Decoupling in the Early Universe and the presence of High Energy Physics in the CMB

with Ana Achúcarro, Sebastian Céspedes, Jinn-Ouk Gong, Gonzalo Palma & Subodh Patil arXiv:1201.4848 & arXiv:1205.0710

Ana Achucarro, Pablo Ortiz, Bin Hu & Jesus Torrado arXiv:1311.2552 & arXiv:1404.7522

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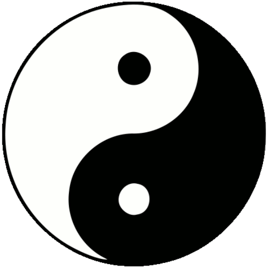
EFT from the perspective of...

EFT FROM THE PERSPECTIVE OF...



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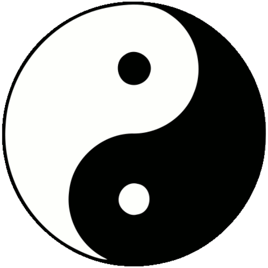

In this talk I will discuss *one* example in which heavy degrees of freedom play an important role in the low energy effective action.

key ingredient: time-dependent background

- Inflation is a mechanism to make otherwise never correlated scales to have been correlated in the past.
- Like this it generates the initial conditions of the Hot Big Bang model (truly, it moves the initial conditions backwards in time).

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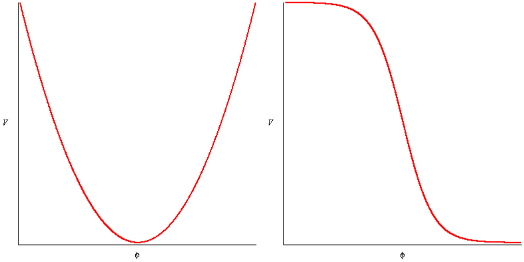
Which are the smoking guns of inflation ?

- red tilt of tensor power spectrum: $P_t = H^2$ (however blue tilt when adding more fields, violating some symmetries)
- quantum nature of the perturbations

VANILLA INFLATION

Scalar field slowly rolling in a very "flat" potential. Inflation happens whenever

$$\epsilon = (V'/V)^2 \ll 1 \quad , \qquad \eta = (V''/V) \ll 1$$



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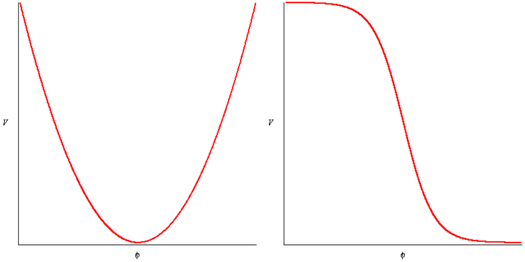

Inflaton potential is radiatively stable to inflaton and graviton corrections (individual corrections looks bad, but then they resum in logs)

$$\epsilon = (V'/V)^2$$

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Effective description: the inflaton can be described as the goldstone boson of broken time-diffeomorphism.

Recipe: Write an action with all the terms that break time-diff

Cheung et al 07.

$$S_\pi = \int d^4x \sqrt{-g} \left[\frac{1}{2} R - \dot{H} \left(\dot{\pi}^2 - k^2 \pi^2 \right) + 2M_2^4 \left(\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi} k^2 \pi^2 \right) - \frac{4}{3} M_3^4 \dot{\pi}^3 + \ldots \right]$$

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This is linked to the curvature perturbation as

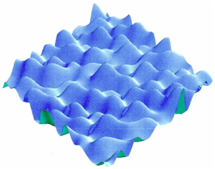
$$\zeta = -H\pi$$

where ζ is the gauge invariant quantity perturbation that is conserved after horizon crossing.

Adding Complexity Natural is different from Simple.

