Title: Marginally Extended EFT of Inflation

Date: Nov 28, 2017 11:00 AM

URL: http://pirsa.org/17110105

Abstract: <p>Extending the EFT of Inflation by adding marginal operators in unitary gauge that can affect the equation of motion for scalar perturbations, we unravel new inflationary models in which the dispersion relations is a sixth order polynomial. In particular we focus on the healthy marginal operators that do not infiltrate ghosts into the equations of motion and allow for gravity to decouple from the Goldstone boson above some energy scale. Various scenarios can arise depending on the parameters in the original theory. In particular, one can consider scenarios in which the mode becomes tachyonic while still it is inside the horizon. More conservatively, one can consider models in which the group velocity of the propagation becomes negative. In these inflationary models, the amplitude of scalar power spectrum gets a modulation factor, which in majority of the cases is much bigger than one. We also show that these marginal operators leave the tensor perturbations intact, and hence the form of tensor power spectrum remains resilient even in the marginally extended EFT of inflation. Due to the enhancement of the scalar power spectrum, the tensor-to-scalar ratio is suppressed by a huge factor..</p>

Marginally Extended EFT of Inflation

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Based on

A. Ashoorioon, R. Casadio, M. Cicoli, G. Geshnizjani, H. J. Kim, *in preparation*

and some earlier works

A. Ashoorioon, R. Casadio, G. Geshnizjani, H. J. Kim, *JCAP 1709 (2017) 09, 008*
A. Ashoorioon, K. Dimopoulos, G. Shiu, M. Sheikh-Jabbari, *JCAP 1402 (2014) 025*

Nov 28th, 2017

Introduction

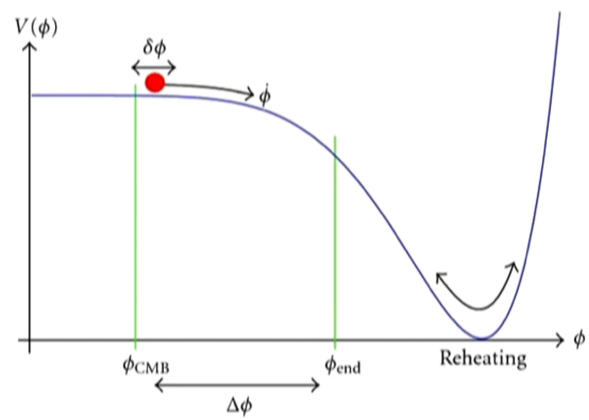
- Inflation: indispensable part of early universe cosmology
- Solves the problems of SBB cosmology. **A. Guth (1981)**
- There are many of models that can realise the paradigm. No shortage in realisation!
- Vanilla Model: Slow-roll Inflation
- Potentially-driven

$$\mathcal{L} = -\frac{1}{2}\mathcal{R} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

- QM fluctuations of the inflation ⟹ scale-invariant two-point function
- Small inflation self-couplings

⇓

- Small non-gaussianity **Maldacena (2003)**



Introduction

- Another class: Kinetically driven Inflation (K-inflation)

Armendariz-Picon, Damour, Mukhanov (1999)

$$\mathcal{L} = -\frac{1}{2}R - p(\phi, X)$$

$$p(\phi, X) = K(\phi)X + L(\phi)X^2 + \cdots \qquad X = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi$$

$$p = p(\phi, X) \qquad \varepsilon = \varepsilon(\phi, X) = 2X\frac{\partial p(\phi, X)}{\partial X} - p(\phi, X)$$

One can build examples where $p \approx -\varepsilon$ ⇒ $a(t) \approx e^{Ht}$

$$c_S^2 = \frac{p_{,X}}{\varepsilon_{,X}} = \frac{p_{,X}}{p_{,X} + 2Xp_{,XX}}$$

Stability requires $c_S^2 \geq 0$ and $c_S^2 \leq 1$ to be able to UV complete the theory.

Adams, N. Arkani-Hamed, et. al (2006)

- Whether it becomes secretly nonlocal is under dispute!

Babichev, Mukhanov & Vikman (2007)

Introduction

- It can be shown that in this case, $\langle \zeta\zeta\zeta \rangle \sim \frac{1}{c_S^4}$

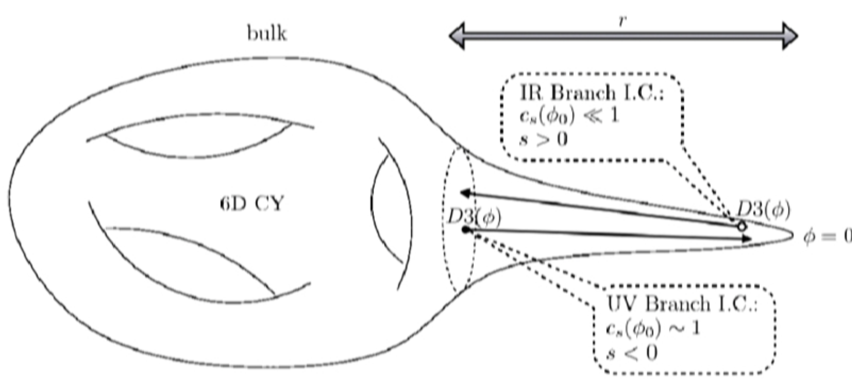
X. Chen, X. Huang, S. Kachru & G. Shiu (2006)

for $c_S^2 \ll 1$, the 3pt functions becomes large!

An example of K-inflatinary models is DBI inflation:

Alishahiha, Silverstein, Tong (2004)

$$\mathcal{L}_{eff} = \int d^4x \left[\frac{1}{2}\mathcal{R} + \frac{1}{g_S}\sqrt{-g}\left(f(\phi)^{-1}\sqrt{1 + f(\phi)\partial_\mu\phi\partial^\mu\phi} + V(\phi) \right) \right]$$



Introduction

- Another class: Ghost Inflation — Arkani-Hamed, Cheng, Luty, Mukohyama (2003)

- Derivatively coupled ghost ϕ which "condenses" in a background where it has a non-zero velocity

$$\langle\dot{\phi}\rangle = M^2$$

does not redshift!

