

The simple reason why classical gravity can entangle

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Ever since gravity-induced entanglement (GIE) experiments have been proposed as a witness of the quantum nature of gravity, more and more theories of classical gravity coupled to quantum matter have been shown to predict GIE, despite the existence of several theory-independent no-go theorems purportedly claiming that it should not be possible. This note explains why this is possible, and why this makes the GIE experiments an even more urgent matter in quantum gravity research.

Two 2017 papers, one by Bose and collaborators [1] and one by Marletto and Vedral [2], generated a lot of excitement around an old idea by Feynman [3] of allowing a mass in a superposition of locations to interact gravitationally with another mass to detect gravity-induced entanglement (GIE): the generation of entanglement between two quantum systems as a result of their gravitational interaction.

The excitement around detecting GIE is due to two factors. First, it would be the first direct observation of a quantum-gravity effect: a prediction of perturbative quantum gravity that differs from a prediction of semiclassical¹ gravity achievable using near-term technology [1, 7–12], making it a concrete target for this generation of experimental physicists. The second reason for excitement, and the main subject of this note, was an argument by Bose *et al.* and Marletto and Vedral [1, 2], based on information-theoretic reasoning, that the experiment would provide a theory-independent certification of the non-classical nature of gravity.

The argument is simple. It is based on a generalisation of the well-known quantum-theoretical fact that local operations and classical communication (LOCC) channels cannot increase the amount of entanglement between two quantum systems [13]. We will call these generalisations and strengthenings [1, 2, 14–16] the *LOCC-like theorems*. In the context of GIE, these no-go theorems are often stated in words as showing that detection of GIE implies that the gravitational interaction is either nonlocal or nonclassical, see figure 1. A clause is then added: since the principle of locality is unassailable, detecting GIE is sufficient to prove that gravity is nonclassical.

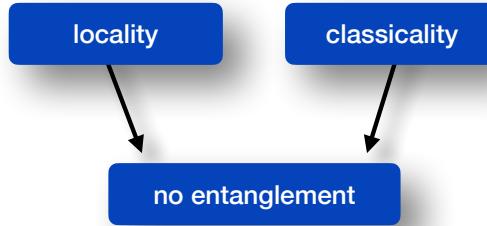


Figure 1. The assumptions of the LOCC-like no-go theorems are often presented as locality and classicality of the gravitational field. However, this presentation hides some important details about the locality assumption. A better presentation is as in figure 3.

However, attempts to apply this theory-independent argument to the GIE experiment has been creating controversy ever since it has been proposed [17–23]. The more recent round of this controversy is the paper by Aziz and Howl [24] followed by the rebuttals by Marletto and Vedral [25] and Diōsi [26]. Besides, it is a simple fact that GIE detection is not enough to rule out theories with classical gravity: Trillo and Navascués have shown that even the Diōsi-Penrose model [27, 28]—the paradigmatic model of classical-gravity-induced collapse modification of quantum theory—predicts GIE [29].

¹ By semiclassical gravity here we mean a theory where the gravitational field is sourced by the expectation value of the energy-momentum tensor. This theory requires non-unitary evolution (spontaneous collapse) to be compatible with observations [4] and, even then, it presents various difficulties with locality and signalling. It is however well-behaved in certain regimes and, indeed, it is the effective framework actually used in essentially all current astrophysical and cosmological applications, as well as in precision tests of general relativity, to couple quantum matter to a classical spacetime geometry [5, 6].

The reason, in the end, is very simple: the assumptions of the no-go theorem are not natural in the context of gravity. Not only are the quantum-matter-with-classical-gravity theories nonlocal in the sense of the no-go theorem, but so is quantum field theory!

In the rest of the note, I will explain what is the locality assumption in the LOCC-like theorems, why it means that simply detecting GIE is not sufficient to certify gravity as a non-classical entity and, finally, argue why the GIE experiments must still be done.

I. TWO DIFFERENT NOTIONS OF LOCALITY

Locality is a crucial notion in modern physics. Like time, it has several layers and distinct aspects, captured in various ways by our mathematical formalisations.

