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Tests and prospects of new physics at very high energy

Beyond the standard basic principles, and beyond conventional matter and space-time. On the possible origin of Quantum Mechanics.

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Abstract. Recent results and announcements by Planck and BICEP2 have led to important controversies in the fields of Cosmology and Particle Physics. As new ideas and alternative approaches can since then more easily emerge, the link between the Mathematical Physics aspects of theories and the interpretation of experimental results becomes more direct. This evolution is also relevant for Particle Physics experiments at very high energy, where the interpretation of data on the highest-energy cosmic rays remains a major theoretical and phenomenological challenge. Alternative particle physics and cosmology can raise fundamental questions such as that of the structure of vacuum and space-time. In particular, the simplified description of the physical vacuum contained in standard quantum field theory does not necessarily correspond to reality at a deeper level, and similarly for the relativistic space-time based on four real variables. In a more general approach, the definition itself of vacuum can be a difficult task. The spinorial space-time (SST) we suggested in 1996-97 automatically incorporates a local privileged space direction (PSD) for each comoving observer, possibly leading to a locally anisotropic vacuum structure. As the existence of the PSD may have been confirmed by *Planck*, and a possible discovery of primordial B-modes in the polarization of the cosmic microwave background radiation (CMB) may turn out to contain new evidence for the SST, we explore other possible implications of this approach to space-time. The SST structure can naturally be at the origin of Quantum Mechanics at distance scales larger than the fundamental one if standard particles are dealt with as vacuum excitations. We also discuss possible implications of our lack of knowledge of the structure of vacuum, as well as related theoretical, phenomenological and cosmological uncertainties. Pre-Big Bang scenarios and new ultimate constituents of matter (including superbradyons) are crucial open subjects, together with vacuum structure and the interaction between vacuum and standard matter.

1 Introduction

In [1], we discuss alternatives to standard cosmology (conventional Big Bang + inflation, ΛCDM) to interpret recent results by *Planck* [2–4] and the possible existence of primordial CMB B-modes. The BICEP2 announcements [5, 6] have finally not been confirmed [7], but further searches for primordial CMB B-modes may yield a positive result. Alternative cosmologies are often closely related to possible new physics and to new space-time geometries. Such scenarios deserve careful attention.

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Galactic dust can be at the origin of the CMB B-modes observed by BICEP2 [7–11]. But as emphasized in [1], if CMB B-modes corresponding to a signature of the early Universe dynamics are finally found, they can, together with the local privileged space direction (PSD) [12, 13] possibly observed by *Planck* [4], provide an unprecedented evidence [14, 15] for the spinorial space-time (SST) we introduced in 1996-97 [16, 17]. Further experimental work will help to clarify the situation [1].

Objections to the cosmic inflation model had already been emitted [18, 19] long before the recent *Planck* [20] and BICEP2 announcements. But the 2013 Planck results [2, 3] gave rise to a controversy [21, 22] on the predictions of inflationary models [23, 24], involving in particular the possible origin of primordial gravitational waves able to generate CMB B-modes. This debate was amplified [25–27] by the March 2014 BICEP2 result. Recent work on inflation can be found in [28–34].

1.1 Alternative cosmologies

Cosmic inflation has been basically an *ad hoc* mechanism to preserve the conventional Big Bang [35] model based on standard Physics and taking standard particles to be the ultimate constituents of matter. But it was already pointed out in [36, 37] that a simple preonic pre-Big Bang approach based on superluminal ultimate constituents (superbradyons) [38] can avoid basic difficulties that had led to cosmic inflation, such as the horizon problem. The flatness problem appears to be naturally solved [14, 15] by the SST cosmic geometry, that can be combined with a pre-Big Bang scenario [1].

The cosmological constant problem can also be avoided in this way [39, 40]. In particular, the preonic structure generates a frequency cutoff limiting the validity of standard quantum field theory (SQFT) and naturally introduces a new dynamical behavior of vacuum [37, 41] that may have deeper consequences [42–44]. Cosmology based on the SST geometry does not require a standard cosmological constant, as the SST curvature term does not follow the usual relativity constraints and dominates the first Friedmann-like equation [13, 44] independently of the global radius of the Universe and even if this radius turns out to be very large [40, 45]. Thus, the evolution of the Universe is basically governed by the SST geometry and not by standard matter and relativity.

