# Signatures of very high-energy and exotic physics in the non-Gaussianities of the Cosmic Microwave Background and Large Scale Structure

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- D. Chialva, arXiv:1108.4203.
- D. Chialva, arXiv:1106.0040.

# Plan of the Talk

Introduction

Observables

Very high-energy physics and standard and modified scenarios in cosmological perturbations theory

Non-Gaussianities (CMBR)

Non-Gaussianities: squeezing limit (LSS)

Conclusions

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# Basics of cosmology

Cosmology:

- a standard model: cosmological principle (homogeneity and isotropy) and a predictive model (Big-Bang valid below certain energies)

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2 \quad \rightarrow \quad \begin{cases} H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{\rm tot} - \frac{\kappa}{a^2} \\ \dot{H}^2 = -4\pi G(\rho_{\rm tot} + p_{\rm tot}) + \frac{\kappa}{2a^2} \end{cases}$$

- experimental measurements and tests: CMB, Large Scale Structure, ...
- a strict relationship with microscopic physics (astrophysics and particle physics)
- a paradigm (inflation) to explain cosmological principle and set up initial conditions for Big Bang: accelerated expansion of the Universe in a short time: guided by $p_V = w\rho_V$, $w < -\frac{1}{3}$
- a mechanism to explain structure formation (inflation): quantum oscillation of fields during inflation and quantum-to-classical transition

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# Inflation needs high-energy

Inflation is remarkable, but needs a UV-complete quantum theory

- origin of the degrees of freedom of the inflaton sector $(\rho_V, p_V)$
- in standard scenarios: background dynamics of scalar field sensitive to Planck-suppressed operators (for example, $\eta$ problem in standard scenario):
- cosmological singularity
- the perturbations for structure formations are quantum and are sensitive to Planckian initial conditions: for scales $E$ observed today the latter are in the (trans-)Planckian regime $E > M_{\text{Planck}} \equiv \sqrt{\frac{hc}{G}}$

But a high-energy quantum theory also benefits from cosmology

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- inflationary dynamics acts as magnifying lens on microphysics
- high precision tests (CMBR physics, astrophysical phenomena)
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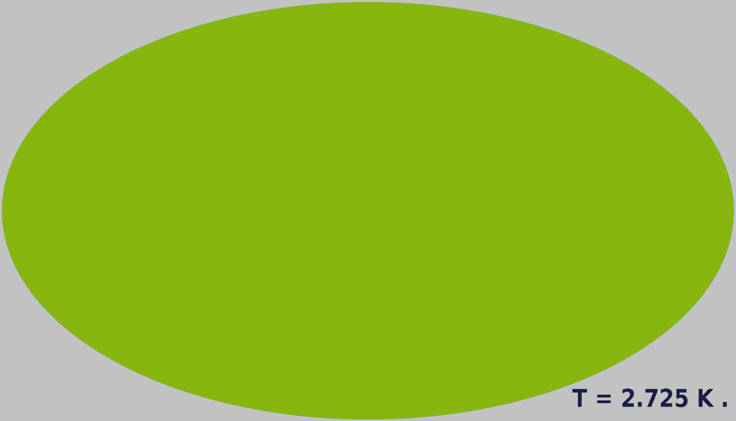
OBSERVABLES

# WMAP and its results

After many years of painstaking research, WMAP yields us a detailed picture of the Universe 300000 years after Big Bang:



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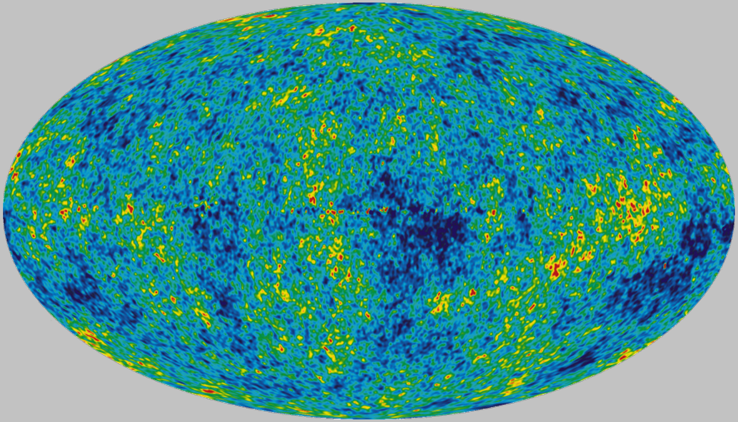

