String Theory on the eve of the LHC. An update

String theory is already forty years old, and it is time to recapitulate what we have learned, what are its major achievements and also what are its ailments now that it may approach its midlife crisis.

The ages of String Theory

The age of discovery. The Veneziano amplitude and its interpretation as a string exchange

The problem with dimensions, tachyons and consistency. Oh my God! 10 dimensions!

The need for supersymmetry and the notion of superstrings

The anomaly cancellation, the heterotic string, the Kaluza-Klein or Calabi-Yau period

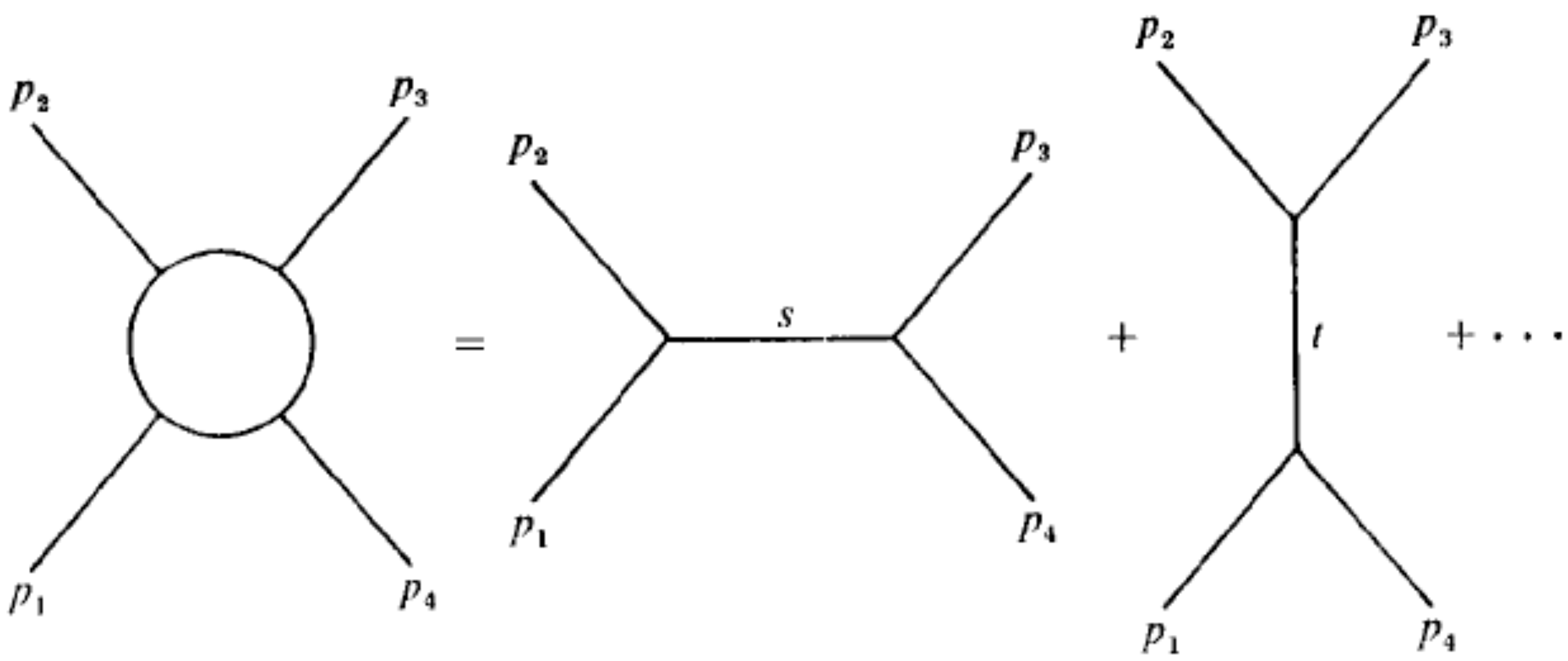
The age of dualities

D-branes. The long sought for sources for strings

BHs and holography.

String landscapes, model building, back to QCD

The Veneziano formula



Motivated by experiment in the exchange of hadronic resonances. Look for amplitudes where the exchange in the s-channel is the same as the exchange in the t-channel:

$$A(s,t) \;=\; \frac{\Gamma(-\alpha(s))\,\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))}$$

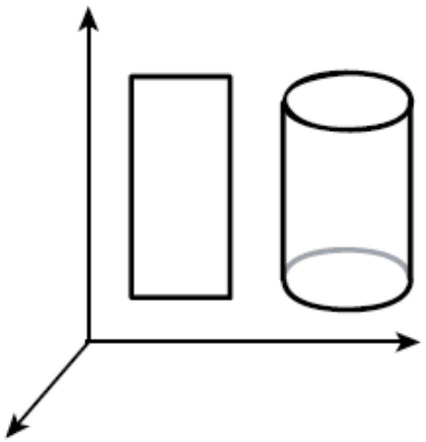
$$\alpha(s) \;=\; \alpha(0) \,+\, \alpha'\, s$$

A formula with hadronic credentials!

