Draft version April 28, 2022
Typeset using LaTeX default style in AASTeX63

The challenge of ruling out inflation via the primordial graviton background

Sunny Vagnozzi[1] and Abraham Loeb[2]

[1]Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
[2]Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA

ABSTRACT

Recent debates around the testability of the inflationary paradigm raise the question of how to model-independently discriminate it from competing scenarios. We argue that a detection of the Cosmic Graviton Background (CGB), the relic radiation from gravitons decoupling around the Planck time, would rule out the inflationary paradigm, as realistic inflationary models would dilute the CGB to an unobservable level. The CGB contribution to the effective number of relativistic species, $\Delta N_{\rm eff,g} \approx 0.054$, is well within the reach of next-generation cosmological probes. We argue that detecting the high-frequency stochastic gravitational wave background associated to the CGB will be challenging but potentially feasible. We briefly discuss expectations within alternatives to inflation, focusing on bouncing cosmologies and emergent scenarios.

Keywords: inflation — gravitational waves — cosmology: observations

1. INTRODUCTION

Inflation, a postulated stage of quasi-de Sitter expansion in the primordial Universe, is widely regarded as the leading paradigm for the very early Universe. Originally introduced to address various fine-tuning problems of the hot Big Bang (hBB) model, inflation provides a compelling mechanism for generating the density perturbations from which structure eventually originated (Starobinsky 1980; Guth 1981; Mukhanov & Chibisov 1981; Linde 1982; Albrecht & Steinhardt 1982). The predictions of some of the simplest inflationary models are in remarkable agreement with observations of the Cosmic Microwave Background (CMB) and the Large-Scale Structure (LSS), which in turn is commonly viewed as a sign of the inflationary paradigm's success.

Despite these successes, inflation is not free of open issues, and over the years criticisms have been raised about its status (see e.g. Ijjas et al. 2014; Martin 2019). One of the major bones of contention is driven by the large flexibility with regards to the predictions of individual inflationary models, and concerns whether or not the inflationary paradigm is falsifiable. We use the term "paradigm" and not "model" since any given inflationary model is clearly falsifiable, whereas these doubts concern the inflationary scenario as a whole. Here we do not seek to take sides in the debate, but simply note that these issues strongly motivate the question of how to *model-independently* discriminate the inflationary paradigm from alternative scenarios for the production of density perturbations.

We address the above question by identifying a signature *de facto* precluded to any realistic inflationary model, and whose observation would thus rule out the inflationary paradigm. The decoupling of primordial gravitons around the Planck time should leave behind a thermal background of relic gravitons: the Cosmic Graviton Background (CGB). An inflationary phase taking place between the Planck era and today would wash out the CGB, rendering it unobservable: an unambiguous CGB detection would therefore pose a major threat to the inflationary paradigm. In this *Letter*, we formalize these arguments and discuss prospects for detecting the CGB.

2. THE COSMIC GRAVITON BACKGROUND

We now discuss the features of the CGB in the absence of inflation. We adopt the working assumption that above the Planck scale point-like four-particle interactions involving two gravitons, whose rate at temperature T is of order

Corresponding author: Sunny Vagnozzi
sunny.vagnozzi@ast.cam.ac.uk

$\Gamma_g \sim T^5/M_{\rm Pl}^4$, kept gravitons in thermal equilibrium in the primordial plasma (see also Zhao et al. 2009; Giovannini 2020). If we assume adiabatic evolution throughout the early stages of the primordial plasma, and therefore that the Universe was radiation dominated up to then, the Hubble rate scales as $H \sim T^2/M_{\rm Pl}$. Comparing the two rates indicates that gravitons decouple at a temperature $T_{g,{\rm dec}} \sim M_{\rm Pl}$ (or equivalently around the Planck time $t_{g,{\rm dec}} \sim t_{\rm Pl}$): besides ruling out inflation, a detection of the CGB would thus provide an experimental testbed for theories attempting to unify quantum mechanics and gravity.