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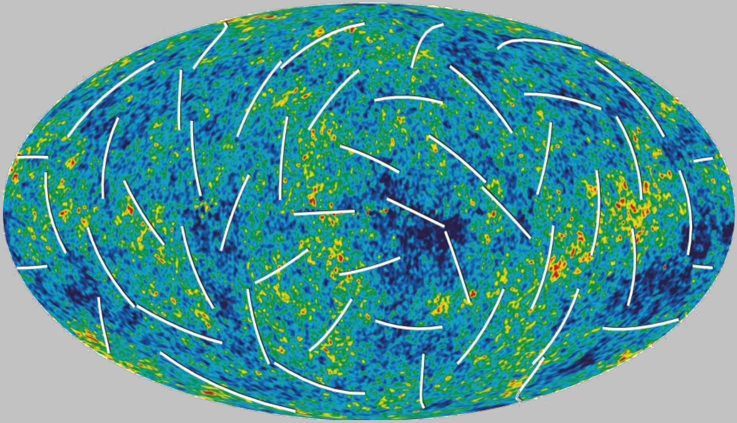
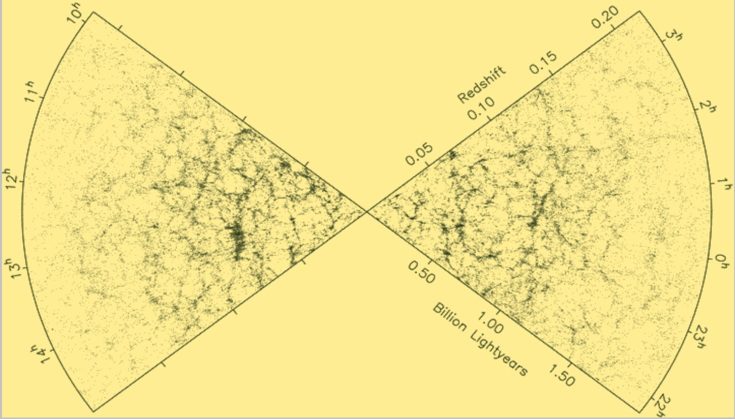


# Some LSS

Large Scale Surveys can also be used to gain information on the perturbations generated during inflation




Two-degree-Field Galaxy Redshift Survey, 2dFGRS

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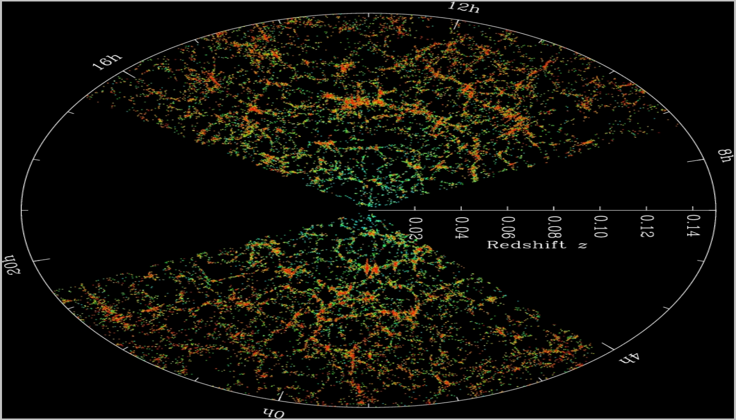
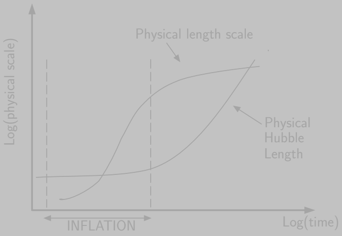



Sloan Digital Sky Survey, SDSS

# Early Universe in the CMBR

Observed perturbations are for example the matter density contrast $\frac{\delta\rho}{\rho}$ (traced for example by galaxies in LSS) or the temperature anisotropy $\frac{\Delta T}{T}$ of the CMBR.

