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Article

Two Dark Clouds on the Space-Time Horizon

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Abstract: (i) Investigations of stellar systems known as wide binaries suggest that Newton's law of gravitation breaks down at low accelerations. This can be explained by proposing a fifth force with $U(1)$ gauge symmetry, whose corresponding gauge boson is the sought for dark matter candidate. (ii) Relativistic causality (i.e. no faster than light signalling) permits nonlocal correlations stronger than those permitted by quantum mechanics. This can be explained if our universe possesses a second 4D spacetime with a signature opposite to ours. (iii) Such a fifth force, and a second spacetime, arise naturally in a recently proposed theory of unification based on an $E_8 \times E_8$ symmetry. Our spacetime arises from breaking of an $SU(2)_R \times U(1)_{YDEM}$ symmetry, and the second spacetime arises from broken electroweak symmetry.

Keywords: gravitation; wide binaries; modified Newonian dynamics; dark matter; supraquantum nonlocal correlations; Bell's inequalities; CHSH inequality; fifth force; unification; quantum nonlocality; Popescu-Rohrlich bound

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1. Gaia DR3 Wide Binaries

Over the last ten years, the Gaia mission [1] has been producing an extraordinarily precise 3D map of stars in the Milky way. This includes mapping their motions, luminosity, temperature and composition. This has helped determine distances to these stars and hence create a data base of their positions and velocities. The third data release of Gaia took place in June, 2022, and it has in particular produced a precious data base of star systems known as wide binaries, in a 200 pc neighbourhood around the solar system. Wide binaries are stellar binaries in which the mean separation of the two stars lies approximately in the range 200 AU to $20,000$ AU (note $20,000$ AU ~ 0.1 pc). These systems are of great theoretical interest because in a statistical analysis of binary orbits over this distance range one can test whether Newton's law of gravitation is being obeyed or not. What is especially significant is that for a binary with an orbital radius of about 2,000 AU, the orbital acceleration is around $a_c \sim 10^{-10}$ cms^{-2}, and it falls below a_c for binaries with larger orbital radii. This a_c happens to be the typical acceleration below which galaxy rotation curves begin to flatten out. For galaxies, the favoured explanation for this non-Keplerian flattening is that there is an enormous invisible halo of dark matter whose gravity speeds up stars in the outer reaches of the galaxy. However, in case an anomaly were to be found, this same explanation via dark matter will not work for wide binaries with separation greater than 2,000 AU, because there simply isn't enough dark matter on this scale in the galaxy. Therefore, it is of great interest to know if the wider ones amongst wide binaries have orbital accelerations which disagree with the Newtonian prediction. If the dark matter hypothesis is correct then there should be an excellent agreement between the observed acceleration and the Newtonian prediction for all separations, including larger than 2,000 AU. Hence, wide binaries are a great discriminator between the dark matter hypothesis and the less popular idea that Newtonian gravitation breaks down when the galactic rotation curve turns flat.

There are enormous challenges in testing the law of gravitation using a single binary star pair. Mass of each star in the binary has to be accurately determined using the mass-luminosity relation. The determination of relative velocity in a single pair is complicated by lack of direct knowledge of the orbit's inclination and eccentricity. Possible presence of an unresolved tertiary, as well as tidal perturbations, further complicate the analysis. Hence, statistical estimates of these parameters must be resorted

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to, by analysing a sample of thousands of wide binaries. Eventually, one examines the distribution of relative velocities to test if there is an excess high velocity tail over the Newtonian prediction.

Over a series of papers and analyses of thousands of wide binaries, two independent groups of researchers, Hernandez et al. [2–4], and Chae [5,6], have broadly come to the following conclusions. For separations R smaller than about 2,000 AU (i.e. accelerations larger than a_c), the orbit obeys Newtonian gravitation. However, for separations larger than about 3,000 AU a clear and systematic departure from the Newtonian prediction is observed. The orbits continue to be Keplerian (i.e. $v \propto R^{-1/2}$) but with an effective gravitational constant of $(1.5 \pm 0.2)G$ instead of G. The Keplerian nature of the orbit is expected because of the dominance of the so-called external field effect (the mean gravitational pull of the Milky Way as felt by the wide binary as a whole). However the inference of an enhanced effective value $1.5G$ is unexpected and signals breakdown of Newtonian gravitation and hence also of general relativity.

