Hints of new physics in the CMB spectra

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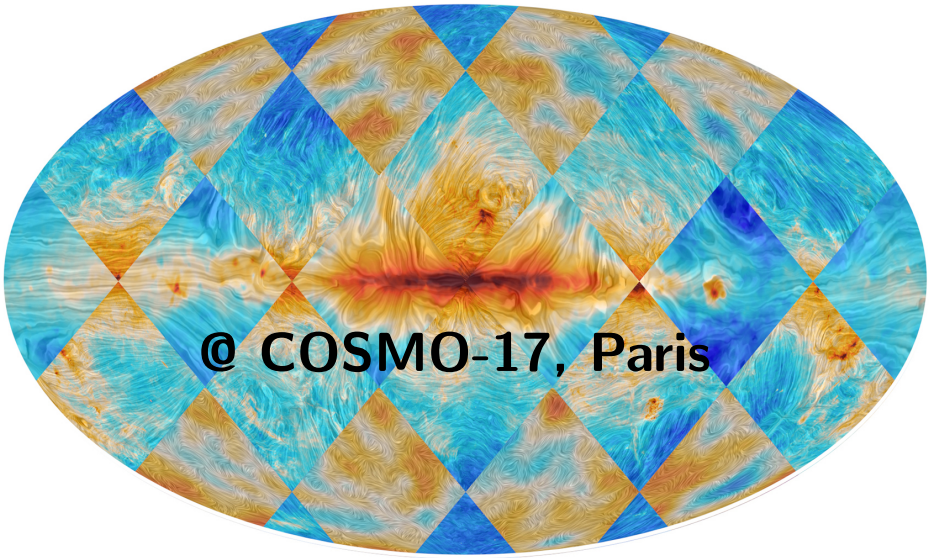


