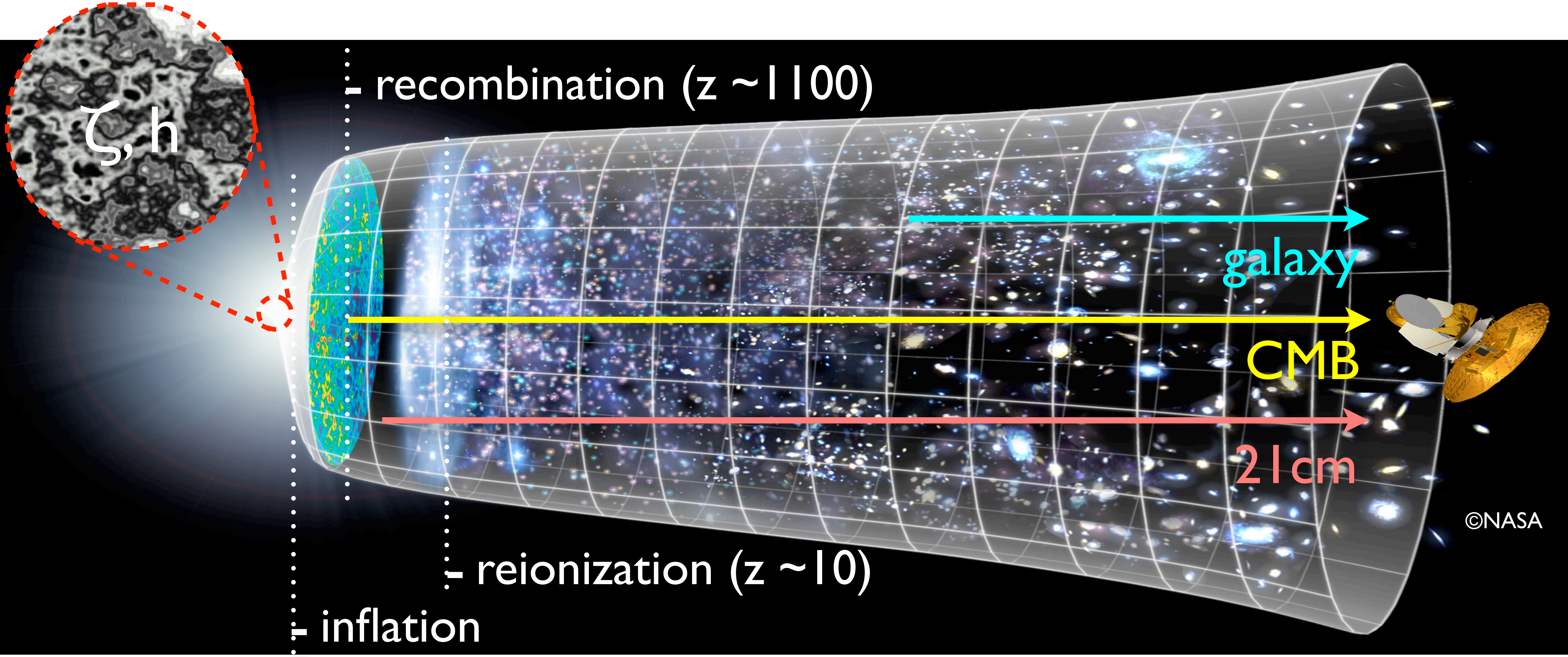
Cosmic isotropy tests with beyond large-scale CMB correlators

Maresuke Shiraishi

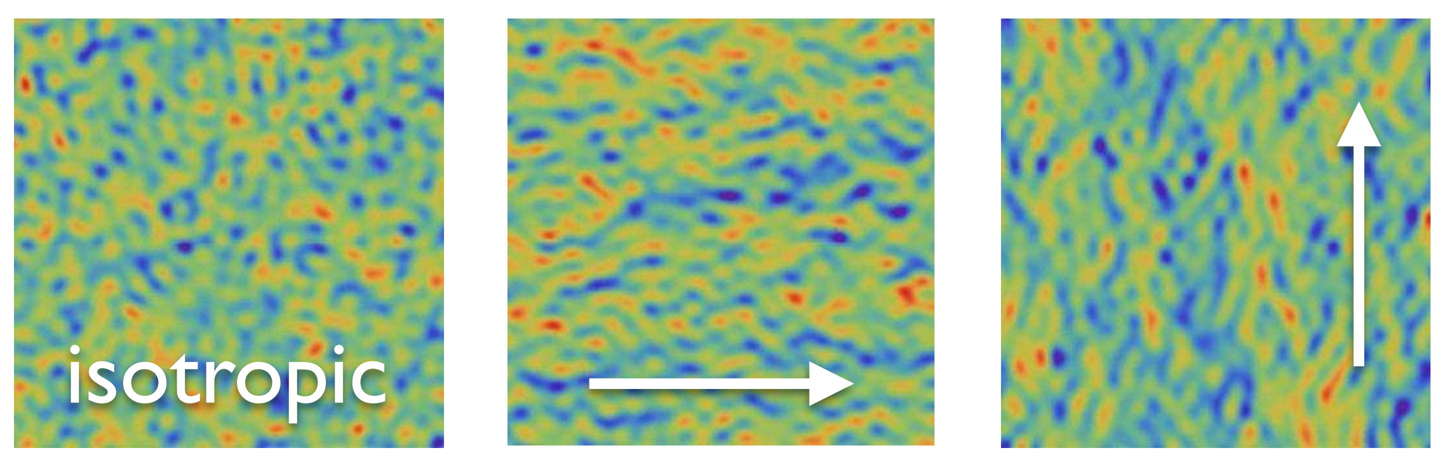
Kavli IPMU



The Universe is
✓ *isotropic*
✓ *homogeneous*
✓ *parity-symmetric*
?????

If $\langle\zeta^2\rangle$ is directional dependent…

Dimopoulos: 0906.0903



Sources?

vector field

$f(\phi)F^2 \quad g(\phi)F\tilde{F}$

$A + A \rightarrow \varphi \rightarrow \zeta \propto E^{vev} \cdot \delta E + \delta E^2$

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

Gaussian vector field with $\langle \delta E_a(\mathbf{k})\, \delta E_b(\mathbf{k}') \rangle \propto (\delta_{ab} - k_a k_b)\, \delta^D(\mathbf{k} + \mathbf{k}')$

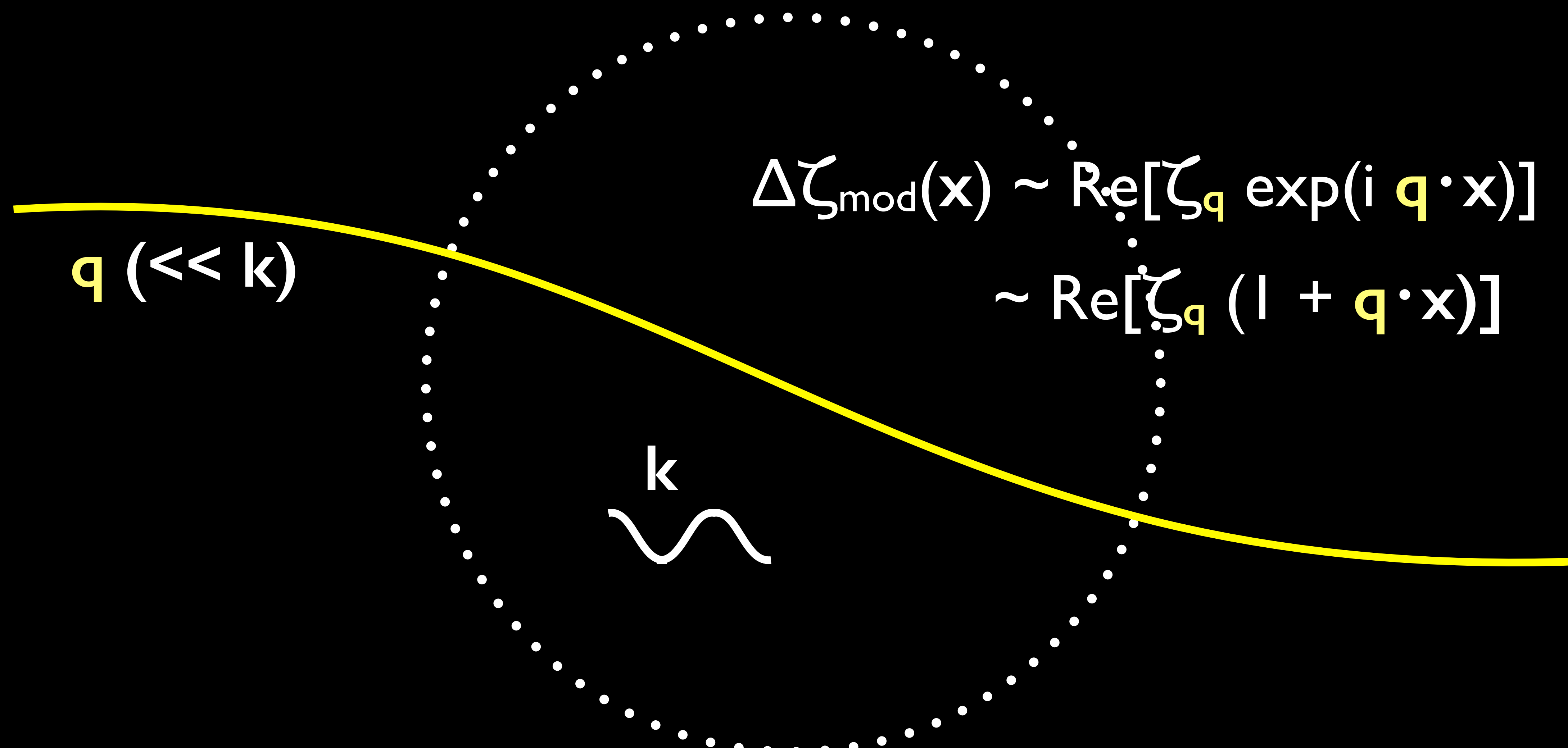
$\langle \zeta^2 \rangle \sim \langle \zeta_{(1)}{}^2 \rangle \propto E_a{}^{vev} E_b{}^{vev} \langle \delta E_a\, \delta E_b \rangle \propto [1 - (\mathbf{k} \cdot \mathbf{E}^{vev})^2]\, \delta^D(\mathbf{k} + \mathbf{k}')$

