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

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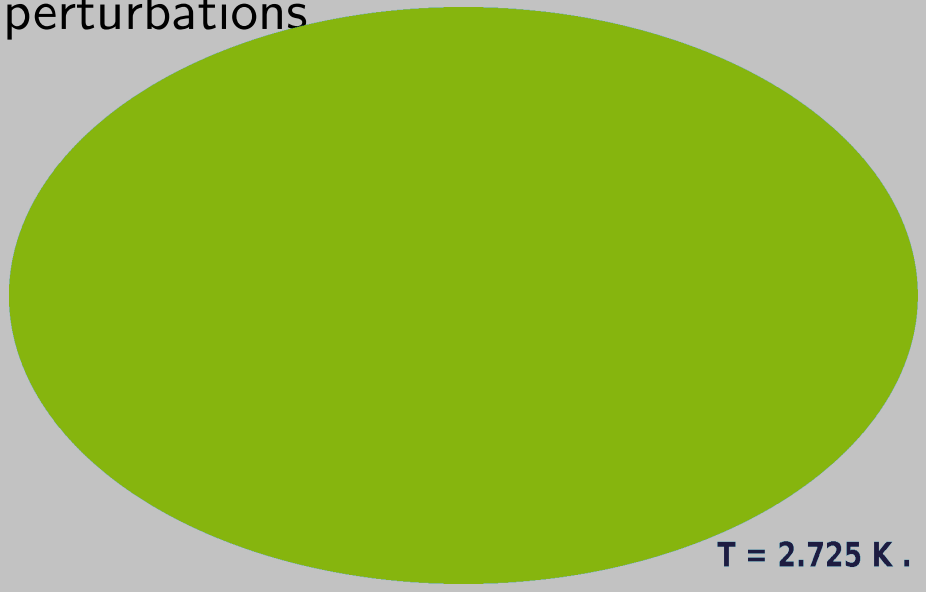
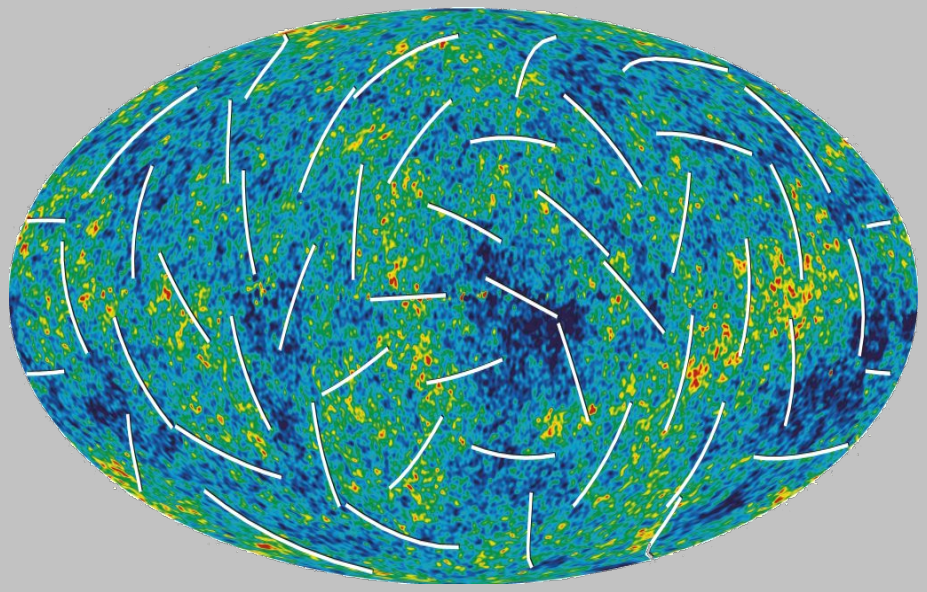
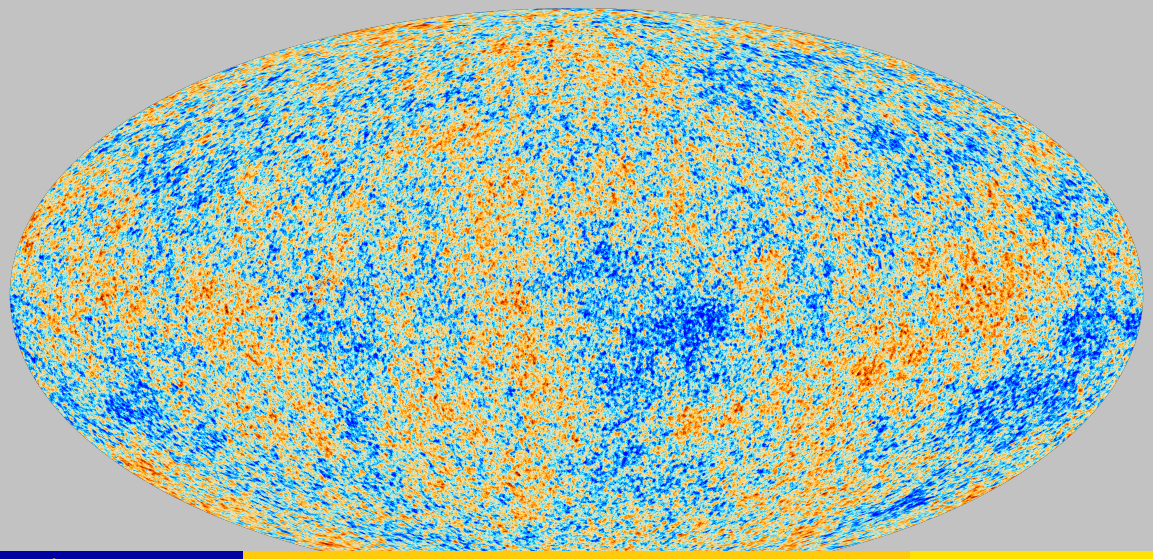
Cobe,Wmap, Planck

