Are we living in a string-dominated universe?

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May 1, 2004

Abstract

The so called holographic solution is a new exact solution to the Einstein field equations. The solution describes a compact self-gravitating object with properties very similar to a black hole. Its entropy and temperature at infinity are proportional to the Hawking result. Instead of an event horizon, the holographic solution has a real spherical boundary membrane, situated roughly two Planck distances outside of the object’s gravitational radius.

The interior matter-state of the holographic solution is singularity free. It consists out of string type matter, which is densely packed. Each string occupies a transverse extension of exactly one Planck area. This dense package of strings might be the reason, why the solution does not collapse to a singularity. The local string tension is inverse proportional to the average string length. This purely classical result has its almost exact correspondence in a recent result in string theory, published by Mathur.

The holographic solution suggest, that string theory is relevant not only on microscopic, but also on cosmological scales. The large scale phenomena in the universe can be explained naturally in a string context. Due to the zero active gravitational mass-density of the strings, the Hubble constant in a string dominated universe is related to its age by $Ht = 1$.

The WMAP measurements have determined $Ht \approx 1.02 \pm 0.02$ experimentally. The nearly unaccelerated expansion expected in a string dominated universe is compatible with the recent supernova measurements. Under the assumption, that the cold dark matter (CDM) consists out of strings, the ratio of CDM to baryonic matter is estimated. We find $\Omega_{CDM}/\Omega_b \approx 6.45$.

Some arguments are given, which suggest that the universe might be constructed hierarchically out of its most basic building blocks: strings and membranes.

1 Introduction

In [11] a new spherically symmetric, exact solution of the Einstein field equations with zero cosmological constant was reported. The starting point leading to its
discovery was to find an alternative singularity-free description for a compact black hole type object. The so called holographic solution, in short "holostar", has a temperature (at infinity) and an entropy proportional to the entropy and temperature of a black hole \[13\]. Instead of an event horizon, the holostar has a boundary membrane consisting out of tangential pressure situated roughly two Planck distances outside its gravitational radius \[12\]. This real physical membrane has the same properties as the - purely fictitious - "membrane" attributed to a black hole by the so-called membrane paradigm \[19, 15\] \((P_{\perp} = 1/(16\pi\rho), \rho = 0)\). This guarantees, that the dynamic action of a holostar on the exterior space-time is practically identical to that of a black hole.\(^1\) The interior matter state is non-singular with a well defined temperature and energy-density at every interior space-time region.

By studying the geometric properties of this new solution (for an extensive treatment see \[12\]) it turned out, that the new solution might also serve as an alternative model for the universe. Far away from the center the geodesic motion of massive particles is virtually indistinguishable from that of a uniformly expanding (or contracting) Friedmann Robertson-Walker (FRW) universe. A very attractive feature of the new model is, that it has practically no free parameters, which could be tuned to observational facts. Therefore this model is very easily falsifiable. Nevertheless, the solution fits almost perfectly - within the measurement errors - to the henceforth available experimental data:

- It predicts a definite relation between the total matter density \(\rho\) and the CMBR-temperature \(T\), which is experimentally verified within a few percent of error: \(\rho/T^4 \approx 2^{6/3} \pi^3 \sqrt{3}/\hbar^4\) in units \(c = G = 1\).
- It predicts a uniform Hubble-type expansion with \(Ht = 1\), exactly. The recent WMAP measurements claim \(Ht = 1.02 \pm 0.02\).
- It predicts a coasting (nearly unaccelerated) expansion with nearly zero deceleration \((q \approx 0)\), which is compatible with the supernova-data, if \(H \approx 60 - 63 \text{ km/s/Mpc}^{-1}\).
- The Hubble constant is related to the microwave-background-temperature, predicting \(H \approx 63 \text{ km/s/Mpc}^{-1}\). This is quite close to the value \(H = 71\) used in the concordance ΛCDM-model \[2\] and fits almost perfectly with other absolute measurements of \(H\), which consistently yield values in the range around \(H \approx 60 \pm 10\).

The expansion in the holostar solution is accelerated, with the proper acceleration falling off over time. The acceleration is not due to a cosmological constant, which is exactly zero in the holostar space-time. Rather, the proper acceleration in the co-moving frame can be traced to the radial dependence of

\(^1\)Black holes are thought to be the most compact self gravitating objects possible, by a vast majority of researchers. However, despite years of research we don’t have any definite answers to our most fundamental questions, such as the microscopic origin of the Hawking entropy, the nature of the singularities, the question of information-loss, unitary vs. non-unitary evolution and other related questions. This makes it necessary to explore alternatives.
the spherically symmetric gravitational potential, which falls off with \( r \) by a power law.

However, the interior matter state of the new solution is puzzling. The interior pressure is highly anisotropic: The radial pressure is negative and exactly equal, but opposite in sign to the positive mass density. The two tangential pressure components are zero. This is the equation of state of a classical string in the radial direction. Thus the interior matter state can be interpreted as a spherical arrangement of radially outlayed strings, attached to a real physical membrane, which constitutes the boundary of the object.

The string tension \( \mu \) falls off with radius: \( \mu = 1/(8\pi r^2) \). The average length \( l \) of the strings at radial position \( r \) is inverse proportional to the tension, \( l = r^2/(2r_0) \), so that \( \mu l = 1/(16\pi r_0) \). \( r_0 \approx 2r_{Pl} \) is a fundamental length, which can be shown to be slightly less than 2 Planck lengths. This result is compatible with a very recent result in string theory [7], according to which the string tension of a large black hole type object falls with its inverse length, so that the "black hole's" interior is filled with strings extending up to the event horizon.

String theory is the domain of particle physicists and is predominantly used to analyze the phenomena at the highest conceivable energies, approaching or surpassing the Planck energy. Why should a solution of the Einstein field equations with an interior matter-state consisting out of strings be relevant to the physics at low energies, such as the present state of the universe? There are three quick answers to this question:

- The dualities of string-theory: If a certain string theory at high energies is equivalent to a dual theory at low energies it is difficult to justify the belief, that string theory should only be relevant at high energies. A particular example for the relevance of string theory at low energies is given in [7].

- The cold dark matter (CDM): There is overwhelming experimental evidence that our universe consists of a large fraction of cold dark, presumably non-baryonic, matter. Not much is known about it, beyond its very existence. Why not add another type of matter to the long list of CDM-candidates: strings.

- The universe itself: The universe, as we see it today, exhibits several properties which can be explained very naturally in a string context.

