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Comment

A response to criticisms on "CMB constraints cast a shadow on CSL model"

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Abstract Our recent letter "*Cosmic Microwave Background Constraints Cast a Shadow On Continuous Spontaneous Localization Models*" (Martin and Vennin Phys Rev Lett 124:080402, 2020, arXiv:1906.04405) has recently been criticised in Ref. (Bengochea et al. Eur Phys J C 80:1021, 2020a) (see also Ref. Bengochea et al. 2020b, arXiv:2006.05313). In this reply, we explain why the arguments presented in those articles are either incorrect or a confirmation of the robustness of our results.

1 Foreword

Everybody agrees that Quantum Mechanics has successfully passed an amazing number of experimental tests, yet there is a broad range of opinions as to whether its theoretical status can be regarded as satisfactory and self-consistent. One possible approach to this state of affairs is the attempt to build alternatives to Quantum Mechanics, the prototypical example being collapse models [4–6]. These theories are interesting because, regardless of one's opinion about Quantum Mechanics, they make different predictions and can, therefore, be falsified. Various setups aiming at testing collapse models have now been studied and a review of their observational status can be found in Ref. [7]. So far, no deviation from the predictions of Quantum Mechanics has been found.

However, all experiments to date have been designed and performed in the lab and the main goal of our letter [1] was to argue that cosmology can also be a crucial arena to test the viability of collapse models, especially the Continuous Spontaneous Localisation (CSL) model [6]. In CSL, the amplitude of the additional, non-standard, terms controlling the dynamics of the collapse is generically proportional to the mass and/or energy density. Therefore, one expects the effect to be maximum for systems characterised by very large energy densities ρ. The system with the largest ρ that is possible to experimentally probe in Nature is the very early universe during the phase of cosmic inflation. Indeed, during inflation, ρ can be as large as $\rho_{\rm inf} \sim 10^{80}\ \mathrm{g} \times \mathrm{cm}^{-3}$, which makes the early universe an ideal playground to further test CSL.

In more details, the possibility to derive meaningful constraints from inflation is based on the following line of reasoning. According to inflation, the Cosmic Microwave Background (CMB) temperature and polarisation anisotropies, and more generally, all the large-scale structures observed in our universe, are nothing but quantum fluctuations of the gravitational and matter fields, amplified by gravitational instability and stretched to cosmological distances by cosmic expansion during inflation. This simple mechanism has a great explanatory power as it allows us, for instance, to understand in details the most recent, high-accuracy, cosmological observations. During inflation (and subsequently), the behaviour of those quantum fluctuations is controlled by the Schrödinger equation. Any modification of this equation thus changes how those fluctuations evolve, with the potential danger to deliver predictions in contradiction with the cosmological measurements. Moreover, as already emphasised, one may expect those modifications to be very substantial since the energy density during inflation is so large. As a consequence, this opens up the possibility to probe CSL in different regimes than those tested in the lab, and to derive meaningful constraints on this class of theories.

Obviously, a legitimate concern is that the Physics of the very early universe is uncertain and rests on speculative considerations. As a consequence, even if it were possible to derive meaningful constraints on CSL, those would necessarily be based on strong assumptions and this would, therefore, greatly reduce their relevance. Fortunately however, inflation relies on well-controlled physical mechanisms and the situation is not as bad as it might seem. Indeed, the two main mechanisms inflation rests on are (i) the fact that pressure

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gravitates, as implied by General Relativity, and we have good reasons to believe it is true, see Ref. [8], and (ii) quantum parametric amplification by a classical source, namely exactly the same mechanism responsible for the Schwinger effect [9], the dynamical Casimir effect [10] (which has been observed in the lab [11]), *etc.* Furthermore, over the last decades, the physical conditions that prevailed in the early universe have been constrained by various high-accuracy measurements, making cosmology not that different from conventional Physics in the lab.

In our letter [1], we have carried out the program described above and derived constraints on the CSL theory. This study has been recently criticised in Ref. [2] (see also Ref. [3]) and, below, we answer those criticisms in detail. It is worth pointing out that Refs. [2,3] do not claim that our calculations are incorrect but rather depict the assumptions on which they are based as being too restrictive, preventing us from drawing meaningful conclusions about CSL. In the following, we explain why we disagree with these deductions.

