Multi-fold Discrete Fractal Spacetime, and the Viability of Local vs. Non-Local Hidden Variables

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Abstract

The multi-fold original paper, in its spacetime reconstruction phase, attributes spacetime to the locations concretized by the random walks, and creation, of (massless) particles, resulting into a discrete, (multi-)fractal spacetime that is non-commutative and yet Lorentz symmetric. The fractal or multi-fractal was inferred from the random walks, but it was actually the only part not explicitly derived. Multi-fold universe are expected to probably have a Cantor-like $\mathcal{E}$-infinity fractal spacetime.

In this paper, we resume these discussions, but now, we provide microscopic interpretations for spatial and temporal, and so spacetime, (multi-) fractal properties of the multi-fold universe, and their observability, only within a range of cosmological scales, as observed in our real universe. We also relate discreteness of spacetime to the complex scalar field of the Higgs boson, and encounter further corroboration of the fundamental role of the massless Higgs boson.

Fractal state space plays a role in interpreting experiments about the Bell theorem, and related hidden variables. The paper discusses two models, which do not imply that the result of Bell experiments would forbid local hidden variables. The Bell Theorem, and handling of EPR entanglements, was the motivation for proposing the multi-fold mechanisms, which implement non-locality with local Physics. Interestingly, with discrete spacetime, the multi-fold W-type hypothesis, massless Higgs boson random walks, and fractal properties, multi-fold universes can support all these models: local physics and hidden variables seem to be reconcilable with the Bell experiments, as was the original intent for the multi-fold theory. And there is no need to give in to super determinism, retro-causality, or to lose free will.

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1. Introduction

In a multi-fold universe [1,8-10,22], gravity emerges from Entanglement through the multi-fold mechanisms. As a result, gravity-like effects appear in between entangled particles ,that they be real or virtual. Long range, massless gravity results from entanglement of massless virtual particles. Entanglement of massive virtual particles leads to massive gravity contributions at very smalls scales. Multi-folds mechanisms also result into a spacetime that is discrete, with a 2D random walk fractal structure, and non-commutative geometry that is Lorentz invariant, and where spacetime nodes and particles can be modeled with microscopic black holes. All these recover General Relativity (GR) at large scales, and semi-classical model remain valid till smaller scale than usually expected. Gravity can therefore be added to the Standard Model (SM) resulting into what we define as SM_G.: the SM with gravity effects non-negligible at its scales. This can contribute to resolving several open issues with the SM and Standard Cosmological model, without new Physics other than adding gravity effects, now no more negligible [1,4-23,61-72,75,78,100,102-160,*162-201*].

Note added on December 9, 2023: References in italic are references added on December 9, 2023.

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Among the multi-fold SM_G discoveries, the apparition of an-always in-flight, and hence non-interacting, right-handed neutrinos, coupled to the Higgs boson is quite notable. The Higgs boson is supposedly always around the right-handed neutrino and its anti-particle, as an isospin doublet [67]. The right-handed neutrino existence results from chirality flips by gravity of the massless Weyl fermions, induced by 7D space time matter and scattering models, and it is hidden behind the Higgs boson or field at the entry points and exit points of the multi-folds [1,40,71,72,120]. Massless Higgs bosons modeled as minimal microscopic black holes mark concretized spacetime location. They can condensate into Dirac Kerr-Newman soliton Qballs to produce massive and charged particles [63,121-123,131,*164,201*]. The Qballs symmetry are induced form the 7D embedding space. Above the energies of the gravity electroweak symmetry breaking, massless particles result from the random walk patterns of the massless Higgs bosons. These patterns are induced also from 7D embedding space. As such the massless Higgs bosons provide a microscopic explanation for a Higgs driven inflation [1,61,64], the gravity electroweak symmetry breaking [67], the Higgs mechanism [4,67], the mass acquisition [1,4,67,*194*], and the chirality of fermions and spacetime [1,4,63,121-124,131,*164*]; all resulting from the multi-fold gravity electroweak symmetry breaking, with the massless Higgs boson. The multi-fold theory has also concrete implications on New Physics like supersymmetry, superstrings, M-theory and Loop Quantum Gravity (LQG) [1,8-21,*188,199*].

Multi-folds are encountered in GR at Planck scales [5,6] and in Quantum Mechanics[2] (QM) if different suitable quantum reference frames (QRFs) are to be equivalent relatively to entangled, coherent or correlated systems [7]. GR, QFT and the SM [1,129,158,*180,190*], superstrings, M-Theory, AdS/CFT correspondence conjecture, and LQG [1,6,12-21,69,129,141,142,148,*188*] are all encountered by the multi-fold theory, or encounter hints of multi-folds. It shows that GR and QM are different facets of something that they cannot well model: multi-folds.

