Beyond the Tensor to Scalar ratio

CMB-S4 collaboration meeting

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Assuming a detection of r has been made.

Then what?

Synergies and challenges
Outline

- How do we know it is from inflation?
  - Look at statistics?
  - Cross-correlations?
- Challenges
  - Foregrounds and secondaries
  - `Intrinsic’ signal
- For discussion: what if we don’t detect a signal w S4?

Beyond r

Targets of interest

- Prediction for PS: $P_t(k) \propto r\left(k/k_*\right)^{n_t}$
  - In SFSR $n_t < 0$. Consistency check
  - But, in SFSR $|n_t| \ll 1$. Hard to do with CMB (see e.g. Dodelson 2014)
  - Can try using multi-messenger approach (Tania Regimbau, Robert Caldwell's talks, see also e.g. Meerburg et al 2015); but scaling really model dependent (see Kinney 2021) $-N_{\rm eff}$?
- Beyond the PS, look at higher order correlation functions, e.g. bispectrum (see e.g. Muresuke 2014, Meerburg et al 2016, Duivenvoorden, Meerburg, Freese 2019)
  - For SFSR, all these are slow-roll suppressed (see e.g. Maldacena & Pimentel 2012).
  - Even when adding additional degrees of freedom there is a bound (Higuchi bound, mass of spin-2 mediator particle is bound, cant be massless, see e.g. Bordin et al 2016);
  - Specifically, correlating e.g. a tensor (γ) with two scalars (ζ) should have zero squeezed NGs even when adding a field. Caveat when breaking isometries of dS (e.g. solid inflation, Endlich et al 2012, Bordin et al 2018) or higher order partially massive particles (Baumann et al 2017)
- So to leading order, perhaps we can use the squeezed limit of tensor NGs to determine if gravitational waves are coming from `inflation' at all

Tensor NGs

Forecasts

- Forecasts show that we can do really well on squeezed limits (see S4 DSR, science book)

Shape: $\langle \mathcal{R}\mathcal{R}\gamma \rangle$ $\langle BTT \rangle$,$\langle BTE \rangle$,$\langle BEE \rangle$	Current	CMB-S4 goal	Conservative	CV-limited
$f_{\rm sky}$	69%	3%	3%	100%
$\sigma(\sqrt{r}\tilde{f}_{\rm NL}^{\rm local})$	28	0.79	1.2	0.052
$\sigma(\sqrt{r}\tilde{f}_{\rm NL}^{\rm equil})$	...	16	24	1.7
$\sigma(\sqrt{r}\tilde{f}_{\rm NL}^{\rm ortho})$	...	4.4	7.4	0.41

- NGs are therefore typically generated away from squeezed limit (equilateral); those in general, unfortunately, are harder to constrain

Cross-correlations (2)

Squeezed NGs

- Assuming there exist tensor NGs. In the squeezed limit, can we cross correlate between different data?
- Example 1: primary CMB x spectral distortions
- Example 2: primary CMB x direct GWs

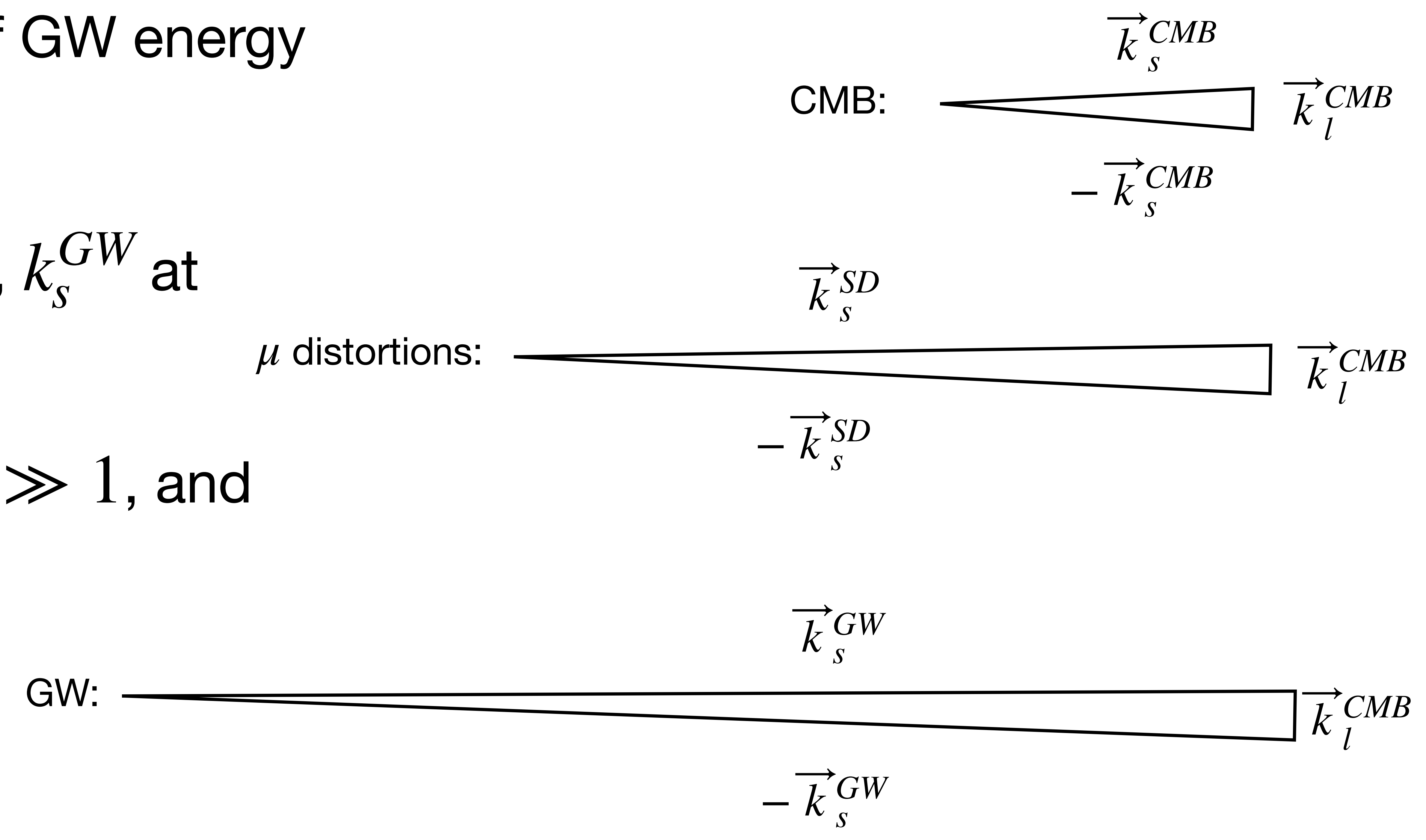
Ex. 2: primary CMB x direct GWs

- Anisotropies in the energy density of primordial GW can be generated from squeezed $\langle \gamma_{k_s} \gamma_{k_s} \zeta_{k_l} \rangle, \langle \gamma_{k_s} \gamma_{k_s} \gamma_{k_l} \rangle$ (Adshead et al. 2020, Malhotra et al. 2021, Dimastrogiovanni et al. to appear)