2 Choice of the collapse operator

A first concern expressed in Ref. [3] is that, although the collapse operator is identified with the smeared mass density in CSL, in a general-relativistic context, the energy density ρ might have to be replaced by a quantity related to the stress-energy tensor $T_{\mu\nu}$, such as T^{μ}_{μ} or $\sqrt{T_{\mu\nu}T^{\mu\nu}}$. In fact, these choices all lead to operators whose matrix elements are of order $\mathcal{O}(\rho_{\rm inf})$ and, from the arguments presented in the foreword, an immediate conclusion is that it is unlikely to modify the main result, at least in absence of very specific cancellations; and, indeed, it is not difficult to reproduce our calculation for such collapse operators, and to simply realise that the result is unchanged.

Let us now show how this can be concretely carried out. For linear perturbations, the collapse operator (let us call it $\hat{C}$ in general) can always be linearly expanded onto the Mukhanov-Sasaki variable $\hat{v}$ and its conjugated momentum $\hat{p}$. In our letter [1], when the collapse operator is the energy density ρ, we find that, in Fourier space, this expansion is of the form

$$\hat{C}_{\boldsymbol{k}} = e^{-\frac{k^2 r_c^2}{2a^2}} M_{\rm Pl}^2 H^2 \sqrt{\frac{\epsilon_1}{2}} \left\{ \left[x_1 + x_2 \epsilon_1 \left(\frac{aH}{k}\right)^2 \right] \frac{\hat{v}_{\boldsymbol{k}}}{a M_{\rm Pl}} + \left[x_3 + x_4 \epsilon_1 \left(\frac{aH}{k}\right)^2 \right] \frac{\hat{p}_{\boldsymbol{k}}}{a^2 M_{\rm Pl} H} \right\}, \quad (1)$$

where $M_{\rm Pl}$ is the reduced Planck mass, a the Friedmann-Lemaître-Robertson-Walker (FLRW) scale factor, H the Hubble parameter, $\boldsymbol{k}$ the wavenumber of the Fourier mode considered, ϵ_1 the first slow-roll parameter and r_c the CSL localisation scale. The quantities x_1, x_2, x_3 and x_4 are numbers of order one that entirely specify the model. As stressed out in our letter [1], these numbers depend on the gauge in which they are defined.[1] For instance, in the longitudinal gauge, during inflation, at leading order in slow roll, we had found $x_1 = -8$, $x_2 = 6$, $x_3 = 2$ and $x_4 = -6$. Using standard techniques in cosmological perturbation theory, one can show that exactly the same decomposition (1) is obtained for the collapse operators proposed in Ref. [3], though with different x_i numbers: when $C = T^{\mu}_{\mu}$, one finds $x_1 = 20$, $x_2 = -24$, $x_3 = 4$ and $x_4 = 24$; while when $C = \sqrt{T_{\mu\nu}T^{\mu\nu}}$, these numbers are simply multiplied by $-1/2$.

This result is not specific to the longitudinal gauge. In the flat gauge for instance, while we had found $x_1 = -8$, $x_2 = x_4 = 0$ and $x_3 = 2$ for $C = \rho$, one obtains $x_1 = 20$, $x_2 = x_4 = 0$ and $x_3 = 4$ for $C = T^{\mu}_{\mu}$, and these numbers are simply multiplied by $-1/2$ when $C = \sqrt{T_{\mu\nu}T^{\mu\nu}}$. The same is also true in the comoving gauge, where $x_1 = -2$, $x_2 = x_4 = 0$ and $x_3 = 2$ when $C = \rho$, while these numbers are simply multiplied by 2 when $C = T^{\mu}_{\mu}$, and by -1 when $C = \sqrt{T_{\mu\nu}T^{\mu\nu}}$.

As a consequence, all results obtained in our letter [1] are simply multiplied by prefactors of order one when working with the alternative collapse operators proposed in Ref. [3]. Since we had found that, for all choices (but one) of the density contrast, the correction to the CMB power spectrum is at least 50 orders of magnitude too large, operators of the form advocated in Ref. [3] cannot compensate for this discrepancy. In fact, this simple exercise just confirms the robustness of our result [1].