- Ghost condensate can fluctuate

$$\phi = M^2 t + \pi$$

- The remaining symmetries of the theory allows for

$$S = \int d^4x \frac{1}{2}\dot{\pi}^2 - \frac{\alpha^2}{2M^2}(\nabla^2\pi)^2 - \frac{\beta}{2M^2}\dot{\pi}(\nabla\pi)^2$$

$$\omega^2 = \alpha^2 \frac{k^4}{M^2}$$

Lorentz-violating

Introduction

- Study all models in a single framework.
- under $t \to t + \xi^0(t, \vec{x}) \Rightarrow \delta\phi \to \delta\phi + \dot{\phi}(t)\ \xi^0(t, \vec{x})$
- One can go to unitary gauge, where $\delta\phi = 0$
- All the perturbations will be in the metric, which now has 3 d.o.f's.
- Besides the 2 transverse components, one has a longitudinal component too.
- Similar to spontaneously broken gauge theory: the Goldstone boson is eaten by the gauge field ⇒ massive spin 1 gauge field
- The NL sigma model of Goldstone ⇒ UV completed to the Higgs theory.
- The NL sigma model of π , will be UV completed to ϕ the Lagrangian
- In the EFT approach to inflation: emphasis is on π

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Outline

- EFT of inflation (EFToI) C. Cheung, P. Creminelli, et al (2007)
- Unification of Various Inflationary models in the EFToI
- Recovering the action for the Goldstone Boson
- Going Beyond the Quartic Order in the Dispersion Relation, $\omega^2 \sim k^{2n} \quad n \geq 3$
- Marginally Extended EFToI (MEEFToI)
- Tensor Perturbations in the MEEFToI
- Scalar Perturbations and tensor/scalar in the MEEFToI

EFT of inflation (EFToI)

C. Cheung, P. Creminelli, et al (2007)

- In unitary gauge, $\delta\phi(t,\vec{x}) = 0$ ⇒ Only the spatial diffs are still unbroken
- Lagrangian is built out of operators that respect the spatial diffs.
  - Any $f(t)$
  - $R_{\mu\nu\rho\sigma}$ and its covariant derivatives contracted to give a scalar
  - g^{00}
  - $K_{\mu\nu}$
  - $\partial_\mu \tilde{t} = \delta^0_\mu$ contracted with any tensor, i.e. g^{00}, R^{00}
  - n_μ and induced metric built out of it and its covariant derivative

$$K_{\mu\nu} = h^\sigma_\mu \nabla_\sigma n_\nu \qquad n^\sigma \nabla_\sigma n_\nu = -\frac{1}{2}(-g^{00})^{-1} h^\mu_\nu \partial_\mu (-g^{00})$$

$$h_{\mu\nu} = g_{\mu\nu} + n_{\mu\nu} \Rightarrow {}^3R_{\alpha\beta\gamma\delta} = h^\mu_\alpha h^\nu_\beta h^\rho_\gamma h^\sigma_\delta R_{\mu\nu\rho\sigma} - K_{\alpha\gamma}K_{\alpha\gamma} - K_{\alpha\gamma}K_{\beta\sigma} + K_{\beta\gamma}K_{\alpha\sigma}$$

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  - g^{00}
  - $K_{\mu\nu}$

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

EFT of inflation (EFToI)

C. Cheung, P. Creminelli, et al (2007)

- Expanding the action around the FRW

$$\delta K_{\mu\nu} \equiv K_{\mu\nu} - K^{(0)}_{\mu\nu} \qquad\qquad \delta R_{\mu\nu\rho\sigma} \equiv R_{\mu\nu\rho\sigma} - R^{(0)}_{\mu\nu\rho\sigma}$$

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_p^2 R - c(t) g^{00} - \Lambda(t) + F^{(2)}(1 + g^{00}, \delta K_{\mu\nu}, \delta R_{\mu\nu\rho\sigma}; \nabla_\mu; t) \right]$$

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where using the symmetries of FRW

$$K^{(0)}_{\mu\nu} = -H h_{\mu\nu} \qquad R^{(0)}_{\mu\nu\rho\sigma} = 2(H+k)^2 h_{\mu[\rho} h_{\sigma]\nu} + \left[\left(\dot{H} + H^2 \right) h_{\mu\sigma} \delta^0_\nu \delta^0_\rho + \text{perm.} \right]$$

- The linear terms are fixed, assuming that given FRW background is a solution.

$$c(t) = -M_p^2 \left(\dot{H} - \frac{k}{a^2} \right) \qquad \Lambda(t) = -M_p^2 \left(3H^2 + \dot{H} + 2\frac{k}{a^2} \right) \qquad k = -1, 0, 1$$

$$S_{EFToI} = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_p^2 R + M_p^2 \left(\dot{H} - \frac{k}{a^2} \right) g^{00} - M_p^2 \left(3H^2 + \dot{H} + 2\frac{k}{a^2} \right) + F^{(2)} \left(1 + g^{00}, \delta K_{\mu\nu}, \delta R_{\mu\nu\rho\sigma}; \nabla_\mu; t\right) \right]$$

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$$\left. + \frac{1}{3!}M_3(t)^4(1+g^{00})^3 - \frac{\bar{M}_2}{2}\delta K^{\mu}{}_{\mu}{}^2 - \frac{\bar{M}_3^2}{2}\delta K^\mu_\nu \delta K^\nu_\mu\right]$$

Unification of Various Inflationary models in the EFToI

- **Slow-roll inflation**

$$M_p^2(\dot{H} - \frac{k}{a^2}) = -\frac{1}{2}\dot{\phi}^2 \qquad V(\phi) = M_p^2(3H^2 + \dot{H} + 2\frac{k}{a^2})$$

$$S_{EFToI} \to \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\partial_\mu\phi)^2 - V(\phi)\right]$$

- **K-inflation**

$$S_{K-inflation} = \int d^4x\ \sqrt{-g}\ P(\frac{1}{2}\dot{\phi}^2 g^{00}, \phi) \qquad X = \frac{1}{2}(\partial_\mu\phi)^2$$

$$M_n^4(t) = \frac{\dot{\phi(t)}^{2n}}{2^n}\frac{\partial^n P}{\partial X^n} \quad \Rightarrow \quad S_{K-inflation} \to S_{EFToI}$$

