Non-local R^2-like inflation, tensor-to-scalar ratio and, Non-Gaussianities

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Based on **arXiv:2003.00629 [hep-th]** (JHEP06(2020)152), **arXiv:1711.08864** [hep-th] (JHEP 03 (2018) 071), **arXiv:2005.09550** [hep-th] (Int.J.Mod.Phys.D 29 (2020) 14, 2043018) in collaboration with **Alexey S. Koshelev, Alexei A. Starobinsky**.

June 7, 2021

Planck CMB map: Scale Invariance

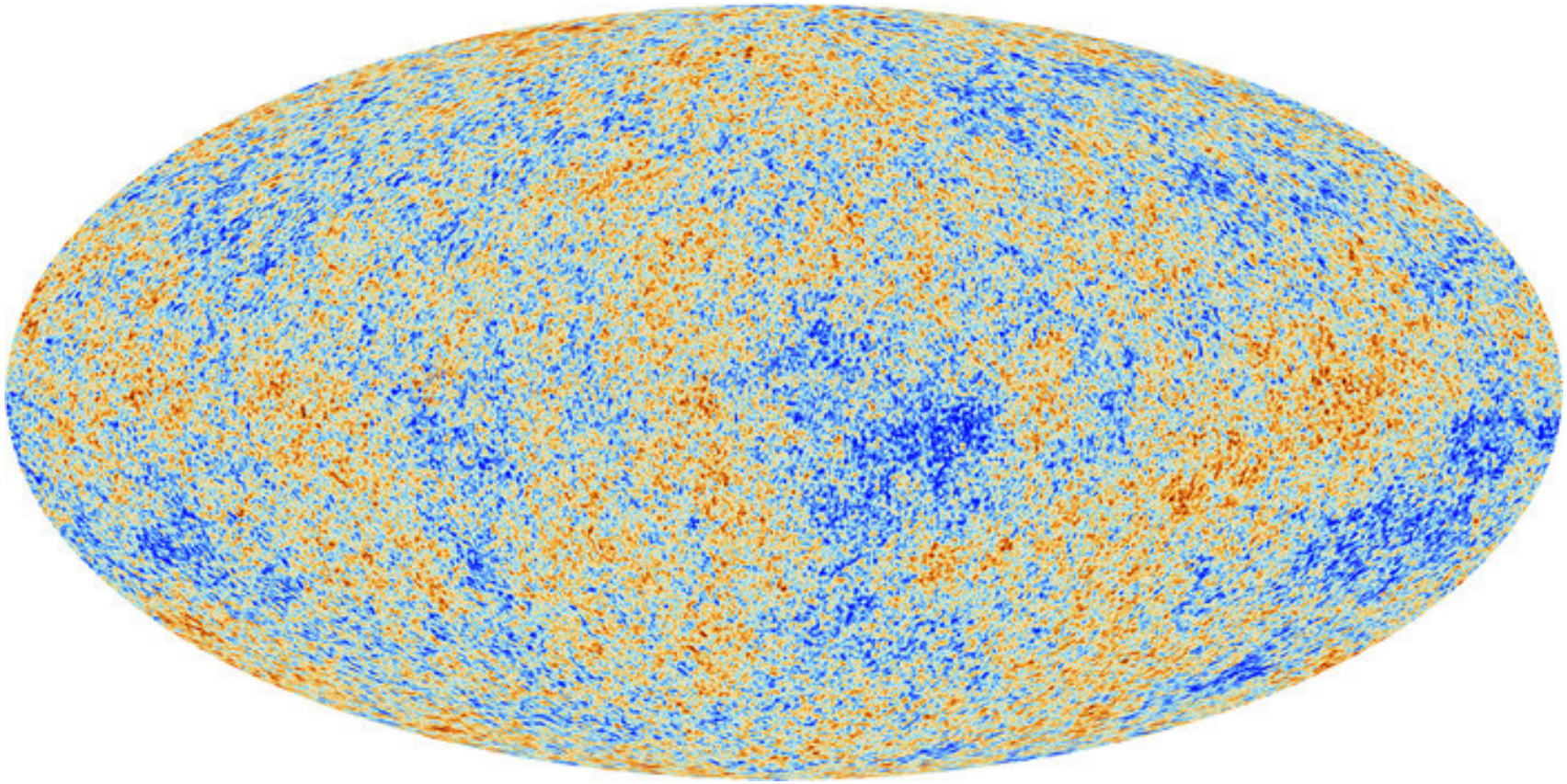


Figure: Planck 2015 CMB map

Inflationary framework

Homogeneous, isotropic and spatially flat geometry

$\Longrightarrow$ Friedmann-Lemaître-Robertson-Walker (FLRW) metric

$ds^2 = -dt^2 + \frac{a(t)^2}{1-kr^2} dr^2 + r^2 d\Omega^2$

The Universe scale factor $a(t)$ increases exponentially ($N = 50 - 60$ number of e-foldings)

$\Longrightarrow$ Hubble parameter $H = \frac{1}{a}\frac{da}{dt}$ almost constant

$\Longrightarrow$ Comoving Hubble radius $(aH)^{-1}$ decreases i.e., $\frac{d}{dt}\left(\frac{1}{aH}\right) < 0$.

$\Longrightarrow$ Slow-roll conditions $\epsilon = -\frac{\dot{H}}{H^2} \ll 1\,, \qquad \eta = \frac{\dot{\epsilon}}{H\epsilon} \ll 1.$ $\Updownarrow$

Modifying General Relativity or addition of hypothetical matter fields

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{1}{m_{\rm P}^2} T_{\mu\nu}\,,$$

$\Updownarrow \qquad \Updownarrow$

Scalaron $\qquad$ Inflaton(s)