The miracle of inflation: quantum perturbations of fields over background




They are related to the primordial perturbations as

Perturbation today

Comoving curvature perturbation

$$\delta \quad = \quad \mathcal{T}(t,k) \quad \mathcal{R}(k)|_*$$

Transfer matrix relating perturbations

Classical primordial: time between horizon exit and re-entering

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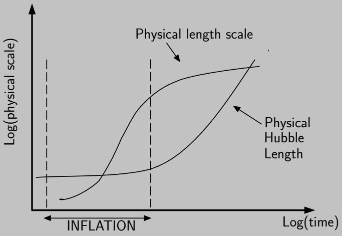


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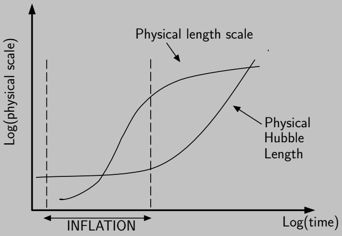


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# Cosmological perturbation theory

Distinguish fields between background and perturbations

$$\Phi(\vec{x}, t) = \phi_0(t) + \phi(\vec{x}, t)\,.$$

Check for degrees of freedom against gauge transformations $x'^{\mu}(x^{\nu})$.
In single-field slow-roll inflation

$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2 M_{\text{Planck}}^2} \ll 1,$$

$$\eta_{\text{sl}} = -\frac{\ddot{H}}{H\dot{H}} - \frac{\dot{H}}{H^2} = -\frac{\ddot{\phi}}{\dot{\phi}H} + \frac{\dot{\phi}^2}{2H^2 M_{\text{Planck}}^2} \ll 1$$

there is only one physical scalar: comoving curvature perturbation $\mathcal{R}$.
It is gauge invariant; on constant conformal time hypersurfaces (flat universe):

$$4\frac{\nabla^2 \mathcal{R}}{a^2} = R^{(3)}$$

$$(R^{(3)} \equiv \text{spatial curvature})\,.$$

Conformalities: $ds^2 = a(\eta)^2(-d\eta^2 + d\vec{x}^2)$, $p_{\text{phys}} = \frac{k}{a}$

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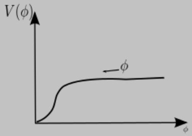


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# Cosmological perturbation theory

Quantize perturbations: observations say fields in inflation are nearly free

$$\mathcal{R}(\vec{x},\eta) = \int \frac{d^3k}{(2\pi)^{\frac{3}{2}}} \left[ Y_{\vec{k}}(\vec{x})\mathcal{R}_k(\eta)\hat{a}_{\vec{k}} + Y^*_{\vec{k}}(\vec{x})\mathcal{R}^*_k(\eta)\hat{a}^\dagger_{\vec{k}} \right],$$

$$[\hat{a}^\dagger_{\vec{k}}, \hat{a}_{\vec{k}'}] = \delta(\vec{k}-\vec{k}') \qquad Y_{\vec{k}}(\vec{x}) = e^{i\vec{k}\cdot\vec{x}}.$$

$\mathcal{R}$ is a non-canonically normalized scalar field. Mode functions $\mathcal{R}_k(\eta) = \frac{f_k}{z}$, where $f \equiv z\mathcal{R}$ is canonically normalized and

$$f''_k + (\omega(k,\eta)^2 - \frac{z''}{z})f_k = 0 \qquad z = \frac{a\dot{\phi}}{H}$$

Here, $\omega(k,\eta)$ is the comoving frequency (we consider isotropic case).

