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Gravitational waves and the (quantum) nature of the primordial seed

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At first glance, the (indirect) measurement of primordial tensor modes by the BICEP2 collaboration supports an inflationary paradigm for early universe cosmology together with *quantum vacuum* fluctuations (*aka* gravitons) as the origin of the spectrum. In this essay we argue the the observed signal may instead be a signature of *semi-classical* sources of perturbations during inflation. In this scenario, despite a large tensor-to-scalar ratio $r \simeq 0.2$, it may be possible to write an effective field theory of a rolling scalar field without super-Planckian excursions. If the results from BICEP2 withstand further scrutiny, measurements of primordial non-Gaussianity with large scale structure surveys, and direct detection of gravitational waves with the new generation of observatories, will be of paramount importance to elucidate the (quantum) origin of structure in the universe.

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Introduction

In inflation, there is a natural mechanism to create a stochastic background of scalar (curvature) and tensor modes through quantum zero-point energy effects. (See [1] for review.) The spectra is given by (in $\hbar = c = 1$ units)

$$\mathcal{P}_S(k) = \mathcal{A}_S \left(\frac{k}{k_\star}\right)^{n_s-1}, \quad \mathcal{A}_S = \frac{1}{2\epsilon_\star c_s^\star}\left(\frac{H_\star}{2\pi M_p}\right)^2, \quad n_s - 1 = -2\epsilon_\star - \eta_\star - \epsilon_s^\star \tag{1}$$

$$\mathcal{P}_T(k) = \mathcal{A}_T \left(\frac{k}{k_\star}\right)^{n_T}, \quad \mathcal{A}_T = 8\left(\frac{H_\star}{2\pi M_p}\right)^2, \quad n_T = -2\epsilon_\star, \tag{2}$$

where $M_p = 1/\sqrt{8\pi G_N} \sim 10^{18}$ GeV, $\epsilon \equiv -\dot{H}/H^2$, $\eta \equiv \dot{\epsilon}/(\epsilon H)$, c_s is the 'speed of sound', $\epsilon_s \equiv \dot{c}_s/(c_s H)$ and a $\star$ denotes a quantity at horizon exit. (Note that, restoring $\hbar$'s, it can easily be shown that the source of fluctuations in (1) and (2) is quantum mechanical and they vanish in the limit $\hbar \to 0$.) Support for inflation has increased since the early detection of cosmic microwave background (CMB) anisotropies by the COBE satellite [2], and later on WMAP [3], to the current state of affairs in light of Planck [4] and BICEP2 [5], which single out the inflationary paradigm as a leading candidate to produce the initial conditions for structure formation.

One of the key features of inflation as a paradigm is that it carries the seed of its own destruction. In other words, it must end or we would not be seeing the structure we observe today. Hence, we ought to have $\dot{H} < 0$, satisfying the null energy condition (NEC). This unavoidably leads to a *red* tilt ($n_T < 0$) for the tensor modes in vacuum, *aka* gravitons, which is arguably one of the main predictions of inflation and ultimately of the quantum nature of gravity. The scalar tilt, on the other hand, may be either red or blue.

The BICEP2 collaboration [5] has reported the measurement of primordial tensor modes with a tensor-to-scalar ratio:

$$r \equiv \frac{\mathcal{A}_T}{\mathcal{A}_S} \simeq 0.2, \tag{3}$$

whereas after a series of precise measurements of temperature fluctuations in the CMB we know $\mathcal{A}_S \simeq 10^{-9}$ [4]. This value for r, assuming (2) holds, would imply $H_\star \simeq 10^{-14}$ GeV, clearly entering the realm of (very) high energy physics. However, despite the remarkable features of the signal, which cannot be overstated, at this point its shape does not unambiguously match the expected primordial tensor spectrum, in particular at sub-horizon scales [5]. One possible interpretation is that BICEP2 may be favoring a blue tilt for primordial GWs [7], which contradicts the prediction for the spectrum of GWs in vacuum during inflation, see (2) [1]. Moreover, a tensor contribution to the temperature spectrum at low ℓ's, currently disfavored by Planck which reported $r < 0.11$ (95% CL) [4], may be hidden by lowering the scalar power with a scale dependent (asymptotically free) running of the spectral index $n_s(k)$. However, most inflationary models predict negligible running. (See [8] for a more comprehensive analysis.)