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- **Ghost inflation** and models with $\mathcal{O}(k^4)$ correction to the dispersion relation

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- **Ghost inflation** and models with $\mathcal{O}(k^4)$ correction to the dispersion relation

$$-\frac{\bar{M}_2(t)^2}{2}\delta K^\mu{}_\mu{}^2 - \frac{\bar{M}_3(t)^2}{2}\delta K^\mu{}_\nu \delta K^\nu{}_\mu \subset \mathcal{L}_{EFToI} \Longrightarrow \omega^2 = \alpha k^2 + \beta k^4$$

$\alpha = 0 \Longrightarrow$ Ghost Inflation **Arkani-Hamed et. al (2003)**

Recovering π in Non-Abelian Gauge Theories

Consider the action of non-Abelian gauge group A_μ^a

$$S_{\rm non-Abelian} = \int d^4x \left(-\frac{1}{4}{\rm Tr}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}{\rm Tr}A_\mu A^\mu\right) \qquad A_\mu = A_\mu^a T^a$$

Under a gauge transformation $A_\mu \to \frac{i}{g}UD_\mu U^\dagger$ where $D_\mu = \partial_\mu - igA_\mu$

$$S_{\rm non-Abelian} \to \int d^4x \left(-\frac{1}{4}{\rm Tr}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2g^2}{\rm Tr}D_\mu U^\dagger D^\mu U\right)$$

$$U = \exp(iT^a\pi^a)$$

$$\exp(iT^a\tilde{\pi}^a(t,\vec{x})) = \Lambda(t,\vec{x})\exp(iT^a\pi^a(t,\vec{x}))$$

→ Restoration of Gauge Invariance

Using the variable $\pi_c \equiv \frac{m}{g}\pi = f_\pi \pi$

$$\frac{1}{2}{\rm Tr}D_\mu U^\dagger D^\mu U = \frac{1}{2}(\partial_\mu\pi_c)^2 - \frac{1}{6f_\pi^2}\left[(\pi_c\partial_\mu\pi_c)^2 - \pi_c^2(\partial_\mu\pi_c)^2\right] \Longrightarrow \Lambda_{cutoff} \propto f_\pi = \frac{m}{g}$$

$m \ll E \ll \frac{4\pi m}{g}$, π is weakly coupled and decoupled from the transverse components

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$m \ll E \ll \frac{4\pi m}{g}$, π is weakly coupled and decoupled from the transverse components

Recovering π from the Spatially Diff-Invariant EFToI

$$t \to \tilde{t} = t + \xi^0(\vec{x}, t) \qquad \vec{x} \to \tilde{\vec{x}} = \vec{x} \quad \Longrightarrow \quad \tilde{g}^{\alpha\beta} = \frac{\partial \tilde{x}^\alpha}{\partial x^\mu} \frac{\partial \tilde{x}^\beta}{\partial x^\nu} g^{\mu\nu}$$

$$\xi^0(x(\tilde{x})) \to -\pi(\tilde{x}) \quad \Longrightarrow \quad \pi(x) \to \tilde{\pi}(\tilde{x}(x)) = \pi(x) - \xi^0(x)$$

Action becomes gauge-inv. under diffs at all order!

✤ Slow-roll case:

$$M_{\rm Pl}^2 \dot{H} g^{00} \to M_{\rm Pl}^2 \dot{H}((1+\dot{\pi})^2 g^{00} + 2(1+\dot{\pi}) g^{0i}\partial_i \pi + g^{ij}\partial_i\pi\partial_j\pi).$$

$$\pi_c = M_p \dot{H}^{1/2} \pi \qquad g_c^{00} = M_p g^{00} \quad \Longrightarrow \quad E_{\rm mix} \sim \dot{H}^{1/2} = \epsilon^{1/2} H$$

- If $E_{\rm mix} \ll H$ is satisfied ($\epsilon \ll 1$) the action for π gives correct predictions up to $\mathcal{O}\left(\frac{E_{\rm mix}}{H}\right)$

Equivalence theorem

Recovering π from the Spatially Diff-Invariant EFToI

✤ K-inflation with $M_2^4 > M_p^2|\dot{H}|$

$$\pi_c \sim M_2^2\pi \longrightarrow E_{\rm mix} \sim \frac{M_2^2}{M_p} \longrightarrow M_2^2 \ll M_p H$$

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

$$c_S^{-2} = 1 - \frac{2M_2^4}{M_p\dot{H}} \qquad \dot{H} < 0 \xrightarrow{c_S < 1} M_2^4 > 0$$

$M_2 \neq 0 \longrightarrow c_S < 1 \longrightarrow$ larger non-gaussianity from $M_2^4\dot{\pi}^3$

Relation between ζ (curvature perturbations) and π :

$g_{ij} = a(t)^2\left[(1+2\zeta)\delta_{ij}\right]$ should be unperturbed in terms of π when mixing with gravity is negligible $\longrightarrow \zeta = -H\pi$

Recovering π from the Spatially Diff-Invariant EFToI

✤ Ghost Inflation-like Scenarios

$$-\frac{\bar{M}_2(t)^2}{2}\delta K^{\mu}{}_{\mu}{}^2 - \frac{\bar{M}_3(t)^2}{2}\delta K^{\mu}{}_{\nu}\delta K^{\nu}{}_{\mu} \subset \mathcal{L}_{EFToI} \quad \Longrightarrow \quad \omega^2 = \alpha k^2 + \beta k^4$$

$$\alpha = 0 \quad \Longrightarrow \quad \omega \propto k^2$$

Arkani-Hamed et. al. (2003)

$$k_{\rm mix} \sim \frac{M_2^2}{M_p} \quad \Longrightarrow \quad E_{\rm mix} \sim \frac{\bar{M} M_2^2}{M_p^2}$$ where $\bar{M} \sim \bar{M}_2$

$$\pi_c \simeq \bar{M}^2 \pi \quad \Longrightarrow \quad P_\zeta^{1/2} \sim \left(\frac{H}{\bar{M}}\right)^{5/4} \quad \Longrightarrow \quad \frac{H}{\bar{M}} \sim 10^{-4}$$

