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TITLE: HYPER-FAST INTERSTELLAR TRAVEL VIA A MODIFICATION OF SPACETIME GEOMETRY

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Hyper–Fast Interstellar Travel via a Modification of Spacetime Geometry

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ABSTRACT:

We analyze difficulties with proposals for hyper–fast interstellar travel via modifying the spacetime geometry, using as illustrations the Alcubierre warp drive and the Krasnikov tube. As it is easy to see, no violations of local causality or any other known physical principles are involved as far as motion of spacecrafts is concerned. However, the generation and support of the appropriate spacetime geometry configurations does create problems, the most significant of which are a violation of the weak energy condition, a violation of local causality, and a violation of the global causality protection. The violation of the chronology protection is the most serious of them as it opens a possibility of time travel. We trace the origin of the difficulties to the classical nature of the gravity field. This strongly indicates that hyper–fast interstellar travel should be transferred to the realm of a fully quantized gravitational theory. We outline an approach to further the research in this direction.

INTRODUCTION:

It is commonly accepted that for an interstellar travel to become of a practical interest and importance one should acquire a capability to complete such a travel within a reasonable interval of time by the clocks of both the traveler and the community remaining on the Earth. In most cases it is the total time of the round trip that one is concerned but, under special circumstances, it might be also the one way time of arrival at a destination.

The troubles with the time of an interstellar travel emerge as the result of an interplay between two major contributing factors, (1) the necessity to cover very large distances to reach even the nearest stars, and (2) the limitation on the maximal speed of a spacecraft imposed by relativity. This speed must be smaller than the speed of light. Equivalently, the world line of the spacecraft must pass inside the local light cone in a neighborhood of each point of this world line.

In Minkowski spacetime (the case of special relativity) the construction of the light cone is global and the distance between the Earth and the star of destination in the frame of reference of the Earth's observer is fixed. Under these conditions the only means to reduce the travel time is to increase the speed of the spacecraft within the limit determined by the null cone. The nature of the limitation on the minimal time of travel in this case is best illustrated by the spacetime diagram (Fig. 1). Points S and R on the world line of the Earth's observer are the events of the start and return of the interstellar expedition, while point A on the world line of the star is the event of the expedition arrival at its destination. The world line of the spacecraft SAR, and with it the the expedition duration for the traveler, can be made as short as desirable by choosing pieces SA and AR sufficiently close to the null cones (moving at a speed sufficiently close to the speed of light with respect to the Earth). Meanwhile, the distance between A and R along the world line AR of the Earth (the duration of the expedition as perceived by Earth's observers) obviously cannot be made less than $2d$, where d is the distance between the Earth and the star of destination in the frame of the Earth.

General relativity opens, at least seemingly, opportunities to circumvent this difficulty. As in the case of special relativity, the speed of the spacecraft is limited by the speed of light, i. e. the world line of the spacecraft should pass inside of the local light cone at each point of the world line. However, the metric and topology of spacetime is not fixed, and presumably can be manipulated. The construction of the null cone is not global in this new setting. The spacetime geometry, and with it the tilt and the opening of the local light cones can be manipulated in a controlled fashion. Such a manipulation allows in some cases to reduce the distance to be covered by the spacecraft, which reduces the time of arrival at the destination as well as the round trip time. In other cases it allows to transform the spacelike separations into the timelike separations, which does not reduce the time of arrival but reduces the round trip time.

It is easy to write down an expression for a spacetime metric that satisfies the basic chronometric requirements of a feasible interstellar flight (cf. the next section for some details and references). Whether such a metric can be generated, supported and controlled in the real physical world without violating the most basic laws of physics, is a different and, perhaps, the most troublesome issue. Whatever the final answer might be, any attempt to analyze the emerging situation demands an expansion of the domain of application of the laws of physics far beyond the conditions for which they were formulated originally.

1. A straightforward computation of the Einstein tensor shows that in all cases gravitational fields corresponding to desirable metrics demand "exotic" matter to be at least a part of their source. Such "exotic" matter violates various commonly accepted energy conditions, including the weak energy condition, which means that it is supposed to have negative energy density. Although the negative energy density is not ruled out by quantum field theory, understanding of its coupling to the gravitational field is incomplete and it shows up sooner than one might expect.

2. In many cases (a good example is the Alcubierre warp drive spacetime) the domain of modified geometry is causally disconnected. This means that the appropriate configuration of the gravitational field cannot be generated, sustained, or controlled as a result of any geometrodynamic evolution unless one has at his disposal tachyonic matter, or some kind of a device capable of emulating tachyonic effects.

