A Conjecture
On the Microscopic Details of Space and Gravity

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Abstract

A Planck-scale model for the microscopic degrees of freedom of space is derived. The model, based on a specific realization of qubits, allows deducing all properties of black holes and the field equations of general relativity. No additions or modifications occur at sub-galactic scales. An extensive list of experimental tests is derived. All agree with data.

The conjectured model implies a maximum mass flow $c^3/4G$, a maximum momentum flow $c^4/4G$, and a maximum luminosity $c^5/4G$ in all processes in nature. These limits, corresponding to about 50 000 solar masses per second, are not exceeded by any known physical or astrophysical process.

The conjectured model also allows visualizing quantum gravity effects, reformulating mathematical problems of general relativity, and deriving limits for elementary particle masses. No contradictions with observations arise. Calculating elementary particle masses appears to be within reach.

Keywords: strand conjecture, general relativity, quantum gravity.

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1 The quest for the origin of space and gravity

The nature of space and gravity remains a matter of intense research. It requires understanding the microscopic degrees of freedom of black holes, the microscopic nature of the vacuum, and the microscopic details of curvature.

The so-called *strand conjecture* proposes a microscopic model for black holes, particles, space and gravity. In order to show that strands are candidates for a unified description of nature, it is necessary – but not sufficient – to show that strands *reproduce* space, curvature and gravitation in all its macroscopic and microscopic aspects. In addition, it is necessary to show that strands provide *more* results about gravitation than the usual description of space using points. Predictions should be as numerous as possible and proposed tests as strict as possible. This is the aim of the present paper.

The strand conjecture uses a single fundamental principle that describes nature at the Planck scale. The model is based on qubits, includes quantum theory, and agrees with all observations about gravitation at sub-galactic scales. Strands also provide several hints for calculating elementary particle masses.

2 The origin of the strand conjecture

When Max Planck discovered the quantum of action $\hbar$ in 1899, he found the underlying quantity that explains the observation of all quantum effects in nature [1]. Bohr described quantum theory as consequence of the minimum observable action value $\hbar$ [2]. Heisenberg introduced the canonical commutation relation and Schrödinger introduced the wave function. Pauli included spin and Dirac the maximum energy speed c. From around 1929 onwards, Dirac regularly mentioned the so-called *string trick* or *belt trick* in his lectures. The trick assumes that particles are connected to spatial infinity by tethers that are unobservable, but whose crossings are observable. With help of the trick, Dirac used to describe spin 1/2 behaviour as result of tethered rotation. Nevertheless, he never published anything about this connection. Answering a letter from Gardner, Dirac wrote that the trick demonstrates that angular momenta below $\hbar/2$ are not possible in nature [3].

Historically, tethers were the first hint that nature might be built from unobservable extended constituents. It took several decades to understand that also the complete Dirac equation could be deduced from unobservable tethers. This was first achieved by Battey-Pratt and Racey in 1980 [4]. Independently, in 1987, Kauffman conjectured a direct relation between the canonical commutation relation – and thus Planck's constant $\hbar$ – and a crossing switch of tethers [5]. Again, without stating so explicitly, the assumption was that tethers are unobservable, whereas their crossings are. In the early twenty-first century, independently of the work by Battey-Pratt and Racey and of that by Kauffman, the string trick again led to the discovery of the relation between crossing switches of unobservable tethers, $\hbar$, wave functions, and the Dirac equation [6]. It thus appeared that *every quantum effect* can be thought as being due to unobservable extended constituents.

Because the term 'string' had acquired a different meaning in the meantime, and because the term 'tether' does not describe the full scope of the involved extended constituents, the alternative term *strand* appeared more appropriate.

A question arises naturally: can unobservable strands also explain gravity? The finite value of black hole entropy [7, 8] and its surface dependence provided first hints. Indeed, it turns out that both the properties of black holes and Einstein's field equations can be deduced from crossing switches of unobservable strands [6]. It thus appeared that *every gravitational effect* can be thought as being due to unobservable extended constituents.

The strand conjecture is also related to the growing interest in qubits: a skew crossing of two strands provides a simple implementation of a qubit [6]. Describing all of nature with strands is thus equivalent to describing all of nature with qubits.

The strand conjecture for fundamental physics appears promising also from another perspective. The central parts of quantum field theory can be summarized by the (modified) statements that all observable action values W obey $W \geq \hbar/2$ and that all observable energy speeds v obey $v \leq c$. General relativity can be summarized by the statement that all observable power values P obey $P \leq c^5/4G$ [9, 10, 11, 12]. These three limit statements based on Planck units imply several consequences. First, all Planck units are invariant and universal limits that encode fundamental aspects of nature. Second, all equations of motion, starting with Dirac's equation and Einstein's field equations, follow from the Planck units [13]. Third, at Plank scales, physics is fundamentally simple, being described by limit statements. Finally, at Plank scales, a description of nature that makes use of only algebra and combinatorics appears possible. In other words, the Planck units suggest the possibility of a complete and unified description of motion with little mathematics. All these consequences are realized by the strand description of nature [6]. In the domain of gravitation, strands allow deducing numerous experimental tests, and a few new results.

3 The strand conjecture

The strand conjecture states: the physical systems found in nature – matter, radiation, space and horizons – are made of strands that fluctuate at the Planck scale but remain unobservable. More precisely, the strand conjecture can be formulated in the following way:

> Space is a *network* of strands. Horizons are *weaves* of strands. Particles are *tangles* of strands. Strands are unobservable. However, crossing switches of skew strands are observable. Crossing switches determine the Planck units G, c and $\hbar$, as illustrated in Figure 1.

Apart from their crossings in space, strands have no observable properties. Strands have no colour, no tension, no mass, no energy. Strands just are. It is easiest to imagine strands as having Planck-size radius. Strands cannot interpenetrate. They *never* form an actual crossing. When the term 'crossing' is used in the present context, only the two-dimensional projection shows a crossing. In three dimensions, strands are *always at a distance*. In particular, crossing *switches* cannot arise through strand interpenetration, but only via strand deformation.

In the strand conjecture, all physical observables – action, momentum, energy, mass, velocity, length, surface, volume, tension, entropy, field intensities, quantum numbers, etc. – arise from combinations of crossing switches. In more fashionable wording: all physical observables *emerge* from strand crossings. Or: all observables are due to qubits.

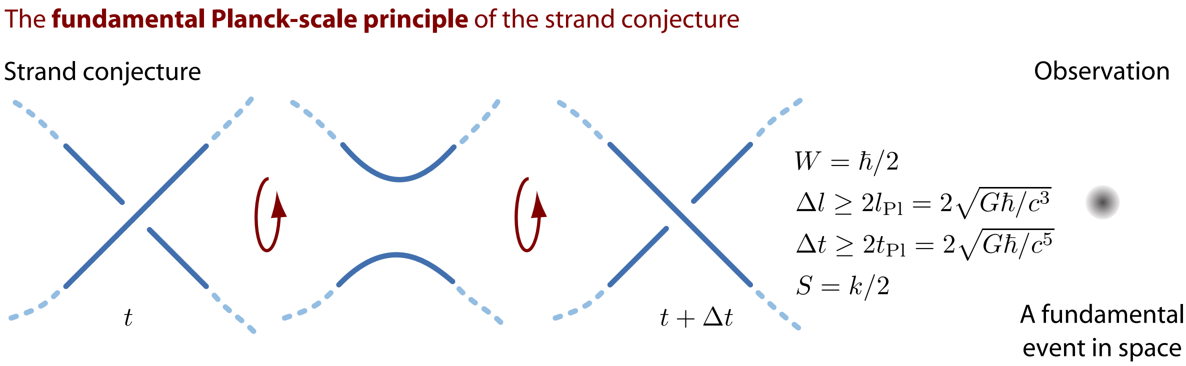

Figure 1: The fundamental principle of the strand conjecture specifies the simplest observation possible in nature: the almost point-like fundamental event results from a *skew strand switch*, or *crossing switch*, at a position in three-dimensional space. The strands themselves are not observable. They are impenetrable and are best imagined as having Planck size radius. The switch defines the action unit $\hbar/2$. The double Planck length limit and the double Planck time limit arise, respectively, from the smallest and from the fastest crossing switch possible. A skew strand crossing is a specific realization of a qubit.

The following sections first discuss the circularity of the fundamental principle and then summarize how crossing switches of fluctuating strands produce quantum theory. After that, the implications, consequences and predictions of crossing switches in the domain of gravitation are explored.

4 The circularity of the fundamental principle

On the one hand, the crossing switch of Figure 1 is assumed to take place in space. On the other hand, space, distances and physical observables are assumed to arise from strands. The apparent circularity can be avoided – to a large degree, but not completely – by increasing the precision of the formulation.

Crossing switches take place in *background space*. In contrast, *physical space*, physical distances and physical observables arise from strands and their crossing switches. When space is flat, background space and physical space coincide. Otherwise, they do not; in that case, background space is (usually) the local tangent space of physical space. A similar situation arises for the concept of time.

