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Tests and prospects of new physics at very high energy

Beyond the standard basic principles and 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 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 finally corrected version of the BICEP2 announcement may turn out to contain new evidence for the SST, we explore other possible implications of this approach to space-time. It turns out that 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. More generally, we discuss possible implications of our lack of knowledge of the structure of vacuum, as well as related theoretical, phenomenological and cosmological uncertainties. Possible 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 possible alternatives to standard cosmology (conventional Big Bang + inflation, ΛCDM) to interpret recent results by *Planck* [2, 3] and, if finally confirmed, the BICEP2 announcements [4, 5]. Alternative cosmologies are often closely related to possible new physics and to new space-time geometries. These unconventional scenarios deserve careful attention.

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The existence of a primordial signal in BICEP2 data is not yet certain [6, 7], as galactic dust can be at the origin of the observed CMB B-modes [8–10]. As explained in [1], if these B-modes really correspond to a signature of the early Universe dynamics, they can, together with the local privileged space direction (PSD) [12, 13] possibly observed by *Planck* [11], provide an unprecedented evidence [14, 15] for the spinorial space-time (SST) we introduced in 1996-97 [16, 17].

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 generation 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 [28–31].

1.1 Alternative cosmologies

Cosmic inflation has been basically an *ad hoc* mechanism to preserve the conventional Big Bang model based on standard Physics and taking standard particles to be the ultimate constituents of matter. But it was already pointed out in [33, 34] that a simple preonic pre-Big Bang approach based on superluminal ultimate constituents [35] can avoid basic difficulties that had led to cosmic inflation, such as the horizon problem. The flatness problem appears to be naturally solved by the SST cosmic geometry, that can be naturally combined with a pre-Big Bang scenario [1]. The cosmological constant problem can also be avoided in this way [36, 37]. 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 [34, 38] that may have deeper consequences [39–41].

Cosmologies involving a variable speed of light and/or modified versions of gravity [42–45] 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 contain more flexible solutions to avoid the cosmological constant problem.

In [45], for instance, using a nonlocal quantum gravity, very strong momentum cutoffs are considered 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 [36–40] 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 in the Universe [1, 41]. A new approach to the renormalization of quantum field theory (QFT) is also introduced in this way.

1.2 New Physics

Cosmology is not the only domain where fundamentally new physics can manifest itself. Particle properties at very high energy can 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 [46–48] requiring further experimental, theoretical and phenomenological work. It is even not yet clear [49] if the observed fall of the UHECR spectrum [50, 51] is a signature of the Greisen-Zatsepin-Kuzmin (GZK) cutoff [52, 53] or corresponds, for instance, to the maximum energies available at astrophysical sources. Furthermore, new physics can generate mechanisms faking the GZK cutoff [38, 46]. It then seems difficult, from this point of view, to reliably interpret data [54, 55] 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. This can generate experimental uncertainties.

The properties of UHECR should be studied as far as possible, including satellite experiments and searching for all kinds of signatures of new physics. Possible connections with the basic physics involved in the early Universe should be explored in detail. Systematic tests of Lorentz symmetry at UHE, as already suggested in 1996-97 [16, 34], should be a basic ingredient of these searches together with tests of all the fundamental principles of standard physics [38, 56].

Simultaneously, the validity of conventional low-energy symmetries at very high energy also deserves a careful study [46, 48], including the search for possible signatures of a transition energy scale between standard physics and new physics with strong symmetry breaking [46, 47].

Besides more indirect signatures, physics at UHE can include:

- New ultimate constituents of matter (like superbradyons [33, 34] that may exist in our Universe as remnants from the early evolution [33, 38]. They can be part of the dark matter [47, 57], with possible decays able to generate UHE particles [16, 58].

- Cosmic anisotropies related to the fundamental space-time structure, as in the case of the local PSD [37, 38] generated by the SST [16, 17] and possibly confirmed by Planck [11, 41]. 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, 41].

Anisotropies of the CMB and similar phenomena can directly influence UHECR propagation. The PSD can also lead to local anisotropies in the vacuum structure au cosmic scale, producing new effects on cosmic-ray propagation at very high energy [37, 38]. New physics can simultaneously produce vacuum inhomogeneities in the present Universe, with unconventional effects on particle structure, propagation and interactions [38, 41] leading potentially to various kinds of signatures.

As already discussed in [34, 59] and in subsequent papers, an illustrative example of the possible effect of new physics on the UHE particle properties can be built considering 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 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 suppress the GZK cutoff, as suggested in [34, 59], but more sophisticated versions can also be considered leading to various scenarios [38, 46]. Acceleration at astrophysical sources would also be altered by such a deformation of relativistic kinematics [38, 60]

1.3 Quantum Fields

New physics can influence the basic structure of vacuum. It can then lead to several kinds of observable effects, including significant modifications of QFT.

In particular, the standard description of quantum fields as harmonic oscillators, with zero modes permanently present in vacuum, can fail at scales where new physics plays a significant role [36, 37].

A new basic physics, beyond quantum dynamics, may then manifest itself and be potentially detectable through UHECR experiments [47, 48] and suitable cosmological observations [37, 41].

2 The structure of vacuum

At this stage, the notion of vacuum itself deserves being discussed more closely.

