Seeking higher spin fields through cosmic symmetry breakings

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If vector field $(s = 1)$
has nonzero
background mode

$$\mathcal{L} = \underbrace{-\frac{1}{2}(\partial\phi)^2 - V(\phi)}_{\text{inflaton}} \underbrace{- \frac{1}{4} f(\phi) F^2}_{\text{coupling to vector field}}$$

inflaton

coupling to vector field

$\mathbf{A} = \mathbf{A}^{vev} + \delta\mathbf{A}$

e.g., Watanabe, Kanno, Soda: 0902.2833

$\rho_\varphi \sim V \gg \rho_A$

☞ stable isotropic inflation

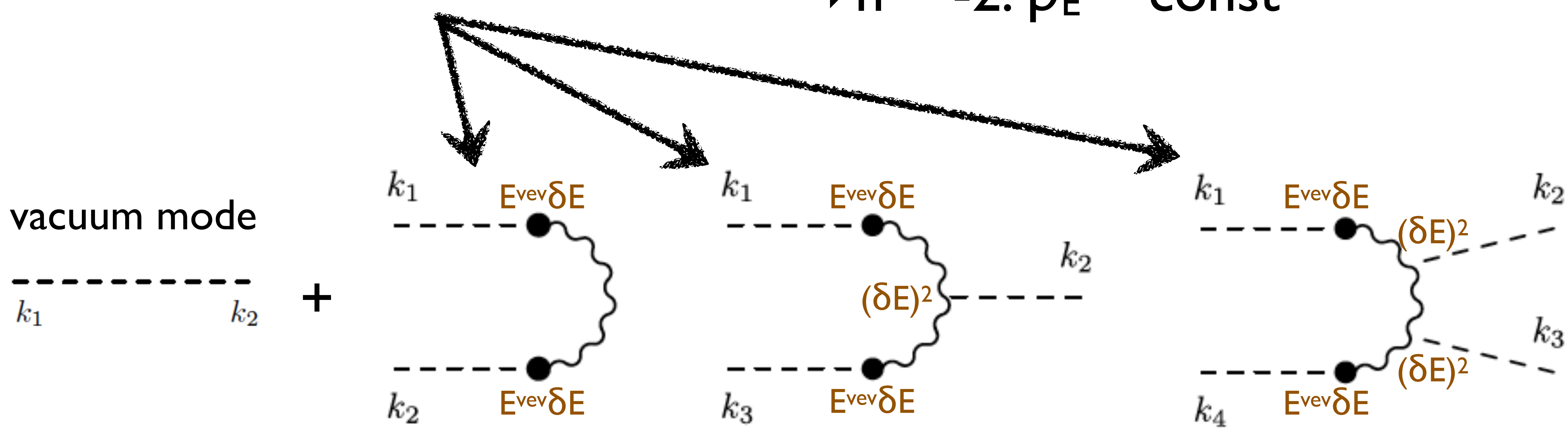
assume $f(\varphi) \propto a^{2n}$

- n > 0: strong coupling regime
- n ≦ 0: electric field dominates
  - ▸ $n = 0$: $\rho_E \propto a^{-4}$
  - ▸ $n = -2$: $\rho_E = \text{const}$

$H_{int}^{(s)} \sim \zeta\,(\mathbf{E}^{vev} \cdot \delta\mathbf{E} + \delta\mathbf{E}^2)$

☝☝ preferred direction!

$H_{int}^{(t)} \sim h_{ab}\,(E_a^{vev}\delta E_b + \delta E_a \delta E_b)$



$\langle\zeta^2\rangle, \langle\zeta h\rangle, \langle h^2\rangle$

$\langle\zeta^3\rangle, \langle\zeta^2 h\rangle,$
$\langle\zeta h^2\rangle, \langle h^3\rangle$

$\langle\zeta^4\rangle, \ldots$

primordial correlators

$<\zeta^2> \sim [\int d\tau]^2 <\zeta^2 (H_{int}^{(1)})^2> \propto E_a E_b <\delta E_a \delta E_b> \propto 1 - (\mathbf{k} \cdot \mathbf{E})^2$

$<\zeta^3> \sim [\int d\tau]^3 <\zeta^3 (H_{int}^{(1)})^2 H_{int}^{(2)}> \propto <\delta E_i \delta E_j> <\delta E_i \delta E_k> E_j E_k$

$$\propto \left[\sum_{s_1=\pm1} \epsilon_i^{(s_1)}(\hat{\mathbf{k}}_1)\epsilon_j^{(s_1)*}(\hat{\mathbf{k}}_1)\right]\left[\sum_{s_2=\pm1} \epsilon_i^{(s_2)}(\hat{\mathbf{k}}_2)\epsilon_k^{(s_2)*}(\hat{\mathbf{k}}_2)\right] \hat{E}_j^{\rm vev}\hat{E}_k^{\rm vev}$$

$$= 1 - \left(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{E}}^{\rm vev}\right)^2 - \left(\hat{\mathbf{k}}_2 \cdot \hat{\mathbf{E}}^{\rm vev}\right)^2 + \left(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{E}}^{\rm vev}\right)\left(\hat{\mathbf{k}}_2 \cdot \hat{\mathbf{E}}^{\rm vev}\right)\left(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2\right)$$

$<\zeta^4> \sim [\int d\tau]^4 <\zeta^4 (H_{int}^{(1)})^2 (H_{int}^{(2)})^2>$

$\propto <\delta E_a \delta E_c> <\delta E_b \delta E_d> <\delta E_a \delta E_b> E_c E_d$

★ quadrupolar statistical anisotropy

Of course, quadrupolar anisotropy also appears in scalar-tensor-cross and tensor-auto correlators: $<\zeta h>$, $<h^2>$, $<\zeta^2 h>$, $<h^3>$, …

If vector field ($s = 1$) couples to axion

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

inflaton = axion

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

$$A''_\lambda + k^2 A_\lambda = 0$$

unpolarized, i.e., $A_+ = A_-$

$$+2\lambda\xi\frac{k}{\tau}A_\lambda$$

A_+ enhanced exponentially!

$$\xi \equiv \frac{\alpha|\dot{\phi}|}{2fH} = \sqrt{\frac{\epsilon}{2}}\frac{\alpha M_p}{f}$$

$A + A \rightarrow \Phi \rightarrow \zeta$

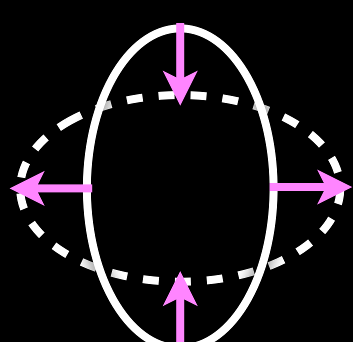
$\zeta_{sou} \propto \delta\varphi_{sou} \propto \mathbf{E}\cdot\mathbf{B}$

↑ pseudoscalar

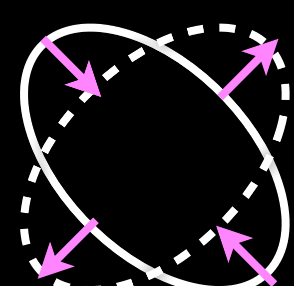
$A_+ + A_+ \rightarrow h^{(+2)}$

★ parity violation

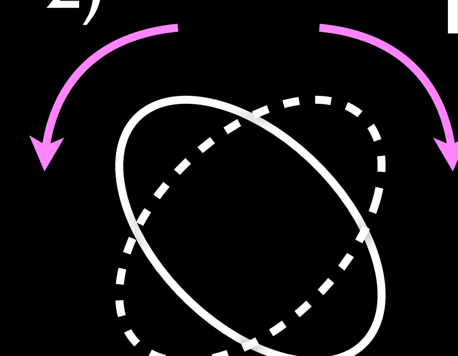
h_+

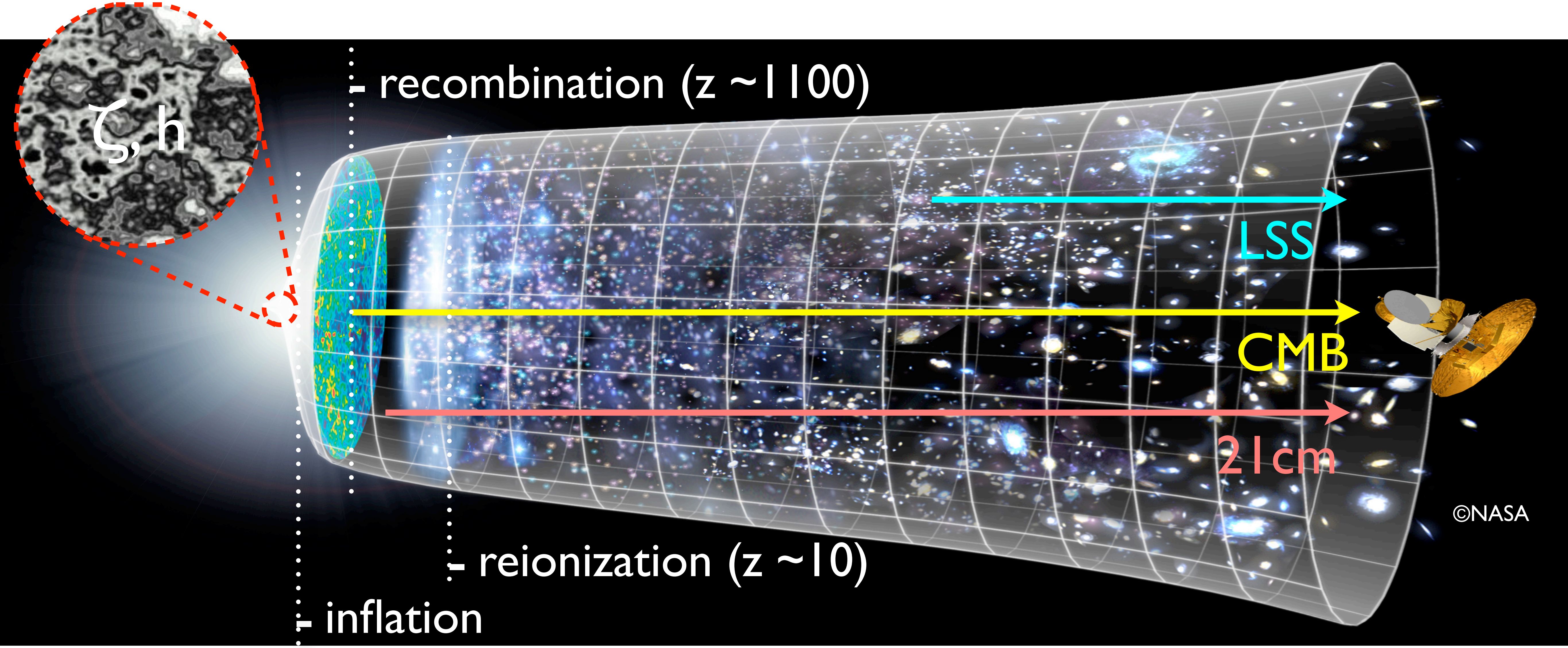


$h_\times$



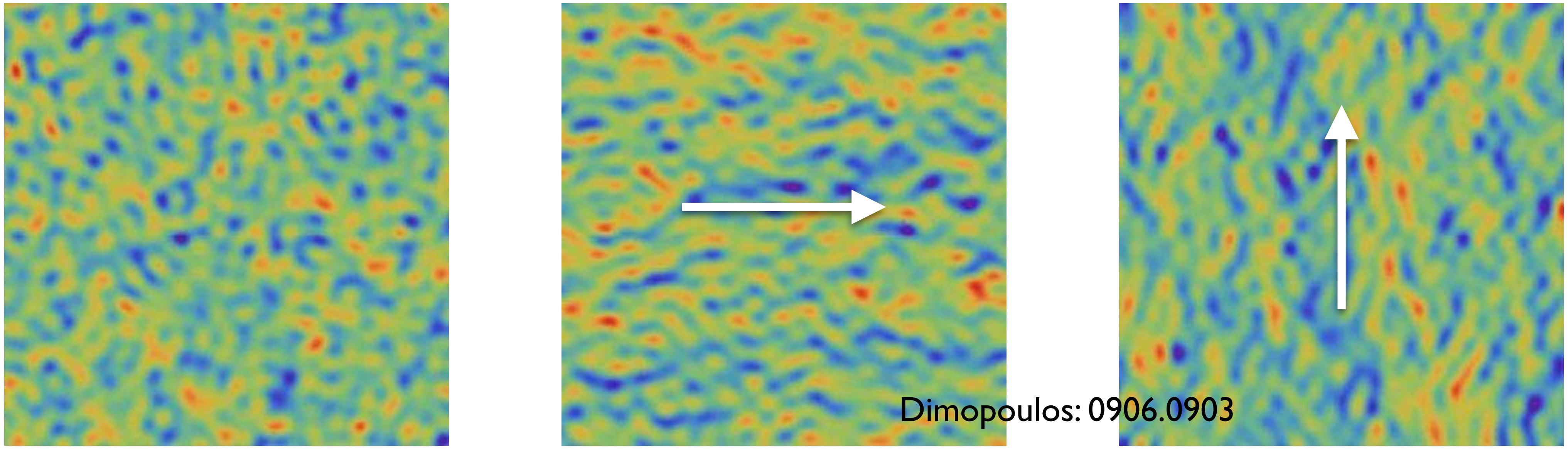
$h^{(+2)} \gg h^{(-2)}$





Isotropic case

Statistical anisotropy creates directional dependence



Dimopoulos: 0906.0903

Parity violation search

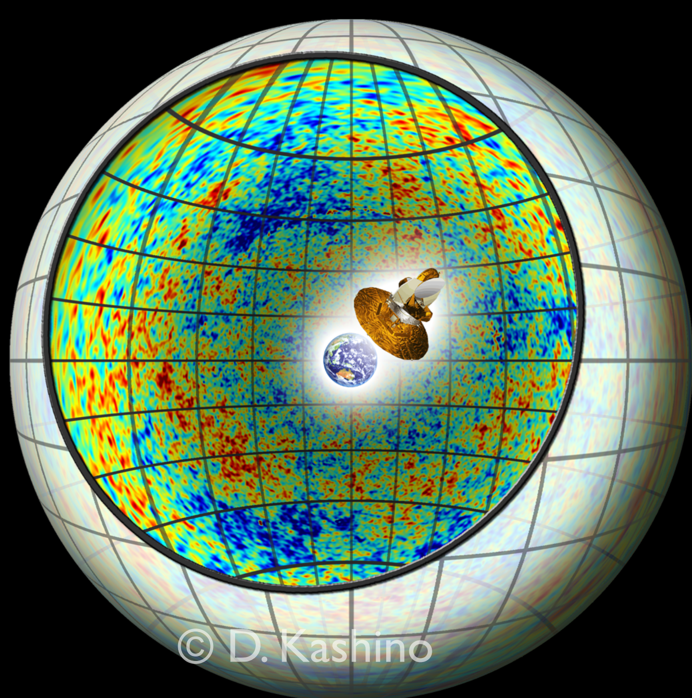
CMB

relic of the primordial fluctuations stretched by the inflationary expansion

$$T/E(n) \sim [h^{(+2)} + h^{(-2)}]\,\Delta_{T/E}^{(t)}$$

$$T/E(n) \sim \zeta\,\Delta_{T/E}^{(s)}$$

$$B(n) \sim [h^{(+2)} - h^{(-2)}]\,\Delta_{B}^{(t)}$$



$$a_{\ell m}^{X} = \int d^2n\, X(n)\, Y_{\ell m}^{*}(n)$$

$$a_{\ell m}^{T/E} \sim [h^{(+2)} + (-1)^{\ell}\, h^{(-2)}]\,\Delta_{T/E}^{(t)}$$

$$a_{\ell m}^{T/E} \sim \zeta\,\Delta_{T/E}^{(s)}$$

$$a_{\ell m}^{B} \sim [h^{(+2)} - (-1)^{\ell}\, h^{(-2)}]\,\Delta_{B}^{(t)}$$

odd parity in ℓ-space

$a_{\ell m}^{T} \sim h^{(+)} + (-1)^{\ell}\, h^{(-)}$ $\qquad$ $a_{\ell m}^{B} \sim h^{(+)} - (-1)^{\ell}\, h^{(-)}$

$C_{\ell 1 \ell 2}^{TT}, C_{\ell 1 \ell 2}^{BB} \sim \langle h^{(+)} h^{(+)} \rangle + (-1)^{\ell 1 + \ell 2} \langle h^{(-)} h^{(-)} \rangle$

$C_{\ell 1 \ell 2}^{TB} \sim \langle h^{(+)} h^{(+)} \rangle - (-1)^{\ell 1 + \ell 2} \langle h^{(-)} h^{(-)} \rangle$

$B_{\ell 1 \ell 2 \ell 3}^{TTT}, B_{\ell 1 \ell 2 \ell 3}^{TBB} \sim \langle h^{(+)} h^{(+)} h^{(+)} \rangle + (-1)^{\ell 1 + \ell 2 + \ell 3} \langle h^{(-)} h^{(-)} h^{(-)} \rangle$

$B_{\ell 1 \ell 2 \ell 3}^{TTB}, B_{\ell 1 \ell 2 \ell 3}^{BBB} \sim \langle h^{(+)} h^{(+)} h^{(+)} \rangle - (-1)^{\ell 1 + \ell 2 + \ell 3} \langle h^{(-)} h^{(-)} h^{(-)} \rangle$

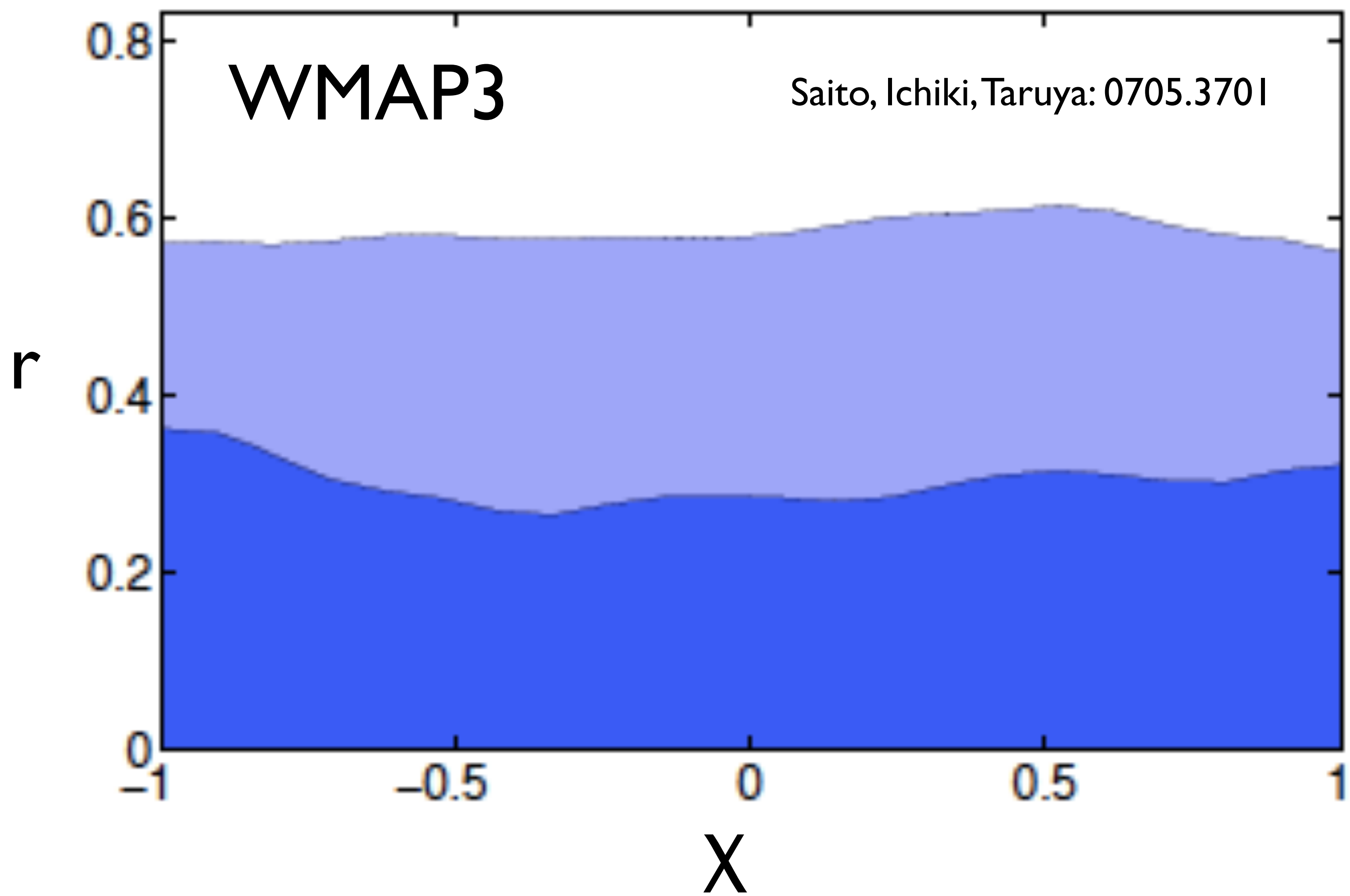
Kamionkowski & Souradeep: 1010.4304, MS, Nitta, Yokoyama: 1107.0682