Observations agree well with homogeneous isotropic background + quantum perturbations







Some LSS

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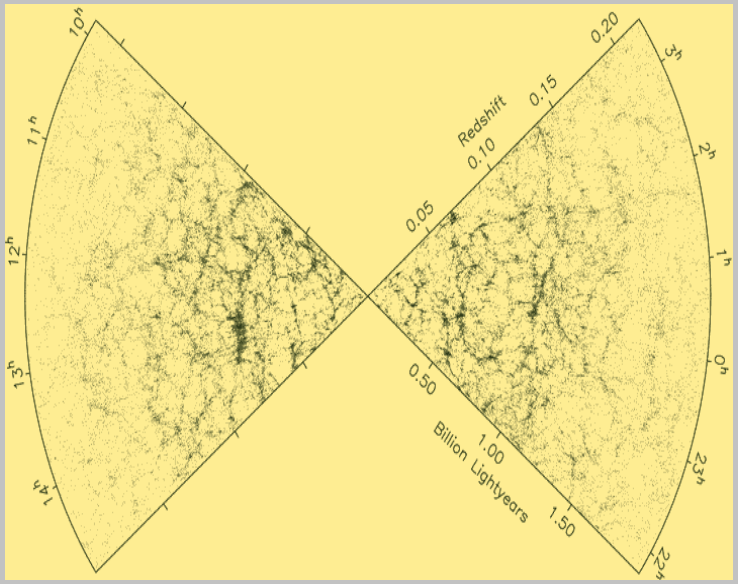
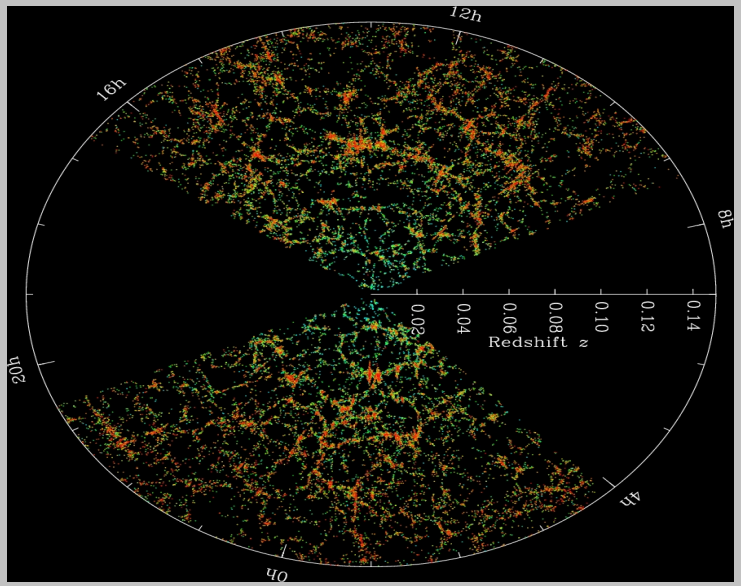