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 (SQFT) just expanded with the Universe expansion after the inflationary period. This is usually considered as a natural hypothesis, but it directly leads to the cosmological constant problem.

What can really be said on the structure of the physical vacuum in a region of our Universe where there is almost no conventional matter? As previously stressed, alternatives to the standard hypothesis exist [36, 37] and can in particular provide a new approach to the cosmological constant [1, 41].

SQFT implies that the zero modes of the harmonic oscillators associated to quantum fields are permanently present in vacuum for all momenta, and similarly for the quantum field condensates associated to spontaneous symmetry breaking. But the Casimir effect itself, such as it is studied and measured [61], does not provide a general experimental proof of such an assertion [62]. In practice, nothing is really known on the internal structure of vacuum in the absence of surrounding standard matter. The possibility that vacuum inhomogeneities influence the propagation of ultra-high energy cosmic rays was considered in [38] and in subsequent papers.

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. Essential components of the present 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.

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 standard matter, but how can this concept be generalized?

2.1 The unknown of vacuum states

Assuming vacuum can be defined, several questions naturally arise. Does vacuum have the same internal structure in all the regions our standard matter Universe, irrespectively 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 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, [37, 38] 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 [37, 63] 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 [64]) is really due to the PSD generated by the SST, such a result suggests in particular the 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 a fundamental space anisotropy.

3 Quantum mechanics

The structure of vacuum and 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 [47, 48] and in [38, 56]. Above a transition energy scale E_{trans} [48, 59], SQM can be progressively replaced by new physics involving possible ultimate constituents of matter [34, 35], 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 [56, 65], in [66, 67] and in other approaches including string theories [68, 69].

In [65], q-deformations of the quantum algebra were considered. In [48, 56], 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 $\Phi(0) = 0$. The commutation relations (4-6) naturally suggest at high energy an intrinsic uncertainty $\Delta_q E \gtrsim [3\ \Phi(p^2)]^{1/2}\ c$ and an uncertainty in the direction of the UHECR.

Such properties of the deformed quantum kinematics considered in (4-6) would potentially be able to generate [38, 48]: 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. 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. Then, new physics beyond SQM can become dominant. This possibility clearly raises the question of the actual dynamical origin of quantum mechanics.

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, vacuum excitations being described by functions of the complex coordinates.

As in the SST the four standard real space-time coordinates are replaced by two complex ones and spinors replace four-vectors, scalar products become naturally complex. Then, the complex quantum wave function Ψ of a scalar particle can be just, for instance, the hermitic scalar product of two SST spinors ξ_1 and ξ_2 : $\Psi = \xi_2^\dagger \xi_1$. The spinors ξ_1 and ξ_2 can be related to two spinorial wave functions.

Quantization can also be a natural property in the SST approach, as the most basic "elementary" particles of the standard model are now representations of the group of space-time transformations.

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

$$\Psi_{sp} (\xi) = F(\mid \xi - \xi_0 \mid^2) \, (\xi - \xi_0) \qquad (7)$$

where the function F contains a suitable cutoff in $\mid \xi - \xi_0 \mid^2$. The wave function Ψ_{sp} clearly violates local standard causality, as it takes nonzero values for present and future values of cosmic time around $\mid \xi_0 \mid$. Thus, F tacitly defines a space-time distance scale λ_{SST} below which causality does no longer hold in the conventional sense used in our standard space-time.

λ_{SST} is then likely to correspond to the space-time scale below which standard physics does no longer hold. Its definition from (7) is previous to the introduction of a characteristic speed relating space and time units. At this stage, only time units are actually present [17, 37].

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

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 normal that its normalization be determined by the requirement of preserving the validity of the fundamental equations. The Pauli exclusion principle for spin-1/2 particles can possibly be generated in this way. This can simultaneously lead to the converse effect for excitations with integer spin.

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

4 Further phenomenological considerations

A pattern reaching quantum mechanics as the result of a pre-Big Bang evolution was presented in [70, 71]. The same approach naturally produces primordial gravitational waves.

As previously stressed, interpreting recent AUGER data [55] as an evidence for the GZK cutoff would be premature as, for instance, mechanisms from new physics (spontaneous decays, effects from the deformation of quantum mechanics [48, 56] as just reminded...) can fake this cutoff with a similar flux suppression [38, 46]. Exploring possible new physics effects in UHECR and cosmological data will require a combined long-term effort. The question of vacuum structure, homogeneity and isotropy is crucial for the study of UHECR propagation.

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 target energy [48, 72]

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. 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 detailed work.

Concerning the grounds of Quantum Mechanics, a natural complement to the SST can be [1] the use of superbradyons [33, 34] 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. Even if the possible existence of superluminal signaling in quantum mechanics [73] remains controversial [74], the impossibility of such a signal propagation in conventional matter would not preclude an underlying superbradyonic vacuum structure.

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. The SST provides the appropriate space-time description of spin-1/2 particles with SU(2), 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.

The question of the origin of Quantum Mechanics is a very fundamental one. It therefore seems necessary to elucidate if it can be understood in terms of a preonic (superbradyonic?) formulation, and in the framework of a specific space-time geometry (SST?).

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