- Long-short mode correlations leads to modulations of GW energy density ($\langle \gamma_{k_s} \gamma_{k_s} \rangle$) arising from different regions

- $\langle CMB - GW \rangle$ probes ultra-squeezed configurations, k_s^{GW} at interferometer or PTA scales

- Needs significant enhancement of squeezed NGs $f_{NL} \gg 1$, and blue tensor spectrum $n_t > 0$

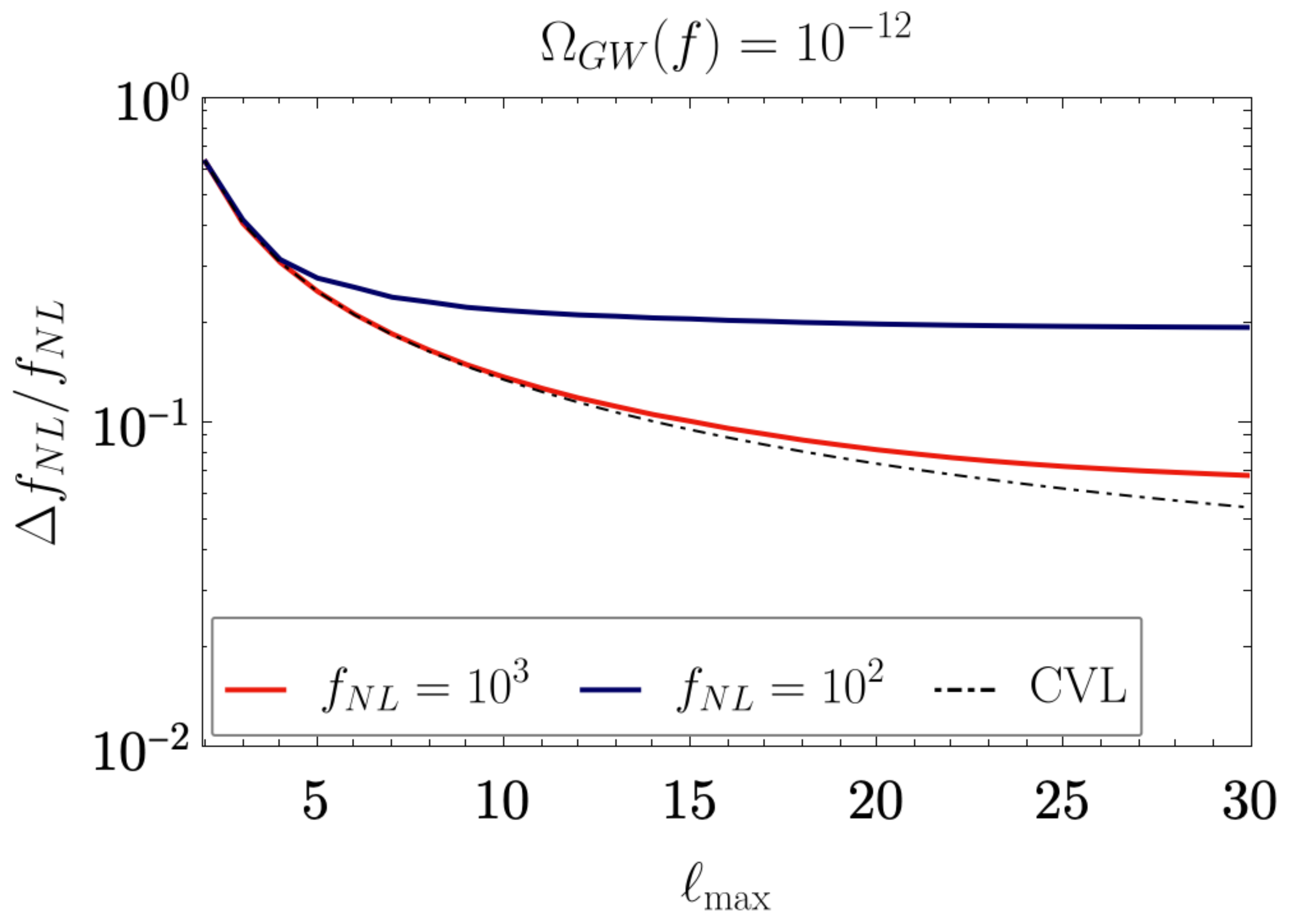


Ex. 2: probing $\langle \gamma\gamma\zeta \rangle$ from $\langle T - GW \rangle$

$\langle T - GW \rangle$ **affected by** $\langle \gamma_{k_s}\gamma_{k_s}\zeta_{k_l} \rangle$ $\qquad f_{NL} = f_{NL}^{\gamma\gamma\zeta}$

$$\delta^{GW}(k_s, \hat{n}) = \int_{k_l \ll k_s} \frac{d^3k_l}{(2\pi)^3}\, e^{-i(\eta_0 - \eta_{in})\hat{n}\cdot\vec{k}_l} f_{NL}(k_l, k_s)\zeta_{k_l}$$

- Observations limited by low angular resolution of GW detectors ($\ell_{\max} \sim 15 - 30$), need a high sensitivity network e.g. futuristic BBO
- Cross-correlations may also help to detect primordial anisotropies in presence of foregrounds
- Can also correlate $\langle E - GW \rangle$ from $\langle \gamma_{k_s}\gamma_{k_s}\zeta_{k_l} \rangle$, and non-zero $\langle B - GW \rangle$ from $\langle \gamma_{k_s}\gamma_{k_s}\gamma_{k_l} \rangle$ could hint to parity violation…



Cross-correlation only forecast for a BBO level experiment

CVL error from $\langle T - GW \rangle$: $\dfrac{\Delta f_{NL}}{f_{NL}} \sim \dfrac{1.4}{\sqrt{\ell_{\max}(\ell_{\max}+2) - 3}}$