The purpose of this essay is to argue that zero-point energy quantum effects may not be the culprit for the spectrum of GWs observed by BICEP2, but rather other sources excited to a semi-classical state during inflation. In other words, isolated gravitons (stretched to cosmological distances) may not be responsible for the tensor spectrum detected by BICEP2, contrary to the common belief [9]. As discussed in [10–12], non-vacuum sources of GW and density perturbations may be behind the observed $\mathcal{A}_S, \mathcal{A}_T$, albeit at a smaller energy scale. These models are motivated by the plethora of possible fields that could be (periodically) active during inflation, e.g. in string theory (see [13] for a review), including the production of semi-classical GWs with a spectrum which does not vanish in the $\hbar \to 0$ limit. An appealing feature of these models is the possibility of having a large tensor-to-scalar ratio without a field incursion into super-Planckian territory. Moreover, if produced by semi-classical processes, it is plausible for the tilt of the GW spectrum to be either blue or red, depending on new parameters (other than Hubble) that control the production mechanism. We argue that measurements of the smoking-gun non-Gaussian features for these models [12, 14, 15] with future large scale structure surveys, such as LSST and Euclid [19], as well as direct observation of GWs with the next generation of observatories [20, 21], e.g. BBO [22] and DECIGO [23], may allow us to distinguish different scenarios and probe the (quantum) nature of the primordial seed.

New sources of primordial perturbations

Density perturbations

Various mechanisms have been proposed to produce the observed density perturbations other than via quantum vacuum effects during inflation, most notably warm [10] and trapped [11] inflationary models inspired by string theory. Building upon ideas originally developed to study black hole absorption [24, 25], together with the effective field theory (EFT) of perturbations during inflation introduced in [26], an EFT approach to study generic classes of dissipative models was put forward in [14, 15]. The main idea is to systematically couple the EFT of inflation to a dissipative sector described by composite scalar, vector and tensor operators $(\mathcal{O}, \mathcal{O}_\mu, \mathcal{O}_{\mu\nu\ldots})$, whose correlation functions are constrained by symmetries. (A similar approach was used to study dissipation in fluids [16].) Then, considering a rolling scalar field ϕ driving inflation[1], and assuming a fluctuation-dissipation theorem relating the noise and 'friction' due to the extra $\mathcal{O}$-sector, we found

$$\mathcal{A}_S^{\mathcal{O}} \simeq \frac{\sqrt{\gamma_\star H_\star} T_{\mathcal{O}}^\star H_\star^2}{c_s \dot{\phi}_\star^2} \simeq \frac{k_\star T_{\mathcal{O}}^\star}{\epsilon_\phi^\star M_p^2}, \tag{4}$$

with γ the friction coefficient, and $k_\star \equiv \sqrt{\gamma_\star H_\star}/c_s$ is the 'sonic/friction horizon' scale at which modes freeze. Note the appearance of M_p is due to the relationship $\dot{\phi}^2 = 2\epsilon_\phi M_p^2 H^2$. From here we can compute the spectral index,

$$n_s^{\mathcal{O}} - 1 = \frac{d \log \mathcal{P}_S^{\mathcal{O}}}{d \log k} \simeq \frac{1}{H_\star} \frac{d}{dt_\star} \log \mathcal{P}_S^{\mathcal{O}} \simeq -\eta_\phi^\star + \frac{1}{2}\left(\epsilon_\gamma^\star - \epsilon_\star\right) + \epsilon_{T_{\mathcal{O}}}^\star - \epsilon_s^\star, \tag{5}$$

where $\eta_\phi \equiv \dot{\epsilon}_\phi/(H\epsilon_\phi)$ and $\epsilon_{T_{\mathcal{O}}} \equiv \dot{T}_{\mathcal{O}}/(T_{\mathcal{O}} H)$; and its running

$$\frac{dn_s^{\mathcal{O}}}{d\log k} \simeq \frac{1}{H_\star}\frac{dn_s^{\mathcal{O}}}{dt_\star} \simeq \frac{1}{H_\star}\frac{d}{dt_\star}\left(-\eta_\phi^\star + \frac{1}{2}\left(\epsilon_\gamma^\star - \epsilon_\star\right) + \epsilon_{T_{\mathcal{O}}}^\star - \epsilon_s^\star\right). \tag{6}$$

We thus notice the entrance of new parameters that control the amplitude and scale dependence of the spectrum.