Cosmologies involving a variable speed of light and/or modified versions of gravity [46–49] can actually be phenomenological ways to incorporate properties generated in the real world by pre-Big Bang dynamics with a space-time beyond the standard one of special relativity. But actually, pre-Big Bang models and new approaches to space-time and vacuum structure [40, 44] contain more flexible solutions to avoid the cosmological constant problem and other difficulties of standard theories.

In [49], for instance, using a nonlocal quantum gravity, very strong momentum cutoffs are introduced through the entire function $exp\ (-p^2/2A^2)$ where the cutoff A is ~ 1 TeV for the standard model field theory and must be lower than 1 MeV when the graviton is introduced. Instead, the pattern considered in [39–43] assumes that the conventional bosonic zero modes and boson fields condense in vacuum only in the presence of surrounding standard matter (including the graviton and gravitational waves), and that this condensation occurs only in the relevant frequency domain. This amounts to a suppression of the standard cosmological constant that can then be replaced by a new object, Λ, decreasing with the matter density of the Universe [1, 44]. A new approach to the renormalization of quantum field theory (QFT) is also tacitly introduced in this way.

Furthermore, both the SST approach with its automatic geometric expansion of the Universe, and the pre-Big Bang pattern considered in [50, 51] with a gravitational instanton at cosmic time $t = 0$, raise the basic question of the primordial fundamental information at the origin of cosmic time. Such a problematics has traditionally been rejected by standard cosmology [1, 40] on the grounds of the quantum uncertainty principle for very small distance and time scales in the Big Bang [35].

In the case of the SST, the notion of time itself depends on a more fundamental geometry and is directly related to the expansion of the Universe. Conventional causality is also questioned.

1.2 New Physics

In his 1931 note introducing the Big Bang hypothesis [35], Georges Lemaître wrote: *"Now, in atomic processes, the notions of space and time are no more than statistical notions: they fade out when applied to individual phenomena involving but a small number of quanta. If the world has begun with a single quantum, the notions of space and time would altogether fail to have any meaning at the beginning; they would only begin to have a sensible meaning when the original quantum has been divided into a sufficient number of quanta".* This view of the origin of the Universe was conceived a few years after the birth of Quantum Mechanics and during the early development of standard particle theory. Lemaître refers to the uncertainty principle.

But more than eighty years after Lemaître's paper, violations of quantum mechanics at very high energy can be considered, together with alternative cosmologies involving new physics.

Cosmology is not the only domain where fundamentally new physics can manifest itself. Particle physics experiments at very high energy can potentially be sensitive to the same new dynamics.

The degree of validity of the standard fundamental principles of Physics for the nature, internal properties, propagation and interactions of ultra-high energy (UHE) particles including the existing ultra-high energy cosmic rays (UHECR) remains by now a basic open question [52–54]. Answering it will require further experimental, theoretical and phenomenological work.

It is even not yet clear [55] if the observed fall of the UHECR spectrum [56, 57] is a signature of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [58, 59] or corresponds, for instance, to the maximum energies available at astrophysical sources. Furthermore, possible new physics can generate simple mechanisms faking the GZK cutoff [41, 52]. It then seems difficult, from this point of view, to reliably interpret present data [60, 61] on UHECR traveling on moderate extragalactic distances.

Similarly, there is no real proof of the validity and precision of models and algorithms used to describe UHECR interactions, especially if QFT can be modified by new physics. This situation can generate significant experimental uncertainties.

The properties of UHECR should be studied as far as feasible, including satellite experiments and searching for all kinds of possible signatures of new physics. Potential connections with the basic physics involved in the early Universe dynamics should be explored in detail. Systematic tests of Lorentz symmetry at UHE, as already suggested in 1996-97 [16, 37], should be a basic ingredient of these searches together with tests of all the fundamental principles of standard physics [41, 62].

Simultaneously, the validity of conventional low-energy symmetries, including internal symmetries, at very high energy also deserves a careful study. Contrary to the usual prejudices, such symmetries do not necessarily become more exact as energy increases [52, 54]. Work on this subject should include the search for possible signatures of a transition energy scale between standard physics and new physics with comparatively strong symmetry breaking [52, 53].

Besides tests of standard principles and more indirect signatures of new phenomena, physics at UHE can concern in particular:

- New ultimate constituents of matter (like superbradyons [36, 37]) that may exist in our Universe as free particles remnants from the early cosmic evolution [36, 41]. They can be part of the dark matter [53, 63], with possible decays able to generate UHE particles [16, 64].