…more in Dimastrogiovanni, Fasiello, Malhotra, Meerburg, Orlando, to appear

Challenges

Challenges for a detection

General limitations

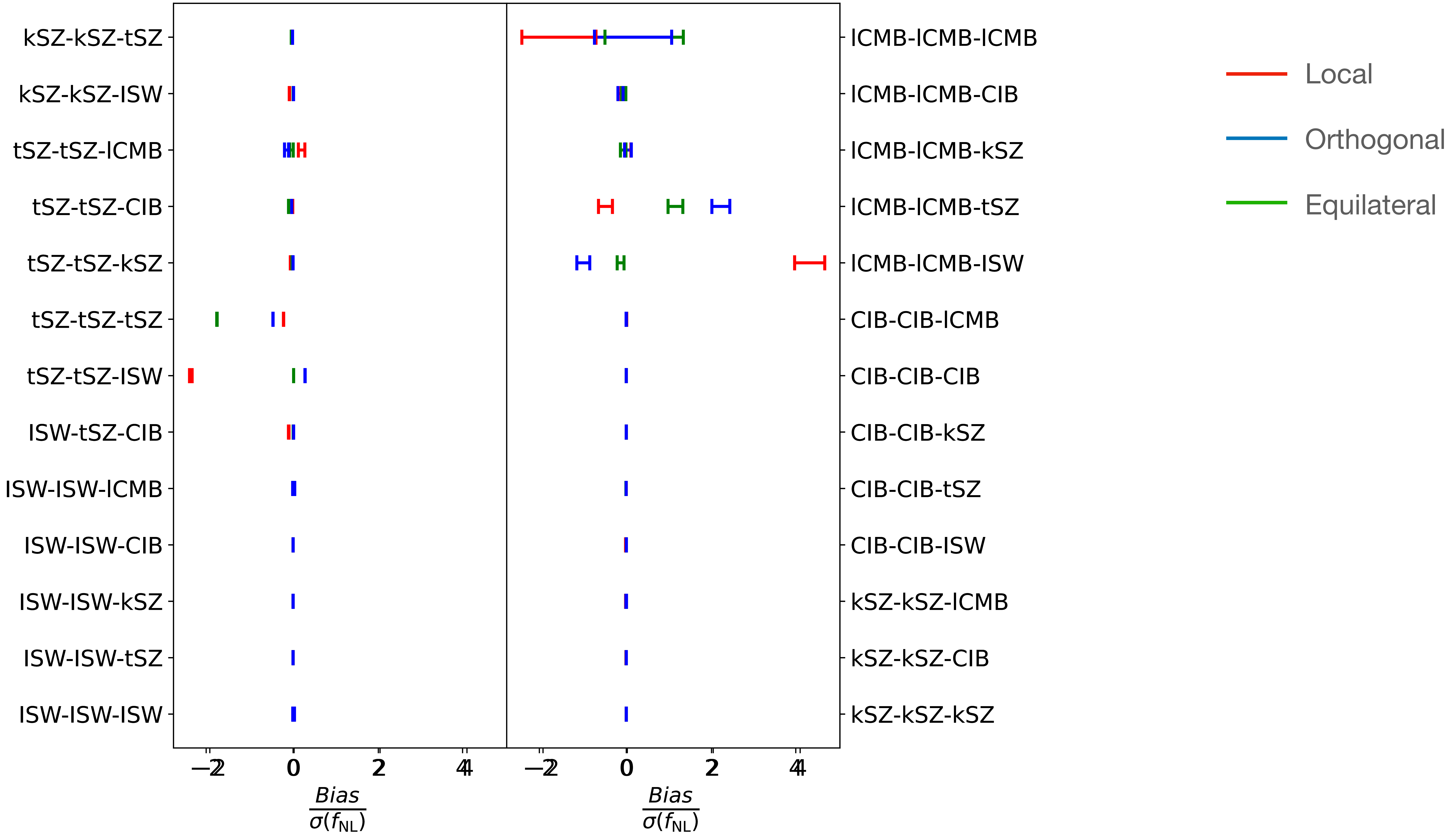
- Sources that look the same/similar (bias)
    - Statistically
    - Spectrally
- Sources that add variance (noise)
- Typically, both occur
- To mitagate:
    - Identify and model / project / de-source
- *note that that we treat these as noise but these are also signal

The CMB bispectrum
Example

- Sources that look the same/similar (bias)
  - E.g. ISW-lensing (see Hill 2018, Coulton et al in prep)
- Sources that add variance (noise)
  - E.g. lensing (but in principle all above sources as well, see Coulton et al 2019)
- Galactic foregrounds; however here we will likely rely on simulations to check if they contain statistics that is similar to signal; obviously cleaning the data, as we do for the PS, will be critical
- Note that higher order statistics in principle have the advantage that there are more dof, which benefits our ability to distinguish it from signal

The CMB bispectrum

Foregrounds (temperature only)