$\Downarrow$

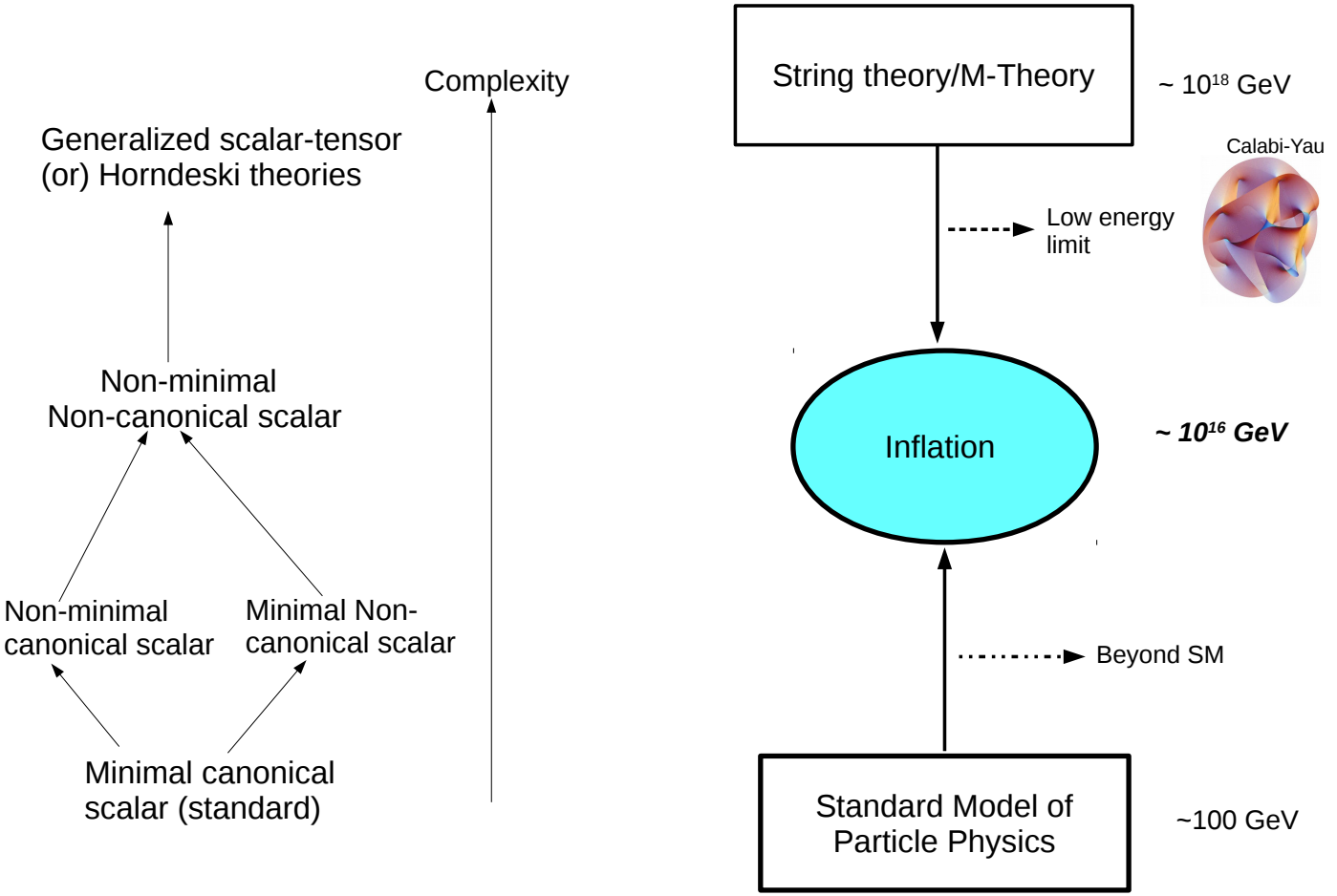
Primordial fluctuations.

Inflationary observables, consistency relations and new physics

- The key observables of inflationary paradigm are related to two and 3-point correlations of primordial fluctuations.
- The two-point correlations give the scalar power spectrum $\mathcal{P}_{\mathcal{R}*} \sim 10^{-9}$ and its tilt $n_s \approx 1 - \frac{2}{N}$, the tensor power spectrum is usually expressed through tensor-to-scalar ratio $r = \frac{\mathcal{P}_{\mathcal{T}}}{\mathcal{P}_{\mathcal{R}}} < 0.064$ and the tilt of tensor power spectrum (n_t) is not YET measured (**Planck 2018**).
- 3-point correlations give non-Gaussianities (also called bispectrum). measured by the parameter f_{NL} and the current constraints are $f_{\rm NL}^{\rm loc} = 0.8 \pm 5.0\,, \quad f_{\rm NL}^{\rm equi} = -4 \pm 43\,, \quad f_{\rm NL}^{\rm ortho} = -26 \pm 21$,at 68% CL.
- In the case of single field inflation there are so-called consistency relations given by (Tensor and Maldacena consistency relations)

$$r = -8n_t, \quad f_{\rm NL}^{\rm sq} = \frac{5}{12}\left(1 - n_s\right)\,.$$

Inflationary model building: Top down vs Bottom up



Taken from KSK (Ph.D. Thesis) arXiv: 1808.03701 [hep-th]

Encyclopedia $\sim$ 300 models

arXiv.org > astro-ph > arXiv:1303.3787

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 15 Mar 2013 (v1), last revised 3 Sep 2013 (this version, v3)]

Encyclopaedia Inflationaris

Jerome Martin, Christophe Ringeval, Vincent Vennin

The current flow of high accuracy astrophysical data, among which are the Cosmic Microwave Background (CMB) measurements by the Planck satellite, offers an unprecedented opportunity to constrain the inflationary theory. This is however a challenging project given the size of the inflationary landscape which contains hundreds of different scenarios. Given that there is currently no observational evidence for primordial non-Gaussianities, isocurvature perturbations or any other non-minimal extension of the inflationary paradigm, a reasonable approach is to consider the simplest models first, namely the slow-roll single field models with minimal kinetic terms. This still leaves us with a very populated landscape, the exploration of which requires new and efficient strategies. It has been customary to tackle this problem by means of approximate model independent methods while a more ambitious alternative is to study the inflationary scenarios one by one. We have developed the new publicly available runtime library ASPIC to implement this last approach. The ASPIC code provides all routines needed to quickly derive reheating consistent observable predictions within this class of scenarios. ASPIC has been designed as an evolutive code which presently supports 74 different models, a number that may be compared with three or four representing the present state of the art. In this paper, for each of the ASPIC models, we present and collect new results in a systematic manner, thereby constituting the first Encyclopaedia Inflationaris. Finally, we discuss how this procedure and ASPIC could be used to determine the best model of inflation by means of Bayesian inference.

