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Special theory of relativity postulated on homogeneity of space and time and on relativity principle

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Abstract: In Special Theory of Relativity time is considered to be the 4th dimension of space – time as a consequence of Lorentz invariance and Minkowski metric, in turn based on the invariance of light speed c. In this paper we'll show that, starting only from universal postulates as homogeneity of space and time and Principle of Relativity, we can obtain space and time transformations (as the Lorentz and Tangherlini – Selleri ones) characterized by an invariant speed generally different than c. These results determine crucial difficulties in the assumption of Minkowski metric and consequently in the interpretation of physical time t as the 4th component of space – time, also introducing a "relativity" feature in the velocity of light c in vacuum being no longer considerable as a necessarily universal invariant quantity and depending on the physical properties of space which originate from quantum vacuum. A novel interpretation of time, coherent with these results, defined as duration of material change in space, i.e. motion, is finally proposed.

Keywords: Special Theory of Relativity, Time, Space, Invariance, Homogeneity, Relativity Principle, Quantum Vacuum

1. Introduction

In its original formulation Special Relativity (SR) is substantially founded on two postulates: the Relativity Principle (RP) and the Constancy of the Speed of Light (CSL) c in the vacuum. In this sense SR is characterized, as partially admitted by Einstein itself [1], by an evident dichotomy. In fact, while the RP (like the postulates of space and time homogeneity and space isotropy too) can be considered as "universal", being general requirements in Physics, the CSL principle has a "special" electrodynamics origin, describing a peculiar property of light arising from Maxwell equations. On these conceptual basis, some different approaches of deriving SR, without using CSL, have been proposed [2, 3, 4]. As discussed in this paper, it can be shown that, considering only homogeneity of space and time, isotropy of space and the RP, leads to Galilean and Lorentz like space – time transformations characterized by an invariant speed. The value of such invariant speed cannot be determined within the theory itself but only by considering deeper principles associated with quantum vacuum features.

Moreover, the same invariant speed can be considered as the maximum one reachable in the Universe, although its value in is not necessarily equal to c (possibly even greater), confirming, at least theoretically, the possibility of superluminal motion (as, for example, that associated to hypothetical tachyons). We have shown these results make problematic the validity of Minkowski metric and the fundamental position of SR, namely $x_4 = ict$, not generally justifiable.

This evidence de facto introduces a relativity feature in the velocity of light that cannot be longer considered a universal invariant entity.

We have also shown that a conceptually similar result can be obtained by adopting a weaker approach in which isotropy of space is valid only in a "preferred" inertial system. In this way we recover the Tangherlini [5,6,7] and Selleri [8,9,10] space and time transformations in which the time transformations don't contain the spatial coordinates, meaning that $x_4 \neq ict$, and the speed of light becomes "relative" to inertial frame in which it is measured.

When the change of the physical properties of quantum vacuum due to kinetic energy of inertial systems is minimal, then the speed of light, when measured, appears to be constant in every inertial frame of reference.

Nevertheless extremely massive bodies as stellar objects are able to change physical proprieties of quantum vacuum of a meaningful amount, allowing measurement of the diminished velocity of light and electromagnetic waves in general. This effect was firstly measured by Shapiro [11].

A bijection test of the commonly accepted model of space – time is presented in order to evaluate the logical correspondence of the Minkowski space-time of SR with a general physical model of the Universe.

A possible origin of the invariant speed obtained through our model in the most general case and its eventual difference with respect to the value c currently assumed is discussed as well as the implications of Tangherlini – Selleri transformations. Finally, a novel interpretation of time, coherent with these results, is proposed.

2. Special Relativity without Light Postulate and General Space – Time Transformations

It can be shown [12] that, given two inertial frames S and S', moving with relative speed v along the x-axis and such that $x = x' = 0$, $y = y'$ and $z = z'$ when $t = 0$, the space and time transformations between the two systems, namely:

$$\begin{cases} x' = X(x,t,v) \\ t' = T(x,t,v) \end{cases} \tag{1}$$

can be obtained by considering only the following "universal" principles:

- homogeneity of space and time (principle A);
- isotropy of space (principle B);
- Relativity Principle (RP);

without requiring CLS at all.