$\langle \zeta^3 \rangle \sim \langle \zeta_{(1)}\zeta_{(1)}\zeta_{(2)} \rangle \neq 0 \qquad \langle \zeta^4 \rangle \sim \langle \zeta_{(1)}\zeta_{(1)}\zeta_{(2)}\zeta_{(2)} \rangle \neq 0$

quadrupolar power asymmetry + anisotropic NG!

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

dipolar modulation from a superhorizon mode



$$\Delta\zeta_{\mathrm{mod}}(\mathbf{x}) \sim \mathrm{Re}[\zeta_{\mathbf{q}} \exp(i\, \mathbf{q}\cdot\mathbf{x})]$$

$$\sim \mathrm{Re}[\zeta_{\mathbf{q}}\, (1 + \mathbf{q}\cdot\mathbf{x})]$$

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

Can we see these?

- TT in $|\ell_1 - \ell_2| = 0, 2$ $|g_{2M}| < 0.01$

Kim & Komatsu 1310.1605
Planck 2015: 1502.02114

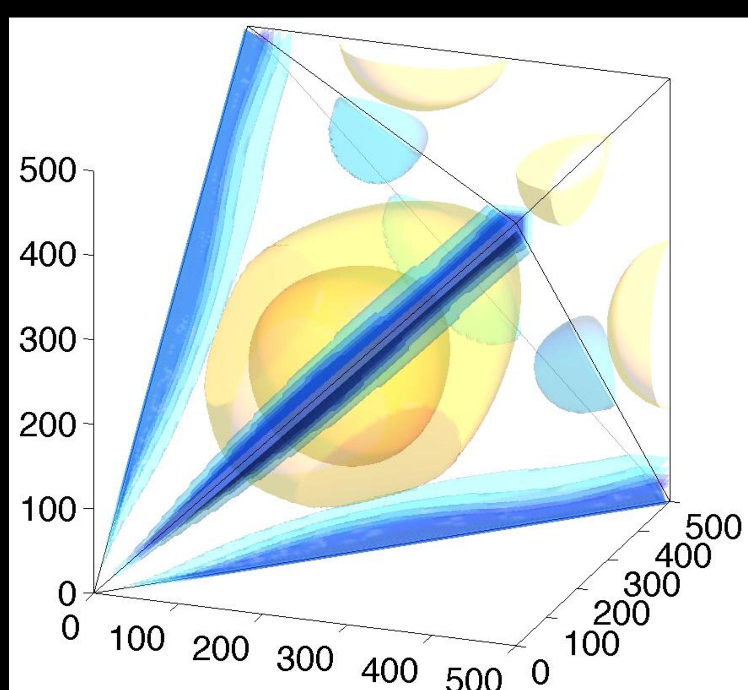
- TT in $|\ell_1 - \ell_2| = 1$ 3σ signal of A_{1M} with $f(k) \propto k^{-0.5}$

Planck 2015: 1506.07135

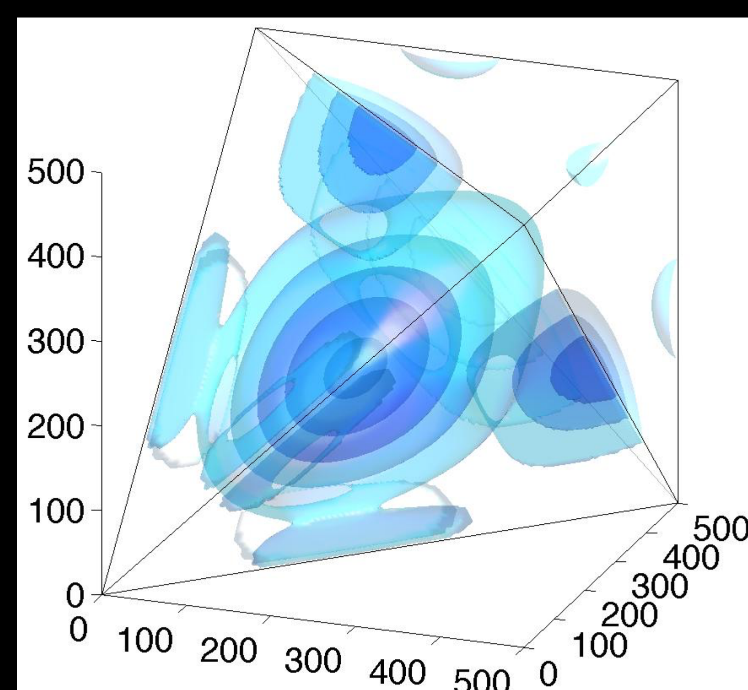
- TTT in $|\ell_1 - \ell_2| \leqq \ell_3 \leqq \ell_1 + \ell_2$ (angle-averaged form)