Comments:	368 pages, 192 figures, uses jcappub. Theoretical justifications, new models and references added
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)
Journal reference:	Phys.Dark Univ. 5-6 (2014) 75-235
Cite as:	arXiv:1303.3787 **[astro-ph.CO]** (or arXiv:1303.3787v3 **[astro-ph.CO]** for this version)

Figure:

Planck 2018: Models of inflation

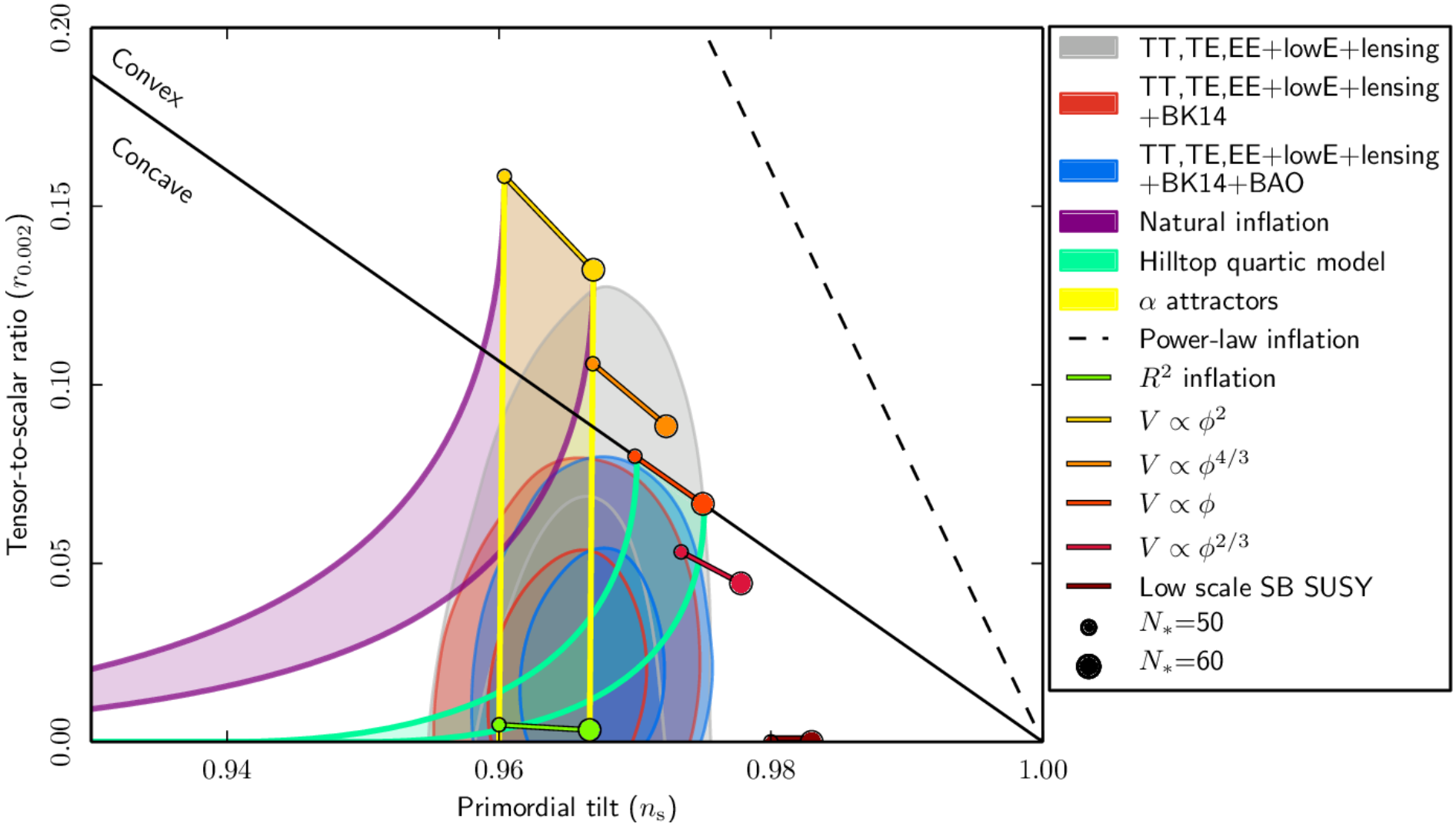


Figure: Spectral index Vs. tensor to scalar ratio

R^2 inflation or Starobinsky inflation

- $\frac{M_p^2}{2}R + \frac{M_p^2}{12M^2}R^2$ is the first model of inflation (A.A. Starobinsky, 1980) with the simplest one parameter extension of GR.
- Inflation in this model is achieved by growth of scale factor in the following manner (given by the solution of trace-equation $\Box R = M^2 R$)

$$\begin{aligned} a(t) &\approx a_0(t_s - t)^{-1/6}\, e^{-r_1(t_s-t)^2/12}\,, \\ H = \frac{\dot{a}}{a} &= \frac{r_1(t_s - t)}{6} + \frac{1}{6(t_s - t)} + \dots\,, \\ R = 6(\dot{H} + 2H^2) &= \frac{r_1^2(t_s - t)^2}{3} - \frac{r_1}{3} + \frac{4}{3(t_s - t)^2} + \dots\,, \end{aligned}$$

  where t_s mark the end of inflation corresponds to the slow-roll parameter $\epsilon = \frac{-\dot{H}}{H^2} \sim 1$
- During inflation H is nearly constant and $\epsilon \ll 1$ which is nothing but " quasi de Sitter (dS) " expansion.

- In the light of recent CMB data, Starobinsky inflation stands out to be the best fit with
$$n_s = 1 - \frac{2}{N}\,, \qquad r = \frac{12}{N^2}\,.$$
- The scalaron mass is constrained as $M \sim 5.5 \times 10^{-5} M_P$ and the Hubble parameter is $H_{\rm inf} \sim \mathcal{O}(10)M$.
- This model features a graceful exit and power-law expansion stage with $a(t) \propto t^{2/3}$ modulated by small oscillations (Starobinsky (1980,1981,1984), Fundamental Interactions, MGPI Press, Moscow, 1984, p. 55-79).
- R^2 model in Einstein frame gives a scalar field with an exponentially flat potential $V \sim \left(1 - e^{-\sqrt{\frac{2}{3}}\frac{\varphi}{M_P}}\right)^2$
- Several Starobinsky like inflationary scenarios with $V \sim \left(1 - e^{-\sqrt{\frac{2}{3B}}\frac{\varphi}{M_P}}\right)^2$ (which gives $r = \frac{12B}{N^2}$) were recently found in the context of String theory/SUGRA.