Two-degree-Field Galaxy Redshift Survey, 2dFGRS



Sloan Digital Sky Survey, SDSS

Observables in cosmological perturbation theory

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

Fields correlator $\rightarrow$ Depend on mode functions $f_k(\eta) = a(\eta)\mathcal{R}_k(\eta)$ /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

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

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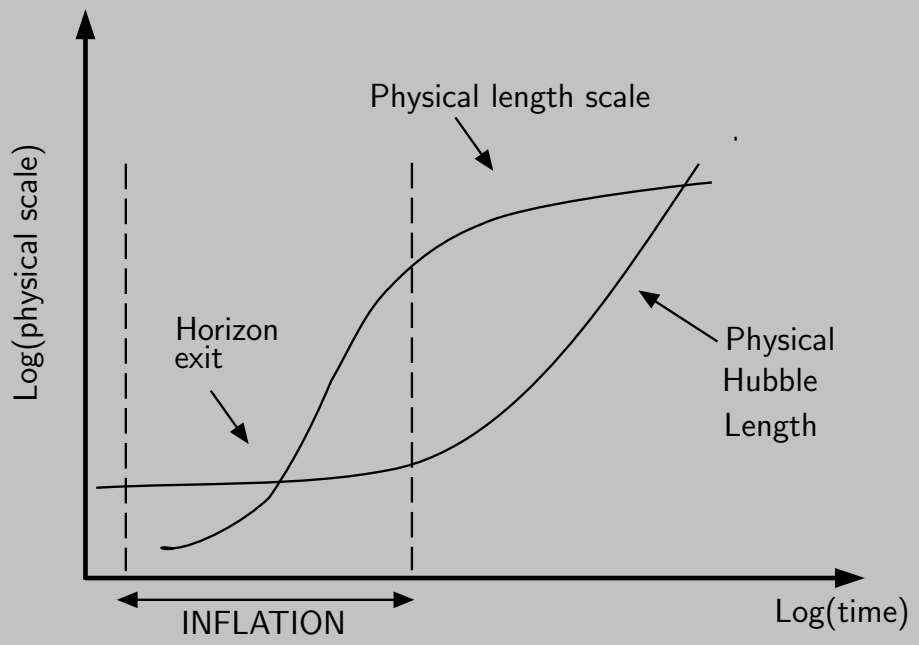
The magnifying glass

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 the were in the (trans-)Planckian regime $E > M_{\text{Planck}} \equiv \sqrt{\frac{hc}{G}}$

Observables in cosmological perturbation theory

I will focus on adiabatic scalar perturbation(s) (slow-roll single-field) and consider new physics above a scale Λ

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

SPECTRUM

$$P_k = \frac{k^3}{2\pi^2} \lim_{\eta \to 0} \langle \mathcal{R}_k(\eta) \mathcal{R}_k(\eta) \rangle$$

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)

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

$$\nu = \frac{3}{2} + \frac{1 - n_s(V)}{2} \qquad n_s = \text{spectral index}$$

Spectrum:

$$P_s(k) \underset{k\to 0}{\sim} \frac{H^2}{4M_{\text{Planck}}^2 \epsilon k^3} \left(\frac{k}{aH}\right)^{1-n_s}$$

Spectrum for modified initial state

Theory valid up to a physical scale Λ. Initial state specified at a certain time η_c.

$$\omega(\eta,k)^2 = k^2\,, \qquad f_k(\eta) = \alpha_k^{\rm mv}\sqrt{-\eta}H_\nu^{(1)}(-k\eta) + \beta_k^{\rm mv}\sqrt{-\eta}H_\nu^{(2)}(-k\eta)\,,$$

$\alpha_k^{\rm mv}, \beta_k^{\rm mv}$ depend on k, Λ, η_c.

