Gravitational Waves Summary Report

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With Raphael Flauger,
Parallel speakers Tania Regimbau, Robert Caldwell, Daan Meerburg, Clem Pryke, Paolo Campeti, Toshiya Namikawa

CMB-S4 Summer 2021 Meeting

Overview

1. Complementarity with direct detection I: phenomena with signals in direct detection and B-modes
    - Is the space of models sufficiently explored?
2. Characterizing an S4 signal:
    - Are we sure we have a primordial signal?
    - Is there evidence in B for something beyond single-field slow-roll
3. Complementarity with direct detection II: phenomena with direct detection and Temp/E-modes

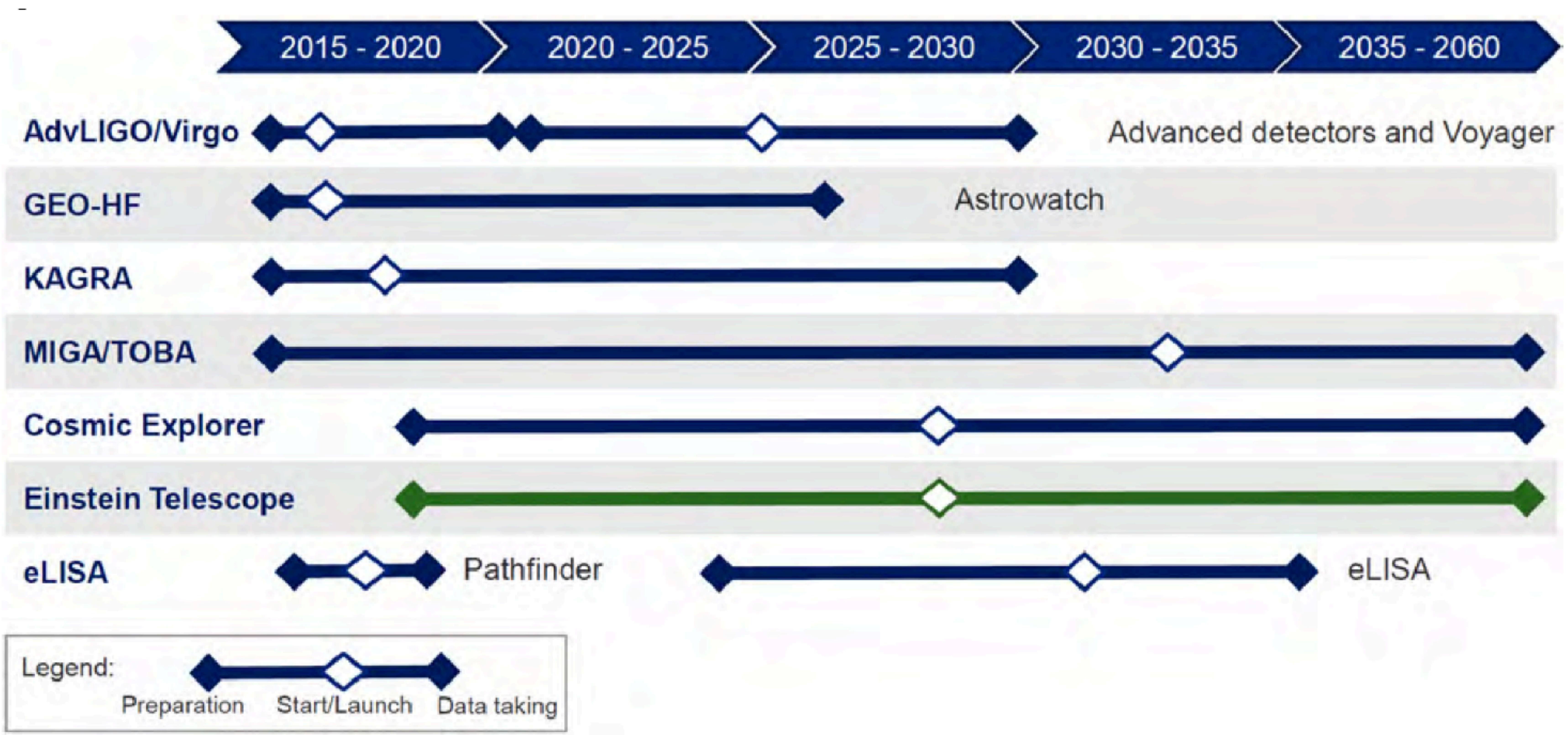
1. Complementarity with Direct Detection I

Stochastic Background: superposition of unresolved sources

- astrophysical (unresolved mergers of compact objects)

- cosmological: primordial GWs, phase transitions, cosmic strings,

Time-line



LIGO/Virgo Search:

2101.12130

2103.08520

Figure: Einstein Telescope

Direct Detection: Stochastic Background

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$

As detector sensitivity increases…

more sources are resolved,

…less astrophysical stochastic background

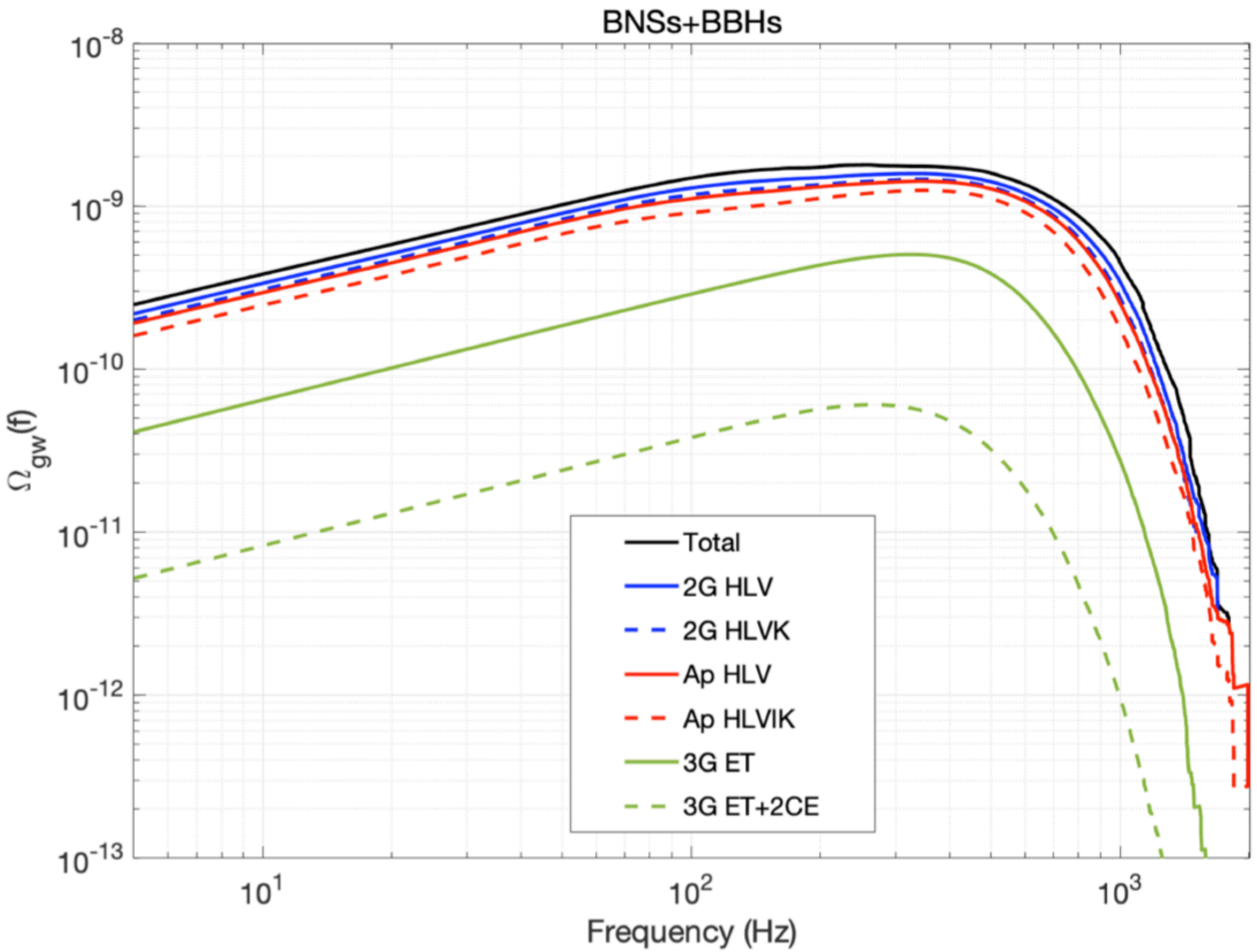


Figure from Tania Regimbau's talk

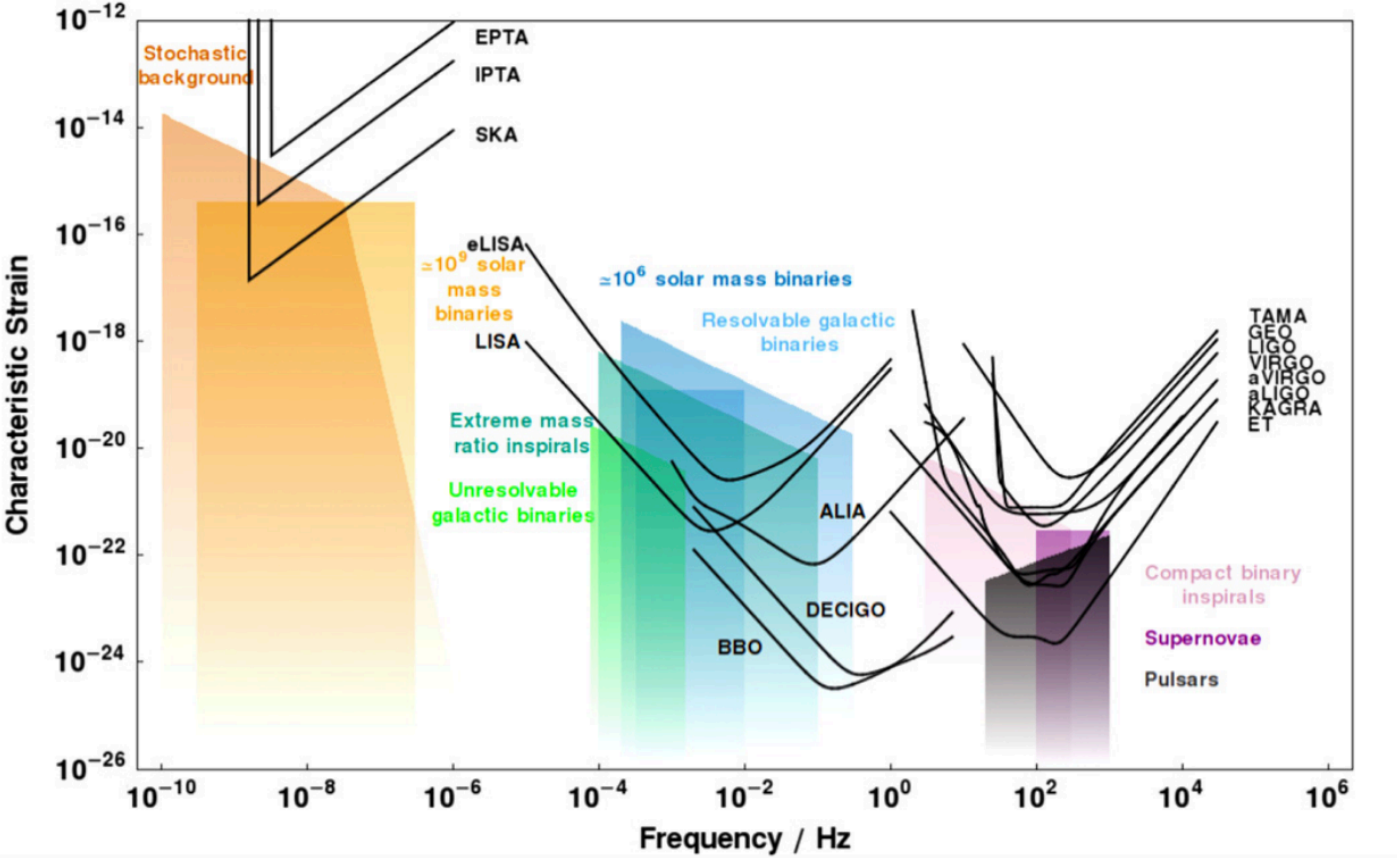


Figure: Moore, Cole, Berry 2014

Signal: cross-correlate detectors

Design and analysis point:

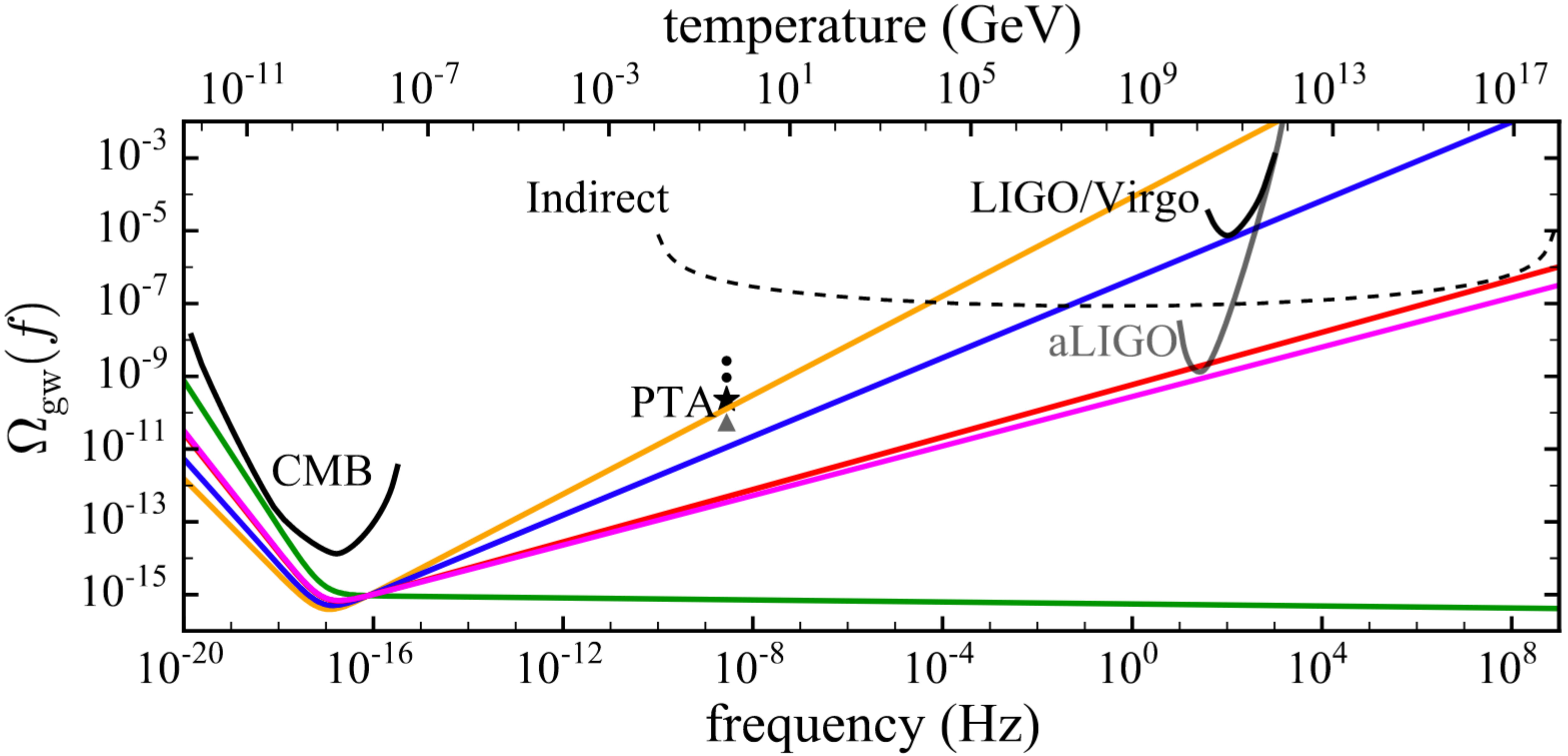
- Frequency domain cross product: $Y = \int \tilde{s}_1^*(f)\tilde{Q}(f)\tilde{s}_2(f)df$
- optimal filter: $\tilde{Q}(f) \propto \frac{\gamma(f)\Omega_{gw}(f)}{f^3 P_1(f) P_2(f)}$ with $\Omega_{gw}(f) \equiv \Omega_0 f^{\alpha}$