Some essential pieces of evidence for the last claim were already pointed out beforehand. I will shortly explain in the following paragraphs, how these definite predictions of the holographic solution are related to its string nature. For a full treatment the reader must be referred to the 150 pages of [12]. There the reader will find some other predictions which are quite compatible with the observation, such as a baryon to photon ratio \( \eta \approx 10^{-9} \), a prediction for the low values of the CMBR-quadrupole moment etc. In [13, 14] an explanation for the origin of the matter-antimatter asymmetry at high temperatures within the holostar space-time is given.
Due to the zero active gravitational mass-density of the strings a string dominated universe expands uniformly with $r \propto t$. This implies $Ht = 1$, which is very well fulfilled in our universe today.\(^2\)

The prediction of nearly unaccelerated expansion in a string dominated universe is also compatible with the recent supernova-measurements. The luminosity-redshift relation for a permanently zero deceleration parameter ($q = 0$) is nearly indistinguishable from the relations predicted by today’s preferred models with $\Omega_\Lambda \approx 0.65 - 0.75$ and $\Omega_m \approx 0.25 - 0.35$, at least in the range of red-shifts covered by the recent surveys ($z < 1.75$). However, with the current available data the best fit $\Lambda$CDM model gives a $\chi^2$-value which is roughly one standard deviation (of the $\chi^2$-test!) lower than the $\chi^2$-value of the holostar model, so that the $\Lambda$CDM model is preferred over the holostar-model at one sigma confidence level.\(^3\) A definite decision with respect to what model provides the best description for the universe most likely will be obtained, when more supernova-measurements in the high $z$-range ($z > 2$) are available, where both models differ substantially in their predictions. See [12] for a detailed discussion.

The relation $Ht = 1$ for a permanently unaccelerated universe is interesting from another perspective. If we take the radius of the observable universe $r$ to lie in the range $13 - 18\text{ Gy}$, this translates to $r \approx t \approx 10^{61}$ in Planck units. If the universe was string-dominated with $r \propto t$ for all time, the expansion will have started out from roughly a Planck volume at the Planck time and Planck temperature. In contrast, the standard FRW-model requires that the scale factor of the observable universe was of order $10^{30}$ Planck-lengths at the Planck-time and Planck-temperature. There appears to be no fundamental reason why the universe has chosen such an odd number.

Uniform expansion in a string dominated universe can also explain the nearly scale-invariant acoustic spectrum found in the CMBR (see for example [9] and references therein), which was mapped by WMAP [2] to a high degree of accuracy. Strings could be an explanation for the recently found deviations in the CMBR-spectrum from a purely Gaussian distribution [3, 4, 5, 6, 17] and for the anisotropies suggested by the analysis of the lower multipoles [16]. Furthermore strings can give a quite natural explanation for the amplitude of the density fluctuations in the CMBR in terms of the GUT-scale $\delta \approx M_{\text{Gut}}^2/M_{\text{Planck}}^2 \approx 10^{-5}$ (see [9], p. 316) and references therein.

Expansion in a string dominated universe has no horizon problem. The relation $r \propto t$, which arises from the zero active gravitational mass-density of the strings, guarantees that the scale factor and the Hubble-distance are always proportional to each other. Inflation is not necessary. Furthermore, a string dominated universe, as described by the holostar solution, has no cosmological constant problem. In the holostar solution the cosmological constant is exactly

\(^2\)The large scale motion of particles must be unaccelerated in a string-dominated universe, because the active gravitational mass-density $\rho + \sum P_i$, which determines the acceleration/deceleration in any local Minkowski frame, is zero for stringy matter.

\(^3\)One standard deviation can hardly be regarded as a statistically significant, unless one is willing to change ones predictions for every third data sample.
A zero cosmological constant is attractive not only from an esthetic point of view. It is well known, that string theory has severe problems with a positive cosmological constant. The apparent necessity for a positive cosmological constant in the standard FRW-type models has led many string theorists to turn to anthropic reasoning. This is unsatisfactory (although maybe unavoidable in the long run). Anthropic arguments are "a posteriori", i.e. they don’t explain why the cosmological constant has taken its particular value. The holographic solution might provide an elegant way out. It enables us to explain the phenomena in a model with zero cosmological constant. If the holographic solution - or a generalization thereof - actually turns out to be the correct description of the universe, this will provide string theorists with invaluable experimental/observational data from the low energy sector, which might be helpful in the understanding of string theory at the high energy limit. It might also provide string theorists with an incentive - and most likely some guidance - to show, why the cosmological constant should be close to zero in a self-consistent unified theory of quantum gravity encompassing all known forces.

Therefore this new solution appears worthwhile to explore, from a theoretical as well as an observational point of view.

In this paper, I will attempt to further develop the ideas and insights reported in [11, 12, 13, 10], with particular emphasis on the interpretation that the interior matter state of the solution consists predominantly out of low energy string-type matter bounded by a 2D membrane.

2 A short introduction to the holographic solution

The holographic solution, on which the calculations presented in this paper are based, solves the Einstein field equations with zero cosmological constant exactly. It’s metric in the usual spherical (Schwarzschild) coordinate system \((t, r, \theta, \phi)\) and with the \((+ - - - )\) sign convention is given by:

\[
 ds^2 = Bdt^2 - Adr^2 - r^2d\Omega^2
\]

with

\[
 B = \frac{1}{A} = \frac{r_0}{r_0} \theta(r - r_h) + \left(1 - \frac{r_+}{r}\right)\theta(r - r_h)
\]

\[
 r_h = r_+ + r_0 \text{ is the boundary of the matter distribution, } r_+ = 2M \text{ is its gravitational radius. } r_0 \text{ is a scale parameter, which has been shown in [10] to be roughly twice the Planck length. Throughout this paper natural units } c = G = \hbar = 1 \text{ will be used.}
\]

The matter fields of the solution, which can be derived from the metric by simple differentiation (see for example [11]), are given by:
\[ \rho = \frac{1}{8\pi r^2} \theta (r - r_h) = -P_r \]  
(3)

\[ P_\perp = \frac{1}{16\pi r_h} \delta (r - r_h) \]  
(4)

\( \rho \) is the energy density, \( P_r \) is the radial pressure, \( P_\perp \) describes the pressure in the two tangential directions.

From equations (3, 4) one immediately sees, that the interior matter state of the new solution is that of a collection of strings, layed out radially and - in a sense - attached to the 2D-membrane, which constitutes the boundary of the matter-distribution.

Remarkably, this new - purely classical - solution fits quite well with the theoretical expectations of string theory, i.e. 1-dimensional strings attached to D-branes, here: a 2D-membrane in 3D curved space. In fact one could say, that this new solution, had it been found earlier, would have in a sense "predicted" strings attached to membranes as one of the basic building blocks of nature.

### 3 A determination of the string’s transverse extension

Let us explore the interior matter state in more detail. According to equation (3) the (positive) string tension \( \mu \) is given by:

\[ \mu = -P_r = \frac{1}{8\pi r^2} \]  
(5)

The tension falls off with an inverse square law. For large \( r \), such as the current radius of the universe \( (r \approx 10^{61} r_P) \), the energy density in the strings is very low, yet almost exactly equal to the mean energy density of the universe as we see it today. For these low energies we can be quite confident that the classical field equation of general relativity are an excellent approximation to the true unified quantum theory of gravity.