In applying principle A to (1), we consider a rod whose extremes are placed, at fixed time, at the position x_1 and x_2 and a clock ticking between t_1 and t_2 placed at a fixed position, then we have, in the frame S:

$$\begin{cases} \left.\dfrac{\partial X(x,t,v)}{\partial x}\right|_{x_1} = \left.\dfrac{\partial X(x,t,v)}{\partial x}\right|_{x_2} \\ \left.\dfrac{\partial T(x,t,v)}{\partial t}\right|_{t_1} = \left.\dfrac{\partial T(x,t,v)}{\partial t}\right|_{t_2} \end{cases} \tag{2}$$

and analogous relations in the frame S'.

Equations (2) state the functions $X(x,t,v)$ and $T(x,t,v)$ are linear with respect both space and time, and since x_1, x_2 and t_1, t_2 are generic, the proportionality factors in (1) are functions of v only, then we can write:

$$\begin{cases} x' = A(v)x + B(v)t \\ t' = C(v)x + D(v)t \end{cases} \tag{3}$$

where A, B, C and D are functions of v only.

Since $x' = 0$ when $x = vt$, the following condition holds:

$$B(v) = -vA(v) \tag{4}$$

Principle B implies the invariance of transformations (3) when changing x to $-x$ (and so x' and v), this gives the conditions:

$$\begin{cases} A(-v) = A(v) \\ B(-v) = -B(v) \\ C(-v) = -C(v) \\ D(-v) = D(v) \end{cases} \tag{5}$$

Relativity Principle requires the inverse transformations of (3) must assume the same form of (3) and moreover, as it has been already shown [3], the combination of postulates B and RP implies the reciprocity of relative speed among two inertial frames S and S' (that is $v_{SS'} = -v_{S'S}$). These two requests, applied to (3), gives, by considering (4) and (5):

$$\begin{cases} A(v) = D(-v)\left[A(v)D(v) - B(v)C(v)\right] \\ B(v) = B(-v)\left[B(v)C(v) - A(v)D(v)\right] \\ C(v) = C(-v)\left[B(v)C(v) - A(v)D(v)\right] \\ D(v) = A(-v)\left[A(v)D(v) - B(v)C(v)\right] \end{cases} \tag{6}$$

The system of (5) and (6) provides:

$$C(v) = \frac{A^2(v) - 1}{B(v)} \tag{7}$$

and:

$$D(v) = A(v) \tag{8}$$

Now inserting (4), (7) and (8) in (3) we can write:

$$\begin{cases} x' = A(v)(x - vt) \\ t' = -\dfrac{A^2(v) - 1}{vA(v)} + A(v)t \end{cases} \tag{9}$$

Now considering a third inertial frame S'', characterized by the coordinate (x'', t'') and moving at speed u with respect to S', we have:

$$\begin{cases} x'' = A(v)A(u)\left\{\left[1+v\dfrac{A^2(v)-1}{vA^2(v)}\right]x-(v+u)t\right\} \\ t'' = A(v)A(u)\left\{\left[-\dfrac{A^2(u)-1}{uA^2(u)}-\dfrac{A^2(v)-1}{vA^2(v)}\right]x+\left(1+v\dfrac{A^2(u)-1}{uA^2(u)}\right)t\right\} \end{cases} \tag{10}$$

the RP implies the coordinates (x'',t'') transform in the same way as (x',t'), that is the transformation (10) must assume the same form as those from S to S', this means the condition (8) must hold, namely:

$$\frac{A^2(u)-1}{u^2A^2(u)} = \frac{A^2(v)-1}{v^2A^2(v)} \tag{11}$$

Since the values of v and u are arbitrary, in the (11) the first and second members are both constants and then we can assume:

$$\frac{A^2(u)-1}{uA^2(u)} = \Lambda \tag{12}$$

where Λ is a constant, having the dimension of the inverse of a squared velocity, independent from the particular inertial frame considered.

