High-energy physics and cosmological perturbations: observing new physics at high energy scales

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Observations agree well with homogeneous isotropic background + quantum perturbations

$T = 2.725 \text{ K}$.
Some LSS

Observations agree well with homogeneous isotropic background + quantum perturbations

Two-degree-Field Galaxy Redshift Survey, 2dFGRS
Sloan Digital Sky Survey, SDSS
Observables in cosmological perturbation theory

Observables: in-in correlators of operators $\hat{O}(\eta)$ at a given time $\eta$:

Fields correlator $\rightarrow$ Depend on mode functions $f_k(\eta) = a(\eta) R_k(\eta)$ / Hilbert space

Good diagnostic of physics at inflationary scales/times

- interactions
- background potential
- dispersion relation, universe expansion

Also good diagnostic of physics much earlier/at higher energies

- form of mode functions/choice of initial state
- corrections to potential
- correction to kinetic terms
Observables in cosmological perturbation theory

Observables: in-in correlators of operators \( \hat{O}(\eta) \) at a given time \( \eta \):

\[
\langle \Omega_{\text{in}} | \hat{O}(\eta) | \Omega_{\text{in}} \rangle = \langle \Omega_{\text{in}} | \bar{T} \left( e^{i \int_{\eta_{\text{in}}}^{\eta} d\eta H_I} \right) \hat{O}(\eta) T \left( e^{-i \int_{\eta_{\text{in}}}^{\eta} d\eta H_I} \right) | \Omega_{\text{in}} \rangle.
\]

Fields correlator \( \rightarrow \) Depend on mode functions \( f_k(\eta) = a(\eta) R_k(\eta) \) /Hilbert space

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

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Inflation acts as magnifying lens on microphysics: growth (stretching) of physical scales $p_{\text{phys}} = \frac{k}{a(\eta)}$.

- Perturbations are sensitive to initial conditions above effective theory cutoff: scales $E$ observed today were in the (trans-)Planckian regime.

$$E > M_{\text{Planck}} \equiv \sqrt{\frac{hc}{G}}$$
I will focus on adiabatic scalar perturbation(s) (slow-roll single-field) and consider new physics above a scale $\Lambda$

Top-down approach: use a UV complete/high-energy model to derive effects

“Bottom-up”: parametrize the effects of high-energy physics.

I will discuss two cases

- modified dispersion relations (Lorentz violation)
- modified initial state
$P_k = \frac{k^3}{2\pi^2} \lim_{\eta \to 0} \langle \mathcal{R}_k(\eta) \mathcal{R}_k(\eta) \rangle$
Spectrum within standard scenario

Lorentzian dispersion and so-called Bunch-Davies/adiabatic vacuum

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

- preservation of de Sitter symmetry group
- “no particles” (adiabatic criterion) at very small scales (mimicking Minkowski)
- certain behaviour of the two-point functions (no antipodal poles)

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

\[ \nu = \frac{3}{2} + \frac{1 - n_s(V)}{2} \quad n_s = \text{spectral index} \]

Spectrum:

\[ P_s(k) \sim \frac{H^2}{4 M_{\text{Planck}}^2 \epsilon k^3} \left( \frac{k}{aH} \right)^{1-n_s} \]
Spectrum for modified initial state

Theory valid up to a physical scale $\Lambda$. Initial state specified at a certain time $\eta_c$.

\[ \omega(\eta, k)^2 = k^2, \quad f_k(\eta) = \alpha_k^{\text{mv}} \sqrt{-\eta} H_\nu^{(1)}(-k\eta) + \beta_k^{\text{mv}} \sqrt{-\eta} H_\nu^{(2)}(-k\eta), \]
\[ \alpha_k^{\text{mv}}, \beta_k^{\text{mv}} \text{ depend on } k, \Lambda, \eta_c. \]

Two-point function, at leading order in slow-roll and $\beta_k^{\text{mv}}$ [Easther et al. 2001, Danielsson 2002]:

\[ P_{\text{mv}}(k) \sim \frac{H^2}{4M_{\text{Planck}}^2 \epsilon k^3} \left( \frac{k}{aH} \right)^{1-n_s} \left( 1 + 2 \text{Re}(\beta_k^{\text{mv}} e^{-i\text{Arg}(\alpha_k^{\text{mv}})}) \right). \]
Spectrum for Lorentz violation

Generic modified dispersion relations

\[ \omega(\eta, k) = a(\eta)\omega_{\text{phys}}(p) = k F \left( \frac{H}{\Lambda} k \eta \right), \quad F(\epsilon \rightarrow 0) \rightarrow 1, \quad H \ll \Lambda. \]