Many approaches:

- add very large number of fields, compute probability distribution for observables



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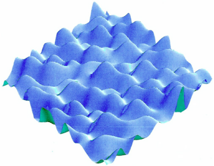

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- add one field, and study in detail the departures from single-field

Inflaton potential is radiatively stable to inflaton and graviton corrections, *but generically not to other fields*

Two field inflation (Third Approach)

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- $M \ll H$ second field is active

Presence of isocurvature perturbations.
"A tiny amount of isocurvature perturbation could affect standard rulers calibration from CMB observations, affect BAO interpretation, and introduce biases in the recovered dark energy properties that *are larger than forecast statistical errors* from future surveys." (Amendola et al. Euclid Theory Group)

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  Interesting since we expect this to happen $(V(\phi)\chi^2 \to H^2\chi^2)$.
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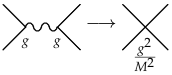

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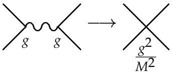

I will present a situation in which this last statement does not hold

A multi field example

$$\mathcal{L} = \frac{1}{2}\phi_{,\mu}\phi^{,\mu} + \frac{1}{2}\psi_{,\mu}\psi^{,\mu} + \frac{1}{2}m^2\phi^2 + \frac{1}{2}M^2\psi^2 + V_{int}(\phi, \psi) \qquad m \ll M$$

How do I compute the lower energy action ?

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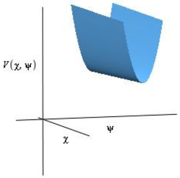
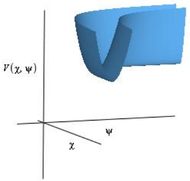
- Background: We need inflation $< \phi > \neq 0$.
    - Without interactions, $< \psi >= 0$.

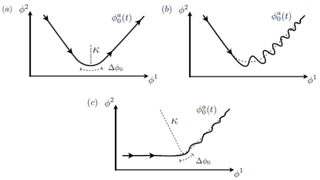


$$\ddot{\mathcal{R}} + 3H\dot{\mathcal{R}} + k^2\mathcal{R} + m^2\mathcal{R} = 0 \qquad (0)$$

$$\ddot{\mathcal{F}} + 3H\dot{\mathcal{F}} + k^2\mathcal{F} + M^2\mathcal{F} = 0 \qquad (1)$$

Now we add an interaction.





$$\ddot{\mathcal{R}} + 3H\dot{\mathcal{R}} + k^2\mathcal{R} + m^2\mathcal{R} = -\frac{\dot{\theta}}{H}\dot{\mathcal{F}}$$

$$\ddot{\mathcal{F}} + 3H\dot{\mathcal{F}} + k^2\mathcal{F} + M_{eff}^2\mathcal{F} = \frac{\dot{\theta}}{H}\dot{\mathcal{R}} \qquad M_{eff}^2 = M^2 - \dot{\theta}^2$$

Funny harmonic oscillators !

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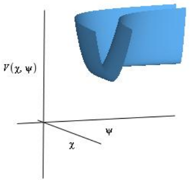

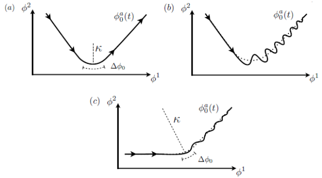

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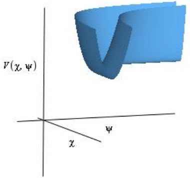

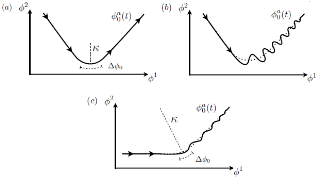

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But, you can still compute an EFT. If $M_{eff} \gg H$, you can solve anatically for F.

$$S \supset \dot{\mathcal{R}}^2 + ... + \dot{\mathcal{R}}\mathcal{F}$$

So your finally theory is a theory for $\mathcal{R}$ with $c_s^{-2} = 1 + 4\frac{\dot{\theta}^2}{M_{eff}^2}$