Solving (12) and, noting that when $v=0$ must be $A(v)=1$, we can write:

$$A(v) = \frac{1}{\sqrt{1-\Lambda v^2}} \tag{13}$$

Transformations (3) then assume the form:

$$\begin{cases} x' = \dfrac{1}{\sqrt{1-\Lambda v}}(x-vt) \\ t' = \dfrac{1}{\sqrt{1-\Lambda v}}(-\Lambda vx+t) \end{cases} \tag{14}$$

It can be easily seen the velocity addition rule can also be obtained by considering the above formulation. If w is the velocity of the frame S'' relative to S we can write:

$$\begin{cases} x'' = A(w)x + B(w)t \\ t'' = C(w)x + D(w)t \end{cases} \tag{15}$$

by considering (10) we have:

$$A(v)A(u)\left[1+v\frac{A^2(v)-1}{vA^2(v)}\right] = A(w) \tag{16}$$

from which, recalling (13):

$$w = \frac{v+u}{1+\Lambda vu} \tag{17}$$

The (14) represents the most general form of space and time transformations (in one dimension) satifying the most universal principles A, B and RP.

Furthermore it can be shown that $\Lambda \geq 0$: from (13) we have $A(v)>0\ \forall v$, on the other hand, from (10) we obtain $A(v)\geq 1$, since $A(w)>0$. The case $\Lambda = 0$ corresponds to Galilean transformations without invariant speed (formally an infinite speed due to absolute simultaneity) while for $\Lambda > 0$ we obtain a set of time and space transformations all characterized by an invariant speed $v_{inv} = \Lambda^{-1/2}$ independent of any inertial frame, whose value nevertheless cannot be determined within the theory itself but must be obtained by considering more fundamental principles.

3. About the Relation between Space and Time in Special Relativity

The relation between the fourth component of space-time and time in special relativity, namely:

$$x_4 = ict \tag{18}$$

is strictly related to Minkowski metric:

$$\Delta s^2 = c^2\Delta t^2 - \Delta x^2 + \Delta y^2 + \Delta z^2 \tag{19}$$

where $(\Delta s)^2$ represents the squared interval between two events. The possibility to assume the (18) substantially depends on the invariance of $(\Delta s)^2$ among inertial frames:

$$c^2t'^2 - x'^2 - y'^2 - z'^2 = c^2t^2 - x^2 - y^2 - z^2 \tag{20}$$

Recalling from the above discussion that the most general space and time transformation satisfying the universal postulates of homogeneity, isotropy and RP, are represented by (14), substituting (14) in (20) we have:

$$\begin{gathered} (\Delta s')^2 = \alpha^2\left(c^2\Lambda^2v^2-1\right)x^2 + \alpha^2\left(c^2-v^2\right)t^2 + \\ +2\alpha^2 v\left(1-c^2\Lambda\right)xt = (\Delta s)^2 = c^2t^2 - x^2 \end{gathered} \tag{21}$$

Equation (21) shows that, in the most general case, the squared interval of the metric is not invariant under the space – time transformations given by (14). In order to obtain the invariance of $(\Delta s)^2$, on which Minkowski metric is based, and the validity of (20), the term in xt in (21) must identically vanishes, this implying:

$$1 - c^2\Lambda = 0 \tag{22}$$

or

$$\Lambda = \frac{1}{c^2} \tag{23}$$

corresponding to the special case of Lorentz space – time transformations.

Nevertheless the (23) gives only a particular value of Λ among all the possible ones compatibles with the principles A, B and RP. In fact the assumption $\Lambda = c^{-2}$ is not required by the internal consistence of the theory itself, since the latter can be built only on the above three principles without referring, as in the "standard" formulation of SR, to CSL that is, in turn, not a logical requirement of the theory itself but rather an experimental suggestion. This means the interpretation of the physical time as directly related to the fourth coordinate of a space-time as a whole, expressed by (18), is not "a priori" justified by universal postulates.

4. The Possible Origin of Invariant Speed and the "Relativity" of the Speed of Light

As we have seen, assuming universal principles of homogeneity of space and time, isotropy of space and RP leads to a version of special relativity without CLS postulate characterized by an invariant speed generally different from c, in which we can't generally assume $x_4 = ict$. This invariant speed originates from a more fundamental and yet undiscovered property of the Universe. Having this quantity the dimension of a ratio between a length and a time it has been proposed [13] it could be related to the conjecture of the discreteness of space – time at a fundamental level and, in particular, to the existence of Planck scale of space (Planck's length l_P) and time (Planck's time t_P).