In section 2, the paper starts by discussing how random walk implies a fractal, or multi-fractal spacetime and how it relates to the space, time and spacetime fractional Schrödinger equations. In section 3, we apply this knowledge to the multi-fold universe to justify what its spacetime is fractal, in a range of cosmic scales, and explain the corresponding astronomical multi-fractal observations. Considerations on the massless Higgs boson are key aspect. It's complex field is argued to be a sign of a discrete spacetime.

In section 4, we discuss how the Bell and CHSH inequalities are considered to imply no local hidden variables, and then rely on different works in the literature on cellular automata, which relate to random walks and discrete spacetime, and on fractal spacetime to show that there are loopholes to these assumptions and that it is possible to have hidden variable despite the experimental confirmation of these inequalities.

We explain that achieving non-locality with locality was expected with the approach taken when introducing the Multi-fold theory. As a result local hidden variables are no more excluded.

2. Random walks, (multi-) fractal and fractional spacetimes and Path Integrals

In [1], we expanded on the combination of encountering random walks, and discrete spacetime, to propose that a multi-fold spacetime could be fractal or multi fractal. Yet, [1] did not really justify why, it rather enumerated arguments in favor of it. It also did not really discuss implications.

[2] Standing in for Quantum Physics in general.

The following few paragraphs come from [1].

We have seen how central the concept of Path Integral to Physics is in general, as well as to characterize the multi-fold spacetime. Yet, early on, Richard Feynman [24] observed that the trajectories of particles, in particular relativistic ones, look like Brownian motion. And before him, Nelson showed that the Schrodinger equation can be derived from Brownian motion [161]. We know that random walk fluctuations are similar to Brownian motion. This observation led to the alternate ways to derive for example Schrödinger equation presented in for example [25].

Ord [26] then showed that one can model such paths with a fractal spacetime. Ord's work, and follow-ups, recover a relationship à la de Broglie, the uncertainty principle, Lorentz covariance, and the Klein Gordon and Dirac equations [26,25]. It can also account foe anti-particles. *Note added on December 9, 2023L it also anticipates that QFT in up to 4D spacetime can be modeled by random walk quantum automata. See [178] and references therein.* Separately, but of course directly related, it is worth noting, as others have, that particle physics and interactions as modeled by Feynman diagrams, also the outcome of Path Integrals, are fundamentally fractal-looking [27]. The one (spatial) dimensional work in [26] seems to point to a possible alternate way to understand and account also for the different paths of the Path Integral.

If spacetime were to be fractal, then a particles could take fractal paths to go from a location to another and that could bring them all over (or significantly all over) the place: something reminiscent of the Path Integral (that could then possibly appear as an approximation of model of that behavior in an non fractal or continuous world. [28] provides a illustration on the evolution of fractional QFT from lattices to continuous spacetime. Anti-particle correspond to back in time path, recovering a key aspect of QFT.

Of course, fractal concepts in the universe only fit a finite range of scales (See additional comments in [1]) . On the other hand, the giant structures recently observed in the universe, as detailed for example in [29], could be also the footprints of random walk paths enlarged by inflation. Note that astronomical results do not support expanded ranges of fractal scales [27], beyond a homogeneity scale ($\sim$ 70 Mpc). We will provide possible explanations for that later on.

The original observations of fractal, and multi fractal, structures have inspired work around scale relativity [30,31], and fractal spacetime proposals initially motivated by [26], as well as the implications and numerology approaches that can be obtained by simply postulating a fractal spacetime [32,33]. Entry points to these works can be found at [1,33-36], including, in particular, discussions and references of the Cantor-like E-infinity fractal spacetime. An interesting note is that the dimensions of such spacetimes can converge towards 4D, and all speed be limited by *c* when reaching continuity. In a fractal or multi fractal spacetime, it is possible to develop new calculus and physics: fractional spaces can be regarded as fractals when the ratio of their Hausdorff and spectral dimension is greater than one [37-42].

Relevant to our activities we note:

- Einstein's GR equation, and solutions including black holes have been formulated in fractional spacetime. See for example [43-45].
- Quantum mechanics has also been defined over fractional spacetime with Schrödinger, Dirac and other field equations, and Fractional space Path Integrals. See for example [46-52]. We note in particular how effective potentials [48,53], albeit usually complex/imaginary, also play a role in emulating the impact of fractional dimensions on the Schrödinger equation. The consistency of the Path Integral in fractional spacetime obtained in [49,51] is a key result that allows us to extend our models to such spacetime. This is an addition [1] that only pointed to the first reference, while it is [51] that actually recovers the generalized fractional uncertainty principle essential to the consistency of the path integral.