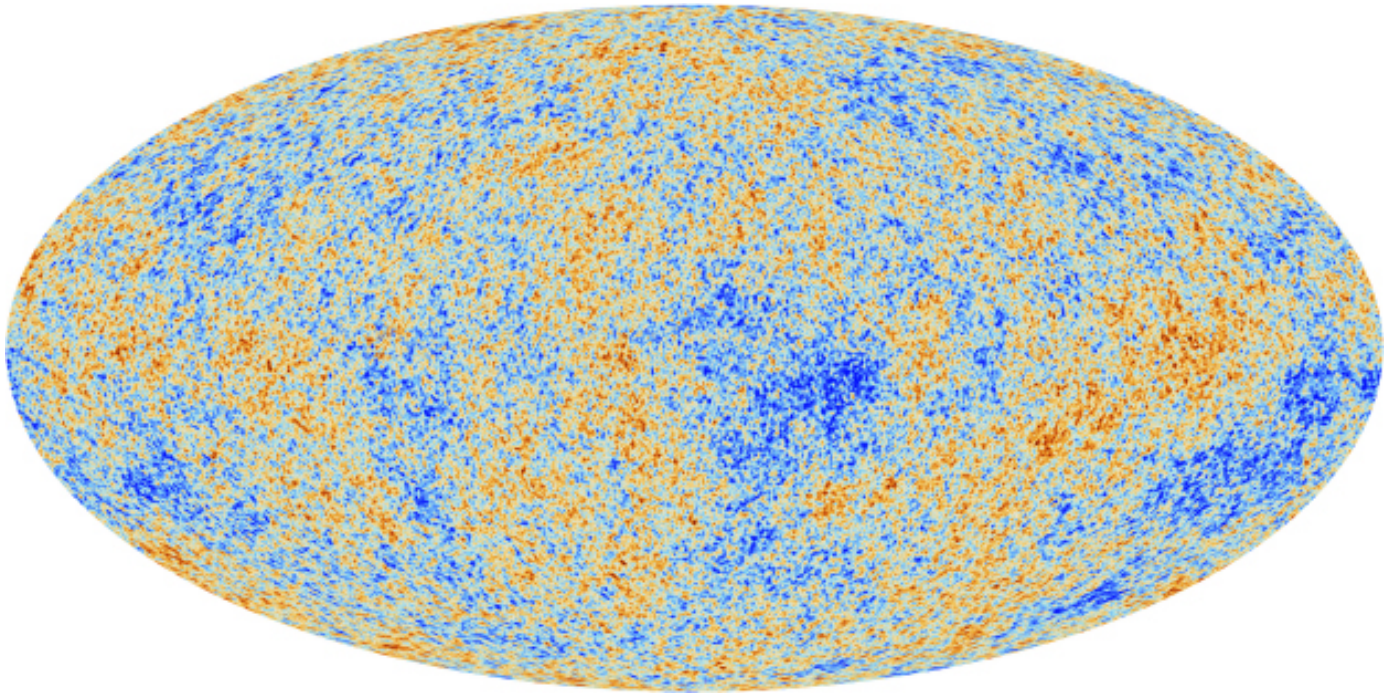
Based on

1512.08977 (PLB), 1612.09253 (PRD), 1702.08756 (JCAP), 1709.xxxxx

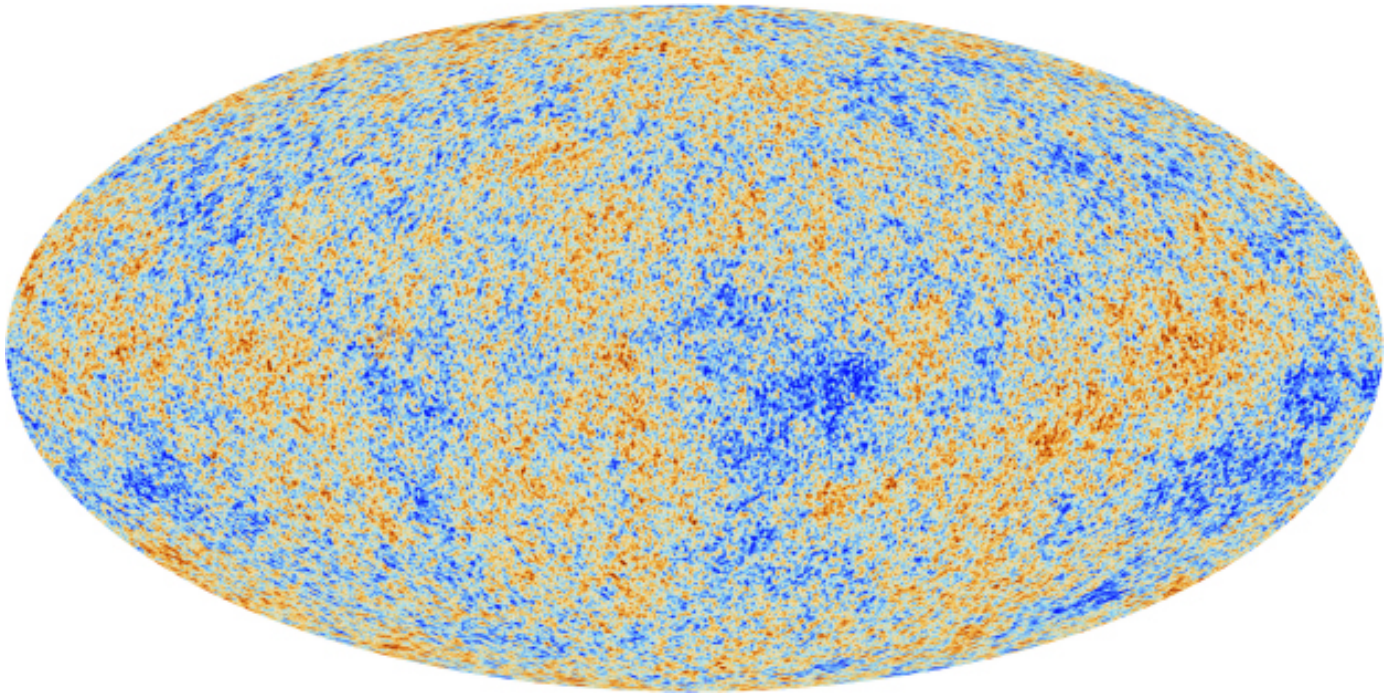
in collaboration with:

Jinn-Ouk Gong, Gonzalo Palma, Domenico Sapone, Stephen Appleby, Dhiraj Hazra, Arman Shafieloo, Wálter Riquelme and Bastián Pradenas

Outline

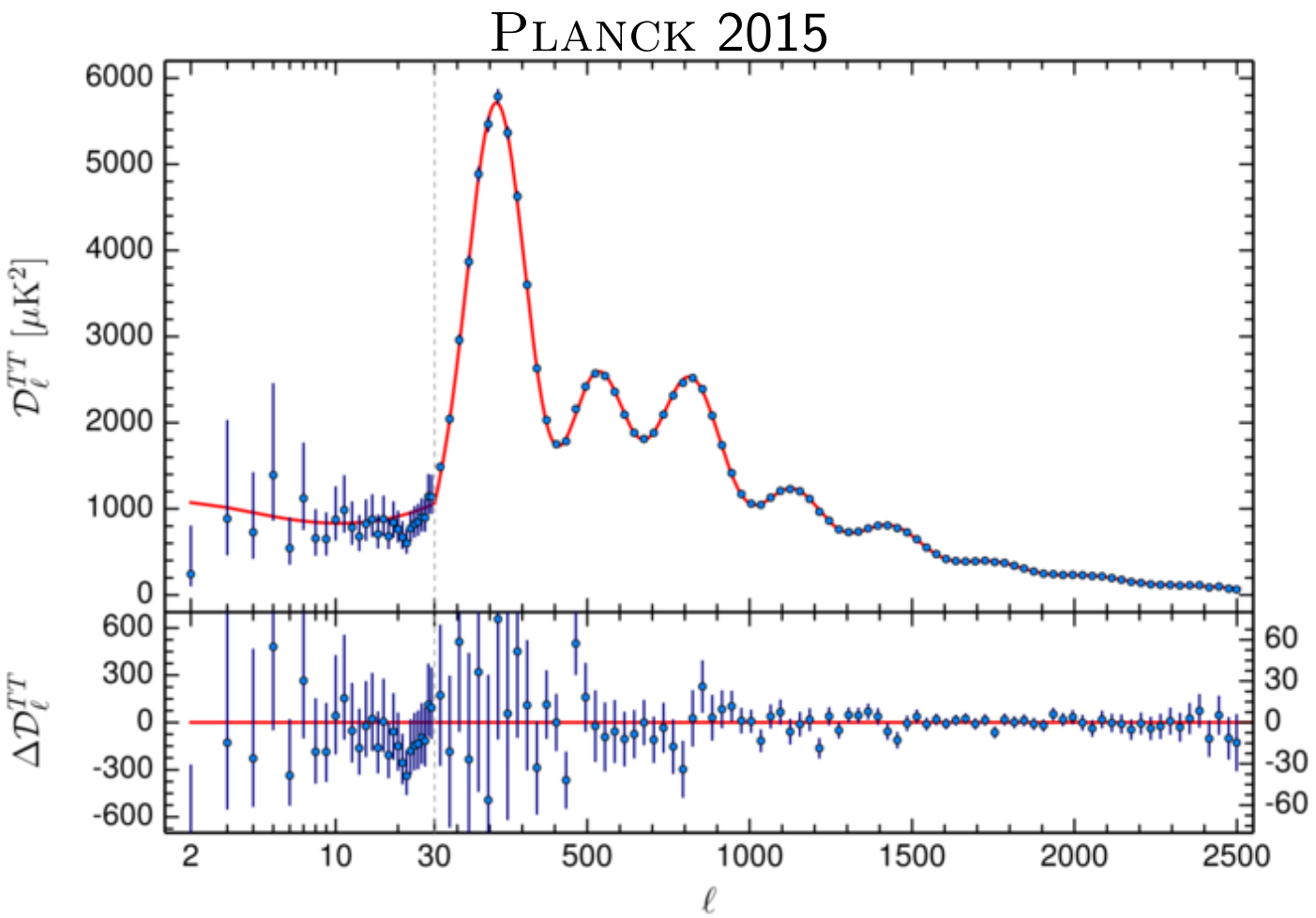


⋆ **Fact:** CMB temperature anisotropies follow nearly scale invariant, almost Gaussian statistics (Consistent with ΛCDM)

