String Theory as a Theory of Species.

Work done with.
Gia Dvali.

What do we get when we consider

Gravity

and

N Species ?

- Black Hole physics and/or Holographic arguments lead to predict the existence of an UV cutoff (The species scale L_N) below which Einsteinian Gravity should be modified.

Note that for N large enough

$$L_N \gg l_{pe}.$$

The questions we will address in this talk are:

- What is the physical meaning of L_N
- What is the natural UV completion of a theory of gravity with species.
- What happens to a B-H when it reaches the species scale.

Our temptative answer is that a theory of gravity with species which is characterized by:

$$\boxed{\underbrace{l_{pe}}_{\text{Planck length}} \;,\; \underbrace{N}_{\text{\# of species}} \;,\; \underbrace{L_N}_{\text{species scale}}}$$

naturally fits into STRING theory with.

$$\boxed{\underbrace{l_{pe}}_{\text{Planck length.}} \;,\; \underbrace{g_s^2 \simeq \frac{1}{N}}_{\text{string coupling.}} \;,\; \underbrace{l_s \simeq L_N}_{\text{string length.}}}$$

In this talk we will present some evidence supporting the conjecture:

$$\boxed{\text{Gravity} + \text{Species} = \text{String theory.}}$$

How universal gravity knows about species?

- Black hole evaporation.
- Holographic bounds on information storage.

Black hole evaporation argument.

For Einstenian semi classical BH's the evaporation time is

$$\tau \sim \frac{M^3}{M_{pe}^4}$$

assuming the BH is a perfect quantum emitter.

The change of temperature by particle emission is:

$$\frac{1}{T} \frac{dT}{dt} \sim \Gamma_{tot}$$

for Γ_{tot} the total rate of particle emission.

$$\tau \sim \frac{M^3}{M_{pe}^4} \iff \text{pure graviton emission } \Gamma_{gr} \sim T\left(\frac{T}{M}\right)^2$$

We can define # of species N by

$$\Gamma_{tot} = N \, \Gamma_{gr}.$$

Semi classical BH requires:

$$\Gamma_{tot} \leq T \qquad (\text{or equivalently } \tau \geq R)$$

i.e

$$\boxed{\frac{1}{T^2}\frac{dT}{dt} \leq 1}$$

The bound is saturated by

$$M_{BH}^2 = M_{pl}^2 N$$

leading to a minimal size for S.C BH's

$$\boxed{L_N = \sqrt{N}\, l_{pl}}$$

and consequently to a "maximum" temperature

$$\boxed{T = \frac{1}{L_N}}$$

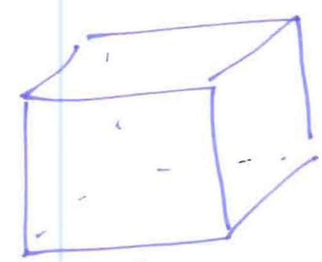
The previous argument leads to the BH definition of species scale: In general in 4+d dimensions

$$\boxed{L_N = (N)^{1/2+d}\, l_{pl}}$$

What is the holographic meaning of this length scale?

The answer is quite straightforward.

Imagine a box of size L and let us compute the maximum number of information bits that can be stored inside.



L

$$R_{gr} = l_{pe}\left[\frac{N}{L}\cdot l_{pe}\right]^{1/1+d} \leq L$$

$$\Rightarrow \quad L \geq l_{pe}\,(N)^{1/2+d} = L_N.$$

i.e the species scale for N species.

In other words: Physical resolution of species requires at least equal # of bits as # of species. The minimal size of the "species detector" is determined by the species scale.

A marginal comment:

In 10 D

$$L_N = N^{1/8} l_{pe}$$

This is a familiar relation in AdS/CFT correspondence, namely:

$$R_{AdS} = (N_c)^{1/4} l_{pe}$$

for $SU(N_c)$ gauge group:

$$N = \# \text{species} = N_c^2 .$$

Other faces of the species Scale :

KK - reduction and KK - species.

Imagine a KK reduction from 5D → 4D

$$M^2_{pl_{(4)}} = M^3_{pl_{(5)}} R \qquad (1)$$

The # of KK species in 4D is

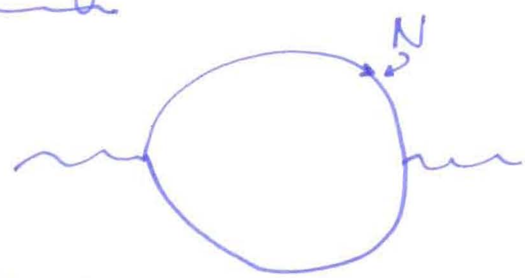
$$N = R M_{pl_{(5)}}$$

So (1) becomes

$$\boxed{M^2_{pl_{(4)}} = M^2_{pl_{(5)}} N}$$

i.e $1/M_{pl_{(5)}}$ is the species scale for "KK - species".