Being massless and thus decoupling while relativistic, primordial gravitons preserve the blackbody form of their spectrum following decoupling, with the effective CGB temperature T_g redshifting with the scale factor a as $T_g \propto 1/a$. Since the entropy density $s = 2\pi^2 g_\star^s(T)T^3/45$ scales as $s \propto a^{-3}$, where $g_\star^s(T)$ is the (temperature-dependent) effective number of entropy degrees of freedom (DoF), we can relate the present-day temperatures of the CGB and CMB, $T_{g,0}$ and $T_{\gamma,0}$ respectively, as follows:

$$\frac{T_{g,0}}{T_{\gamma,0}} = \left(\frac{g_\star^s(T_0)}{(g_\star^s(T_{\rm Pl})-2)} \right)^{1/3} , \tag{1}$$

where $g_\star^s(T_0) \simeq 3.91$ is the present-day effective number of entropy DoF *excluding* gravitons (accounting for photons and neutrinos), and $g_\star^s(T_{\rm Pl})$ is the effective number of entropy DoF prior to graviton decoupling, *including* gravitons. Accounting only for Standard Model (SM) DoF up to the Planck scale, above the electroweak (EW) scale $g_\star^s(T_{\rm Pl})-2 \simeq 106.75$. Precise measurements of the CMB frequency spectrum from COBE/FIRAS fix $T_{\gamma,0} \approx 2.7\,{\rm K}$ and therefore under these minimal assumptions the present-day CGB temperature is predicted to be $T_{g,0} \simeq (3.91/106.75)^{1/3}T_{\gamma,0} \approx 0.9\,{\rm K}$, making the CGB about 3 times colder than the CMB.

Lacking a precise knowledge of the type of new physics lying beyond the TeV scale, the assumption of only considering SM DoF up to the Planck scale is conservative, but likely somewhat unrealistic, as one might expect several additional DoF to appear in the "desert" between the EW and Planck scales. If so, $g_\star^s(T_{\rm Pl})$ in the denominator of Eq. (1) can only increase, decreasing $T_{g,0}$ with respect to the previous estimate $T_{g,0} \approx 0.9\,{\rm K}$, which therefore should be viewed more as a conservative upper bound on $T_{g,0}$. However, the exact numbers are highly model-dependent and depend on the specific new physics model. For instance, $T_{g,0} \approx 0.7\,{\rm K}$ in a supersymmetric-like scenario where $g_\star^s(T_{\rm Pl})$ doubles, whereas $T_{g,0} \approx 0.4\,{\rm K}$ in a hypothetical scenario where $g_\star^s(T_{\rm Pl})$ increases by an order of magnitude.

3. CAN INFLATION BE RULED OUT?

Our assumption of adiabatic evolution from $T_{\rm Pl}$ down to present times breaks down whenever comoving entropy is generated, e.g. during reheating at the end of inflation. An inflationary phase alters the relation between $T_{g,0}$ and $T_{\gamma,0}$ in Eq. (1), as the latter would be determined by the dynamics of reheating, which however can at most produce out-of-equilibrium graviton excitations, unless the effective gravitational constant $G_{\rm eff}$ was significantly higher at reheating. Since the scale factor increases exponentially during inflation, the CGB temperature itself is exponentially suppressed by a factor of e^{-N}, with N the number of e-folds of inflation.

We can estimate an extremely conservative upper limit on $\widetilde{T}_{g,0}$ in the presence of a phase of inflation (the tilde distinguishes the present-day graviton temperature with and without inflation), using the facts that *a)* solving the horizon and flatness problems requires $N \gtrsim 60$, and *b)* reheating should occur at $T_{\rm rh} \gtrsim 5\,{\rm MeV}$ in order not to spoil Big Bang Nucleosynthesis predictions (de Salas et al. 2015). From these requirements we find that $\widetilde{T}_{g,0} \lesssim 50\,\mu{\rm K}$, implying that inflation would dilute the CGB to an unobservable level. More generically, we find the following upper limit:

$$\widetilde{T}_{g,0} \ll 0.25 \left(\frac{T_{\rm rh}}{\rm GeV} \right)^{-1} e^{60-N}\,\mu{\rm K}\,. \tag{2}$$