- Cosmic anisotropies related to the fundamental space-time structure, as in the case of the local PSD [40, 41] generated by the SST [16, 17] and possibly confirmed by Planck [4, 44]. Combined with parity violation, the PSD can potentially explain the observed CMB anisotropy involving an asymmetry between the two hemispheres defined by this privileged direction [12, 44].

Anisotropies of the CMB and similar phenomena may directly influence UHECR propagation. The PSD can also lead to local anisotropies in the vacuum structure, with possible new effects on cosmic-ray propagation [40, 41]. New physics can simultaneously produce vacuum inhomogeneities in the present Universe, with unconventional effects on particle structure, propagation and interactions [41, 44] leading potentially to various kinds of signatures. This will in particular be the case if the vacuum structure depends on the presence of surrounding matter as suggested in [39, 40].

1.3 Deformation of kinematics and possible similar phenomena

Possible deformations of the particle kinematics were already discussed in [37, 65] and in subsequent papers as a way to test Lorentz symmetry at very high energy.

To possibly account for Lorentz symmetry violation (LSV), and assuming the existence of a privileged local rest frame (the vacuum rest frame, VRF) we considered the high-energy equation:

$$E \simeq p\,c + m^2\,c^3\,(2\,p)^{-1} - p\,c\,\alpha\,(p\,c\,E_a^{-1})^2/2 \tag{1}$$

where the momentum modulus p is assumed to be $\ll\ E_a\ c^{-1}$, m is the mass of the particle, α a positive constant describing the strength of the deformation and E_a an effective fundamental energy scale. Then, a possible negative deformation term violating Lorentz symmetry:

$$\Delta E \simeq -\,p\,c\,\alpha\,(p\ \ c\,E_a^{-1})^2/2 \tag{2}$$

would become larger than the standard positive mass term $m^2\ c^3\ (2\ p)^{-1}$ above a transition energy E_{trans}:

$$E_{trans} \simeq \alpha^{-1/4}\,(E_a\,m)^{1/2}\,c \tag{3}$$

This mechanism can possibly suppress the GZK cutoff, as suggested in [37, 65]. But more sophisticated versions can also be considered, leading to various scenarios [41, 52].

Acceleration at astrophysical sources would also be altered by such a deformation of relativistic kinematics [41, 66] and can possibly be used to test LSV models.

Similarly, energy-dependent deformations can be considered for all basic principles of standard physics, including quantum mechanics [41, 54]. In all cases, a transition energy similar to E_{trans} can exist. A simple hypothesis would be that the value of E_{trans} corresponds to a common transition energy for all kinds of deformations, associated to the scale at which new physics starts to become dominant. But the contrary cannot be excluded, if a specific law of standard physics (or even a class of particles) turns out to be more sensitive to new physics effects.

1.4 Quantum Fields

As previously emphasized, new physics can play a crucial role in the basic structure of vacuum and potentially lead to several kinds of observable effects, including significant modifications of QFT. In particular, the standard description of bosonic quantum fields as harmonic oscillators with the zero modes permanently condensed in vacuum can fail at scales where new physics plays a significant role or in situations different from those directly accessible to our laboratory experiments [39, 40].

QFT was built on the grounds of laboratory measurements. But a new basic physics, beyond standard quantum dynamics or just best adapted to the reality of vacuum in most of the Universe, may manifest itself in other situations. It can be potentially detectable through UHECR experiments and other cosmic-ray studies [53, 54], as well as in suitable cosmological observations [40, 44].

A crucial question is: why should the harmonic-oscillator zero modes of bosonic quantum fields be permanently present in vacuum even in the absence of surrounding conventional matter, as postulated by standard quantum field theory (SQFT)? In [39, 40] and in [43, 44], we argued that this is not necessarily the case and that the cosmological constant problem can be solved in this way.

In [39] and in subsequent papers, we considered the possible role of a preonic structure in the generation of the local interactions that in SQFT are dealt with through the concept of gauge invariance leading to the standard gauge bosons and to their zero-mode condensation in vacuum. Taking for simplicity a lattice description, one can attempt to relate the standard gauge interactions to the nearest-neighbour couplings between local excitations. But in such a preonic picture, there is no obvious need for the conventional principle of local gauge invariance such as it is formally at the origin of gauge bosons in SQFT. Gauge fields rather appear as tool to describe the reaction of the fundamental preonic structure to the perturbations generated by conventional matter fields.

