Primordial Perturbations from Dilaton-induced Gauge Fields

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based on KC, K-Y. Choi, H. Kim and C.S. Shin, arXiv:1507.04977

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Early universe inflation provide an appealing mechanism to generate cosmic perturbations.

Vacuum fluctuations of the inflaton and graviton in de Sitter space lead to

1) nearly scale-invariant and Gaussian scalar curvature perturbation with

$$\mathcal{P}_s = \left(\frac{H}{2\pi}\right)^2 \left(\frac{H}{\dot\phi}\right)^2 = \frac{1}{8\pi^2\epsilon}\left(\frac{H}{M_P}\right)^2 \simeq 2\times 10^{-9} \quad \left(\epsilon = -\frac{\dot H}{H^2} = \frac{1}{2M_P^2}\left(\frac{\dot\phi}{H}\right)^2\right)$$

2) nearly scale-invariant tensor perturbation with

$$\mathcal{P}_t = \frac{2}{\pi^2}\left(\frac{H}{M_P}\right)^2$$

➔ * Inflation scale determined by the tensor-to-scalar ratio:

$$r \equiv \frac{\mathcal{P}_t}{\mathcal{P}_s} = 16\epsilon \simeq 0.2\left(\frac{H}{10^{14}\,\mathrm{GeV}}\right)^2$$

* Slightly red-tilted tensor spectrum: $\dfrac{d\ln\mathcal{P}_t}{d\ln k} = -2\epsilon = -\dfrac{r}{8}$

How firm the connection between “r” and “H” is?

Is there any alternative way to generate tensor perturbation?

“Gauge fields produced by rolling scalar field during the inflation epoch might be the dominant source of tensor perturbation.”

Example: Rolling axion $\chi(t)$ with $\mathcal{L}_{\rm int} = \frac{\chi(t)}{4f} F^{\mu\nu}\tilde{F}_{\mu\nu}$

Anber, Sorbo ‘2010; Barnaby, Namba, Peloso ‘2011; Barnaby, Pajer, Peloso ‘2012; Cook, Sorbo ‘2013; Shiraishi, Ricciardone, Saga ‘2013; Mukohyama, Namba, Peloso, Shiu ‘2014; Ferreira, Sloth ‘2014, ….

➔ Helicity-dependent effective mass of gauge field in de Sitter background

$$\delta m^2_{A_\pm}(k,\tau) = \pm\frac{2k\xi}{\tau} \quad \left(\xi = \frac{1}{2f}\left(\frac{1}{H}\frac{d\chi}{dt}\right) = \text{axion coupling} \times \text{evolution rate}\right)$$

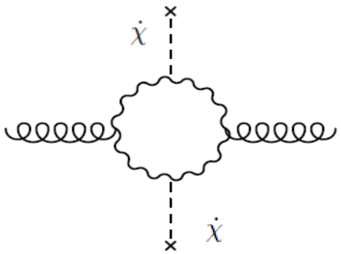
$$ds^2 = dt^2 - a^2(t)d\vec{x}^2 = a^2(\tau)\left(d\tau^2 - d\vec{x}^2\right) \quad \text{with } a(\tau) \simeq -\frac{1}{H\tau}$$

➔ Rolling axion causes a tachyonic instability of A_+, leading to an exponential growth of A_+ around the time of horizon crossing: $A_+ \propto e^{\pi\xi}$

Gravitational waves (GW) produced by axion-induced gauge fields:

$A_+ \propto e^{\pi\xi}$ ➔ chiral GW with $\mathcal{P}_t^{(\mathrm{axion})} \propto \left(\frac{H}{M_P}\right)^4 e^{4\pi\xi}$ $\left(\mathcal{P}_t^{(\mathrm{vacuum})} = \frac{2}{\pi^2}\left(\frac{H}{M_P}\right)^2\right)$

$\left(\xi = \frac{1}{2f}\left(\frac{1}{H}\frac{d\chi}{dt}\right)\right)$



If ξ is large enough, $\mathcal{P}_t^{(\mathrm{axion})}$ can dominate over $\mathcal{P}_t^{(\mathrm{vacuum})}$, and then the tensor power spectrum may be large enough to be observable even when the inflation scale is relatively low, e.g. $r = \mathcal{O}(10^{-2})$ even when $H \ll 10^{14}\,\mathrm{GeV}$.