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

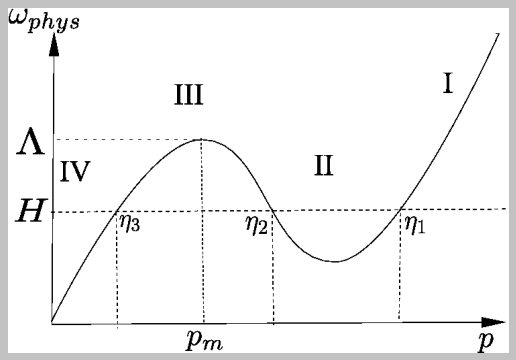
$$P_{\rm mv}(k) \underset{k\to 0}{\sim} \frac{H^2}{4M_{\rm Planck}^2\epsilon k^3}\left(\frac{k}{aH}\right)^{1-n_s}\left(1 + 2\,{\rm Re}(\beta_k^{\rm mv} e^{-i{\rm Arg}(\alpha_k^{\rm mv})})\right).$$

Spectrum for Lorentz violation

Generic modified dispersion relations

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

Quite different from the standard scenario only if adiabaticity is violated



$$f_k(\eta) = \begin{cases} \varsigma_k\, u_1(\eta,k) & \mathrm{I}:\ \eta < \eta_{\mathrm{I}}^{(k)} \\ B_1\,\mathcal{U}_1(\eta,k) + B_2\,\mathcal{U}_2(\eta,k) & \mathrm{II}:\ \eta_{\mathrm{I}}^{(k)} < \eta < \eta_{\mathrm{II}}^{(k)} \\ \alpha_k^{\text{mdr}}\ u_1(\eta,k) + \beta_k^{\text{mdr}}\ u_2(\eta,k) & \mathrm{III}:\ \eta_{\mathrm{II}}^{(k)} < \eta < \eta_{\mathrm{III}}^{(k)} \\ D_1\,\mathcal{V}_1(\eta,k) + D_2\,\mathcal{V}_2(\eta,k) & \mathrm{IV}:\ \eta_{\mathrm{III}}^{(k)} < \eta \end{cases}$$

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

Spectrum $$P_{\text{mdr}}(k) \underset{k\to 0}{\sim} \frac{H^2}{4M^2_{\text{Planck}}\,\epsilon k^3}\left(1 + 2\,\mathrm{Re}(\beta_k^{\text{mdr}})\right).$$

Spectrum: signatures of high-energy physics

Main universal feature

- modulation of the spectrum (oscillation features)

Features distiguishing (classes of) initial states

- different amplitude and period of oscillations

Spectrum: physical interpretation of signatures

- the observer interprets the oscillations as due to particle creation $\rightarrow$ pattern of interference due to "positive" and "negative energy" modes

$$N_{\text{part}} \sim \int_k |\beta_k|^2 \tag{1}$$

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

Non-Gaussianities: BISPECTRUM

$$B(\vec{k}_1, \vec{k}_2, \vec{k}_3, \eta) \equiv \langle \mathcal{R}(k_1)\mathcal{R}(k_2)\mathcal{R}(k_3)\rangle|_{\eta\sim 0}$$

Non-Gaussianities

In the standard slow-roll single-field (only adiabatic) Lorentz-invariant scenario with adiabatic vacuum: strong suppression .

Traditional parametrization:

$$B(\vec{k}_1, \vec{k}_2, \vec{k}_3, \eta) = (2\pi)^7 \delta(\sum_i \vec{k}_i) \Big(-\frac{3}{5} f_{NL} \Big) \Big(\frac{H^2}{4\epsilon M^2_{\text{Planck}}} \Big)^2 \frac{4 \sum_i k_i^3}{\prod_i 2k_i^3} F(k_1, k_2, k_3)$$

$$f_{NL} \approx -\frac{\dot{H}}{H^2} \ll 1$$

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

Standard scenario [Maldacena, 2002]

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

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

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

Modified dispersion relation Enhancements [Chialva, 2011]