Starobinsky-like potentials

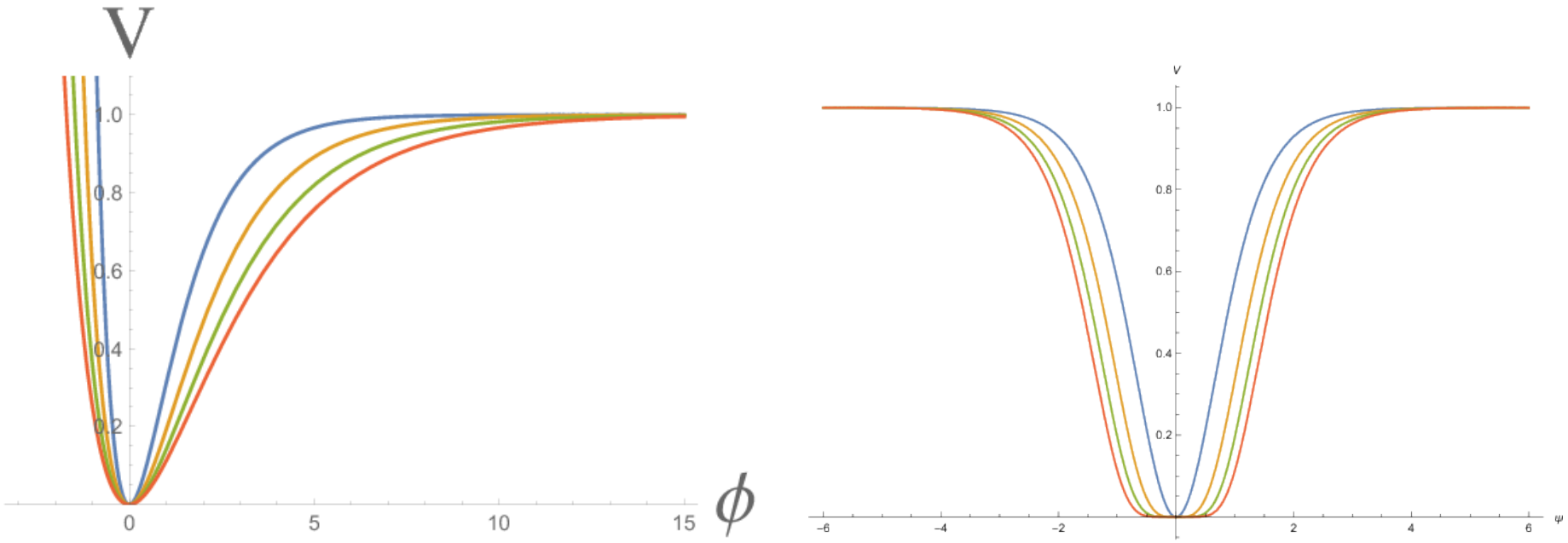


Figure: E-model and T-model

General shape of potentials consistent with Planck. Can be distinguished within (pre-)reheating considerations (S. S. Mishra, V. Sahni, A. A. Starobinsky arXiv:2101.00271 [hep-th].)

Foundations of R^2 model

- R^2 inflation was first motivated from conformal anomaly of gravity which in short given by (See review by M. J. Duff hep-th/9308075)

$$G_{\mu\nu} = 8\pi G \langle T_{\mu\nu} \rangle \,,$$

where $\langle T_{\mu\nu} \rangle$ is the expectation value of the quantum energy momentum tensor.

- In $D = 4$ it is known that

$$\langle T^{\mu}_{\mu} \rangle = b \left(W + \frac{2}{3} \Box R \right) + b' \mathcal{G} + \delta \Box R \implies \Box R = M^2 R \,,$$

where W, $\mathcal{G} = R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R^{\mu\nu\rho\sigma} R_{\mu\nu\rho\sigma}$ are Weyl square and the Gauss-Bonnet terms. The coefficients depend on the no. of massless (conformal) scalar and vector fields.

Neglecting contribution from GB term we get $\Box R \approx M^2 R$.

Renormalized R^2 gravity: K. S. Stelle and beyond

- It was long ago shown by K. S. Stelle (1977) that R^2 gravity with a Weyl square term $(R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 2R_{\mu\nu}R^{\mu\nu} + \frac{1}{3}R^2)$ is renormalizable but however a tensor ghost appear in the theory that spoils unitarity.
- Any finite derivative extension of Stelle gravity will introduce further ghost instabilities into the theory due to Ostrogradsky theorem.
- Infinite derivative (non-local) extension of Stelle gravity evades Ostrogradsky theorem.
- Further advancements in trace anomaly computations (A. O. Barvinsky, Scholarpedia (2015), I. L. Buchbinder and I. L. Shapiro, QFT with applications to quantum gravity (2021) indicate appearance of non-localities in the quantum effective action of gravity.)

Non-locality is the crucial for UV physics

- Studies of Non-local quantum field theories existed even from 1950's from the seminal works of M. Born, R. Feynman, H. J. Bhabha, Pais, and Ulenbeck, Efimov, Moffat, Krasnikov, Kuzmin, Tomboulis etc. Many approaches towards quantum gravity such as further developments of semi-classical approach to quantum gravity (where non-locality emerges with non-analytic form factors), string theory (string and branes are non-local objects and their interaction carries vertex terms involving infinite derivatives $e^{\Box/\mathcal{M}_s^2}$), causal sets, non-commutative theories, loop quantumgravity and asymptotic safety strongly indicate non-locality is the crux to achieve a UV compete theory that is renormalizable and Unitary arXiv: 2005.09550 (Koshelev, KSK, A. A. Starobinsky), arXiv: 2105.08167 (L. Buoninfante)

AID gravity captures the long standing quests to build a much needed consistent theoretical and phenomenological path towards quantum gravity:

Analytic Infinite derivative (AID) gravity

$$S = \int d^4x\sqrt{-g}\left(\frac{M_p^2}{2}R + \frac{1}{2}\left[R\mathcal{F}_R\left(\Box_s\right)R + W_{\mu\nu\rho\sigma}\mathcal{F}_W\left(\Box_s\right)W^{\mu\nu\rho\sigma}\right]\right).$$

Here the first term with M_p being the reduced Planck mass is the canonical Einstein-Hilbert General Realtivity (GR) Lagrangian, R as usual is the Ricci scalar, while the part in brackets is the higher derivative modification of GR. The crucial ingredient here is higher derivative formfactors $\mathcal{F}$ which further turn out to be analytic non-polynomial, i.e. essentially non-local, functions of the covariant d'Alembertian $\Box$. Hereafter, we use $\Box_s = \Box/\mathcal{M}_s^2$ with $\mathcal{M}_s$ being the scale of non-locality and $W_{\mu\nu\rho\sigma}$ denotes the Weyl tensor.