Let us stress again that this 50-orders-of-magnitude difference is ultimately related to the very high energy at which inflation proceeds. One would require a new physical scale to absorb these 50 orders of magnitude, or substantial modifications to the theory; but it is clear that the solution cannot merely come from discussing how an energy density can be extracted from the stress-energy tensor, which can only account for order-one modifications.

Finally, let us point out that if the goal of this discussion was to find a collapse operator that is not ruled out by cosmological experiments, we have already identified one in our letter [1], namely the energy density evaluated in the flat threading. When derived from a more fundamental theory, CSL should thus come with a prescription for the density contrast, which we find has to match that particular choice (all other possibilities being ruled out). This is a non-trivial condition that any attempt to embed CSL in the general relativistic context should satisfy, and it may help to guide such attempts. This was our main conclusion, which we reiterate.

[1] This does not mean that the collapse operators considered here are not gauge invariant, but rather that they coincide with the density contrast in different gauges.

3 Localisation in field space

A second concern expressed in Ref. [3] is the fact that, while for quantum particles, the notion of "localisation" naturally applies to their physical positions (hence the smearing procedure is performed in physical space in CSL, over a distance r_c), in a field-theoretic context, it may also apply to the value of the fields themselves, and a smearing procedure in field space may also have to be carried out, say over a field-value "distance" Δ.

We first notice that the collapse operator is not the physical position *per se* in CSL, but rather the mass density operator. As a consequence, although for quantum particles, this induces the localisation of physical positions indeed, for fields, this also entails the localisation of the field values. Indeed, in our letter [1], we explicitly compute the wavefunction associated to each Fourier mode of the Mukhanov-Sasaki field, $v_{\boldsymbol{k}}$, and we find that $\Psi(v_{\boldsymbol{k}})$ gets peaked as the collapse proceeds. Since this occurs when the wavelength associated to $\boldsymbol{k}$ crosses out r_c, this means that r_c, a physical distance, is also associated to a localisation process for the field value, so the two mechanisms are not distinct.

It is then worth pointing out that in Ref. [12], a relativistic version of CSL is proposed, see appendix B, where the field-space smearing procedure is carried out through the Bel-Robinsor tensor, which is constructed from the Weyl tensor, which itself vanishes for FLRW metrics. Therefore, in the context of cosmology, that smearing procedure would become trivial. More generally, still in appendix B of Ref. [12], it is then shown that this smearing procedure reduces to the standard formulation of CSL anyway. In the context of FLRW cosmology, this boils down to introducing the scale factor at the required places, which gives exactly the equation we have been using.

Although this does not preclude the possibility to build other relativistic versions of CSL where field-space localisation plays a non-trivial role, our main argument remains: those would have to pass the test of cosmology and beat the 50 orders of magnitude, which is a non-trivial requirement.

In passing, it is also argued in Ref. [3] that the amplitude of the CSL terms could be taken as time-dependent, which would lead to different constraints. Again, since a fully satisfactory version of relativistic CSL is not yet available, one can speculate on the various additional features it could have, but let us point out that in Ref. [12], following Ref. [13], it is proposed that the amplitude of the CSL terms depend on the Weyl tensor, which would indeed induce space-time dependence of the corrective terms. However, as already stressed, the Weyl tensor vanishes in FLRW so this would lead to a constant amplitude of the CSL terms. In case this happens, it is also argued in Ref. [3] (and stated again in Ref. [2]) that one could assume the corrective terms to depend on the Ricci scalar. In FLRW, this is nothing but the Hubble parameter H, which happens to be quasi-constant during inflation, leading to no time dependence again. In fact, because of the maximal symmetry de-Sitter space-times enjoy, introducing dependence of the parameters of the theory on geometrical quantities cannot lead to effective time dependence of the couplings, so this argument does not seem to apply to the present context either. Again, this demonstrates that introducing "reasonable" modifications that would be capable of substantially modify our result is not trivial, a fact that reinforces the robustness of our conclusions. Obviously, in the subsequent radiation era, H does depend on time and so would the CSL terms (if taken to be Ricci-dependent), as we have studied (although in a slightly different context) in Ref. [14].

4 Semi-classical gravity

A last criticism put forward in Refs. [2,3], which is not specifically directed towards our works [1,15] but rather towards the whole community of primordial cosmologists and to the standard formulation of inflation (which, admittedly, we use), states that a quantisation of small fluctuations during inflation cannot be carried out consistently and, instead, advocates the use of semi-classical gravity based on the equation $G_{\mu\nu} = \langle T_{\mu\nu}\rangle / M_{\mathrm{Pl}}^2$.