However, $\widetilde{T}_{g,0} \lesssim 50\,\mu{\rm K}$ is a very conservative upper limit, for two reasons. Firstly, in most realistic models inflation typically proceeds for more than 60 e-folds, leading to further exponential suppression [see Eq. (2)]. Next, although reheating at scales as low as $T_{\rm rh} \simeq \mathcal{O}({\rm MeV})$ is observationally allowed, models realizing this in practice are very hard to construct (see e.g. Kawasaki et al. 1999; Hannestad 2004; Khoury & Steinhardt 2011). It if far more likely that, if inflation did occur, reheating took place way above the EW scale, further tightening the upper bound on $T_{g,0}$.

One may be tempted to evade these conclusions invoking models of *incomplete inflation* (e.g. Freivogel et al. 2006) with a limited number of e-folds $46 \lesssim N \lesssim 60$: however, if inflation is indeed the solution to the flatness problem, such models are essentially ruled out by current stringent bounds on spatial curvature (Vagnozzi et al. 2021), as argued explicitly in Efstathiou & Gratton (2020). Even if $N < 60$, bringing $\widetilde{T}_{g,0}$ to a detectable level still requires an extremely low reheating scale, typically harder to achieve within models of incomplete inflation.

A caveat to our previous results is our assumption of inflation occurring at sub-Planckian scales. Specifically, $T_{\rm rh} > M_{\rm Pl}$ is required for the CGB not to be washed out by inflation. However, on general grounds there are serious concerns about the consistency of trans-Planckian effects both during inflation and at reheating (e.g. Brandenberger & Martin 2013; Brandenberger & Kamali 2022). A specific concern takes the form of the trans-Planckian censorship conjecture, which sets tight limits on the maximum inflationary scale $\Lambda_{\rm inf}^{\rm max}$ and the reheating temperature: $\Lambda_{\rm inf}^{\rm max}\,, T_{\rm rh} \ll M_{\rm Pl}$ (Bedroya & Vafa 2020; Bedroya et al. 2020; Kamali & Brandenberger 2020).

More importantly, the lack of detection of inflationary B-modes indicates that $\Lambda_{\rm inf}^{\rm max}$ is at least four orders of magnitude below the Planck scale. For instantaneous reheating, the reheating temperature is obviously limited to $T_{\rm rh} < \Lambda_{\rm inf}^{\rm max}$, as reheating to higher temperatures would violate (covariant) stress-energy conservation. For non-instantaneous reheating, $T_{\rm rh}$ is of course even lower (see also Cook et al. 2015). Therefore, we deem it very safe to assume that $T_{\rm rh} \ll M_{\rm Pl}$, corroborating all our earlier findings. In summary, within realistic inflationary cosmologies one does not expect to be able to detect the relic thermal graviton background – conversely, a convincing detection thereof would rule out the inflationary paradigm.

4. DETECTABILITY OF THE CGB

We now investigate whether detecting the CGB is experimentally feasible, considering our benchmark $T_{g,0} \approx 0.9\,{\rm K}$ case. Given its behaving as an extra radiation component, the natural question to ask is how much the CGB contributes to the effective number of relativistic species $N_{\rm eff}$. This quantity, denoted by $\Delta N_{{\rm eff},g}$, is given by:

$$\Delta N_{{\rm eff},g} \equiv \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\frac{\rho_g}{\rho_\gamma} = \frac{8}{7}\left(\frac{11}{4}\right)^{\frac{4}{3}}\left(\frac{g_\star^s(T_0)}{(g_\star^s(T_{\rm Pl})-2)}\right)^{\frac{4}{3}}\,. \tag{3}$$

For $g_\star^s(T_{\rm Pl})-2 = 106.75$, we therefore find that $\Delta N_{{\rm eff},g} \approx 0.054$, as expected for a species with 2 spin DoF decoupling above the QCD phase transition.

