Oscillations in the CMB bispectrum

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on behalf of the Planck Collaboration

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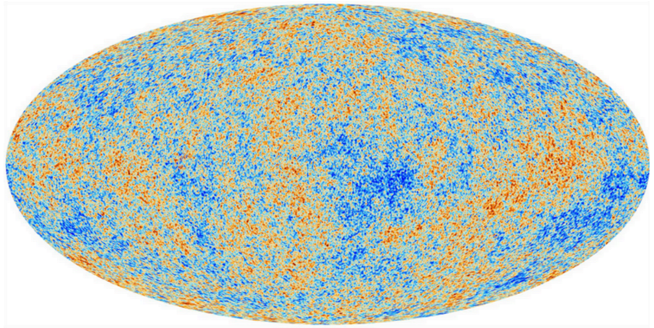
CMB bispectrum



From primordial potential to CMB multipoles

$$a_{lm}^{\mathrm{CMB}} = \int d^3\mathbf{k}\ \mathbf{\Phi}(\mathbf{k})\ \mathbf{\Delta}_{\mathrm{transfer}}(\mathbf{k})\ \mathbf{Y_{lm}}(\hat{\mathbf{k}})$$

From primordial bispectrum to CMB bispectrum

$$\langle \Phi(k_1)\Phi(k_2)\Phi(k_3)\rangle \xrightarrow{\mathbf{\Delta}_{\mathrm{transfer}}(\mathbf{k})} \langle a_{l_1m_1}a_{l_2m_2}a_{l_3m_3}\rangle \simeq B_{l_1l_2l_3}^{\mathrm{CMB}}$$

Each inflation model (Lagrangian + initial conditions) predicts a CMB bispectrum shape (although often unmeasurably small).

$$\mathcal{L}(\Phi, g_{\mu\nu}, \dots) \longrightarrow B_{l_1l_2l_3}^{\mathrm{CMB}}$$

Oscillations in the primordial potential

Several theoretical mechanisms of inflation lead to oscillations:

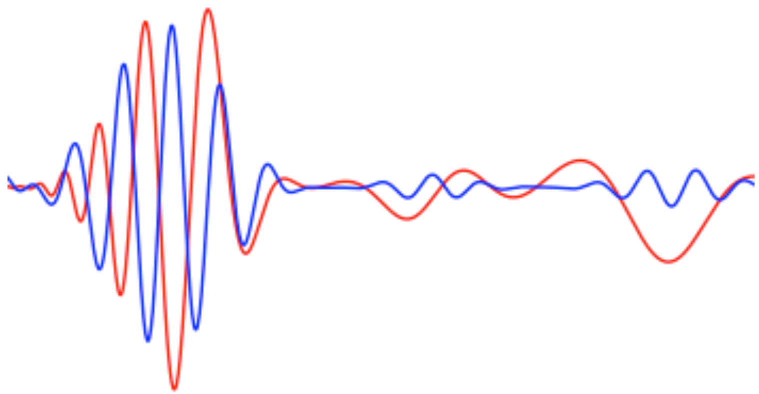
Resonance models

Features in slow-roll parameters / potential

Excited states / Non Bunch-Davies vacua

Hubble scale collider physics (although not enough signal for CMB)

All of these induce oscillations in the power spectrum and/or bispectrum.



What is the theoretical motivation?

How did Planck constrain these models?

PART 1: RESONANCE MODELS

The UV problem of inflation

The slow roll potential of inflation **must be protected from quantum corrections** of form

$$\Delta\mathcal{L} = \frac{\mathcal{O}_\Delta}{\Lambda^{\Delta-4}}$$

Λ : UV scale $\quad\quad$ Δ : Operator dimension

Planck scale sensitivity is both a problem for model building and a chance to learn about quantum gravity.

Eta problem: Flatness of potential i.e. $\eta << 1$ sensitive to $\Delta \leq 6$ operators.

Large field models (large B-modes): Sensitivity to infinite series of operators of arbitrary dimension.