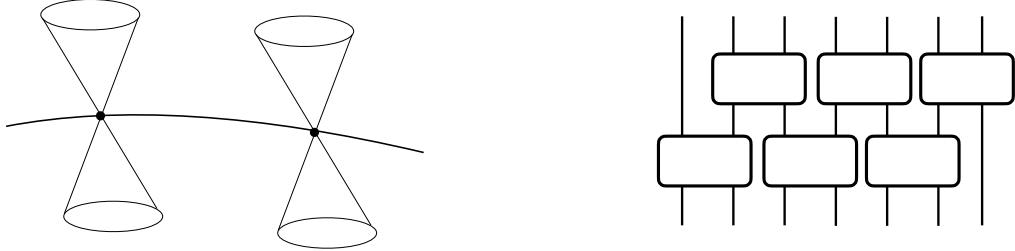
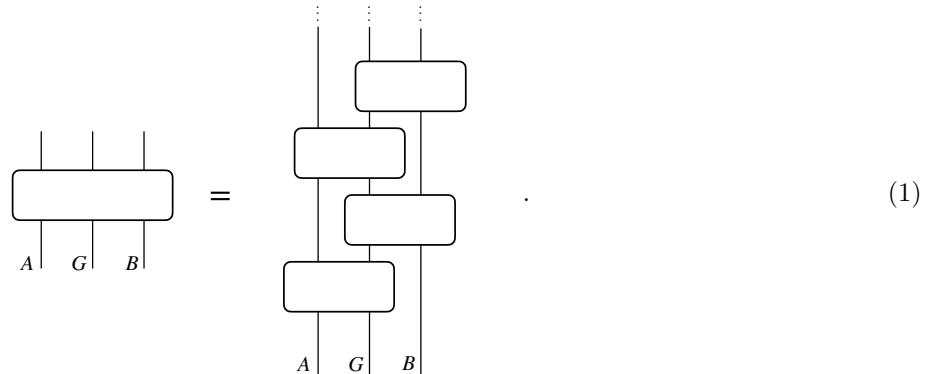


Figure 2. *Two different notions of locality used in physics.* Left, a depiction of a spatiotemporal notion of locality, where information travels within lightcones. Right, a depiction of subsystem, or circuit, locality, where each line represents a system, and the boxes represent operations acting on at most two systems at a time. The first is the notion of locality most salient to relativity and field theory, while the latter is native to information theory and quantum foundations. It is the subsystem notion of locality that is involved in the LOCC-like no-go theorems.

When we say “the world is local” we are normally referring to a *spatiotemporal* notion of locality. With the advent of the theories of special and general relativity, the principle of relativistic locality—no signal travels faster than the speed of light—has become a foundational principle of physics. Microcausality—the commutation of operators at spacelike-separated events—is taken as axiomatic in quantum field theory, arguably the most successful physical theory of all time. Detecting a violation of relativistic locality in the form of faster-than-light signalling would be an epoch-shifting moment, and theories like Bohmian mechanics that violate relativistic locality at an ontological but non-detectable level are seen with distrust.

However, the LOCC-like theorems rely on a *different* notion of locality, based not on spacetime regions, but on *systems*. This form of locality is of particular interest in quantum foundations and quantum information research. An operation or a channel is *local* in this sense if it only acts on a strict subset of the systems under consideration. For the purposes of this work, we will call *mediation* the specific locality assumption that goes in the no-go theorems. Mediation states that the time evolution of the two masses and the gravitational field can be broken down in operations that act on the gravitational field and one mass or on the gravitational field and the other mass and never on the two masses at once. That is, we can write the time evolution as the following circuit diagram:



Some of classical gravity and quantum matter models do not satisfy mediation, and that is the simple reason they can entangle. As we will see, it is only this form of locality that goes into the LOCC-like no-go theorems, and this makes them weak. In fact, while the subsystem notion of locality is natural in information-theoretic settings, it is not really a thing in spacetime-based theories. One might have the impression that mediation is a consequence of relativistic locality, or that the two go hand-in-hand. However this is not the case.

Relativistic locality does not imply mediation.

Wheeler-Feynman absorber theory [30, 31] is an example of a relativistically local theory with no mediator [21]. Even standard relativistically-local QFTs only feature mediation in specific gauges² [21, 32, 33] and, even then, they do so only approximately [32, 33].