Gravitational waves

The production of GWs from additional degrees of freedom excited during inflation was studied in detail in [12]. Since GWs produced at a frequency ω will be redshifted away by a factor $\left(\frac{H}{\omega}\right)^4$ until they reach the Hubble horizon and freeze, we consider processes with $\omega \simeq H$. Computing the spectrum for a gas of particles at thermal equilibrium (under some simplifying assumptions) we obtain [12]

$$\mathcal{P}_T^{\mathcal{O}} \simeq f_{\mathcal{O}}^\star \frac{(T_{\mathcal{O}}^\star)^2}{M_p^2}, \tag{7}$$

where $f_{\mathcal{O}} \equiv \rho_{\mathcal{O}}/M_p^2 H^2$, and $\rho_{\mathcal{O}}$ is the energy density in the additional degrees of freedom. As it is illustrated in this simple example, and shown in detail in [12], if the fraction of energy density

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[1] Let us emphasize the EFT approach in principle allows us to study also strongly coupled or more exotic models [14, 26].

injected into the $\mathcal{O}$-sector is *large*, e.g. $f_{\mathcal{O}} \simeq 10^{-1} - 10^{-2}$, this mechanism can easily compete with vacuum fluctuations when $T_{\mathcal{O}} \gg H$.

Tensor-to-scalar ratio & the Lyth bound

From our previous analysis it is straightforward to compute the tensor-to-scalar ratio

$$r_{\mathcal{O}} \equiv \frac{\mathcal{A}_T^{\mathcal{O}}}{\mathcal{A}_S^{\mathcal{O}}} \simeq \epsilon_\phi^\star f_{\mathcal{O}}^\star \frac{T_{\mathcal{O}}^\star}{k_\star} \equiv \lambda_{\mathcal{O}}^\star \, r_{BD}, \tag{8}$$

with[2]

$$\lambda_{\mathcal{O}} = \frac{f_{\mathcal{O}}^\star}{16} \frac{T_{\mathcal{O}}}{k_\star}, \qquad r_{BD} \equiv 8 \frac{\dot{\phi}_\star^2}{H_\star^2 M_p^2} = 16 \epsilon_\phi^\star. \tag{9}$$

Therefore, depending on the parameters, $\lambda_{\mathcal{O}}$ may be larger (or smaller) than one. Moreover, from here we notice the field range for the rolling scalar field driving inflation may not become super-Planckian. This can be implemented in generic multi-field models, however, dissipative models are in essence ‘single-field’, since a single degree of freedom controls the density perturbations [14, 15]. It is then important to ask whether the EFT is under control. Since the computation of the number of e-foldings is not modified, we have [27]

$$N_e \simeq \sqrt{8}\, r_{BD}^{-1/2}\, \Delta\phi/M_p \to \Delta\phi/M_p \simeq \mathcal{O}(1) \sqrt{\frac{r_{\mathcal{O}}}{0.01}} \left(\frac{1}{\lambda_{\mathcal{O}}}\right)^{1/2}. \tag{10}$$

From here it follows $\lambda_{\mathcal{O}} \geq 20$ forbids super-Planckian excursions for $r_{\mathcal{O}} \simeq 0.2$. In our specific example, that is the case provided (up to $\mathcal{O}(1)$ numbers)

$$H_\star \lesssim 10^{-8} M_p \simeq 10^{10} \text{ GeV}, \tag{11}$$

for $f_\star \simeq 0.1$ and $\gamma_\star \simeq \mathcal{O}(10) H_\star$ (see below). Hence dissipative scenarios can *naturally* accommodate the observed $\mathcal{A}_S, \mathcal{A}_T$ with $H_\star \ll 10^{14}$ GeV.

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[2] For simplicity, in what follows we consider $c_s = 1$. See [17] for a discussion of $c_s < 1$ models.

Blue tilt?