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

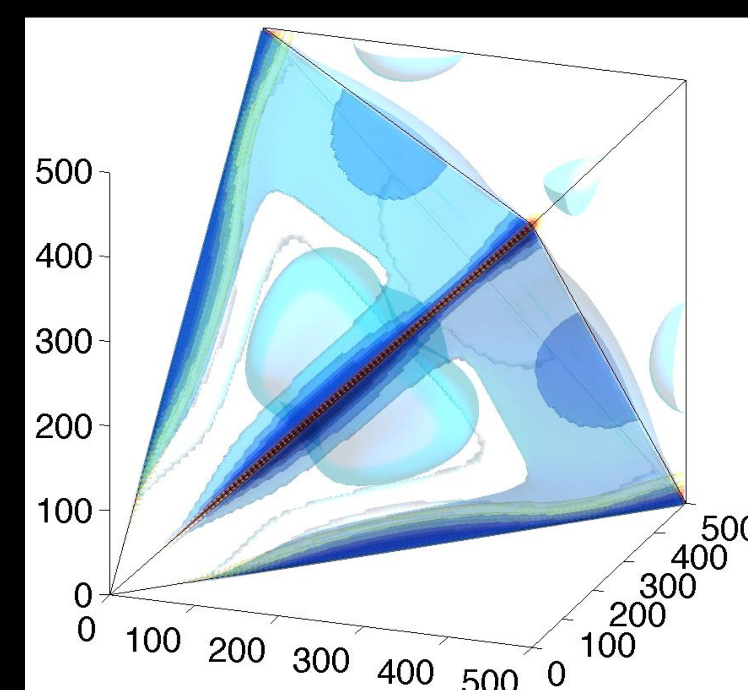
MS, Komatsu, Peloso, Barnaby: 1302.3056



$-10.7 \le c_0 \le 16.7$



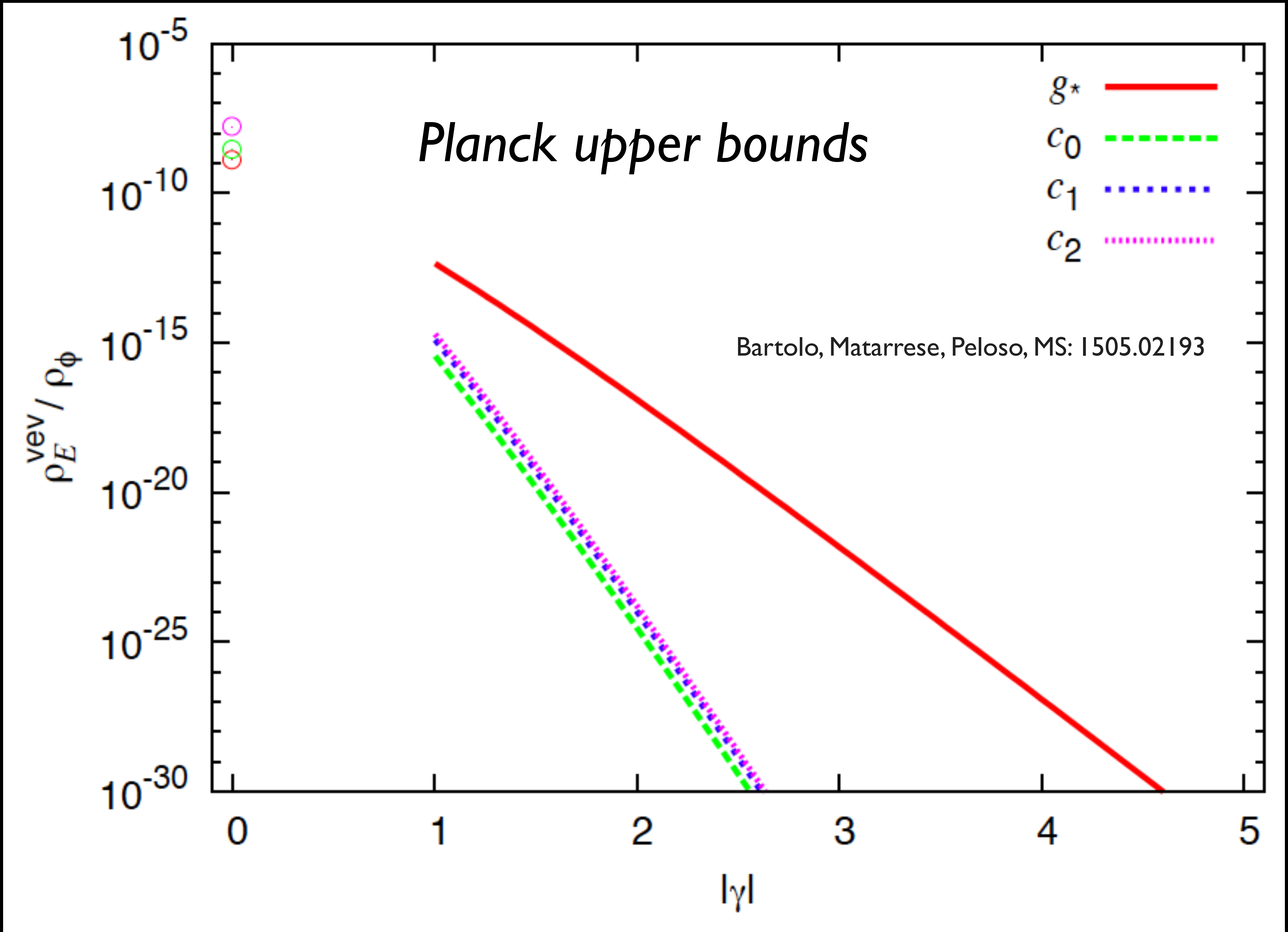
$-89 \le c_1 \le 324$



$-57 \le c_2 \le 47$

Planck 2015: 1502.01592

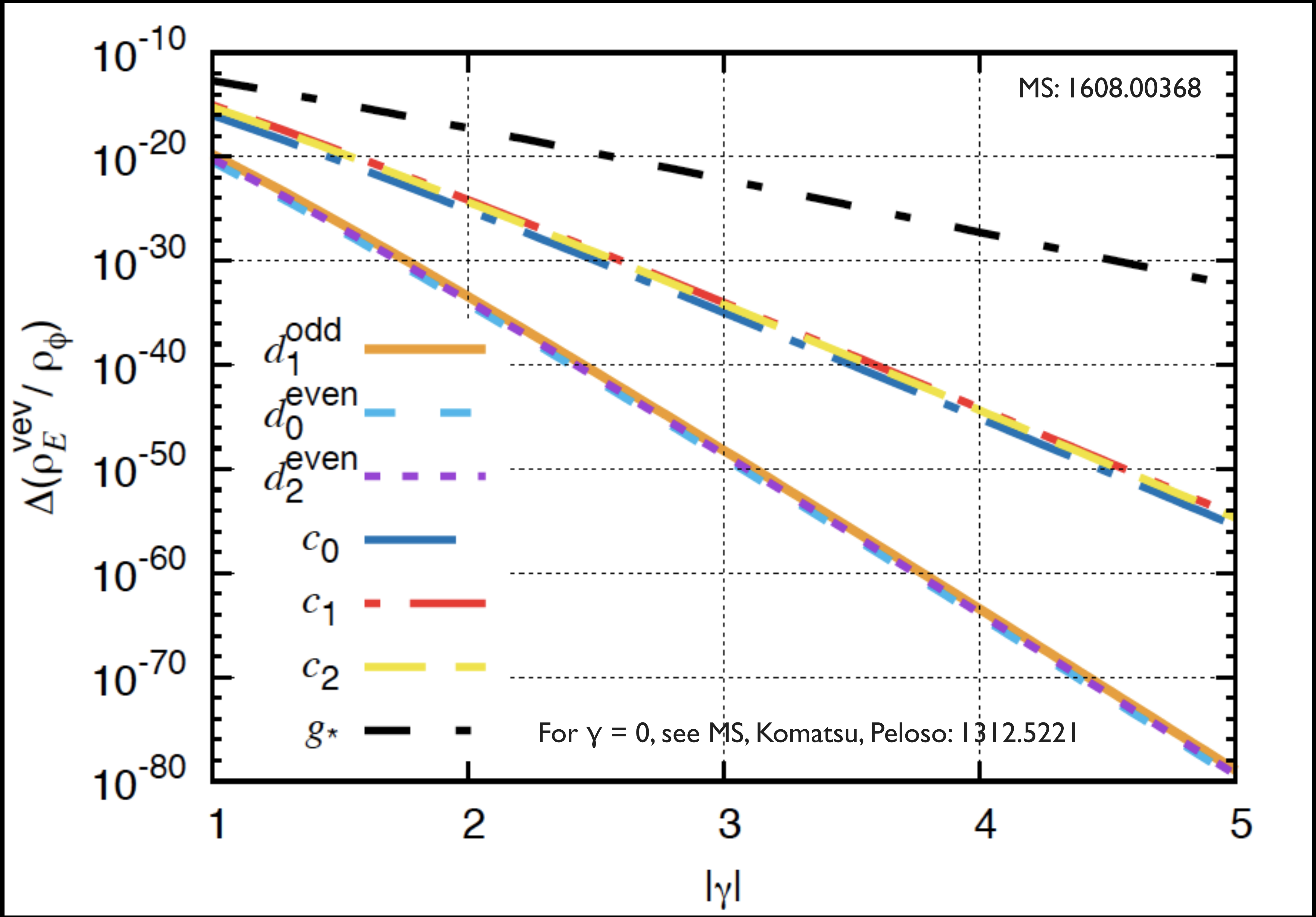
$$\mathcal{L} \supset f(\phi)\left(-\frac{1}{4}F^2 + \frac{\gamma}{4}F\tilde{F}\right)$$



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

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

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



Beyond large-scale CMB correlators

★ anisotropic 3D galaxy power

MS, Sugiyama, Okumura: 1612.02645
(published in PRD 2days ago)

※2D analysis with C_ℓ^{Gal} $|g_{2M}| < 0.1$ (SDSS DR5) Pullen & Hirata: 1003.0673

2D (L^2) vs. 3D (k^3)!

$$P^s(\mathbf{k}, \hat{n}) = \underbrace{P_m(\mathbf{k}, \hat{n})}_{\text{angle dep.}} \left[b + \underbrace{f(\hat{k}\cdot\hat{n})^2}_{\text{RSD}} \right]^2$$

BipoSH decomposition $= \sum_{\ell\ell' LM} \pi_{\ell\ell'}^{LM}(k) X_{\ell\ell'}^{LM}(\hat{k}, \hat{n})$

$$X_{\ell\ell'}^{LM}(\hat{k}, \hat{n}) \equiv \{Y_\ell(\hat{k}) \otimes Y_{\ell'}(\hat{n})\}_{LM}$$

$$= \sum_{mm'} \mathcal{C}_{\ell m \ell' m'}^{LM} Y_{\ell m}(\hat{k}) Y_{\ell' m'}(\hat{n})$$

$$X_{\ell\ell'}^{00}(\hat{k}, \hat{n}) = (-1)^{-\ell} \frac{\sqrt{2\ell+1}}{4\pi} \mathcal{L}_\ell(\hat{k}\cdot\hat{n}) \delta_{\ell,\ell'}$$

orthonormality: $\int d^2\hat{k} \int d^2\hat{n} X_{\ell\ell'}^{LM}(\hat{k}, \hat{n}) X_{\tilde{\ell}\tilde{\ell}'}^{\tilde{L}\tilde{M}*}(\hat{k}, \hat{n}) = \delta_{L,\tilde{L}} \delta_{M,\tilde{M}} \delta_{\ell,\tilde{\ell}} \delta_{\ell',\tilde{\ell}'}$