II. THE STRUCTURE OF THE NO-GO THEOREMS

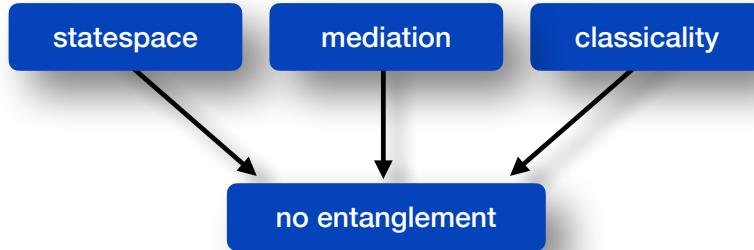


Figure 3. A better representation of the assumptions of the LOCC-like no-go theorems. Statespace means that gravity can be assigned an independent statespace like in equation (2), mediation means the evolution of the two masses and gravity factorises as (1), classicality is that gravity has a classical statespace.

The LOCC-like no-go theorems are proven within a metatheoretic framework, a *space of theories* like constructor theories [34] or generalised probabilistic theories [35, 36]. In these frameworks, a system is specified by a statespace, a set of transformations, and a set of measurements. Whether a system is classical, quantum, or otherwise is a property of that triple.

The first step in the derivation of the no-go theorems is to assume that the two masses A and B and the gravitational field G can each be assigned a respective statespace.³ More precisely, one assumes that the time-evolution of the A and B systems can be written as a time-evolution involving a third system, G , which starts uncorrelated from then and is later ignored,

$$\begin{array}{c} \text{---} \\ | \quad | \\ \text{---} \end{array} = \begin{array}{c} \text{---} \\ | \quad | \\ \text{---} \\ G \\ \nabla \end{array} . \tag{2}$$

The second step is to assume that the time evolution of the AGB system takes the form of a *mediation*, that is, it can be written as a sequence of operations involving only system A and G , or system B and the G as in equation (1).

Finally, they prove that evolutions of this form cannot lead to increased entanglement between A and B unless G is non-classical in some precise sense, due to having non-commuting observables [14] or non-simplex statespace [15].

² Take QED, for example: In the Coulomb gauge, also known as radiation gauge, there is a direct interparticle interaction via the (quantum) Coulomb potential which spoils the mediation assumption.

³ Within quantum theory, this would correspond to the assumption that the Hilbert space factorises as $\mathcal{H}_A \otimes \mathcal{H}_G \otimes \mathcal{H}_B$.

We note that the three assumptions of statespace, locality, and a classicality are not logically independent: the locality and classicality assumption can only be made after the statespace assumption.

The theorems are correct. The problem with them is that they are not that relevant to gravity. Note that at no point the proof invokes any spatiotemporal notion of locality. In fact, at this level of generality there is no way to formulate a spatiotemporal notion of locality. The only locality assumption, mediation, is based on subsystems and, as stated above, this is not a natural assumption.

A theorem that showed that mediation is necessary for respecting the no-signalling principle would cut much deeper. This is evidently not possible, since both QED in the Coulomb gauge and Wheeler-Feynman absorber theory lack a mediator [21] but are both nonsignalling, as mentioned above.

The statespace assumption itself is also quite problematic in the context of field theories such as electromagnetism and gravity due to the constraints [17]: the physical Hilbert space is not the tensor product of a matter Hilbert space and a gravity Hilbert space, but the subset of such tensor product where the various constraints, such as Gauss law for electromagnetism, hold weakly. Additionally, theories like the Dioši-Penrose model do not assign an statespace to gravity.

Summarising:

- (i) The LOCC-like theorems do *not* rely on relativistic (spacetime) locality anywhere.
- (ii) They *do* rely on mediation, which is a circuit-style assumption that generically fails in relativistic field theories, including ones that are perfectly causal.
- (iii) GIE rules out *classical, mediation-local* gravity; it does not rule out *classical, relativistically local* gravity models that violate mediation.

