A Conjecture
On the Microscopic Details of Space and Gravity

Christoph Schiller
cs@motionmountain.net

May 2019

Abstract

The conjecture that space is made of a network of fluctuating strands appears to explain the three-dimensionality of space, its Lorentz-invariance in the absence of gravity, the possibility of spatial curvature, and the existence of black hole horizons. Black hole horizons appear to be one-sided weaves of fluctuating strands. Such weaves of strands appear to reproduce black hole thermodynamics and all black hole properties. As a consequence, strands lead to the emergence of general relativity, without additions or modifications. In particular, strands imply 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, including black hole mergers. The conjecture allows the deduction of experimental predictions and the visualization of theoretical results about black holes, particle masses and quantum gravity. No contradictions with observations appear to arise.

Keywords: strand conjecture, general relativity, quantum gravity.

PACS numbers: 04.20.-q (classical general relativity), 04.60.-m (quantum gravity).

1 The quest for the origin of space and gravity

The nature of space and gravity remains a matter of intense research. Searches for the microscopic degrees of freedom of black holes, the microscopic nature of quantum foam and the microscopic details of curvature are ongoing.

The so-called *strand conjecture* proposes a microscopic model for black holes, space and gravity. The model uses a single fundamental principle that describes nature at the Planck scale. The model includes quantum theory, agrees with all observations so far, and provides some uncommon experimental predictions. This is detailed in the following.

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 tethered to spatial infinity by unobservable strings. Using the trick, Dirac used to describe spin 1/2 behaviour as result of tethered rotation. Nevertheless, he never published anything about this connection [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]. Then, in 1991, Kauffman conjectured a direct relation between the canonical commutation relation – and thus Planck's constant $\hbar$ – and a crossing switch of tethers [5]. In the early twenty-first century, independently of the work of Battey-Pratt and Racey and of that of 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. It thus appeared that *every quantum effect* can be thought as being due to unobservable extended constituents [6].

A question arises naturally: can unobservable tethers can also explain gravity? The finitude of black hole entropy [7, 8], its surface dependence, and the discovery of a maximum force value in gravity [9, 10, 11] provided first hints. It indeed turns out that the properties of black holes and Einstein's field equations can be deduced from crossing switches of unobservable tethers [6]. It thus appeared that *every gravitational 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 extended constituents, the alternative term *strand* appeared more appropriate. Strands allow to easily visualize gravitational and quantum effects. At the same time, they also allow deducing several experimental tests of the conjecture.

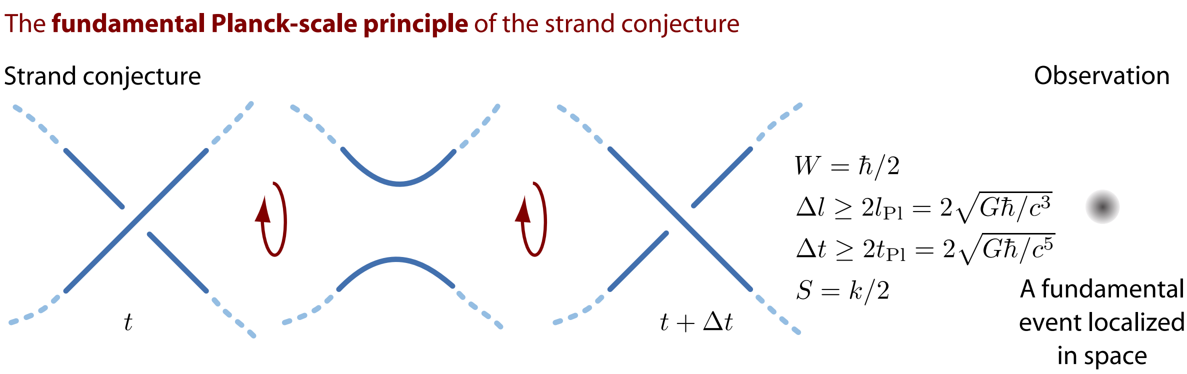

Figure 1: The fundamental principle of the strand conjecture specifies the simplest observation possible in nature: the almost point-like fundamental event results from a *skew strand switch*, or *crossing switch*, at a given position in three-dimensional space. The strands themselves are not observable, 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.

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 configuration behaviour 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 strands.