→ **We need a symmetry to control these corrections!**

Shift symmetry and axions

Use a **shift symmetry** to make the potential exactly flat

$$\Phi \to \Phi + \mathrm{const.}$$

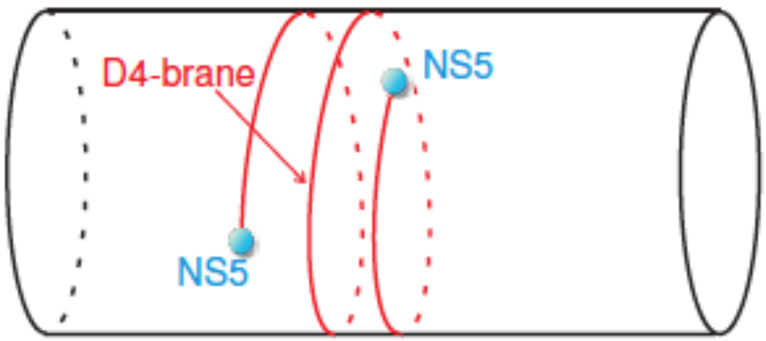
Slightly break the shift symmetry (e.g. by a small mass term) to get slow roll.

→ **radiatively stable / technically natural** theory

This symmetry is obeyed e.g. if the inflaton is an axion (**natural inflation**).

UV complete model with approximate shift symmetry: **Axion monodromy inflation.** Also allows super-Planckian fields.

$$V(\varphi) = \mu^3 \varphi + \Lambda^4 \cos\left(\frac{\varphi}{f}\right)$$



Silverstein et al.

Oscillating potentials and resonances

Axion (monodromy) inflation, or more generally approximate discrete shift symmetry, motivate the search for observable consequences of oscillating potentials.

Oscillation in BG evolution → **Oscillations in the couplings**

e.g. Vertex:

$$\int d\tau \; \tau \;\; \sin(\omega t) \; e^{i(k_1+k_2+k_3)\tau}$$

Chen et al. 2008

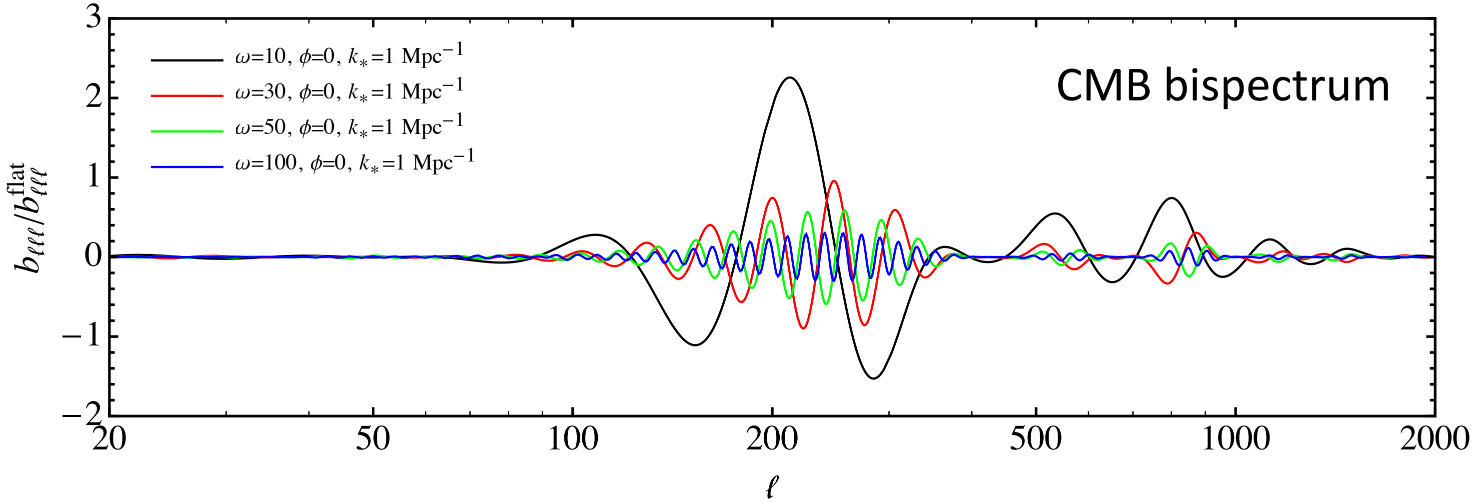
Resonance between couplings and modes

$$B(k_1, k_2, k_3) = \frac{f_{NL}}{(k_1 k_2 k_3)^2} \sin\left(\omega \ln(k_1 + k_2 + k_3) + \varphi\right)$$