A contribution to $N_{\rm eff}$ of this size is a factor of 3 below the sensitivity of current probes – for instance, $\sigma_{N_{\rm eff}} = 0.17$ from the final full-mission *Planck* measurements (Aghanim et al. 2020). However, this number is well within the reach of a combination of next-generation CMB and LSS surveys. For instance, even after marginalizing over the total neutrino mass, Brinckmann et al. (2019) forecast a sensitivity of $\sigma_{N_{\rm eff}} \simeq 0.021$ combining CMB data from CMB-S4 (Abazajian et al. 2016) and LiteBIRD (Matsumura et al. 2014) with galaxy clustering and cosmic shear data from Euclid (Amendola et al. 2013), whereas with a PICO-like experiment (Sutin et al. 2018) in place of CMB-S4+LiteBIRD the sensitivity improves to $\sigma_{N_{\rm eff}} \simeq 0.017$. Therefore, if the benchmark $0.9\,{\rm K}$ CGB were present, CMB-S4+LiteBIRD+Euclid would be able to detect it through its imprint on $N_{\rm eff}$ at $\simeq 2.5\sigma$, whereas PICO+Euclid would be able to do so at $\simeq 3.2\sigma$.

Should the CGB contribution to $N_{\rm eff}$ be detected, the reader may wonder how we know that the excess radiation density is associated to the CGB, rather than simply another dark radiation component. To remove this ambiguity, we therefore turn our attention to the stochastic background of (high-frequency) gravitational waves (GWs) inevitably associated to the CGB. [1] It is useful to think in terms of characteristic strain h_c, i.e. the dimensionless strain which would be produced due to the passing stochastic GW background in the arms of an interferometer with arms of equal length L in the x and y directions, $h_c(\nu) \simeq \Delta L/L$. The characteristic CGB strain $h_g(\nu)$ is given by:

$$h_g(\nu) = \frac{1}{\nu}\sqrt{\frac{3H_0^2}{2\pi^2}\Omega_g(\nu)} \approx 1.26\times10^{-27}\left(\frac{\nu}{\rm GHz}\right)^{-1}\sqrt{h^2\Omega_g(\nu)}\,. \tag{4}$$

where $h^2\Omega_g(\nu)$ is the CGB spectral energy density in units of the present-day critical density:

$$h^2\Omega_g(\nu) = \frac{15}{\pi^4}h^2\Omega_{\gamma,0}\left(\frac{T_{g,0}}{T_{\gamma,0}}\right)^4 F(x_g)\,, \tag{5}$$

with h the reduced Hubble parameter, $h^2\Omega_{\gamma,0}$ the photon density parameter today, $x_g \equiv h\nu/(k_BT_{g,0})$, and $F(x_g) \equiv x_g^4/(e^{x_g}-1)$. It is easy to show that the CGB spectrum peaks at frequencies $\nu \approx 75\,{\rm GHz}$, making it a source of a

[1] The CGB stochastic GW background can be distinguished from the stochastic GW background which would be produced by non-thermal gravitational fluctuations at reheating, as the latter would not be of the blackbody form, and its strength would be orders of magnitude below that of the CGB as long as the reheating temperature satisfies $T_{\rm rh} \ll M_{\rm Pl}$, which as argued in Sec. 3 can be safely assumed.