Naturally, if you oscillate too strongly, you will enter a full 2-field theory. To know which is the limit: Plug your solution back to the full equation. You get the following condition:

$$\frac{\ddot{\theta}}{\dot{\theta}} \ll M_{eff} \quad , \quad \text{note that} \quad \frac{\ddot{\theta}}{\dot{\theta}H} \quad \text{need not be small}$$

which can also be written in terms of the sound speed

$$\frac{d}{dt} ln\left(cs^{-2} - 1\right) \ll M_{eff}$$

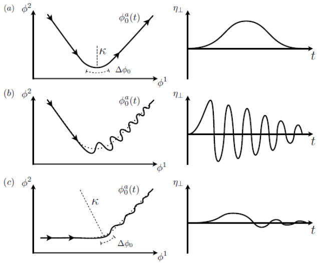

Figure 5: Examples of turns for different background parameters: (a) $T_M \ll T_\perp$ and $\Delta\phi_0 \sim \kappa$. (b) $T_M \sim T_\perp$ and $\Delta\phi_0 \sim \kappa$. (c) $T_M \sim T_\perp$ and $\Delta\phi_0 \ll \kappa$.

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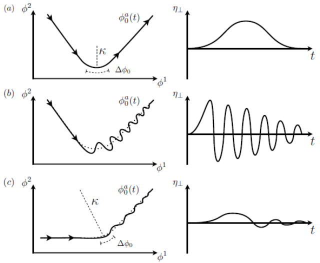

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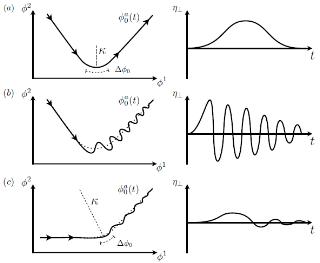

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$$P_{\mathcal{R}}(k) = \left. \frac{H^2}{\epsilon\, c_s} \right|_{k=aH} + f(\dot{c_s})$$

- Field in oscillating background $\rightarrow$ resonant particle production (e.g reheating) (*Mizuno et al., Konieczka et al. Battefeld et al*)
- Adiabatic condition ensures we are not in this regime ($\frac{\dot{\omega}_+}{\omega_+^2} \ll 1$)

Bounds on the speed of sound

Time independent *vs* time dependent speed of sound:

time independent:

- observations: $c_s > 0.02 \quad (95\% CL)$ from $f_{NL} \sim 1/c_s^2$
- theory: sets a new cutoff $\Lambda^4 \sim \dot{H} c_s^5$

time dependent:

- observations: ?
- theory: ?

We will try to adress this last part.

OBSERVABLES: 2PT FUNCTION

Main observable: Very well studied and *all* we need if the statistics are gaussian.

- In-in formalism (perturbation theory from the action)

$$\mathcal{H}_{interaction} = \int d^4x\, a^3 M_{\rm Pl}^2 \epsilon H^2 \left\{ \dot{\pi}^2 (1 - c_s^{-2}) \right\} \to \frac{\Delta \mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R},0}} = k \int d\tau (1 - c_s^{-2}) \sin(2k\tau)$$

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- GSR (perturbation theory from the EOM) (Steward & Hu et al)

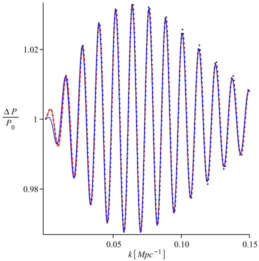
$$v'' + \left[c_s^2 k^2 - a^2 H^2 \left(2 + 2\epsilon - 3\eta' - 3s + 2\epsilon(\epsilon - 2\eta' - s) + s(2\eta' + 2s - t) + \eta' \xi' \right) \right] v = 0 \,,$$

$$\text{write} \qquad v'' + \left[c_s^2 k^2 - 2a^2 H^2 \right] v = f(cs, \dot{c_s}, \ddot{c_s}) v$$

$$\rightarrow \frac{\Delta \mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R},0}} = k \int d\tau \, [G(k\tau, cs, \dot{c_s}, \ddot{c_s}) \sin(2k\tau) + F(k\tau, cs, \dot{c_s}, \ddot{c_s}) \cos(2k\tau)]$$