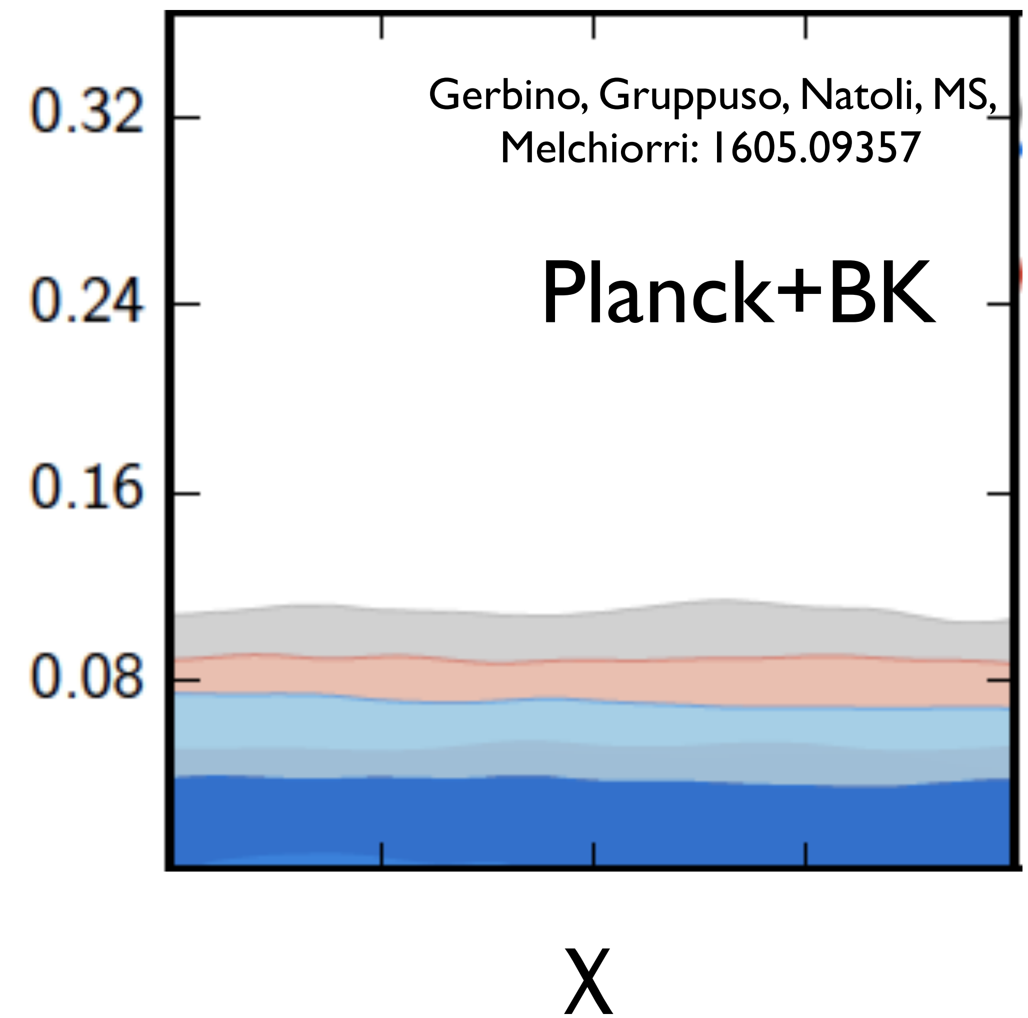
GW correlators	CMB correlators	
$\langle h^{(+)} \cdots h^{(+)} \rangle = p \langle h^{(-)} \cdots h^{(-)} \rangle$	$\Sigma \ell_n$ = even	$\Sigma \ell_n$ = odd
P-even (p = +)	TT, BB, TTT, TBB	TB, TTB, BBB
P-odd (p = -)	TB, TTB, BBB	TT, BB, TTT, TBB

TB in $|\ell_1 - \ell_2| = 0$

$C^{BB} \sim P_h^{(+)} + P_h^{(-)} \sim r\, P_\zeta$

$C^{TB} \sim P_h^{(+)} - P_h^{(-)} \sim r\, \chi\, P_\zeta$



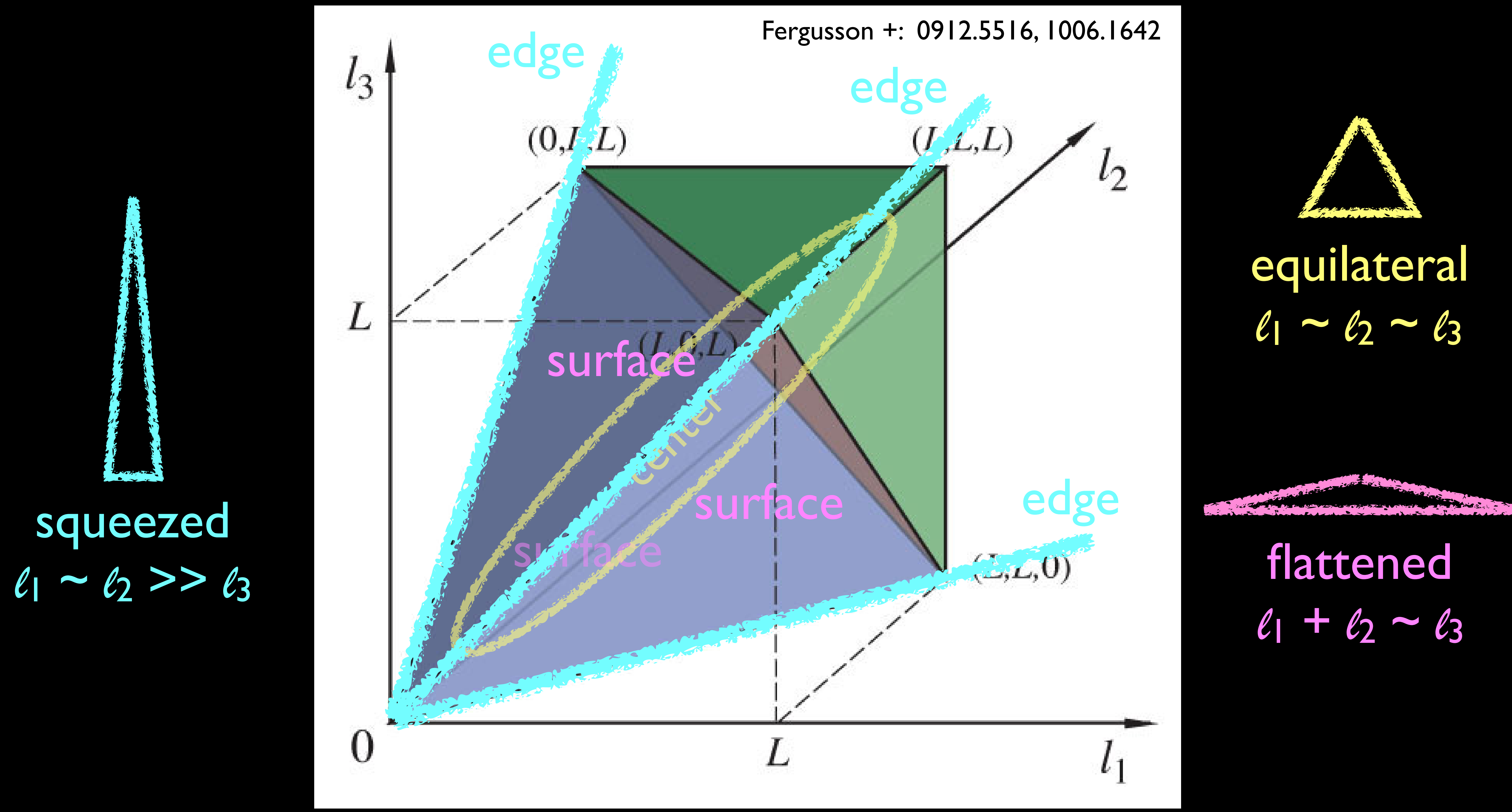


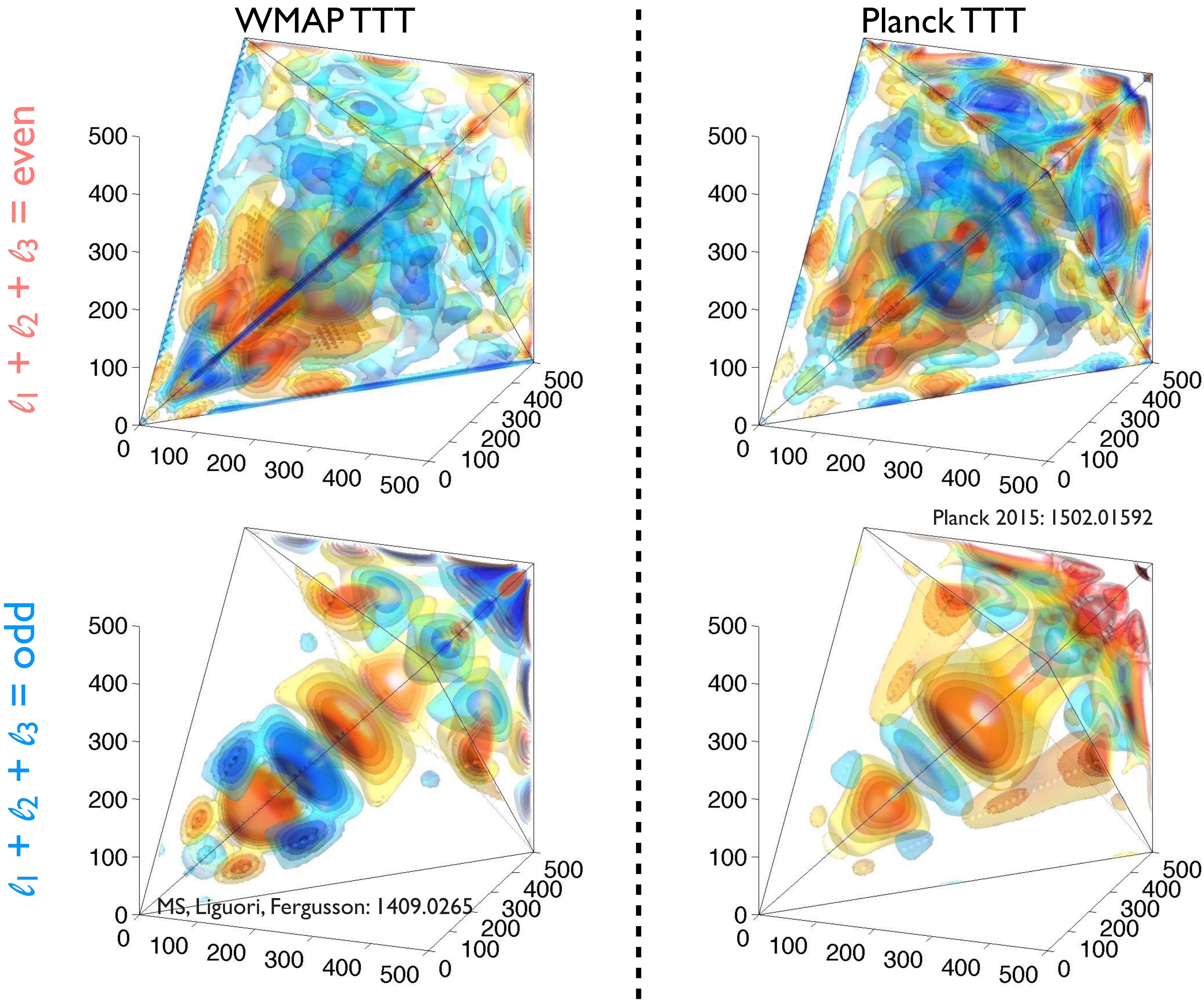
$$\left(\frac{S}{N}\right)^2_{TB} = \sum_\ell (2\ell+1)\frac{(C_\ell^{TB})^2}{C_\ell^{TT} C_\ell^{BB}}$$

unconstrained since $C_\ell^{TT} >> C_\ell^{BB} \sim C_\ell^{TB}$

CMB (angle-averaged) bispectrum

$$B_{\ell_1\ell_2\ell_3} \equiv \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \left\langle \prod_{n=1}^{3} a_{\ell_n m_n} \right\rangle \quad |\ell_1 - \ell_2| \leq \ell_3 \leq |\ell_1 + \ell_2|$$

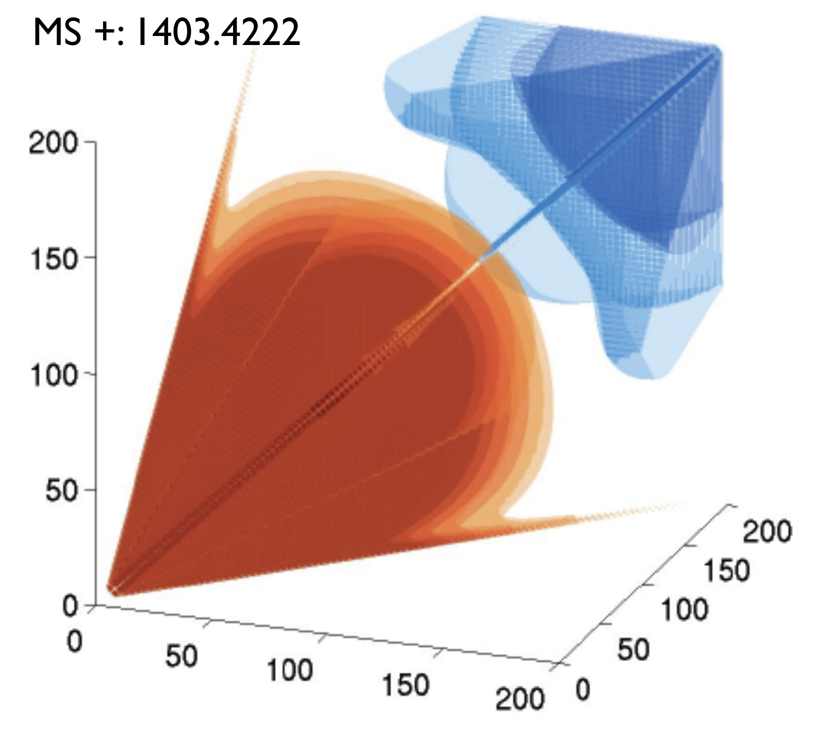



WMAP TTT
Planck TTT
$\ell_1 + \ell_2 + \ell_3$ = even
$\ell_1 + \ell_2 + \ell_3$ = odd
Planck 2015: 1502.01592
MS, Liguori, Fergusson: 1409.0265

★ tensor NG

$$f_{\rm NL}^{\rm tens} \equiv \lim_{k_i \to k} \frac{\langle h_{\mathbf{k}_1}^{(+)} h_{\mathbf{k}_2}^{(+)} h_{\mathbf{k}_3}^{(+)} \rangle}{\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle |_{f_{\rm NL}^{\rm eq}=1}}$$

f_{NL}^{tens} / 10^2	Even	Odd	All
SMICA			
T	2 ± 15	120 ± 110	4 ± 15
T+E	0 ± 13		
SEVEM			
T	2 ± 15	120 ± 110	5 ± 15
T+E	4 ± 13		
NILC			
T	3 ± 15	110 ± 100	5 ± 15
T+E	1 ± 13		



consistent with WMAP limits: MS +: 1409.0265
f_{NL}^{tens} / 10^2 = 4 ± 16 (even), 80 ± 110 (odd)

1σ signals of parity-odd NG

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

Barnaby, Namba, Peloso: 1102.4333
Cook & Sorbo: 1307.7077
MS, Ricciardone, Saga: 1308.6769

$$\xi \equiv \frac{\alpha |\dot{\phi}|}{2fH} < 3.3$$

P-odd TTE and TEE are very informative ☞ $\delta f_{NL}(T+E)$ / $\delta f_{NL}(T)$ ~ 0.1

Let's see Planck 2018

※ usual P-even scalar case: ~ 0.5

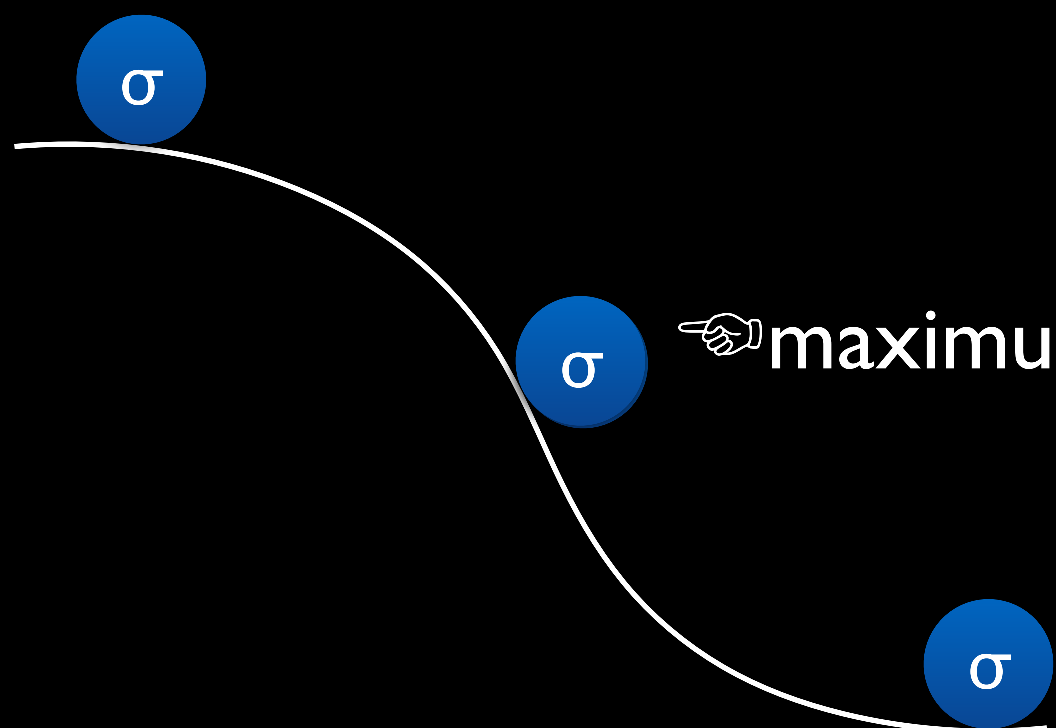
$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{2}(\partial\sigma)^2 - V(\sigma) - \frac{1}{4}F^2 - \frac{\alpha}{4f}\sigma F\tilde{F}$$