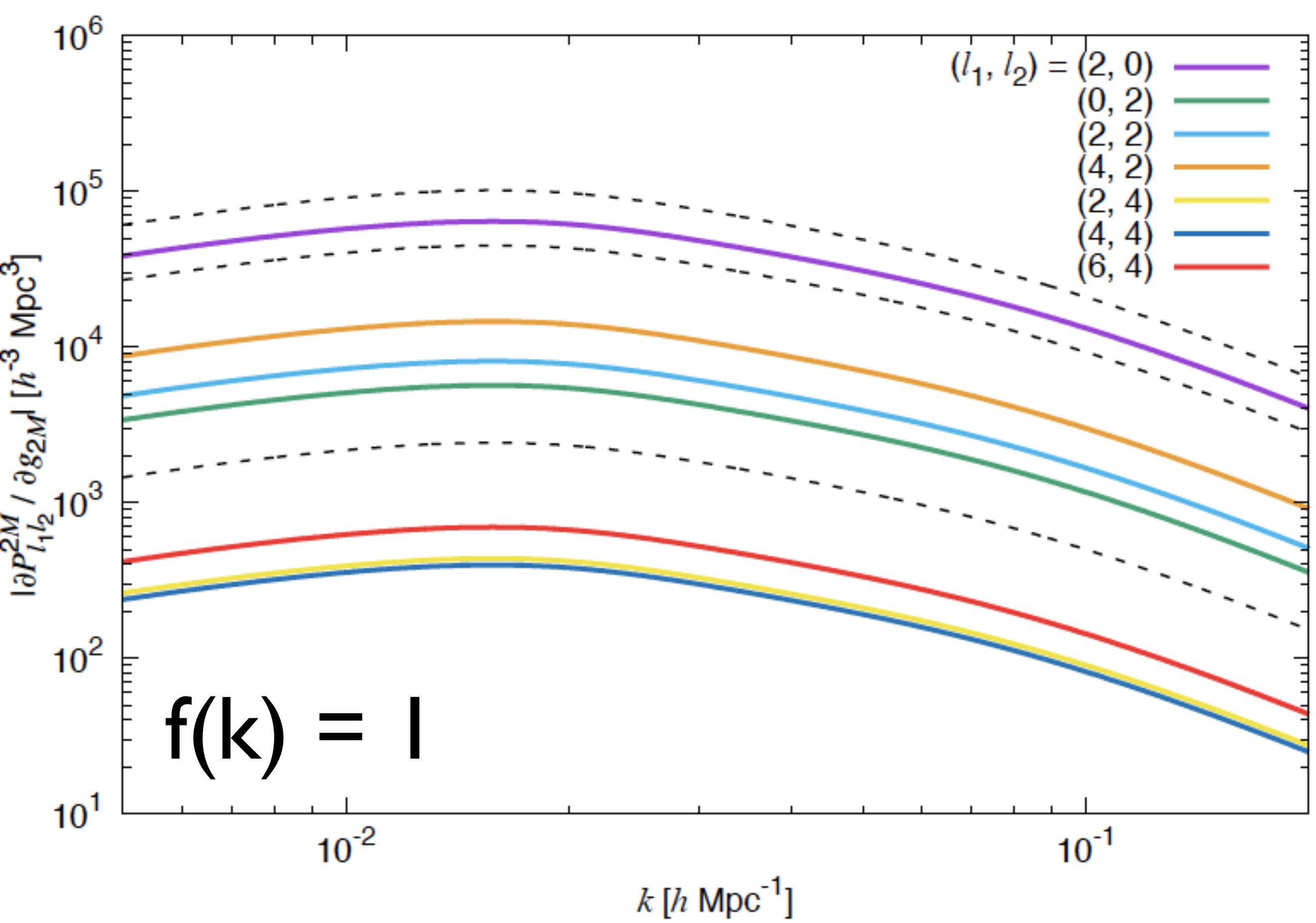
reduced BipoSH coeff. $$P_{\ell\ell'}^{LM} \equiv \pi_{\ell\ell'}^{LM}(-1)^L\sqrt{\frac{(2L+1)(2\ell+1)(2\ell'+1)}{(4\pi)^2}}\begin{pmatrix}\ell & \ell' & L\\ 0 & 0 & 0\end{pmatrix}$$

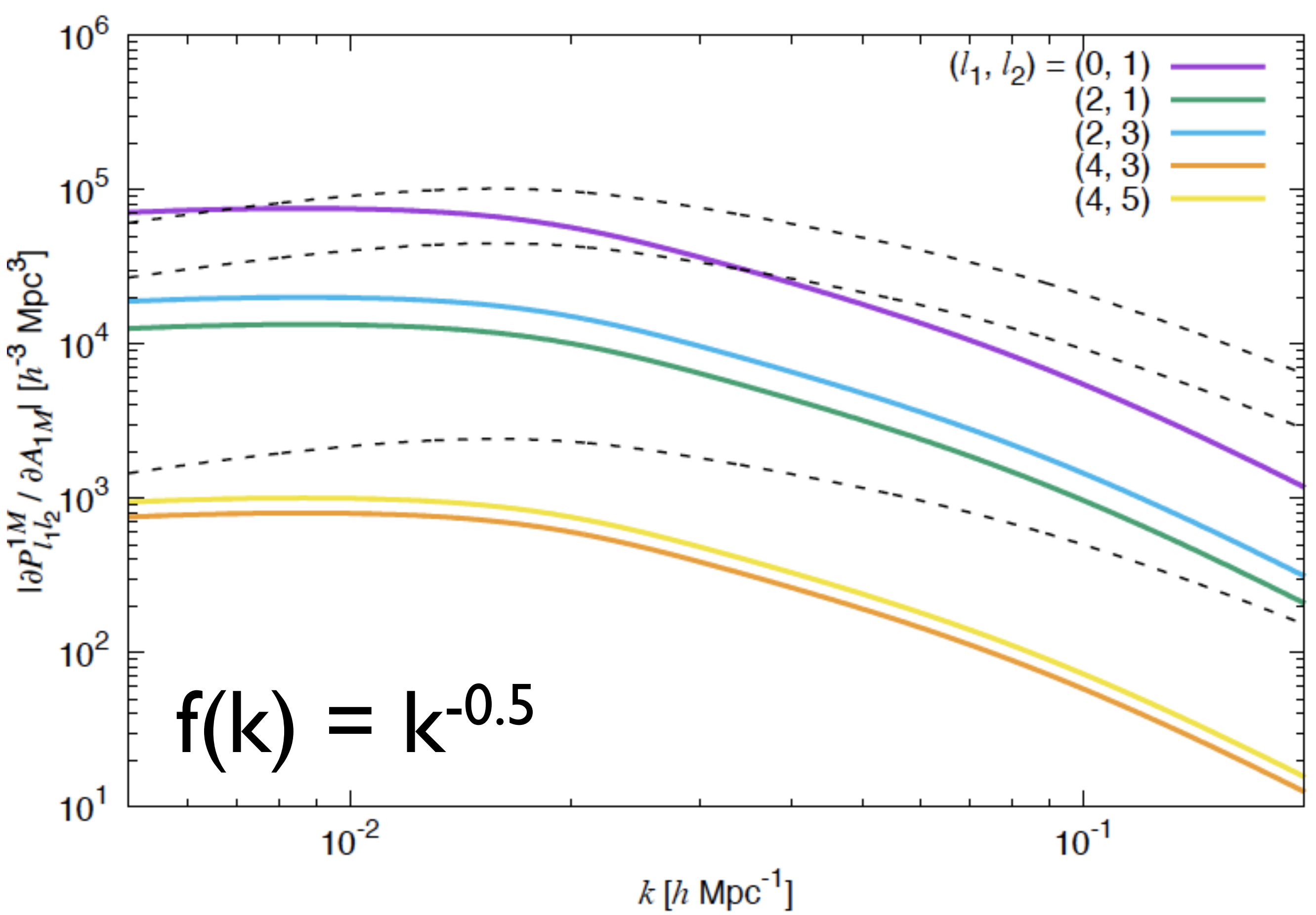
if isotropic, i.e., $P_m = P_m(|\mathbf{k}|)$ $$P_{\ell\ell'}^{LM} = P_\ell(k)\delta_{\ell,\ell'}\delta_{L,0}\delta_{M,0}$$