Credits: Will Coulton

The CMB bispectrum

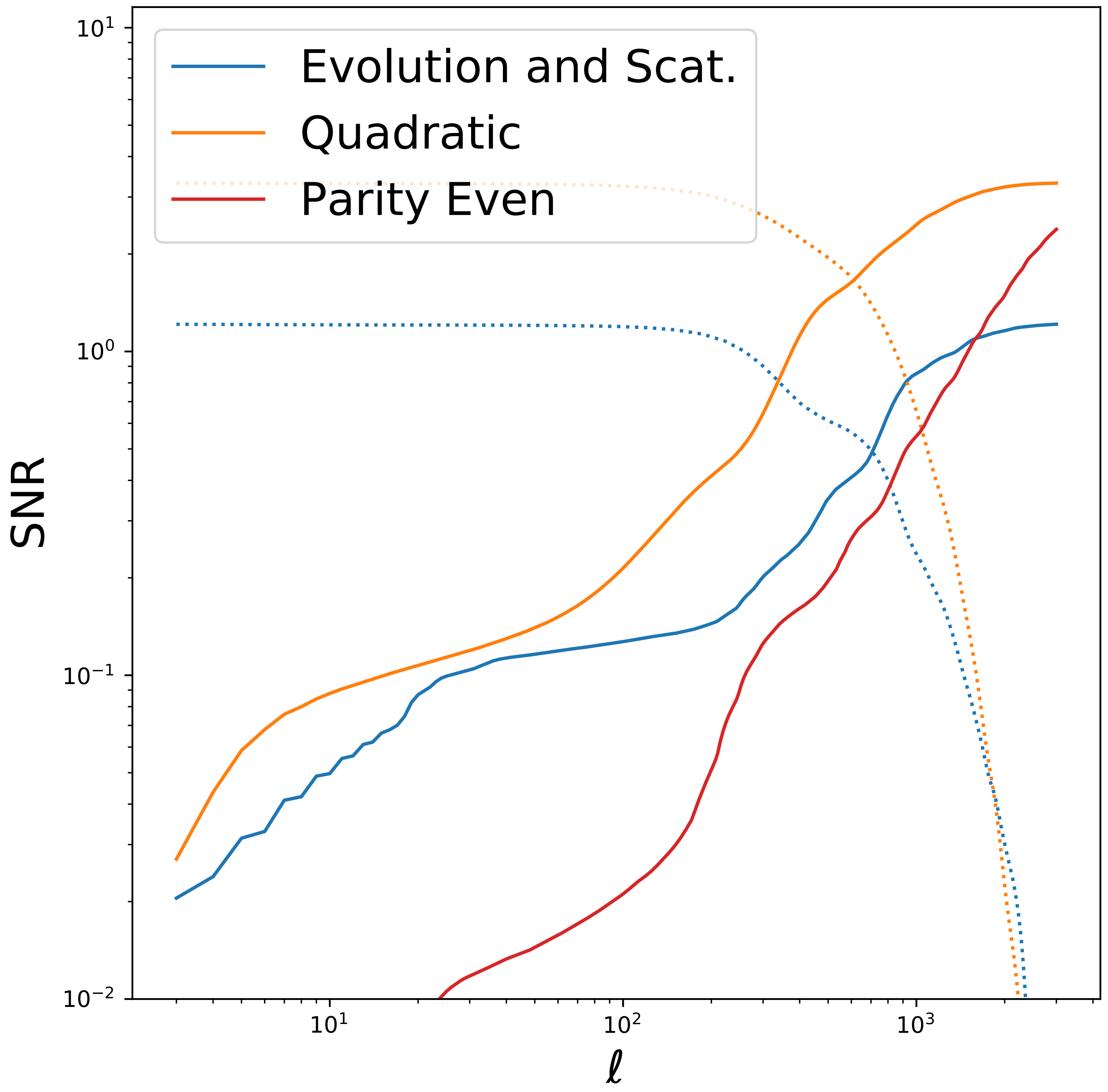
Intrinsic bispectrum

- Besides primordial and secondary sources, the CMB will also contain intrinsic bispectra, simply due to non-linear evolution of perturbations

- These could also be possible sources of confusion (and extra variance);

- Good news is that while they could be detectable with upcoming surveys (see Coulton 2021), they likely would not interfere with search for primordial NGs

Detectability w S4



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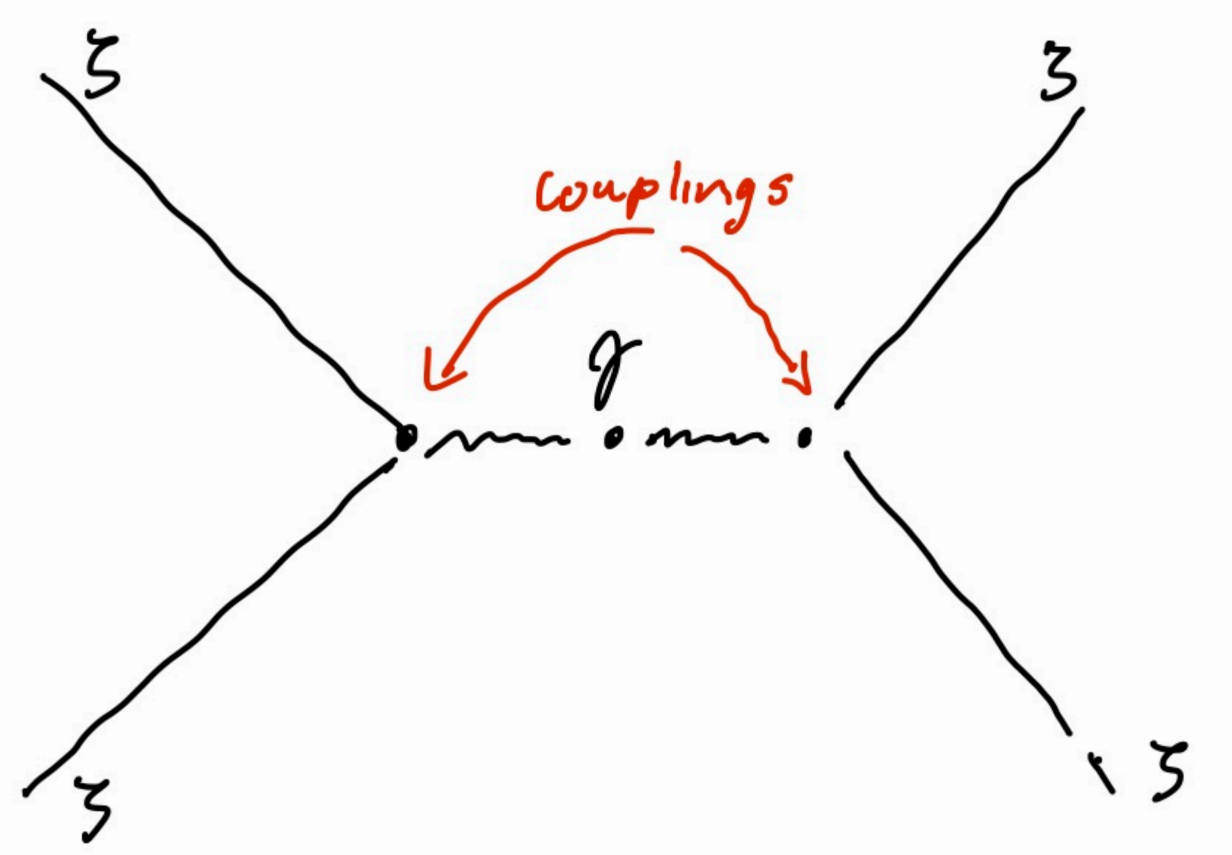
Discussion and conclusions