(Tania Regimbau's talk)

$\gamma(f)$ may be much less than one depending on detector relative orientation and separation

$\tilde{Q}(f)$ Should be optimized for the analysis you are doing

Signals? Require blue tilt



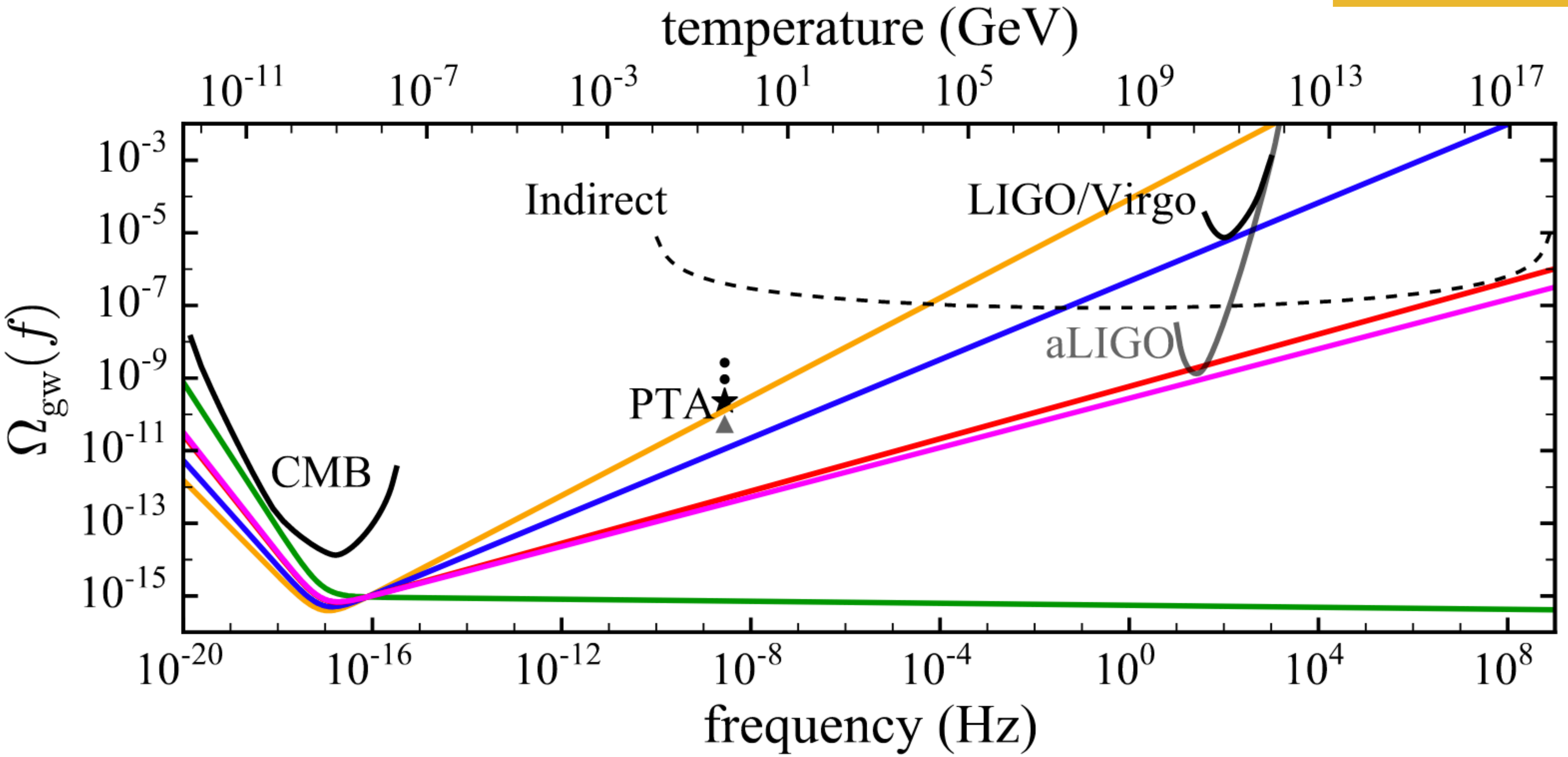
Single-field slow-roll

$n_t = -r/8$

$r = 0.11$

Figure: Lasky et al 1511.05994

Signals? Require blue tilt



$n_t = 0.68$

$n_t = 0.54$

$n_t = 0.36$

$n_t = 0.34$

Single-field slow-roll

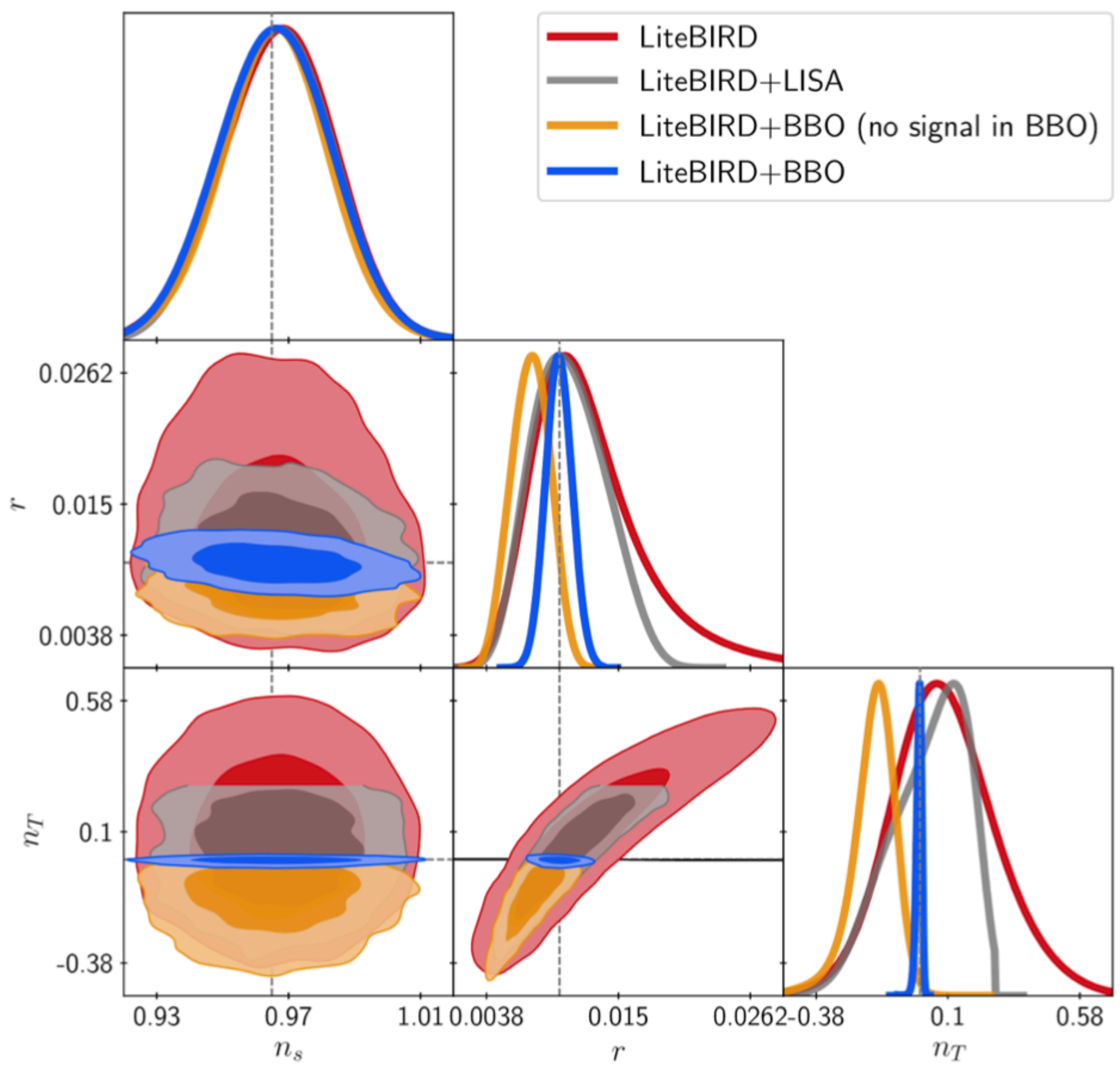
$n_t = -r/8$

$r = 0.11$

Figure: Lasky et al 1511.05994

Inflationary consistency relation $n_T = -r/8$

- Large lever-arm CMB/interferometers
- Case r = 0.01
- LiteBIRD alone
- LiteBIRD + LISA
- LiteBIRD + BBO
- Not even LiteBIRD + BBO can distinguish scale-invariance from consistency relation