This could lead to the assumption:

$$\Lambda = \left(t_P / l_P\right)^2 \tag{24}$$

at a first look virtually justified assuming a generalized uncertainty principle [14, 15], obtained combining some results of General Relativity and Quantum Mechanics:

$$\Delta x = \Delta x_{QM} + \Delta x_{GR} \geq \hbar / 2\Delta p + 2\left(l_P^2 / \hbar\right)\Delta p \tag{25}$$

where Δp is the uncertainty in the moment of a given particle. According to this reasoning, the discovery of the Planck scale should arise from a synthesis of some elements of general relativity and quantum field theory, as well as from the result of the main different proposals of quantum gravity, suggesting the existence of a universal minimum length [13,14] probably considerable as model – independent.

However, apart from the very crucial debate about the observational vs ontological nature of the Planck scale, still far from being clear [16], we must remember the result given by (24) is obtained by assuming for l_P and t_P the following expressions:

$$l_P = \sqrt{\frac{\hbar G}{c^5}}; \qquad t_P = \sqrt{\frac{\hbar G}{c^3}} \tag{26}$$

both containing c as fundamental physical constant, because they are themselves based on " traditional" SR (that assumes the CLS postulate) and consequently unusable to prove the logical chain:

$$\Lambda = \left(t_P / l_P\right)^2 \rightarrow \left(\hbar G / c^5\right) / \left(\hbar G / c^3\right) = c^{-2} \tag{27}$$

Equation (27) in fact depends on the metric given by (19) and, consequently, on the validity of (23) which instead it should be able to prove.

The above discussion evidences that, in the most general case, the invariant speed is not equal to c, namely it doesn't represent the actual speed of light in vacuum (whose value, as we will see, can generally vary although it could be equal to the assumed value c in the most cases, far from very massive bodies) but is related to a more fundamental and invariant property of the underlying quantum vacuum and can be considered as the actual maximum possible speed in the Universe [17].

The above picture is coherent with the assumption that fundamental arena of the universe is quantum vacuum, in which speed of light depends on the physical properties of quantum vacuum itself mainly represented by energy density and its electromagnetic properties [18,19]. This view is also supported by the possible interpretation of quantum vacuum as a condensate [15] (like, for example, the Bose – Einstein one) that could also explain, as recently proposed within the axions theory [20], the dark matter problem of cosmology [21].

According to this model, the speed of light in vacuum can change as the above quantum vacuum properties changes.

Similar conclusions, although based on a different theoretical model than that used in [15, 18], have been obtained in two others very recent studies [22, 23]. In the first one, realized by Urban et al. [22], the quantum vacuum is considered as filled by pairs of virtual particles characterized by fluctuating energy levels, producing the correspondent fluctuations of the speed of light in vacuum. In the second one, realized by Leuchs and Sanchez – Soto [23], the speed of light has been related to a sort of impedance of the quantum vacuum that, in turn, would be associated only with the sum of the square of electric charges of virtual particles but not on their masses.

Therefore, the very crucial conclusion we can obtain is that the speed of light varies as the property of quantum vacuum change, suggesting that c couldn't be considered as a universal and invariant constant nor as the maximum speed reachable in the Universe, it being not necessary equal to the invariant speed given by Λ. This latter consideration adds further theoretical reasoning to the possibility of superluminal motion as already suggested by several past and recent studies [24, 25].

The possibility of different values of the invariant speed (even not finite) obtained in the formulation of SR without CLS, has deep consequences on synchronization of clocks located in two different inertial frames and, consequently, on the concept and measurement of simultaneity, which now appear different from that introduced in the "standard" SR.