At the time of writing [1], we were not aware of [54], which is an extensive review of fractional quantum mechanics. The book initial part motivates path integral association to Lévy flights [55] vs. Brownian motions, with Brownian motion associated to a 2D spacetime trajectory versus fractional trajectories associated to $0 < \alpha \leq 2$, where α represents the Lévy index, and involves spatial self-similarity. α is also equal to the Hausdorff dimension of the resulting trajectory, and the fractional dimension of the associated fractional calculus and path integral involved.

α-based Lévy flights can be justified if spacetime is to be fractal, as for example argued in [56], with the invariant set theory, that we will revisit in section 4.3, or by many of the analyses (or intuition / numerology motivated models) presented in references listed above in this section.

Alternatively, and more aligned with the reasoning so far, α-based Lévy flights come, not from the path integral with $\alpha = 2$, but by adding to the random walks the notion of pauses, for other time consuming activities, between Brownian jumps. It is known as the Lévy flight foraging hypothesis [57]. These jumps could be motivated by other interactions, or activities potentially taking place at each reached / concretized spacetime location.

Also note that we speak of spacetime fractional calculus, but the above discussion of Lévy flights, only discussed spatial fractional behavior. One can extend this to a time fractional derivative described by the time fractional Schrödinger equation, with a fractional parameter $0 < \beta \leq 1$ [54,58].

The spacetime fractional Schrödinger equation covers self-similarity/fractal behavior in both spatial and temporal dimensions. These different approaches are described in [54]. [432,433] shows that these latter two fractional Schrödinger equations can be equivalently modeled with a complex effective potential in the standard Schrödinger equation. It is important, and we will get back to it.

Time fractional temporal diffusion or Schrödinger equation can be seen as considering a non-Markovian diffusion instead of a pure Markovian one as behind Brownian motions [54,58,59,60].

3. Multi-fold random walks

Now, let us explain why multi-fold spacetimes are fractal, or multi-fractal, so that we can justify the behaviors listed in section 2.

As proposed in [1,6], a multi-fold spacetime can be reconstructed from random walks, as Brownian motions. In [1,61], we model how this supports models of inflation, universe expansion and dark energy effects with positive cosmological constant *(Note added on December 9 2023: it is actually strictly positive per [188])*, or even model the Ultimate Unification [1,62,63].

In [64-69], we argue that massless the Higgs boson (i.e., the Higgs field prior, or at energies higher than, the multi-fold gravity electroweak symmetry breaking) are the main components responsible for the random walks that create and/or concretize spacetime. During inflation, the random walks add particle pair creations leading to the exponential behavior [1,61].

Our reasoning relied heavily on a few considerations:

- The ability to associate the potential involved with inflation and slow roll to the Higgs potential.
- The presence of the Higgs boson (massive below the energy of the gravity electroweak symmetry breaking) at the entry and exit of multi-folds, and in the folds (to maintain mass in the multi-folds per [1]). This is needed to match the fold structure with the spacetime structure.

- The role of the Higgs in enabling a in-flight right handed neutrino [1,70,71], themselves, key to implementing multi-folds with wormholes, which may or may not be desirable [72].
- The Higgs boson as isospin doublet with the right-handed neutrino [67].
- The fact that the Higgs potential seems to model the collective behaviors of the massless Higgs bosons in ways that QFT can handle [4,15-17,64,67,*164*].

With this, the massless Higgs field models the massless Higgs bosons everywhere spacetime is concretized and involved in random walks, à la Brownian motion, or rather à la Lévy flights, where $\alpha \neq 2$ can be because of interactions at a given point, occupation by others (e.g. collisions, or exclusions for fermions), concretization of un-concretized spacetime locations, and / or rather creation of new particles (e.g., during early ages or at high energy). So, it is normal to expect that, while the path integral is rather a fractional path integral, with α moving to 2 (at very small scales) as we move away from the big bang (but still smaller than 2 because of these other considerations of collisions, interactions, concretization of not yet concretized spacetime locations, creation of particle pairs, annihilation, etc.). This time or scale evolution of α, also suggests rather a multi-fractal structure of spacetime. *Note added on December 9, 2023: Note that does not necessarily mean supersymmetry, e.g., simply because we do not have systematic avoidance of the random walk. See [188] and reference therein.*

In our humble opinion, this is the strongest microscopic interpretation encountered so far to justify a fractal (multi-fractal universe), and to explain of current fractal observation only within a certain cosmological scale range. We just saw that this is aligned with astronomical observations. As already indicated this is not the case for scales much larger than 70 Mpc. There are plausible explanations for that upper limit: as discussed in [16], at very small scales, entanglement between neighboring (for a path) new concretized spacetime locations create, per the multi-fold mechanisms, attractive effects (it was potentially modeled as a negative (or less positive) cosmological "constant" when running the gravity couplings in [16]), when close to the UV fixed point encountered in our analysis of asymptotic safety of gravity [16]. This effect, reduces the foraging lapses, and ties up the paths. This is equivalent to bringing α back to 2. As a result, above a certain astronomical scale, fractal or multi-fractal structure will not form or they will break apart. Such a variation in scales also implies multi-fractal behaviors: α changes. It is in accordance with astronomical observations. To our knowledge, this is the only microscopic explanation to the (multi) fractal observations at cosmological scales.

