Relativity 2.0:

New 'Gedankenexperimente' on time, space, and matter

Ralf R. Lenke[1], submitted 20.04.2022, Version 1.1

Abstract

Albert Einstein's special relativity theory (SRT) is a consistent implementation of the principle of relativity, i.e. the independence of the laws of nature from the observer's state of motion. In the case of the general relativity theory (GRT), the assumption of the equivalence of acceleration and gravitation is added. Einstein's RT is essentially a purely mathematical theory in which the question of why our universe fulfils the principle of relativity remains unanswered.

In this work, we continue the considerations of *Huygens*, *Doppler*, *Lorentz*, *Poincaré* and *de Broglie* and thus also arrive at the theory of relativity on an alternative, physically very descriptive path. Ultimately, in this path, the principle of relativity is not the starting point, but is implicit. It turns out that for light in any case, but also for matter waves, the SRT is nothing more than the Doppler effect. Thus, both the principle of relativity - and consequently SRT – as well as quantum mechanics are based on the wave character of nature.

As a consequence, it seems only natural to want to explain GRT via the wave character of nature, since it is already common to speak of gravitational lenses. In fact, this gravitational lensing model can be further extended in order to arrive at an equivalent and also very descriptive representation of GRT.

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The transverse light path in the Michelson-Morley experiment

The key experiment for the relativity theory (RT) was the Michelson-Morley experiment (MME), which aimed to find a unique reference frame for the propagation of electromagnetic waves. But the result was surprising: no matter where, who and how you measure, the vacuum light speed always has the same value, regardless of the speed of the light source and, above all, the speed of the receiver. This meant that the classical Galileo transformations were no longer compatible with the principle of relativity. The Lorentz transformations and Einstein's RT followed. The idea of an ether as a carrier medium for electromagnetic waves was rejected.

The Michelson-Morley interferometer is still an important measuring instrument in experimental physics today and has recently been driven to incredible accuracy in the case of gravitational wave detectors. This interferometer is used to measure differences in the time of flight of light on two mutually perpendicular light paths of exactly the same length. To do this, a light beam is split at a semi-transparent 45°-mirror. At the ends of the two light paths, the light beams are each reflected by a mirror in order to overlap again after passing by the 45°-mirror a second time. The interference pattern of the two reunited light beams then provides information about the path differences in the two light paths. Further details of this experiment are described in detail elsewhere.

The MME was supposed to measure the velocity $\vec{v}$ of the reference frame in which the observer is located relative to the carrier medium of the electromagnetic waves, the so-called *ether*. This should have been possible because, according to classical theory, the transit time of the light in the two interferometer arms depends on the relative velocity $\vec{v}$: In an interferometer arm that is perpendicular to $\vec{v}$, the light travels in the direction of the interferometer arm only with the reduced velocity

$$c_y = \sqrt{c^2 - v^2} = c \;/\; \gamma$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

whereby here, as is generally the case, the vertical direction has been defined as the y-axis. The x-axis points in the direction of the velocity $\vec{v}$.

In the interferometer arm, which runs parallel to $\vec{v}$, the light has the relative velocities $c_{+x} = c - v$ on the way to the reflector and $c_{-x} = c + v$ on the way back. This would result in an average running time that is slower by a factor of γ^2 compared to the case when the interferometer is at rest relative to the ether.

The transit time in the two interferometer arms should therefore have differed by a factor of γ. But since no effect was measured, there was ultimately nothing left to do but assume that objects in the direction of motion are Lorentz-contracted by the factor γ.

It is astonishing, however, that contrary to our everyday understanding, only the relative motion is relevant. This means that every observer sees a Lorentz contraction in a reference system that is moving relative to him. It is the same with time dilation: every observer sees that time passes more slowly in a reference frame that is moving relative to him. There is no such thing as a “Lorentz expansion” and “time constriction”. Responsible for this is the phenomenon of simultaneity of events at different locations, which also depends on the relative motion. More on this later.

For all three phenomena: time dilation, Lorentz contraction and simultaneity, there are numerous plausibility explanations, but there is still no intrinsic explanation as to why our universe works the way it does. A clue could be provided by the transverse light path at the MME, i.e. the light path perpendicular to $\vec{v}$. Surprisingly, at least to our knowledge, it has never been investigated in more detail why the light, after reflection at the 45°-mirror, hits the reflector at all, which has moved on in the meantime? Whereby “hit” is meant at exactly the same place as in the case of the stationary interferometer. For one thing, the principle of relativity would otherwise be violated, and for another, the smallest deviation would be detectable on the high-precision equipment for the gravitational wave experiments.