The strand conjecture asserts that a description of nature *without* a background space and time is impossible. Any observation of a *change* implies the use of (background) time; any observation of *difference* between objects or systems implies the use of separation in (background) space. Observations, comparisons and measurements require background space. It is impossible to define crossing switches, qubits, or Planck units without a background. In fact, a local background space – usually observer-dependent – is *required* to describe *any* observation, or simply, to talk about nature.

Every use of the term 'observation' or 'observable' or 'physical' implies and requires the use of a background space and time. All the illustrations of this paper are drawn in background space. Physical space – an observable in general relativity – then arises through crossing switches of strands. The local background space agrees with physical space only locally, where the crossing switches being explored are taking place. The need for a background space is rooted in a deeper issue.

An axiomatic description of nature is *impossible*. The reason is the contrast between *nature* and its precise *description*. The properties of a precise description of nature and the properties of nature itself *differ* and *contradict* each other. A precise description of nature requires axioms, sets, elements, functions, and in particular space, time, and points in space and time. In contrast, due to the uncertainty relations, at the Planck scale, nature itself does not provide the possibility to define points in space or time; in fact, space and time are emergent. Due to the uncertainty relations, neither sets, nor elements, nor axioms appear to exist in nature at the most fundamental level.

Because of the impossibility of an axiomatic description, any description of nature requires a limited degree of *circularity*. In particular, any description requires a limited degree of circularity in its definition of time and space. By its use of background space, the strand conjecture thus emphasizes that a fully axiomatic description of nature is impossible. Publications making the opposite claim are not found in the literature so far, even though Hilbert asked for an axiomatic description of physics in his famous sixth problem. Axiomatic descriptions are only possible for parts of physics – such as quantum theory, or electrodynamics, or special relativity – but not for physics as a whole.

To resolve the contrast between nature and its description, a certain limited circularity is *unavoidable* in fundamental physics. Such a limited circularity is built into the fundamental principle. Indeed, strands reproduce the basic circularity of fundamental physics: space is defined with the help of particles – for example, via *rulers* made of matter – and particles are defined with the help of space – for example, via energy and spin that are *localized* in three dimensions. Despite this circularity, a description of nature with the help of strands is possible: physical space and gravitation can be seen to arise from strands fluctuating in a background space; and quantum theory arises once (flat) physical space is defined.

Due to the use of background space, the strand conjecture *cannot* be tested by asking whether it is an *axiomatic* description of nature; it is not. No unified description of nature can be axiomatic. A unified description of nature must be circular. However, the strand conjecture *can* be tested by asking whether it is a *consistent*, *complete* and *correct* description of nature; so far, this appears to be the case [6].

An example for the difference between an axiomatic description and a consistent, complete and correct description is the dimensionality of space. The number of dimensions of (background and physical) space is not a consequence of the fundamental principle or of some axiom; the number of dimensions is assumed in the fundamental principle right from the start. Only three dimensions allow a description of nature that is consistent, complete, and correct: only three dimensions allow crossing switches, allow particle tangles, allow spin 1/2, allow Dirac's equation, and allow Einstein's field equations.

5 From strands to quantum theory

This section provides a short summary of references [6] and [13], which explain how quantum theory and quantum field theory are deduced from strands.

Starting from the fundamental principle and Dirac's belt trick, one finds that *tangles* of fluctuating strands in flat (physical) space describe particles and wave functions: The wave function of a particle is

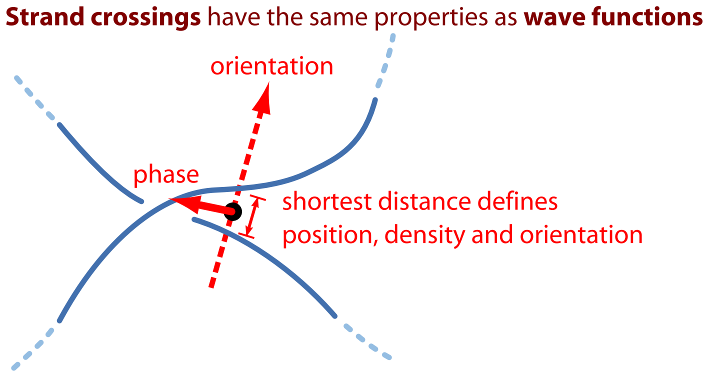

Figure 2: A configuration of two skew strands, called a *strand crossing* in the present context, allows defining density, orientation, position, and a phase, the same properties that characterize a wave function. The freedom in the definition of phase is at the origin of the choice of gauge – for each gauge interaction. For a full tangle, the density, the phase, and the two (spin) orientation angles define, *after spatial averaging,* the two components of the Dirac wave function Ψ of the particle and, for the mirror tangle, the two components of the antiparticle.

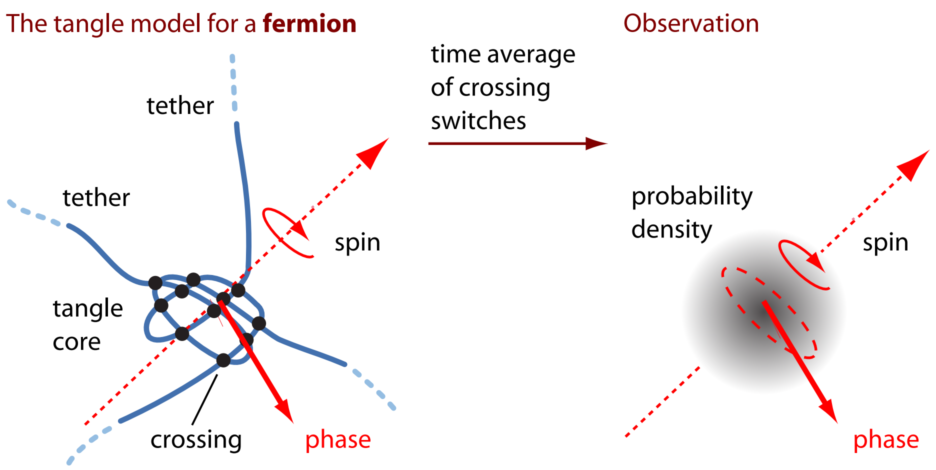

Figure 3: In the strand conjecture, the wave function and the probability density are due, respectively, to crossings and to crossing switches at the Planck scale. The wave function arises as time average of crossings in fluctuating tangled strands; a Hilbert space also arises. The probability density arises as time average of the crossing switches in a tangle. The *tethers* – strands that continue up to large spatial distances – generate spin 1/2 behaviour under rotations and fermion behaviour under particle exchange. The tangle model also ensures that fermions are massive and move slower than light.

the *strand crossing density* of its fluctuating tangle. In other words, wave functions arise as *local time averages* of strand crossings. More specifically, to get the value of the wave function at a certain position in space, the local time average of the strand crossings at that position is taken, over a time scale of (at least) a few Planck times. In this way, a density and a phase can be defined, for each 'position' in space. As usual for quantum theory, also in the strand conjecture physical space and time have to be defined before defining the concept of wave function.

The probability density for a particle is the *switch density* of its fluctuating tangle. Probability densities thus arise as local time averages of strand crossing *switches*.

When the discussion is limited to fluctuating tangles that are *rational*, i.e., unknotted, strands produce a Hilbert space, the quantum phase, interference, and freedom in the definition of the absolute phase value. Rational tangles allow defining antiparticles as mirror tangles. Fluctuating rational tangles made of two or more strands imply spin 1/2 behaviour under rotation and, above all, Dirac's equation. The tangle model for quantum particles is illustrated in Figure 2 and Figure 3. For systems of several particles, tangles reproduce fermion behaviour and entanglement. Strands are fully equivalent to textbook quantum theory and predict the lack of any extension or deviation. No new physics arises in the domain of quantum theory. Strands thus only *visualize* quantum theory; they do not modify it. The visualization can be expressed by saying that every quantum effect is due to crossing switches – and vice versa. The visualization of quantum effects with strands requires that strands remain unobservable in principle, whereas their crossing switches are observable. References [6] and [13] show in more detail how to deduce quantum theory and quantum field theory from strands.

Exploring all possible tangles, it appears that rational, i.e., unknotted tangles reproduce the known spectrum of elementary particles and their properties [6]. Every massive elementary particle is represented by an infinite family of rational tangles made of two or three strands. The family members differ among them only by the number of attached braids. Three generations for quarks and for leptons arise, as well as a massive W, Z and Higgs. The Higgs itself is represented by a braid.

Models for the massless bosons also arise. In particular, a photon is a twisted strand. Photons are emitted or absorbed by chiral tangles, i.e., by fermion tangles that are electrically charged. Figure 4 illustrates the strand model for quantum electrodynamics. Only three kinds of massless bosons arise, and their generator algebras correspond to the symmetry algebras of the three gauge interactions [6].

Rational tangles also promise to explain the values of the inertial mass of particles: inertial mass is related to the *complexity* of the tangle core. More complex tangles have higher masses than less complex tangles. The predicted mass sequences agree with observations – with one exception that can be explained with another effect [6].

In short, any deviation from the standard model would falsify the strand conjecture. This terse summary of quantum theory allows proceeding to the exploration of space and gravity.

