UV-protected Natural Inflation: Primordial Fluctuations and non-Gaussian Features

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Outline

- Introduction
- Gravitational enhanced friction (GEF) in a nutshell
- Cosmological perturbations in the GEF inflation
- Non-Gaussianities in the GEF inflation
- UV-protected natural inflation
- Conclusions

Introduction

Latest cosmological data agree impressively well with the Universe that is on large scales

- homogeneous,
- isotropic
- spatially flat

A flat FRW Spacetime!

A theoretical puzzle:

A flat FRW Universe

$$ds^2 = -dt^2 + a(t)^2 d\vec{x} \cdot d\vec{x}$$

is *extremely fine tuned* solution of GR!

A simple idea to solve this puzzle is *Inflation*:

an exponential (accelerated and homogeneous) expansion of the early Universe.

Slow Roll Inflation

A scalar field ϕ is a good candidate of an Inflaton as

$$\rho = \frac{1}{2}\dot{\phi}^2 + V \ , p = \frac{1}{2}\dot{\phi}^2 - V$$

By geometrical identity (Raychaudhuri eq.)

$$\ddot{a} \propto -(\rho + 3p) \propto -(\dot{\phi}^2 - V)$$

$$\Downarrow$$

$$\begin{array}{lcl} \dot{\phi}^2 & \ll & V \ , \text{ Inflation happens ("slow roll")} \\ \dot{\phi}^2 & \sim & V \ , \text{ Inflation ends} \end{array}$$

Q: How do we achieve the slow roll for sufficient time?

Slow Roll Inflation

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$$\dot{\phi}^2 \ll V \ , \text{ Inflation happens (“slow roll”)}$$
$$\dot{\phi}^2 \sim V \ , \text{ Inflation ends}$$

Q: How do we achieve the slow roll for sufficient time?

(1) Let V have a non-trivial (positive) minimum,
(2) increase friction, or (3) fine-tune V to be flat.

Increasing friction

Let us ignore the gravity for a moment. Our goal is to achieve

$$E \simeq V,\ \tilde{\epsilon} \equiv -\frac{\dot{E}}{E^2} \ll 1 \text{ and } \tilde{\delta} \equiv \frac{\dot{\tilde{\epsilon}}}{\epsilon E} \ll 1$$

in a non-equilibrium point of V for a long time.

The friction must dominate over the acceleration:

$$\tilde{\mu}\dot{\phi} \simeq -V'$$

In order to have an almost constant energy, the friction coefficient must also be roughly constant. In this case,

$$\tilde{\epsilon} \simeq \frac{V'^2}{V^2}\frac{1}{\tilde{\mu}} \text{ and } \tilde{\delta} \simeq -2\frac{V''}{V}\frac{1}{\tilde{\mu}} + 2\tilde{\epsilon}$$

Slow roll is achieved if $\tilde{\mu}$ is large and roughly constant.

To form structures like galaxies, $\tilde{\mu}(E)$ must be an increasing function of E.

Increasing friction II

There are two ways to implement the friction:

$$(1)\ \ddot{\phi} + \tilde{\mu}\dot{\phi} = -V' \text{ and}$$

$$(2)\ \mu\left(\ddot{\phi} + 3E\dot{\phi}\right) = -V' \text{ with } \tilde{\mu} = 3E\mu$$

The friction dominates over the acceleration if

$$\tilde{\tilde{\delta}} \equiv \frac{\ddot{\phi}}{\tilde{\mu}\dot{\phi}} \ll 1.$$

As a result,

(1) $\tilde{\tilde{\delta}} \sim 3\tilde{\delta}(E/\tilde{\mu})$ is a new parameter controlling the system if $\tilde{\mu} \not\propto E$. $\Rightarrow$ New d.o.f.!

(2) $\tilde{\tilde{\delta}} \sim \tilde{\delta} \Rightarrow$ Good starting point to avoid new d.o.f.

Increasing friction with gravity

Let us now introduce gravity. Since the gravitational Hamiltonian density in the FRW Univ. is $\mathcal{H} = 3M_p^2 H^2$, we may identify

$$V \sim \mathcal{H},\; E \sim H.$$

The slow roll is then achieved by the Friedmann eqn

$3M_p^2 H^2 \simeq V$ and $\tilde{\mu} = 3H\mu(H)$ if no new DoF is added.