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

- ◉inflaton Φ does not directly couple to A and sustains a stable inflation due to $V_\Phi >> V_\sigma$

- ◉pseudoscalar σ enhances A, generating sourced modes

$$A + A \rightarrow \sigma \rightarrow \Phi \rightarrow \zeta^{(sou)}$$
$$A + A \rightarrow h^{(sou)}$$



☜maximum speed @ $\tau = \tau_*$

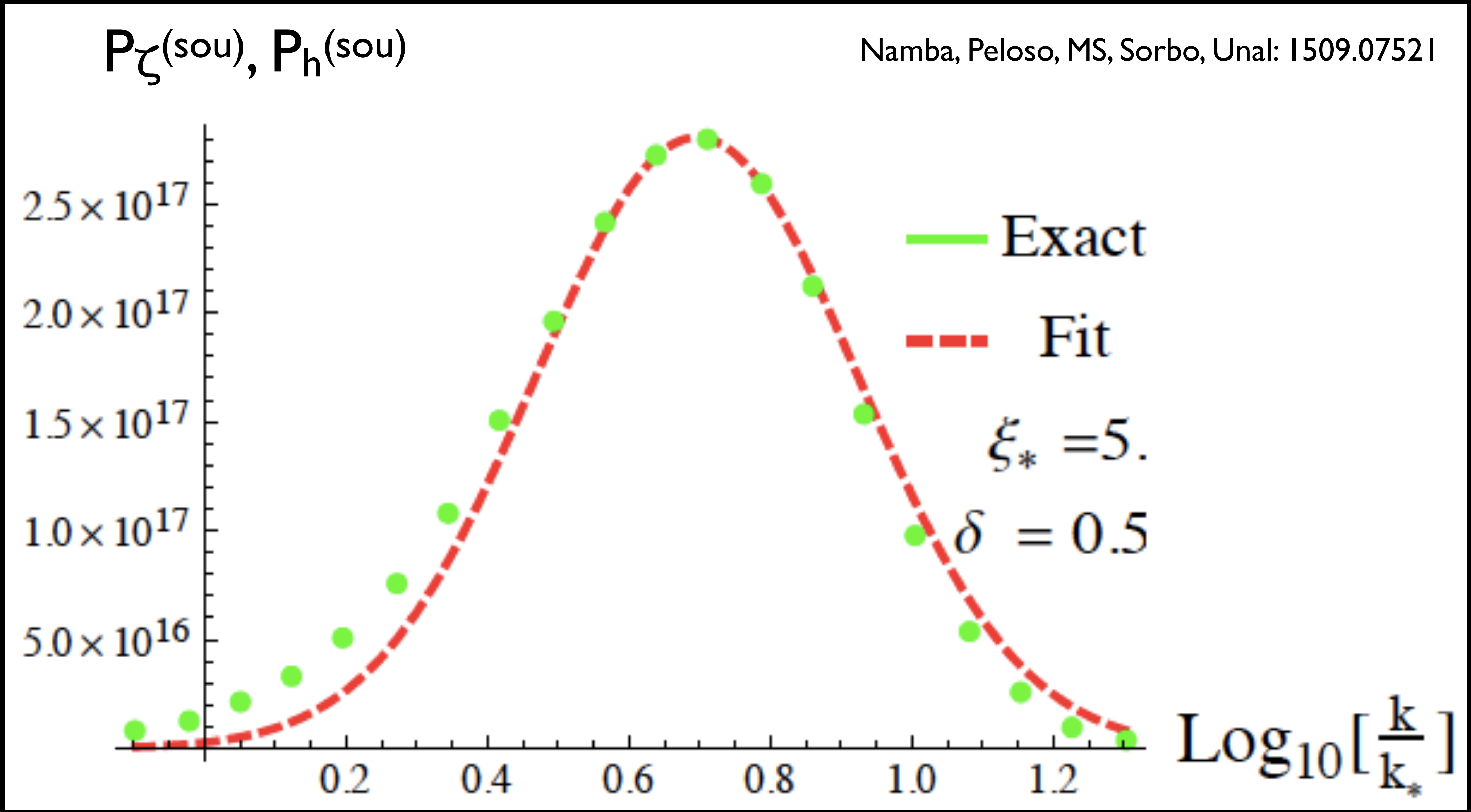
☝ Then σ is maximally amplified!

$$\xi \propto \dot{\sigma}$$

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

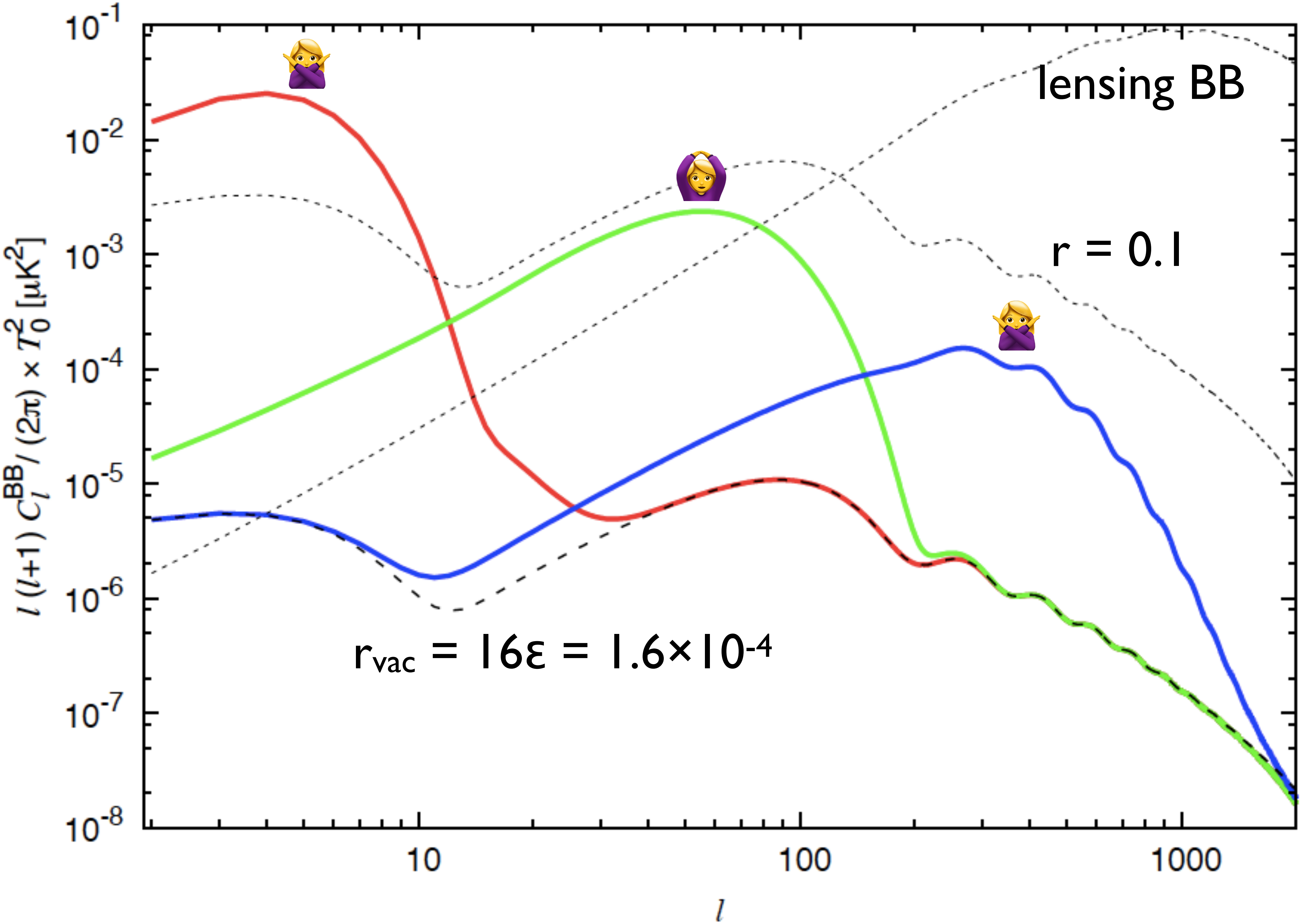
Namba, Peloso, MS, Sorbo, Unal: 1509.07521

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



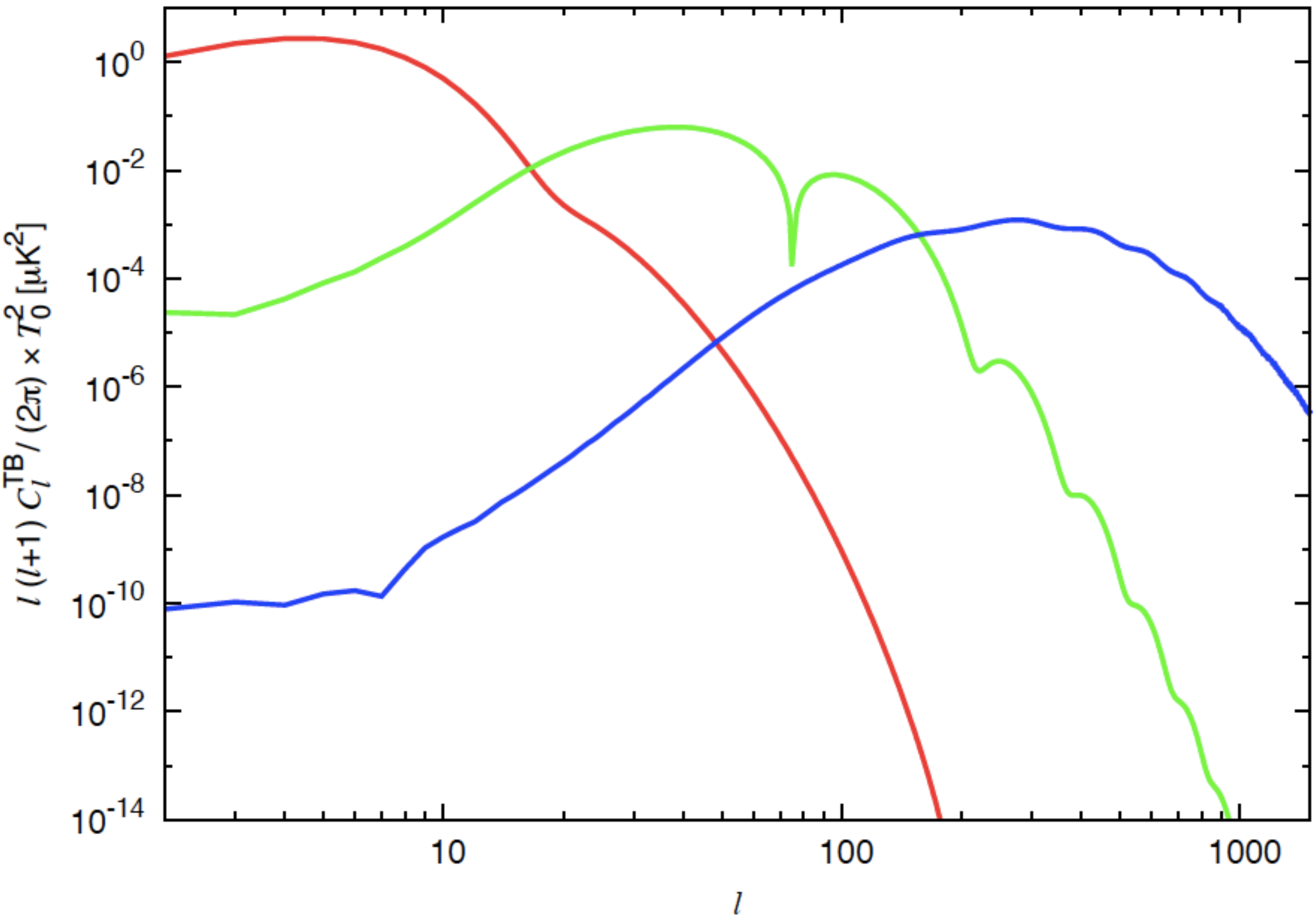
Depending on k_*, a detectable peak appears in B-mode spectrum!

BB



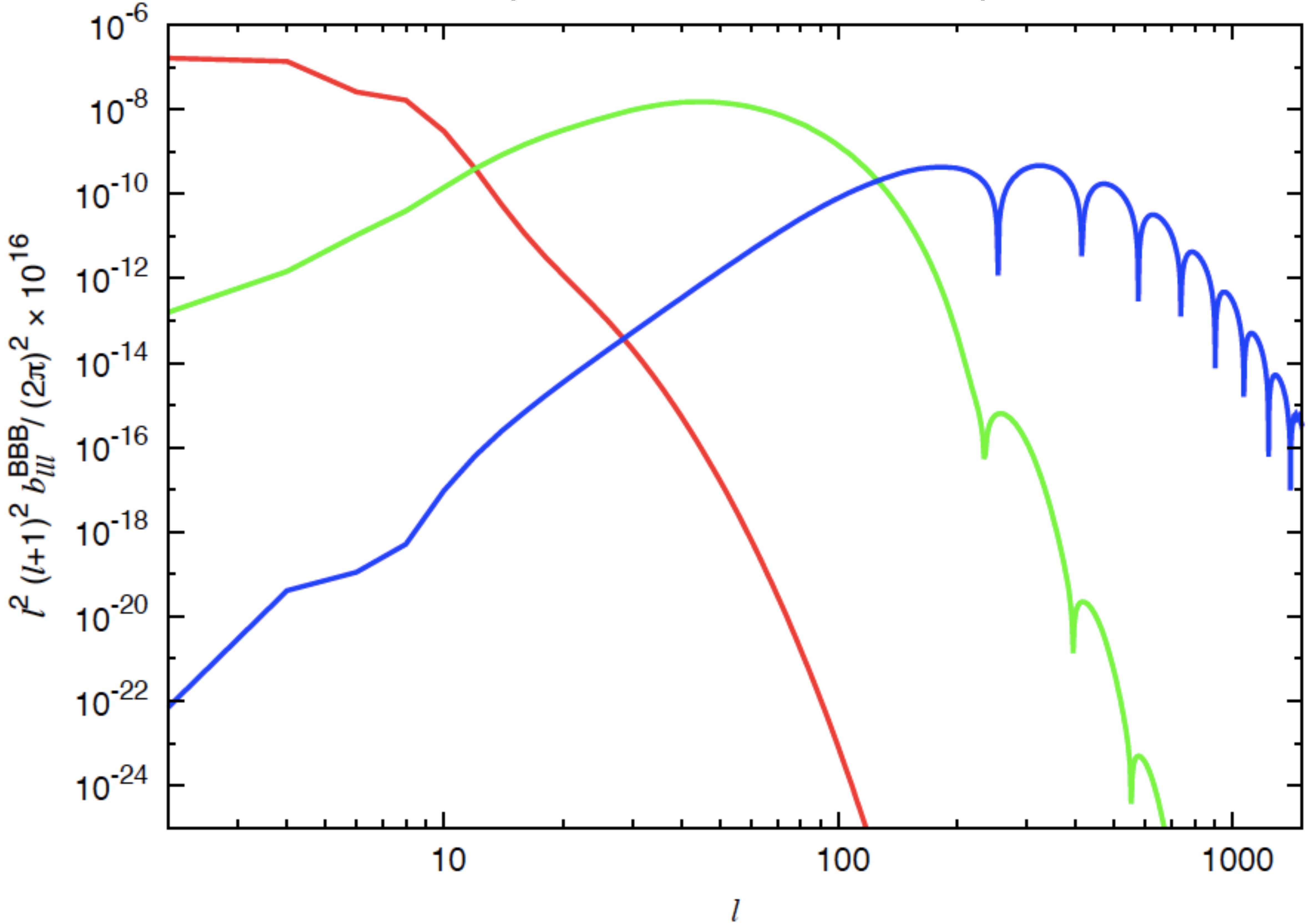
green case (l_{peak} ~ 50) is easier to see!

TB



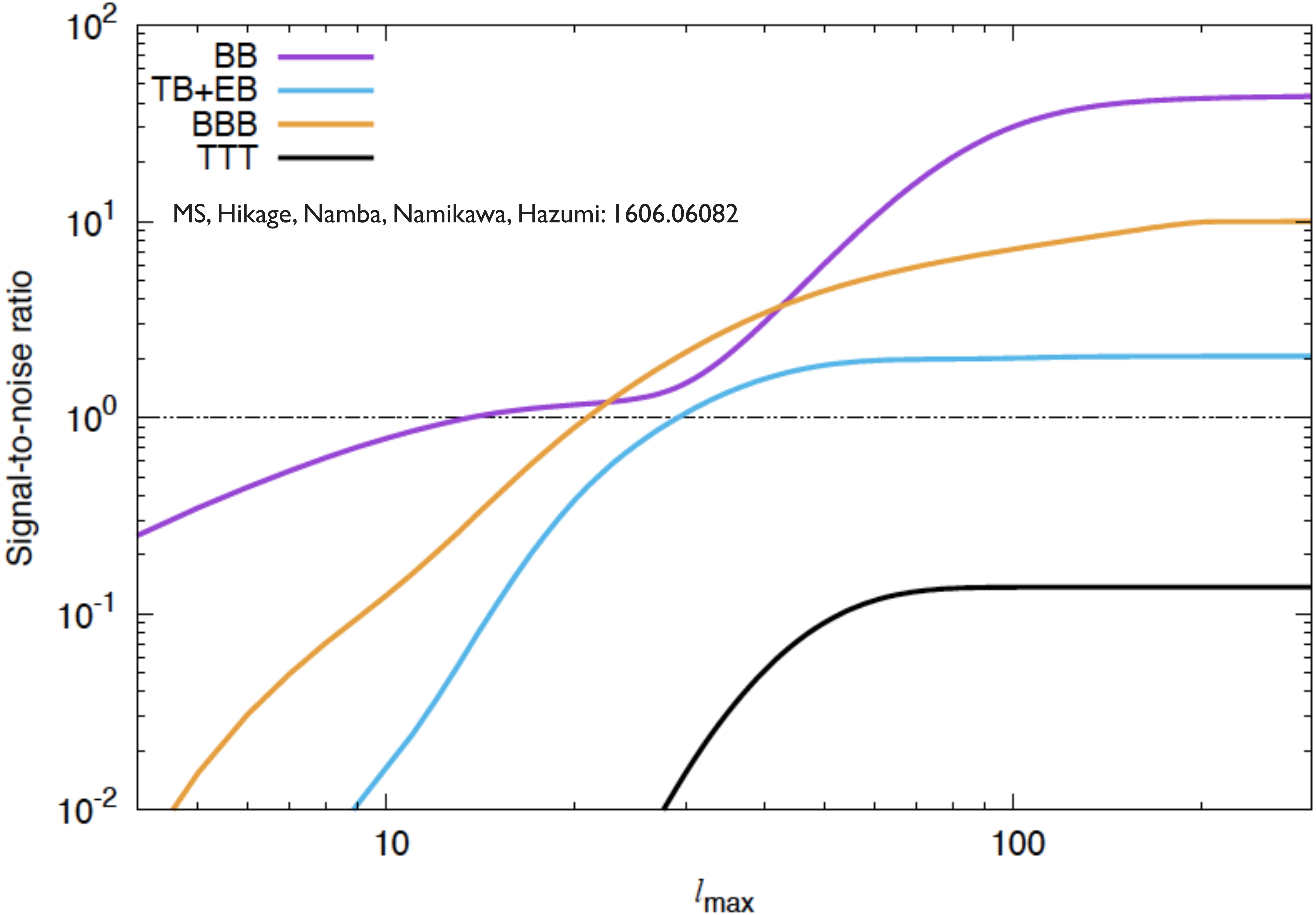
TB ~ $\langle h_{+2} h_{+2} \rangle - \langle h_{-2} h_{-2} \rangle \sim P_{+2}^{(sou)}$

