

Supporting abstract relational space-time as fundamental without doctrinism against emergence

Sascha Vongehr^a

Department of Physics, Nanjing University, Nanjing 210093, P. R. China

The present paper aims to contribute to the substantivalism versus relationalism debate and to defend general relativity (GR) against pseudoscientific attacks in a novel, especially inclusive way.

This work was initially motivated by the desire to establish the incompatibility of any ether theories with accelerated cosmic expansion and inflation (motto: where would a hypothetical medium supposedly come from so fast?). The failure of this program is of interest for emergent GR concepts in high energy particle physics. However, it becomes increasingly important to guard scientific results against their misrepresentation by fundamentally anti-scientific agendas. We therefore argue that although it is not known whether the perceived space-time is fundamental (rather than a condensed state or a particular membrane), in a fundamental theory, space-time must be abstract relational: fundamental space-time is the consistent spatial-temporal arrangement of events.

To pursue its own goals, this work should be accessible to a wide audience: physicists, philosophers of science, those being tempted by anti-relativity theories, but also those who vigorously defend some orthodox relativity that is not actually supported by GR. It must thus be extensive in order to satisfy the different parties' desire to have included and understood their respective positions.

Keywords: Relativity; Metric Expansion; Pseudoscience; Substantivalism; Relationalism

1	Introduction	2
1.1	<i>Differentiating abstract views, substance views, and pseudo-science</i>	5
2	The strong basis of an abstract relational space-time	7
2.1	<i>Special relativity as a role model of relational resolution</i>	16
3	Critical evaluation of the arguments	19
4	Why substance-views are attractive tools also for modern physics	25
4.1	<i>Causality preserving superluminal velocity but no time-travel</i>	28
5	References	32

^a Electronic mail: vongehr@usc.edu

1 Introduction

Firstly a word directed at philosophers of science and particle physicists who demand high level terminology and formalism before seriously considering anything as even potentially belonging to their field: That many physicists and maybe even part of the educated lay public are able to comprehend at least the gist of this work is vital to its aim of fighting pseudoscience. Sophisticated terms often mislead even the most educated in closely related fields. For example, “substantivalism” is actually an “ontic commitment” to the points of space-time and in that sense not at all what a physicist likely thinks it means and what we will casually call “substance-views”. The latter includes a variety of concepts ranging from naïve ethers up to emergent relativity in cutting edge modern particle physics models, where perceived space-time regions do not coincide with regions of particles of an underlying hypothetical substance. A display of great sophistication comes with discussing indeterminism due to the “hole argument¹”, but such are complexities concerning aspects that anyways likely reside outside of the domain of applicability of general relativity (GR) while even naïve ethers ensure determinism plainly by an naïve “living through time” of the underlying substance (as will be explained). We will instead focus on what we think is vital to the issue, display almost no equations, and the terminology will be relatively simple.

The relevance of this work is enumerated as follows. This work aims to:

(I) Contribute to the substantivalism versus relationalism, absolutism versus relativism debates by

(I.I) supplying an up to date support of relationalism and relativism while partially summarizing known positions, partially presenting some novel expositions (“expansion-

paradox”, relational nature of light, improved arguments against cosmologically preferred reference frames and time travel),

(I.II) clarifying, in the light of modern physics, why the support for relationalism should not come from physics, but from philosophy itself; that it is incorrect and possibly misleading to base one’s view on contemporary or even the best future physics.

(II) Support proper science and philosophy against anti-scientific agendas in the “war against science”, which is not unrelated to the “science wars” and fought by increasingly influential and merging forces like the religious right, creationism, esoteric “alternative medicine”, anti-Semitism (anti-Einstein) ether theories, etc. This item includes

(II.I) clarifying that the growing perception of “establishment conspiracy” demands this work should be presented accessibly to two groups in particular: (A) Educators and physicists who actively defend relationalism and relativism with false arguments; who thereby do more harm than help the cause, and (B) the many lay people that are nowadays interested in philosophy and physics and are thus exposed and tempted by pseudoscience. We sincerely wish that a peer-reviewed work will find direct use by for example science bloggers on the internet who participate in widely followed discussions with anti-scientists on a daily basis.

The stated purposes are intimately connected and should not be separated into different publications. For example, (I.II) above is not merely an obsession with what logic compels us to. Moreover, any bias in favor of currently favored “established” science

would disqualify us in the eyes of that part of the intended readership that perceives science to be effectively caught up in conspiracies (II.I) in one way or another^b.

In GR, space-time is *dynamic*, which means that it reacts to the energy-momentum distribution. Nevertheless, orthodox GR can be described as a “relativity is kinematics” position^{2,3}, i.e. an *abstract-view* (relationalism, structuralism) where the dynamics emerges from symmetries rather than from any concrete mechanism that could facilitate visualization and acceptance by a wider lay public. The idea that relativistic kinematics arises from the *dynamics* of objects interacting with their background space is actually disfavored by orthodox GR, because such an interpretation treats the background as too real, too “substantiated”; it seems to resurrect the background as a medium or ether, while background independence is the mark of distinction of GR. Some ideas in high energy particle physics (e.g. the stringy universe on a membrane, Higgs mechanism, etc.) seem to clash with an orthodox position. However, mentioning modern physics becomes a popular way of introducing esoteric pseudoscience, in this case in order to promote abstruse ether theories, which is still today partially driven by an anti-Semitic hidden agenda that aims to discredit Albert Einstein. This paper argues that no ether theory of a space-substance can possibly be a fundamental theory of space-time: Abstract relational space-time prevails at the fundamental level; alternatives do not make sense fundamentally, and this is independent of any future success or failure of a background independent theory.

^b “Ontic structural realism” is as distant from direct realism as transcendental idealism. The main motivation for still insisting on the term “realism” is to keep out irrationality and mysticism. The war on science tries to empower irrational agendas dangerous to all of us. Philosophers should thus appreciate this work as an important effort although our aim precludes participation with most of the philosophical terminology and although we feel that realism versus idealism etc debates constitute mere exercises in

Many believe that our main thesis is well established and any further argument unnecessary, but such confidence has resulted in neglect. The use of by now rather weak arguments underestimates and strengthens the enemy. We feel that arguments must bear witness of a sympathetic reading and proper understanding of all involved parties – everything else is just a hardening of frontlines.

1.1 Differentiating abstract views, substance views, and pseudo-science

GR explains well how space-time behaves on large and medium length scales, but it is silent about any underlying microscopic nature. Theories like GR and thermodynamics derive their beauty and strength from being grounded in self-consistency which is valid regardless of the nature or even of some reality (existence) of any underlying microscopic physics. GR regards space-time as no more than the relational description that allows space-time events involving energy densities to be consistently arranged relative to one another. This concept of “space-time is pure arrangement” (*abstract-view*) discourages the point of view that space may be successfully described by the assumption of it being “something”, some substance whose properties and dependence on (abstract relational) time give rise to it being describable by GR in such good approximation (something or *substance-view*).

