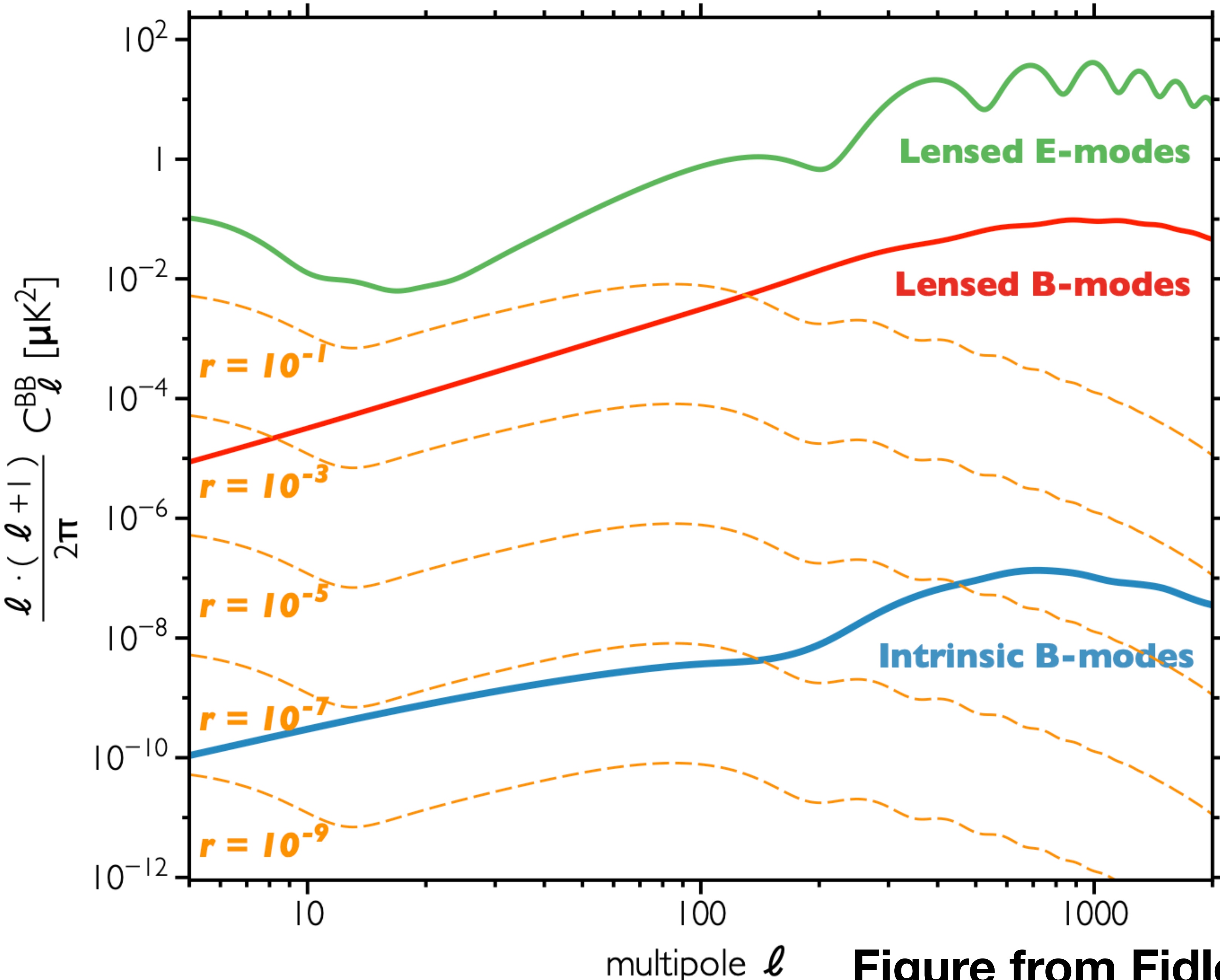
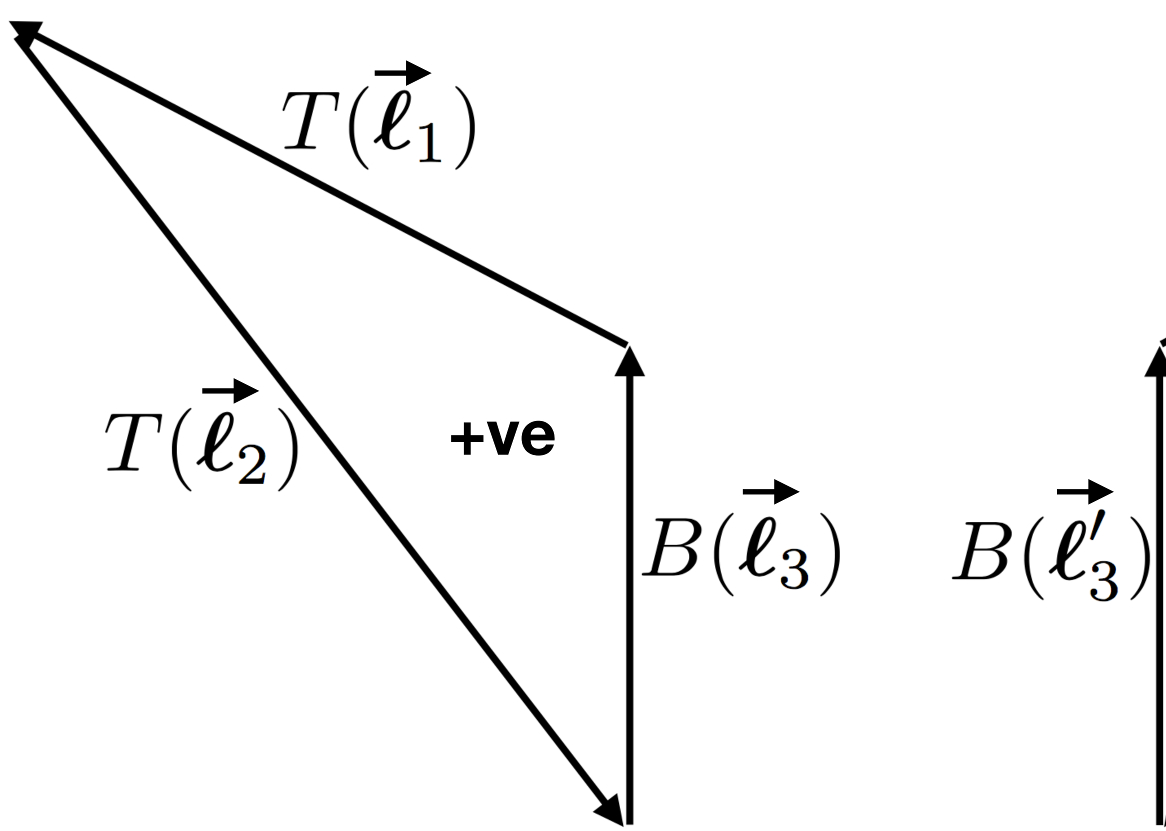


