Quantum Mechanics, Nonlocality, Relativity and Quantum Entanglement
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1. Quantum Mechanics, the Measurement Problem and Locality

The measurement problem in quantum Mechanics

Quantum mechanics (QM) uses the abstract mathematics of q-numbers. Due to the Heisenberg Uncertainty Principle $\Delta x \, \Delta p \geq h/2$, we cannot provide the x and p as initial c-number quantities for an action S (Lagrangian) describing the propagation of the QM wave function ψ, so we cannot predict the outcome of a QM experiment unless we convert the q-numbers into c-numbers that can be read by a classical measuring apparatus.

In the standard QM (Copenhagen interpretation) this conversion to an eigenstate is promoted by the “collapse” or “reduction” of the wave function ψ. This collapse occurs everywhere in space, so it is a nonlocal phenomenon that is in serious contradiction with our intuitive need for locality and the continuous behavior of physical processes at the classical level. The “jump” in the wave function occurring in the collapse takes place in a fraction of a second, so Shrödinger’s cat is both alive and dead for only a split second.

Is Physics Local or Nonlocal?

Isaac Newton was not happy with the “action at a distance” or nonlocal feature of his gravity theory. We learn about this from his much quoted statement:

That Gravity should be innate, inherent and essential to Matter, so that one Body may act upon another at a Distance thro a Vacuum, without the mediation of any thing else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity, that I believe no Man who has in philosophical Matters a competent Faculty of thinking, can ever fall into it.

Isaac Newton, Papers and Letters on Natural Philosophy and related documents, pg. 302. Harvard University Press, Cambridge, Massachusetts, 1958.

The violation of John Bell’s inequality (J. S. Bell, Speakable and Unspeakable in Quantum Mechanics, Collected papers on quantum philosophy (Cambridge University Press, Cambridge, 2004) has been verified by experiment (A. Aspect, J. Dalibard and G. Rogers, Phys. Rev. Lett. 49, 1804 (1982)).

Quantum entanglement (QE) is intrinsically a non-local phenomenon. It conforms with Newton’s absolute space and a preferred frame of reference.

Communication through space between two space-like separated events is instantaneous (“spooky” action at a distance). Would Newton have accepted this description of Nature? Probably not.

In Einstein’s classical GR, gravity is propagated through spacetime with a finite speed v_g . There are no discontinuous jumps and gaps in the propagation of gravity communication. The nonlocal and discontinuous nature of QM and, in particular, QE was troubling to Einstein and Schrödinger. The famous paper of Einstein, Podolsky and Rosen (EPR) forcefully showed how QM departs completely from any classical line of thought.

EPR did consider spacetime influences by threatening QM with “spooky” action at a distance because of which they claimed that QM was incomplete.

There are currently two positions taken by physicists with respect to the tension between QM and Special Relativity (SPR).

1. QE is a purely QM phenomenon and spacetime plays no physical role in its description. The wave function is a pure state such as

   $$|\Psi >= 1/\sqrt{2}[|00\ldots0)> + |11\ldots1>]$$

   and the correlation between the two qubit values is not influenced by spacetime considerations such as SPR.

2. Should spacetime, SPR and GR play a role in explaining QE? QE is a macroscopic phenomenon in which the spatial (space-like) separation in QE experiments can be 18 kilometers. How can such a macroscopic phenomenon not be influenced by events in spacetime? How can the apparent local and continuous behavior of classical electromagnetic (EM) and gravity disturbances be reconciled with the nonlocal and discontinuous behavior of QE?

   Can the tension between SPR, GR and QM be resolved?

Quantum field theory (QFT) and quantum gravity (QG) can be nonlocal theories. These theories have no divergences as in local QFT and QG. They satisfy unitarity and the perturbation theory produces amplitudes that are finite to all orders (see: JWM, Eur. Phys. J. Plus **126**, 43 (2011); **126,** 53 (2011)).

Can local QFT and unrenormalizable QG, which suffer from divergences be consistent with nonlocal QM and QE?

Locality and the vanishing commutation of QFT operators at space-like distances (microcausality) must be made consistent at short distances with QM measurements and nonlocal, nonrelativistic QM.

Does strict causality hold at the QG Planck length ~ 10^{-33} cm?

For those who remain troubled by the abandonment of a causal spatial description of entangled states, changing QM does not help matters.