The following section gives a short summary on how crossing switches of fluctuating strands produce quantum theory. Then, the implications and consequences of these same crossing switches in the domains of gravity are explored.

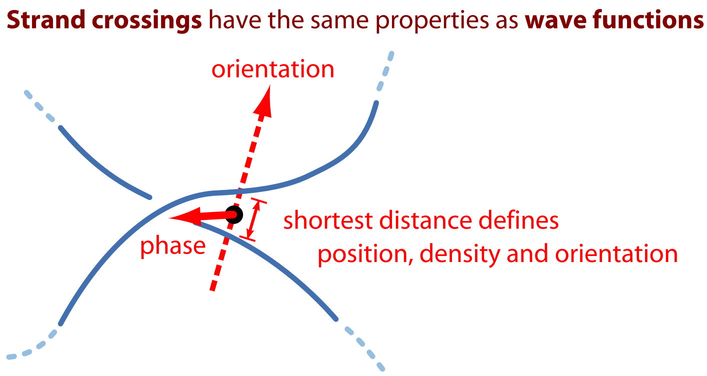

Figure 2: A configuration of two skew strands, called a *strand crossing* in the present context, allows defining density, orientation, position, and a phase, the same properties that characterize a wave function. The freedom in the definition of phase is at the origin of the choice of gauge – for each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

4 From strands to quantum theory

Starting from the fundamental principle and Dirac's belt trick, one finds that *tangled* fluctuating strands in flat space describe particles and wave functions: Wave functions arise as *time averages* of strand crossings. In addition, probability densities arise as 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. Fluctuating tangles imply spin 1/2 and, above all, Dirac's equation. The general approach is illustrated in Figure 2 and Figure 3. For systems of several particles, tangle 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 requires that strands remain unobservable in principle, whereas their crossing switches are observable. Reference [6] shows the details.

Exploring all possible tangles, it appears that rational, i.e., unknotted tangles reproduce the known spectrum of elementary particles [6]. Every massive elementary particle is represented by an infinite family of rational tangles made of two or three strands. The family members differ 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.

Rational tangles also promise to explain the values of particle masses: inertial mass is related to the *complexity* of the tangle core. More complex tangle cores have higher masses than less complex tangles [6].

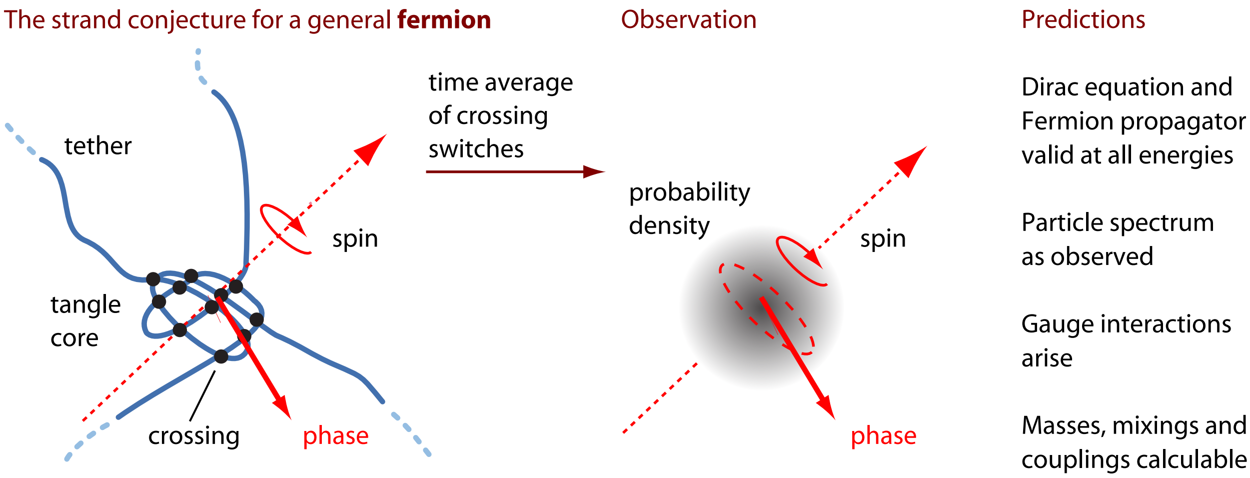

Figure 3: In the strand conjecture, the wave function and the probability density are due, respectively, to crossings and to crossing switches at the Planck scale. The wave function arises as time average of crossings in fluctuating tangled strands; a Hilbert space also arises. The probability density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