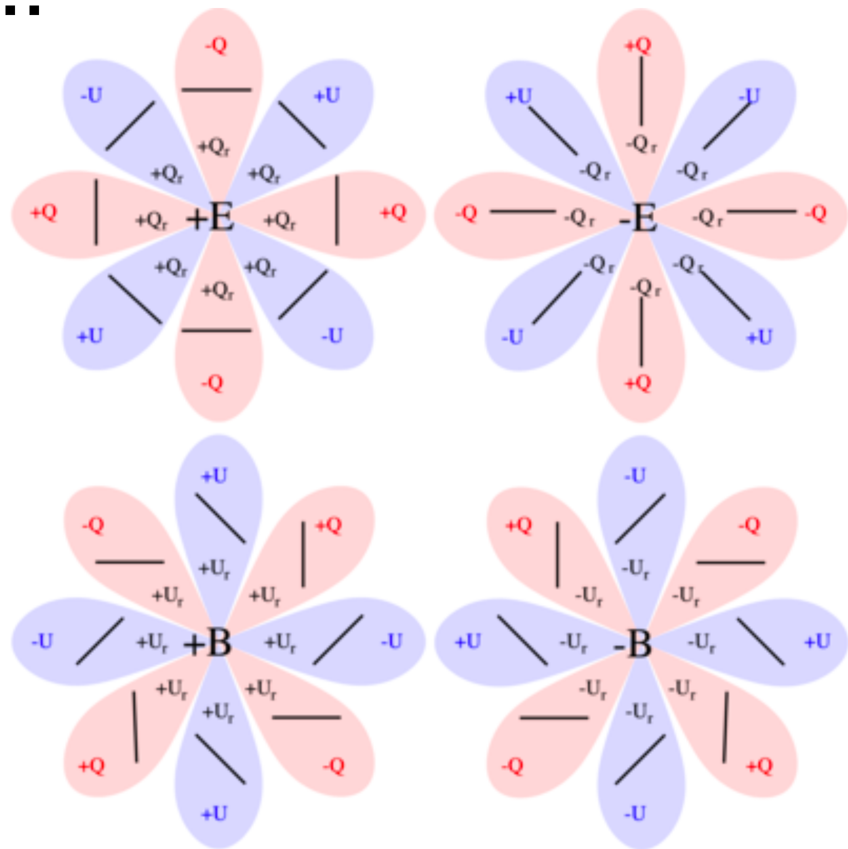
Figure from Fidler et al (2015)

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

Parity-odd Intrinsic Bispectrum

- TB and EB power spectra vanish.
- What about BTT, BTE.. bispectra?
- Not zero!! But need a different estimator..