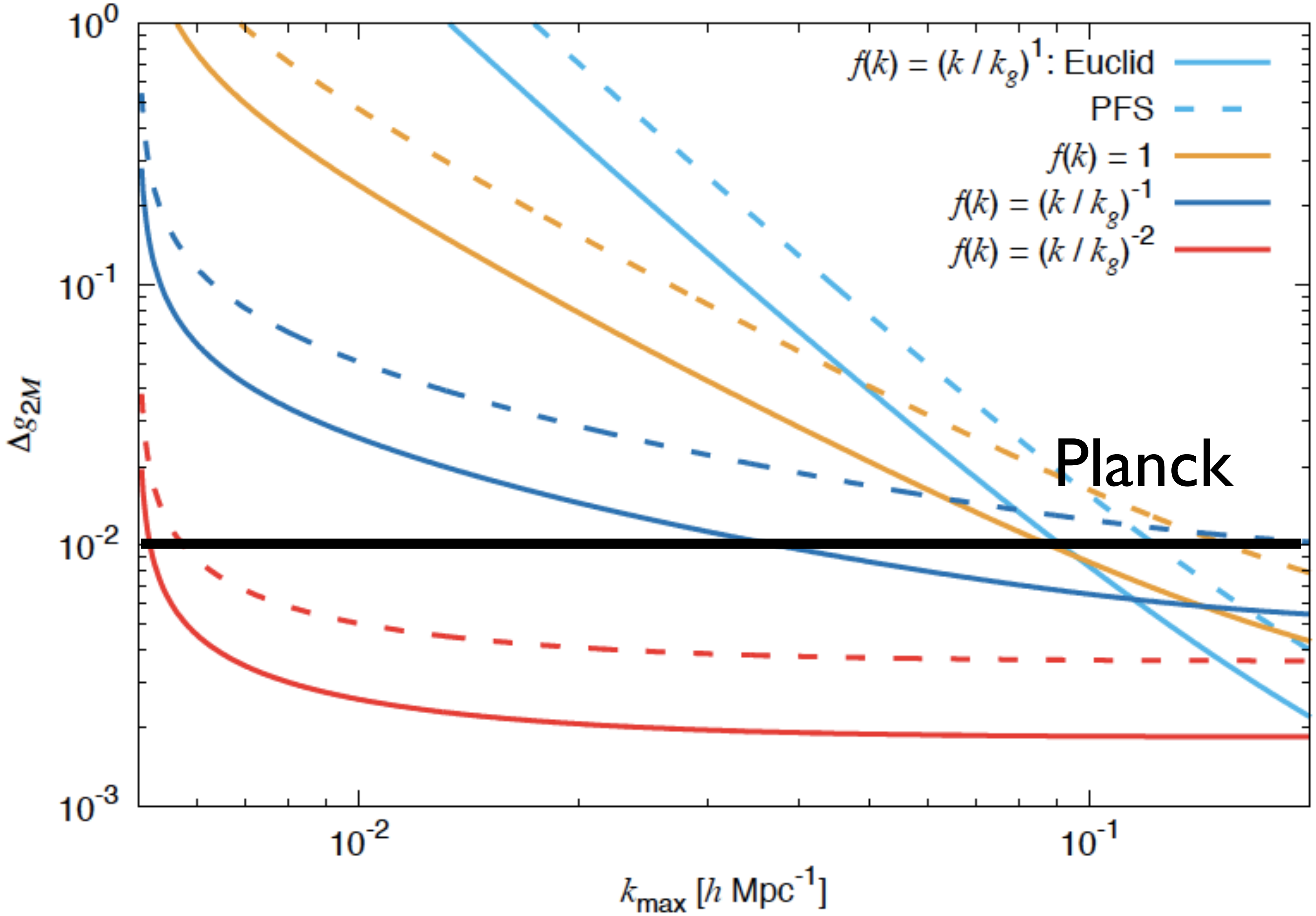
if anisotropic,
the L ≧ 1 components
also become nonzero!

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

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







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}

$f(k)$	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

$\Delta A_{\rm 1M}$

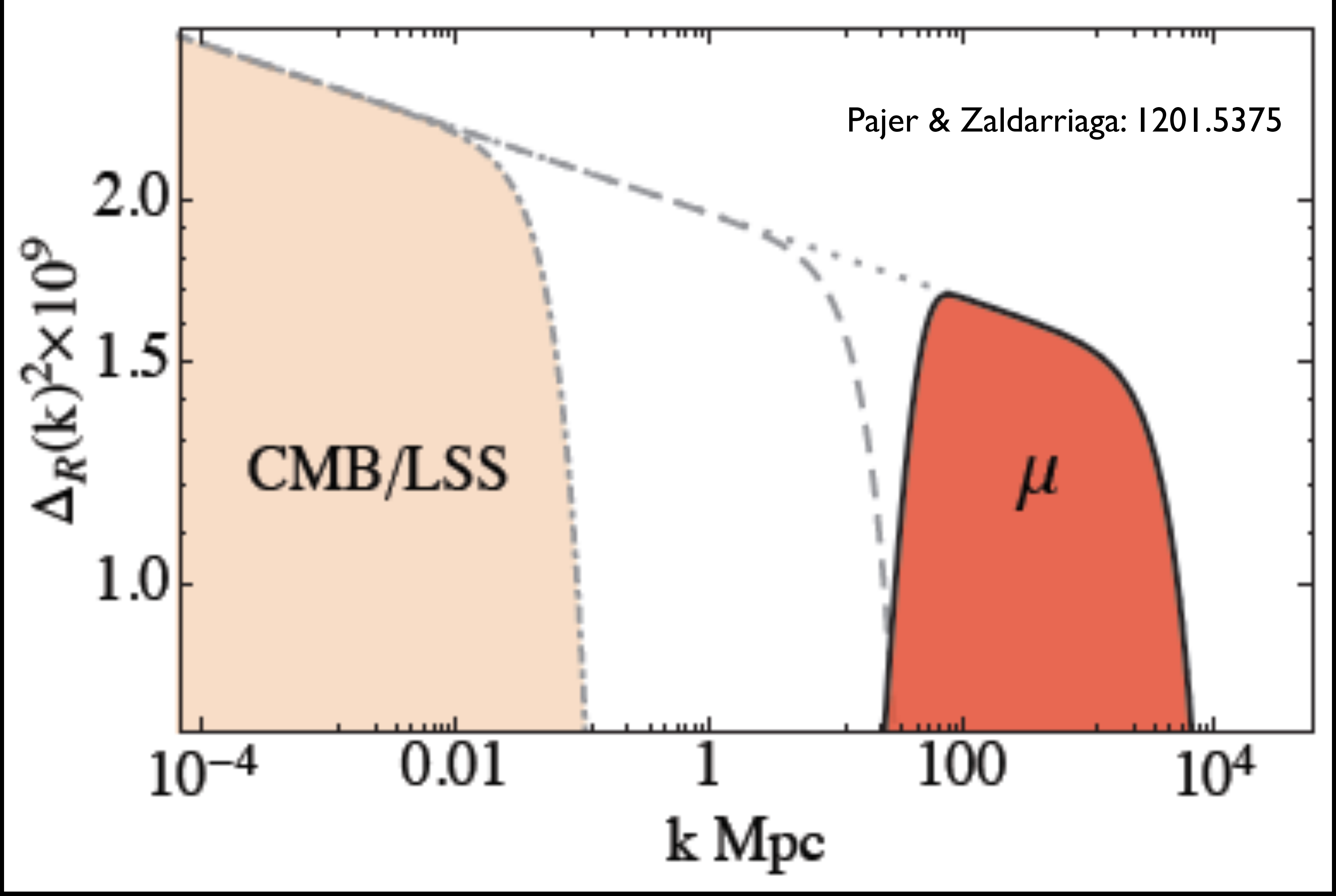
$f(k)$	SDSS	CMASS	PFS	Euclid
$(k/k_A^c)^{-1/2}$	4.4 (7.2)	2.4 (5.0)	1.6	0.84
$(1 - k/k_A^q)^2$	1.4 (2.9)	0.70 (2.0)	0.48	0.26

More future?

