Current and future constraints on gravitational wave non-Gaussianities

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07 / Mar / 2019
Accelerating Universe in the Dark @YITP

In single-field slow-roll inflation based on GR

GWs are monochromatic

nearly scale-invariant
symmetric (isotropic, parity-even, …)
almost Gaussian

Non-Gaussianity (NG) in the tensor sector is a key indicator to specify the true inflationary model

① extra field: e.g. vector field ($\lambda = \pm 1$)

▫$h_{ij} \sim (E_i E_j + B_i B_j) / M_{pl}^2$ ☞ NG GW is sourced

$$\mathcal{L} = -\frac{1}{4}F^2 \qquad A_\lambda'' + k^2 A_\lambda = 0$$

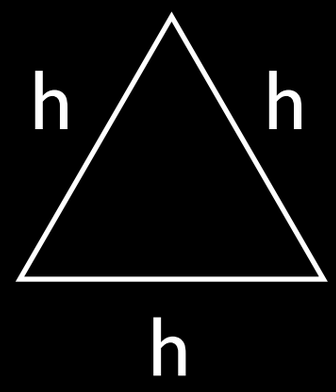
no effective production…

if A couple to pseudoscalar $-\frac{\alpha}{4f}\phi F\tilde{F} \quad +2\lambda\xi\frac{k}{\tau}A_\lambda$

A_+ enhanced exponentially!

[e.g., Sorbo: 1101.1525, Barnaby +: 1210.3257]

A_+ production is effective at intermediate scales



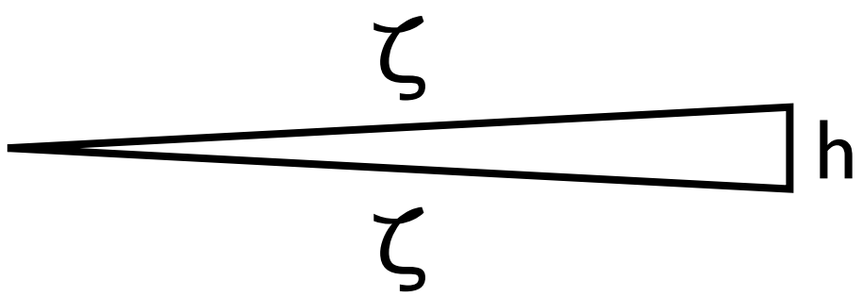
If primordial magnetic fields (PMFs) survive after inflation, they continue to generate tensor NGs

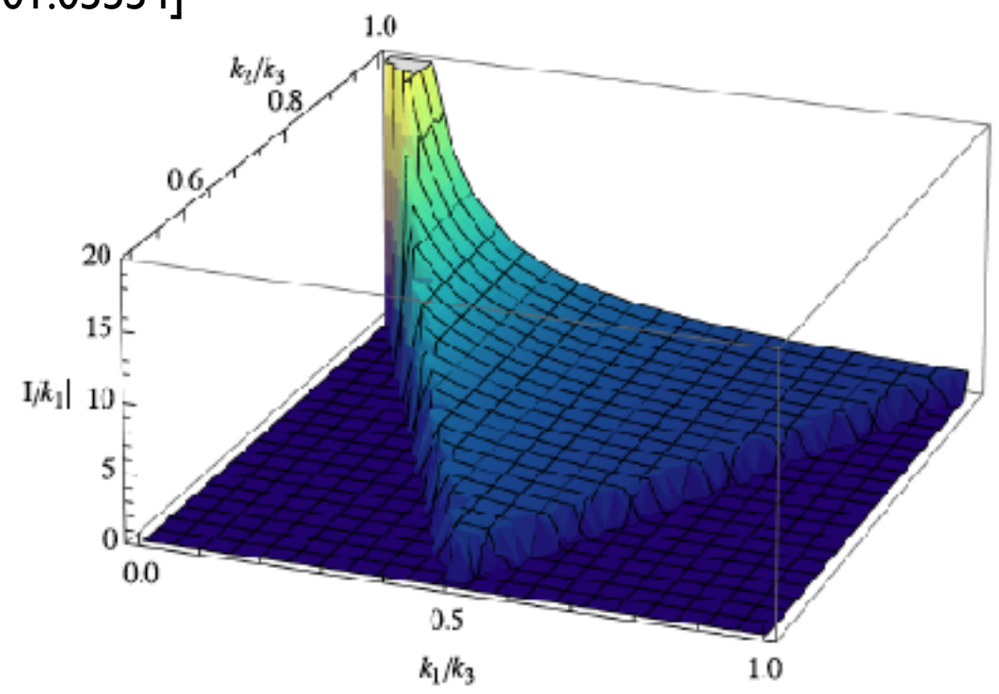
☞ squeezed type if PMF power is scale-invariant [MS +: 1103.4103]

② modification of gravity: e.g. massive gravity

[Domènech, Hiramatsu, Lin, Sasaki, MS, Wang: 1701.05554]

$$\mathcal{L} \sim M_p^2 \frac{m_g^2}{H^2} h_{ij} (\partial_i \zeta)(\partial_j \zeta)$$