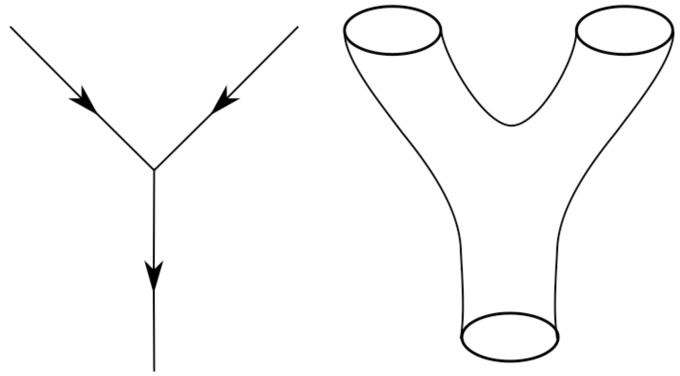
The microscopic formulation

The only sensible way to derive this formula was based on the exchange of relativistic string. There are many technical aspects to it. But the requirements of Lorentz invariance, decoupling of negative metric states, and unitarity did not leave many options

Free open and closed strings



Few interactions allowed



Open strings with N BC's

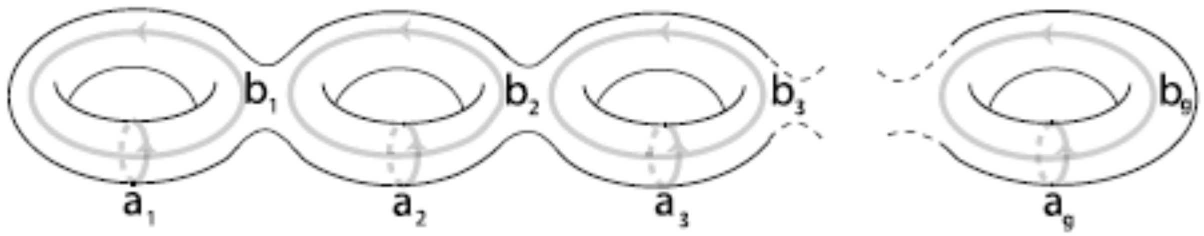
Tachyons disappear when working in D=10 and with space-time supersymmetry

E&M is not just unified with gravity, it is inseparable. The ultimate Einstein dream

The consistent theory always contains a spin two particle with the right couplings to reproduce GR at low energies

m_p for M Planck!!, and D=10 (sorry)

The world sheet approach



Feynman diagrams are replaced by world-sheet diagrams. Hence we can use the power of Riemann surface theory to probe perturbation theory. In the case of closed strings there is essentially one diagram per loop. The complex moduli of the RS play an important role in the analytic details of the amplitudes. The first non-trivial result is that string can only propagate in backgrounds allowing the world-sheet theory to be conformal invariance. This leads at low-energies to the Einstein equations! The UV behavior of the supersmmetric theories in so good, that there are no UV divergences, they can be converted into IR divergences... The proof has not been carried out rigorously to all orders, but there are plenty of arguments supporting this conclusions.

$$R_{\mu\nu} = 0$$

(plus high derivative corrections...)

Anomaly cancellation and the superstring types

The theories considered contained chiral fermions in higher dimensions. Our experience with the SM is that there is little room for such theories without anomalies. The fermion quantum numbers are severely limited, and more so as the number of dimensions of space-time increase. It was found around 1984 that only four types of string theories were consistent with general covariance and gauge symmetries: gravitational and gauge anomalies in all their varieties. These theories come with the gravity sector, i.e. the graviton and gravitini plus a number of p-form fields called the Ramond fields. All the theories below in D=10 and the last one in D=11.

Type IIB $\quad C_0, \quad C_2 \quad C_4$ (with self-dual field strength)

Type IIA (Similar assignments with odd forms)

Heterotic $\quad E_8 \times E_8 \quad SO(32)$

11-dimensional supergravity as the low-energy limit of M-theory

Objects and forms

A 0-dimensional object has a 1-d world line $$\int A_a \, dx^a$$

A 1-dimensional object has a 2-d world line $$\int A_{ab} \, dx^a \wedge dx^b$$

A (p-1)-dimensional object has a (p-1)-d world line $$\int A_{a_1 a_2 \ldots a_p} \, dx^{a_1} \wedge dx^{a_2} \wedge \ldots dx^{a_p}$$

We can assign a flux for a p-surface. For our strings, where are the surfaces where the Ramond fields can thread their flux through?