Meerberg et al (2016)

Parity-odd Intrinsic Bispectrum

- These B modes will be correlated with the scalars. Ie:
    - $\langle BTT \rangle, \langle BET \rangle, \langle BEE \rangle \neq 0$
- Bispectrum same order as power spectrum!
- Boltzmann eqs. B modes are only sourced by vector and tensor sources!
- Non lensing contributions to these bispectra probe tensor and vector modes!
- SNR will increase as lensing B modes are removed!

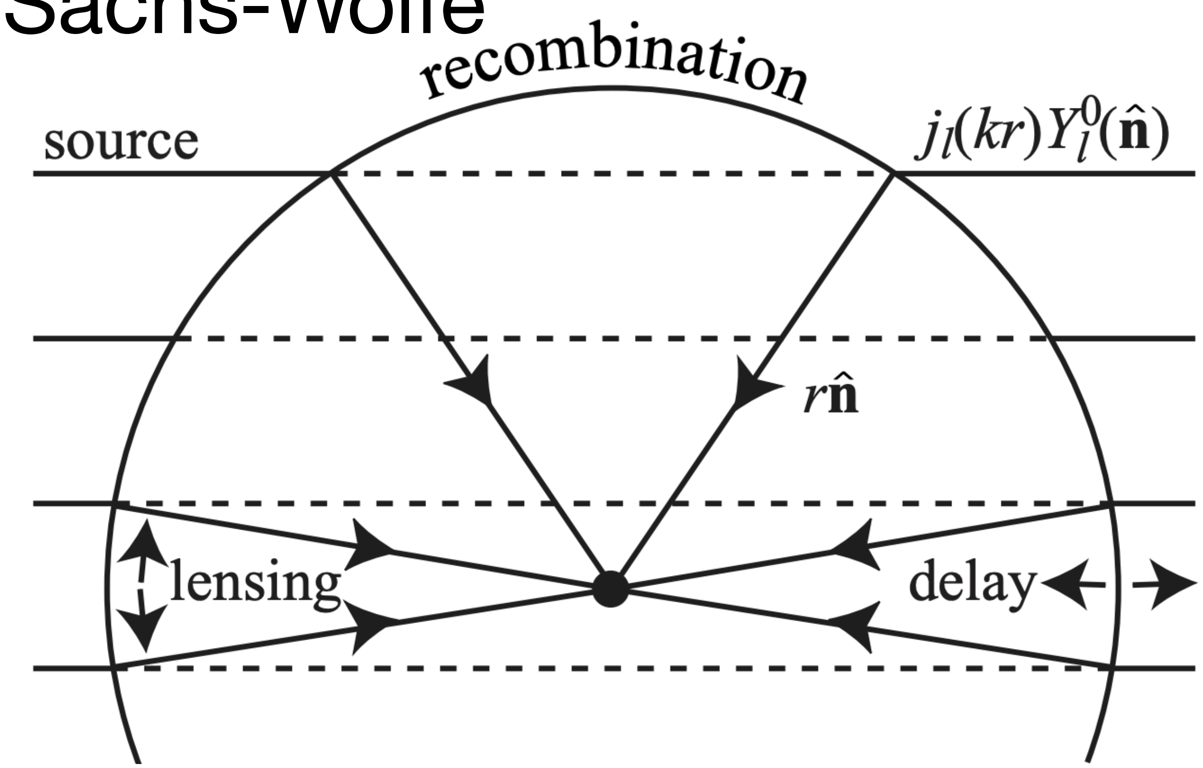
Benke et al (2010,2011) Fidler et al (2015)

Sources at second order: Lensing-like

- We will be focusing on sources at recombination.
- However will have to contend with late-time sources:

$$< TTT > \propto < T \nabla \tilde{T} > \cdot < \nabla \phi T >$$

- Any contribution that is correlated to lensing potential in lensing maps sources a bispectrum
    - E.g. Lensing-Integrated Sachs-Wolfe
- Additional lensing effects:
    - Time delay
    - Emission angle



Goldberg and Spergel 1999, Hu and Cooray (2000), Lewis et al (2017)