2. Variable Speed of Light, Bimetric Gravity and Bimetric Quantum Communication

Is it possible to explain QM entanglement as being caused by a spacetime mechanism? This requires that quantum information be transmitted with a speed $v_c > c$. If this is possible, we have to confront the question whether the transmission of quantum information violates the no signalling postulate.

In 1992-93, I published papers on variable speed of light (VSL) as an alternative to inflation as a solution to initial value problems in cosmology (JWM, Int.J.Mod.Phys.D2:351-366,1993, arXiv:gr-qc/9211020; JWM,, Found.Phys. 23 (1993) 411-437, arXiv:gr-qc/9209001).

Local Lorentz invariance is broken spontaneously: SO(3,1) -> O(3). Minkowski spacetime spontaneously becomes absolute space and time: O(3) X R (Newton) fractions of seconds after the big bang.

Bimetric gravity geometry is based on the metric (B and b= constants).

(M. A. Clayton and JWM, Phys.Lett. B460 (1999) 263, arXiv:gr-qc/9812481;
Phys.Lett. B506 (2001) 177, arXiv:gr-qc/0101126)

$$\hat{g}_{\mu\nu} = g_{\mu\nu} + B\partial_\mu\phi\partial_\nu\phi. \qquad \hat{g}_{\mu\nu} := g_{\mu\nu} + b\psi_\mu\psi_\nu.$$

$$\bar{g}^{\mu\nu} = \hat{g}^{\mu\nu} + \frac{B}{K}\hat{\nabla}^\mu\phi\hat{\nabla}^\nu\phi - \kappa\frac{\hat{\mu}}{\mu}BK\hat{T}^{\mu\nu}, \qquad K = 1 - B\hat{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi.$$

Here, $\hat{g}_{\mu\nu}$ is the matter metric that couples to the matter tensor $\hat{T}^{\mu\nu}$ and $g_{\mu\nu}$ is the the pseudo-Riemannian metric of gravity. The action is

$$S = S_{\rm grav} + S_\phi + \hat{S}_{\rm M}, \quad S_{\rm grav} = -\frac{1}{\kappa}\int d\mu(R[g] + 2\Lambda), \quad \kappa = 16\pi G/c^4 \quad d\mu = \sqrt{-g}\ d^4x$$

$$S_\phi = \frac{1}{\kappa}\int d\mu\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right], \quad \frac{\delta S_{\rm M}}{\delta\hat{g}_{\mu\nu}} = -\frac{1}{2}\hat{\mu}\hat{T}^{\mu} \quad \hat{\nabla}_\nu\left[\hat{\mu}\hat{T}^{\mu\nu}\right] = 0, \quad \mu = \sqrt{-g}$$

The double Minkowski light cone structure of the bimetric geometry is

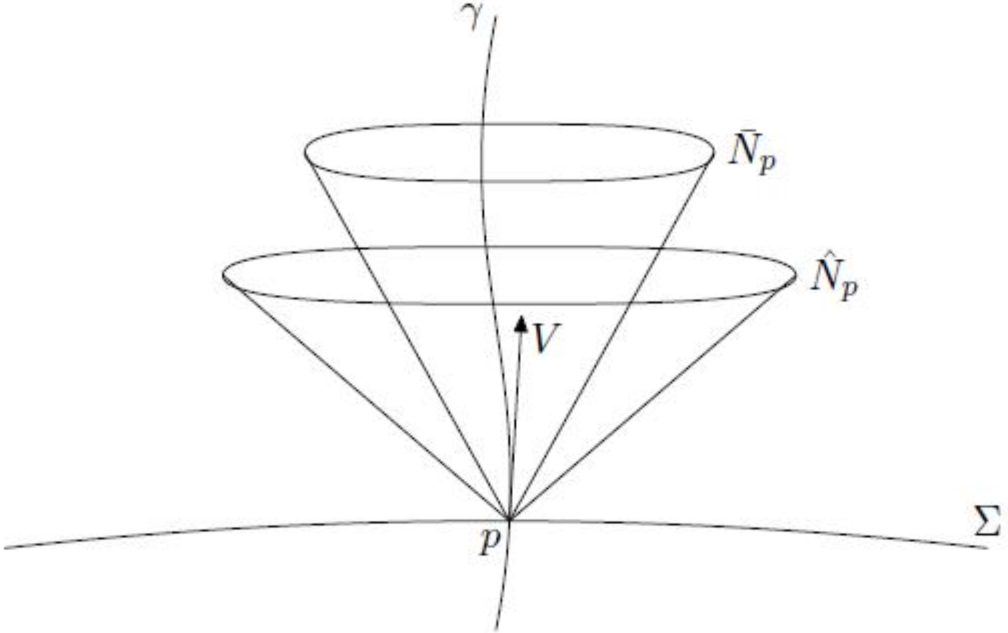

FIGURE 1. A timelike trajectory γ intersecting a spacelike hypersurface Σ at a point p. The cones $\hat{N}_p$ and $\bar{N}_p$ represent the null cones of $\hat{g}_{\mu\nu}$ and $\bar{g}_{\mu\nu}$, respectively. We have shown the case where $b > g$.