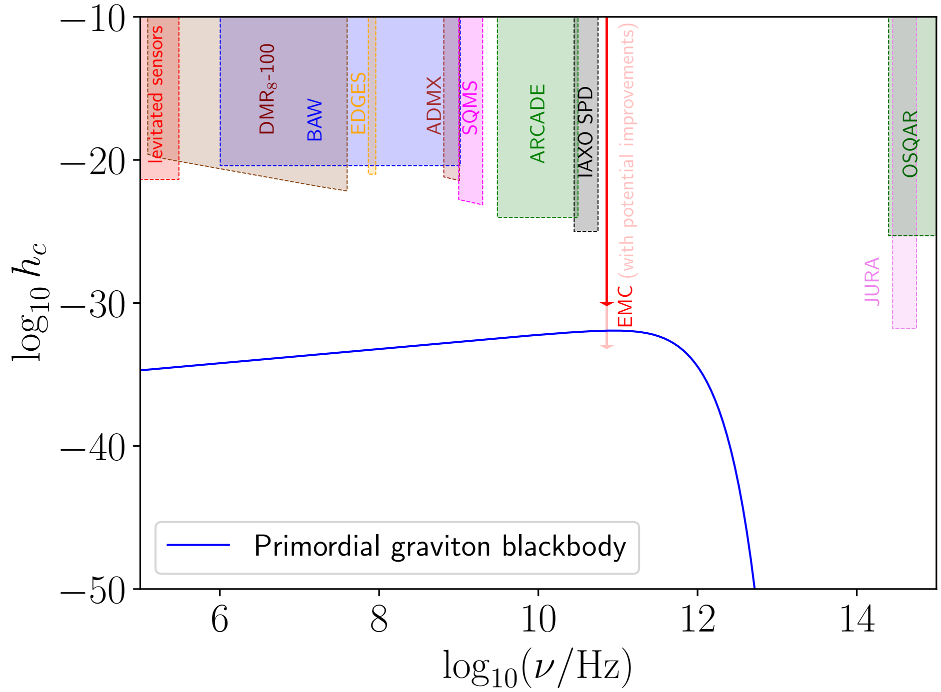

Figure 1. Strain of the CGB stochastic background of high-frequency GWs, alongside the sensitivities of various detector concepts discussed in the main text. The red line ("EMC") refers to enhanced magnetic conversion, with the more transparent extension referring to potential future technological improvements discussed in the main text.

high-frequency GWs. Fig. 1 shows the characteristic CGB strain alongside demonstrated or forecasted sensitivities of various detector concepts (see Aggarwal et al. 2021).

Aside from optically levitated sensors (Arvanitaki & Geraci 2013) and bulk acoustic wave (BAW) devices (Goryachev & Tobar 2014), all probes in Fig. 1 exploit the *inverse Gertsenshtein effect* (IGE), whereby GWs convert to photons within a strong magnetic field (Gertsenshtein 1962). While apart from small prototypes dedicated instruments exploiting the IGE do not exist, Ejlli et al. (2019) showed how constraints on high-frequency GWs can be obtained re-interpreting data from ongoing or planned axion experiments: in Fig. 1 this includes ADMX, SQMS, IAXO SPD, JURA, OSQAR, and DMRadio$_8$-100 (an upscaled version of DMRadio, see Domcke et al. 2022). The IGE can also be exploited in strongly magnetized astrophysical environments (Chen 1995; Domcke & Garcia-Cely 2021), recasting observations from radio telescopes such as EDGES (Bowman et al. 2018) and ARCADE (Fixsen et al. 2011). For more details on these detector concepts, see Aggarwal et al. (2021); Berlin et al. (2021); Domcke et al. (2022).

Unfortunately, as is clear from Fig. 1, all these detector concepts fall short of the CGB signal by several orders of magnitude. The only promising probe is enhanced magnetic conversion (EMC), a proposal to enhance the efficiency of IGE-based magnetic conversion detectors by seeding the conversion volume with locally generated auxiliary EM fields, e.g. EM Gaussian beams (GBs) oscillating at the frequency of the GW signal searched for (Li & Yang 2004; Baker et al. 2008). Until recently, EMC appeared to be well beyond technological reach, particularly due to the requirement of a GB geometric purity at the 10^{-21} level to reach strain levels of $h_c \sim 10^{-30}$ at $\nu \sim \mathcal{O}(100)\,\mathrm{GHz}$.