e.g. Weyl gravity

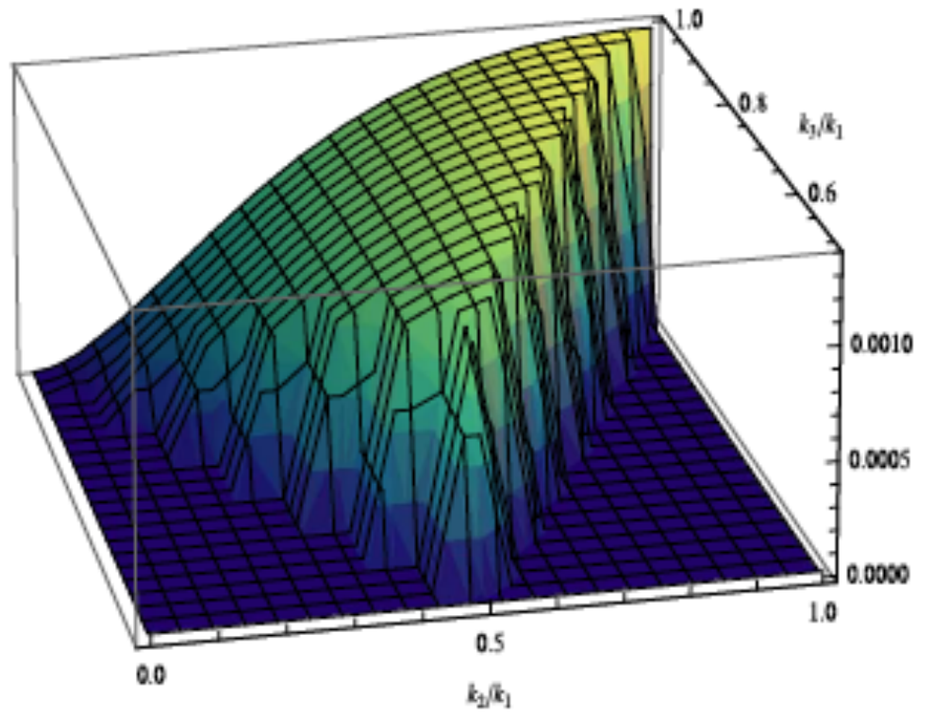
$\mathcal{L} \sim f(\phi)\widetilde{W}W$ ☞ P-odd <hhζ>

[Bartolo & Orlando: 1706.04627, Bartolo, Orlando, MS: 1809.11170]

$\mathcal{L} \sim \frac{f(\phi)}{\Lambda^2} W^3$ ☞ P-even <hhh>

[MS +: 1108.0175]

$\mathcal{L} \sim \frac{f(\phi)}{\Lambda^2} \widetilde{W} W^2$ ☞ P-odd <hhh>



There are already observational bounds from CMB!

★ *tensor f_{NL} parameters normalized by the scalar bispectra*

equilateral <hhh>

$$f_{\rm NL}^{ttt,{\rm eq}} \equiv \lim_{k_i \to k} \frac{B^{2\ 2\ 2}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}}{B^{\zeta{\rm eq}}_{k_1k_2k_3}(f^{\zeta{\rm eq}}_{\rm NL}=1)}$$

squeezed <hhh>

$$f_{\rm NL}^{ttt,{\rm sq}} \equiv \lim_{\substack{k_1 \to 0 \\ k_2 \to k_3}} \frac{B^{2\ 2\ 2}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}}{B^{\zeta{\rm loc}}_{k_1k_2k_3}(f^{\zeta{\rm loc}}_{\rm NL}=1)}$$