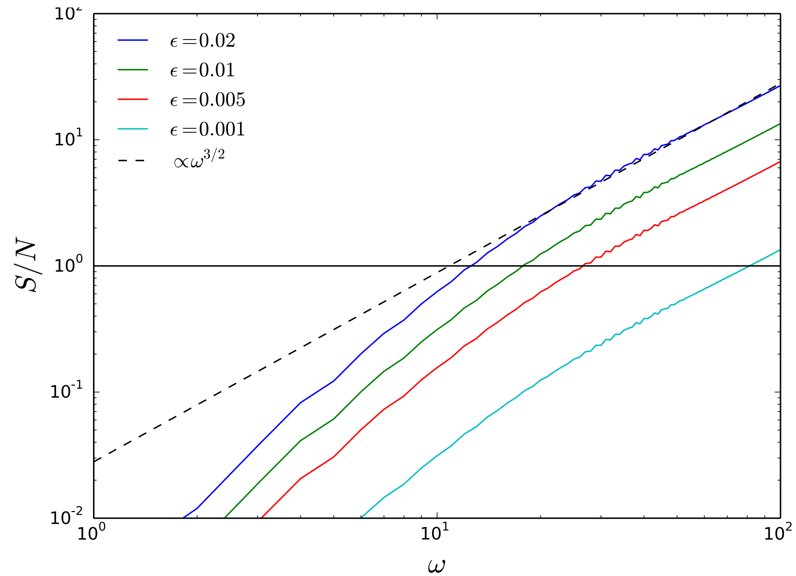
Non-gaussianity in these models could be observably large!

Projection to the CMB and forecast

$$B(k_1, k_2, k_3) \xrightarrow{\Delta_{\text{transfer}}(\mathbf{k})} B^{\text{CMB}}_{l_1 l_2 l_3}$$



EFTI prediction (*Behabani 2013*) based signal-to-noise forecast:



Münchmeyer, Meerburg, Wandelt, PRD 2015

Estimator via separable expansion

Estimation requires separability:

$$B(k_1, k_2, k_3) = f(k_1)g(k_2)h(k_3)$$

Resonance bispectrum is not separable!

Modal expansion (Fergusson, Liguori, Shellard): Expand any shape as

$$B(k_1, k_2, k_3) = \sum_{p,r,s} c_{prs} q_p(k_1) q_r(k_2) q_s(k_3)$$

Problem: With a general basis, and ~1000 modes, **limited to ω<50**

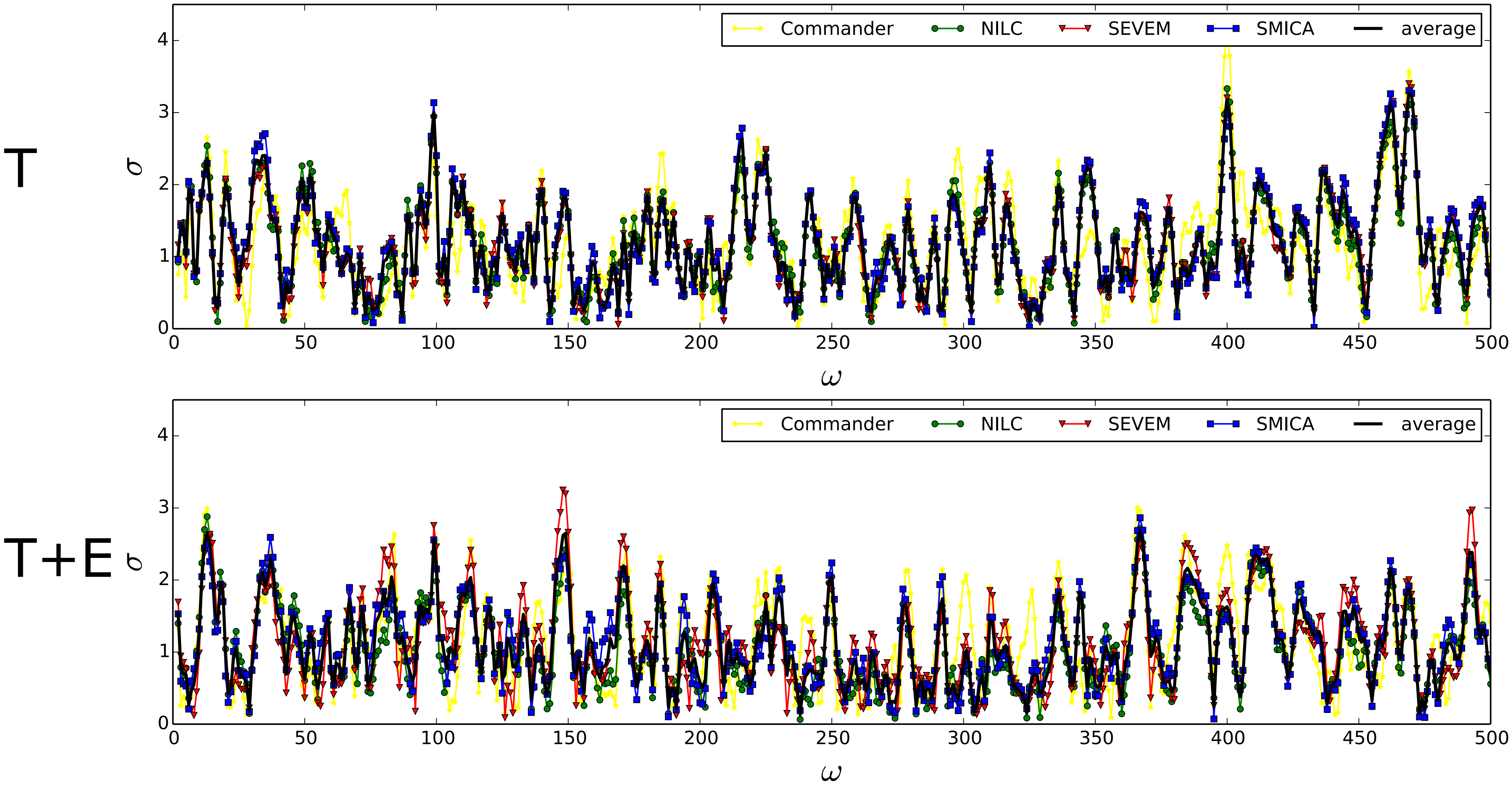
New idea *(Münchmeyer, Meerburg, Wandelt, PRD 2015)***:**

