A THEORY OF GRAVITY WITH PREFERRED FRAME AND
CONDENSED MATTER INTERPRETATION

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ABSTRACT. Does relativistic gravity provide empirical arguments against theories with a preferred frame like de Broglie-Bohm pilot wave theory? We present here a viable metric theory of gravity with preferred frame which gives a negative answer to this question.

The theory has the same equations as Logunov’s “relativistic theory of gravity” (RTG) but a less restrictive causality condition. It has not only a preferred frame, but allows even a condensed matter interpretation – a variant of the ADM decomposition splits the metric into density, velocity and stress tensor of some hypothetical medium so that continuity and Euler equations hold.

The theory shares many nice properties of RTG (EEP, Einstein equations in a natural limit, no big bang and black hole singularities, local energy and momentum densities for the gravitational field and a symmetry preference for a flat universe), but is also compatible with standard ΛCDM cosmology.

We also give a first principles derivation of the Lagrangian.

1. Motivation

Relativistic gravity seems to provide a powerful argument against theories which require a preferred frame: For general solutions of general relativity, no preferred frame is available. In particular, there seems to be no natural preferred frame for solution of general relativity which describe the gravitational collapse resulting in a black hole, a process which seems to happen during supernova explosions and in the centers of galaxies.

As a consequence of this argument, theories which require a preferred frame are incompatible with general relativity. This does not completely explain the strong prejudice against such theories, which are widely considered as fringe for the single reason that they need a preferred frame. Nonetheless, given that the arguments against a preferred frame in a special-relativistic context are purely metaphysical, the incompatibility of a preferred frame with general relativity is the only empirical argument against a preferred frame.

It is remarkable that there is a theory which requires a preferred frame which has nonetheless survived these strong prejudices, and which becomes (if the number of citations of Bohm’s paper [4] shown in [7] p.54 can be used as a criterion) increasingly popular: The pilot wave interpretation of quantum theory. This survival

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1For example, Motl [44] argues “I wonder whether [Bohmists] actually believe that there always exists a preferred reference frame, at least in principle, because such a belief sounds crazy to me (what is the hypothetical preferred slicing near a black hole, for example?).”
would have been impossible without strong advantages of this theory: It’s simplicity, compatibility with realism, the beauty of its additional equation, its ability to derive what quantum theory has to postulate — the measurement theory — and the absence of almost all quantum strangeness gives this theory large explanatory power.

Moreover, pilot wave theory is not the only way to interpret quantum theory which relies on a preferred frame. As well, attempts to interpret the collapse of the wave function as some real process, by modifying the Schrödinger equation, also require a preferred frame [8]. A preferred frame is necessary also in Nelson’s stochastic interpretation of quantum theory [12].

This is not an accident: It follows from Bell’s theorem [3] that any realistic interpretation — “realistic” understood in the sense used in this theorem, which needs only an extremely weak notion of realism — needs a preferred foliation, if it wants to avoid causal loops or backward causation. Thus, an incompatibility of relativistic gravity with a preferred foliation would lead to an incompatibility of Bell’s notion of (non-local) realism with relativistic gravity.

This would be an extremely important insight. Bell’s notion of realism can be interpreted as an implicit part of the scientific method in general: A methodological preference for realistic theories can be identified with the methodological requirement to search for realistic explanations of observable correlations. In the domain of special relativity, no conclusive empirical evidence against realism is possible or even imaginable: It is always possible to introduce a hidden preferred frame to preserve realism. In particular, to explain the correlations predicted by quantum theory, we can use some version of pilot wave theory which depends on a choice of a preferred frame.

Thus, the question if relativistic gravity is compatible with a preferred frame is not only important for the fate of several sufficiently popular interpretations of quantum theory, but also for an extremely important question about the very foundations of science itself: The viability of classical realism, as understood by EPR [6] and Bell [3].

A third independent motivation of this paper is the question if relativistic gravity is compatible with a recently proposed condensed matter interpretation for the standard model of particle physics [16]. This interpretation has remarkable explanatory power: A simple lattice of cells allows to obtain all observed particles of the standard model, in particular all three generations of fermions. The gauge group of the SM (and its action on the fermions) is shown to be the maximal possible gauge group which fulfills a few natural postulates. Even if this theory is not yet complete — in particular, spontaneous symmetry breaking, which is necessary to give the fermions mass, is not yet considered — these results seem sufficient to take this interpretation seriously.

This interpretation obviously also requires a preferred frame. But it requires even more: The theory of gravity should be compatible with the condensed matter interpretation of the standard model fields. The most natural way to obtain such a compatibility is to give the gravitational field a condensed matter interpretation too. So, the second question is if this is possible — if there is a viable theory of gravity in the relativistic domain which allows a condensed matter interpretation.

But there is also a fourth independent question — the quantization of gravity. Even if string theory claims to have solved this problem, the current situation
of this theory does not seem to be very satisfactory [22], so that this problem is far away from being finally solved. Now, if relativistic gravity could be described by a theory with preferred frame, the notorious “problem of time” of canonical quantum gravity [9] would disappear. A condensed matter interpretation would be also useful: Last but not least, we already know very well how to quantize classical condensed matter theories.

2. Introduction

Thus, we have four completely independent motivations from different parts of the foundations of physics to consider the following two questions:

• Is relativistic gravity compatible with a preferred foliation?
• Is it, moreover, possible to give a condensed matter interpretation for the gravitational field?

In this paper, we give a positive answer to above questions by presenting a metric theory of gravity with these properties.