An important interlude

Duality in Electromagnetism

Source free E&M

$$\begin{aligned} \nabla \cdot (\mathbf{E} + i\,\mathbf{B}) &= 0\,, \\ \frac{\partial}{\partial t}(\mathbf{E} + i\,\mathbf{B}) + i\nabla \times (\mathbf{E} + i\,\mathbf{B}) &= 0. \end{aligned}$$

$$\begin{aligned} \mathbf{B} &\to \mathbf{E} \\ \mathbf{E} &\to -\mathbf{B} \end{aligned}$$

$$(\mathbf{E} + i\,\mathbf{B}) \to e^{i\phi}(\mathbf{E} + i\,\mathbf{B})$$

Regular source E&M

$$\begin{aligned} \nabla \cdot (\mathbf{E} + i\,\mathbf{B}) &= q \\ \frac{\partial}{\partial t}(\mathbf{E} + i\,\mathbf{B}) + i\nabla \times (\mathbf{E} + i\,\mathbf{B}) &= \mathbf{j}_e\,. \end{aligned}$$

Duality modified E&M

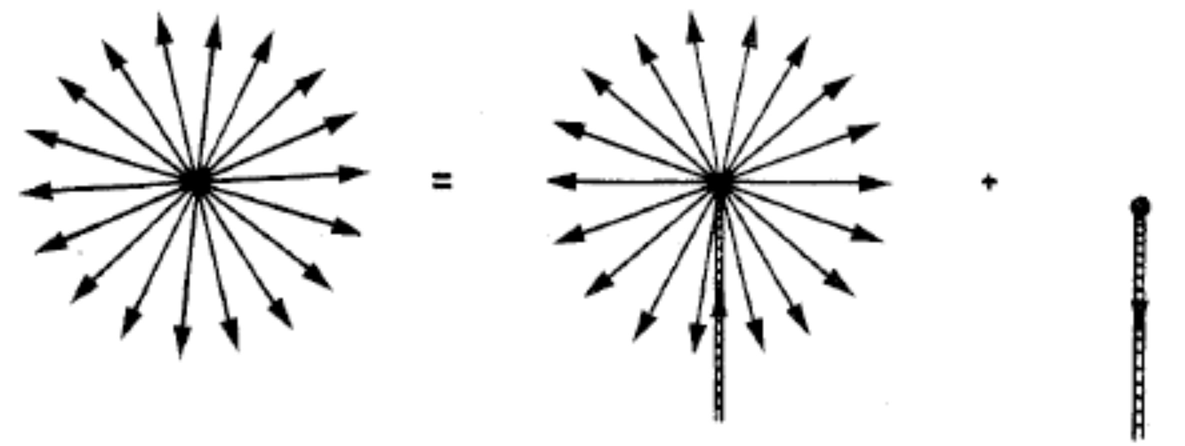
$$\begin{aligned} \nabla \cdot (\mathbf{E} + i\,\mathbf{B}) &= (q + ig) \\ \frac{\partial}{\partial t}(\mathbf{E} + i\,\mathbf{B}) + i\nabla \times (\mathbf{E} + i\,\mathbf{B}) &= (\mathbf{j}_e + i\,\mathbf{j}_m)\,. \end{aligned}$$

$$(q + ig) \to e^{i\phi}(q + ig)$$

A quantum surprise

Quantum mechanics couples to vector potentials, not just to the electric and magnetic fields. If we try to formulate QM in the presence of a monopole we get some physical conditions.

This is the first explanation of charge quantization. It was given by Dirac in the 30's, and essentially all modern derivations are equivalent to this one.



$$\frac{qg}{2\pi} = n\,(\hbar)$$

Monopole-charge

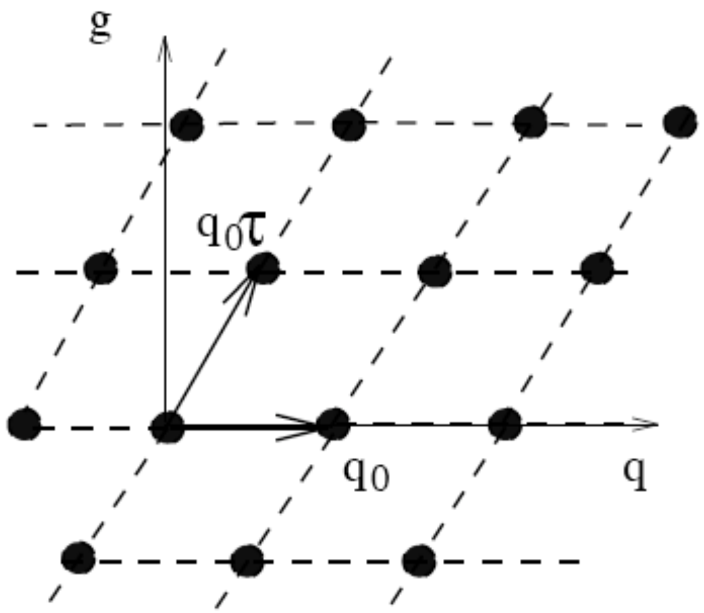
$$\frac{q_1 g_2 - q_2 g_1}{2\pi} = n_{12}\,(\hbar)$$

Dyon-dyon

Charge Lattice, Duality (S,T,U)

It is easy to solve the DSZ quantization conditions, and kinematically we get a charge lattice with a CP-violating angle. The different ways of defining the unit cell are related by simple transformations. These are the duality transformations. More precisely, S-duality

$$q + ig = q_0(n_e + n_m \tau)$$



$$\tau \equiv \frac{\theta}{2\pi} + \frac{2\pi i m_0}{q_0^2}$$

$$(n_m, n_e) \to (n_m, n_e) \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}^{-1}$$