$$\mathcal{F}_R\left(\Box_s\right) = \sum_{n=0}^{\infty} f_{Rn}\Box_s^n, \quad \mathcal{F}_W\left(\Box_s\right) = \sum_{n=0}^{\infty} f_{Wn}\Box_s^n.$$

AID gravity $\rightarrow$ Quantum gravity? (See Alexey S. Koshelev's talk today and L. Buoninfante's talk tomorrow)

SFT inspired Non-local gravity/AID gravity

Non-local gravity is a formulation aimed to construct UV complete (ghost free) theory of gravity. It has several motivations including String field theory (String and branes are non-local objects and their interaction carries vertex terms involving infinite derivatives $e^{\Box/\mathcal{M}_s^2}$). N. V. Krasnikov (1987), Y. V. Kuzmin (1989), Tomboulis (1997), Modesto (2011), Biswas et al (2011), Koshelev et al (2016,2017)

(See Alexey S. Koshelev's talk today and Luca Buoninfante's talk tomorrow)
Non-locality in our scheme is introduced by inserting infinite derivatives in the action. The non-local extension of Stelle gravity is

$$S = \int d^D x \sqrt{-g} \left[\frac{M_P^2}{2} R + \frac{\lambda}{2} \left(R \mathcal{F}_R(\Box_s) R + W_{\mu\nu\rho\sigma} \mathcal{F}_W(\Box_s) W^{\mu\nu\rho\sigma} \right) \right] .$$

$\mathcal{F}_i$'s are analytic. The theory is Analytic Infinite Derivative (AID) gravity.

EOM of AID theory (FLRW case)

Equations of motion (EOM) of this theory are given by

$$E^{\mu}_{\nu} \equiv -\left[M_p^2 + 2\lambda\mathcal{F}\left(\frac{\Box}{\mathcal{M}_s^2}\right)R\right]G^{\mu}_{\nu}\delta^{\mu}_{\nu} - \frac{\lambda}{2}R\mathcal{F}\left(\frac{\Box}{\mathcal{M}_s^2}\right)R\delta^{\mu}_{\nu}$$
$$+ 2\lambda\left(\nabla^{\mu}\partial_{\nu} - \delta^{\mu}_{\nu}\Box\right)\mathcal{F}\left(\frac{\Box}{\mathcal{M}_s^2}\right)R + \lambda\mathcal{K}^{\mu}_{\nu} - \frac{\lambda}{2}\delta^{\mu}_{\nu}\left(\mathcal{K}^{\sigma}_{\sigma} + \bar{\mathcal{K}}\right) = 0\,,$$

where

$$\mathcal{K}^{\mu}_{\nu} = \frac{1}{\mathcal{M}_s^2}\sum_{n=1}^{\infty} f_n \sum_{l=0}^{n-1}\partial^{\mu}\frac{\Box^l}{\mathcal{M}_s^{2l}}R\partial_{\nu}\left(\frac{\Box}{\mathcal{M}_s^2}\right)^{n-l-1}R\,, \bar{\mathcal{K}} = \sum_{n=1}^{\infty} f_n \sum_{l=0}^{n-1}\frac{\Box^l}{\mathcal{M}_s^{2l}}R\left(\frac{\Box}{\mathcal{M}_s^2}\right)^{n-l}$$

The trace equation is

$$E = M_p^2 R - 6\lambda\Box\mathcal{F}\left(\frac{\Box}{\mathcal{M}_s^2}\right)R - \mathcal{K}^{\mu}_{\mu} - 2\mathcal{K} = 0\,.$$

R^2-like inflation in AID gravity

- EOM of AID gravity even though looks complicated they can be solved by a simple equation which is exactly the trace equation of local R^2 gravity

$$\Box R = M^2 R \implies \mathcal{F}\left(\frac{\Box}{\mathcal{M}_s^2}\right) R = \mathcal{F}\left(\frac{M^2}{\mathcal{M}_s^2}\right) R\,.$$

  Since the CMB observations indicate scale invariance we expect $M \ll M_s \lesssim \mathcal{M}_s$.

- Using the above trace equation the trace equation for AID non-local gravity become

$$\left[M_P^2 - 6\lambda M^2 \mathcal{F}_R\left(\frac{M^2}{\mathcal{M}_s^2}\right)\right] R - \lambda \mathcal{F}_R^{(1)}\left(\frac{M^2}{\mathcal{M}_s^2}\right)(\partial^\mu R \partial_\mu R + 2M^2 R^2) = 0$$

- It was showed that the only solution of the above equation for $R \neq 0$ (See Appendix C of 1711.08864) is

$$\mathcal{F}_R^{(1)}\left(\frac{M^2}{M_s^2}\right) = 0, \;\; \frac{M_P^2}{2\lambda} = 3M^2 \mathcal{F}_1, \quad \text{where } \mathcal{F}_1 \equiv \mathcal{F}_R\left(\frac{M^2}{\mathcal{M}_s^2}\right)$$

Hierarchy of scales

Figure: Hierarchy of mass scales in non-local R^2-like inflation.

This can be seen heuristically by expanding the quadratic Ricci scalar part of the action as

$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R + \frac{M_p^2}{12M^2}R^2 + \mathcal{O}\left(\frac{M_p^2 R\Box R}{M^2\mathcal{M}_s^2}\right)\right].$$

In the high curvature regime $R \gg M^2$ local quadratic curvature term is naturally dominant and it is known to be scale invariance.