Then, a tempting hypothesis can be that the generation of gauge fields occurs only if in the above picture the preonic nearest-neighbour couplings are altered in such a way that they depend on position, time and direction (leaving aside PSD effects) due to the presence of surrounding free particles. Gauge bosons just compensate the effect of matter fields, but their presence is not required otherwise.

In this scenario, the zero modes of gauge fields do not need to be permanently present in vacuum, and the structure of vacuum in the absence of standard matter can be substantially different from the SQFT pattern. A similar picture, leading to the same conclusions, can be built even if the distance scale for the generation of gauge fields is much larger than that of elementary preonic interactions. In all cases, the material generation of gauge bosons as free particles would be a result of standard particle interactions as it happens in accelerator experiments.

The situation can be similar for Higgs-like fields, that play a crucial role in particle structure and propagation but may not need to be permanently condensed in vacuum in the absence of surrounding free particles. Like in the case of gauge bosons, the preonic vacuum can possibly generate a Higgs-like structure as a response to the presence of propagating standard matter. Then, one can expect the same kind of dynamics to hold for all boson fields.

2 The structure of vacuum and the unknown of vacuum states

At this stage, the notion itself of vacuum deserves being discussed more closely, having in mind possible experimental and observational tests. The physical vacuum is usually defined as the lowest-energy state of standard matter such as postulated by SQFT. But is such a definition really appropriate, and can it survive (even as an approximation) in the presence an underlying preonic sturcture?

Standard cosmology and particle physics assume that the structure of vacuum (not explicitly described) is the same everywhere, and that the vacuum of standard quantum field theory just expanded with the Universe expansion after the inflationary period. This is usually considered as a natural hypothesis, even if it directly leads to the cosmological constant problem.

But what can really be said, for instance, on the structure and properties of the physical vacuum in a region of our Universe where there is almost no conventional matter? As previously stressed, alternatives to the standard hypotheses exist [39, 40] and have not been disproved. They can in particular provide a new approach to QFT and to the cosmological constant [1, 44].

SQFT postulates that, even in the absence of surrounding standard matter, the zero modes of the harmonic oscillators associated to bosonic quantum fields are permanently present in vacuum for all momenta, and similarly for the quantum field condensates associated to spontaneous symmetry breaking. But even in existing laboratory experiments, the Casimir effect itself, such as it is studied and measured [67], is far from providing a general experimental proof of the validity of this conventional scenario [68]. Furthermore, the harmonic-oscillator structure of bosonic quantum fields is based on standard quantum-mechanical concepts including the uncertainty relations. But quantum mechanics can be deformed or just fail at very small distance scales [41, 62]. Preonic structures do not necessarily follow the laws of quantum mechanics, even if they are expected to naturally generate them for standard matter above some critical distance scale.

In practice, nothing is really known about the internal structure and dynamical properties of vacuum in the absence of surrounding standard matter or in far-away regions of the Universe. The possibility that vacuum inhomogeneities influence the propagation of cosmic rays was considered in [41] and in subsequent papers. The effective particle spectrum and interactions would be locally sensitive to such inhomogeneities and to the vacuum structure.

SQFT has a peculiar feature. It is a theory of the interactions of standard particles, that are excitations of the physical vacuum. But it does not contain any information on the fundamental structure of this vacuum where conventional quantum fields can even condense. Thus, the formal vacuum structure is built from objects that are initially vacuum excitations.

Essential components of the present standard versions of Particle Physics and QFT have been built using ideas and mechanisms previously developed in Condensed Matter Physics. But condensed matter (solids, liquids...) has rather well-known structures pre-existing to excitations such as phonons, quasiparticles, solitons... that are the analogues of conventional "elementary" particles in the basic mechanisms considered. Nothing similar exists in SQFT.

What are the theoretical and phenomenological consequences of this lack of knowledge of the deep structure of the standard vacuum? And how can we define the vacuum at the scale of the Universe in a more general approach? Vacuum is usually defined as the ground state of the matter we can study in laboratory experiments, but how can this concept be generalized at the cosmic level?

