Aspects of Non-Gaussianity in Primordial Tensor Modes

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Contents

Why Use Effective Field Theory

Constructing a model for inflation

- Define a model with a particular type of potential and kinetic term, motivated by particle physics and check inflationary conditions
- The Action for a single field slow roll inflation (minimally coupled to gravity) model:

$$\mathcal{S} = \int d^4x\sqrt{-g}[R + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)]$$

- Model $V(\phi)$ such that, $\frac{\partial V}{\partial \phi}(\epsilon)$ and $\frac{\partial^2 V}{\partial \phi^2}(\eta) << 1$ and produce sufficient amount of perturbation

Different potential or kinetic term $\rightarrow$ Different models

EFT of Inflation

C. Cheung, P. Creminelli, A.L. Fitzpatrick, J. Kaplan, L. Senatore, JHEP 03 (2008) 014

- Inflation has to end at some time, Condition $\longrightarrow \epsilon, \eta \sim 1$
- Symmetry of the system $\rightarrow$ Broken time diffeomorphism

Allowed terms in the Lagrangian:

- Unitary gauge: $\delta\phi = 0$
- Terms that are invariant under all diffeomorphism: $R_{\mu\nu\rho\sigma}$ and its co variant derivatives, contracted to give a scalar
- Generic function of time $f(t)$
- $\partial_\mu t \Rightarrow \delta^0_\mu$ and we can use g^{00} component and polynomials of it
- Covariant derivative of $\partial_\mu t$ which can be written as combination of extrinsic curvature $K_{\mu\nu}$ and g^{00} and their covariant derivative

In unitary gauge the action is:

$$\mathcal{S} = \int d^4x\sqrt{-g}F\left(R_{\mu\nu\sigma\rho}, K_{\mu\nu}, g^{00}, \nabla_\mu, t\right)$$

In unitary gauge the form of the action:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{pl}^2 R - \Lambda(t) - c(t)g^{00} + \frac{1}{2}M_2(t)^4(g^{00}+1)^2 - \frac{\bar{M}_1(t)^3}{2}(g^{00}+1)\delta K^\mu_\mu - \frac{\bar{M}_2(t)^2}{2}\delta K^{\mu 2}_\mu - \frac{\bar{M}_3(t)^2}{2}\delta K^\nu_\mu K^\mu_\nu + \frac{M_3(t)^4}{3!}(g^{00}+1)^3 - \frac{\bar{M}_4(t)^3}{3!}(g^{00}+1)^2\delta K^\mu_\mu - \frac{\bar{M}_5(t)^2}{3!}(g^{00}+1)\delta K^{\mu 2}_\mu - + ..\right] \quad (1)$$

- Three degrees of freedom $\rightarrow$ Curvature perturbation, 2 tensor perturbations
- $c(t)$ and $\Lambda(t)$ can be fixed by background evolution
- Setting $M_{1,2,3..} = \bar{M}_{1,2,3..} = 0 \rightarrow$ Slow-roll inflation
- Keeping higher derivative terms we will get $P(x, \phi)$

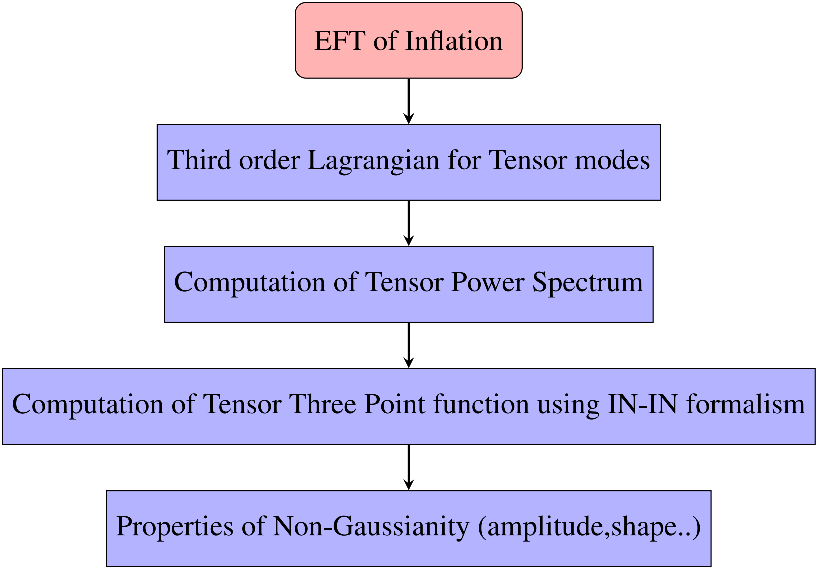
WHY Tensor Non-Gaussianity?