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

$$\to \sum_j \left(\frac{\Lambda}{H}\right)^{1-\frac{1}{n}} \frac{1}{|\partial^n_y S_{0\beta}(\{x\}, y_*)|^{\frac{1}{n}}} |\beta^*_{\vec{k}_j}| \frac{1}{k_t},$$

for any critical point configuration $\partial^m_y S_{0\beta}(\{x\}, y)|_{y=y_*} = 0 \quad \forall\, m < n\,.$

Non-Gaussianities: sensitivity to very high energy physics

Modified inital 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

Non-Gaussianities: sensitivity to very high energy physics

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

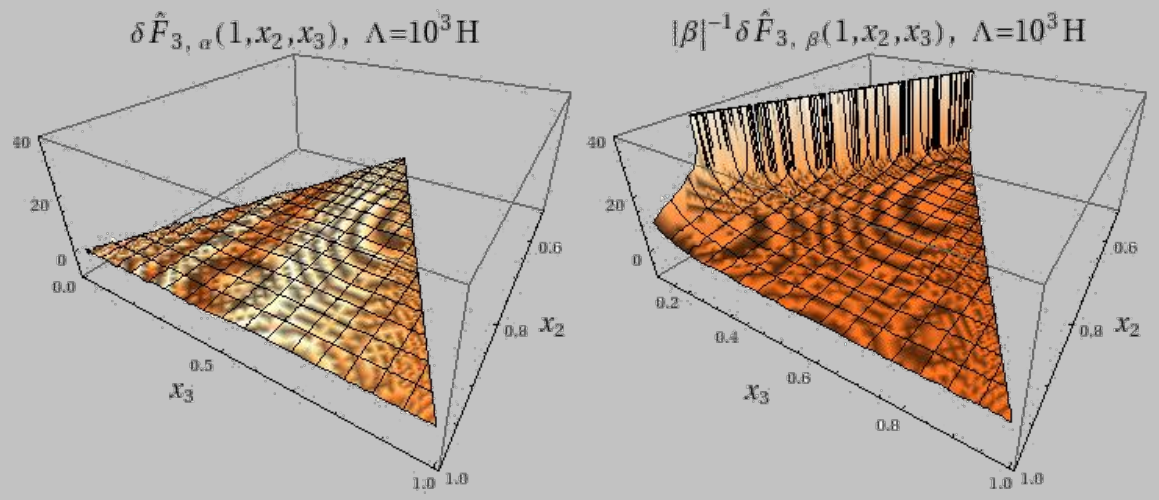


Figure : a) Bispectrum for standard scenario, b) Leading β contribution for modified dispersion relation of figure 2.

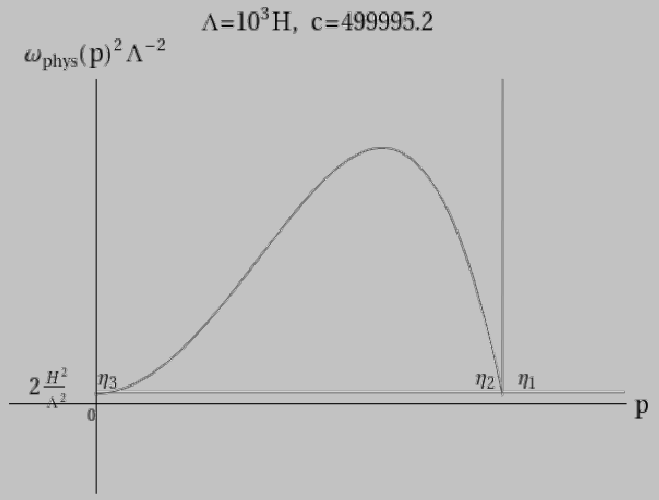


Figure : Dispersion relation used for b).

Non-Gaussianities: squeezed limit (LSS)

$$B(\vec{k}_1, \vec{k}_2, \vec{k}_3, \eta)|_{k_1 \ll k_2 \sim k_3 \sim k_S}$$

$$\left(\frac{k_1}{k_S} = \text{sensitivity of observation} \right)$$

Squeezed limit in the Standard Scenario

Powerful "generic" features

- non-Gaussianities peaked at late times $\eta \sim 0$ (horizon crossing, particle creation)
- "squeezed" $\mathcal{R}_{k_1}$ 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 $\frac{k_1}{k_S}$

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

Squeezed limit with new high-energy physics.