BBB ($\ell_1 + \ell_2 + \ell_3$ = even)



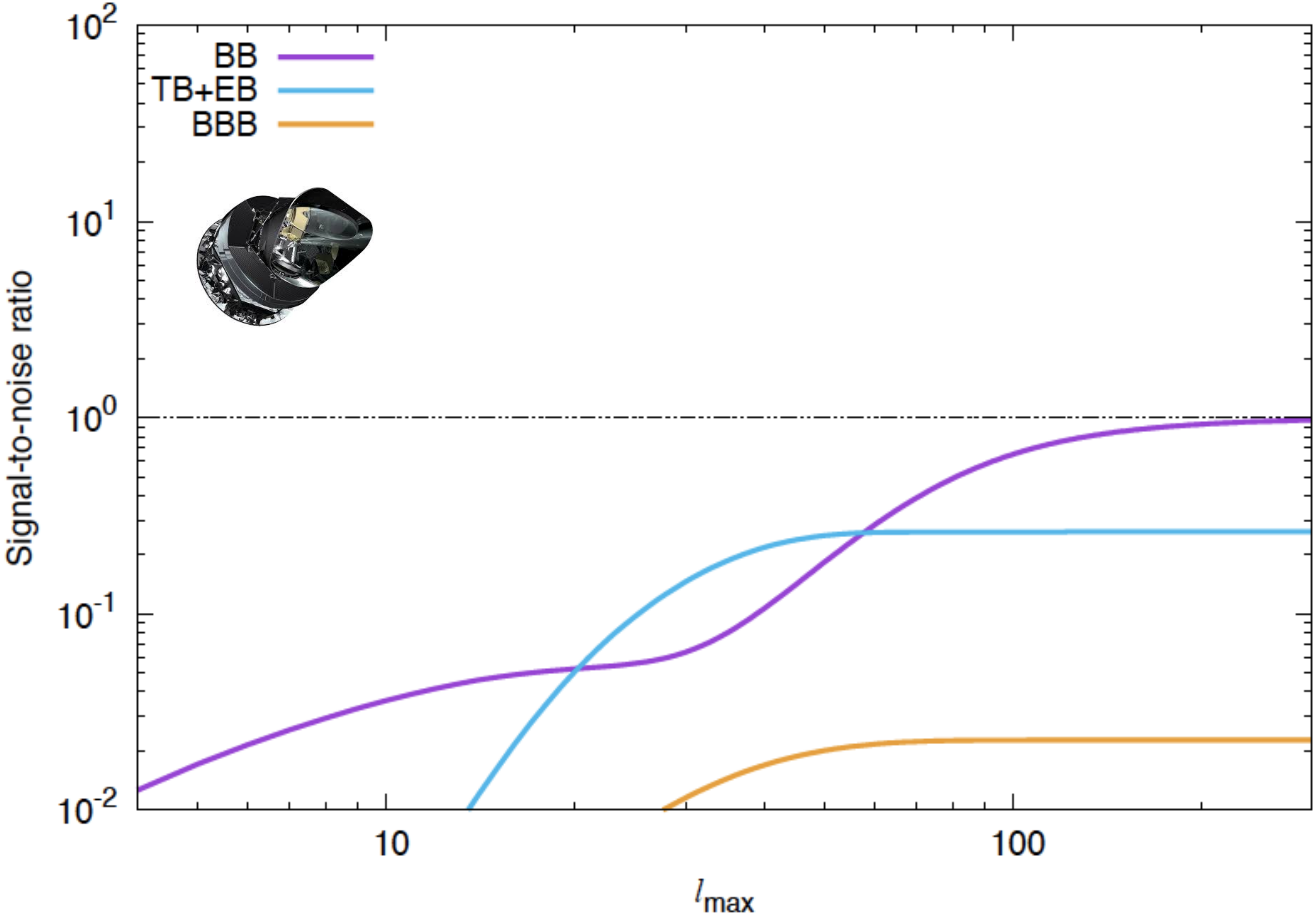
BBB ~ $\langle h_{+2}^{(sou)} h_{+2}^{(sou)} h_{+2}^{(sou)} \rangle$

ideal noiseless CV-limit (f_{sky} = 1)

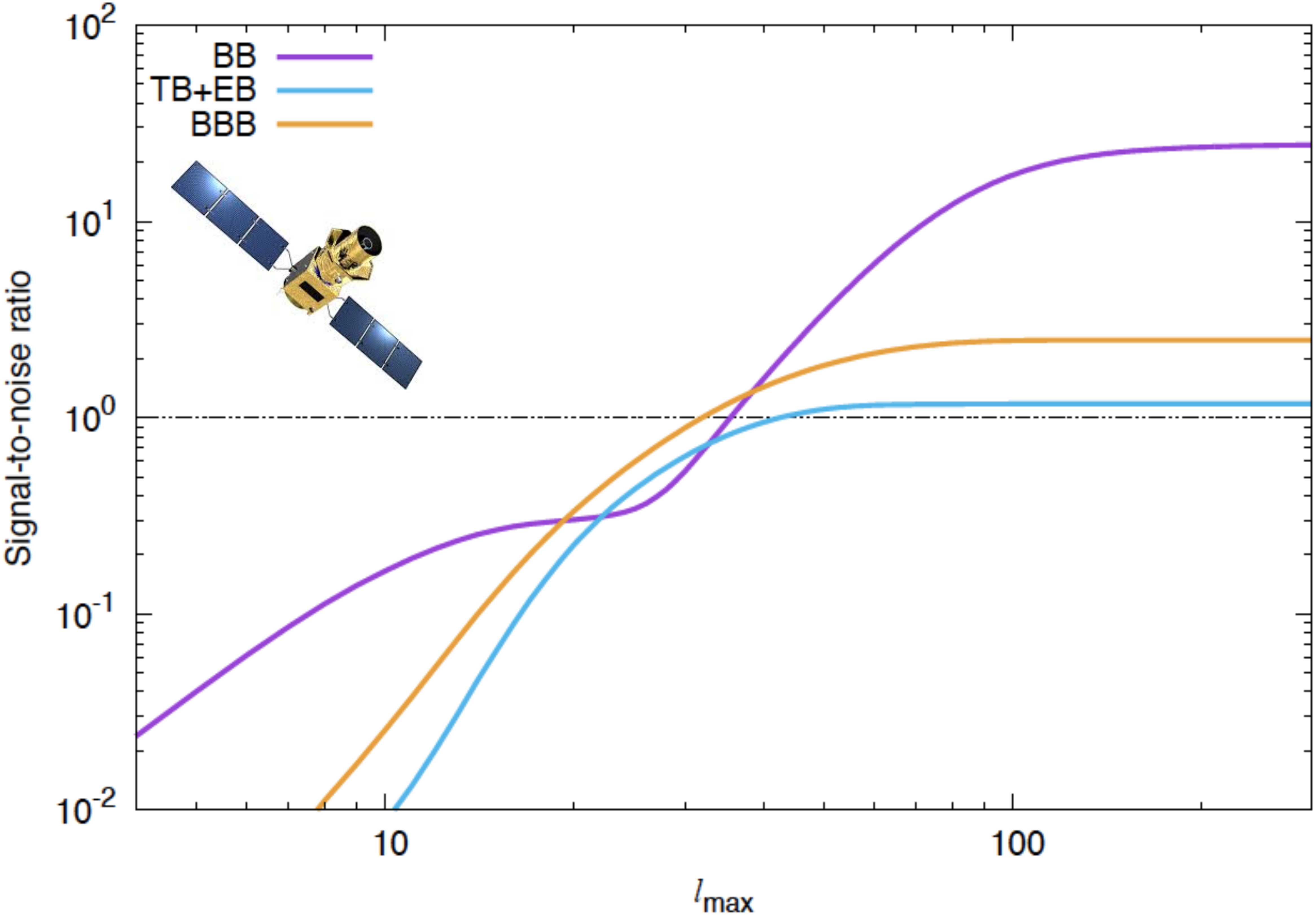


TTT is undetectable, but BBB is detectable

Planck (f_{sky} = 0.7)



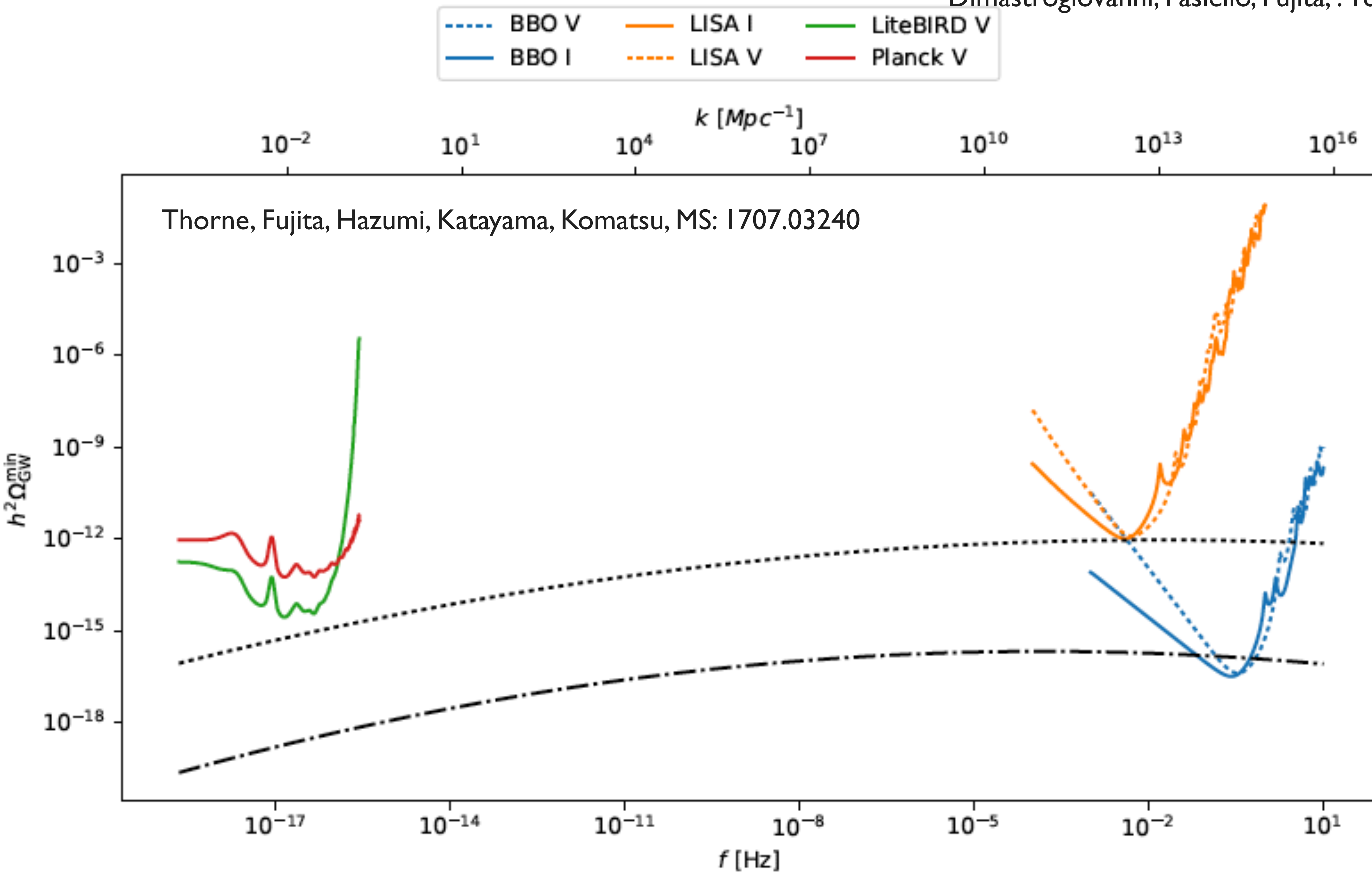
LiteBIRD (f_{sky} = 0.5)



S/N BB > BBB > TB+EB > 1!!

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

Dimastrogiovanni, Fasiello, Fujita, : 1608.04216



☞ tensor NG >> scalar NG

Agrawal, Fujita, Komatsu: 1707.03240

Statistical anisotropy search

Interesting (ℓ_1,ℓ_2) configurations

inflation			CMB		
parity symmetry	rotational symmetry	models	$\lvert \ell_1 - \ell_2 \rvert = 0$	$\lvert \ell_1 - \ell_2 \rvert = 1$	$\lvert \ell_1 - \ell_2 \rvert = 2$
○	○	standard inflation	XX, TE	-	-
×	○	$f(\Phi)^*FF$, $f(\Phi)^*RR$	all	-	-
○	×	$f(\Phi)F^2$ + $\mathbf{A}^{\rm vev} \neq 0$	XX, TE	TB, EB	XX, TE
×	×	$f(\Phi)^*FF$ + $\mathbf{A}^{\rm vev} \neq 0$	all	all	all

※ XX ≡ TT, EE, BB, all ≡ XX, TE, TB, EB

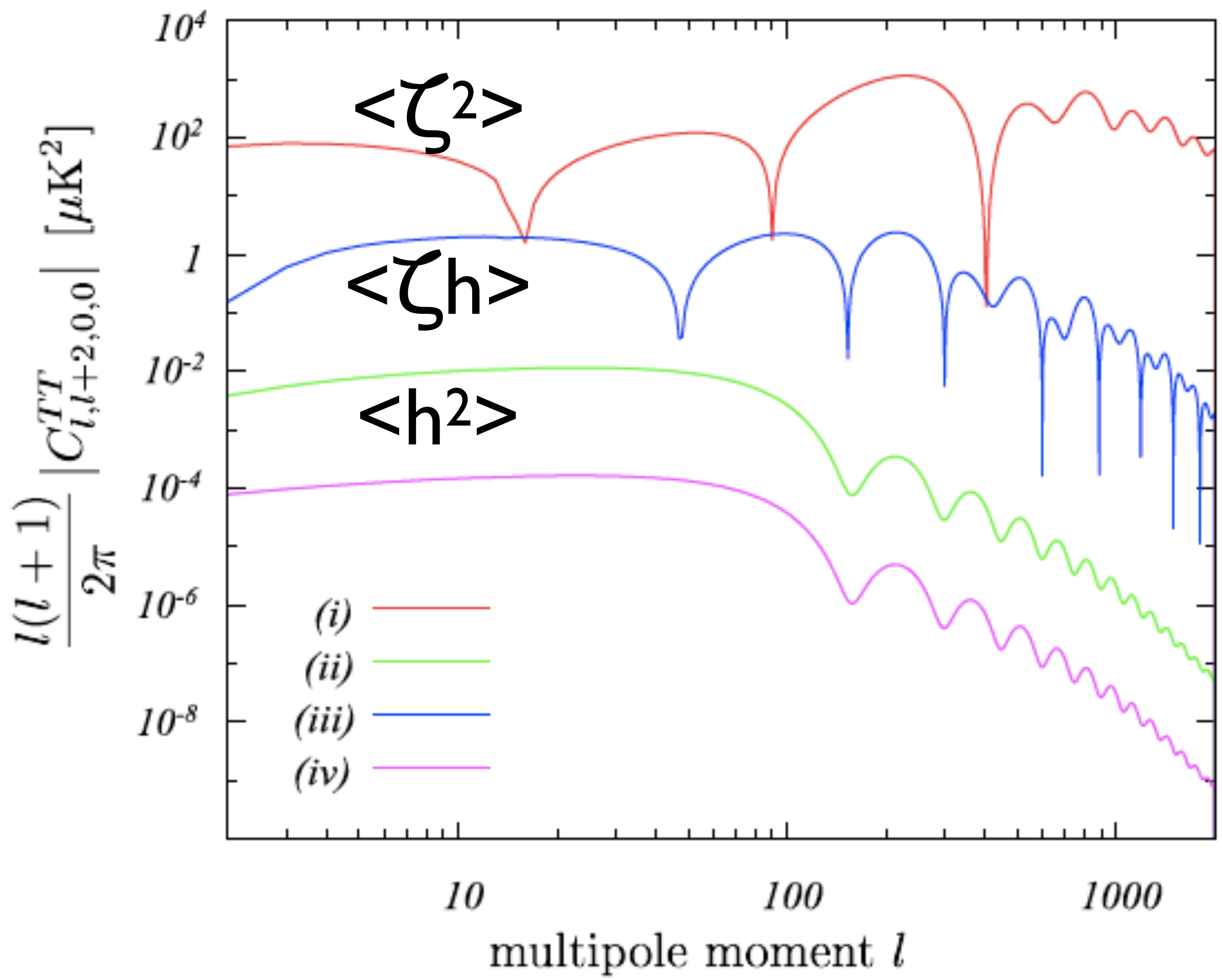
Bartolo, Matarrese, Peloso, MS: 1411.2521

