

# A Conjecture on Gravitation

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## Abstract

A Planck-scale model for the microscopic degrees of freedom of space is derived from an idea by Dirac. The conjectured model, based on fluctuating one-dimensional strands, allows deducing all properties of black holes and the field equations of general relativity. The strand conjecture predicts the lack of additions or modifications to general relativity at sub-galactic scales. The strand conjecture also predicts the lack of modifications to quantum theory. 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 microscopic, macroscopic or astrophysical process.

In the domain of quantum gravity, the strand conjecture predicts the lack of new effects. In addition, the conjecture allows deriving limits for elementary particle masses. No contradictions with observations arise.

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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 that is based on one-dimensional fluctuating components that are called *strands*. The strand conjecture uses a single fundamental principle that describes nature at the Planck scale.

In order to show that strands are candidates for a unified description of nature, it is necessary – but by far 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 derive these results from a *single* fundamental principle that unifies these 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.

It appears that the strand conjecture agrees with all observations about gravitation at sub-galactic scales. It also appears that strands include quantum theory. In addition, strands provide hints for calculating elementary particle masses. The predictions are numbered.

## 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 whose crossings are observable.

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]. This deduction is summarized below. It thus appeared that *every gravitational effect* can be thought as being due to unobservable extended constituents whose crossings are observable.

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 Planck scales, physics is fundamentally simple, being described by limit statements. Finally, at Planck 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 appear to be realized by the strand description of nature [6].

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.

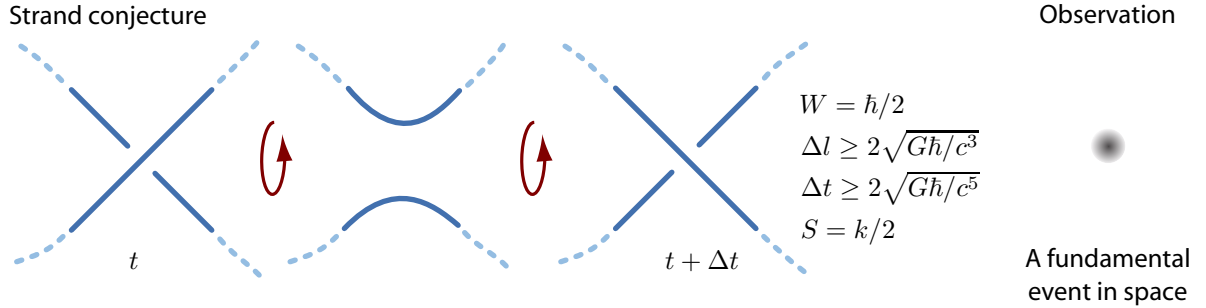
### 3 The strand conjecture

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 – exchanges of over- and underpass – are observable. Crossing switches determine the Planck units  $G$ ,  $c$  and  $\hbar$ ; this fundamental principle is illustrated in Figure 1.

In simple terms, the strand conjecture appears to deduce space, horizons, gravity, but also particles and gauge interactions, with all their observable properties and their laws of evolution, from

The **fundamental Planck-scale principle** of the strand 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 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  $\hbar$ . The double Planck length limit and the double Planck time limit arise, respectively, from the smallest and from the fastest crossing switch possible. The paper plane represents background space, i.e., the local tangent Euclidean space.

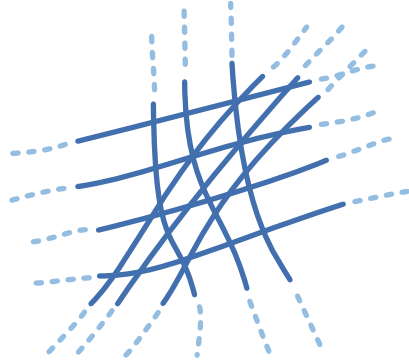
Figure 1. The following sections provide a summary of this claim for the topics related to gravitation. For particle physics, gauge interactions, and the standard model, the claim has been explored elsewhere [6].

Apart from their crossings in space – a strand segment passing over another – strands have *no* observable properties. Strands have no colour, no tension, no mass, no energy; these and all other observables arise from crossings. In order to visualize the minimum length in nature, it is easiest to visualize 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, a crossing *switch* – the change from an overpass to an underpass – 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.

This paper explores gravity at sub-galactic scales. It first derives space from the fundamental principle of strands, then continues with the derivation of horizons and with the derivation of the field equations. Then the consequences and testable predictions of crossing switches in the domains of space and gravitation are explored, taking care that as many of the known tests of general relativity as possible are covered. The appendices discuss the circularity of the fundamental principle and briefly summarize how crossing switches of fluctuating strands produce quantum theory [6]. In the following main part, the consequences and testable predictions of crossing switches in

### The strand conjecture for the **vacuum**



### Observation

Nothing  
(for long  
observation  
times)

Virtual pairs  
(for short  
observation  
times)

**Figure 2:** 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.

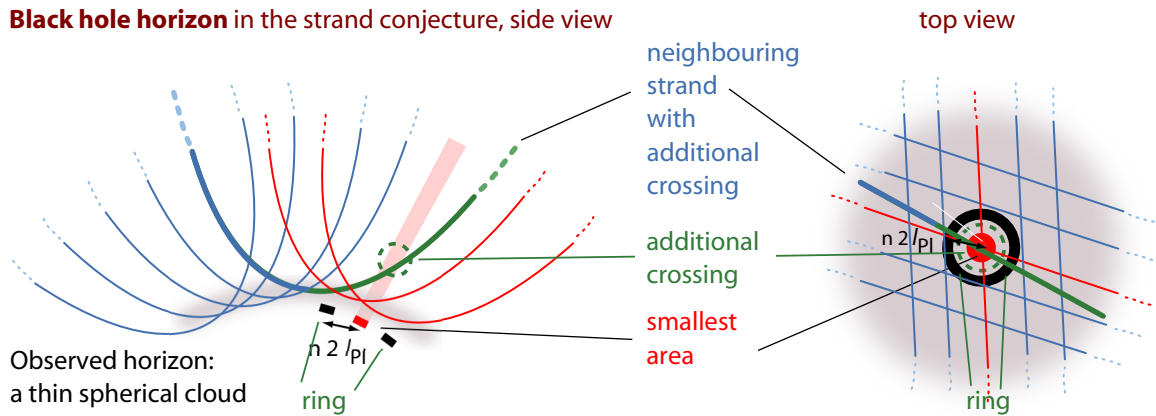
the domains of space and gravitation are explored.