If ξ is an increasing function of time, which is a plausible possibility, the tensor perturbation can have a large positive spectral index: Mukohyama et. al. '2014

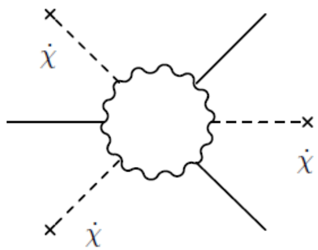
$$\frac{d\ln\mathcal{P}_t^{(\mathrm{axion})}}{d\ln k} = 4\pi\xi\frac{d\ln\xi}{d\ln k} + \ldots = 4\pi\xi \times \mathcal{O}(\epsilon) > 0 \quad \left(\frac{d\ln\mathcal{P}_t^{(\mathrm{vacuum})}}{d\ln k} = 2\frac{d\ln H}{d\ln k} = -2\epsilon < 0\right)$$

➔ Chiral and blue-tilted tensor perturbation which can be large enough to be observable even when H << 10^{14} GeV!

However this scenario is severely constrained by the observed scalar perturbation.

Any rolling scalar field inevitably mixes with the scalar curvature perturbation!

So, regardless of whether the rolling axion corresponds to the inflaton or not, the axion-induced gauge fields affect the scalar perturbation, e.g



Barnaby, Namba, Peloso '2011

➔ $f_{NL}^{\rm eq} \propto \left(\frac{H}{M_P}\right)^6 e^{6\pi\xi} \propto \left(\mathcal{P}_t^{(\rm axion)}\right)^{3/2}$

If the tensor perturbation is generated mostly by the axion-induced gauge fields, the tensor-to-scalar ratio "r" is bounded by the non-Gaussianity of the scalar perturbation: Ferreira, Sloth '2014

1) $r < 10^{-2}\epsilon^2 \left(f_{NL}^{\rm eq}\right)^{2/3}$ when the axion is rolling until the end of inflation

➔ "r" is too small to be observable.

2) $r < 10^{-2} \left(f_{NL}^{\rm eq}\right)^{2/3} / (\Delta N)^2$ when the axion is stabilized before the end of inflation

(ΔN = Efoldings from the horizon exit of the CMB scale to the axion stabilization)

➔ "r" = O(10^{-2}) might be allowed if the axion is stabilized soon after the CMB scale exits the horizon.

Another scenario yielding a different form of tensor perturbation:

Rolling dilaton $\sigma(t)$ with $\mathcal{L}_{\rm int} = -\frac{1}{4}e^{\sigma(t)/\Lambda}F^{\mu\nu}F_{\mu\nu}$

➔ Effective mass of gauge field with different time-dependence

Bamba, Yokoyama '2004; Barnaby, Namba, Peloso '2012, …

$$\delta m^2_{A_\pm}(\tau) \simeq -\frac{n(n-1)}{\tau^2} \quad \left(n = \frac{1}{\Lambda}\left(\frac{1}{H}\frac{d\sigma}{dt}\right) = \text{dilaton coupling} \times \text{evolution rate} > 2\right)$$

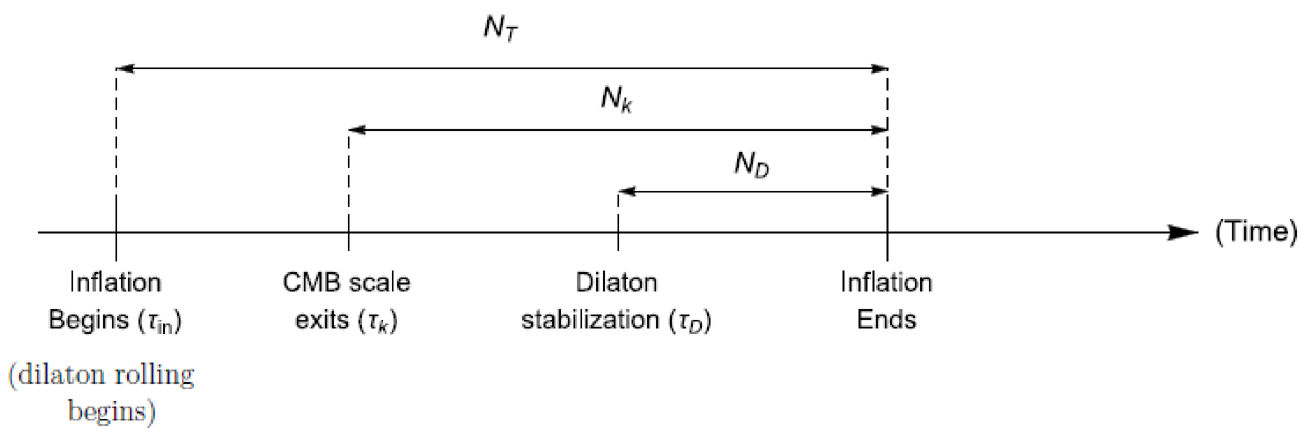
Similar to the axion case, rolling dilaton causes a tachyonic instability of gauge field, so leads to an exponential growth of gauge field.