The holostar solution allows us to determine the total number of strings attached to the boundary membrane by a simple argument. It is very well known, that any one string introduces a deficit angle \( \Delta \varphi \) in the flat (background) geometry proportional to the string tension (see for example [8, p. 313]):

\[ \Delta \varphi = 8\pi \mu = \frac{1}{r^2} \]  
(6)

The holostar solution, however, describes a curved space-time. For a large holostar the curvature at the membrane - almost - induces a spherical topology, nearly indistinguishable from a black hole of the same gravitational mass. Let us denote by \( N_p \) the number of strings (or rather string segments) attached to the boundary membrane. The individual deficit angles of all strings must add
up (almost) to the solid angle of the sphere.\textsuperscript{4} We therefore get the condition $N_p \Delta \varphi = 4\pi$, from which the following important result follows:

$$N_p = 4\pi r^2 = A$$  \hfill (7)

For large holostars this relation is exact to order $\Delta N_p \approx 1$. $A$ is the proper area of the membrane measured in Planck units. We find, that $N_p$ strings segments, laid out radially on a flat Minkowski background space, actually induce a curvature in this background space via the individual deficit angles of the strings. If we lay out a large number of string segments with the right tension in the radial direction we can "create" a large black hole type object of arbitrary size by an explicit construction.

Equation (7) tells us, that every string segment occupies a membrane segment of exactly one Planck area. This result is a genuine prediction of classical general relativity. There is no other argument involved than the validity of the field equations (with zero cosmological constant), spherical symmetry and the argument, that the deficit angles of all strings must add up to the solid angle of the sphere for a large black hole type object.

This result can be derived by an independent argument: For any classical string the string tension $\mu = -P_r$ is nothing else than the energy per unit length, i.e. $\mu = \delta E/\delta l$. Now consider a large holostar and imagine a thin spherical concentric shell situated at radial position $r$ with proper thickness $\delta l$. This thin shell will be punctured by $N_p$ radial strings. If $\delta l$ is chosen small enough, no strings will "end" within the shell. The energy $\delta E$ per string segment is $\mu \delta l$, so that the total energy in the shell is given by:

$$E = N_p \delta E = N_p \mu \delta l = \frac{N_p \delta l}{8\pi r^2}$$

where $\mu = -P_r = 1/(8\pi r^2)$ from the holostar equations was used.

Let us compare this energy to the energy of the shell calculated from the holostar solution. The proper volume of any thin concentric shell is $\delta V = 4\pi r^2 \delta l$. Using the holostar-expression for the interior energy-density $\rho = 1/(8\pi r^2)\delta l$ the total energy in the shell can be calculated from the product of energy-density times proper volume:

\textsuperscript{4}This simple "summing up" of deficit angles over a (fixed!) flat background space works, despite the non-linearity of the field equations: The holostar solution resides in the "linearized sector" of the field equations. In any spherically symmetric problem a string equation of state $\rho + P_r = 0$ has the effect to reduce the generally non-linear equations to a single linear one order differential equation of a single variable, the time coefficient of the metric $B$. The matter-density and principal pressures are linear combinations of $B$ and its first and second derivatives (the second derivative of $B$ is only required for the tangential pressure). See \textsuperscript{11} for a somewhat more detailed discussion.

Or stated somewhat differently: It is the zero active gravitational mass-density of the strings, which allows us to construct string theory in a linear perturbation expansion over a fixed flat background geometry (at least for a spherically symmetric problem), despite the non-linearity of the field equations in the general case! Therefore in the opinion of this author the major criticism that is often leveled against string theory, that it "does not take the non-linearity of gravity properly into account", "relies on a perturbation expansion over a flat (Minkowski) background" or "requires some pre-geometry" looses much of its bite.
\[ E = \rho \delta V = \frac{\delta l}{2} \]

Setting both energies equal we find that the number of strings puncturing any spherical surface at radial position \( r \) is given by \( N_p = 4\pi r^2 = A \), i.e. exactly the result that was obtained by the deficit angle argument. However, the second derivation is more general. It refers to any interior concentric thin shell at arbitrary radial position \( r \). Therefore the string separation in the tangential direction is \textit{universal}: Any radial string-segment in the holostar’s interior has a tangential extension of exactly one Planck area.

\[ A_\perp = A_{Pl} = \frac{Gh}{c^3} \]

What does this result imply for the interior structure of a compact self-gravitating object, described by the holostar solution?

Loosely speaking the boundary membrane has \( N_p \) string segments attached and every string segment occupies a Planck area of the membrane. The tangential (positive) pressure in the membrane can be thought to be created by the transverse “wigglings” of the strings attached to the boundary membrane.\(^5\)

Within the interior of the holostar solution the tangential pressure components are zero. The negative radial pressure is nothing else than the tension of the strings. The string tension - and therefore the energy-density of the strings - grows, as we approach the center. The transverse extension of the strings is universal, meaning that the strings are \textit{densely packed throughout the whole interior}. If one approaches the holostar’s center, the number of radially outlayed strings puncturing any sphere concentric to the center declines, as the proper area of the sphere becomes smaller. The center is reached when there is just one string segment of roughly Planck length left, filling out roughly a Planck volume.\(^6\)

We can picture the holostar solution as the densest possible collection of radially outlayed strings. The holostar’s \textit{curved} classical space-time arises from an explicit construction, by laying out a maximally dense package of string segments radially on a flat Minkowski background space-time. It is clear from this construction, that the holographic solution is the most compact non-singular spherically symmetric solution for a self-gravitating object.

This construction actually might be at the heart of the answer, why a holostar does not collapse under it’s own gravity to a singularity, although its boundary lies just a few Planck-distances outside of its gravitational radius: If we take string-theory and it’s prediction of a minimum transverse dimension of the strings seriously, we logically have to accept that it is exactly this minimum

\(^5\)Note, that the membrane has no mass-energy, only tangential pressure. This is obvious in the string-picture, because mass-energy resides in the string’s longitudinal dimension (at least for large strings): A string-segment of zero-length has zero mass-energy. All string segments are perpendicular to the membrane and the membrane has zero thickness. Therefore the membrane’s mass-energy must be zero.

\(^6\)There might be modifications to this statement at very high energies, as classical general relativity is expected to break down at the Planck-energy.
transverse dimension that prevents the formation of singularities and at the same
time allows us to construct arbitrarily extended singularity free self-gravitating objects, nearly as compact as black holes, whose number of fundamental degrees of freedom (strings!) are real\(^7\) and don’t scale with volume, but with area.

4 On the relation between string length and tension

We have already seen, that the number of string segments attached to the
holostar’s boundary membrane is \(N = A\). Any string segment has two end
points. In the very simple analysis in this section we are only interested in
the long strings, which end on the boundary membrane. Any closed string in
the interior is expected to shrink to small overall size, suggesting a particle
interpretation. We will neglect the contribution of closed strings (=particles?)
in the following argument.

If there are no closed strings in the interior space-time, the two end-points of
every string must end on the boundary membrane, which is the only structure
in the holostar space-time resembling a D-brane. According to string theory,
"loose" string ends should end on D-brands. Therefore any one string will
consist out of two segments, attached to the membrane and extending radially
into the holostar’s interior. The interior string ends will join at some radial
coordinate position \(r\) within the interior space-time. See figure 11 for a crude
pictorial representation.