Strand *cosmology* is not covered here; it will be explored in a subsequent paper. In cosmology, the strand conjecture is completed by the statement that nature consists of a *single strand*. A typical strand segment comes from the cosmological horizon, is tangled into some particle, and returns to the horizon; there it follows along the horizon surface, enters the interior again at another position, is tangled into some other particle in the interior, and returns back to the horizon; this occurs for a large number of times. This model of cosmology implies various testable predictions about cosmological observables, including dark energy and dark matter.

## 4 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 network is illustrated in Figure 2. 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, light realizes  $c$ , atomic processes realize  $\hbar$ , and black holes realize  $c^4/4G$ . In contrast, no physical system can realize the smallest length. To measure the smallest length, a single strand would have to be observed; this is impossible. For the same reason, also the smallest time interval  $2\sqrt{G\hbar}/c^5$  cannot be observed.



**Figure 3:** 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.

In summary, vacuum is conjectured to be a consequence of fluctuating strands. The fundamental principle suggests that, microscopically, vacuum is a three-dimensional network of strands. 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 apparent circularity of the fundamental principle is discussed in Appendix A. The strand conjecture thus implies that in the absence of gravity, (local) Minkowski space, i.e., (local) flat space-time, arises at *all* measurable scales and energies, down to Planck scales. Nothing surprising or unusual about physical space is predicted to occur, up to Planck energy.

## 5 From strands to horizons and black holes

This section shows that the fundamental principle for strands explains both horizons and black holes, and that strands allow deducing black hole thermodynamics in a simple way.

In the strand conjecture, *woven* fluctuating strands define horizons and explain their behaviour and properties. In simple terms, the strand conjecture implies 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. (One-sidedness means that there ‘nothing’, not even unobservable strands, is on the other side of the horizon.) A schematic illustration of a Schwarzschild black hole, both as a cross section and as a top view, is given in Figure 3. 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: there is one crossing for each smallest area.

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. This number will depend on the surface area and the surface shape of the horizon. In a horizon, crossing switches *propagate* from one crossing to the next, over the surface of 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  $T$  needed to circumnavigate a *spherical*, non-rotating horizon of area  $4\pi R^2$  at the speed of light, all crossings of the horizon switch. This yields:

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

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 3 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

$$N = 2 + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \dots + \frac{1}{n!} + \dots = e = 2.718281\dots \quad (2)$$

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 3; 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

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

where  $k$  is the Boltzmann constant. This is the expression discovered by Bekenstein [7]. No Barbero-Immirzi parameter is necessary. 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 3 illustrates, strands also imply that horizon entropy is located at and slightly above the horizon. This agrees with expectations. 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 [14].

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 directly yield a logarithmic correction to the black hole entropy

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

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 – though it agrees with expectations.

In short, strands appear to imply the energy  $E$  and the entropy  $S$  of spherical black holes. In addition, the ratio  $E/2S$  determines the *temperature* of such black holes:

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

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 reproduce all thermodynamic properties of black holes.

## 6 General relativity from strands

In this section, the results above are used to show 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 [15]. 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

$$\delta E = \delta Q , \quad (6)$$

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

$$\delta E = \frac{c^2}{8\pi G} a \delta A . \quad (7)$$

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

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



where  $d\Sigma^b$  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

$$\int T_{ab}k^a d\Sigma^b = \frac{c^4}{8\pi G} \int R_{ab}k^a d\Sigma^b , \quad (9)$$

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

$$T_{ab} = \frac{c^4}{8\pi G} (R_{ab} - (R/2 + \Lambda) g_{ab}) , \quad (10)$$

where  $R$  is the Ricci scalar and  $\Lambda$  is an undetermined constant of integration. These are Einstein's field equations of general relativity. The value of  $\Lambda$  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, Jacobson's paper shows: space is made of microscopic degrees of freedom; and gravity is due to these 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.

As explained in section 5, 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. However, the result must be taken with caution.

The above deduction of the field equations is independent of the details of the fluctuations and independent 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 [16, 17, 18, 19, 20, 21, 22]. Finding the correct microscopic degrees of freedom among the proposals in the literature is *not possible* using arguments from gravity or quantum gravity alone.

Among the proposed microscopic models of space, strands might be seen as the simplest one. However, the simplicity of the strand conjecture is *not* a sufficient argument in its favour.

Promising candidates for the microscopic degrees of freedom of space and gravity must also reproduce the standard model of particle physics and explain the fundamental constants. This is the only way to distinguish among the various candidate microscopic models. Given that strands appear to reproduce the Lagrangian of the standard model [6], it is worth exploring them also in the domain of gravitation.

In summary, in the strand conjecture, the field equations appear as consequences of fluctuations of impenetrable, featureless, unobservable strands. The ability to reproduce general relativity is not unique to the strand conjecture. In other terms, strands imply general relativity – including the Hilbert action – but is not the only approach doing so. Despite the non-uniqueness, *the smallest failure to reproduce general relativity would falsify the strand conjecture.*

The strand conjecture for space also resembles other, independent investigations which conclude that vacuum is made of fluctuating lines [23, 24]. However, these investigations do not subscribe to the fundamental principle of the strand conjecture.