6 From strands to space

In the strand conjecture, *tangles* of fluctuating strands define particles and explain their quantum behaviour. In contrast, a *network* of fluctuating strands is conjectured to yield (physical) space. The net-

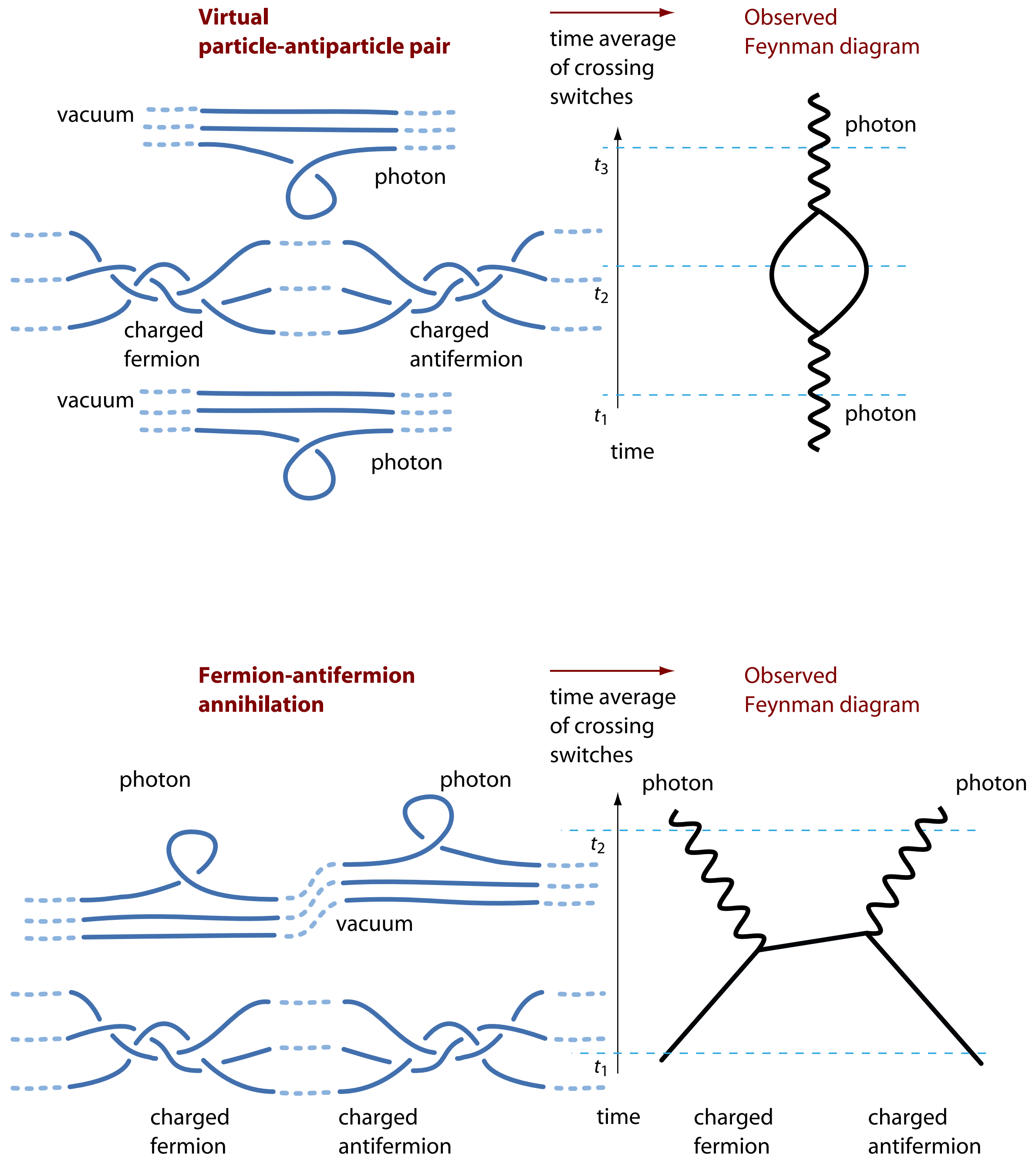

Figure 4: An illustration of two Feynman diagrams of QED in the tangle model.

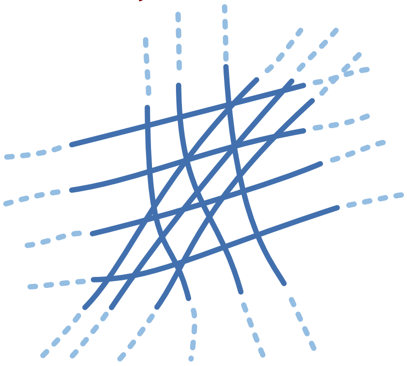

Figure 5: A simplified and idealized illustration of the strand conjecture for a flat vacuum. For sufficiently long time scales, the lack of crossing switches leads to a vanishing energy density; for short time scales, particle–antiparticle pairs, i.e., rational tangle–antitangle pairs, arise.

work is illustrated in Figure 5. In particular, a network of *untangled* strands models *empty, flat* (physical) space. The time-average of the fluctuations, on a scale of a few Planck times, yields three-dimensional (physical) space, including its continuity, homogeneity, isotropy and Lorentz-invariance. On sufficiently long time scales, there are (on average) *no* crossing switches, and thus neither matter nor energy – just empty space. Strands thus predict that *no deviation* from the continuity, homogeneity, isotropy, dimensionality and Lorentz-invariance of (physical) flat space can be observed – at any energy – *despite* the existence of a smallest length $2\sqrt{G\hbar/c^3}$.

Strands imply that in contrast to the highest speed, to the smallest action and to the highest force, *the smallest length cannot be observed.* Indeed, no physical system can realize the smallest length. In contrast, light, atoms and black holes do realize c, $\hbar$ and $c^4/4G$. To measure the smallest length, a single strand would have to be observed, which is impossible. For the same reason, also the smallest time interval $2\sqrt{G\hbar/c^5}$ cannot be observed. It seems that the simplest experimental way to get *near* to the smallest length is to determine the electric dipole moment of elementary particles.

In summary, vacuum is conjectured to be a consequence of fluctuating strands. Strands provide the microscopic details of space in the network of the vacuum. In contrast to other proposals, the strand conjecture implies that space has the *same* number of dimensions and the *same* topology at Planck scales and at macroscopic scales. The strand network model of the vacuum thus contrasts with the usual idea of quantum foam. In the absence of gravity, flat space-time thus arises at all scales and energies, down to Planck scales. Nothing surprising or unusual is predicted to occur up to Planck energy. So far, these predictions agree with observations and with expectations [14]. Any evidence for the contrary would falsify the strand conjecture.

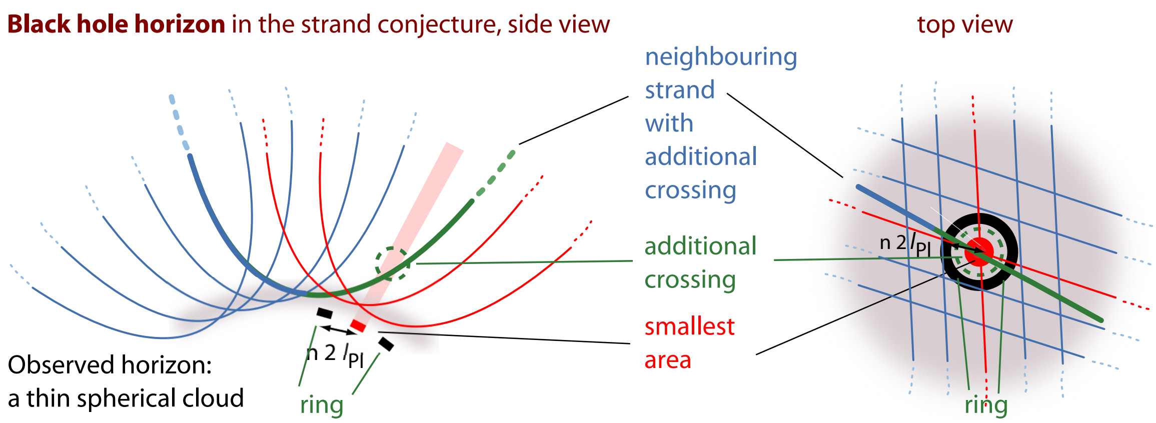

Figure 6: The strand conjecture for a Schwarzschild black hole: the horizon is a cloudy or fuzzy surface produced by the crossing switches of the strands woven into it. Due to the additional crossings on the side of the observer, the number of micro-states per smallest area is larger than 2.

7 From strands to horizons and black holes

In the strand conjecture, *woven* fluctuating strands define horizons and explain their behaviour, properties and spectrum. In particular, woven strands imply black hole thermodynamics in a simple way, as shown in this section. In simple terms, the strand conjecture posits that

> Horizons are one-sided, tight *weaves*.

In this statement, *one-sided* means that all strands leave the horizon on the side of the observer. A schematic illustration of a Schwarzschild black hole, both as a cross section and as a top view, is given in Figure 6. For a black hole, and for any other horizon, all strands come in from far away, are *woven* into the horizon, and leave again to far away. If strands are imagined as having Planck radius, the weave of strands forming a horizon is as *tight* as possible.