So, let's consider how the light reflects off a moving 45°-mirror. As in the case of the interferometer arm parallel to $\vec{v}$, the light has the velocity $c - v$ relative to the mirror. This results in a virtual mirror surface stretched by a factor of $1 / (1 - v / c)$. “Virtual” because the mirror surface is moving while being hit by the light beam. However, light is reflected from this virtual mirror surface in exactly the same way as from a stationary one, which can easily be deduced from Huygens' elementary wave principle. But a 45°-mirror stretched by this factor alone would not direct the light exactly to the reflector of the transverse interferometer arm. This is only the case if the 45°-mirror is also compressed by the factor γ. Strictly speaking, this means that the result of the MME, the Lorentz contraction, is already anticipated at the 45°-mirror.

Much more interesting now, however, is the appearance of the reflected light beam shown in Fig. 1, which can be derived very easily using plausibility considerations or calculations analogous to the Doppler effect:

The transversely drifting light beam

This transversally drifting light beam points exactly in the y-direction, but additionally has the transversal velocity component $c_x = v$. For the velocity component in the y-direction, $c_y = c\ /\ \gamma$ applies. The wave fronts are now no longer perpendicular to the direction of the light beam, but the following relationships apply to the wave vector $\vec{k}$ - which is still perpendicular to the wave fronts - and its components: $k_x\ /\ k = v\ /\ c$ and $k_y\ /\ k = 1/\gamma$. Since the length of the wave fronts remains unchanged during reflection at a plane (virtual) mirror surface, it follows that the light beam is narrower by the factor γ after reflection at the moving 45°-mirror. This is the Lorentz contraction!

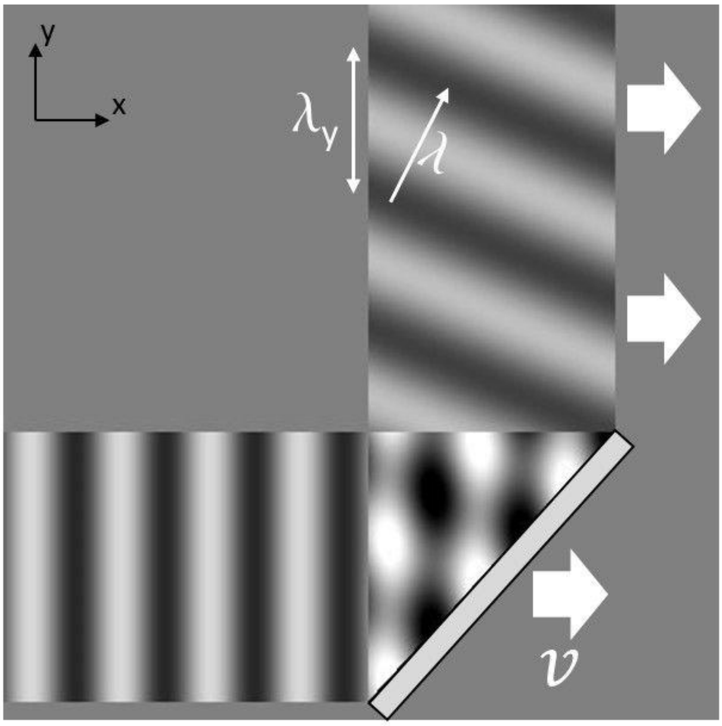

Fig. 1: The transversely drifting light beam is generated, for example, by reflection from a moving 45°-mirror. In this figure, the mirror moves to the right with velocity $\vec{v}$ and thus generates in the y-direction a light beam drifting sideways with velocity $\vec{v}$, whose amplitude before and after reflection at the mirror is shown here.

But what does an observer, let's call him Bob, who is moving along with the mirror and the laterally drifting light beam see? According to the principle of relativity, he must see the same thing as an observer at rest, let's call her Alice, at a non-moving Michelson-Morley interferometer. That means: a “normal” light beam of unchanged width, which is reflected at a stationary 45°-mirror and propagates with the speed of light c in the y-direction, with wave fronts parallel to the x-axis.