3. All known configurations of modified spacetime geometry involved in a hyper–fast travel, when considered in conjunction with the principle of general covariance, invariably lead to a capability of building a time travel machine. Basic theorems characterizing the causal structure of spacetime [Geroch & Horowitz, 1979] tell one that, as a consequence, such spacetime geometry cannot be a result of any geometrodynamic evolution unless there are some means to contribute to the spacetime structure externally (spacetime singularities, appropriate boundary conditions, tachyonic effects, quantum effects, topological effects, etc.).

The recent literature presents quite a few attempts to asses compatibility of the idea of modified spacetime geometry as a means of hyper–fast travel with basic concepts of physics (we will provide a more detailed account and references in subsequent sections). Unfortunately, most of this literature has a tendency to rely on standard theoretical constructions without any modifications or with minimal modifications, frequently without clear understanding of their relations to observations. The results are all too predictable. This approach leads one rather fast and in a relatively trivial fashion to ruling out virtually all particular geometry modification proposals on the ground of their nonphysical nature via seemingly plausible arguments. The arguments are relying heavily on rather involved computations and contain numerous assumptions necessary for their tractability. Some of these assumptions are questionable, others leave one with the impression that they might be circumvented via more sophisticated designs. In brief, the trouble with this direction of thought is that it does not provide an understanding of the common mechanism of the failure.

The arguments of more general nature, less computationally demanding, and appealing to more basic and dependable arguments are scattered in the literature, but have not been systematically used for more balanced assessment of the problems and prospects of the field. In this paper we attempt to do so having as goals (1) to determine the restrictions imposed on modifications of spacetime geometry, (2) to determine the nature and the origin of these restrictions, (3) to formulate the conditions on the mechanism that might circumvent the restriction, and (4) to evaluate possible realizations of such mechanism.

SPACETIME GEOMETRY MODIFICATION AND HYPER–FAST INTERSTELLAR TRAVEL:

There are numerous examples of spacetimes with tilted null cones (where the travel distance is reduced), such as Godel Universe [Godel, 1949], cosmic strings spacetimes [Deser, 't Hooft, 1984], traversable wormhole [Morris & Thorne, 1988], and the recently suggested warp drive spacetime [Alcubierre, 1994]. Although all of these examples are useful for improving our understanding of the related issues, in the context of an interstellar travel achieved by technological means only traversable wormholes and the warp spacetime are of a possible interest as they involve only local modifications of spacetime geometry and topology. The transformation of the spacelike separations into the timelike ones, thus reducing the round trip time, is illustrated by what is frequently called the Krasnikov tube [Krasnikov, 1995; Everett, Roman, 1997]. We are going to use for illustrating the idea of hyper–fast interstellar travel via spacetime geometry modification the two most recent proposals — Alcubierre warp drive and the Krasnikov tube. They utilize two different features of modified spacetime null cones. Other proposals work in a way similar to one of these two and pose the same kind of difficulties in their realization.

Alcubierre Warp Drive Spacetime:

Alcubierre warp drive spacetime is the best studied example of modifying spacetime geometry for the purpose of hyper–fast interstellar travel. The basic idea of the Alcubierre warp drive is to modify the spacetime geometry to the one expressed by the metric (dimensions y and z are omitted as they are irrelevant for an explanation of the basic effect)

$$ds^2 = -dt^2 + (dx - v_s\, f(r_s)\, dt)^2$$

where $r_s = |x - x_s|$, $v_s(t) = dx_s(t)/dt$; and $x_s(t)$ f are arbitrary smooth functions such that $x_s(0) = 0$, $x_s(T) = d$, $f(\xi) = 1$ for $0 \leq \xi < R - \epsilon$, $f(\xi) = 0$ for $\xi \geq R$, while ϵ, T and R are arbitrary positive parameters. If $v_s(t) \equiv 0$ this metric reduces to the Minkowski metric, in which case ($v_s f \equiv 0$) the null cone at all points of spacetime is determined by the left and the right future directed null vectors

$$\mathbf{l} = \partial_t - \partial_x, \qquad \mathbf{r} = \partial_t + \partial_x$$

In the warp drive spacetime, where $v_s f$ changes from point to point of spacetime, the left and the right future directed null vectors are given by

$$\mathbf{l} = \partial_t + (v_s f - 1)\, \partial_x, \qquad \mathbf{r} = \partial_t + (v_s f + 1)\, \partial_x$$

The change of the future null cone is shown pictorially in Fig. 2. One can observe that as $v_s f$ grows the null cone tilts to the right while the opening of the cone narrows down in such a way that some curves that used to be spacelike in Minkowski geometry become timelike and vice versa.