The strand conjecture for horizons allows to determine the *energy* of a spherical horizon. Energy E has the dimension action per time. Because every crossing switch is associated with an action $\hbar$, the horizon energy is found by determining the number $N_{\rm cs}$ of crossing switches per unit time. In a horizon, crossing switches propagate from one crossing to the next, over the whole tight weave. Since the horizon weave is tight, the propagation speed is one smallest crossing per shortest switch time: switch propagation thus occurs at the speed of light c. In the time T that light would take to circumnavigate a spherical (non-rotating) horizon of radius R, all crossings of the horizon switch. This yields:

$$E = \frac{N_{\rm cs}}{T} = \frac{c^4}{4G}\,\frac{4\pi R^2}{2\pi R} = \frac{c^4}{2G}\,R \quad . \tag{1}$$

Strands thus reproduce the relation between energy (or mass) and radius of a Schwarzschild black hole.

Strands also determine the number of micro-states per horizon area. Figure 6 shows that for each smallest area on the horizon, i.e., for each area that contains just one strand crossing, the effective number N of possible micro-states *above* that smallest area turns out to be larger than 2. This excess occurs because of the neighbouring strands that sometimes cross *above* that smallest area. The crossing probability above the smallest area depends on the distance at which the neighbouring strand leaves the horizon; this yields

$$N = 2 + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + ... + \frac{1}{n!} + ... = \mathrm{e} = 2.718281... \tag{2}$$

In this expression, the term 2 is due to the two options at the very bottom of the minimal surface; the term $1/2!$ arises from the neighbouring ring shown in Figure 6; and the following terms are due to the subsequent rings. Expression (2) yields the entropy of the horizon. The resulting value S of the horizon *entropy* is related to the black hole surface A as

$$\frac{S}{k} = \frac{A}{4\,G\hbar/c^3} \ , \tag{3}$$

where k is the Boltzmann constant. This is the expression discovered by Bekenstein [7]. In the strand conjecture, the finiteness of the entropy is thus due to the *discreteness* of the microscopic degrees of freedom. The surface dependence of the entropy and the factor $1/4$ – including the lack of factors like $\ln 2$ – are due to the *extension* of the microscopic degrees of freedom. As Figure 6 illustrates, strands also imply that horizon entropy is located at and slightly above the horizon. This agrees with expectations.

The strand conjecture for a spherical horizon leads to poles and thus to an axis. For a spherical horizon, the axis can point into different directions and the horizon sphere can have different orientations around the axis. These possibilities yield a logarithmic correction to the black hole entropy

$$\frac{\Delta S}{k} = -\frac{3}{2}\,\ln \frac{A}{4G\hbar/c^3} \ . \tag{4}$$

In the strand conjecture, the logarithmic correction thus has a simple geometric origin. However, the value is much too small to be tested in experiments.

In short, strands appear to imply the energy and the entropy of spherical black holes. In addition, the ratio of the two quantities determines the *temperature* of black holes. The result is

$$T_{\mathrm{BH}} = \frac{\hbar c}{4\pi k}\,\frac{1}{R} \ . \tag{5}$$

For example, the temperature implies that black holes radiate. Strands also reproduce the negative specific heat of black holes. As a consequence, strands reproduce black hole *evaporation:* radiation and evaporation are due to strands detaching from the horizon. If a single strand detaches, a photon is emitted. If a tangle of two or three strands detaches, a massive particle is emitted. When all strands have detached, the complete black hole has evaporated.

In summary, strands thus reproduce all thermodynamic properties of black holes.

8 Predictions about black holes

- Strands imply that the thermodynamic relations can be generalized to *any* horizon. The relations can be extended to rotating black holes, to charged black holes, and to horizons of irregular shapes.

- Quantum theory, and also strands, imply that not only horizons, but also every curved vacuum region has temperature. The simplest imaginable case is that of a locally accelerated observer of negligible mass in flat space. The local vacuum temperature T observed by an observer undergoing acceleration a is given by the *Fulling–Davies–Unruh effect*

$$T = \frac{\hbar}{2\pi\, kc}\, a \quad . \tag{6}$$

  The expression is equivalent to the expression for black hole temperature; it appears after inserting the relativistic acceleration-length limit $L = c^2/a = 2R$ for accelerating systems. Again, it is not clear whether the Fulling–Davies–Unruh effect can ever be observed. In any case, the expression agrees with all calculations performed so far. In contrast to an accelerating observer, an inertial observer in infinite flat space measures a vanishing vacuum temperature.

- Black holes evaporate. Just before the completion of the evaporation process, black holes still radiate with a luminosity near but below the maximum possible value, the Planck power $c^5/4G$. Before the final evaporation step, black holes radiate with much smaller luminosity.

- The strand conjecture for black holes confirms and visualizes a result by Zurek and Thorne from the 1980s: the entropy of a black hole is the logarithm of the number of ways in which it could have been made [15].

- The strand conjecture and its statistical effects also imply that white holes do not exist.

- Strands confirm that every horizon is a physical system that on the one hand can be seen as an extreme form of (curved) space, and on the other hand can be described an extreme form of matter. Both points of view lead to tight, one-sided weaves as models for horizons.

- The strand conjecture automatically implies that the horizon area of a small black hole is *quantized* in multiples of the smallest area $4G\hbar/c^3$. This implication has been already deduced in the past [16]. However, strands also imply that area quantization of black holes is not observable directly, because in principle, no apparatus can have the sensitivity to detect this smallest area value. Such an apparatus would have to be able to count and thus observe strands.

- Strands imply that horizons are not surfaces, but thin cloudy volumes. Strands thus imply that black hole horizons resemble stretched horizons.

- Together with the strand description of black hole evaporation, strands also illustrate the lack of black holes with microscopic mass values. The Planck limits for energy density, size, temperature and luminosity imply that black holes have a mass that is larger than the Planck mass. The weave model of horizons also implies that elementary particles, which are tangles and not weaves, are *not* black holes.

- Being weaves, black holes have *no hair*, i.e., no nuclear charges, no baryon number, no lepton number or other quantum numbers. In a previous paper [6] it became clear that all these quantum numbers are only defined for tangles; these quantum numbers do not make sense for weaves. The *no-hair theorem* is thus natural in the strand conjecture.

- Strands also imply that the horizon entropy, the horizon energy and the horizon temperature are *limit values* for all physical systems of the same size.
- The fundamental principle also implies that in all processes near or far from horizons, the power and luminosity limit $P \leq c^5/4G = 0.90709(3) \cdot 10^{52}$ W and the force and momentum flow limit $F \leq c^4/4G = 3.0257(2) \cdot 10^{43}$ N are always valid. These limits – $50\,756(3)$ solar masses per second, times c and times c^2 – are predicted to apply to every process in nature [9, 10, 11, 12]. (A solar mass of $1.9885(1) \cdot 10^{30}$ kg is assumed.)

  No Earth-bound processes approach the force and power limits, by far. Astrophysical observations are necessary to check the limits. Galaxies, quasars, galaxy clusters, and blazar jets all emit below 10^{-5} solar masses per second. In supernovae and hypernovae, both accretion and emission are below 10^{-2} solar masses per second. Gamma ray bursts emit at most 1 solar mass per second. The fastest observed and simulated accretion processes achieve 10 solar masses per second. The highest observed luminosities so far are those observed in black hole mergers by LIGO and VIRGO [17]. The record peak power, at present, is for the event GW170729 and has a value of 230 ± 80 solar masses per second [18]. All these values are well below the (modified) Planck limit of $50\,756(3)$ solar masses per second.

  Present data therefore does not yet allow to distinguish between the modified Planck luminosity limit $P \leq c^5/4G$ and the conventional Planck limit $P \leq c^5/G$ that is four times larger. Future discoveries might change this and allow a direct test of this detail of general relativity and of the strand conjecture.
- In any physical system, strand crossings can be more or less tight, and switch more or less frequently. The limit case for a system of size R and energy E directly yields

$$\frac{2\pi}{\hbar c}\, ER \geq \frac{S}{k} \quad . \tag{7}$$

  This is *Bekenstein's entropy bound*. The strand conjecture implies that equality is realized by horizons – and only by horizons – because horizons are the strand configurations that are as tight as possible and whose crossings switch as rapidly as possible. This agrees with expectations.
- Being weaves, the electric charge of black hole horizons is limited. Electric charge is a result of the interlacing of strands [6]. The charge Q is limited by the number N of strands that make up the weave. A non-rotating black hole has $N \sim R \sim M$. This yields

$$\frac{Q^2}{4\pi\epsilon_0} \leq GM^2 \quad , \tag{8}$$

  which is the established charge limit for a Reissner-Nordström black hole.
- Being weaves, black holes can be either non-rotating or rotating. The strands in the weave provide a limit to the angular momentum of a black hole. Angular momentum, like spin, is a result of strand crossings [6]. The angular momentum J is limited by the number of crossings N_{c} that make up

the weave. For an uncharged black hole, $N_{\rm c} \sim R^2 \sim M^2$. Strands thus imply $J \sim M^2$. More precisely, using $E = J\omega$ and $v_{\rm equator} \leq c$ yields $\omega \leq c/R$ and thus

$$J \leq \frac{2G}{c} M^2 \ . \tag{9}$$

This is the usual angular momentum limit for a Kerr black hole. The limit also arises by requiring the equatorial rotation speed to be at most the speed of light. A higher angular momentum would contradict the fundamental principle, and in particular the time limit of crossing switches. So far, the angular momentum limit for extremal black holes agrees with observations [19].