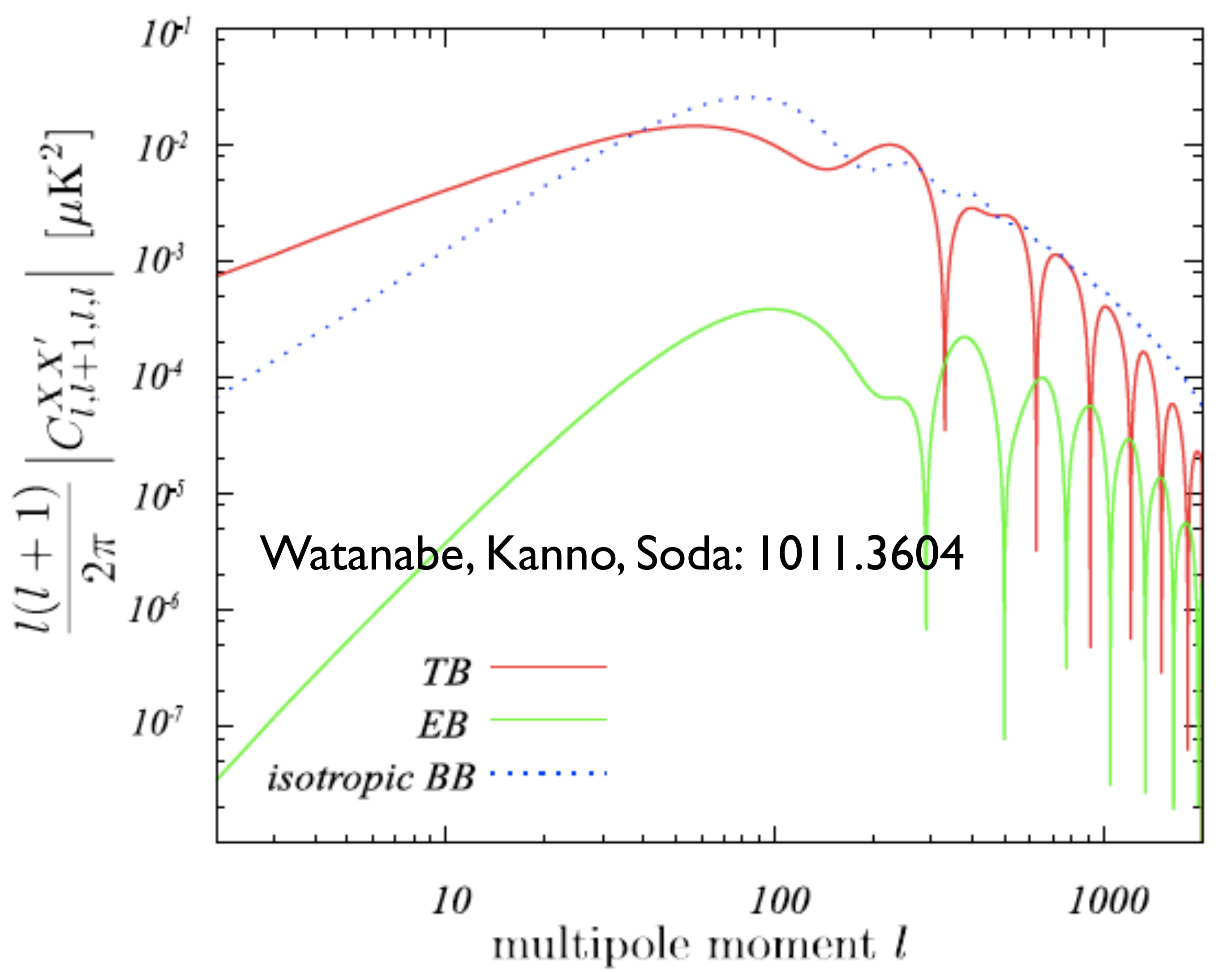
off-diagonal components contain pure anisotropic information

primordial correlators: parity ○ isotropy ×

$|\ell_1 - \ell_2|$ = even in TT, TE, EE, BB

$|\ell_1 - \ell_2|$ = odd in TB, EB





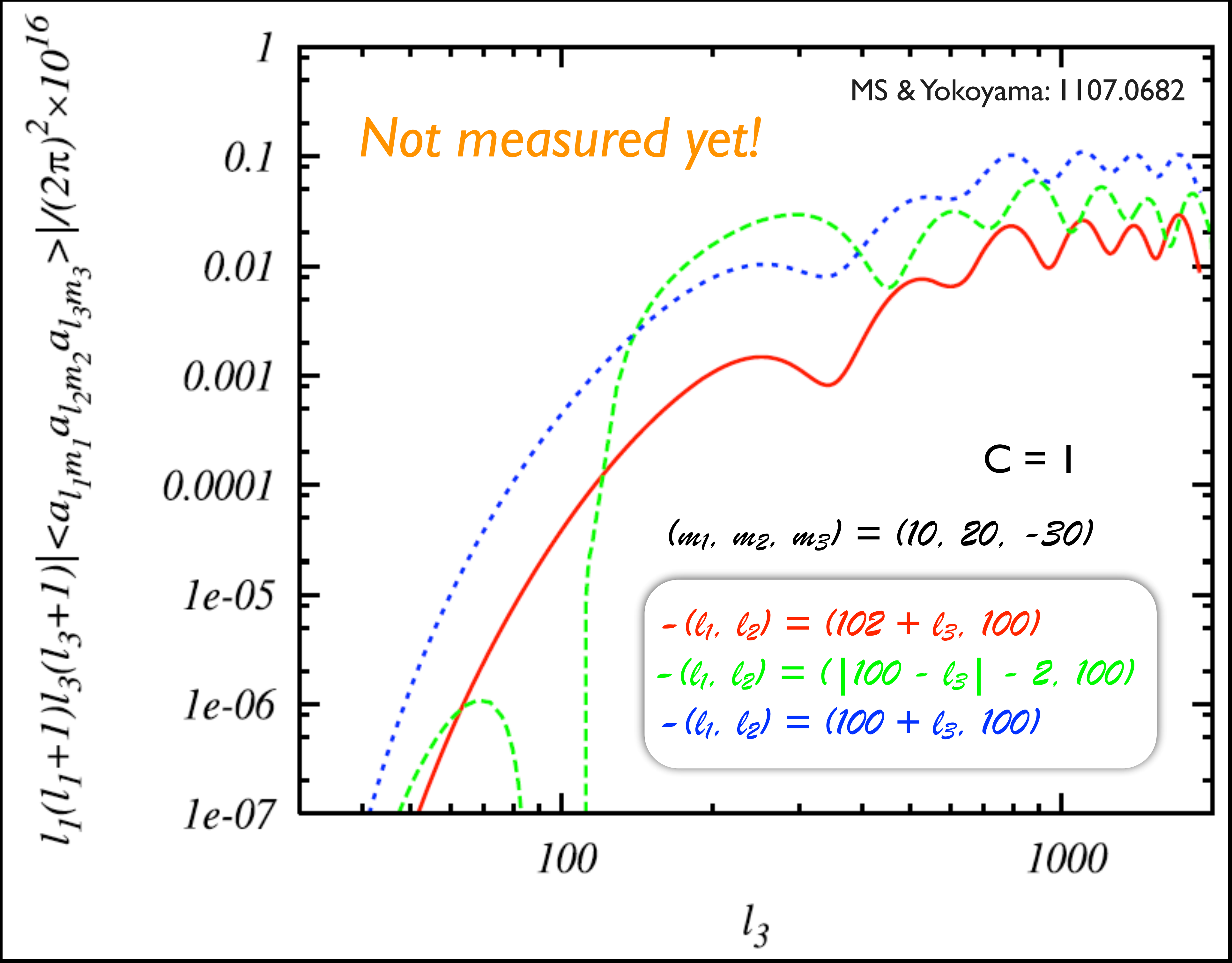
$$\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k}_1+\mathbf{k}_2)P(k_1)\left[1+g_*(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{p}})^2\right]$$

Planck 2015: $g_* = 0.23^{+1.70}_{-1.24}\times 10^{-2}$

off-diagonal componets of TE, EE, BB, TB, EB have NOT measured yet!

primordial correlators: parity ○ isotropy × Gaussianity ×

~~triangle condition: $|\ell_1 - \ell_2| \leq \ell_3 \leq |\ell_1 + \ell_2|$~~



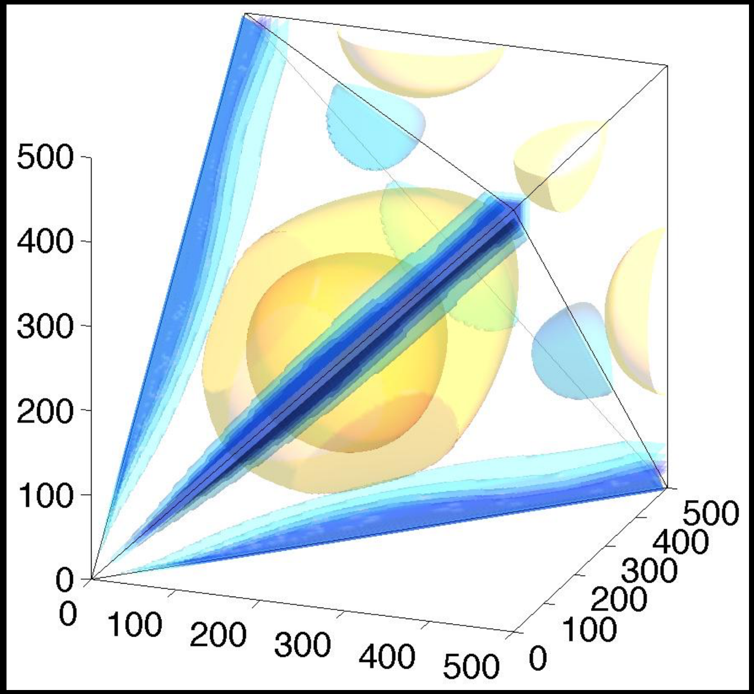
Isotropic measurement of anisotropic bispectrum

$$B_{\ell_1\ell_2\ell_3} \equiv \sum_{m_1m_2m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \langle a_{\ell_1m_1}a_{\ell_2m_2}a_{\ell_3m_3}\rangle$$

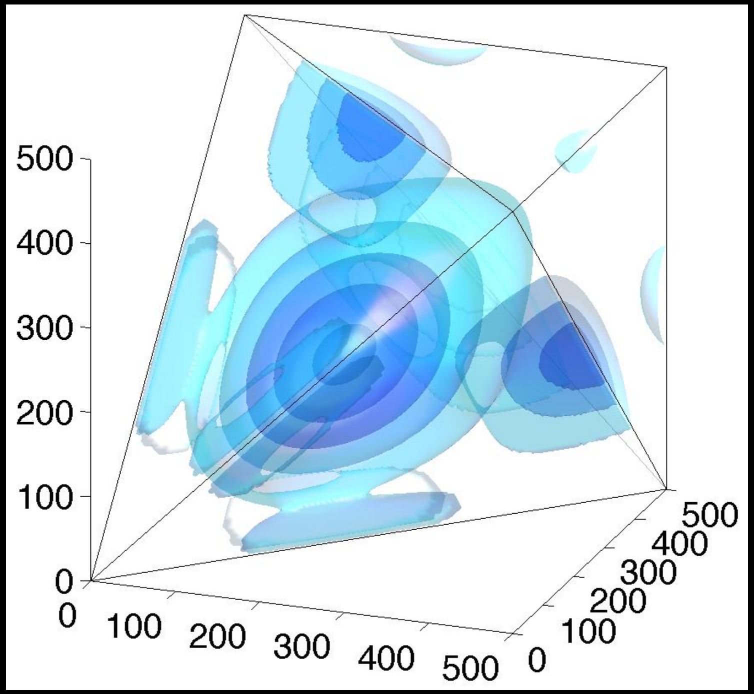
$$= \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix}^{-1} \int \frac{d^2\hat{\mathbf{A}}}{4\pi} \langle a_{\ell_1m_1}a_{\ell_2m_2}a_{\ell_3m_3}\rangle$$

$$\int \frac{d^2\hat{\mathbf{A}}}{4\pi} B_\zeta(k_1,k_2,k_3) = \sum_n c_n P_n(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)P_\zeta(k_1)P_\zeta(k_2) + (2 \text{ perm})$$

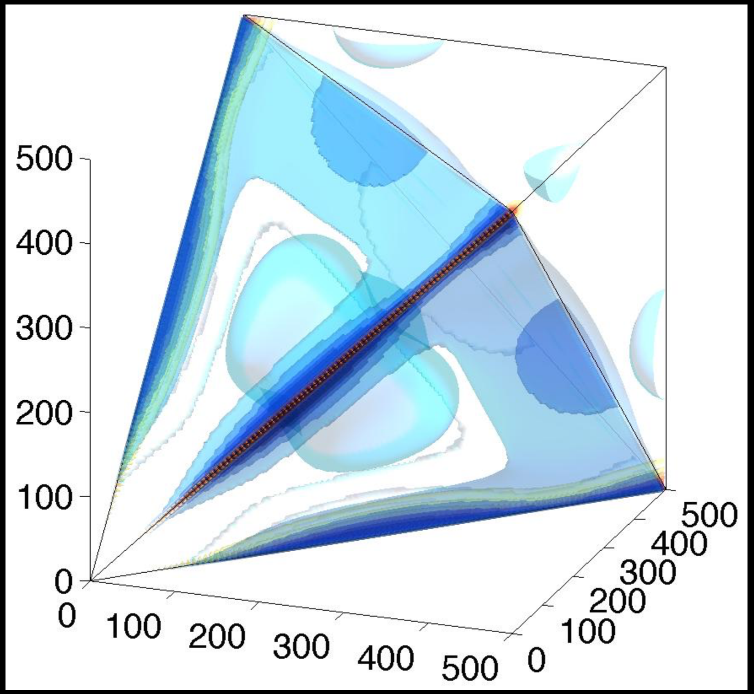
MS, Komatsu, Peloso, Barnaby: 1302.3056



$-10.7 \le c_0 \le 16.7$



$-89 \le c_1 \le 324$



$-57 \le c_2 \le 47$

Planck 2015: 1502.01592

$$\mathcal{L} \supset f(\phi)\left(-\frac{1}{4}F^2 + \frac{\gamma}{4}F\tilde{F}\right)$$

❖electric part: $\mathbf{E} \equiv \mathbf{E}^{\mathrm{vev}} + \delta\mathbf{E} = -\frac{\sqrt{f(\phi)}}{a^2}\mathbf{A}' = -\frac{\sqrt{f(\phi)}}{a^2}\left(\frac{\mathbf{V}}{\sqrt{f(\phi)}}\right)'$

when $f(\varphi) \propto a^{-4} \propto \tau^4$ $\quad$ E^{vev} = const

‣EOM of perturbations: $\delta V_\lambda'' + \left(k^2 + \frac{4\lambda\gamma}{\tau}k - \frac{2}{\tau^2}\right)\delta V_\lambda = 0$

$$|\delta E_+| \approx \frac{\mathrm{e}^{2\pi|\gamma|}}{|\gamma|^{3/2}}\frac{3H^2}{2^{5/2}\sqrt{\pi}k^{3/2}} \qquad |\delta E_+| \gg |\delta E_-|$$

❖curvature correlators:

$\zeta_{sou} \propto \mathbf{E}_{vev} \cdot \delta\,\mathbf{E} + \delta\mathbf{E}^2$

$= \zeta_{(1)} + \zeta_{(2)}$

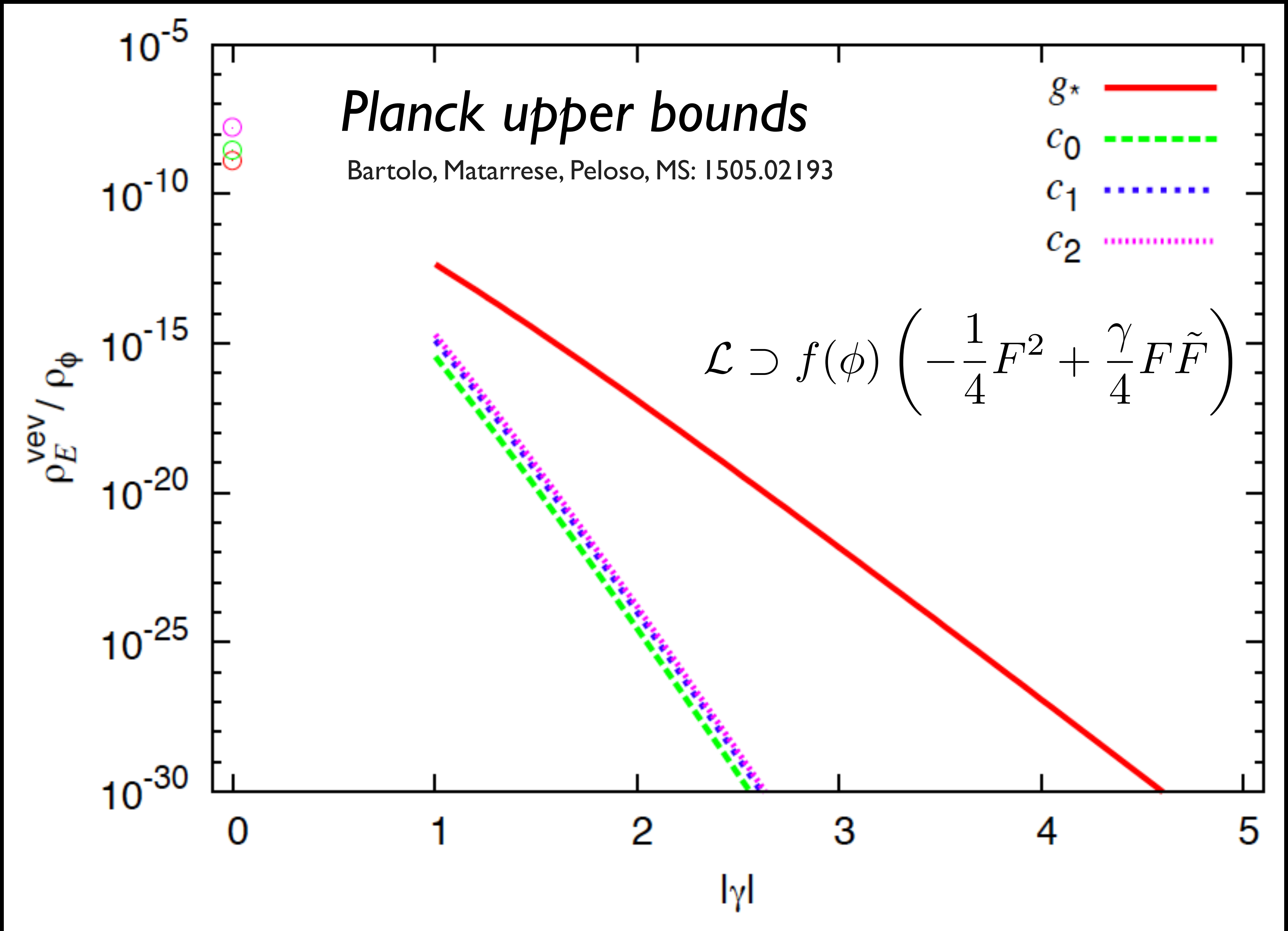
$\langle\zeta_{sou}^2\rangle \sim \langle\zeta_{(1)}^2\rangle \propto E_{vev}^2\ \delta E^2$

$\langle\zeta_{sou}^3\rangle \sim \langle\zeta_{(1)}\zeta_{(1)}\zeta_{(2)}\rangle \propto E_{vev}^2\ \delta E^4$

$\langle\zeta_{sou}^4\rangle \sim \langle\zeta_{(1)}\zeta_{(1)}\zeta_{(2)}\zeta_{(2)}\rangle \propto E_{vev}^2\ \delta E^6$

|γ| > 1: $g_* \simeq -\frac{3N_{\rm CMB}^2}{2\pi\epsilon}\frac{{\rm e}^{4\pi|\gamma|}}{|\gamma|^3}\frac{\rho_E^{\rm vev}}{\rho_\phi}$, $c_0 = -\frac{2N_{\rm CMB}}{9\pi}\frac{{\rm e}^{4\pi|\gamma|}}{|\gamma|^3}g_*$, $c_1 = -\frac{3c_0}{2}$, $c_2 = \frac{c_0}{2}$

|γ| = 0: $g_* \simeq -\frac{48\,N_{\rm CMB}^2}{\epsilon}\frac{\rho_E^{\rm vev}}{\rho_\phi}$, $c_0 = -\frac{16}{3}N_{\rm CMB}g_*$, $c_2 = \frac{c_0}{2}$.



parity violation in the scalar sector

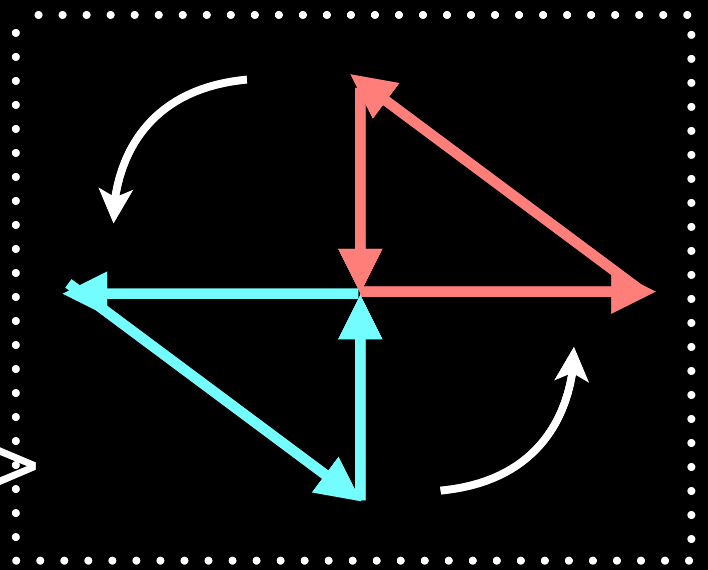
MS: 1608.00368

parity tranformation $\zeta(\mathbf{k}) \rightarrow \zeta(-\mathbf{k})$ cf. $h^{(s)}(\mathbf{k}) \rightarrow h^{(-s)}(-\mathbf{k})$

Rotational invariance enforces parity invariance in 2 and 3-pt correlators

$$\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\rangle = \langle\zeta(-\mathbf{k}_1)\zeta(-\mathbf{k}_2)\rangle$$

$$\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle = \langle\zeta(-\mathbf{k}_1)\zeta(-\mathbf{k}_2)\zeta(-\mathbf{k}_3)\rangle$$