Sources at second order: Quadratic

- Through the Boltzmann equations we evolve moments of the distribution function (the brightness)

$$\delta + \Delta(\eta, \mathbf{x}, \mathbf{n}) = \frac{\int \mathrm{d}p p^3 f(\eta, \mathbf{x}, p\mathbf{n})}{\int \mathrm{d}p p^3 f^0}$$

- Brightness is related to the temperature perturbation as:

$$\frac{1+\Delta}{\Delta_0} = \left(\frac{1+\delta T}{T}\right)^4 = 1 + 4\delta T + 6\delta T \delta T + \ldots$$

- Thus there are contributions to the observed temperature fluctuations of the form:

$$\delta T^{(2)} = \frac{1}{4}\Delta^{(2)} - \frac{3}{32}\Delta^{(1)}\Delta^{(1)}$$

- Additionally gravitational redshifting of the CMB introduces an identical term

Pettinari et al (2013), Fidler et al (2014), Huang & Vernizz (2013)

Sources at second order: Evolution and Scattering

- Gravitational evolution of initial perturbations
  - Is non-linear and couples the independent modes
  - Evolution generates non-scalar modes: Vorticity and tensor perturbations
- Second order scattering effects. E.g:
  - Linear order: over-dense regions are potential wells-> CMB cold spot
  - Second order: additionally the scattering rate is also increased - marginally hotter spot!
- These processes encode new information from recombination era!

Pettinari et al (2013), Fidler et al (2014), Beneke et al (2011)

CMB Sources at second order: Evolution and Scattering at a high level

- To compute these terms we need to solve the second order Boltzmann equations
- Now we have (schematically)

$$a^{(2)X}_{\ell m} \sim \int \frac{\mathrm{d}^3\mathbf{k_1}\mathrm{d}^3\mathbf{k_2}}{(2\pi)^6} T^{(2)X}_{\ell}(\mathbf{k}_1, \mathbf{k}_2)\Phi(\mathbf{k}_1)\Phi(\mathbf{k}_1 - \mathbf{k}_2)$$

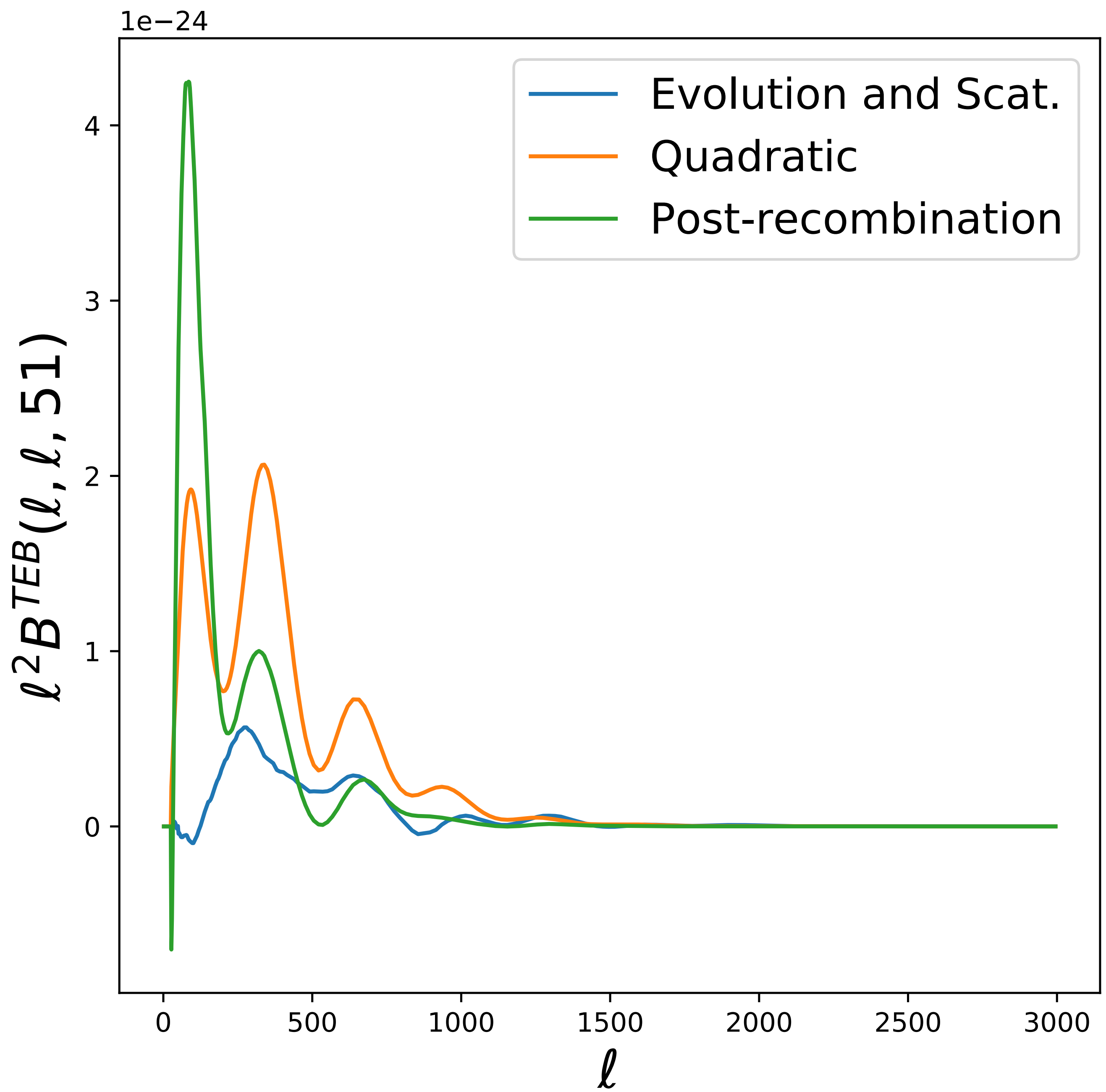
where $T^{(2)X}_{\ell}(k, \eta_0)$ - are second order transfer functions
- encode physics of evolution