- Inflation, a good candidate to produce (Primordial) Gravitational Wave $\rightarrow$ *Tensor Perturbations*
- Small tensor-to-scalar ratio $r = \left(\frac{\mathcal{P}_T}{\mathcal{P}_S}\right) \leq 0.064$, Planck, 2018
- r determines the scale of inflation $(V^{\frac{1}{4}} = 3.3 \times 10^{16} r^{\frac{1}{4}} GeV)$
- The field excursion value also depends on $r \rightarrow$ $\Delta\phi_0 \sim \mathcal{O}(1)(r/0.01)^{\frac{1}{2}} M_{pl}$
- Production of gravitational waves:
    - **vacuum fluctuations?**
    - other sources?
    - Both can produce scale invariant tensor power spectrum $\Longrightarrow$ **'r' is NOT ENOUGH**
- Different models produce NON-GAUSSIANITY with distinct **shape** (momentum dependence) : can serve as an additional probe for PGW
- More observables depending on chirality and momentum configuration

WHY Tensor Non-Gaussianity?

- **Recent status from Planck**: $\frac{f_{NL}^{tens}}{10^2} = 4 \pm 15\ (68\%\ C.L.)$
- Constraint on tensor-scalar-scalar correlation using WMAP: $g_{tss} = -48 \pm 28\ (68\%\ C.L.)$, JCAP (2010)
  CMB-S4 can improve it by an order of magnitude [arXiv:1610.02743]
- **LiteBIRD**$\Rightarrow$ Precise whole sky maps of E and B modes: will tighten the constraint on f_{NL}^{tens}, J. Low. Temp. Phys. (2014)
- **LISA** will probe three point function of GW; can comment on its origin, [arXiv:1806.02819]
- BBO, DECIGO distant future observations, will probe GW directly

Model independent templates of three point function is needed for these observations


EFT of Inflation
Third order Lagrangian for Tensor modes
Computation of Tensor Power Spectrum
Computation of Tensor Three Point function using IN-IN formalism
Properties of Non-Gaussianity (amplitude,shape..)

The Lagrangian

- The spatial component of the metric can be written as,

$$g_{ij} = a^2(t)[(1 + 2\zeta(t,x)\delta_{ij}) + \gamma_{ij}] \quad (2)$$

where $\zeta(t,x)$ is scalar perturbation and $\gamma_{ij}(x,t)$ is tensor fluctuation

- Use transverse traceless gauge, $\rightarrow \gamma_{ii} = 0$ and $\partial_j \gamma_{ij} = 0$
- Most General Graviton Lagrangian,

$$S_3^T = \int d^4x \sqrt{-g} \left[\frac{M_{pl}^2}{8} \left(\dot{\gamma}_{ij}^2 - \frac{(\partial_k \gamma_{ij})^2}{a^2} \right) - \frac{\bar{M}_3^2}{8} \dot{\gamma}_{ij}^2 \right. \\ \left. - \frac{M_{pl}^2}{8} (2\gamma_{ik}\gamma_{jl} - \gamma_{ij}\gamma_{kl}) \frac{\partial_k \partial_l \gamma_{ij}}{a^2} - \frac{\bar{M}_9}{3!} \dot{\gamma}_{ij} \dot{\gamma}_{jk} \dot{\gamma}_{ki} \right] \quad (3)$$