2.1 The SST approach

It follows from the above discussion that, assuming vacuum can be consistently defined, several questions naturally arise. Does vacuum have the same internal structure in all the regions of our standard matter Universe, irrespectively for instance of the local matter density? And what are, actually, the internal structure and energy density of vacuum? What is their dynamical origin, and what is the natural space-time geometry for the physical vacuum?

A possible attempt to answer these fundamental questions can be based on the SST geometry.

In the SST approach [1], where each point of the cosmic space-time is described [16, 17] by a SU(2) spinor ξ involving two complex coordinates instead of the four standard real ones, the cosmic time t (the age of the Universe) is given by the modulus $\mid \xi \mid$ of the cosmic spinor. This automatically leads, already in the absence of standard matter and of any cosmological constant [40, 41], to the standard relation between relative velocities and distances at cosmic scale with a ratio H (velocity/distance) equal to the inverse of the age of the Universe $H = t^{-1}$.

It seems then reasonable to assume [40, 45] that the relation $H\,t = 1$ is the natural asymptotic limit as the cosmic time t tends to infinity and the matter density vanishes. The dark energy density would vanish in the same limit, together with the acceleration of the Universe expansion.

Such a scenario is naturally compatible with Pre-Big Bang models [1, 15] that do not in general involve an inflationary period and can directly exhibit the dynamics of the ultimate constituents of matter. Again, the question of vacuum structure is a major issue.

For a comoving observer at ξ, the PSD is defined as the set of space-time points whose associated cosmic spinor differs from ξ by a complex phase [14–17]. As there is no analog of this phenomenon in the conventional space-time, the PSD can introduce really new properties in the structure of vacuum, matter, quantum fields... It provides an explicit evidence for the existence of new physics directly generated by the SST geometry. Similarly, SST and the PSD, if relevant, can strongly influence past and present Cosmology introducing really new features.

If the asymmetry observed by Planck (and previously by WMAP [69]) is really due to the PSD generated by the SST, such a result suggests in particular the possible existence of local anisotropies of matter and energy density in the early Universe. Similarly, the notion of a locally isotropic vacuum can fail in the presence of such a fundamental (local) space anisotropy that breaks local rotation invariance but not the original cosmic SU(2) space-time symmetry.

3 Quantum mechanics

The structure of the physical vacuum and the space-time geometry are crucial to understand the origin and the validity domain of quantum mechanics.

The possibility that standard quantum mechanics (SQM) ceases to hold at high enough energy and at low enough distances was already considered in [53, 54] and in [41, 62]. Above a transition energy scale E_{trans} [54, 65], SQM can be progressively replaced by new physics involving possible ultimate constituents of matter [37, 38], a new space-time geometry [16, 17], a new dynamics... Then, SQM would remain valid as a low-energy limit for standard particles.

Deformed Heisenberg algebras and scenarios with non-commutative space-time have been considered in [62, 70], in [71, 72] as well as in other approaches including string theories [73, 74].

In [70], q-deformations of the quantum algebra were considered. In [54, 62], we considered possible commutation relations between momentum components where the commutators vanish in the zero-momentum limit and become significant at UHE. An explicit example was:

$$\Delta p_x \, \Delta p_y \gtrsim \Phi(p^2) \tag{4}$$

$$\Delta p_y \, \Delta p_z \gtrsim \Phi(p^2) \tag{5}$$

$$\Delta p_z \, \Delta p_x \gtrsim \Phi(p^2) \tag{6}$$

where x, y and z stand for three orthogonal space directions, and $\Phi(0) = 0$.

Together with LSV and in the presence of a VRF, the commutation relations (4-6) naturally suggest an intrinsic energy uncertainty $\Delta_q E \gtrsim [3 \ \Phi(p^2)]^{1/2} \ c$ that may produce observable effects at high enough energy and, possibly, a detectable uncertainty in the direction of the UHECR.

Such properties of the deformed quantum kinematics considered in (4-6) would potentially be able to generate [41, 54]: i) a deformation of the UHECR flux faking the GZK cutoff even in the presence of Lorentz symmetry violation (LSV) strong enough to suppress it; ii) a possible failure of the UHECR accelerating sources in the same energy region ; iii) an apparent lack of anisotropy of the UHECR flux, even in the presence of identifiable point sources.

In this scenario, the transition energy E_{trans} would be reached for quantum mechanics if the intrinsic uncertainty $\Delta_q E$ becomes larger than the mass term $m^2 \ c^3 \ (2 \ p)^{-1}$ at high enough energy. Above this E_{trans} , new physics beyond SQM can become dominant. Considering this possibility clearly raises the question of the actual dynamical origin of quantum mechanics.