And what about the wavelength λ? Again using plausibility considerations or the Doppler effect, it can be shown that the distance of the wave fronts in the y-direction, i.e. both the length λ_y (see Fig. 1) in the case of the laterally drifting light beam and the wavelength λ_0 in the case of the light beam at rest, remain the same in Alice's as well as in Bob's reference frame. This also makes it immediately obvious that there is no Lorentz contraction perpendicular to $\vec{v}$. Because of $\lambda_0 = \lambda_y$, the frequency of the waves in the y-direction in the case of the light beam at rest, or parallel to Bob's laterally drifting y-axis, is proportional to the corresponding component of the speed of light c or c_y respectively. Thus, from Alice's point of view, the frequency of the light beam at rest in Bob's reference system is smaller by the factor γ than in the case of the light beam at rest in her own system. Consequently, due to the Doppler effect, from Alice's point of view, Bob's clocks go slower by a factor of γ.

Note: To derive relativistic time dilation, we have not used the usual but impractical light clock of a light pulse propagating between two mirrors. This is because both technical and biological clocks count oscillations.

And what is it about the inclined wave fronts? Why does Bob see horizontal wave fronts, although Alice sees a transversely drifting light beam with inclined wave fronts? Well, it has to do with simultaneity. Bob's time not only passes more slowly, but it also experiences a delay in the direction of $\vec{v}$, i.e. a negative phase shift. In Fig. 1, for example, by just the time it takes the right-hand side of a wave front to reach the original height of the left-hand side. Up to now, this phenomenon of simultaneity has always been explained with a conductor who sends a light pulse from the middle of a moving train to the end and beginning of the train. For him, according to the principle of relativity, the two light pulses arrive at the same time, but from Alice's point of view on the platform they do not. In the following, however, it will become obvious that the explanation derived here with the oblique wave fronts is much more profound.

One could now assume that the transversely drifting light beam is simply a light beam with a somewhat unusual geometric shape. However, this is only the case in a first approximation: According to Fourier optics, a light beam always has a finite coherence length, a certain divergence and ideally a Gaussian profile. This results in a certain spectral width in the frequency and tangential component of the wave vector. The distribution of these spectral components changes when changing from a light beam at rest to a transversely drifting light beam, as do the amplitudes of the electromagnetic fields and, when changing to the photon image, their frequency and particle flux density. This results in further transformation equations, which we cannot go into more detail at this point. We will limit ourselves here to the first approximation of a parallel light beam and to the transformation equations of space and time.

So far, it has been shown how time dilation, length contraction and simultaneity can be represented in a simple geometric and intuitive way with the transversely drifting light beam. If one extends these lines of thought further, one also arrives, for example, at the relativistic addition theorem of velocities, light refraction and diffraction at a rotating glass pane or a rotating grating and so on. Fig. 2 explicitly shows why Bob sees the same relativistic time dilation in Alice's reference frame as Alice sees in his.

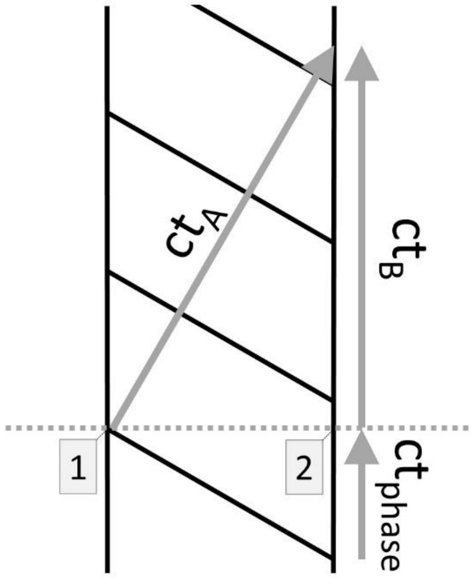

Fig. 2: Illustration of the principle of relativity with regard to time dilation. While the laterally drifting light beam travels over its entire width from 1 to 2, a point on a wave front travels the distance ct_A from Alice's point of view. For Bob, on the other hand, the time elapses that the laterally drifting light beam needs to cover the distance ct_B. From Alice's point of view, Bob's time passes more slowly by a factor of γ. Now let's look at Alice from Bob's point of view as she passes Bob from point 2 to 1. Between 1 and 2, time in Bob's system experiences another phase shift corresponding to the length ct_{phase}. But the total length $ct_B + ct_{phase}$ is now just longer than ct_A by a factor of γ. Thus, from Bob's point of view, Alice's time also goes slower by the factor γ.