What about temporal fractional behavior? Typical examples of non-Markovian random walks are investigated in [73], with touristic (higher probability to go to less visited nodes) and avoidance walks (the opposite). Other examples would be foraging at a node as a function of past path (beyond just considering the previous node) and (associated) foraging history. There is no doubt that the multi-fold random walk with creation of new spacetime location, interaction with other particles (even if just collisions), relations to new particles etc., has a little bit of all that, after all it is described by a path integral that consider all the past history of a path.. Brownian random walks were only an approximation, and true foraging is not just changing the pattern of the walk but also rending it non-Markovian. In fact, at the core, the notion of Path Integral, involve all the past history of the paths, it is inherently non-Markovian. It is only because we know that probably only recent history matters that the behavior appear like Markovian / Brownian random walks, as illustrated for example in [74]. It motivates why the multi-fold spacetime is not just spatially fractional, but also temporally fractional.

Again, we will note that, to our knowledge, the previous paragraph is the first microscopic interpretation of the fractional aspect of spacetime, beyond the handwaving justifications by analogy with exotic diffusion, discussed in [54,58] (e.g. See reference 1 – 7 in [58], they are all primarily spatial arguments), that are not the type of microscopic interpretations we needed. Yes, there are also arguments about Euclidicity, i.e., support of Wick rotations, which could be invoked, but again, that is not a microscopic interpretation.

Interestingly, we already encountered, one way or another in [1,4,67,68,75], that prior to the gravity electroweak symmetry breaking, the Higgs field is complex, something typically understood as modeling the instabilities of the field leading to the gravity electroweak symmetry breaking, rather than a tachyonic behavior [76,77].

Yet, in the previous section, we mentioned something important, but the reader may have missed it. [1,44,53] show that the effective potential to add to the conventional non-fractional spacetime Schrödinger equation, for equivalent behavior, is complex with an imaginary part, when it includes a temporally fractional part, which we just physically motivated. Just as in [1] for the multi-fold effects, a similar result extends to fractional QFT for scalars (massive or massless). Imaginary parts can be identified as bringing in imaginary mass contributions. We interpret this as more a model of the fractional nature of the multi-fold spacetime than, or in addition to, the instability aspects. Furthermore, it also implies that the massless Higgs field is indeed central to the random walk, and all the effects proposed built on it [1,62,64-69]. Eventually, it confirms our counter arguments presented in [75]. It is also corroborated by the idea of 2D conformal fields appearing in all candidate theories for quantum gravity [78-80]. 2D conformal fields can represent a free massless boson path integral in 2D [68,80]. Did we hear massless boson random walk?

About [75], the latter is in fact consistent as it was argued, in reference 3 of [75], that fields with gauge fields with complex connections are problematic, and, for example, can't be unitary. Well, [52,53] shows the same result for the fractional spacetime Schrödinger equation (due to the fractional time aspect). However, with spacetime reconstruction, we do know the actual microscopic physics behind the models (fractional QFT or fractional spacetime Schrödinger equation), and can vouch for unitarity. In other words, and as announced in [75], this aspect is due to the limitations of QFT and QM to model these microscopic interpretations. They only succeed at doing so with approximations.

On the other hand, the fractional spacetime Schrödinger equation comes also with the loss of energy conservation; again something that does not necessarily happen microscopically, but may explain why GR, and its energy stress pseudo tensor are not conserved [1,23,69], in a conventional model. *Note added on December 9, 2023: See more details on this topic explaining the issues with pseudo stress energy tensors, and what s actually happening in [200].*

Eventually, flipping the discussion around, the SM ,with its model of a complex Higgs field above electroweak symmetry breaking, hints and indicates that spacetime is discrete (to justify the random walk structure with Lévy flights, where $\alpha \neq 2$), and (multi)fractal (because complex), as we had established in [1,68], thereby settling a controversial issue in Physics, especially when considering also the 2D dominant behavior and non-commutative and Lorentz symmetry properties established in [1,62-69]. None of those are ultimately incompatible. And, as mentioned, the discrete and fractional spacetime can be seen as a strong hint that the Higgs boson, with its complex field, and therefore imaginary mass, is the, or a, main contributor to these random walks above the electroweak symmetry breaking, where 2-D then 3-D dominate, before 4-D.