5 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 space. The network is illustrated in Figure 5. In particular, a network of *untangled* strands models *empty* space. The time-average of the fluctuations, on a scale of a few Planck times, yields three-dimensional space, including its continuity, homogeneity, isotropy and Lorentz-invariance. On longer 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, and Lorentz-invariance of space can be observed, despite the existence of a smallest length $2\sqrt{G\hbar/c^3}$. (For the same reason, also the smallest time interval $2\sqrt{G\hbar/c^5}$ cannot be observed.) Equivalently, strands predict that every attempt to detect deviations from continuity leads to the creation and observation of particle–antiparticle pairs [6].

Networks and tangles are not possible in more or less than three dimensions. Networks, tangles, particles, measurement devices, observers and the three-dimensionality of space arise only together. In the strand conjecture, no alternative number of dimensions is possible: tangles do not exist in other dimensions.

The strand conjecture assumes that a background space is always possible, at all energy scales. The background space is not set by the system in question, but is defined by the observer. Strands assume that observation implies the definition of a background. Observation without background is impossible.

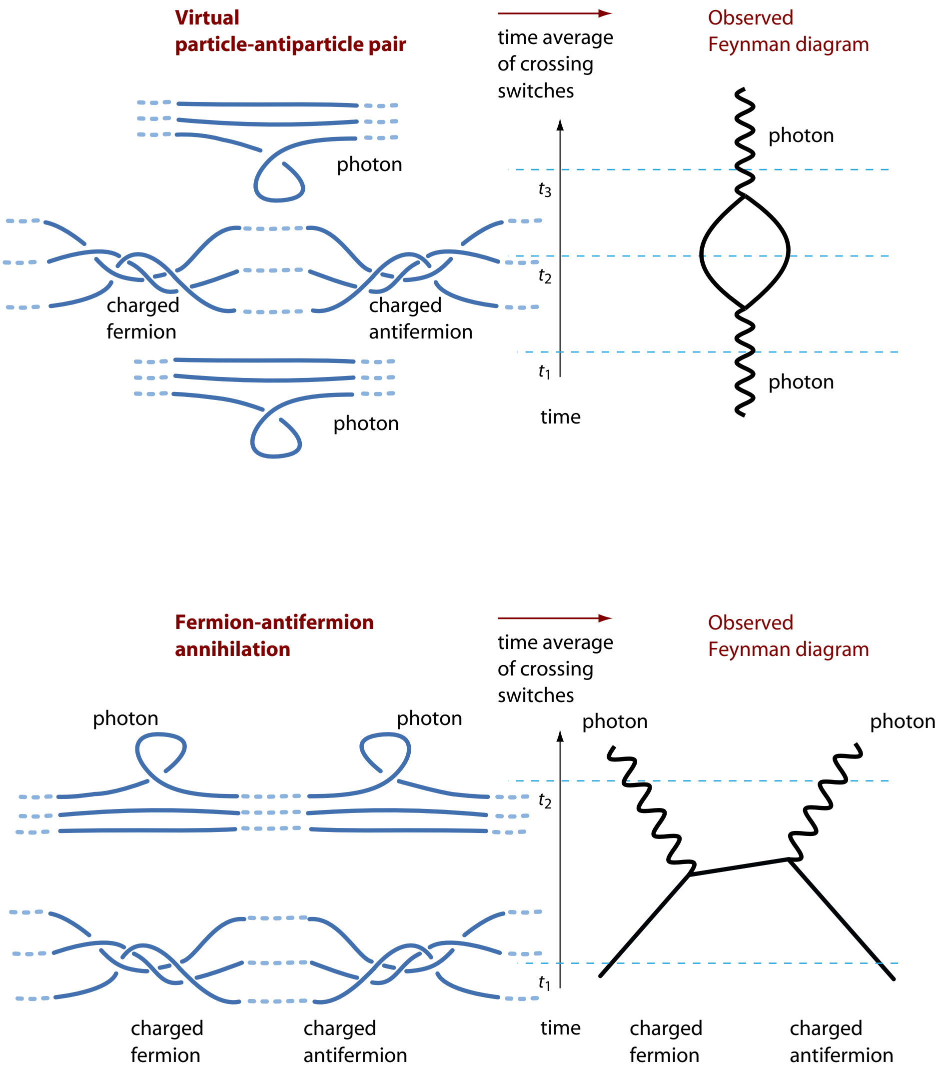

Figure 4: An illustration of two Feynman diagrams of QED in the tangle model.