We start with an “obligatory part” which contains all we need to justify our positive answer:

• In section 3 we give the definition of the theory as a metric theory with a preferred frame.
• In section 4 we define a condensed matter interpretation of the theory;
• In section 5 we show the equivalence of the equations of our theory with those of the “relativistic theory of gravity” (RTG) and consider the differences.
• In section 6 we evaluate the viability of the theory. Where possible we reuse results about RTG.

This is all we need for the main point of the paper: It solves the question of existence of a viable theory of gravity with preferred frame and condensed matter interpretation.

But our theory does not look inferior in comparison with GR. Instead, it has even several advantages in comparison with GR: In particular, we have local energy and momentum densities for the gravitational field, the classical big bang and black hole singularities of GR do not appear in this theory, we obtain a symmetry explanation why the universe is flat on the large scale and a term which enforces inflation ($a''(\tau) > 0$) in the early universe. Some questions which are not essential for answering our two questions we have moved into appendices. In particular, we present there a nice first principles derivation of the Lagrangian. We also consider if standard arguments against the Lorentz ether are applicable against our theory.

But a sufficiently detailed consideration of some of these questions is beyond the scope of this paper and has to be left to future papers. In particular these are questions which need methodological and philosophical considerations or are related to quantization and the violation of Bell’s inequality. Other interesting questions we have not considered at all and left to future research. In particular, the research in analog gravity [2, 17, 19] as well as in the geometric theory of defects [10] [11] applies various parts of the mathematical apparatus of metric theory of gravity in condensed matter theory. The connection between these directions of research and our condensed matter interpretation for gravity is certainly worth to be considered in detail.
3. Definition of the theory

The theory of gravity [15] we want to present here is defined in the following way: Similar to GR and other metric theories of gravity, we have the gravitational field $g_{\mu\nu}(x)$ together with some unspecified number of matter fields $\varphi_m(x)$. Different from GR, these fields are not defined on an arbitrary four-dimensional manifold, but on a classical Newtonian spacetime $\mathbb{R}^3 \times \mathbb{R}$, with a set of preferred coordinates $X^i$ (for the spatial directions) and $X^0 = T$ (for time). We use latin indices $X^i$ for the spatial coordinates ($1 \leq i \leq 3$) and greek indices $X^\alpha$ for all four coordinates ($0 \leq \alpha \leq 3$).

In the preferred coordinates, the action of the theory is

\[ S = -\frac{1}{16\pi G} \int (R + 2\Lambda + \gamma_{\alpha\beta} g^{\alpha\beta} X^\alpha X^\beta) \sqrt{-g} d^4 x + \int L_{\text{matter}} \sqrt{-g} d^4 x \]

where $L_{\text{matter}}$ a covariant Lagrangian for the matter fields. Introducing the diagonal matrix $(\gamma_{\alpha\beta}) = \text{diag}(\Upsilon, -\Xi, -\Xi, -\Xi)$, one can rewrite this as

\[ S = -\frac{1}{16\pi G} \int (R + 2\Lambda + \gamma_{\kappa\lambda} g^{\kappa\lambda}) \sqrt{-g} d^4 x + \int L_{\text{matter}} \sqrt{-g} d^4 x \]

We also need — for reasons which become clear below — an additional “causality condition” that the preferred time $T = X^0$ has to be time-like everywhere. With this additional condition, the definition of the theory is already complete.

It is also useful to have a formulation in “parametrized form”, valid in general coordinates $x$. In this formulation, the preferred coordinates $X^\alpha$ appear as scalar functions $X^\alpha(x)$ on the manifold:

\[ S = -\frac{1}{16\pi G} \int (R + 2\Lambda + \gamma_{\alpha\beta} g^{\mu\nu} X^\alpha_{,\mu} X^\beta_{,\nu}) \sqrt{-g} d^4 x + \int L_{\text{matter}} \sqrt{-g} d^4 x \]

The Euler-Lagrange equations for the $g_{\mu\nu}$ give

\[ G^\mu_{\nu} = 8\pi G (T_m)^\mu_{\nu} + (\Lambda + \frac{1}{2} \gamma_{\kappa\lambda} g^{\kappa\lambda}) \delta^\mu_{\nu} - g^{\mu\rho} \gamma_{\nu\rho} \]

while variation over the $X^\alpha$ in (3) gives the harmonic equations

\[ \partial_\mu (g^{\mu\alpha} \sqrt{-g}) = \Box X^\alpha = 0, \]

which are also a consequence of the equations (4). The harmonic equation has (modulo constants) the form of a conservation law

\[ \partial_\mu t^\mu_{\kappa} = 0 \]

with an (densitized) energy-momentum tensor defined by

\[ t^\mu_{\kappa} = \frac{1}{8\pi G} \gamma_{\nu\rho} g^{\mu\nu} \sqrt{-g} \]

The equations of motion (4) allow to split this energy-momentum tensor into a “matter part”

\[ (T_m)^\mu_{\kappa} = (T_m)^\mu_{\kappa} \sqrt{-g} \]

and a “gravitational part”

\[ (T_g)^\mu_{\kappa} = \frac{1}{8\pi G} \left( \delta^\mu_{\nu} (\Lambda + \frac{1}{2} \gamma_{\kappa\lambda} g^{\kappa\lambda}) - G^\mu_{\nu} \right) \sqrt{-g} \]

so that

\[ t^\mu_{\kappa} = (T_m)^\mu_{\kappa} + (T_g)^\mu_{\kappa} \]
4. The condensed matter interpretation