- The combined limit relation for black holes that are both charged and rotating – the Kerr-Newman case – can also be deduced in this way. In particular, strands predict that the g-factor for such black holes is 2. Strands make this prediction (at tree level in the elementary particle case) for all rotating systems for which mass and charge rotate at the same speed. This result can also be expressed as a limit. Black holes – and any other electrically charged body – obey, at tree level, a limit on the ratio between the magnetic moment μ and the angular momentum J:

$$|\frac{\mu}{J}| \leq \frac{\sqrt{G}}{c} \ . \tag{10}$$

Strands thus confirm the conjecture proposed by Barrow and Gibbons.[20]. So far, all observations and thought experiments agree with the limit. In the strand conjecture, this limit derives from three connections: the horizon is a rotating weave (or the particle is a rotating tangle); secondly, the charge, being due to crossings, rotates with the mass; and thirdly, the crossings cannot rotate faster than the speed of light. If this inequality is violated, the strand conjecture is falsified.

- Horizons are tight, one-sided weaves. This implies that any matter tangle that falls towards a horizon and reaches it is essentially flat. As a result, at most one Planck mass can arrive at a horizon during a Planck time. This yields the mass rate limit

$$\frac{{\rm d}m}{{\rm d}t} \leq \frac{c^3}{4G} \tag{11}$$

that is valid in general relativity, and in nature in general. So far, this limit, $1.00928(3) \cdot 10^{35}$ kg/s, or $50\,756(3)$ solar masses per second, is not violated by any observation – including black hole mergers. It could be interesting to check existing numerical simulation packages of general relativity against this limit.

- The strand conjecture limits energy density (and pressure) to the (corrected) Planck value:

$$\frac{E}{V} \leq \frac{c^7}{16\,G^2\hbar} = 2.8958(1) \cdot 10^{112}\ {\rm J/m^3} \ . \tag{12}$$

The energy density limit implies a lower size limit for black holes, for particles and for any localized system. Therefore, strands do not allow singularities in nature, neither dressed nor naked. Cosmic censorship is automatically realized in the strand conjecture. So far, the density limit and the lack of singularities agrees with observations.

- Strands illustrate both the *hoop conjecture* and the *Penrose conjecture:* for a given mass, because of the minimum size of crossings, a spherical horizon – a tight weave – has the smallest possible diameter. Other possible weave shapes have larger size. The strand conjecture thus naturally implies that, for a given mass value, black holes are the densest objects in nature. This agrees with expectations.
- The thermodynamic properties of strands also suggest that shape oscillations of black hole horizons are damped extremely strongly.
- In principle, a horizon could also be modelled by a tight ball, a tight clew, or a tight skein of strands. A horizon could thus be made of many strands in an involved three-dimensional tight tangle. At first sight, such a configuration would seem to be more dense than a tight weave. However, such a configuration is physically indistinguishable from a woven horizon, because only crossing switches at the surface of the ball would be possible and thus be observable.
- The strand network of the vacuum implies that Minkowski space is stable against the formation of black holes and against the spontaneous formation of singularities. This confirms the result found some time ago by Christodoulou [21].
- The strand conjecture implies that black holes (with all their quantum properties) are impossible in higher dimensions; higher dimensions do not allow to form stable weaves. Black holes can be imagined in higher dimensions only if quantum effects are neglected.
- Strands suggest that black holes can *reflect* an incoming quantum particle, instead of swallowing it, but that the probability is *extremely* low: the incoming particle must have an energy so low that its wavelength is comparable to the size of the black hole. For such a low energy, the particle strands are similar in shape to vacuum strands, and the motion of the scattered particle around the black hole resembles the motion of vacuum strands around the travelling black hole. This low probability agrees with expectations [22].
- Two-sided weaves are imaginable in principle. In such weaves, some of the tethers leave the weave on one side, and some of the tethers leave on the other side. However, neither tight nor loose two-sided weaves make physical sense: they are not stable.
- The weave model of horizons implies that *nothing* can be observed behind the horizon. In simple terms, nothing is 'inside' a black hole. In particular, strands suggest the lack of a singularity inside black holes. These statements are valid for observers outside the black hole. For an observer falling into the black hole, the situation changes, as such an observer describes the 'black hole' with a three-dimensional strand network instead of with an (almost) two-dimensional strand weave. The two descriptions can be transformed into each other with suitable deformations of the involved strands.

9 General relativity from strands

In this section, it is shown that strands imply general relativity.

In 1995, in a path-breaking paper, Jacobson showed that the thermodynamic properties of black holes imply Einstein's field equations of general relativity [23]. He started with the following thermodynamic properties:

- an entropy–area relation of $S = A\,kc^3/4G\hbar$,
- a temperature–acceleration relation of $T = a\,\hbar/2\pi kc$,
- a relation between heat and entropy of $\delta Q = T\delta S$.

Using these three properties, the basic thermodynamic relation

$$\delta E = \delta Q \quad , \tag{13}$$

which is valid *only* in case of a horizon, yields the first principle of horizon mechanics

$$\delta E = \frac{c^2}{8\pi G} a\,\delta A \quad . \tag{14}$$

This expression can be rewritten, using the energy–momentum tensor T_{ab}, as

$$\int T_{ab} k^a \mathrm{d}\Sigma^b = \frac{c^2}{8\pi G} a\,\delta A \quad , \tag{15}$$

where $\mathrm{d}\Sigma^b$ is the general surface element and k is the Killing vector that generates the horizon. The Raychaudhuri equation allows rewriting the right-hand side as

$$\int T_{ab} k^a \mathrm{d}\Sigma^b = \frac{c^4}{8\pi G} \int R_{ab} k^a \mathrm{d}\Sigma^b \quad , \tag{16}$$

where R_{ab} is the Ricci tensor that describes space-time curvature. This equality between integrals implies that the integrands obey

$$T_{ab} = \frac{c^4}{8\pi G}\,\left(R_{ab} - (R/2 + \Lambda)\,g_{ab}\right) \quad , \tag{17}$$

where R is the Ricci scalar and Λ is an undetermined constant of integration. These are Einstein's field equations of general relativity. The value of Λ is thus not fixed by the thermodynamic properties of horizons.

As Jacobson explained, the field equations are valid everywhere and for all times, because a suitable coordinate transformation can put a horizon at any point in space and at any instant of time. Achieving this just requires a change to a suitable accelerating frame of reference.

In other words, the field equations result from *thermodynamics of space*. Given that horizons and black holes are thermodynamic systems, so is curved space. The reason is that both curved space and horizons can be transformed into each other. In simple words: Space is made of microscopic degrees of freedom; and gravity is due to microscopic degrees of freedom.

Jacobson's argument implies that space is a thermodynamic system in *three* spatial dimensions. The argument assumes three dimensions from the start; the argument does not work for other numbers of dimensions.

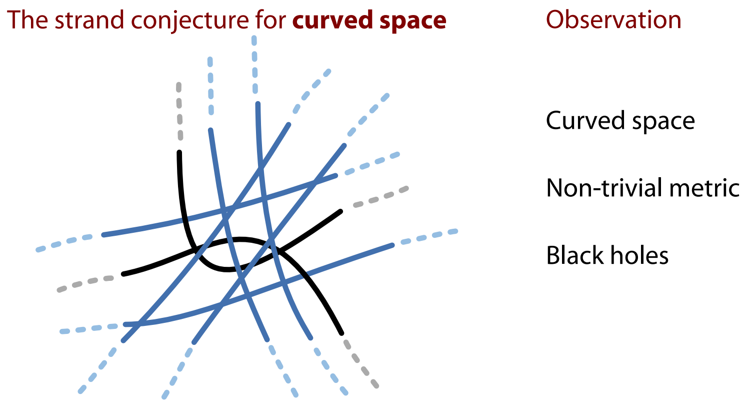

Figure 7: An illustration of the strand conjecture for a curved vacuum. The strand configuration is half way between that of a horizon and that of a flat vacuum. The black strands differ in their configuration from those in a flat vacuum.

The above deduction of the field equation is independent of the details of the fluctuations or of the microscopic model of space, as long as the three thermodynamic properties given at the start are valid. Since Jacobson's result, various kinds of microscopic degrees of freedom for space have been conjectured, including those found in references [24, 25, 26, 27, 28, 29, 30]. Finding the correct microscopic degrees of freedom among the proposals in the literature is probably not possible using arguments from gravity or quantum gravity alone. Also the simplicity of the strand conjecture is not a sufficient argument in its favour. Promising candidates for the microscopic degrees of freedom should also reproduce the standard model of particle physics. Given that strands appear to achieve this [6], it is worth exploring them also in the domain of gravitation.