- Two free EFT parameters : $\bar{M}_3$, $\bar{M}_9$ associated to $\delta K_\mu^\nu K_\nu^\mu$ and $\delta K_\mu^\nu \delta K_\nu^\rho \delta K_\rho^\mu$ describes the scenario

The Power Spectrum of Tensor Modes

- **The leading order EFT contribution is reflected in tensor sound speed which can differ from 1**

$$c_\gamma^2 = \frac{M_{pl}^2}{M_{pl}^2 - \bar{M}_3^2} \tag{4}$$

- Fourier transform of the tensor modes

$$\gamma_{ij}(x,t) = \int \frac{d^3k}{(2\pi)^3} \left[\epsilon_{ij}^{+}(\mathbf{k})\gamma_{\mathbf{k}}^{+}(t) + \epsilon_{ij}^{-}(\mathbf{k})\gamma_{\mathbf{k}}^{-}(t)\right] e^{i\mathbf{k}.\mathbf{x}} \tag{5}$$

$\epsilon_{ij}^{s}(\mathbf{k})$ are polarization tensor and $s = (+,-)$ is the helicity index

- We will stick to Bunch Davies Vacuum
- The power spectrum is given by,

$$\left\langle \gamma_k^s \gamma_{k'}^{s'} \right\rangle = \delta_{ss'}(2\pi)^3 \delta^{(3)}(\mathbf{k} - \mathbf{k}') \frac{H^2}{M_{pl}^2 c_\gamma} \frac{1}{k^3} \tag{6}$$

- **Limited momentum and chirality options**

Three point Function

There is no Parity violating term

- Eight Combinations of correlators : $\left\langle\gamma^+_{k_1}\gamma^+_{k_2}\gamma^+_{k_3}\right\rangle$, $\left\langle\gamma^-_{k_1}\gamma^-_{k_2}\gamma^-_{k_3}\right\rangle$, $\left\langle\gamma^+_{k_1}\gamma^+_{k_2}\gamma^-_{k_3}\right\rangle$ and its two cyclic permutations, $\left\langle\gamma^+_{k_1}\gamma^-_{k_2}\gamma^-_{k_3}\right\rangle$ and its two cyclic permutations.
- All of the correlators are not independent

Interaction Hamiltionian,

$$H_{int} = \int d^3x\, a^3 \left[\frac{M_{pl}^2}{8}\left(2\gamma_{ik}\gamma_{jl} - \gamma_{ij}\gamma_{kl}\right)\frac{\partial_k\partial_l\gamma_{ij}}{a^2} + \frac{\bar{M}_9}{3!}\dot{\gamma}_{ij}\dot{\gamma}_{jk}\dot{\gamma}_{ki}\right] \tag{7}$$

Three point Correlation Function: AN, SP, [Phys. Rev. D **98**, 083520]

$$\left\langle \gamma_{k_1}^{s_1}\gamma_{k_2}^{s_2}\gamma_{k_3}^{s_3} \right\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3}) \\ F(s_1k_1, s_2k_2, s_3k_3)\left(\frac{64H^4}{c_\gamma^2 M_{pl}^4}\frac{A(k_1,k_2,k_3)(s_1k_1+s_2k_2+s_3k_3)^2}{k_1^3k_2^3k_3^3} \right. \\ \left. +\frac{4\bar{M}_9 H^5}{M_{pl}^6}\frac{1}{k_1k_2k_3}\frac{1}{(k_1+k_2+k_3)^3}\right) \qquad (8)$$

$$A(k_1,k_2,k_3) = \frac{K}{16}\left(1-\frac{1}{k^3}\sum_{i\neq j}k_i^2k_j - \frac{4k_1k_2k_3}{K^3}\right) \text{ and}$$

$$F(x,y,z) = -\frac{1}{64x^2y^2z^2}(x+y+z)^3(x+y-z)(x-y+z)(y+z-x)$$

- The size of the higher order EFT term is measured by $\bar{M}_9$
- $\bar{M}_9 \leq M_{pl} \Rightarrow$ contribution of higher order of term $\sim \mathcal{O}\left(\frac{H}{M_{pl}}\right)^5$