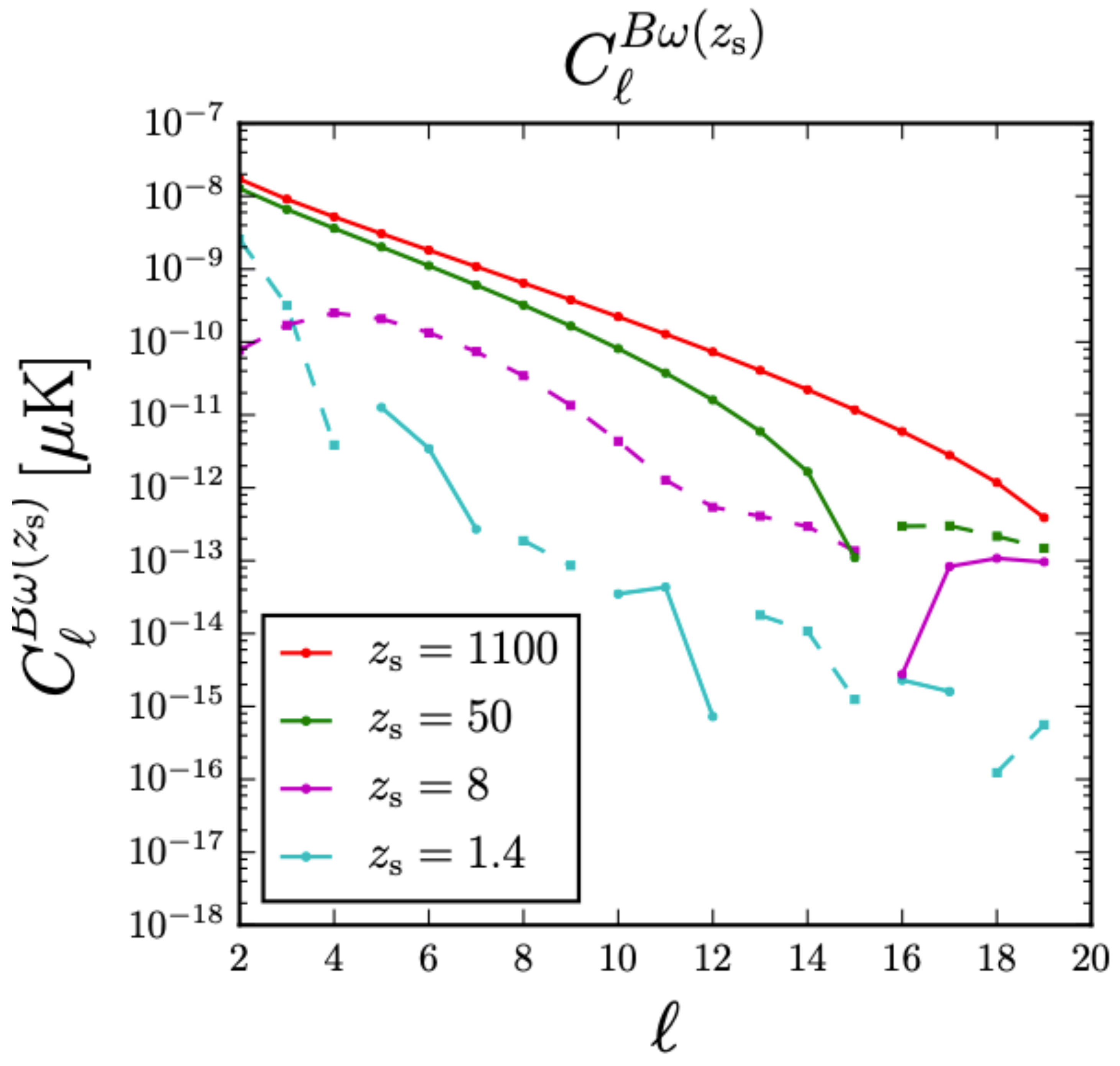


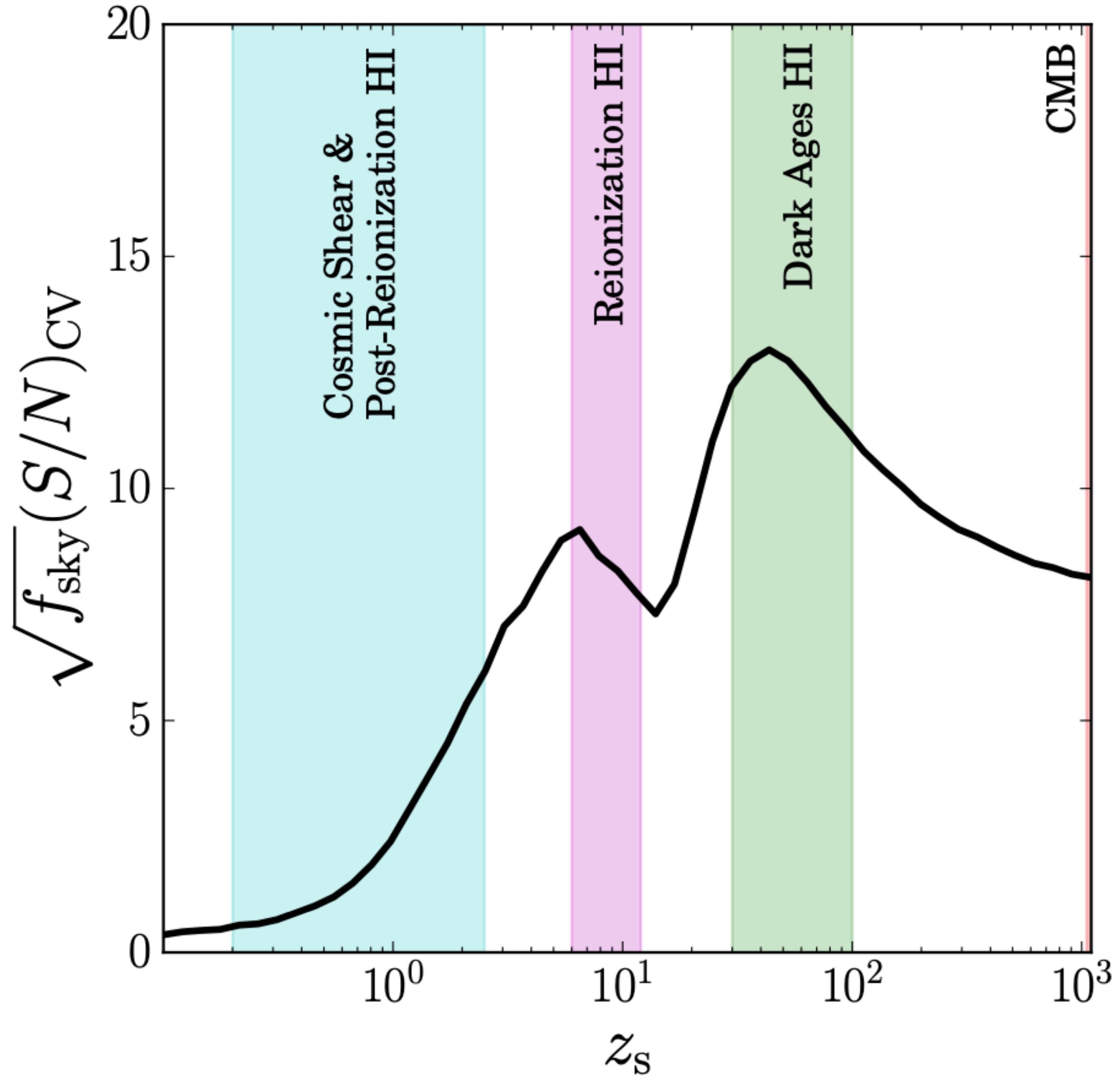
- If we detect r we should
  - Confirm it is from inflation
  - Look for statistics beyond the PS
- Challenges are well characterized for CMB only measurement, but we should think more about those for cross correlations (general synergies)
- Think more how to practically constrain GWs using large scale structure
- If we don't detect r?
  - Could still constrain (Maldacena) consistency relation
  - Could also look for trispectra which could potentially probe spin-2 fields (and higher) (see e.g. Bordin et al 2016)
  - Obviously, constraining trispectra will open up a new can of worms, machine learning?