A typical enhancement of friction could be

$$\mu(H) = 1 + \frac{H^2}{M^2}.$$

$$\mu\left(\ddot{\phi} + 3H\dot{\phi}\right) = -V' \Rightarrow t_{\text{eff}} \simeq \frac{t}{\sqrt{\mu}} \text{ as } \frac{\dot{\mu}}{\mu H} \ll 1.$$

If $H^2 \gg M^2$ during inflation, scalar field's clock is moving slower than observer's clock and friction is enhanced!

Gravitationally Enhanced Friction (GEF): Realization

In order to realize the enhanced friction in a covariant manner, we promote the rescaling to all coords.

$$\partial_\mu \to \sqrt{\mu}\partial_\mu,\ \mu = 1 + \frac{H^2}{M^2}$$

By noticing that during slow roll, $G^{\mu\nu} \simeq -3H^2 g^{\mu\nu}$.

The enhanced friction is covariantly realized by shifting the kinetic action

$$\mathcal{L} \sim g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \to \left(g^{\mu\nu} - \frac{G^{\mu\nu}}{M^2}\right)\partial_\mu\phi\partial_\nu\phi$$

Thanks to Bianchi identities, this action has the properties:

- EoM of ϕ is shift and *curved* Galilean invariant [Talk by P. Moyassari]: $\phi \to \phi + c + c_\alpha \int_{\gamma,x_0}^{x} \xi^\alpha$
- Propagates only spin 0 (scalar) and spin 2 (graviton) particles (no higher derivatives, Lapse and Shift are still Lagrange multipliers)
- Makes harder for a scalar field to roll down its own potential!

Full action of the GEF inflation

$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}\Delta^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - V\right],$$

$$\text{where } \Delta^{\alpha\beta} \equiv g^{\alpha\beta} - \frac{G^{\alpha\beta}}{M^2}.$$

In a FRW background, the Friedmann and field eqs read

$$H^2 = \frac{1}{3M_p^2}\left[\frac{\dot\phi^2}{2}\left(1+9\frac{H^2}{M^2}\right) + V\right], \quad \partial_t\left[a^3\dot\phi\left(1+3\frac{H^2}{M^2}\right)\right] = -a^3V' \ .$$

During slow roll in the high friction limit ($H^2/M^2 \gg 1$), the eqs are simplified as

$$H^2 \simeq \frac{V}{3M_p^2} \ , \quad \dot\phi \simeq -\frac{V'}{3H}\frac{M^2}{3H^2} \ .$$

Power of the GEF mechanism

Consistency of the eqs requires the slow roll parameters to be small, i.e.

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1 \ , \quad \delta \equiv \frac{\ddot{\phi}}{H\dot{\phi}} \ll 1 \ .$$

By explicit calculation, one can show that

$$\epsilon \simeq \frac{V'^2 M_p^2}{2V^2}\frac{M^2}{3H^2}, \quad \delta \simeq -\frac{V'' M_p^2}{V}\frac{M^2}{3H^2} + 3\epsilon = -\eta + 3\epsilon \ , \quad \eta \equiv \frac{V'' M_p^2}{V}\frac{M^2}{3H^2}.$$

We see that, no matter how big the slow roll parameters of GR are

$$\epsilon_{GR} \equiv \frac{V'^2 M_p^2}{2V^2} \qquad \text{and} \qquad \eta_{GR} \equiv \frac{V'' M_p^2}{V},$$

there is always a choice of scale $M^2 \ll 3H^2$, during inflation, such that slow roll parameters are small.

Cosmological perturbations in the GEF inflation

ADM form

$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)^2$$

- Use the gauge $\delta\phi = 0$
- then: $h_{ij} = a^2[(1 + 2 \underbrace{\zeta}_{\text{curvature perturbation}})\delta_{ij} + \underbrace{\gamma_{ij}}_{\text{gravitational waves}}]$
- Vary wrt the constraints N, N^i, substitute back into the action and canonically normalize ζ and γ_{ij}
- $N = 1 + \frac{\Gamma}{H}\dot{\zeta}$, $N^i = -\frac{\Gamma}{H}\partial_i\zeta + \frac{\Sigma}{H^2}\partial_i\partial^{-2}\dot{\zeta}$
- $\Gamma(\dot{\phi}, H, M) \simeq 1 + \frac{2}{3}\epsilon$, $\Sigma(\dot{\phi}, H, M) \simeq \epsilon H^2$ for $H \gg M$

