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"Gravitationally Lensed Gravity" from a Spacetime Perspective

The curvature of spacetime in General Relativity

leads to an astonishing effect on gravity itself

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Abstract

A gravitational lens is mass-curved spacetime. Light that propagates freely, locally always on the fastest way, follows curved paths in it. The same applies to all effects propagating with the speed of light, also to gravity itself. They all have to follow the curvature of spacetime. A gravitational lens not only enhances the light from background objects but concurrently also their gravitational effect !

The "Gravitationally Lensed Gravity" (GLG) is a still scarcely noticed peculiar feature of general relativity. In [1] I presented a thought experiment to make the existence of this effect plausible. Here these considerations are described in terms of future and past light cones or null cones commonly used in relativity theory to illustrate the causal structure of spacetime. In the framework of general relativity, the GLG effect can be understood as a consequence of the folding of the past null cone by a gravitational lens.

Starting from the basic ideas of the theory, the terms are introduced and applied. The extensive description on textbook level should be understandable also for beginners. In order not to obstruct the view on the essential physical relations, I avoid a mathematical formalism and use instead diagrams and figures, based on realistic numerical calculations, to reinforce my logical argumentation. Experts will recognize many long-known facts, but may still be surprised by the resulting conclusions.

First, I present some particular aspects of the historical evolution of the concept of gravitational lensing and give a brief overview of the work of other authors on the subject GLG. I then explain the limitations of the applicability of the "Newtonian Limit" and move on to the key role of the speed of gravity in understanding GLG. Finally, I use a simple example to illustrate the possible significance of the GLG effect.

With this work I intend to elicit greater interest in "Gravitationally Lensed Gravity" and to initiate a broader discussion about it.

Introduction

"If you see a star or a galaxy 5 times brighter because of a gravitational lens, does it also mean you experience 5 times the gravity from that star or galaxy ? In other words: Is the gravity focused by the lens effect, too ? And if so, how strong is this effect ?" This question can be found in the archive of an astronomy forum on the Internet [2]. Similar questions have been raised for discussion in other physics forums. The idea that gravitational lenses by curving spacetime affect not only light but all effects propagating at the speed of light in the same way seems quite obvious to non-experts. Usually, the idea of deflected or focused gravitational fields also arouses some interest of the responding experts. However, the community of relativity theorists restricts the analogy to gravitational light deflection to energy flows propagating at the speed of light, which can be described by wave equations. For fields, on the other hand, it is generally not accepted so far. Thus, the article titled "Does Gravity Fall Down?" [3] deals with the deflection of gravitational waves by gravitational lenses, as does the flyer titled "Gravity bending gravity" of the LIGO Scientific Collaboration [4].

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In contrast, the article "Gravity bends electric field lines" by Thanu Padmanabhan [5], in which the validity of the analogy is confirmed for the electric field, received little attention in the community. This fate is shared by all publications on the subject of "Gravitationally Lensed Gravity", of which there are already several.

Since the authors use different terminology to describe the effect depending on the context under consideration, these papers have so far stood incoherently on their own without reference to each other and are difficult to find. In the following paragraphs, I will acknowledge my previous findings chronologically according to their publication date with a short description of the respective origins of the idea and its potential significance as described by the authors themselves.

Fig. 1: "Seeing quintuple" shows the object 2M1310-1714 in the Virgo galaxy cluster. A pair of massive galaxies in the foreground generates a ring with four bright images of a distant quasar in the background and a fifth much fainter image in the very center between the galaxy pair. Credit: ESA/Hubble & NASA T. Treu, ack. J. Schmidt [6]

The trigger of a broader discussion and the establishment of the idea of gravitational lensing was Einstein's short note "Lens like action of a star by the Deviation of Light in the Gravitational Field" in the journal Science [7] in 1936. However, this is more due to Einstein's popularity and reputation than to his own conviction. Almost apologetically, he reveals in the introductory sentence that he performed the calculations for R. W. Mandl and published them at his request. In doing so, he preserves the memory of the Czech electrical engineer and amateur scientist - and rightly so, because without his imagination, enthusiasm and perseverance, this impetus would not have happened. Einstein himself considered the subject irrelevant, since the resulting phenomena were not observable anyway according to his estimation.

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Therefore, he – like most of his contemporaries – did not pay further attention to earlier publications of such ideas (e.g. by Eddington), if he was aware of them at all (see [8], [9]).

After Einstein's publication, the astronomer Fritz Zwicky took up the subject and saw galaxies and galaxy clusters as more promising candidates for gravitational lensing. The magnification of such natural lenses could enable the observation of extremely distant objects behind them that would otherwise be beyond the reach of our telescopes [10]. The recent discovery of an image of what is believed to be a single star, magnified about several thousand times by a gravitational lens, is an impressive confirmation of this idea. The star was nicknamed "Earendel", an Old English word meaning “morning star”, or “rising light”, because the light that we see today left the star just 900 Mio. years after the Big Bang [11] [12].

The fact that (weak) gravitational waves should propagate in gravitational fields like light does (e.g. [13]), led Joseph Weber, the pioneer in experimental gravitational wave research, already 50 years ago to the idea of a focusing of gravitational waves from the cosmic background by the gravitational lens of the galactic center of the Milky Way. In this he saw a possible reason for the directionality of his measurement results [14]. Even though the critical analysis by J. K. Lawrence made this explanation for Weber's measurement results seem implausible, it brought the realization that focusing by the interior gravitational field of a spherical mass distribution can produce a much higher intensification than the outer field [15]. L. Kh. Ingel' confirmed this result and identified stars like the Sun as suitable "antennas" for focusing gravitational waves (and neutrino beams) to distances within the solar system - with potential application even for interstellar communication [16].

This idea of the "transparent Sun" and the possibility of observing gravitational waves and neutrino beams focused through it was analyzed in more detail then (e.g. [17]), among others by Robert J. Nemiroff [18]. He wondered whether gravitational fields are also focused by the effect of a gravitational lens. In his article "Can a gravitational lens magnify gravity?" [19] from 2005, he put this question up for discussion and presented well-founded estimations of possible tests by means of space probes and high-precision clocks, which seemed to be technically feasible already at that time. From this – as far as I know – first publication on the subject also comes the name "Gravitationally Lensed Gravity", which I abbreviate as "GLG".

Nemiroff sees a potential explanation for the existence of the GLG effect in the fact that virtual gravitons (hypothetical quanta of gravity) should also be subject to the curvature of spacetime and should follow the same paths – the so-called null geodesics – as the photons of the light ("Virtual Equivalence Principle" in [20]). As a possible consequence he mentions a "gravitational jitter", fluctuations or ripples, which result from the superposition of numerous gravitational fields of background sources focused by distant stars. An extreme effect would be a rupture of an object by the tidal forces in such a caustic of focused gravity generated by a black hole.

Only a few days later, Russell Anania and Michael Makoid published their article "Ab Initio Calculation of the Anomalous Acceleration of Pioneer 10 In Vacuo" on the preprint server arXiv [21]. There they also present the idea that the static gravitational field of sources beyond the Sun is focused through it and thus leads to the observed anomalous acceleration of the spacecraft in the direction towards the Sun. They call their description the "optical model of gravitational forces" and explain with it also the galactic rotation curves without help of dark matter with elementary formulas of the geometrical optics [22]. They see their simple description only as a first approximation to an ideal model.

Ten years later, Qiubao Pan published a similar idea [23]. He also justifies his "Classically Consistent Field Theory" with the fact that hypothetical exchange particles of gravity should follow the same paths in curved spacetime as photons. As potential gravitational lenses which bend and focus gravitational fields of other sources, he mentions both the central black hole and the galactic disk of the Milky Way and – as an example within the solar system – Jupiter, which could deform the gravitational field of the Sun in outward direction and may affect Saturn when it is just lined up with the Sun and Jupiter.

A detailed elaborated version of such a model is presented by Alexandre Deur 2021 in his article "Relativistic corrections to the rotation curves of disk galaxies" [24]. Like Pan, Deur sees parallels in the self-interaction of gravity to the strong interaction (QCD), in which the exchange particles (gluons) also interact with each other. Thus he justifies that a perturbation-theoretical treatment of gravity in the framework of the post-Newtonian approximation is inadequate.

His "Mean-field lensing model" works like the earlier approaches of the other authors: the global mass distribution creates a curvature of spacetime and acts as a gravitational lens which deforms the field of a certain source. Virtual gravitons follow the same paths as photons, or in other words, field lines are bent in the same way as light rays from the same source [5].

The contribution to the gravitational field strength caused by this source then corresponds to the flux density of its field lines. Using realistic mass distributions in the disks of galaxies, Deur calculates their bending effect on the field of the central masses and obtains gravitational forces that result in flat rotation curves – without adding Dark Matter !

From this model follows: The thinner the shape of the galactic disk, the larger the difference to the Newtonian result. The apparently larger fraction of Dark Matter in galaxies of the thin disk type compared to thicker ellipsoids is made obsolete by this simpler explanation with natural features of gravity itself.

The works presented above share a common notion of "Gravitationally Lensed Gravity": gravity, described as curvature of spacetime, acts on gravity, described as a field. The field lines/exchange particles follow lightlike paths (null geodesics), are bent transversely and thus redistributed. The thereby changed flux density of the field lines/exchange particles corresponds to the changed field strength contribution to the resulting gravitational field. This role distribution of a curving gravity in the shape of spacetime and a curved gravity in the shape of a field is artificial and serves only the comprehensibility. The curved gravity acts back on the curving gravity – by curving it, too. All these contributions are merged into a self-consistent overall solution, the resulting gravitational field aka spacetime curvature.

The "Gravitationally Lensed Gravity" could explain the flat rotation curves of disk galaxies and the structure formation in the early universe as well [25]. According to "Occam's razor", it would be preferable to alternative explanations as Dark Matter or modified gravitation theories (e.g. MOND), since it has no free parameters and thus requires fewer assumptions. This is not yet sufficient reason to believe it to be true, but it is a good reason to examine it more closely.

Even if it turns out that the GLG would not be sufficient to completely make obsolete the Dark Matter, this fascinating effect should be thoroughly investigated. In [1] I presented a thought experiment, arguing only with the fundamental physical principles of causality, consistency and continuity. Without "Gravitationally Lensed Gravity" contradictions to one or more of these basic principles arise. But this is rather due to our incomplete understanding of general relativity than to inconsistencies of the theory itself. Further investigations on this subject could well provide groundbreaking results !

The "Newtonian limit"

In 1687, Sir Isaac Newton presented his Universal Law of Gravitation in his "Principia". According to this law, two masses M and m are subject to mutual forces of attraction F of equal magnitude, which are proportional to both masses and inversely proportional to the square of their distance r. The force on one mass acts in the direction of the other mass.

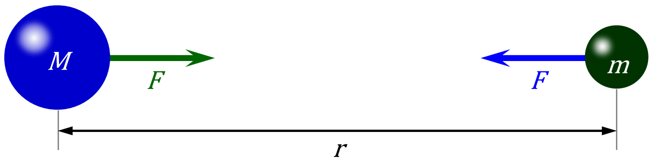

Fig.2: Mutual attraction of two masses

In form of an equation with the gravitational constant G Newton's law writes:

$$F = G \cdot \frac{M \cdot m}{r^2} \tag{1}$$

As a matter of course Newton was thinking in absolute time and absolute space. Kepler's laws of planetary motion are obtained correctly only if his gravitation acts instantaneously: The momentary force acting on one mass from a distance is determined by the location of the other mass at that exact instant.

Newton did not agree with the notion of gravity as a direct action from a distance of one mass upon the other. He wrote in a letter to Richard Bentley: "... that one body may act upon another at a distance through a vacuum, without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity ..." [26]. However, Newton was satisfied with the mathematical formulation of his universal law, which describes quantitatively exactly *how gravity works* and was confirmed by the experimental findings. He did not see it as his mission to publish hypotheses on the question of *what gravity is* and how it is transmitted: "... but whether this agent be material or immaterial, I have left to the consideration of my readers." [27].

Newton thus criticized the interpretation of gravity as an *immediate* action at a distance, but not its character as an *instantaneous* action at a distance. Although it was already known at that time that even light is not transmitted instantaneously but has a finite speed.

In 1676, the Danish astronomer Ole Rømer found that light needs about 10 minutes to cross the radius of the Earth's orbit. For this purpose, he used the regular eclipses of Jupiter's moon Io behind the planet, which he regarded as a constantly running clockwork. The distance between Jupiter and Earth changes during the half year that Jupiter is observable in the night sky. These eclipses seem to occur earlier and earlier when the distance decreases and later and later when the distance increases again. Newton, who was extensively engaged in the study of light throughout his life, accepted Rømer's explanation with a finite speed of light [28]. However, the well measurable travel times of light over large distances in the solar system, over which also gravity is effective, did not bring him on the thought of a delay of gravitational effects. He considered the phenomena of light and gravity to be completely independent of each other and abandoned considerations of an effect of gravity on his postulated light corpuscles [29].

Pierre-Simon Laplace, French mathematician and astronomer, worked extensively on celestial mechanics, on which he published a five-volume book. One aspect of this work was the analysis of the stability of the solar system using Newton's law of gravity.

He also tested the hypothesis of a fluid mediating gravity and estimated its necessary velocity to be at least one hundred million times the speed of light to be compatible with the long-standing existence of the lunar orbit. This result can be found in the volume IV published in 1805 [30]. Laplace thus confirmed the instantaneous effect of the Newtonian gravitation.

With the establishment of his special relativity theory in 1905, Albert Einstein abolished absolute time and absolute space. All frames of reference moving uniformly relative to each other are equivalent. Moving clocks seem to go slower, moving objects seem to be shorter in the direction of motion. Observers moving with respect to each other disagree about the simultaneity of two events at different locations. But they do agree about the causal sequence of events and about the speed of light, for which every observer with his own resting measuring rods and clocks finds the same value and this in any direction. From the theory it follows that no information and no effect can be transmitted with a speed greater than that of light. Einstein thus faced the problem of integrating the instantaneously acting gravity into his theory building.

"In free fall you do not feel your weight." In this sudden inspiration, Einstein recognized the connection between gravity and his special theory of relativity. Following this "happiest thought of his life" [31] he formulated his equivalence principle of general relativity and arrived years later at the description of gravity as a curvature of the geometry of spacetime. Mass, energy and pressure cause this curvature, which in turn determines the motion of masses and the propagation of light. Movements exclusively under the influence of gravity are treated as "free fall", the free-falling objects do not "feel" any force, this term is obsolete for Einstein's gravity. His field equations have a completely different structure than the simple Newtonian formula, which, moreover, is based on other premises – absolute time and absolute space. Nevertheless, Einstein's gravity must accomplish to reproduce the results of the instantaneously acting Newtonian gravity, which is excellently confirmed by observations, without exceeding its own speed limit of the speed of light. How to overcome this dilemma ?