Quite different from the standard scenario only if adiabaticity is violated

\[
\begin{align*}
\omega_{\text{phys}}(p) &= k F \left( \frac{H}{\Lambda} k \eta \right), \\
F(\epsilon \rightarrow 0) &\rightarrow 1, \\
H &\ll \Lambda.
\end{align*}
\]

\[
f_k(\eta) = \begin{cases} 
\varsigma_k u_1(\eta, k) & \text{I: } \eta < \eta_1^{(k)} \\
B_1 U_1(\eta, k) + B_2 U_2(\eta, k) & \text{II: } \eta_1^{(k)} < \eta < \eta_2^{(k)} \\
\alpha_k u_1(\eta, k) + \beta_k mdr u_2(\eta, k) & \text{III: } \eta_2^{(k)} < \eta < \eta_3^{(k)} \\
D_1 V_1(\eta, k) + D_2 V_2(\eta, k) & \text{IV: } \eta_3^{(k)} < \eta
\end{cases}
\]

- choose adiabatic vacuum for \( u_1 \) at early times/small scales
- backreaction constraints WKB violation interval: \( \Delta = \frac{\eta_1 - \eta_2}{\eta_1} \ll 1 \),
- universal behaviour \( \beta_k^{mdr} = [i\beta(F; \eta_1, k)\Delta + O(\Delta^2)]e^{-\frac{2i}{\epsilon} \Omega(F)\epsilon \eta_1} \varsigma_k \),

Spectrum

\[
P_{mdr}(k) \sim_{k \rightarrow 0} \frac{H^2}{4M_{\text{Planck}}^2 \epsilon k^3} \left( 1 + 2 \text{Re}(\beta_k^{mdr}) \right).
\]
Main universal feature

- modulation of the spectrum (oscillation features)

Features distinguishing (classes of) initial states

- different amplitude and period of oscillations
the observer interprets the oscillations as due to particle creation $\rightarrow$ pattern of interference due to “positive” and “negative energy” modes

$$N_{\text{part}} \sim \int_k |\beta_k|^2$$

[Recall that the particle concept is not well-defined in non-static backgrounds. But it relates easily to experiments.]
Non-Gaussianities: BISPECTRUM

\[ B(\vec{k}_1, \vec{k}_2, \vec{k}_3, \eta) \equiv \langle R(\vec{k}_1) R(\vec{k}_2) R(\vec{k}_3) \rangle |_{\eta \sim 0} \]
In the standard slow-roll single-field (only adiabatic) Lorentz-invariant scenario with adiabatic vacuum: strong suppression.

Traditional parametrization:

\[
B(\vec{k}_1, \vec{k}_2, \vec{k}_3, \eta) = (2\pi)^7 \delta(\sum_i \vec{k}_i) \left(-\frac{3}{5} f_{NL}\right) \left(\frac{H^2}{4eM_{\text{Planck}}^2}\right)^2 \frac{4}{\prod_i 2k_i^3} F(k_1, k_2, k_3)
\]

\[
f_{NL} \approx -\frac{\dot{H}}{H^2} \ll 1
\]
Example: Einstein-Hilbert coupling $H(\ell) = \int d^3x \ a^3(\frac{\phi}{H})^4 \frac{H}{M_{\text{Planck}}^2} \mathcal{R}^2 \partial^{-2} \mathcal{R}'$

Standard scenario [Maldacena, 2002]

$$F(k_1, k_2, k_3, \eta)_{\text{BD}} = \frac{1}{k_1 + k_2 + k_3} \equiv \frac{1}{k_t}$$

Modified initial state Enhancement for folded [Chen et al. 2007, Holman-Tolley 2008]

$$F(k_1, k_2, k_3) \sim 1 - \sum_j \text{Re} \left[ \beta_{k_j}^* k_t \frac{1 - e^{i(\sum_{h \neq j} k_h - k_j)\eta_c}}{\sum_{h \neq j} k_h - k_j} \right] \frac{1}{k_t} \frac{k_j = \sum_{h \neq j} k_h}{k_t} \Rightarrow |\beta_{k_j}| \frac{k_t \eta_c}{k_t} \left( = |\beta_{k_j}| \frac{\Lambda}{H} \frac{1}{k_t} \right)$$

Modified dispersion relation Enhancements [Chialva, 2011]

$$\delta F(k_1, k_2, k_3) \sim 1 + \sum_{j=1}^{3} \text{Re} \left[ (\beta_{k_j}^{\text{mdr}})^m \frac{\Lambda}{H} \int_{y_\parallel} y' \ k_t g(\{k_{h \neq j}\}, k_j, y') e^{i \frac{\Lambda}{H} S_0(\{k_{h \neq j}\}, k_j, y')} \right] ,$$

$$\rightarrow \sum_j \left( \frac{\Lambda}{H} \right)^{1 - \frac{1}{n}} \frac{1}{|\partial^n y S_0(\{x\}, y*)|^{\frac{1}{n}} |\beta_{k_j}^*| \frac{1}{k_t}} ,$$

for any critical point configuration $\partial^m y S_0(\{x\}, y)|_{y=y*} = 0 \ \forall \ m < n$.
Non-Gaussianities: sensitivity to very high energy physics