Another possible deformation of quantum mechanics able to produce significant effects would be, for instance, to replace the standard commutation relation $[x_i \ , \ p_i] \ = \ i \ h/2\pi$ where h is the Planck constant, x_i a position coordinate and p_i the associated momentum, by:

$$[x_i \ , \ p_i] \ = \ i \ U(p) \, h/2\pi \tag{7}$$

where $U(p)$ would be an operator depending of the momentum modulus p but also on the particle considered. Then, the uncertainty relations can be slightly different for different standard particles.

3.1 SST and the possible origin of quantum mechanics

Do the complex wave functions used in SQM have a specific dynamical origin? The SST geometry can possibly provide a simple answer to this question, as vacuum excitations are expected to be described by functions of the spinorial complex coordinates and scalar products are naturally complex.

In the SST geometry, the four standard real space-time coordinates are replaced by two complex ones, and spinors replace four-vectors. Scalar products are complex like the coordinates from which they are buit. Then, the complex quantum wave function Ψ of a scalar particle can be, for instance, the hermitic scalar product of two SST spinors ξ_1 and ξ_2 : $\Psi \ = \ \xi_2^\dagger \, \xi_1$. ξ_1 and ξ_2 can in turn be associated to two spinorial wave functions possibly corresponding to the constituents of the scalar particle. The additivity of quantum wave functions would then be related to the additivity of spinors.

Quantization can also emerge as a natural property in the SST approach, as the most basic "elementary" particles of the standard model (the fermions like quarks and leptons) are now representations of the group of space-time transformations and can be naturally formed as vacuum excitations.

In the SST, a classical wave function for a spin-1/2 particle around a space-time origin ξ_0 can be, for instance:

$$\Psi_{sp} \, (\xi) = F(\mid \xi - \xi_0 \mid^2) \, (\xi - \xi_0) \tag{8}$$

together with:

$$\Psi^*_{sp} \, (\xi) = F(\mid \xi - \xi_0 \mid^2) \, (\xi - \xi_0)^* \tag{9}$$

where * stands for complex conjugate (opposite spin) and the real function F contains a suitable cutoff in $\mid \xi - \xi_0 \mid^2$. The wave functions Ψ_{sp} and Ψ^*_{sp} clearly violate local standard causality. They take nonzero values for present and future values of cosmic time around $\mid \xi_0 \mid$, and replace distances on the S^3 space-like hypersphere [1] associated to ξ_0 (all the SST points such that $\mid \xi \mid = \mid \xi_0 \mid$) by direct spinorial distances on the SST. Thus, F tacitly defines a space-time distance scale λ_{SST} below which causality does no longer hold in the conventional sense used for our standard space-time.

λ_{SST} is then likely to correspond to the space-time scale below which standard physics does not apply. Its definition from (8) and (9) is previous to the introduction of a characteristic speed relating space and time units. At this stage of the description, only time units are actually present [17, 40]. We expect, however, a relevant velocity scale to arise from the basic dynamical process that generates such a spin-1/2 particle. Similarly, the propagation of the particle will be associated to a critical speed. Distance scales will thus emerge together with matter generation and propagation.

Vacuum excitations with complex wave functions spreading over larger (space-time) distance scales can naturally be described as combinations of plane waves, leading to practical definitions of h, energy and momentum. Then, uncertainty relations will naturally be generated.

A crucial question remains to be dealt with: that of the quantization of vacuum excitations. In other words, why are there particles instead of just waves? However, if the spinorial wave function of the spin-1/2 excitation describes a deformation of the vacuum structure, it seems reasonable that its normalization be determined by the requirement of preserving the validity of the same (preonic) fundamental equations that generate the physical vacuum. Just as the vacuum structure would be a unique solution of these equations, the same can happen for a spinorial excitation of each relevant degree of freedom. The Pauli exclusion principle for spin-1/2 particles can also be generated in this way, if the vacuum structure does not allow for several identical spin-1/2 deformations at once.

Such a situation can simultaneously lead to the converse effect for excitations with integer spin. Assuming, for instance, that a scalar excitation can be associated to a combination of two spin-1/2 waves (fermion and antifermion), Bose statistics should in principle emerge in a similar way to the standard quark model. At this stage, there is no obvious need for a fundamental harmonic-oscillator structure leading to zero modes permanently condensed in vacuum.