The Lorentz Transformations

In connection with the normal and laterally drifting light beam, there are 4 outstanding directions: Wave fronts that are parallel to the x-axis, tilted wave fronts, and the distances ct_A and ct_B in Fig. 2. From these 4 distances, the space-time transformations between Alice's and Bob's reference frames, i.e. the Lorentz transformations, can be derived graphically. To do this, we must realise that wave fronts are lines (in 2D) of constant time, and distances are given by their width. Consequently, it is obvious to choose the x-axis as Alice's x_A-axis, because in the case of the light beam at rest, everything happens simultaneously on the wavefronts that are parallel to the x-axis. In the reference frame that is moving relative to Alice, on the other hand, everything happens simultaneously on the inclined wave fronts. They thus specify the x_B-axis. Alice's time is given by the distance ct_A in Fig. 2 and Bob's time, from Alice's point of view, by the distance ct_B. However, the ct_A- and ct_A-axes must run opposite the light beam. According to these considerations, Alice's and Bob's “space-time coordinates” are shown in Fig. 3. This representation corresponds to the so-called *symmetrical Minkowski diagram*, from which the Lorentz transformations can be derived immediately.

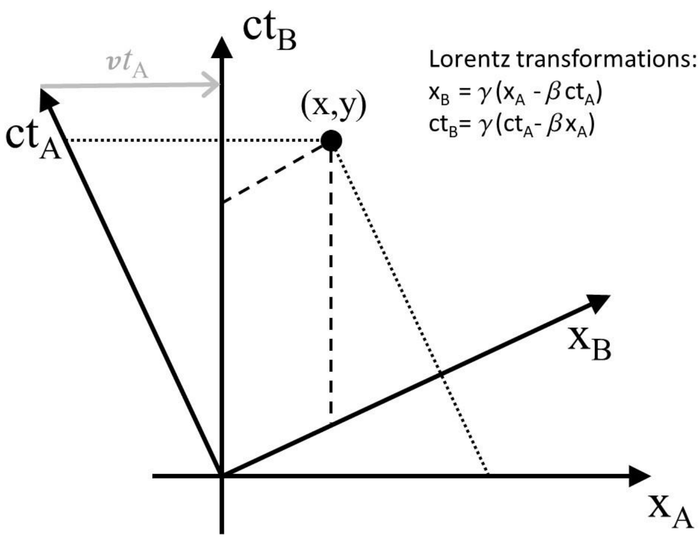

Fig. 3: The symmetrical Minkowski diagram. For reasons of convention, in this representation the normal and the laterally drifting light beam run from top to bottom, i.e. in the negative y-direction. The x_A- and x_B-axes correspond to the respective wave fronts of the stationary and the transverse light beam, respectively. The ct_A- and ct_B-axes run counter to the laterally drifting or normal light beam. The easiest way to test this combination is to consider how the origins of the reference frames and how lengths move relative to each other, i.e. how the points $(0, ct_B)$, $(0, ct_A)$, $(x_B, 0)$ and $(x_A, 0)$ transform into the respective other reference frame. This representation is known as the *symmetrical Minkowski diagram*. If one represents the point (x, y) in both the $x_A t_A$- and the $x_B t_B$-system, one immediately obtains the Lorentz transformations after elimination of x and y.

E_0=mc²

Let us consider a laterally drifting resonator instead of a laterally drifting light beam. Then energy is stored in the resonator in the form of an electromagnetic wave. Since the resonator is moving sideways, the distance between the resonator mirrors and the wavelength λ_y in the direction of the resonator do not change. From Alice's point of view, however, the actual wavelength λ is smaller by a factor of γ, as can be seen in Fig. 1. In the laterally drifting resonator, however, this is no longer so directly recognisable, as waves travelling backwards and forwards are superimposed. This results in a standing wave with wave fronts parallel to the x-axis, but with a wave running in the x-direction superimposed.