Exploit the effective 1d property of the shape

$$B(k_1, k_2, k_3) \propto \sin(\omega \ln(k_1 + k_2 + k_3)) = \sum_i \alpha_i \sin(\omega_i (k_1 + k_2 + k_3))$$

Now 1000 modes cover full frequency range of interest **ω<1000**

Results from Planck 1

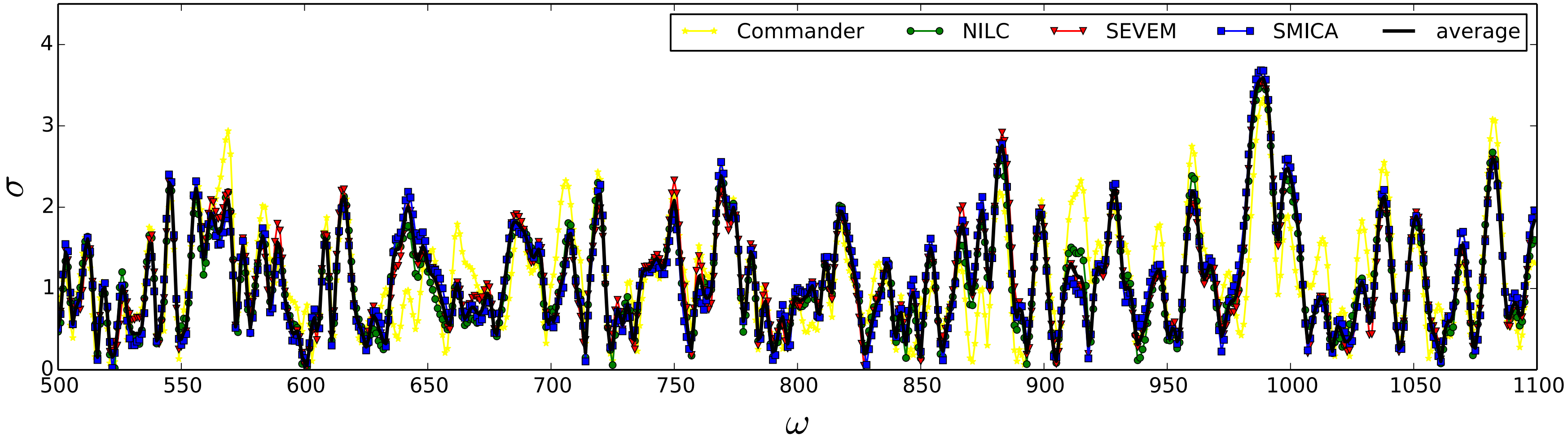


Y axis: local significance (maximized over phase).
Results **compatible with Gaussianity after look- elsewhere correction**.