Curvature perturbation spectrum

- $\mathcal{L}_{\zeta^2} = \frac{1}{2}[\zeta'^2 - c_s^2(\partial_i\zeta)^2 + \frac{z''}{z}\zeta^2]$ with $c_s^2 = 1 - \mathcal{O}(\epsilon)$
- $\langle\hat{\zeta}_k\hat{\zeta}_{k'}\rangle = (2\pi)^3\delta^{(3)}(k+k')\frac{2\pi^2}{k^3}\mathcal{P}_\zeta$ where $\mathcal{P}_\zeta = \frac{H^2}{8\pi^2\epsilon c_s M_p^2}$
- spectral index: $n_s - 1 = \frac{d\ln\mathcal{P}_\zeta}{d\ln k} \approx -2\epsilon - 2\delta$
- running of the spectral index: $\frac{dn_s}{d\ln k} \approx -6\epsilon\delta - 2\delta\delta' + 2\delta^2$

Matching with the WMAP data, $\mathcal{P}_\zeta = 2\times 10^{-9}$, we get a relation

$$\frac{M^2}{H^2} = \frac{10^9}{8\pi^2}\frac{V^3}{V'^2 M_p^6}$$

Note that scalar perturbations are slightly sub-luminal.
Can this lead to observational consequences?
(Any non-Gaussianity due to the new non-linear interaction?)

Gravitational wave spectrum

- $\mathcal{L}_{\gamma^2} = \frac{1}{2}[\gamma_{ij}'^2 - c_{gw}^2(\partial_k \gamma_{ij})^2 + \frac{z_t''}{z_t}\gamma_{ij}^2]$ with $c_{gw}^2 = 1 + \mathcal{O}(\epsilon)$
- $\langle \hat{\gamma}_k \hat{\gamma}_{k'} \rangle = (2\pi)^3 \delta^{(3)}(k + k') \frac{2\pi^2}{k^3} \mathcal{P}_\gamma$ where $\mathcal{P}_\gamma = \frac{2H^2}{\pi^2 c_{gw}(1+\epsilon/3) M_p^2}$
- spectral index is red: $n_t = \frac{d \ln \mathcal{P}_\gamma}{d \ln k} \approx -2\epsilon$
- tensor to scalar ratio: $r = \frac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta} = 16\epsilon = -8 n_t$

Note that GWs are slightly "super-luminal", but this does not mean "acausal" since the causal structure is set by the propagation of GWs.

Is the Lyth bound modified?

The Lyth bound tells us that detectable gravitational waves require super-Planckian field variation, $\Delta\phi \gtrsim 2 \text{ to } 6 M_p$ [Lyth 1997].

Under GEF, this bound reads

$$\left(\frac{r}{0.1}\right)^{1/2} \lesssim \frac{H}{20M} \frac{\Delta\phi}{M_p} \frac{50}{N_e}.$$

Although at first sight the bound seems to allow detectable GWs for sub-Planckian values of the field, in fact, it requires the canonically normalized inflaton [$\tilde{\phi} \sim (H/M)\phi$] to be super-Planckian.
In this sense, the Lyth bound is not modified.

GEF saves $\lambda\phi^4$ model

The $\lambda\phi^4$ model predicts a red spectrum:

$$V = \frac{\lambda}{4}\phi^4, \quad n_s - 1 \simeq -\frac{40}{3}\frac{M^2}{H^2}\frac{M_p^2}{\phi_i^2} \simeq -5\epsilon$$

$$N_e = \frac{5}{3(1-n_s)}.$$

For $n_s - 1 = -0.03$, one obtains

$$\epsilon \simeq 0.0167, \; N_e \simeq 56, \; r \simeq 0.1 \text{ and}$$

$$\frac{\phi_i}{M_p} \simeq 7 \times 10^{-2}\left(\frac{0.1}{\lambda}\right)^{1/4}, \; \frac{H}{M_p} \simeq 5 \times 10^{-5}, \; \frac{M}{M_p} \simeq 2 \times 10^{-7}\left(\frac{0.1}{\lambda}\right)^{1/4},$$

The values are compatible with the WMAP data.

Non-Gaussianity in the GEF inflation

- We compute the non-Gaussian feature of the scalar fluctuations from the cubic action.
- We use the comoving gauge variable, ζ, since it is conserved outside the horizon (at least at order ϵ).
- The leading order effect appears in the bispectrum or the three-point function. Since $\mathcal{L}_{\zeta^3}^{GEF} \sim \mathcal{O}(\epsilon^2)$, we get $f_{NL} \sim \langle\zeta^3\rangle/\langle\zeta^2\rangle^2 \sim \mathcal{O}(\epsilon)$.