The question of whether gravity must and/or can be quantised is of course a long-standing one. Although semi-classical gravity has received many criticisms, the status of which are summarised *e.g.* in Ref. [16] (there are even claims that it is already ruled out either by actual, table-top, experiments such as Page and Geilker experiment [17,18], or that it leads to superluminal signalling when combined with the standard collapse postulate [19], or that it is proven inconsistent by thought experiments such as Eppley and Hannah's experiment [20]), the modern consensus seems to be that those arguments and experiments are not decisive enough to invalidate semi-classical gravity. As a consequence, we agree that arguing in favour of an inflationary mechanism based on this approach might still be a defendable position even if it is held by a minority of physicists. However, the criticism laid out in Refs. [2,3] against the standard approach of quantising the perturbations of both the metric and the matter fields around a classical background, comes with various statements that are worth commenting on.

Firstly, we notice that this criticism has nothing to do with CSL or with how the collapse proceeds in the early universe: as a matter of fact, effective collapse models have been used either in the context of semi-classical gravity, see for instance Refs. [21,22], or in the standard context, see Ref. [23], thus showing that this issue is, in some sense, disconnected from the main question discussed in our paper. On general grounds, we think that, in order to investigate the consequences of

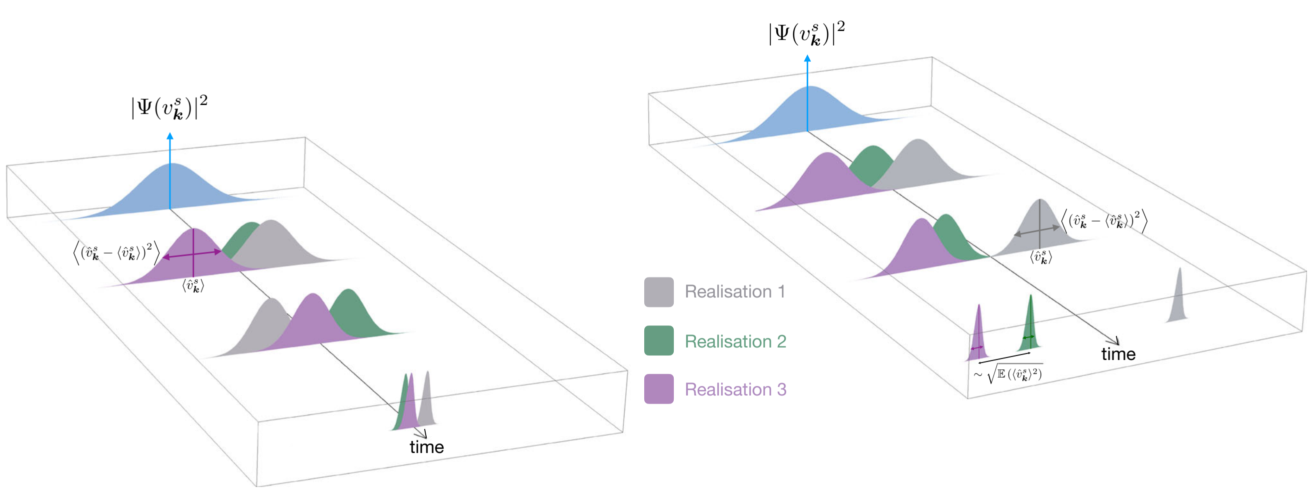

Fig. 1 In the framework of CSL, the wave-function of the perturbations $\Psi(v^s_{\boldsymbol{k}})$ (where $s = \mathrm{R}, \mathrm{I}$ denotes the real and imaginary parts of the Mukhanov-Sasaki variable $v_{\boldsymbol{k}}$), taken to be a Gaussian in the context of inflation, is a stochastic quantity. As a consequence, its quantum mean value $\langle \hat{v}^s_{\boldsymbol{k}} \rangle$ and quantum dispersion $\langle (\hat{v}^s_{\boldsymbol{k}} - \langle \hat{v}^s_{\boldsymbol{k}} \rangle)^2 \rangle$ are random variables. In the present case, however, the quantum dispersion $\langle (\hat{v}^s_{\boldsymbol{k}} - \langle \hat{v}^s_{\boldsymbol{k}} \rangle)^2 \rangle$ turns out to be a deterministic function. In the left panel, we have represented the stochastic "trajectories" of this wave-function for three different realisations. The means $\langle \hat{v}^s_{\boldsymbol{k}} \rangle$ evolve randomly while the dispersions continuously (and deterministically) decrease with time. At the final time, the dispersion of the means, $\mathbb{E}[\langle \hat{v}^s_{\boldsymbol{k}} \rangle^2]$ (the stochastic average of the means vanishes $\mathbb{E}[\langle \hat{v}^s_{\boldsymbol{k}} \rangle] = 0$) is not small compared to the width of the wave-functions, $\mathbb{E}[\langle (\hat{v}^s_{\boldsymbol{k}} - \langle \hat{v}^s_{\boldsymbol{k}} \rangle)^2 \rangle] = \langle (\hat{v}^s_{\boldsymbol{k}} - \langle \hat{v}^s_{\boldsymbol{k}} \rangle)^2 \rangle$, and our criterion is not satisfied. In this case, the different wave-functions representing different realisations are not sufficiently separated to account for the emergence of different outcomes. In the right panel, on the contrary, our criterion is satisfied and different realisations do correspond to well-separated outcomes