Therefore the total number of strings \(N_s\) is half the number of segments
attached to the membrane:

\[
N_s = \frac{N_p}{2} = 2\pi r_h^2
\]

The number of string segments puncturing a concentric spherical shell with
radius \(r\) and radial thickness \(dr\) is given by

\[
dN_p = 8\pi r dr
\]  

We would like to derive a relation between the string length and its tension. In general relativity length measurements are observer-dependent. In the
holostar space-time there are two natural ways to measure the length of a string.
An asymptotic observer at infinity will determine the string length by measuring
(or calculating) the time of flight of a photon travelling along the full length of
the string. A geodesically moving observer in the holostar’s interior space-time,
however, will find it more natural to measure the string length by determining
the proper time it takes himself to travel along the full length of the string.

\footnote{not just fictitious "boundary states" on a locally undetectable surface in vacuum, whose position can only be determined by knowing the whole space-times future - the event horizon}
4.1 Point of view of an asymptotic observer at spatial infinity

Let us first discuss the viewpoint of the asymptotic observer. The local speed of light in the radial direction in the holostar’s interior, measured by an observer at rest to the coordinate system, can easily be read off from the metric. It is given by:

\[ c_r = \frac{r_0}{r} \]  

With \( dl = dr/c_r \) the length of a string segment \( L_\nu \), ranging from radial coordinate position \( r \) to the boundary membrane then is given by:

\[ L_\nu(r) = \int_r^{r_b} dl = \int_r^{r_b} \frac{r}{r_0} dr = \frac{r_b^2 - r^2}{2r_0} \]  

The total length of all string-segments is given by integrating over all string
segments \(dN_p\)

\[
L_{tot} = \int_0^{r_h} L_p \, dN_p = \frac{\pi r_h^4}{r_0}
\]  

(11)

With \(N_s = N_p/2\) the mean string length follows

\[
\bar{L} = \frac{2L_{tot}}{N_p} = \frac{r_h^2}{2r_0}
\]  

(12)

We see that the mean string length, as measured by an observer at infinity, is inverse proportional to the local value of the string tension at the membrane. The product of string tension and average string length is constant and given by:

\[
\mu \bar{L} = \frac{1}{16\pi r_0}
\]  

(13)

This value is equal to the pressure of the membrane of a zero mass-holostar with \(r_+ = 0\) and \(r_h = r_0\).

It is also possible to calculate the energy of a string segment. For any one string segment, its total energy is nothing else than the integral over \(dE = \mu dl\).

An asymptotic observer at infinity will calculate the energy to be

\[
E_p(r) = \int_r^{r_h} \mu dl = \frac{1}{8\pi r_0} \ln \left(\frac{r_h}{r}\right)
\]  

(14)

The total energy is given by an integral over all string segments \(dN_p\):

\[
E_{tot} = \frac{r_h^2}{4r_0}
\]  

(15)

so that the mean energy per string amounts to

\[
\bar{E} = \frac{1}{8\pi r_0}
\]  

(16)

Therefore the mean energy and mean length of the strings in the holographic solution are related to the (local) value of the string tension at the boundary membrane in the following way:

\[
\frac{\bar{E}}{\bar{L}} = 2\mu = \frac{1}{A} = \frac{1}{4S}
\]  

(17)

4.2 Point of view of the geodesically moving interior observer

The geodesically moving observer has a different measure of length: His own proper time \(\tau\) of travel along the string length. It can be shown that \(r = \tau\) for a geodesically moving observer \[12\], so that this observer will see quite a different
picture. For him space-time has the appearance of being flat. The string length, measured in units of proper time of travel, is nothing else than

\[ L_p(r) = r_h - r \]  

so that the total length of all string-segments amounts to nothing else than the volume of a sphere in flat 3D-space:

\[ L_{tot} = \int_0^{r_h} L_p \, dN_p = \frac{4\pi}{3} r_h^3 \]  

The mean string length then is proportional to the holostar’s gravitational radius:

\[ \bar{L} = \frac{2r_h}{3} \]  

The mean string length, as measured by a geodesically moving observer, is inverse proportional to the pressure in the boundary membrane, whereas the (local) string tension at the boundary membrane is inverse proportional to the square of the string length (measured by the geodesically moving observer).

The mean energy residing in a string segment is calculated by the geodesically moving observer in the same way as the asymptotic observer, as an integral of the tension over the whole string length, with \( dE = \mu \, dl \). A geodesically moving observer moves nearly radially. Due to the radial boost-invariance of the holostar space-time the geodesically moving observer measures the same string tension as the stationary observer. We find

\[ E_p(r) = \int_r^{r_h} \mu \, dl = \frac{1}{8\pi r} \left( 1 - \frac{r}{r_h} \right) \]  

The total energy again follows from an integral over all string segments \( dN_p \):

\[ E_{tot} = \frac{r_h}{2} \simeq M \]  

We get the remarkable result, that the total energy residing in all of the strings, as measured by a geodesically moving observer, is nothing else than the gravitating mass of the holostar.

The mean energy per string then amounts to

\[ \bar{E} = \frac{1}{4\pi r_h} \]  

which is one fourth of the pressure in the boundary membrane. For the geodesically moving observer the mean string energy and the mean string length are related to the string tension at the boundary by

\[ \frac{\bar{E}}{\bar{L}} = 3\mu \]
5 A coordinate system of strings and Mach’s principle

The radially outlayed strings define a more or less rigid coordinate system within the whole holostar’s interior. If we are far away from the center, this “coordinate system” is nearly flat. This has to do with the fact, that the radial metric coefficient $g_{rr} = r/r_0$ becomes very large at appreciable distances from the center. Consider an observer at radial coordinate position $r$ far away from the center. Any proper sphere with the observer at its center appears extremely flattened in the radial coordinate direction. Take the observer’s radial coordinate position to be $r \approx 10^{61}$, corresponding to the current Hubble-radius of the universe (in natural units). Place a sphere with proper radius $r_p \approx 10^{61}$ around this observer, i.e. $r = r_p$. Due to the immense shrinkage of radial ruler distances, this sphere covers a radial coordinate interval range $\delta r = r_p / \sqrt{g_{rr}} \approx 10^{30}$. This is a factor of $10^{30}$ smaller than $r_p$. Instead of reaching back to $r - r_p = 0$ the sphere only reaches back to radial coordinate position $r - \delta r = 10^{60} - 10^{30} = 10^{60}(1 - 10^{-30})$.

The interior radial metric coefficient $g_{rr} = r/r_0$ induces an enormous shrinking of radial ruler-distances. Viewed in the stationary $(t, r, \theta, \varphi)$ coordinate system a proper sphere whose origin is situated far away from the center is an extremely "thin", almost membrane-like structure. For a geodesically moving observer the sphere is even "thinner", due to Lorentz contraction in the radial direction [12]. The strings passing through this proper sphere are parallel to each other for all practical purposes. The total number of string segments passing through any such sphere is equal to its cross-sectional area in the direction perpendicular to $\partial r$

$$N = \pi r_p^2 = \frac{A_p}{4}$$  \hfill (25)

where $A_p$ is the proper area of the sphere’s boundary, measured in Planck units. This result is independent from the position of the observer (there might be a small correction for $r \approx r_{Pl}$). Therefore this result holds locally within any arbitrary space-time region of the holostar’s interior. We find the remarkable result, that the number of string segments (i.e. the number of fundamental degrees of freedom) in any interior spherically symmetric region of the holographic solution is exactly equal to the Hawking entropy.