The theory allows a condensed matter interpretation. In a variant of the ADM decomposition \[1\] we can split the gravitational field \( g_{\mu\nu} \) into a scalar \( \rho \), a three-vector \( v^i \) and a three-metric \( \sigma^{ij} \):

\[
\begin{align*}
\hat{g}^{00} \sqrt{-\hat{g}} &= \rho, \quad (11a) \\
\hat{g}^{0i} \sqrt{-\hat{g}} &= \rho v^i, \quad (11b) \\
\hat{g}^{ij} \sqrt{-\hat{g}} &= \rho v^i v^j - \sigma^{ij}. \quad (11c)
\end{align*}
\]

Their condensed matter interpretation becomes obvious if we look what happens with the harmonic equations (5). They become

\[
\begin{align*}
\partial_t \rho + \partial_i (\rho v^i) &= 0, \quad (12a) \\
\partial_t (\rho v^j) + \partial_i (\rho v^i v^j - \sigma^{ij}) &= 0. \quad (12b)
\end{align*}
\]

These are the continuity and Euler equations well-known from condensed matter theory if we identify \( \rho \) with the density of some fundamental medium, \( v^i \) with its velocity, and \( \sigma^{ij} \) with its stress tensor.

What about the matter fields? If there would be other media interacting with our medium, this would require some momentum exchange, thus, some additional interaction terms in the Euler equation (12b). Now the equations (12) hold also in the case of interaction with matter fields. But there is a simple solution of this problem: The matter fields have to be interpreted as fields which describe some other material properties of the same medium instead of properties of other media.

This condensed matter interpretation is, obviously, possible only if \( \rho(x) > 0 \). This condition translates into \( \hat{g}^{00} \sqrt{-\hat{g}} > 0 \), or in general coordinates \( g^{\mu\nu} \partial_\mu T(x) \partial_\nu T(x) > 0 \) for absolute time \( T(x) \). Thus, \( T(x) \) has to be time-like, the Einstein causality defined by the effective metric \( g_{\mu\nu} \left( x \right) \) has to be compatible with the absolute causality defined by absolute time \( T(x) \). This “causality condition” is an additional restriction which does not follow from the equations of motion. But this is quite natural for a condensed matter theory – the condition \( \rho(x) > 0 \) does not follow from the equations of motion too.

5. Connection to the Relativistic Theory of Gravity (RTG)

The Lagrangian (2) of the theory itself is not new. For \( \Xi, \Upsilon > 0 \) and \( \Lambda < 0 \) we can define

\[
\Lambda = -\frac{m^2}{2}, \quad \Xi = -\eta^{11} \frac{m^2}{2}, \quad \Upsilon = \eta^{00} \frac{m^2}{2}. \quad (13)
\]

In these denotations, we obtain a constant (vacuum) solution

\[
\hat{g}_{\mu\nu}^{\text{vac}} = \eta_{\mu\nu} = -\Lambda^{-1} \gamma_{\mu\nu}, \quad (14)
\]

and the equation (4) reduces in the Newtonian limit around \( g_{\mu\nu}^{\text{vac}} \) to

\[
(\Delta - m^2) V = \kappa \rho_{\text{matter}}. \quad (15)
\]

This suggests to interpret the action (2) as defining a bimetric theory on a Minkowski background with massive graviton. This has been proposed by Freund, Maheshwari and Schonberg 1969 \[47\] and appears in a two-parameter family of Lagrangians constructed by Ogievetsky and Polubarinov 1965 \[46\] as the case \( q = 0 \), \( p = -1 \). Later, the Lagrangian has been rediscovered by Logunov and coworkers,
which have named the theory "relativistic theory of gravity" (RTG). Because this name is widely used (see [31]–[43]) and neutral we will use it too (instead of, say, FMS theory).

One could think that the relation between our theory and RTG is similar to the relation between the Lorentz ether interpretation and the Minkowski spacetime interpretation of special relativity. But this is wrong – there exists an important physical difference. Above theories have different causality conditions: In our theory, the time coordinate $T$ should be time-like, while in RTG the light cone of the effective metric $g_{\mu\nu}(x)$ should be inside the light cone of the background metric $\eta_{\mu\nu}$, a difference which leads to different physical predictions, as we will see below.

This difference itself is a consequence of the different role of the background metric in above theories.

In RTG the metric $\eta_{\mu\nu}(x)$ defines a physical Minkowski background. The gravitational field is a spin 2 field $h_{\mu\nu}$ which moves on this Minkowski background and defines the effective metric $g_{\mu\nu}(x)$ by

$$h^{\mu\nu} = g^{\mu\nu}\sqrt{-g} - \eta^{\mu\nu}\sqrt{-\eta}.$$  

Conceptually all fields, the gravitational field as well as the matter fields, move on the Minkowski background $\eta_{\mu\nu}(x)$. Gravitational interaction leads to an effective replacement of $\eta_{\mu\nu}(x)$ by the effective metric $g_{\mu\nu}(x)$. But this gravitational interaction cannot violate the Einstein causality of the background metric $\eta_{\mu\nu}(x)$. As a consequence, the light cone of $g_{\mu\nu}(x)$ should be inside the light cone of the background $\eta_{\mu\nu}(x)$.

In our theory we can express the "Minkowski background" $\eta_{\mu\nu}(x)$ of RTG in terms of the constants $\gamma_{\alpha\beta}$ of the Lagrangian and the preferred coordinates $X^\alpha(x)$ as

$$\frac{m^2}{2}\eta_{\mu\nu}(x) = \gamma_{\alpha\beta}X^\alpha_{,\mu}(x)X^\beta_{,\nu}(x).$$

But it plays no physical role. It possibly defines a particular solution (for $\Lambda < 0$ and no matter fields), but even this is not obligatory. The effective metric $g_{\mu\nu}(x)$ is not defined in terms of the $\eta_{\mu\nu}(x)$, but by \(\text{[\[1\]}}\) in terms of the condensed matter fields $\rho$, $v^i$ and $\sigma^{ij}$. And it is, therefore, \(\text{[\[1\]}}\), combined with $\rho(x) > 0$, which leads to the additional causality condition that $T$ has to be time-like.