Scalar perturbations: two point correlations

- To study perturbations around quasi dS

$$ds^2 = a^2(\eta)\left[-(1+2\Phi)\,d\eta^2 + ((1-2\Psi)\,\delta_{ij} + 2h_{ij})\,dx^i dx^j\right] .$$

- During inflation $\Phi + \Psi \approx 0$. $\delta W_{\mu\nu\rho\sigma} \propto (\Phi + \Psi)\, K_{\mu\nu\rho\sigma} \approx 0$. The curvature perturbation

$$\mathcal{R} = \Psi + H\frac{\delta R}{\dot{\bar{R}}} = \Psi + \frac{24H^3}{24H\dot{H}}\Phi \approx -\frac{1}{\epsilon}\Psi .$$

- The second order action for the scalar perturbations is ($c_s = 1$)

$$\delta^2 S^{(s)} = \frac{1}{2\mathcal{F}_1\bar{R}}\int d\tau d^3x\sqrt{-\bar{g}}\Upsilon\frac{\mathcal{W}\left(\frac{\bar{\Box}}{\mathcal{M}^2}\right)}{\mathcal{F}_R\left(\frac{\bar{\Box}}{\mathcal{M}^2}\right)}(\bar{\Box} - M^2)\Upsilon .$$

Predictions of AID non-local R^2 inflation: Scalar part

- $\Upsilon = 2\bar{R}\Psi$ is the canonical variable. To avoid any ghost degree of freedom we need to impose

$$\mathcal{W}(\Box_s) = 3\mathcal{F}_1 e^{2\gamma_s(\Box_s)},$$

where γ_s is an entire function of d'Alembertian operator. Then, we can express the form factor $\mathcal{F}_R$ in analytic form as

$$\mathcal{F}_R(\Box_s) = \mathcal{F}_1 \frac{3e^{\gamma_s(\Box_s)}\left(\Box - M^2\right) + \left(\bar{R} + 3M^2\right)}{3\Box + \bar{R}},$$

The power spectrum and the scalar spectral index are the same as in the local model (with adiabatic vacuum)

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{16\pi^2\epsilon^2}\frac{1}{3\lambda\mathcal{F}_1\bar{R}}\bigg|_{k=aH}, \quad n_s \equiv \frac{d\ln\mathcal{P}_{\mathcal{R}}}{d\ln k}\bigg|_{k=aH} \approx 1 - \frac{2}{N},$$

Predictions of AID non-local R^2-like inflation: Tensor part

- In the action we have Weyl square term with AID operators in it. Therefore, it is natural to expect the tensor power spectrum gets modified compared to local model. This is exactly what happens, the second order action for tensor perturbations become ($c_1 = 1$)

$$\delta^2 S_{(T)} = \frac{1}{2}\int d^4x\sqrt{-\bar{g}}\, h^{\perp}_{ij}\, e^{2\gamma_T\left(\Box_s - \frac{2\bar{R}}{3\mathcal{M}_s^2}\right)}\left(\bar{\Box} - \frac{\bar{R}}{6}\right) h^{\perp ij}\,,$$

which is related to the form-factor as

$$\mathcal{F}_W\left(\Box_s\right) = \frac{\mathcal{F}_1\bar{R}}{\mathcal{M}_s^2}\frac{e^{\gamma_T\left(\Box_s - \frac{2}{3}\frac{\bar{R}}{\mathcal{M}_s^2}\right)} - 1}{\Box_s - \frac{2\bar{R}}{3\mathcal{M}_s^2}}\,.$$

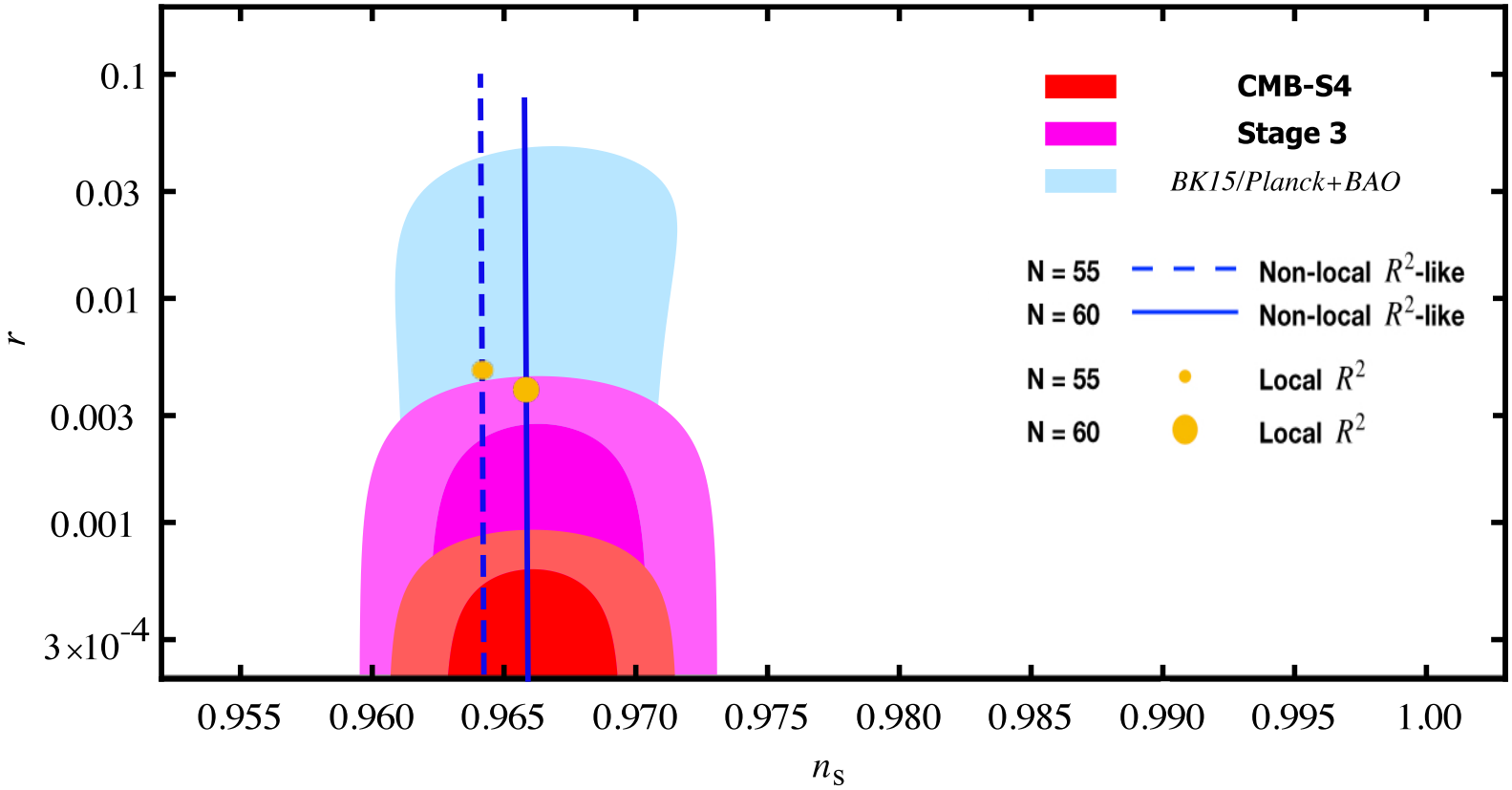
- Computing the tensor power spectrum in the leading order in slow-roll we obtain

$$\mathcal{P}_{\mathcal{T}}\big|_{k=aH} = \frac{H^2}{\pi^2\lambda\mathcal{F}_1\bar{R}}\, e^{-2\omega\left(\frac{\bar{R}}{6\mathcal{M}_s^2}\right)}\,.$$