Note also, that the matter-density (as well as the string tension) within any sphere with proper radius comparable (or smaller) to the radial coordinate position of it’s center ($r_p < \approx r$) is nearly uniform with a deviation from homogeneity of the order $1/\sqrt{r}$. For a proper sphere with radius equal to today’s Hubble-length ($r_p \approx 10^{61} r_{Pl}$), situated at radial coordinate position $r = 10^{61} r_{Pl}$ the matter-density differs at most by $1 \pm 10^{-30}$. This makes it clear, that at large distances from the center the holographic solution is indistinguishable from a homogeneous FRW-model for all practical purposes.

The coordinate system provided by the strings consists out of real matter, so we are led to a very Machian viewpoint. The Newton bucket finally knows -
locally! - why it must accelerate with respect to the global frame produced by all of the other matter within the universe. Rotation against the string-frame is locally detectable, irrespective of the relative alignment of the rotation axis. Inertial motion with respect to the string frame, however, will only be detectable in the direction perpendicular to the strings, due to the boost invariance of any sufficiently small local frame in the string’s longitudinal direction. Any perpendicular component of the motion is expected to produce an anisotropy in the frame of an observer moving with nearly constant velocity, which should be measurable in principle. In fact, such anisotropies have already been detected\cite{16}, although their interpretation stands out.

Although the coordinate system provided by the strings is real, one must keep in mind that the string tension/energy is so low, and the strings are packed so densely, that we will not be able to detect their presence directly. The active gravitational mass-density of a string is zero, so we cannot detect a string by it’s direct gravitational acceleration. There is none. What one can observe - in principle - is the deficit angle induced by the strings with respect to a flat geometry. The deficit angle produces ”tidal forces”, which can be observed in principle. However, according to equation\cite{16} the deficit angle for a single string is $\Delta \varphi \approx 10^{-122}$ rad at our current position $r \approx 10^{63} r_{Pl}$. Such a small deficit angle is not observable, neither for a single string nor any extended space-time region accessible to direct measurements, such as the solar system. The tidal action of the strings manifests itself only in the very large scale structure of the universe, approaching the local Hubble-radius.

6 Does the cold dark matter consist of low energy strings?

The holostar solution has been shown in\cite{12} to be an astoundingly accurate model for the universe, as we see it today. For the further discussion I will assume that the holostar solution actually is the essentially correct description for the universe.\footnote{Naturally, this is just an assumption. Compared to the intense study of the FRW-type solutions the properties of the holographic solution are not very well known. Yet the theoretical and observational evidence accumulated so far justifies the assertion, that the holographic solution has a fairly high \textit{potential} to explain many of the phenomena that are unexplained in the standard FRW-model. Whether it - or a generalization thereof - will eventually explain all the phenomena is an open question. As for any other solution of the Einstein field equations, it will have to be the tedious task of comparing theoretical predictions with the vast amount of observational data, that must guide us to select the solution, that nature has chosen from the various theoretically possible choices. The holostar solution is \textit{one} such choice. So far it fared well. Yet it is waiting to be falsified. This should not be difficult, as it has practically no free parameters that could be adapted to observation and it does not provide many handles for modification. One can attempt generalize the solution to the charged and/or rotating case. These generalizations most likely will not significantly change the general picture. The charged holostar solution discussed in\cite{10} has the same total interior matter state as the uncharged solution. The only difference is, that part of the interior mass-energy is of electro-magnetic origin.}
If this is the case, the form of the stress-energy tensor of the holostar solution suggests that the universe might actually be a string dominated structure, in the sense that the dominant type of matter resides in strings whereas the "ordinary" matter (in form of particles) is just a correction/perturbation.

This expectation is quite in agreement with the dynamical mass-estimates from astronomical observations, which seem to imply, that a large fraction of matter in our universe is not in the form of baryonic (ordinary) matter, but resides in a so called Cold Dark Matter component (CDM). The currently favored FRW-type models quite clearly require CDM in order to explain the observational facts. This does not necessarily mean, that CDM must exist: The experimental determination of the CDM-contribution to the total energy-density is model-dependent. A different model for the universe, such as the holographic solution, might require quite a different fraction of CDM in order to reconcile the model with the observations, possibly even no CDM at all. Yet if the existence of non-baryonic matter turns out to be a real phenomenon, it seems reasonable to assume that the CDM might be nothing else than low-energy strings.

Can we estimate the proportion of "stringy matter" with respect to the "normal" matter (=particles) in the holostar model of the universe?

The starting point for this estimation will be, that at very high energies, i.e. at the string scale, strings and particles should be thermalized. The energy density of a string degree of freedom will be comparable to the energy density of a particle degree of freedom. If we can determine the fundamental ratio of string to particle degrees of freedom in thermal equilibrium, we at least know the (approximate) ratio of the energy densities at the string scale. Our next task is to estimate how this ratio evolves to the low energy, low density region of the universe, as we see it today.

At high temperatures the ratios of the respective degrees of freedom of strings to particles can be calculated quite easily. There is one catch: This ratio will be calculated in the context of general relativity (GR). Although the properties of the holostar solution suggest that GR is a remarkably accurate description to the phenomena, even at very high energies, GR is expected to break down at the string scale. Whether this break-down will be rather moderate or catastrophic is not clear at our current state of knowledge. The implicit assumption in the following derivation is, that GR will only suffer a moderate break-down. If this is actually the case, we can interpret the numerical figures derived later as a fairly reliable order of magnitude estimate.

From the argument given in section 3 we know, that there are \( N_p = A \) string segments attached to the membrane of any sufficiently large holostar, where \( A \) is the membrane’s area. However, the total number of strings within the holostar is just half this number, as explained in section 4, at least as long as the number of closed interior loops is small.\(^9\) See also Figure 11.

\(^9\)There is some reason to believe, that the number of interior closed loops is in fact small. Any interior closed loop will tend to shrink to its smallest possible size. This suggests, that an interior closed loop will represent particles, which justifies the neglection of closed loops: When we compare the number of degrees of freedom of strings to particles, we should not count the particle-degrees of freedom when we determine the string-degrees of freedom and
In [13] the number of particles in thermal equilibrium at ultra-relativistic energies in a holostar has been calculated to be \( N = A/(4\sigma) \), where \( \sigma \) is the entropy per particle. The exact value of \( \sigma \) depends on the specifics of the thermodynamic model. The main parameter of the model is the ratio of fermionic to bosonic (particle) degrees of freedom. The dependence of \( \sigma \) on this ratio is very moderate. For all practical purposes \( \sigma \) lies in the range 3.15 – 3.3, which is quite close to the entropy per boson \( (\sigma \approx 3.6) \) or the entropy per fermion \( (\sigma = 4.2) \) of an ultra-relativistic gas with zero chemical potential.