- Non-gaussianity: $\frac{\mathcal{L}_{\dot{\pi}(\nabla\pi)^2}}{\mathcal{L}_2} \sim \left(\frac{H}{\bar{M}}\right)^{1/4} \Longrightarrow f_{\rm NL}^{\rm equil.} \sim \left(\frac{\bar{M}}{H}\right) \sim 10^4$
- More exact treatment of non-gaussianity $\Longrightarrow f_{\rm NL}^{\rm equil.} \sim 10^2$

Arkani-Hamed et. al. (2003)

Tensor Perturbations in the EFT of Inflation

- $g_{ij} = a^2(\delta_{ij} + \gamma_{ij})$ $\gamma_{ii} = 0\,,$ $\partial_i \gamma_{ij} = 0\,,$
- $(1+g^{00})^n$ do not contribute to the action of tensor perturbations.
- From the extrinsic curvature squared terms:

$$\mathcal{L}_{EFToI} \supset -\frac{\bar{M}_3^2}{2}\delta K^{\mu}{}_{\nu}\delta K^{\nu}{}_{\mu}$$

$$S_\gamma = \frac{M_{\rm Pl}^2}{8}\int d^4x\sqrt{-g}\left[\left(1-\frac{\bar{M}_3^2}{M_{\rm Pl}^2}\right)\dot{\gamma}_{ij}\dot{\gamma}_{ij} - \frac{1}{a^2}\partial_l\gamma_{ij}\partial_l\gamma_{ij}\right] \Longrightarrow c_T^2 \equiv \frac{1}{1-\frac{\bar{M}_3^2}{M_p^2}}$$

- Subliminal branch, $\bar{M}_3^2 < 0\,, c_T \leq 1$ $|\bar{M}_3| \uparrow \Longrightarrow c_T \downarrow$

$|\bar{M}_3| \to M_p \Longrightarrow c_T \to \frac{1}{\sqrt{2}}$ $r \equiv \frac{P_T}{P_S}$ can increase up to $\sqrt{2}\,r$

- Superluminal branch, $\bar{M}_3^2 > 0, c_T > 1$

$|\bar{M}_3| \to M_p \Longrightarrow c_T \to \infty$ r could be suppressed indefinitely

Going Beyond the Quartic Dispersion Relation, $\omega^2 \sim k^{2n} \quad n \geq 3$

- Why not $\omega^2 \sim k^{2n} \quad n \geq 3$

- If $\omega^2 \sim k^{2n}$

C. Cheung, P. Creminelli, et al (2007)

$[\omega] \sim E$ so if $E \to sE \Rightarrow k \to s^{1/n} k$

$t \to s^{-1} t \qquad x \to s^{-1/n} x$

$$\int dt d^3x \left[M^2 \dot{\pi}^2 - k^2 {M'_n}^{6-2n} \left(\frac{\partial_i^n \pi}{a^n}\right)^2 \right] \longrightarrow \pi \to s^{\frac{3}{2n} - \frac{1}{2}} \pi$$

To keep the quadratic part of the action scale-invariant

Going Beyond the Quartic Dispersion Relation, $\omega^2 \sim k^{2n} \quad n \geq 3$

- Why not $\omega^2 \sim k^{2n} \quad n \geq 3$

- If $\omega^2 \sim k^{2n}$

C. Cheung, P. Creminelli, et al (2007)

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To keep the quadratic part of the action scale-invariant

$$\dot{\pi}(\nabla \pi)^2 \longrightarrow s^{\frac{7-3n}{2n}} \dot{\pi}(\nabla \pi)^2$$

In the low energy, i.e. $s \to 0$, for $n \geq 3$, the operator becomes strong!

Going Beyond the Quartic Dispersion Relation, $\omega^2 \sim k^{2n} \quad n \geq 3$

- But wait, what if

$$\int dt d^3x \left[M^2 \dot{\pi}^2 - M_m'^{6-2m} (\frac{\partial_i^m \pi}{a^m})^2 - M_n'^{6-2n} (\frac{\partial_i^n \pi}{a^n})^2 \right] \quad \begin{matrix} n \geq 3 \\ m \leq 2 \end{matrix}$$

$$\omega^2 \sim \alpha \ k^{2m} + \beta \ k^{2n}$$

so that $\omega \sim H$, $\quad \omega^2 \sim \alpha \ k^{2m}$

or what if the theory becomes Lorentz-invariant completely at low energies

$$\int dt d^3x \left[M^2 \dot{\pi}^2 - M_1'^4 (\frac{\partial_i \pi}{a})^2 - M_n'^{6-2n} (\frac{\partial_i^n \pi}{a^n})^2 \right]$$

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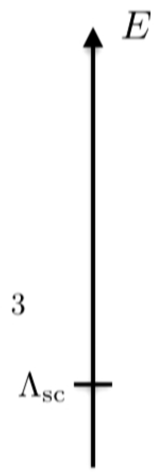

$$\omega^2 \sim k^{2n} \quad n \geq 3$$

Marginally Extended EFToI (MEEFToI)

- How to generate such higher dimensional dispersion relations?

$$\delta K_{ij} \supset (\partial_i \partial_j \pi + \partial_i g_{0j}),$$

- Maybe if we can build scalars from $(\nabla_{\mu_1 \mu_2 \cdots \mu_{n-2}} \delta K_{\nu\delta})^2$ we can generate such terms.