- We compute these by numerically solving the Boltzmann equation at second order
  - Use the public code: SONG
- Compute our observable: $\langle a^{(2)X}_{\ell_1 m_1} a^{(1)Y}_{\ell_2 m_2} a^{(1)Z}_{\ell_3 m_3}\rangle$

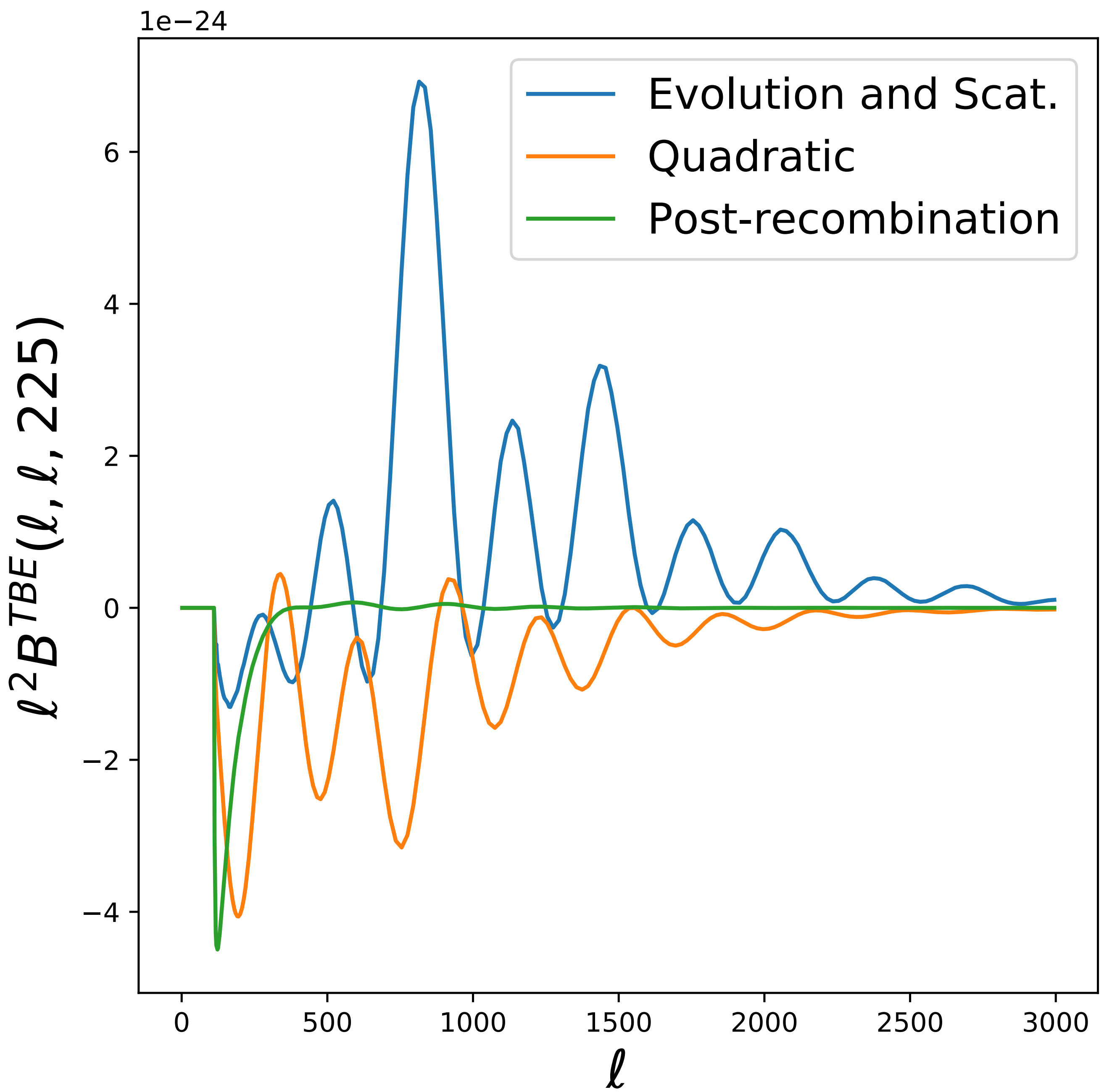
Pettinari et al (2013), Fidler et al (2014), Pettinari et al (2014)