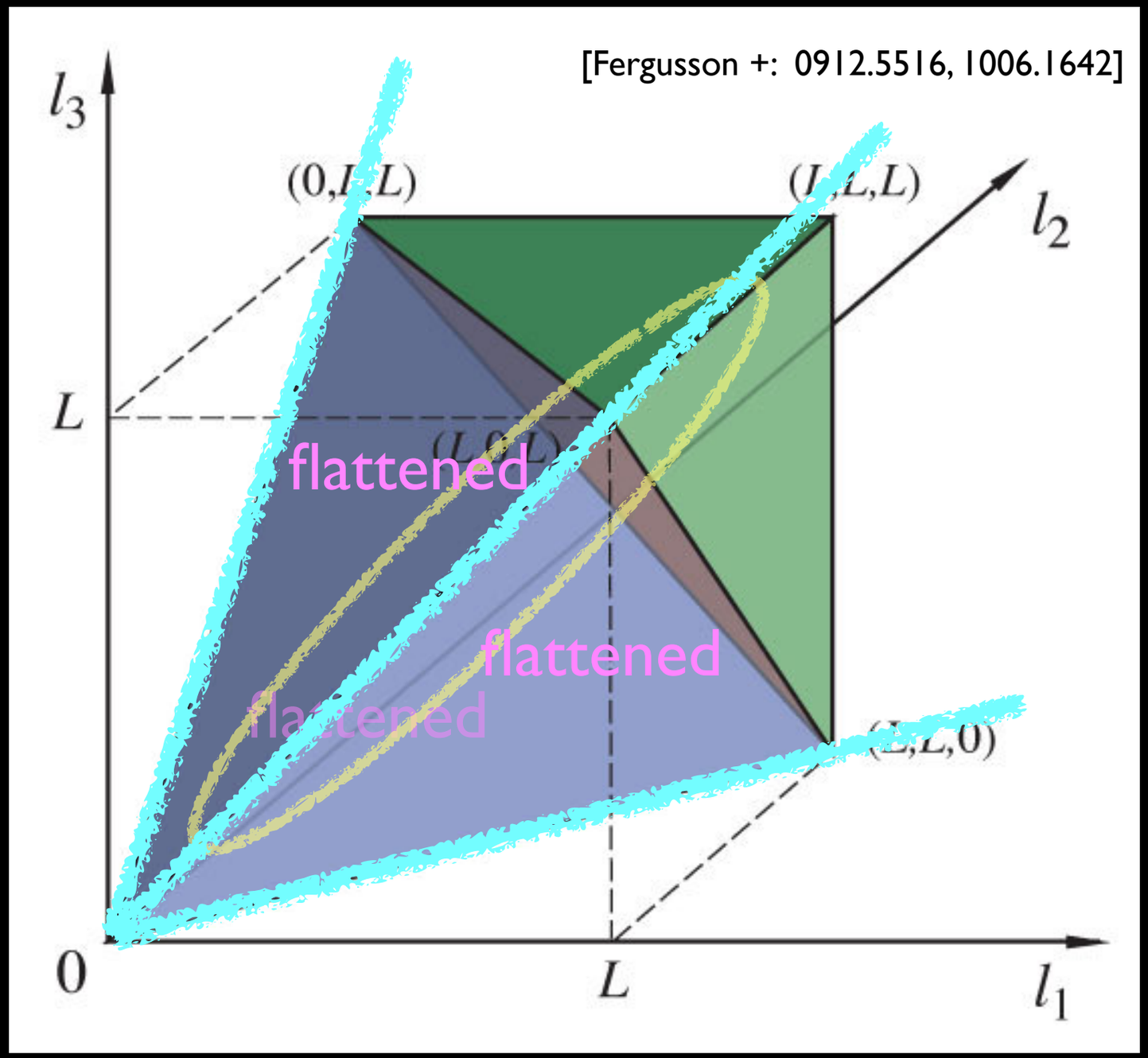
squeezed <hζζ>

$$f_{\rm NL}^{tss,{\rm sq}} \equiv \lim_{\substack{k_1 \to 0 \\ k_2 \to k_3}} \frac{B^{2\ 0\ 0}_{\mathbf{k}_1\mathbf{k}_2\mathbf{k}_3}}{B^{\zeta{\rm loc}}_{k_1k_2k_3}(f^{\zeta{\rm loc}}_{\rm NL}=1)}$$

CMB (angle-averaged) bispectrum

$$B_{\ell_1\ell_2\ell_3} \equiv \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \left\langle \prod_{n=1}^{3} a_{\ell_n m_n} \right\rangle \quad \propto \langle hhh \rangle, \langle hh\zeta \rangle, \langle h\zeta\zeta \rangle$$

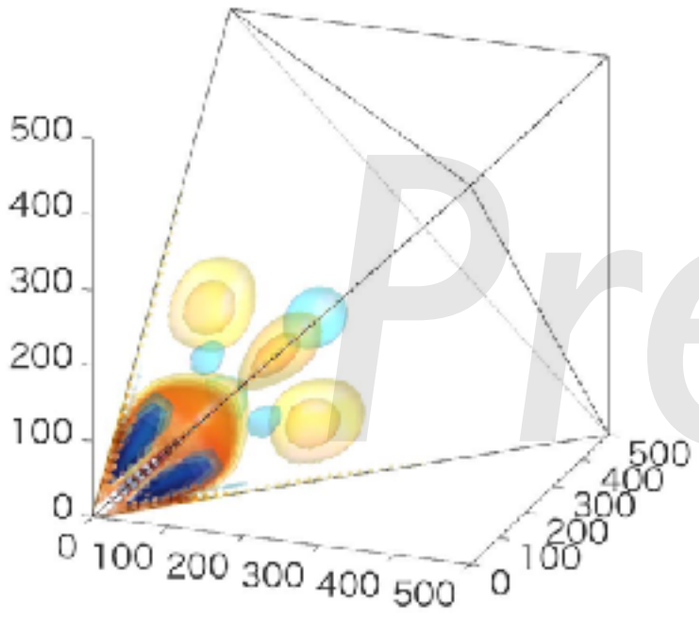
squeezed
$\ell_1 \sim \ell_2 >> \ell_3$



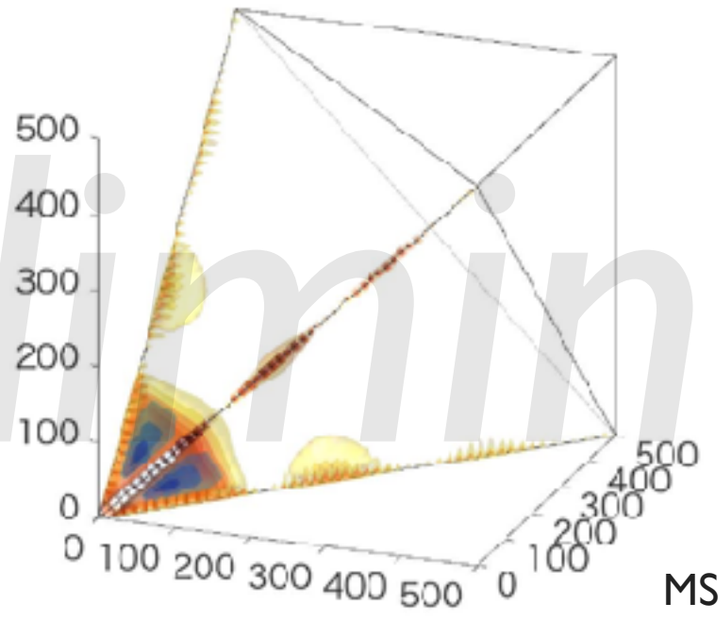
equilateral
$\ell_1 \sim \ell_2 \sim \ell_3$