COMPARISON

$$1 - cs^{-2} = Be^{-\beta(\tau - \tau_0)^2}$$



GSR
In-in
points: numerical

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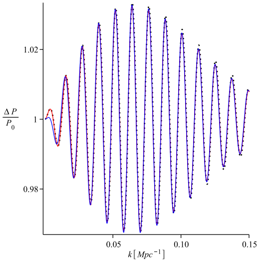
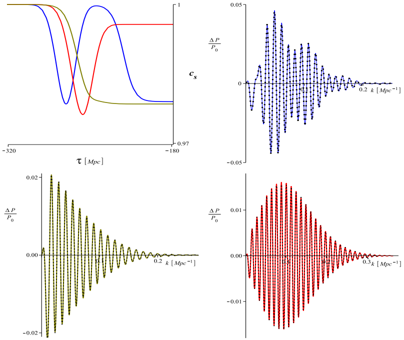
Sharp feature approximation:

$$\frac{\Delta\mathcal{P}_\mathcal{R}}{\mathcal{P}_{\mathcal{R},0}} = \mathcal{D}\left(\frac{k\tau_0}{\beta}\right)\left[p_1(k\tau_0)*\sin(k\tau_0)+p_2(k\tau_0)*\cos(k\tau_0)\right]$$





GSR

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points: numerical

Other Mechanism

Oscillations in the power spectrum are ubiquitious in modification of vanilla inflation

- Particle production, Non BD initial conditions, initial fast roll...
- transient variations of the Hubble ($\eta > 1$ for $\Delta t \ll H$): just as before. Same amount of incognita.

$$\frac{\Delta \mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R},0}} = \mathcal{D}\left(\frac{k\tau_0}{\beta}\right)\left[p_1'(k\tau_0) * \sin(k\tau_0) + p_2'(k\tau_0) * \cos(k\tau_0)\right]$$

Steps in the Hubble parameter can generate the same signal in the power spectrum. We need more observables

OBSERVABLES: 3 PT FUNCTION

Effective theory dictates that:

$$S_3 = \int d^4x\, a^3 M_{\rm Pl}^2 \frac{\epsilon}{H} \left\{ 2\dot{c}_s c_s^{-3} \mathcal{R}\dot{\mathcal{R}}^2 + (1 - c_s^{-2})\dot{\mathcal{R}}[\dot{\mathcal{R}}^2 - \frac{1}{a^2}(\nabla\mathcal{R})^2] \right\} ,$$

$c_s \neq 1$ *implies* the appearance of 3th order interactions.

$$\Delta B\,(k_1 k_2 k_3) = c_1 \frac{\Delta P_R}{P_R} + c_2 \frac{\partial}{\partial k}\frac{\Delta P_R}{P_R} + c_3 \frac{\partial^2}{\partial^2 k}\frac{\Delta P_R}{P_R}$$

c_i functions of k_1, k_2, k_3 (i.e. shape dependent) (Achucarro et al '12)

Observables: 3 pt function

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c_i functions of k_1, k_2, k_3 (i.e. shape dependent) (Achucarro et al '12)

We have a well defined theory (that could reveal the presence high energy physics in the CMB) with very distinct obsevarbles.

Are these features present in the data ?

Parametric Bounds

$$1 - cs^{-2} = Be^{-\beta(\tau - \tau_0)^2}$$

We need values for (B, β, τ_0) that:

- do not excite the heavy field $\rightarrow$ we need to impose the adiabatic condition.
- produce observable effects (and are not computationally expensive) $\rightarrow$ reduction happens in a particular window of time.
- are in the perturbativity bound.

Perturbativity

The breaking of perturbation theory may be a sign of the breaking of unitarity.

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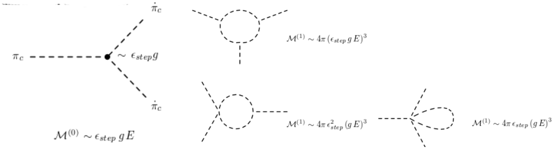
The breaking of perturbation theory may be a sign of the breaking of unitarity.