Modified initial state and Modified dispersion relations

Common features
▶ oscillating shape function $F$
▶ enhancements
▶ greater enhancements for interactions that scale with more powers of $\frac{1}{a}$: stronger sensitivity to higher derivative couplings

Distinctive features
▶ different patterns of oscillations
▶ different magnitude of enhancements and enhancements for different configurations
Physical interpretation:

- **Standard scenario**: the largest contribution to non-Gaussianities is at late times (\( \sim \) horizon crossing):

- **High energy physics scenarios**: particle creation \( \rightarrow \) non-Gaussianities sizable also at early times and enhanced by
  - interference effects from negative-\( / \)positive-energy components
  - cumulative effect from time integration (consequence of time evolution)
Example: Einstein-Hilbert action cubic coupling

\[ \delta \hat{F}_3,_{\alpha}(1,x_2,x_3), \Lambda=10^3 H \] \[ |\beta|^{-1} \delta \hat{F}_3,_{\beta}(1,x_2,x_3), \Lambda=10^3 H \]

**Figure**: a) Bispectrum for standard scenario, b) Leading $\beta$ contribution for modified dispersion relation of figure 2.

\[ \omega_\text{phys}(p)^2 \Lambda^{-2} \]

**Figure**: Dispersion relation used for b).
Non-Gaussianities: squeezed limit (LSS)

\[ B(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \eta) \Big|_{k_1 \ll k_2 \sim k_3 \sim k_S} \]

\[ \left( \frac{k_1}{k_S} = \text{sensitivity of observation} \right) \]
Squeezed limit in the Standard Scenario

Powerful “generic” features

- non-Gaussianities peaked at late times $\eta \sim 0$ (horizon crossing, particle creation)

- “squeezed” $R_{k_1}$ is superhorizon ($|k_1\eta| \ll 1$) at peak time, acts as background for the other perturbations shifting their exit-of-horizon times

- limit determined by spectral index $n_s$, and of local form at leading order in $\frac{k_1}{k_S}$

\[
\langle R_{\vec{k}_1} R_{\vec{k}_2} R_{\vec{k}_3} \rangle_s \sim \frac{(2\pi)^3}{k_1 \ll k_S} \delta \left( \sum_i \vec{k}_i \right) \left( 1 - n_s \right) P_s(k_1) P_s(k_S) O(\varepsilon) \sim k_1^{-3}
\]
Squeezed limit with new high-energy physics.

New physics $\rightarrow$ new general features

- particle creation $\rightarrow$ non-Gaussianities sizable already at earlier time
  \[ \eta_{\Pi} \sim -\frac{\Lambda}{Hk_S}, \text{ enhanced by interference and accumulation in time} \]

- although $k_1$ is small (but non-zero), possibly $|k_1\eta_{\Pi}| \gtrsim 1$, so perturbation depending on $k_1$ may be subhorizon at non-Gaussianities production

Example $H(i) = -\int d^3 \mathbf{x} a^3 \left( \frac{\dot{\phi}}{H} \right)^4 \frac{H}{M_{\text{Planck}}^2} \mathcal{R} \partial^2 \mathcal{R}'$ [Agullo et al. 2010, Chialva 2011]

\[
\delta \beta \left\langle \mathcal{R}_{-k_1} \mathcal{R}_{k_2} \mathcal{R}_{k_3} \right\rangle \sim \left( 2\pi \right)^3 \delta \left( \sum_i \mathbf{k}_i \right) B P_s(k_1) P_s(k_S),
\]

\[
B_{\text{mv}}^{\mu v} = \sum_{j=2}^{3} \begin{cases} 
-4 \epsilon \frac{k_S}{k_1} v_{\theta_j}^{-1} \text{Re} \left[ \beta_{k_S}^{\mu v*} \right] & \text{if } |k_1\eta_c v_{\theta_j}| \gg 1 \\
-4 \epsilon k_S \eta_c \text{Im} \left[ \beta_{k_S}^{\mu v*} \right] & \text{if } |k_1\eta_c v_{\theta_j}| \ll 1
\end{cases}
\]