- Let us focus on the sextic correction, $k^2 + \alpha k^4 + \beta k^6$

- Let us build all the legitimate operators like $(\nabla_{\mu_1} \delta K_{\nu\delta})^2$ that can be added to the EFToI Lagrangian

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$$\mathcal{L}_{\rm EFToI} = \mathcal{L}^{non-marg.}$$
$$= \frac{M_2^4}{2!}(g^{00}+1)^2 + \frac{\bar{M}_1^3}{2}(1+g^{00})\delta K^\mu{}_\mu - \frac{\bar{M}_2^2}{2}(\delta K^\mu{}_\mu)^2 - \frac{\bar{M}_3^2}{2}\delta K^\mu{}_\nu \delta K^\nu{}_\mu$$

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$$\mathcal{L}_{\rm MEEFToI} = \mathcal{L}^{non-marg.} + \mathcal{L}^{(marg.)}$$

$$= \frac{M_2^4}{2!}(g^{00}+1)^2 + \frac{\bar{M}_1^3}{2}(1+g^{00})\delta K^\mu{}_\mu - \frac{\bar{M}_2^2}{2}(\delta K^\mu{}_\mu)^2 - \frac{\bar{M}_3^2}{2}\delta K^\mu{}_\nu \delta K^\nu{}_\mu$$

$$-\frac{\delta_1}{2}(\nabla_\mu \delta K^{\nu\gamma})(\nabla^\mu \delta K_{\nu\gamma}) - \frac{\delta_2}{2}(\nabla_\mu \delta K^\nu{}_\nu)^2 - \frac{\delta_3}{2}(\nabla_\mu \delta K^\mu{}_\nu)(\nabla_\gamma \delta K^{\gamma\nu}) - \frac{\delta_4}{2}\nabla^\mu \delta K_{\nu\mu}\nabla^\nu \delta K^\sigma_\sigma.$$

Tensor Perturbations in MEEFToI

- After the implementation of transverse-traceless gauge:

$$-\frac{\delta_1}{2}(\nabla_\mu \delta K^{\nu\gamma})(\nabla^\mu \delta K_{\nu\gamma})$$

$$\downarrow$$

$$\frac{\delta_1}{2}\left[-\frac{H^2}{2}\left(\partial_0\gamma_{ij}\right)^2+\frac{1}{4a^2}\left(\partial^2_{0m}\gamma_{ij}\right)^2-\frac{1}{4}\left(\partial_0^2\gamma_{ij}\right)^2\right]. \rightarrow$$

- The other operators yield exactly zero, after the TT gauge is imposed
- To get rid of the ghost, $\delta_1 = 0$
- Result for tensor perturbations in MEEFToI remains the same as EFToI.

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- The other operators yield exactly zero, after the TT gauge is imposed
- To get rid of the ghost, $\delta_1 = 0$
- Result for tensor perturbations in MEEFToI remains the same as EFToI.
- This is further confirmation of P. Creminelli et al (2014) conjecture on the resilience of the form of the orthodox prediction for the tensor modes.

Scalar Perturbations in MEEFTol

- After the Stuckelberg procedure in de Sitter limits

$$\mathcal{L}_n^{(non-marg.)} = M_p^2\dot{H}(\partial_\mu\pi)^2 + 2M_2^4\dot{\pi}^2 - \frac{\bar{M}_2^2}{2}\left(9H^2\dot{\pi}^2 - 3H^2\frac{(\partial_i\pi)^2}{a^2} + \frac{(\partial_i^2\pi)^2}{a^4}\right) - \frac{\bar{M}_3^2}{2}\left(3H^2\dot{\pi}^2 - H^2\frac{(\partial_i\pi)^2}{a^2} + \frac{(\partial_j^2\pi)^2}{a^4}\right)$$

$$\begin{aligned}\mathcal{L}_n^{(marg.)} = &-\frac{1}{2}\delta_1\left(\frac{k^6\pi^2}{a^6} - \frac{3H^2k^4\pi^2}{a^4} - \frac{k^4\dot{\pi}^2}{a^4} + \frac{4H^4k^2\pi^2}{a^2} - 6H^4\dot{\pi}^2 - 3H^2\ddot{\pi}^2\right)\\ &-\frac{1}{2}\delta_2\left(\frac{k^6\pi^2}{a^6} + \frac{H^2k^4\pi^2}{a^4} - \frac{k^4\dot{\pi}^2}{a^4} + \frac{6H^4k^2\pi^2}{a^2} - 9H^2\ddot{\pi}^2\right)\\ &-\frac{1}{2}\delta_3\left(\frac{k^6\pi^2}{a^6} + \frac{3H^2k^4\pi^2}{a^4} + \frac{H^2k^2\dot{\pi}^2}{a^2} - 9H^4\dot{\pi}^2\right)\\ &-\frac{1}{2}\delta_4\left(\frac{k^6\pi^2}{a^6} + \frac{H^2k^4\pi^2}{2a^4} + \frac{9H^4k^2\pi^2}{2a^2} + \frac{3H^2k^2\dot{\pi}^2}{a^2} + \frac{27}{2}H^4\dot{\pi}^2\right).\end{aligned}$$

- To get rid of them, $\delta_1 = -3\delta_2 \xrightarrow[\delta_1 = 0]{} \delta_1 = \delta_2 = 0$

Scalar Perturbations in MEEFTol

- In terms of

$$A_1\ddot{\pi} + B_1\dot{\pi} + \left(C_1\frac{k^6}{a^6} + D_1\frac{k^4}{a^4} + F_1\frac{k^2}{a^2}\right)\pi = 0\,.$$

or casting it in terms of $u_k = a\pi_k$:

$$u_k'' + \frac{2k^2H^3(\delta_3+3\delta_4)}{aA_1}u_k' + u_k\left(\frac{C_1}{A_1}\frac{k^6}{a^4} + \frac{D_1}{A_1}\frac{k^4}{a^2} + \frac{F_1}{A_1}k^2 - \frac{a''}{a}\right) = 0\,,$$

$$A_1 = -2M_p^2\dot{H} + 4M_2^4 - 9H^2\bar{M}_2^2 - 3H^2\bar{M}_3^2 + 2H^4F_0(k,\tau)$$

$$F_0(k,\tau) = \frac{9}{2}\delta_3 + \frac{27}{4}\delta_4 - \frac{k^2}{2a^2H^2}(\delta_3+3\delta_4)$$

$$C_1 = \delta_3 + \delta_4$$

$$F_1 = -2M_p^2\dot{H} - 3H^2\bar{M}_2^2 - \bar{M}_3^2H^2 + 3H^4\left(\delta_3 + \frac{3}{2}\delta_4\right)$$

Scalar Perturbations in MEEFTol

$$c_S^2(\tau) = \frac{F_1}{G_1 + G_2\tau^2 k^2}$$

$$G_1 \equiv -2M_p^2\dot{H} + 4M_2^4 - 9H^2\bar{M}_2^2 - 3H^2\bar{M}_3^2 + 9H^4(\delta_3 + \frac{3}{2}\delta_4)$$

$$G_2 \equiv -H^4(\delta_3 + 3\delta_4)$$

$$\frac{k}{aH} = k|\tau| \to \infty \quad \Longrightarrow \quad c_S \to 0$$

$$\mathcal{L}_{\rm int} = \frac{M_2^4}{2}\left(\partial_i\pi\partial^i\pi\right)^2 \quad \Longrightarrow \quad \Lambda^4_{\rm cut-off} = 16\pi^2\frac{2M_p^2\dot{H}c_s^5}{(1-c_s^2)} \to 0$$ when $c_S \to 0$

Such a theory becomes strongly coupled in the UV!