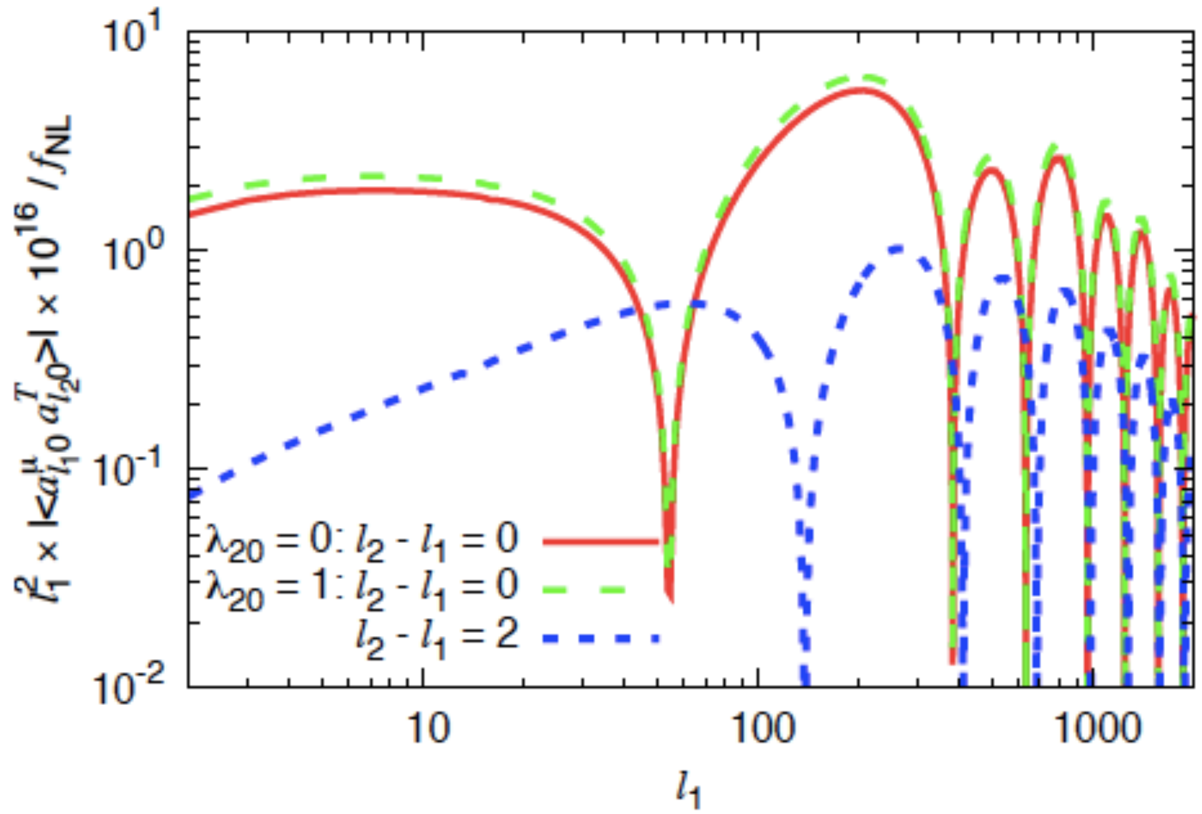
★ Anisotropic Tμ correlations

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



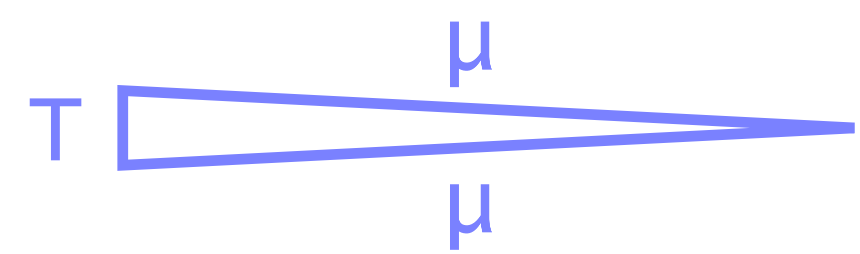
$$B_\zeta(k_1,k_2,k_3)=\frac{6}{5}f_{\rm NL}P_\zeta(k_1)P_\zeta(k_2)\left[1+\sum_M\lambda_{2M}\left(Y_{2M}(\hat{\mathbf{k}}_1)+Y_{2M}(\hat{\mathbf{k}}_2)\right)\right]+(2\ \mathrm{perm})$$