This is why these theorems, while logically correct, do not have the same “theory-independent bite” that Bell’s theorems [37–39] have. The assumptions in Bell’s two theorems such as no superdeterminism, (relativistic) locality, Reichenbach’s principle of decorrelating explanation are totally natural and desirable properties for a physical theory. One can argue the Bell inequality violations at spacelike separation rule out local hidden variable models because we care a lot about no superdeterminism. In contrast, one cannot use GIE to rule out classical gravity, because the other two assumptions in the theorem, statespace and locality, are not that important in current physical practice.

theory	GIE?	assumption dropped	good candidate?
Newtonian QM	✓	statespace	✗ (no gravitational waves)
semiclassical GR	✗	none	✗ (possibly inconsistent)
perturbative QG, Lorenz gauge	✓	classicality, (statespace ?)	✓
perturbative QG, Coulomb gauge	✓	statespace	✓
hybrid models	mediation and/or statespace	depends	depends

Table I. *How different concrete theories (or classes of theories) sit with respect to the LOCC-like no-go theorems.* “GIE?” indicates whether the theory predicts gravity-induced entanglement between two nearby test masses in a BMV-type setup, “assumption dropped” indicates which assumption of the no-go theorems is not satisfied, “good candidate?” is a rough assessment of whether the theory is normally taken seriously as a candidate effective description in the relevant regime. By “hybrid models” I mean the class of various theories that feature classical gravity and quantum matter, such as the Dioši-Penrose [27, 28], Tilloy-Dioši [40], and the Oppenheim [41] models. In the Aziz-Howl computation [24], the mediation assumption fails

III. WHY THE GIE EXPERIMENTS ARE STILL CRUCIAL

The Bose *et al.* and Marletto and Vedral papers promised us a simple way to prove once and for all that gravity is non-classical. Under closer scrutiny, their argument does not go through. But this does not make the GIE experiments less important!

The theory-independent approach of ruling out entire classes of (existing or hypothetical) theories with a single experiment is a relatively new addition to scientific practice: we have been ruling out theories way before inventing no-go theorems. What we need to do is good-old theory verification and falsification: take the various theories that are compatible with everything that is known about gravity, carefully compute detailed predictions in specific experimental setups, and compare with empirical data.

The alternative theories of classical gravity coupled with quantum matter differ in their quantitative predictions in the GIE experiment regarding how entanglement rates, maximal entanglement, and decoherence rates depend on the various parameters of the experiments, such as the masses of the object in superposition, their distance, the duration of the experiment and so on.

Regardless of no-go theorems, GIE experiments, carefully analysed and performed, will be a landmark moment in the history of physics because they will allow testing the predictions of various different theories of the gravitational interaction.

IV. IS GIE A QUANTUM EFFECT AFTER ALL?

In the regime relevant to these experiments, our standard effective description of gravity is perturbative quantum gravity: the (nonrenormalisable but perfectly predictive, order-by-order) quantum field theory of linearised metric perturbations on a background, expected to be valid at these energies and distances. This theory tells us that, during the experiment, the gravitational field is in a highly non-classical state [23, 42, 43]: it is in a quantum-controlled superposition of semiclassical states, which is very far from a classical state. So, according to the theory, the GIE is due to a superposition of field configurations, a genuine quantum property. If we incorporate lessons from general relativity, we understand that this state is a quantum superposition of diffeomorphically-inequivalent spacetime geometries [44, 45].

These are not theory-independent statements, of course. From the point of view of other models, the experiment would be telling us something different. So how could GIE be a quantum effect?

Consider the question: is single-particle interference a genuinely quantum effect? Despite common folklore, local classical models *can* predict interference [46, 47], so mere interference is not a sign that matter is quantum. However, we still say that interference is a quantum effect, because there is a *quantitative* difference between the predictions of these classical models and of quantum theory, and experiment favours quantum theory.

The situation with GIE is analogous. The difference between quantum and classical gravity theories is not qualitative but quantitative. *If* we detect GIE, and *if* the predictions are quantitatively aligned with perturbative quantum gravity and in strong tension with the other theories, we will be able to say that we detected the first direct experimental sign of quantum gravity. It is not the mere fact *that* gravity can entangle, but the *rate and amount* of entanglement that will tell us whether gravity is classical or quantum after all. No need for no-go theorems.

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