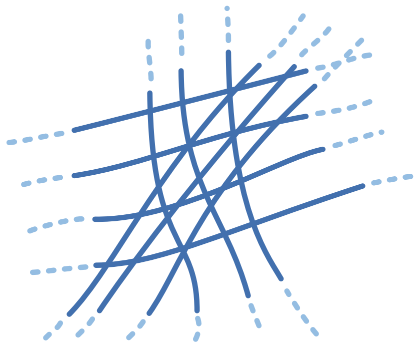

Figure 5: An illustration of the strand conjecture for a flat vacuum: for sufficiently long time scales, the lack of crossing switches leads to a vanishing energy density; for short time scales, particle–antiparticle pairs, i.e., rational tangle–antitangle pairs, arise.

In short, strands provide a specific model of the vacuum, i.e., of what is often called quantum foam. Fluctuating strands are conjectured to be the microscopic degrees of freedom of space. 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. In the absence of gravity, flat space-time arises at all scales and energies, down to the smallest length and up to Planck energy. In particular, nothing surprising or unusual is predicted to occur at smallest scales, i.e., at highest energies. Also, the stability of Minkowski space is automatic in the strand model. So far, these predictions agree with observations and with expectations [12].

6 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, as shown now.

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_{cs} of crossing switches per unit time. In a horizon, crossing switches propagate over the 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

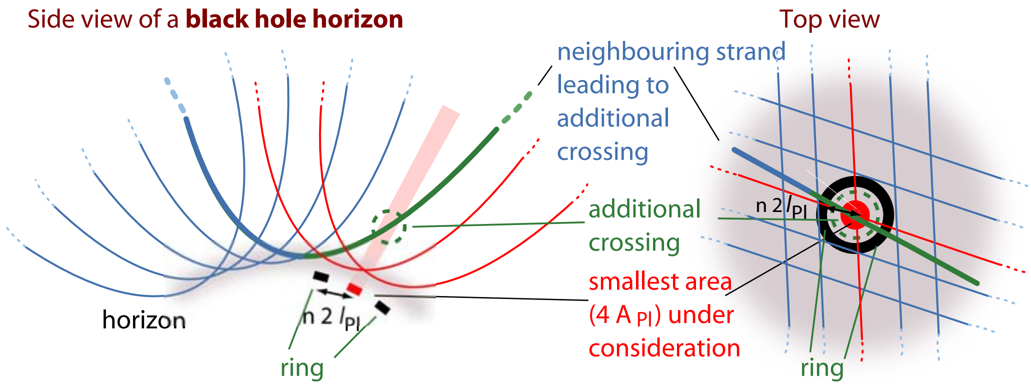

Figure 6: The strand conjecture for a Schwarzschild black hole: the horizon is a cloudy or fuzzy surface produced by the crossing switches of the strands woven into it. Due to the additional crossings on the side of the observer, the number of microstates per smallest area is larger than 2.

crossings of the horizon switch. This yields:

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

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

Strands also determine the number of microstates 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 microstates *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

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

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 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.

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

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

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

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

Strands thus reproduce all thermodynamic properties of black holes. For example, strands reproduce their negative specific heat. Strands also reproduce black hole *evaporation:* evaporation is 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.

7 Predictions about black holes

- 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.
- 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 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 radiate with the maximum possible luminosity: the Planck power $c^5/4G$. Before evaporation, 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 [13].
- 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 [14]. 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.
- 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 at least 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 $P \leq c^5/4G$ and the force (and momentum flow) limit $F \leq c^4/4G$ are valid. The limits are predicted to apply to every process in nature. So far, all observations, including all black hole mergers observed by LIGO, and all calculations [9, 10] confirm these limits.
- 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. So far, this agrees with expectations.
- Being weaves, horizons are minimal surfaces; they have *simple* topology. Because toroidal weaves are expected to be unstable, toroidal black holes are expected not to occur. The same applies to wormholes.
- 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 $N \sim R$ and thus yields

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

  This 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 $N_{\rm c}$ that make up the weave. For a 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. So far, the limit for extremal black holes agrees with observations [15].