Fig. 3 represents spacetime geometry determined by the warp drive metric which is pictured in t-x coordinates by the world tube of radius R and thickness ϵ with axis given by $x_s(t)$. The spacetime geometry outside the tube is Minkowski geometry. Inside the tube the geometry is also flat but the light cones are tilted with respect to the outside cones. The wall of the tube represents the curved domain of spacetime.

Suppose now that $x_s(t)$ represents the world line of a spacecraft with a device on board that enables it to modify spacetime geometry to that given by the warp drive metric. The spacecraft is then surrounded by the bubble (warp bubble) with the wall containing curved spacetime and moving at a coordinate speed $v_s(t)$. The case $v_s > 1$ would be nonphysical in the original geometry of spacetime for a spaceship constructed of standard matter as its world line would be passing outside the null cone (superluminal motion). However, as it is easy to see in Fig. 3, the ship's warp bubble tilts the null cones inside of it in such a way that the world line of the ship becomes timelike and physically acceptable for any $v_s(t)$, including superluminal. It is clear that the proper time of any Earth's observer coincides with the coordinate time $\tau_e = t$ as the Earth is outside the warp bubble at all times. The expression for the warp drive metric implies that the proper time of the ship also coincides with t. To summarize, the elapsed time of the trip coincides with the coordinate time by the clocks of both Earth and the ship. If the coordinate distance to the star of destination is d then the time of arrival at the destination is

$$\tau_e = \tau_s = \frac{d}{v_s}$$

where v_s is not restricted by the speed of light and can be made as large as it is desirable. This means that the time of arrival at the destination can be made arbitrary short by both the clock of the Earth and the clock of the ship.

We put off temporarily a discussion of difficulties present in the Alcubierre warp drive proposal. Instead, we introduce a different idea which seems to avoid some of them.

Krasnikov Tube:

A modification of spacetime geometry known as Krasnikov tube is, perhaps, the least studied of all proposals. Although it shares some of the difficulties (among them the most serious) with other ideas along the same directions, it avoids some of them. In any case, it is different enough to deserve a brief introduction.

Krasnikov tube idea is based on modifying spacetime geometry to the one determined by the metric

$$ds^2 = -(dt - dx)\,(dt + k(t,x)dx)$$

where $k = 1 - (2-\delta)\,\theta_\epsilon(t-x)\,[\theta_\epsilon(x) - \theta_\epsilon(x+\epsilon-d)]$, and θ_ϵ is a smooth monotonic function, such that $\theta_\epsilon(\xi) = 1$ when $\xi > \epsilon$ and $\theta_\epsilon(\xi) = 01$ when $\xi < 0$, while δ and $\epsilon < d$ are arbitrary small positive parameters. Obviously, in the case $k \equiv 1$ (or, equivalently, $\delta \equiv 2$) the Krasnikov tube metric reduces to the Minkowski metric. The interesting case, however, is that of δ being a small positive number.

The future null cone of such geometry is changing from point to point and is determined at a point by the left and the right future null vectors

$$\mathbf{l} = k\,\partial_t - \partial_x, \qquad \mathbf{r} = \partial_t + \partial_x$$

The change of the future null cone as k is changing from 1 to $-1+\delta$ is depicted in Fig. 4 (the cone tilts to the left and opens wider). One can observe that when $k < 0$ the vector $\mathbf{l}$ shows in the direction of decreasing value of t.

The Krasnikov tube metric subdivides spacetime in three regions (cf. Fig. 5). The first one is the outside region $\{x < 0\} \cup \{x > d\} \cup \{x > t\}$. The metric in it is the Minkowski metric ($k = 1$). Future light cones in the region are determined by null vectors $\mathbf{l}_O = \partial_t - \partial_x$ and $\mathbf{r}_O = \partial_t + \partial_x$. The second region is shaded in Fig. 5. Spacetme is curved in it. The third region $\{x < t - \epsilon\} \cap \{\epsilon < x < d - \epsilon\}$ is flat ($k = \delta - 1$). The future light cones in it are determined by null vectors $\mathbf{l}_I = -(1-\delta)\,\partial_t - \partial_x$ and $\mathbf{r}_I = \partial_t + \partial_x$. The cones are open wider than in the outside region to such an extent that along some future directed timelike curves coordinate t is decreasing (the curves go back in coordinate time).