The RTG causality condition is stronger: If the light cone of $g_{\mu\nu}(x)$ is inside the light cone of $\eta_{\mu\nu}$, then every time coordinate $X^0$ of the background metric $\eta_{\mu\nu}$ will be time-like for $g_{\mu\nu}(x)$ too, so that every causal RTG solution also defines causal solutions of our theory. The reverse is not true, as we will see below.

6. Empirical viability

It remains to find out if our theory is empirically viable. Fortunately, the equivalence of the equations of our theory and RTG simplifies this task – we can reuse many of the results obtained for RTG: Once every solution of RTG defines a solution of our theory, in the domain where RTG is viable our theory will be viable too. Nonetheless, let’s give a short overview over the most interesting points:

First, because we have a metric theory of gravity, with a standard covariant matter Lagrangian, the Einstein equivalence principle holds exactly.
6.1. **No vDVZ discontinuity.** We obtain the Einstein equations in the natural limit $\Xi, \Upsilon \to 0$. While this seems obvious if we look at the Lagrangian and the equations of motion, it requires more detailed consideration, because in the case of the Fierz-Pauli mass term it seems equally obvious but is wrong – it leads to the van Dam-Veltman-Zakharov discontinuity \cite{24,25,26,27}. In \cite{30}, the discontinuity is understood as a consequence of an infinite mass for the spin-0 component, which does not disappear if the mass for the spin-2 component becomes zero. The RTG mass term is not of Fierz-Pauli type, so that with $m \to 0$ the masses of above spins go to zero and no discontinuity appears.

6.2. **Afraid of ghosts?** While the Fierz-Pauli mass term is not viable, it is the only one which does not lead in the linear approximation to tachyons or ghosts. Indeed the linear approximation of RTG contains a ghost because of the spin-0 component. Ghosts are supposed to lead to negative energies and instabilities, therefore there is a strong prejudice against them. But gravity is instable anyway, thus, this argument is hardly decisive. Moreover, it has been shown by Loskutov \cite{32} that the flow of gravitational energy from an isolated source is positive-definite. Grishchuk, who has heavily criticized RTG in \cite{23,29} and mentioned these problems as part of his critique in \cite{29}, has later demonstrated (together with Babak) “the incorrectness of the widely held belief that the non-Fierz-Pauli theories possess negative energies and instabilities” \cite{30}.

We conclude that there exists a GR limit, and that the presence of a ghost in the linear approximation does not question the viability of the theory.

On the other hand, even for arbitrary small $\Xi, \Upsilon$ there remains a surprisingly large number of qualitative differences with GR.

6.3. **Trivial topology.** All solutions of our theory have trivial topology. Thus, an observation of nontrivial topology would falsify our theory without falsifying GR. Once no nontrivial topology has been observed yet, this additional prediction of our theory is in agreement with observation.

Given that not only sci-fi authors, but also some physicists like the fact that GR allows nontrivial topologies and consider this to be an advantage of GR, it has to be noted that following Popper’s methodology the prediction of our theory of trivial topology is an additional falsifiable prediction (that means, additional empirical content) of our theory, thus, has to count as an advantage of our theory.

6.4. **Preference for a flat universe.** Another important difference is a symmetry preference for the FRW universe with zero curvature parameter $k = 0$: Only the flat FRW universe can be homogeneous in our theory. While the observation of a curved Friedman universe would not directly falsify our theory – to define some harmonic coordinates on these solutions is possible – these solutions would have a center, or would have to break translational symmetry otherwise. This would be a strong symmetry argument against the new theory. Thus, different from GR our new theory strongly prefers $k = 0$ for the homogeneous FRW approximation.

This preference is in sufficiently nice agreement with observation. Instead, for GR it is a problem to explain the approximate flatness of the observable universe – the so-called flatness problem. In GR, one needs inflation to solve it.
6.5. **Big bounce instead of big bang.** There are other important differences in cosmology. The harmonic ansatz for the flat homogeneous universe is

\[(18) \quad ds^2 = a^6(t)dt^2 - \beta^4 a^2(t)(dx^2 + dy^2 + dz^2).\]

For proper time \(d\tau = a^3dt\) this gives the usual FRW-ansatz for the flat universe with some scaling factor \(\beta > 0:\)

\[(19) \quad ds^2 = d\tau^2 - \beta^4 a^2(\tau)(dx^2 + dy^2 + dz^2).\]

This leads to \((p = k\varepsilon, 8\pi G = c = 1):\)

\[(20a) \quad 3 \left( \frac{\dot{a}}{a} \right)^2 = -\frac{1}{2} \frac{\Upsilon}{a^6} + \frac{3}{2} \frac{\Xi}{a^2} + \Lambda + \varepsilon,\]

\[(20b) \quad 2 \frac{\ddot{a}}{a} + \left( \frac{\dot{a}}{a} \right)^2 = + \frac{1}{2} \frac{\Upsilon}{a^6} + \frac{1}{2} \frac{\Xi}{a^2} + \Lambda - k\varepsilon.\]

The \(\Upsilon\)-term influences only the early universe, its influence on later universe may be ignored. But, if we assume \(\Upsilon > 0\), the qualitative behavior of the early universe changes in a remarkable way. From \((20a)\) for \(\dot{a} = 0\) we obtain a lower bound \(a_{min}\) for \(a(\tau)\) defined by

\[(21) \quad \frac{\Upsilon}{a^6_{min}} = 3 \frac{\Xi}{\beta^4 a^2_{min}} + 2\Lambda + 2\varepsilon,\]

and \((20b)\) gives \(\ddot{a} > 0\) for this value. Instead of a big bang, we obtain a big bounce.