alternatives to a given standard formalism, it is clearer to study one alteration at a time rather than to introduce several variations at once.

Secondly, in our letter [1], we have introduced a criterion for deciding whether or not the wave-function has collapsed, which is based on the requirement that the average width of the wave-function be much smaller than the dispersion of its mean value, see Fig. 1 where we explain the rationale behind this criterion. In Ref. [2], it is argued that such a criterion may apply in the standard matter-metric quantisation procedure, but is not the appropriate one in semi-classical gravity. We do not really understand why this comment is relevant for our work since we did not consider semi-classical gravity in our letter. Furthermore, and more importantly, it is then stated that our conclusions strongly rely on this criterion since, quoting Ref. [2], it "*has very relevant implications regarding what the values of the CSL parameters should be, and whether or not they are compatible with CMB observations*" and "*Their argument against CSL is that [...] it fails to achieve a sufficient localization of the relevant wave functions in the inflationary context*". At this point, there might be a misunderstanding of the calculation performed in our letter [1], from which we reproduce Fig. 3, see Fig. 2 here. In this plot, we have represented the constraints inferred from the CSL power spectrum, which is given by

$$\mathcal{P}_v(k) = \mathcal{P}_v(k)\big|_{\mathrm{std}} \left\{ 1 + \gamma \Delta \mathcal{P}_v(k) - \frac{\mathbb{E}[\langle (\hat{v}^s_{\boldsymbol{k}} - \langle \hat{v}^s_{\boldsymbol{k}} \rangle)^2 \rangle]}{\mathbb{E}[\langle \hat{v}^s_{\boldsymbol{k}} \rangle^2]} \right\}, \tag{2}$$

where $\mathcal{P}_v(k)|_{\mathrm{std}}$ is the standard, almost scale-invariant, power spectrum, and $\gamma = 8\pi^{3/2} r_c^3 \lambda$, λ being the mean rate of collapse. We see that CSL introduces two types of corrections, $\Delta \mathcal{P}_v(k)$ and $\mathbb{E}[\langle (\hat{v}^s_{\boldsymbol{k}} - \langle \hat{v}^s_{\boldsymbol{k}} \rangle)^2 \rangle] / \mathbb{E}[\langle \hat{v}^s_{\boldsymbol{k}} \rangle^2]$, the explicit form of which is given in Ref. [1], and which turn out to be strongly scale dependent; the latter corresponding exactly to our collapse criterion, as explained in Fig. 1. We emphasise that this second type of corrections is necessarily present in the CSL power spectrum regardless of the interpretation it receives. If $\gamma \to 0$, the first correction vanishes and the second one tends towards one since, then, $\langle \hat{v}^s_{\boldsymbol{k}} \rangle \to 0$ (indeed, in absence of CSL corrections, the dynamics is deterministic and the mean remains zero). In this limit, the power spectrum vanishes, as expected since only the CSL terms are able to break the homogeneity of the initial vacuum state. In order to recover an almost scale-invariant power spectrum the two corrections must be sub-dominant. In Fig. 2, the "CMB-painted" region corresponds to a regime where CSL correctly accounts for the emergence of primordial fluctuations, that is to say where the two types of corrections are sub-dominant (hence, the power spectrum is almost scale-invariant and the collapse criterion is satisfied). The region dashed with vertical bars, on the contrary, represents a regime where CSL fails to satisfactory describe the properties of cosmological perturbations. The