Tensor to scalar ratio

The tensor to scalar ratio in R^2-like inflation in AID gravity gives

$$r = \frac{12}{N^2} e^{-2\gamma_T \left(\frac{-\bar{R}}{2\mathcal{M}_s^2}\right)} \Bigg|_{k=aH} .$$



Tensor to scalar ratio and single field consistency relation

The tensor tilt in this model is

$$n_t \equiv \left.\frac{d\ln\mathcal{P}_{\mathcal{T}}}{d\ln k}\right|_{k=aH} \approx -\left.\frac{d\ln\mathcal{P}_{\mathcal{T}}}{dN}\left(1+\frac{1}{2N}\right)\right|_{k=aH}$$
$$\approx -\frac{3}{2N^2} - \left(\frac{2}{N}+\frac{3}{2N^2}\right)\frac{\bar{R}}{2\mathcal{M}_s^2}\gamma_T^{(\dagger)}\left.\left(-\frac{\bar{R}}{2\mathcal{M}_s^2}\right)\right|_{k=aH},$$

Modified consistency relation and possibility of blue tilt

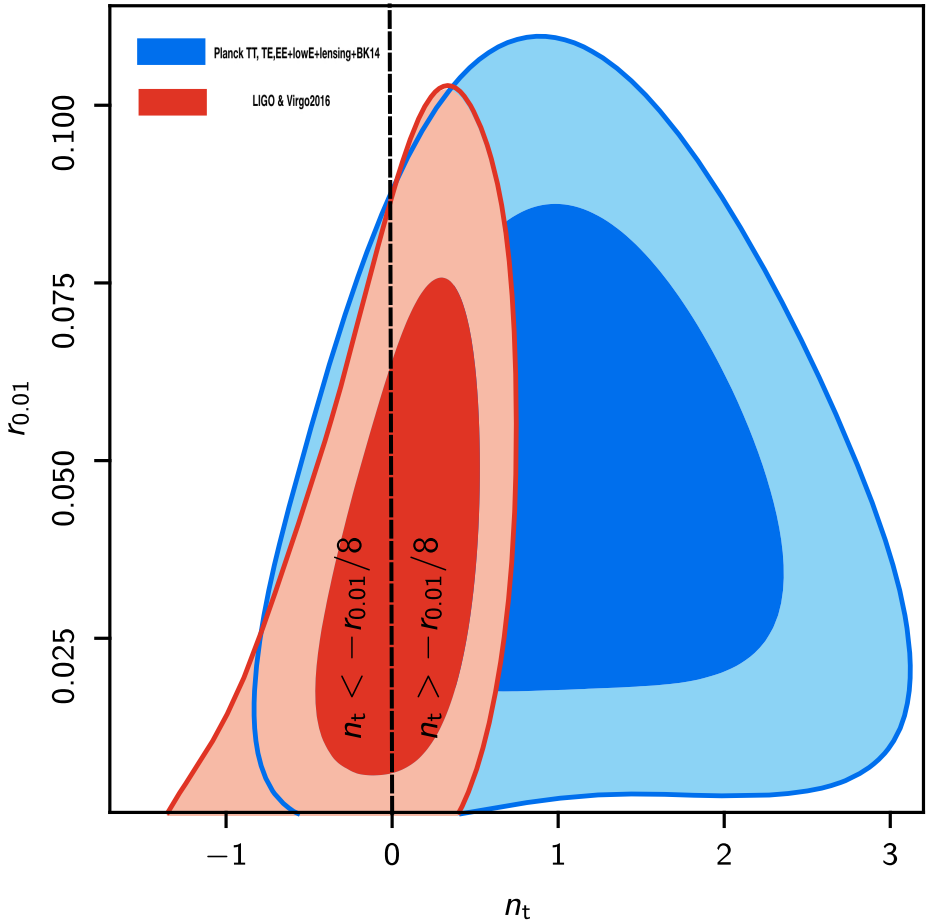
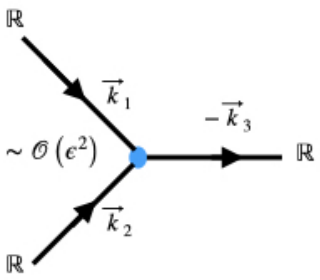


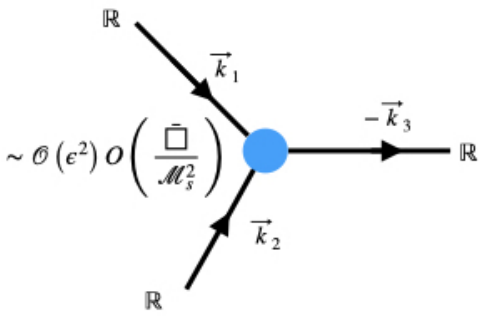
Figure: The (n_t, r) plane of latest Planck 2018.

Beyond two-point correlations: Scalar Non-Gaussianities

- Beyond two point correlations it is interesting to see if there will be non-Gaussianities in non-local R^2-like inflation.
- How non-locality effects the interactions of various curvature modes ? and Can they be detectable ?



Cubic interactions in local R^2 inflation



Cubic interactions in Non-local R^2-like inflation

Figure: In the above plot $\mathbb{R} = \{\mathcal{R}, \partial\mathcal{R}, \mathcal{D}^\mu\partial\mathcal{R}\}$ imply various tree level interactions of different modes of the curvature perturbation in the local R^2 and the non-local R^2-like inflation. $O\left(\frac{\bar{\Box}}{\mathcal{M}_s^2}\right)$ is some analytic non-local operator.