Different $\omega(k,\eta)$'s yield different mode functions. Also, given equal $\omega(k,\eta)$, different mode functions define different vacuum choices.

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# Observables in standard theory

Observables: in-in correlators at a given time. Example, operator $\widehat{\mathcal{O}}\ \eta_0$:

$$\langle\Omega|\widehat{\mathcal{O}}(\eta_0)|\Omega\rangle = \langle\Omega|\,\bar{T}\left(e^{i\int_{\eta_\Omega}^{\eta_0} d\eta H_I}\right)\widehat{\mathcal{O}}(\eta_0)\,T\left(e^{-i\int_{\eta_\Omega}^{\eta_0} d\eta H_I}\right)|\Omega\rangle\,.$$

where $H_I$ = interaction Hamiltonian from expansion in perturbations.

Basic building block: Whightman function

$$G(\vec{x},\eta,\vec{x}',\eta') = \langle\Omega|\mathcal{R}(\vec{x},\eta)\mathcal{R}(\vec{x}',\eta')|\Omega\rangle \qquad G_k(\eta,\eta') = \frac{H^2}{\dot{\phi}^2}\frac{f_k(\eta)}{a(\eta)}\frac{f_k^*(\eta')}{a(\eta')}.$$

Famous example: power spectrum

$$P_k = \frac{k^3}{2\pi^2}\lim_{\eta\to 0} W_k(\eta,\eta)$$

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where $H_I$ = interaction Hamiltonian from expansion in perturbations.

Basic building block: Whightman function

$$G(\vec{x},\eta,\vec{x}',\eta') = \langle\Omega|\mathcal{R}(\vec{x},\eta)\mathcal{R}(\vec{x}',\eta')|\Omega\rangle \qquad G_k(\eta,\eta') = \frac{H^2}{\dot{\phi}^2}\frac{f_k(\eta)}{a(\eta)}\frac{f_k^*(\eta')}{a(\eta')}.$$

Famous example: power spectrum

$$P_k = \frac{k^3}{2\pi^2}\lim_{\eta\to 0} W_k(\eta,\eta)$$

## Very high-energy physics and standard and modified scenarios in cosmological perturbations theory

# The basic ingredients in quantisation, standard scenario

Observables: correlators of curvature perturbation

$$G_W(\{x_1, \dots, x_n\}) = \langle\Omega|\mathcal{R}(x_1)\dots\mathcal{R}(x_n)|\Omega\rangle$$

Information needed:

- the fields and their equation of motion
- the state $|\Omega\rangle$

Standard choices:

Bunch-Davies vacuum

$$\hat{a}_k(\eta \to -\infty)|\Omega_{BD}\rangle = 0$$

- preservation of de Sitter symmetry group
- "no particles" (WKB criterion, flat coordinates) at very small scales (mimicking Minkowski)
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Lorentzian dispersion relation

$$\omega(k,\eta)^2 = k^2$$

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Is the standard vacuum choice well motivated?

Already at classical level: absence of global always timelike Killing vector .

Validity of (inflationary) general relativity picture unjustified at arbitrary high energy scales .

Let us suppose new physics at scale $\Lambda$ : boundary conditions (vacuum $|\Omega\rangle$) should be given at scale $\Lambda$ by the new theory.

Question for high energy theorists: can you determine $|\Omega\rangle$ from the high energy theory?

More humble phenomenological approach: would there be observable consequences of having different prescriptions for $|\Omega\rangle$ at scale $\Lambda$?

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- Lorentz invariance tested up to certain scales,
- effective theory for perturbations on backgrounds naturally breaks Lorentz (coordinate adapted to homogeneity of background field, example ghost inflation)
- quantum gravity effects (brane-world, Horava theory, ...)
- higher-derivative corrections to the effective action are unsuppressed at earlier times since $a(\eta) \underset{\eta \to -\infty}{\longrightarrow} 0 \Rightarrow \frac{p(\eta)}{\Lambda} = \frac{k}{a(\eta)\Lambda} \to \gg 1$

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# Mode functions and creation operators.