- 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, strand predict that the g-factor for such black holes is 2. Strands make this prediction (at tree level) for all rotating systems for which mass and charge rotate at the same speed.
- 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

$$\frac{{\rm d}m}{{\rm d}t} \leq \frac{c^3}{4G} \tag{10}$$

that is valid in general relativity – and in nature in general. So far, this limit agrees with observations – also in the case of black hole mergers.

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

$$\frac{E}{V} \leq \frac{c^7}{16\, G^2 \hbar} \ . \tag{11}$$

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 formation of singularities. This confirms the result found some time ago [16].
- The strand conjecture and its statistical effects imply that white holes do not exist, and neither do wormholes.
- 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 [17].
- 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, tight two-sided weaves make no physical sense: they are not stable. And unstable two-sided weaves would be physically indistinguishable from one-sided weaves.
- 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 strand network instead of with a strand weave. The two descriptions can be transformed into each other with suitable deformations of the involved strands.

8 General relativity from strands

In 1995, in a path-breaking paper, Jacobson showed that the thermodynamic properties of black holes imply Einstein's field equations of general relativity [18]. 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

$$\delta E = \delta Q \quad , \tag{12}$$

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

$$\delta E = \frac{c^2}{8\pi G} a \, \delta A \quad . \tag{13}$$

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

$$\int T_{ab} k^a \mathrm{d}\Sigma^b = \frac{c^2}{8\pi G} a \, \delta A \quad , \tag{14}$$

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

$$\int T_{ab} k^a \mathrm{d}\Sigma^b = \frac{c^4}{8\pi G} \int R_{ab} k^a \mathrm{d}\Sigma^b \quad , \tag{15}$$

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

$$T_{ab} = \frac{c^4}{8\pi G} \left(R_{ab} - (R/2 + \Lambda) \, g_{ab} \right) \quad , \tag{16}$$

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 explains, 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.

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 [19, 20, 21, 22, 23, 24, 25]. 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

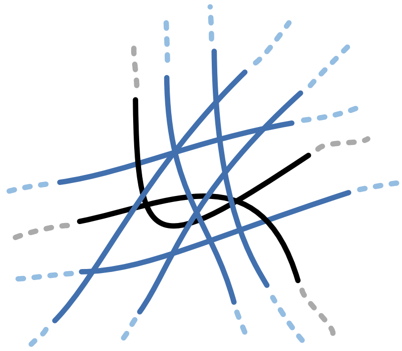

Figure 7: An illustration of the strand conjecture for a curved vacuum. The strand configuration is half way between that of a horizon and that of a flat vacuum. The black strands differ in their configuration from those in a flat vacuum.

physics. Given that strands appear to achieve this [6], it is worth exploring them also in the domain of gravitation.

As explained in section 6, 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. In other terms, the strand conjecture asserts that the field equations appear as consequences of fluctuations of impenetrable, featureless, unobservable strands. The strand conjecture for space is also corroborated by other, independent investigations that conclude that vacuum is made of fluctuating lines [26, 27].

9 Curvature from strands

Strands 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

$$\kappa \sim \frac{1}{r^3} \quad . \tag{17}$$

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 given by the inverse smallest length:

$$\kappa \leq \frac{1}{l_{\text{min}}} = \sqrt{\frac{c^3}{4G\hbar}} \quad . \tag{18}$$