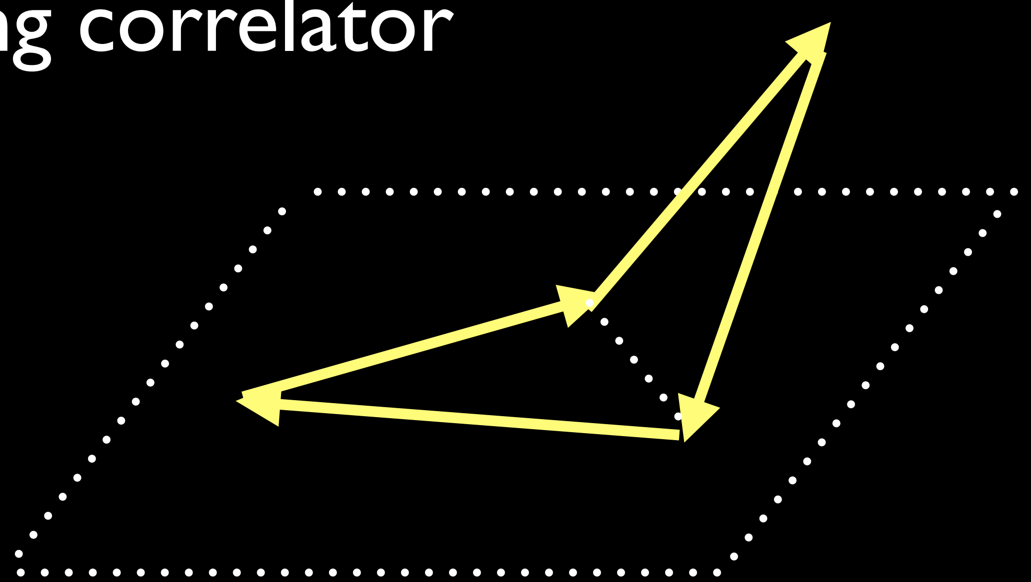


4-pt is the lowest-order parity-violating correlator

$$\langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle \in \mathbf{C}$$

$$\neq \langle\zeta(-\mathbf{k}_1)\zeta(-\mathbf{k}_2)\zeta(-\mathbf{k}_3)\zeta(-\mathbf{k}_4)\rangle$$

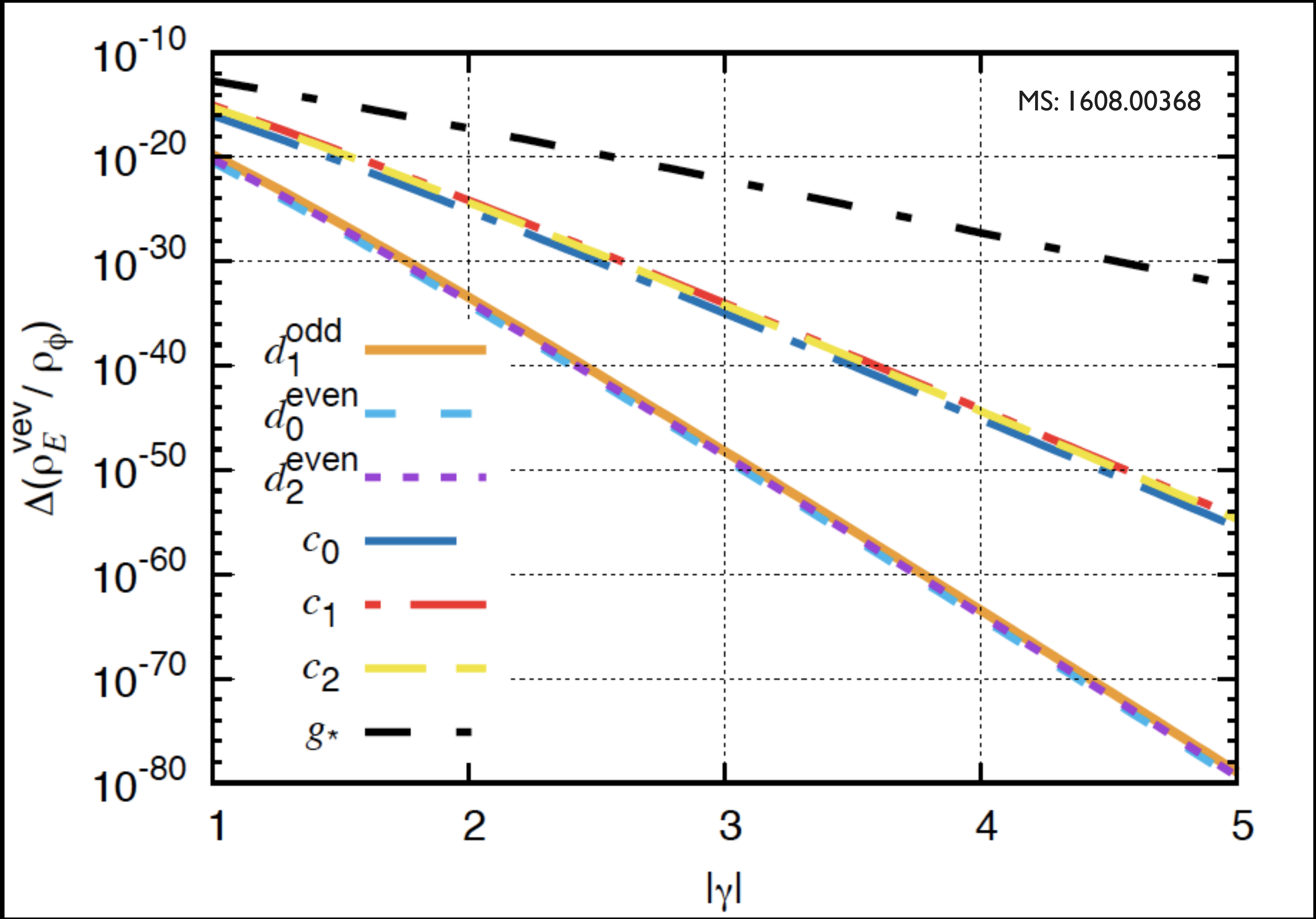
$$= \langle\zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\zeta(\mathbf{k}_4)\rangle^*$$



$$\left\langle \prod_{n=1}^{4} \zeta_{\mathbf{k}_n} \right\rangle = (2\pi)^3 \int d^3K \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{K})\delta^{(3)}(\mathbf{k}_3 + \mathbf{k}_4 - \mathbf{K}) P_\zeta(k_1) P_\zeta(k_3) P_\zeta(K) \mathcal{T}_{\hat{k}_3}^{\hat{k}_1}(\hat{K}) + (23 \text{ perm})$$

$$\mathcal{T}_{\hat{k}_3}^{\hat{k}_1}(\hat{K}) = \sum_n d_n^{\text{even}} \left[P_n(\hat{k}_1 \cdot \hat{k}_3) + P_n(\hat{k}_1 \cdot \hat{K}) + P_n(\hat{k}_3 \cdot \hat{K}) \right] \quad \Sigma_{n=1,4}\, \ell_n = \text{even}$$

$$+ i \sum_n d_n^{\text{odd}} \left[P_n(\hat{k}_1 \cdot \hat{k}_3) + P_n(\hat{k}_1 \cdot \hat{K}) + (-1)^n P_n(\hat{k}_3 \cdot \hat{K}) \right] \left[(\hat{k}_1 \times \hat{k}_3) \cdot \hat{K} \right] \quad \Sigma_{n=1,4}\, \ell_n = \text{odd}$$



Beyond large-scale CMB correlators

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \rangle = (2\pi)^3 P_\zeta(k_1) \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2) \left[1 + \sum_M g_{2M} f(k_1) Y_{2M}(\hat{k}_1) \right]$$

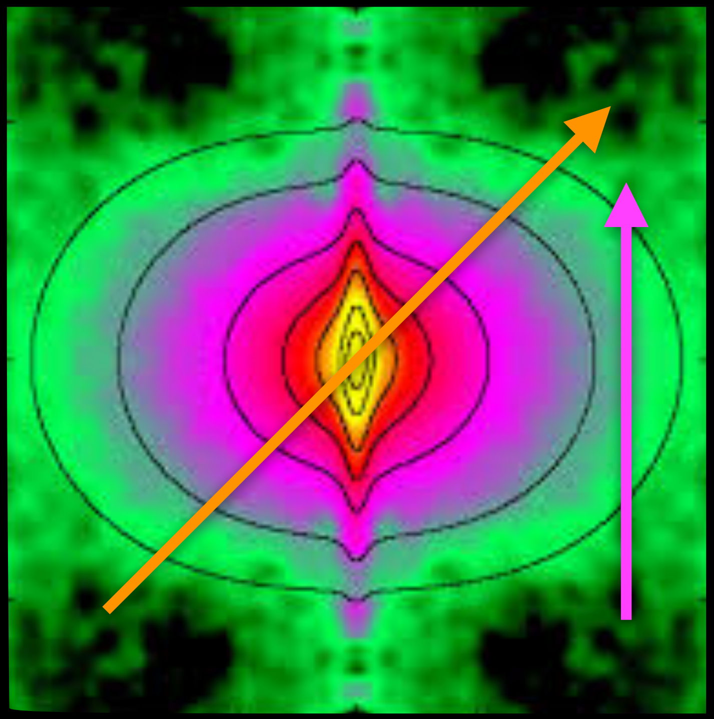
$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \rangle = (2\pi)^3 P_\zeta(k_1) \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2) \left[1 + 2 \sum_M A_{1M} f(k_1) Y_{1M}(\hat{x}) \right]$$

★ anisotropic 3D galaxy power

MS, Sugiyama, Okumura: 1612.02645

$$P^s(\mathbf{k},\hat{n}) = P_m(\mathbf{k},\hat{n},\hat{p})\left[b + f(\hat{k}\cdot\hat{n})^2\right]^2$$

directional dep. RSD



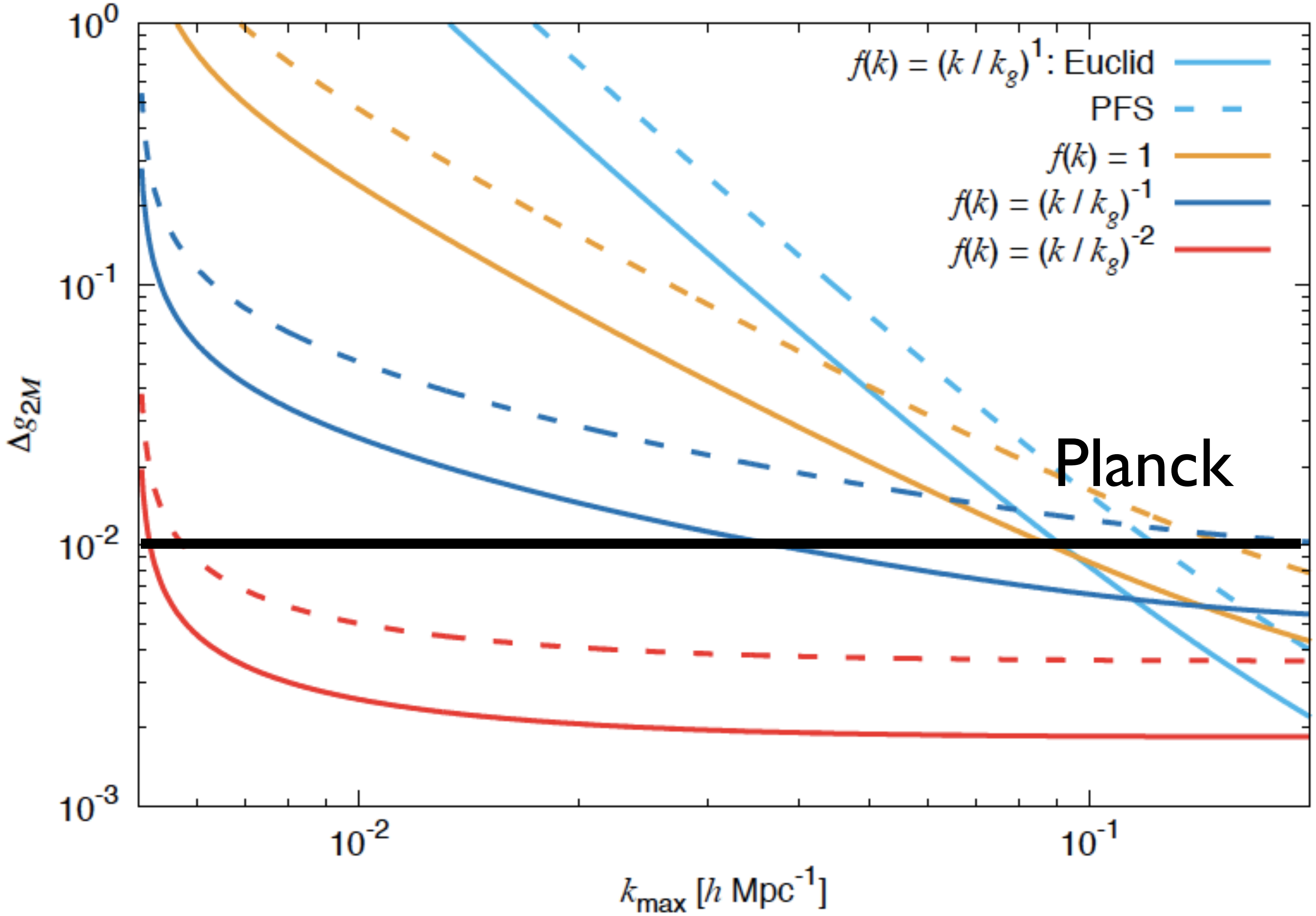
BipoSH decomposition $\propto \sum_{\ell\ell' LM} P_{\ell\ell'}^{LM}(k)\{Y_\ell(\hat{k})\otimes Y_{\ell'}(\hat{n})\}_{LM}$

if isotropic, i.e., $P_m = P_m(|\mathbf{k}|)$ $\quad P_{\ell\ell'}^{LM} = P_\ell(k)\delta_{\ell,\ell'}\delta_{L,0}\delta_{M,0}$

if anisotropic,
the L ≧ 1 components
also become nonzero!

$$P_{\ell\ell'}^{2M}(k) = P_{\ell'}(k)\sqrt{\frac{5}{4\pi}}(2\ell+1)\begin{pmatrix}\ell & \ell' & 2\\ 0 & 0 & 0\end{pmatrix}^2 g_{2M}f(k)$$

$$P_{\ell\ell'}^{1M}(k) = P_\ell(k)\sqrt{\frac{3}{\pi}}(2\ell'+1)\begin{pmatrix}\ell & \ell' & 1\\ 0 & 0 & 0\end{pmatrix}^2 A_{1M}f(k)$$



for f(k) = 1

$$\Delta g_{2M}^{\rm 3D} \simeq \sqrt{\frac{48\pi^3}{V k_{\rm max}^3}}$$

vs.

$$\Delta g_{2M}^{\rm 2D} \simeq \sqrt{\frac{8\pi}{f_{\rm sky} \ell_{\rm max}^2}}$$

Δg_{2M} / 10^{-2}

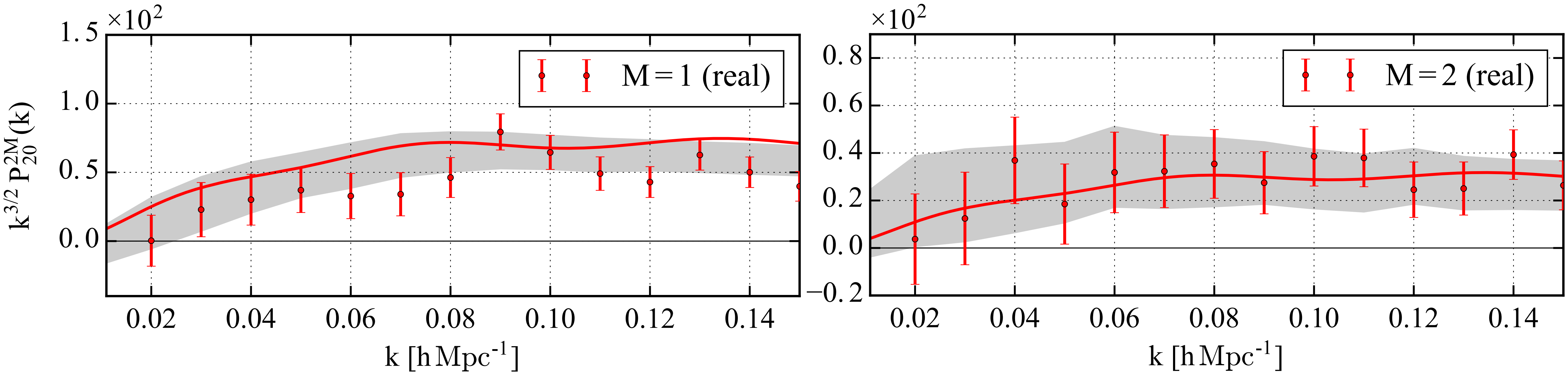
$f(k)$	SDSS	CMASS	PFS	Euclid
$(k/k_g)^1$	1.2 (3.3)	0.55 (2.4)	0.40	0.22
1	2.3 (5.1)	1.1 (3.5)	0.78	0.43
$(k/k_g)^{-1}$	2.8 (3.5)	1.7 (2.5)	1.0	0.55
$(k/k_g)^{-2}$	0.93 (0.65)	0.66 (0.51)	0.36	0.19

ΔA_{1M} / 10^{-2}

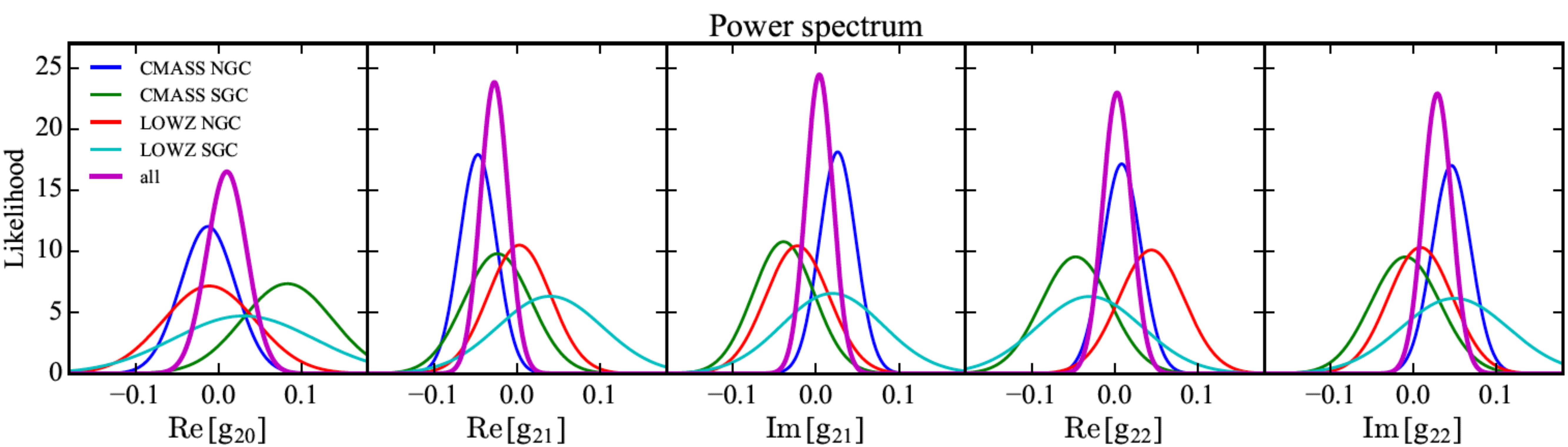
$f(k)$	SDSS	CMASS	PFS	Euclid
$(k/k_A^c)^{-1/2}$	4.4 (7.2)	2.4 (5.0)	1.6	0.84
$(1-k/k_A^q)^2$	1.4 (2.9)	0.70 (2.0)	0.48	0.26