A hyper-fast interstellar travel utilizing the Krasnikov tube is best illustrated by spacetime diagram (Fig. 5). The spacecraft is moving from Earth to the destination star along the timelike world line SA in the outside region. The arrival time by the clock of the spacecraft can be made small if the line SA is close to the null cone (i. e. the speed of the ship with respect to Earth is close to the speed of light). The time of arrival by the Earth clock (pictured by SA' cannot be made smaller than d and is very large. However, the ship carries on board a device that changes the spacetime metric during its flight to the destination forming the Krasnikov tube metric. On the way back the ship is moving along the world line AR which is future directed in the modified metric but carries the ship back in coordinate time (which coincides with the proper time of the Earth). Thus it becomes possible to complete the round trip for a short interval of time by both ship's and Earth's clocks.

DIFFICULTIES OF MODIFYING THE SPACETIME GEOMETRY:

It is clear that hyper-fast interstellar travel utilizing modified spacetime geometry does not involve any violations of local causality or any other known physical principles as far as motion of spacecrafts is concerned. However, the generation and support of modified spacetime geometries (such as the Alcubierre warp bubble and the Krasnikov tube) does create problems, the most significant of which are a violation of the weak energy condition and a violation of the causality protection.

Exotic Matter:

A straightforward computation of Einstein tensor and the energy-momentum tensor for Alcubierre and Krasnikov metrics shows that the regions of curved spacetime in both cases are filled with matter. In the case of the Alcubierre warp bubble the matter is supposed to have the negative energy density everywhere in the wall of the bubble (of the external radius R and thickness ϵ) [Alcubierre, 1994; Pfenning & Ford, 1997]. In the case of the Krasnikov tube the expression for the energy-momentum density is more complicated and its evaluation is possible only for a particular choice of the function k [Everett & Roman, 1997]. However, any reasonable choice of this function (smooth and monotonically decreasing in of the wall from 1 on the outside to $-1+\delta$ on the inside, yields qualitatively the same picture. The energy density must be negative near the inner side of the wall and positive on the outer side of it. In any case, the source of the gravity field modifying the spacetime geometry in a desirable fashion always contains, at least partially, matter with a negative energy density, which is often called exotic matter. In other words, the weak energy condition is violated.

Violation of the weak energy condition is ordinarily considered inadmissible in the classical theory, and with good reasons. In brief, existence of negative masses produces effects that do not contradict basic laws of physics but never have been observed in reality. However, quantum fields are commonly thought to be capable of violating the weak energy condition. The violation of the weak energy condition is restricted by the quantum inequality [Ford & Roman, 1996]. The inequality implies that the larger is the average negative energy over a sampling interval of time the shorter must be the duration of this interval. Application of the inequality in conditions generated by the modified geometries has been recently used to estimate the amount of negative energy required to produce the modifications such as the Alcubierre warp drive [Pfenning & Ford, 1997], the Krasnikov tube [Everett & Roman, 1997], and Morris-Thorne traversable wormholes [Ford & Roman, 1996]. The results are discouraging and similar in all the cases, as they yield absolutely nonphysical orders of magnitude for the energy. To illustrate the situation it is enough to say that to make a Krasnikov tube 1 meter long and 1 meter wide the energy required is of the order of 10^{16} galactic masses.

The significance of these results should not be overestimated. They are based on the quantum inequality the validity of which has been established originally in flat spacetimes, and later in the quantum field theory on a curved background. This means that they neglect the back reaction of quantum matter fields on the gravity field (treated classically). There are examples of modified spacetime geometry where the quantum inequality is violated. Among them are "critical" wormholes [Krasnikov, 1994: Yurtsever, 1991] and Misner space with massless scalar field in the conformal vacuum state [Krasnikov, 1996]. The point, however, is that the relevance of the estimates is dubious in the context of spacetime geometry modifications. Essentially, the restrictions are applicable only to exotic matter that does not modify spacetime geometry.

In order to make relevant estimates it is necessary to use a theory taking into account full coupling between the gravitational field and matter fields. The standard procedure of coupling quantum fields to gravity through the regularized expectation value of the energy-momentum tensor is unlikely to provide dependable results for exotic quantum matter. What one really needs is a procedure of coupling the quantum gravity field with quantum matter fields. Unfortunately, such a procedure has not been developed in general case. Our proposal would be to develop it for the cases of particular modified spacetime geometries.

