CMB lensing and primordial squeezed non-Gaussianity

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work with Antony Lewis & Donough Regan (arXiv: 1201.1010)

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Berkeley Cosmology seminar April 10th, 2012

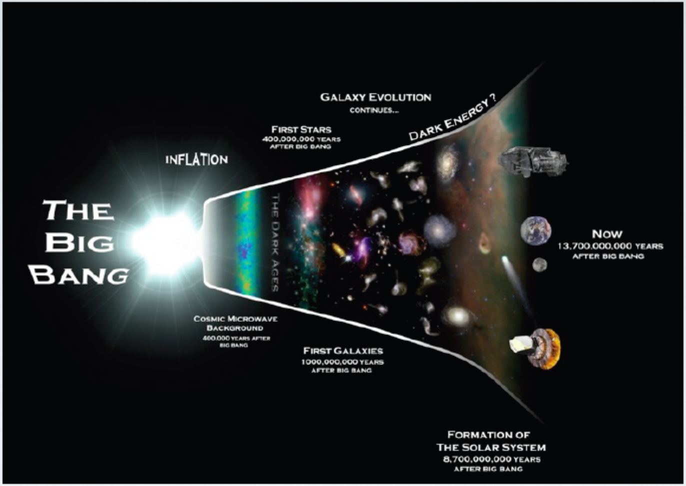
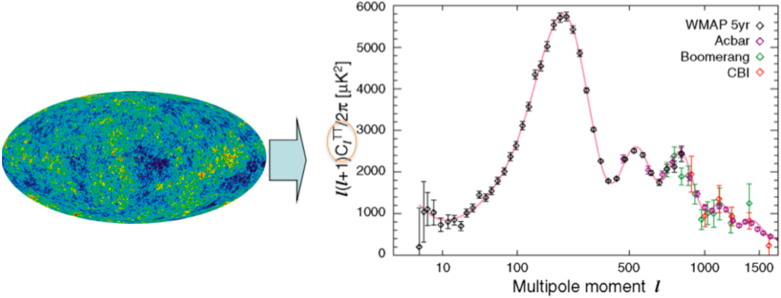


Image: http://planck.cf.ac.uk/

$$\Delta T(\hat{n}) = \sum_{lm} T_{lm} Y_{lm}(\hat{n})$$



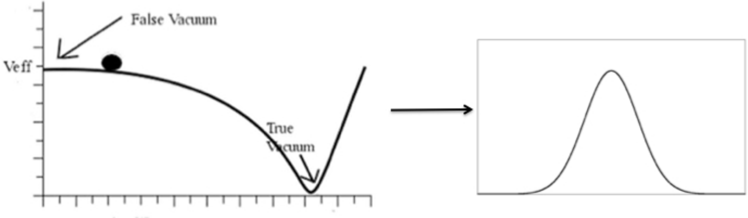
WMAP team

$$< T_{lm} T_{l'm'} >= \delta_{ll'} \delta_{mm'} C_l$$

μ=0

$$< T_{lm} T_{l'm'} T_{l''m''} >=< \cancel{T_{lm}} >< T_{l'm'} T_{l''m''} >= 0$$

Fix: horizon & flatness problem



- single scalar field
- canonical kinetic energy
- slow roll
- standard vacuum

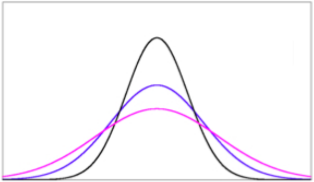
BREAK CONDITIONS $\longleftrightarrow$ NON-GAUSSIANITIES

Skewness - Bispectrum

$$\langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle = (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\Phi(k_1,k_2,k_3)$$

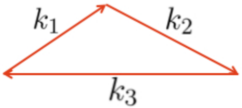
Kurtosis - Trispectrum

$$< \Phi(k_1)\Phi(k_2)\Phi(k_3)\Phi(k_4) > \neq 0$$



$$\Phi(k) \xleftrightarrow{\Delta_l(k)} T_{lm} = 4\pi(-i)^l \int d^3k \Delta_l(k) \Phi(k) Y_{lm}(k)$$

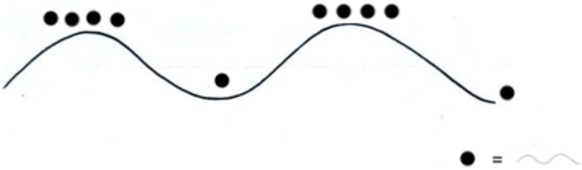
$$\langle \Phi(\mathbf{k}_1)\Phi(\mathbf{k}_2)\Phi(\mathbf{k}_3)\rangle = (2\pi)^3 \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B_\Phi(k_1, k_2, k_3) \qquad primordial$$