Constraints from the BOSS-CMASS data

Sugiyama, MS, Okumura: 1704.02868



data is consistent with anisotropies due to survey geometries



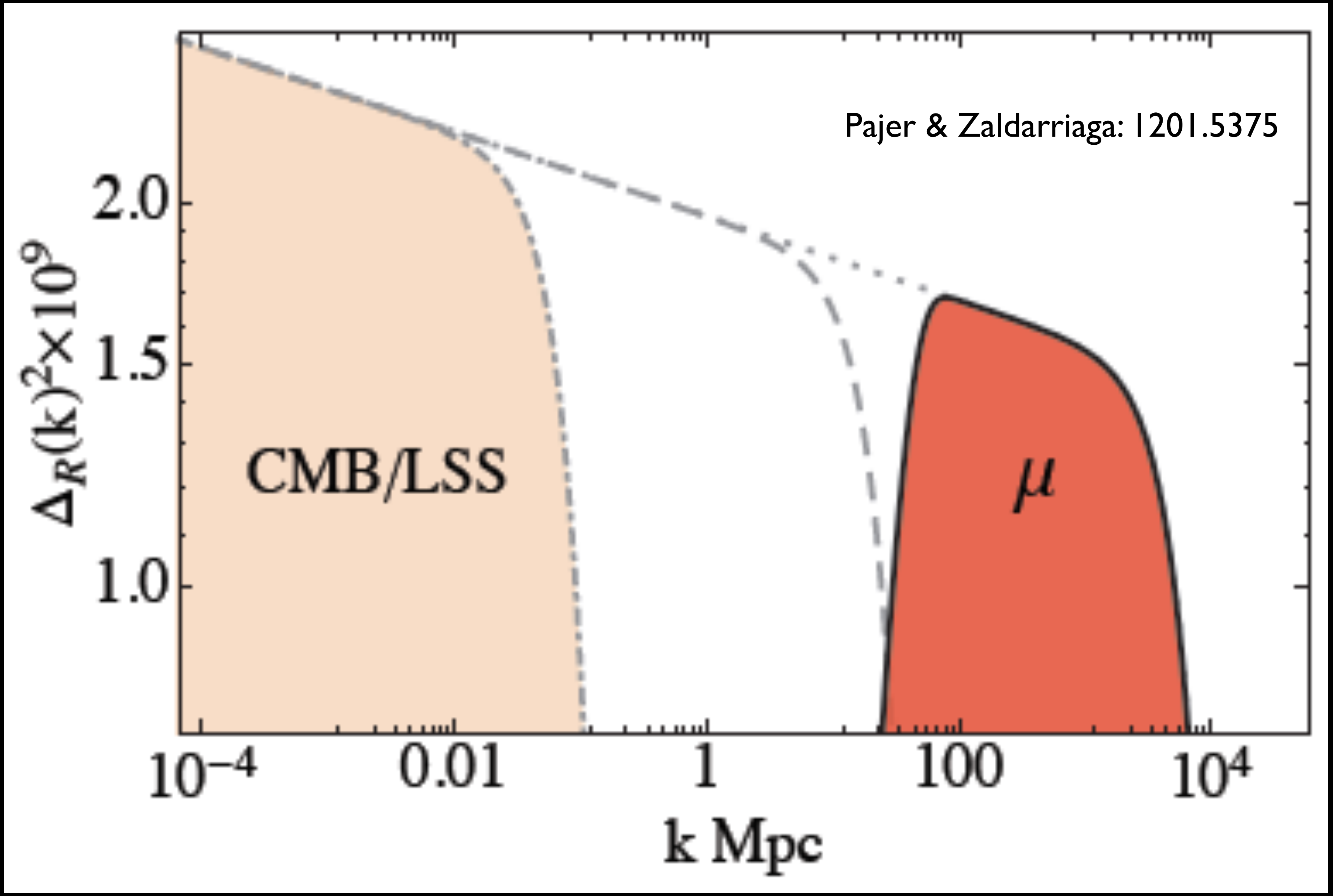
-0.09 < g_* < 0.08 (95%CL) vs. -0.0225 < g_* < 0.0363 (Planck2015)

⭐ Anisotropic Tμ correlations

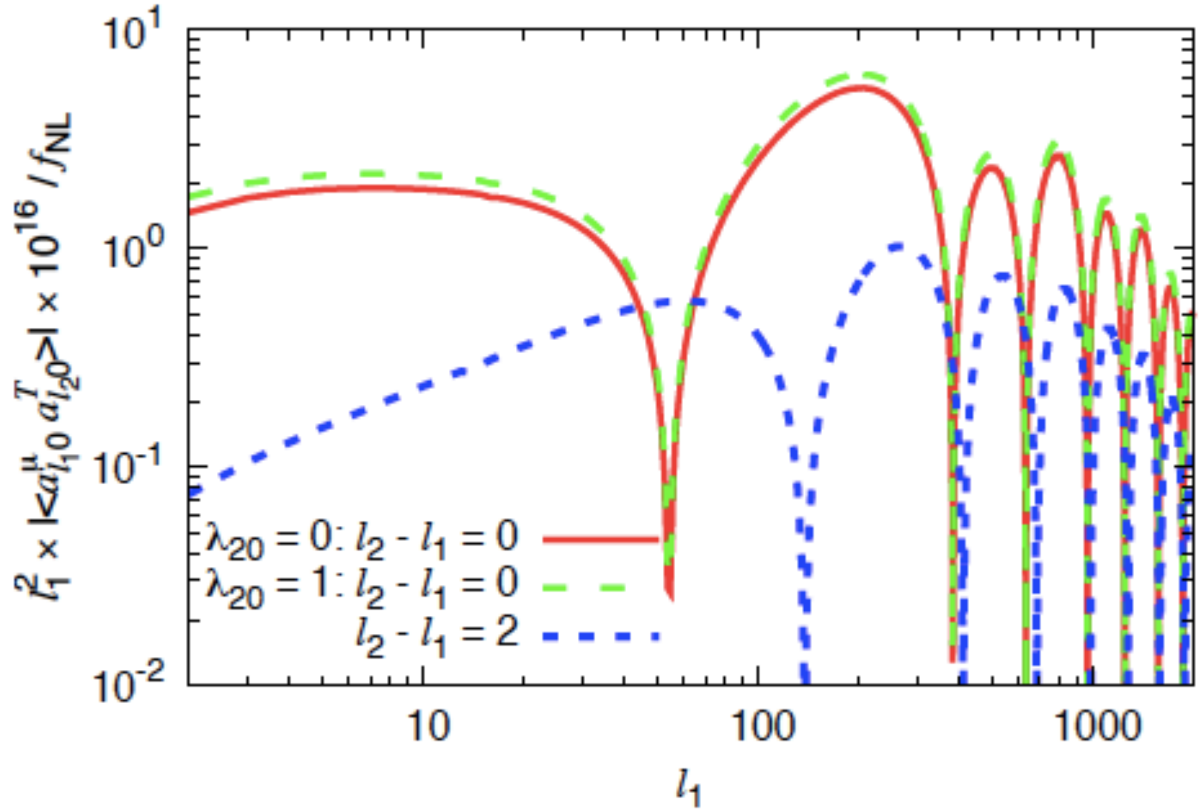
energy injections due to acoustic waves distort CMB's blackbody (BB)!

✤ $z > 2\times10^6$: $e^- + \gamma \rightarrow e^- + 2\gamma$ — N_γ changes, BB is restored

✤ $5\times10^4 < z < 2\times10^6$: $e^- + \gamma \rightarrow e^- + \gamma$ — N_γ = const, BB is not restored



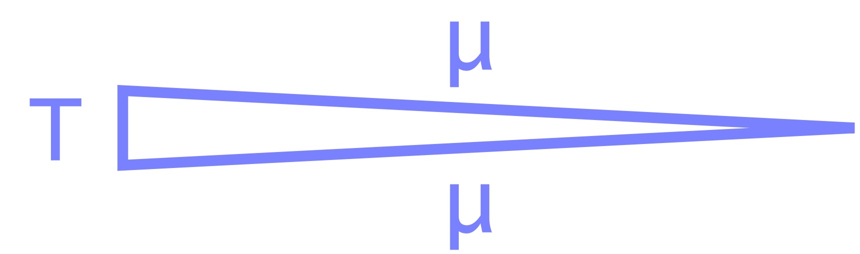
$$B_\zeta(k_1,k_2,k_3) = \frac{6}{5} f_{\rm NL} P_\zeta(k_1) P_\zeta(k_2) \left[1 + \sum_M \lambda_{2M} \left(Y_{2M}(\hat{\mathbf{k}}_1) + Y_{2M}(\hat{\mathbf{k}}_2) \right) \right] + (2\ \mathrm{perm})$$



$\mu \sim \zeta\zeta$

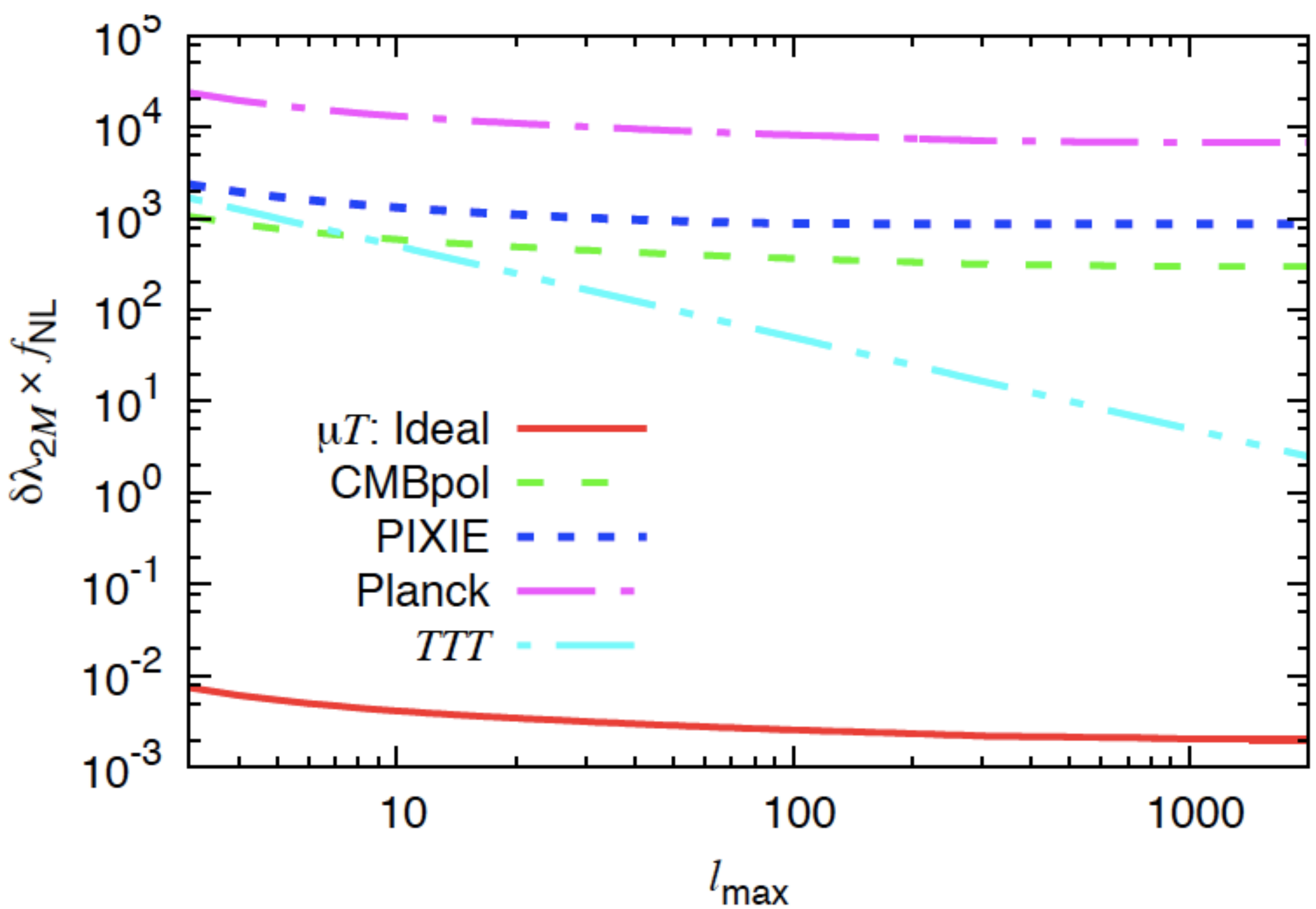
$T \sim \zeta$

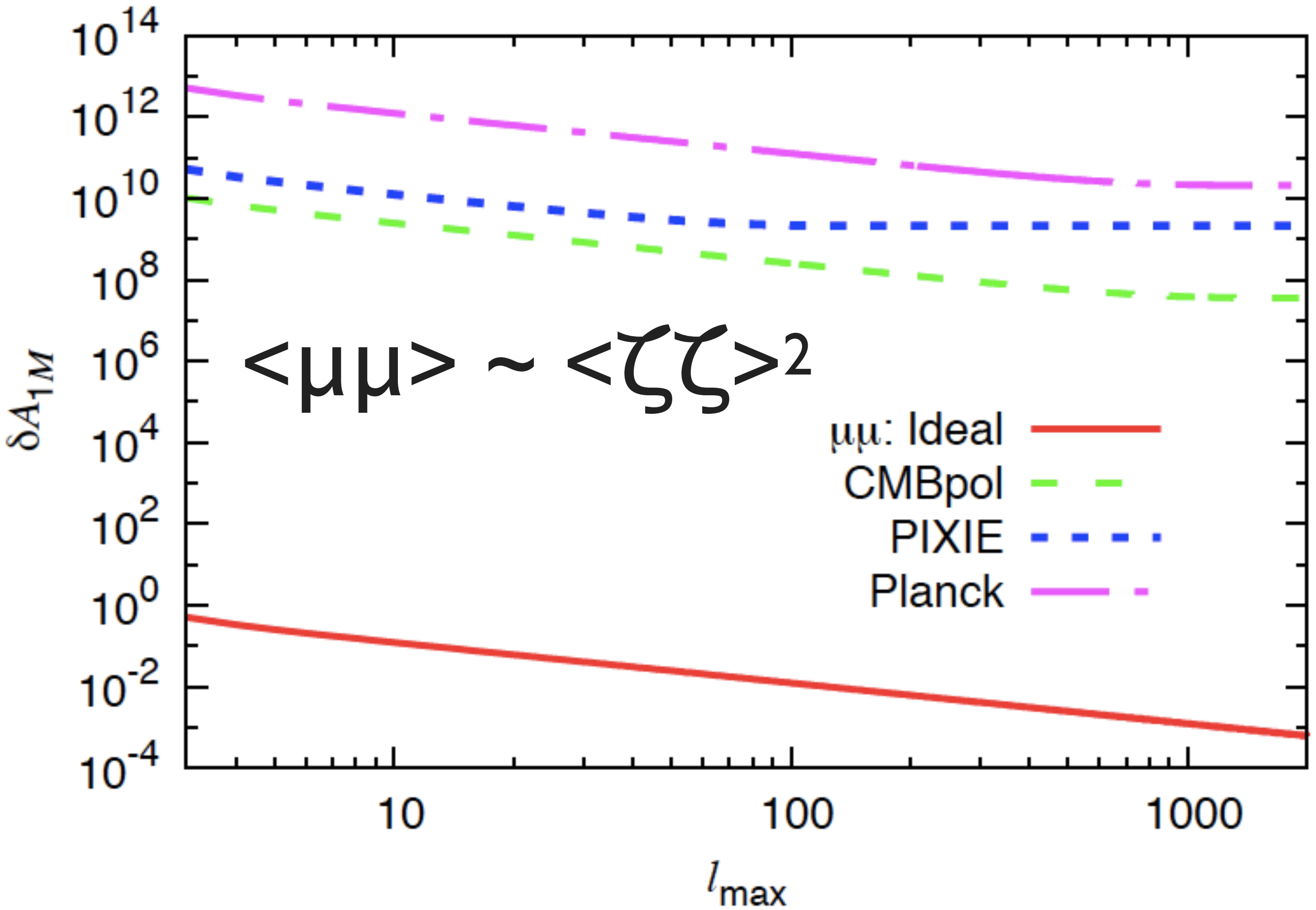
$\rightarrow \langle T\mu \rangle \sim \langle \zeta\zeta\zeta \rangle$



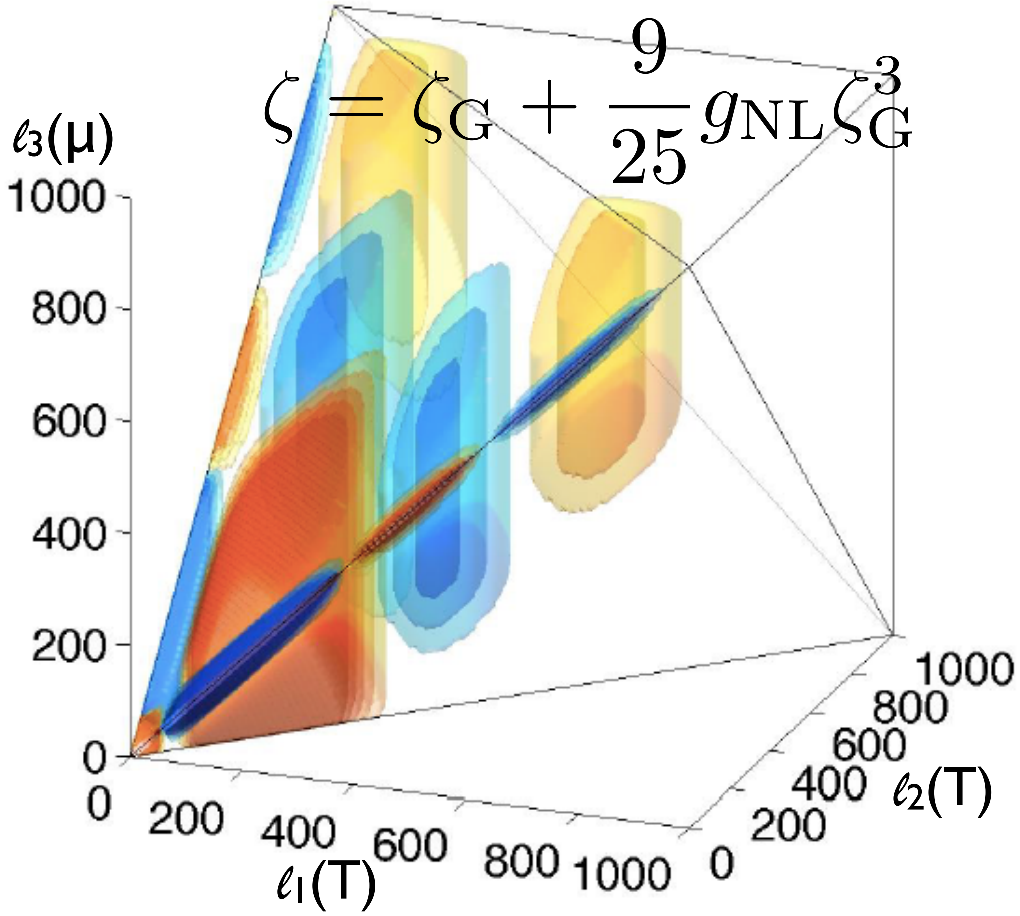
off-diagonal components!