Violations of causality and chronology protection:

The idea of hyper-fast travel via spacetime geometry modification encounters obstacles of a more serious nature. The first one can be observed in the Alcubierre warp drive if the gravity field is assumed to be generated, supported and controlled from the ship. It is easy to see (Fig. 3) that the the world line of the front of the bubble passes everywhere outside of local null cones (moving at a superluminal speed) if $v_s > 1$. The depth of the layer moving superluminally is determined by the condition $v_s f < 1$. The energy density of matter filling this layer is nonzero. This means that the layer either should consist of tachyonic matter, or be replenished all the time from the ship which also requires tachyons. This conclusion is usually taken harder than it should be. Nontrivial and positive part of it is that if there were tachyons the ship that itself consists of nontachyonic matter could be moved superluminally. Besides, absence of tachyons (i.e. fields violating local causality) does not mean by itself that a local object cannot act on events off its causal future. In particular, the metric itself can, in some cases, act as a tachyon field [Krasnikov, 1995]. Simpler yet, one can place automatic devices along the route well before the time of the expedition and program them to emulate a desirable tachyonic effect. The natural name for such an arrangement could be the jump gate. It is easy to see that none of these issues show up in Krasnikov tube, which is the main reason why it has been introduced.

The second and the most serious obstacle is that all known configurations of modified spacetime geometry involved in a hyper-fast travel make it possible to build geometries with timelike closed curves (time travel). Fig. 6 shows how it can be done with Alcubierre warp drive and Krasnikov tube. According to basic theorems characterizing the causal structure of spacetime [Geroch & Horowitz, 1979] such spacetime geometry cannot be a result of any geometrodynamic evolution (chronology protection violation). The situation could change if there were some means to contribute to the spacetime structure externally (spacetime singularities, appropriate boundary conditions, tachyonic effects, quantum effects, topological effects, etc.), which would amount to an evolution with the initial conditions changing during the evolution.

This is an exciting and unresolved problem in general relativity [Krasnikov, 1996]. We do not go into details here because we do not feel at this time that the time travel should survive in the final account. The important point is that in the classical theory any attempt to introduce varying conditions resulting in globally superluminal phenomena unavoidably leads to time travel. The reason for that is general covariance of the theory, in particular its slicing independence. This feature does not survive in quantum gravity. The general covariance is broken. The Schrödinger equation and constraints are attached to one slicing [Kheyfets & Miller, 1996], the slicing being determined, roughly speaking, by quantum "ether". The varying conditions and related superluminal effects in expectation values are caused by this quantum gravitational vacuum and take place only in this slicing. This means that superluminal phenomena might survive while the time travel does not. All of this is possible only in a truly quantum gravitational system differing in essential way from the one with the state functional expressed by a Gaussian centered at a classical solution [Kheyfets & Miller, 1995].

CONCLUSION:

Our review and analysis of the current state of the theory concerning hyper-fast interstellar travel via modifications of spacetime geometry based on general relativity leads us to the following conclusions:

1. No violations of local causality or any other known physical principles are involved for as far as hyper-fast motion of spacecrafts in spacetimes with modified geometries is concerned.
2. Generation, sustaining and control of gravitational fields modifying spacetime geometry presents several problems.
   a) A necessity to use as sources of gravity fields matter with negative energy density.

      Up to day analysis of this problem, including the quantitative estimates, cannot be considered as satisfactory. It essentially neglects the back reaction of quantum matter fields on the gravity field and downplays possible gravitational effects. Better understanding of coupling between quantum matter fields and the gravity field is needed to improve the situation. It is our opinion that analysis of the problem in quantum gravity might be crucial.

   b) Violation of local causality in some modified spacetime configurations.

      Some modified spacetimes (cf. Alcubierre warp drive) require tachyonic effects for their generation, sustaining and control. The issue has been investigated only partially. Better understanding of tachyon–like effects produced by gravity fields is necessary. It is conceivable that such effects, especially when they are of quantum origin, will not lead to contradictions with observations.

c) Chronology protection violation.