## 7 Predictions about physical space

Strands imply testable predictions about physical space. *If any is refuted, the strand conjecture is falsified.*

- P 1. Strands predict the lack of trans-Planckian effects. If any effect due to space or time intervals equal or smaller than the minimal values can be observed – such as in electric dipole moments, in higher order effects in quantum field theory, in discrete space or time – the strand conjecture is falsified. So far, this agrees with observations.
- P 2. Strands predict that physical space is three-dimensional, unique and well-behaved. Any evidence for other dimensions, other topologies, fermionic coordinates, non-commuting aspects, quantum foam, crystal behaviour, different vacuum states, or any other deviation from a well-behaved pseudo-Riemannian space-time manifold would directly falsify the strand conjecture. The reason for writing ‘pseudo-Riemannian’ instead of ‘pseudo-Euclidean’ will be given below, in Section 10, which explores curvature. So far, these predictions about physical space agree with observations, and also with expectations [25].
- P 3. The strand conjecture for space and 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, for all energies. This agrees with observations.
- P 4. 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 [26].
- P 5. 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.

## 8 Predictions about black holes

Strands allow to draw testable conclusions about black holes. *If any of the following predictions is wrong, the strand conjecture is falsified.*

- P 6. Strands imply that the horizon entropy, the horizon energy and the horizon temperature are *limit values* for all physical systems of the same size. These limits arise directly from the Planck limits built into the strand conjecture. So far, they agree with observations. In particular, strands imply the limit

$$\frac{m}{L} \leq \frac{c^2}{4G} \quad (11)$$

for every physical system of size  $L$ . The limit has a value of  $3.3666(1) \cdot 10^{26}$  kg/m or about 1/6 of a solar mass per km. Equality is predicted to be valid only for black holes. The strand conjecture thus naturally implies that, for a given mass value, black holes are the densest objects in nature. Strands thus illustrate and imply 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. This agrees with expectations.

- P 7. Both quantum theory and the strand conjecture imply that an accelerated observer in flat space observes a temperature. The local vacuum temperature  $T$  observed by an observer undergoing acceleration  $a$  appears after inserting the relativistic acceleration-length limit  $L = c^2/a = 2R$  for accelerating systems into the temperature of black holes derived above. The resulting temperature value is

$$T = \frac{\hbar}{2\pi kc} a \quad (12)$$

and is called the *Fulling–Davies–Unruh effect*. In the strand conjecture, the thermal particles detected by the accelerating observer arise from the vacuum strands that he encounters. The expression is thus equivalent to the expression for black hole temperature. It is not clear whether the Fulling–Davies–Unruh effect can ever be observed experimentally. In any case, the expression for the temperature 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. This occurs both in quantum theory and in the strand conjecture. These results will be of interest in the cosmological situations discussed in the upcoming paper.

P 8. Strands imply that black holes *evaporate*. Through fluctuations, single strands or tangles of strands can detach from the horizon weave. The strand conjecture allows to deduce several predictions about evaporation.

- First of all, the emission of particles will depend on the size of the black hole and on the tangling of the particle tangles, i.e., on particle mass values.
- For large black holes, the emission of single strands – photons – is *more probable* than the emission of particles with two or three strands, which include gravitons and fermions. For large black hole, the evaporation is a low probability process, and the evaporation rate of such a black hole is small. All this agrees with expectations.
- For small black holes, the curvature of the black hole helps the emission of massive particle tangles. The relative probability for the emission of massive particles in black hole radiation is predicted to *increase* for smaller black holes.
- The smaller the black hole, the more the total luminosity *increases*.
- Black holes evaporate until the horizon weave has completely *dissolved* into separate strands.
- 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  $c^5/4G$ .

All these predictions agree with predictions made in the research literature [27]. Whether they agree with future observations remains to be seen.

P 9. 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 [28]. 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 to observe strands.

P 10. Together with the strand description of black hole evaporation, strands predict and 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 with a central void, are *not* black holes. This agrees with expectations and observations.

P 11. The strand conjecture and its statistical effects also imply that white holes do *not exist*. This agrees with observations.

P 12. Because horizons are weaves in the strand conjecture, black holes are predicted to 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 topological

properties of tangles and are only defined for tangles. All quantum numbers except electric charge – which is defined as tangle chirality – do not make sense for weaves. The *no-hair theorem* is thus natural in the strand conjecture. It is ironic that the strand conjecture can also be seen as a way to describe particles and horizons *only* with hair, if one uses "hair" as a synonym for "strand". Using this terminology, one could say that the "hair conjecture" implies the no-hair theorem.

- P 13. The fundamental principle of the strand conjecture 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 – one quarter Planck mass per Planck time, or 50 756(12) solar masses per second, times  $c$  and times  $c^2$  – are predicted to apply to every process in nature [9, 10, 11, 12]. Here, a solar mass of  $1.9885(5) \cdot 10^{30}$  kg is assumed.

No Earth-bound process approaches the force and power limit, 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 [29]. The record peak power, at present, is for the event GW170729 and has a value of  $230 \pm 80$  solar masses per second [30]. All these values are well below the (modified) Planck limit of 50 756(12) 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.*

- P 14. In the strand conjecture, 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

$$\frac{dm}{dt} \leq \frac{c^3}{4G} \quad (13)$$

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(12) 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.

- P 15. The strand conjecture *limits* energy density (and pressure) to the (corrected) Planck value:

$$\frac{E}{V} \leq \frac{c^7}{16 G^2 \hbar} = 2.8958(1) \cdot 10^{112} \text{ J/m}^3 \quad (14)$$

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.

- P 16. 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

$$\frac{2\pi}{\hbar c} ER \geq \frac{S}{k} . \quad (15)$$

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.

- P 17. Horizons are weaves of strands. As a consequence, the electric charge of black hole horizons is limited. Electric charge is a result of the *chiral* linking of strands [6]. When a fixed number of strands is given, weaves with a *larger* number of chiral links lead to a *smaller* horizon radius than for an uncharged black hole.

In the strand conjecture, the horizon radius is smallest when all crossings are chiral. As a result, the electric charge  $Q$  of a black hole is limited. More precisely, the charge 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 the limit

$$\frac{Q^2}{4\pi\epsilon_0} \leq GM^2 , \quad (16)$$

which is the established charge limit for a Reissner-Nordström black hole. However, no observations that allow testing the region near the limit are available so far. In fact, it is expected that this will never happen.

The number of strands determines the irreducible mass of a black hole. Together with the charge limit, the usual mass formula for charged black holes arises.