Bimetric quantum geometry

A bimetric quantum information communication model interprets $\hat{g}_{\mu\nu}$ as a microscopic quantum matter metric that can communicate quantum information with speed $v_{qm} > c$ (JWM, Int. J. Mod. Phys. D13, 75 (2004), arXiv:quant-ph/030206). The null cone attached to $g_{\mu\nu}$ continues to have v=c.

The amount of entanglement of a QM bipartite system is given by the density matrix of its von Neuman entropy. For a pure non-entangled state, the speed of transmitted signals travels with the classical SP value c. For entangled states, QM superluminal signals can travel in the quantum metric $q_{\mu\nu}$ light cone, providing a spacetime description of QM entanglement.

When the QM system suffers decoherence, it rapidly becomes a classical one with the single Minkowski light cone determined by $g_{\mu\nu}$.

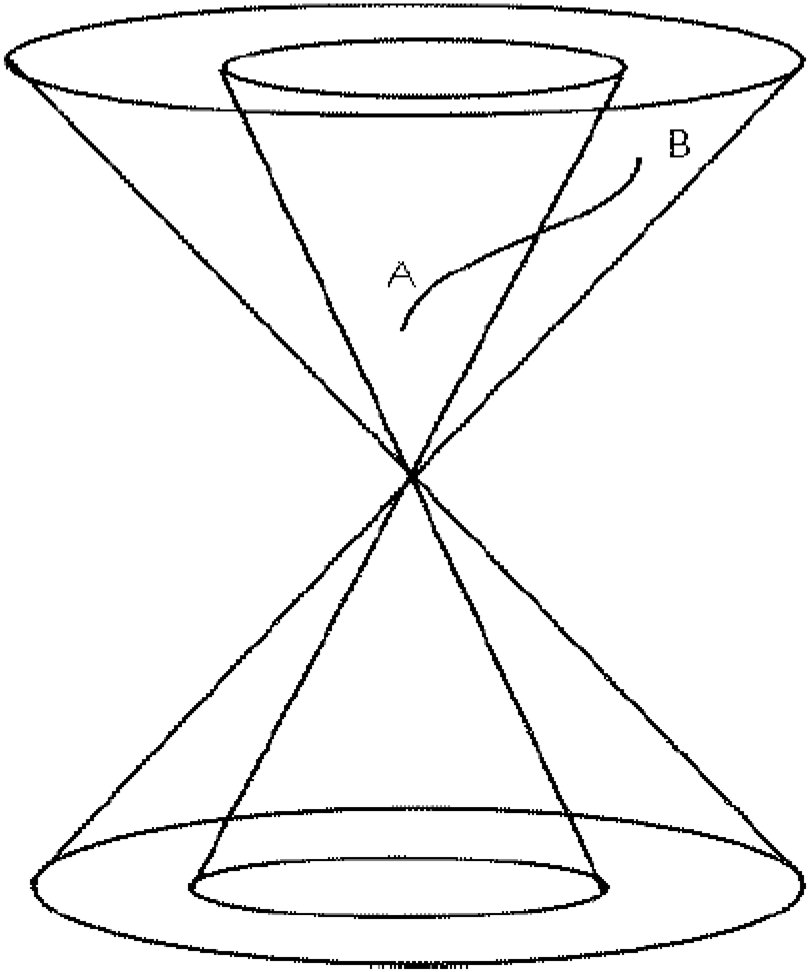

Fig. 1. Bimetric light cones showing the timelike communication path between the two entangled states at A and B in the quantum mechanical metric $\hat{g}_{\mu\nu}$.