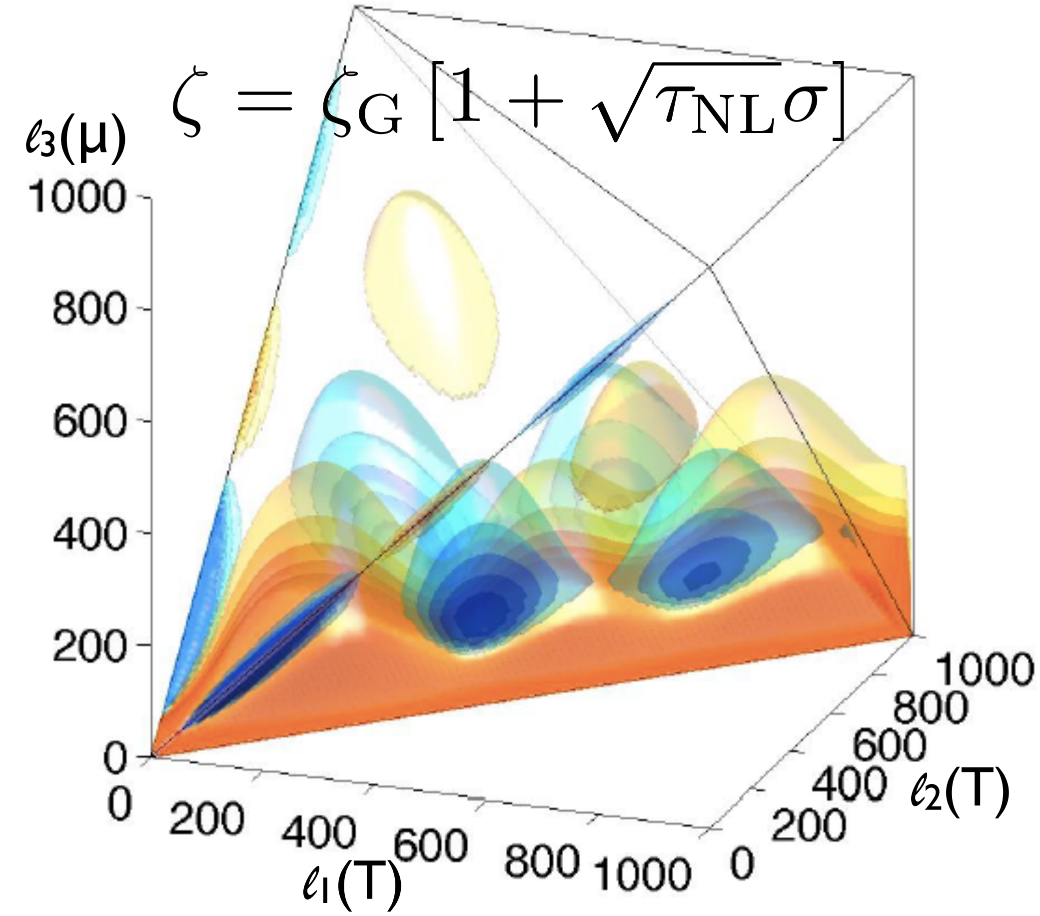
MS, Liguori, Bartolo, Matarrese: 1506.06670

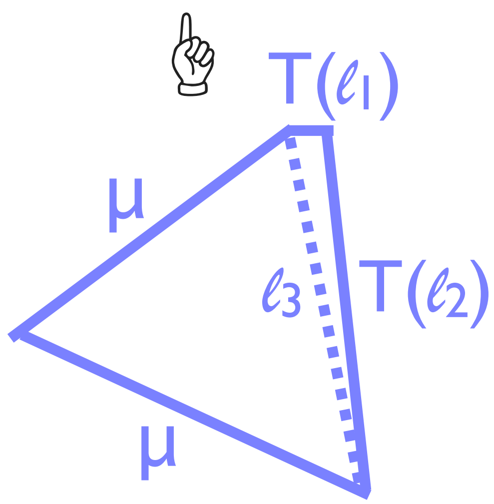




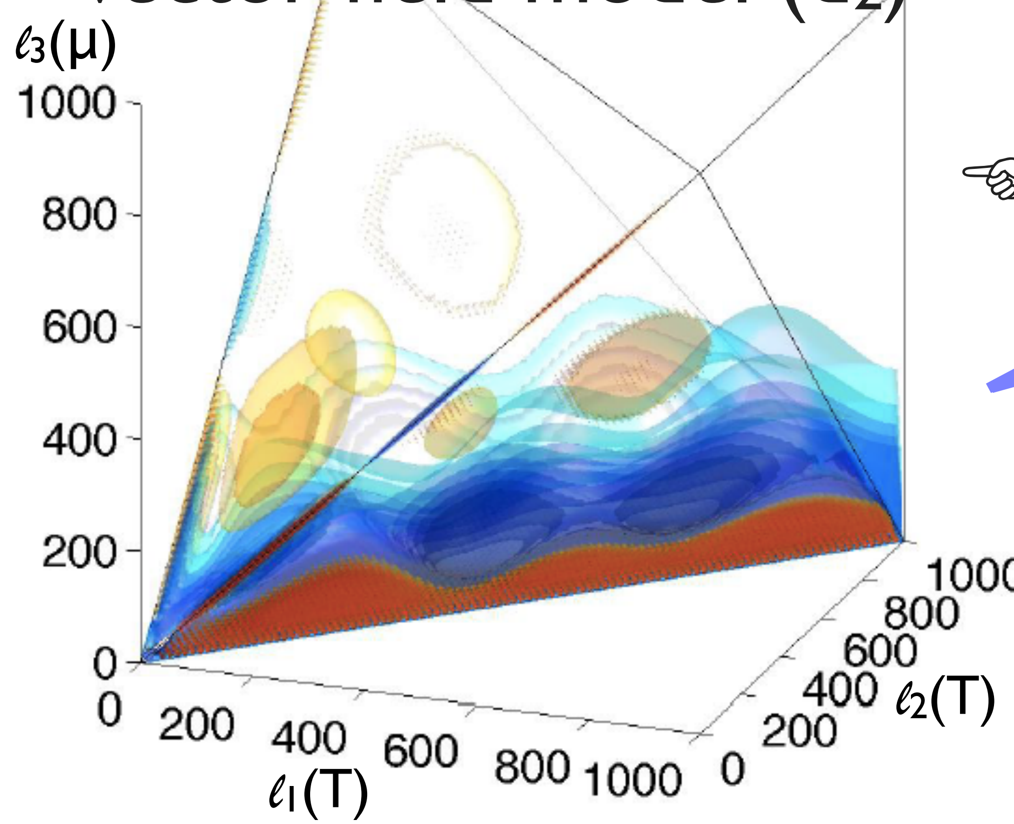
⭐TTμ correlations   <TTμ> ~ <ζζζζ>

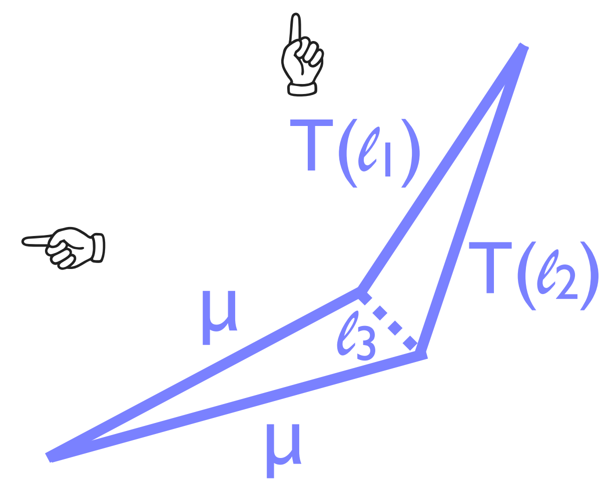






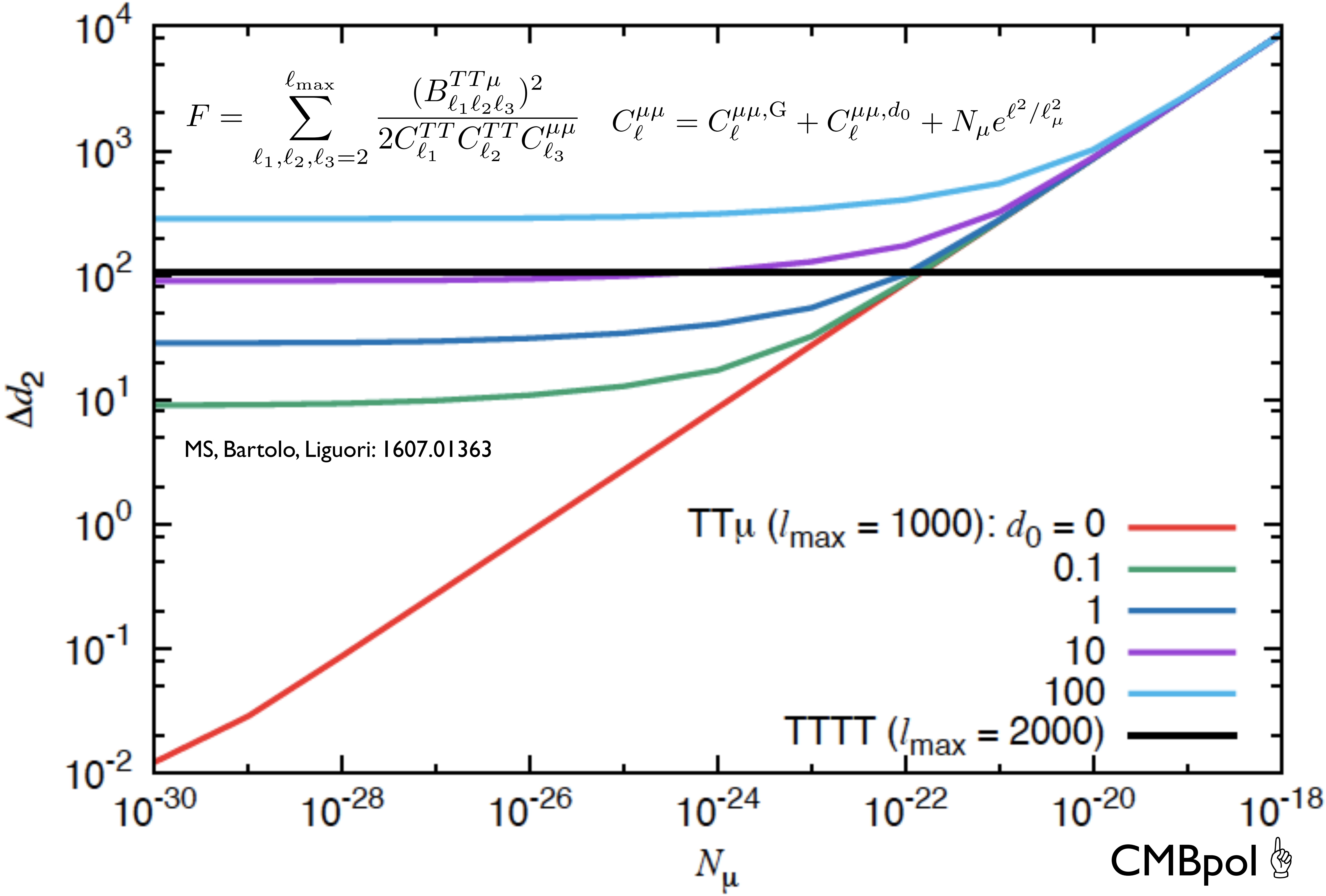
vector field model (d_2)





Bartolo, Liguori, MS: 1511.01474

MS, Bartolo, Liguori: 1607.01363


$F = \sum_{\ell_1,\ell_2,\ell_3=2}^{\ell_{\max}} \frac{(B^{TT\mu}_{\ell_1\ell_2\ell_3})^2}{2C^{TT}_{\ell_1}C^{TT}_{\ell_2}C^{\mu\mu}_{\ell_3}}$
$C^{\mu\mu}_\ell = C^{\mu\mu,\mathrm{G}}_\ell + C^{\mu\mu,d_0}_\ell + N_\mu e^{\ell^2/\ell_\mu^2}$
MS, Bartolo, Liguori: 1607.01363
TTμ (l_{max} = 1000): d_0 = 0
0.1
1
10
100
TTTT (l_{max} = 2000)
Δd_2
N_μ
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-30}
10^{-28}
10^{-26}
10^{-24}
10^{-22}
10^{-20}
10^{-18}

CMBpol

⭐ Anisotropic 21cm power spectrum

MS, Munoz, Kamionkowski, Raccanelli : 1603.01206

advantage
- tomography: $20 < z < 50$
- small scale: $k < 10^2$ Mpc^{-1}

$$\ell^2 C_\ell^N = \frac{(2\pi)^3 T_{\rm sys}^2(\nu)}{\Delta\nu\, t_o f_{\rm cover}^2}\left(\frac{\ell}{\ell_{\rm cover}(\nu)}\right)^2 \quad \ell_{\rm cover}(\nu) \equiv \frac{2\pi D_{\rm base}}{\lambda}$$

SKA: $D_{\rm base}$ = 6km, $f_{\rm cover}$ = 0.02, t_o = 5yr
FRA: $D_{\rm base}$ = 100km, $f_{\rm cover}$ = 0.2, t_o = 10yr

$f(k)$ g_{2M}	CVL 21 cm	SKA	FRA	CVL CMB T	CVL CMB T + E
$(k/k_g)^2$	5.0×10^{-10} (3.2×10^{-9})	4.2 (22)	1.4×10^{-5} (6.6×10^{-5})	5.5×10^{-4}	3.2×10^{-4}
$(k/k_g)^1$	6.7×10^{-8} (4.3×10^{-7})	20 (95)	3.6×10^{-4} (1.7×10^{-3})	1.5×10^{-3}	8.3×10^{-4}
1	7.9×10^{-6} (5.0×10^{-5})	33 (150)	1.3×10^{-3} (6.3×10^{-3})	3.4×10^{-3}	1.9×10^{-3}
$(k/k_g)^{-1}$	3.8×10^{-4} (2.4×10^{-3})	17 (78)	1.3×10^{-3} (7.2×10^{-3})	4.3×10^{-3}	2.1×10^{-3}
$(k/k_g)^{-2}$	3.2×10^{-4} (2.0×10^{-3})	3.4 (16)	4.2×10^{-4} (2.4×10^{-3})	6.1×10^{-5}	3.7×10^{-5}

$f(k)$ A_{IM}	CVL 21 cm	SKA	FRA	CVL CMB T	CVL CMB T + E
$1-k/k_A$	8.0×10^{-7} (5.1×10^{-6})	13 (62)	6.4×10^{-4} (3.3×10^{-3})	1.3×10^{-3}	9.3×10^{-4}
$(1-k/k_A)^2$	1.4×10^{-7} (8.7×10^{-7})	14 (64)	6.9×10^{-4} (3.6×10^{-3})	1.5×10^{-3}	1.0×10^{-3}

	CMB anisotropy	galaxy	CMB distortion	21cm
scale [Mpc^{-1}]	10^{-4} - 10^{-1}	10^{-3} - 10^{-1}	10^{+1} - 10^{+4}	$< 10^{+2}$
pow: Δg_{2M}, ΔA_{1M}	10^{-2}	10^{-2} (CMASS) 10^{-3} (PFS)	>> 1 (CMBpol) 10^{-2} (CVL)	> 1 (SKA) 10^{-5} (CVL)
bis: Δc_2	10	10 (2020's?) [e.g. 1507.05903 (SKA), 1607.05232 (LSST)]	10^{2} (CMBpol) 10^{-3} (CVL)	10^{-2} (CVL) [1506.04152]
tris: Δd_2	100	?	10^{4} (CMBpol) 10^{-2} (CVL)	?

Beyond spin-1 fields

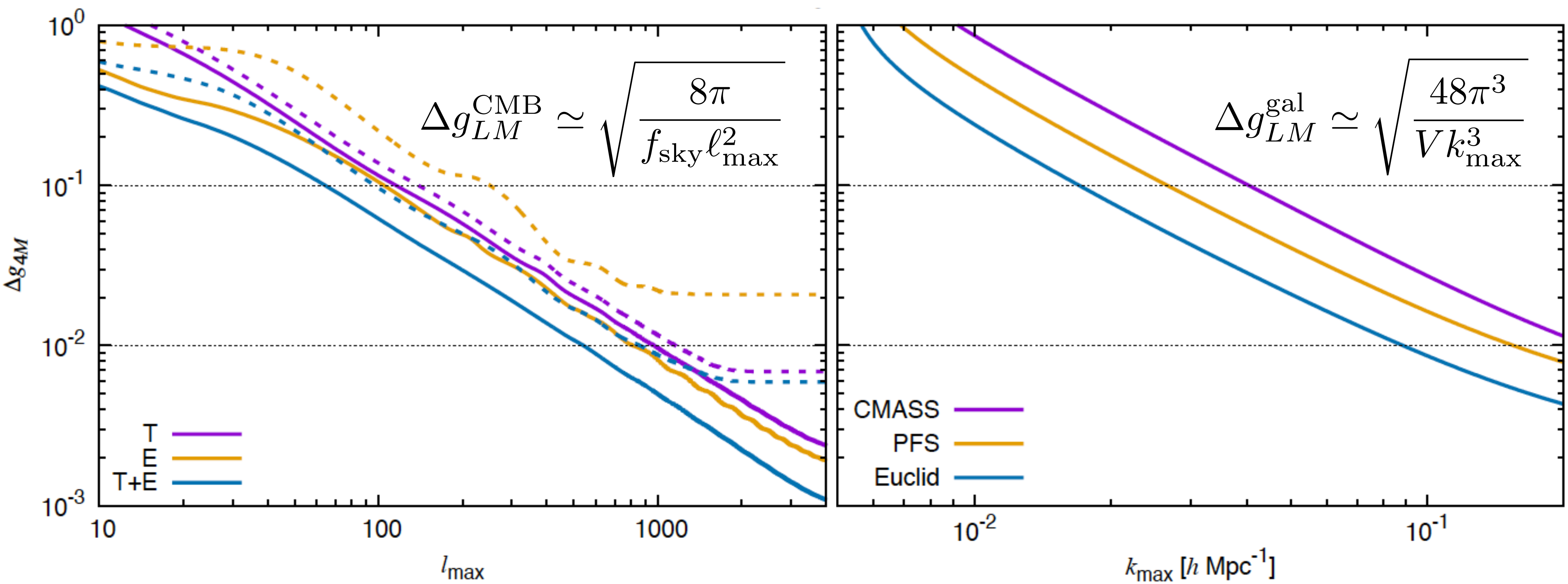
$$S \supset g_s H^2 \int \mathrm{d}^4x\, e^{3Ht} \exp(I(\phi)) \sigma_{i_1 \cdots i_s} \sigma^{i_1 \cdots i_s}$$

$$g_{LM} = \frac{2\pi^2 c_s\, [\Gamma(s+1)]^2}{\Gamma(\frac{1-L}{2})\Gamma(\frac{2+L}{2})\Gamma(\frac{2s-L+2}{2})\Gamma(\frac{2s+L+3}{2})} \frac{2\Gamma(\frac{2s+3}{2})}{2\Gamma(\frac{2s+3}{2}) + c_s\sqrt{\pi}\Gamma(s+1)} Y^*_{LM}(\hat{p})$$

$$\sim \frac{c_s}{\sqrt{s}} \frac{2\pi^2}{\Gamma\left(\frac{1-L}{2}\right)\Gamma\left(\frac{2+L}{2}\right)} Y^*_{LM}(\hat{p}) \quad (s \gg 1) \qquad c_s \propto \frac{g_s^2 \langle\bar{\sigma}\rangle^2 N_k^2}{\epsilon H^2 M_{\rm pl}^2}$$

s nonvanishing components: g_{2M}, g_{4M}, …, $g_{(2s-2)M}$ and $g_{(2s)M}$

Baltolo, Kehagias, Liguori, Riotto, MS, Tansella: 1709.05695



$g_{(2s)M}$ is almost independent of s, so $g_{(2s)M} \sim 10^{-3}$ will be detectable