However, Ringwald et al. (2021) argued that reaching the above benchmark limit is more than feasible, exploiting state-of-the-art superconducting magnets utilized in near-future axion experiments to generate the required EM signal, then enhanced by a GB produced by a MW-scale 40 GHz gyrotron. While this still leaves us 2 orders of magnitude short of the CGB peak strain, realistic improvements in the development of gyrotrons, single-photon detectors (SPDs), and superconducting magnets, can bring the projected sensitivity down to $h_c \sim 10^{-32}$, sufficient to detect the CGB in our benchmark scenario. We estimate that an increase in the gyrotron available power to $\sim 100\,\mathrm{MW}$ (which is realistically achievable) over a stable running time of $\sim 1\,\mathrm{month}$ (which is much more challenging), alongside improvements in SPDs dark count rates to $\sim 10^{-5}\,\mathrm{s}^{-1}$, would result in a sensitivity to strains of order $h_c \sim 10^{-33}$, sufficient to detect our benchmark CGB. All quoted sensitivities can be further improved by increasing the reflector size, and the intensity and length of the magnets. Therefore, measuring strains as small as $h_c \sim 10^{-33}$ at $\nu \sim \mathcal{O}(100)$ GHz, and detecting the benchmark CGB, might be more than feasible in the not-too-far-off future.

5. ALTERNATIVES TO INFLATION

Our previous discussion raises the question of whether an unambiguous CGB detection would also spell trouble for alternative paradigms, where density perturbations are produced during a non-inflationary phase. While the answer to this question is highly model-dependent, we wish to provide a brief qualitative assessment limited to two well-motivated paradigms: bouncing cosmologies and emergent scenarios.

Within bouncing cosmologies, the challenge is to produce a thermal CGB in first place. This is hard to achieve during the contracting phase, when the characteristic energy scale is typically $\Lambda_c \ll M_{\rm Pl}$ (e.g. Brandenberger & Peter 2017). Another possibility is one where a relatively long bouncing phase with energy density around the Planck scale occurs between the initial contracting phase and the later hBB expansion (e.g. Cai 2014), in which case a thermal CGB would be generated and would survive the phase transition between the bouncing and expanding phases.

In emergent scenarios, the Universe emerges from an initial high density state with matter in global thermal equilibrium, and producing the CGB is far less unlikely. A particularly well-studied emergent scenario is the string gas proposal of Brandenberger & Vafa (1989), where the Universe originates from a quasi-static Hagedorn phase of a string gas at temperature close to the Hagedorn temperature, before a T-dual symmetry breaking-driven phase transition connects to the hBB expansion. On general grounds, the energy density in the emergent phase is close to the Planck density, making it likely for gravitons to be in thermal equilibrium and therefore for a CGB to be generated.

However, the initial state in string gas cosmology is not a thermal state of particles but of strings, giving a different scaling of thermodynamical quantities. It is therefore unlikely that the string gas CGB takes the blackbody form, although it is in principle possible that its spectral energy density may be higher than our benchmark CGB, enhancing detection prospects. Fully exploring these points requires a dedicated study, going beyond the scope of our work.

6. CONCLUSIONS

Despite its enormous success, recent debates around the inflationary paradigm raise the question of how to *model-independently* discriminate it from competing scenarios for the production of primordial density perturbations. In this *Letter*, we have argued that a detection of the Cosmic Graviton Background (CGB), the left-over graviton radiation from the Planck era, would rule out the inflationary paradigm, as realistic inflationary models dilute the CGB to an unobservable level. The CGB contribution to the effective number of relativistic species $\Delta N_{{\rm eff},g} \approx 0.054$ is well within the reach of next-generation cosmological probes, whereas detecting the associated stochastic background of high-frequency GWs in the $\nu \sim \mathcal{O}(100)$ GHz range is challenging but potentially feasible. We also argued that the CGB may be detectable within well-motivated alternatives to inflation such as bouncing and emergent scenarios. We hope that this work will spur further investigation into the possibility of model-independently confirming or ruling out the inflationary paradigm with upcoming observations (for similar endeavors see e.g. Chen et al. 2019).