With all these considerations, we have shown that (multi-fold) spacetime is (multi) fractal. With [6], these results extend to GR-based universes, like our real universe. In all these cases, the numerological considerations, as in section 2, can now be repeated. In particular, spacetime may be a Cantor-like E-infinity fractal spacetime, where dimensions can converge towards 4D, at larger scales, and speed be limited by *c* when reaching ~ continuity. Both following [1], and now following the present paper, we expect that the structure of spacetime is Cantor-like E-infinity fractal at very small 4-D scales, before appearing essentially continuous at larger scales, and non-commutative and then 3D then 2D discrete as scales decrease.

4. Bell inequalities and related entanglement experiments

The 2022 Nobel prize in Physics [81] was awarded for work on entanglement proofs built around Bell's inequalities [82-89] and associated CHSH generalized inequalities [88,90,91]. CHSH stands for John Clauser, Michael Horne, Abner Shimony, and Richard Holt. Accordingly, it is conventionally admitted that these experiments showed that reality is non-local, and there are no local hidden variables, or they would violate statistical independence per the Kochen-Specker theorem [88,92]. In other words, Einstein would have been wrong when he proposed the EPR thought experiment [93].

Yet, there are some underlying assumptions behind the Bell inequalities and experiments to prove their violations, and many have tried to find loopholes to the experimental results, to little avail: they failed or their approaches are not widely accepted.

4.1 Invalidating the implications of the Bell inequalities by showing the viability of local hidden variable

However, it does not mean that there is no possible way around the results of the Bell and CHSH experiments . To be fair, such proposed ways around are controversial, and not necessarily widely accepted. They typically turn around abandoning statistical independence which could be achieved with backward causation, super determinism with conspiracy of nature, denial of free will, but also in other circumstances that can be encountered in nature without the need of the previous explanations [88].

For example, in terms of super determinism, let us consider [94,95]. ‘t Hooft shows that it is possible to model any quantum system with a local classical system, i.e. with local hidden variables. He explicitly constructs them, as fast changing (cyclic) variables. And he argues that the assumptions of the Bell setup are not realistic. Doing so, his local hidden variable are compatible with the experimental results of violation of the Bell inequalities: they do not imply forbidding such hidden variable anymore. His proofs works on a finite discrete spacetime / lattice. This is important.

Therefore, ‘t Hooft proves that, on a lattice, it is possible to build classical hidden variable describing any quantum system. Then, he argues for disagreement on assumptions behind Bell’s theorem to explain that experimentation seems to violate. If these assumptions are not natural, or aren’t satisfied by experimentation setup then their results are not in conflict with the model built by ‘t Hooft. This is where the approach is probably the least convincing for many.

4.2 Multi-fold theory and ‘t Hooft approach

In a multi-fold universe, spacetime is discrete. With a positive cosmological constant, one can expect an asymptotic de Sitter behavior that is therefore finite, which match the assumption of ‘t Hooft for its analysis. *Note added on December 10, 2023: See [199] for a proof that the cosmological constant is strictly positive.*

Therefore, the approach of ‘t Hooft can be applies, and therefore the classical model or a quantum system can be built as proposed, including the cyclic fast fluctuating variables.

If the real universe spacetime is not a finite lattice, nothing is conclusive, at least until the proof and construction is extended to it. Because the multi-fold universe was proposed to address non-locality with local physics, we would like to adopt the first part of ‘t Hooft proposal: local hidden variable are possible, without requiring invoking non-causality/retro-causality, or super determinism (as well as free will, but we will see a weaker statement next that may be more acceptable). We are not saying that these may not be what happens, but we would prefer not to bring these up.

Note added on December 9, 2023: [94,95], are based on underlying quantum cellular automata [206], as are the proposal that random walks model QFT up to 4D [178,202-204]. This explains why, in multi-fold universe, which is discrete, QFT models so well nature, and the SM, at scales were spacetime appear continuous, and how the models of [94,95] applies to our real universe. Also [205] appears is a recent addition to this analysis by 't Hooft, where he analyzes aspects of the impact on the SM. Accordingly, it finds that the massless Higgs boson is the massless Goldstone boson associated to a Global quasi symmetry of the SM Lagrangian/Hamiltonian under translation of the Higgs scalar field by a complex spinor constant, which would explain the mass hierarchy problem. For the rest, we do not share the fermionic field and supersymmetry considerations based on the multi-fold considerations and [199], but we see the fast varying fields needed for the model as the random walks of the massless Higgs boson and the effects of the jumps from W-type multi-fold hypothesis [108]: these are the fast varying components required.

Assuming that Bell's (or CHSH) inequalities would be found violated in a multi-fold universe, then there are issues with Bell's theorem assumptions and the setup of experiments. However, so far, we do not know of a real multi-fold universe. It seems a non-falsifiable proposition.