The local SPR metric is given by

$$ds^2 \equiv \eta_{\mu\nu} dx^\mu dx^\nu = c_g^2 dt^2 - (dx^i)^2 \qquad \eta_{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$$

The metric is determined by ($s_{\mu\nu}$ = $\hat{g}_{\mu\nu}$):

$$s_{\mu\nu} = g_{\mu\nu} + \alpha q_{\mu\nu} \qquad d\hat{s}^2 \equiv \hat{g}_{\mu\nu} dx^\mu dx^\nu = (\eta_{\mu\nu} + \alpha \partial_\mu \phi \partial_\nu \phi) dx^\mu dx^\nu$$

$$d\hat{s}^2 = c_0^2 dt^2 \left(1 + \frac{\alpha}{c_0^2} \dot{\phi}^2\right) - (\delta_{ij} - \alpha \partial_i \phi \partial_j \phi) dx^i dx^j \quad (i, j = 1, 2, 3) \quad \dot{\phi} = d\phi/dt.$$

where c_0 = c. If we assume that $\partial_i \phi \approx 0$, then we get

$$c(t) = c_0 \left(1 + \frac{\alpha}{c_0^2} \dot{\phi}^2\right)^{1/2}.$$

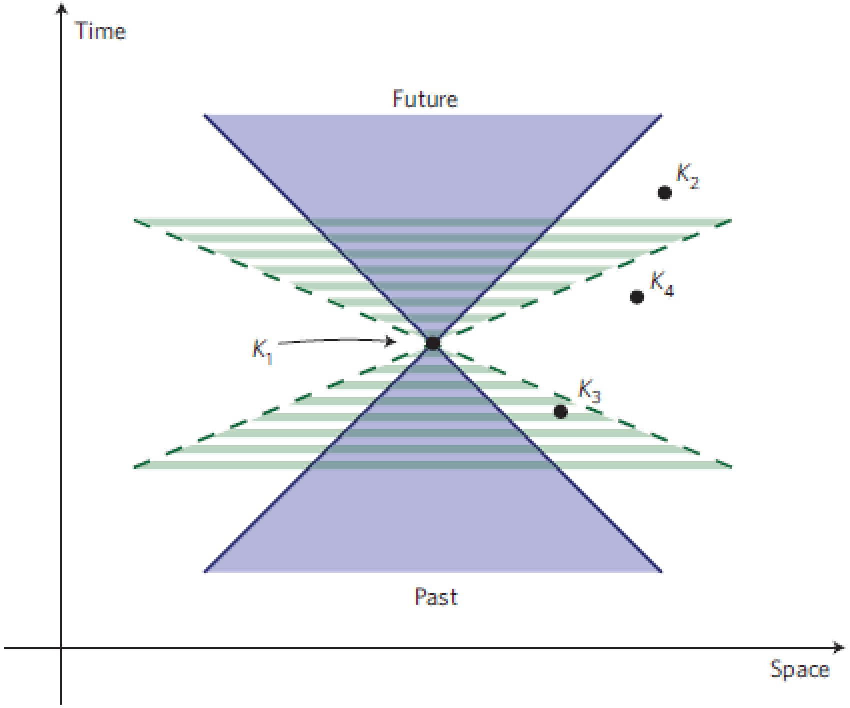

Figure 1 | Spacetime diagram in the privileged reference frame. In the (shaded) light cone delimited by solid lines, causal influences propagate up to the speed of light c, whereas in the v-cone (hatched region), causal influences travel up to the speed v. An event K_1 can causally influence a space-like separated event K_2 contained in its future v-cone and can be influenced by an event K_3 that lies in its past v-cone, but it cannot directly influence or be influenced by event K_4 outside its v-cone.

J-D. Bancal[1]*, S. Pironio[2], A. Acín[3,4], Y-C. Liang[1], V. Scarani[5,6] and N. Gisin[1]

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A local relativistic measurement of an entangled bipartite state is

$$S(\rho_m)(\sigma) = -\mathrm{Tr}_m \rho(\sigma) \log \rho(\sigma) \quad i\hbar c_0 \frac{\delta\psi(\sigma)}{\delta\sigma(x)} = \mathcal{H}_{\mathrm{int}}(x)\psi(\sigma)$$

Tomonaga-Schwinger equation. σ denotes a spacelike surface.

$S(\rho_m)(\sigma)$ is the relativistic entropy of the subsystems A and B. $\rho_A = \mathrm{Tr}_B|\psi\rangle\langle\psi|$ Is the reduced density matrix. In the nonrelativistic limit S reduces to the pure bipartite entropy measure of entanglement.

For non-entangled state $\psi(\sigma)$ can be expressed as a tensor product $\psi_A(\sigma) \otimes \psi_B(\sigma)$, $S(\rho_m)(\sigma) = 0$, $\hat{g}_{\mu\nu} = g_{\mu\nu}$ and no signal is transmitted between A and B .