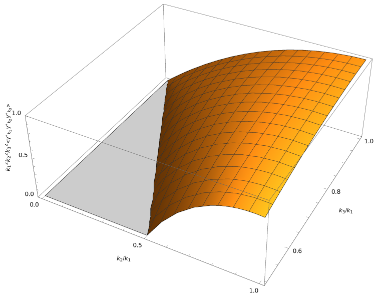


Figure: The amplitude of bispectrum due to the higher order EFT term, peaked in equilateral limit, $k_1 = k_2 = k_3$

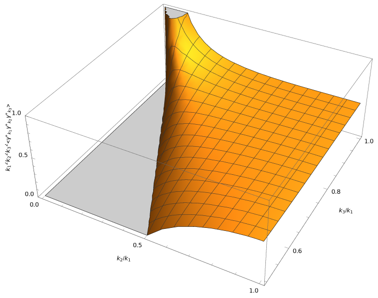


Figure: The amplitude of bispectrum due to lowest order EFT term peaked in squeezed limit, $k_1 \ll k_2 \sim k_3$

Squeezed limit configuration is much larger than equilateral limit

The Template

- The template for non-linearity parameter $f_{NL}^{T} \sim \frac{\langle\gamma\gamma\gamma\rangle}{\frac{18}{5}[\frac{2\pi^2}{k^3}\mathcal{P}_\zeta(k)]^2}$ where $\mathcal{P}_\zeta$ is the dimensionless scalar power spectrum. Using $\mathcal{P}_\zeta(k) = \frac{H^2}{8\pi^2 M_{pl}^2 c_s \epsilon}(\frac{k}{k_*})^{n_s-1}$
-

$$f_{NL}^{+++}|_{eq} = f_{NL}^{---}|_{eq} \sim \frac{5}{18}\left(\frac{c_s\epsilon}{c_\gamma}\right)^2\left(\frac{459}{2} - \frac{\bar{M}_9 H}{2M_{pl}^2}c_\gamma^2\right) \quad (9)$$

- Amplitude of non-Gaussianity is small and the characteristic is determined by lowest order EFT term

Tensor bispectrum due to vacuum fluctuation will be hard to detect even for next generation CMB missions

EFT of (P)reheating

- End of Inflation $\rightarrow$ Inflaton decays into other particles $\Rightarrow$ The process of (P)reheating
- With same broken time diffeomorphism the Lagrangian for one extra degree of freedom χ for (p)reheating can be written as,

O. Özsoy, J. T. Giblin, E. Nesbit, G. Şengör and S. Watson, PRD (2017)

$$\mathcal{S}_\chi = \int d^4x\sqrt{-g}\left[-\frac{\alpha_1(t)}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi + \frac{\alpha_2(t)}{2}(\partial^0\chi)^2 - \frac{\alpha_3(t)}{2}\chi^2 + \alpha_4\chi\partial^0\chi\right] \tag{10}$$

$$\mathcal{S}_{g\chi} = \int d^4x\sqrt{-g}\left[\beta_1(t)\delta g^{00}\chi + \beta_2(t)\delta g^{00}\partial^0\chi + \beta_3(t)\partial^0\chi - (\dot{\beta}_3(t) + 3H(t)\beta_3(t)\chi)\right] \tag{11}$$

If we set $\alpha_1 = 1$, $\alpha_3 = m_\chi^2 + 2\frac{g^2M_{pl}^2}{m_\phi^2}(3H^2 + \dot{H})$ and set other coefficients to zero we can get back the two field reheating scenario.