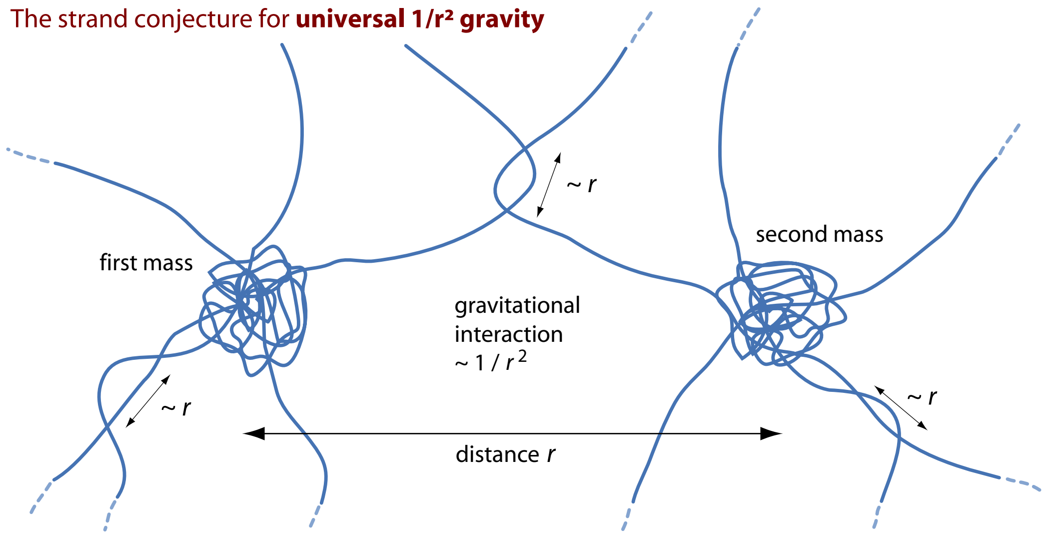

Figure 8: Gravitational attraction results from strands. When speeds are low and curvature is negligible, as illustrated here, mass tethers result in a $1/r^2$ attraction. The average length of twisted pairs of tethers scales with r and leads to a $1/r^3$ decay of curvature. These results are valid for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

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. This corroborates the lack of singularities.

In short: strands visualize curvature.

10 Gravity at low curvature and speeds

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

In the strand conjecture, every mass, i.e., every system of tangles, is connected to the border of space by tethers. And 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:
$$a = \frac{2\pi\, kc}{\hbar} T \quad , \tag{19}$$
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. The temperature T is thus given by
$$T = \frac{E}{2S} = \frac{2G\hbar}{kc}\frac{M}{A} \quad . \tag{20}$$
Using $A = 4\pi r^2$ yields a temperature at the enclosing sphere given by
$$T = \frac{G\hbar}{2\pi\, kc}\frac{M}{R^2} \quad . \tag{21}$$
Inserting this expression into the Fulling–Davies–Unruh acceleration a yields
$$a = G\,\frac{M}{r^2} \quad . \tag{22}$$
This is universal gravitation, as discovered by Robert Hooke and popularized by Isaac 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 [28]. 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:
$$F = T\frac{\mathrm{d}S}{\mathrm{d}x} \quad . \tag{23}$$
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
$$\frac{\mathrm{d}S}{\mathrm{d}x} = \frac{2\pi\, kc}{\hbar}\, m \quad . \tag{24}$$
Using the vacuum temperature T found in expression (21), we get an expression for the gravitational force given by
$$F = G\,\frac{Mm}{R^2} \quad . \tag{25}$$
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 [29]. 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.

It is not straightforward to estimate the entropy for the process of adding a particle tangle to the vacuum network. Since tangle fluctuations leading to particle motion are rare, the entropy is much smaller than the maximum possible value. For a free particle made of three strands, the crudest approximation yields vanishing mass, like that of the vacuum network. More precisely, the gravitational mass m of particles is automatically positive and much smaller than the Planck mass:

$$m \ll \sqrt{\hbar c/4G} \ . \tag{26}$$

This agrees with observations. The analogy between thermal effects and gravitational attraction promises to allow determining the gravitational mass of a particle. For example, describing particle mass as a thermodiffusion coefficient implies that more complex particle tangles have higher mass. The same connection was already deduced for inertial mass in a completely different way in a previous publication [6]. With the elementary particle tangles given there, the expected sequence of mass values yields, for example,

$$m_\tau < m_{\mathrm{top}} \ . \tag{27}$$

More precise estimates of particle masses will require the development of appropriate approximations and suitable computer simulation programs able to simulate a wide range of length scales simultaneously.

In short, 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.

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 general relativity. No other deviations from general relativity are predicted to occur at high energies. For example, the observation of a fifth force, of supersymmetry or of supergravity would falsify this prediction.

In addition, as argued in a forthcoming 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*.

For *sub-galactic* distances and *everyday* energies, 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.

- 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.
- 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 [30].
- 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 [30].
- 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 fo 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.
- 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. So far, this prediction agrees with data.