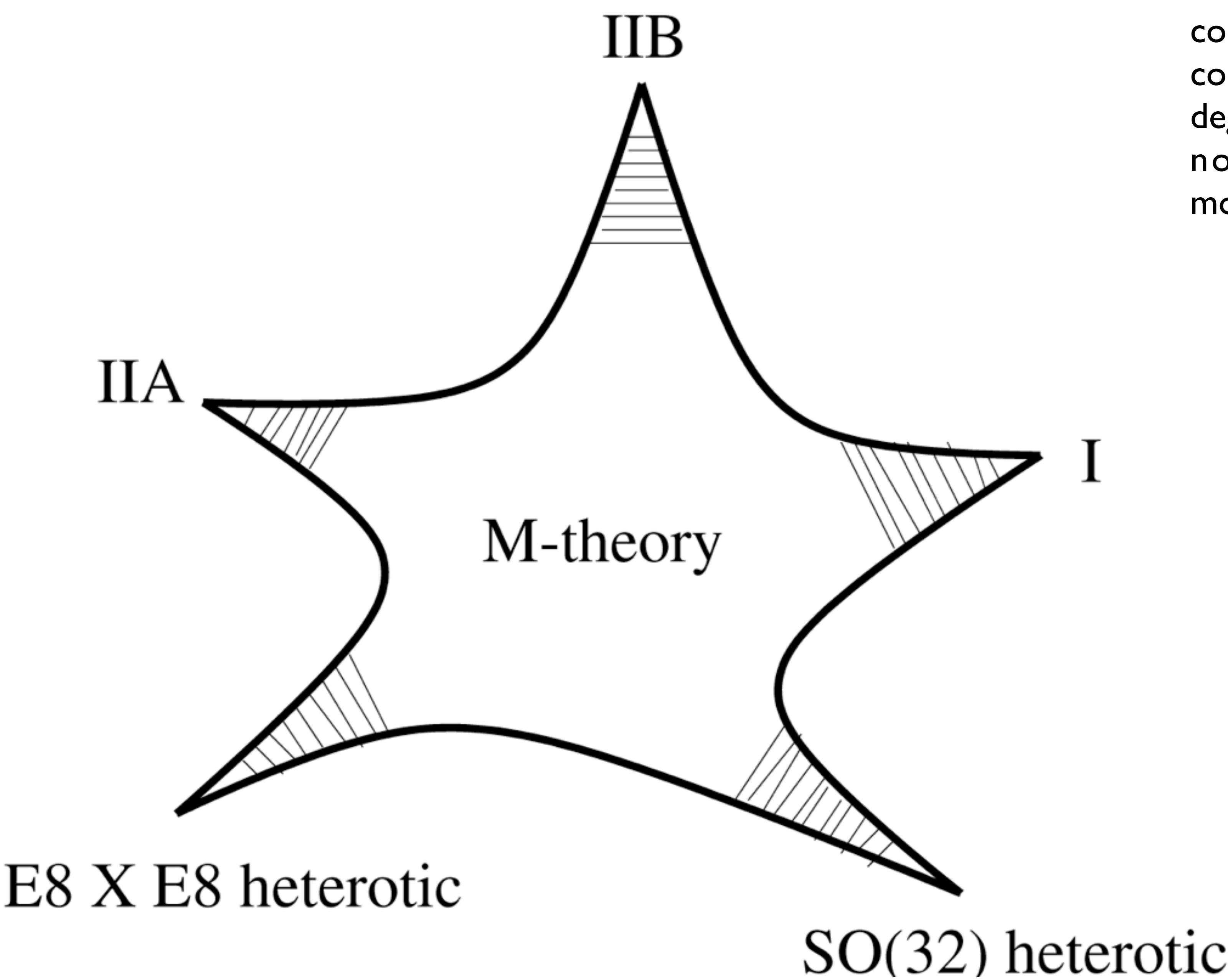
$$\tau \to \frac{\alpha\tau + \beta}{\gamma\tau + \delta}$$

$$T: \quad \tau \to \tau + 1, \quad S: \quad \tau \to \frac{-1}{\tau}$$

End of interlude

The web of dualities

Using S,T,U dualties many of the assumed fundamental strings are equivalent, but most of the time in the sense of duality. A weakly coupled theory is equivalent to a strongly coupled one. Hence the weakly coupled degrees of freedome may turn out to be highly non-trivial solition configurations (like monopoles in the case of Dirac)