- 5σ detection in LiteBIRD but no detection in BBO: bias on r, we can detect departure from scale-invariance at CMB scales due to large red-tilt



Blue Tilt?

You can do it with non-minimal (but well-motivated) field content during inflation:

Nearly flat inflationary potential

➡ Approximate shift-symmetry for the inflation

➡ Inflation is an axion (natural inflation)

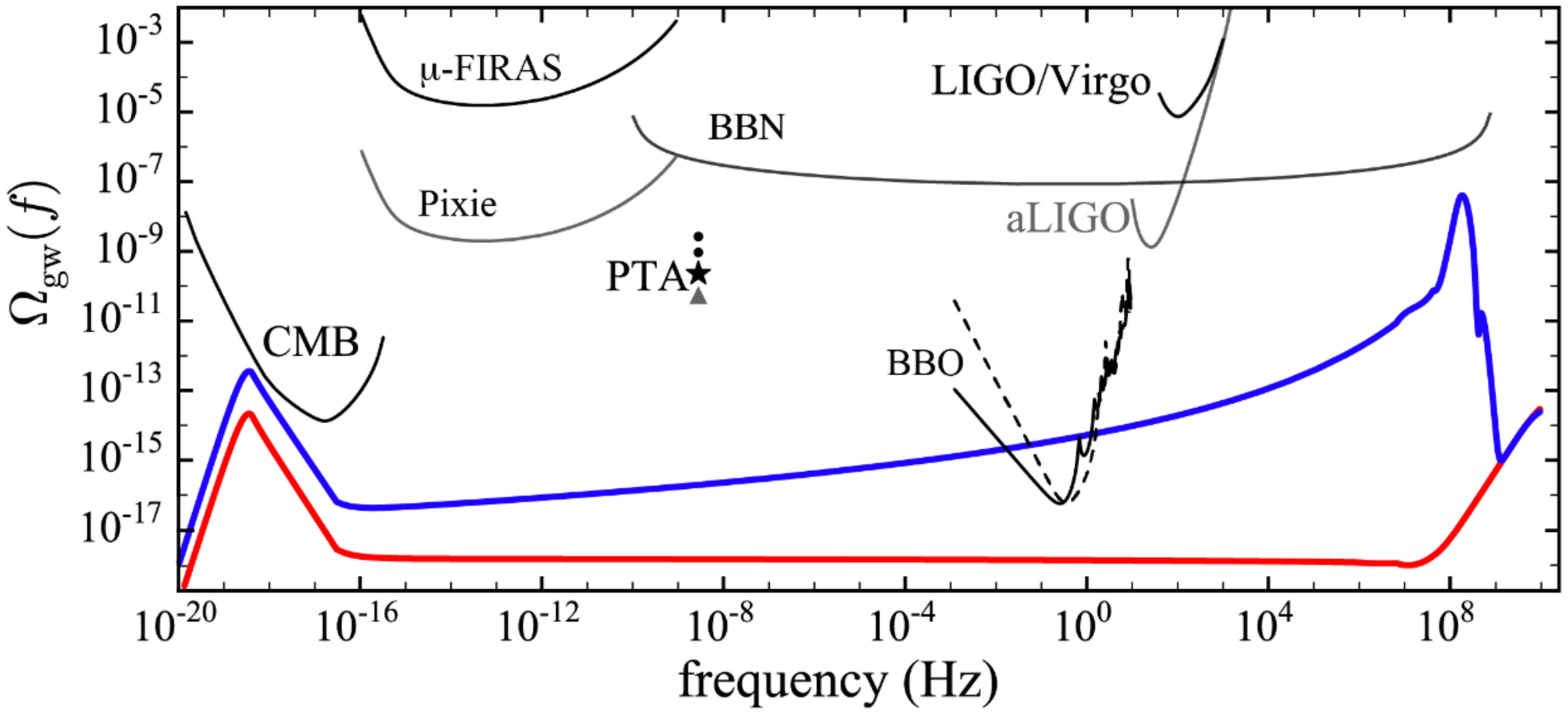
➡ Expect couplings to gauge fields

$$\mathcal{L} = \underbrace{-\frac{1}{2}(\partial\phi)^2 - U(\phi)}_{\text{Inflaton}} - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \underbrace{\frac{\lambda}{4f}\phi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}}_{\text{Coupling: sourced fluctuations}} + \ldots$$

Adshead, Wyman; Dimastrogiovanni, Fasiello, Fujita; Caldwell, Devulder….