Bispectrum: three-point correlation function

As in the power spectrum, the bispectrum of ζ is defined by the three-point correlation function:

$$\langle\hat{\zeta}(\tau,\mathbf{k}_1)\hat{\zeta}(\tau,\mathbf{k}_2)\hat{\zeta}(\tau,\mathbf{k}_3)\rangle \equiv (2\pi)^3\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\zeta(k_1,k_2,k_3).$$

One can evaluate the three-point correlator by using the in-in formalism [Maldacena 2002, Weinberg 2005]. In the lowest order,

$$\begin{aligned}&\langle\hat{\zeta}(0,\mathbf{k}_1)\hat{\zeta}(0,\mathbf{k}_2)\hat{\zeta}(0,\mathbf{k}_3)\rangle\\ &\quad = -i\int_{-\infty}^{0} d\tau a\langle 0|[\hat{\zeta}(0,\mathbf{k}_1)\hat{\zeta}(0,\mathbf{k}_2)\hat{\zeta}(0,\mathbf{k}_3),\hat{H}_{int}(\tau)]|0\rangle,\end{aligned}$$

where we have set the initial and final times as $\tau_i=-\infty$ and $\tau_f=0$, respectively. The interaction Hamiltonian is given by

$$\hat{H}_{int}(\tau) = -\int d^3x\hat{\mathcal{L}}^{GEF}_{\zeta^3}.$$

The 3-pt fn can be calculated from each term of the int Hamiltonian:

- $H_{int}^{(1)}(\tau) = -c_1 a^3 \int d^3x \zeta \dot{\zeta}^2$

  $$B_\zeta^{(1)} = \frac{c_1 H^4}{16\epsilon_s^3 M_p^6} \frac{1}{(k_1 k_2 k_3)^3} \left(\frac{k_2^2 k_3^2}{K} + \frac{k_1 k_2^2 k_3^2}{K^2} + \mathrm{sym} \right),$$

- $H_{int}^{(2)}(\tau) = -c_2 a^3 \int d^3x \dot{\zeta}^3$

  $$B_\zeta^{(2)} = \frac{3c_2 H^5}{8\epsilon_s^3 M_p^6} \frac{1}{k_1 k_2 k_3 K^3},$$

- $H_{int}^{(3)}(\tau) = -c_3 a \int d^3x \partial_i^2 \zeta \dot{\zeta}^2$

  $$B_\zeta^{(3)} = \frac{3c_3 H^6}{4\epsilon_s^3 c_s^2 M_p^6} \frac{1}{k_1 k_2 k_3 K^3},$$

where $k = |\mathbf{k}|$, $K = k_1 + k_2 + k_3$ and "sym" denotes the symmetric terms with respect to $k_1,\ k_2,\ k_3$.

- $H_{int}^{(4)}(\tau) = -c_4 a \int d^3x \zeta (\partial_i \zeta)^2$

$$B_\zeta^{(4)} = \frac{c_4 H^4}{16\epsilon_s^3 c_s^2 M_p^6} \frac{1}{(k_1 k_2 k_3)^3} \times \left[(\mathbf{k}_1 \cdot \mathbf{k}_2 + \mathbf{k}_2 \cdot \mathbf{k}_3 + \mathbf{k}_3 \cdot \mathbf{k}_1) \left(-K + \frac{k_1 k_2 + k_2 k_3 + k_3 k_1}{K} + \frac{k_1 k_2 k_3}{K^2} \right) \right],$$

- $H_{int}^{(5)}(\tau) = -c_5 a \int d^3x \dot{\zeta} (\partial_i \zeta)^2$

$$B_\zeta^{(5)} = \frac{c_5 H^5}{32\epsilon_s^3 c_s^2 M_p^6} \frac{1}{(k_1 k_2 k_3)^3} \left[\frac{k_1^2 (\mathbf{k}_2 \cdot \mathbf{k}_3)}{K} \left(1 + \frac{k_2 + k_3}{K} + \frac{2 k_2 k_3}{K^2} \right) + \mathrm{sym} \right],$$

- $H_{int}^{(6)}(\tau) = -c_6 a \int d^3x \dot{\zeta} \partial_i \zeta \partial_i \chi$

$$B_\zeta^{(6)} = \frac{c_6 H^4}{32\epsilon_s^2 c_s^2 M_p^6} \frac{1}{(k_1 k_2 k_3)^3} \left[\frac{(\mathbf{k}_1 \cdot \mathbf{k}_2) k_3^2}{K} \left(2 + \frac{k_1 + k_2}{K} \right) + \mathrm{sym} \right],$$