To focus on some concrete substance instead, is from the outset motivated by a concrete physical *thing*, the substance, and thereby to be differentiated from alternatives to GR that try to partially substitute dark energy in recent epoch accelerated expansion or dark matter, like MOND⁴ for instance. “Einstein-Aethers”⁵ introduce terms to field equations

rhetoric between different language preferences, that opposing camps basically say the same about what

or actions that have effects on especially small length or low acceleration scales, say in order to modify computations of galaxy rotation rates while not touching Mercury's perihelion shift. Modern ethers like quintessence^{6,7}, scalar-tensor theory^{8,9}, dark fluid¹⁰ or Chameleon scalar field^{11,12} are motivated by the observations of accelerated cosmic expansion; TeVeS¹³ was introduced considering everything from early nucleon synthesis down to the whimsy Pioneer anomaly^c. Such work motivates further tests of GR that at times constitute advanced ether-drift experiments¹⁴. Such investigations are *not* pseudoscience, on the contrary.

Especially 20th century physics has taught that progress is often inspired by *concrete* models, by way of considering the *measurement tools* (operational arguments involving light rays, Heisenberg microscope, instrumentalism) and via principles that connect with *hands-on-physical* situations like a free falling lift (weak equivalence), an interacting wave packet (uncertainty), and many more (noisy transmission channels, etc). This alone justifies occasionally deceptively naïve questions like “If space is a substance that has to itself expand or multiply during expansion – what would it imply?” even if one does *not* believe in such substances. Regardless of one's preference, a rigid opinion foregoes on the benefits that opposed views bring to model-building. As long as concrete space-substance models are tools in the just described manner and within the strict confines of scientific rigor, they do also not yet constitute pseudoscience.

Among several signs that indicate the presence of pseudoscience, an unmistakable one is the extremism of advertising a hypothetical space-substance as more fundamental than

one cannot talk about meaningfully anyways (Wittgenstein).

any abstract view. It is an open question whether the space-time we directly perceive is the fundamental abstract one or maybe rather a condensed vacuum state¹⁵, one particular stratum among many, or a membrane in a much more complex, maybe even non-covariant bulk space-time. Nevertheless, we are committed to an abstract point of view on the nature of fundamental space-time and this automatically supports orthodox GR.

2 The strong basis of an abstract relational space-time

One can list many reasons for favoring an abstract-view. The listing here starts with the generally better known ones (G1 to G6) and strengthens them at times (e.g. G3), goes on to consider thermodynamics (T1 and T2), and then adds arguments concerning space-time and its expansion (S1 to S4). A further category deals with the purported intuitiveness (I1 and I2) of space-substance models. This classification avoids getting lost, but the items partially overlap and could be put in a different order, e.g. one may like to employ Occam's razor (G6) to cut an infinite regress short (G5). How briefly something is mentioned has no relation to its importance, as will be immediately evident from G1.

G1) A very important fact is that an *operationally* justified *axiomatic* basis yields Riemann geometry as the observed geometry in the philosophically correct sense of a-priori; a term physics often misappropriates. Many authors have dealt with this particular

^c Radio signal data reveal the velocity and distance of spacecraft. After all known forces are taken into consideration, it appears that a very small sunward acceleration of $a = (0.874 \pm 0.133) \text{ nm/s}^2$ remains for both Pioneer probes. The product of light velocity c and Hubble constant H is by coincidence (?) close to a .

subject thoroughly and there is little disagreement involved that would be relevant to our task here.

G2) Around the time that special relativity (SR) was developed, the famous ether drift experiments^{16,17,18} showed that the then prominent ether models were either wrong or hidden from any conceivable experiment. SR's successes and the whole notion of relativity dissolved the "space is something" away. GR drove this point home further. For instance, the event horizon singularities around black holes were resolved to be merely coordinates inconveniently chosen. This leaves the same flavor behind as a proper explanation of SR's twin-paradox, namely that any absolute notions will only get you into trouble.

G3) GR's localization (gauging) of SR's global symmetry is as such not a symmetry breaking, but GR in a sense breaks even its own local Lorentz symmetry via its cosmology. Cosmology leads to an average background of galaxies and a cosmic microwave background (CMB). This provides access to a unique reference frame in which that background appears isotropic. This universal big-bang reference frame has certainly greater significance than just another inertial frame like some hypothetical intergalactic spaceship. Accordingly, it inspired substance-views via rubber sheet and raisin dough models that illustrate the metric expansion of the universe. However, GR cosmology never conflicts with the underlying relativistic paradigm (coordinate covariance) and therefore strengthens the conclusion that any imagined "rubber sheet" stays hidden from our observation not only practically, but *on principle*. Many defenders of orthodox GR are satisfied at this stage, although even "*on principle*" unobservable things may still exist metaphysically. But one can strengthen the argument further.

Without any classical time existing before the big-bang for something waiting to happen, one cannot call the symmetry breaking entirely “spontaneous”. Nevertheless, spontaneous symmetry breaking is involved and the analogy with an upright standing stick falling over into some random direction very fitting: it has to fall in some direction; according to the quantum mechanical (QM) relative state description¹⁹ it falls in many directions; there is no justification to regard any direction as special. This robs the CMB frame of its significance.

G4) Symmetries are power tools in physics, e.g. when applying conservation laws rather than integrating over time. Symmetries are the origin of what seems like divine coincidence in descriptions that only realize these symmetries implicitly. Facts of nature seem to conspire against a perpetual motion machine, always throwing in some effect that yet again makes a novel design unworkable. Theories that make the responsible symmetries explicitly manifest are powerful and beautiful for the same reason: the symmetries. In the context of relativity theory, the translation of complicated dynamics (forces) into mere kinematics is of surprising beauty again and again in every considered instance, like explaining Lorentz contraction or cosmic expansion (see also S2 below). To summarize all of gravity physics as a localized (gauged) $SO(1,3)$ -group symmetry is extremely beautiful.

G5) An abstract viewpoint avoids an infinite regress: If space is something, like an ether, where is that ether? If in another space, then where and what is that other space? Substance-views favor considering the substance’s perhaps higher dimensional embedding, which is actually welcomed from a modern perspective. However, an infinite tower of spaces in spaces as well as some weird circular construction would be a

fundamental theory that is *not* itself a substance view anymore, but highly non-trivial and abstract. One needs to provide an abstract relational fundament for the thereby lowest stratum in order to break an infinite regress off and be left with a finite series of space-substances in spaces-substances. An ultimately fundamental theory must by definition explain everything without reference to another, more fundamental one.

G6) If different views are equally consistent with all observations, an application of Occam's (Ockham's) razor should be considered: given two equally powerful theories, the more parsimonious one, the one with less ingredients should be favored. If the preferred frames and the substance-like aspects of space-time are fundamentally hidden, they are likely more ballast than providing didactic convenience. Occam's razor is a popular argument and relates to more fundamental kinds of parsimony, like Leibniz equivalence, i.e. the identification of indiscernible states. Many would think it an oversight not to list it, although it is a weak argument given the ever improving ability to discern.

GR has so much in common with thermodynamics (TD) that it basically may be nothing but the TD of space-time³, which would for example explain why so many proposals (Carlip lists eight²⁰ different ones) for the nature of black holes (BH) all produce the same dependence between the entropy and the area of the BH. The fact that joining BH always increases the total area A may be no more than the second law of TD, which states that the entropy S in a closed system cannot decrease. GR and TD are grounded in consistency which is valid independent of the nature of and even of the existence of any underlying microscopic nature.