In his article "Aberration and the Speed of Gravity" [32] Steve Carlip explains that a field strength which always points in the direction of the former (retarded) position of the source does not allow stable orbits. But if also *velocity-dependent* components are considered then it is achievable that the field strength points in the direction of the present (instantaneous) position of the source. Such velocity-dependent components of the field strength are known from electrodynamics, which was suitably formulated already before the special relativity theory.

Also in general relativity, velocity-dependent components ensure that the current gravitational field strength = free-fall acceleration points in the direction of the current position of the source, more precisely: in the direction of the present position *as extrapolated* from the past position, the past velocity and the past acceleration of the source. In this way, the speed limit of the speed of light is respected: the current effect is based on the information transmitted at the speed of light from the former location of the source. As well, the (apparently) instantaneous effect is implemented: the current field strength points in the direction of the (extrapolated) current position of the source. That it has to be this way follows from the principle of relativity, according to which observers moving with respect to each other must come to the same conclusions about the results of physical processes.

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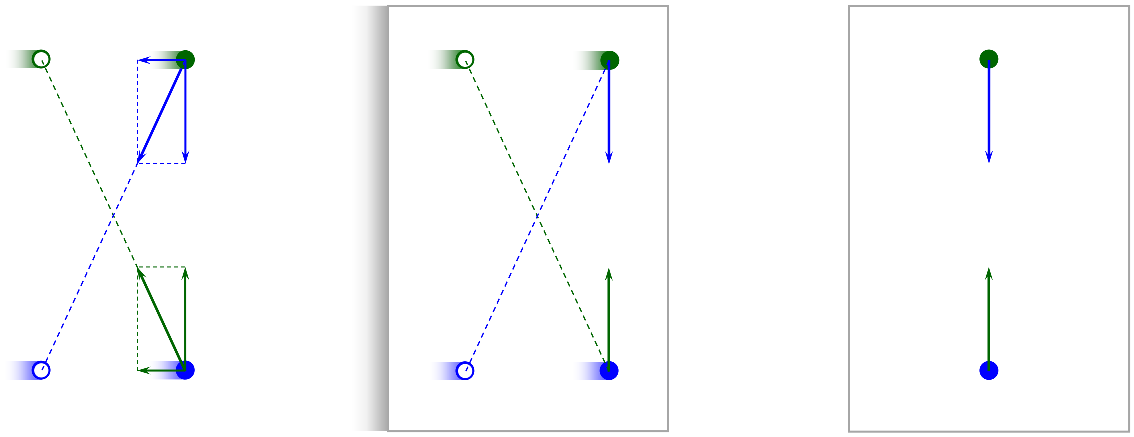

Fig.3: Two masses moving horizontally from left to right at the same speed. Filled circles symbolize the current positions of the masses, empty circles their previous positions. Left: If the force on each mass would act in the direction of the previous position of the other mass, decelerating horizontal force components would occur. Middle: The force acts in the direction towards the current position of the other mass. Right: Only then it is ensured that this is also true in the co-moving frame of reference, in which both masses are at rest (imagine a massless rod between them, which keeps them at a constant distance).

In Fig. 3 left forces are shown between two parallel moving masses acting *in the direction towards the former position* of the other mass. As sketched in the figure, force components occur which slow down the movement of the masses - and this without any further external impact ! This obviously cannot be correct. In the co-moving frame of reference (right), the two masses are at rest. In this frame, the force must act on each mass in the direction of the position of the other mass. This is fulfilled exactly when in the external reference frame the force acts on each mass *in the direction towards the present position* of the other mass (Fig. 3 middle).

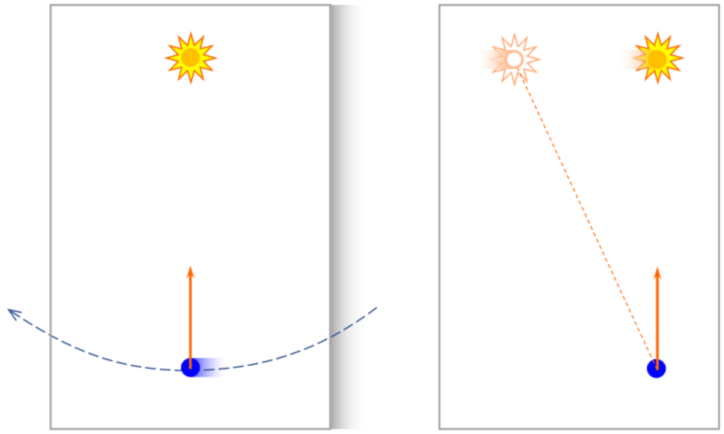

Fig. 4: Left: In a simplified model the earth on its circular orbit is accelerated radially towards the sun resting in the center. Right: In the momentary rest frame of the earth (symbolized by the gray frame) the sun appears to be moving. Here the acceleration points in the direction of the present and not the former position of the sun.

Fig. 4 left shows the rest frame of the sun. The earth moves tangentially on its circular orbit and the acceleration acts radially towards the sun. This, in turn, requires that the acceleration in the Earth's rest system always act in the direction of the Sun's current position. Unlike light, which seems to come from a deviating earlier position of the sun, no such aberration occurs with gravity. It behaves as if it would act instantaneously.

To compare the strength of Einstein's gravity with Newton's, one has to solve the field equations. For the external gravitational field of a resting homogeneous sphere of mass M, Karl Schwarzschild managed this only a few months after the publication of Einstein's field equations.

From the Schwarzschild solution, the following expression is obtained for the locally measured gravitational field strength = free-fall acceleration g (according to [33], but here in SI units, c is the speed of light):

$$g = G \cdot \frac{M}{r^2} \cdot \frac{1}{\sqrt{1 - \frac{G}{c^2} \cdot \frac{2M}{r}}} \tag{2}$$

For large distances r or small masses M the root approaches the value of 1 and for this weak field limit (2) takes the form of the Newtonian expression (1):

$$g = \frac{F}{m} = G \cdot \frac{M}{r^2} \tag{3}$$

This is not surprising, because the Schwarzschild solution is just made to regain this "Newtonian limit". It is excellently confirmed by the perihelion precession of Mercury, the light deflection in the vicinity of the Sun and the Shapiro delay of signals passing close to the Sun [34].

In the Newtonian theory of gravity, the gravitational effects of two or more celestial bodies superpose. The total field strength results as vectorial sum of the contributions of the individual celestial bodies. This knowledge has led, for example, to the discovery of the planet Neptune: From irregularities in the orbital motion of the planet Uranus, the French mathematician Urbain Le Verrier was able to calculate the position of another planet he suggested, which was actually found there in 1846 by the German astronomer Johann Gottfried Galle [35]. Of course, the linear superposition of weak gravitational fields must be provided by Einstein's theory as well, otherwise it would not describe the astronomical observations correctly.

Newton's law of gravity is still widely used for astrophysical calculations. It is considered to be a *sufficiently good approximation of general relativity* for the mostly applicable case of *small velocities* (in relation to the speed of light) and *weak fields*. With the exception of the close vicinity of their central black holes, the motion of whole galaxies is still calculated with Newton's law of gravity. Thereby, the finite propagation speed of gravity and the curvature of spacetime are neglected.

Even gravitational lenses, actually the most obvious expression of the curvature of spacetime, are usually viewed by observing astrophysicists in a highly simplified way as thin lenses and calculated with the help of geometrical optics. The paths of photons, strictly speaking curved null geodesics in a four-dimensional spacetime, are approximated as straight rays in a three-dimensional Euclidean space with a kink in a lens plane. A locally varying function of the deflection angle is put in this lens plane, and from this intensity gain maps in an abstract source plane are calculated. Depending on the position and movement of a source in this plane, its expected gain and temporal intensity curve can be inferred.

More elaborate models involve a spatial variation of the speed of light, resulting from the (everything seemingly slowing down) gravitational potential of the "lens mass" as a small linear perturbation on a Minkowski spacetime. This acts like a locally varying "refractive index" in a three-dimensional Euclidean space – Einstein described it similarly already in 1911 [36]. But even here the gravitational potential of the mass distribution is not obtained by solving Einstein's field equations – Newton's law of gravity is simply assumed to be the valid approximation. Behind these effective ways of looking at things, the actual cause – the curvature of spacetime – remains completely hidden [37] [38] [39].

Nevertheless, the aforementioned methods of gravitational lensing experts can help to calculate how "Gravitationally Lensed Gravity" acts in certain mass distributions, and thus make predictions for observations. Why the GLG should exist, however, can only be understood relativistically. Essential is the finite speed of gravity, which otherwise is practically irrelevant.

Minkowski's four-dimensional spacetime

„From now on space-in-itself and time-in-itself are destined to be reduced to shadows, and only a sort of union of the two will retain an independent existence.“ This is the famous statement made by Herrmann Minkowski, professor in Göttingen and a former teacher of Einstein, at the meeting of the Society of German Natural Scientists and Physicians in 1908 [40]. There he introduced his four-dimensional spacetime with its special metric, which since then sets the stage for Einstein's special theory of relativity. In particular, it allows a simple geometrical representation of the coordinate transformations found by Hendrik Antoon Lorentz between reference systems moving uniformly relative to each other. The square of the four-dimensional "interval" Δs^2 between two considered events is an invariant under such coordinate transformations (e.g. [41]):

$$\Delta s^2 = c^2\Delta t^2 - (\Delta x^2 + \Delta y^2 + \Delta z^2) = c^2\Delta t'^2 - (\Delta x'^2 + \Delta y'^2 + \Delta z'^2) \quad (4)$$

This square form reflects by the minus sign the physical difference between space and time and stands in equal measure for their unity in mutual dependency. It is equivalent to the Lorentz transformations between the coordinate systems.

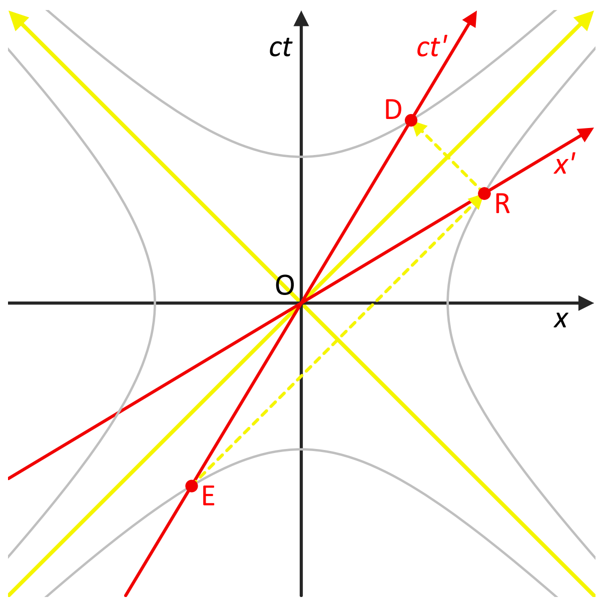

Fig. 5: Two-dimensional Minkowski diagram. In it, a direction of the space is represented as a horizontal x-axis and the time as a vertical ct-axis. Thus both axes have the dimension of a length. The oblique x'- and ct'-axes are the coordinate axes of a moving reference frame.

Since it is impossible to sketch a coordinate system with four perpendicular axes – one for the time coordinate t and three for the space coordinates x, y and z – on a sheet of paper, we will take a closer look at certain cross sections through this spacetime.

First, we consider only movements in one space dimension, which we call x-direction. We set the y- and z-coordinates to zero and do not consider them further. The position x together with the time t can then be represented in a two-dimensional diagram.

Fig. 5 sows a Minkowskian type two-dimensional spacetime diagram. The coordinate system with the horizontal x-axis and the vertical ct-axis belongs to an observer at rest at $x = 0$. The oblique red arrow ct' corresponds to the "world line" of her colleague moving uniformly and straight. He passes her at the spacetime point O. At this moment both zero their wrist watches.

The world lines of two light photons coming from opposite directions and moving towards each other along the x-direction are drawn in yellow. At the coordinate origin O they meet at the time $t = t' = 0$ at the location $x = x' = 0$ and then move on in their opposite directions. According to special relativity, the speed of light is always measured as c, regardless of its direction. Because of $x = \pm ct$, the slopes of the yellow world lines of light are therefore just ± 1.

The time t on the clock of the observer resting at $x = 0$ keeps running on and on. Her coordinates pass successively through all points on the ct-axis, which is therefore her world line in the Minkowski diagram.

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Also the time t', which the clock of the moving observer indicates, continues to run while he moves away from the meeting point O on his world line, the red arrow. He considers himself to be at rest at the location $x' = 0$. The red arrow thus corresponds to the set of all events with $x' = 0$, but with changing time t', so it is nothing else than the time axis ct' of the coordinate system of the moving observer.

The spatial x'-axis of his coordinate system is the straight line consisting of all events with $t' = 0$ that occur simultaneously with the event O at the coordinate origin. To find one such event, we use Einstein's definition of simultaneity: The moving observer emits a photon in $+x'$-direction at the time $ct' = -1$ (event E), which is reflected back to him (R) and detected by him at the time $ct' = +1$ (D). Assuming the constancy and direction independency of the speed of light c, he concludes that the reflection took place exactly at the time midway between the time of emission and detection, namely just at $t' = 0$. The reflection event R therefore lies on the sought x'-axis. From the times of emission, reflection and detection, it follows for the position where the reflection took place, $x' = +1$. From the symmetry in the Fig. 5 it is clear that the x'-axis in the Minkowski diagram is obtained by mirroring the ct'-axis at the world line of the photon travelling in positive direction.

So we obtain a diagram with two coordinate systems, the rectangular one of the "resting" observer and the oblique one of the "moving" observer. They assign different coordinate values to each event except of O. From this diagram these coordinate values can be read and the coordinate transformations can be determined. In Fig. 5 unit hyperbolas are drawn in light gray. Where they intersect the ct, ct', x and x' axes, these have the value +1 and -1 respectively.

The two observers do not agree on simultaneity. As already mentioned, for him the event R takes place simultaneously to O. For her, however, it takes place later, as it lies above her x-axis. Because of this relativity of simultaneity, time alone is not sufficient to define the sequence of events unambiguously !

Minkowski's square of the spacetime interval (4) helps to create order here. We consider objects moving with constant velocity v through the origin O:

$$\Delta s^2 = c^2 t^2 - x^2 = c^2 t^2 - v^2 t^2 = (c^2 - v^2) \cdot t^2 \tag{5}$$

$$\Delta s^2 > 0 \quad \text{for} \quad v^2 < c^2 \tag{6}$$

$$\Delta s^2 = 0 \quad \text{for} \quad v^2 = c^2 \tag{7}$$

$$\Delta s^2 < 0 \quad \text{for} \quad v^2 > c^2 \tag{8}$$

The squares ensure that directional signs of x or v make no difference. Positive interval squares are called "timelike". An event which lies timelike to the event O can be reached from it by an object which moves with a velocity of the amount $v < c$.