flattened
$\ell_1 + \ell_2 \sim \ell_3$

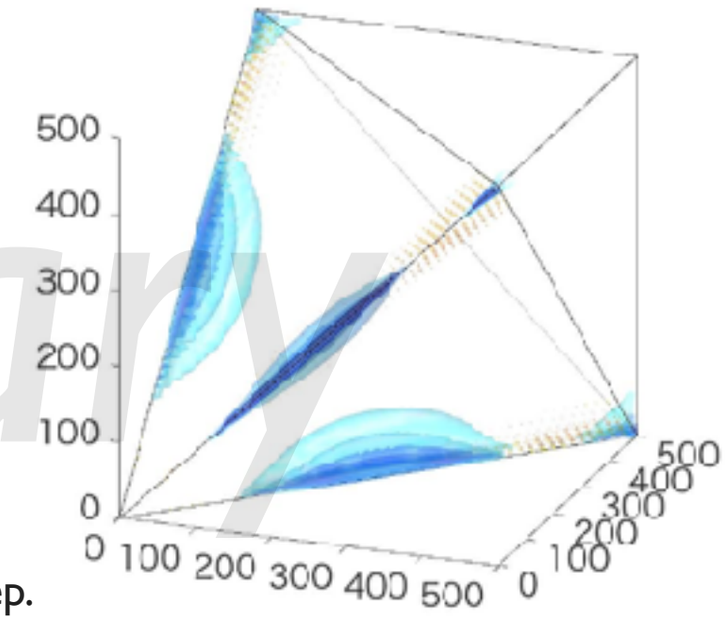
Theoretical prediction of TTT



$f_{NL}^{ttt,eq}$



$f_{NL}^{ttt,sq}$

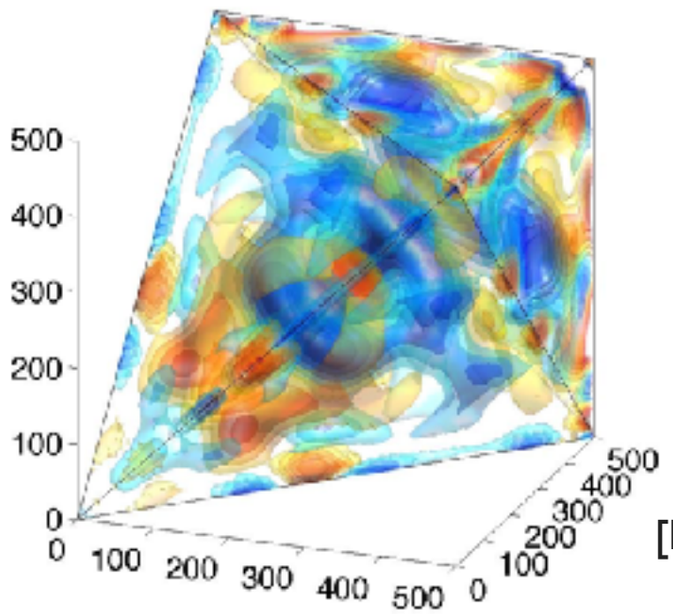


$f_{NL}^{tss,sq}$

MS in prep.

vs.

Observed TTT



[Planck 2015: 1502.01592]

Observational bounds

	$f_{NL}^{ttt,eq}$	$f_{NL}^{ttt,sq}$	$f_{NL}^{tss,sq}$
WMAP T-only	600 ± 1500 [1409.0265]	220 ± 170 [1304.7277]	84 ± 49 [1710.06778]
Planck 2015 T-only	400 ± 1500 [1502.01592]	290 ± 180 [1502.01594]	-
Planck 2015 T+E	0 ± 1300 [1502.01592]	-	-

- axion-U(1) model: $\xi \equiv \frac{\alpha|\dot{\phi}|}{2fH} < 3.3$

[Cook & Sorbo: 1307.7077, MS +: 1308.6769]

- axion-SU(2) model: $\frac{r^2}{\Omega_A} < 500$

[Agrawal +: 1707.03023]