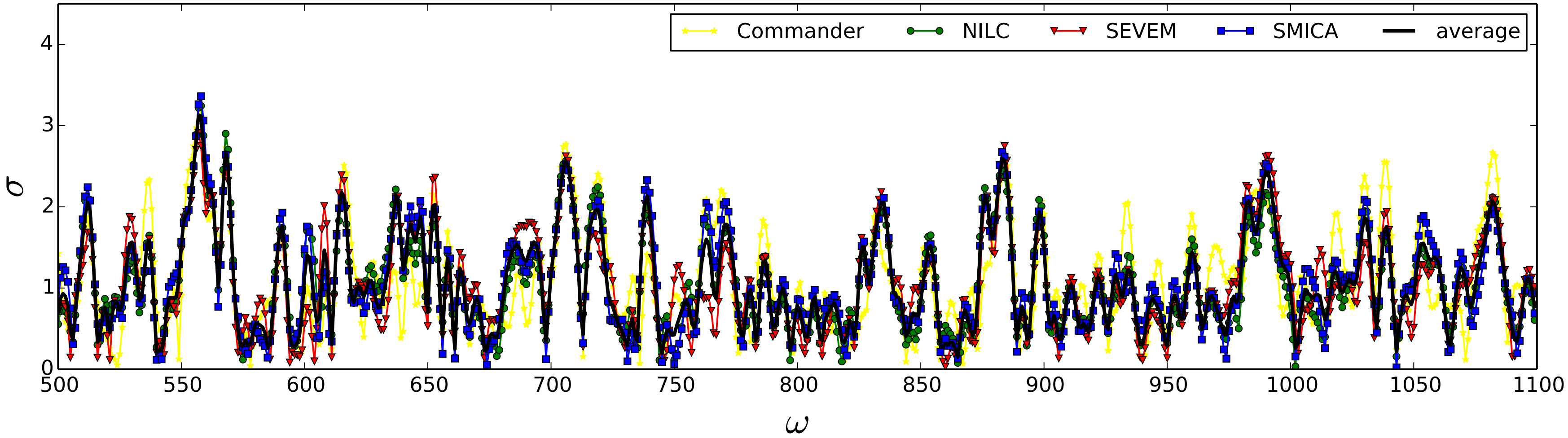
Planck 2015 results. XVII. Constraints on primordial non-Gaussianity.

Results from Planck 2

T



T+E



Y axis: local significance (maximized over phase).
Results **compatible with Gaussianity after look- elsewhere correction**.

Planck 2015 results. XVII. Constraints on primordial non-Gaussianity.

Look elsewhere effect

We search in a large frequency space and maximize over model parameters (phase φ). → **Crucial to correct for look elsewhere effect in significances.**

Standard method: compare to the expectation from Gaussian simulations. But this estimator is too computationally demanding.

Our method: **analytic approximation to the estimator PDF:**

$$P(\{\hat{A}_{\omega_i}^{\sin,\cos}\}) = \mathcal{N}(\mu = 0, \Sigma) \qquad \Sigma = \frac{F_{ij}}{F_{ii}F_{jj}}$$

Look-elsewhere corrected significances:

Single peak significance: 0.5σ

Multi peak significance: 0.6σ

Clearly no sign of non-Gaussianity.

PART 2: FEATURE MODELS

Brief violations of slow-roll

Motivation in part phenomenological: Weak signs of oscillations in the power spectrum.

Various slow-roll parameters can become temporarily large.

A (step-) feature in the potential can drive the inflaton away form slow roll. **LINEAR** oscillations emerge as it relaxes back to the attractor solution.

$$B(k_1, k_2, k_3) = \frac{f_{NL}}{(k_1 k_2 k_3)^2} \sin\left(\omega(k_1 + k_2 + k_3) + \varphi\right)$$

New in Planck 2015: **exploit the separability of this shape**. Previously only modal expansion.