As explained in section 7, strands do reproduce the existence and the properties of black holes and horizons, including their thermodynamic and quantum properties. Strands thus fully reproduce Jacobson's argument: strands lead to general relativity.

In summary, in the strand conjecture, the field equations appear as consequences of fluctuations of impenetrable, featureless, unobservable strands. In other terms, strand qubits imply general relativity – including the Hilbert action. Any failure to do so would falsify the strand conjecture. The strand conjecture for space is also corroborated by other, independent investigations which conclude that vacuum is made of fluctuating lines [31, 32].

10 Curvature from strands

Strands also help to *visualize* space and curvature. The fundamental principle of the strand conjecture implies: *Flat* space is a network of fluctuating strands. *Curvature* is an inhomogeneous crossing (switch) density in the vacuum network. An illustration of curvature is given in Figure 7.

The value of curvature κ around a mass is due to the tether crossing switch density induced by the mass. As illustrated in Figure 8, this yields the proportionality

$$\kappa \sim \frac{1}{r^3} \quad . \tag{18}$$

Simply speaking, a factor $1/r^2$ is due to Gauss' law, and a factor $1/r$ is due to the average size of twisted pairs of tethers – the virtual gravitons. The third power in the decrease of the curvature around a mass is thus due to the three dimensions of space.

Strands imply a limit to curvature κ. It given by the inverse smallest length:

$$\kappa \leq \frac{1}{l_{\text{min}}} = \sqrt{\frac{c^3}{4G\hbar}} \quad . \tag{19}$$

This limit implies the lack of singularities in nature. So far, this prediction is not in contrast with observations.

The Ricci scalar has the same dimensions as the cosmological constant Λ, i.e., an inverse square length. Strands imply that the Ricci scalar R is non-zero in a region of space only if tangles, i.e., if massive particles are found in that region. The behaviour is as expected. The maximum value for the Ricci scalar R is given by inverse minimum area:

$$R \leq \frac{1}{l_{\text{min}}^2} = \frac{c^3}{4G\hbar} \quad . \tag{20}$$

This corroborates the lack of singularities.

In short: strands visualize curvature.

11 General relativity: validity and predictions

Strands suggests that gravity, like all other space-time effects, is due to tangle *tether* fluctuations and deformations. This statement also specifies when gravity breaks down. Deviations from general relativity only occur when, instead of tethers, tangle *cores* fluctuate and are deformed. Such core deformations yield the electromagnetic and the nuclear interactions [6]. In other terms, in the strand conjecture, both quantum theory and the standard model can be seen as *high-energy deviations* from or, better, as *high-energy complement* of general relativity. At high energies, no other deviations from general relativity are predicted to occur. For example, the observation of a fifth force, of supersymmetry or of supergravity would falsify the strand conjecture.

In addition, as argued in an upcoming paper, deviations from general relativity also occur at *galactic scales*. Both quantum theory and the strand conjecture imply that for galactic and larger distances, quantum effects due to the cosmological horizon *cannot be neglected*. As argued in the upcoming paper, these large-scale quantum effects have important consequences that resemble modified Newtonian dynamics (MOND) [33]. In turn, this has consequences for dark matter and also for dark energy.

For *sub-galactic* distances and *everyday* energies, strand predict that general relativity holds. For example, black holes and gravitational waves occur. In these cases, cosmological horizon effects can be neglected, and so can the other interactions. These cases yield a number of detailed predictions on general relativity.

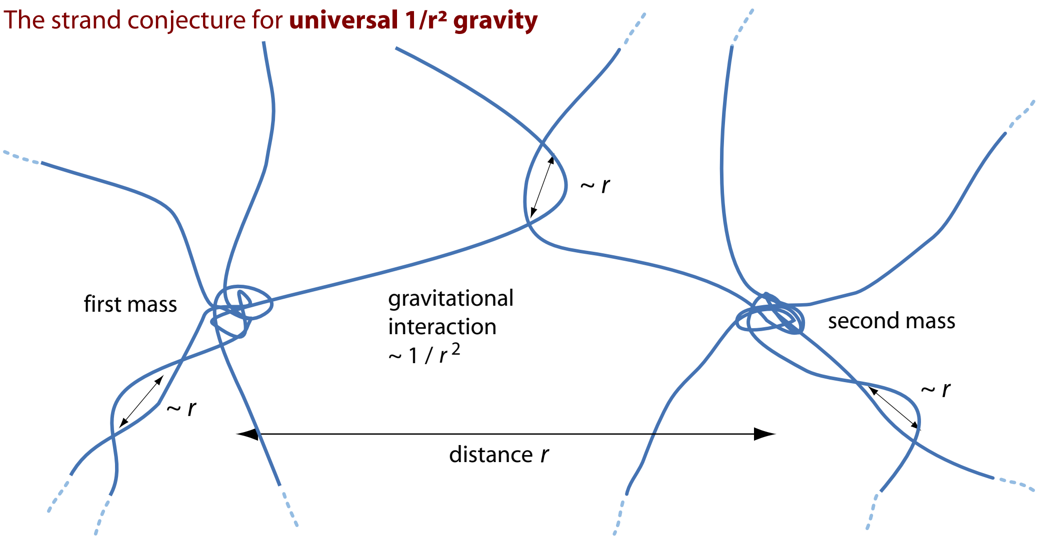

Figure 8: Gravitational attraction results from strands. When speeds are low and curvature is negligible, as illustrated here, mass tethers result in a $1/r^2$ attraction. The average length of twisted pairs of tethers scales with r and leads to a $1/r^3$ decay of curvature. These results are valid for infinite space, i.e., when no cosmological horizon is present.

- The Planck units c, $\hbar$ and G are invariant limit values. This is predicted to hold without any restriction. This prediction agrees with observations.
- The strand conjecture for the photon [6] implies that light moves with speed c. There is no variable speed of light, no time-dependent speed of light, no time-dependent energy of light, i.e., no 'tired' light, and no energy-dependent speed of light. Strands predict the lack of dispersion, birefringence and opacity of the vacuum. As a consequence of the fundamental principle, the maximum energy speed in nature is c, at all energy scales, in all directions, at all times, at all positions, for every physical observer. In short, the strand conjecture predicts no *observable* violation of Lorentz-invariance. This agrees with observations.
- The strand conjecture predicts that there are *no* observable effects of the flat vacuum. For example, 'space-time noise' or 'particle diffusion' do not exist. Strands imply the lack of any degradation of distant star images. This agrees with observations [35].
- Strands imply no deviations from special relativity appear for any measurable energy scale, as long as gravity plays no role. No 'double' or 'deformed special relativity' holds in nature, even though a maximum energy-momentum for elementary particles does exist. Whenever special relativity is not valid, general relativity, or quantum field theory, or both together need to be used. This agrees with observations.
- Strands imply that the equivalence principle holds in all its forms. This agrees with observations [34].

- Strands imply *no* effect of torsion and *no* effect of higher derivatives of the metric on the motion of massive bodies. Strands thus appear to suggest that conformal gravity does not apply to nature. In fact, strands exclude all theories with post-newtonian behaviour that differs from general relativity. All this agrees with observations, in weak and in strong gravitational fields, including double pulsars and black hole mergers [34].
- As a consequence of the fundamental principle, there is a maximum power or luminosity $c^5/4G$, a maximum force or momentum flow $c^4/4G$, and a maximum mass change rate $c^3/4G$ in nature. For the test of each of these flow limits, a physical surface must be defined; the flow limits then hold for the flow through the surface. The flow limits are valid for all energy scales, for all directions, at all times, at all positions, for every physical observer. These predictions agree with observations, though only few experimental observations so far, such as black hole mergers, provide values approaching these limits. Despite the availability of data, such experimental tests are not yet discussed in the reference literature [34], but are beginning to appear [17].
- Strands predict that the integrated luminosity of the universe is limited by $c^5/4G$. This limit is predicted to apply also in case of multiple simultaneous supernovae or hypernovae or black hole mergers. So far, this prediction agrees with data.
- The invariant limit $c^2/4G$ is predicted to apply to the ratio of mass and length (diameter) of all physical systems. Equality is predicted to be valid only for black holes, consistent with the hoop conjecture. Again, there is no observation or thought experiment that invalidates the limit. The limit has a value of $3.3666(1) \cdot 10^{26} \mathrm{kg/m}$ or about 1/6 of a solar mass per km.
- As a consequence of the fundamental principle, there is a smallest action $\hbar$, a minimum distance, a minimum time interval, a maximum curvature, a maximum mass density in nature, and many other such limits. The limit values are given by the modified Planck values, where G is replaced by $4G$. In particular, the conjecture predicts that there are no singularities in nature and that the evolution of space-time does not produce spikes. All these limits and their consequences agree with observations.
- Due to the existence of a maximum force, there is a 'gravitational indeterminacy relation' for the measurement of the energy E and the size l of physical systems [13], given by

  $$\frac{\Delta E}{\Delta l} \leq \frac{c^4}{4G} \quad . \tag{21}$$

  Again, it appears that this relation is best tested with collisions that involve one or two black holes. So far, all observations agree with the relation. Various similar relations among other observables with the same right hand side – or even with other powers of c – can also be deduced.
- Because the fluctuating strand network generates physical space, physical space has three dimensions, at all distance and energy scales, in all directions, at all times, at all positions, for every physical observer. So far, this is observed.
- Strands do not produce fermionic coordinates, anti-commuting coordinates, or non-commutative space. So far, this is observed.