- $\frac{\mathcal{L}_n}{\mathcal{L}_2}\Big|_E \ll 1$
- no big loop corrections (Cannone et. al, Hu et. al)

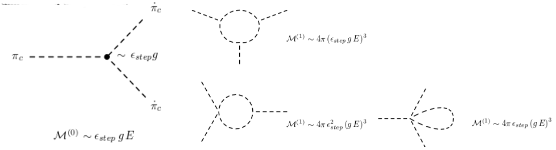


From here: $\ln(\beta) < 14$.

Perturbativity

The breaking of perturbation theory may be a sign of the breaking of unitarity.

- $\frac{\mathcal{L}_n}{\mathcal{L}_2}\Big|_E \ll 1$
- no big loop corrections (Cannone et. al, Hu et. al)



From here: $\ln(\beta) < 14$.

Differences with constant c_s ?

- Interaction happens well inside horizon
- Vertices are time dependent

Search in the Power Spectrum

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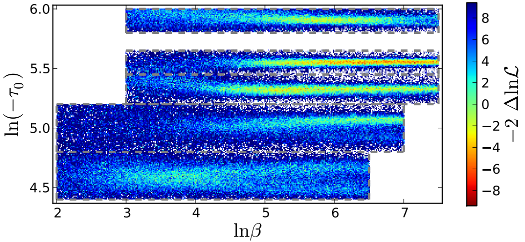

$$1 - cs^{-2} = Be^{-\beta(\tau-\tau_0)^2}$$

$$\mathcal{O}(\epsilon, \eta) \ll |B| \ll 1 \,,$$

$$\frac{50}{N_{\rm CMB}^2} < \beta \ll \frac{2e}{B^2} \,,$$

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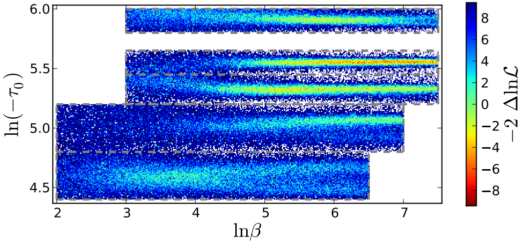

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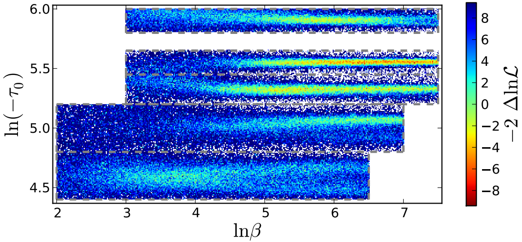

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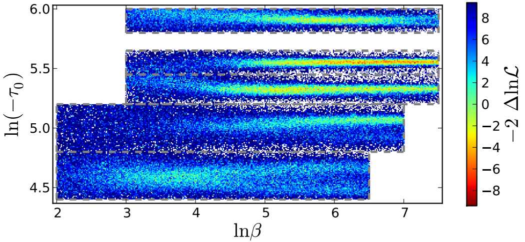

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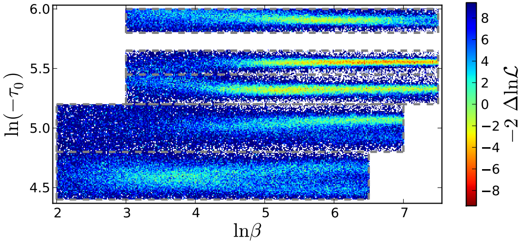
SEARCH IN THE POWER SPECTRUM



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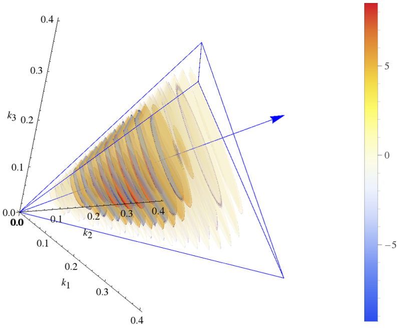
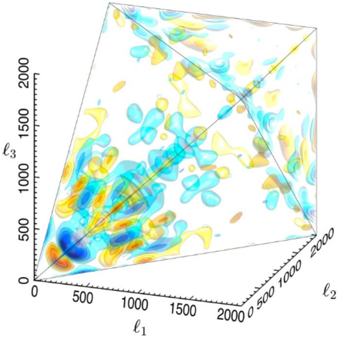
- Correlations can come to rescue.