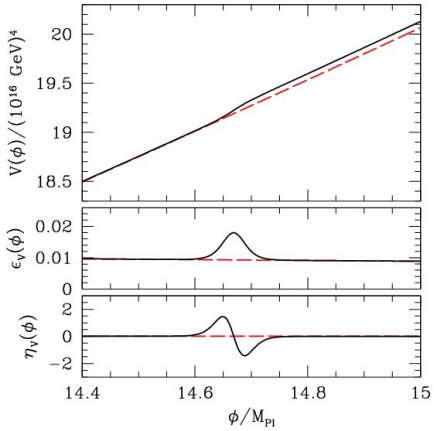


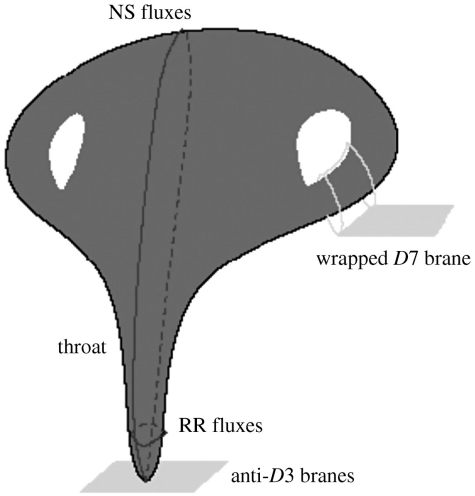
- ⋆ **Fact:** CMB temperature anisotropies follow nearly scale invariant, almost Gaussian statistics (Consistent with ΛCDM)
- ⋆ **Question:** Is there evidence of small deviations?

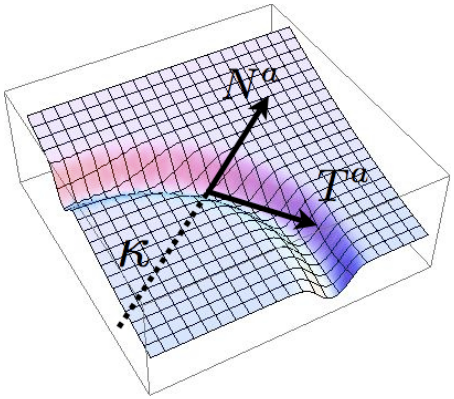
From the observational side

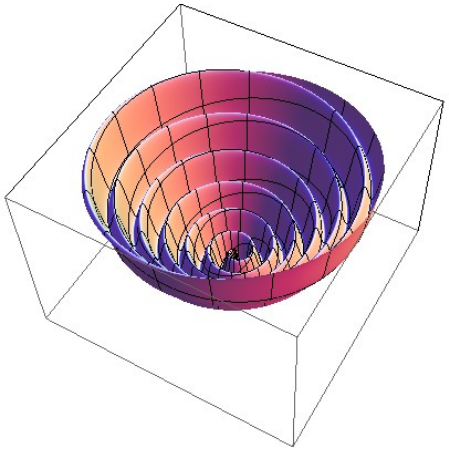


From the theoretical side

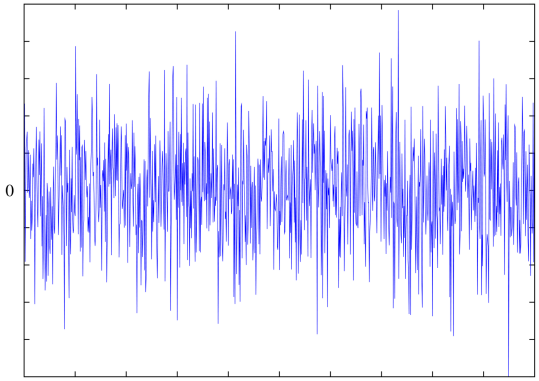






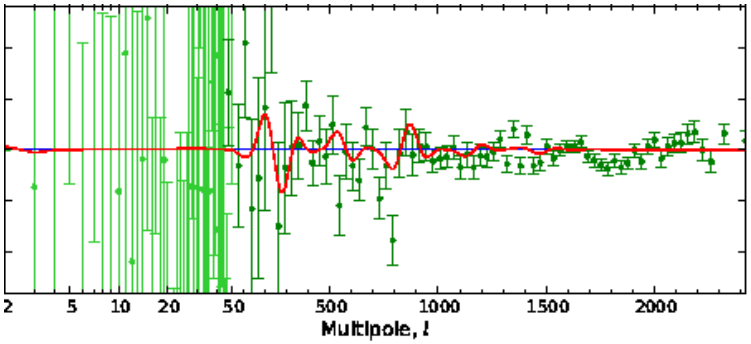


Is that noise?

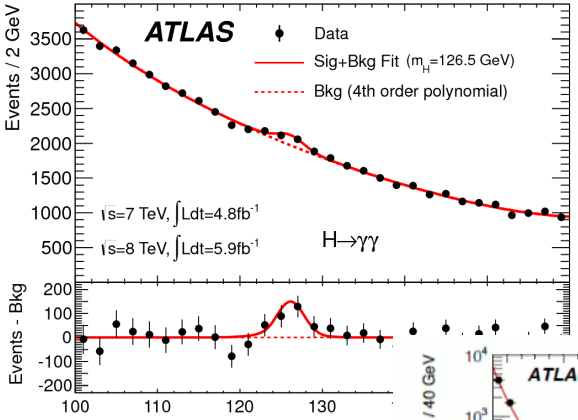


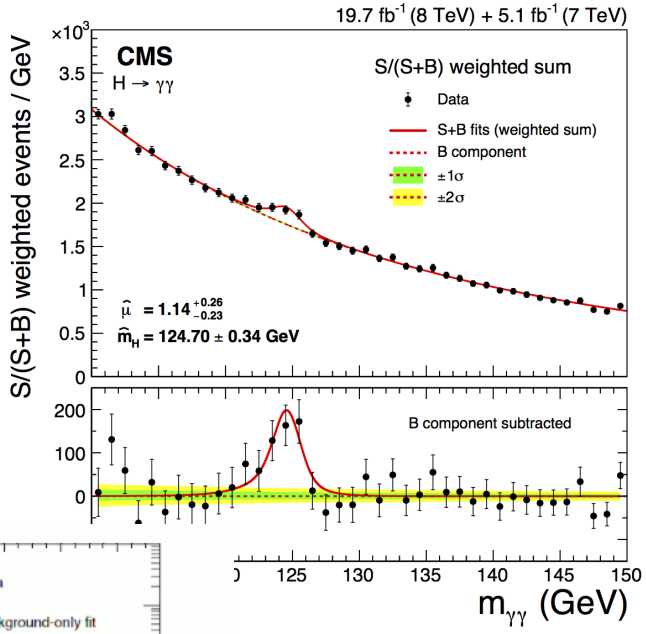
Check different channels!