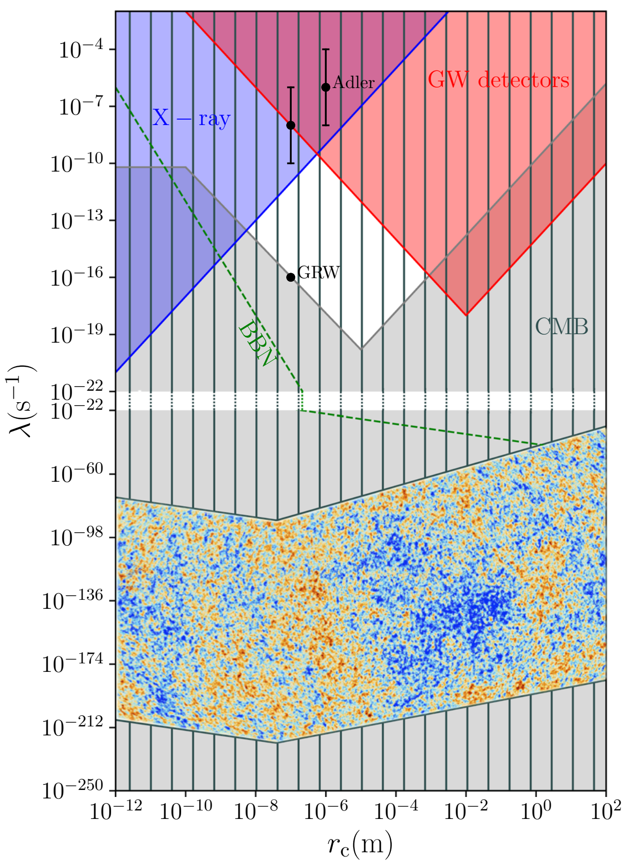

Fig. 2 Observational constraints on the two parameters r_c and λ of the CSL model. The white region is allowed by laboratory experiments while the unbarred region is allowed by CMB measurements (one uses $\Delta N = 50$ for the pivot scale of the CMB, $H_{\rm inf} = 10^{-5} M_{\rm Pl}$ and $\epsilon_1 = 0.005$). The two allowed regions are incompatible. The green dashed line stands for the upper bound on λ if inflation proceeds at the Big-Bang Nucleosynthesis (BBN) scale. Taken from Ref. [1]

dashed region above the "CMB-painted" one represents the region where the first correction dominates and the second one is negligible. In this region, the power spectrum strongly deviates from scale-invariance but the collapse criterion is satisfied. The lower region dashed with vertical bars (that is the one for $\lambda \lesssim 10^{-212}\,\mathrm{s}^{-1}$), below the "CMB-painted" one, corresponds to the opposite situation: the correction $\Delta\mathcal{P}_v$ is negligible but the collapse criterion is not satisfied. The values of the CSL parameters that are in agreement with laboratory experiments, on the other hand, lie in the white region. Now, the problem we highlight in Ref. [1] is that this white area falls in the upper dashed region, which corresponds to where the first type of CSL corrections to the CMB power spectrum are too large but where the second type of corrections are small. We see that the main conclusion of our letter [1] is in fact reached in a regime where the collapse criterion is always satisfied and, hence, does not have any discriminatory power. In other words, had we ignored our collapse criterion, the incompatibility between the lab and CMB con-