- In order to avoid this problem we consider the case where $\delta_3 = -3\delta_4$
- From now on whenever I refer to MEEFTol, I mean that such a condition is imposed.

Scalar Perturbations in MEEFToI

- In terms of $x = k\tau$

$$\frac{d^2u_k}{dx^2} + \left(\frac{F_1}{G_1} + \frac{D_2x^2}{G_1} + \frac{C_2x^4}{G_1} - \frac{2}{x^2}\right)u_k = 0$$

$$c_S^2 = \frac{F_1}{G_1}$$

$$C_2 \equiv (\delta_3 + \delta_4)H^4 = -2\delta_4 H^4$$

$$D_2 \equiv D_1 H^2 = \left(-2M_p^2\dot{H} - 3H^2\bar{M}_2^2 - \bar{M}_3^2H^2 + H^2\frac{\delta_4}{2}\right)H^2$$

- To avoid superluminality $0 \leq c_S^2 \leq 1$ **A. Adams, N. Arkani-Hamed, et al. (2006)**

- $c_S^2 < 0$ is possible but I do not focus on it here!

- There could be higher-point interactions in the theory, perturbation can have $c_S = 1$

$$4M_2^4 - 6H^2\bar{M}_2^2 - 2H^2\bar{M}_3^2 - 9H^4\delta_4 = 0$$

- Introducing $x' \equiv c_S x$

$$\frac{d^2u_k}{dx'^2} + \left(1 + \alpha_0 x'^2 + \beta_0 x'^4 - \frac{2}{x'^2}\right)u_k = 0$$

$$\alpha_0 \equiv \frac{D_2}{G_1c_S^4} = \frac{D_2G_1}{F_1^2} \qquad \beta_0 \equiv \frac{C_2}{G_1c_S^6} = \frac{C_2G_1^2}{F_1^3} \qquad P_S = \gamma_S P_S^{\mathrm{B.D.}} = \gamma_S\frac{H^2}{8\pi^2c_S\epsilon}$$

- Substantial values of α_0 and β_0 can be obtained even with $c_S = 1$

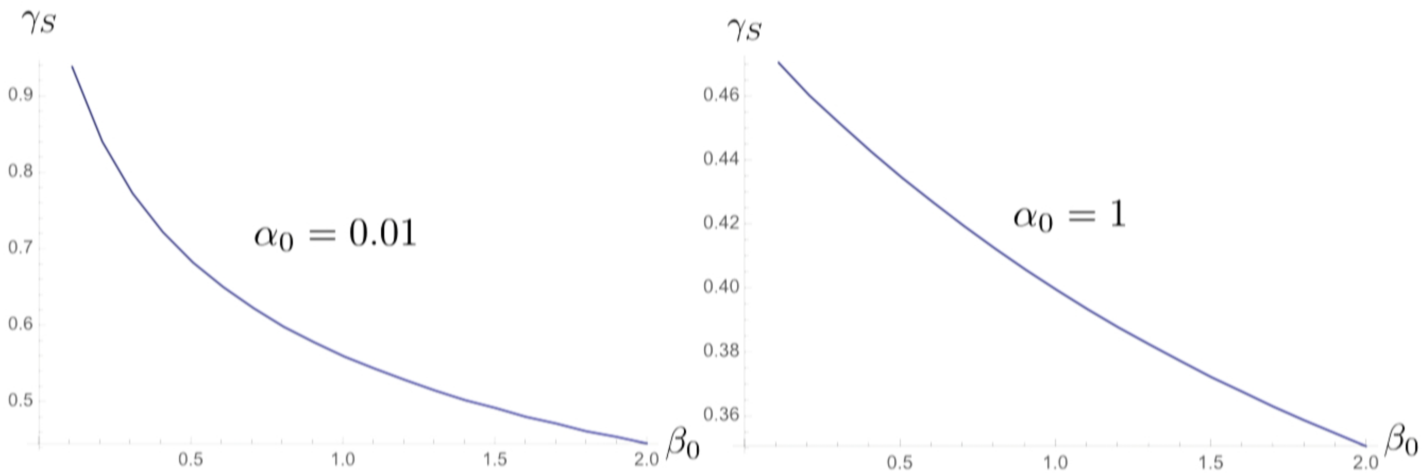
Scalar Perturbations in MEEFToI

- $\alpha_0\ ,\beta_0 > 0$ ⟹ $D_2/G_1 > 0$ and $C_2/G_1 > 0$

$$D_2 = -\frac{2\alpha_0}{\beta_0 c_S^4}\delta_4 H^4 \Longrightarrow \mathrm{sgn}(D_2\delta_4) < 0$$

For example if $\delta_4 > 0$, $C_2 = -2\delta_4 H^4 < 0$ ⟹ $G_1 < 0$ ⟹ $D_2 < 0$

$$\bar{M}_2^2 + H^2\frac{\delta_4}{2} < |\bar{M}_3|^2$$



As α_0 and β_0 increases, power spectrum gets suppressed!