A wavelength that is smaller by a factor of γ means that the frequency f and thus the energy of a photon is larger by a factor of γ compared to the resonator at rest. The number of photons, however, does not change. The energy therefore increases by the factor γ in the moving resonator. But if energy has to be expended to set something in motion, this means that something has an inertial mass. If E_0 is the energy in the resonator at rest, then you have to put the energy $(\gamma - 1)E_0$ into it to set it in motion. For small velocities, this term converges to $^1/_2\, v^2 \,/\, c^2 E_0$. On the other hand, in the classical case the kinetic energy is $^1/_2\, mv^2$. Equating both terms gives:

$$E_0 = mc^2$$

But what does this expression actually mean? On the left side is the energy of a wave packet. We are therefore in the wave model of physics. On the right side is a mass, i.e. we are in the particle model. The formula $E_0 = mc^2$ thus reflects in a certain sense the wave-particle dualism of our physical understanding of the world. This standing wave in a resonator is thus the simplest model system for a "particle" with mass and velocity $\vec{v}$. It can be used, for example, to simulate diffraction experiments of mass-bearing particles.

Until now, we had still used the principle of relativity when changing from Alice's to Bob's frame of reference: Bob sees parallel wave fronts because, according to the principle of relativity, he must see the same thing as Alice when a beam of light is at rest relative to him. But if we now use the wave model in physics, i.e. matter waves from quantum mechanics, then the principle of relativity is a consequence of our considerations: The wave functions of matter waves, which in the highly relativistic boundary case also follow the dispersion relation $\omega = ck$ (with $\omega = 2\pi f = E / \hbar$, $|\vec{k}| = 2\pi / \lambda = |\vec{p}| / \hbar$, E Energy, $\vec{p}$ Impulse), experience the same Doppler effect as electromagnetic waves, i.e. the same tilting of the wave fronts and thus just as much a length contraction, a temporal phase shift in the direction of $\vec{v}$ and a reduction of the frequency, i.e. a time dilation. Thus, Bob sees the same light beam as Alice because his scales and he himself "bend" together with the light beam. Thus, everything is consistent in itself and RT and quantum mechanics are based on the same principle: the wave character of nature.

Gravity

Albert Einstein's GRT is based on the postulate of the equivalence of acceleration and gravitation. Accordingly, a laterally drifting light beam is also accelerated in a gravitational field. Fig. 4 shows approximately a freely falling transversely drifting light beam at two points in time. Due to the gravitational acceleration, the right light beam has a greater transversal velocity and thus more tilted wave fronts. According to the present interpretation of GRT, this is related to the curvature of space-time. However, compared to this rather mathematical interpretation, we prefer a more physically descriptive one. In fact, Fig. 4 is reminiscent of the refraction of light during the transition from an optically thinner to an optically denser medium, whereby the ratio of the refractive indices is now replaced by the ratio of the γ factors. This interpretation is also justified insofar as, after the previous considerations, nothing speaks against the assumption of a carrier medium for electromagnetic waves any more, and - this is our first and only hypothesis - also for matter waves. However, this carrier medium, let us call it "vacuum dielectric", has a special property, as we will see in a moment:

That these two light beams in Fig. 4 must look like this - at least locally - and thus in particular with regard to the tilting of the wave fronts, can be deduced from the analogy between acceleration and gravitation. Fig. 4 can represent both a freely falling beam of light as seen by an observer in a gravitational field, as well as a light beam at rest observed from an accelerated reference frame. Due to the principle of relativity, all observers in the respective other reference frame see a beam of light drifting transversely at the speed $\vec{v}$ with the same tilt angle. However, the exact tilt angle of the wave fronts depends on both the relativistic time dilation, i.e. the transit time of the light in the y-direction, as well as on Lorentz contraction in the x-direction. But this means that, as with the MME, we have a factor γ in the y-direction and a factor γ^2 in the x-direction. Consequently, our vacuum dielectric must have an anisotropic refractive index with $n_y = n_{\parallel} = \gamma$ and $n_x = n_{\perp} = \gamma^2$.

And how large is γ or v^2? A detailed derivation can be found in the textbooks on GRT. Ultimately, in the Newtonian limiting case of small velocities, the following relationship between v^2, the kinetic energy E_{kin} and the potential energy E_{pot} must apply: $v^2 = 2E_{kin}/m = 2E_{pot} \,/\, m$. Therefore, for the gravitational field with a mass M at its centre, we obtain:

$$\gamma = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}}$$

Here G is the gravitational constant. The radius r is the distance to the centre of gravity from the point of view of a distant observer outside the gravitational field without Lorentz contraction, or rather the circumference divided by 2π, since lengths perpendicular to the direction of the gravitational field remain unchanged.