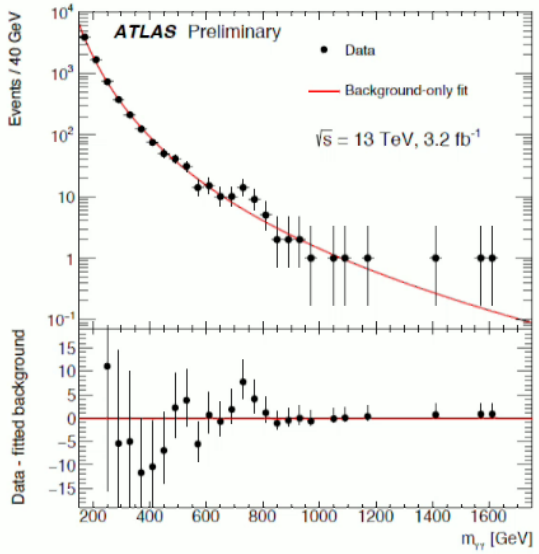
Or signal?



Bumps in other data sets:







The aim is to...

see how **features** in the scalar power spectrum (data) propagate to other spectra:

- ⋆ Bispectrum/Power spectrum correlation
- ⋆ Bispectrum/Bispectrum correlation
- ⋆ Tensor/Scalar power spectrum correlation
- ⋆ Galaxy clustering/Weak lensing power spectra

General Idea

1. Split the theory into slow-roll/fast parts
2. Compute the fast corrections via in-in formalism / de Sitter mode function $\Rightarrow$ Fourier integrals
3. Invert

$$\Delta\mathcal{S}_i = \mathcal{S}_i(A) \qquad \& \qquad \Delta\mathcal{S}_j = \mathcal{S}_j(A)$$

$$\boxed{\Delta\mathcal{S}_i(A) \to A(\Delta\mathcal{S}_i) \to \Delta\mathcal{S}_j(\Delta\mathcal{S}_i)}$$

Bispectrum/Power Spectrum Correlation

The bispectrum template reads

Appleby/Gong/Hazra/Shafieloo/SS '15,

Palma '14

$B(P)$ with $k_1 = k,\ k_2 = xk,\ k_3 = yk$

$$B_{\mathcal{R}}(k_1, k_2, k_3) \propto \left[\left(1 + x^2 + y^2\right)\frac{x + y + xy}{16} + \frac{x^2 + y^2 + (xy)^2}{8} - \frac{xy}{8}\right](1 - n_{\mathcal{R}}) + \frac{xy}{8}\alpha_{\mathcal{R}}$$

The power spectrum is hidden in

$$1 - n_{\mathcal{R}} = d\log P_{\mathcal{R}}/d\log k$$

and

$$\alpha_{\mathcal{R}} = d^2\log P_{\mathcal{R}}/d\log k^2$$

Prediction of $f_{\rm NL}^{\rm sq,eq}$

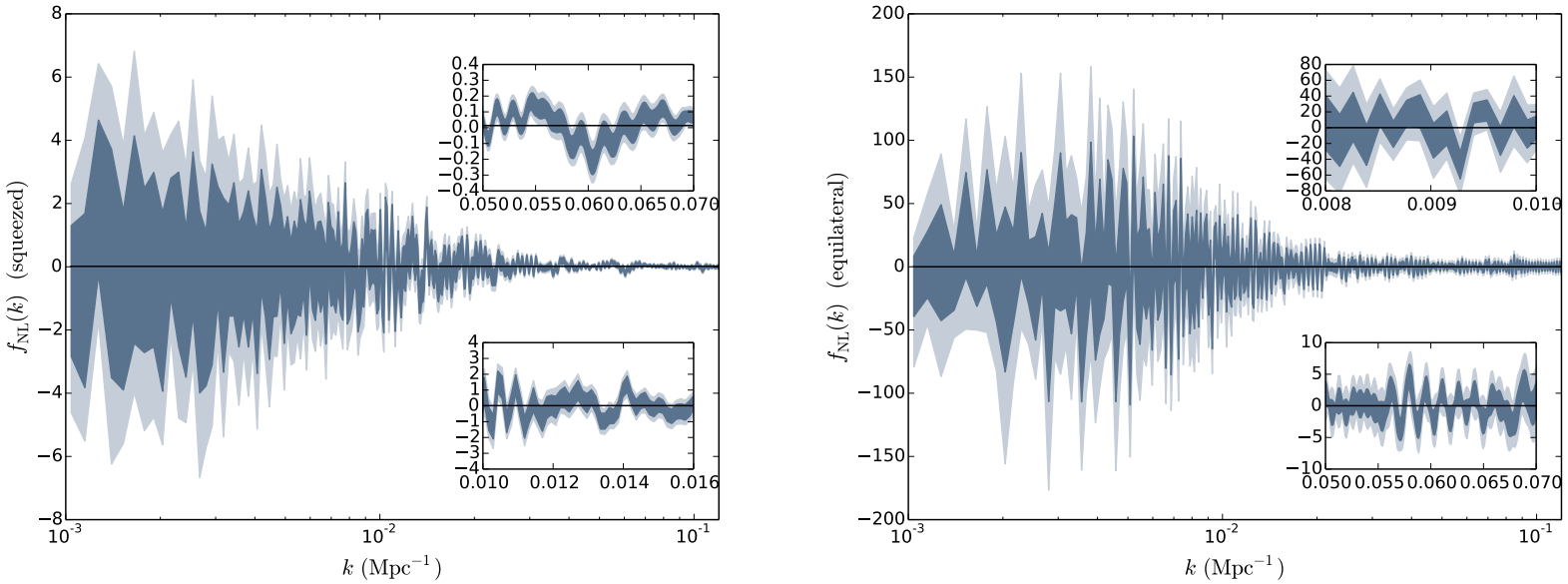


Figure: $f_{\rm NL}$ in the (left) squeezed and (right) equilateral limit. The dark (light) band encloses 68% (95%) of the reconstructed $\mathcal{P}_{\mathcal{R}}$. The plot covers the entire range considered in this work, $k = (10^{-3}, 0.12)$ Mpc^{-1}. The inset plots exhibit certain k-bands of interest.