The ratio of the number of strings with respect to the number of particles in the holostar-solution then is given by:

\[
\kappa = \frac{N_s}{N} = 2\sigma
\]  

(26)

Now we proceed to the second task.

It has been shown in [12], that the motion of particles within the interior holostar space-time conserves the ratio of the energy-densities of different particle species. This is true for geodesically moving massless and massive particles, as well as for massive particles following an arbitrary trajectory. The energy (and entropy-) densities of the different particle species in the holostar’s interior space-time evolve proportional to \( 1/r^2 \propto 1/t^2 \), irrespective of particle-type.

This is a theoretical result. However, there is some observational evidence that this characteristic feature of the holostar solution actually might hold in our universe, at least for fundamental particles: The energy densities of electrons and photons are nearly equal in our universe. See [12] for a more detailed discussion.

There is even some evidence, that this assumption might - approximately - hold for compound particles, such as baryons.\(^{10}\)

What is the case with stringy matter? Here the answer is trivial: The interior stress energy tensor of the holostar solution is that of an ensemble of strings. The energy density of the strings at any radial position is nothing else than the quantity in the 00 slot of the stress-energy tensor, i.e. \( \rho_s = 1/(8\pi r^2) \).

Therefore, for "stringy matter" \( \rho_s \propto 1/r^2 \propto 1/t^2 \) holds as well.

\(^{10}\) A nice feature of the static holostar solution is, that one determine the total number of ultra-relativistic particle degrees of freedom \( f \) at ultra-high temperatures, when all particles are relativistic, experimentally and theoretically. This has been done in [13]. A lower bound for \( f \) can be derived from the observational data (total matter-density of the universe, CMBR-temperature), according to which \( f \approx 6350 \). The theoretical result is \( f = 2^{13/2}4\pi r_0^2 \), where \( r_0 \) must be evaluated at the temperature in question. There is some evidence that \( r_0^2 \approx 12/\pi \approx 4 \) at the Planck-energy, so that the theoretical value amounts to \( f \approx 7250 \). If one assumes that the ratios of the energy-densities of all fundamental particle species in the the holostar space-time with respect to each other are conserved, one must regard the proton, as the lightest compound particle, as a "repository" for the frozen out degrees of freedom at the Planck scale.

An electron has four degrees of freedom, so the proton to electron mass ratio must be roughly given by \( f/4 \). Using \( f \approx 7250 \) one comes quite close to the true value: \( f/4 \approx 1810 \), whereas \( m_p/m_e \approx 1836 \).
Based on these theoretical and observational insights let us make the general assumption, that the expansion of the universe - as described by the holostar model - conserves the relative energy- and entropy densities of the different species of matter.

We are almost ready. We have determined the ratio of the energy densities of strings and particles at high temperatures, and by the above proposal this ratio should also be - approximately - the ratio of the energy densities at any energy.

For a numerical prediction we need the entropy per particle $\sigma$. At very high energies, i.e. where both particles and strings are thermalized, it is quite likely that we have a phase with unbroken supersymmetry. Therefore it seems most appropriate to take $\sigma = 3.23$, which is the (mean) entropy per ultra-relativistic particle in a holostar which consists out of equal numbers of fermionic and bosonic degrees of freedom. With this figure the ratio of stringy matter to baryonic matter turns out as:

$\kappa = \frac{\rho_s}{\rho_b} = 6.45$ \hspace{1cm} (27)

This ratio is quite close to the ratio of CDM to baryonic matter determined by WMAP, according to which $\kappa \approx 6$.

The crucial assumption that the ratio of the energy densities of different species is conserved throughout the expansion might hold only approximately. The various phase transitions that occurred during the expansion of the universe from the Planck scale to the low energy scale today might modify this assumption. Whereas there is some sound theoretical as well as observational evidence, that this assumption is true when the chemically decoupled particle species move geodesically (i.e. below the electron-positron mass-threshold), one cannot expect a priori that the ratios are unaffected during the complicated phase transitions that took place at early times, such as the transition from the quark-gluon plasma to the hadronic phase.

One must also keep in mind, that the WMAP-determination of $\kappa$ is model dependent, and we are talking here about two very different models for the universe. One should therefore compare the ratio in equation (27) to some other estimates of the fraction of cold dark matter to baryonic (or rather "luminous") matter, which are more robust. The analysis of the rotation curves of galaxies and clusters of galaxies appear to give higher values. For example, the dynamical mass-estimates for the Coma-cluster point to a ratio of $\kappa \approx 15 - 20$.\footnote{Peacock estimates the mean mass-to-light ratio for baryonic matter $M/L \approx 14/h \approx 20$, in units so that $M/L = 1$ for the sun. The mass to light ratio for the COMA-cluster has been consistently estimated to be $M/L \approx 300 - 400$. If we take the matter in the COMA-cluster as representative for the CDM-fraction, we get roughly 15-20 for the fraction of CDM-matter to baryonic matter.}
7 Is the universe constructed hierarchically out of strings and membranes?

If strings (and boundary membranes) are the basic building blocks of nature, as string-theory claims - albeit so far not with too much experimental support - it is natural to assume that all of the matter we see today should be constructed out of these basic entities. How does this theoretical expectation compare to the low-energy world we happen to live in today?

Our current understanding is, that the basic building blocks of the universe are particles and black holes (in the centers of galaxies, in quasars or as remnants from super-massive stars). Point-like particles and black holes, which are vacuum-solutions of the field equations 12 don’t very much look like they could be composed out of strings and membranes.

The claim, that the universe itself might be nothing else than a very large holostar appears even more preposterous: The holostar has a center. In contrast, the current preferred model of a homogeneous and isotropic Friedman Robertson-Walker (FRW) universe assumes from the start, that there is no preferred point in space (however a preferred time!).

This assumption about how the universe ought to be is called the cosmological principle. It has guided us quite well, so far. Yet it is important to remember, that the cosmological principle is not a law of nature, but just a convenient assumption, which allows us to explain the phenomena by a solution of the field equations with fairly moderate mathematical complexity. Furthermore the cosmological principle, taken seriously, forces us to cope with some nasty problems, such as how to explain the remarkable homogeneity and isotropy of the CMBR. This particular problem is known as the "horizon problem". One of its solutions is inflation. But if we truly believe in inflation, the universe as a whole is chaotic. We just happen to live in one of its inflated subcompartments. Depending on the initial conditions, the primordial chaos will slip in, sooner or later. 13 Therefore if we are honest, the very idea that was devised so "save" the cosmological principle at the same time signals its downfall.

Is then the proposal of a hierarchically constructed universe a madman’s idea which goes against all experience and common sense? I believe not so. Black holes, the universe and maybe even particles can be explained quite consistently in terms of strings and membranes. A successful model at the classical level is the holographic solution.

7.1 Black holes

As should have become clear from section 2 of this paper, the holographic solution suggests, that a large black hole type object can be constructed simply by laying out strings attached to a spherically symmetric boundary membrane

12 The classical black hole solutions have vacuum everywhere, except for the "matter" that must be attributed to the point- or ring-like central singularities.