The bispectrum

Squeezed bispectrum slice



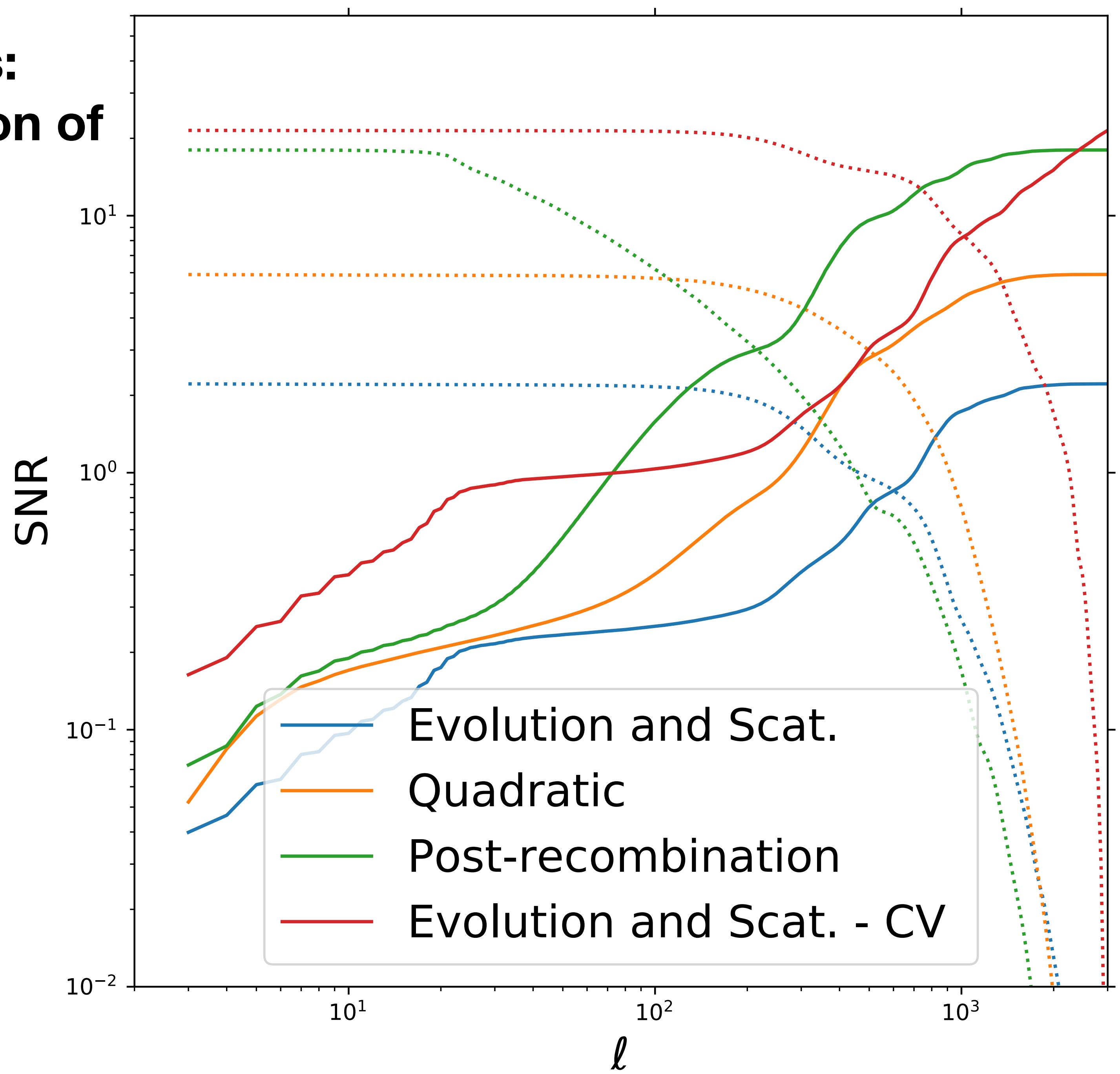
Equilateral bispectrum slice



What are contributes to this bispectrum?