Prediction of $f_{\rm NL}$

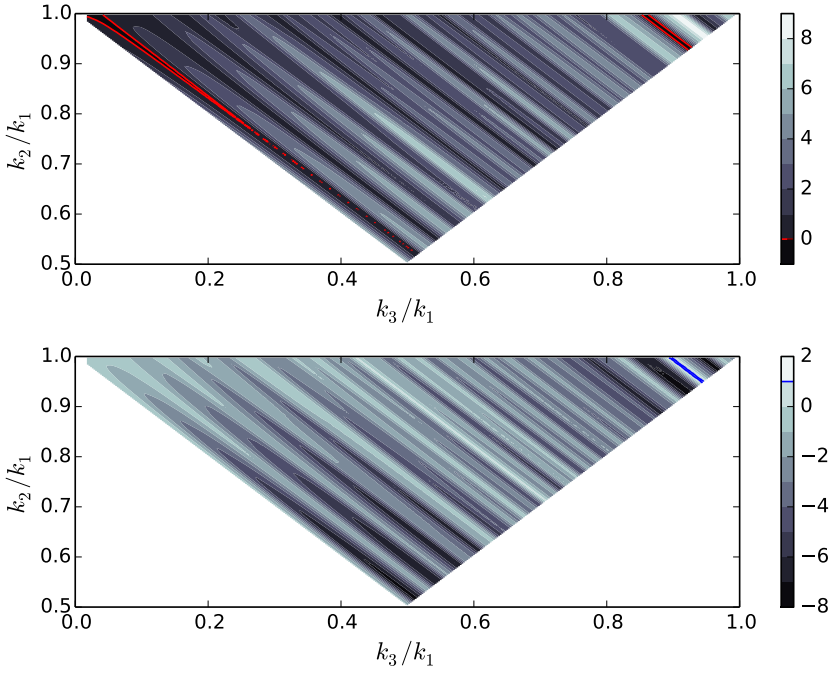


Figure: Heat maps of $f_{\rm NL}^{+2\sigma} - f_{\rm NL}^{\rm fid}$ (top) and $f_{\rm NL}^{-2\sigma} - f_{\rm NL}^{\rm fid}$ (bottom) as a function of k_3/k_1 and k_2/k_1, with $k_1 = 0.06{\rm Mpc}^{-1}$. Regions of interest are $f_{\rm NL}^{+2\sigma} - f_{\rm NL}^{\rm fid} < 0$ and $f_{\rm NL}^{-2\sigma} - f_{\rm NL}^{\rm fid} > 0$, red (blue) contours in the top (bottom) panel, indicating areas where the featureless expectation value lies outside the 95% contours.

Bispectrum Consistency Relations (Jinn-Ouk's talk)

Using these methods we can also produce 3-point consistency relations for a generic situation where there are features in both the potential and kinetic terms of the scalar perturbations

$$S_3 \supset \int d^4x a^3 \epsilon m_{\rm Pl}^2 \left[c_1 \dot{\mathcal{R}}^2 \mathcal{R} + \frac{c_2}{a^2} \mathcal{R} (\nabla \mathcal{R})^2 \right]$$

After computing with in-in and inverting with Fourier we get

$$\int_{-\infty}^{\infty} dk e^{-i(1+x+y)k\tau} \frac{S_{\mathcal{R}}(k,x,y)}{(2\pi)^4} k \frac{8}{2\pi i} = \frac{(1+x^2+y^2)}{2(xy)^2(1+x+y)^4} (c_2\tau)''' - \frac{(x+y+xy)}{(xy)^2(1+x+y)^4} (c_1\tau)'''$$

Main idea:

we may now fix 2 triangle configurations, solve the algebraic system for c_1, c_2, and plug them back to the bispectrum

An example of the concistency relation

In general: Gong/Palma/SS '17

Any 3 measurments of S at $\vec{k}$,$\vec{q}$,$\vec{p}$ are related:

$$S_{\mathcal{R}}(k, xk, yk) = A_{\vec{x}|\vec{x}_1\vec{x}_2} S_{\mathcal{R}}\left(\omega_1 k, x_1 k, y_1 k\right) + B_{\vec{x}|\vec{x}_1\vec{x}_2} S_{\mathcal{R}}\left(\omega_2 k, x_2 k, y_2 k\right)$$

Example: Equilateral/Flattened

$$S_{\mathcal{R}}(k,x,y) = \frac{18(x+y+xy) - 15(1+x^2+y^2)}{(1+x+y)^2} S_{\mathcal{R}}\left(\frac{1+x+y}{3}k, 1, 1\right) - 16\frac{x+y+xy-(1+x^2+y^2)}{(1+x+y)^2} S_{\mathcal{R}}\left(\frac{1+x+y}{2}k, 1/2, 1/2\right)$$

Bispectrum Featured Templates

Inspired by the form of the consistency relation we can construct templates for the featured bispectrum:

$$\begin{aligned} S_{\mathcal{R}}(k,x,y) =& S_{\alpha_1,\alpha_2}(x,y)\sin[\omega_1 k(1+x+y)+\phi] \\ &+ S_{\beta_1,\beta_2}(x,y)\sin[\omega_2 k(1+x+y)+\phi] \end{aligned}$$