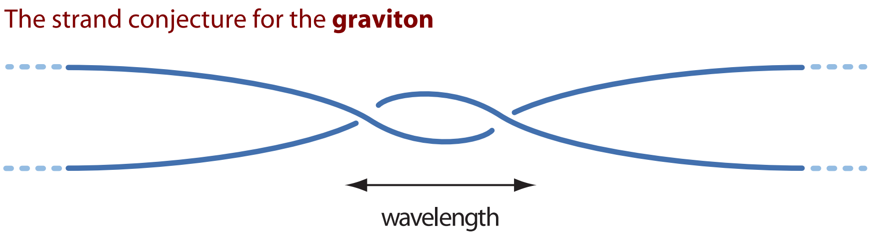

Figure 9: The strand conjecture for the graviton: a twisted pair of strands has spin 2, boson behaviour and vanishing mass.

- Because of strands, space is unique, isotropic and homogeneous. There are no different vacuum states, nor phase transitions between them. Together with the discussion of section 14 below, this implies the lack of cosmic strings, domain walls and regions of negative energy. This agrees with observations.
- Because the fluctuating strand network generates space, the topology of space and of the universe is trivial. This agrees with observations so far.
- It makes no sense to speak of a strand density, because strands are not observable. Predictions of the strand conjecture therefore must depend on crossing switch density only. Predictions must never depend on strand density itself. So far, this is the case.
- The strand conjecture predicts that a flat infinite space would have a vanishing vacuum energy and a vanishing cosmological constant. The strand conjecture predicts the same result also from quantum field theory [6]. The often-cited discrepancy by a factor of 10^{120} between the value of the observed vacuum energy density and the value predicted from quantum field theory does *not* arise in the strand model. The vacuum energy and the cosmological constant in the presence of a cosmological horizon is predicted to be small and positive, as detailed in the upcoming paper. All this is observed.
- In the case of tangles, configurations of highest energy or momentum cannot achieve the strand limit of the fundamental principle. As a result, the tangle model for elementary particles implies that no such particle can have an energy, mass or momentum larger than the Planck values. All cosmic radiation studies so far confirm the prediction.
- Gravitons have spin 2. Gravitons return to their original state after a rotation by π. Gravitons are massless bosons. These properties are realized by twisted pairs of strands. The tangle model of the graviton is illustrated in Figure 9. The model agrees with expectations, including $1/r^2$ gravity and the observation of gravitational waves of spin 2 with velocity c. All this is observed.
- Single gravitons cannot be detected: strands imply the indistinguishability between graviton observation from ordinary quantum fluctuations of the detector. Equivalently, in the strand conjecture, graviton absorption does not lead to particle emission. The lack of graviton detection agrees with data so far.
- Figure 9 and Figure 8 predict that parity violation by gravity does not occur and that it will not be observed. So far, this agrees with observations.

- Strands imply that the gravitational constant G does not run when energy is increased from everyday values to higher values. In this domain, G is not renormalized. The finite strand diameter should not have measurable effects near the Planck scale. This prediction agrees with expectations and with data, though the available data is sparse.
- Strands appear to suggest that gravitation is asymptotically safe – though this issue needs more exploration.
- Strands imply that elementary particles are not black holes, because tangles have no hollow, i.e., no strand-free central void.
- The strand conjecture implies that in a double-slit experiment with electrons, electrons pass both slits at the same time, because the core splits in two pieces during passage – though in different fractions at every passage. Therefore the gravitational fields of the electrons arises on both slits, for every passage, though in different fractions at every passage.
- Strands imply that the wave function Ψ is the crossing density due to the tangle core – and therefore an imaginary number – whereas the gravitational potential φ is the crossing density of tether twists – and therefore a real number. Similarities and differences between Ψ and φ arise, including similarities and differences between entanglement and gravitation.
- Strands also suggest that non-trivial quantum gravity effects – i.e., effects other than black hole thermodynamics, particle masses and gauge interactions – cannot be observed. And despite many attempts, no such effect has been found yet.

In short, strands predict that there are *no* measurable deviations from general relativity, as described by the Hilbert action, at *sub-galactic* distances. The predictions agree with all observations so far. The mentioned predictions are unspectacular; the same predictions are made by most approaches that contain both general relativity and quantum theory as limiting cases. Nevertheless, the future discovery of any deviation from general relativity at sub-galactic scales would falsify the strand conjecture. So would the observation of any non-trivial quantum gravity effect or of any additional interaction.

12 Gravity at low curvature and speeds

In everyday situations, the effects of tethers can be simplified. In these cases, relative speeds are much lower than the speed of light c and spatial curvature can be neglected. This simplifies gravity.

In the strand conjecture, every mass, i.e., every system of tangles, is connected to the border of space by tethers. Also, every space-time effect, including gravity, is due to the behaviour of tangle tethers. The nearer a mass is to a second mass, the more frequently the tethers from the two masses cross. Figure 8 illustrates the situation. The strand conjecture states:

> Everyday *gravitation* is due to tether crossings and their influence on tether fluctuations.

Around every mass, the tethers crossings fluctuate; averaged over time, the fluctuations lead to a crossing switch density. This density corresponds to a density of virtual gravitons. The crossing switch density leads to a local temperature of space, and to a local negative potential energy. There are several ways to show that the crossing switch density around a spherical mass leads to universal $1/r^2$ gravity. Each way is a simplification of Jacobson's original argument.

1. Given a spherical surface A enclosing a gravitating mass M at its centre, the acceleration a of a test mass located somewhere on the surface is related, through the Fulling-Davies-Unruh effect, to the local vacuum temperature T:

$$a = \frac{2\pi\, kc}{\hbar} T \ , \tag{22}$$

where k is the Boltzmann constant. The vacuum temperature is found by dividing the energy E contained inside the sphere by *twice* the maximum possible entropy S for that sphere [13]. The temperature T is thus given by

$$T = \frac{E}{2S} = \frac{2G\hbar}{kc}\frac{M}{A} \ . \tag{23}$$

Using $A = 4\pi r^2$ yields a temperature at the enclosing sphere given by

$$T = \frac{G\hbar}{2\pi\, kc}\frac{M}{R^2} \ . \tag{24}$$

Inserting this expression into the Fulling–Davies–Unruh acceleration a yields

$$a = G\,\frac{M}{r^2} \ . \tag{25}$$

This is universal gravitation, as discovered by Hooke and popularized by Newton. Since spatial curvature was neglected, and since the central mass was assumed to be at rest, this expression is only valid for large distances and small speeds.

2. An alternative deduction of universal $1/r^2$ gravity from black hole entropy was given by Verlinde [36]. The gravitational force F on a test mass m is given by the vacuum temperature T created by the central mass M and by the change of entropy S with distance x that is induced by the motion of the test mass:

$$F = T\frac{\mathrm{d}S}{\mathrm{d}x} \ . \tag{26}$$

The change of entropy $\mathrm{d}S/\mathrm{d}x$ when a test mass m moves by a distance x can be determined from the tangle model in a simple manner. When the test mass m moves by a (reduced) Compton wavelength, the mass – the tangle core – has rotated by a full turn: the entropy change is thus $2\pi k$ per (reduced) Compton wavelength. Thus we have

$$\frac{\mathrm{d}S}{\mathrm{d}x} = \frac{2\pi\, kc}{\hbar} m \ . \tag{27}$$

Using the vacuum temperature T found in expression (24), we get an expression for the gravitational force given by

$$F = G\,\frac{Mm}{R^2} \ . \tag{28}$$

In short, strands imply universal gravity.

3. A further analogy for the attraction of a test mass by a large mass is the process of *thermodiffusion*. Thermodiffusion is the motion of a molecule in a fluid solvent with a temperature gradient. Recent research has shown that the *thermodiffusion coefficient* – describing the speed of the motion – is determined by the entropy of solvation [37]. Translated into the strand conjecture, the motion of a test mass due to gravity can be seen as motion along the temperature gradient of the vacuum. In this (partial) analogy, the gravitational mass of a particle – describing the speed of the motion – is given by the entropy that arises when the particle tangle is added to the vacuum.
4. Figure 8 can also be seen as illustrating how virtual gravitons lead to universal $1/r^2$ gravity. The image gives and idea about how strands reproduce semiclassical (quantum) gravity.

In summary, everyday gravity can be described with strands in various equivalent ways: as fluctuation hindrance via tether crossings, as a process lowering entropy, as thermodiffusion, or as exchange of virtual gravitons. It is probable that additional ways will appear in future.

13 Predictions about particle masses

The analogy between thermodynamic effects and gravitational attraction promises to allow determining the gravitational mass of a quantum particle. In particular, the value of gravitational mass is predicted to depend on the tangle structure of the particle.