Cross-correlations (1)

Curl lensing

- For sake of confidence, can we confirm the primordial nature of the GWs using other tracers?
- In the large scale structure, very challenging to 'constrain' tensor modes. (See e.g. Masui & Pen 2012, Schmidt et al 2013, Chisari et al 2014, Biagetti & Orlando 2020, `fossil' effects are promising)
- One example is curl lensing; presence of large scale primordial GWs can induce lensing signal with odd parity structure.
- In principle detectable; would provide proof of existence of large scale gravitational waves (Sheere, van Engelen, Meerburg, Meyers 2016)

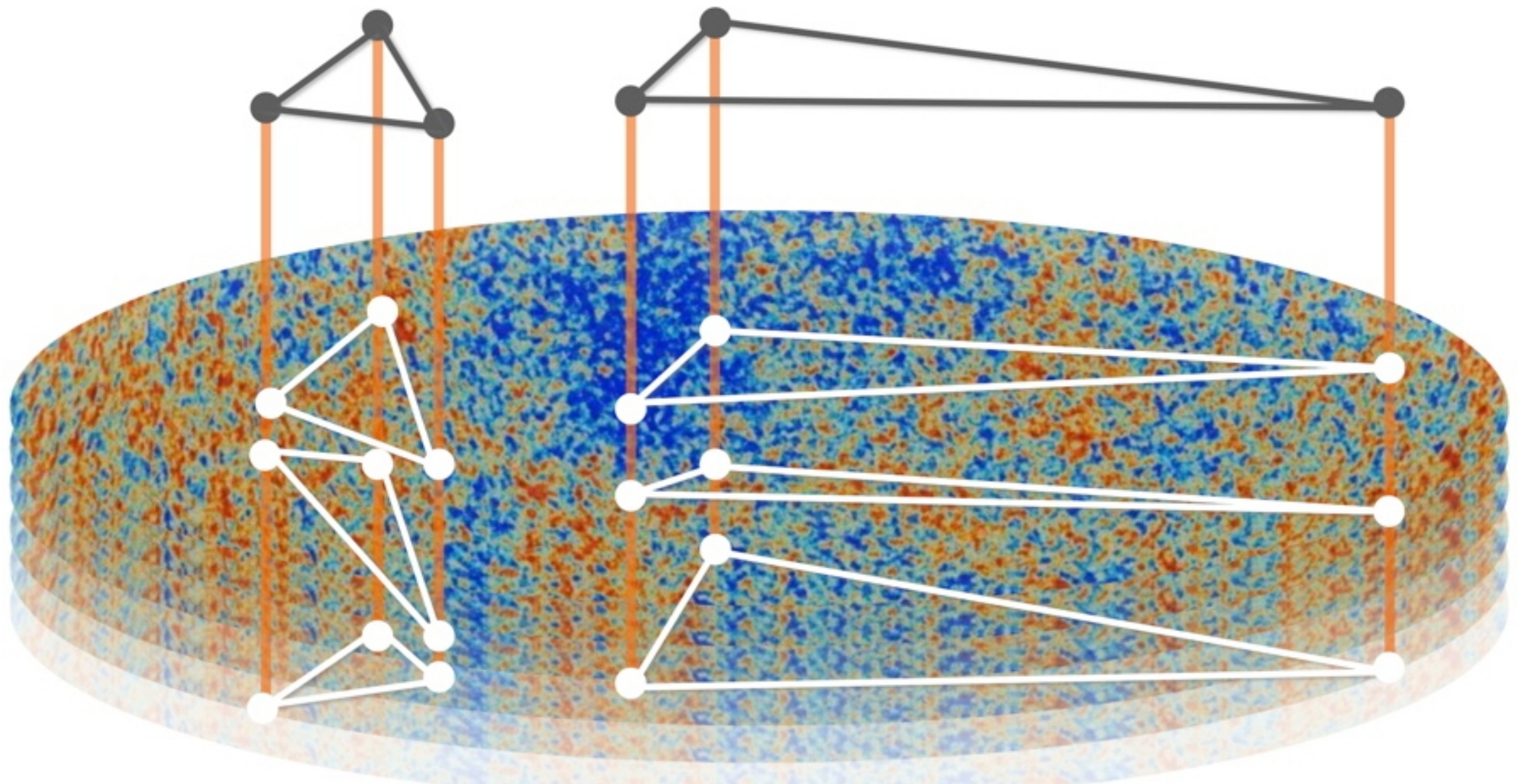


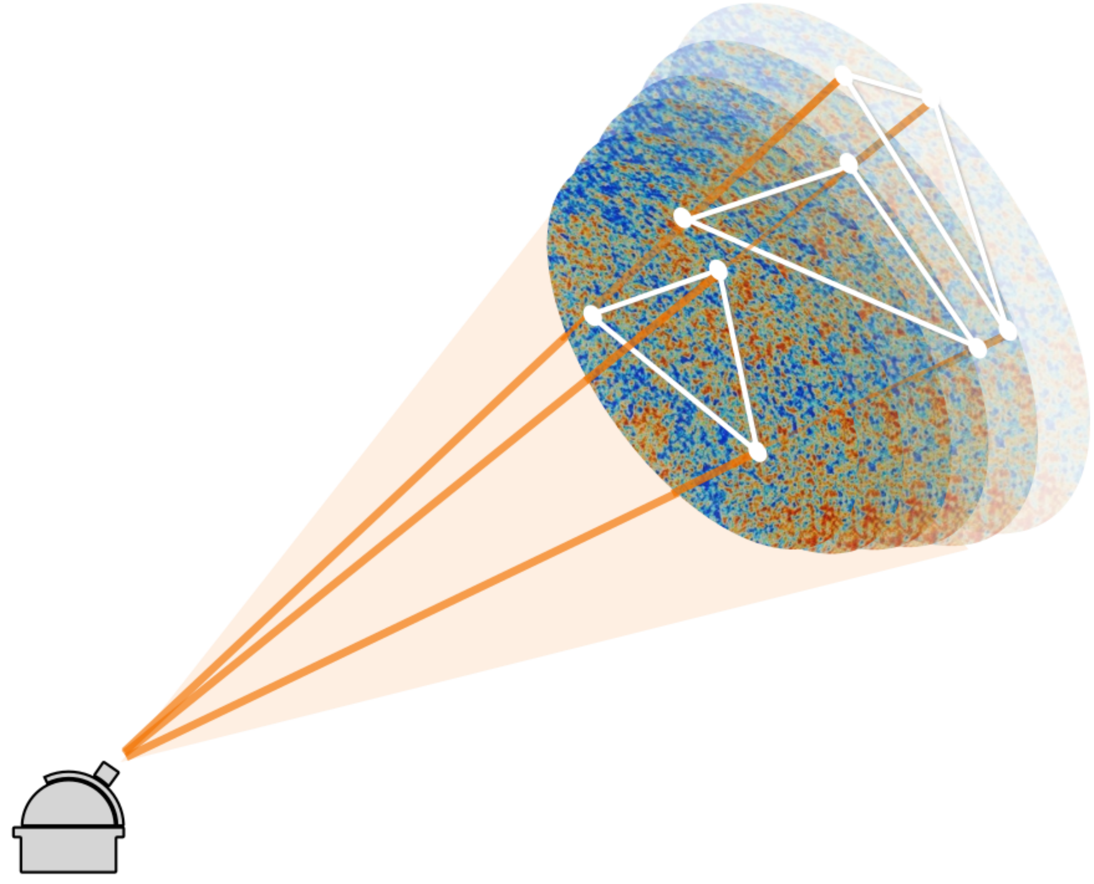


Intermezzo

Why is it hard to constrain non-local NG in the CMB?