PREDICTIONS FOR THE BISPECTRUM

our prediction - primordial bispectra



data - *not primordial*



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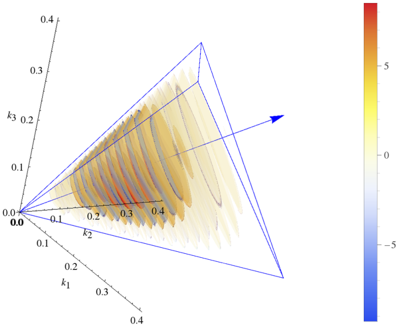

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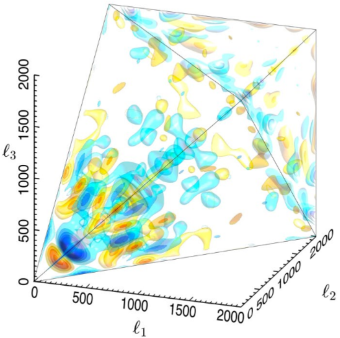

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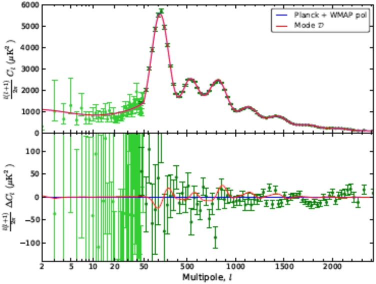
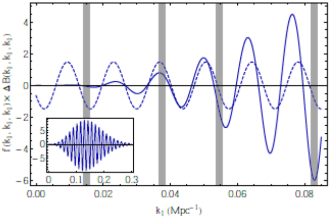
However, they found at 2.3σ the presence of an oscillation in the bispectrum which looks that the prediction of one of our fits.





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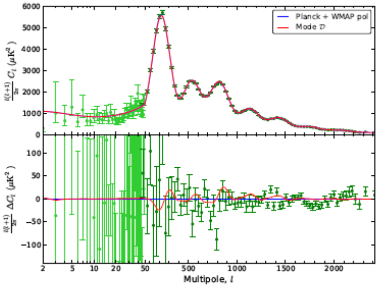

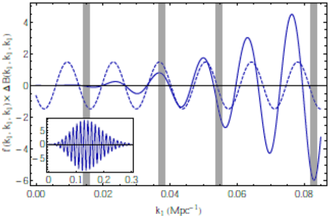

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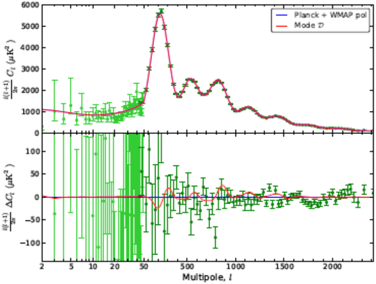

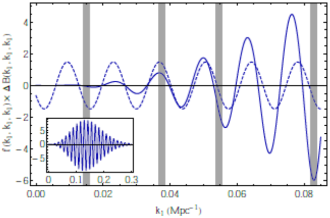

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Polarization data will also constraint better our model, since it is *sensitive* to higher multipole

EVIDENCE FOR FEATURES IN THE DATA

- $\Delta\chi^2$ is not the ultimate number for assesing if a model is better than other. Ultimately we need to calculate the *evidence*
- In Bayesian language, this mean taking into account the prior for the parameters.
- If one observable is a prediction of another one, we need to take into account this effects *once*, hence the power of theories that predicts specific correlation between different observables

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We still need to

- Find this phenomenology in more realistic scenarios
- Restrict better the parameter space (loops corrections in de Sitter with time-dependent vertices)
- Analyse new polarisation data coming shortly, and lobby for an enlargemente of the bispectrum feature search