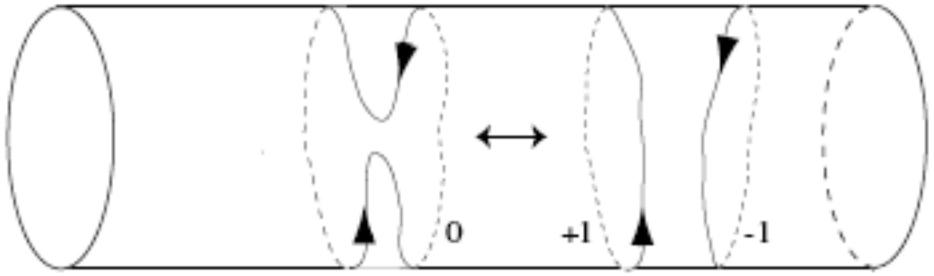


Elementary states

↕

Solitonic states

T-duality



It represents the same property as duality in a Coulomb gas in two dimensions. We can have standard particle-like excitations, as well as having the string wrap around the compactified dimensions. The energy of the state is invariant under the exchange of momentum and winding states

$$\alpha' = l_s^2 \qquad T = \frac{1}{2\pi\alpha'}$$

$$p = \frac{n}{R} \leftrightarrow w = m\,R \qquad R \to \frac{\alpha'}{R}$$

The road to reality

Kaluza-Klein compactifications

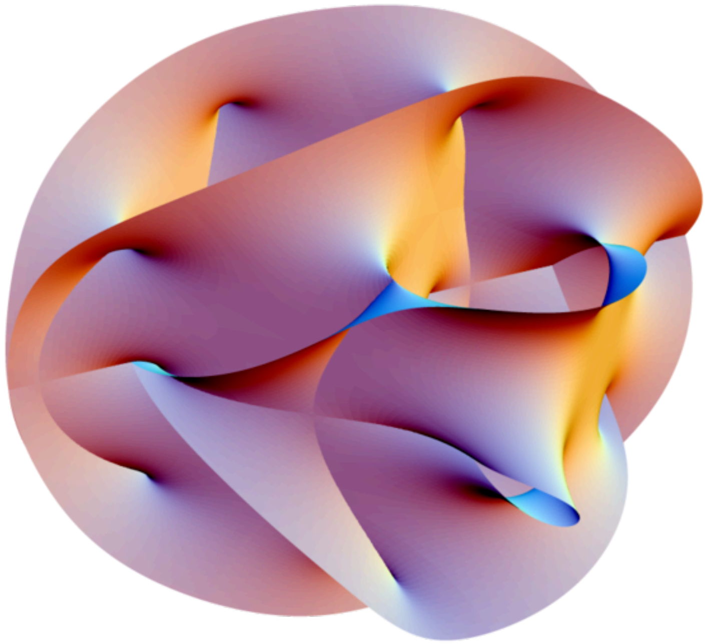
Brane worlds and brane intersections

F-theory constructions

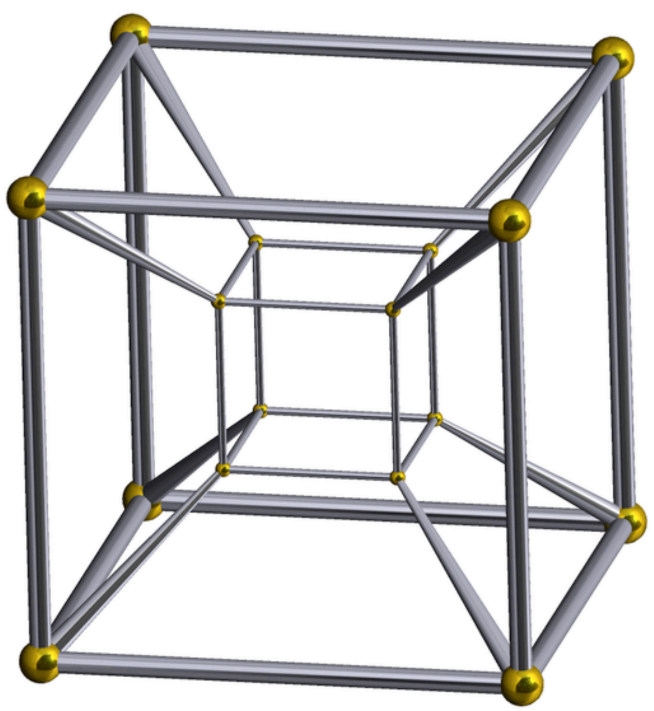
KK-compactifications with bundles (hair)