For α = B ≠ 0 spacetime is described by the quantum metric:

$$d\hat{s}^2 \equiv \hat{g}_{\mu\nu} dx^\mu dx^\nu = (\eta_{\mu\nu} + \alpha\partial_\mu\phi\partial_\nu\phi) dx^\mu dx^\nu \ .$$

It is now possible to transmit signals at “superluminal” speeds.

Four Partite Experiments

Gisin and collaborators have considered 4 party experiments to check whether a "v-causal" scenario can allow for non-hidden quantum communication.

They check that the inequality $S \leq 7$ can be violated with the 4 qubit system:

$$\begin{aligned} |\Psi\rangle \; = \; & \frac{17}{60}|0000\rangle + \frac{1}{3}\,|0011\rangle - \frac{1}{\sqrt{8}}|0101\rangle + \frac{1}{10}\,|0110\rangle \\ + \; & \frac{1}{4}|1000\rangle - \frac{1}{2}|1011\rangle - \frac{1}{3}|1101\rangle + \frac{1}{2}|1110\rangle \qquad (9) \end{aligned}$$

They find that hidden influences of any v-causal mechanism for quantum correlations can never remain hidden. It necessarily permits faster than light communication $v_c > c$.

In classical physics, information is communicated with v=c. Information affects events in the future light cone. Quantum information (QI) is communicated with $v=v_{QI}$. Consider the smallest light cone $ds^2 = 0$ with θ_{QI} the angle of the cone to the vertical. Then $v_{QI} = 0$ corresponds to $\theta_{QI} = 0$, $\theta_{QI} = c$ to $\theta_{QI} = \pi/4$, and $v_{QI} = \infty$ to $\theta_{QI} = \pi/2$ (R. Garisto, quant-phys/0212078). We can define an inverse speed

$$w_{QI} = \cot\theta_{QI} = \left(\frac{c_0}{v_{QI}}\right)$$

Then, $v_{QI} = c_0 = c$ and ∞ correspond to $w_{QI} = 1$ and 0, respectively. Now $0 \leq w_{QI} \leq 1$ is the quantum metric $q_{\mu\nu}$ light cone swept out by the time dependence of c = c(t) for $B = \alpha \neq 0$.

The quantum metric $q_{\mu\nu}$ light cone is triggered by a measurement of a quantum system and allows the propagation of quantum information at superluminal speeds prohibited by the classical SPR light cone.

The case $\theta_{QI} = \pi/2$ only covers half of space so it is spatially incomplete. In principle we could have $\theta_{QI} > \pi/2$, then quantum entities could interact with others backwards in time, and for $\theta_{QI} > 3\pi/4$ quantum information can travel back through the past lightcone and $v_{QI} = -c$.

Lorentz invariance can be defined two ways: one-way and two-way signalling of light. Distance and time measurements are based on two-way signalling of light. Such measurements can then be used to measure one-way communication.

We can define an inverse speed:

W= (QI round trip time)/ (light round trip time)

We have for $v_{QI} = c$ Lorentz invariance and W=1.

“Hidden variable” models have been ruled out for v_{QI} = c. Morever, collapse of the wave function models with v_{QI} = c cannot exist, because they are intrinsically nonlocal.

Spatial completeness means that all information is present at every point in space. Classical mechanics is spatially incomplete, for it is local.

QM that is spatially incomplete would be local and quantum information would differ from point to point.

Relativistic QFT relies on being spatially complete (complete Hilbert space), so in this sense it is nonlocal.

Models with $c < v_{QI} < \infty$ are spatially incomplete and would require a preferred frame of reference. Their two-way signalling breaks Lorentz invariance, because in a frame moving with speed v with respect to the preferred frame , $W' = W(1 - v^2)/(1 - v^2W^2) \sim W(1 - v^2)$. For small $W = W_{QI}$ we can tell the difference between W' and W.

We have assumed for the above arguments that quantum information is stored in spacetime. But QM can be interpreted so that quantum information is outside spacetime. For the bimetric model all quantum information is stored in the "quantum metric" $q_{\mu\nu}$ and spacetime is physical as in classical SPR and GR.