Pittordis and Sutherland [7], and Banik et al. [8] come to essentially the opposite conclusion, from their study of Gaia data, and report that there is no departure from the Newtonian prediction. Hernandez and Chae [9] reject Banik et al's conclusions in their response written in December, 2023. In a fresh analysis in a February, 2024 paper Chae [10] addresses the data quality issues raised by Banik et al. and reaffirms his earlier results. This is how things stand at present, and in the assessment of the present author, there is strong evidence for breakdown of Newtonian gravitation and hence of general relativity (GR). It is significant that this breakdown is found to happen at the same acceleration a_c that is picked out by galaxy rotation curves. The reader is also invited to listen to the elegant OSMU24 lecture given by Hernandez on this subject, on March 29, 2024 [11]. Data from the forthcoming Gaia runs DR4 and DR5 should further help ascertain present results.

What does this imply for fundamental theoretical physics? Does it mark the end of the dark matter idea? Not quite. One of the goals of the present essay is to explain that the breakdown of Newtonian gravitation and of GR does not imply end of the dark matter hypothesis. On the contrary, the breakdown signals that there is a (long range) fifth force felt by ordinary (electrically neutral) matter, which dominates gravitation only at accelerations below a_c. This fifth force must be described by a gauge symmetry, which results from symmetry breaking of a unified interaction in the early universe. This new force must mimic cold dark matter on cosmological scales. The (massless) gauge bosons corresponding to this gauge field are the sought for dark matter. They make their presence felt in galaxies and in wide binaries, not via their particulate nature, but by their classical counterpart - this latter being a Coulomb-like condensate mean field. An analogy will be helpful: gravitons are quanta of gravitation, but the entity that holds stars together in a galaxy is not gravitons per se, but the classical gravitational Coulomb-like inverse square field resulting as a 'graviton condensate'. Much the same way that massless photons are quanta of the electromagnetic field, and yet we have physically realistic classical Coulomb forces between electrically charged particles. In our own research, we have discovered a new $U(1)$ gauge symmetry, which we dubbed dark electromagnetism $U(1)_{DEM}$. The source charge for this new force is square root of mass $\sqrt{m}$, and its quantum is the so-called massless dark photon. This is the dark matter to look for in the laboratory, instead of the elusive weakly interacting massive particle. Dark matter exists, but we have been looking for it in the wrong place. We now explain how this $U(1)_{DEM}$ force arises naturally in our unification program, and it also explains the observed gravitational anomalies in cosmology, galaxies, and also wide binaries. This fifth force mimics cold dark matter on cosmological scales, and mimics Milgrom's MOND on galactic and on wide binary scales when accelerations fall below a_c. These results were recently reported in our paper Finster et al. [12].

We have recently proposed a unification of interactions, motivated by search for a reformulation of quantum field theory which does not depend on a classical time parameter [13,14]. The theory is a matrix-valued relativistic Lagrangian dynamics on a noncommutative underlying space labeled by quaternions/octonions. The trace-class Lagrangian of the theory possesses an $E_8 \times E_8$ symmetry which after symmetry breaking at the electroweak scale gives rise to six forces, i.e. two new ones in addition to the four already known. The proposed branching of $E_8 \times E_8$ gives rise to the electroweak sector $SU(2)_L \times U(1)_Y$ which spontaneously breaks via the Higgs mechanism to $U(1)_{\text{em}}$ and also gives rise to the short-range weak force. There also arises the right-handed counterpart $SU(2)_R \times U(1)_{YDEM}$ which we name darkelectro-grav, because symmetry breaking, by a second Higgs, turns this into classical general relativity, and the unbroken dark electromagnetism $U(1)_{DEM}$. The other two forces that arise are $SU(3)_{\text{color}}$ describing QCD, and its newly predicted (likely short range and extremely weak) counterpart $SU(3)_{\text{grav}}$. The only fundamental fermions which arise are the already known three generations of standard model fermions, in addition to three types of right handed sterile neutrinos. All the $(248 + 248 = 496)$ degrees of freedom (d.o.f.) of $E_8 \times E_8$ are accounted for: the two Higgs are composites which account for $(144 + 144)$ d.o.f. The fermions account for another $144 = (96 + 96/2)$ and the bosons (and spacetime d.o.f.) account for $(64 = 32 + 32)$ [13].