- P 18. 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,  $N_c \sim R^2 \sim M^2$ . Strands thus imply  $J \sim M^2$ . More precisely, using  $E = J\omega$  and  $v_{\text{equator}} \leq c$  yields  $\omega \leq c/R$  and thus

$$J \leq \frac{2G}{c} M^2 . \quad (17)$$

This is the usual angular momentum limit for a Kerr black hole. The limit 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 [31].

As mentioned, the irreducible mass is given by the number of strands that make up the black hole. Strands thus predict that the total mass of a rotating black hole is a monotonous function of the irreducible mass and the rotational energy, where the function also realizes the angular momentum limit. Including the low spin limit yields the usual mass formula for rotating black holes.

- P 19. Strands also allow to deduce the combined limit relation for black holes that are both charged and rotating – the Kerr-Newman case. Strands also 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, due to the belt trick [6]. (Speculating wildly, it could be that rotating black holes might realize gigantic belt tricks, involving a huge number of tethers.)

Strands allow to express the results on charged black holes as a limit. In the strand conjecture, black holes – and any other electrically charged body – obey, at tree level, a limit on the ratio between the magnetic moment  $\mu$  and the angular momentum  $J$ :

$$\left| \frac{\mu}{J} \right| \leq \frac{\sqrt{G}}{c}. \quad (18)$$

Strands thus confirm the conjecture proposed by Barrow and Gibbons [32]. So far, all observations and thought experiments agree with the limit. In the strand conjecture, this limit was derived from three connections: the horizon is a rotating weave; secondly, the electric charge, being due to chiral 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.*

- P 20. 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 on horizons lead to tight, one-sided weaves as models for horizons. Horizons "mix" space and matter. This agrees with expectations.
- P 21. The thermodynamic properties of strand fluctuations also suggest that shape oscillations of black hole horizons are *damped* extremely strongly. This agrees with theoretical expectations.
- P 22. For observers outside the black hole, 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 or of a tightly concentrated mass inside black holes.

In principle, a horizon could also be modelled by a tight ball, a tight clew, or a tight skein of strands. A black hole 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.

- P 23. Strands imply that horizons are not surfaces, but *thin cloudy volumes*. Strands thus imply that black hole horizons resemble stretched horizons. An observer falling into the black hole experiences a three-dimensional strand network instead of an (almost) two-dimensional strand weave. The two descriptions can be transformed into each other with suitable deformations of the involved strands. The strand conjecture thus provides a model of a black hole that resembles a ‘firewall’ and a ‘fuzzball’.
- P 24. The strand network of the vacuum and the weave model of black holes imply that Minkowski space is *stable* against the spontaneous formation of black holes and against the spontaneous formation of singularities. This confirms the result found by Christodoulou [33].
- P 25. 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. Strands imply that black holes can be imagined in higher dimensions only if quantum effects are (at least partially) neglected. However, this statement is hard to verify.
- P 26. 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 [34].

## 9 Predictions about general relativity and its validity

In the derivation of section 6, the cosmological horizon was not taken into account. This implies that for *sub-galactic* distances, when the horizon has no influence, and for *everyday* energies, strands predict that general relativity holds. In these cases, cosmological horizon effects can be neglected, and so can the other interactions. For example, gravitational waves do occur. The case of sub-galactic distances yields detailed predictions on different aspects of general relativity and quantum gravity. *If any of the following predictions is wrong, the strand conjecture is falsified.*

- P 27. The Planck units  $c$ ,  $\hbar$  and  $G$  are invariant limit values. This is predicted to hold without any restriction, at all energies and all scales. This prediction agrees with all observations.



P 28. 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 [35].

P 29. 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 [35], but are beginning to appear [29].

The maximum force can also be deduced as the maximum possible force between two black holes [10, 11]. The existence of a maximum force is inextricably tied to the minimum size of masses. In all thought experiments, the lack of point masses and the lack of infinite mass densities leads to and is equivalent to a maximum force in nature.

P 30. 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 all observations [29].

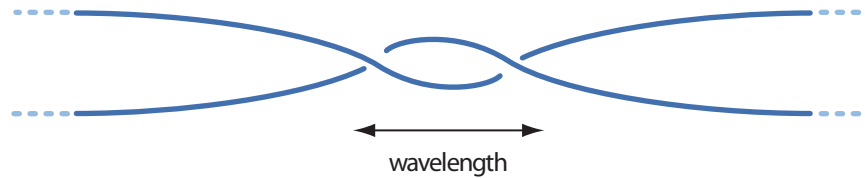
P 31. As a consequence of the fundamental principle, there is a smallest action  $\hbar$ , a minimum distance, a minimum time interval, a maximum curvature, a maximum mass density in nature, and many other such limits. The limit values are given by the modified Planck values, where  $G$  is replaced 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.

P 32. Due to the existence of a maximum force in the strand conjecture, there is a ‘gravitational indeterminacy relation’ for the measurement of the energy  $E$  and the size  $l$  of physical systems [13], given by

$$\frac{\Delta E}{\Delta l} \leq \frac{c^4}{4G} . \quad (19)$$

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.

#### The strand conjecture for the graviton



**Figure 4:** The strand conjecture for the graviton: a twisted pair of strands has spin 2, boson behaviour and vanishing mass.

- P 33. 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.
- P 34. Strands do not produce fermionic or anti-commuting coordinates, or non-commutative space. So far, this is observed to be the case.
- P 35. 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 13 below, this implies the lack of cosmic strings, domain walls and regions of negative energy. This agrees with observations.
- P 36. Because the fluctuating strand network generates space, the topology of space and of the universe is trivial. This agrees with observations so far.
- P 37. 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.
- P 38. 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 are predicted to be small and positive, as detailed in the upcoming paper. All this is observed.
- P 39. 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.
- P 40. Gravitons have spin 2. Gravitons return to their original state after a rotation by  $\pi$ . Gravitons are massless bosons. These properties are realized by twisted pairs of strands. The tangle

model of the graviton is illustrated in Figure 4. The model agrees with expectations, as it leads to  $1/r^2$  gravity, as shown in section 11 below, and to gravitational waves of spin 2 with velocity  $c$ . This agrees with observations.