\[
B_{\text{mdr}}^{\mu v} = \sum_{j=2}^{3} \begin{cases} 
-4 \epsilon \frac{k_S}{k_1} \frac{1}{1+\cos(\theta_j)} \text{Re} \left[ \beta_{k_S}^{\mu v*} \right] & \text{if } \mathbf{k}_1 \parallel \mathbf{k}_j \\
4 \epsilon \left( \frac{\Lambda}{H} \right)^{\frac{1}{\kappa+1}} \left( \frac{k_S}{k_1} \right)^{\frac{1}{\kappa+1}} \Gamma \left( \frac{1}{\kappa+1} \right) \text{Im} \left[ \beta_{k_S}^{\mu v*} e^{i \frac{\pi}{2} \text{sign}(F(\kappa))} \right] & \text{if } \mathbf{k}_1 \parallel \mathbf{k}_j \\
4 \epsilon \frac{\Lambda}{H} \text{Im} \left[ \beta_{k_S}^{\mu v*} \mathcal{O}(1) \right] & \text{if } \frac{\Lambda}{H} \frac{k_1}{k_S} \gg 1 \\
4 \epsilon \left( \frac{\Lambda}{H} \right)^{\frac{1}{\kappa+1}} \left( \frac{k_S}{k_1} \right)^{\frac{1}{\kappa+1}} \Gamma \left( \frac{1}{\kappa+1} \right) \frac{\text{Im} \left[ \beta_{k_S}^{\mu v*} e^{i \frac{\pi}{2} \text{sign}(F(\kappa))} \right]}{(\kappa+1) |F(\kappa)| \frac{1}{\kappa+1}} & \text{if } \frac{\Lambda}{H} \frac{k_1}{k_S} \ll 1
\end{cases}
\]
Squeezed limit: signatures of high energy physics

All-couplings analysis using effective theory for single-field inflation. [Chialva 2011]

**Standard scenario** (Lorentz unbroken)

- **local** form of the bispectrum $\sim k_1^{-3}$
- **negligible** amplitude $f_{NL} \sim (1 - n_s) = O(\varepsilon)$

**Modified initial state**

- **non-local** $\sim k_1^{-4}$, if $|k_1 \eta c \nu_{\theta_j}| \gg 1 \left( \frac{k_1}{k_S} \frac{\Lambda}{H} \gg 1 \right)$
- for any coupling in a Lorentz invariant theory $k_1^{-n}$, $n_{\text{max}} = 4$
- **amplitude enhanced**

**Modified dispersion relations**

- for $\frac{\Lambda}{H} \frac{k_1}{k_S} \ll 1$: leading contribution **local** but amplitude enhanced $f_{NL} \sim \varepsilon \frac{\Lambda}{H}$ (new higher derivative coupling suppressed by powers of $\frac{k_1}{k_S}$)
- for $\frac{\Lambda}{H} \frac{k_1}{k_S} \gg 1$: **non-local**, leading terms grow as $\sim k_1^{-4}$, higher-derivative couplings can grow $k_1^{-n}$ $n > 4$ but suppressed by $\left( \frac{H}{\Lambda} \right)^m$, $m \geq n$
Squeezed limit: example of estimate

Example: Einstein-Hilbert cubic coupling.

If we can probe only down to \( \frac{k_1}{k_S} \gtrsim 10^{-2} \), using

\[
\begin{align*}
\varepsilon & \sim |\mu| \sim 10^{-2}, \\
H & \sim 10^{-5} M_{\text{Planck}}, \\
\Lambda & \sim 10^{-3} M_{\text{Planck}} \\
|\beta_{k}^{mv}| & \leq \sqrt{\varepsilon |\mu|} \frac{H M_{\text{Planck}}}{\Lambda^2}, \\
\mu & \equiv \eta_{sl} - \varepsilon
\end{align*}
\]

(WMAP) 
(GUT) 
(backreaction)

\[
\Downarrow
\]

\[
|\mathcal{B}^{mdr}| \lesssim \begin{cases} 
10^{-1} \frac{k_S}{k_1} (1 - n_s) & \text{if } \vec{k}_2 \parallel \vec{k}_3 \\
10^{\frac{n - 1}{\kappa + 1}} \left( \frac{k_S}{k_1} \right)^{\frac{1}{\kappa + 1}} (1 - n_s) & \text{if } \vec{k}_2 \parallel \vec{k}_3 \\
10(1 - n_s) & \text{if } \frac{\Lambda}{H} x_1 \ll 1
\end{cases}
\]

Diego Chialva  (UMons)  
New high-energy physics in the sky  
EPS-hep 2013
Conclusions, Planck and after Planck

We have seen that primordial perturbations could provide us with a window on very high-energy physics.

What can Planck data tell us about this?

Search for modified initial state

- the additional parameters give good fit to spectrum data, but parameters quite constrained (fine tuned parameter space)
- the analysis of Non-Gaussianities (bispectrum) did not make use of freedom in parameter space (but best-fit spectrum models have to high oscillations to be tested at present). Results using four exemplary templates gave only $1\sigma$.

What about future Planck and after Planck?

- Lorentz violation in non-Gaussianities? Too much parameter space?
- Shape function and resonances?
- LSS?