The world line of the object then runs from O into the upper quadrant of the diagram Fig. 6 bounded by the yellow world lines of light. An event which can be reached from O by light or any interaction propagating at the speed of light is "lightlike" to the event O. It has the interval square zero to it and lies on a world line of light above O.

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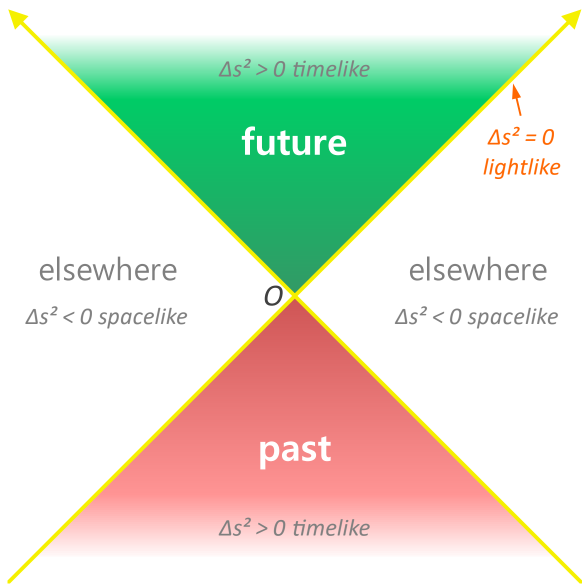

Fig. 6: The causal structure of the Minkowski spacetime

The upper quadrant including the world lines of light bounding it forms the *absolute future* of the event O, that is the set of all events which O *can causally influence*. Also the events in the lower quadrant have a positive interval square. Together with the world lines of light it forms the *absolute past* of the event O, i.e. the set of all events by which O *can be causally influenced*.

Negative interval squares are obtained for events in the quadrants to the left and right of O. Here one finds events that cannot be reached from O or cannot reach O without exceeding the speed of light. They do not have any causal relation to O. Whether they take place before, simultaneously or after depends on the observer. Thus, they are not arranged in time with respect to O. It is only sure that they take place *elsewhere*. They are said to lie "spacelike" to O.

Future and past in light cones

If one adds another spatial dimension y to the Minkowski diagrams, one can still display the now three-dimensional diagrams as perspective projections on two-dimensional screens or on paper.

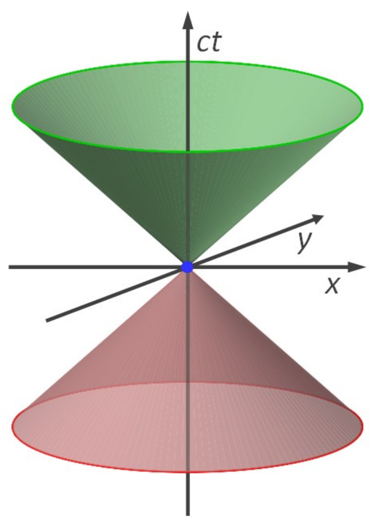

Fig. 7: Future and past light cone or null cone (This graphic and similar ones in this article were created with Matplotlib [42])

Let us first consider the future light cone of the event O, a burst of light at time $t = 0$ at the location $(x , y) = (0 , 0)$. Due to the isotropy of the light propagation in the xy-plane, we are no longer dealing with photons travelling away in $+x$ and $-x$ direction only, but with an expanding circle of photons, whose radius r increases in time. For the Minkowski diagrams this means that the V-shaped diagonally upward diverging world lines of light become part of the mantle surface of an upward opened cone, which stands on its tip in the event O. Correspondingly, below O there is the past light cone with apex in O.

The mantle surface of this double cone is the set of all events which have the interval zero to the event O. Therefore it is also referred to as "null cone".

$$\Delta s^2 = c^2t^2 - (x^2 + y^2) = c^2t^2 - r^2 = 0 \quad (9)$$

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The lower half, the mantle surface of the past null cone, comprises the set of all coordinates of possible past events from which the present event O can be influenced by means of effects propagating at the speed of light. Correspondingly, the mantle surface of the future null cone contains all coordinates of possible future events which the present event O can influence by effects propagating at the speed of light. These effects are of course not restricted to light. Thus, *c* more generally denotes the "*velocity of causality*".

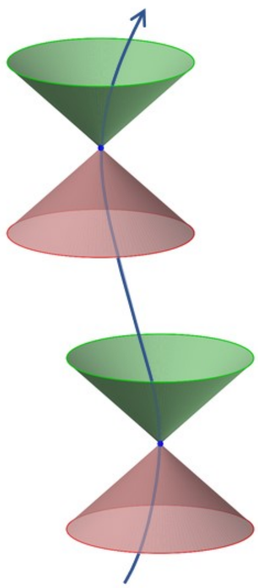

Fig.8: Future and past light cones on a world line of a particle with rest mass

For objects with rest mass applies: Their complete world line lies inside the double cone to any point on this world line. Nowhere it may exit one of these cone shells, because this would mean that its speed is exceeding the speed of light in that exit point.

But how can the light cone description of the light propagation in a two-dimensional plane be of any use for the understanding of our spatial three-dimensional world ?

In many cases, we can actually also represent the propagation of light in three-dimensional space by light cones. To do this, we use the symmetries at hand to infer information about the third spatial dimension which is not shown in the diagrams.

Starting from a single point source, light propagates spherically symmetrically into the empty space. Each two-dimensional cross-section through the source looks identical and represents the three-dimensional light propagation. And the temporal propagation of light in such a two-dimensional cross-sectional plane can be captured with the light cone diagram (see Fig. 9).

Even the case of a point source and a spherical gravitational lens, considered in detail later, still exhibits sufficient symmetry. This arrangement is symmetrical with respect to rotation about the axis through the source and the center of the lens. Any cross-sectional plane that includes this axis contains sufficient information to reconstruct the full three-dimensional propagation of light from it (see Fig. 18).

"Gravity Null Cones"

After this general introduction of the concept, I would now like to apply the light cone description to the scenarios already presented in [1]. *The approach that I will take is highly idealized: if a quantity is in principle measurable, I will treat it as measurable* (adopted from [38]).

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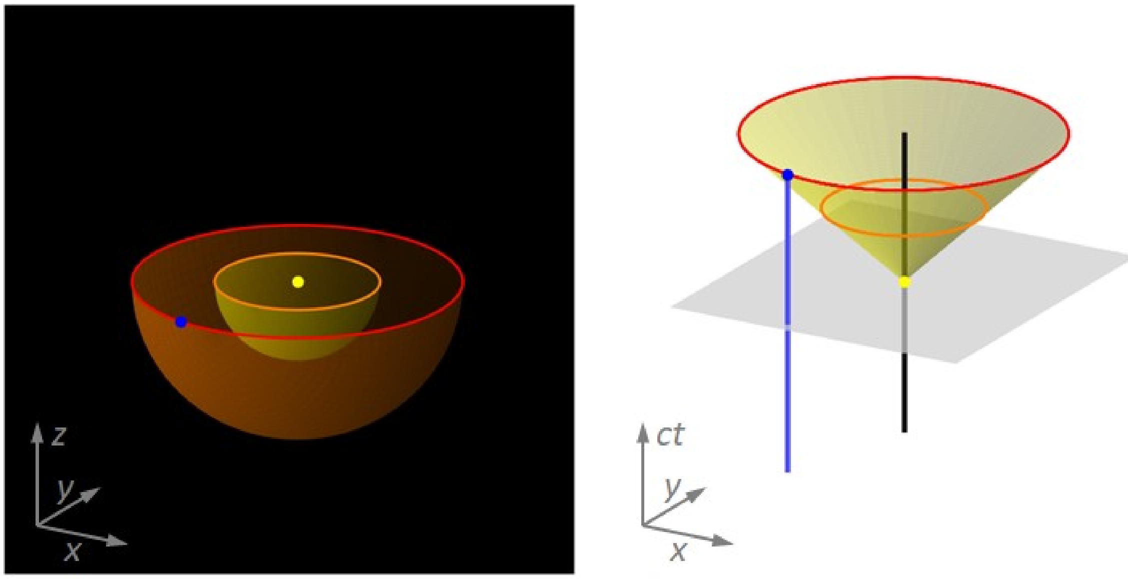

Fig. 9: Correspondence between the spatial representation and the light cone: An expanding spherical shell of photons is shown on the left at different times as orange and red transparent spherical surfaces. These appear as concentric circles in the cross-section through the xy-plane and can be found on the surface of the light cone on the right.

We consider a star which undergoes a sudden mass loss Δm by isotropic emission of the equivalent energy amount ΔE throughout a light burst. Shown in Fig. 9 is the spherically symmetric expanding shell of photons from the light burst at three successive times: yellow shows it at the time of the burst, orange at a later time, and red still later, when it just reaches the observer (blue) resting at a constant distance from the star.

As long as the shell of light energy (the photons) has not reached the observer she measures the unchanged gravitational field strength = free-fall acceleration g. When the shell of photons passes by, she measures a narrow-peaked intensity pulse. At the same time the gravitational field strength drops by Δg. These ideas are based on the following principles:

Birkhoff theorem:

The gravitational field outside a spherical symmetric expanding shell of emitted energy stays unchanged, whereas inside the shell it is determined only by the reduced residual mass of the star remaining in the center (see e.g. [41]). This statement combines the following consequences of causality and consistency.

Causality:

The sudden decline of the gravitational field strength carries information about the sudden mass reduction of the star. This information cannot propagate faster than the light.

Consistency:

The sudden decline of the gravitational field strength constitutes a monopole-like disturbance of the gravitational field, which according to the Einstein field equations cannot propagate freely. It remains bound to the expanding shell of light energy, so it cannot propagate slower than the light [43] [44].

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For weak gravitational fields of single masses, the distance law according to Newton (3) applies. Together with the equivalence of mass and energy this results in the absolute change of the field strength Δg [1]:

$$\Delta g = \frac{G}{r^2} \cdot \Delta m = \frac{G}{r^2} \cdot \frac{\Delta E}{c^2} = \frac{4\pi G}{c^2} \cdot \frac{\Delta E}{4\pi r^2} = \frac{4\pi G}{c^2} \cdot \frac{\Delta E}{A} \quad (10)$$

On the right side of this equation the distance r does not appear any more. The absolute change of the gravitational field strength at the position of the observer is determined only by the local areal density of the energy flux which passes her, completely independently of the distance at which the source is located. Here this is naturally due to the fact that for the *intensity of an isotropically emitted energy flow* the same distance law applies as for the *gravitational field strength of a spherically symmetrical source*. However, the result is not limited to this special case of its derivation, but is generally valid.

The considerations above corroborate the propagation of a change of the *gravitational field* with speed of light. For *gravitational waves* this is well confirmed by the simultaneous measurement of a gamma-ray burst signal from the merger of two neutron stars [45]. But also "static" gravitational fields propagate continuously from their source with the speed of light and therefore should more precisely be referred to as "stationary". They appear unchanged as long as the source remains unchanged. As soon as the source changes, e.g. by the mass loss described above, the corresponding change of the gravitational field propagates together with the radiated energy at the speed of light and reaches the location of observation *retarded*, i.e. delayed by the travel time of the light.

Already Minkowski used past light cones in his lecture [40] to describe the gravitational field, after demonstrating this by means of the retarded Liénard-Wiechert potentials of electrodynamics.

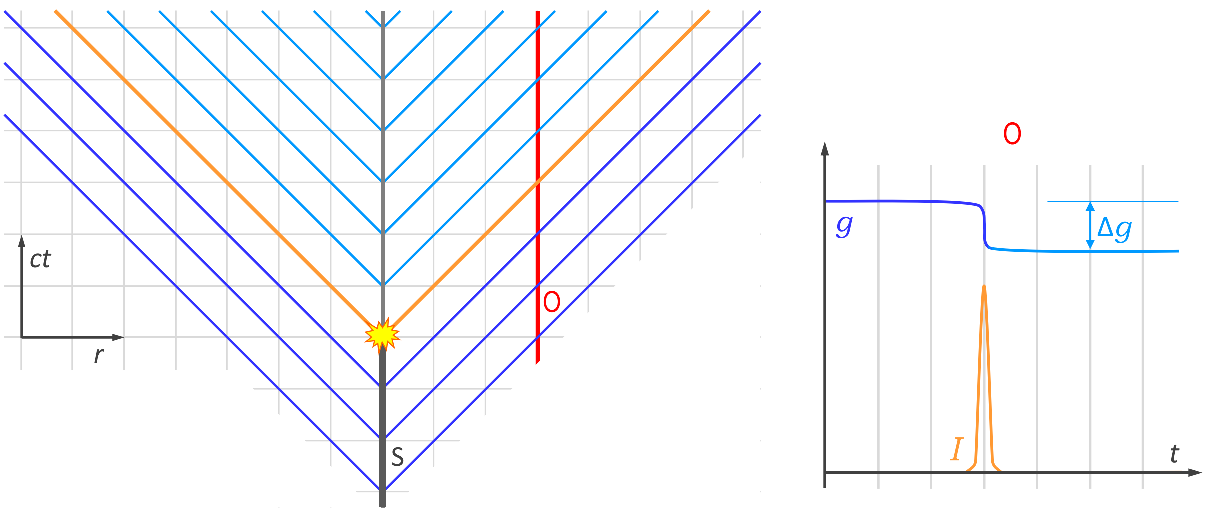

Fig. 10: Left: Two-dimensional Minkowski diagram with cross-sections of the future null cones of gravity (blue) and light (orange) emanating from the world line of the star S. At time zero the mass of the star decreases by emission of light throughout a burst. Right: Temporal curves of the "measured" quantities light intensity I and gravitational field strength g at the location of the observer O resting in constant distance with corresponding parallel world line. She measures both the intensity peak and the decrease of the field strength with a time delay due to the finite propagation speed c of light and gravity. For a better clarity in the diagram on the left further still earlier null cones are not shown, because their tips would not be visible. The diagram thus shows only a section of the stack of future null cones lying one inside the other, which can be imagined as continuing downward and upward.

The vacuum itself cannot store information, electric and magnetic fields as well as gravity cannot rest, they were caused by properties and states of motion of their sources in the past, propagate with speed of light, arrive at the location of the observer and superpose there to the currently observed resulting total field.

The notion of "static" fields or metrics needs to be replaced by the notion of "stationary" fields that are continuously updated and "refreshed with identical information" as long as the sources do not change. Fields and metrics are not properties of space itself, but effects caused by sources and only transmitted through space and time. This is expressed by the idea of the future null cones. Starting from the source in its tip at the bottom, light and gravity can propagate upwards in its mantle surface. The lines along which this happens are called "null geodesics". In the "flat" Minkowski spacetime these null geodesics are straight lines starting from the tip of the cone. Looking into the future null cone right from above, you can see as projection of the null geodesics the straight light rays emanating from the center in the *xy*-plane.