New physics $\rightarrow$ new general features

- particle creation $\rightarrow$ non-Gaussianities sizable already at earlier time $\eta_{\rm II} \sim -\frac{\Lambda}{H k_S}$, enhanced by interference and accumulation in time
- although k_1 is small (but non-zero), possibly $|k_1 \eta_{\rm II}| \gtrsim 1$, so perturbation depending on k_1 may be subhorizon at non-Gaussianities production

Example $H_{(I)} = -\int d^3x\, a^3 (\frac{\dot\phi}{H})^4 \frac{H}{M^2_{\rm Planck}} \mathcal{R}'^2 \partial^{-2} \mathcal{R}'$ [Agullo et al. 2010, Chialva 2011]

$$\delta_\beta \langle \mathcal{R}_{\vec{k}_1} \mathcal{R}_{\vec{k}_2} \mathcal{R}_{\vec{k}_3} \rangle \underset{k_1 \ll k_S}{\simeq} (2\pi)^3 \delta(\sum_i \vec{k}_i)\, \mathcal{B}\, P_s(k_1) P_s(k_S)\,,$$

$$\mathcal{B}^{\rm mv} = \sum_{j=2}^{3} \begin{cases} -4\,\epsilon\, \frac{k_S}{k_1}\, v_{\theta_j}^{-1} {\rm Re}\big[\beta^{\rm mv*}_{k_S}\big] & \text{if } |k_1 \eta_c v_{\theta_j}| \gg 1 \\ -4\,\epsilon\, k_S \eta_c\, {\rm Im}\big[\beta^{\rm mv*}_{k_S}\big] & \text{if } |k_1 \eta_c v_{\theta_j}| \ll 1 \end{cases}$$

$$\mathcal{B}^{\rm mdr} = \sum_{j=2}^{3} \begin{cases} \left[\begin{array}{ll} -4\,\varepsilon\, \frac{k_S}{k_1} \frac{1}{1+\cos(\theta_j)} {\rm Re}\Big[\beta^{\rm mdr*}_{k_S}\Big] & \text{if } \vec{k}_1 \nparallel \vec{k}_j \\ 4\,\varepsilon \big(\frac{\Lambda}{H}\big)^{1-\frac{1}{\kappa+1}} \big(\frac{k_S}{k_1}\big)^{\frac{1}{\kappa+1}} \Gamma\big(\frac{1}{\kappa+1}\big) \frac{{\rm Im}\Big[\beta^{\rm mdr*}_{k_S}\, e^{i\frac{\pi}{2}\frac{{\rm sign}(F^{(\kappa)})}{\kappa+1}}\Big]}{(\kappa+1)|F^{(\kappa)}|^{\frac{1}{\kappa+1}}} & \text{if } \vec{k}_1 \parallel \vec{k}_j \end{array} \right] & \text{if } \frac{\Lambda}{H}\frac{k_1}{k_S} \gg 1 \\ 4\,\varepsilon\, \frac{\Lambda}{H}\, {\rm Im}\big[\beta^{\rm mdr*}_{k_S}\, \mathcal{O}(1)\big] & \text{if } \frac{\Lambda}{H}\frac{k_1}{k_S} \ll 1 \end{cases}$$

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 $|k_1 \eta_c v_{\theta_j}| \gg 1$ ($\frac{k_1}{k_S}\frac{\Lambda}{H} \gg 1$)
- for any coupling in a Lorentz invariant theory k_1^{-n}, $n_{\max} = 4$
- 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

$$\varepsilon \sim |\mu| \sim 10^{-2}, \qquad H \sim 10^{-5} M_{\text{Planck}}, \qquad \text{(WMAP)}$$

$$\Lambda \sim 10^{-3} M_{\text{Planck}} \qquad \text{(GUT)}$$

$$|\beta_k^{\text{mv}}| \leq \sqrt{\varepsilon|\mu|}\frac{HM_{\text{Planck}}}{\Lambda^2}, \qquad \mu \equiv \eta_{\text{sl}} - \varepsilon \qquad \text{(backreaction)}$$

$$\Downarrow$$

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

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 1σ.

What about future Planck and after Planck?

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