13 The cosmological constant and/or the "big rip" might force us to modify this statement.
in an overall spherically symmetric pattern. Although the object resulting from this construction is not a black hole, in the sense that it doesn’t contain an event horizon, it retains all essential features of a black hole, most notably its Hawking temperature and entropy. This has been shown in great detail in [13, 12]. Yet the main results can be derived quite effortlessly from the presentation given in this paper:

The number of strings within the holostar’s interior has been shown to be equal to \(N_s = A/2\). For any local observer far away from the centre we even have \(N_s = A/4\), according to the discussion in section 5. The strings quite evidently constitute the fundamental degrees of freedom of the holostar solution. It is well known, that the entropy of any large macroscopic system is proportional to its number of fundamental degrees of freedom. Therefore the holostar solution predicts \(S \propto A\) (in Planck units) with a factor of proportionality of order unity. An entropy proportional to area implies a temperature at infinity \(T_\infty \propto 1/M\), i.e. a temperature proportional to the Hawking temperature, via the thermodynamic relation \(1/T = \partial S/\partial E\), and using the fact that the total energy \(E\) of the holostar measured at infinity is equal to its gravitating mass \(M\). Now \(A \propto r_h^2 \propto M^2\) so that \(\partial S/\partial E \propto M\). This argument demonstrates, that the holostar is compatible with Hawking’s results for black holes, at least up to a possibly different constant factor.

Furthermore the holostar’s boundary membrane, whose properties are exactly equal to the - fictitious - membrane attributed to a black hole via the membrane paradigm, guarantees that the holostar’s dynamical action on the exterior space time is practically equivalent to that of a classical black hole: We know from the membrane paradigm that all (exterior) properties of a black hole can be described in terms of its fictitious membrane [19, 15].

Therefore the assumption, that the black hole type objects in our universe are rather singularity free holostars, built out of strings and membranes, is a viable alternative to the black hole solutions, which are built out vacuum, principally non-localizable event-horizons and singularities.

Furthermore, it is well known that the Hawking entropy can be derived rigorously in the context string theory [18], although so far only for extreme or near extreme black holes. Whereas the string-origin of the Hawking entropy should be more than obvious from this elegant derivation, the classical vacuum black hole solutions don’t have anything in common with strings.\(^\text{14}\) The string nature of the holographic solution is manifest. One might wonder what route mainstream physics would have taken, if the Hawking entropy-area law had been first derived in the context of string theory and the holographic solution had been known at that time.

### 7.2 The universe

What is with the universe itself? In [12] a fair amount of evidence has been compiled demonstrating quite clearly, that the holographic solution - or an ex-

\(^{14}\)Some authors have interpreted the ring-singularity in the Kerr-black hole in terms of strings. See [1] for such an attempt.
tension thereof - might develop into an alternative model for the universe. Some of the evidence was summarized in the introduction of this paper. The evidence is not yet conclusive. Yet there is reason to be optimistic: The holographic solution has practically no tunable parameters. It is easily falsifiable. Despite its "rigid" structure all of the predictions derived so far were verified observationally within the experimental errors. Furthermore, the holographic solution would answer a lot of unanswered questions, such as the origin of the matter-antimatter asymmetry in curved space-times [13, 14], the horizon problem of the standard cosmological models [12], the cosmological constant problem, the problem of singularities, information-loss, unitary vs. non-unitary evolution, just to name a few.

If the holographic solution, or an extension thereof, actually turns out to be a realistic model of the universe, our program to construct the universe hierarchically out of its basic building blocks, strings and membranes, is almost complete.

7.3 Particles

One question remains: How do "point-like" particles fit into this hierarchical picture? All of the fundamental particles of the Standard Model, i.e. the three generations of quarks and leptons, appear to be point-like up to the highest energy scales. There is no experimental evidence yet for any sub-structure.

On the other hand, point-like particles are the cause for severe problems, already on the purely classical level (see for example the infinite self-energy of any point-like classical particle). Some of the difficulties can be circumvented in quantum field theories. But although renormalization techniques are powerful tools to control most - and in some situations all - of the infinities, it is not yet clear, whether a unified description for all the phenomena can be devised, that incorporates point-like particles as one of its basic building blocks. String theory suggests otherwise.

The holographic solution itself suggests that elementary particles might be extended objects of roughly Planck size: The smallest conceivable holostar has its membrane situated at \( r_h = r_0 \). It has a finite boundary area \( A_0 = 4\pi r_0^2 \). It is easy to see from equation (2) that such an "elementary" holostar has zero gravitational mass: The exterior space-time of such an object is flat Minkowski space. Elementary particles are characterized by extremely small masses in natural units. For example, the proton’s mass is \( m_p \approx 10^{-19} \) in units of the Planck mass. Therefore, as a first approximation the masses of elementary particles can be considered to be zero. Although it is quite clear, that a spherically symmetric, uncharged holostar solution cannot describe any realistic particle with non-zero spin and charge, the solution suggests quite strongly - and quite in agreement with string theory - that we can have extended particle-type objects with masses comparable to the extremely low masses of elementary particles: The "elementary" zero mass holostar has a boundary area comparable to the Planck area.

Therefore it is suggestive to interpret "particles" in the hierarchical picture.
that has emerged from the previous discussion not as point-like, but as a spatially bounded collection of strings and membranes.

Due to the small transverse extension of the strings the interior "structure" of a particle composed out of strings will only become apparent at energies approaching the Planck energy. At energies well below the Planck energy such a particle can be treated as point-like for all practical purposes.

In the Appendix to this paper a toy-model which "constructs" the Standard Model of particle physics out of strings and membranes is given. This naive attempt to reduce the beautiful machinery of the full 9+1D string theory (or 10+1D M-theory) to the drawing of suggestive pictures in three spatial dimensions, quite curiously does a good job in "explaining" some characteristic features of the Standard Model of Particle Physics. It might prove useful to promote the imagination of string theorists to devise a realistic model.

The true nature of the fundamental particles of the Standard Model will most likely have to be answered by the yet to be found unified theory of quantum gravity. String theory appears as the most promising candidate to achieve the unification of all "forces" into a self consistent picture. Little experimental guidance did we have so far in accomplishing this monumental task. But the situation might have changed. We now have a solution to the Einstein field equations with zero (!) cosmological constant, which is constructed out of strings and membranes and at the same time appears to describe the low-energy phenomena in the universe, as we see it today, rather well. This solution - or an extension thereof - combined with the dualities of string theory, might eventually turn out to be a better guide to our understanding of the phenomena at any high or low energy, than we ever had before.

8 Discussion

The holographic solution has been interpreted as a model for the universe. In this picture the universe is nothing else than a large black hole type object, whose interior matter state is dominated by strings. The strings are layed out radially. The transverse extension of the strings in 3D space has been determined to be exactly one Planck area, regardless of the holostar’s size.