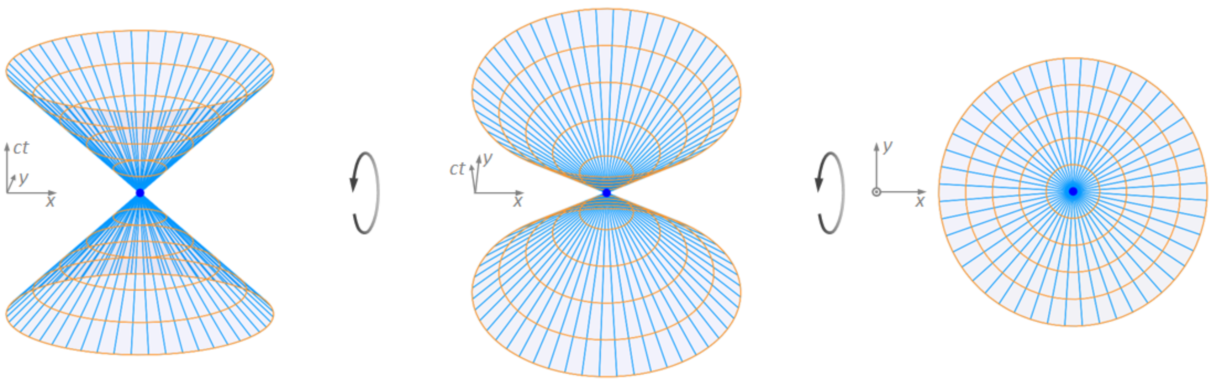

Fig. 11: Light rays (blue) and wavefronts (orange) on the double cone from different perspectives.
Left: The cone opening upwards is the future light cone. From an event at time zero (blue dot), the light propagates on straight lines isotropically in the xy-plane. The radius of the wavefront grows proportionally to the elapsed time. Because of the reversibility of the light paths, the past light cone opened downwards is obtained by mirroring the future light cone on the xy-plane, which corresponds to a reversal of the directions of propagation. Photons starting anywhere on this past light cone in the direction towards the event at the top of the cone (blue dot) arrive there simultaneously.
Right: Looking into the future null cone exactly from above, i.e. in the opposite direction of the ct-axis, one can see the projection onto the xy-plane showing the spatial course of the photon paths in this plane, the light rays. The concentric orange circles of the wavefronts are the "milestone marks" of the photons in the xy-plane at different points of time. They correspond to the "contour lines" on the future (or past) light cone.

Sergei M. Kopeikin revived the original idea to describe the causal structure of the gravitational field with future and past null cones and introduced the term "gravity null cone". He used it in connection with the determination of the speed of gravity from the measured change of the delay of radio waves from a quasar, which was caused by the comoving gravitational field of Jupiter passing near the line of sight [46] [47].

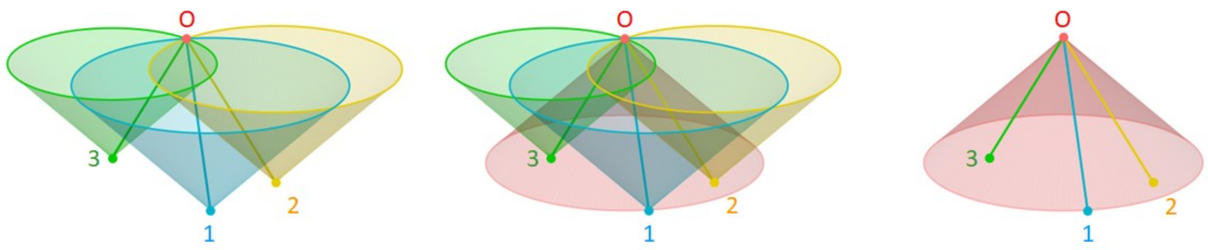

Fig. 12: Left: The three future null cones of the events 1, 2 and 3 intersect at the event O of their simultaneous observation. Middle: The null geodesics 1-O, 2-O or 3-O lie respectively on the future null cones of the events 1, 2 or 3, but also on the past null cone of the event O. Right: The clearest representation is that of the three null geodesics on the past null cone of event O.

In Fig. 12 left three future null cones of three events at different locations and at different times in the past are shown which are intersecting at one point O. This point represents the simultaneous arrival at an observer of the light of three planets emitted at different times in the past. It can as well stand for the arrival of their weak gravitational fields at the location of observation, where they are superposed. Somewhat clearer is the right figure with the past null cone of the observer. At the time of the observation, she is in the tip of the downward open cone mantle. The null geodesics, along which the light and the gravitational contributions from the three planets reach the observer, are drawn as colored straight lines. They arrive at the observer from different directions.

Following the sequence in [1], we next consider three stars, each of which suffers a sudden mass loss by isotropic emission of the corresponding amount of energy as a light burst. The physical relations can be depicted most clearly with the past null cone of the observer in three-dimensional Minkowski diagrams. Fig. 13 shows the past null cone for different times of observation, right at a later time than left.

Fig. 13: Two pictures of the past null cone of an observer at different times, on the left earlier, on the right later. Observer O records the light and gravitational field strength of three stars located at different distances from her.

The observer and the three stars are located in a spatial plane, which corresponds to the horizontal plane in the diagrams. In the vertical direction again, the temporal axis is plotted with increasing times upwards. The world line of the observer O is the straight vertical blue line. The three stars resting relative to her are represented by the black world lines parallel to hers. Their intersection points with the past null cone mark those events or states whose effects in the form of light or gravitational fields currently arrive at the observer. The blue and yellow null geodesics start at these intersection points, which correspond to the individual stars at different times in the past, and arrive at the same time at the observer coming from different directions. The effects transmitted along them superpose there.

The burst events of the three stars are marked by the yellow dots on their world lines. They take place at different times. The associated loss of mass is symbolized by the thicker worldline below and thinner worldline above these dots. Fig. 13 left shows the situation at the moment when the observer O is just passed by the photon shell of the light burst of star 2.

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Together with the intensity pulse she measures a decrease of the gravitational field strength. The light pulse of star 1 has already passed her earlier, the associated decrease of the gravitational field strength she has already recorded, too. Only star 3 seems to her still unchanged, of its burst event she cannot know yet because of the delay along the null geodesic due to the finite speed of light.

The situation for a later time is shown on the right. The past null cone has moved upwards and with it all intersections with the world lines of the stars. Its peak is higher on the observer world line corresponding to the later time of observation. Now the observer sees star 3 shining up and measures the decrease of its gravitational field strength. Between the depicted times on the left and on the right, the gravitational field strength of star 1 appears unchanged to the observer. Nevertheless, it is constantly updated along the null geodesic from the star to the observer, which moves upwards in time together with the whole past null cone. Since the state of star 1 did not change between the earlier and later intersection of its world line with the past null cone, the observer consequently does not detect any change of its gravitational effect, which reaches her delayed.

For the weak gravitational fields assumed here, the effects of the individual stars simply superpose. The effective total field strength is calculated as vectorial sum of the single contributions. This was already so with Newton and is still correct after Einstein.

The past null cone represents the causal structure of the spacetime. It is the consequence of the finite speed of propagation of light and gravity. The more distant an object is from the observer, the longer light and gravity need to travel from this object to the observer. She sees the object in its earlier state at the time of the light emission and is subject to its gravitational effect corresponding to this state. The deeper into the space we look, the further we look back into the past.

All events (states of objects) in the mantle surface of the cone can affect the spacetime point of observation in the tip of the cone. If one extends the null cone further into the past and into larger distances, additional intersections with world lines of more distant objects can exist. Then also exist corresponding null geodesics, the paths of light-fast effects from these objects in their past states to the observer in the present.

In three-dimensional space, one must drop the restriction to a plane and capture the full solid angle 4π to account for effects from all possible directions. However, a four-dimensional null cone can then no longer be vividly imagined.

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Curved spacetime acts as gravitational lens

In the language of general relativity, a gravitational field *is identified with* the curvature of spacetime. This determines the movement of the masses and is determined by the masses. The American physicist John Archibald Wheeler has summarized this notion in the following famous two short sentences [48]: "Spacetime tells matter how to move; matter tells spacetime how to curve."

So, we now have to extend our considerations from the uncurved "flat" Minkowski spacetime to globally curved spacetimes, so-called "Lorentz manifolds". They embody gravity as a geometric effect. In these, free-falling local reference frames are described as Minkowski spacetime, where the laws of special relativity, i.e. the Lorentz transformations, apply. This reflects the equivalence principle of general relativity ("Einstein's elevator").

To illustrate the meaning of "curvature" of spacetime and the resulting effects, let us imagine an "outside" cartographer resting so far away from a spherical mass that its gravitational field there is negligible. He describes the spacetime in his vicinity as Minkowski spacetime, his rest system is a Euclidean space.

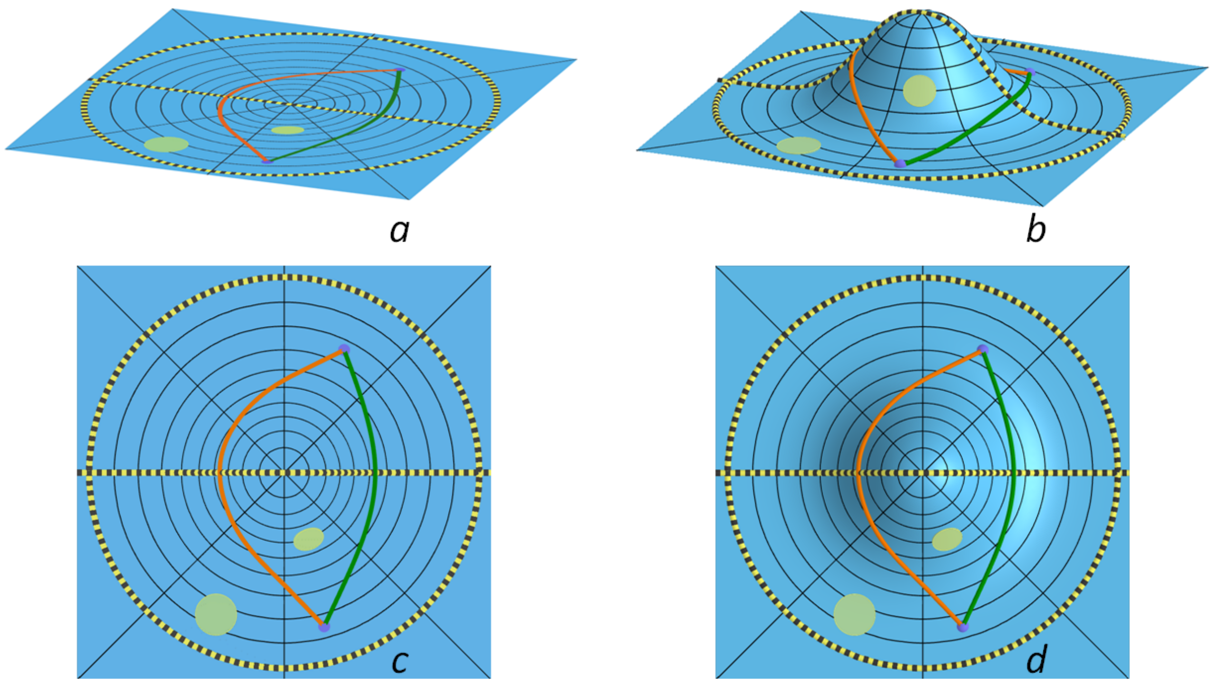

Fig. 14: Space curvature in the vicinity of a mass: The diameter of a circle around a mass in its center is determined by placing measuring rods next to each other. It is found to be larger than that of a circle with the same circumference in a Euclidean plane. This corresponds to the situation of a bulging surface which "cannot be flattened without wrinkles", for example the surface of a hill (b). Of course, a cross-sectional plane through the center of mass is not bulged (a), rather the mass causes an "intrinsic" curvature, which means that the unit length in this plane seems to vary depending on location and direction (c). The measuring rods seem to shrink in the radial direction of the gravitational field strength, so that more of them are needed to lay out the diameter. This intrinsic curvature is similar to that of a hiking map: A distance along a contour line can be measured directly by applying a tape measure, but perpendicular to the contour lines distances are projected shortened from the bird's eye view into the plane (d). Note: the lines shown in these diagrams are not contour lines, they are lines of equal distance along the slope. (Graphics: GeoGebra [49]).

The cartographer wants to draw a plane map of a cross-sectional plane through the center of the mass. For this purpose, he sends helpers who have the task to measure distances between resting marks distributed in the plane and to transmit the results to him. He equips the helpers with clocks and measuring rods that resemble his own.

He instructs them to lay the measuring rods in a line end to end to measure the distances. In this way, starting from the cartographer, they also measure the circumference of the circle in the center of which the mass is located and its diameter. How they manage to measure through the mass remains their secret.

The cartographer finds that he can enter the positions of marks in his vicinity, on the circle and further outside on his map without any problems and that a constant scale applies to their distances. But the closer the marks are to the central mass, the greater the deviations become. In particular, he finds that the ratio of circumference to diameter of the circle is less than pi. The diameter determined locally by his helpers by laying out with measuring rods is thus larger than expected for a Euclidean plane.

Distances in radial direction, which is the direction of the gravitational field strength, are shown shorter on the map than distances in tangential direction. And this shortening also varies with the distance from the mass. The situation reminds the cartographer of the measurement of a hill (Fig. 14) or a trough. The "extrinsic" curvature of such convex or concave surfaces, which "cannot be ironed flat without wrinkles", is projected onto plane maps from a bird's eye view. Thereby, distances on the maps in the direction of the slope of the surfaces appear shorter than those in the direction of the contour lines.

The plane maps then have location and direction dependent units of length. This so-called "metric" allows the distances measured on the map to be converted into the locally measured physical distances on site. The "extrinsic" curvature of the convex surface is transferred by the metric into the "intrinsic" curvature of the planar map. These "globally" varying and direction dependent length units across the map cause the shortest connections to be shown curved on the map. The tautly tensioned green fiber between the two blue dots, which follows the surface of the hill, appears curved from a bird's eye view.

But of course, the cartographer knows that it is impossible that the measured cross-sectional plane is really convex. So he must state that this cross-sectional plane itself already has an intrinsic curvature. For symmetry reasons, this is valid for all cross-sectional planes through the centrally symmetrical gravitational field of the spherical mass, thus generally for the space surrounding it.

Interesting: Already this simple hill analogy of a "space curvature" allows a second tightly stretched fiber (orange) between the two dots, which follows a different path. This would not be possible in a flat plane without the hill and is a first hint to the crucial role of curvature ! In fact, in the gravitational field, two massless fibers should be able to be stretched on the two paths shown between the dots. They thereby avoid the mass in the center ! If the fibers always have the same tension force, the total force which the dots exert on each other is larger than it would be with only one fiber connecting them.