Yet, as [6] shows that multi-folds are encountered by GR at Planck scales, the real universe is maybe multi-fold, and, in that case, we may have proven that Bell's assumptions are not naturally satisfied. Or have we?

4.3 Fractal invalidation of CHSH experiments results

Another class of models of universes can explain violation of the CHSH inequalities due to the loss of statistical independence. In this case, it would be due to the nature of the state space and its associated mathematical measures used in computing the statistical independence [98]. The quantum mechanic model is sometimes called Invariant Set Theory (IST) [56,96,97], that we already mentioned in section 2.

In [98,99], it is shown that as experiments do not compute the different correlation terms of the CHSH inequality, violation of the premises may occur on a fractal state space without violating the Bell inequality. This would significantly impact the implications of the 2022 Nobel prize winning results if the state space of the universe were to be fractal.

In [98], related analysis explains more intuitively why a fractal state space would impact the statistical independence needed by the bell theorem: if space state is fractal, for a choice made by Bob, the states that are actually physically available to Alice are now reduced to the ones that would fall on the fractal structure, versus in between the gaps (and there are many in a fractal structure). Therefore, the statistical assumption of the Bell Theorem is violated by nature, and the Bell theorem and its inequalities do not hold in such a universe. Again the 2022 Nobel prize winning results, would not mean much.

More importantly, that is a weaker example of free will that we see as easier to comprehend and accept.

Also note that [99] argues that there can be no continuous variable in the state space for the IST. *Note added on December 10, 2023: This recovers some of 't Hooft claims in [205].*

4.4 Multi-fold fractal spacetime

With its discrete, fractal, non-commutative yet Lorentz invariant spacetime, a multi-fold universe would have a fractal state space. Per the previous section, in a multi-fold universe, local, realistic hidden variables are a priori not ruled out by the experiments violating the Bell or the CHSH inequalities.

Spacetime being discrete, we also recover a discrete state space (at least around spacetime variables). This is what matters.

With this we can already conclude that the results of 4.2 can apply to multi-fold universe but do not necessarily require, the otherwise concerning assumptions on super determinism (or retro causality).

5. Multi-fold theory and The Bell Theorem: Non-locality with Locality

The Einstein Podolsky Rosen (EPR) paradox, the Bell theorem, and its experiments violating the Bell and CHSH inequalities are at the core of the motivation for the multi-fold mechanisms, as discussed in [1,9,10,22,100,*195*].

It is therefore worth wondering if more can be said, or proved, on the Bell theorem in a multi-fold universe.

The multi-fold mechanisms were introduced to allow entangled particles to instantaneously interact with each other via the paths allowed on the multi-fold that meet at the exit point [1,9,10,22,100].

5.1 Multi-fold mechanisms

The basic idea and principles behind the introduction of multi-folds is that entanglement, and associated 4D non-local reality, must be supported by spacetime, in whatever dimensions needed, without violating the no supra luminosity principle that nothing can propagate faster than light. In other words, the theory and mechanisms come from postulating that entangled particles must have a growing pathway that allows a path, as understood in path integrals, from one particles to always be in contact with a path from the other entangled particle.

It implies the need for ways to connect particles at different 4D spacetime locations through additional spacetime pathways. These could be wormholes following GR [*195*]. However they lead to challenges in explaining how they would be in 4D spacetimes or outside (embedding spacetime or tangent spacetime), yet not observed so far, how to address traversability, or how to ensure that the required kinematics and dynamics are compatible with GR. (*Note added on December 9, 2023: See [195], for details and answers to these questions*).

Multi-folds, mechanisms and mappings are illustrated in figure 1. Accordingly, one can understand why at any time, a path integral path associated to each particle can remain in contact with a path of the other entangled particle.

Multi-folds and associated mapping mechanisms [1], were introduced, in a multi-fold universe as we do not know if it models well our real universe, as an alternative that does not have any embeddings, GR kinematics and dynamics or traversability restrictions. They can be seen as adding handles attached to entangled particles in 4D spacetime (background spacetime). Figure 2 illustrates this with an intuitive simple 2D analogy in 3D. The reader needs to consult [1,*185,191,191,195*] for the actual mechanisms and mappings.