T1) The analogy with TD suggests an underlying microscopic world from which GR is emergent. However, taking the analogy seriously, it would also suggest that the physics of a microscopic level can only ever give rise to orthodox GR just as statistical mechanics can only give rise to TD. Since TD is based on consistency alone, no discovery in the microscopic world can possibly change TD. TD is only modified on nano-technological scales (finite system TD). Hence, the analogy further rejects drawing on ether theories in order to argue against GR and it suggests that any space-substance model can at most suggest corrections to GR that are valid at the microscopic scale. Instead of supporting space-substance views, the analogy even discourages corrections on medium length scales that could influence galaxy rotation rates or account for the Pioneer anomaly.

T2) The TD-analogy can at most encourage substance-views as intermediate level tools on the way to an abstract resolution. TD is itself based on self-consistency of a few, very general assumptions. It is also understood as emergent from statistical *mechanics* of the microscopic world, and the micro level of atoms and molecules is a substance-view. However, the emergence is only consistent if that substance is already understood to be only a rough approximation to an abstract quantum picture. For QM it has not yet been fully worked out, but it is already clear that QM is equally based on self-consistency. In case of QM, an emergence from hidden variables is impossible because of the nature of quantum entanglement. To those who doubt that such is sufficiently proven we can only say that this work cannot also be about QM, but a parallel treatment that considers issues like infinite regress etc. obviously exists and is consistent with the gist of this work, namely that the *fundamental* level is *on principle abstract relational*.

We would now like to differentiate out several aspects that all concern *space-time*, how time and space are inseparably fused.

S1) Newtonian “space-time” is really just space *in* time, while the unique spatial direction is never in doubt or contested by different observers. In Minkowski space-time, singling out a time-direction t is almost as arbitrary as singling out a z -axis in space and claiming that only x - y -planes are really existent while the z -axis would be just a convenient picture that illustrates the stacking of x - y -planes but fundamentally different from the nature of directions inside the x - y -planes.

S2) When considering a homogeneous universe, classical expansion *through* space and GR’s Friedmann-Robertson-Walker (FRW) description fit together seamlessly. The way in which a cloud of Newtonian dust expands *through* space is entirely consistent with the global FRW picture describing the same process via the universe expanding as a whole. This further example of an instance where beautiful symmetry evokes the feeling of conspiracy in nature is paradoxical: in the Newtonian/SR description, the underlying space stays the same, uninvolved stage, while in the GR picture, space expands in the concrete sense that there is more of it than before; the latter is obvious when considering closed or compactified^d universes. To put it in the most paradoxical form, we call it the “expansion-paradox”: *Space expands globally, while locally it seems to expand nowhere.* The abstract-view resolves this paradox with help of *space-time* not being space *in* time: The four dimensional whole is one unchanging consistent arrangement (“block universe”) where time is already taken care off. The smaller space in the past is simply a different region of the whole. It did *not* grow into the larger space of today; it is still in the past!

^d E.g. space is periodically repeating and thus has no boundary but nevertheless only finite volume.

This is a strong argument for orthodox GR, because it implies that the whole growth-of-space problematic becomes almost a pseudo problem after adopting an abstract point of view.

S3) GR does not imply a unique history. Such fatalism, if true, would strongly argue against GR. The “block universe” should not be misunderstood as implying determinism beyond the gravitational sector (that is masses and gravity forces, but not for example the strong force in atomic nuclei). One can release a compressed spring between the two halves of a spinning sphere and thereby push the two halves apart. This triggers gravity waves that from the gravity sector alone, i.e. from the stable mass distribution of a sphere, would not have been predicted. Secondly, there are quantum physical aspects to be considered. Philosophers would rightly judge it a grave mistake to take QM as the basis for the plurality of possibilities instead of asking how QM may be derived from contingency/fecundity. Nevertheless, it is convenient that one can nowadays point towards a well established, mathematically formalized theory: QM and SR are consistently combined in relativistic quantum field theory (RQFT) and something similar will be achieved with GR. The relative state interpretation¹⁹ and the “many worlds” interpretation²¹ (MWI) [an attractive and pedagogic terminology not without disadvantages like the “parallel” branches at times describing orthogonal states] allow for the plurality of possibilities in physics. QM allows a consistent structure that includes all possibilities of block universes on an equal footing and in a sense mutually interacting, interfering, being entangled. It thereby removes the apparent fatalism of the block universe. This is completely independent of whether GR is to be quantized (existence of gravitons) or not in order to combine QM and GR.

S4) The abstract-view prepares a final resolution of the *relational nature of time*. This is important here, because some refuse to treat time the way that space-time demotes it. It seems to them that only “actual” dynamics can develop the future according to physical laws so that the 4D picture “ends up” consistently constrained. Widely accepted terminology can be misunderstood in this way. For instance, one of the nowadays most fundamental principles in physics concerns the “variation of the action-integral” that “settles” on the stationary solution. Does this not imply a “real flow” of time with some sort of Darwinian selection process for the stationary solution? “Flow of time” also leads to an infinite regress (what further time allows time to flow?). The key to an acceptance of space-time is not so much that time is just as plain as space, but the realization that QM negates local realistic interpretations of fundamental space²², too. In other words: one may as well accept the pseudo Riemannian space-time like one commonly accepts space, because the latter is equally only in our heads. Proponents of the block universe should refrain from pushing their favorite picture too far into one that invokes direct realism.

Lastly, we address the often advertised didactic value, the intuitiveness of space-substance views, which indeed helps at times, but which cannot justify pushing such models as fundamental.

I1) Hands on intuitive models can hinder insight, too. In eternal chaotic inflation for example, the everywhere expanding space does not squeeze the already present pocket universes. Moreover, the infinite space in every pocket universe is accommodated by bending into the time direction, something that probably cannot be intuitively described

with any model. The intuitive models encourage people to plainly refuse to accept observations like the accelerated expansion of the universe on grounds that their present model of a substance would never behave that way – expanding substances normally push towards the outside and squeeze anything inside. If intuitiveness triggers inertness, it may negate what was won through didactic.

Metric expansion can also be intuitively viewed as the significant scale (Planck length) becoming smaller. Substances whose fundamental units shrink or split at a certain rate as given by the Hubble constant are also concrete physical. However, here we have already an intuitiveness that helps the intelligent model builder while it is above the comprehension of the lay public. Although expansion and shrinkage are dual descriptions and moreover the time reversals of each other anyway, expansion is for some reason more acceptable.

I2) Consistency of conscious perception of an observer (CON) is fundamentally the basis of physics (P), which in turn is the basis of our common models of practical value in the everyday world of mesoscopic masses and sizes (M) which contains substance with its permanence, conservation of volume and so on. I.e.: $CON \rightarrow P \rightarrow M$. The misconception that leads people to believe in substance-views is the following:

If in P, like for example in GR, we spot things that seem just like, behave similarly to something in M, it proves that something like that M-structure is the foundation of P, i.e. “ $M \rightarrow P$ ”. Another, different universe has a different M, and M_j leads to observing P_j instead. That considering entities of M_i (say particles) is helpful in dealing with P_i is because P_i is talking about the properties of M_i .