Scalar Perturbations in MEEFTol

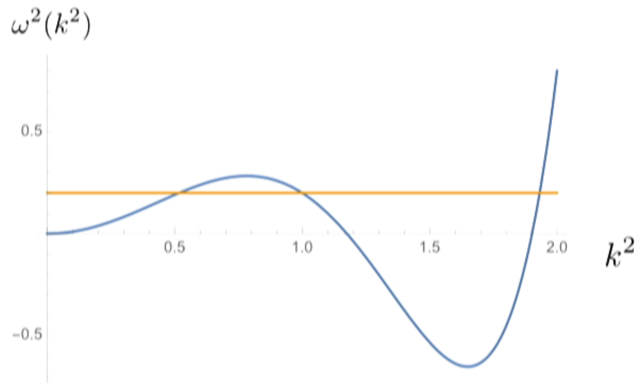
- $\alpha_0 < 0$ and $\beta_0 > 0$ ⟹ $D_2/G_1 < 0$ and $C_2/G_1 > 0$

$$D_2 = -\frac{2\alpha_0}{\beta_0 c_S^4}\delta_4 H^4 \Longrightarrow \mathrm{sgn}(D_2\delta_4) < 0$$

For example if $\delta_4 > 0$, $C_2 = -2\delta_4 H^4 < 0$ ⟹ $G_1 < 0$ ⟹ $D_2 > 0$

$$|\bar{M}_3|^2 < \bar{M}_2^2 + H^2\frac{\delta_4}{2}$$

- $\frac{\alpha_0^2}{5} < \beta_0 < \frac{\alpha_0^2}{4}$ Modes become tachyonic for a while inside the Hubble radius!



Scalar Perturbations in MEEFTol

- $\alpha_0 < 0$ and $\beta_0 > 0$ $\Rightarrow$ $D_2/G_1 < 0$ and $C_2/G_1 > 0$

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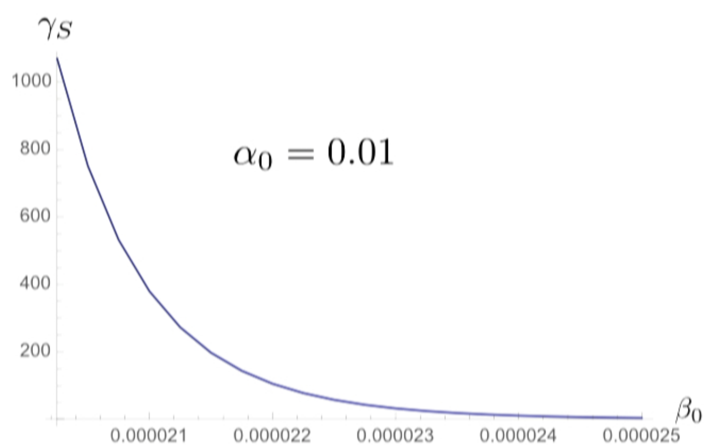

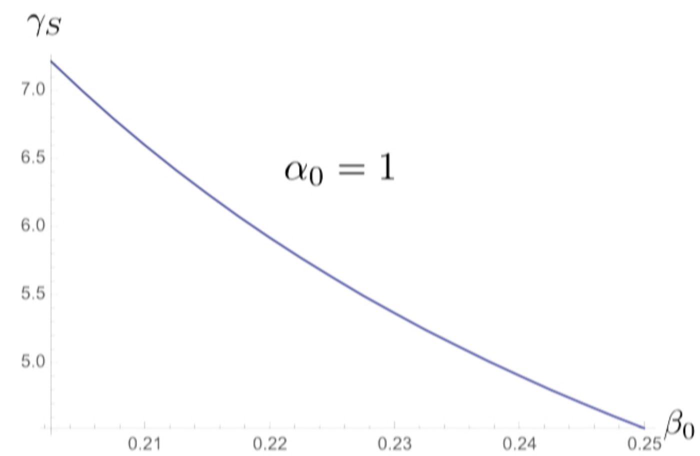

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For example if $\delta_4 > 0$, $C_2 = -2\delta_4 H^4 < 0$ ⟶ $G_1 < 0$ ⟶ $D_2 > 0$

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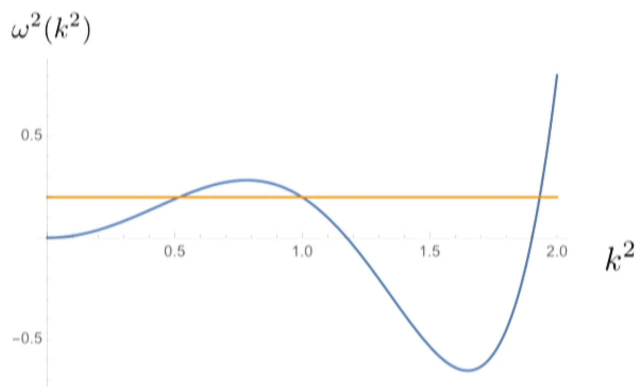
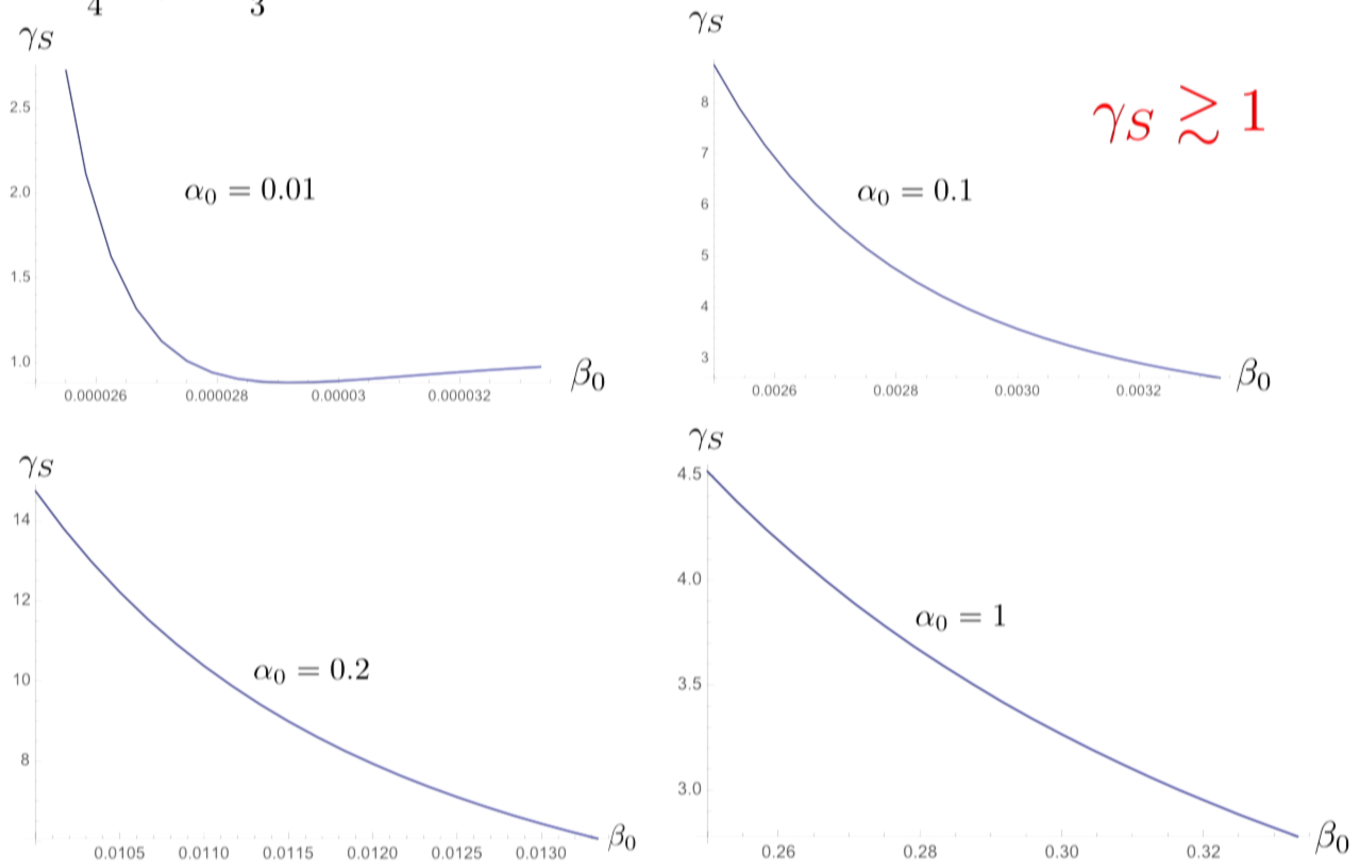