ACKNOWLEDGEMENTS

We are grateful to Robert Brandenberger, Massimo Giovannini, Will Kinney, Nick Rodd, and Luca Visinelli for useful discussions and suggestions. S.V. is supported by the Isaac Newton Trust and the Kavli Foundation through a Newton-Kavli Fellowship, and by a grant from the Foundation Blanceflor Boncompagni Ludovisi, née Bildt. S.V. acknowledges a College Research Associateship at Homerton College, University of Cambridge. A.L. is partially supported by the Black Hole Initiative at Harvard University, which is funded by grants from the John Templeton Foundation and the Gordon and Betty Moore Foundation.

REFERENCES

Abazajian, K. N., et al. 2016, arXiv e-prints, arXiv:1610.02743. https://arxiv.org/abs/1610.02743

Aggarwal, N., et al. 2021, Living Rev. Rel., 24, 4, doi: 10.1007/s41114-021-00032-5

Aghanim, N., et al. 2020, Astron. Astrophys., 641, A6, doi: 10.1051/0004-6361/201833910

Albrecht, A., & Steinhardt, P. J. 1982, Phys. Rev. Lett., 48, 1220, doi: 10.1103/PhysRevLett.48.1220

Amendola, L., et al. 2013, Living Rev. Rel., 16, 6, doi: 10.12942/lrr-2013-6

Arvanitaki, A., & Geraci, A. A. 2013, Phys. Rev. Lett., 110, 071105, doi: 10.1103/PhysRevLett.110.071105

Baker, Jr., R. M. L., Stephenson, G. V., & Li, F. 2008, AIP Conf. Proc., 969, 1045, doi: 10.1063/1.2844941

Bedroya, A., Brandenberger, R., Loverde, M., & Vafa, C. 2020, Phys. Rev. D, 101, 103502, doi: 10.1103/PhysRevD.101.103502

Bedroya, A., & Vafa, C. 2020, JHEP, 09, 123, doi: 10.1007/JHEP09(2020)123

Berlin, A., Blas, D., Tito D'Agnolo, R., et al. 2021, arXiv e-prints, arXiv:2112.11465. https://arxiv.org/abs/2112.11465

Bowman, J. D., Rogers, A. E. E., Monsalve, R. A., Mozdzen, T. J., & Mahesh, N. 2018, Nature, 555, 67, doi: 10.1038/nature25792

Brandenberger, R., & Kamali, V. 2022, arXiv e-prints, arXiv:2203.11548. https://arxiv.org/abs/2203.11548

Brandenberger, R., & Peter, P. 2017, Found. Phys., 47, 797, doi: 10.1007/s10701-016-0057-0

Brandenberger, R. H., & Martin, J. 2013, Class. Quant. Grav., 30, 113001, doi: 10.1088/0264-9381/30/11/113001

Brandenberger, R. H., & Vafa, C. 1989, Nucl. Phys. B, 316, 391, doi: 10.1016/0550-3213(89)90037-0

Brinckmann, T., Hooper, D. C., Archidiacono, M., Lesgourgues, J., & Sprenger, T. 2019, JCAP, 01, 059, doi: 10.1088/1475-7516/2019/01/059

Cai, Y.-F. 2014, Sci. China Phys. Mech. Astron., 57, 1414, doi: 10.1007/s11433-014-5512-3

Chen, P. 1995, Phys. Rev. Lett., 74, 634, doi: 10.1103/PhysRevLett.74.634

Chen, X., Loeb, A., & Xianyu, Z.-Z. 2019, Phys. Rev. Lett., 122, 121301, doi: 10.1103/PhysRevLett.122.121301