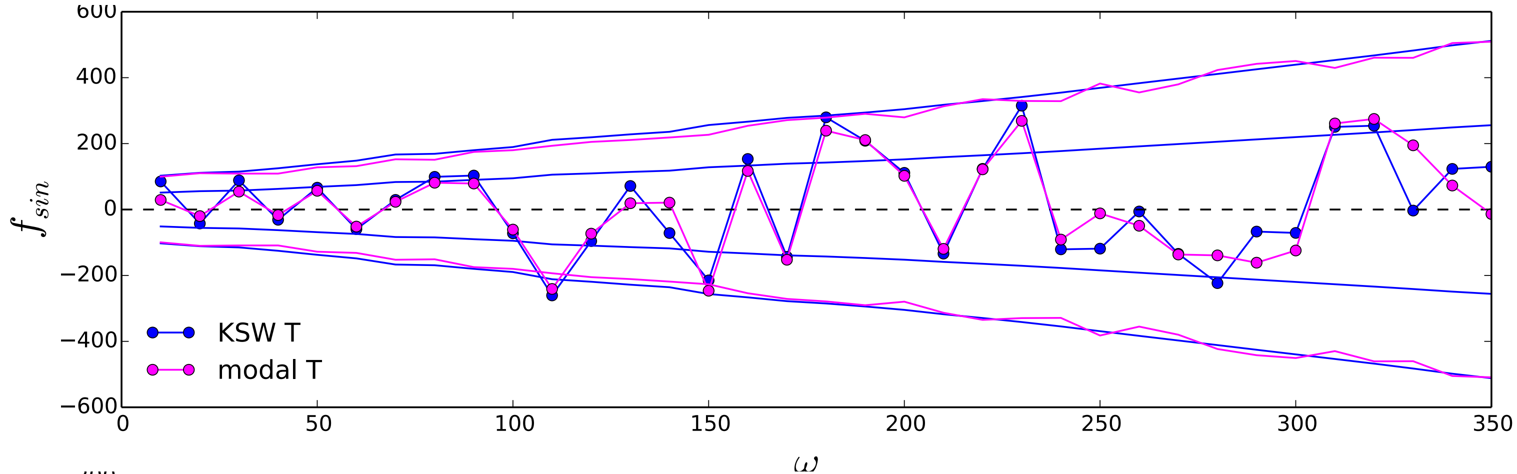
We search up to ω_{max}= 3000 (compared to modal ω_{max}= 350). Effective multipole periodicity $\Delta l \approx 10$.

Method in Münchmeyer, Bouchet, Jackson Wandelt. 2014, JCAP

Comparison of methods

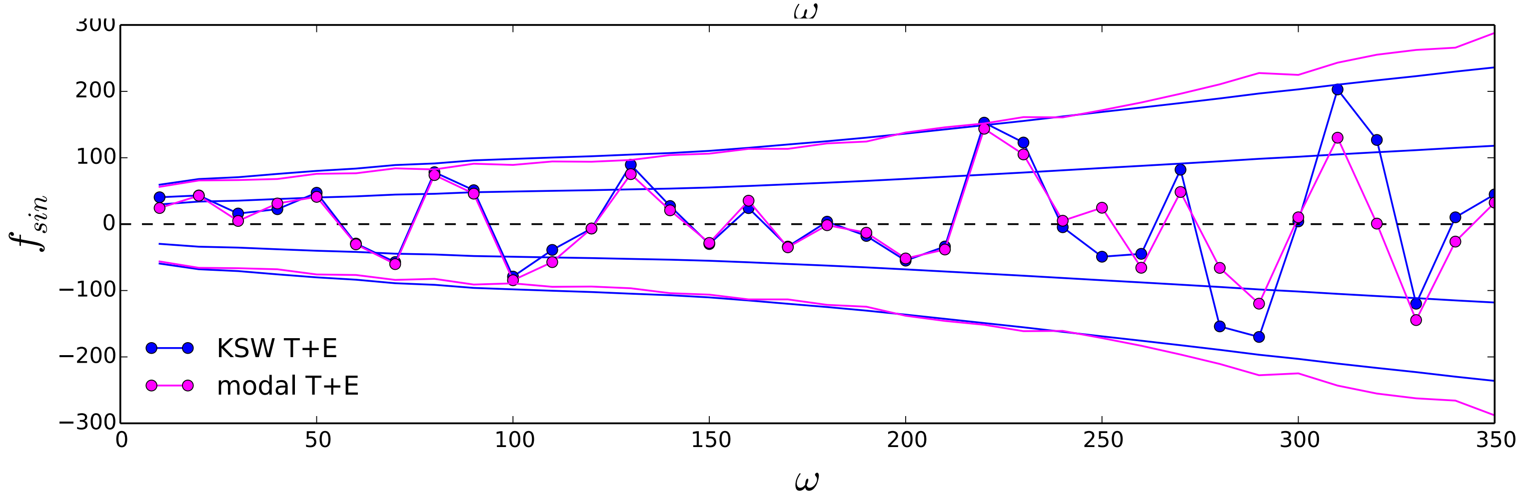
Smica T

(Φ=0)