Note that this solves several problems of GR: First, we have no big bang singularity. In some sense, a singularity has to be considered as one of the strongest arguments against a theory at all, comparable with internal inconsistency. Thus, that the big bang singularity disappears is a strong argument in favour of our theory.

Second, there are two problems of cosmology which are solved in standard cosmology by inflation theory: The flatness problem and the cosmological horizon problem. Primack \[13\] describes the horizon problem in the following way: First, “the angular size today of the causally connected regions at recombination \((p^+ + e^- \rightarrow H)\) is only \(\Delta\theta \sim 3^{\circ}\). Yet the fluctuation in the temperature of the cosmic background radiation from different regions is very small: \(\Delta T/T \sim 10^{-5}\). How could regions far out of causal contact have come to temperatures that are so precisely equal? This is the ‘horizon problem’.” \((13)\) p.56 Then, in the standard hot big bang picture “the matter that comprises a typical galaxy, for example, first came into causal contact about a year after the big bang. It is hard to see how galaxy-size fluctuations could have formed after that, but even harder to see how they could have formed earlier”. \((13)\) p.8.

These problems do not exist in our theory – with a big bounce instead of a big bang there was enough time before to establish causal contact. Thus, this difference does not question the viability of our theory, but, instead, defines an advantage in comparison with GR.

On the other hand, the evolution of an FRW universe defines the most important difference between our theory and RTG: RTG requires \(\Lambda < 0\), for two reasons: First, an FRW universe which increases forever without an upper bound for \(a(t)\) necessarily violates the RTG causality condition. This follows already from the

\[\text{On the other hand, current big bang theory gives some upper bound for } a_{min}, \text{ which allows to obtain an upper bound for } \Upsilon.\]
ansatz (15) – whatever the background \( \eta_{\mu\nu} \), it is sufficient to use a large enough \( a(t) \) to get a wider light cone. And, second, we obtain \( \eta_{\mu\nu} \) as a stable vacuum solution \((\varepsilon = 0, a = \beta = 1 \text{ in } \text{(20)})\) only if \( \Lambda < 0 \).

Above reasons do not hold in our theory, so one is free to use the standard \( \Lambda \)CDM scenario with \( \Lambda > 0 \) to explain the observationally favoured accelerated expansion. Thus, one does not need some quintessence as in RTG [42] to explain the observed expansion rate.

On the other hand, a theory which has a vacuum state and stable solutions oscillating around this vacuum seems metaphysically more satisfactory. For these reasons, we would prefer, if possible, the choice \( \Lambda < 0 \). It also leads to an oscillating universe – another reason to prefer it metaphysically. But even in this case, our theory seems better compatible with the data. In particular, Gehlaut, Geetanjali, and Lohiya [48] argue that a universe with linear expansion rate \( a(t) = t \) (coasting) is compatible with observation. Now, for a sufficiently large value of \( \Xi \) equation (20a) would give \( a^2 \sim \Xi/2\beta^4 \) for values far away from the extrema \( a_{\text{min}}, a_{\text{max}} \), thus, an approximate coasting in these regions. But in RTG large values are excluded as well by the causality condition. It requires

\[
\frac{\Xi}{\beta^4} < -\frac{\Lambda}{a_{\text{max}}^4},
\]

which restricts the influence of this term in (20). No such restriction exists in our theory – its causality condition is fulfilled for all FRW universes. Thus, different from RTG, we can use the best fit with observation for \( \Xi \), and in particular enforce approximate coasting with values of \( \Xi/\beta^4 \) as large as we like.

6.6. Frozen stars instead of black holes. Another domain where even an extremely small \( \Upsilon > 0 \) leads to important qualitative differences to GR is the gravitational collapse. Here, the situation is identical to RTG, and we can refer the reader to sec. 11 of [34] (see also [35], [37], [38], [39], [40]). The gravitational collapse stops shortly before horizon formation, and, as the result of the collapse, a “frozen star” with size slightly greater than its Schwarzschild horizon remains. The difference exists only in a small environment of the Schwarzschild radius. Outside this environment, the GR solution is a good approximation.

This effect appears also in other theories of gravity with non-zero graviton mass [30]. Their common property is that the mass term depends on the flat background and therefore is able to feel locally that time dilation relative to the background becomes extremal.

In principle it seems possible to observe surface radiation. But, first, it is highly redshifted, by a redshift factor \( z \) defined (in GR approximation) by

\[
(1 + z) = \left(1 - \frac{R_S}{R}\right)^{-\frac{1}{2}},
\]

where [43] gives (for RTG) a lower bound \( z \gtrsim 10^{23}M_\odot/M \). Second, only a small part of the surface radiation reaches infinity. Most of it simply falls back on the surface because of gravitational lensing. The part which is able to reach infinity is (in GR approximation) defined by

\[
\frac{d\Omega}{2\pi} = 1 - \left[1 - \frac{27}{4} \left(\frac{1 - R_S/R}{R_S/R}\right)^2\right]^{\frac{1}{2}}.
\]
which gives \( z^{-2} \) for large \( z \)\(^{[14]}\). The observable flux at distance \( D \) of a black hole with surface temperature \( T \) for frequency \( \nu \) in the surface frame will be

\[
F_{\nu} = \frac{2h\nu^{3}}{c^{2}} \frac{e^{-h\nu/kT}}{1 - e^{-h\nu/kT}} \frac{\pi R_{a}^{2}}{D^{2}} \frac{d\Omega}{2\pi}.
\]