Tensor Powerspectrum

- For any source the equation of motion of tensor modes:

$$\gamma_{ij}'' - 2\frac{a'}{a}\gamma_{ij}' + c_\gamma^2 \Delta\gamma_{ij} = \boxed{\frac{2}{M_p^2}\Pi_{ij}^{ab}T_{ab}} \tag{12}$$

We have: $\Pi_{ij}^{ab}T_{ab} = -\alpha_1 \Pi_{ij}^{ab}\partial_a\chi\partial_b\chi$

- The powerspectrum can be given as,

$$\left\langle \gamma_{ij}(k,\tau)\gamma^{ij}(k,\tau')\right\rangle \propto \alpha_1^2 \int G_k(\tau,\tau')G_k(\tau,\tau'') \left\langle \chi(p,\tau')\chi(k-p,\tau')\chi(p',\tau'')\chi(k'-p',\tau'')\right\rangle \tag{13}$$

Where the Green's function takes the form:

$$G_k(\tau,\tau') = \frac{1}{c_\gamma^3 k^3 \tau'^2}\left[\left(1 + c_\gamma^2 k^2 \tau\tau'\right)\sin c_\gamma k(\tau-\tau') + c_\gamma k(\tau'-\tau)\cos c_\gamma k(\tau-\tau')\right]\Theta(\tau-\tau')] \tag{14}$$

Tensor Powerspectrum

AN, SP, Eur.Phys.J.C 80 (2020) 12, 1158

- If $\alpha_1 \neq 1$ the, χ will have a non-trivial sound speed, $c_\chi = \dfrac{\alpha_1}{\alpha_1 + \alpha_2}$
- We need to solve the equation of motion of χ particles:

$$\chi_c''(k,\tau) + \omega^2(k,\tau)\chi_c(k,\tau) = 0 \tag{15}$$

where,

$$\omega^2(k,\tau) = k^2 c_\chi^2 + a^2(\tau)\frac{\alpha_3}{\alpha_1+\alpha_2} - \frac{a''}{a} \tag{16}$$

- We expand the EFT parameters in leading order in time such that $\dfrac{\alpha_3}{\alpha_1+\alpha_2} = \dfrac{g}{2}(\phi-\phi_0)^2$, $\phi_0 = \phi(\tau - \tau_0)$
- The power spectrum will take the form,

$$\langle \gamma_{ij}(k,\tau)\gamma^{ij}(k',\tau)\rangle = \frac{\delta(k+k')}{4\pi^5 M_p^4}\frac{H}{k^6\, c_\gamma^6 c_\chi^3}\frac{(g\dot{\phi})^{3/2}}{\tau_0^3}\left(1+\frac{1}{4\sqrt{2}}\right)$$

$$\times\left(c_\gamma k\tau_0\cos(c_\gamma k\tau_0) - \sin(c_\gamma k\tau_0)\right)^2\left(\ln\frac{\sqrt{g\dot{\phi}}}{H}\right)^2 \tag{17}$$

Tensor Powerspectrum

- $\frac{(c_\gamma k\tau_0 \cos(c_\gamma k\tau_0) - \sin(c_\gamma k\tau_0))^2}{c_\gamma^3 k^3 \tau_0^3}$ gives maximum value for $c_\gamma k\tau_0 = 2.46$
- Effective enhancement due to sound speed: $\frac{1}{c_\gamma^3 c_\chi^3}$
- Setting $g = 1$, $H = 10^{13}\text{GeV}/c^2$, $M_p = 2.48 \times 10^{18}\text{GeV}/c^2$ and $\dot{\phi} = \sqrt{2\epsilon}HM_p$ for $c_\gamma = 1$ the contribution become significant for $c_\chi = 0.02$
- c_γ determines the peak frequency of the signal, smaller c_γ leads to higher peak frequency
- For $c_\chi < 1$ the resonance band become broadened and there is an enhancement in particle production
- Non-canonical term modifies the speed of inflation pushing the system to the broad parametric regime
    - q parameter of Mathieu equation: $q_{NCR} >> q_{CR}$
    - Growth over much larger range of k