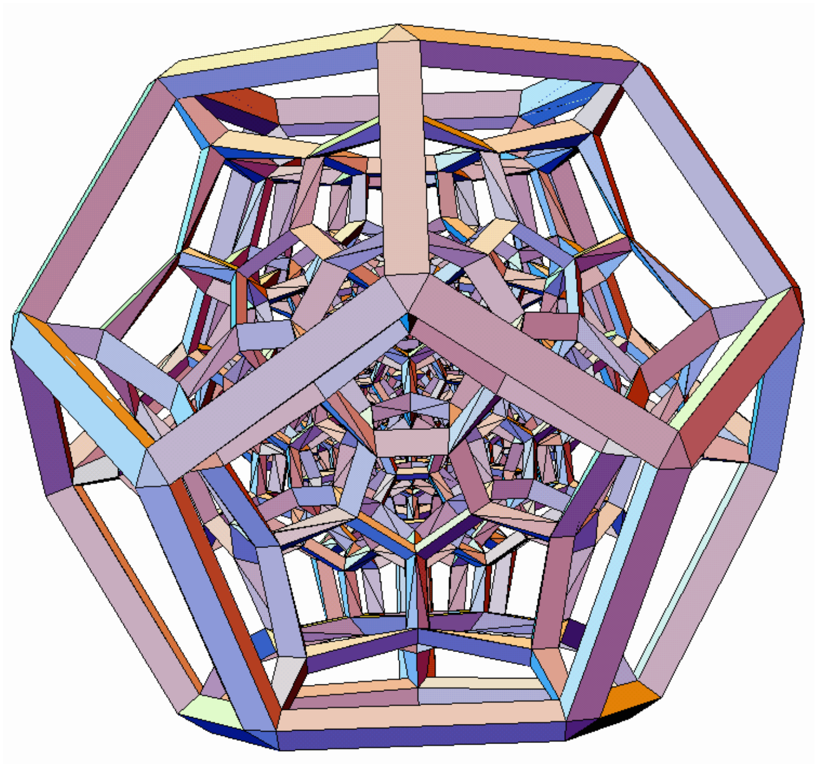
Compactifications ahoy! KK first

(Is String Theory Kakania?)



$\times \; M_{1,3}$





Some nice features

Physical quantum numbers are formulated in terms of geometrical and topological quantities. For instance:

Number of generations

Structure of the gauge group

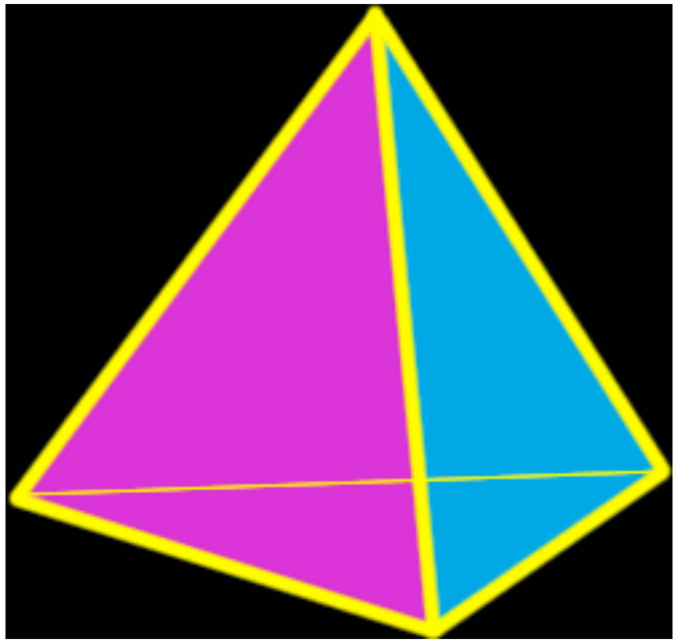
Yukawa couplings and mass textures

Keywords:

Euler number

Chern classes

Intersection numbers

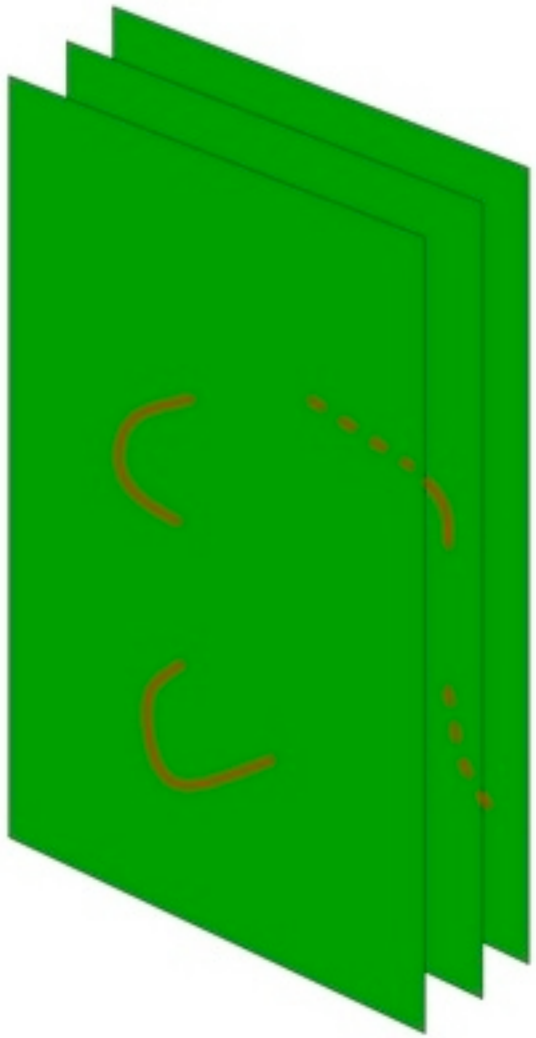


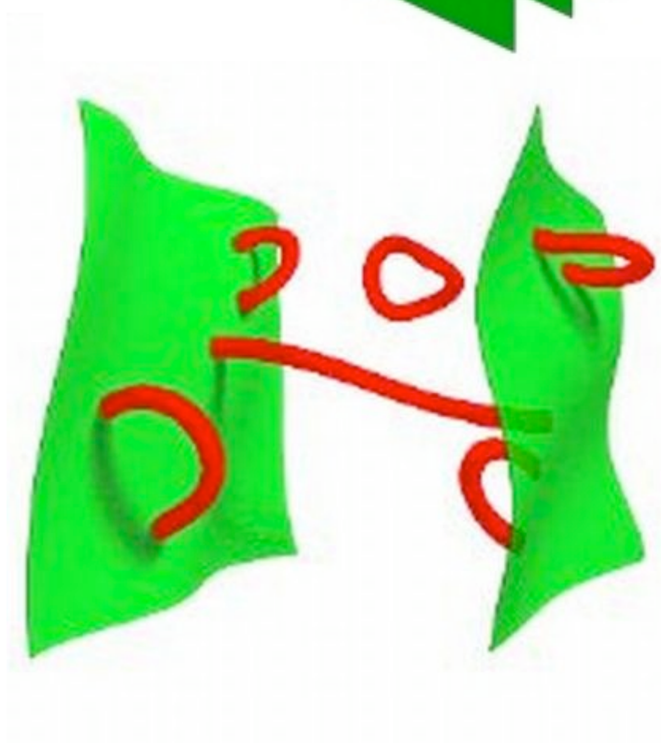
$$\chi(\text{Euler}) = V - E + F$$

Large number of options, and also a large number of extra light field associated to the deformations of the geometry. These are the MODULI fields

We need Calabi-Yau manifolds, orbifolds and some other variations. Sophisticated algebraic geometry involved.