As we have seen, the invariant speed could be related to deepest features of quantum vacuum and, for this reason, its value will be calculable only after the elaboration of a more complete theory of quantum vacuum itself based on the results discussed in [15,18] that is currently in progress. Nevertheless, as we'll show in the following, it is possible to adopt, through weaker demands about the validity of the universal postulates A, B and RP, an approach able to permit the calculation of relative duration of change among two generic inertial frames S and S', assuming the value of the speed of light substantially constant in the Universe as long as it can be considered flat, as the most recent experimental evidences show.

The proposed approach is based on the use of Tangherlini transformations [5] given by the equations:

$$\begin{cases} x' = \gamma(x - vt) \\ t' = \gamma^{-1} t \end{cases} \tag{28}$$

where $\gamma = \left(1 - v^2/c^2\right)^{-1/2}$ is the Lorentz factor, v the relative velocity and c the speed of light whose interpretation in this model will be clear in the following discussion.

The transformations (28) have been initially introduced by Tangherlini in the case where the clocks, positioned in the two inertial frames S and S', are synchronized with each other by a sort of superluminal – speed signal (as, for example, through hypothetical tachyons) travelling at infinite velocity (a possibility, as we have seen, not theoretically prohibited by the above formulation of (14)), but they are also valid [5] when the two clocks are synchronized in a resting "special" inertial frame and subsequently used for the synchronization of all the other clocks located in the moving inertial frames in the instant when they meet the rest clocks. This method obviously leads to the inequality of different inertial frames among which the "preferred" one is that where the first synchronization of clocks takes place.

This "speciality" corresponds to an anisotropy of the speed of light in the inertial frame S' according to the equation [5]:

$$c' = c / \left[1 + (v/c)\cos\alpha\right] \tag{29}$$

where c is the speed of light in the inertial frame S, c' is the speed of light in the inertial frame S' and α is the light angle counted from the x' axes.

It is now interesting to recall that the (29) is able to reproduce the results of Michelson – Morley experiments, as well as the Sagnac effect [26] and to keep Maxwell equations to be invariant [5].

More recently Selleri [8, 9, 10] has shown that the transformations (28) can be obtained from a wider class of space and time transformations of the form:

$$\begin{cases} x' = \frac{1}{R}(x - vt) \\ y' = y \\ z' = z \\ t' = Rt + e_1(x + vt) \end{cases} \tag{30}$$

where $R = \left(1 - v^2/c^2\right)^{1/2}$ and e_1 is a "synchronization" parameter whose value characterizes the simultaneity of distant events or, equivalently, the method of synchronization in the "preferred" inertial frame S and must be set to zero [8].

Perhaps the most important feature of (28) and (30) with $e_1 = 0$ is the transformation for physical time and its independence from the space dimensions, showing that time, interpreted as duration, is not directly related to space.

It is very interesting to note that the transformations (28) and (30) don't satisfy the invariance condition (20), giving further evidence to the conclusion that generally $x_4 \neq ict$.

We have seen that a procedure of clocks synchronization different than the Lorentz one leads to different classes of space and time transformations in which we cannot assume the validity of Minkowski metric invariance, as also occurring in the general case represented by transformations (14) when $\Lambda \neq c^{-2}$.

Nevertheless, we must underline a deep difference between the transformations (14) and those given by (28) - (30): in the first case (Lorentz like transformations), given two inertial frames S and S', the velocity of light in S, being measured by the observers located in S and S' is always the same; in the second case (Tangherlini – Selleri transformations) the velocity of light c', measured in S' by an observed located in S and given by (29), depends on the angle α and it is differente than the velocity measured in S' where it is always $c' = c$. In this sense the absolute simultaneity associated to the duration – space independence, expressed by the last of (30) with $e_1 = 0$, results in the anisotropy of the coordinate velocity of light in the moving inertial frame. It cannot be excluded this anisotropy could be related to a corresponding anisotropy of quantum vacuum due to the motion of S'.

5. "Bijection Test" does not Confirm Model of Space – Time as a Fundamental Arena of the Universe

In order to verify the level of adequacy of the currently accepted space-time model as a fundamental arena of the

Universe at a logical level, we can use the bijection function of set theory. A given element in the "model" set exactly corresponds to only one element in "Universe" set.