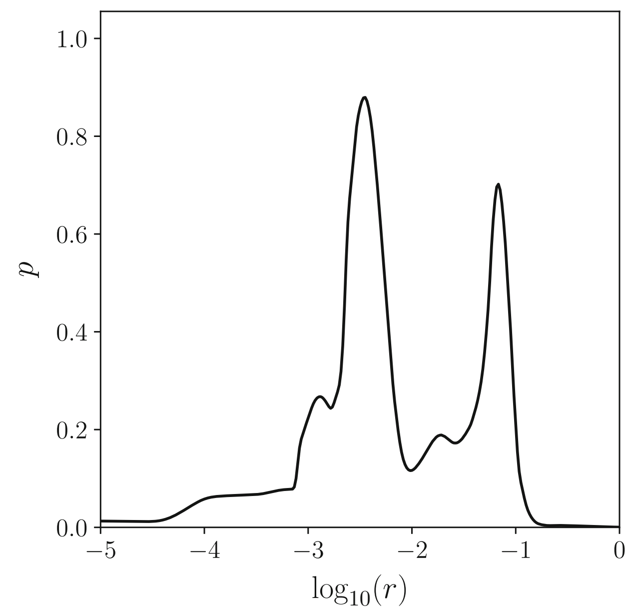

Fig. 3 Posterior distribution on the tensor-to-scalar ratio r, averaged over all physical single-field models of inflation as listed in Ref. [32] (where each model is weighted by its Bayesian evidence), using the Planck 2013 data and the results of Ref. [33]

strains would have remained exactly the same. Therefore, claiming that the collapse criterion (which, we still think, is well justified) plays a role in ruling out CSL theories is clearly incorrect.

Thirdly, in Refs. [2,3], it is stated that the standard approach where matter and metric are quantised is problematic because field commutation relations are not compatible with the full spacetime causal structure. We believe that this remark refers to Eq. (14.1.2) of Ref. [24] where it is noted that, in a theory of Quantum Gravity, one may expect the metric quantum operator $\hat{g}_{\mu\nu}$ to satisfy $\left[\hat{g}_{\mu\nu}(x), \hat{g}_{\alpha\beta}(x')\right] = 0$ when x and x' are space-like separated, while the very definition of "space-like separated" requires to specify the metric itself, rendering this criterion ill-defined. Two important remarks are in order. First, let us recall that what is merely done in the standard approach to inflation is to quantise small fluctuations around a classical background, as we do, for instance, for phonons on top of a classical crystal. Therefore, none of the issues that usually plague attempts to build theories of Quantum Gravity are present in this context (recall that the energy scale of inflation is observationally known to be, at least, five orders of magnitude below the Planck scale), and for small linear fluctuations, the standard techniques of quantum field theory can be applied safely. Therefore, we believe that this criticism does not apply to the perturbative calculation of the inflationary power spectrum. Second, in known constructions of Quantum Gravity, the small-fluctuation limit precisely reduces to the standard approach where fluctuations of both the metric and the matter fields are quantised in a gauge-invariant way, and not to semi-classical gravity, see *e.g.* Ref. [25] in the case of string theory and Ref. [26] in the case of loop quantum gravity. As a consequence, if one is looking for insight from Quantum Gravity, one is naturally led to the standard matter-metric quantisation, and not to semi-classical gravity.

Fourthly, in Ref. [2], another potential issue is put forward, the so-called "gauge problem", which is related to the problem of how the background and the perturbations are split. Let us stress that this question has nothing to do with the quantisation of perturbations and is already present at the classical level. As noticed in Ref. [2], the Bardeen formalism offers an elegant way to deal with this issue. Ref. [2] argues that it is still unsatisfactory because it is valid only at first order in the perturbations. Even if it were correct, that would not be a problem for calculations of the power spectrum, which do not go beyond that order. But in any case, the gauge-invariant formalism for cosmological perturbations has long been extended to higher orders, see *e.g.* Ref. [27] where relevant quantities are constructed in several gauges at second order, and Ref. [28] where a non-perturbative, covariant construction is derived. In fact, it seems rather ironical that the issue of gauge invariance is brought by Ref. [2] into the debate, given that, contrary to the standard approach, semi-classical gravity has a clear gauge ambiguity. Indeed, since fluctuations in the metric and the matter field are treated differently in semi-classical gravity, and because gauge transformations mix those different types of fluctuations, different gauges necessarily give rise to different results [29]. Therefore, the gauge burden seems to be rather on the semi-classical gravity proponents.