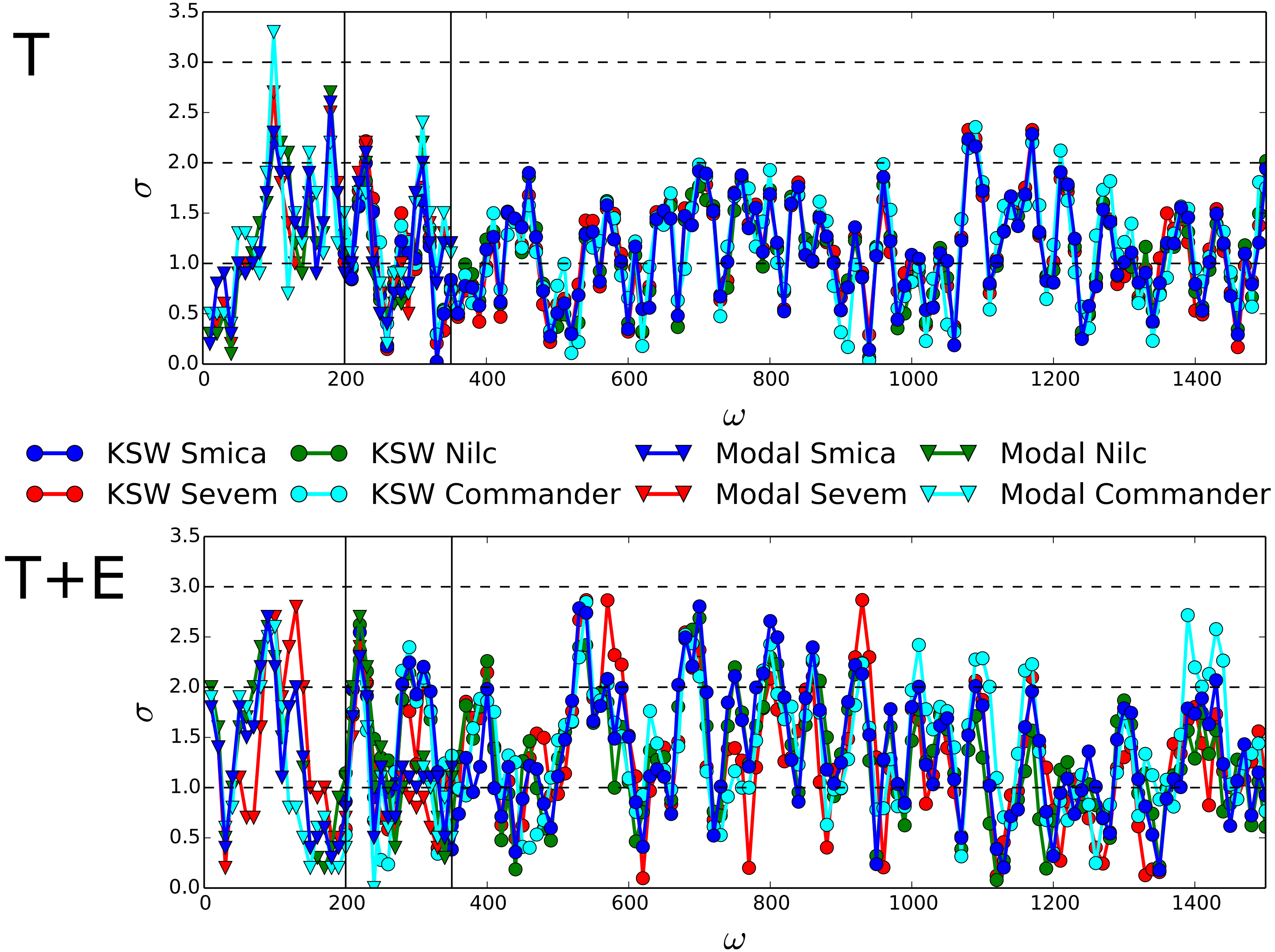
Smica T+E

(Φ=0)



Good agreement between methods in T and T+E.

Planck results 1 (0<ω<1500)



T and T+E compatible with Gaussianity.