Blue Tilt + other features

GW signal is parity violating, chiral, non-Gaussian:



Left circularly polarized

Right

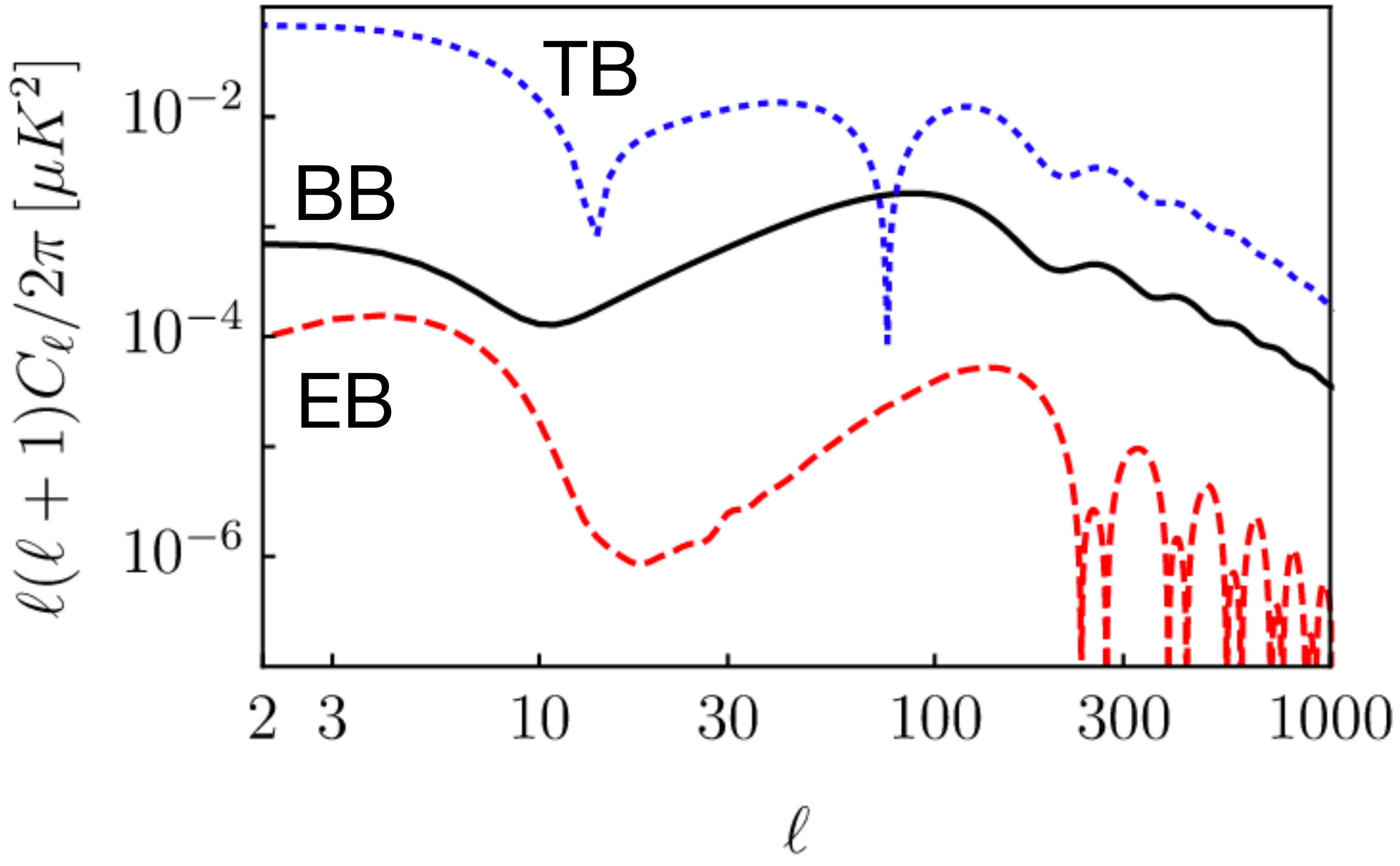


Figure: Caldwell, Devulder, 1706.03765

Benchmark models

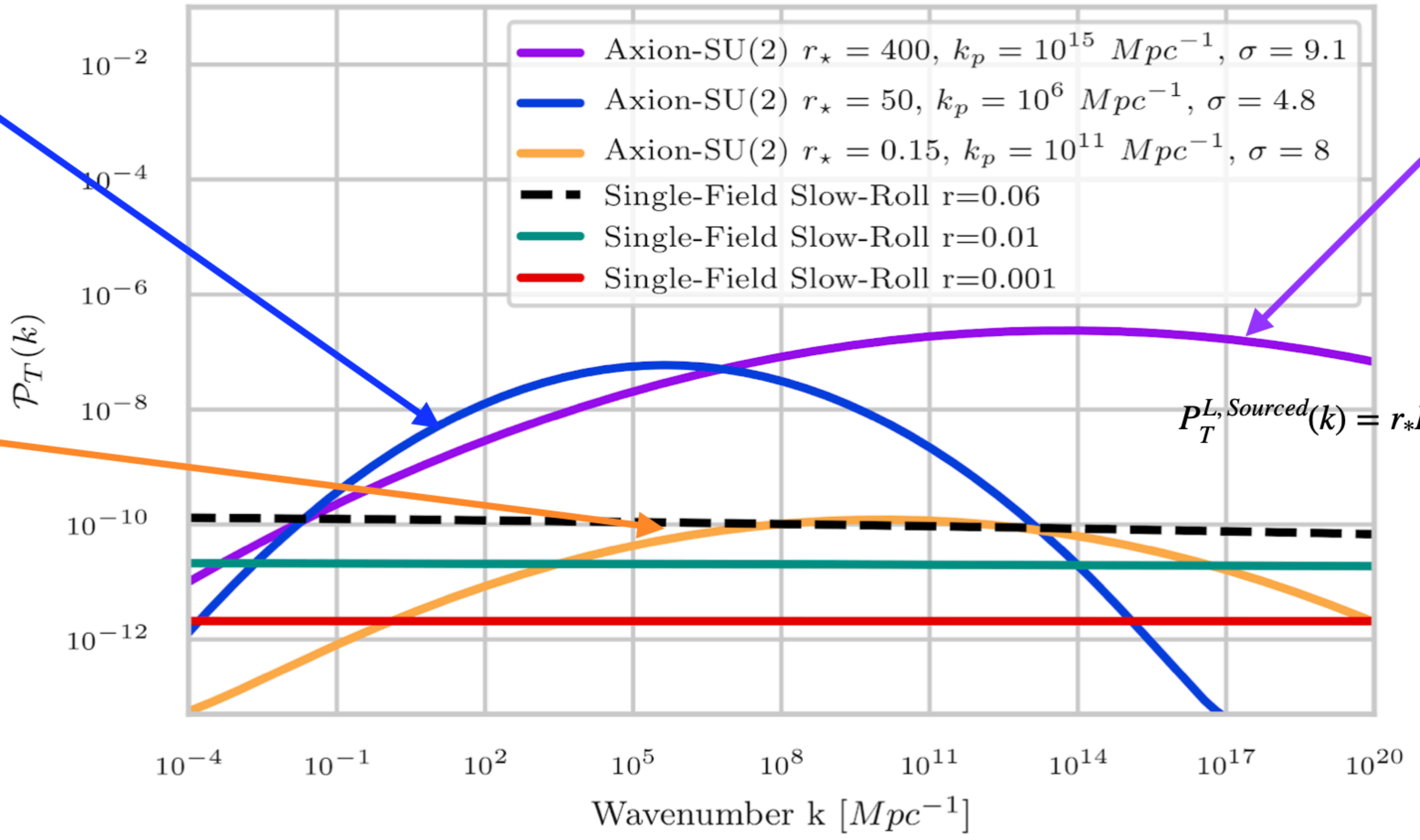
satisfying BICEP2/Planck upper bound on r

AX3 model

peaks in PTA range

AX2 model

peaks in space interferometers range but is not detectable at CMB scales



AX1 model

peaks in space interferometers range

$$P_T^{L,\,Sourced}(k) = r_* P_R(k) \exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{k}{k_p}\right)\right]$$

Paolo Campeti slide: used optimal filter function for this analysis (from 2101.02713)

Expected?

Generic field content is well-motivated

Parameter values that match current data and give large observable signals look a bit contrived

Is the space of models well-explored?