In a multi-fold universe, spacetime locations in between which there is entanglement are now linked by these handles, and the handles are constructed so that some aspects between the two end points can always be in instant contact. Of course, the action from multi-folds mechanisms, mapped in 4D are more complex; Figure 2 is just for illustration purpose. *Note added on December 9, 2023: See [195], for more details.*

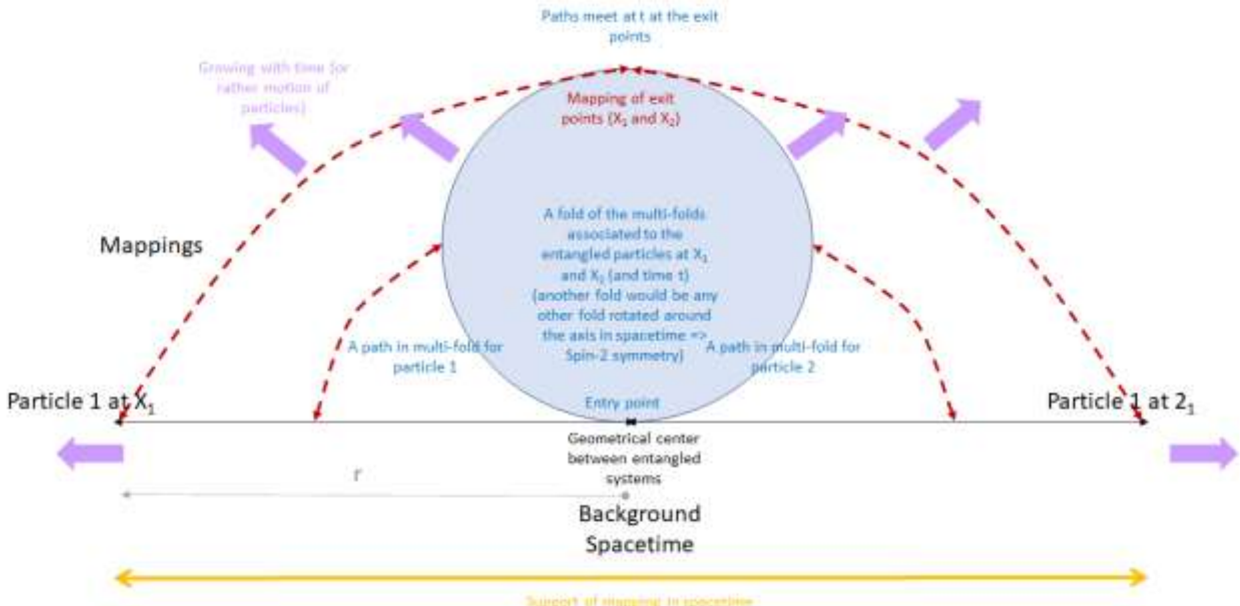

Figure 1 illustrates, in a simplified manner, the multi-folds, multi-fold mechanisms, their kinematics and mappings for two entangled particles moving in opposite directions.

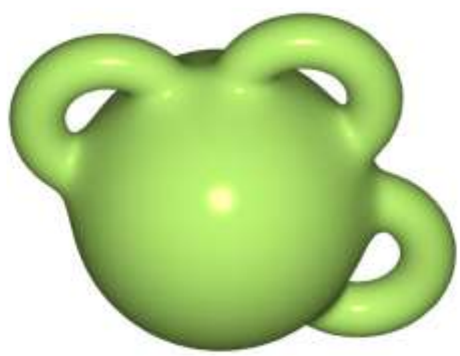

Figure 2: It illustrates 4D multi-fold spacetime as the 2D surface (background spacetime) of the 3D spheres. The effects of multi-folds, their mechanisms and mappings amount to connect the spacetime locations where entangled systems are with the handles. It is a simplified picture. The true mechanisms are rather represented by figure1, and in [1,185,191,191,195].

Doing so is possible by ensuring that at least a path of the path integral associated to the wave function of each particle can propagate in the handles and so always be in contact with each other in the handle. This is a unique connection versus all the other models that may have considered entanglement and gravity like those discussed in [101], and ER=EPR/GR=QM as discussed in [102,103]: multi-folds must be traversable for at least one path integral path. No energy (or other conserved quantity) is in fact lost as this can be as small as desired (compensated by a coupling constant) and multi-fold deactivation recovers any energy in flight [1,8-10,*185,191,191,195*]. All the other models linked to such ideas, typically based on wormholes, do not consider opening paths to the path integrals; most probably because of the traversability challenges.

Disentanglement results in collapse of the multi-folds, starting from the exit points, in ways analogous to a progressive wavefunction collapse [1 *195*].

In general, multi-folds are single tenants, i.e. no other physics take place in the multi-folds with the exceptions mentioned later on. [1,*195*] also relies on additional principles like hierarchical considerations. This is because we do not observe any additional phantom interactions.