- P 41. Single gravitons cannot be detected, for two reasons. First, strands imply the indistinguishability between graviton observation from any other quantum fluctuation of or at the detector. Equivalently, in the strand conjecture, graviton absorption does not lead to particle emission. Secondly, even if gravitons were detectable, in the strand conjecture, they have an extremely small cross section, of the order of the square of the Planck length. This implies a low detection probability, as expected [36]. The lack of graviton detection agrees with data so far.
- P 42. Strands, as Figure 4 and Figure 6 imply, predict that parity violation by gravity does *not* occur and that it cannot and will not be observed. So far, this agrees with observations.
- P 43. Strands imply that the gravitational constant  $G$  does not run when energy is increased from everyday values to higher values. In the whole energy domain,  $G$  is not renormalized. In particular, the finite strand diameter is predicted not have measurable effects near the Planck scale. This prediction agrees with expectations and with data, though the available data is sparse.
- P 44. Strands appear to suggest that gravitation is asymptotically safe – though this issue needs more exploration.
- P 45. Strands imply that ‘geons’ do not exist: for topological reasons, such configurations appear to be impossible.
- P 46. 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 field of an electron arises on both slits, for every passage, though in different fractions at every passage. Such an experiment might be possible one day.
- P 47. Strands imply that the wave function  $\Psi$  is the crossing density due to the tangle core – and therefore an imaginary number – whereas the gravitational potential  $\varphi$  is the crossing density of tether twists – and therefore a real number. Many similarities and many differences between  $\Psi$  and  $\varphi$  arise, including similarities and differences between entanglement and gravitation.
- P 48. 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 detected yet.

P 49. In the strand conjecture, all particles, and thus also all masses, have tethers. The tethers are unobservable; only their crossing switches are. In particular, 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 occur when, instead of tethers, tangle *cores* fluctuate and are deformed. Such core deformations indeed yield the electromagnetic and the nuclear interactions, as shown in reference [6]. In other terms, in the strand conjecture, both quantum theory and the standard model of particle physics 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.*

P 50. As argued in an upcoming paper, deviations from general relativity could 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 and have consequences about modified Newtonian dynamics (MOND) [37], dark matter, and dark energy.

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. The strand conjecture would also be falsified by the observation of any non-trivial quantum gravity effect, or by the observation of any additional interaction, as explained in Appendix B.*

## 10 Curvature from strands

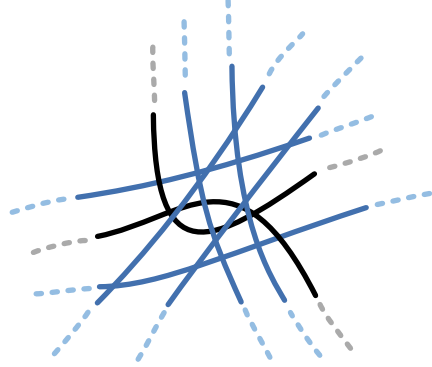
Strands also help to *visualize* space and curvature. The fundamental principle of the strand conjecture implies: *Flat* space is a network of fluctuating strands. *Curvature* is an inhomogeneous crossing (switch) density in the vacuum network. An illustration of spatial curvature is given in Figure 5. Space-time is locally Minkowski, and curvature can evolve. Strands thus lead to a pseudo-Riemannian space-time.

The value of curvature  $\kappa$  around a mass is due to the tether crossing switch density induced by the mass. As illustrated in Figure 6, this yields the proportionality

$$\kappa \sim \frac{1}{r^3} . \quad (20)$$

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.

### The strand conjecture for **curved space**



### Observation

Curved space

Non-trivial metric

Black holes

**Figure 5:** 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.

Strands imply a limit to curvature  $\kappa$ . It is given by the inverse smallest length:

$$\kappa \leq \frac{1}{l_{\min}} = \sqrt{\frac{c^3}{4G\hbar}} . \quad (21)$$

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

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:

$$R \leq \frac{1}{l_{\min}^2} = \frac{c^3}{4G\hbar} . \quad (22)$$

This corroborates the lack of singularities.

In short: strands visualize and limit curvature.

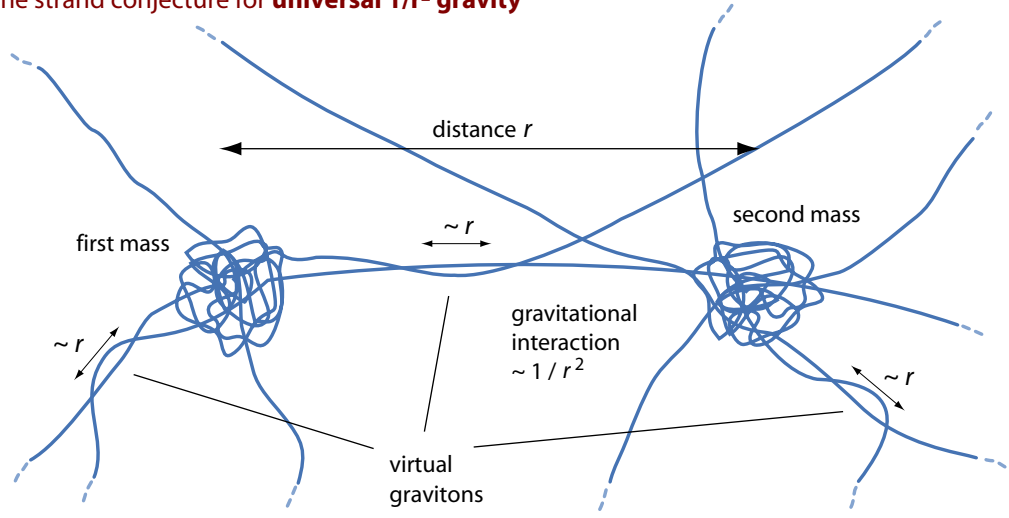
## 11 Gravity at low curvature and speeds

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, in the strand conjecture, 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 6 illustrates the situation. The strand conjecture states:

Everyday *gravitation* is due to tether pair twists and their influence on tether fluctuations.