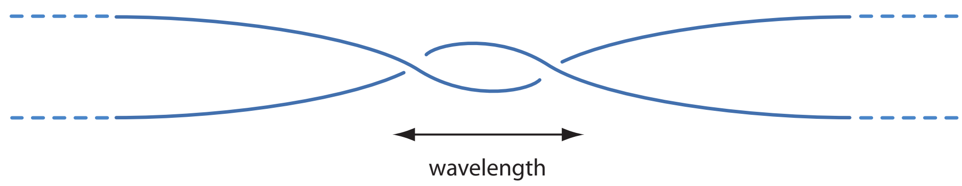

Figure 9: The strand conjecture for the graviton: a twisted pair of strands has spin 2, boson behaviour and vanishing mass.

- 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 corrected Planck values, where G is replaced by $4G$. There are no singularities in nature. All this agrees with all observations.
- Because the fluctuating strand network generates space, 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 or anticommutative space. So far, this is observed.
- 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 12 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.
- 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 vacuum energy and the cosmological constant in the presence of a cosmological horizon is predicted to be small and positive, as detailed in a forthcoming paper. 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.
- The gravitational constant G does not run with energy. G is not renormalized. This prediction agrees with expectations and with data, though the available data is sparse.
- Strands suggest that gravitation is asymptotically safe – though this issue needs more exploration.
- The strand conjecture predicts that there are *no* observable effects of space-time foam. For example, 'space-time noise' or 'particle diffusion' do not exist. This agrees with observations [31].
- Strands imply that the wave function Ψ is the crossing density of 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. 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 mentioned predictions are unspectacular; the same predictions are made by most approaches that contain general relativity and quantum theory as limiting cases. The predictions agree with all observations so far. 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 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 structure that would provide options for dark matter, for dark energy or for new physics.

Topologists have only started exploring the issue of defects in strand configurations. One example is reference [32]. Another example is the exploration of mutually touching infinite cylinders [33]. So far, these studies do not seem helpful for the search of additional defect types in the vacuum network.

A different search method is required. 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

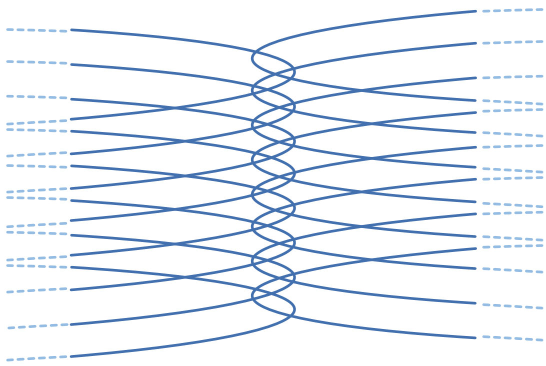

Figure 10: A speculative model for an extended defect in space.

are expected to decay into a mixture of gravitons, classical black holes, 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 and toroidal black holes also leads to negative results. Such configurations are expected to collapse and to decay into elementary particles because of the fluctuations of the strands. In the same way, wormholes or black holes with non-trivial topology should be unstable against decay into particles and classical black holes. Two-sided plane weaves, i.e., weaves in which strands leave on both sides, are also expected to decay, mainly into elementary particles.

Are there *three-dimensional* defects? Expanding the discussion in section 7 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. It appears that all defects can be constructed from curvature, from particles and from horizons. In short, the does not seem to be room for additional three-dimensional defects in the strand conjecture.

In fact, the interior of a black hole could also be seen as a three-dimensional defect. It has zero energy. A 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 strand conjecture appears to predict the absence of additional static and dynamic defects in space. 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 appears to 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.

13 Summary

From one fundamental principle, the strand conjecture appears to explain both general relativity and quantum field theory. At sub-galactic scales, strands predict the validity of general relativity. 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 can be tested in black hole mergers. Strands further predict the lack of non-trivial observable quantum gravity effects and the lack of unknown dark matter particles. Strands 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, introduces no new parameters, is simple, and predicts the lack of new physics in the domain of gravity and quantum field theory. The consequences of strands for galactic and for cosmological scales, and especially for the issues of dark energy and dark matter, will be explored in a forthcoming paper.

References

[1] M. Planck, *Über irreversible Strahlungsvorgänge*, *Sitzungsberichte* der königlich preußischen Akademie der Wissenschaften zu Berlin (1899) 440–480.

[2] N. Bohr, *Atomtheorie und Naturbeschreibung*, Springer (1931).

[3] M. Gardner, *Riddles of the Sphinx and Other Mathematical Puzzle Tales*, Mathematical Association of America (1987) page 47.