Finally, in Ref. [2], it is correctly noticed that one way to observationally distinguish the two approaches would be to measure the stochastic background originated from primordial quantum gravitational waves. In the semi-classical approach, the signal is indeed predicted to be so small that it should not be detected. If, on the contrary, there is a detection, this would strongly support the idea that small fluctuations must be quantised and would certainly completely rule out the semi-classical approach. Primordial gravitational waves can be observed either directly or by measuring the B-mode polarisation in the CMB. For the moment, no signal has been reported and, from the 2018 Planck data release [30], we have for the tensor-to-scalar ratio $r_{0.002} < 0.1$ at 95% Confidence Level (CL), an upper limit which becomes $r_{0.002} < 0.056$ if, in addition, the BICEP2/Keck Array BK15 data are used. Future experiments such as LiteBIRD [31] will be able to reach $r \sim 10^{-3}$. In Ref. [2], it is claimed that most inflationary models predict values of r that should already have been seen, and that the standard treatment of inflation is already under pressure, a conclusion that is clearly incorrect. Such a statement about what is predicted by "most models" would require to actually count the number of models per value of r, something which the authors of Ref. [2] have not done. In order to study this claim with well-justified methods, we display in Fig. 3 the posterior distribution on the tensor-to-scalar ratio, obtained by averaging over all physical single-field models of inflation as listed in *Encyclopædia Inflationaris* (that contain ~ 200 models), see Refs. [32,33], where each model is weighted by its Bayesian evidence, obtained with the Planck 2013 data. This combines information about how the proposed models of inflation populate different values for r, and observational constraints (prior to the last Planck 2018 release and its combination with BICEP2/Keck Array). One can see that there are roughly two populations of models (two bumps in the posterior distribution): (i) those predicting values of r in the range $[10^{-2}, 10^{-1}]$ (those were only weakly disfavoured in 2013 but they have been more strongly discarded since then), and (ii) those predicting values of r in the range $[10^{-3}, 10^{-2}]$, which correspond to plateau models (a prototypical example being the Starobinsky model [34]), which are not only in perfect agreement with the data, but which will be probed by the next generation of CMB experiments. The statement made in Ref. [2] that most models cannot account for the current upper bound on r is therefore ungrounded, as revealed by this analysis of the landscape of inflationary models.

5 Afterword

Before closing this rebuttal, we would like to make a few additional remarks. We, of course, agree with the authors of Refs. [2,3] that the correct relativistic CSL theory is not yet known: we made this point very clear in our letter [1]. Therefore, exploring the consequences of the CSL mechanism for cosmic inflation necessarily involves some extrapolation. In fact, the whole discussion in Ref. [2] (see also Ref. [3]) boils down to the question of what extrapolation is more likely, which, at this stage, is subjective. Facing this situation, we think it is more reasonable, at least in a first step, to study the minimal extension and investigate what comes out of it. Only if serious problems arise can we be forced to consider more exotic possibilities. Contrary to what is claimed in Refs. [2,3], we do not think that having a vast landscape of possibilities is an attractive feature of a theory: instead, constrained theoretical frameworks lead to more restrictive predictions, and can be better tested. Otherwise, the Pandora's box is open and we loose any explanatory power. The discussion presented here clearly shows that the results of Ref. [1] are robust and none of the suggestions presented in Refs. [2,3] seem able to alter this conclusion.

Finally, the main point of our letter [1] is not that, using its most conservative extension, CMB data seem to cast a vague shadow on CSL: it is rather that it does so by at least 50 orders of magnitude! We agree that the formalism may have to be modified at high energies. Our main result is that these modifications should have a drastic effect in order to overcome those 50 orders of magnitude. If we consider for instance, as we did in our letter [1], a possible running of the fundamental parameters, this running would have to be extremely strong. If we consider, instead, other possible collapse operators, then, although we have shown that the operators proposed in Ref. [3] are helpless, we already had proposed a solution in our letter [1], and this consists in considering the energy density evaluated in a very specific threading (namely the "flat" threading, leading to what is called "δ_m" in Ref. [1]).

In other words, the main result of Ref. [1] is not at all the claim that inflation rules out CSL (no such claim was ever made in our letter) but rather that the corrections to the standard framework that may appear at high energies must be very specific in order to be compatible with cosmological data; this, of course, raises the question of whether this is likely or even possible at all. On a more positive note, this result can also be taken as a useful guide to build extensions to the CSL framework. In any case, it is interesting to see that cosmology can play a relevant role in developing our understanding of Quantum Mechanics, a remark on which one should get consensus from everyone.

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