It is not enough to reply that considering structures known from M helps because we are used to M and acquainted with those structures. Brains and thought structures (memes) are selected via evolution and this can still be interpreted as the struggle for survival in a world that is fundamentally made out of M_i -structures. A better counter argument is that any P_i is structured in such a way that it gives rise to exactly the world M_i in which concepts of M_i are familiar. This is a more anthropic than evolutionary argument, because the crux is: if there are different $P_i \rightarrow M_i$ universes possible, it is not surprising that M_i -structures find use when dealing with P_i , even if we were for some strange reason unfamiliar with our own M_i .

There is a good reason to insist on such hairsplitting. The stated misconception is to be rejected because it says “*it proves that something like that M-structure is the foundation of P*”. It should not be rejected as pseudoscience in cases where “*it hints at that something like that M-structure may well be involved at this stage in P*”. Parties dug in on *both sides* of the abstractness versus hidden substances debate would do good to split these hairs and subsequently spend less energy fighting straw men. In fact, once we agree on a *fundamentally* abstract level, the misconception becomes ironically true, i.e. $CON \rightarrow P \rightarrow M$ implies its own reversal and $M_i \rightarrow CON_i$ via its self-consistency as a now free floating abstraction. Once M_i is fully understood to be based on something purely abstract, it will also be known how M_i and CON_i are just dual formulations of each other.

2.1 Special relativity as a role model of relational resolution

It would disrupt the flow of the above listing of arguments that establishes the desirability of relational, abstract resolutions in the first place, but it should not be left out

in a work aimed at an audience interested in physics and philosophy, also because it has to the author's knowledge never been presented in this way and strongly supports the main gist of Section 2: SR almost completes the relational resolution of the concept of space-time. This was alluded to in the above (S4) and shall now be presented in detail.

Considering kinematics, the special relativistic aspect is the addition of rules about how to draw light paths and hence spatial and time like directions into a space-time diagram. One can understand much about SR by just drawing such Minkowski diagrams without calculating. The twin paradox can be understood in this way, and looking from our vantage point today, nothing surprises about persons having aged differently after traversing different paths through space-time; one should be surprised if they did not.

Drawing Minkowski diagrams and thereby understanding the geometrical nature of Lorentz contraction, one can already start to fathom how SR in a sense gets rid of space-time. If we want to attain the point of view of the light, namely see the world from the light's own rest frame, we will find that the more we accelerate to travel along with the light, the shorter the travel time becomes due to the time dilation. The travel distance Lorentz-contracts ever more and the light's energy red-shifts away to being undetectable. Since light travels with light velocity, it has neither itself time to exist nor is there space for it in-between emission and reception! QM supports this "non existence" of light: source and receptor exchange interaction quanta (photons) and the interaction that light carries is in case of each photon and regardless of the photons' red-shifted energy always exactly one minimum interaction quantum. Consider also that "no event takes place in the source itself as a precursor to the click in the counter"²³. This is remarkable already without the quantum aspects: All that happens in a fundamental description is that two

objects interact without there being time or space directly involved. Nevertheless, if one takes all these interactions between objects and observers together, then from a different point of view, the light may have traveled millions of years over vast stretches of space, and so space-time emerges from such space-less, time-less (instantaneous) interactions.

SR does not resolve the time that the objects “undergo” in between interactions, and trying to model everything as made out of light would be getting carried away. However, one learns two aspects from the expose: 1) SR is a role model for relational resolutions, for turning apparently concrete things abstract, because it does so via good operational physics: the measured aspect is ideally not implicitly involved in the way one measures, or worse, part of the measuring device. SR measures lengths in space-time utilizing the best standard possible on principle, namely one that cannot change its length, because it actually has zero length. 2) In a satisfactory resolution, space-time, and that includes time, is expected to be replaced by a net- or web-like relational structure that rips it completely apart from its ordinarily assumed order: Events are linked and any link represents plainly the fact of an interaction, but neither length nor direction. The links in the spin-network²⁴ of loop quantum gravity²⁵ (LQG) represent areas between the volumes at the nodes and in this sense do not get rid of space quite like the description here suggests.

3 Critical evaluation of the arguments

The main aim of this paper has been achieved in the above and none of the comments below shall be misunderstood as going back on the main gist, namely that the nature of space-time *is fundamentally abstract* and not even a future success of an Einstein-ether theory would change this in any way. However, certain reservations should be included for completeness. This will strengthen the argument rather than weaken it, because such procedure proves that one was well aware of the objections yet nevertheless concluded in favor for an abstract relational understanding. Let us therefore revisit some of the listed arguments:

G3) touches on several difficult issues. GR has certain cosmological solutions that demand the whole of space-time be given as one unit with some consistent topology. Consider two pulses of light being emitted into diametrically opposite directions. In case of some closed or periodically identified solutions, they must cross each others paths again. This establishes the antipode to the event of emission, regardless of how fast the emitter moved, i.e there is a preferred cosmological reference frame. It is much harder to convince oneself that a cosmic reference frame exists also without a closed topology, but it can be done: If one wanted to distribute all matter in a universe so that it is equally distributed (in terms of positions and of velocities of all particles) relative to any arbitrary inertial frame $S(v)$ having velocity v along some x -direction say, there would only be one (partial) solution to it: to have all energy in form of light traveling with light velocity; half of it travels to the left and an equal amount goes to the right. Moreover, because of Doppler shifts, that amount should be either zero or infinity, otherwise it cannot be the

same for all reference frames. I.e.: the big-bang has already broken Lorentz symmetry. There is no way to have it start completely Lorentz symmetric and then somehow classically break that symmetry. One should not accept symmetry breaking too readily as an added ingredient to a naïve picture. A symmetric stick put upright on a horizontal surface has an equal probability to fall in any direction. If Minkowski space is established already however, one cannot put a Lorentz symmetric probability distribution into a future light cone in order to let the CMB frame be spontaneously chosen. In fact, if one could do so, *both* aspects, topology and matter content, would not necessarily introduce *the same* special reference frame. A coincidence would then justify expecting the preferred frames to also be coincident with some ether due to some undiscovered physics.

G4) Beautiful symmetry is a strong indicator but no guaranty for significance in fundamental physics. This could be the main insight that quaternion division algebras and octonion non-associative algebras for example may ultimately result in. Their beauty has been admired for centuries now and captivated many, but no fundamental role in physics has been found, and not for lack of trying. Of course a number of people are captivated to such a degree that they will reject these statements.

G5) With insisting on regarding GR abstractly, an infinite regress is cut short. However, although this is attractive, one needs to be open to the possibility that it may have been cut one or more steps too short. A higher dimensional embedding was only early on perceived as a nuisance rather than an opportunity. Nowadays, many favor to have as many dimensions in the fundamental space-time as needed to embed all standard-model symmetries. The latter means that the standard model “ $U(1) \times SU(2) \times SU(3) \times P(3,1)$ ” would ask for at least $1+2+3+3 = 9$ space and one time dimensions, which points towards

string theories. Some even argue that two time dimensions are necessary^{26,27} in order to embed otherwise hidden symmetries.