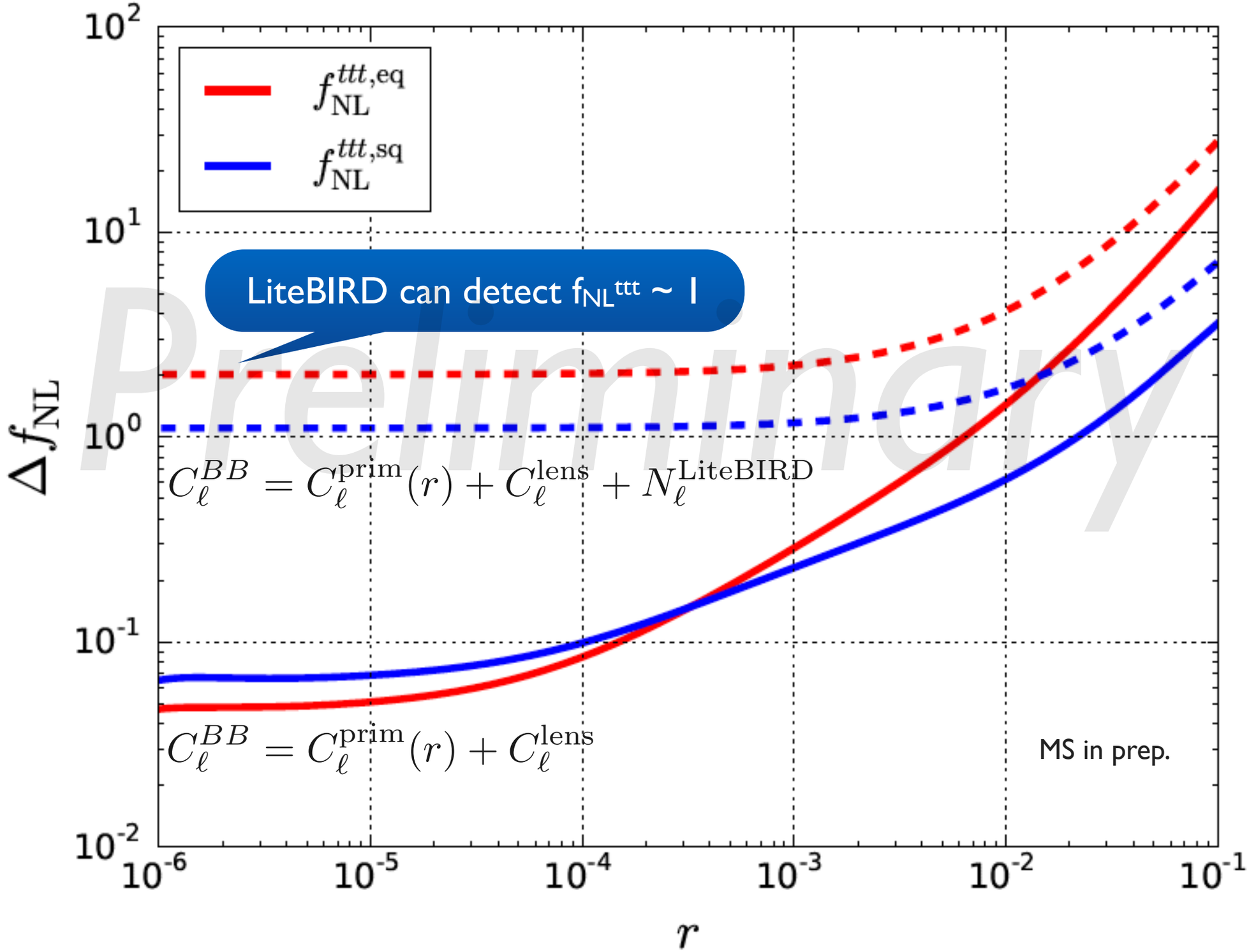
$B_{1Mpc} < 3nG$

$\frac{m_g^2}{H^2} < 30$

In the next decade

Potential of B-mode bispectrum

$$F = \sum_{\ell_1 \ell_2 \ell_3} \frac{\left(B^{BBB}_{\ell_1 \ell_2 \ell_3}\right)^2}{6 C^{BB}_{\ell_1} C^{BB}_{\ell_2} C^{BB}_{\ell_3}} \qquad \Delta f_{\rm NL} = \frac{1}{\sqrt{F}}$$

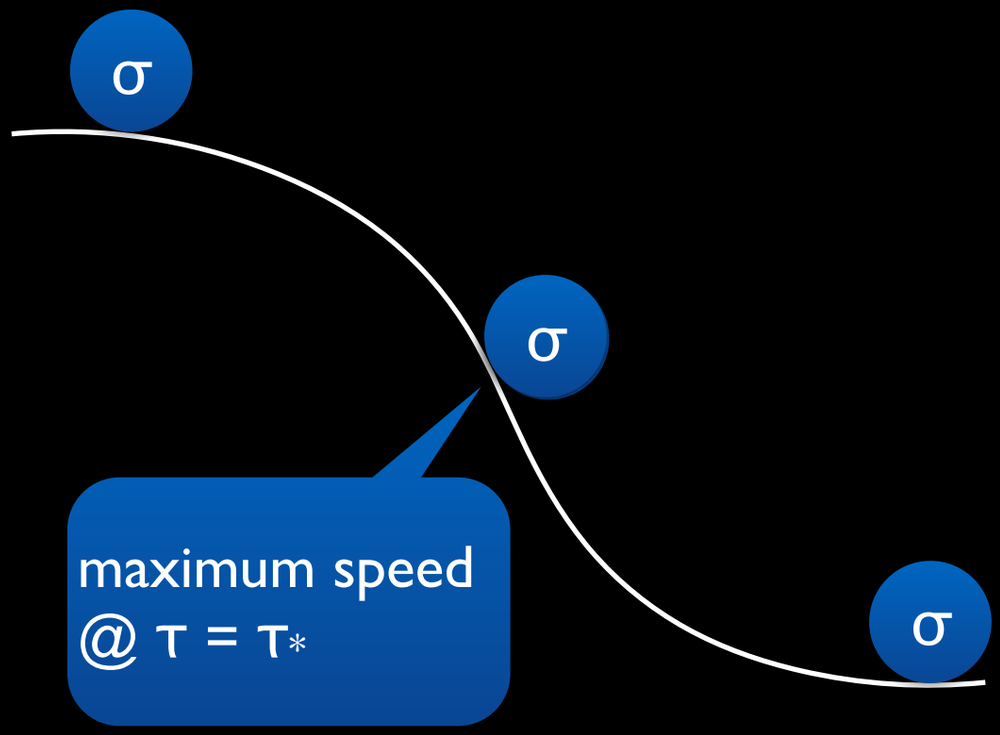


Scale-dependent NGs

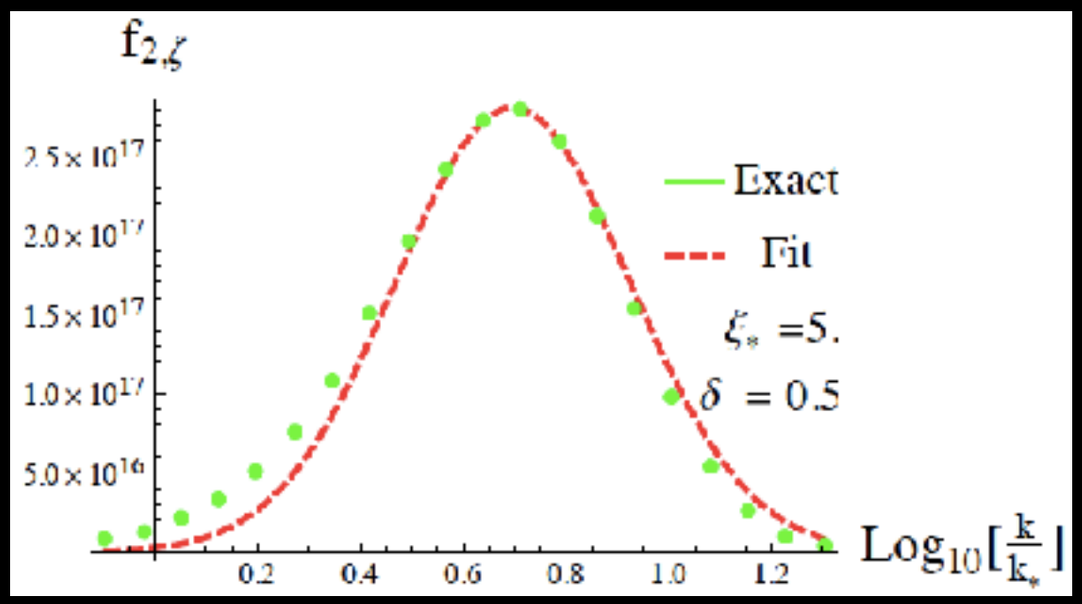
$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{2}(\partial\sigma)^2 - V(\sigma) - \frac{1}{4}F^2 - \frac{\alpha}{4f}\sigma F\tilde{F}$$