For the new sources of GWs an approximate scale invariance in the two-point function is expected provided we are in a quasi-steady state, with particles periodically produced during inflation, with $f_{\mathcal{O}} < 1$, as the universe expands with $|\dot{H}| \ll H^2$. However, in the expression (7) it is clear that the tilt of the tensors is controlled by new parameters:

$$n_T^{\mathcal{O}} = \frac{d \log \mathcal{P}_T^{\mathcal{O}}}{d \log k} \simeq \frac{1}{H_\star} \frac{d}{dt_\star} \log \mathcal{P}_T^{\mathcal{O}} \simeq \epsilon^\star_{f_{\mathcal{O}}} + 2\epsilon^\star_{T_{\mathcal{O}}}, \tag{12}$$

with $\epsilon_{f_{\mathcal{O}}} \equiv \dot{f}_{\mathcal{O}}/(H f_{\mathcal{O}})$. Using $f_{\mathcal{O}} = \rho_{\mathcal{O}}/(M_p^2 H^2)$, which in thermal equilibrium behaves like $f_{\mathcal{O}} \propto T_{\mathcal{O}}^4/H^2$, then it follows $n_T^{\mathcal{O}} \simeq 2(3\epsilon_{T_{\mathcal{O}}} + \epsilon)$, which could be positive provided $\rho_{\text{tot}} \simeq M_p^2 H^2$ decreases faster than $\rho_{\mathcal{O}}$. For this simplified example, the tilt of the tensor spectrum shifts towards *blue* with large $|\dot{H}|$, unlike vacuum fluctuations.

Non-Gaussianity: The smoking-gun

The non-Gaussianity of the tensor modes was discussed in [12]. Even though the GWs are produced away from the vacuum, the spectrum becomes Gaussian since different production times are independent and the number of gravitons becomes *large*. This can be contrasted with the three-point function (or bispectrum) for tensor modes in the vacuum [28].

On the other hand, because of the interactions which are guaranteed to be present in the scalar sector due to the (non-linearly realized) symmetries in the EFT [14], one can have *large* non-Gaussianities in the density perturbations $\simeq f_{\text{NL}} \mathcal{A}_S^{1/2}$. In particular, we showed $f_{\text{NL}}^{\text{eq}} \simeq -\frac{\gamma}{4Hc_s^2}$ of the equilateral type. Moreover, we found that dissipative mechanisms leave a specific imprint in the full shape (k_i-dependence) of the bispectrum $B(k_1, k_2, k_3)$, namely a relationship between equilateral ($k_1 \sim k_2 \sim k_3$) and folded ($k_1 \sim k_2 \sim k_3/2$) contributions: $f_{\text{NL}}^{\text{fold}} \simeq -\frac{1}{2} f_{\text{NL}}^{\text{eq}}$ [14], with negligible local (or squeezed) component ($k_1 \ll k_2 \sim k_3$) [15].The current bounds on non-Gaussianity from the Planck collaboration, including $f_{\text{NL}}^{\text{eq}} = -42 \pm 75$, are a remarkable achievement [30]. However, presently they have not constrained dissipative models significantly, in particular this bound can be translated to $\gamma \lesssim 10^2 H$ (for $c_s = 1$) [29].

Conclusions

In this essay we argued that the spectrum of primordial tensor modes imprinted in the BICEP2 data [5] may be a signature of semi-classical rather than (quantum) vacuum fluctuations. Furthermore, in this scenario n_T can take either a positive or negative value without jeopardizing the basic features of inflation, and without resorting to violations of both the NEC and Lorentz Invariant UV completions of gravity. Furthermore, the EFT for a rolling scalar field ϕ driving inflation (and producing the additional degrees of freedom responsible for dissipation and a GW background) is under control without super-Planckian excursions, provided $H_\star \lesssim 10^{10}$ GeV.

If BICEP2 is confirmed by future experiments [33], to pinpoint non-vacuum processes or whether primordial (stretched) single gravitons are responsible for the signal, a measurement of non-Gaussianity would be required. Therefore, using future large scale structure surveys to study primordial non-Gaussianity within an EFT framework [31, 32] has become increasingly promising and may herald new discoveries. Given the size of the signal, $\mathcal{A}_T \simeq 10^{-10}$, the new generation of GW detectors will also be able to accurately dissect a stochastic background of primordial GWs [22, 23], as well as to probe a (so far) unexplored range of frequencies. Here EFT methods have been extensively used to study GWs from various sources [34], and will continue to play a prominent role in the advent of GW astronomy/cosmology. These measurements will ultimately allow us to reconstruct the initial conditions for structure formation, and shed light on the nature of fluctuations seeded 10^{-34} seconds after the big bang!

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