After quantization

$$\mathcal{R}_k(\eta) = \frac{f_k(\eta)}{z}\hat{a}_k^\dagger + \frac{f_k^*(\eta)}{z}\hat{a}_k\,.$$

STANDARD SCENARIO

Lorentzian dispersion and Bunch-Davies vacuum

$$\omega(\eta,k)^2 = k^2\,, \qquad f_k(\eta) = \frac{\sqrt{\pi}}{2} e^{i\frac{\pi}{2}\nu + i\frac{\pi}{4}}\sqrt{-\eta}H_\nu^{(1)}(-k\eta)\,,$$

$\nu = \frac{3}{2} + \frac{1-n_s}{2}$, $n_s = 1 - 6\epsilon + 2\eta_{\rm sl}$ is the spectral index.

Two-point function:

$$P_s(k) \underset{k\to 0}{\sim} \frac{H^2}{4M_{\rm Planck}^2\epsilon k^3}$$

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Theory valid up to a scale $\Lambda$. Vacuum specified at a certain time $\eta_c$.

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$\alpha_k^{\rm mv}, \beta_k^{\rm mv}$ depend on $k, \Lambda, \eta_c$.

Two popular possibilities:

- Effective Boundary Action: $\eta_c$ is the same for any $k$ and not depending on the scale $\Lambda$ (so the theory has two scales $\eta_c^{-1}$ and $\Lambda$)
- New Physics HyperSurface: vacuum specified for each mode k when the physical momentum $p(\eta_c) = \Lambda \to \eta_c(k) = \frac{\Lambda}{kH}$

Two-point function, at leading order in slow-roll and $\beta_k^{\rm mv}$:

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Generic modified dispersion relations

$$\omega(\eta, k) = k\, F\left(\frac{H}{\Lambda} k\eta\right), \qquad F(x \to 0) \to 1, \qquad H \ll \Lambda.$$

Quite different from the standard scenario only if adiabaticity is violated at some early time.

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$\Omega(y_k) = \int^{y_k} U(y'_k) dy'_k, \qquad U(y_k) \equiv F + \epsilon^2\left(-\frac{\partial_y^2 F}{4F^2} + 3\frac{(\partial_y F)^2}{8F^3} - \frac{1}{F y_k^2}\right),$

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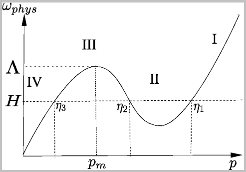


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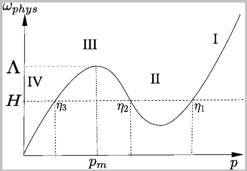


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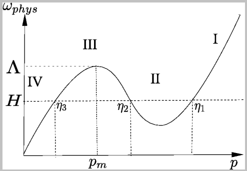


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Observations and consistency put constraints on the Bogoljubov parameters.

- observations on the spectral index

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Non-Gaussianities (CMBR)

# Non-Gaussianities

Non-Gaussianities: three- and higher-point correlators are non-zero.
Leading contribution in perturbation theory: bispectrum

$$\langle \mathcal{R}_{\vec{k}_1}(\eta)\mathcal{R}_{\vec{k}_2}(\eta)\mathcal{R}_{\vec{k}_3}(\eta)\rangle = (2\pi)^3\delta(\sum_i \vec{k}_i)F(\vec{k}_1,\vec{k}_2,\vec{k}_3,\eta),$$

$\eta \sim 0$ late time when all $k_{1,2,3}$ have exited the horizon

Two aspects:

- obviously accounting the interactions during inflation
- could it be sensitive also to higher energy physics (modified scenarios)?