All spacetime geometry modifications, when considered within classical general relativity, allow to design spacetimes containing closed timelike curves (time travel). The fact that such spacetimes cannot be produced as a result of causal geometrodynamic evolution, in our (as well as some other authors) opinion still does not rule them out as there are means to interfere with this evolution (one of the simplest ideas is the jump gate). The source of the time travel effect invariably associated with hyper–fast travel is the general covariance of the classical theory of gravity. Only quantum gravity, where the general covariance is broken for essentially quantum states, there is a hope to have hyper–fast travel without time travel.

It appears that only quantum gravity is in principle capable to give a key to a possibility of hyper–fast travel free of the difficulties encountered in classical general relativity. Accordingly, we suggest to undertake an investigation in quantum gravity having the following goals:

1. To design quantum gravitational configurations resulting in modification of an expectation value space-time geometry suitable for hyper–fast interstellar travel yet excluding time travel;
2. To investigate the configuration of the source of the gravity field necessary to generate, support and control such a modified geometry.
3. To investigate coupling between quantum gravity and quantum matter fields having as a goal to estimate possible contribution of gravitational effects towards forming modified geometries.
4. In particular, to investigate a possible contribution of quantum gravitational effect to tachyon–like phenomena and to the effects similar in their nature to these produced by the negative energy density matter.

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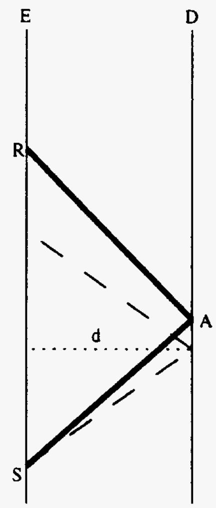

Fig. 1. Interstellar travel in Minkowski spacetime.

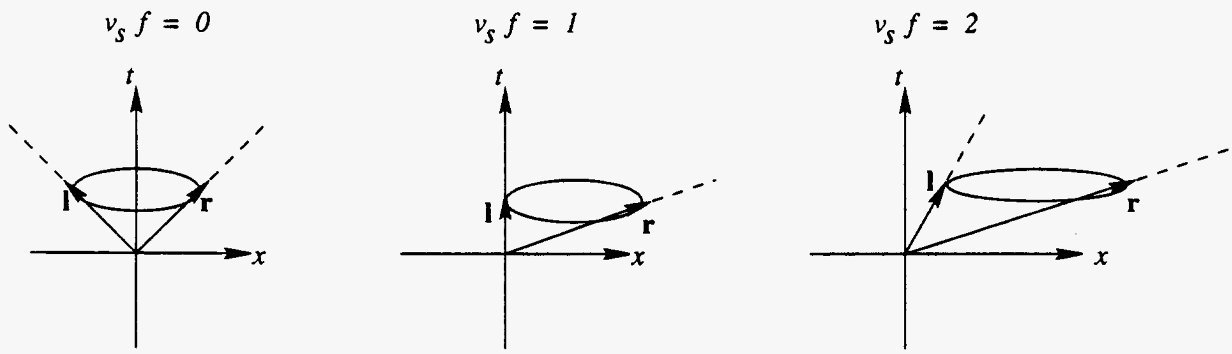

Fig. 2. Light cones in Alcubierre warp drive spacetime for different values of $v_s f$.

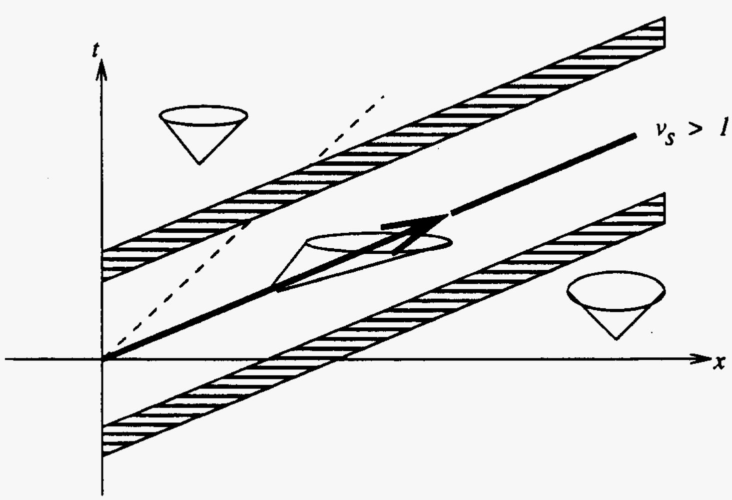

Fig. 3. A hyper-fast ("superluminal") Alcubierre warp bubble.

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