Induced Gravity.



Λ UV cutoff of the q.f. theory :

$$M^2_{pl_{(4)}} = N \Lambda^2$$

i.e The species scale for "induced gravity" is the UV cutoff of the underlying Q.F. Theory.

The previous comments naturally lead to the following general picture:

In a theory with Gravity + Species we have:

- Two naturals length scales L_N and l_{pe}.
- A bound on BH's size (and temperature) L_N $\left(\frac{1}{L_N}\right)$
- A natural UV cutoff L_N
- A relation between l_{pl} and L_N as:

$$L_N = (N)^{1/d+2}\, l_{pe}.$$

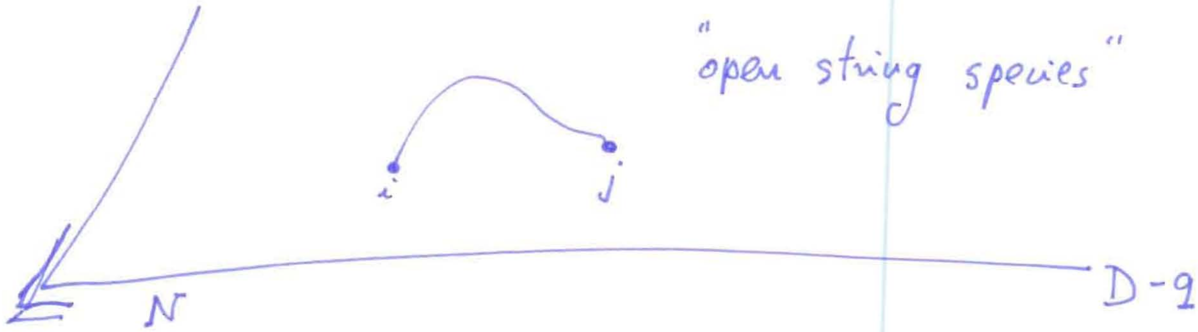
This structure strongly reminds weakly coupled string theory with the identifications:

$$L_N \longleftrightarrow l_{string}$$

$$N \longleftrightarrow 1/g_s^2$$

i.e string theory as a "theory of species".

The simplest toy model where we can consistently put together species and gravity is open string theory with Chan-Paton factors i.e D-branes.



$$\# \text{ species} = N^2$$

Requiring the "gravitational tension" of the N D-9 branes to be smaller or equal to the string tension

$$R^{-2} = N\, T_9\, G_{(10)} = N g_s M_s^2 \leq M_s^2$$

leads to the bound

$$\boxed{N^2 = g_s^{-2}} \quad \text{i.e} \quad \boxed{N_{species} = \frac{1}{g_s^2}}$$

and to L_N as l_{st} i.e to the string length as the resolution scale for Chan-Paton species.

The species scale and the String / BH correspondence.

Let us imagine gravity + species with L_N the species scale.

– What happens when a BH reaches the species scale?

At that point:

$$S = N \qquad (\# \text{ of species})$$
$$R = L_N$$
$$T = 1/L_N$$

Moreover:

$$\boxed{M_{BH} = N L_N^{-1}} \qquad (1)$$

Let us interpret (1) as the mass formula for a string state with $N = \sqrt{N_{osc}}$.

This string state will be a black hole (BH/string correspondence) if

$$\sqrt{N_{osc}} = \frac{1}{g_s^2} = N$$

i.e

When the BH reaches the species scale becomes a string state with $N_{osc} = N^2$. (Horowitz-Polchinski Transition)

So the dictionnary is:

Gravity + Species	String Theory
BH reaches L_N	BH becomes string state
$S = N_{species}$	$S = 1/g_s^2$
$N_{species}$	$\sqrt{N_{osc}} \equiv N_R$ = "Regge species"

Maximal "species temperature" versus Hagedorn temperature.

In string theory # of states grows with energy like

$$\exp(l_s E)$$

leading to an entropy

$$S = E\, l_s$$

and to the Hagedorn temperature:

$$T_H = \frac{1}{l_s}$$

The physics of Hagedorn temperature is that when we reach this temperature the energy pumped into the string is used to create new "Regge species" instead of increasing the energy of the particles.