2. Characterizing an S4 signal

The features above suggest ways to characterize any (sufficiently large!) signal

Two goals:

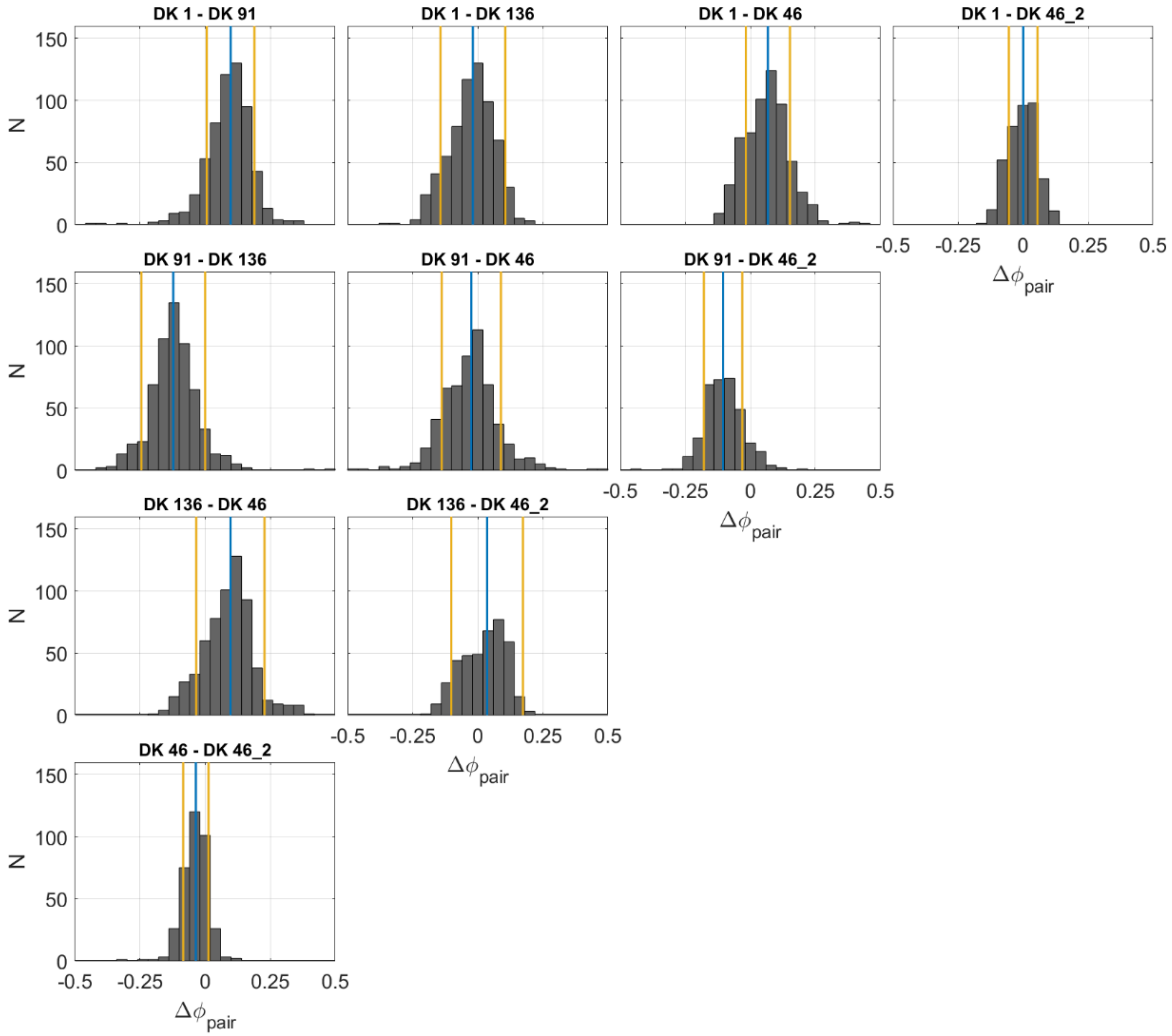
- Is this a primordial signal?
- Does it disfavor single-field slow-roll?

Challenges for EB

Mis-calibrating the absolute polarization angle:

$$C_\ell^{\prime TB} = C_\ell^{TE} \sin(2\alpha)$$

$$C_\ell^{\prime EB} = \frac{1}{2}\left(C_\ell^{EE} - C_\ell^{BB}\right) \sin(4\alpha)$$



Clem Pryke's talk; see 2012.05934 for BICEP3 results

-upshot: more to learn about how to do this

But, if signal does not overlap, less confusion

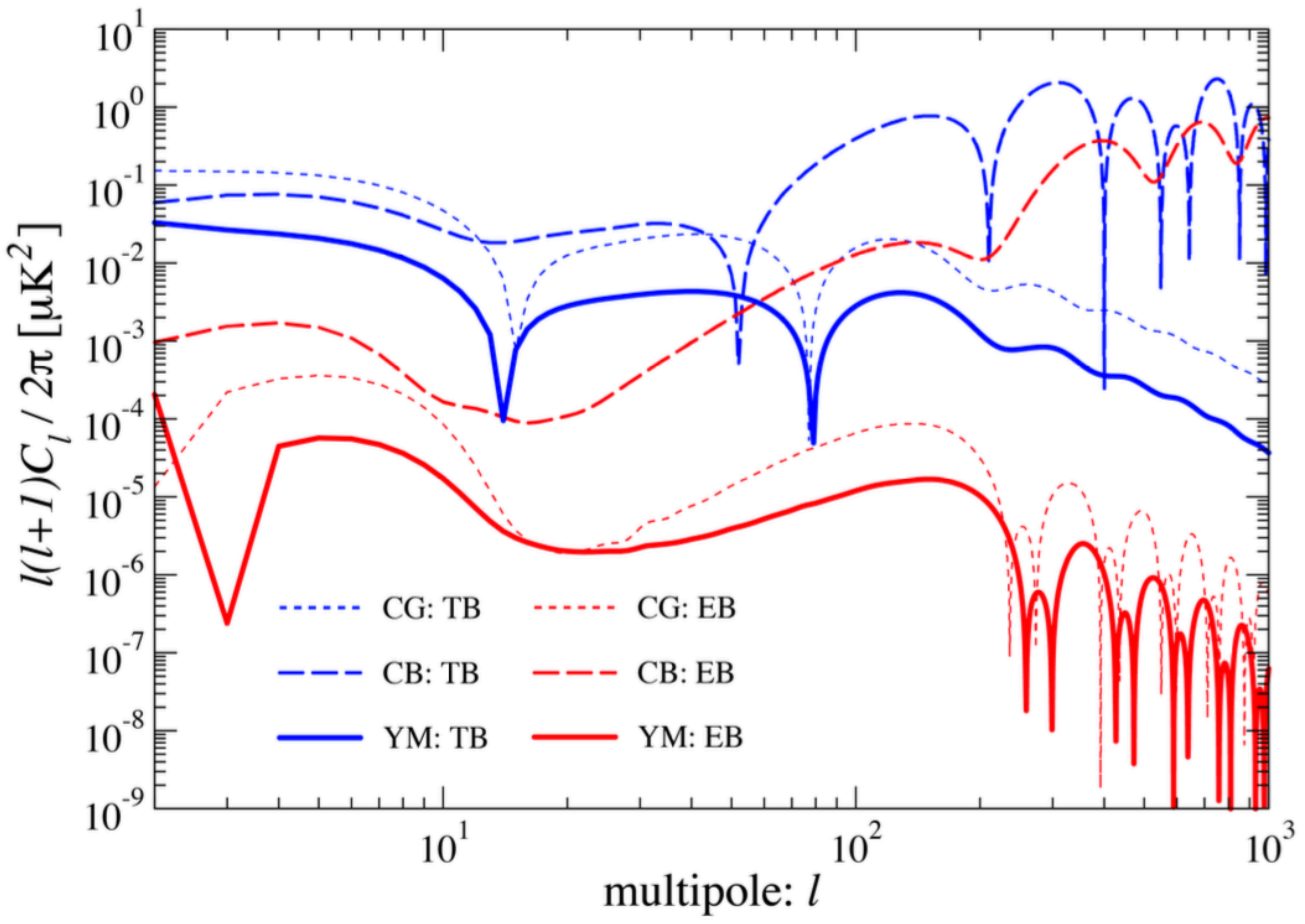


Fig. 10. The parity-violating cosmic polarization signals $\langle TB\rangle$ and $\langle EB\rangle$ from three different scenarios are shown. YM: the scenario based on the flavor-space locked gauge field presented in this article. CG: chiral gravity. CB: cosmic birefringence. We note that the YM and CG signals are similar. The CB signals strongly resemble the $\langle TE\rangle$ and $\langle EE\rangle$ power spectra shown in Fig. 9. For reference, the CB signal assumes a rotation angle $\Delta\theta = 1°$.