Thus, clocks in a gravitational potential go slower by the factor γ and in the direction of the gravitational field lengths are Lorentz-contracted. Furthermore, γ diverges when r_s goes towards $2GM \,/\, c^2$. This is the so-called *Schwarzschild radius*, the radius of a black hole.

The space around a simple centre of gravity can thus be described by a gravitational lens with an anisotropic refractive index with:

$$n_{\perp} = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}}$$

$$n_{\parallel} = n_{\perp}^2$$

where ⊥ and || refer to the direction to the centre of gravity. This corresponds to the exact, so-called *Schwarzschild solution* of GRT for a simple centre of gravity and this anisotropy in velocity is known as the *Shapiro retardation*. With the interpretation presented here, i.e. an optically anisotropic lens, the deflection $\Delta\varphi$ of a light beam at a centre of gravity with radius R_M can be derived in a few lines. In a first approximation, one obtains:

$$\Delta\varphi \approx \frac{4GM}{R_M c^2}$$

This is the value that was also measured during the solar eclipse around 100 years ago and predicted by Einstein, making him famous overnight.

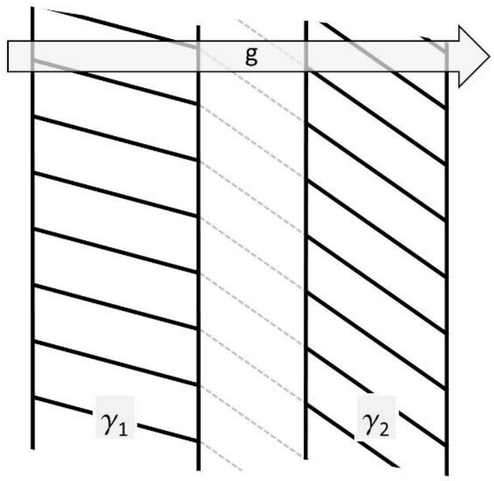

Fig. 4: Light beam falling in a gravitational field $\vec{g}$. Approximate representation of a transversely drifting light beam, accelerated by gravity in the x-direction, at two points in time. In the y-direction, the distance between the wave fronts does not change, which is indicated by the dashed lines.

The edge of all we know

We have thus found a somewhat different, physically clearer and internally consistent model for the implementation of the principle of relativity. The alternative derivation of the Special RT succeeded solely on the basis of common knowledge from wave optics and the principle of relativity. Moreover, if one assumes that the Doppler effect also applies to matter waves, which ultimately follow the same dispersion relation as electromagnetic waves, then the principle of relativity is no longer a postulate, but a consequence of the wave character of nature. This would be the connecting link between RT and QM.

Note: In this article, we have only used the transverse Doppler effect, as this illustrates the SRT very clearly. Waves in the x-direction together with the longitudinal Doppler effect naturally lead to the same results. This will be described elsewhere.

Every good model raises many new questions: Are matter waves real or just a mathematical tool? The answer is perhaps *Ockham's razor principle* – “keep it simple” – which Einstein also often followed. Why should something that behaves like a wave not also be a wave? The simplest model system for a matter-bearing particle is the standing electromagnetic wave in a resonator. Of course, we do not know what the “resonator mirrors” are in a matter wave, i.e. what keeps the matter waves in a bound state? And so there are many more open questions. However, if one accepts matter waves as real and thus the existence of a “vacuum dielectric” with variable, anisotropic “refractive index”, as described in the section on Gravitation, then one comes to the following conclusion: The equivalence of inert and heavy mass means nothing other than that the “vacuum dielectric” is a completely dispersion-free medium, not only for any kind of electromagnetic waves, but also for gravitational waves and matter waves! But with this we have reached the limit of our knowledge, because such a medium cannot be explained with any of our current models. The fascinating thing is that we can put this limit into words now.

Acknowledgements

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References

There is a large selection of textbooks on SRT. For GRT, mainly the book by Michael Ruhrländer was used: *Aufstieg zu den Einsteingleichungen*, Pro BUSINESS GmbH (2014).

Addendum: Only when translating this article into English did a generally unknown source emerge which, using the longitudinal Doppler effect, comes to similar conclusions with respect to SRT as those made here, see: https://heinz-heinzmann.eu/Special-Relativity.pdf