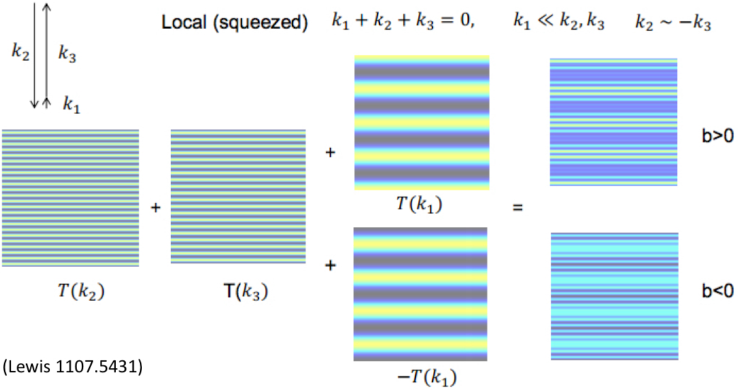


$$B_{l_1 l_2 l_3} \sim < T_{l_1 m_1} T_{l_2 m_2} T_{l_3 m_3} > \qquad CMB$$

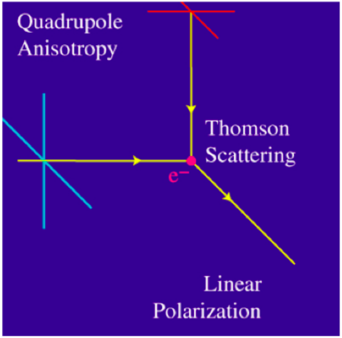
$$B(k_1, k_2, k_3) = 2f_{\rm NL}\left[P(k_1)P(k_2) + P(k_2)P(k_3) + P(k_3)P(k_1)\right]$$

$$\Phi = \Phi_L + f_{\rm NL}^{\rm local}\Phi_L^2$$

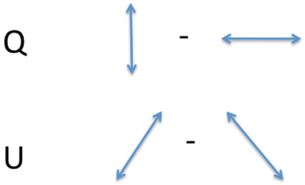




(Lewis 1107.5431)



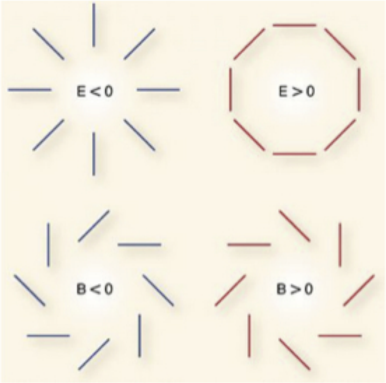
(Hu)

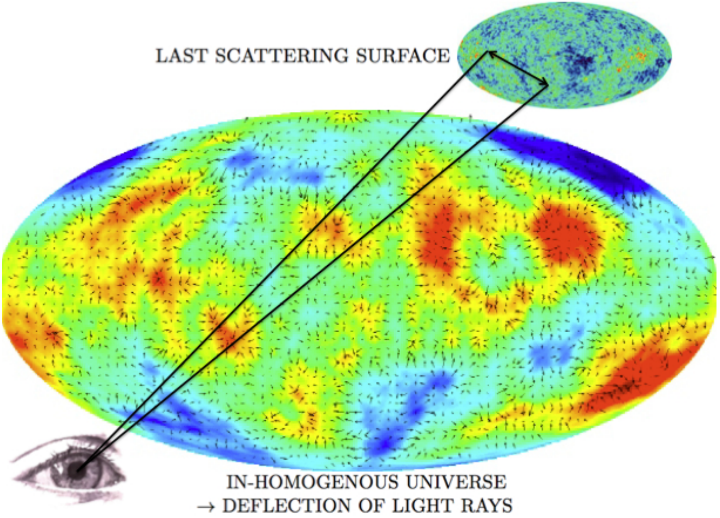


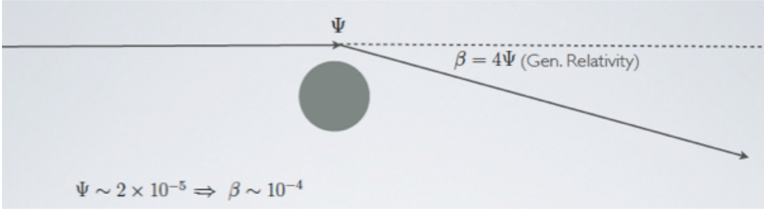
Detector measures EM radiation in plane $= I + Q \cos 2\phi + U \sin 2\phi$