From Robert Caldwell

Bispectrum

Tensor NGs

Forecasts

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

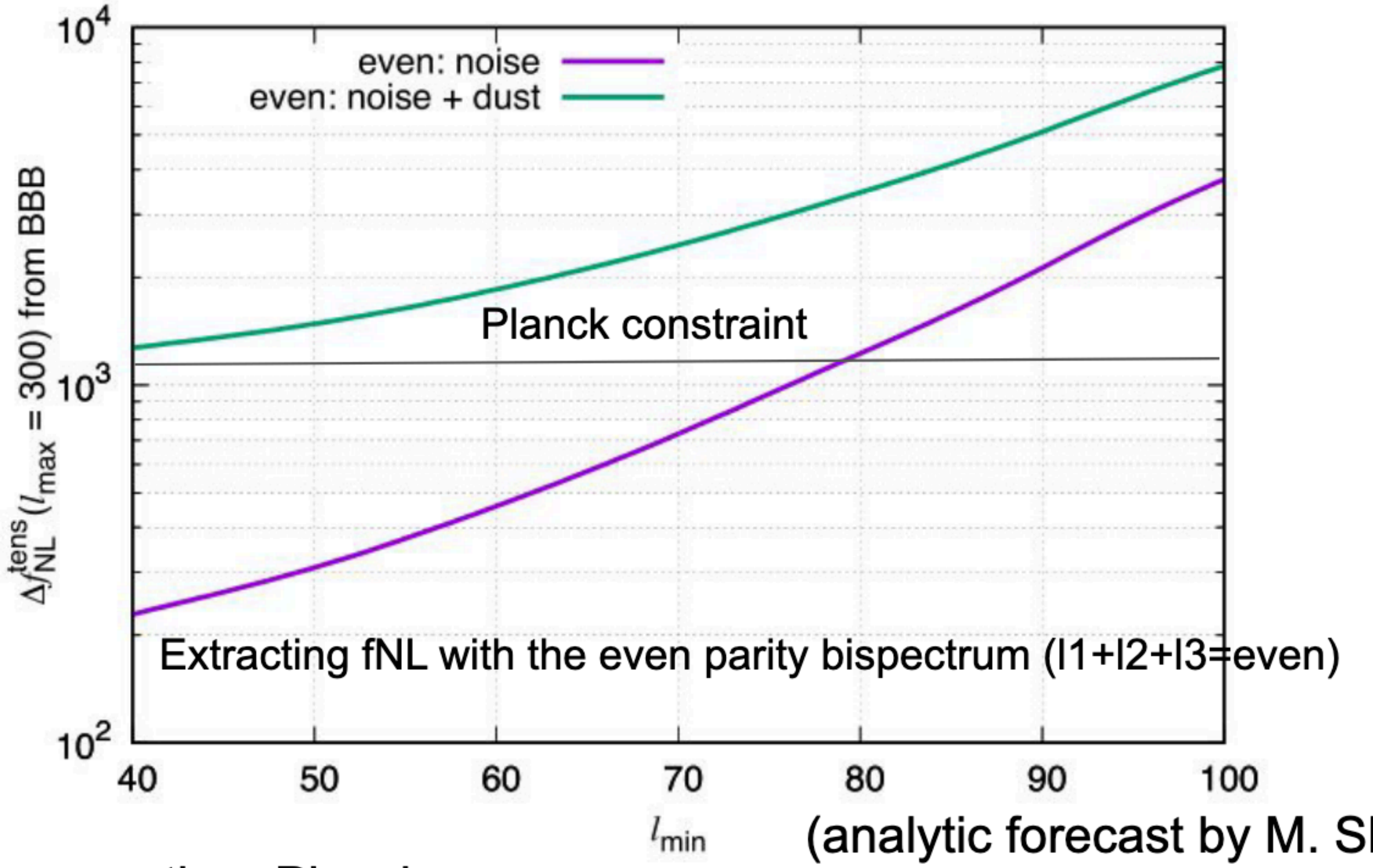
Shape: $\langle \mathcal{R}\mathcal{R}\gamma \rangle$ $\langle BTT \rangle$,$\langle BTE \rangle$,$\langle BEE \rangle$	Current	CMB-S4 goal	Conservative	CV-limited
$f_{\rm sky}$	69%	3%	3%	100%
$\sigma(\sqrt{r}\tilde{f}_{\rm NL}^{\rm local})$	28	0.79	1.2	0.052
$\sigma(\sqrt{r}\tilde{f}_{\rm NL}^{\rm equil})$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

Slide from Daan Meerburg

SNR of fNL from BICEP: Large-scale filtering

- An analytic forecast when including noise and dust for BK15



(analytic forecast by M. Shiraishi)

BK15: constraint is worse than Planck

BK18: constraint would be much better than Planck

- Although the best way to constrain tensor non-Gaussianity is to use B-mode bispectrum, the tensor non-Gaussianity can also produce T and E bispectrum and is constrained by Planck T/E