μ ~ ζζ

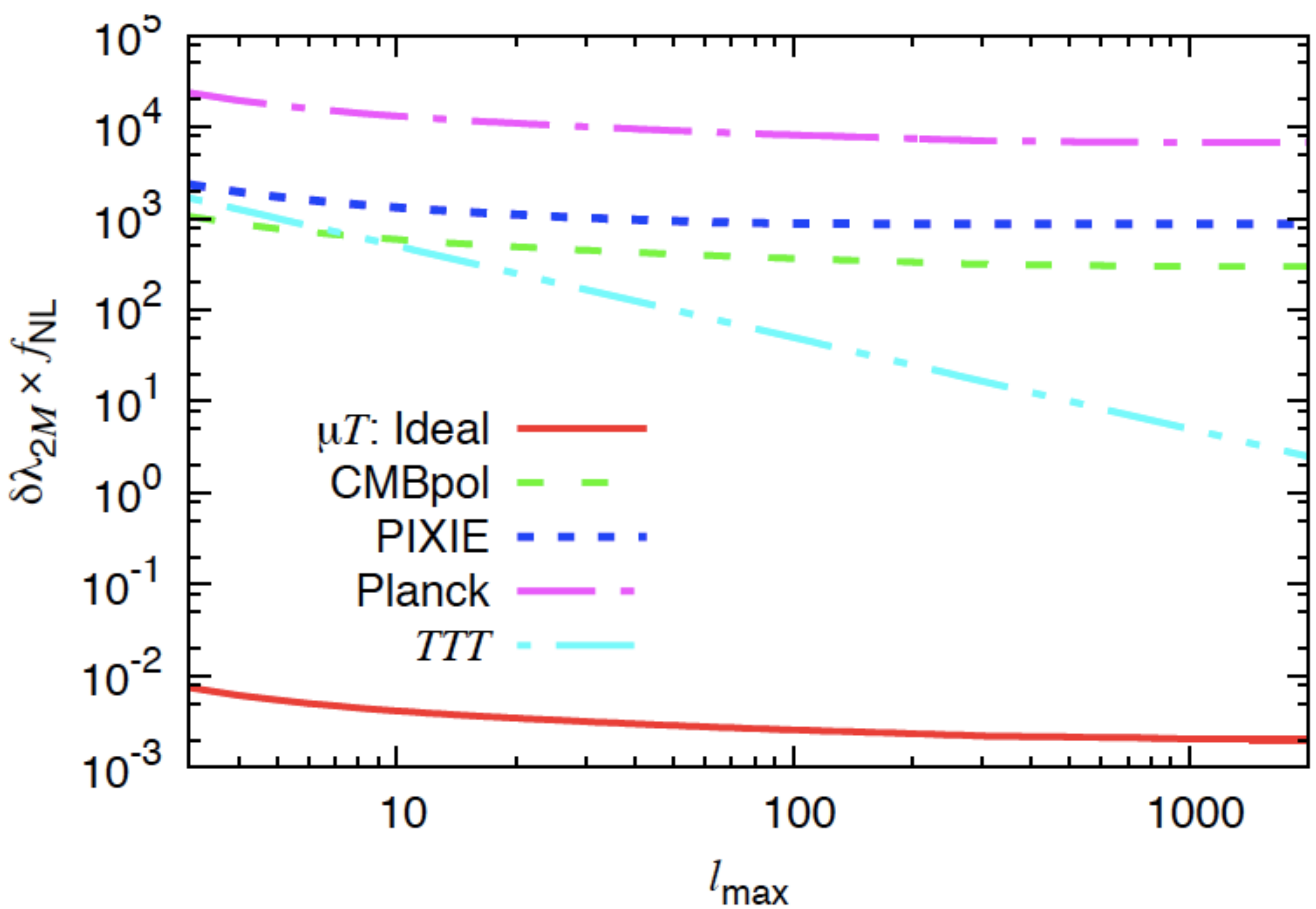
T ~ ζ

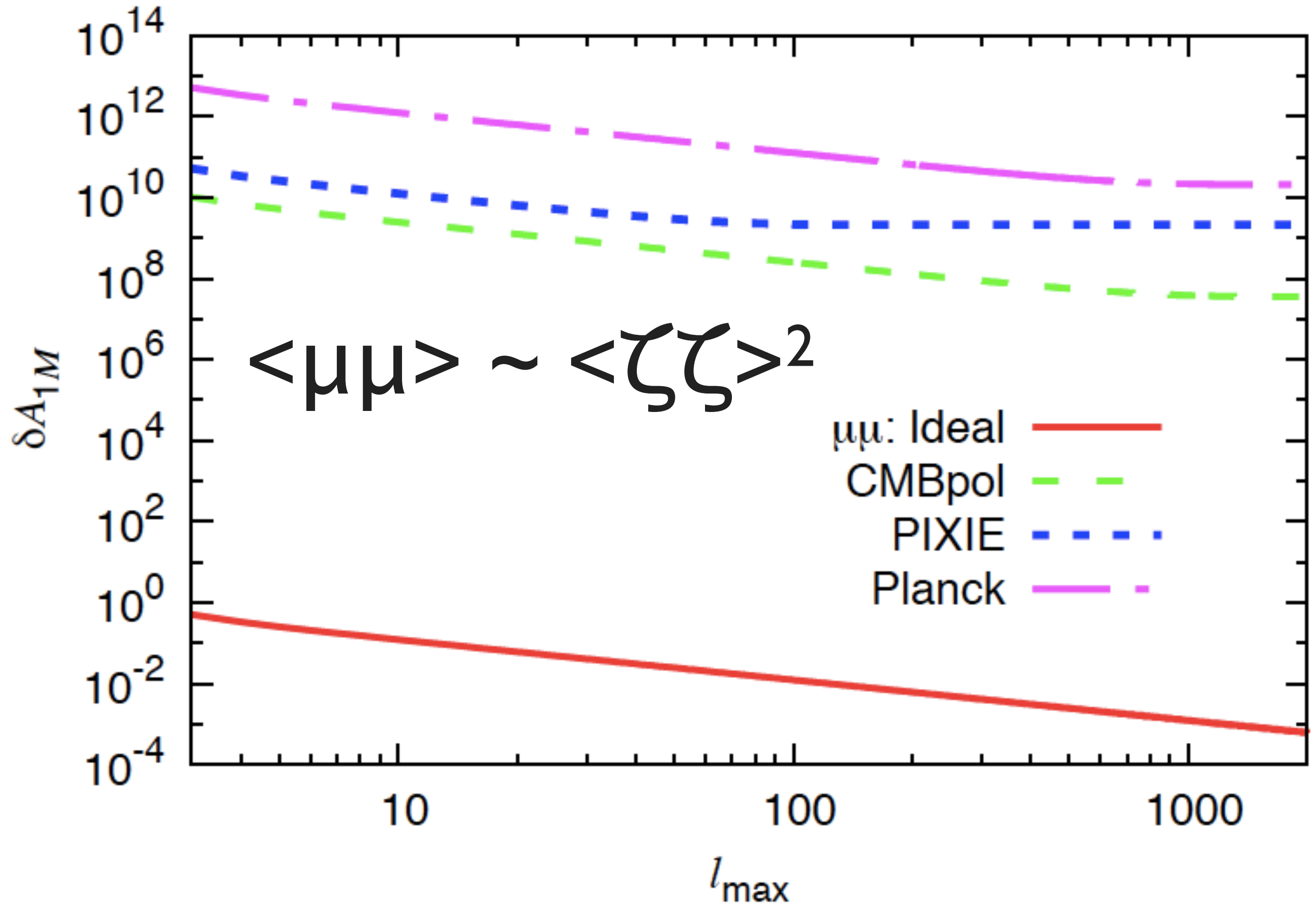
→ <Tμ> ~ <ζζζ>



off-diagonal components!

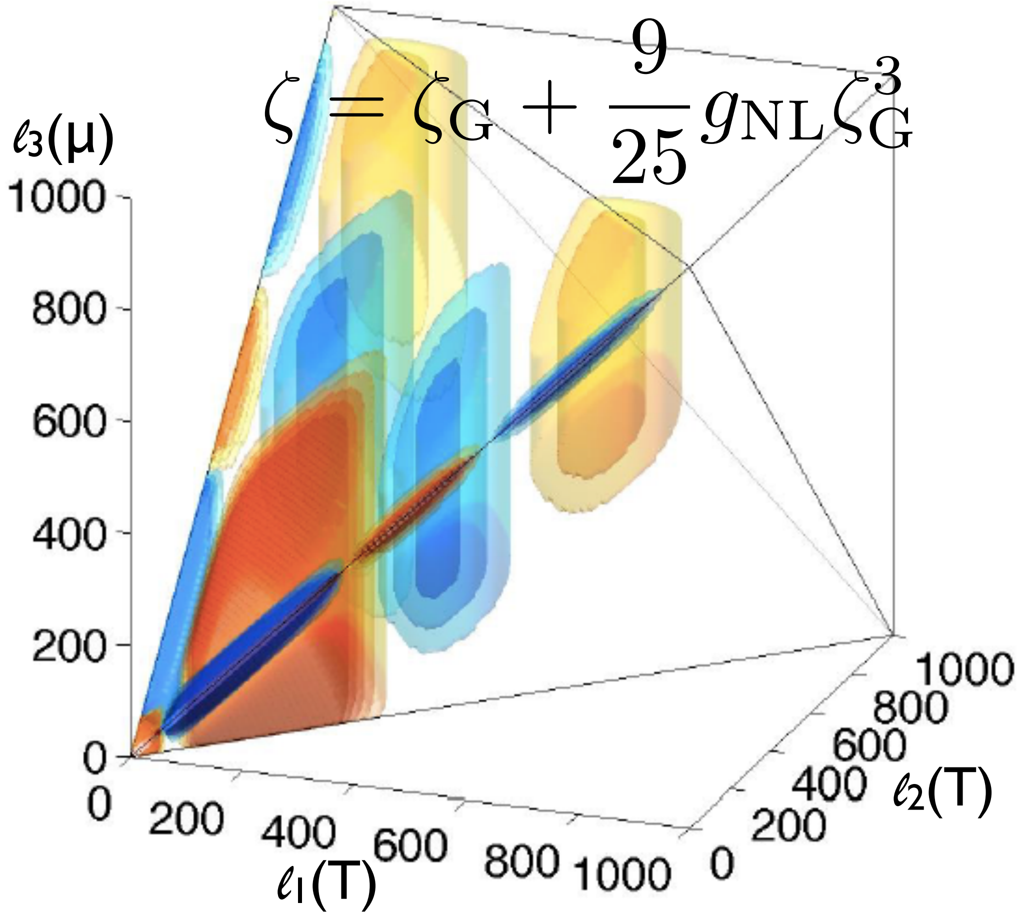
MS, Liguori, Bartolo, Matarrese: 1506.06670