Maximum local significance:

3.2σ

Expectation (from Gaussian simulations):

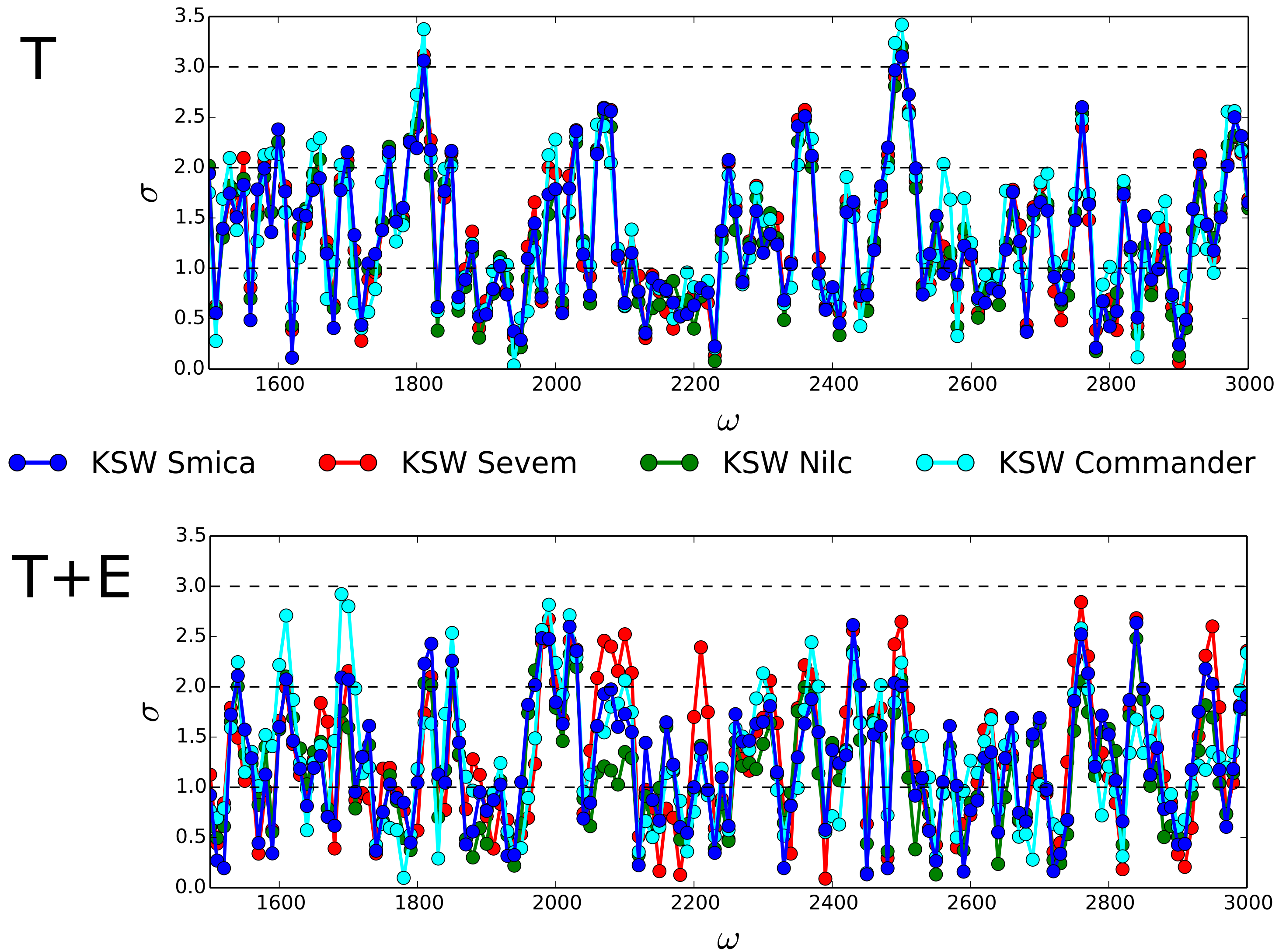
3.1σ ±0.3 σ

Planck 2015 results. XVII. Constraints on primordial non-Gaussianity.

Planck results 2 (1500<ω<3000)

T

T+E



T and T+E compatible with Gaussianity. No T and T+E peaks.

Maximum local significance:

3.2σ

Expectation (from Gaussian simulations):

3.1σ ±0.3 σ

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Conclusions

Optimal estimators in temperature and polarization.

No evidence for linear or logarithmic oscillations in the bispectrum. Results **are fully compatible with Gaussianity**, considering the "look elsewhere" effect.

First search for high frequency resonance bispectra. No evidence (this does not exclude the model).

Planck has also constrained modified resonance and feature models, as well as several shapes from excited initial states.

The 2015 release narrows error bars by factor ~2 and extends the frequency range considerably.

Work on a **combined analysis with the power spectrum** is in progress.

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

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Thank you