Cook, J. L., Dimastrogiovanni, E., Easson, D. A., & Krauss, L. M. 2015, JCAP, 04, 047, doi: 10.1088/1475-7516/2015/04/047

de Salas, P. F., Lattanzi, M., Mangano, G., et al. 2015, Phys. Rev. D, 92, 123534, doi: 10.1103/PhysRevD.92.123534

Domcke, V., & Garcia-Cely, C. 2021, Phys. Rev. Lett., 126, 021104, doi: 10.1103/PhysRevLett.126.021104

Domcke, V., Garcia-Cely, C., & Rodd, N. L. 2022, arXiv e-prints, arXiv:2202.00695. https://arxiv.org/abs/2202.00695

Efstathiou, G., & Gratton, S. 2020, Mon. Not. Roy. Astron. Soc., 496, L91, doi: 10.1093/mnrasl/slaa093

Ejlli, A., Ejlli, D., Cruise, A. M., Pisano, G., & Grote, H. 2019, Eur. Phys. J. C, 79, 1032, doi: 10.1140/epjc/s10052-019-7542-5

Fixsen, D. J., et al. 2011, Astrophys. J., 734, 5, doi: 10.1088/0004-637X/734/1/5

Freivogel, B., Kleban, M., Rodriguez Martinez, M., & Susskind, L. 2006, JHEP, 03, 039, doi: 10.1088/1126-6708/2006/03/039

Gertsenshtein, M. E. 1962, Sov. Phys. JETP, 14, 84

Giovannini, M. 2020, Prog. Part. Nucl. Phys., 112, 103774, doi: 10.1016/j.ppnp.2020.103774

Goryachev, M., & Tobar, M. E. 2014, Phys. Rev. D, 90, 102005, doi: 10.1103/PhysRevD.90.102005

Guth, A. H. 1981, Phys. Rev. D, 23, 347, doi: 10.1103/PhysRevD.23.347

Hannestad, S. 2004, Phys. Rev. D, 70, 043506, doi: 10.1103/PhysRevD.70.043506

Ijjas, A., Steinhardt, P. J., & Loeb, A. 2014, Phys. Lett. B, 736, 142, doi: 10.1016/j.physletb.2014.07.012

Kamali, V., & Brandenberger, R. 2020, Eur. Phys. J. C, 80, 339, doi: 10.1140/epjc/s10052-020-7908-8

Kawasaki, M., Kohri, K., & Sugiyama, N. 1999, Phys. Rev. Lett., 82, 4168, doi: 10.1103/PhysRevLett.82.4168

Khoury, J., & Steinhardt, P. J. 2011, Phys. Rev. D, 83, 123502, doi: 10.1103/PhysRevD.83.123502

Li, F.-Y., & Yang, N. 2004, Chin. Phys. Lett., 21, 2113, doi: 10.1088/0256-307X/21/11/011

Linde, A. D. 1982, Phys. Lett. B, 108, 389, doi: 10.1016/0370-2693(82)91219-9

Martin, J. 2019, arXiv e-prints, arXiv:1902.05286. https://arxiv.org/abs/1902.05286

Matsumura, T., et al. 2014, J. Low Temp. Phys., 176, 733, doi: 10.1007/s10909-013-0996-1

Mukhanov, V. F., & Chibisov, G. V. 1981, JETP Lett., 33, 532

Ringwald, A., Schütte-Engel, J., & Tamarit, C. 2021, JCAP, 03, 054, doi: 10.1088/1475-7516/2021/03/054

Starobinsky, A. A. 1980, Phys. Lett. B, 91, 99, doi: 10.1016/0370-2693(80)90670-X

Sutin, B. M., et al. 2018, Proc. SPIE Int. Soc. Opt. Eng., 10698, 106984F, doi: 10.1117/12.2311326

Vagnozzi, S., Loeb, A., & Moresco, M. 2021, Astrophys. J., 908, 84, doi: 10.3847/1538-4357/abd4df

Zhao, W., Baskaran, D., & Coles, P. 2009, Phys. Lett. B, 680, 411, doi: 10.1016/j.physletb.2009.09.018