The $U(1)_{DEM}$, which has the desired properties of the dark matter fluid, is sourced by square-root of mass $\pm\sqrt{m}$. The plus sign is for matter and minus sign for anti-matter. Like signs attract and opposite signs repel, under the dark electromagnetic force. Our universe, being matter dominated as opposed to anti-matter dominated, largely has only $+\sqrt{m}$ particles. Thus for all practical purposes, dark electromagnetism in our universe is an attractive only force, unlike ordinary electromagnetism.

The motivation for introducing the charge $\pm\sqrt{m}$ is the experimental fact that the square roots of the masses of the electron, up quark, down quark are in the ratio $(1/3, 2/3, 1)$. This should be contrasted with their electric charge ratios $(1, 2/3, 1/3)$ which remarkably happen to be the same across all three generations whereas the mass ratios for the second and third generation show no obvious pattern. In order to be able to explain this puzzle, we proposed $\pm\sqrt{m}$ as the charge for $U(1)_{DEM}$ (for all three generations) and interchanged the relative position of the right handed electron and right handed down quark (as also those of their heavier counterparts) in their color assignment for $SU(3)_{\text{grav}}$. The electron is a triplet of $SU(3)_{\text{grav}}$ and the down quark is a singlet. This enabled us to theoretically derive the strange mass ratios for the second and third generation [15], and in an analogous derivation, also the parameters in the CKM quark mixing matrix [16].

The remarkable property of the $U(1)_{DEM}$ force is that it is proportional to square-root of mass, not to mass. Every massive particle experiences this force due to another massive particle, but unlike in general relativity where the gravitational field is generated by the energy-momentum tensor, dark electromagnetism (DEM) is generated by the current $\sqrt{m}u^i$ of square-root mass. Massless particles such as the photon and the dark photon do not experience DEM, whereas the dark photon mediates it (Abelian symmetry). $U(1)_{DEM}$ is a relativistic theory like Maxwell's electrodynamics is, and it has a non-relativistic Coulomb limit which falls as inverse square of an effective distance R_{eff}, where $R_{\text{eff}}^2 = RR_H$ with R_H being the cosmological Hubble radius. Consequently for today's universe, we can compare Newtonian gravitation and the DEM force between two masses as [12]

$$F_{\text{grav}} = -G\frac{m_1 m_2}{R^2}, \qquad F_{DEM} = -A\frac{\sqrt{m_1}\sqrt{m_2}}{R} \tag{1}$$

Both are attractive forces, and the Hubble parameter H_0 for today's universe has been absorbed in the coupling constant A of DEM. This coupling constant A was shown, from first principles, to be such that DEM dominates over Newtonian gravitation at very low accelerations, and the cross-over point coincides with the critical acceleration a_c. Clearly, we see that DEM has the required MONDian behaviour - acceleration is proportional to square-root mass and falls inversely with distance, which is what produces flat galaxy rotation curves and explains the Tully-Fisher relation as well. We also showed that on cosmological scales, the potential energy of the relativistic DEM field mimics the gravitational effect of cold dark matter. The MONDian fall off also explains the dynamics being observed in wide binary orbits for separations larger than 3,000 AU.

Modified gravity vs. dark matter is not an either-or situation. Rather, the dark photon, being the quantum of dark electromagnetism and hence the sought for dark matter, gives rise to a classical MONDian modification of general relativity. Dark matter is there, and it mimics relativistic MOND.

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Laboratory searches should now be geared towards looking for the massless dark photon. For one recent proposal in this direction see [17].