Further work on the subject is clearly required, considering in particular suitable ultimate constituents of matter, possible explicit vacuum structures and relevant pre-Big Bang patterns.

4 Further theoretical and phenomenological considerations

The possibility that quantum mechanics be violated in a superbradyonic scenario was already pointed out in [16, 38], even if the study of LSV was give priority. A pattern reaching quantum mechanics as the result of a pre-Big Bang evolution was developed in [50, 51].

As previously stressed, interpreting recent AUGER data [61] as an evidence for the GZK cutoff would be premature. For instance, mechanisms from new physics (spontaneous decays, effects from the deformation of quantum mechanics [54, 62] as just reminded...) can fake this cutoff with a similar flux suppression [41, 52]. Exploring possible new physics effects in UHECR and cosmological data is a crucial task that will require a combined long-term effort.

The consequences of possible deformations of quantum mechanics for quantum uncertainty and particle properties at high energy deserve a close study, including more precise theory as well as experimental data at very high energy (UHECR...) and cosmological observations.

New physics can also be totally or partially compatible with the GZK cutoff, and produce effects at higher energies. In this case, some exceptional events can perhaps be observed. In the presence of LSV, UHECR with exceptionally high energy can present atypical interaction properties if the energy deformation becomes of the same order as the energy of a nuclear target [54, 75].

The implications of possible new physics for QFT Feynman diagrams, renormalization, non-perturbative phenomena... are also an important subject that requires close investigation.

In the presence of a PSD and of a local anisotropy, the modified Friedmann equations considered in [1] must be completed by a third equation describing: i) the anisotropy of matter and energy distribution; ii) the effects of the anisotropic vacuum structure. This equation should in particular account for the effect observed by Planck. But with these requirements, it is not clear if such an equation can be efficiently written using the standard space-time where the PSD cannot be automatically identified by geometric means. On the other hand, this is the only form of space-time directly available for conventional measurements. The question obviously requires further detailed work.

Concerning the grounds of Quantum Mechanics, a natural complement to the SST can be [1] to incorporate superbradyons [36, 37] as the ultimate constituents of matter. A superbradyonic vacuum would naturally allow for long-distance correlations even in the absence of superluminal propagation of signals in standard matter. And even if the possible existence of superluminal signaling in quantum mechanics [76] remains controversial [77, 78], the impossibility of such a signal propagation in conventional matter would not preclude an underlying superbradyonic vacuum structure.

Recent work [79] tends to confirm the existence of a natural link between wave-particle duality and the uncertainty principle in quantum mechanics. The modern formulation of the uncertainty principle uses entropy rather than standard deviation as the uncertainty measure [80]. Wave-particle duality is expressed through the wave-particle duality relations (WPDRs) formulated in 1995-96 [81, 82]. Introducing the SST and possible preonic structures in this kind of analyses deserves consideration.

5 Conclusion and comments

New physics has become an urgent matter for both Particle Physics and Cosmology. Many basic questions remain unanswered, and an exceptional amount of work remains to be performed.

Obviously, research on new physics is full of uncertainties and will require trials at any step before finding the right path. The PSD can, in this context, be a powerful hint if the Planck observation really corresponds to a fundamental signature. In this case, the SST appears as a natural candidate to describe the fundamental space-time. It provides the appropriate space-time description of spin-1/2 particles with the SU(2) group, and appears to present other important advantages such as automatically providing the $H\,t = 1$ law or being particularly well suited to incorporate Quantum Mechanics.

Although the PSD hint leading to the SST looks exceptionally clear, other indications possibly leading to new physics can exist in experimental and observational data. Alternatives to the SST must also be explored to understand the Planck result on the privileged space direction. Consequences of the PSD for angular momentum conservation in particle physics are also an open question [1].

The subject of the origin of Quantum Mechanics is a very fundamental one and, by now, looks particularly mysterious. It therefore seems necessary to elucidate if it can be naturally understood in terms of a preonic (superbradyonic?) underlying vacuum structure and in the framework of a specific space-time geometry (the SST?). From a long-term point of view, the study of possible associated deformations of standard particle physics at high energy will help to experimentally test explicit theoretical patterns. But such a phenomenology is a difficult task in practice.

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