Since mass is due to tangle structure, the mass values of all elementary particles are predicted to be positive, fixed, unique and constant in time and space. The strand conjecture also implies that the gravitational and the inertial mass of elementary particles are equal, because in both cases, mass is due to tether fluctuations: inertial mass describes how a rotating mass advances through the vacuum with the belt trick (see reference [6]), whereas gravitational mass describes the virtual gravitons around a mass (as just explained). In the strand conjecture, these are two descriptions of the same process. Therefore, inertial and gravitational mass are equal - at least for infinite, flat space. But the tangle model allows to say even more about particle masses.

Describing particle mass as a thermodiffusion coefficient implies that *more complex* particle tangles have *higher* gravitational mass. The same connection was already deduced for inertial mass in a completely different way previously [6]. This connection yields the correct mass sequences for all hadrons and predicts normal mass ordering for neutrinos.

It is not straightforward to estimate the entropy for the addition of a particle tangle to the vacuum network. But one statement follows directly: because tangle fluctuations leading to particle motion are rare, the entropy is positive and it is much smaller than the maximum possible value. The gravitational mass m of elementary particles is thus predicted to be positive but also much smaller than the Planck mass:

$$0 < m \ll \sqrt{\hbar c/4G} \; . \tag{29}$$

This agrees with observations – and gives a general approach to the mass hierarchy problem.

Deducing upper limits for the mass values of elementary particles is possible [6]. This requires estimating the probability of the string trick, i.e., of tethered rotation. An estimate of tether shape probabili-

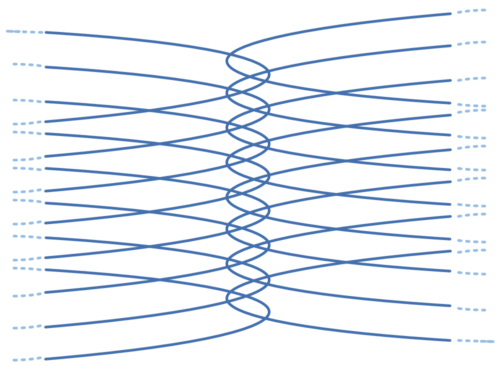

Figure 10: A hypothetical extended defect in space.

ties, using a tight tangle core circumference of around 6 Planck lengths, yields upper limits for the mass m of an elementary particle with four strand tethers and one with six strand tethers given by

$$m_4/m_{\mathrm{Pl}} < (\mathrm{e}^{-6})^4 \approx 10^{-10} \text{ respectively, } m_6/m_{\mathrm{Pl}} < (\mathrm{e}^{-6})^6 \approx 10^{-15}. \quad (30)$$

These numbers are upper limits for the mass values of the corresponding elementary particles. The measured mass ratios lie between about $4 \cdot 10^{-30}$ for neutrinos – which have six tethers – and about $3 \cdot 10^{-17}$ for the top quark – which has four tethers. The estimates are thus correct but rough. More precise estimates of particle masses will require the development of appropriate approximations or suitable computer simulation programs able to simulate a wide range of length scales simultaneously, and thus allow to determine the probability of tethered rotation. This is an open challenge. The failure to reproduce the correct mass value of a single particle (at a single energy value) would falsify the conjecture.

14 Further defects in space

In the strand conjecture, particles, horizons and curved regions are *defects* in the strand network that describes space. It is legitimate to ask whether the strand network allows for additional types of defects or structures that would provide options for dark matter, for dark energy or for new physics.

In the strand conjecture, particles are rational tangles, thus *localized* defects in the strand network, and horizons are weaves, thus *two-dimensional* defects. Are there other options?

An example of a possible *one-dimensional* defect is illustrated in Figure 10. The illustration can be seen as the image of a one-dimensional defect – such as a cosmic string or a cylindrical black hole. Are such defects stable against fluctuations? The strand conjecture suggests that they are not. Such defects are expected to decay into a mixture of gravitons, matter and radiation particles. However, the details remain a topic for research.

Further *two-dimensional* defects could also exist. Figure 10 could also be the cross section of a two-dimensional defect, such as a domain wall. But exploring the stability of domain walls, wormholes, time-like loops, toroidal black holes or black holes with other non-trivial topologies also leads to negative results. Such configurations are expected to collapse and to decay into elementary particles and classical black holes, due to the fluctuations of the involved strands. Two-sided plane weaves, i.e., weaves in which strands leave on both sides, are also expected to decay, mainly into elementary particles. Horizons, being weaves, are minimal surfaces. In short, physical horizons have *simple* topology.

Are there *three-dimensional* defects? Expanding the discussion in section 8 above, it appears that *tight* macroscopic three-dimensional defects are physically indistinguishable from two-dimensional defects, because no crossing switches are possible in the volume. The question then is whether *loose* macroscopic three-dimensional defects exist. But it appears that all imaginable defects can be constructed from curvature, from particles and from horizons.

In fact, the interior of a black hole could also be seen as a three-dimensional defect. It has zero energy. But it is also not observable, thus of no physical importance.

Another frequently discussed type of volume defect is a macroscopic region of negative energy. Energy being action per unit time, and action being connected to crossing changes, strands do not allow the construction of regions with negative energy. In contrast, strands do allow the construction of regions with lower energy than their environment, as in the Casimir effect: in such regions, field fluctuations are simply constrained by the boundaries. In short, the does not seem to be room for additional three-dimensional defects in the strand conjecture.

In summary, the strand conjecture appears to predict the absence of additional defects in space, whether static or dynamic. However, a definite topological treatment of the question is missing, including the existence of higher-dimensional defects. The strand conjecture predicts that the more spectacular defects conjectured in the past – linear defects such as cosmic strings, surface defects such as wormholes and domain walls, and volume defects such as negative-energy regions – *do not appear* in nature. As shown elsewhere, strands also predict the lack of additional elementary particles [6]. Strands thus predict the lack of specific dark matter particles or defects. Conversely, strands appear to predict that gravitational lensing is always due to conventional matter or to black holes. Any discovery of a new elementary particle would falsify the strand conjecture.

15 Outlook and Tests

The strand conjecture requires to change some habits of thoughts. On the one hand, it is not easy to think about nature as made of strands. On the other hand, the conjecture has the charm of deriving all macroscopic observations about gravitation and about the standard model directly from the Planck scale.

The promise of the conjecture to calculate particle masses should be followed on. Such calculations will allow a definite test of the conjecture.

It probable that the present paper has not checked all aspects of gravitation. In this case, additional tests of the conjecture are possible. For example, additional test of black hole properties or tests of additional Planck limits could be possible. Additional strand defects might arise, despite the above discussions.

The strand conjecture can be compared to the "it from bit" program: a crossing switch can be seen as a kind of "bit", in fact, as a model for a "qubit". The emergence of observables ("it") from crossing switches ("bit") thus resonates with Wheeler's program. It will be instructive to continue exploring the comparison.

The details and consequences of the strand conjecture for cosmology, especially for the nature of dark matter and of dark energy, should be explored. They will allow to test the model.

The strand conjecture differs from holography in quantum gravity more than it resembles it, though deducing closer connections might be possible. In particular, the relation between strands and conformal symmetry, conformal field theory and conformal gravity should be investigated.

Through their combination of continuity and discreteness, strands imply that various technical and mathematical problems about gravitation – see the collection by Coley [38] – acquire a different flavour. Problems about singularities and higher dimensions loose their critical status. Issues about horizons – formation, stability, entanglement and minimal mass – become more accessible. Technical difficulties, such as the motion of test particles, the Newtonian limit, the positive energy theorem, the stability of Minkowski space-time, the definition of angular momentum appear more tractable than without strands. It seems especially promising to explore the definition and properties of ADM mass using strands.

Deriving the limit on the ratio between viscosity and entropy density found by Kovtun, Son and Starinets [39] should also be possible with the help of strands.

Alternatives to the strand conjecture of any kind should also be explored. The strand conjecture would be falsified by finding an inequivalent model of nature, describing both space and particles, that explains the Lagrangians of general relativity and of the standard model – and the fundamental constants.

16 Summary

The conjecture of strands fluctuating at Planck scales provides a description of space and gravity that is correct, complete and consistent. Strands also provide a model for qubits. Though no direct observation of strands is possible, the experimental consequences of their existence can be checked. At sub-galactic scales, strands predict the validity of general relativity and all black hole properties, without any measurable deviation. Strand imply the existence of a maximum mass flow rate $c^3/4G$, a maximum force value $c^4/4G$ and a maximum power value $c^5/4G$, all of which are not exceeded in observations so far. Strands further predict the lack of non-trivial observable quantum gravity effects and the lack of unknown dark matter particles. Strands solve the mass hierarchy problem and imply that the gravitational mass of elementary particles can be calculated from their tangle details.

The strand conjecture agrees with all data at sub-galactic scales, is hard to vary, is simple, and predicts the lack of new physics in the domain of gravitation. As long as no new physics at sub-galactic scales is discovered, and as long as the predictions about particle physics given in reference [6] are not falsified, strands remain a candidate for a unified description. The deviations from general relativity that strands imply at galactic and cosmological scales and their consequences for the issues of dark energy and dark matter will be explored in an upcoming paper.

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