Our proposal is that $U(1)_{DEM}$ is the left-over unbroken symmetry from $SU(2)_R \times U(1)_{YDEM}$, when the universe makes a transition from the deSitter phase to the present Friedmann cosmology phase at the epoch of electroweak symmetry breaking. It is very encouraging that our conclusion is identical to what Milgrom has to say [18] about the MOND-deSitter connection: "...one may conjecture that the MOND-cosmology connection is such that local gravitational physics would take exactly the deep-MOND form in an exact de Sitter universe. This is based on the equality of the symmetry groups of dS^4 and of the MOND limit of the Bekenstein-Milgrom formulation [19], both groups being $SO(4,1)$. The fact that today we see locally a departure from the exact MOND-limit physics – i.e. that the interpolating functions have the form they have, and that a_c is finite and serves as a transition acceleration – stems from the departure of our actual space-time from exact dS^4 geometry: The broken symmetry of our space-time is thus echoed in the broken symmetry of local physics." This further reinforces our view that $U(1)_{DEM}$ is the theoretical origin of (relativistic) MOND, and is a left-over unbroken symmetry from $SU(2)_R \times U(1)_{YDEM}$, with the broken $SU(2)_R$ becoming the GR-dominated near zone.

We also note that the generalisation of general relativity to an $SU(2)_R \times U(1)_{YDEM}$ gauge theory gives us a renormalisable quantum theory of gravity, for the same reason that the electroweak gauge theory is renormalisable. And general relativity is not renormalisable for the same reason for which the four-point weak interaction theory is not: both are low energy broken symmetry theories with dimensionful coupling constants.

2. Supra-Quantum Nonlocal Correlations

Bell's theorem implies that quantum mechanics is incompatible with local hidden variable theories. Bell's inequality is the statement that if measurements are performed independently on two space-like separated particles of an entangled pair, the assumption that outcomes depend on hidden variables implies an upper bound on the correlations between the outcomes. Quantum mechanics predicts correlations which violate this upper bound. The Clauser-Horne-Shimony-Holt (CHSH) inequality [20] is a specific Bell inequality in which classical correlations (i.e. local hidden variables exist) can take the maximum value of 2. Quantum mechanics violates this bound, allowing for a higher bound on the correlation, which can take the maximum value $2\sqrt{2}$, and is known as the Tsirelson bound [21]. In an important work, Popescu and Rohrlich [22] showed that the assumption of relativistic causality (i.e. no faster than light signalling permitted) allows for an even higher bound on the CHSH correlation, this value being 4.

Why is the bound coming from causality higher than the Tsirelson bound? In a recent paper we showed that there are relativistic causal dynamical theories which violate the Tsirelson bound. We showed [23] that the pre-quantum theory of trace dynamics [24] (on which our $E_8 \times E_8$ unification is based, and from which quantum theory is emergent as a thermodynamic approximation) permits the CHSH correlation to take values higher than $2\sqrt{2}$. We interpreted our findings to suggest that quantum theory is approximate, and emergent from the more general theory of trace dynamics. Experimental detection of a correlation larger than $2\sqrt{2}$ will be of significance no less than what the wide binaries are telling us.

There is also the famous EPR paradox, as to how quantum mechanics manages to violate Einstein separability, while obeying relativistic causality. That is, given a correlated system, measurement on one particle in the entangled pair results in a measurable influence on the other particle in the pair, even though the second particle is outside the light cone of the first one. We now demonstrate that, as a consequence of the above-discussed $SU(2)_L \times U(1)_Y$ and $SU(2)_R \times U(1)_{YDEM}$ symmetries, Einstein separability is *not* violated in this process. Quantum theory and special relativity are entirely consistent with each other, because our universe possesses a second 4D spacetime with flipped signature and flipped light-cone: events that are spacelike separated in our spacetime are in fact timelike separated

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in the flipped 4D spacetime. We show that this second spacetime, along with the first, also enables quantum correlations to beat the Tsirelson bound, and to reach the Popescu-Rohrlich value of 4.

Let us begin by recalling the quantitative form of the CHSH inequality. Consider a physical system S with two subsystems S_1 and S_2 that are space-like separated. A, B, A', B' are physical observables which take values 1 or -1, with A, A' being measured in S_1 and B, B' being measured in S_2. Let $P_{AB}(a,b)$ denote the probability of getting the result $A = a$ and $B = b$ when A and B are measured. Then the correlation $E(A,B)$ is defined as follows:

$$E(A,B) = P_{AB}(1,1) + P_{AB}(-1,-1) - P_{AB}(1,-1) - P_{AB}(-1,1) \quad (2)$$

The CHSH correlation F is defined as the expression

$$F = E(A,B) + E(A',B) + E(A,B') - E(A',B') \quad (3)$$

In a classical theory, i.e. one that admits local hidden variables, the CHSH correlation is bounded as $|F| \leq 2$.