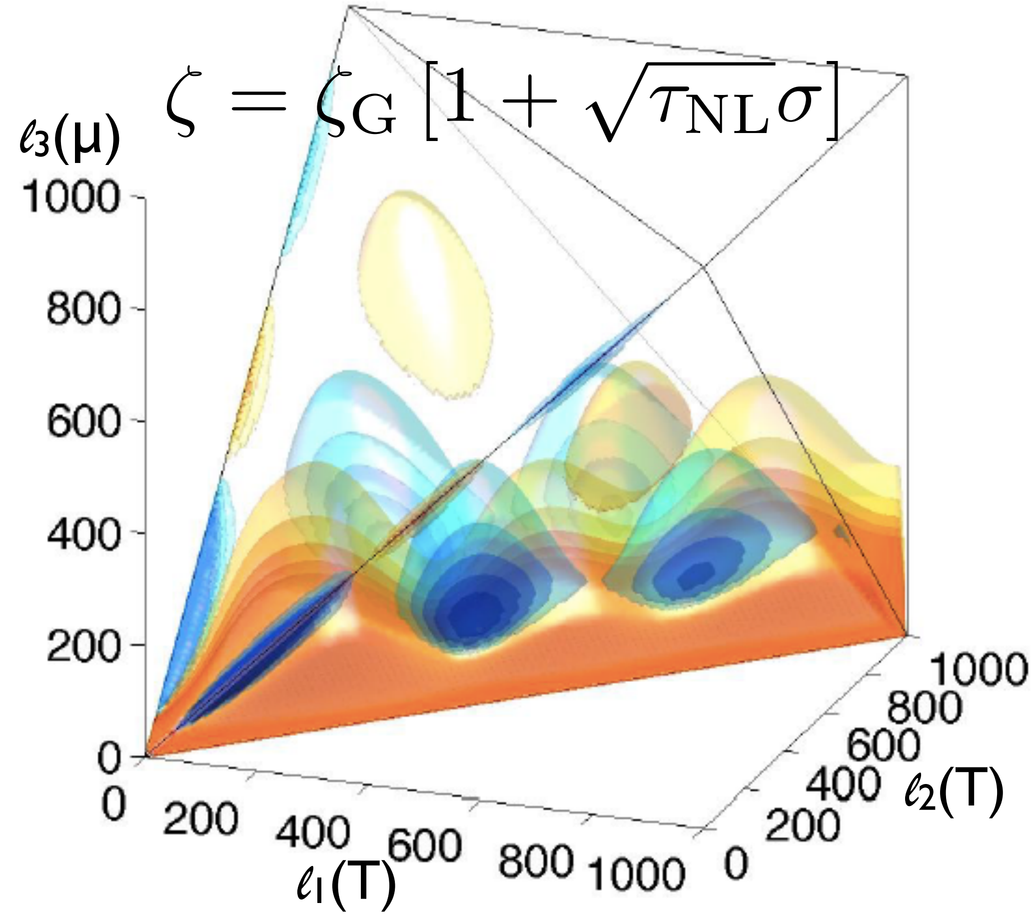


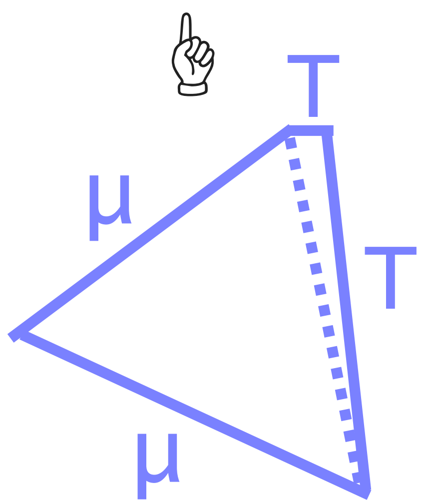
TTμ correlations   <TTμ> ~ <ζζζζ>

$$\zeta = \zeta_{\rm G} + \frac{9}{25} g_{\rm NL} \zeta_{\rm G}^3$$

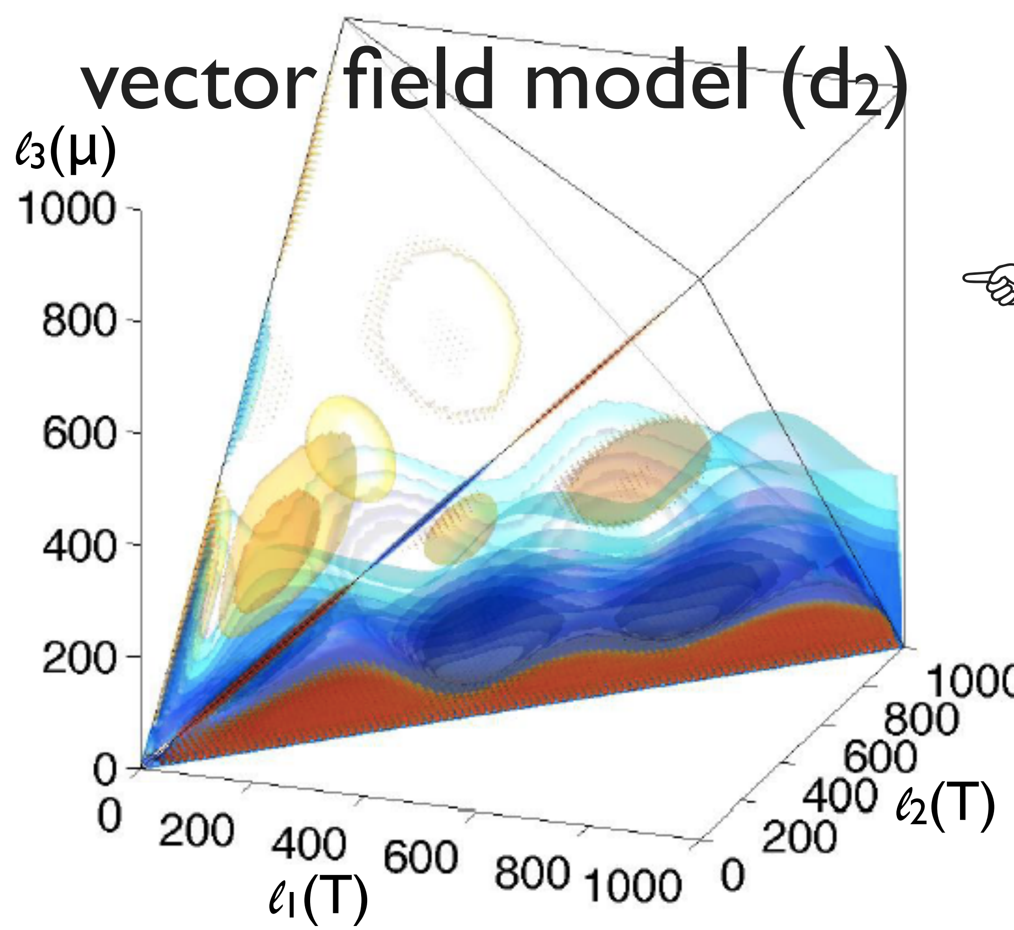


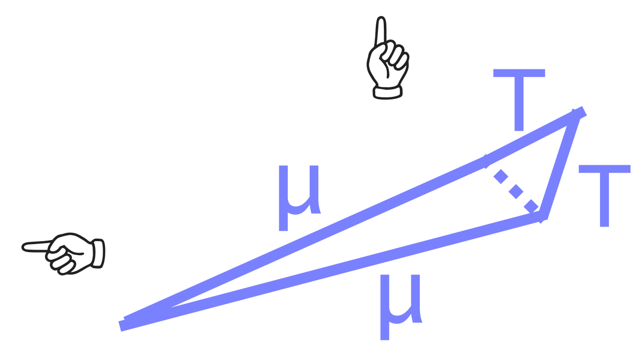
$$\zeta = \zeta_{\rm G} \left[1 + \sqrt{\tau_{\rm NL}}\sigma\right]$$





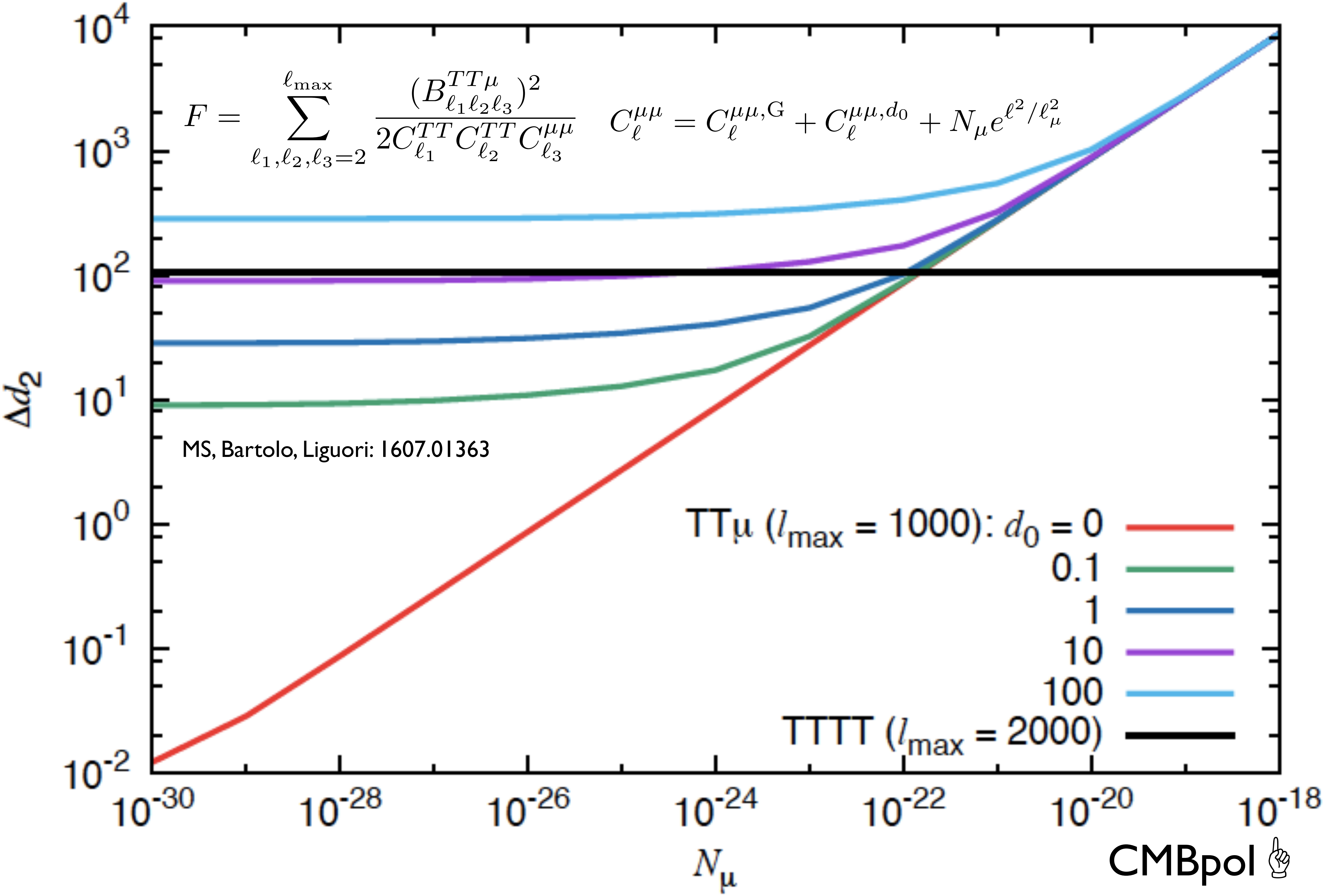
vector field model (d_2)





Bartolo, Liguori, MS: 1511.01474

MS, Bartolo, Liguori: 1607.01363


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

$f(k)$ g2M	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}

$f(k)$ AIM	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)	?