The strand conjecture for **universal  $1/r^2$  gravity**



**Figure 6:** Gravitational attraction results from strands. When speeds are low and curvature is negligible, as illustrated here, twisted tether pairs, i.e., virtual gravitons, from a mass lead to 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.

Around every mass, the tethers crossings fluctuate; averaged over time, the fluctuations lead to a crossing switch density. This density of tether pair twists corresponds to a density of virtual gravitons. The resulting 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.

- A. 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  $T$ :

$$a = \frac{2\pi kc}{\hbar} T \quad , \quad (23)$$

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

$$T = \frac{E}{2S} = \frac{2G\hbar}{kc} \frac{M}{A} \quad . \quad (24)$$

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

$$T = \frac{G\hbar}{2\pi kc} \frac{M}{R^2} \quad . \quad (25)$$

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

$$a = G \frac{M}{r^2} . \quad (26)$$

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.

- B. An alternative deduction of universal  $1/r^2$  gravity from black hole entropy was given by Verlinde [38]. 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:

$$F = T \frac{dS}{dx} . \quad (27)$$

The change of entropy  $dS/dx$  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

$$\frac{dS}{dx} = \frac{2\pi kc}{\hbar} m . \quad (28)$$

Using the vacuum temperature  $T$  found in expression (25), we get an expression for the gravitational force given by

$$F = G \frac{Mm}{R^2} . \quad (29)$$

In short, strands imply universal gravity in the same way as Verlinde’s entropic gravity does. Strands can be seen as a specific model of entropic gravity.

- C. 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 [39]. 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.
- D. Figure 6 can also be seen as illustrating how virtual gravitons lead to universal  $1/r^2$  gravity. In flat space, the density of tether pair twists decays automatically with  $1/r^2$ . The image thus gives an idea about how strands reproduce the classical limit of 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.

## 12 Predictions about particle masses

So far, the strand conjecture has not predicted anything new. But new predictions about particle masses are within reach. *If any of the following predictions is refuted, the strand conjecture is falsified.*

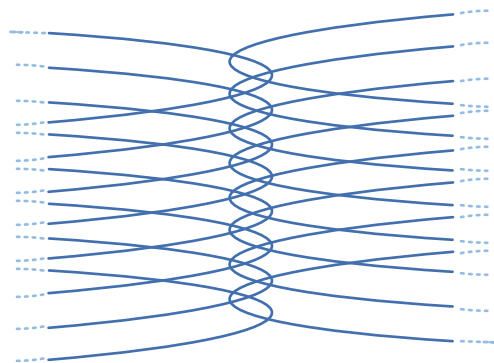
- P 51. Strands, through the analogy between thermodynamic effects and gravitational attraction, promise to allow determining the gravitational mass of quantum particles. In particular, the value of gravitational mass is predicted to depend on the tangle structure of the particle – and on nothing else. Since particle mass is due to tangle structure, the mass values of all elementary particles are predicted to be positive, fixed, unique, calculable and constant in time and space. *Therefore, if particle masses would vary over space or time, the strand model would be falsified.*
- P 52. The strand conjecture also implies that the gravitational and the inertial mass of elementary particles is due to tether fluctuations: *whereas* gravitational mass describes the virtual gravitons around a mass (as just explained), and *inertial* mass describes how a rotating mass advances through the vacuum with the belt trick (as described in reference [6]). In the strand conjecture, it turns out that these two processes are exactly the same. Therefore, inertial and gravitational mass are equal – for infinite, flat space. Strands thus imply that the equivalence principle holds, in its weak and strong form. This agrees with observations [35]. But the tangle model allows to say even more about elementary particle masses.
- P 53. It is not straightforward to estimate the entropy for the addition of an elementary 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:

$$0 < m \ll \sqrt{\hbar c/4G} . \quad (30)$$

This inequality agrees with observations – and provides a general answer to the mass hierarchy problem.

- P 54. Strands imply that falling particles are fluctuating and diffusing tangles. 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. This agrees or is compatible with observations [6]. *If neutrino masses would not obey normal ordering, the strand conjecture would be falsified.*





**Figure 7:** A hypothetical extended defect in space.

P 55. Strands allow deducing upper limits for the mass values of elementary particles [6]. This requires estimating the probability of the string trick, i.e., of tethered rotation. An estimate of tether shape probabilities, 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

$$m_4/m_{\text{Pl}} < (e^{-6})^4 \approx 10^{-10} \text{ respectively, } m_6/m_{\text{Pl}} < (e^{-6})^6 \approx 10^{-15}. \quad (31)$$

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 any single energy value, would falsify the strand conjecture.*

### 13 Predictions about further defects in space

In the strand conjecture, particles, horizons and curved regions can be seen as *defects* in the strand network that describes flat empty 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 can be seen as rational tangles, thus *localized* defects – neglecting their size, one could call them *zero-dimensional* defects – in the strand network. Horizons are weaves, thus *two-dimensional* defects. Are there other options? Some of the following predictions are, by nature, less certain than those given so far.

P 56. An example of a possible *one-dimensional* defect built with strands is illustrated in Figure 7. The illustration can be seen as a potential candidate for a cosmic string or a thin 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 – and thus not to be observable. However, the details remain a topic for research.