[1] also discusses an interesting way to understand spin as a representation of rotation (wavefunction or multi-folds) due to the distribution of paths picked on the multi-folds. *Note added on December 9, 2023: It would explain this internal symmetries, as internal (microscopic) black hole (as particles) behavior could also explain others [201].*

Note that the multi-fold mechanisms of figure 1 are the first ones that we picked based on the reasoning presented above. One could imagine other mechanisms that result in the same effective potential, or effective curvature, or simply postulated that such curvature or potential appear. Doing so however may not lead to the same ability to predict what happens in the surroundings spaces, (e.g., in spaces embedding or tangent/dual to the 4D spacetime). The beauty of the approach provided above is that a single postulate (the multi-folds as proposed in figure 1 and [1]) allow us to consistently deduct everything that is described in the theory and recover many touch points with explanation for the real universe and for results or mysteries from conventional physics or New Physics theories like strings, M-theory, Group Field Theory, non-commutative geometry, or LQG. *Note added on December 10, 2023: [195] provides more insights on how our choices and principles for the multi-folds [1,185,191,191,195], can be justified.*

The outcome is that we achieve non-locality with local physics plus the multi-fold mechanisms, and, as an interesting consequence, we see gravity emerge from entanglement [1,9,10,22,100,104]. This is the E/G conjecture, factual in multi-fold universes [100], as a fundamental multi-fold property or principle: spacetime rearranges itself with multi-folds to supports the properties of entanglement [22].

This way, non-local requirements, supporting non-local hidden variables, per the conventional view, can actually be implemented with local hidden variables, and reality is real (because [1] proposes that the spin may related to the rotation of the wave function), non-local yet local. While we cannot find a multi-fold universe where to test the Bell, or the CHSH, inequalities, we can still conclude that, if the universe real is multi-fold,

- Then the Bell or CHSH inequalities violation experiments predict non-local reality and hidden variables. But they can be implemented with local realities.
- Alternatively, under the right setup, some experiments will not violate the Bell or CHSH inequalities.
- Nothing can be said as a result about free will or imply super determinism, it may or may not apply.

5.2 Discrete spacetime, with positive cosmological constant and the W-type multi-fold hypothesis

A finite discrete spacetime, with a strictly positive cosmological constant *(Note added on December 9, 2023: Note that it is actually strictly positive in a multi-fold universe and in our real universe, as shown in [199])*, as in the multi-fold theory [1] matches a finite lattice as in section 4. The W-type multi-fold hypothesis [105], completes a model that matches 't Hooft discussed in section 4.1. Indeed, within a finite spacetime, as is a multi-fold universe, or for any finite wave function support domain, the jumps between spacetime locations proposed with the W-type hypothesis, are analogous to the cyclic fast varying functions of 't Hooft [95]. *Note added on December9, 2023: This is combined, scale wise, with the moves of the massless Higgs bosons are the fast changing variables behind the larger scale continuous physics. The W-type multi-fold hypothesis ensures that the massless Higgs bosons are themselves also subject to faster variables due to the jumps.*

Accordingly, per [95], one can construct classical models for quantum physics in multi-fold universes, and so local hidden variable. This is consistent with the previous section, but obtained through a quite different reasoning. And one does not need to bring in super determinism or retro-causality. In fact, now, we have shown that we can have just a discrete spacetime, and have the view of section 4.3 still hold.

Even further, we can relax any free will limitations (for now). Indeed, a key point of the above is that the justification that experimental violations of the Bell or CHSH inequalities would not forbid causal local reality and local hidden variable, does not require any more the scenarios of [88], or super determinism.

5.3 Fractal spacetime

It is interesting that section 4.3 concludes the same indetermination in the presence of a fractal state space, achieved, in our case, via the multi-fold discrete fractal spacetime [1].

It seems that multi-fold spacetime is (multi) fractal resolve non-locality as multi-fold mechanisms enabled non-locality with local physics. It was hinted in [1]: with fractal random walks, local regions may indeed be non-local. We reached that result by relying on two quite different approaches.

6. Conclusions

The paper provides microscopic justifications and interpretations, based on random walks for multi-fold spacetimes to be fractal. Doing so, we also justify the complex scalar field used for the Higgs boson in QFT, at the electroweak symmetry breaking, and why it hints at a discrete fractal spacetime. Multi-fold universe are expected to probably have a Cantor-like E-infinity fractal spacetime behavior.

We also showed that in multi-fold universes, the violation, if ever, of the Bell, or CHSH, inequalities do not necessarily imply no local hidden variables. In fact these are possible in multi-fold universe and do not require abandoning free will or accepting super determinism or retro-causality.

The fast variables proposed by ‘t Hooft can be linked to the massless Higgs random walks, and the W-type multi-fold hypothesis. Overall we have encountered further corroboration of the fundamental role played by the massless Higgs boson in the SM.

[6] and all the ability of the multi-fold theory to address open issues with the SM (actually with the SMG), and the standard cosmological model [1,4-23,61-72,75,78,100,102-160, *162-201*], extends these results to our real universe.

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