where

$$S_{\alpha_i,\beta_i}(x,y) \supset S_{\rm eq}, S_{\rm ortho}, S_{\rm flat}$$

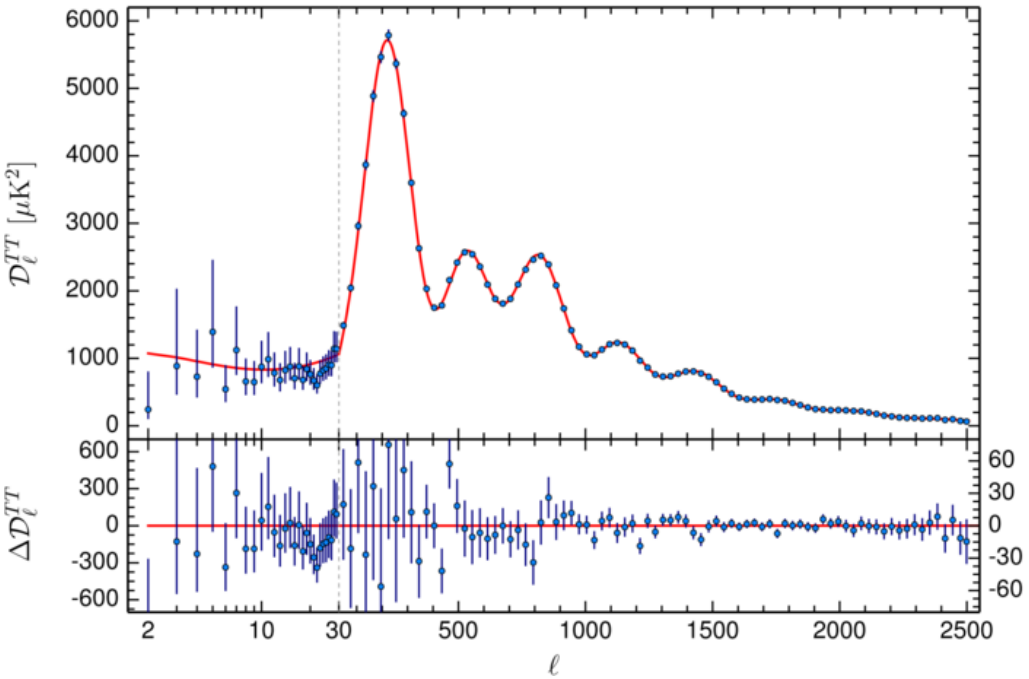
Multifrequency distribution favoured from Planck data.

We can play the same game for the tensor power spectrum:

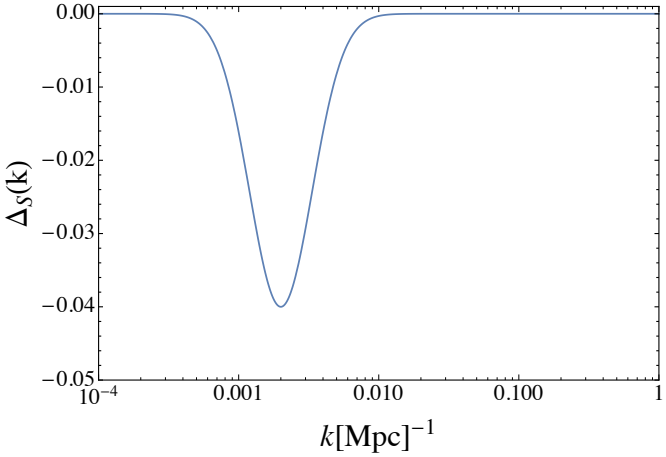
Result:

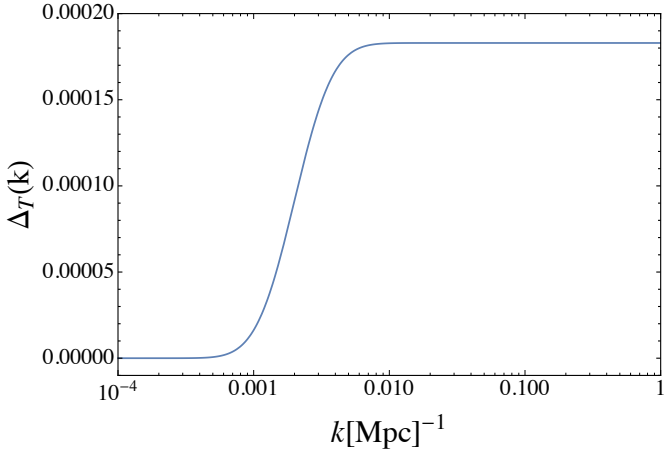
$$\frac{\Delta\mathcal{P}_T}{\mathcal{P}_0} = -6 \iint d\ln k \;\; \epsilon \frac{\Delta\mathcal{P}_S}{\mathcal{P}_0}$$

Palma/Pradenas/Riquelme/SS '16

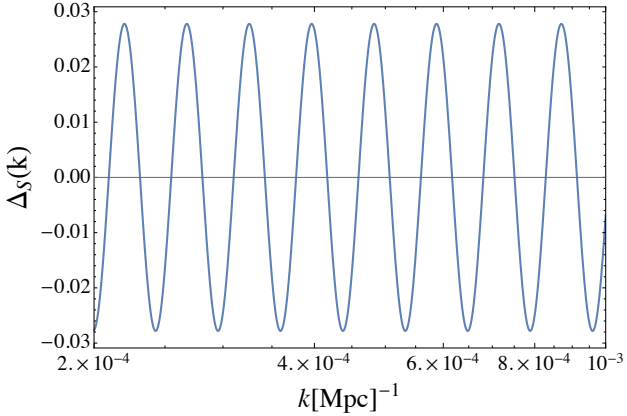


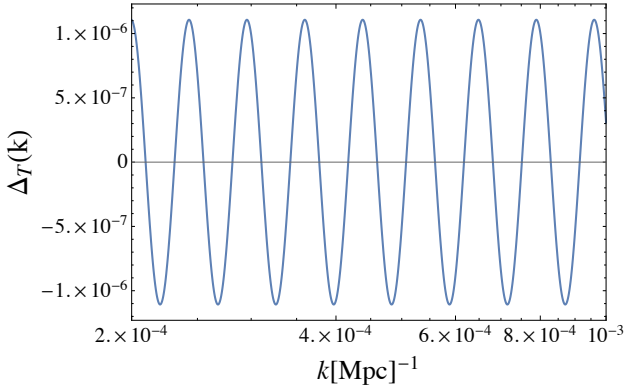
Gaussian feature





Resonant feature





Late time spectra

Matter Power Spectrum

$$P_r(z;\ k) = P_{\mathcal{R}} \times P_m(z;\ k)$$

Galaxy Clustering Power Spectrum

$$P^{\rm spec}_{\gamma\gamma}(z, k_r, \mu_r) = \frac{D^2_{Ar}(z)H(z)}{D^2_A(z)H_r(z)} b(z)^2 \left(b\sigma_8(z) + f\sigma_8(z)\mu^2\right)^2 \frac{P_r(z;\ k)}{\sigma_8^2(z)} + P_{\rm shot}$$