Stokes' parameters

$$\text{observed Q, U} \rightarrow E, B$$

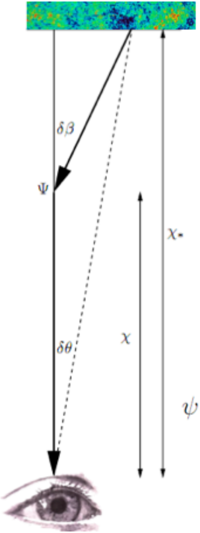



LAST SCATTERING SURFACE
IN-HOMOGENOUS UNIVERSE
→ DEFLECTION OF LIGHT RAYS



~ 50 clumps gives deflection $\sqrt{50} \times 10^{-4} \sim 2arcmin \rightarrow l \sim 3000$

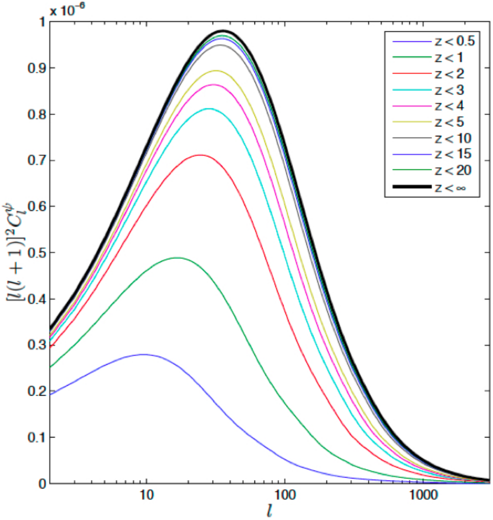
- Lensing dominates on small scales
- Lensing has $\sim 3\%$ effect on main acoustic peaks (degree scale)



$$\tilde{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}') = T(\hat{\mathbf{n}} + \boldsymbol{\alpha})$$

$$\alpha = \nabla_{\hat{n}} \psi(\hat{n})$$

$$\psi(\hat{\mathbf{n}}) \equiv -2 \int_0^{\chi_*} \mathrm{d}\chi \, \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{\mathbf{n}}; \eta_0 - \chi)$$

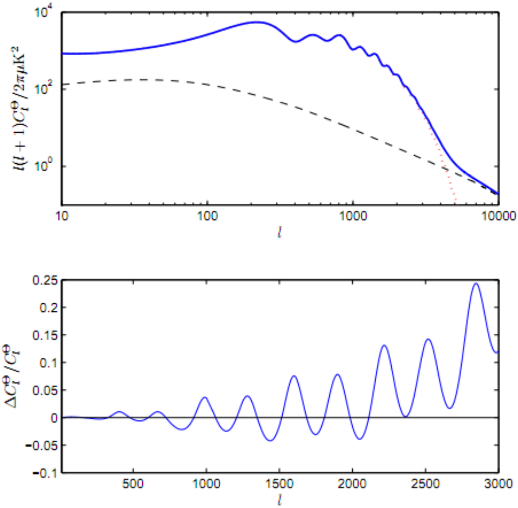


Probe 0.5 < Z < 6

Break degeneracies

Constrain parameters
(e.g. neutrino mass)

(Lewis 0601594, & all
unlabeled figures hereafter)

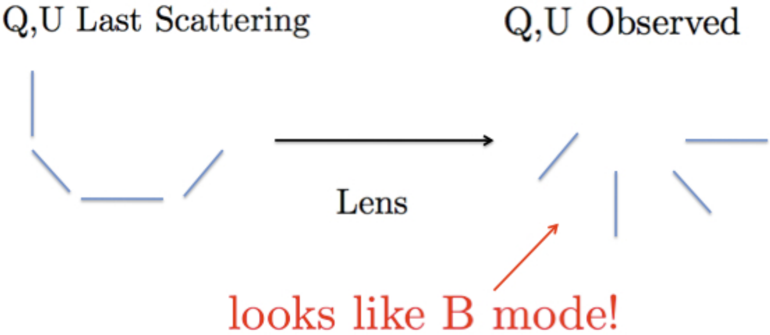

10^4
10^2
10^0
$l(l+1)C_l^\Theta/2\pi\mu K^2$
10
100
1000
10000
l
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
$\Delta C_l^\Theta/C_l^\Theta$
500
1000
1500
2000
2500
3000
l