The traditional non-gaussian parameter $f_{NL}$

$$F(\vec{k}_1,\vec{k}_2,\vec{k}_3,\eta) = (2\pi)^7\delta(\sum_i \vec{k}_i)\left(-\frac{3}{5}f_{NL}\,P^2_{\mathcal{R}}\right)\frac{4\sum_i k_i^3}{\prod_i 2k_i^3}$$

Non-Gaussianities in the standard slow-roll single-field scenario: very suppressed

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Three-point function

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Modified elements in the modified scenarios:

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# Example: Einstein-Hilbert action cubic coupling

Example: in Einstein-Hilbert action, cubic coupling

$$H_{(I)} = -\int d^3x\, a^3\, (\frac{\dot\phi}{H})^4\, \frac{H}{M^2_{\rm Planck}}\, \mathcal{R}'^2_c \partial^{-2} \mathcal{R}'_c\,.$$

Bispectrum

$$\begin{aligned} F(k_1, k_2, k_3, \eta) &\equiv \langle \mathcal{R}_{c,\,\vec{k}_1}(\eta) \mathcal{R}_{c,\,\vec{k}_2}(\eta) \mathcal{R}_{c,\,\vec{k}_3}(\eta) \rangle \\ &= 2{\rm Re}\Bigg( -i(2\pi)^3 \delta(\sum_i \vec{k}_i) \left(\frac{\dot\phi}{H}\right)^4 \frac{H}{M^2_{\rm Planck}} \int_{\eta_{\rm in}}^{\eta} d\eta'\, \frac{a(\eta')^3}{k_3^2} \prod_{i=1}^{3} \partial_{\eta'} G_{k_i}(\eta, \eta') \\ &\qquad + \text{permutations} \Bigg). \end{aligned}$$

# Example: Einstein-Hilbert action cubic coupling

## Standard scenario

$$F(k_1,k_2,k_3,\eta)_{\text{BD}} \propto \text{Re}\left[\int_{-\infty(1-i\varepsilon)}^{\eta} d\eta' \, e^{i(k_1+k_2+k_3)\eta'} + \text{permutations}\right] \approx \frac{1}{k_1+k_2+k_3} \equiv \frac{1}{k_t}$$

## Modified vacuum scenario (leading correction in $\beta$)

$$\delta_\beta F(k_1,k_2,k_3,\eta) \propto \sum_{j=1}^{3} \text{Re}\left[\beta^*_{k_j} \int_{\eta_{\text{in}}=\eta_c}^{\eta} d\eta' \, e^{i(\sum_{h\neq j} k_h - k_j)\eta'} + \text{permutations}\right]$$

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## Enhancement

$$\left.\frac{\hat{F}_{3,\beta}}{\hat{F}_{\text{BD}}}\right|_{k_j=\sum_{h\neq j} k_h} \simeq |\beta_{k_j}| \frac{k_t \eta_c}{k_t} \quad \left(= |\beta_{k_j}| \frac{\Lambda}{H} \frac{1}{k_t} (\text{NPHS})\right)$$

for folded configuration $k_j = \sum_{h\neq j} k_h$

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$$S_0(\{x_{h\neq j}\}, x_j, y') = \int^{y'} dy'' \left( \sum_{h\neq j} \omega(x_h, y'') - \omega(x_j, y'') \right), \quad y \equiv \frac{H}{\Lambda} k_{max} \eta, \quad x_i = \frac{k_i}{k_{max}}$$

Enhancement

$$\frac{\hat{F}_{3,\beta}}{\hat{F}_{\mathrm{BD}}} \simeq \sum_j \left( \frac{\Lambda}{H} \right)^{1-\frac{1}{n}} \frac{1}{|S_{0\beta}^{(n)}(\{x\}, y_*)|^{\frac{1}{n}}} |\beta^*_{\vec{k}_j}|,$$

for any configuration such that there is a critical point

$$\partial_y^n S_{0\beta}(\{x\}, y)|_{y=y_*} \equiv S_{0\beta}^{(n)}(\{x\}, y_*) \neq 0, \qquad \partial_y^m S_{0\beta}(\{x\}, y)|_{y=y_*} = 0 \qquad \forall\, m < n\,.$$