Weak Lensing Power Spectrum

$$P_{\kappa,ij}(\ell) = \int_0^{\chi_H} \frac{d\chi}{\chi^2}\, W_{\kappa,i}(\chi) W_{\kappa,j}(\chi)\, P_{\rm NL}(\chi;\ k = \ell/\chi)$$

Featured templates

$$\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = C\sin\left[\frac{2k}{k_f}+\phi\right] \quad \text{(turns)}$$

$$\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = C\sin\left[\Omega\log(2k)+\phi\right] \quad \text{(axions)}$$

$$\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = \exp\left\{f(k)\right\}-1 \quad \text{(step)}$$

$$f(k) = C\left[\left(-3+\frac{9k_f^2}{k^2}\right)\cos(2k/k_f)+\left(15-\frac{9k_f^2}{k^2}\right)\frac{\sin(2k/k_f)}{2k/k_f}\right]\frac{k/k_d}{\sinh(k/k_d)}$$

$$\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = C\left(\frac{\pi e}{3}\right)^{\frac{3}{2}}\left(\frac{k}{k_d}\right)^3 e^{-\frac{\pi}{2}\left(\frac{k}{k_d}\right)^2} \quad \text{(particle production)}$$

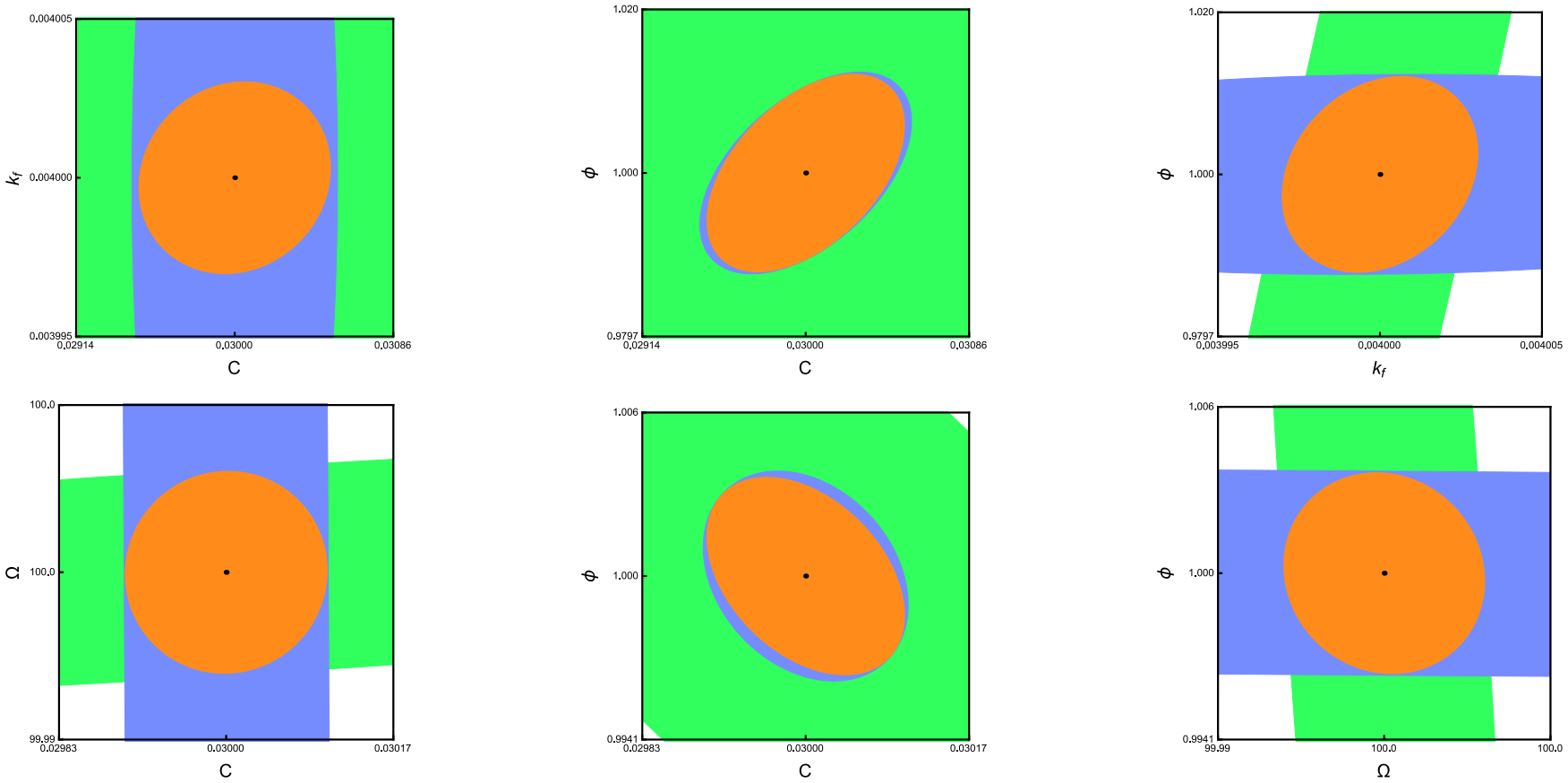
$$\frac{\Delta\mathcal{P}}{\mathcal{P}_0}(k) = \left[\sin(2k/k_f)+\frac{k_f}{k}\cos(2k/k_f)\right]D(k)-\frac{1}{2}\frac{k_f^2}{k}\sin(2k/k_f)\frac{d}{dk}D(k) \quad \text{(heavy fields)}$$

$$D(k) = \frac{4\sqrt{\pi}C}{36}\frac{k}{k_d}\exp\left\{-\frac{k^2}{k_d^2}\right\}$$

with $\mathcal{P}_0(k) = A_s\left(\frac{k}{k_0}\right)^{n_s-1}$

CMB + WL + GC

Palma/Sapone/SS '17 (prelim)