- First, tensors decay
- Second, and this is general for scalar/tensor NG in the CMB, on small scales NG are severely affected by blurring (See Kalaja, Meerburg, Pimentel & Coulton 2020)
- As a result, the improvement on NGs of these types does not improve as mode-counting
- Interestingly, higher n-point functions can exceed mode counting (e.g. trispectrum)





Ex. 1: primary CMB x spectral distortions

- Spectral distortions are generated by the injection of energy from the dissipation of acoustic waves in the photon-baryon fluid.

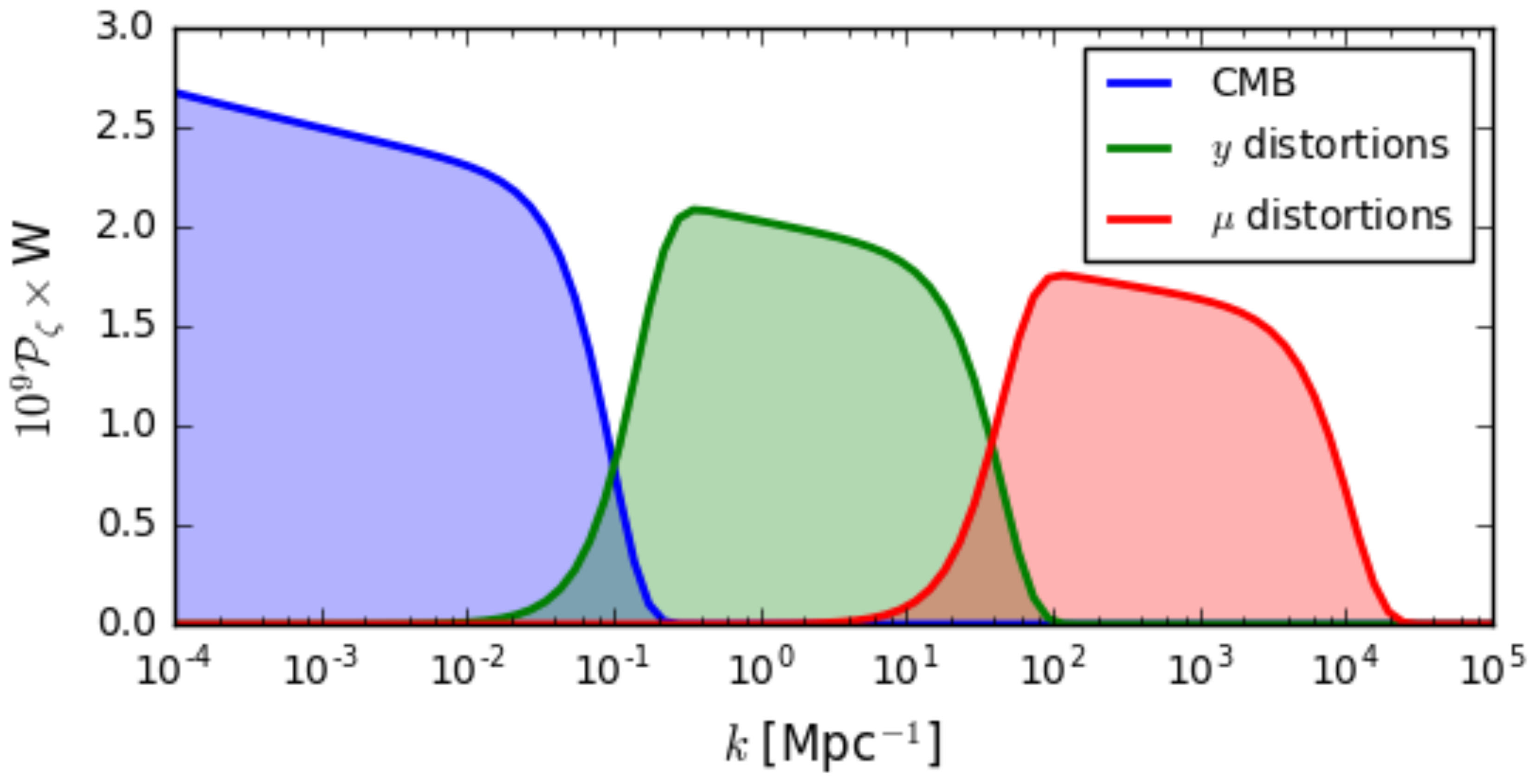
- They are quadratic in primordial perturbations: $\mu, y \sim \zeta^2, \gamma^2$

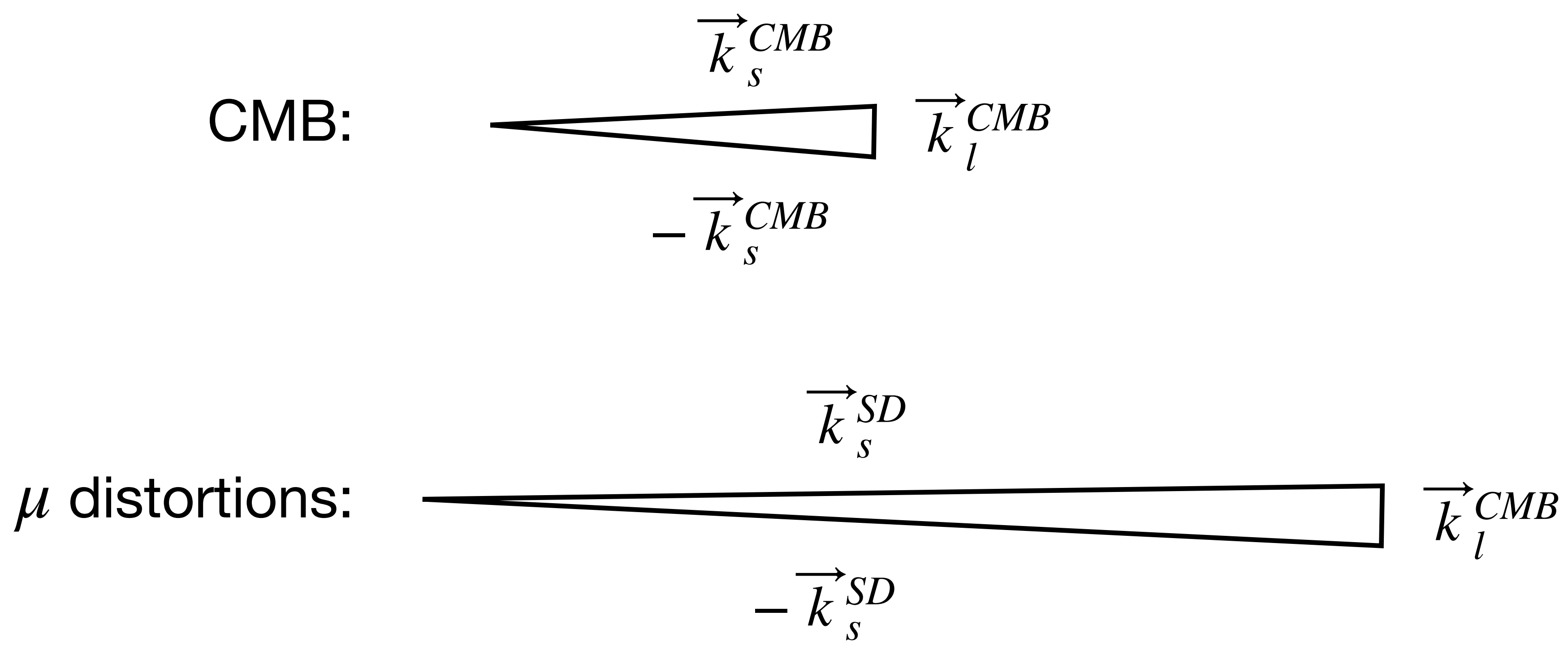
- Probe scales smaller than primary CMB.