It was shown, that the large scale properties of the universe as we see it today arise naturally in a string context. The zero active gravitational mass-density of the strings implies $Ht = 1$ and predicts a nearly unaccelerated expansion. Both predictions are experimentally fulfilled to a rather good accuracy.

The possibility was explored, whether the cold dark matter observed in the universe might consist out of stringy matter. An argument was given which allowed us to estimate the ratio of cold dark matter to baryonic matter. The estimated ratio $\Omega_{CDM}/\Omega_b \approx 6.45$ is quite close to the experimental result $\Omega_{CDM}/\Omega_b \approx 6$ determined by WMAP. The argument relies on the characteristic property of the interior holostar space-time, according to which the (local) ratio of the energy- and entropy densities of the fundamental particle species remain constant during the expansion. This theoretically derived property has some
experimental support in the observation, that the energy-densities of photons and electrons in the universe are nearly equal.

Some arguments were given, that the universe might be constructed hierarchically out of its most basic building blocks: strings and membranes. In this hierarchical picture, black holes (or rather large black hole type objects) are nothing else than a scaled down version of the holographic solution. The classical holographic solution clearly demonstrates the inherent string nature of any large compact self-gravitating object. The entropy area law for black holes arises naturally from the string nature of the solution: The number of string segments puncturing the spherical boundary membrane of the holographic solution is proportional to the membrane’s area. Every string segment occupies a membrane segment of Planck area. The total number of fundamental degrees of freedom (the strings) scales with area. In contrast to a black hole, the holostar has no event horizon. Its singularity free interior matter state can be interpreted as the densest spherically symmetric package of strings. This maximally dense package is the fundamental reason why a holostar does not collapse to a singularity, regardless of its size, although its spherically symmetric boundary membrane lies barely two Planck distances outside of its gravitational radius.

The holographic solution is an exact solution of the Einstein field equations with zero cosmological constant. It is well known, that string theory has severe problems with a non-zero (positive) cosmological constant. The holographic solution suggests, that the phenomena can be explained in terms of an exact solution of the field equations with zero cosmological constant, if we take the string interpretation of the field equations seriously.

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A Are particles a collection of strings and membranes? - a toy model

The purely classical holographic solutions seem to suggest, that the universe basically consists of a collection of strings and membranes. In this appendix I explore the question, whether it might be possible to incorporate the "fundamental" particles of the Standard Model of particle physics into this hierarchical picture.

Note, that this section can not and should not be considered as predictive science, not even by it’s own author. It is primarily based on the drawing of suggestive pictures, which attempt to capture some of the very abstract results of string theory in a pictorial representation, guided - or rather misguided - by intuition alone, and not backed by any serious calculation. The author does know nothing about string theory! This section doesn’t even intend to propose a serious model for a fundamental particle. The sole purpose of this appendix is to illustrate in the most handwaving manner possible, that there is a fair chance to actually find a construction in the fully developed string formalism in 10 or 11 dimensions, that explains the properties of the fundamental particles of the Standard model in terms of strings and membranes.

Having given ample warning, I will proceed to "construct" the particles of the Standard Model out of one-dimensional strings and two-dimensional membranes situated in a space of three spatial dimensions.\textsuperscript{15} The starting point to this construction is the observation, that

- the basic building blocks of the universe - in 4D space-time - appear to be strings and 2D-membranes, according to the string-interpretation of the holostar solution
- strings are extended objects, whereas particles are confined to a small volume

If we would like to build particles from strings and membranes, we must arrange the strings in some closed, bounded structure. Unfortunately, there are unlimited possibilities to produce closed objects out of strings and membranes. Therefore we have to reduce the possibilities to a manageable number.

To accomplish this feat, we first observe, that an object with entropy 1 consists of four membrane segments, each of Planck size, according to the Hawking entropy formula. It therefore seems appropriate to construct our "particles" out of basic building blocks, consisting out of 4 membrane segments combined into one spherical membrane with 4 string ends attached:

Let us denote this basic building block with the term \textit{s1} (for entropy = 1).

Second, we want to construct the fermions of the Standard Model. How many basic s1-objects do we require? In \textbf{13} the thermodynamics of the holostar’s interior matter state was discussed. If one assumes that the interior matter state

\textsuperscript{15}Quite clearly already the starting point of the construction has nothing to do with string theory, which is a theory in 10 or 11 space-time dimension.
consists of a gas of ultra-relativistic fermions and bosons, the entropy of an ultra-relativistic fermion turns out somewhat larger than 3, quite independent from the specifics of the model. This suggests, that fermionic particles should be constructed out of three s1-objects (or - more generally - out of 12 membrane segments of Planck area).

Third, we need a notion of charge. For this we note, that there are two different possibilities how a string can attach to the s1-objects. Either the string attaches to two membrane segments on the same s1-object, or it forms a link between two different s1-objects. In string theory it is known, that charge can be interpreted as an interactions "within a brane", whereas gravity is interpreted as interactions "between branes". With this notion in mind, we label any string attached to the "same brane" (=s1-object) with a "charge" $Q = 1/3$.

Now let us construct all possible combinations of strings and membranes, with the constraint, that every one of the 12 membrane segments of the three s1-objects has one string end attached.

Curiously, we find four different "particle species". Even more curiously, these particle species (with our strange "notion" of charge) correspond exactly to the first generation of particles in the Standard Model.

We have an "electron". There are three string segments attached to the same s1-object, which sum up to a total "charge" $Q = 1$. The other three string segments form links between different s1-objects. The construction is
We have a "neutrino". All six string segments form links between different s1-objects, there are no "charge loops". The construction is symmetric.

We have an (anti-) "down quark". One s1-object contains a "charge loop". The other five string segments connect to different s1-objects. The total "charge" is $Q = 1/3$. The construction is not symmetric. The s1-object that contains the charge can be distinguished from the other two "uncharged" s1-objects. We require a symmetry, that symmetrizes (or anti-symmetrizes) the three possible configurations, i.e. a symmetry that "rotates" the "charge" between the three s1-objects: "Color".

We have an "up quark": Two of the s1-objects harbor a "charge loop". The total "charge" is $Q = 2/3$. Again the construction is not symmetric and we find "Color".

These are all possible combinations with the rules given beforehand.

One more handwaving argument suggests itself: As long as the "particles" are at large distances from each other, each can preserve it's own identity. The different particle species are distinguishable. But when the particles come very close to each other, the individual bonds between the s1-objects will break up, leaving only the s1-objects. The different fermionic particles are unified into one description, the GUT scale. If the energy is turned up even higher, the s1-objects will break up too, so that there will only be mixture of membranes and strings left, with no other discernable sub-structure: The string scale. We find that the pictorial toy-construction makes the "handwaving pictorial prediction",
that the string scale will be higher than the GUT-scale.

I will leave it as an exercise to the reader, to "prove" geometrically, that the g-factor of a rotating charged black hole is exactly 2, under the premise that "charge = strings attaching to the same membrane" and "mass = strings attaching to a different membrane". See Misner-Thorne-Wheeler, p. 1149 for the required geometrical insight to perform this deed.
Figure 5: down quark

Figure 6: up quark

u: $Q=2/3$, 3 colors