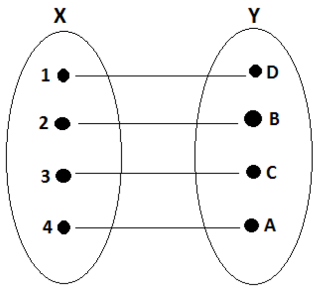

Figure 1*. A bijective function, $f : X \rightarrow Y$, where set Universe X is* $\{1,2,3,4\}$ *and set model Y is* $\{A,B,C,D\}$ *. For example,* $f(1) = D$ *.*

In the physical Universe, the following five elements are perceived by senses: matter, energy (all types of electromagnetic energy), space, change and time as duration of changes, running in space. These are perceivable elements of Universe set X. The sixth element of the Universe set X is the observer, which perceives the other five elements. Using a bijective function, we can transform these six elements of the Universe set X into six elements of model set Y as shown in fig. 2.

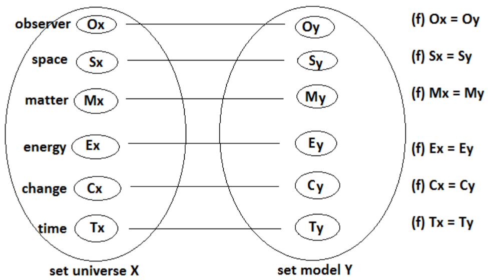

Figure 2*. The correspondence between the elements in the Universe set and the model set.*

Observer has experimental evidence that matter can transform in energy and that matter is made out of the energy. Furthermore, particles spontaneously appear from space and disappear back in it leading to the assumption that also space is a type of energy (named quantum vacuum). Element of matter M_x, element of space S_x and element of energy E_x in the set X are elements of subset EX (Energy subset of X). Element of matter M_y, element of space S_y and element of energy E_y in set Y are elements of subset EY (Energy subset of Y). In the Universe set X we have four fundamental elements. In the model set we also have four fundamental elements:

$$\begin{gathered} X:\{O_x, C_x, T_x, \{EX\}\} \\ Y:\{O_y, C_y, T_y, \{EY\}\} \\ EX:\{E_x, S_x, M_x\} \\ EY:\{E_y, S_y, M_y\} \end{gathered} \tag{31}$$

In this picture space and time are two different elements in the Universe set X and two different elements in the model set Y. Time T_x does not enter subset EX and time T_y does not enter subset EY. Bijection test then shows that space is energy and time is duration of energy changes. The manifold of Minkowski space-time in SR has no "bijective" correspondence in physical Universe. Bijection test also shows that timeless approaches [27], which would like abolishing time as a fundamental quantity, are failing.

As seen in chapters 3 and 4 universal theoretical postulates do not require time is directly related to space. In experiments with a clock we measure physical time as duration of material changes which run in a concrete physical space: time is related with space as a duration of change in space, being not the 4th dimension of space but only a mathematical parameter measuring this change which still exists as such.

6. Time as Duration Excludes Time Travel of Massive Bodies and Particles

The interpretation of true physical time as duration of changes, happening in 3D space, is also able to give a simple physical reason to justify the Hawking chronology protection conjecture which purpose, as known, is to prevent time travels into past, supposing the impossibility of stable closed time-like curves [28].

In fact, so far, several objections have been advanced against its validity saying that it might break down and an "anti-chronology" protection conjecture might hold because there is no law of physics preventing the appearance of closed time-like curves [29].

In this paper we have shown that, if we refers only to "universal" principles, as space and time homogeneity and RP, we cannot generally assume $x_4 = ict$, indicating that is a wrong view predicting the possibility for massive bodies and elementary particles to travel in time, simply because time itself couldn't be a physical "component" of the universal arena but only a mathematical measure of the motion duration of the changes happening in space.

From this point of view also interpretation of positron as an electron which moves backward in time [30] appears non adequate. We suggest here that particles and their respective antiparticles have origin in quantum vacuum where time represent the duration of their motion and existence between appearance and annihilation.