[e.g., Barnaby +: 1206.6117, Cook & Sorbo: 1307.7077, Ferreira & Sloth: 1409.5799]

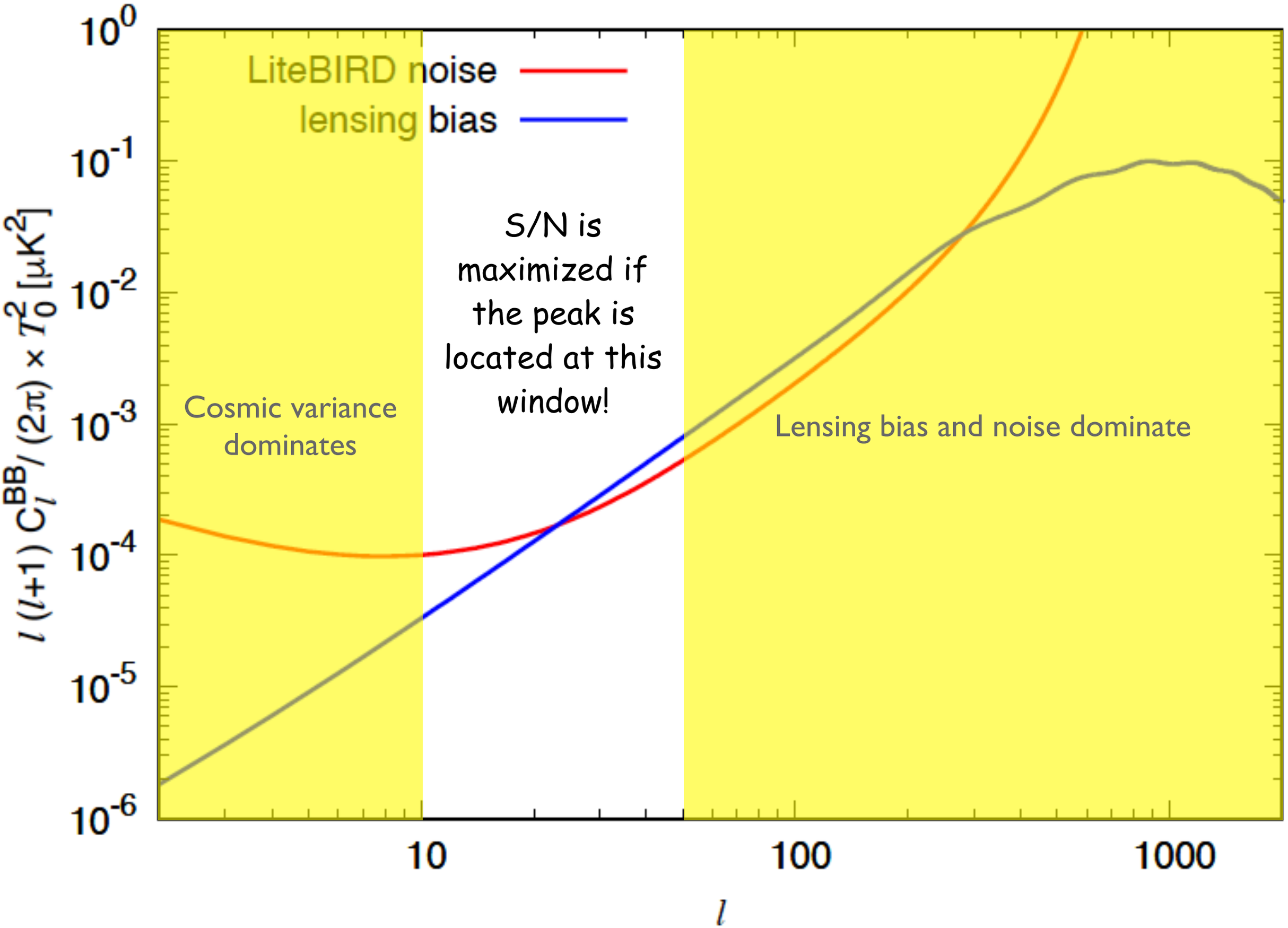
$$V_\sigma(\sigma) = \frac{\Lambda^4}{2}\left[\cos\left(\frac{\sigma}{f}\right) + 1\right]$$