- P 57. Further *two-dimensional* strand defects could also exist. Figure 7 could also be the cross section of a two-dimensional defect, such as a domain wall. But first explorations of the stability of domain walls, wormholes, time-like loops, toroidal black holes or black holes with other non-trivial topologies lead 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 (or curved) weaves, i.e., weaves in which some strands leave on one side and other strands leave on the other side, are also expected to decay, mainly into elementary particles – and thus not to be observable.
- P 58. In the strand conjecture, horizons, being weaves of fluctuating strands, are *minimal* surfaces. In short, strands predict that physical horizons have *simple* topology. Toroidal horizons appear to be unstable in the strand conjecture – and thus not to be observable.
- P 59. Strands allow to explore the possibility of *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. First explorations appear to suggest 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. Given that the interior is not observable, it is of no physical importance.
- P 60. Strands allow statements about a frequently discussed type of volume defect: 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, there does not seem to be room for additional three-dimensional defects in the strand conjecture.
- P 61. The strand conjecture does not allow additional spatial dimensions, and does not allow black holes or other structures in higher dimensions. This restriction arises from the inclusion of quantum effects into gravity in the fundamental principle. *If higher dimensions are ever observed, the strand conjecture is falsified.* Conversely, mathematical results in higher dimensions *cannot* be used to falsify the strand conjecture.
- P 62. Strands also predict the lack of additional elementary particles, as shown in reference [6] and summarized in Appendix B. In particular, strands predict the lack of specific dark matter

defects and of dark matter particles. 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 or of dark matter of any kind would falsify 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, including a complete survey of higher-dimensional defects, is still lacking.

## 14 Outlook and Tests

The strand conjecture requires to change some habits of thought. 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 general relativity (at sub-galactic scales) directly from the Planck scale. Also, the standard model of particle physics arises from the Planck scale, as argued in [6]. And so far, no deviations from these two descriptions have been observed.

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 conjecture even further.

The promise of the strand conjecture to calculate particle masses must be pursued. Such calculations will allow the most stringent test of the conjecture.

Exploring rotating and charged black holes remains an open topic. The same applies to the relation between the strand model of black holes and ‘fuzzballs’ and ‘firewalls’. These explorations might lead to additional tests of the strand conjecture.

Exploring additional Planck limits could also be possible. For example, deriving the limit on the ratio between viscosity and entropy density found by Kovtun, Son and Starinets [40] should also be possible with the help of strands.

Also additional strand defects might arise, despite the above exploration. *Any contradiction with observations would invalidate the strand conjecture.*

Through their combination of continuity and discreteness, strands imply that various technical and mathematical problems about gravitation – see the collection by Coley [41] – acquire a different flavour. Problems about singularities and higher dimensions lose 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.

The strand conjecture can also be compared in more detail to Wheeler’s “*it from bit*” program. A crossing switch can be seen as a model for a qubit. The emergence of observables and systems (“it”) from crossing switches (“qubit”) resembles Wheeler’s program. It will be instructive to

continue exploring the comparison. In this context, the compatibility of the strand conjecture with *entropic gravity*, shown above in section 11, is suggestive.

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.

One could also explore how much the tangle model for the graviton can be related to the *twistor* approach to nature.

Finally, all possible alternatives to the strand conjecture, of any sort, should also be explored. *The strand conjecture can be falsified by finding any other inequivalent model of nature that describes both space and particles, i.e., that explains the Lagrangians of general relativity and of the standard model of particle physics, with their fundamental constants.*

## 15 Summary

The conjecture that nature is made of strands fluctuating at Planck scales provides a description of space and gravity that is correct, complete and consistent. 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 of all black hole properties, without any measurable deviation. Strands 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 any observation 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 suggest 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.

## 16 Acknowledgments and Declarations

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## Appendix A 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.

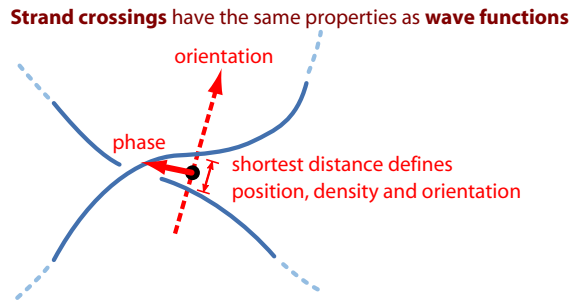
Crossing switches take place in *background space*. In the strand conjecture, background space is the tangent space of physical space. In contrast, *physical space*, physical distances and physical observables arise from strands and their crossing switches. When space is flat, background space and physical 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.

In nature, 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. In nature, observations, comparisons and measurements require background space. Indeed, a local background space – usually observer-dependent – is *required* to describe *any* observation, or simply, to talk about nature. In the strand conjecture, it is equally impossible to define crossing switches or Planck units without a background. The strand conjecture asserts that a description of nature *without* a background space and time is impossible.

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. In fact, the need for a background space to describe nature 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, (physical) 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, i.e., at Planck scales.

Because of the impossibility of an axiomatic description at the Planck scale, 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.

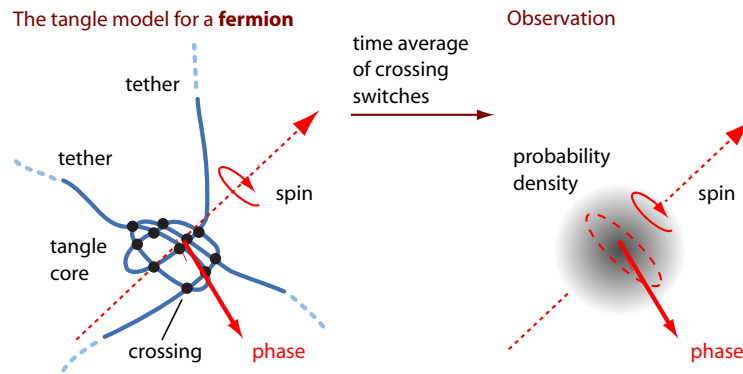


**Figure 8:** A configuration of two skew strands, called a *strand crossing* in the present context, allows defining density, orientation, position, and a phase, the same properties that characterize a wave function. The freedom in the definition of phase is at the origin of the choice of gauge. For 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  $\Psi$  of the particle and, for the mirror tangle, the two components of the antiparticle.

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. In particular, strands reproduce the basic circularity of the foundations of 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 (local) background space; 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.



**Figure 9:** 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 (see text).

## Appendix B From strands to quantum theory and the standard model

This appendix provides an extremely short summary of references [6] and [13], which explain how quantum theory and quantum field theory are deduced from strands, including the Lagrangian of the standard model.