- $H_{int}^{(7)}(\tau) = -c_7 a \int d^3x \dot{\zeta}^2 \partial_i^2 \chi$

$$B_\zeta^{(7)} = \frac{3\tilde{c}_7 H^5}{8\epsilon_s^3 M_p^6} \frac{1}{k_1 k_2 k_3 K^3}, \quad \tilde{c}_7 \equiv \epsilon c_7 .$$

By using the Wick's theorem, we obtain the contribution from field redefinition $\zeta \to \zeta + (\epsilon/2 + \delta/2)\zeta^2$:

$$B_\zeta^{\rm redef}(k_1, k_2, k_3) = \frac{(\epsilon+\delta)H^4}{16\epsilon_s^2 c_s^2 M_p^4}\left(\frac{1}{k_1^3 k_2^3} + \frac{1}{k_2^3 k_3^3} + \frac{1}{k_3^3 k_1^3}\right).$$

In the squeezed limit,

$$B_\zeta^{(1)}(k_1, k_2 \to k_1, k_3 \to 0) = \frac{3\epsilon}{2} P_\zeta(k_1) P_\zeta(k_3),$$

$$B_\zeta^{(4)}(k_1, k_2 \to k_1, k_3 \to 0) = -\frac{3\epsilon}{2} P_\zeta(k_1) P_\zeta(k_3),$$

$$B_\zeta^{\rm redef}(k_1, k_2 \to k_1, k_3 \to 0) = 2(\epsilon + \delta) P_\zeta(k_1) P_\zeta(k_3).$$

Other terms are sub-dominant in this limit, and thus we get the consistency relation:

$$\frac{12}{5} f_{NL} = \frac{B_\zeta(k_1, k_2 \to k_1, k_3 \to 0)}{P_\zeta(k_1) P_\zeta(k_3)} = 1 - n_s$$

Natural Inflation

In natural inflation, the field ϕ is a pseudo-Nambu-Goldstone Boson with decay constant f and periodicity $2\pi f$ [Freese et al 1990].

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - me^{i\frac{\phi}{f}}\bar{\psi}(1+\gamma_5)\psi - \bar{\psi}\not{D}\psi - \frac{1}{2}\mathrm{Tr}F_{\alpha\beta}F^{\alpha\beta}\right],$$

- where ψ is a fermion charged under the (non-abelian) gauge field with field strength $F_{\alpha\beta}$, $\not{D} = \gamma^\alpha\mathcal{D}_\alpha$ is the gauge invariant derivative and $m \sim f$ is the fermion mass scale after spontaneous symmetry breaking.
- The action is invariant under the chiral (global) symmetry $\psi \to e^{i\gamma_5\alpha/2}\psi$, where α is a constant.
- This symmetry is related to the invariance under shift symmetry of ϕ, i.e. $\phi \to \phi - \alpha\, f$.

Natural Inflation II

- Suppose the chiral symmetry is broken at energies $f >$TeV (like in the QCD axion case) [chiral anomaly induces $(\phi/f)F\tilde{F}$]
- a potential of pNGB ϕ is produced by the instanton effect:

$$V(\phi) \sim \Lambda^4 \left[1 \pm \cos\frac{\phi}{f}\right]$$

which is protected from QG UV corrections by the restoration of global shift symmetry $\phi \to \phi + c$ as $\Lambda/M_p \to 0$

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  which is protected from QG UV corrections by the restoration of global shift symmetry $\phi \to \phi + c$ as $\Lambda/M_p \to 0$
- If $\Lambda \sim 10^{16}$ GeV (GUT scale), inflation is produced with

$$n_s - 1\,(\propto \epsilon) \simeq -\frac{M_p^2}{8\pi f^2}$$

- so $n_s - 1 \simeq -0.04 \to f > M_p$
  $\Rightarrow$ The potential may not be protected from QG UV corrections.

GEF saves Natural Inflation

Once again we can increase the friction so that

$$\epsilon \rightarrow \frac{\epsilon_{old}}{\mu} \Rightarrow n_s - 1 \sim -\frac{M_p^2}{8\pi f \mu}$$

For large enough friction μ, we have $f \ll M_p$

All the coupling scales are sub-Plankian!
(i.e. no UV modifications of the potential)

The new coupling $G^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi$ is the unique that

- *does not* introduce any new d.o.f.
- *is invariant* under the global unbroken symmetry $\phi \rightarrow \phi + c$.