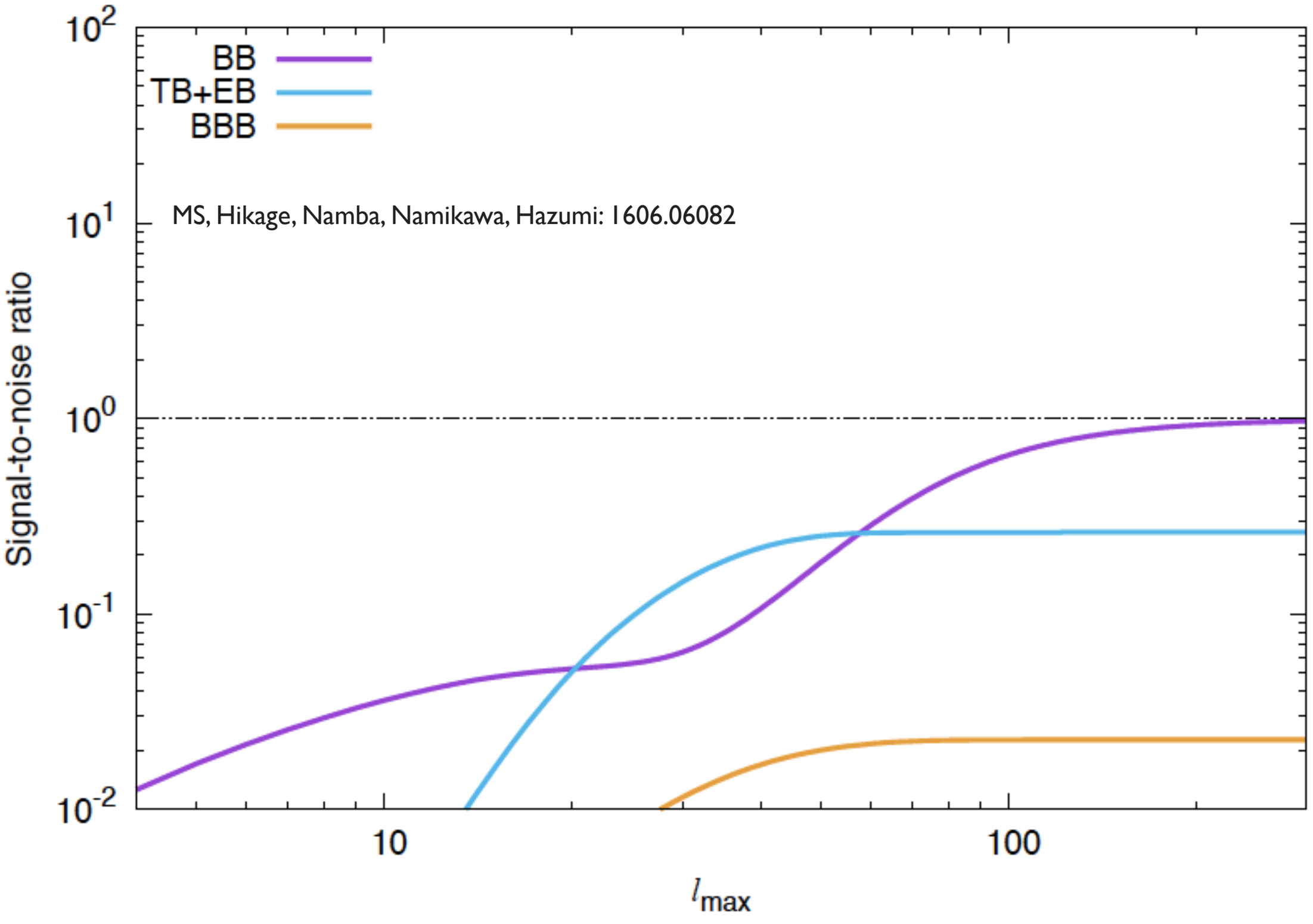
Source modes roughly have a peak @ $k \sim k_* = -\tau_*^{-1}$



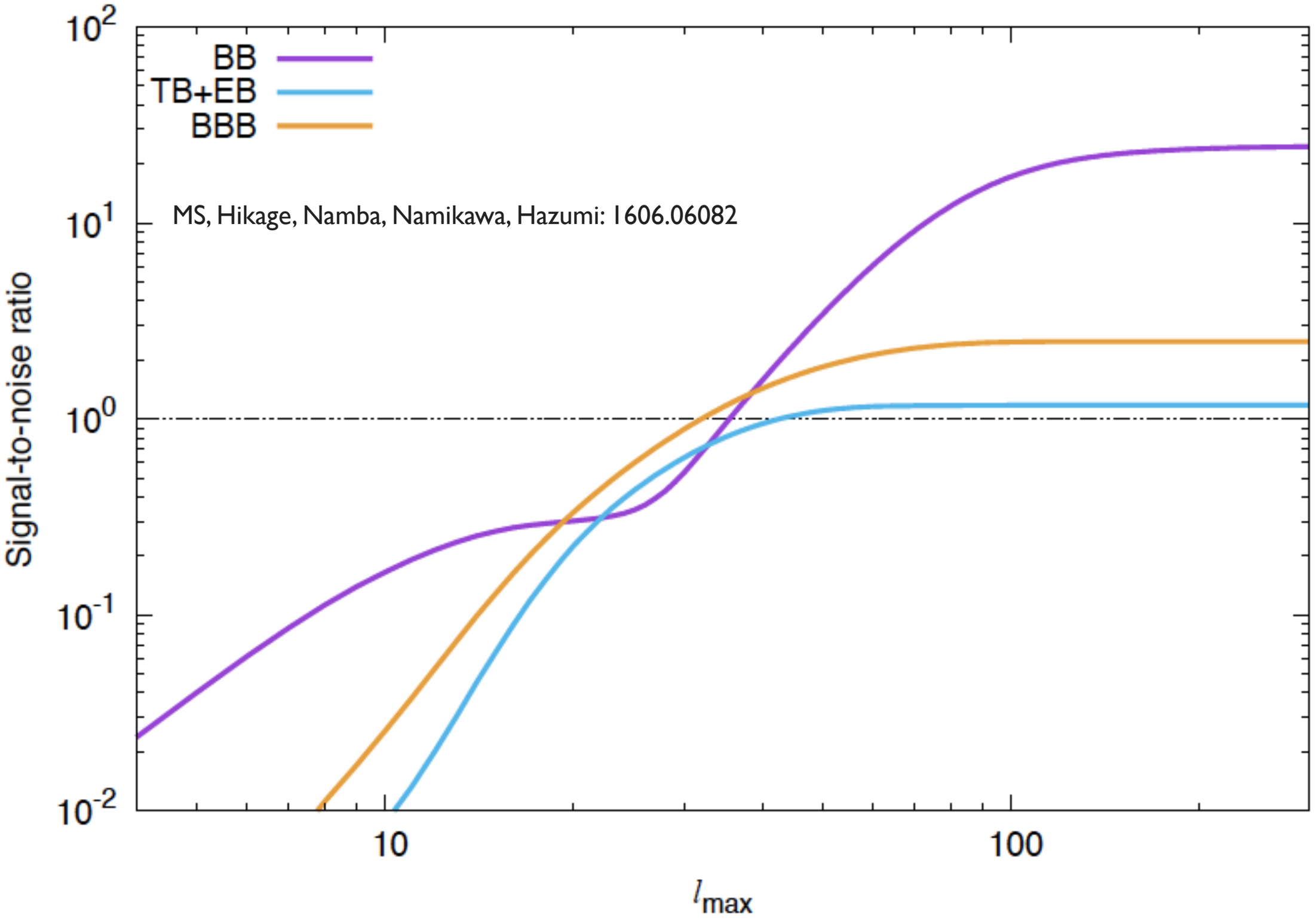
[Namba, Peloso, MS, Sorbo, Unal: 1509.07521]