It should be noted that the green curve of the *shortest* connection between the two blue dots shown in Fig. 14 does *not* correspond to the path of a light ray. This would only be the case if the local clocks were running at the same speed everywhere – in other words: if there was no curvature of time. But the speed of the clocks – and thus also of the light – appears slower closer to the central mass. Taking this into account a different curve results for the path of the light, the *fastest* path between the two dots, which runs further outside and is more curved (not drawn).

As just announced, the cartographer notices: The closer to the mass – i.e. the deeper in the gravitational potential – the local clocks of his helpers on site are, the slower they go. Seen from a distance, not only the movements of the hands of their clocks appear to him to be in slow motion, but all movements including the propagation of light. In radial direction, movements seem to progress even slower due to the apparent shortening of the measuring rods in the direction of the gravitational field. Observers on site do not notice anything of all this. They age according to the indication of their local clocks and always determine with them and their local measuring rods the same constant value c for the speed of light.

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The cartographer records the propagation of a laser beam on his map by marking the position of the wavefronts there in regular time intervals according to his clock. "On paper" a curved trace results, whose wavefront marks are closer together nearer to the mass, see Fig. 15 d. With "naive view", i.e. assumption of the validity of a constant scale – that of his vicinity – for the whole map, the speed of light does appear to be not constant along the light path. Where the marks are closer together "on paper", it appears lower – in his "outsider" coordinates. The situation is similar to the animation of the movement of GPS satellites [50], where the points *on the screen* also move at varying speeds, since the projection of the celestial sphere onto the flat screen (the "map") results in varying scaling.

On the map, "naively viewed" – i.e. without taking into account the metric of general relativity – it appears as if the speed of light has varying values < *c*, as would be the case with a spatially varying and, moreover, direction-dependent refractive index in a Euclidean space.

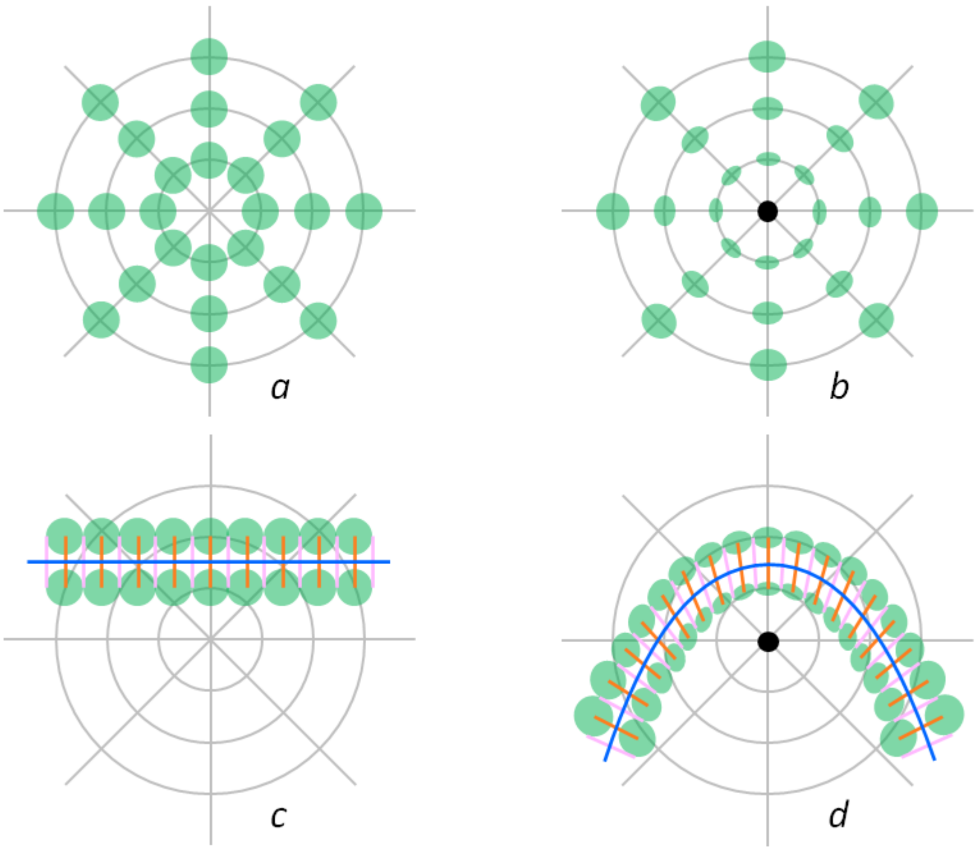

Fig. 15: Maps of light propagation in the plane, on the left in empty space without gravitational field and on the right in the gravitational field of a mass in the center. The Huygens elementary waves are shown as filled circles or ellipses for better clarity. (a): The propagation of light is determined to be independent of the location and the direction. Everywhere on the map we get the same circles as Huygens elementary waves. With them the propagation of a wavefront can be constructed. The construction (c) shows the expansion of the Huygens elementary waves after half an oscillation period of the light, thus from maximum (orange) to minimum (pink). Full circles are shown, so that the reversibility of the propagation direction becomes directly visible. As expected, light propagates along a straight line here. (b): On the map of the gravitational field, the Huygens elementary waves are found to be location-dependent ellipses whose short axes point towards the center in the direction of the gravitational field strength. The dimensions of the ellipses become the smaller and their ellipticity the stronger, the closer to the central mass they are. (d): The construction with the help of these Huygens elementary waves now results in a curved propagation of the light. The curvature increases the closer the light comes to the central mass.

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Fig. 14 shows two green circles, a larger one at the foot and a smaller one on the slope of the hill. They lie on the curved surface like two round picnic blankets. From a bird's eye view, the circle on the slope appears more compressed into an ellipse. The boundaries of these circles can also be interpreted as wavefronts of Huygens' elementary waves emanating from the centers of the circles. After a time interval read on the clock of the outside cartographer, the elementary waves have reached different extensions. The circle closer to the central mass appears smaller and more compressed into an ellipse.

In these Huygens elementary waves, which appear differently sized and deformed on the map, the curvatures of space *and* time are reflected. They cause the apparent global variation of the speed of light with both its location- and its direction-dependency (see also Fig. 15). With Huygens' principle, the curved paths of light can be constructed from this [36]. In the end, it was this analogy to a refractive index, which suggested the name "lens", and thus obscured the actual cause behind it: the intrinsic curvature of spacetime. But this does not only bend light !

Gravitational lenses fold null cones

In Fig. 16 two maps of the outside cartographer are shown with the path of the light rays or null geodesics (blue) and the wavefronts (orange) in the vicinity of a homogeneous spherical mass of finite density and around a black hole of the same mass. The externally registered apparent reduction of the speed of light in the gravitational field and the resulting lag of the wavefronts is clearly visible. The graphics were calculated using the interior and exterior Schwarzschild metrics.

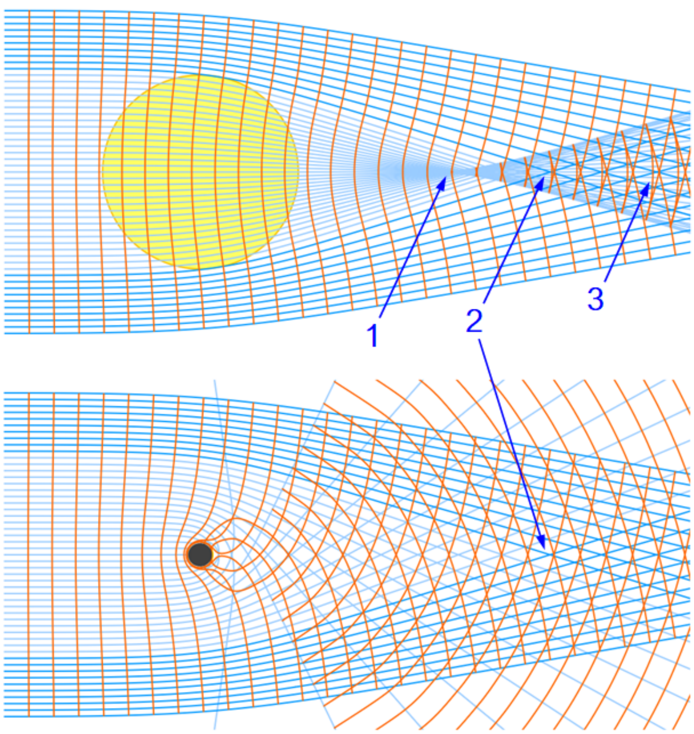

Fig. 16: Parallel rays (blue) and plane wavefronts (orange) coming from the left encounter a transparent star or a black hole of the same mass. In their vicinity, the curvature of spacetime leads to an apparently spatially varying speed of light. This results in a delay of the wavefronts and thus causes a deflection of the rays – even without the intervention of a refractive index of the matter.

According to the Birkhoff theorem, the latter is the only spherically symmetric vacuum solution of Einstein's field equations of general relativity. This has important consequences: the gravitational fields outside spherical mass distributions are determined only by the total mass, they do not contain any information about its compactness, i.e. the radial density distribution. Thus, for equal total masses, the gravitational fields surrounding them are indistinguishable.

So the darker colored rays in the graphics, which run outside the mass distributions in both cases, follow identical paths.

All rays which just pass the edge of the star in the upper image meet on the symmetry axis at (2). There the intensity is raised. Rays that pass the star at a somewhat greater distance meet somewhat further to the right on this axis. Thus, a line of increased intensity is generated.

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Rays crossing the star, however, will be even more concentrated in a veritable focus at (1). It is closer to the star and has maximum intensity. There the wavefront forms a cusp. In the further course of the caustic from these transmitted rays the wavefront is folded. Beside the intersecting outer sections there is an inner part which has been delayed most. It is to be emphasized once again that here exclusively the effect of the spacetime curvature is shown. A refractive index of the stellar matter as optical medium was not considered. A front of neutrinos moving with almost the speed of light would therefore behave in the same way and also the front of a gravitational wave [51].

As shown in the lower picture, wavefronts cannot overcome a black hole. Rays or null geodesics cannot emerge from a black hole again. A focus of such high quality as with a transparent mass (1) therefore does not occur here. Only the outer crossing sections of the wavefronts continue to propagate. The inner regions get stuck at the black hole, or more precisely: they wrap around it. For the sake of clarity, these wound-up regions of the wavefronts have been omitted from Fig. 16. However, the effects caused by the external field are identical in both cases. In the following we will restrict our considerations to the case of transparent mass distributions as gravitational lenses. Black holes are not regarded any further here.

What exactly is it that distinguishes space or spacetime in the area where the rays are focused and the wavefronts are folded?

Nothing at all ! Often this area is so far away from the mass distribution that there is only a negligible curvature. Accordingly, the rays continue as straight lines.

The focusing is nothing more than the superposition of the rays coming from afar. The curvature and the thereby caused change of direction of the rays has happened long before in the closer vicinity of the "lensing" mass distribution. The curvature of the spacetime there makes it possible that not only one single straight ray exists between a source and an observer, but several curved ones. These rays arrive at the observer coming from different directions and superpose here as if they came from different sources.

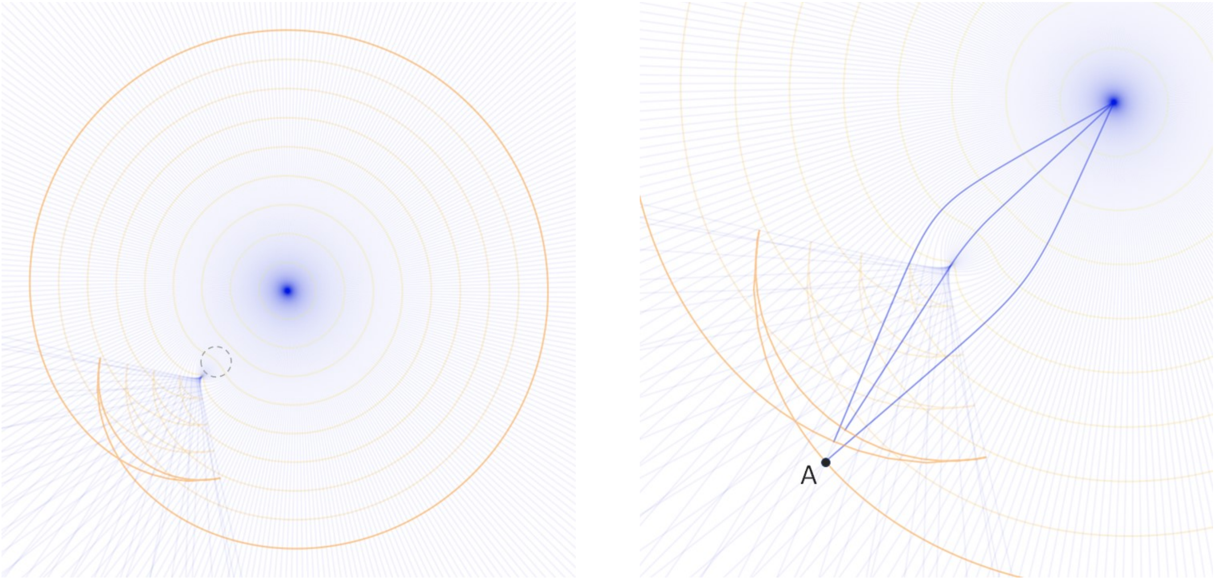

Fig. 17: Map of the propagation and folding of the wavefronts or of the photon shell of a light burst in a plane containing a gravitational lens (dashed circle). The lagging of the wavefronts in the region of the gravitational lens and the associated curvature, deflection and focusing of the light rays can be clearly seen. Behind the focus exists a caustic with self-intersecting and folded wavefronts. Shown on the right is the moment when the first section of the folded photon shell reaches observer A.

Fig. 17 shows the result of a numerical calculation of the effect of a gravitational lens (dashed circle) on the route of the null geodesics in its vicinity. Similar drawings can already be found in publications of the research group around Sjur Refsdal, whose work was groundbreaking for the understanding of gravitational lensing [52] [53].

In my "Gravitational Lens Gedankenexperiment" [1], I consider a star that emits a burst of light and suffers a sudden loss of mass. The gravitational lens allows three different curved paths for the light from the star to the observer "Alice" (A). So she sees the star in three different directions. The photons are more delayed the closer to the center of the gravitational lens they pass. Subsequently, the photon shell is folded so that three sections pass the observer one after the other. This means that she sees the star shine up brightly three times, once in each of the three directions.