The tangle model for quantum particles is illustrated in Figure 8 and Figure 9. They visualize that crossings have similar properties to wave functions, and time-averaged crossing switches have the same properties as probability densities.

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 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 local time average of the *crossing switch density* of its fluctuating tangle. A detailed exploration [6, 13] shows that strands produce a Hilbert space, the quantum phase, interference, contextuality, and freedom in the definition of the absolute phase value.

Defining antiparticles as mirror tangles is possible. Fluctuating rational tangles made of two or more strands imply spin 1/2 behaviour under rotation and, above all, Dirac’s equation [4]. For systems of several particles, tangles reproduce fermion behaviour and entanglement. Tangles of

strands are fully equivalent to textbook quantum theory and predict the lack of any extension or deviation up to Planck energy. For example, the principle of least action is the *principle of fewest crossing switches*. In this way, strands also explain the origin of the principle of least action.

And 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 from strands. In addition, tangles also allow to deduce quantum *field* theory.

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 either two or three strands. Quarks are made of two strands; the other massive elementary particles are made of three strands. Three generations for quarks and for leptons arise. The Higgs itself is represented by a braid. The family members for each elementary particle differ among them only by the number of attached braids. The structure of each elementary particle tangle explains the spin value, parity, charge and all other quantum numbers.

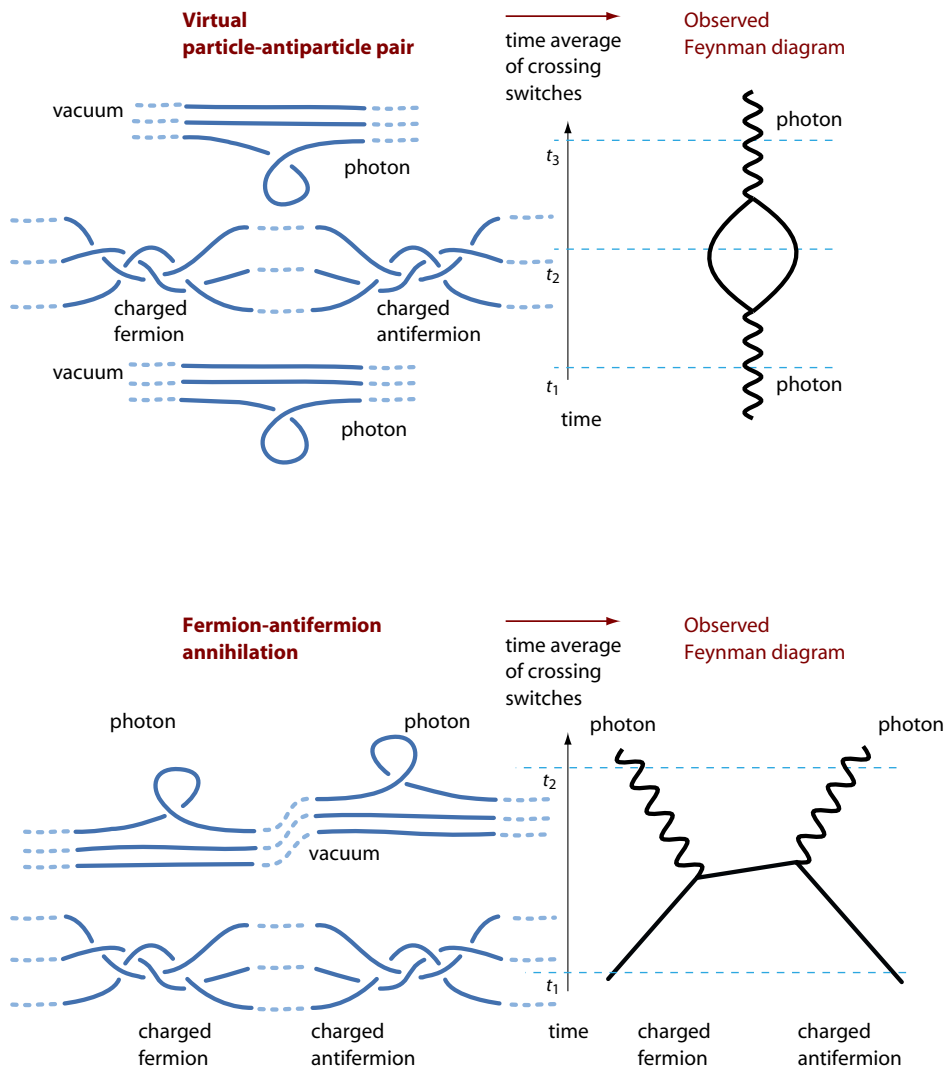
Models for the *massless bosons* also arise. In particular, a photon is a single, twisted strand. Photons are emitted or absorbed by chiral tangles, i.e., by fermion tangles that are electrically charged. Figure 10 illustrates the strand model for quantum electrodynamics. Only three kinds of massless bosons arise, each due to one Reidemeister move. The boson generator algebras turn out to be the well-known  $U(1)$ , broken  $SU(2)$  and  $SU(3)$  of the three gauge interactions [6]. (The way that the massless bosons of  $SU(2)$  acquire mass is also explained.)

A detailed investigation shows that tangles reproduces all Feynman graphs observed in nature – and no other ones. The correct coupling between fermions and bosons also arise. Particle mixings appear naturally. In fact, the full Lagrangian of the standard model arises, without any addition or modification.

Interestingly, rational tangles also promise to explain the values of the inertial mass of particles. Inertial mass, like gravitational mass, is related to the *complexity* of the tangle core. More complex tangles have higher masses than less complex tangles. Neutrinos are massive Dirac fermions. The predicted mass sequences agree with observations – with one exception that can be explained with another effect [6].

In short, strands imply that no new particles, no new interactions, no other energy scales and no other effects are observable in nature. *Any observed deviation from the standard model of particle physics with massive neutrinos would falsify the strand conjecture.* This terse summary of the implications on quantum field theory allows proceeding to the exploration of space and gravity.





**Figure 10:** An illustration of two Feynman diagrams of QED in the tangle model.

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