[4] E. Battey-Pratt and T. Racey, *Geometric model for fundamental particles*, International Journal of Theoretical Physics **19** (1980) 437–475.

[5] L.H. Kauffman, *Knots and Physics*, World Scientific (1991).

[6] C. Schiller, *A conjecture on deducing general relativity and the standard model with its fundamental constants from rational tangles of strands*, Physics of Particles and Nuclei **50** (2019) 259–299.

[7] J. D. Bekenstein, *Black holes and entropy*, Physical Review D **7** (1973) 2333–2346.

[8] S.W. Hawking, *Particle creation by black holes*, Communications in Mathematical Physics **43** (1975) 199–220.

[9] V. de Sabbata and C. Sivaram, *On limiting field strengths in gravitation*, Foundations of Physics Letters **6** (1993) 561–570.

[10] G.W. Gibbons, *The maximum tension principle in general relativity*, Foundations of Physics **32** (2002) 1891–1901.

[11] C. Schiller, *General relativity and cosmology derived from principle of maximum power or force*, International Journal of Theoretical Physics **44** (2005) 1629–1647.

[12] D. Christodoulou and S. Klainerman, *The Global Nonlinear Stability of the Minkowski Space*, Princeton University Press (1993).

[13] W.H. Zurek and K.S. Thorne, *Statistical mechanical origin of the entropy of a rotating, charged black hole*, Physical Review Letters **54** (1985) 2171–2175.

[14] J.D. Bekenstein, *Black holes: classical properties, thermodynamics and heuristic quantization*, preprint at arxiv.org/abs/gr-qc/9808028.

[15] C.S. Reynolds, *Observing black holes spin*, preprint at arxiv.org/abs/1903.11704.

[16] D. Christodoulou, *The Formation of Black Holes in General Relativity*, European Mathematical Society (2009), preprint available at arxiv.org/abs/0805.3880.

[17] M.Yu. Kuchiev, *Reflection, radiation and interference for black holes*, Physical Review D **69** (2004) 124031.

[18] T. Jacobson, *Thermodynamics of spacetime: the Einstein equation of state*, Physical Review Letters **75** (1995) 1260–1263.

[19] G. 't Hooft, *Crystalline Gravity*, International Journal of Modern Physics A **24** (2009) 3243–3255.

[20] L. Susskind, *New concepts for old black holes*, preprint at arxiv.org/abs/1311.3335.

[21] C. Rovelli, *Zakopane lectures on loop gravity*, preprint at arxiv.org/abs/1102.3660.

[22] T. Padmanabhan, *Dark energy: mystery of the millennium*, AIP Conference Proceedings **861** (2006) 179–195.

[23] T. Padmanabhan, *Thermodynamical aspects of gravity: new insights*, Report on Progress in Physics **73** (2010) 046901.

[24] T. Padmanabhan, *Atoms of spacetime and the nature of gravity*, Journal of Physics: Conference Series **701** (2016) 012018.

[25] G. Amelino-Camelia, *Quantum-spacetime phenomenology*, Living Reviews in Relativity **16** (2013) 5.

[26] S. Carlip, *Dimension and dimensional reduction in quantum gravity*, Classical and Quantum Gravity **34** (2017) 193001.

[27] M. Botta Cantcheff, *Spacetime geometry as statistic ensemble of strings*, preprint at arxiv.org/abs/1105.3658.

[28] E.P. Verlinde, *On the origin of gravity and the laws of Newton*, Journal of High Energy Physics **04** (2011) 029.

[29] S. Duhr and D. Braun, *Why molecules move along a temperature gradient*, PNAS **103** (2006) 19678–19682.

[30] C.M. Will, *The confrontation between general relativity and experiment*, Living Reviews in Relativity **17** (2017) 4.

[31] F. Tamburini, C. Cuofano, M. Della Valle and R. Gilmozzi, *No quantum gravity signature from the farthest quasars*, preprint at arxiv.org/abs/1108.6005.

[32] Louis H. Kauffman and Pedro Lopes, *The Prevalence of Persistent Tangles*, preprint at arxiv.org/abs/1904.05951.

[33] P.V. Pikhitsa and S. Pikhitsa, *Mutually touching infinite cylinders in the 3D world of lines*, preprint at arxiv.org/abs/1705.04019.