Parity odd SNR for a PICO like experiment
(assuming 90% of lensing B modes removed)

Dotted Lines:
SNR as a function of
Minimum ℓ

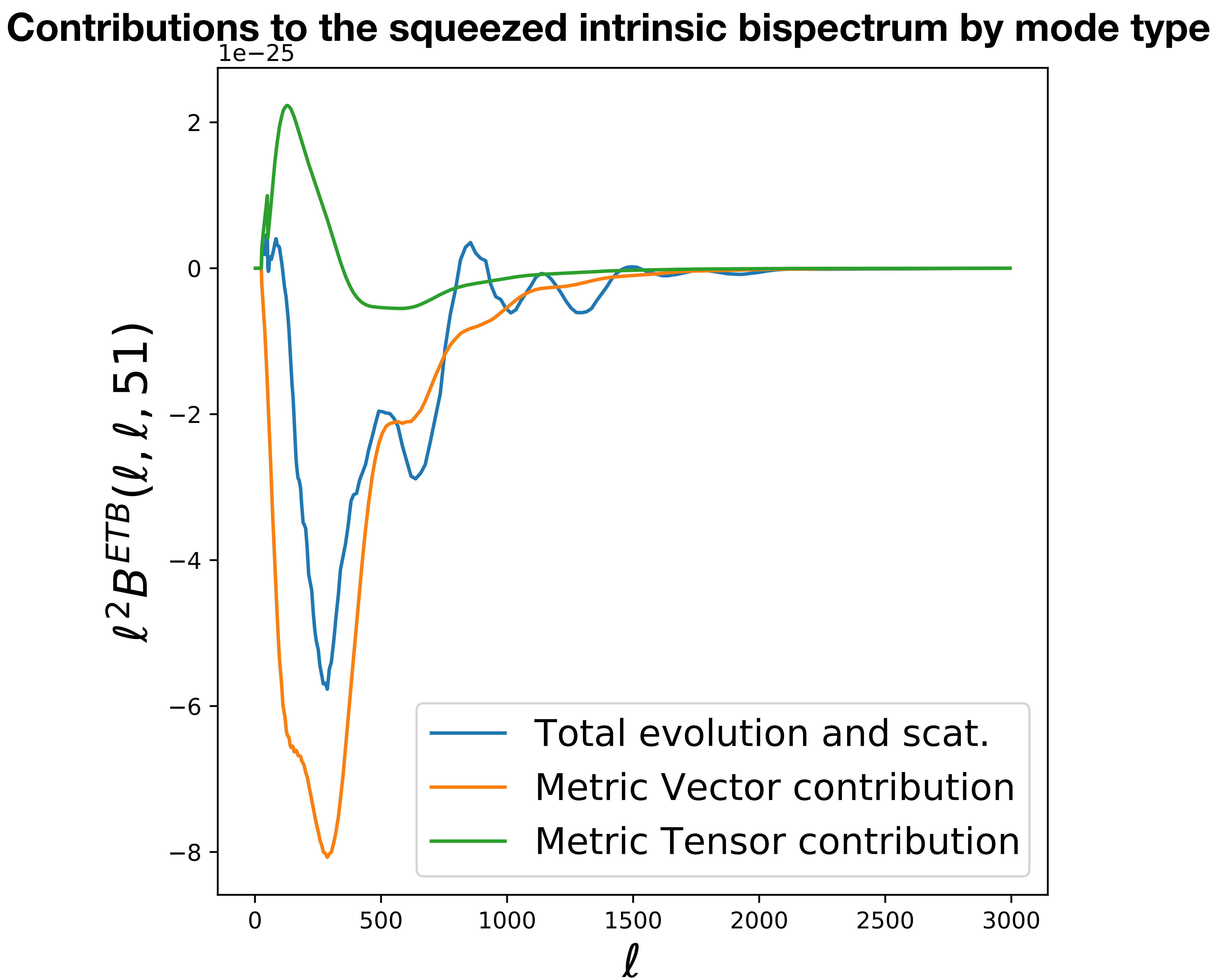


Solid Lines:
SNR as a function of
Maximum ℓ

CV assumes 99% delensing

Coulton (2103.08614)