Prematurely abstract views like the bootstrap models of the strong force must fail. We may still discover strata that invite to ask what things they consist of (atoms, nucleons, quarks, strings, ...) before an abstract relational fundament is fully justified. Sciences generally (e.g. sociology/biology) suggest emergence from lower layers every few orders of magnitude. Heisenberg uncertainty and the fact that (for high resolution needed) large energy hides itself behind event horizons do not conclusively prove that the lowest stratum has been unequivocally identified as being the Planck level. QM uncertainty can be modeled as due to an underlying medium having a temperature proportional to the Heisenberg constant²⁸. Quantization can also be emergent^{29,30} or of topological nature. Only QM-entanglement in Einstein-Podolsky-Rosen³¹ (EPR) situations stands out as the single promising proof for that QM is not emergent.

It is important to keep in mind that the support of fundamental abstractness cannot be based on cutting the infinite regress short but on the fact that even allowing a partial, circular, or infinite regress will result in an abstract model that is far from what proponents of intuitive models desire.

G6) Occam's razor must be sparingly applied in order to avoid cutting out important aspects, like cosmological time, that further progress may require again. Einstein himself shaved off the cosmological constant Λ , but one had to re-introduce it. Λ is not a hidden variable, but it was similarly cut out because it was felt to be unnecessary and disturbing the beauty of the equation. QM hidden variables have been shown to not exist consistently; they are *not* merely cut out because they are hidden or unnecessary! Hidden

variables that *can* exist consistently may not hide for ever but perhaps point to improved theories. Modern physics keeps its tools as rich as possible[°].

T1) strongly repels pseudoscientific attacks against GR, but it does not support fundamental abstractness. In fact, the TD-analogy supports that space-substance toy models should be useful for considering those corrections to GR that are expected near the Planck length scale.

S1) Since many people do not agree on the boost rotations in $SO(1,3)$ being acceptable as rotations at all, this is a weak argument for an abstract point of view. S1 just clarifies what is meant by space-time versus space living in time.

S2) The concept of abstract metric expansion is superior to the concept of expansion *of* space, which has been argued to be very problematic^{32,33}. Although such arguments aim to support an abstract view and orthodox interpretation of GR, one should not agree with them, especially whenever they favor expansion *through* space instead. The growth of a hypothetical space-substance is the biggest difficulty for ether models. The violation of a continuity equation (non conservation of substance) is the most immediate counter argument against any space-substance. Therefore, avoiding mentioning expansion *of* space does not unequivocally help the cause. For the substance-view, missing the “*seems to*” in our introduction of the expansion-paradox (see S2) turns it into a contradiction: In an expanding volume of substance, substance cannot by some magic only globally have appeared already without having been locally supplied somewhere - or everywhere, but still with a *locally* acting mechanism. Units of substance must also locally expand; flow in from the sides, or “rain” from a higher dimension on the top. There is also the question

[°] This is similar to leaving all terms that are not strictly forbidden by symmetry inside a Lagrangian,

about the “costs” of new material. The abstract-view should feel easy about that, because mere emptiness comes for free even if we expand some *of* it rather than just *through* it. Moreover, only a semi-classical description needs energy to bend space. GR does neither have gravitational energy nor is there time-translation invariance that would support global energy conservation. The substance-view may only counter that in quantum descriptions, the energy due to bending space is more palpable and one might well suppose that QM will eventually have something to say about the growth of space, even if it does not cost any energy per se.

The argument S2 did for simplicity draw on closed or compactified universes. In a flat and infinite universe it is harder to argue that there is more total space later in cosmological time t_c , because from inside the universe, t_c is determined by observation of the average background, or better the temperature T of the CMB. The cosmological principle states that the background is from anywhere in the universe observed to be about the same, changing only with t_c . However, if two regions far from each other (in space-time) experience different temperatures T , it hardly violates the cosmological principle, because it may only imply that the regions are at different times t_c . A model clearly violates the principle if it leads to a background that is not isotropic. It is not obvious that an everywhere isotropic background can or cannot be modeled relying on boosts between equally valid reference systems merely traveling *through* space. Hubble flow is defined as the recession velocity $v = D H$ at any distance D away from the observer and for a given Hubble constant H . H describes the cosmic expansion and depends on t_c , too. The difficult question is thus: If space does not itself expand, can one

because statistical mechanics will populate the spectrum given enough temperature.

setup a large scale homogeneous situation where any boosted object asymptotically joins the Hubble flow and thus finally observes an isotropic CMB all around it? A coordinate change can make the FRW model look like Minkowski space-time, but homogeneity of constant time surfaces is lost³⁴.

Not all important issues have been dealt with yet. It is well known that GR cannot be the last word on fundamental physics. That GR and QM are incompatible can be traced back to the singularities that GR predicts. At the singularities, GR breaks down to be a theory of physical processes. From an operational standpoint, singularities are generally strictly unphysical because only infinite energy would provide enough resolution to observe one. Substance models avoid singularities from the outset. However, there are several abstract suggestions that also avoid singularities (string theory, LQG). Moreover, contrasting the success of substance analogies for modeling event horizons³⁵ they fail to reproduce the internal of GR black regions like BH. This is related to their difficulties with metric expansion, namely the vanishing of space-substance in BH contradicts the permanence (conservation law, continuity equation) of substance. However, while cosmic expansion is an observed fact, the internal of BH is *not* observable. There are plenty of models that give rise to the observable features of astronomical BH while being different from GR only on the inside of the BH, or at least they differ only starting from very close to the event horizons. This makes the singularity/BH issue less interesting for a discussion about fundamental abstractness.

4 Why substance-views are attractive tools also for modern physics

The main aim has been completed: The author's position supports an abstract relational view of space-time and thereby supports an orthodox interpretation of GR (Section 2). This was supported by a preemption of possible objections (Section 3) while staying firm. The following section further ensures that the part of the audience that strongly favors intuitive substance models may be appeased in discovering that the author is sympathetic to their position and can neither be accused of ignorance about their arguments nor of conspiring against them. This should more effectively corrode the support for pseudoscience than a hardening of positions in yet another "war against XYZ". A sizable fraction of very active anti-Einstein type of pseudoscience that sometimes wastes precious time of scientists and editors has been driven to extremes by exactly those occurrences where scientists treated them with arrogance in order to fight pseudoscience. Often "well known truths" are hurled without addressing the discredited model. Especially embarrassing to the authors' profession are those "well known truths" that are due to misinterpretations by popular science. For example, SR and causality together do *not* preclude all information carrying signals with superluminal speed $v > c$ ³⁶. People who believe in naïve ether theories know this, because it is one of the interesting didactic advantages of such models that they facilitate intuition about certain aspects of Minkowski space-time (Section 4.1). Many physicists refuse to make use of ether models as a didactic tool but also never spend time considering the issue properly within orthodox SR, where it is more difficult. One cannot be entirely surprised by that some people start embracing conspiracy theories while obviously incorrect arguments are kept being addressed at them. Our aim here is to make a work available that understands the

advantages of even naïve substance-models and acknowledges the existence of (yet nowhere employs) those convenient but incorrect arguments, and nevertheless stays firmly on the side of fundamentally abstract relational space-time supporting GR.