However, contrary to the axion case where only A_+ grows only around the time of horizon crossing, in the dilaton case both A_+ and A_- grow continuously in the superhorizon limit:

$$e^{\sigma/2\Lambda}A_\pm \propto \frac{1}{|k\tau|^{n-1}} \quad \text{in the superhorizon limit } |k\tau| \to 0$$

$$\rightarrow \quad \rho_{A_\pm} \propto \frac{1}{a^4}\left(\frac{1}{|\tau|}\right)^{2n} \propto a^{2(n-2)} \quad \left(ds^2 = a^2(\tau)(d\tau^2 - d\vec{x}^2) \text{ with } a \simeq -\frac{1}{H\tau}\right)$$

Because the dilaton-induced gauge field grows continuously in the superhorizon limit, its consequences are strongly time-dependent (= scale-dependent):



Perturbations produced by the dilaton-induced gauge fields depend exponentially on

$$\Delta N_1 = N_T - N_k$$

(Efoldings from the beginning of dilaton rolling to the horizon exit of the CMB scale)

$$\Delta N_2 = N_k - N_D$$

(Efoldings from the horizon exit of the CMB scale to the dilaton stabilization)

(In order for tensor perturbation generated by the dilaton-induced gauge fields is large enough to be observable, while satisfying the constraints on scalar perturbation, the dilaton can not be an inflaton, and is required to be stabilized before the end of inflation.)

Perturbations from dilaton-induced gauge fields: KC, K-Y. Choi, H. Kim, C.S. Shin '2015

$$\mathcal{P}_s^{(\mathrm{dilaton})} \simeq \frac{3\times 2^{4n-5}\Gamma^4(n+\frac{1}{2})n^2}{\pi^6(n-2)^5(2n-1)^4}\left(\frac{H}{M_P}\right)^4 e^{2(n-2)((N_T-N_k)+2(N_k-N_D))}$$

$$f_{NL}^{(\mathrm{dilaton})} \simeq \frac{5\times 2^{6n+1}\Gamma^6(n+\frac{1}{2})n^3}{\pi^3(n-2)^7(2n-1)^6}\epsilon^3\mathcal{P}_s^{(\mathrm{vacuum})}e^{2(n-2)((N_T-N_k)+3(N_k-N_D))}$$

$$\mathcal{P}_t^{(\mathrm{dilaton})} \simeq \frac{2^{4n-2}\Gamma^4(n+\frac{1}{2})}{27\pi^6(n-2)^3}\left(\frac{H}{M_P}\right)^4 e^{2(n-2)((N_T-N_k)+2(N_k-N_D))}$$

$$(n-2\approx \mathrm{constant}\gg \mathcal{O}(\epsilon))$$

➔ $$\frac{d\ln\mathcal{P}_s^{(\mathrm{dilaton})}}{d\ln k}\simeq\frac{d\ln\mathcal{P}_t^{(\mathrm{dilaton})}}{d\ln k} = -2(n-2)+\mathcal{O}(\epsilon) < 0$$ (strongly red-tilted)

We are interested in the possibility of

$\mathcal{P}_t^{(\mathrm{dilaton})} \gg \mathcal{P}_t^{(\mathrm{vacuum})}$, but $\mathcal{P}_s^{(\mathrm{dilaton})} \ll \mathcal{P}_s^{(\mathrm{vacuum})}$

which would allow the tensor-to-scalar ratio "r" to be large enough to be observable even when H << 10^{14} GeV, while satisfying the observational constraints on scalar perturbation: spectral-index, non-Gaussianity, statistical anisotropy.

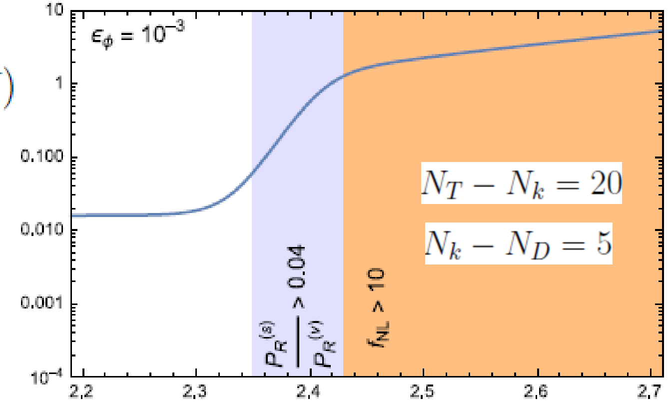
Tensor-to-scalar ratio "r" compatible with the constraints on scalar perturbation