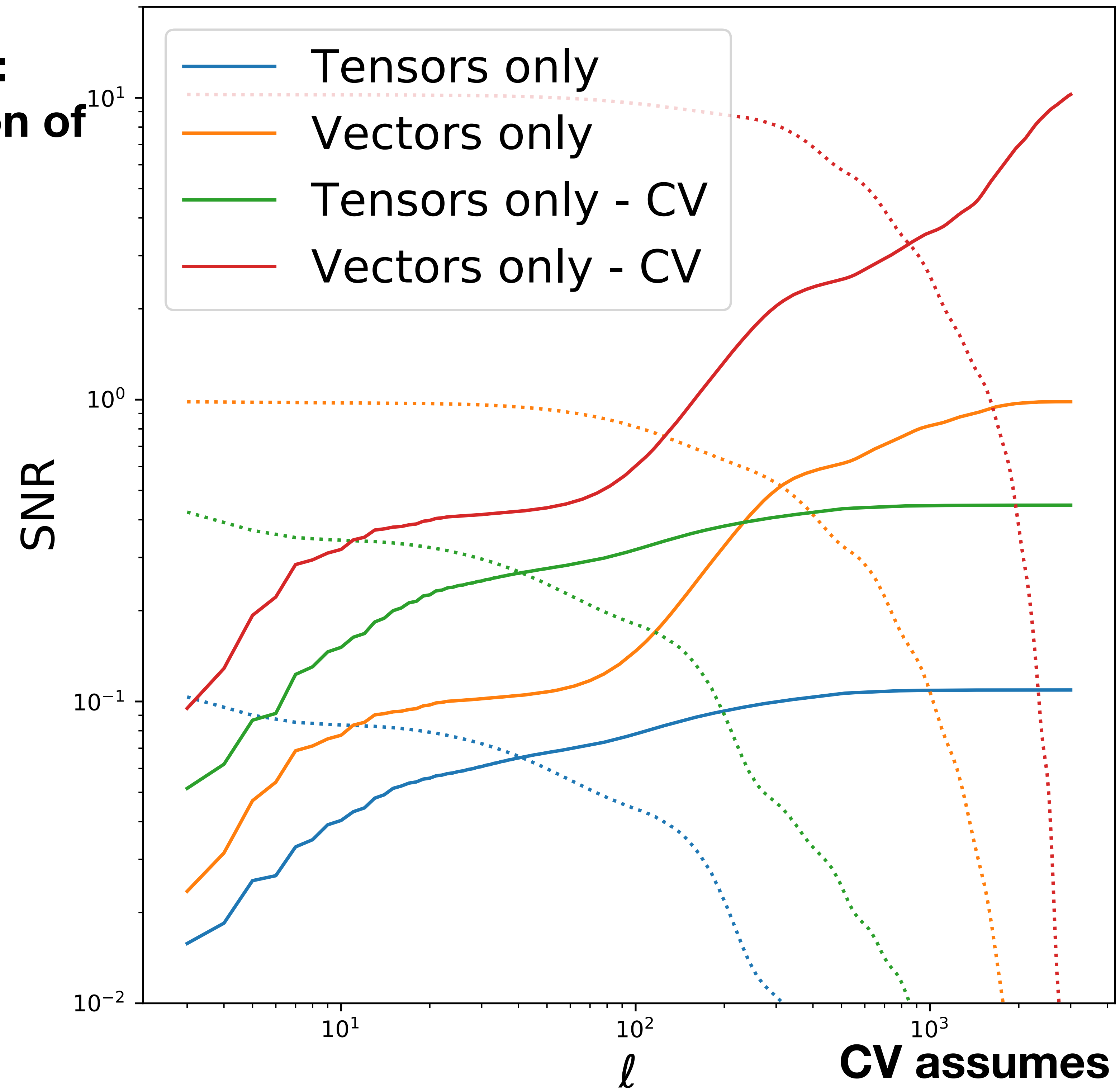
The intrinsic bispectrum components



How well could these non-scalar modes be measured?

Parity odd SNR for a PICO like experiment (assuming 90% of lensing B modes removed)

Dotted Lines: SNR as a function of Minimum ℓ



Solid Lines: SNR as a function of Maximum ℓ

CV assumes 99% delensing

Conclusions

- Upcoming experiments will provide unprecedented precision
- An opportunity to measure new physical effects in the CMB
    - We get these effects for free!!
- Probe the cosmological model with both increased power and from new angles
    - Non-scalar sources at recombination?

Thanks!