The flux visible in infinity decreases by a factor \((1 + z)^{-1}\) because of time dilation. The frequency in the surface frame is \((1 + z)\nu\). This gives for large \( z \)

\[
F_{\nu} = \left( \frac{kT}{1 + z} \right)^{3} F(\frac{h(1 + z)\nu}{kT}) \frac{\pi R_{a}^{2}}{D^{2}} \frac{D^{2}}{8}
\]

with

\[
F(\lambda) = \frac{2\lambda^{3}}{h^{2}c^{2}} \frac{e^{-\lambda}}{1 - e^{-\lambda}}.
\]

Thus, for small \( \frac{kT}{1 + z} \) it will become invisible. Thus, we would need extremely large surface temperatures \( T_{\text{surf}} \sim z \) to be able to see the surface radiation at large distances. On the other hand, in principle the heating by infalling matter could provide sufficient energy to reach such temperatures. To decide if this happens, we would need the relation between energy and temperature for the material of the frozen star\(^{3}\). We obviously cannot have reliable data for such extremal temperatures, thus, cannot make reliable predictions that something should be visible. The mere theoretical possibility of visible surface radiation clearly does not endanger the viability of the theory.\(^{4}\)

In a similar way it seems extremely unlikely that the impact of infalling matter leads to observable effects. In principle, an ideal point-like elastic infalling body would bounce back from the surface of a frozen star\(^{[34]}, [40]\). But this idealization fails already for comets falling on the Earth. For the frozen stars, it follows from\(^{[21]}\) that even a minor scattering away from the vertical direction is sufficient to prevent even an ideal elastic body to reach infinity. Thus, even if, because of energy conservation, an infalling body has enough energy to go back to infinity, it seems extremely unlikely that this leads to observable effects different from those predicted by GR.

Thus, the existence of a surface for black hole candidates does not endanger the viability of our theory. Instead, the central black hole singularity which is unavoidable in GR provides a strong argument against GR.

6.7. **No closed causal loops.** The last important difference with GR is that closed causal loops are forbidden by the causality condition. The time coordinate \( T \) is a global time-like function. This causality condition is not automatically enforced by the equations of the theory. Instead, it is possible to construct solutions which violate it, and even solutions where this violation is not present in the initial conditions but happens only after some time\(^{[4]}\). These solutions contain regions with \( \rho \leq 0 \) and are therefore physically meaningless. But it is not physically meaningless

\(^{3}\)Moreover, we would also have to assume the validity of the EEP for such extremal redshifts.

\(^{4}\)On the other hand, we have to admit that GR has here an advantage in predictive power: It predicts uniquely that no surface radiation should be visible and would be falsified if we would observe surface radiation from black hole candidates.

\(^{5}\)Such solutions can be constructed using solutions which violate the RTG causality condition, for example an FRW-like solution with \( a(t) \) becoming too large. Then one can choose such another time coordinate \( T \) which is time-like for the background metric \( \eta_{\mu\nu} \) but not for \( g_{\mu\nu}(x) \).
that condensed matter equations for some valid initial state with \( \rho > 0 \) everywhere evolve into a state with \( \rho = 0 \) somewhere: Materials sometimes tear into parts. The condensed matter approximation becomes of course inapplicable if this happens. But the effect itself is a quite natural one. Broken materials do not cause any metaphysical problems comparable to the breakdown of causality in GR solutions with closed causal loops.

The situation is also better than in RTG: First, the causality condition of our theory is less restrictive. In particular, the RTG causality condition may be violated for solutions very close to the vacuum solution. It becomes violated, for example, for gravitational waves on the vacuum background, for an unlimited expansion of the universe, and for every FRW solution in the limit \( m \to 0 \). Instead, there is a safe distance between the vacuum solution which gives \( \rho = 1 \) and solutions which lead to \( \rho = 0 \). Then, FRW solutions never violate the causality condition of our theory. But, more important, what happens if an RTG solution starts to violate the RTG causality condition is not clear at all. There is no natural replacement which becomes applicable if RTG fails which is comparable to an atomic microscopic theory if the continuous condensed matter approximation fails.

Anyway, solutions containing closed causal loops have not been observed yet, thus, the non-existence of such solutions in our theory does not endanger its empirical viability.

7. Discussion

We have presented here a metric theory of gravity with preferred frame and condensed matter interpretation which is not only viable: Some of the differences between this theory and GR define interesting advantages of our theory. It has no nontrivial topologies, no closed causal loops, no big bang singularity, predicts \( a''(\tau) > 0 \) in the very early universe, no horizon formation during the gravitational collapse, and a symmetry preference for the observed flat \((k = 0)\) FRW universe.

While our theory shares the equations with the “relativistic theory of gravity” (RTG), its less restrictive causality condition becomes physically important in FRW cosmology: Different from RTG, it is compatible with \( \Lambda > 0 \) and therefore with the currently favoured \( \Lambda \)CDM model.

Given these results, we can give a positive answer to our two questions: Once a viable theory of gravity with preferred frame and a condensed matter interpretation exists, relativistic gravity does not give any empirical evidence nor against theories with preferred frame like pilot wave theories, nor against classical realism, nor against condensed matter interpretation of the standard model fields as the one presented in [16].

Based on the advantages we have found one could justify even stronger claims. But there is no need to do this in this paper: The theories which have motivated our questions – pilot wave theory, realism, and the condensed matter model [16] – have strong enough own advantages in comparison with their relativistic competitors.

