String Theory as a Theory of Species

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Abstract. In this talk I summarize my recent work with Gia Dvali on the dynamics of theories containing gravity and weakly coupled particle species.

1. Gravity and Species

What makes gravity special and different from any other form of interaction in Nature is that the scale setting the intensity of the interaction, namely the Planck scale, is also fixing the bound on information storage [1] [2]. This double role of the Planck scale is at the core of the holographic meaning of gravity. The existence of N weakly coupled particle species, where by that we will mean particles with decay width much less than their mass , entails a minimum amount of information of N bits. The species scale L_N is simply defined as the minimum size where this information can be stored setting a length scale below which physical resolution of species becomes gravitationally impossible [3]. In asymptotically flat space-time of dimension $D = 4 + d$ this scale is given by:

$$L_N = N^{\frac{1}{D-2}} L_D \tag{1}$$

with L_D the Planck length in D dimensions. In this sense a theory of N weakly coupled species is characterized by two length scales L_D and L_N related by (1). The aim of this talk is to show that a theory of species fits into a weakly coupled string theory with the species scale playing the role of the string scale [4].

2. Proving the Species Scale: Black Holes

The simplest way to prove the species scale is to consider the effect of species on black hole physics [5]. In particular on the evaporation of neutral black holes with negative specific heat. One immediate consequence of the existence of particle species is to increase the rate of evaporation of semiclassical black holes reducing the evaporation time $\tau = \frac{M_{bh}^3}{M_{pl}^4}$ by a factor of N. This means that the black hole stops to behave semi-classically at

$$\tau = N.R(M_{bh}) \tag{2}$$

with $R(M_{bh})$ the gravitational radius. The previous semi-classicality bound sets - as the minimal possible size for Einstenian black holes - the species scale L_N. Thus we can already conclude that quantum mechanically a theory of gravity with species possesses a natural UV cutoff L_N larger than the Planck scale beyond which Einstenian gravity should be modified.

A hint on how to proceed in order to UV complete the theory between the Planck scale and the species scale comes from the expression of the mass and entropy of the black hole when it reaches the species scale, namely:

$$M_{bh} = N L_N^{-1} \tag{3}$$

and

$$S = N \tag{4}$$

Expression (3) is formally identical to the mass formula for a string state with number of oscillators $N_{osc} = N^2$ and string length $l_s = L_N$. Moreover , at least asymptotically , the entropy of such string state goes like $\sqrt{N_{osc}}$ in agreement with (4). However, in order to interpret this string entropy as a Bekenstein-Hawking entropy we should require

$$S = \sqrt{N_{osc}} = (\frac{l_s}{L_{Pl}})^8 \tag{5}$$

corresponding to a black hole of size equal to the string length. This leads to the well known black hole string correspondence [6] relation $\sqrt{N_{osc}} = \frac{1}{g^2}$ for g the string coupling.

Hence we can formally map the theory of gravity and N species into a string theory by the following rule of correspondences:

$$L_N \to l_s \tag{6}$$

and

$$N \to \frac{1}{g^2} \tag{7}$$

Under this form of correspondence the standard relation

$$L_{Pl} = g^{\frac{1}{4}} l_s \tag{8}$$

becomes the definition (1) of the species scale in ten dimensions. The correspondence (6) and (7) naturally maps some features of black hole physics in the presence of weakly coupled species into the dynamics of black holes once we complete gravity in the UV with string theory. In particular in the presence of N species the black hole entropy is bounded by the number of species:

$$S > N \tag{9}$$

corresponding to the bound on the black hole entropy in string theory

$$S > \frac{1}{g^2} \tag{10}$$

Similarly the maximum Hagedorn temperature $T = \frac{1}{l_s}$ corresponds to the Hawking temperature of the smallest possible black hole in the presence of species, namely $\frac{1}{L_N}$. In summary when in a theory of species a black hole reaches the species scale it becomes a string mode with number of oscillators given by $\sqrt{N_{osc}} = N$. It is important to stress that the existence of a length scale - different to the Planck scale - where gravity should be UV completed is a necessary requirement of any consistent theory of species coupled to gravity.

3. Chan Paton "species"
Probably the most natural frame for defining a theory with species and gravity is open string theory with Chan Paton factors attached at the end points of the string. For n different Chan

Paton factors the number of species is $N = n^2$. In this particular case the resolution scale for these species is just the string length. This leads to the bound

$$L_N > l_s \tag{11}$$

which obviously implies a bound on the number of D-9 branes we can pile up one on the top of each other. Since D-branes gravitate with a tension $T_9 = \frac{M_s^{10}}{g}$ the collective gravitational source created by a stuck of n of them is

$$R^{-2} = nT_9 G_{10} = ngM_s^2 \tag{12}$$

The bound (11) appears as a consequence of requiring that R should not exceeds the string length. In fact for $R = l_s$ we get

$$N = n^2 = \frac{1}{g^2} \tag{13}$$

that leads to $L_N = l_s$.

The species scale plays a natural role in the definition of gravitational holographic duals of theories without gravity. In a theory without gravity and N species, the number of degrees of freedom for the regularized theory defined in a finite box of volume one, depends on the UV cutoff Λ - we have decided to choose - as $\frac{N}{\Lambda^3}$. This number must be equal to the number of holographic degrees of freedom of the five dimensional gravity dual theory i.e $\frac{A(\Lambda)}{G_5}$ for $A(\Lambda)$ the corresponding regularized boundary area [7]. However the number of species is given by the standard relation (1) so we get

$$A(\Lambda) = \frac{L_N^8 . G_5}{G_{10} \Lambda^3} \tag{14}$$

leading to the well known AdS/CFT [8] result $A(\Lambda) = \frac{R^3}{\Lambda^3}$ for $R = L_N$ the species scale.

4. Strings at Strong Coupling
In the previous sections we have mapped theory of species into weakly coupled string theory. A natural question is of course what happens when we move into strongly coupled string theory. Consistency with the picture we have presented until now would require the existence of a weakly coupled dual description with g_d the dual string coupling with

$$N_d = \frac{1}{g_d^2} \tag{15}$$

the effective number of species of the dual description and with

$$L_N^d = N_d^{\frac{1}{8}} L_{10} \tag{16}$$

the dual species scale. As an example let us consider the case of M-theory as the strong coupling description of type IIA string theory. In this case the weakly coupled species in the dual description are the D-0 branes [9]. The number of those species is $n = \frac{R}{L_{11}}$ for $R = l_s . g$. Now it is easy to check that

$$L_{11} = n^{\frac{1}{8}} L_{10} \tag{17}$$

i.e the eleven dimensional Planck length becomes the species scale of the dual theory. Moreover we get

$$n = g^{\frac{2}{3}} \tag{18}$$

leading to define the dual coupling as

$$g_d = g^{-\frac{1}{3}} \tag{19}$$

which is the one we get when we move from the string frame into he M-theory frame: $X \to g^{\frac{1}{3}}X$, for X the matrix coordinates of D-0 branes. In summary the meaning of L_{11} is to set the species scale for the weakly coupled dual D-0 species.

5. Concluding Remarks

The conjecture we are putting forward in this talk is that a natural answer to the question: What is string theory? could be, the UV completion of a theory of species and gravity with the species scale as the string scale. It is important to stress that the need for an UV completion above the Planck scale is a direct and quite universal consequence of the holographic interplay between black hole dynamics and the underlying information encoded in the existence of particle species.

Acknowledgments

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