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# Non-Gaussianities: sensitivity to very high energy physics

## Modified vacuum

- oscillations on the shape function
- enhancements for the folded configuration
- greater enhancements for interactions that scale with more powers of $\frac{1}{a}$: stronger sensitivity to higher derivative couplings

## Modified dispersion relations

- oscillations on the shape function (features depend on the dispersion)
- enhancements possible for different configurations depending on the dispersion relation
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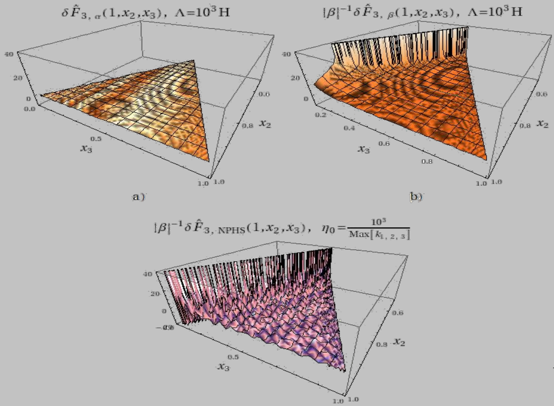


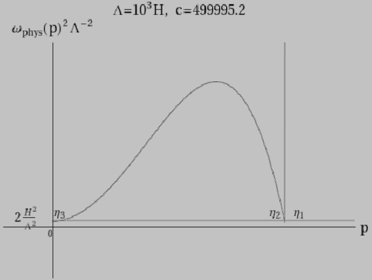


Leading $\beta$ bispectrum correction for a) standard scenario, b) modified dispersion relation of figure 2, c) modified vacuum.

Dispersion relation used for b).

Non-Gaussianities: squeezing limit (LSS)

# Squeezing limit and very high energy physics

Large Scale Structure observations survey tracers of matter/halo distribution that depend on the primordial perturbation, in particular non-Gaussianities in the squeezing limit $k_1 \ll k_2 \sim k_3 \sim k_S$. $k_1^{-1}$ is the probed large scale.

Advantages of the squeezing limit for theory: relies upon very general features, capable of constraining (falsify?) entire classes of models.

# Squeezing limit and very high energy physics

Standard scenario

Bispectrum fully determined by general argument:

- dominant contribution to non-Gaussianities come for late times $\eta \sim 0$ (horizon crossing)
- squeezing limit $k_1 \ll k_{2,3} \rightarrow$ perturbation depending on $k_1$ is superhorizon $(k_1\eta \ll 1)$ at the time of dominant contribution , acts as background for the other perturbations shifting their exit-of-horizon times
- bispectrum determined by spectral index $n_s$, and of the local form at leading order in $\frac{k_1}{k_S}$

$$\langle \mathcal{R}_{\vec{k}_1}\mathcal{R}_{\vec{k}_2}\mathcal{R}_{\vec{k}_3}\rangle_s \underset{k_1 \ll k_S}{\simeq} (2\pi)^3\delta(\sum_i \vec{k}_i)(1-n_s)P_s(k_1)P_s(k_S)\,.$$

- correction of the order $\left(\frac{k_1}{k_S}\right)^2$ and higher, their form is model dependent

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# Squeezing limit and very high energy physics

## Modified scenarios

New general constraining arguments and new contribution invalidating standard argument

- contribution to non-Gaussianities at much earlier times $\eta_c, \eta_{\mathrm{II}}$ from particle creation
- although $k_1$ is small, possibly $k_1\eta_c, k_1\eta_{\mathrm{II}} > 1$, so perturbation depending on $k_1$ is not superhorizon
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# Example: Einstein-Hilbert action cubic coupling, squeezing