Now consider what restrictions does the condition of relativistic causality (no faster than light signalling) impose on joint probabilities and hence on F. If the observer S_1 measures the observable A, then the probability of A taking the values 1 or -1 is independent of whether S_2 measures B or B'. It can hence be shown that F can take the maximum value 4; each of the four correlations in the expression for F can be as large as 1 or as small as -1.

For a quantum system in a pure state ψ, the correlation $E(A,B)$ is given by the expectation value $E(A,B) = \langle\psi|AB|\psi\rangle$ where A and B are self-adjoint operators for the corresponding physical observables. Given this, can F_{quantum} take the maximum value of 4 allowed by relativistic causality? The answer is a surprising no! The maximum allowed value for F in quantum mechanics is $2\sqrt{2}$, the Tsirelson bound. To see this note that the operators satisfy $A^2 = B^2 = A'^2 = B'^2 = I$ and one can write

$$F^2 = \langle 4I - [A,A'][B,B'] \rangle \quad (4)$$

In the classical case, $[A,A'] = 0$ or $[B,B'] = 0$ giving that $|F| \leq 2$ as we have seen above. In the quantum mechanical case note that

$$||[A,A']|| \leq 2\,||A||\,||A'|| \leq 2, \quad ||[B,B']|| \leq 2\,||B||\,||B'|| \leq 2 \implies F^2 \leq 8 \implies |F| \leq 2\sqrt{2} \quad (5)$$

Hence the Tsirelson bound, which falls short of the Popescu-Rohrlich bound. Supra-quantum correlations ($F > 2\sqrt{2}$) are not permitted in quantum mechanics. Why this deep discord between special relativity and quantum mechanics? It is in league with the discord presented by the EPR paradox, and the resolution of both the discords is the same: the existence of a hitherto un-noticed second 4D space-time in our universe.

To visualise what we propose, consider a 2-torus $S^1 \times S^1$ and a path MN joining two points M and N on the first circle, having a radius R_1 larger than the radius R_2 of the second circle. Let MN' be a path shorter than MN and joining two points M and N' on the shorter circle. Now, and this is the key point, identify N and N' as identical entities in the physical universe. An observer in our universe (the circle R_1) is unaware of the existence of the circle R_2 (this being the second spacetime, accessible only to entangled quantum systems). When a quantum measurement is made by observer S_1 at point M, the influence travels independently through both the paths but arrives at $N = N'$ faster through the shorter path. In our spacetime (the larger circle) this looks like a non-local influence whereas it is perfectly local through the other spacetime (the shorter path). Einstein separability is preserved, along with relativistic causality.

Now, in our universe, let the observer S_1 be at the 4D spacetime point $(0,0,0,0)$ and S_2 be at (t,x,y,z) with t a timelike coordinate and (x,y,z) spacelike. As we will justify below, both S_1 and S_2 are also in a flipped second 4D spacetime in which S_1 has coordinates $(0,0,0,0)$ and S_2 has

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coordinates (t', x', y', z') with (x', y', z') timelike and t spacelike. Events that are spacelike separated in our spacetime are timelike separated in the flipped spacetime, and vice versa.This is how a quantum influence that is apparently nonlocal in our spacetime is local through the flipped spacetime which has its own distinct lightcone. This is also how the EPR paradox is resolved. Special relativity does not preclude our universe possessing such a second spacetime - in the latter also the laws of special relativity are obeyed, with the roles of space and time reversed.