Appendix A. Reconsideration of old arguments against the Lorentz ether

Answers to the question how to improve the presentation of this theory have been almost predictable – to avoid the e-word. Now, there is indeed an important difference between the ether theories of the past and the theory presented here: The
old ether theories were theories about the electromagnetic field only. The theory presented here is about gravity, but also all other matter fields have to describe various properties of the ether. Thus, naming this theory “ether theory” could be indeed misleading, and the characterization of this theory as a theory of gravity with preferred frame and condensed matter interpretation seems more accurate. So I have chosen to follow this recommendation here.

But this seems justified only up to a certain point. One could think of avoiding the e-word as a sort of cheating – once the e-word is not used, referees may forget to apply the long list of popular anti-ether arguments against our theory. This is certainly not my intention. There is no reason to be afraid of these arguments, as we want to show here.

Now there is certainly no reason to consider arguments against ether theories which have nothing in common with the theory presented here. The only old ether theory which is worth to be considered is the Lorentz ether. In some sense, the Lorentz ether can be considered as the no-gravity limit of the theory presented here: In this limit, the effective metric reduces to the Minkowski metric $g_{\mu \nu}(x) = \eta_{\mu \nu}$, with a preferred frame defined by the constant function $T(x) = t$, and a quite trivial condensed matter interpretation: Constant density $\rho = \text{const}$, no motion $v^i = 0$, and isotropic constant stress tensor $\sigma^{ij} = \text{const} \delta^{ij}$. This is quite close to the Lorentz ether, if we ignore that the Lorentz ether was a theory only about the EM field, and that time dilation and length contraction have been effects of the ether on some external matter, while in our theory all matter fields have to describe “ether” properties and time dilation and length contraction are therefore “ether”-internal effects. Having in mind these differences, let’s consider if the classical arguments against the Lorentz ether are applicable against our theory:

- **The Lorentz ether does not describe gravity.** Our theory describes gravity.
- **The formulas for time dilation and length contraction in the Lorentz ether are ad hoc and require some unexplained conspiracy to make the preferred frame unobservable.** One can derive the general Lagrangian of our theory from a simple postulate (see appendix B). In this derivation relativistic symmetry appears closely connected with the action equals reaction symmetry inherent in the Lagrange formalism. Note also that we need no fine-tuning to obtain the Einstein equations in the GR limit $\Xi, \Upsilon \to 0$.
- **The Lorentz ether is only about the electromagnetic field. But we know today that the other forces follow similar equations with the same speed of light.** In our theory all fields describe properties of the medium.
- **It seems strange that usual matter goes through the ether without feeling any resistance.** This applies only to external matter. Once other “matter fields” have to describe waves of properties of the medium itself, one does not expect such a resistance. Waves in an elastic medium do not feel any resistance.
- **It seems strange that the effects (time dilation and length contraction) caused by the ether on very different types of external matter are identical.** In our theory, all types of matter are only different material properties of the same ether, and it is at least not implausible that the variables which define the energy-momentum tensor – density, velocity and stress – have some common effects on all other material properties. This also explains the universal character of gravitational interaction – all internal degrees
of freedom give some contribution to the overall energy-momentum tensor and are influenced by this tensor.

- The Lorentz ether violates the “action equals reaction” principle: The matter is influenced by the ether, but there is no reverse influence of matter on the stationary and incompressible ether. Our theory has a Lagrange formalism. This guarantees the “action equals reaction” principle. The medium is compressible and instationary.

- There are no observable differences in the predictions of the Lorentz ether and special relativity. For our theory important and interesting physical differences exist in comparison with general relativity (see section 6) as well as with RTG.

Thus, there is a quite long list of arguments against the Lorentz ether which are simply inapplicable against our theory. But this list is not complete – there are also some other arguments, which we do not want to consider here in detail. This does not mean that we are afraid of them – they are invalid too, but for other reasons, not related with gravity and the particular properties of our theory.

But these other reasons are beyond the scope of this paper. We would have to consider questions far beyond the questions we have considered here, like discrete models (“atomic ether”) which give the condensed matter interpretation in its large distance limit and their quantization, various methodological (“metaphysical”) questions, in particular positivism versus realism, theory-dependence of observability and the meaning of simplicity and explanatory power, the explanatory and empirical power of hidden variable theories in general, the whole EPR-Bell discussion and the relation between the hidden preferred frame and the CMBR frame. All this is worth to be done in detail in future research. Given that some of the following short replies are more or less in conflict with “common wisdom” and therefore require justification, it is even necessary. Therefore these replies are simply intended to give an idea about the general line of argumentation:

- Field theory is preferable in general in comparison with old-fashioned “mechanical models”. Beyond the point that fashion should not be a scientific argument, the situation is even reverse – mechanical models are preferable from point of view of simplicity as well as empirical content.

- The preferred frame is in principle unobservable with local clocks. While this holds for the continuous theory considered here, it will almost certainly not hold for a more fundamental theory of an “atomic ether”. The symmetry group of this more fundamental theory will probably be $E(3) \times E(1)$ instead of the Poincare group, and the preferred frame will therefore be observable in principle. Then, de facto the preferred frame itself is easily observable with high accuracy – it is simply the CMBR frame. Last but not least, the violation of Bell’s inequality, even if it does not allow to identify the preferred frame, requires violations of Einstein causality in any realistic causal explanation, and should be therefore considered as an indirect observation of a preferred frame.

- Ether theories are purely classical theories. We need quantum theories. Fact is that quantization in agreement with GR principles (in particular background freedom) can be considered as impossible after the failure during the last eighty years. Instead, we know how to quantize condensed matter theories – one has to quantize the discrete “atomic ether” theory, which is
a regularization of the continuous field theories. A separate quantization procedure for the gravitational field is as unnecessary as a separate quantization procedure for “phonon field theory” in standard condensed matter theory.