LiteBIRD noise
lensing bias
S/N is maximized if the peak is located at this window!
Cosmic variance dominates
Lensing bias and noise dominate
$l\,(l+1)\,C_l^{BB}/(2\pi) \times T_0^2\ [\mu K^2]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10
100
1000
l

Planck (f_{sky} = 0.7)



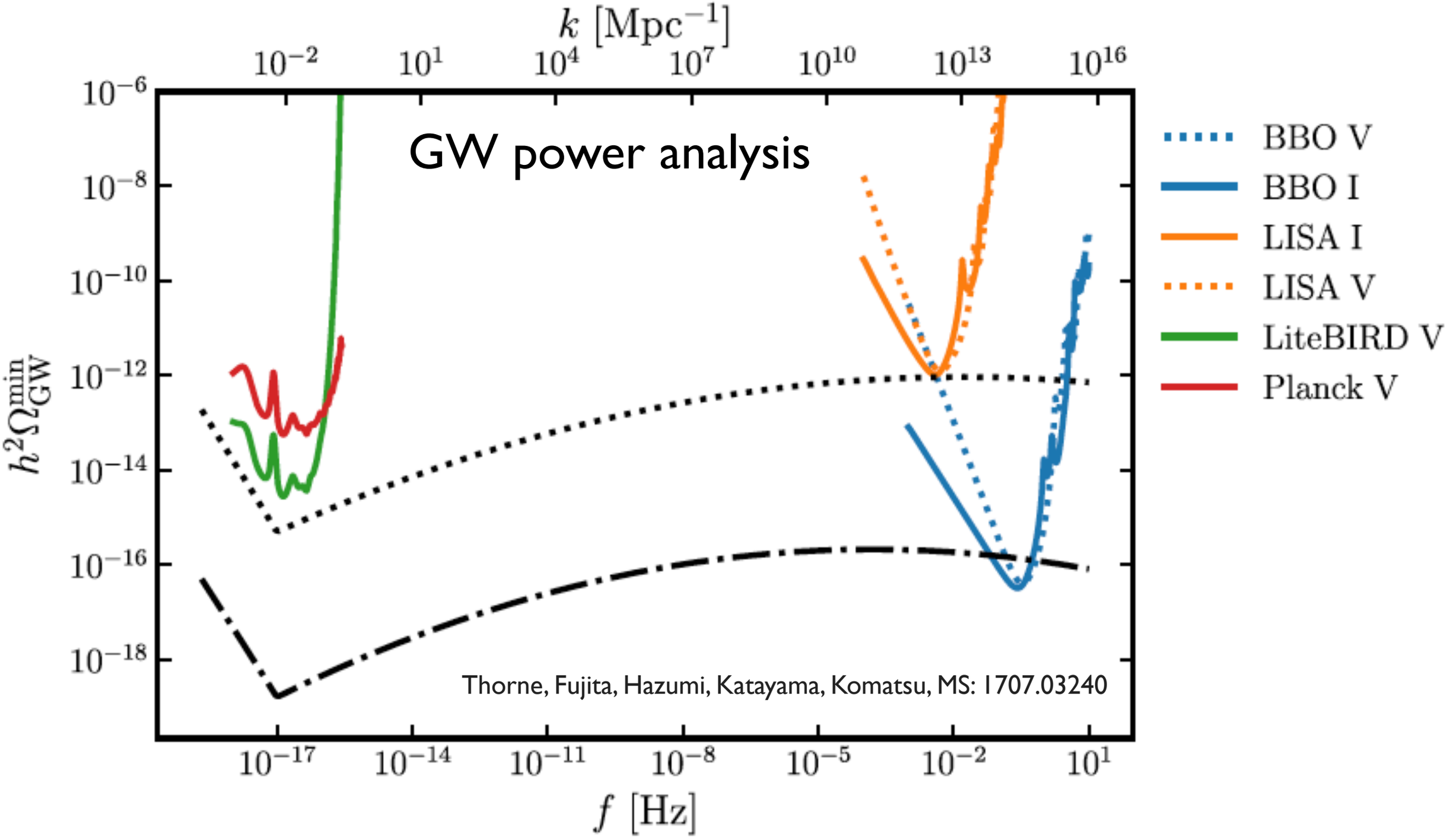
LiteBIRD (f_{sky} = 0.5)



S/N BBB > 2!!

GW interferometers can access small-scale signal

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{\lambda}{4f}\chi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$



similar results are expected in the GW bispectrum analysis

Summary

✤So far, no >2σ signal of $f_{NL}^{ttt,eq}$ / $f_{NL}^{ttt,sq}$ / $f_{NL}^{tss,sq}$ in CMB temperature and E-mode polarization maps

✤Planck 2019 T+E bounds on $f_{NL}^{ttt,eq}$ are coming soon!

✤B-mode NG search is very meaningful & promising!

- BBB (e.g. axions, gauge fields, PMFs)
- BTT (e.g. massive gravity)
- BBT (e.g. Weyl gravity)

Of course there are also other possible models

✤direct measurement by GW interferometer is also informative (especially for the scale-dependent NG)

Please see MS in prep. (coming soon) for details