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Example: cubic non-higher-derivative coupling

$$\delta_\beta F(k_1, k_2, k_3, \eta) \propto \sum_j \mathrm{Re}\left[\beta^*_{k_j} \frac{1 - e^{i(\sum_{h\neq j} k_h - k_j)\eta_c}}{\sum_{h\neq j} k_h - k_j}\right]$$

Dominant contribution when $k_j = k_{2,3} \sim k_S$ ($\theta_j$ angle between $k_1, k_j$):

$$j = 2 \text{ or } 3 \qquad \sum_{h\neq j} k_h - k_j \underset{k_1 \ll k_{2,3}}{\simeq} k_1(1 + \cos\theta_j) \equiv k_1\, v_{\theta_j}\,.$$

Leading correction to the bispectrum

$$\delta_\beta \langle \zeta_{c,\vec{k}_1} \zeta_{c,\vec{k}_2} \zeta_{c,\vec{k}_3} \rangle_{\mathrm{mv}} \underset{k_1 \ll k_S}{\simeq} (2\pi)^3 \delta(\sum_i \vec{k}_i)\, \mathcal{B}^{\mathrm{mv}}\, P_s(k_1) P_s(k_S)\,,$$

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Dominant contribution when $k_j = k_{2,3} \sim k_S$:

$$j = 2 \text{ or } 3: \qquad S_0(\{x_{h\neq j}\},x_j,y',1) \underset{x_1\ll 1}{\simeq} x_1\, \tilde{v}_{\theta_j}(y').$$

Leading correction to the bispectrum

$$\delta_\beta \langle \zeta_{c,\vec{k}_1} \zeta_{c,\vec{k}_2} \zeta_{c,\vec{k}_3} \rangle_{\mathrm{mv}} \underset{k_1 \ll k_S}{\simeq} (2\pi)^3 \delta(\sum_i \vec{k}_i)\, \mathcal{B}^{\mathrm{mv}}\, P_s(k_1) P_s(k_S),$$

$$\mathcal{B}^{\mathrm{mv}} = \sum_{j=2}^{3} \mathcal{B}_{(j)}^{\mathrm{mv}}, \qquad \mathcal{B}_{(j)}^{\mathrm{mv}} = \begin{cases} -8\,\epsilon\, \frac{k_S}{k_1}\, \mathrm{Re}\left[\beta_{k_S}^{\mathrm{mdr}*}\right] |\gamma(1, -\frac{H}{\Lambda})|^2, & \text{if } \frac{\Lambda}{H} x_1 \gg 1 \\ 4\,\epsilon\, \frac{\Lambda}{H} \sum_{j=2}^{3} \mathrm{Im}\left[\beta_{k_j}^{\mathrm{mdr}*} \mathcal{I}_j\right]_{k_{j=2,3}=k_S} & \text{if } \frac{\Lambda}{H} x_1 \ll 1 \end{cases}$$

# Example: Einstein-Hilbert action cubic coupling, squeezing

## Modified dispersion relations

Example: cubic non-higher-derivative coupling

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# Non-Gaussianities: sensitivity to very high energy physics

## Modified vacuum

- local form of the bispectrum $\sim k_1^{-3}$
- negligible amplitude $\sim \epsilon$

## Modified vacuum

- non-local $\sim k_1^{-4}$, if $|k_1 \eta_c v_{\theta_j}| \gg 1$ ($\frac{\Lambda}{H} \gg 1$)
- for any coupling in a Lorentz invariant theory $k_1^{-n}$, $n = 4$ is the largest possibility for $n$
- amplitude enhanced
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# Conclusions and punch line

- fundamental theories could benefit from the "largest laboratory ever", now yielding accurate data
- on the other hand, theories of the early Universe necessarily need a ultraviolet complete theory,
- fundamental theory and cosmology can make huge progresses together. Could we have also a true experimental validation?
- we have found that modification of the theory at high-energy could lead to different shapes and enhanced non-Gaussianities (visible perhaps in the CMBR), or non-local behaviour and enhanced non-Gaussianities in the squeezing limit (visible perhaps via the halo bias)

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