Reduced bispectrum f_{NL}

- To calculate bi-spectrum, first we expand our action to cubic order to the leading order in slow-roll parameter. We consider the mode functions $\mathcal{R} \approx -\Psi/\epsilon$ given by $\Box\mathcal{R} = M^2\mathcal{R}$
- New Interactions arise via the commutation relation in dS approximation $\Box\nabla_\mu\mathcal{R} = \nabla_\mu\Box\mathcal{R} + \frac{\bar{R}}{4}\nabla_\mu\mathcal{R}$.
- Our obtained cubic order action in $\mathcal{R}$ of AID gravity in the leading order slow-roll approximation is

$$\begin{aligned}\delta^{(3)}S_{(S)} =& 4\epsilon M_p^2 \int d\tau d^3x \Big\{ T_1^*\mathcal{R}\nabla\mathcal{R}\cdot\nabla\mathcal{R} + T_2^*\mathcal{R}\mathcal{R}'^2 + T_3^*\mathcal{H}^2\mathcal{R}^3 \\ &+ T_4^*\mathcal{H}\mathcal{R}\mathcal{R}\mathcal{R}' + T_5^*\mathcal{H}^{-1}\nabla\mathcal{R}\cdot\nabla\mathcal{R}\mathcal{R}' + T_6^*\mathcal{H}^{-1}\mathcal{R}'^3 \\ &+ T_7^*\mathcal{H}^{-2}\mathcal{R}'\nabla\mathcal{R}\cdot\nabla\mathcal{R}' \Big\},\end{aligned}$$

where T_i's are dimensionless constants.

f_{NL} for standard configurations

From the observational point of view, three configurations of reduced bi-spectrum f_{NL} for squeezed ($k_1 \to 0, k_2 = k_3 = \frac{K}{2}$), equilateral ($k_1 = k_2 = k_3 = K$) and orthogonal ($k_1 = k_2 = K/4, k_3 = K/2$) are the most relevant.

$$f_{NL}^{sq} \approx \frac{5}{12}(1-n_s) - 23\epsilon^2\left[e^{\gamma_S\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)} - 1\right] - \frac{4\bar{R}_*}{\mathcal{M}_s^2}\epsilon^3 e^{\gamma_S\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)}\gamma_S^{(\dagger)}\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)$$

$$f_{NL}^{eq} \approx \frac{5}{12}(1-n_s) - 49\epsilon^2\left[e^{\gamma_S\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)} - 1\right] - \frac{9\bar{R}_*}{\mathcal{M}_s^2}\epsilon^3 e^{\gamma_S\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)}\gamma_S^{(\dagger)}\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)$$

$$f_{NL}^{ortho} \approx \frac{5}{12}(1-n_s) - 43\epsilon^2\left[e^{\gamma_S\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)} - 1\right] - \frac{22\bar{R}_*}{3\mathcal{M}_s^2}\epsilon^3 e^{\gamma_S\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right)}\gamma_S^{(\dagger)}\left(\frac{\bar{R}_*}{4\mathcal{M}_s^2}\right).$$

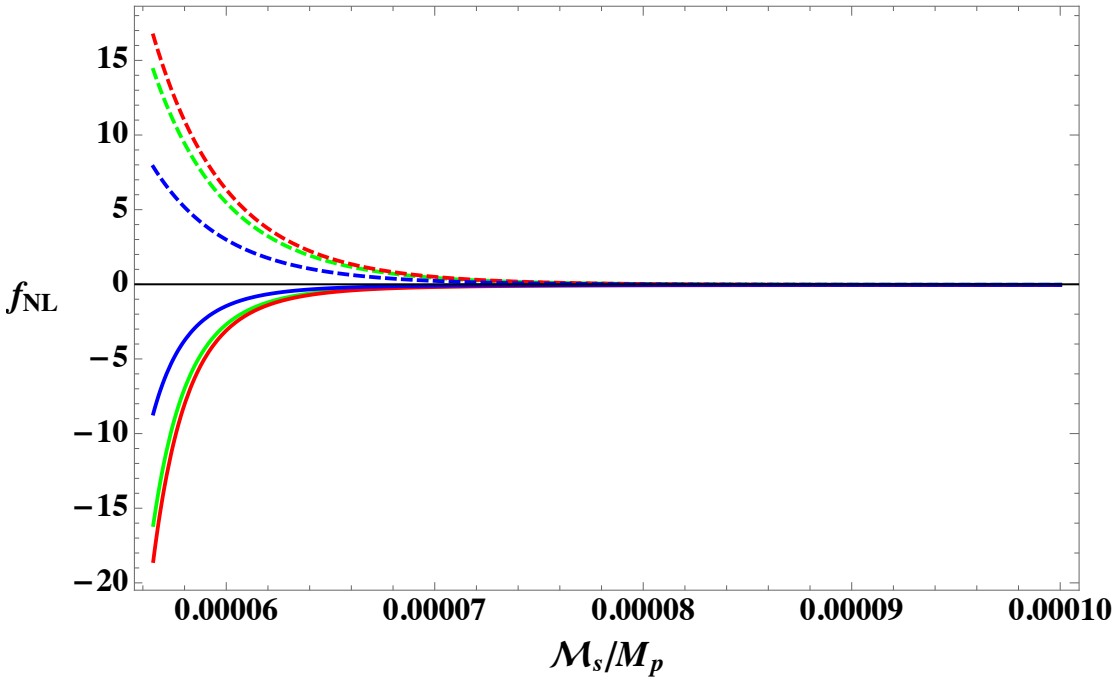


Figure: In the above plots, f_{NL} versus the scale of non-locality $\mathcal{M}_s$ (in the units of M_p) is depicted for squeezed (blue), equilateral (red), and orthogonal (green) configurations for the polynomial entire functions γ_T given by eqs. (4.19) and (4.20) of arXiv:2003.00629 and represented by solid and dashed lines respectively. Here $N = 55$ of e-foldings is assumed. In the limit $\mathcal{M}_s \to M_p$ the predictions of the local R^2 model are recovered.

Conclusions

- AID non-local gravity is the significant advancement over the Stelle's fourth oder theory of gravity and is potential to be UV complete.
- Non-local R^2-like inflation in this theory gives us two unique predictions: (1) Modified consistency relation (2) Tensor blue tilt is possible (which is often argued to rule out inflation) (3) Non-Gaussianities (which is often feature of multifield non-canonical models).
- What if we add additional matter fields coupled to scalaron in the non-local gravity? We should see their signature through special shapes of NGs.
- How to fix non-local form factors theoretically? (From string field theory or by further understanding quantum gravity, see Koshelev and Luca's talk)? or Asymptotic Safety approach, see Frank Saueressig's talk).

Thank you for your attention

Stay tuned to arXiv for further results!