Scalar Perturbations in MEEFTol

- $\frac{\alpha_0^2}{4} \le \beta_0 \le \frac{\alpha_0^2}{3}$ Modes never become tachyonic until the last turning point.



Tensor/Scalar Ratio in MEEFTol

$$r = 16\epsilon \frac{c_S}{c_T}\frac{1}{\gamma_S} \quad \Longrightarrow \quad n_T = -\frac{c_T\gamma_S}{c_S}\frac{r}{8},$$

- For $0 \le c_S \le 1$, reduction of c_S can lower r indefinitely.
- For subluminal branch for tensor perturbations, r can at most be enhanced by $\sqrt{2}$
- NL evolution of the mode inside the horizon during inflation can change r too:
  - If $\omega^2(k) > 0$ and $\frac{d\omega^2(k)}{dk} > 0 \Longrightarrow \gamma_S \lesssim 1$
  - If $\omega^2(k) < 0$ and/or $\frac{d\omega^2(k)}{dk} < 0 \Longrightarrow \gamma_S \gg 1$

Non-Gaussianity in MEEFTol: Why do I expect it to be small?

- Correspondence between the Dispersion Relation and Excited States:

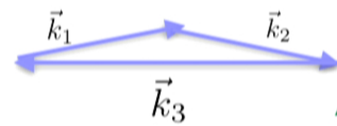
$$\omega^2(k) \xrightarrow{\text{evolution inside the horizon}} \pi_k \to \frac{\alpha_k}{\sqrt{2k}} e^{-ik\tau} + \frac{\beta_k}{\sqrt{2k}} e^{ik\tau} \qquad \beta_k \neq 0$$

- Realization of Super-Excited States with $|\beta_k| \gg 1$

Ashoorioon, Casadio, Geshnizjani, Kim (2017)

- Such super-excited states create two type of NG

- Flattened configurations, $k_1 + k_2 \simeq k_3$



X. Chen, et. al (2005)

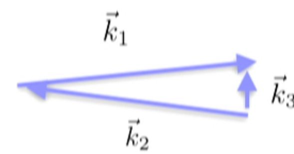
Ashoorioon, Shiu (2010

For $c_S \approx 1$this enhancement is lost after projection on the 2D CMB surface!

Holman & Tolley (2007)

$$f_{\rm NL}^{\rm flat.-obs.} \propto \epsilon$$

- Local configuration, $k_1 \simeq k_2 \gg k_3$



Agullo & Parker (2010)

$$f_{\rm NL}^{\rm local} \sim \epsilon \frac{k_3}{k_1} \lesssim \mathcal{O}(4-5)$$

Ashoorioon et al (2013)

Conclusion and Outlook and Outlook for Future Works

- Effective Field Theory of Inflation unifies all inflationary models.
- The emphasis is on the inflaton perturbations rather than the inflaton model.
- inf. pert. transform non-lin. under the time dif.
- they can be eaten by the metric in unitary gauge which now has 3 d.o.f
- Theory of the Goldstone mode can be constructed out of the quantities that respect the space. diff.
- In the original EFToI, up to massive operators in the unitary gauge was considered.
- We supplemented the theory with marginal operators (MEEFToI).
- We showed that there is a sector in the theory which is physically viable.

Conclusion and Outlook and Outlook for Future Works

- The dispersion relation is sixth order in the UV, evolving to the Lorentzian dispersion in IR.
- The quartic and sextic correction, not necessarily small!
- For the part of param. space that $\omega^2(k) > 0$ ⟹ $\gamma_S \lesssim 1$
- For such dispersion relations, the tensor-to-scalar ratio is suppressed.
- Enhancement of local and flattened non-gaussianity type in such models.
- Despite having higher dimensional operators, still $c_S = 1$ can be achieved!

- Computing the bispectrum explicitly.

- How about higher order corrections $k^{2n},\ n \geq 4$ to the dispersion relation?

Thank you for

your attention!