Planck constraints

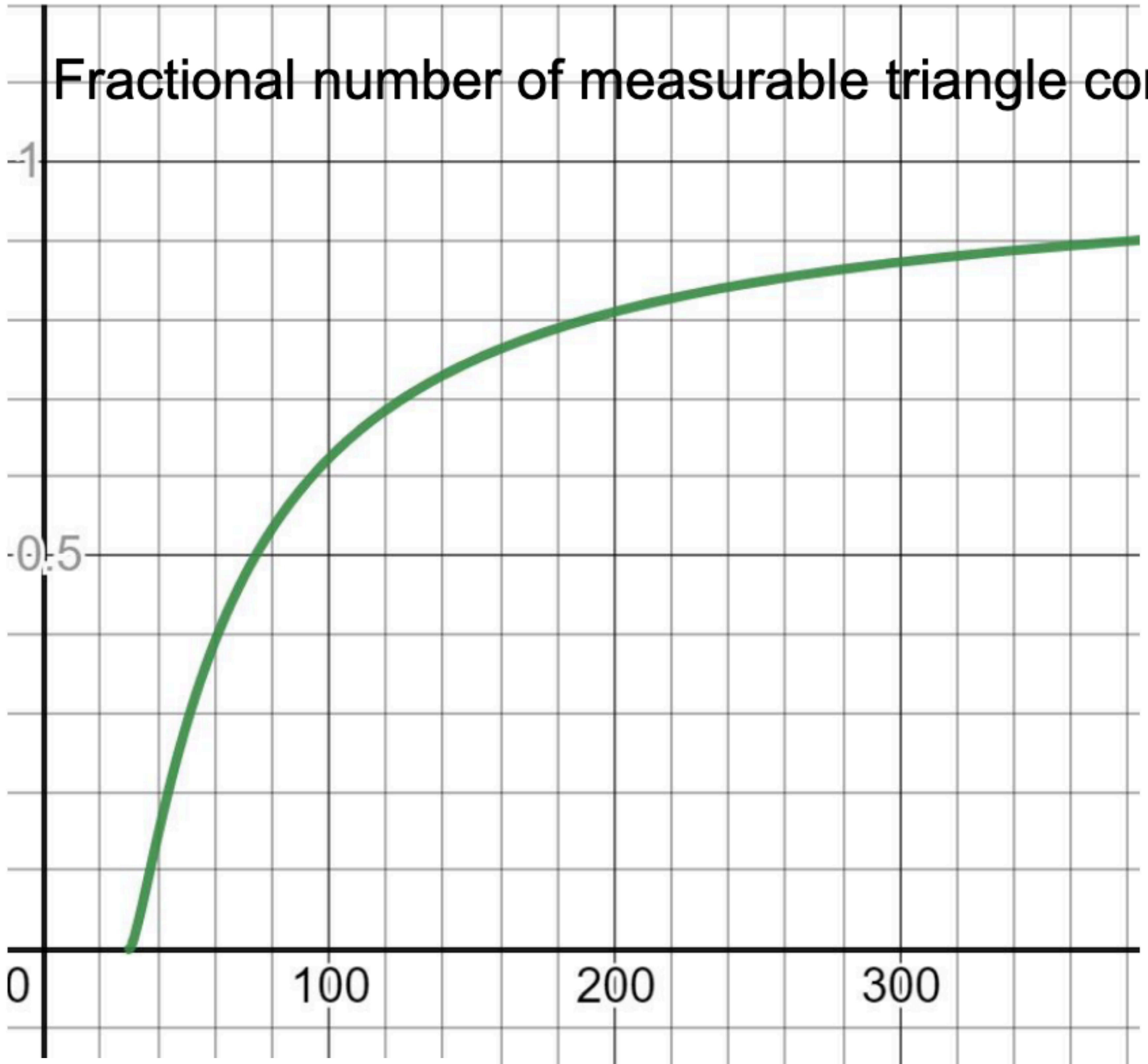
$$\sigma(f_{NL}^{tens}) = 1100$$ (Planck Collaboration 2018)

$$f_{\rm NL}^{\rm tens} \equiv \lim_{k_i \to k} \frac{B_{\rm h}^{+++}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)}{F_{\zeta}^{\rm equil}(k_1, k_2, k_3)}$$

Slide from Toshiya Namika

SNR of fNL from BICEP: Additional mode loss

- Restriction of triangle configuration by timestream filtering



$\ell_x = 30$

$$F = 1 - \frac{2\theta}{\pi} - \frac{2\ell_x}{\pi\ell}|\cos\theta| \qquad \sin\theta = \frac{\ell_x}{\ell}$$

- SNR estimate with a realistic simulation

  - 3D binned estimator is applied to BK18 B-modes
  (flat-sky counterpart of Bucher et al. 2016, Coulton & Spergel 2019)

$$b_{ijk} = \frac{1}{N_{ijk}} \int d^2 n B^{\rm f}_i(n) B^{\rm f}_j(n) B^{\rm f}_k(n) \qquad B^{\rm f}_i(n) = \int d^2\ell e^{i\ell n} f_{i.\ell} B_\ell$$

$$f^{\rm tens}_{NL} = \sum_{I=ijk} b_I^{f_{\rm NL}=1} {\rm Cov}_I^{-1} b_I$$

$\Rightarrow$ $\sigma(f^{\rm tens}_{NL}) \sim 600$

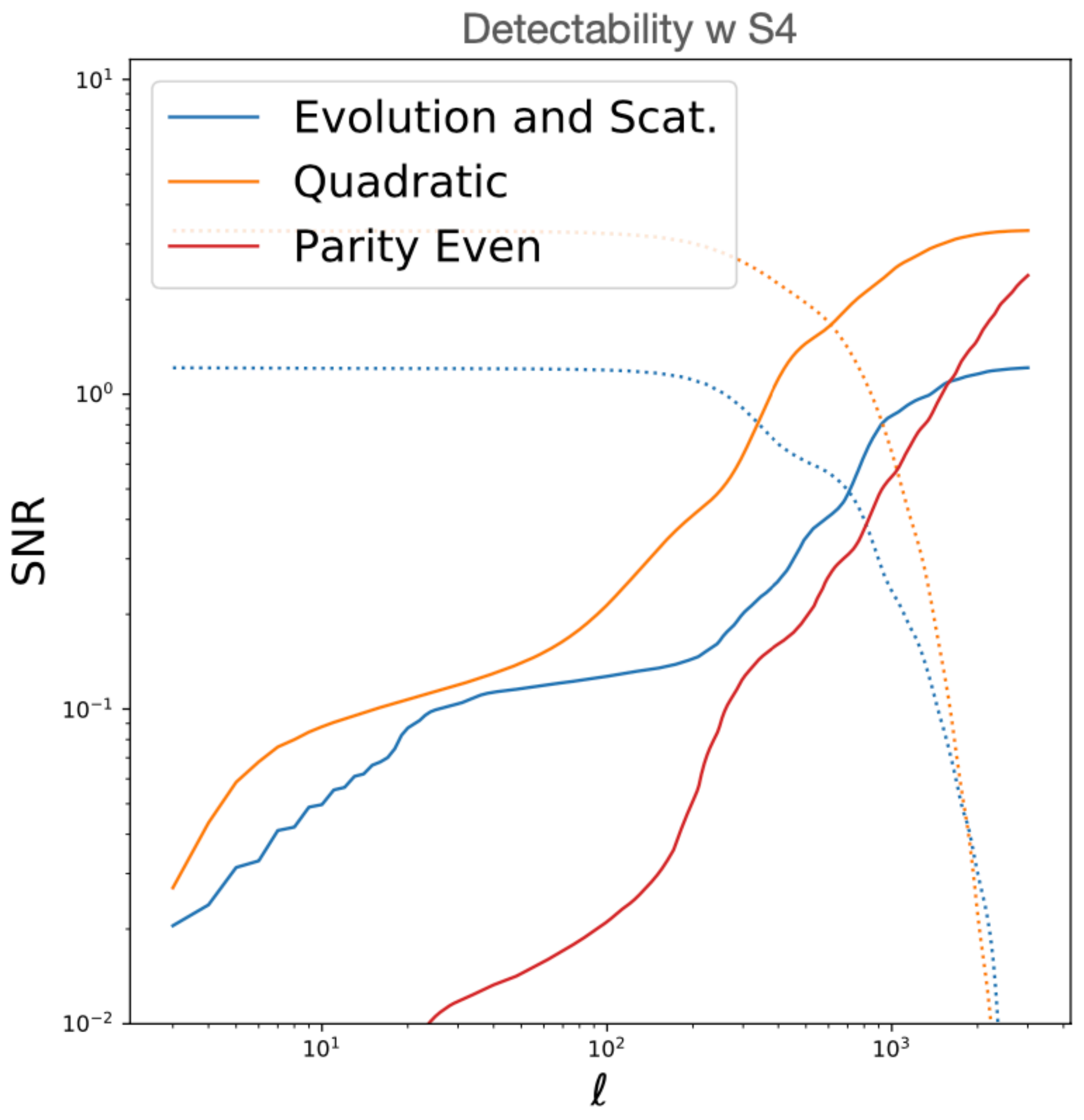
From Toshiya Namikawa's talk

Intrinsic Bispectrum?

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



Credits: Will Coulton

Slide from Daan Meerburg

3. Complementarity with Direct Detection II

- Phase Transitions within the dark sector
- Topological Defects
- Exotic compact objects from dark matter
- Individual merger events
- New source of stochastic background (or other signals, like bursts)

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