UV-protected Natural Inflation

Inspired by Natural Inflation, we will consider the following tree-level Lagrangian for a single pseudo-scalar field ϕ [Germani & Kehagias 2010]

$$\mathcal{L} = \sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}\Delta^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - me^{i\frac{\phi}{f}}\bar{\psi}(1+\gamma_5)\psi - \bar{\psi}\not{\mathcal{D}}\psi - \frac{1}{2}\mathrm{Tr}F_{\alpha\beta}F^{\alpha\beta}\right],$$

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- The action is invariant under the chiral (global) symmetry $\psi \to e^{i\gamma_5\alpha/2}\psi$, where α is a constant.
- This symmetry is related to the invariance under shift symmetry of ϕ, i.e. $\phi \to \phi - \alpha\, f$.

Red spectrum from UV-protected Inflation

Small field branch:

$$V(\phi) \simeq \Lambda^4 \left(2 - \frac{\phi^2}{2f^2}\right)$$

- $n_s - 1 \simeq -\frac{1}{3}\frac{M^2}{H^2}\frac{M_p^2}{f^2} < 0 \Rightarrow$ Red spectrum!

Matching with $\mathcal{P}_\zeta = 2 \times 10^{-9}$ and $1 - n_s = 0.04$,

$$\boxed{\frac{\Lambda^2}{M_p^2} = \frac{\pi\sqrt{6}}{10^5\sqrt{5}}\frac{\phi_i}{f}, \qquad \frac{M}{H} = \frac{\sqrt{3}}{5}\frac{f}{M_p}}$$

- Consistent with the theoretical hierarchies of scales to protect the potential:

$$M \ll M\frac{M_p^2}{\Lambda^2} \ll f \ll M_p$$

- GW signal is small. Large field branch?

Red spectrum from UV-protected Inflation II

Large field branch:

$$V(\phi) \simeq \frac{1}{2}m^2\phi^2 \ , \quad m \equiv \frac{\Lambda^2}{f}$$

- $n_s - 1 = -\frac{3}{2N_e} < 0 \Rightarrow 1 - n_s = 0.03$ for $N_e = 50$.

Matching with $\mathcal{P}_\zeta = 2 \times 10^{-9}$ and $1 - n_s = 0.03$,

$$\phi_i^6 = 384\pi^2 \times 10^{-9}\frac{M^2 M_p^8}{m^4}, \quad \phi_i^4 = 8 \times 10^2 \frac{M^2 M_p^4}{m^2}$$

- Consistent with the theoretical hierarchies of scales to protect the potential:

$$\frac{M_p}{\Lambda}\sqrt{Mf} \ll \phi \ll f \ll M_p \text{ and } \Lambda \ll M_p$$

- GW signal is potentially detectable: $r \simeq 16\epsilon \simeq 0.08$

Non-Gaussianity from UV-protected Inflation

NG can be generated by the inverse decays of gauge fields if the inflaton is identified as a pseudo-scalar [Barnaby & Peloso 2010]:

$$f_{NL}^{\rm equil} \simeq 4.4 \times 10^{10} \mathcal{P}_\zeta^3 \frac{e^{6\pi\xi_i}}{\xi_i^9}, \quad \xi_i \equiv \frac{\dot{\phi}}{2f_i H} = \xi \frac{f}{f_i}, \quad \xi \equiv \frac{\dot{\phi}}{2fH}.$$

At sufficiently large $\xi_i \gtrsim \mathcal{O}(1)$, $f_{NL}^{\rm equil} \simeq 8400$, which excludes axion-like inflation models by the observations.

In the small field branch of the UV-protected inflation,

$$\xi \equiv \frac{\dot{\phi}}{2fH} \simeq \sqrt{\frac{\epsilon}{6}} \frac{M}{H} \frac{M_p}{f} = \frac{\sqrt{\epsilon}}{5\sqrt{2}} \simeq 2 \times 10^{-2} \ll 1.$$

No NG is generated by the gauge field that produces the inflaton potential, but we also have

$$\xi_i \simeq 2 \times 10^{-2} \ \frac{f}{f_i},$$

which allows a detactable signal for $f_i \sim 10^{-2} f$.

Conclusions

- By increasing the friction, inflation can be obtained with the SM Higgs or a pNGB.
- The friction can be enhanced by nonminimally coupling the Einstein tensor to the kinetic term of the Inflaton.
- This coupling is unique: *does not increase* no. of propagating d.o.f.
- Consistent with WMAP 7-years result.
- Non-Gaussianities from single-field inflation models with GEF are small.
- The parity violating interactions may produce detectable NG.