perturbative

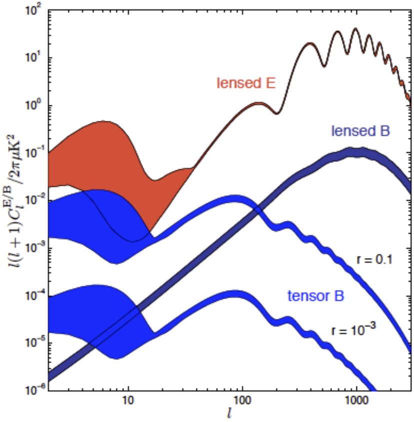
$$\tilde{\Theta}(\mathbf{x}) = \Theta(\mathbf{x}') = \Theta(\mathbf{x} + \nabla\psi)$$

$$\Big\downarrow \text{Taylor expand}$$

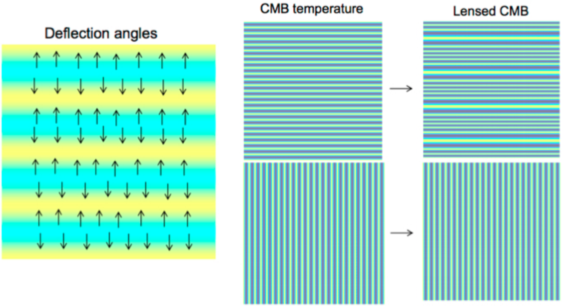
$$\tilde{C}_l^{\Theta} \approx C_l^{\Theta} + \int \frac{\mathrm{d}^2\mathbf{l}'}{(2\pi)^2} \left[\mathbf{l}' \cdot (\mathbf{l} - \mathbf{l}')\right]^2 C^{\psi}_{|\mathbf{l}-\mathbf{l}'|} C^{\Theta}_{l'} - C_l^{\Theta} \int \frac{\mathrm{d}^2\mathbf{l}'}{(2\pi)^2} (\mathbf{l} \cdot \mathbf{l}')^2 C^{\psi}_{l'}$$



$$\tilde{C}_l^B \neq 0 \quad \text{for primordial} \quad B(\mathbf{l}) = 0$$

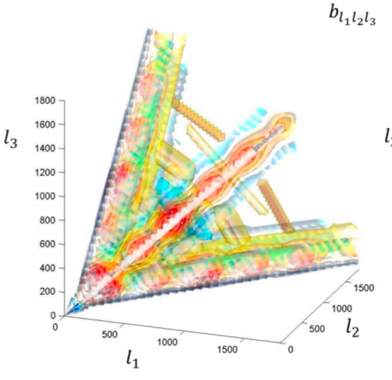

lensed E
lensed B
tensor B
r = 0.1
r = 10^-3
$l(l+1)C_l^{E/B}/2\pi\mu K^2$
l
10
100
1000

Lensing is anisotropic

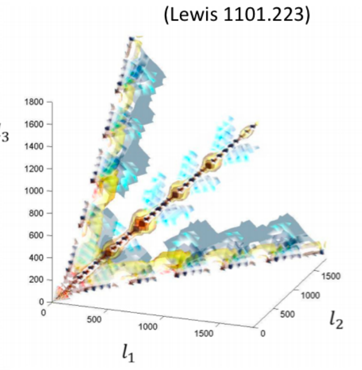


Large scale lenses correlated to temperature

⟶ Lensing induced bispectrum



Local f_{NL}



CMB lensing

How does lensing affect primordial squeezed non-Gaussianity?

$$\tilde{T}(\mathbf{l}) = \int \frac{d^2\mathbf{x}}{2\pi} T(\mathbf{x} + \boldsymbol{\alpha}) e^{-i\mathbf{l}\cdot\mathbf{x}} \longleftarrow \text{non-perturbative}$$

squeezed triangles with $l_1 \ll l_2, l_3$

large scale l_1 mode $\sim$ unlensed

$$\langle T(\mathbf{l}_1)\tilde{T}(\mathbf{l}_2)\tilde{T}(\mathbf{l}_3)\rangle \approx \langle \tilde{T}(\mathbf{l}_1)\tilde{T}(\mathbf{l}_2)\tilde{T}(\mathbf{l}_3)\rangle = \frac{1}{2\pi}\tilde{b}_{l_1 l_2 l_3}\delta(\mathbf{l}_1 + \mathbf{l}_2 + \mathbf{l}_3)$$