- $\langle CMB - \mu \rangle$: sensitivity to very squeezed NGs

- Previous work considered scalar NGs with $\langle T\mu \rangle, \langle E\mu \rangle$. (see e.g. Pajer and Zaldarriaga 2012, Emami et. al. 2015, Shiraishi et. al. 2015, Ota 2016, Ravenni et al. 2017, Cabass et. al. 2018)

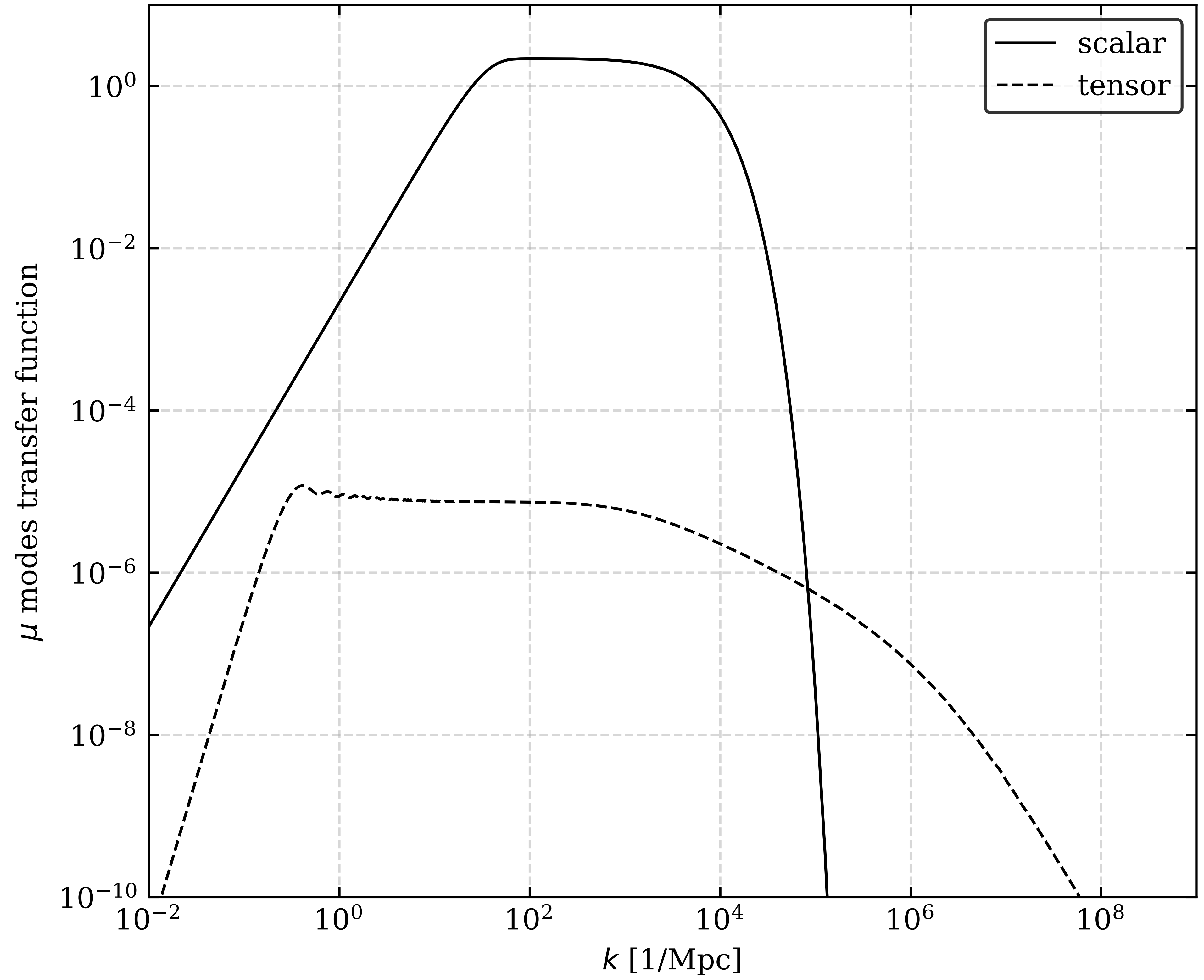
- In the cosmic variance limit, $\sigma(f_{NL}^{\rm loc}) \ll 1$





Ex. 1: tensor NGs from $\langle CMB - \mu \rangle$

see, e.g., Chluba et. al. 2015



- γ vs ζ : μ transfer function:
  - pro: γ transfer function probe a larger window of scales than ζ
  - con: γ transfer function is 5 orders of magnitude smaller than ζ
- Net effect: detecting squeezed $\langle \gamma_l \gamma_s \gamma_s \rangle, \langle \zeta_l \gamma_s \gamma_s \rangle$ is going to be challenging, any signal is obscured by $\langle \gamma_l \zeta_s \zeta_s \rangle, \langle \zeta_l \zeta_s \zeta_s \rangle$
- A large independent amplification on γ is needed, no viable models currently in literature (Orlando, Meerburg, Patil, to appear)
- On squeezed $\langle \gamma_l \zeta_s \zeta_s \rangle$:
  - probed by $\langle B\mu \rangle$
  - Signal is vanishing if bispectrum is isotropic (similar to $\langle BT \rangle$ and $\langle BE \rangle$)
  - Need to introduce primordial anisotropies
  - Off diagonal $\langle B\mu \rangle$ would be sourced by anisotropic NGs

$$\sigma(f_{NL}^{\gamma\zeta\zeta,\,L}|_B) \sim 10 \left(\frac{0.01}{r_{\rm CMB}}\right)^{1/2} \sigma(f_{NL}^{\zeta\zeta\zeta}|_{T+E})$$

Orlando, Meerburg, Patil, to appear