Remarkably, the second spacetime also easily explains the mystery of supra-quantum nonlocal correlations, and allows quantum mechanics to beat the Tsirelson bound and reach the Popescu-Rohrlich (PR) value of 4. To see this, note that in the quantum case we must rewrite the CHSH expression (3) as a sum of two expressions F_I and F_{II}, one for each 4D spacetime, because quantum communication is happening independently through both the spacetimes:

$$F = F_I + F_{II} \equiv \big(E(A,B) + E(A',B) + E(A,B') - E(A',B')\big)_I \\ + \big(E(A,B) + E(A',B) + E(A,B') - E(A',B')\big)_{II} \tag{6}$$

which gives

$$F^2 = \big\{\langle 4I - [A,A'][B,B'] \rangle\big\}_I + \big\{\langle 4I - [A,A'][B,B'] \rangle\big\}_{II} \implies F^2 \leq 8 + 8 \implies F \leq 4 \tag{7}$$

instead of $2\sqrt{2}$. Thus, the second 4D spacetime enables quantum mechanics to saturate the PR bound. However, as we explain below, in order to experimentally detect supra-quantum nonlocal correlations, one must probe the weak interaction length scale $\sim 10^{-17}$ cm and hence perform a Bell test around the electroweak scale of about 100 GeV. This might become possible at particle accelerators in the near future, as researchers are seriously discussing testing Bell's inequalities in accelerators [25].

What is the origin of this second 4D spacetime? In our $E_8 \times E_8$ unification theory, each E_8 branches as $E_8 \to SU(3)_{\rm ST} \times E_6$; and while the matter and field content is determined by the two copies of the exceptional group E_6, the two copies of $SU(3)_{\rm ST}$ between them determine the underlying spacetime. It is a 6D spacetime with $SO(3,3)$ symmetry [i.e. signature is 0; three timelike and three spacelike directions]. And it is characterised by the six imaginary directions of the complex split biquaternion (Clifford algebra $Cl(3)$; three vectors and three bivectors) as follows:

$$x_6 = it_1\hat{l} + it_2\hat{m} + it_3\hat{n} + x_1\hat{i} + x_2\hat{j} + x_3\hat{k} \tag{8}$$

where $i = \sqrt{-1}$. The magnitude of this vector is

$$|x_6|^2 = x_6\tilde{x}_6 = \tilde{x}_6 x_6 = -t_1^2 - t_2^2 - t_3^2 + x_1^2 + x_2^2 + x_3^2 \tag{9}$$

It describes a space-time interval in 6D spacetime with signature $(3,3)$ and having the symmetry group $SO(3,3)$. The Dirac operator D_6 is

$$D_6 = i\hat{l}\frac{\partial}{\partial t_1} + i\hat{m}\frac{\partial}{\partial t_2} + i\hat{n}\frac{\partial}{\partial t_3} + \hat{i}\frac{\partial}{\partial x_1} + \hat{j}\frac{\partial}{\partial x_2} + \hat{k}\frac{\partial}{\partial x_3} \tag{10}$$

and the square of D_6 gives the Klein-Gordon operator

$$D_6^2 = -\frac{\partial}{\partial t_1^2} - \frac{\partial}{\partial t_2^2} - \frac{\partial}{\partial t_3^2} + \frac{\partial}{\partial x_1^2} + \frac{\partial}{\partial x_2^2} + \frac{\partial}{\partial x_3^2} \tag{11}$$

This 6D spacetime splits into two copies of 4D spacetime with relatively flipped signatures [26]. Geometry of our spacetime is given by gravitation via the general theory of relativity $[SU(2)_R \times U(1)_{YDEM}]$. Whereas the geometry of the second 4D spacetime is given by the weak force $[SU(2)_L \times U(1)_Y]$. The weak force is left-handed gravity: it is a spacetime symmetry masquerading as an internal symmetry! This helps understand why weak force violates parity; so should gravitation [27]. The two

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4D spacetimes share one time and one space direction. In other words, the two additional dimensions beyond 4D are timelike, not spatial. Experiments needed to probe the second spacetime will have to be at the weak interaction length scale 10^{-17} cm.

3. The Road Ahead

Wide binaries and supra-quantum nonlocal correlations are two dark clouds on the spacetime horizon. They are indicating that our present understanding of gravitation and of spacetime structure is incomplete. We might need to generalise general relativity, and have a fifth force to understand wide binary dynamics and other gravitational anomalies. Supra-quantum nonlocal correlations, along with the weak force, are a possible indicator that our universe possesses a second flipped 4D spacetime with its own distinct light-cone. This also helps get rid of the infamous quantum nonlocality puzzle. These predictions arise naturally from our $E_8 \times E_8$ unification and will be tested by experiments in the near future.

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