With the advent of stringy universe-on-a-membrane models^{37,38,39}, what is in our sense substance-views has entered the main-stream. In contrast to LQG, string theory also has gravitons that interact and thereby “give rise” to the force of gravity, which is counter the GR concept of there being no gravitational force, but just geodesics through curved space-time instead^f. More seriously, rest mass in the standard model, i.e. even pure inertia against non-gravitational acceleration is widely thought to be a permanently ongoing interaction with Higgs particles. The dynamics of inflaton fields is necessary in modeling the inflation of the early universe. Thus, the *dynamics leading to kinematics* concept is deeply rooted in modern physics.

Partially motivated by the debatable feeling that nothingness cannot have any properties, space is respected as “something” because it does have properties, as there are gauge field impedances due to for example electro-magnetic (EM) permeabilities, and the fact that space is effectively showing tension and inertia against bending and stretching, which may give rise to GR in the first place. QM shows that space is never merely emptiness, but teeming with stuff if one just looks closely enough. That this is in some sense created by the measurement act (looking closely) should not render this point moot; Unruh temperature due to acceleration at event horizons exists without specifically looking for it; BH evaporate also without a conscious observer around. Space might be

^f String theory’s present description does of course not imply that it cannot find a better, background independent description in the future. However, the fact that it presently does use such language is in stark contrast to the sanctioned use of preferred frames in order to describe SR.

quite tangible as an actual web of strings, the inside of a droplet of a super fluid like Helium III⁴⁰, or the surface of a large pond of some fluid. It was already shown⁴¹ in 1945 that a crystal-like Dirac-sea mimics SR Lorentz contraction and mass-energy increase^g. That GR could be an emergent property in a condensed-matter QM theory has a long history (reviewed thoroughly elsewhere^{42,43,35}). Space-time in GR is similar to stressed matter⁴⁴; there is a close analogy between sound propagation in background hydrodynamic flow and field propagation in curved space-time⁴⁵, and so on. One visualizes the vacuum as analogous to the ground state of a condensed matter system and ordinary matter as analogous to excited states of this system. For example the absence of large scale rotation in the universe follows then simply from super-fluids being irrotational.

In the substance-view, relativity emerges because observers are also made from the excitations, are out of pseudo particles of an underlying material. This has been pedagogically well discussed elsewhere, for example starting with Newtonian fluid dynamics³⁶. As mentioned above: substance-views can be powerful as didactic toy models: The rubber sheet or raisin dough illustrates the isotropic Hubble law observed during cosmic expansion. One can after some exercise at this quickly recall in front of one's inner eye, i.e. plainly see (visually imagine), how clocks made from excitations of a background undergo time dilation relative to the background *and* each other. Conveyor belt and fluid pond models are both good for this. Most intuitive are of course the fluid models: As suggested by Landau's dispersion curve below the roton minimum, smoke-ring like vortices in super fluids can carry negative mass. Such to velocity anti-parallel

^g A moving Burgers screw dislocation in a crystal contracts to $L' = \gamma L$, where $\gamma = 1/(\nu/c)^2$ and c is the

aligned momentum has been experimentally confirmed⁴⁶. Collision partners are then pulled rather than pushed away. Therefore, the fact that exchange particles may carry attractive forces can be demonstrated in front of high school pupils long before mentioning virtual particles going backwards in time and suchlike; the latter being something not everybody is ready or able to accept as more than mathematical wizardry.

Space-substance models prove comprehensibly that SR and causality together do *not* preclude all information carrying signals with superluminal speed $v > c$. Evidence is piling up for non-locality and for QM tunneling being faster than expected⁴⁷, perhaps instantaneous^{48,49,50}. A space-substance could accommodate such due to processes being extremely fast relative to the space-substance rather than just relative to the tunnel barrier.

4.1 Causality preserving superluminal velocity but no time-travel

Since this paper is addressing a wide audience, some without advanced mathematical training yet strong interest in science, it is well worth to exemplify the didactic power of substance models in case of two also in philosophy widely discussed issues, namely time travel and the strictness of fundamental limits, as there is the velocity of light as the maybe most prominent. Substance models can be enlightening here and thus deserve to be taught widely provided they are presented with the understanding that SR gets the same results entirely without referring to any preferred background.

velocity of transverse sound. The energy is the dislocation's potential energy at rest divided by f .

If space is like a fluid's surface, high energy events^h may lead to large (e.g. solitary rogue) waves superposing non-linearly, wave crests breaking and fluid splashingⁱ. Splashed fluid travels “above” the surface carrying away otherwise unaccounted for energy and momentum. Though sounding like exotic pseudoscience, this is the same as the string-theory membrane inspired and well received “particles can be kicked off our 4 dimensional manifold ...”⁵¹. Most such string models permit only gravity (closed strings) to leave the membrane, but very high energy collisions might let whole parts of the membrane (also made from strings) come off and travel through the bulk. Such considerations suggest a resolution of the Greisen-Zatsepin-Kuzmin (GZK) cosmic ray paradox^j similar to but still somewhat more natural than has been proposed before^{52,53}: If extreme high energy events lead to splashing of an underlying medium, the splashed parts would travel outside of the surface or membrane that makes up the observable universe and thus outside of the CMB. Gravity, as opposed to EM forces, reaches into the bulk next to the membrane and pulls the splashed parts back. While the origin is far away, the secondary sources would be at the re-entry of splashed parts into the observable universe close to the observer.

^h Low energies involve small amplitudes A and wave lengths λ longer than the liquid's inter particle distance. Increasing energy, one will first observe that the velocity of light gets dependent on A and λ . This is to be expected in almost any QM gravity proposal.

ⁱ Volovic⁴⁰ claims that the next lower one of the alternating strata of effective-standard-model-physics and underlying-super-fluid-vacuum in a tower of unknown extend is principally inaccessible from inside any layer. High energy experiments cannot focus pseudo particles so much as to render the underlying fluid locally above its lambda point.

^j The GZK limit applies to cosmic rays from distant sources. Rays with energies above $5 \times 10^{19} eV$ interact with the CMB to produce pions, yet some are observed to have $3 \times 10^{20} eV$. Five very-high-energy cosmic rays detected between 1993 and 2003 were traced to colliding galaxy clusters $4.5 \times 10^8 ly$ from us.