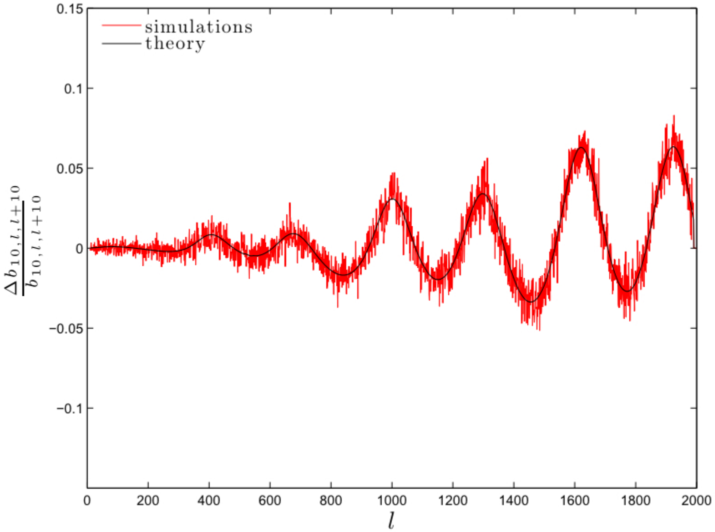
lensed bispectrum in terms of unlensed bispectrum

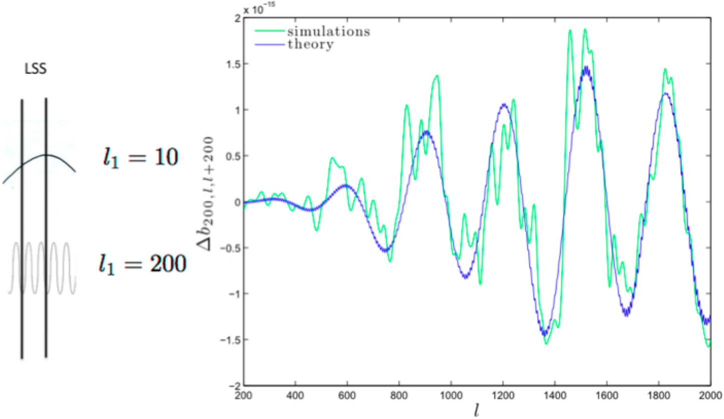
$$\tilde{b}_{l_1 l_2 l_3} \approx \int \frac{d^2\mathbf{r}}{2\pi}\frac{d^2\mathbf{l}'}{2\pi} b_{l_1 l'_2 l'_3} e^{i\mathbf{r}\cdot(\mathbf{l}'-\mathbf{l})} \exp\left(-\frac{l'^2}{2}[\sigma^2(r) + \cos 2\phi_{l'r} C_{\mathrm{gl},2}(r)]\right)$$

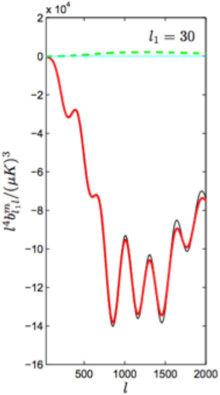
Lensed correlation functions
(see Lewis 0601594)

$$l_1, l \equiv |\mathbf{l}_3 - \mathbf{l}_2|/2, \phi_{ll_1} \qquad b_{l_1 l_2 l_3} = \sum_m \bar{b}^m_{l_1 l}\, e^{mi\phi_{ll_1}}$$

$$\tilde{b}^m_{l_1 l} \approx \int r dr J_m(lr) \int dl' l' b^m_{l_1 l'} e^{-l'^2\sigma^2(r)/2} \sum_n I_n[l'^2 C_{\mathrm{gl},2}(r)/2] J_{2n+m}(l'r)$$


simulations
theory
0.15
0.1
0.05
0
−0.05
−0.1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
l
$\frac{\Delta b_{10,l,l+10}}{b_{10,l,l+10}}$