Consider a 2-party system Alice and Bob. With measurement settings x and y and measurement results a and b, respectively. The conditional probability distribution p(a,b|x,y) is the probability of results a,b when the settings x,y are chosen. A pure common cause explanation of p(a,b|x,y) assumes additional variables labeled λ which we identify with our quantum matter field ϕ.

$$p(a,b|x,y) = \sum_{\lambda} \rho(\lambda) p(a|x,\lambda) p(b|y,\lambda)$$

where $\rho(\lambda)$ denotes the probability that the variable has the value λ = ϕ. In a v-causal model, the quantum information carried by ϕ propagates continuously from a common past of Alice and Bob (N. Gisin, arXiv: 1210.7308). Here the quantum information is communicated in the wider open light cone of the quantum metric $q_{\mu\nu}$.

A bimetric explanation of p(a,b|x,y) combines the local field ϕ propagating at speeds $v_c > c$ in the quantum metric $q_{\mu\nu}$ lightcone.

3. Satellite Experiment to Test Quantum Information v > c Communication (JWM et al. Class. Quantum Grav. 29, 2401 (2012), arXiv:1206.4949).

settings.

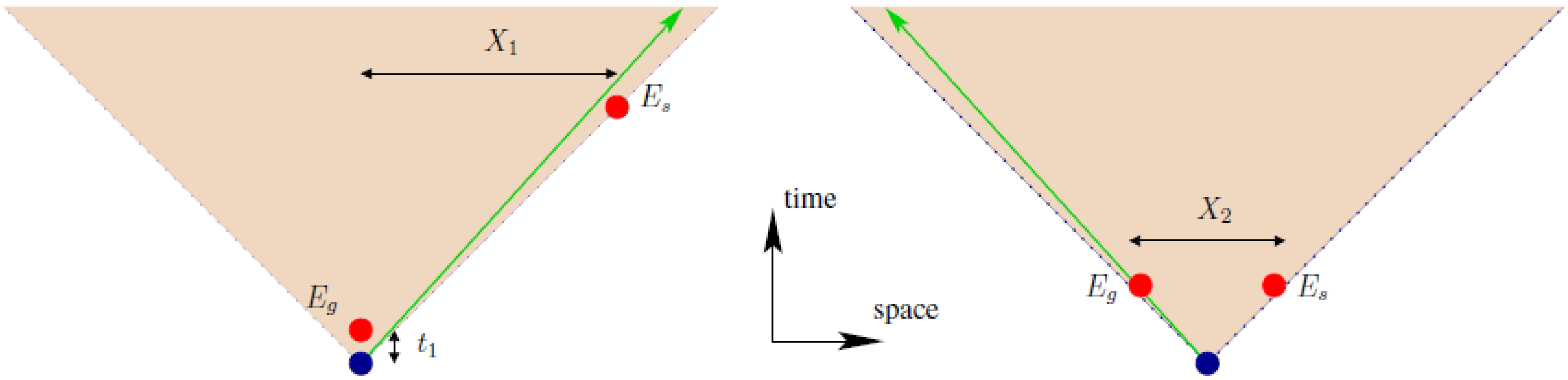
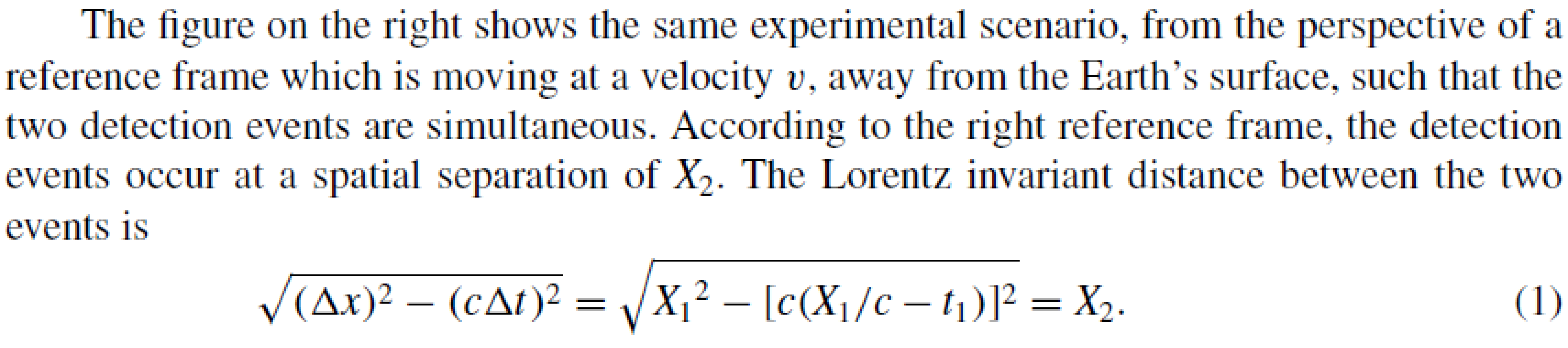