too large scale-dependence

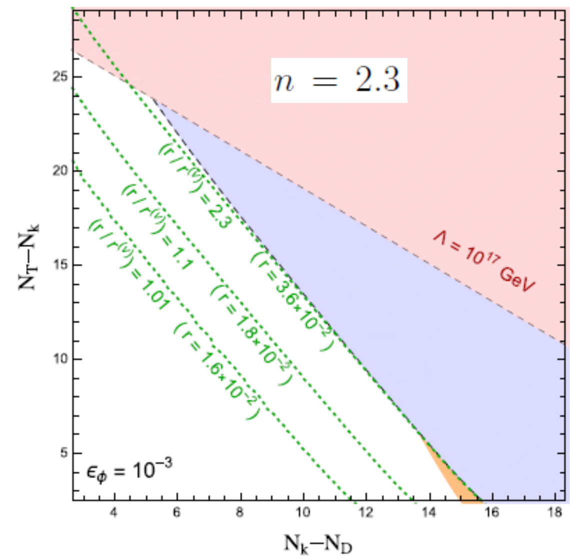
too large non-Gaussianity

$\epsilon = 10^{-3}$

$(H \simeq 3 \times 10^{13}\,\mathrm{GeV})$



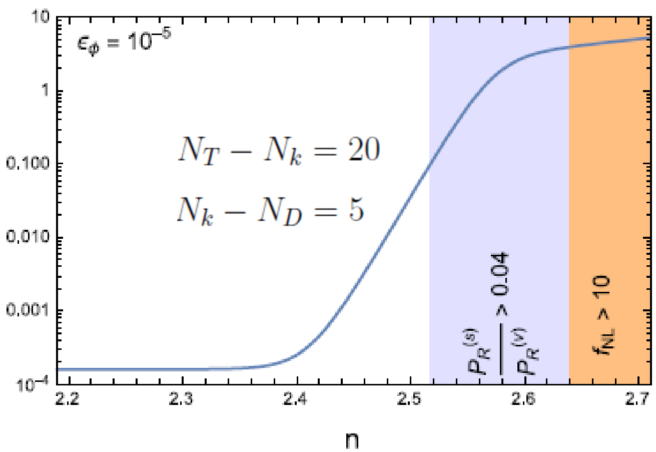
$$n = \frac{1}{\Lambda}\left(\frac{1}{H}\frac{d\sigma}{dt}\right)$$

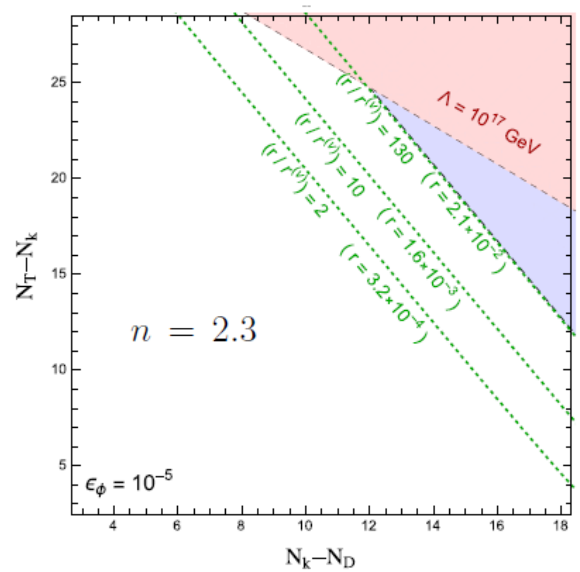


too strong back reaction from dilaton or gauge fields

$\epsilon = 10^{-5}$

$(H \simeq 3 \times 10^{12}\,\mathrm{GeV})$





"r" can be large enough ($>10^{-2}$) even when H << 10^{14} GeV!

Possible origin of tensor perturbation

* Vacuum fluctuation of graviton

  Slightly red-tilted tensor perturvation, negligible non-Gaussianity,

  and $\frac{H}{M_P} \simeq 10^{-4}\sqrt{r}$

* Gauge fields produced by rolling spectator axion

  Chiral, strongly blue-tilted tensor perturbation, non-negligible equilateral

  non-Gaussianity in scalar perturbation, and $\frac{H}{M_P} \ll 10^{-4}\sqrt{r}$

* Gauge fields produced by rolling spectator dilaton

  Strongly red-tilted tensor perturbation, non-negligible local non-Gaussianity

  and statistical anisotropy in scalar perturbation, and $\frac{H}{M_P} \ll 10^{-4}\sqrt{r}$

Conclusion

Tensor perturbation produced mostly by dilaton-induced gauge fields during the inflation epoch can be large enough to be observable ($r > 10^{-2}$) even when the inflation scale is relatively low ($H << 10^{14}$ GeV).

Such scenario can give rise to several distinctive observational signatures such as strongly red-tilted tensor perturbation and non-negligible local non-Gaussianity in scalar perturbation.