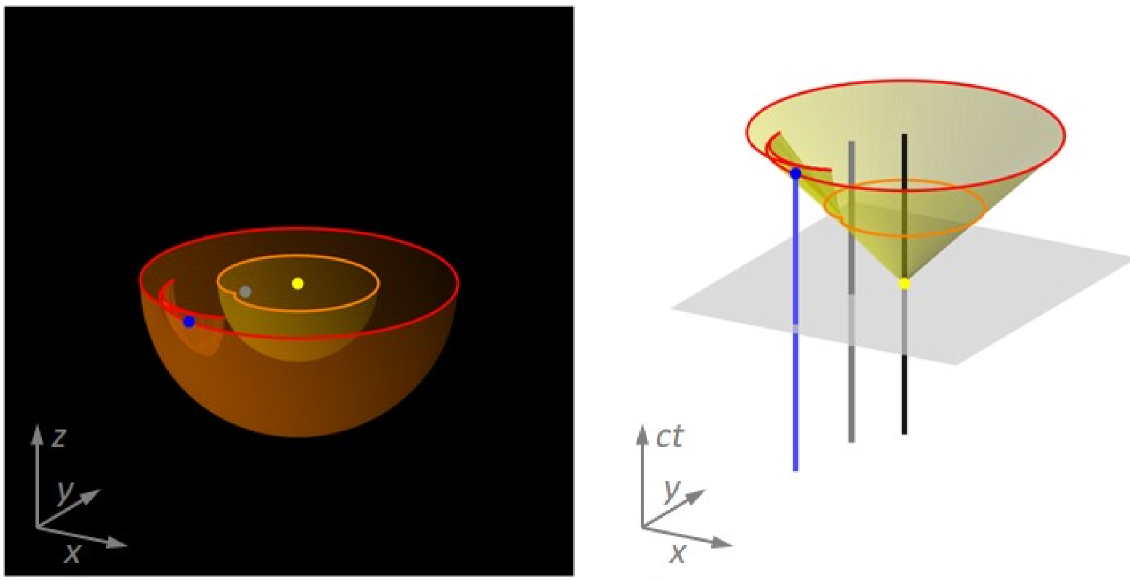

Fig. 18: Spatial and light-cone representation of the effect of a gravitational lens (gray dot) on an expanding shell of photons. Shown on the left is the photon shell at two discrete times as orange and red transparent surfaces. Their cross-sections through the xy-plane appear as deformed or folded closed curves, which are also found on the light cone on the right. The deformed and folded closed curves in the cross-sectional plane are symmetric with respect to the axis through the star and the gravitational lens. By rotation of the curves around this axis, the three-dimensional photon shells are obtained.

Shown in Fig. 18 (similar as in Fig. 9) are the spatial representation on the left and the light cone representation on the right of an expanding shell of photons, here in a spacetime curved by a mass. The photon shell is deformed and folded during its expansion, which can be seen in the cross-section through the *xy*-plane. In this cross-sectional plane, deformed and folded closed curves are present, which are also found on the light cone as contour lines of constant time at different levels according to the temporal *ct*-axis.

The light burst event of the star is symbolized by the yellow dot. Shown in orange is the photon shell after it has already passed the mass acting as a gravitational lens (gray dot). It shows a pointed dip where a focus of increased intensity exists. Shown in red at an even later time, the photon shell has expanded further, intersected and folded itself. Its outer section is just passing the observer (blue dot).

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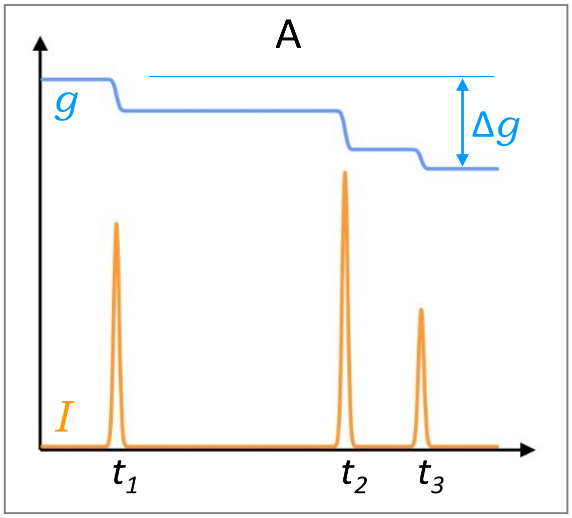

Fig. 19: Temporal curves of the "measured" intensity and gravitational field strength at the location of observer A

As long as the photon shell has not reached the observer A yet, she measures an unchanged gravitational field strength = free-fall acceleration g. At time t_1 the photons of the outer section pass her and she measures a first intensity pulse. Simultaneously the gravitational field strength drops. Later the two other sections of the folded photon shell will pass her, too, and she will detect two more intensity pulses and simultaneous drops of the gravitational field strength, which propagate together with the speed of light along all null geodesics emanating from the star. The gravitational lens causes three of these null geodesics to pass the observer.

After the complete passage of the photon shell constant conditions should prevail again.

The dominant part of the gravitational field strength at the observer's location is caused by the gravitational lens itself. But since this does not change, it provides a constant background and is not considered further here. For the weak field strength contribution of our star one can assume a linear dependence on its mass. The light burst has reduced its mass by a certain fraction. Its gravitational field strength contribution should also have decreased by the same fraction in relation to its value before the arrival of the first sign of the light burst event. In the region of the folding of the photon shell a light pulse arrives three times, accordingly a decrease of the gravitational field strength occurs also three times. Thus, the total decrease is larger than in the part without a folding, where only a single decrease takes place. But if this larger total decrease is to correspond to the same fraction of the previous value, then this must also have been correspondingly larger. The simplest assumption is that an individual contribution not only to the light intensity but also to the gravitational field strength has to be assigned to each of the three null geodesics arriving at the observer. These contributions superpose just as if they came from different sources. This is the effect called "Gravitationally Lensed Gravity" (GLG).

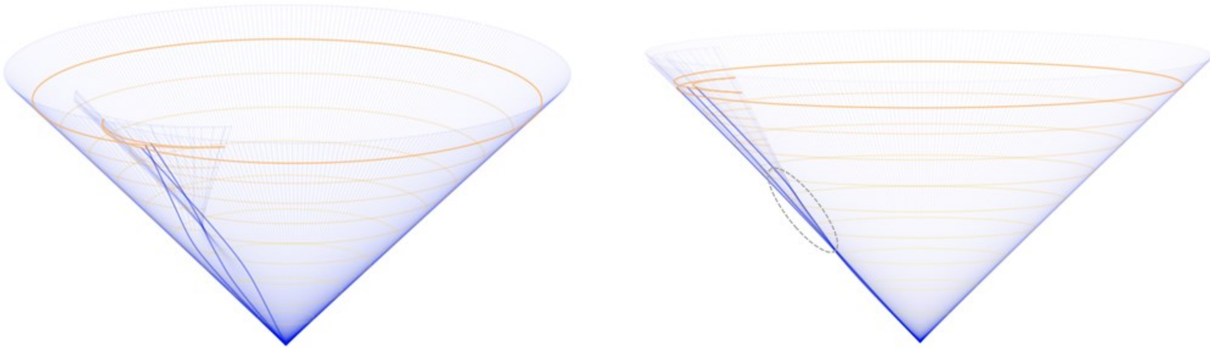

Fig. 20: Deformation, self-intersection and folding of the future light cone by a gravitational lens. The folded wavefronts resp. the photon shell of the light burst from Fig. 17 are found in the light cone representation as "contour lines" with respect to the vertical temporal ct-axis. In the view on the right, the larger slope corresponding to the apparent reduction of the speed of light in the region of the gravitational lens and the thereby caused delay of the null geodesics can clearly be seen.

Fig. 20 shows the corresponding folded future light cone, which starts from the burst event of the star. It is the set of all null geodesics (blue lines) starting from the star at the spacetime point in the apex of the cone. Each point on the future light cone is reached from the apex on one (or more) of these null geodesics,

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other paths from the apex to a point on the cone are not possible since they would require exceeding the speed of light on parts of such paths. In this sense, the null geodesics are "taut" similar to the fibers in Fig. 14.

On the right, the folded future light cone is turned in such a way that one looks almost perpendicularly at the cross section through the star and the gravitational lens. In the dashed area of the gravitational lens the speed of light appears to be reduced, here a dent is formed in the cone's mantle, which changes towards the top into a pointed indentation. There the focus is located, through which three null geodesics pass. Adjacent to it the region of self-intersection and folding of the cone mantle starts. The line of self-intersection consists of points where two null geodesics cross each other.

The light ray passing through the spherical mass distribution is slowed down the most. Its incline becomes larger, which corresponds to an apparent reduction of the speed of light. However, this appears only to the outside cartographer in such a way, on site with local measuring rods and clocks no change of the speed of light is detectable. Along this null geodesic no signal can advance faster and no effect can propagate faster. This dent and folding of the light cone dictate the causal structure for all effects which propagate with light velocity. Even gravity is not excluded from it – for gravitational *waves* this is already general consensus.

The different travel times of the light on the three null geodesics lead to the fact that photons of the light burst simultaneously emitted by the star arrive at the observer at different times. On the other hand, they mean that the three different views ("images") of the star, which the observer sees simultaneously, consist of photons emitted at different times, thus showing the star in states at different times of its past. Here the representation with the help of the past light cone is convenient.

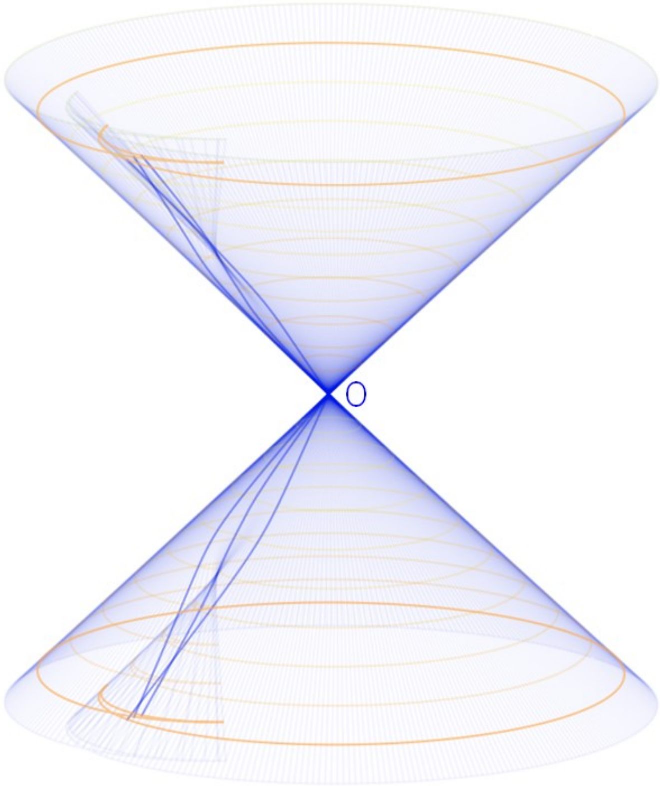

Fig. 21: Future and past light cone of the event O folded by a gravitational lens

The past light cone can be obtained from the future light cone by mirroring at the spatial *xy*-plane and corresponds to a reversal of all directions of propagation, what looks like a backward running of the time.

The future light cone of an observer is folded by a gravitational lens as well. Fig. 21 shows in the upper part the future light cone of an observer who triggers a flash light in the point O of spacetime. After time *t,* the light has passed the mass distribution acting as gravitational lens and forms a folded front of the light flash, which's *xy* cross section is drawn as the orange folded closed curve on the future light cone.

Light, which would have been emitted at the past time -*t* from the locations of the folded front in the opposite directions, would arrive at the observer in O simultaneously.

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This construction of the past light cone corresponds to a mirroring at the *xy*-plane through O. It is based on the assumption of a static arrangement of the observer and the gravitational lens, since only then the reversibility of the light propagation is valid.

Thus, past light cones are folded in the same way as future light cones. Fig. 21 shows three null geodesics on the future light cone, which start from O and reach different locations of the folded front of the light flash at the time *t*. Also shown are their counterparts on the past light cone, i.e. null geodesics emanating from different locations at the same time -*t* and arriving at O all together.

If the three null geodesics start *at the same time in the past* from different locations, they just can originate *from different objects* there. Their effects superpose in O and are measured by the observer as total effect. This is nothing special and was already so without gravitational lens (see Fig. 12).

It becomes more interesting, if one considers three null geodesics, which originate *from only one object at different times of the past*.

The above used restriction to static arrangements of observer and gravitational lens served only for the illustrative justification of the existence of foldings at past light cones. For moving gravitational lenses, the calculations of null geodesics and past light cones become more elaborate, but no significant changes result. Also in the succeeding Fig. 22 parallel world lines are shown corresponding to static arrangements. However, it is immediately obvious that the reasoning for curved world lines of moving objects would not change. Thus, the following conclusions are generally valid.

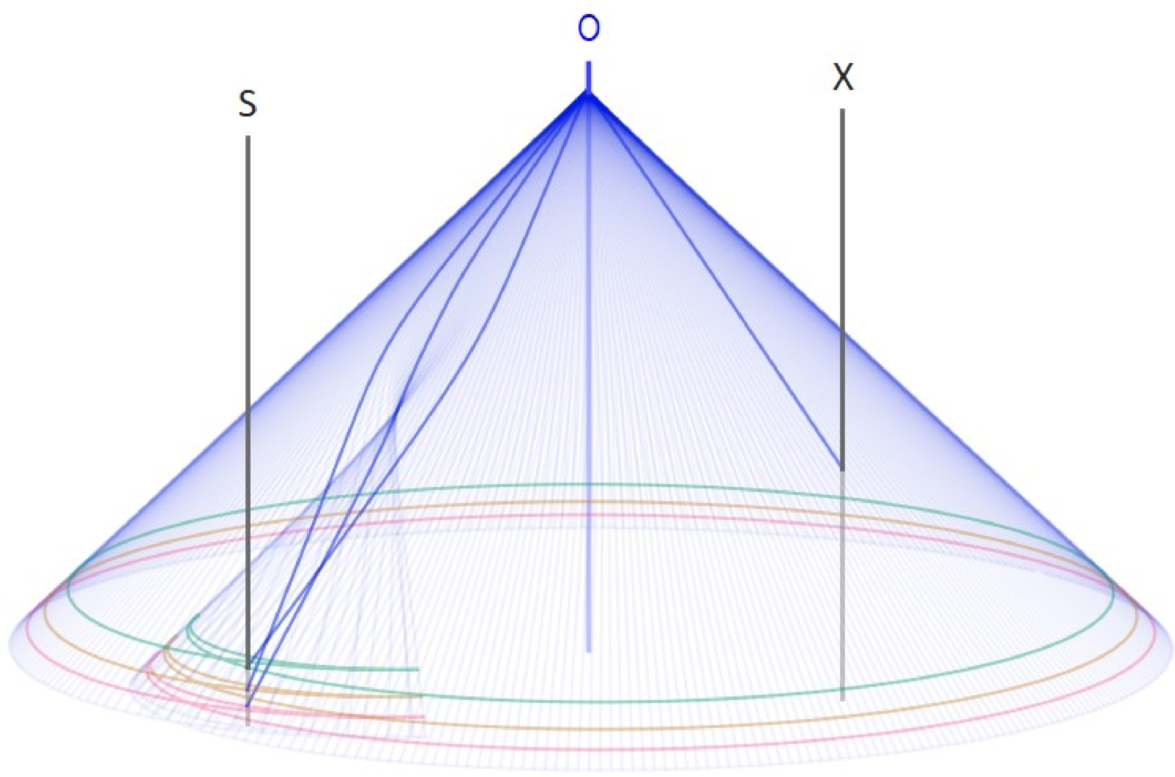

Fig. 22: The three intersection points of the world line of the star S with the past null cone are connected by three null geodesics to the point of observation in the cone tip. The observer O is far away from the gravitational lens, in her surroundings there is no significant gravitational field present, there Minkowski's description of spacetime applies. In the region of the cone top the cone is not deformed but completely regular. The three null geodesics from our star S arrive at the observer O from different directions, like those from the intersections with the world lines of other objects X, too.