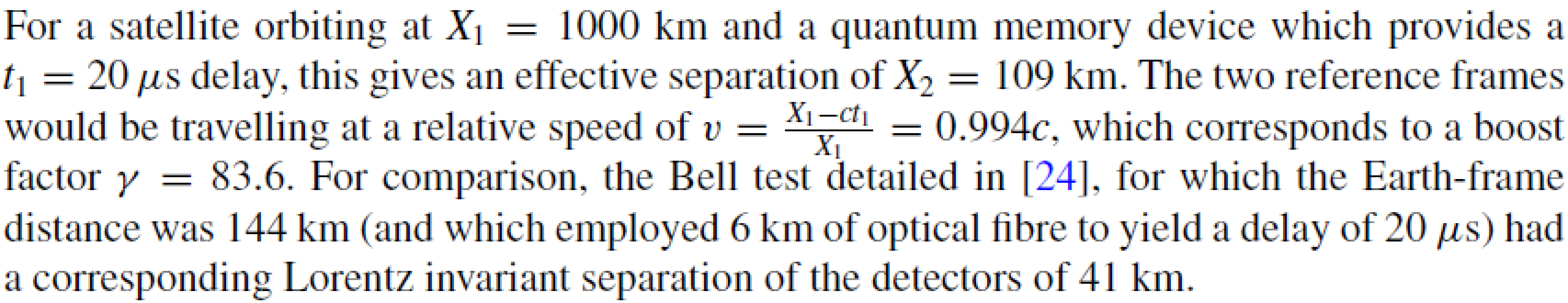
Figure 3. Effective distance between receivers in an asymmetric Bell experiment. Left: spacetime diagram of the experiment in Alice's frame, with two measurement events E_g and E_s on the ground (Alice) and on a satellite (Bob) respectively. Right: spacetime diagram from perspective of reference frame in which the measurement events E_g and E_s are simultaneous. The effective spatial separation of the measurement events X_2 is much smaller than the altitude of the orbiting satellite. In each case the green arrow indicates the velocity of the other frame.

Figure illustrates an “asymmetric” Bell test experiment. Figure on left is Alice’s frame, ground station with entangled photon. Emission is coloured blue and reception events are red dots, E_G (Alice) a short time t_1 after the emission event, and E_s occurring later on an orbiting satellite (Bob) at altitude X_1 above ground level.



The figure on the right shows the same experimental scenario, from the perspective of a reference frame which is moving at a velocity v, away from the Earth’s surface, such that the two detection events are simultaneous. According to the right reference frame, the detection events occur at a spatial separation of X_2. The Lorentz invariant distance between the two events is

$$\sqrt{(\Delta x)^2 - (c\Delta t)^2} = \sqrt{X_1{}^2 - [c(X_1/c - t_1)]^2} = X_2. \qquad (1)$$



For a satellite orbiting at $X_1 = 1000$ km and a quantum memory device which provides a $t_1 = 20\ \mu$s delay, this gives an effective separation of $X_2 = 109$ km. The two reference frames would be travelling at a relative speed of $v = \frac{X_1 - ct_1}{X_1} = 0.994c$, which corresponds to a boost factor $\gamma = 83.6$. For comparison, the Bell test detailed in [24], for which the Earth-frame distance was 144 km (and which employed 6 km of optical fibre to yield a delay of 20 μs) had a corresponding Lorentz invariant separation of the detectors of 41 km.

Any Bell Test of $v_c > c$ can only provide a Lower Bound on v_c

The two entanglement measurement events at Eg and Es will be causally related by the quantum $q_{\mu\nu}$ metric, if quantum correlations are observed. It is possible by changing the delay on the ground, or by changing the distance to the satellite in an eccentric orbit, the measurement events may cease to be in causal contact, according to the quantum metric, in which case the quantum correlations will be decreased or vanish.