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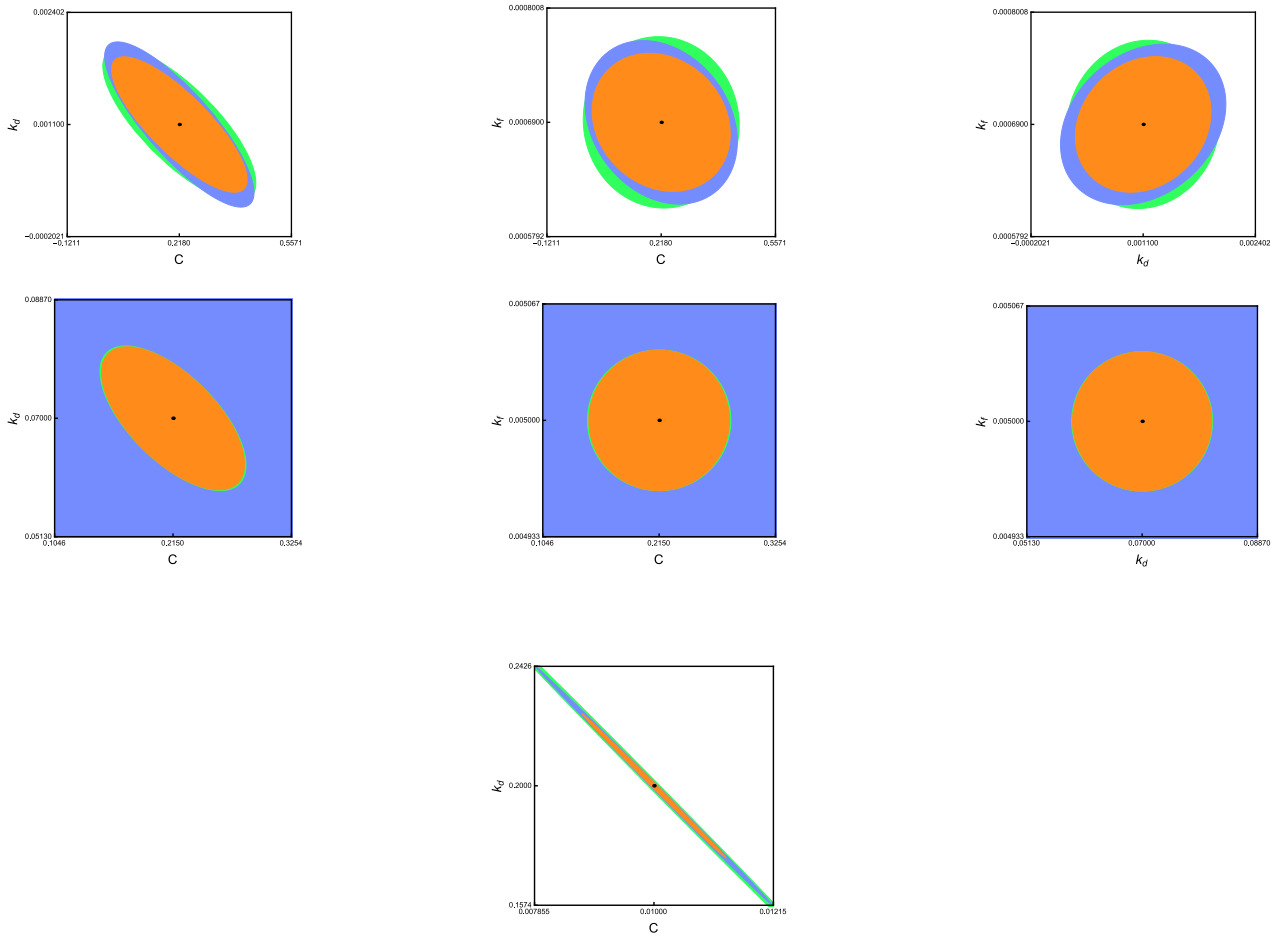


Conclusions

Features are present in Planck/Wmap and well motivated theoretically. We should look for them in different observables

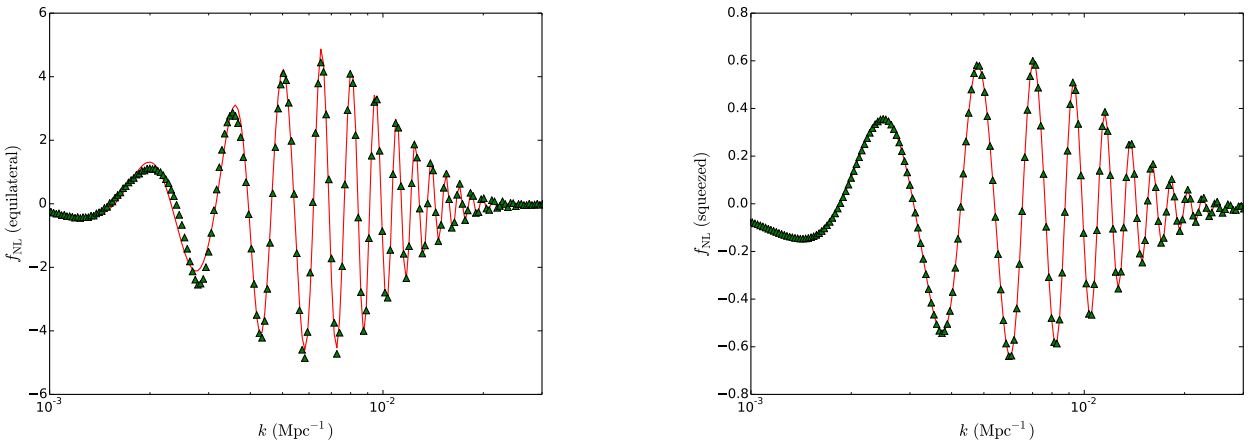
- ⋆ Propagation of features in the bispectrum (potential features)
- ⋆ Consistency relations/templates for the featured bispectrum
- ⋆ Propagation of features in the tensor power spectrum: persistence of scale invariance
- ⋆ Propagation of features in the late-time power spectra: LSS forecasts

Future directions

- ⋆ This is a tool to produce multiple templates for any n-point function
- ⋆ Features in late-time observables: matter bispectrum?

Merci!

We may test this formula using numerical computation of the bispectrum for a known model with a feature in the potential:
$V(\phi) = \frac{1}{2} m^2 \phi^2 \left[1 + \alpha \tanh \left(\frac{\phi - \phi_0}{\Delta \phi} \right) \right]$



Again, we may test these formulas using numerical computation of the bispectrum for a known model with a feature in the potential: $V(\phi) = \frac{1}{2}m^2\phi^2\left[1 + \alpha \tanh\left(\frac{\phi-\phi_0}{\Delta\phi}\right)\right]$.

For two sets of random values of x's and y's