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The past light cone is to be understood as the "complete" set of all null geodesics with the same endpoint, the tip of the cone. For each point on the folded cone there exists one (or more) null geodesics leading from it to this tip, the observation event. Moreover, the null geodesics can be "ordered" according to the angle of the direction from which they arrive at the observation point, and are "unique": for each direction there exist only one possible null geodesic, which theoretically can extend arbitrarily far back into the past. So, obviously there are natural limits to the mathematical description, but they are not important for our further considerations here, because we will continue to operate within overlookable pasts.

There are three points of intersection of the world line of the star with the folded past light cone [37]. They correspond to three different times of the emission of the light, which follows the null geodesics to the top of the cone and arrives there simultaneously at the observer. If we now assume that the light burst event takes place at the middle one of the three intersection points, we can read directly from this illustration that the observer sees light from the star simultaneously from three different directions, showing it at three different times in the past in three different states before, during and after its light burst. If one assumes that the past null cone of gravity is identical with the past light cone, then it is obvious that there are also three contributions of the gravitational effect of the star, corresponding to its mass at the three different past times, also arriving simultaneously at the observer and superposing there.

This consistency results from the speed of causality, the speed of light, with which the information about the sudden mass change of the star propagates in the form of light as well as in the form of a change of the gravitational field strength.

At this place it is to be emphasized that the consideration of the light burst event here serves in particular as an auxiliary means to make plausible the continuous actualization of the gravitational effect with the speed of light along the null geodesics. Once this is understood, one may dispense with the light burst event, indeed with light in general. Naturally, the gravitational effect will spread the information about their mass just as well from not shining objects with the speed of light.

In the case considered here are both the star and the observer at such a great distance from the gravitational lens that they are practically not affected by any curvature of spacetime in their vicinities. For the star, this means that its emitted luminous flux is isotropic, as is its gravitational field in its near surroundings. The same information "is fed into" all null geodesics emanating from it at the same time. All these null geodesics are equivalent, the star's future light cone in its neighborhood is "regular".

Likewise regular is the past light cone in the neighborhood of the observer. The history of the course of the incoming null geodesics is not directly ascertainable by the observer, how should it be detectable ? She considers all arriving null geodesics as equivalent, the information and effects transmitted by them superpose in the same way as it would be the case without gravitational lens. Here the principle "seeing is believing" applies (M. A. Abramowicz [54]). The observer cannot distinguish the *instantaneous local effects* of the three "images" – the three perspectives on the one star provided by the gravitational lens – from the effects of three real existing stars without presence of a gravitational lens. Only observations over longer times (or from different locations) and the use of a suitable model of the world will enable the observer to recognize the "objective reality" of the gravitational lens arrangement. But this does not change her subjective perception of the momentary local effects.

The independence of the null geodesics

I would like to emphasize here another very important – if not even decisive – argument for the existence of the effect: the independence of the null geodesics from each other. For this purpose, I compare the effects of gravitational lenses of the same mass but different densities on the path of the null geodesics.

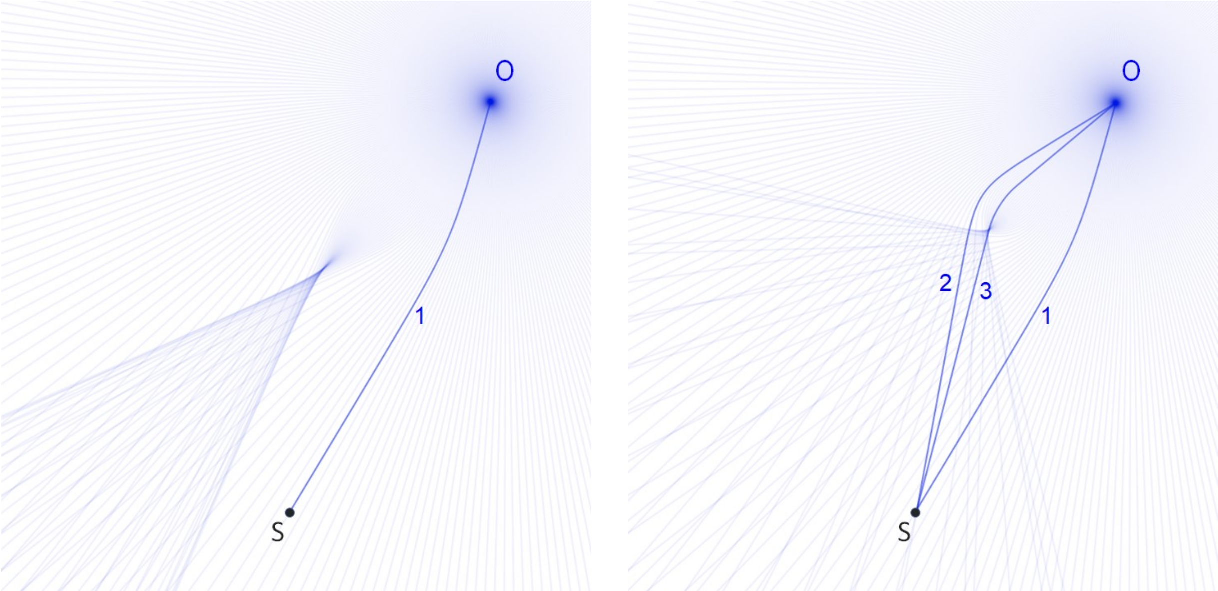

Fig. 23: The maps show the paths of the null geodesics in the vicinity of gravitational lenses of the same mass, on the left with smaller, on the right with larger density. The null geodesic 1 running in large distance from the mass distributions is identical in both cases. There, the gravitational field does not provide any information about the radial density profile of the spherical-symmetric mass distribution (Birkhoff theorem). The effects, which are transmitted along this null geodesic, are the same. With the more compact mass distribution on the right, two further null geodesics exist. Effects are also transmitted along these. Thus, the total effect arriving at the observer O must increase accordingly.

Fig. 23 shows maps of the paths of the null geodesics in the vicinity of gravitational lenses with the same mass but different densities. Far away from the mass, its gravitational field is small in the vicinity of the source S (our star) and the observer O. Because of Birkhoff's theorem, the gravitational field outside the mass distributions is identical in both cases. Thus, the conditions for S in the two cases do not differ, and also not those for O.

In both cases the null geodesic 1 between star and observer runs only through the gravitational field outside the mass distributions of the gravitational lens. So also this is identical in both cases, as well as the luminous flux and the gravitational effect, which reach the observer from the star along it. In the case of the more compact mass distribution on the right, however, two further null geodesics 2 and 3 exist, along which also light and gravitational effect arrive from the star at the observer. Because of longer travel time along 2 and even longer along 3, light and gravitational effect must have left the star appropriately earlier, so that they arrive at the observer simultaneously with the light and gravitational effect of 1 and add up there. These three contributions are independent of each other, they "know" nothing about each other. At the location of the star no information about the compactness of the mass distribution of the gravitational lens exists. The effects emanating from the star do not "know" how the further paths of their null geodesics will be, and whether these will be curved by the gravitational lens in such a way that they will meet once again at the observer or somewhere else. They cannot "coordinate" here to avoid an increase of the total effect there. Once put on the way, the effects of our star arrive at the observer from different directions, just as if they came from different sources, and superimpose there to an increased total effect.

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Sticking with Newton's law of gravitation is not compatible with the picture of folded past null cones, which provides several null geodesics between star and observer. Which direction and which distance of the one gravitational source should be inserted into Newton's law of gravitation ? When exactly should the necessary decrease of gravitational field strength take place, if the mass of the star suddenly decreases during a light burst ?

These questions already give an idea of the complicated "epicyclism" that would be necessary to "save" Newton's law of gravity as an approximation for weak fields even in the presence of a gravitational lens, instead of considering the simplest explanation, the GLG.

The "GLG-Challenge"

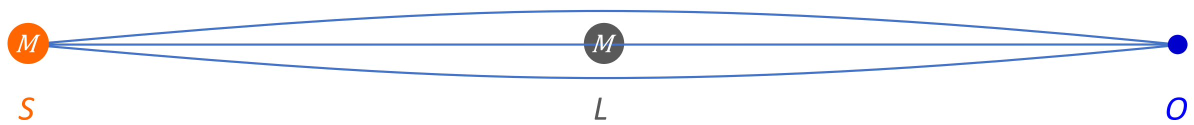

Fig. 24: Schematic sketch of the gravitational microlensing effect with arrangement of star S, lens L, and observer O.

The following simple calculation example shall clarify the potential significance of the "Gravitationally Lensed Gravity". Let us imagine a compact mass L and a star S, which lies directly behind this mass, seen from the observer O. Now let the compact mass in the foreground magnify the intensity of the light from the star in the background due to its gravitational lensing effect. Such microlensing events have indeed been observed, e.g. in 1993 within the MACHO project one with more than 6-fold amplification [55]. For simplicity, we assume that the amplification factor is exactly 6 and that the distance r from the star to the compact mass is the same as from the observer to the compact mass. Furthermore, let the two masses M be equal and the compact mass transparent but without a "normal" refractive index for the considered radiation. We can just as well consider the enhancement of the current density of neutrinos from the star, which are emitted isotropically with (almost) the speed of light. Fig. 24 shows the considered arrangement.

Which field strength g "measures" the observer ?

According to Newton, it is simply the sum of the field strength contributions from the compact mass and from the star twice as far away:

$$g = \frac{G \cdot M}{r^2} + \frac{G \cdot M}{(2r)^2} = \frac{5}{4} \cdot \frac{G \cdot M}{r^2} \tag{11}$$

The "Gravitationally Lensed Gravity", on the other hand, predicts that the gravitational field strength caused by the star S at the observer O is amplified by the gravitational lens L in the same way as the intensity of its radiation [1], in our example by a factor of 6. This gives:

$$g = \frac{G \cdot M}{r^2} + 6 \cdot \frac{G \cdot M}{(2r)^2} = \frac{10}{4} \cdot \frac{G \cdot M}{r^2} \tag{12}$$

The gravitational field strength predicted by the GLG is in this example *twice as large* as the one calculated according to Newton !

Interesting is also the fact, already mentioned in connection with Fig. 16, that the transmitted part is omitted in the case of a black hole. So a black hole of the same mass should produce a *smaller* amplification of the gravitational effect of the star at the observer !

I sincerely hope that these provocative statements will encourage theorists to conduct their own analyses of this specific example and publish the results.

It has to be mentioned that the effect is so pronounced only when the compact lens mass is very close to the line of sight to the star as seen from the observer. Like the amplification of the light intensity, the amplification of the gravitational field strength should also disappear quickly when the arrangement is no longer given in this way.

The gravitational lens only causes a curvature of the paths of the photons, no additional photons are generated. Thus, only a *redistribution* of the light flow takes place: the intensity is strongly increased at some locations and weakly decreased at many others. It works correspondingly for the gravitational field strength. Explained vividly, the field lines are bent and thus redistributed by the curvature, concentrated at some places, there the field strength increases, thinned out at other places, there the field strength decreases.

Conclusions

In view of a spectacular image of the Hubble Space Telescope from a gravitational lens, which obviously produces several images of a background object, nobody would think of describing the total incoming light intensity of all these images with the conventional $1/r^2$-distance law for the single object. But for its gravitational effect exactly this is done by sticking to the validity of Newton's law also in such a case.

This is certainly due to the overwhelming success of Newton's law of gravity, which is much easier to handle than Einstein's field equations and has excellently proven itself in the range of the solar system – with the exception of a tiny deviation in Mercury's orbit. Thus, one has come to apply Newton's law of gravitation also to scales of galaxies and galaxy clusters and to assume Dark Matter in the just required distribution to explain the respective observations.

The question about the propagation speed of the gravitational field is usually answered with "speed of light", but seems to have no further consequences except for gravitational waves. Gravitational fields don't show any aberration, so they apparently act instantaneously – just as Newton formulated it.

But the situation changes fundamentally if a curvature of spacetime induced by a mass comes into play, acting as a gravitational lens. There, all effects propagating with the speed of light must obey this curvature and follow the same curved paths, the null geodesics.

Then the effects originating from an object are deflected and can meet again, superpose and thus be locally amplified in the further course. That this must also be true for the gravitational field becomes clear if one considers the sudden mass loss of a star during a light burst event. Both the light and the change of the gravitational field transport the same information about the mass loss. Consistency requires that they propagate together at the speed of light along the same null geodesics.

More formally one can argue with the causal structure of the spacetime and retarded effects. The relations in the plane, in which the star, the gravitational lens and the observer are located, can be well described with the folded past null cone of the observer. All effects, which arrive at her simultaneously from all directions in the plane and superpose, reach her along certain null geodesics. For every point on the past null cone a null geodesic exist which provides a potential connection of it with the tip of the cone, the event of observation. In the region of the folding of the past null cone, there are three intersection points with the world line of the star, from which three null geodesics start and arrive at the observer from different directions, as well as further null geodesics from other objects.

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The three images of the star she sees seem "real", they are not different from the images of the other objects she sees. Like those, they also bring a contribution of a gravitational effect. The three images of the star are not "mirages", they are as effective on the observer as the images of the other objects. Which of the three images of our star should she otherwise distinguish as "the real object" and which dismiss as "mere illusions" ?

This "seeing is believing" principle refers to the local momentary subjective perception of the observer. Of course, with the help of a suitable model of the gravitational lens, she can understand that there is only one star. And with the help of the "Gravitationally Lensed Gravity" even, why it nevertheless acts on her like three stars.

The findings from these considerations in the two-dimensional plane can be transferred simply to the three-dimensional space. However, the four-dimensional spacetime can then no longer be represented vividly. In order to capture all influences acting on her, an observer has to follow backwards the null geodesics in all directions in the full solid angle 4π and check whether they intersect the world line of an object. This intersection point determines the past "retarded" state of the object, the effect of which currently arrives at her. Due to the curvature of spacetime in the environment of a gravitational lens it can happen that several of the null geodesics arriving at her from different directions intersect the world line of the same object at different times in the past. Since these null geodesics are independent of each other, they are to be treated as if they came from different objects. Neither was known in the moments of "emission" from the object that they would be curved and would meet again, nor is directly detectable at the moment of "reception" at the observer that they were curved and to what extend.