However the asymptotic string entropy

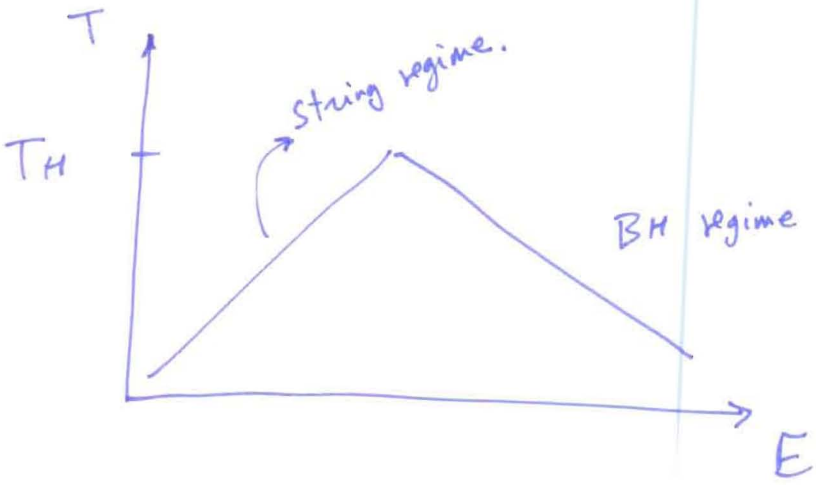
$$S_{str} = E l_s$$

is the entropy of a BH of size l_s:

$$S_{BH} = (E\, l_{pe})^2 = E\,(E\, l_{pe}^2) = E R \underset{(R=l_s)}{=} S_{str}$$

So when we reach the Hagedorn temperature the string state (again the BH/string correspondence) becomes a BH.

Thus if when the BH reaches the species scale becomes a string state then $1/L_N$ is the corresponding Hagedorn temperature.



Entropy Bound:

A natural bound in String Theory on BH entropy is

$$S_{BH} \geq \frac{1}{g_s^2}$$

(Since when $S_{BH} = \frac{1}{g_s^2}$ the BH becomes a string state)

The species bound on entropy is

$$S_{BH} \geq N$$

Both agree if $N = \frac{1}{g_s^2}$ i.e

The UV completion of a theory of species is string theory with $L_N = \ell_s$ and $\frac{1}{g_s^2} = N$

- Weakly coupled string theory in the IR is equivalent to gravity with an effective # of species equal to $\frac{1}{g_s^2}$

What happens at strong (string) coupling?

We should expect some form of duality:

$$g_s \to g_s^{(D)}$$

with
$$\hat{N} = \frac{1}{g_s^{(D)\,2}}$$

the effective # of species of the dual description.

and with
$$\hat{L}_N = (\hat{N})^{1/8}\, l_{pe}$$

the species scale for the dual description.

Let us see how this picture fits with M-theory as the strong coupling version of (IIA) string theory.

The species interpretation of M-theory with $n = \frac{R}{l_{11}}$ the # of KK (D-0) species will be:

$$l_{11} = n^{1/8}\, l_{10}$$

with l_{11} the <u>species scale</u>.

In M-theory

$$R = l_s\, g_s$$

i.e (D-0 brane $\longleftrightarrow$ KK mode)

So using $n = \frac{R}{l_{11}}$ we get:

$$\boxed{l_{11} = g_s^{1/12}\, l_{pe}}$$

Thus if we identify $l_{11} = \hat{L}_N$ the "dual species scale" we get:

$$\hat{L}_N = \left(\frac{1}{g_s^D}\right)^{1/4} l_{pe}$$

i.e $g_s^D \equiv \frac{1}{g_s^{1/3}}$

and
$$\hat{N} = \frac{1}{g_s^{D\,2}} = g_s^{2/3} = n \quad (\#\ \text{D-0 branes}).$$

Why $g_s^D = \frac{1}{g_s^{1/3}}$?.

D-0 brane Matrix model:

$$\frac{1}{g_s}\int dt \, \mathrm{Tr}\, F F$$

$$\rightsquigarrow \quad \frac{1}{g_s} |\phi \times \phi|^2$$

$$\Longrightarrow \quad \frac{1}{g_s^D} |\hat{\phi} \times \hat{\phi}|^2 \qquad \text{for } g_s^D = \frac{1}{g_s^{1/3}}$$

$$\phi = g_s^{1/3}\,\hat{\phi}$$

(string to M-theory transformation)

In other words:

> l_{11} is the species scale for the dual strong coupling description for light D-0 branes.

In summary:

weak coupling: $l_s > l_P$

l_s = "species scale."

strong coupling: $l_P > l_s$

l_P = "species scale."

A final speculative comment:

We have observed that consistent coupling to gravity of a theory with species requires a stringy UV completion with $l_s = L_N$.

We can always define a decoupling (of gravity) planar limit with

$$l_{pe} \to 0$$
$$N \to \infty$$
$$L_N \to \text{finite.}$$

This double limit seems to produce a theory without gravity with a "mass gap".