Considering a pond of fluid, splashed drops may reenter the surface after traveling “over” it with higher than the low energy wave speed c observed^k by observers living inside the surface. A mathematical model based on this picture is at low energies special relativistic inside the surface, yet *from the outset* allows faster than light phenomena that obviously do not violate causality. The splashed substance carries at least the information that a high energy experiment has indeed taken place. Superluminal information carrying phenomena need not to violate causality and a space-substance model shows comprehensively why: the signal travels at most instantaneous relative to the cosmological space-substance, i.e. it is *tied to one and only one reference frame!* Since SR is valid inside the surface, there are inertial systems relative to which the superluminal splashing goes backwards in time, but in none does it splash into their backwards light-cone (which is their actual past and coincides with the space-substance’s past). No equations are needed to prove it: We all take baths and know that no wave or splashed drop visits the water’s past. Imagine you stand next to a pond watching some sentient beings made from the pond’s surface waves: the futility of their efforts to invent a time-machine is ridiculously apparent. A space-substance giving rise to GR in as far as it is confirmed by observations renders the idea of time-travel equally ridiculous: Excitations of a substance just cannot visit a previous state of the substance that plainly *does not exist anymore*. Deriving such results as far as they apply to SR from an abstract-

^k Observers that are made out of the waves on the pond chose as their “light” the fastest excitations with few internal properties. Having no better measure, light must be used to measure light, thus it always has the same speed c . All objects are made out of simple waves trapping each other in patterns (pseudo particles). A pattern moving relative to the liquid’s molecules experiences (absolute) time dilatation: A light-clock is a simple light wave bouncing between mirrors. If the clock moves with close to the speed of light, bouncing light needs much cosmological time to reach the receding front mirror. The universe of these observers is special relativistic. A Minkowski space-time diagram suffices to establish that systems at

view point needs many pages, equations and diagrams³⁶. In the case of GR, there is no way yet to bring such results home within an abstract-view.

Membrane models allow for superluminal speeds whenever the speed of what is light inside a particular membrane is slow relative to the (maybe also covariant) bulk space. Yet even if eventually our universe cannot be modeled similarly, it does not alter the fact that anything inside SR *can* be modeled as emergent from a hidden background: This proves very generally that no proposal using SR and faster than light travel that is *bound to one preferred frame* violates causality. Into this group of issues that involve propagations that are *bound to one single preferred frame* belong the very important issue of QM non-locality (EPR³¹ paradox) and more specifically the “splitting” of worlds due to entanglement in the MWI²¹, but also the Scharnhorst⁵⁴ effect and possibly instantaneous QM tunneling. Tunneling time delay is measured relative to the tunneled barrier and investigated ones were basically at rest relative to the CMB. If the world splits into possibilities with the split’s hyper surface connecting two entangled measurement events far apart (the here worst case scenario), it is still so that every possible parallel universe afterwards has *one* such split surface at its beginning, i.e. only *one* preferred frame relative to which information propagated instantaneously; the latter does not need to coincide with a preferred frame due to cosmological time. QM effects like tunneling do not require much energy, so one should mention that a space-substance does support infrared effects braking Lorentz invariance⁵⁵, e.g. due to longitudinal sound waves rather than transverse surface waves in the naïve pond liquid model.

rest in the pond also undergo time dilatation as measured from moving patterns. The observers cannot measure how they are moving relative to the pond.

Proofs of that causality and Lorentz invariance allow superluminal signals³⁶ and attempts at replacing the Lorentz group by different transformations to provide a kinematical basis for high energy physics that breaks Lorentz invariance (e.g. lower velocity of high frequency light^{56,57,58}) usually do *not* argue for fundamental reference frames. For the Scharnhorst effect, the metal plates break Lorentz invariance. If there are two pairs of plates in relative motion, we expect Hawking's chronology protection conjecture or similar to show that signals cannot be turned around or reflected so that they end up in the past light cone. One can probably argue similarly in the case of two fast moving tunnel barriers. However, no experimental evidence excludes the possibility that QM processes like tunneling and entanglement/wave-function collapse occur instantaneously relative to a cosmological reference frame, as firstly suggested by Hardy⁵⁹. Such is seldom put forward using this language, but is occasionally implied by stating that QM violates the strong equivalence principle⁶⁰ and that causality is therefore a global question of topology^{61,62}. One cannot categorically exclude that tunnel delay time may be instantaneous relative to the CMB, and one should find out whether one could test this by doing what basically amounts to ether-drift experiments employing tunnel barriers, as has not been suggested before.

5 References

¹ Earman, J., Norton, J.: What price substantivalism? The hole story. *Brit. J. for the Phil. of Science* **38**, 515-525 (1987)

-
- ² Janssen, M.: Drawing the line between kinematics and dynamics in special relativity. *Studies in Hist. and Phil. of Mod. Phys.* **40**, 26-52 (2009)
- ³ Padmanabhan, T.: Gravity: the inside story. *Gen. Rel. Gravity* **40**, 2031-2036 (2008)
- ⁴ Milgrom, M.: A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophys. J* **270**, 365 (1983)
- ⁵ Bonvin, C., Durrer, R., Ferreira, P. G., Starkman, G., Zlosnik, T. G.: Generalized Einstein-Aether theories and the Solar System. *Phys. Rev. D* **77**, 024037 (2008)
- ⁶ Caldwell, R. R., Dave, R., Steinhardt, P. J.: Cosmological Imprint of an Energy Component with General Equation of State. *Phys. Rev. Lett.* **80**, 1582–1585 (1998)
- ⁷ Ratra, B., Peebles, P. J. E.: Cosmological consequences of a rolling homogeneous scalar field. *Phys. Rev. D* **37**, 3406–3427 (1988)
- ⁸ Sanders, R. H.: A stratified framework for scalar-tensor theories of Modified Dynamics. *Astrophys. J.* **480**, 492-502 (1997)
- ⁹ Sanders, R. H.: Solar System constraints on multi-field theories of modified dynamics. *Mon. Not. R. Astron. Soc.* **370**, 1519-1528 (2006)
- ¹⁰ Arbey, A.: Dark Fluid: A complex scalar field to unify dark energy and dark matter. *Phys. Rev. D* **74**, 043516 (2006)
- ¹¹ Khoury, J., Weltman, A.: Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space. *Phys. Rev. Lett.* **93**, 171104 (2004)
- ¹² Khoury, J. and Weltman, A.: Chameleon cosmology. *Phys. Rev. D* **69**, 044026 (2004)
- ¹³ Bekenstein, J. D.: Relativistic gravitation theory for the modified Newtonian dynamics paradigm. *Phys. Rev. D* **70**, 083509 (2004)

-
- ¹⁴ Consoli, M., Pagano, A., Pappalardo, L.: Vacuum condensates and ‘ether-drift’ experiments. *Phys. Lett. A* **318**, 292–299 (2003)
- ¹⁵ ‘t Hooft, G.: *In Search of the Ultimate Building Blocks*. Cambridge Univ. Press, Cambridge (1997)
- ¹⁶ Michelson, A. A., Morley, E. W.: On the Relative Motion of the Earth and the Luminiferous Aether. *Philos. Mag.* **24**, 449-463 (1887)
- ¹⁷ Illingworth, K. K.: A Repetition of the Michelson-Morley Experiment Using Kennedy’s Refinement. *Phys. Rev.* **30**, 692-696 (1927)
- ¹⁸ Miller, D. C.: The Ether-Drift Experiment and the Determination of the Absolute Motion of the Earth. *Rev. Mod. Phys.* **5**, 203-242 (1933)
- ¹⁹ Everett, H.: “Relative State” Formulation of Quantum Mechanics. *Rev Mod Phys* **29**, 454-462 (1957)
- ²⁰ Carlip, S.: Symmetries, horizons and black hole entropy. *Gen. Rel. and Gravitation* **39**, 1519-1523 (2007)
- ²¹ DeWitt, B. S., Graham, N.: *The Many Worlds Interpretation of Quantum Mechanics*. Princeton University Press, Princeton NJ (1973)
- ²² Hardy, L.: Nonlocality for Two Particles without Inequalities for Almost All Entangled States. *Phys. Rev. Lett.* **71**, 1665-1668 (1993)
- ²³ Ulfbeck, O., Bohr, A.: Genuine Fortuitousness. Where Did That Click Come From? *Found. Phys.* **31**, 757- 774 (2001)
- ²⁴ Rovelli, C., Smolin, L.: Spin networks and quantum gravity. *Phys. Rev. D***52**, 5743-5759 (1995)