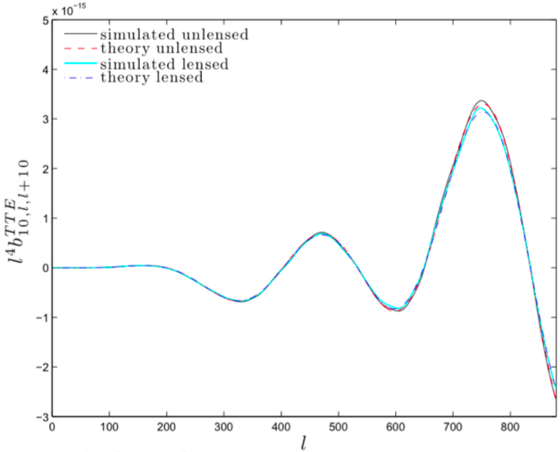

LSS
$l_1 = 10$
$l_1 = 200$
x 10^-15
simulations
theory
$\Delta b_{200,l,l+200}$
l



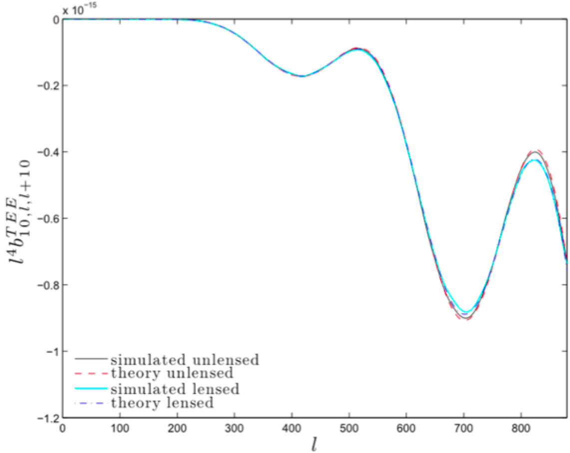
Full sky, $l_{max} = 2000$, no noise full sky b_{l_1,l_2,l_3} :

$\sim 96\%$ correlated $m = 0$

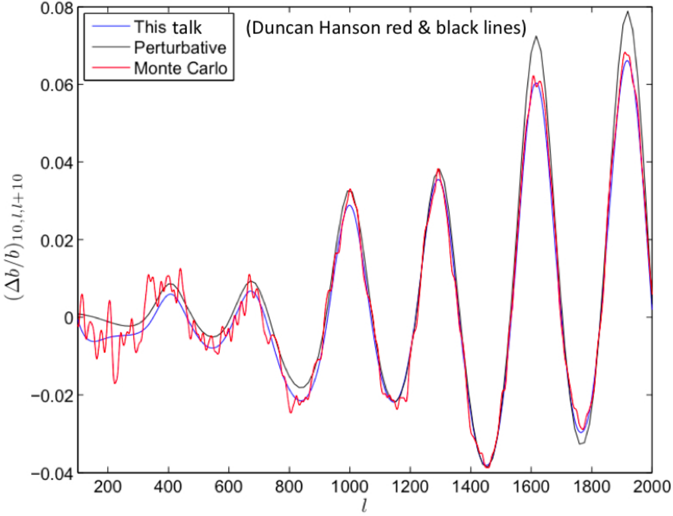
$\sim 99\%$ correlated $m = 0$ and $m = 2$



$$\tilde{b}^{(XTE)m}_{l_1 l} \approx \frac{1}{2}\int r dr \int dl' l' b^{(XTE)m}_{l_1 l'} e^{-l'^2\sigma^2(r)/2} \sum_n I_n[l'^2 C_{\mathrm{gl},2}(r)/2]$$
$$\times [J_{2n+m+2}(l'r)J_{m+2}(lr) + J_{2n+m-2}(l'r)J_{m-2}(lr)]$$



$$\tilde{b}^{(XEE)m}_{l_1 l} \approx \frac{1}{4}\int r dr \int dl' l' b^{(XEE)m}_{l_1 l'} e^{-l'^2\sigma^2(r)/2} \sum_n I_n[l'^2 C_{\mathrm{gl},2}(r)/2]$$
$$\times\, [2J_{2n+m}(l'r)J_m(lr) + J_{2n+m+4}(l'r)J_{m+4}(lr) + J_{2n+m-4}(l'r)J_{m-4}(lr)]$$


This talk
Perturbative
Monte Carlo
(Duncan Hanson red & black lines)
0.08
0.06
0.04
0.02
0
−0.02
−0.04
$(\Delta b/b)_{10,l,l+10}$
200
400
600
800
1000
1200
1400
1600
1800
2000
l

Measuring non-zero primordial non-Gaussianity can constrain models of inflation

Quick and accurate approximation of lensing effect on squeezed primordial non-Gaussianity

Change in primordial squeezed shape can be $\gtrsim 10\%$ due to lensing

But neglecting lensing smoothing does not significantly bias estimators