The results of application of the "Bijection test" to the existence of close time - like curves in General Relativity is entirely similar to that of the existence of time as a 4th dimension of space in Special Theory of Relativity. These curves can be considered as purely mathematical entities having no necessary existence in the physical Universe. A given theoretical model could allow closed time - like curves as mathematical objects, but this does not mean that one can truly travel in physical time.

7. Conclusions

In this paper we have shown the fundamental relationship assumed in SR between space and time, namely $x_4 = ict$, cannot be justified by the universal postulates of homogeneity of space and time and the Relativity Principle but only by the introduction of the postulate of constant speed of light (CLS) in vacuum, a priori not justifiable ontologically nor logically within the SR itself. We have shown that, dropping the CLS principle, a modified version of SR, satisfying the homogeneity of space and time and the isotropy of space, can be developed. This theory is characterized by an invariant speed whose value is not necessarily equal to the usually accepted speed of light in the vacuum, namely c.

The invariant speed emerging from the theory can also be considered as the maximum reachable speed in space and it could be related to some deep, although not yet completely understood, invariant physical properties characterizing quantum vacuum (as, for example, the constant ratio of space and time Planck scales, in which, anyway, the role of the constant c should be reinterpreted), while the observed speed of light would be related to the actual properties of quantum vacuum, that could be different than the invariant ones in each specific situation .

We have shown another evidence supporting this interpretation could arise from the adoption of weaker postulates, including the homogeneity of space and time, but where isotropy of space holds in a "preferred" inertial frame in which the clocks synchronization, that can be only obtained when the two clocks meet each other, is realized. In this way we can obtain a set of space and time transformations, like the Tangherlini and Selleri ones, in which the relation between t' and t doesn't depend on space (so we also have $x_4 \neq ict$) and the speed of light acquires a "relative" meaning since its value, in the inertial frame S', is anisotropic.

The results presented in this paper can be summarized in the following remarkable key points.

The formulation of the SR based on the adoption of homogeneity and isotropy principles without considering CSL postulate, states a clearly ontological and operative distinction between the "physical" time t and the "coordinate" time x_4 that makes generally no possible the identification of time as a "spatial" coordinate of a four – dimensional space–time as a whole.

As a result, also the use of Minkowski metric, founded on the invariance of the space–time interval $(\Delta s)^2$ in turn based in the assumption $x_4 = ict$, becomes problematic.

In order to coherently interpret the above results, a novel definition of physical time as duration of changes occurring in a 3D space, until now ignored by the present "timeless approaches" in physics, is then proposed.

"Relativity" of time as duration of material change is extended on light which "relative" velocity depends on the physical properties of space originating from quantum vacuum.

Our results imply some very crucial questions to be further and deeper studied. First of all, as we have seen, the model of a SR without CSL postulate, doesn't allow, as such, the determination of the value of the universal invariant speed emerging from it, that plays a key role in its connection with the most fundamental structure of a space – time and, ultimately, with the underlying quantum vacuum we think determines it.

A second aspect, revealed by the loose of general validity of the equation $x_4 = ict$, concerns the need for the elaboration of a new metric of space, eventually including the Minkowski one as a particular case.

But the most crucial consequence emerging from our model is perhaps represented by the change required in the conception of mass and energy with respect to the "commonly" accepted ones in SR, based on the validity of Lorentz transformations that, as we have shown in this paper, are not the only possible ones if we refer to the most universal postulates of homogeneity of space and time and Relativity Principle.

A last but not least important aspect requiring further improvements concerns the new definition of simultaneity implied by the space and time transformations different than the Lorentz ones and, particularly, by the Tangherlini – Selleri equations giving the anisotropy of light speed in different inertial frames in relative motion.

The fundamental points above summarized are currently being studied and will be discussed in some forthcoming papers. Our results open a fundamental question in physics: they suggest a new interpretation of physical time and a need for a reformulation of SR based on more fundamental physical principles characterizing the quantum vacuum.

These results furthermore provide the basis for the development of a novel 3D model of physical space, viewed as the fundamental arena of the Universe, based on a "Planck metric" (directly related to the Planck scale) in which time is the duration of material changes.

The proposed model could also give valuable insights to the superluminal motion theory and to quantum vacuum based theory of gravitation.

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