-
- ²⁵ Ashtekar, A., Tate, R.: Lectures on Non-Perturbative Canonical Gravity. World Scientific Publishing, Singapore (1996)
- ²⁶ Bars, I., Deliduman, C., Minic, D.: Lifting M-Theory to Two-Time Physics. Phys. Lett. B **457**, 275-284 (1999)
- ²⁷ Vongehr, S.: Examples of Black Holes in Two-Time Physics. hep-th/9909077 (1999)
- ²⁸ Grössing, G.: The Vacuum Fluctuation Theorem: Exact Schrödinger Equation via Nonequilibrium Thermodynamics. Phys. Lett. A **372**, 4556-4563 (2008)
- ²⁹ 't Hooft, G.: Quantum gravity as a dissipative deterministic system. Class. Quant. Grav. **16**, 3263-3279 (1999)
- ³⁰ Adler, S.: Quantum Theory as an Emergent Phenomenon. Cambridge (2004)
- ³¹ Einstein, A., Podolsky, B., Rosen, N.: Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. **47**, 777-780 (1935)
- ³² Peacock, J. A.: A diatribe on expanding space. arXiv:0809.4573 (2008)
- ³³ Francis, M. J., et al.: Expanding Space: the Root of all Evil? Publ. Astron. Soc. Austral. **24**, 95-102 (2007)
- ³⁴ D. N. Page: No superluminal expansion of the universe. arXiv:gr-qc/9303008 (1993)
- ³⁵ Barcelo, C., Liberati, S., Visser, M.: Analogue Gravity. Living Rev. Relat. **8**(12), 1-113 (2005)
- ³⁶ Liberati, S., Sonogo, S., Visser, M.: Faster-than-c Signals, Special Relativity, and Causality. Annals of Physics **298**, 167–185 (2002)
- ³⁷ Brax, P., van de Bruck, C., Davis, A. –C.: Brane World Cosmology. Rept. Prog. Phys. **67**, 2183-2232 (2004)

-
- ³⁸ Khoury, J.: A Briefing on the Ekpyrotic/Cyclic Universe. arXiv:astro-ph/0401579 (2004)
- ³⁹ Khoury, J., Ovrut, B. A., Steinhardt, P. J., Turok, N.: The Ekpyrotic Universe: Colliding branes and the origin of the hot big bang. *Phys Rev D* **64**, 123522 (2001)
- ⁴⁰ Volovik, G. E.: The Universe in a Helium Droplet. *Int. Series of Monographs on Phys.* **107** (2003)
- ⁴¹ Frank, C. F.: On the equations of motion of crystal dislocations. *Proceedings of the Physical Society of London, A* **62**, 131-134 (1945)
- ⁴² Volovik, G. E.: Superfluid Analogies of Cosmological Phenomena. *Phys. Rept.* **351**, 195-348 (2001)
- ⁴³ Chapline, G.: Quantum Model for Spacetime. *Mod. Phys. Lett. A* **7**, 1959-1965 (1992)
- ⁴⁴ Sakharov, A.: Vacuum quantum fluctuations in Curved Space and the Theory of Gravitation. *Sov. Phys. Dokl.* **12**, 1040-1041 (1968)
- ⁴⁵ Unruh, W. G.: Experimental Black Hole Evaporation? *Phys. Rev. Lett.* **46**, 1351-1353 (1981)
- ⁴⁶ Tucker, M. A. H., Wyatt, A. F. G.: Direct evidence for R^- rotons having antiparallel momentum and velocity. *Science* **283**, 1150-1152 (1999)
- ⁴⁷ Eckle P., et al.: Attosecond Ionization and Tunneling Delay Time Measurements in Helium. *Science* **322**, 1525 (2008)
- ⁴⁸ Stahlhofen, A. A., Nimtz, G.: Evanescent modes are virtual photons. *Europhys. Lett.* **76**, 189-195 (2006)

-
- ⁴⁹ Haibel, A., Nimtz, G.: Universal Relationship of Time and Frequency in Photonic Tunneling. *Ann. Physik* **10**, 707-712 (2001)
- ⁵⁰ Esposito, S.: Universal photonic tunneling time. *Phys. Rev. E* **64**, 026609-1 8 (2001)
- ⁵¹ Arkani-Hamed, N., Dimopoulos, S., Dvali, G.: The hierarchy problem and new dimensions at a millimeter. *Phys. Lett. B* **429**, 263-272 (1998)
- ⁵² Sigl, G.: Particle and Astrophysics Aspects of Ultrahigh Energy Cosmic Rays. *Lect. Notes Phys.* **556**, 259–300 (2000)
- ⁵³ Sigl, G.: Ultra-High Energy Cosmic Rays: A Probe of Physics and Astrophysics at Extreme Energies. *Science* **291**, 73–79 (2001)
- ⁵⁴ Scharnhorst, K.: On propagation of light in the vacuum between plates. *Phys. Lett. B* **236**, 354-359 (1990)
- ⁵⁵ Volovik, G. E.: Reentrant violation of special relativity in the low-energy corner. *JETP Lett.* **73**, 162-165 (2001)
- ⁵⁶ Amelino-Camelia, G.: Testable scenario for relativity with minimum length. *Phys. Lett. B* **510**, 255-263 (2001)
- ⁵⁷ Bruno, N. R., Amelino-Camelia, G., Kowalski-Glikman, J.: Deformed boost transformations that saturate at the Planck scale. *Phys. Lett. B* **522**, 133-138 (2001)
- ⁵⁸ Abdo, A. A., Ackermann, M., Ajello, M., et. al.: A limit on the variation of the speed of light arising from quantum gravity effects. *Nature* **462**, 331-334 (2009)
- ⁵⁹ Hardy, L.: Quantum Mechanics, Local Realistic Theories, and Lorentz-Invariant Realistic Theories. *Phys. Rev. Lett.* **68**, 2981-2984 (1992)

⁶⁰ Drummond I. T., Hathrell, S. J.: QED vacuum polarization in a background gravitational field and its effect on the velocity of photons. *Phys. Rev. D* **22**, 343-355 (1980)

⁶¹ Shore, G. M.: Superluminal phenomena shed new light on time. *Int. J. of High-Energy Phys.* **42** (CERN Courier) 28606 (2002)

⁶² Shore, G. M.: Accelerating photons with gravitational radiation. *Nucl. Phys. B* **605**, 455-466 (2001)