**Appendix B. Derivation of the Lagrangian**

We have already used the so-called “parametrized formalism” where we use four explicit scalar functions \( X^\alpha(x) \) for the “preferred coordinates” \( X^\alpha \) in terms of general coordinates \( x^\mu \). In particular, the Lagrangian presented in this form is given by (28) and looks covariant if one forgets about the geometric meaning of the \( X^\alpha(x) \) as preferred coordinates and considers them as usual scalar fields.

The key of the derivation is the observation that in the parametrized formalism Euler-Lagrange equations for the “fields” \( X^\alpha(x) \) can be defined as usual by

\[
\frac{\delta S}{\delta X^\alpha} = \frac{\partial L}{\partial X^\alpha} - \partial_\mu \frac{\partial L}{\partial X^\alpha_{,\mu}} + \partial_\mu \partial_\nu \frac{\partial L}{\partial X^\alpha_{,\mu\nu}} - \cdots
\]

give valid equations of motion \(^6\) and, especially nice, give for the translational symmetry \( X^\alpha \rightarrow X^\alpha + c^\alpha \) of the Lagrangian automatically Noether conservation laws

\[
\frac{\delta S}{\delta X^\alpha} = \partial_\mu t^\mu_\alpha
\]

with

\[
t^\mu_\alpha = -\frac{\partial L}{\partial X^\mu_{,\alpha}} + \partial_\nu \frac{\partial L}{\partial X^\mu_{,\alpha\nu}} - \cdots.
\]

Assuming that we have a four-dimensional parametrized field theory with preferred coordinates \( X^\alpha(x) \), the following postulate is sufficient for the derivation of the general Lagrangian:

**Postulate 1.** The energy-momentum tensor \( t^\mu_\alpha \) defined by (30) has the following properties:

1. For some invertible constant matrix \( c^{\alpha\beta} \) the tensor \( g^{\alpha\beta} = c^{\alpha\gamma} t^\gamma_\alpha \) is symmetric.
2. The \( g^{\alpha\beta} \) are among the independent field variables.

Indeed, this postulate gives together with (29)

\[
\frac{\delta S}{\delta X^\alpha} = c_{\alpha\mu} \partial_\nu g^{\mu\nu}
\]

In the four-dimensional case, one can identify the variables \( g^{\alpha\beta} \) with the usual metric variables \( g_{\alpha\beta} \) by

\[
g^{\alpha\beta} = g^{\alpha\beta} \sqrt{\det(g_{\mu\nu})}, \quad g_{\alpha\beta} = g_{\alpha\beta} \sqrt{\det(g^{\mu\nu})},
\]

so that (31) becomes

\[
\frac{\delta S}{\delta X^\alpha} = c_{\alpha\mu} \partial_\nu (g^{\mu\nu} \sqrt{g}),
\]

\(^6\)The only difference from the standard proof for fields is that variations \( X^\alpha + \delta X^\alpha \) may not define a valid system of coordinates. But for small enough \( \delta X^\alpha \) with finite support, which are sufficient for the proof, this problem does not appear.
but the variables $g^{\alpha \beta}$ may be used as well as the independent variables. We can define now constants $\gamma_{\alpha \beta}$ by

$$c_{\alpha \beta} = - (8\pi G)^{-1} \gamma_{\alpha \beta}. \quad (34)$$

With these $\gamma_{\alpha \beta}$ the action

$$S_0 = -(16\pi G)^{-1} \int \gamma_{\alpha \beta} g^\mu \nu X^\alpha \_\mu X^\beta \_\nu \sqrt{-g} d^4x \quad (35)$$
defines a particular solution of (31). As usual, the general solution $S$ of the inhomogeneous problem (31) is the sum of this particular solution $S_0$ and the general solution of the corresponding homogeneous problem, which is in our case

$$\frac{\delta (S - S_0)}{\delta X^\alpha} = 0. \quad (36)$$

Thus, $S - S_0$ should not depend on the preferred coordinates $X^\alpha$. But this is simply a well-known way to define the action of GR. So we obtain

$$S - S_0(g_{\alpha \beta}, X^a) = S_{GR}(g_{\alpha \beta}) + S_{matter}(g_{\alpha \beta}, \varphi_m) \quad (37)$$

where only the term $S_0$ depends on the preferred coordinates $X^\alpha$, while $S_{GR}$ and $S_{matter}$ are covariant, and only $S_{matter}$ depends on the matter fields $\varphi_m$. This action may differ from (2) because it can contain non-minimal interactions with matter fields in $S_{matter}$ and higher order terms like $R^2, R^\mu \nu R_{\mu \nu}$ and so on in $S_{GR}$. But our context is that of an effective field theory, so there is no reason to restrict the action to the lowest order terms (2). All higher order terms may be present, they will be simply suppressed in the large distance limit.

Note that this derivation not only derives the gravity part $S_0 + S_{GR}$ of the action, but also the main property – covariance – of the matter part $S_{matter}$, or, in other words, the Einstein equivalence principle. The main ingredients of this derivation of relativistic symmetry are the action-equals-reaction symmetry of the Lagrange formalism and the choice of the $g_{\mu \nu}$ (or, equivalently, of the $g^\mu \nu$) as independent variables so that the conservation laws do not depend on the matter fields $\varphi_m$: \[\frac{\delta}{\delta X^\alpha} \frac{\delta}{\delta \varphi_m} S = \frac{\delta}{\delta \varphi_m} \frac{\delta}{\delta X^\alpha} S = \frac{\delta}{\delta \varphi_m} (c_{\alpha \mu} \partial_\nu g^\mu \nu \sqrt{-g}) = 0. \quad (38)\]

How restrictive is our postulate? This is an interesting question which we have to leave to future research.

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