The expression for three point function :

$$\langle \gamma^{s1}(k_1)\gamma^{s2}(k_2)\gamma^{s3}(k_3)\rangle_{so} = -\left(\frac{2}{(2\pi M_p)^2}\right)^3 \frac{\alpha_1^3}{(\alpha_1+\alpha_2)^3}\frac{H^{12}\tau_0^6}{g^3\dot{\phi}^3 k_1^3k_2^3k_3^3 c_\gamma^9} \left(\ln\frac{\sqrt{g\dot{\phi}}}{H}\right)^3 \times \prod_{i=1}^{3}\Big(c_\gamma k_i\tau_0\cos(c_\gamma k_i\tau_0)-\sin(c_\gamma k_i\tau_0)\Big)\left(\mathcal{A}_k+\mathcal{B}_k\right) \quad (18)$$

$$\mathcal{A}_k = \frac{(g\dot{\phi}_0)^{\frac{7}{2}}}{124416 c_\chi^9 H^9\pi^3\tau_0^9}\frac{\left(k_1^4+(k_2^2-k_3^2)^2-2k_1^2(k_2^2+k_3^2)\right)}{k_1^2k_2^2k_3^2} \times\left(-3(81\sqrt{2}+16\sqrt{3})\right)\pi\tau_0^2H^2c_\chi^2 \times\Big\{k_1^4+k_1^2(6k_2^2-2k_3^2)+(k_2^2-k_3^2)^2+4k_1^3k_2s_1s_2 +4k_1k_2(k_2^2-k_3^2)^2s_1s_2\Big\}+5\,perms, \quad (19)$$

$$\mathcal{B}_k = \frac{(g\dot{\phi}_0)^{\frac{7}{2}}}{124416 c_\chi^9 H^9\pi^3\tau_0^9}\frac{\left(k_1^4+(k_2^2-k_3^2)^2-2k_1^2(k_2^2+k_3^2)\right)}{k_1^2k_2^2k_3^2}g\dot{\phi} \times 2(243\sqrt{2}+32\sqrt{3})(k_1^2+k_2^2+k_3^2+2(2k_1k_2s_1s_2+2k_1k_3s_1s_3+2k_2k_3s_2s_3)). \quad (20)$$

In $c_\chi \to 0$ only B_k contributes

Three Point Function

- We use the same definition of f_{NL}
-

$$f_{NL}^{+++,eq} = \frac{1945.07 g\dot{\phi}_0 \left(\ln \frac{\sqrt{g\dot{\phi}_0}}{H} \right)^3}{M_p^2 c_\gamma^7 c_\chi^3 k_1^3 \tau_0^3} \times \left(c_\gamma k_1 \tau_0 \cos(c_\gamma k_1 \tau_0) - \sin(c_\gamma k_1 \tau_0) \right)^3 \times \left(\frac{c_s \epsilon}{c_\gamma} \right)^2 \tag{21}$$

$$f_{NL}^{+++,sq} = \frac{3457.89 g\dot{\phi} \left(\ln \frac{\sqrt{g\dot{\phi}}}{H} \right)^3}{M_p^2 c_\gamma^7 c_\chi^3 k_2^3 \tau_0^3} \prod_{i=1}^{3} \left(c_\gamma k_i \tau_0 \cos(c_\gamma k_i \tau_0) - \sin(c_\gamma k_i \tau_0) \right) \times \left(\frac{c_s \epsilon}{c_\gamma} \right)^2 \tag{22}$$

Quadrupolar modulation of tensor power spectrum can be calculated in order to discuss detectability

Theoretical issues with standard inflationary cosmology:

- **Swampland Criteria**:
  - The field excursion by scalar fields in field space is bounded by $\Delta\phi < \mathcal{O}(1)M_{pl}$.
  - The potential of a scalar field which rolls and dominates the energy density of the universe has to satisfy the condition $\frac{V'(\phi)}{V(\phi)} \sim \sqrt{2\epsilon} > cM_{pl}^{-1}$ with $c \sim \mathcal{O}(1) \Rightarrow$ Problem for inflation
- **Trans-Planckian Censorship Conjecture**: Length scales smaller than Planck scale can never exit the Hubble Horizon $\Rightarrow r < 10^{-30}$

Need to look at the theoretical side of inflation for solution

The general solution to Mukhanov-Sasaki equation:

$$v_k(\eta) \sim \alpha H_\nu^{(1)}(-k\eta) + \beta H_\nu^{(2)}(-k\eta) \tag{23}$$

with, Normalization condition: $|\alpha|^2 - |\beta|^2 = 1$

Bunch Davies Vacuum $\Rightarrow \eta \to -\infty; \alpha = \sqrt{\frac{\pi}{2}}; \beta = 0$

Non Bunch Davies State $\Rightarrow$ finite initial time η_0; $\beta \neq 0$; $\to$ Bogolyubov transformation of Bunch Davies state

NBD states are excited states built upon BD state and β is the measure of excitation

The Non-Bunch Davies States

With a model $\beta_k^{s/t} \sim \beta_0^{(s/t)} e^{-\frac{k^2}{(M_{(s/t)} a(\eta_0))^2}}$; $M_{(s/t)}$ scale of new physics, backreaction constraint on β:

$$\beta_0^{(s/t)} \leq \sqrt{\epsilon \eta'} \frac{H M_{pl}}{M_{(s/t)}^2}; \quad M_{(s/t)} > H \tag{24}$$

The scalar and tenor power spectrum:

$$P_\zeta(k) = \frac{H^2}{8\epsilon M_{pl}^2} |\alpha_k^s + \beta_k^s|^2 \tag{25}$$

and,

$$P_\gamma(k) = \frac{2H^2}{M_{pl}^2} |\alpha_k^t + \beta_k^t|^2 \tag{26}$$

Solution to SC

- **Swampland Criteria**: $\epsilon \sim c^2$, Consistency relation: $r = 16\epsilon$

The observational upper-bound on r is violated

- NBD state modifies the consistency relation:

$$r = 16\epsilon \frac{\Gamma_t}{\Gamma_s} \tag{27}$$

  - $\Gamma_s \gg 1$ is a possibility but it can violate the scalar non-Gaussianity bound
  - **Starting the tensor modes in NBD state while keeping scalar modes in BD state can give a valid scenario with $c \sim 0.9$**

- **TCC requirement**: $r < 10^{-30}$
- To increase r we need $\frac{\Gamma_t}{\Gamma_s} \gg 1$
- We need both scalar and tensor modes to start in NBD states
- Small value of ϵ saves the scalar non-Gaussianity bound
- To enhance Γ_t we need a large Γ_s:

$$\beta_0^{(t)} \leq \frac{\sqrt{\eta'}}{8\pi^2 P_\zeta} \left(\frac{H}{M_{(t)}} \right)^2 \sqrt{\Gamma_s} \tag{28}$$

- **A possible scenario to conform r with observational bound**: $M_{(s)} \sim 20H; M_{(t)} \sim 10H; \beta_0^s \sim 10^{11}; \beta_0^t \sim 10^{12}$

$$r < 0.001$$

Non-canonical scenario

AN, SP, [arXiv:2003.14066]

EFT modifies the propagation speed of scalar and tensor perturbations and the consistency relation becomes:

$$r = 16\epsilon \frac{\Gamma_t}{\Gamma_s} \frac{c_s}{c_t}$$

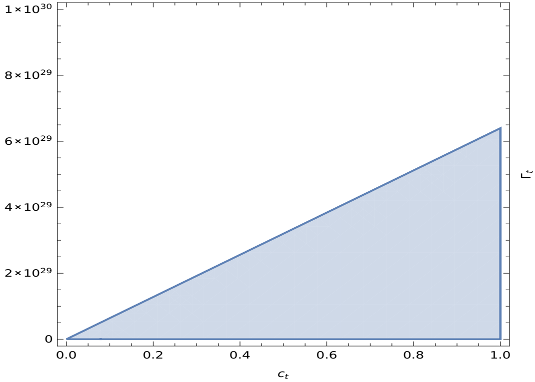


Figure: Allowed region for $r < 0.064$

Non-Gaussianities from NBD states

- Auto-correlators: amplitude does not get enhanced due to the definition of $f_{NL} \sim \dfrac{\langle\gamma\gamma\gamma\rangle}{P_\zeta P_\zeta}$:
  - Einstein-Hilbert part : $f_{NL}|_R \propto r^2$
  - $\bar{M}_9$ part : $\dfrac{H}{M_{pl}}$ factor further gets suppressed due to requirement of TCC, $f_{NL} \sim 10^{-21}$
  - But shape of both the correlators get modified due to NBD
  - The presence of $k_i + k_j - k_l$ **the folded limit is zero**; whereas the scalar non-Gaussianity peaks at folded limit for NBD states

- $(\gamma\gamma\zeta)$ correlator : generated from $\delta K_\mu^\nu \delta K_\nu^\mu \Rightarrow$ This operator modifies the sound speed
- Detection of this signal will signify a non-trivial propagation speed for tensor modes
- Amplitude: $f_{NL}|_{\gamma\gamma\zeta} \sim r c_t (c_t^{-2} - 1) \dfrac{\Gamma_t}{\Gamma_s}$,

  The signal strength can be large for $r \dfrac{\Gamma_t}{\Gamma_s} > 1$
- In these following shape: Signal gets peaked at : $c_t(k_2 + k_3) = c_s k_1$, $c_s k_1 + c_t k_3 = c_t k_2$, $c_s k_1 + c_t k_2 = c_t k_3$ the signal gets an additional enhancement of $|c_t k \eta_0|$

Non-Gaussianities from NBD states

- $(\gamma\zeta\zeta)$ correlator: Probe for broken spatial diffeomorphism
- Type of interaction:

$$\frac{F_Y}{2a^2}\left(\frac{\gamma_{ij}\partial_i\pi\partial_j\pi}{2a^2}\right)$$

- F_Y does not obey consistency condition and can be lage
- Affects the scalar power spectrum through quadrupole moment
- Small scale tensor modes affect scalar modes of cosmological scale
- Squeezed limit amplitude: $f_{NL}|_{\gamma\zeta\zeta} \propto \frac{\Gamma_s}{\Gamma_t}\frac{k_s}{k_l}$
- Large amplitude can be achieved if $\frac{\Gamma_s}{\Gamma_t} > 1$

Summary

- EFT ensures analysis of correlation functions in a generic way
- Tensor modes from Vacuum fluctuations:
  - Two distinct operators contribute to the bispectrum signal
  - The amplitude of bispectrum is generically small and maximum contribution is proportional to r^2
  - Observationally squeezed limit is more favorable
- Tensor modes generated from (P)reheating:
  - A large class of models is analyzed
  - Non-trivial sound speed enhances the signal strength of both GW powerspectrum and bispectrum
  - c_γ determines the peak frequency of the signal

Summary

NBD state and vacuum fluctuations:

- NBD state can bypass Swampland criteria and TCC
- The signal strength of auto correlators does not get any enhancement
- Mixed correlator ($\gamma\gamma\zeta$) that probes sound speed gets an significant enhancement in signal strength
- $\gamma\zeta\zeta$ correlator that probes breaking of spatial diffeomorphism also gets enhanced

Future scope

- Consistent estimation of the EFT parameters can be done using data
- Fisher forecast with exact specifications of telescope can shed some light about the allowed regions of EFT parameters detectable by upcoming observation
- **Choice of initial state is non-trivial**
  - One such choice can be entanglement between scalar and tensor states
  - This state induces non-trivial features in the scalar powerspectrum

Thank You