The scenario of a light burst of a star – a supernova – in the background of a gravitational lens was already considered by Sjur Refsdal in 1964. He showed theoretically how to use the travel time difference of the light of two images for the determination of the Hubble constant [56]. But it was not until five years after his death, in 2014, that the Hubble Space Telescope first found such a supernova in a background galaxy, imaged multiple times by a gravitational lens. It is named "SN Refsdal" in his memory. A detailed model of the gravitational lens and the differences in the travel times of the light from the individual images even made it possible to correctly *predict* the appearance of the supernova in one of the images [57]. In the meantime, another supernova, "SN Requiem", has been found in a background galaxy, which has already lit up in three images and is expected to appear in the fourth image around the year 2037 and in the fifth image around 2042 [58]. Such a cosmic spectacle makes obvious how little sense it makes to try to describe the current gravitational effect of this star on us with Newton's law for the individual star. Which mass should we attribute to it - the one before or the one after its supernova event ?

This question seems irrelevant, because the gravitational effect coming from this distant star is anyway immeasurably small, whether it is amplified or not. But the amplification of the gravitational effect does not only concern the one star, but just as well the whole host galaxy, in which it is located !

The calculation example for the GLG microlensing effect makes clear that this effect can become quite significant, but also depends sensitively on how the masses are arranged with respect to each other. This strong dependence on the shape of the mass distribution should help to recognize the GLG effect, if one measures the gravitational lensing of a flat disk galaxy, which one looks exactly sideways at the edge. On the other hand, such shape-dependent deviation from Newton's law of gravity should not occur in mass distributions with rather spherical symmetry or low density. Indeed, it was found that the dynamics in ultra-diffuse galaxies can be well explained by Newton's law of gravitation and the visible matter alone [59]. This observation is still subject of a vivid debate.

However, apart from an immediate astrophysical "usability" of the GLG, the physical questions raised here reveal inconsistencies or at least incompleteness of the previous theoretical descriptions. The "Gravitationally Lensed Gravity", on the other hand, provides a maybe surprising, but yet simple and coherent description of the physical effects within the framework of general relativity.

There is no fundamental principle known, which speaks against the GLG ! Otherwise, experts in physics forums could clearly deny the questions about the GLG – similar to patent offices rejecting flatly any application for a "perpetuum mobile" with reference to the physical law of conservation of energy.

There is still very little known about the GLG, an intensive discussion about it did not take place in the community of relativity theorists so far. In any case, a closer study of the topic promises an important gain in knowledge: The confirmation of the GLG would undoubtedly be a little sensation, but also the refutation with resolution of the alleged inconsistencies would be an important contribution to extend the theoretical descriptions to the so far neglected cases, which the Hubble Space Telescope brings before our eyes so impressively.

I would be pleased if, through this work, I have provided to one or the other an interesting perspective on the fascinating field of "Gravitationally Lensed Gravity", this still barely explored white spot in general relativity.

Acknowledgement

I would like to thank the many people who dreamed of, built, repaired, operated, and shared with us the many wonders they discovered all around us with its help, the magnificent Hubble Space Telescope. Fascinated, I was looking at the image of a gravitational lens and what I suddenly saw in it surprised and amazed me – without this deeply impressive experience, this article would not exist.

Thanks are also due to all the researchers and teachers who strive to present scientific findings in a way that is understandable to laypeople, especially all those who kindly answered my questions about general relativity. I very much appreciate the many experts and laypeople who share their enthusiasm for science in an inspiring way on YouTube, discuss questions in forums in an engaged and respectful manner, or carefully create high-quality articles on Wikipedia.

Big thanks to my family for their encouragement and especially to my wife for her support, understanding and patience.

References

[1] A. Boenke, „Gravitationally Lensed Gravitation," Preprints, 18 Februar 2021. [Online]. Available: https://www.preprints.org/manuscript/202102.0413/v1.

[2] gravitylens101, „Mehr Gravitation durch Gravitationslinsen," Umwelt Wissenschaft, 27 Juli 2015. [Online]. Available: https://umwelt-wissenschaft.de/forum/5-2-dunkle-materie/480-mehr-gravitation-durch-gravitationslinsen. (Translated by the author of this article.)

[3] D. Rubin, I. Szapudi, B. J. Shappee and G. S. Anand, „Does Gravity Fall Down? Evidence for Gravitational-wave Deflection along the Line of Sight to GW170817," The Astrophysical Journal Letters, Bd. 890, Nr. 1, p. L6, 10 Februar 2020. PDF

[4] LIGO-Scientific-Collaboration, „Gravity bending gravity: Are any of the O3A LIGO-VIRGO detections gravitationally lensed?," 2021. [Online]. Available: https://www.ligo.org/science/Publication-O3aLensing/flyer.pdf.

[5] T. Padmanabhan, „Gravity bends electric field lines," in Sleeping Beauties in Theoretical Physics, Cham, Springer International Publishing Switzerland, 2015, pp. 279-292. PDF

[6] ESA/Hubble & NASA, T. Treu; Acknowledgment: J. Schmidt, „Seeing Quintuple," 9 August 2021. [Online]. Available: https://esahubble.org/images/potw2132a/.

[7] A. Einstein, „Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field," Science, New Series, Bd. 84, Nr. 2188, pp. 506-507, 4 Dezember 1936. PDF

[8] J. Renn, T. Sauer and J. Stachel, „The origin of gravitational lensing: A postscript to Einstein's 1936 Science paper," Science, Bd. 275, Nr. 5297, pp. 184-186, 1997.

[9] J. Renn and T. Sauer, „Eclipses of the Stars. Mandl, Einstein, and the early history of gravitational lensing," in Revisiting the Foundations of Relativistic Physics. Festschrift in Honor of John Stachel, A. Ashtekar et al., Hrsg., 2003, pp. 69-92.PDF

[10] F. Zwicky, „Nebulae as gravitational lenses," Physical Review, Bd. 51, Nr. 4, p. 290, 1937. PDF

[11] B. Welch et al., „A highly magnified star at redshift 6.2," Nature, Bd. 603, Nr. 7903, pp. 815-818, 2022. PDF

[12] NASA and S. T. S. I. (STScI), „Record Broken: Hubble Spots Farthest Star Ever Seen," NASA Hubblesite, 30 März 2022. [Online]. Available: https://hubblesite.org/contents/news-releases/2022/news-2022-003.

[13] T. Y. Thomas, „On the propagation and decay of gravitational waves," Journal of Mathematical Analysis and Applications, Bd. 3, Nr. 2, pp. 315-335, 1961. PDF

[14] J. Weber, „Anisotropy and polarization in the gravitational-radiation experiments," Physical Review Letters, Bd. 23, Nr. 3, p. 180, 1970. PDF

[15] J. K. Lawrence, „Focusing of gravitational radiation by interior gravitational fields," Il Nuovo Cimento B (1971-1996), Bd. 6, Nr. 2, pp. 225-235, 1971. PDF

[16] L. K. Ingel', „Gravitational focusing," Astronomicheskii Zhurnal, Bd. 50, p. 1331, 1973. PDF

[17] Y. N. Demkov and A. M. Puchkov, „Gravitational focusing of cosmic neutrinos by the solar interior," Physical Review D, Bd. 61, Nr. 8, p. 083001, 2000. PDF

[18] R. J. Nemiroff and C. Ftaclas, „Our Sun as a gravitational lens," American Astronomical Society Meeting Abstracts#, Bd. 190, p. 38.01, 1997.

[19] R. J. Nemiroff, „Can a gravitational lens magnify gravity? A possible solar system test," The Astrophysical Journal, Bd. 628, Nr. 2, p. 1081, 2005. PDF

[20] R. J. Nemiroff, „How Fundamental is the Curvature of Spacetime? A Solar System Test," in Gravity Research Foundation's 2006 Essay Contest, 2006. HTML

[21] R. Anania and M. Makoid, „Ab Initio Calculation of the Anomalous Acceleration of Pioneer 10 In Vacuo," arXiv e-prints, pp. astro-ph/0502582, 2005. PDF

[22] M. Makoid and R. Anania, „Ab initio Calculation of Galactic Rotation Curves in vacuo," APS April Meeting Abstracts, p. S1.006, 2007. PDF

[23] Q. Pan, „A Classically Consistent Self-Interacting Field Theory I: A non-Newtonian gravitational theory and its application in Astrophysics," 2015. [Online]. Available: DOI: 10.13140/RG.2.1.5018.6962. DOCX

[24] A. Deur, „Relativistic corrections to the rotation curves of disk galaxies," The European Physical Journal C, Bd. 81, Nr. 3, pp. 1-10, 2021. PDF

[25] A. Deur, „Effect of gravitational field self-interaction on large structure formation," Physics Letters B, Bd. 820, p. 136510, 2021. PDF

[26] I. B. Cohen, Isaac Newton's Papers & Letters on Natural Philosophy, Cambridge, Mass. and London: Harvard University Press., 1978, repr. 2014.

[27] N. Sfetcu, „About God in Newton's correspondence with Richard Bentley and Queries in Opticks," 13 Februar 2019. PDF

[28] L. Bobis and J. Lequeux, „Cassini, Rømer, and the velocity of light," Journal of Astronomical History and Heritage, Bd. 11, pp. 97-105, 2008. PDF

[29] K. M. Pedersen, „The velocity of light and the colour changes of Jupiter's satellite," Res Publ Sci Stud, Bd. 40, pp. 1-41, 2017. PDF

[30] K. T. McDonald, „Laplace and the Speed of Gravity," Joseph Henry Laboratories, Princeton University, 2018. [Online]. Available: https://www.hep.princeton.edu/~mcdonald/examples/laplace.pdf.

[31] A. Pais, 'Subtle is the Lord...' The Science and the Life of Albert Einstein, New York: Oxford University Press, 1982.

[32] S. Carlip, „Aberration and the speed of gravity," Physics Letters A, Bd. 267, Nr. 2-3, pp. 81-87, 2000. PDF

[33] K. Brown, Reflections on Relativity, Lulu.com, 2018. HTML

[34] I. I. Shapiro, „Fourth test of general relativity," Physical Review Letters, Bd. 13, Nr. 26, p. 789, 1964.

[35] J. G. Galle, „Account of the discovery of Le Verrier's planet Neptune, at Berlin, Sept. 23, 1846," Monthly Notices of the Royal Astronomical Society, Bd. 7, p. 153, 1846. PDF

[36] A. Einstein, „Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes," Annalen der Physik, Bd. 35, Nr. 10, pp. 898-908, 1911. PDF

[37] J. Ehlers, „Foundations of gravitational lens theory (geometry of light cones)," Annalen der Physik, Bd. 9, Nr. 3-5, pp. 307-320, 2000. PDF

[38] J. Ehlers, S. Frittelli and E. T. Newman, „Gravitational lensing from a space-time perspective," in Revisiting the Foundations of Relativistic Physics: Festschrift in Honor of John Stachel, Bd. 234, 2003, p. 281.

[39] V. Perlick, „Gravitational lensing from a spacetime perspective," Living reviews in relativity, Bd. 7, Nr. 1, pp. 1-117, 2004. PDF

[40] H. Minkowski, „Raum und Zeit: Vortrag, gehalten auf der 80. Naturforscher-Versammlung zu Köln am 21. Sept. 1908," in Teubner, 1909. HTML-GER , HTML-ENG

[41] W. Rindler, Relativity: Special, General, and Cosmological, Oxford: Oxford University Press on Demand, 2006.

[42] J. D. Hunter, „Matplotlib: A 2D Graphics Environment," Computing in Science & Engineering, Bd. 9, Nr. 3, pp. 90-95, 2007.

[43] M. Kutschera, „Monopole gravitational waves from relativistic fireballs driving gamma-ray bursts," Monthly Notices of the Royal Astronomical Society, Bd. 345, Nr. 1, pp. L1-L5, 17 Juli 2003. PDF

[44] K. D. Olum, E. Pierce and X. Siemens, „Detectability of gravitational effects of supernova neutrino emission through pulsar timing," Physical Review D, Bd. 88, Nr. 4, p. 043005, 2013. PDF

[45] B. P. Abbott et al., „Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A.," The Astrophysical Journal Letters, Bd. 848, Nr. 2, p. L13, 2017. PDF

[46] S. M. Kopeikin, „The post-Newtonian treatment of the VLBI experiment on September 8, 2002," Physics Letters A, Bd. 312, Nr. 3-4, pp. 147-157, 2003. PDF

[47] S. M. Kopeikin and E. B. Fomalont, „Gravimagnetism, causality, and aberration of gravity in the gravitational light-ray deflection experiments," General Relativity and Gravitation, Bd. 39, Nr. 10, pp. 1583-1624, 2007. PDF

[48] J. A. Wheeler, Geons, Black Holes, and Quantum Foam: A Life in Physics, New York: W W Norton & Co, 1998, p. 235.

[49] GeoGebra_GmbH, „GeoGebra," [Online]. Available: https://www.geogebra.org/.

[50] Wikipedia, „Global Positioning System," [Online]. Available: https://de.wikipedia.org/wiki/Global_Positioning_System.

[51] T. Stratton and S. R. Dolan, „Rainbow scattering of gravitational plane waves by a compact body," Physical Review D, Bd. 100, Nr. 2, p. 024007, 2019. PDF

[52] U. Borgeest and S. Refsdal, „Der Gravitationslinseneffekt," Physikalische Blätter, Bd. 40, Nr. 1, 1984. PDF

[53] R. Kayser and S. Refsdal, „The difference in light travel time between gravitational lens images," Astronomy and Astrophysics, Bd. 128, pp. 156-161, 1983. PDF

[54] M. A. Abramowicz, "Black holes and the centrifugal force paradox," Scientific American, vol. 268, no. 3, pp. 74-81, 1993.PDF

[55] C. Alcock et al., „Possible gravitational microlensing of a star in the Large Magellanic Cloud," nature, Bd. 365, Nr. 6447, pp. 621-623, 1993. PDF

[56] S. Refsdal, „On the possibility of determining Hubble's parameter and the masses of galaxies from the gravitational lens effect.," Monthly Notices of the Royal Astronomical Society, Bd. 128, Nr. 4, pp. 307-310, 1964. PDF

[57] P. Kelly, S. Rodney, T. Treu and M. Jäger, „Caught in the act: Hubble captures first-ever predicted exploding star," 16 12 2015. [Online]. Available: https://www.spacetelescope.org/news/heic1525/.

[58] S. A. Rodney et al., „A gravitationally lensed supernova with an observable two-decade time delay," Nature Astronomy, Bd. 5, Nr. 11, pp. 1118-1125, 2021. PDF

[59] P. E. M. Piña et al., „No need for dark matter: resolved kinematics of the ultra-diffuse galaxy AGC 114905," Monthly Notices of the Royal Astronomical Society, 2021. PDF

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