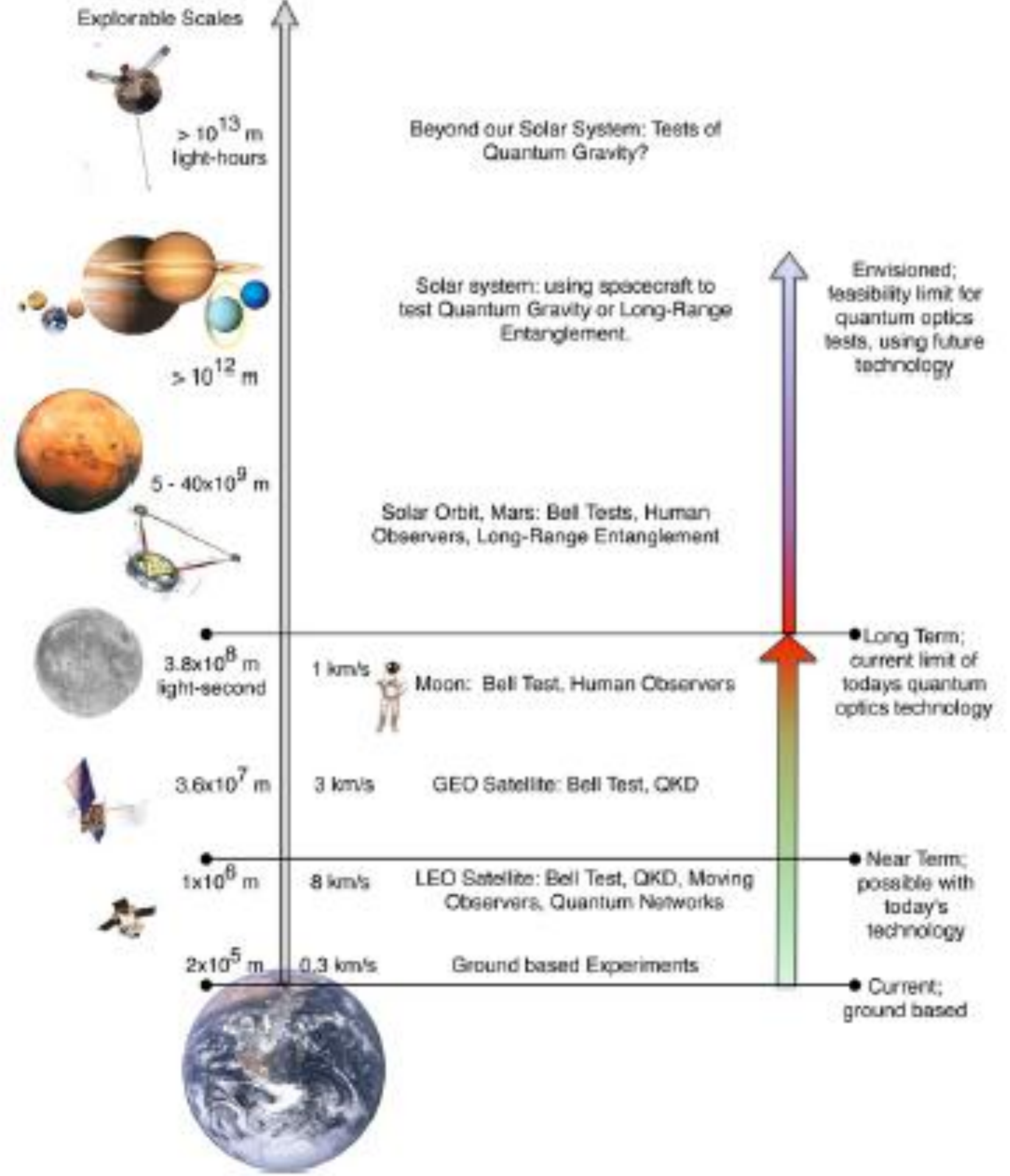


Figure 1. Overview of the distance and velocity scales achievable in a space environment explorable with man-made systems, with some possible quantum optics experiments at each given distance.

4. Summary

Can the weird features of quantum entanglement be explained in a way that can be understood with relativity, spacetime and quantum mechanics?

Gisin and his collaborators (2012) have demonstrated that in 4 partite scenarios, faster than light influences cannot remain hidden but necessarily lead to faster than light communication.

This requires a change in our understanding of relativity. Either QM is strictly nonlocal or relativity and possibly QM must be modified.

Bimetric gravity and bimetric quantum communication may provide a theoretical model for modifying relativity, so that quantum entanglement is explained in a logical way without violating locality and continuous propagation of quantum information.

Bimetric qeometry may lead to a violation of local Lorentz invariance when faster than light communication is invoked in quantum entanglement.

The planned satellite experiment can test the Bell inequalities and the strength of quantum correlations over significantly larger distances. Hopefully, the experiment will provide new understanding of the fundamental nature of quantum mechanics and spacetime.

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