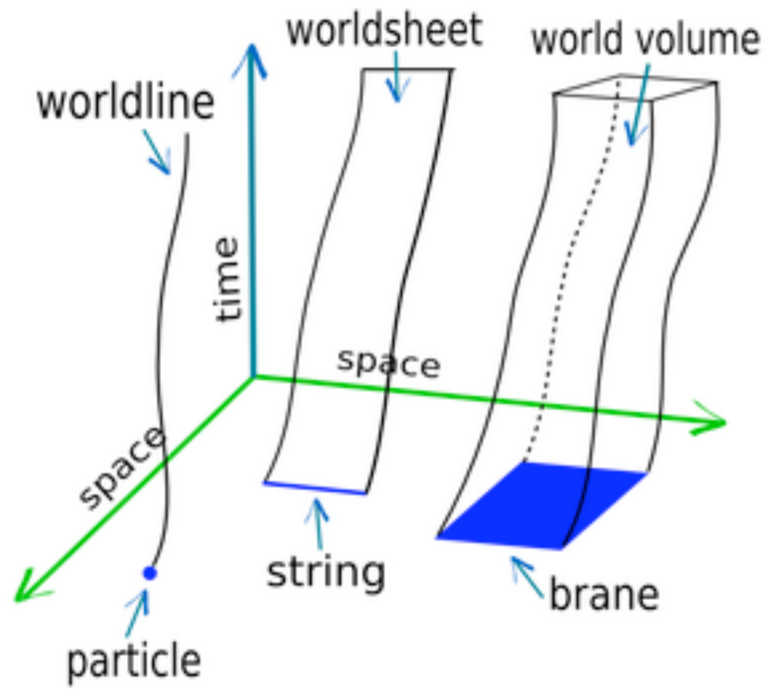
Strings find their missing sources

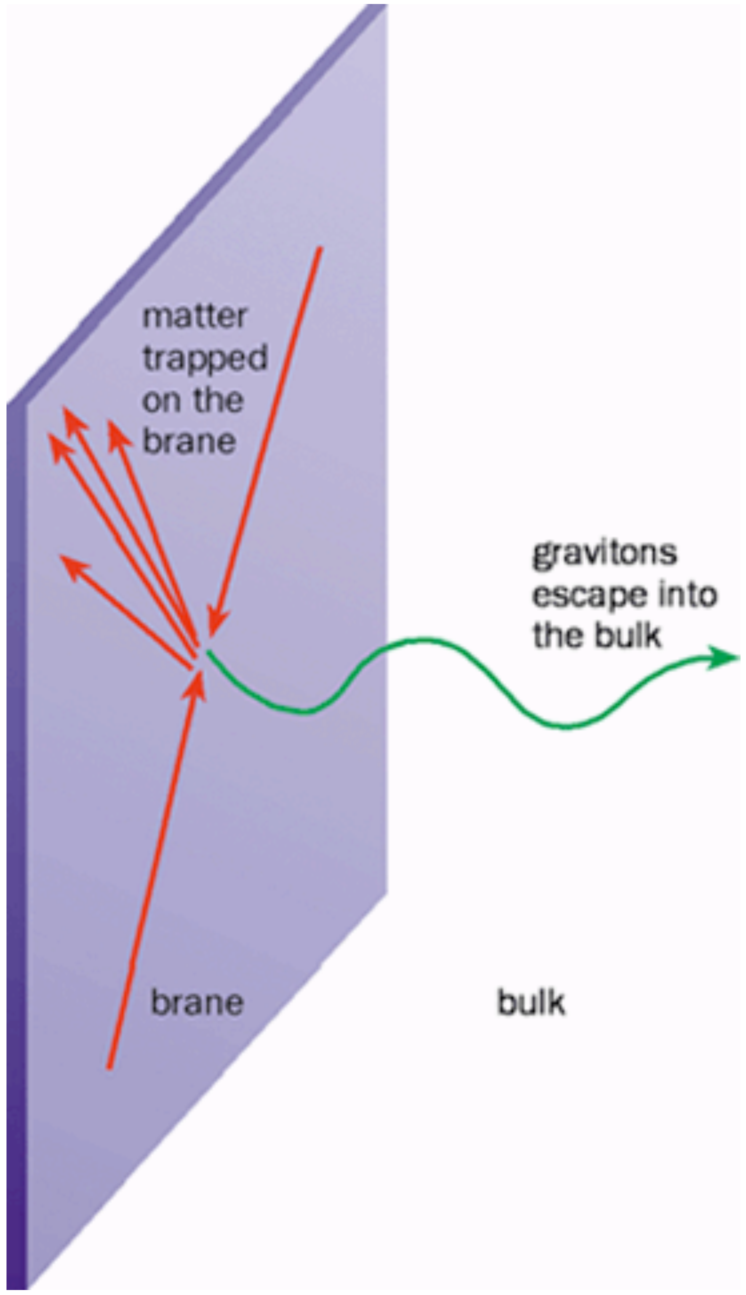




Polchinski realized that if we do not require Lorentz invariance naively for the open strings we find immediately a collection of object that represent the analogues of solitons for string theory, as well as the sought for sources for the Ramond fields.

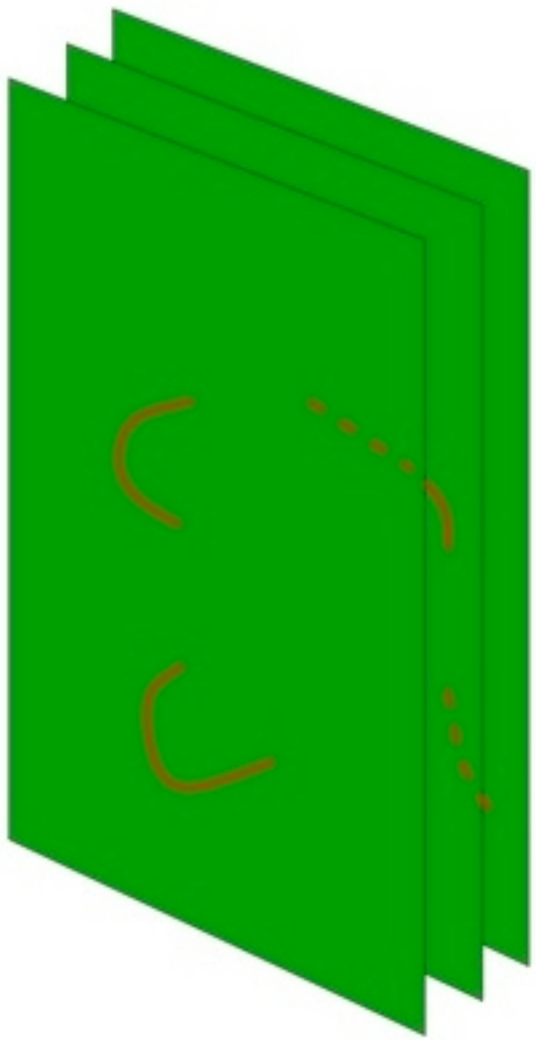
This puts the string dualities in a different perspective. In fact many of the examples with non-trivial solutions include BHs with horizons. The D-branes provide a macroscopic description of the horizon before back-reaction effects produce the Einstein throats. The bulk is dominated by gravity, the brane contains the fields of the SM





The precursor to these scenarios can be found in Horava and Witten. The main idea is that we live in a three-brane that moves in a higher dimensional space. Only the gravitational multiplets live in the bulk. We are brane-bound mammals!

Brane intersections



The more successful models so far come in two varieties:

I. Brane intersection with fluxes to fix moduli

II. CY spaces with non-trivial bundles

III. The new kid on the block: F-theory. A special way of compactifying type IIB string theory. There are interesting phenomenological models but a lot remains to be done

Some of the highlights so far is to obtain the quantum numbers of the chiral fermions without too much extra

Some plausible, and interesting textures of their mass matrices also follow, but often there are too many extra light objects

Gauge coupling unification is reasonably well accommodated, but it is not clear whether this is a prediction or an input

A lot to be understood about supersymmetry breaking and the implications for cosmology and we as the CC cancellation to such accuracy.

Although often repeated in some circles, String Theory does not predict low energy supersymmetry

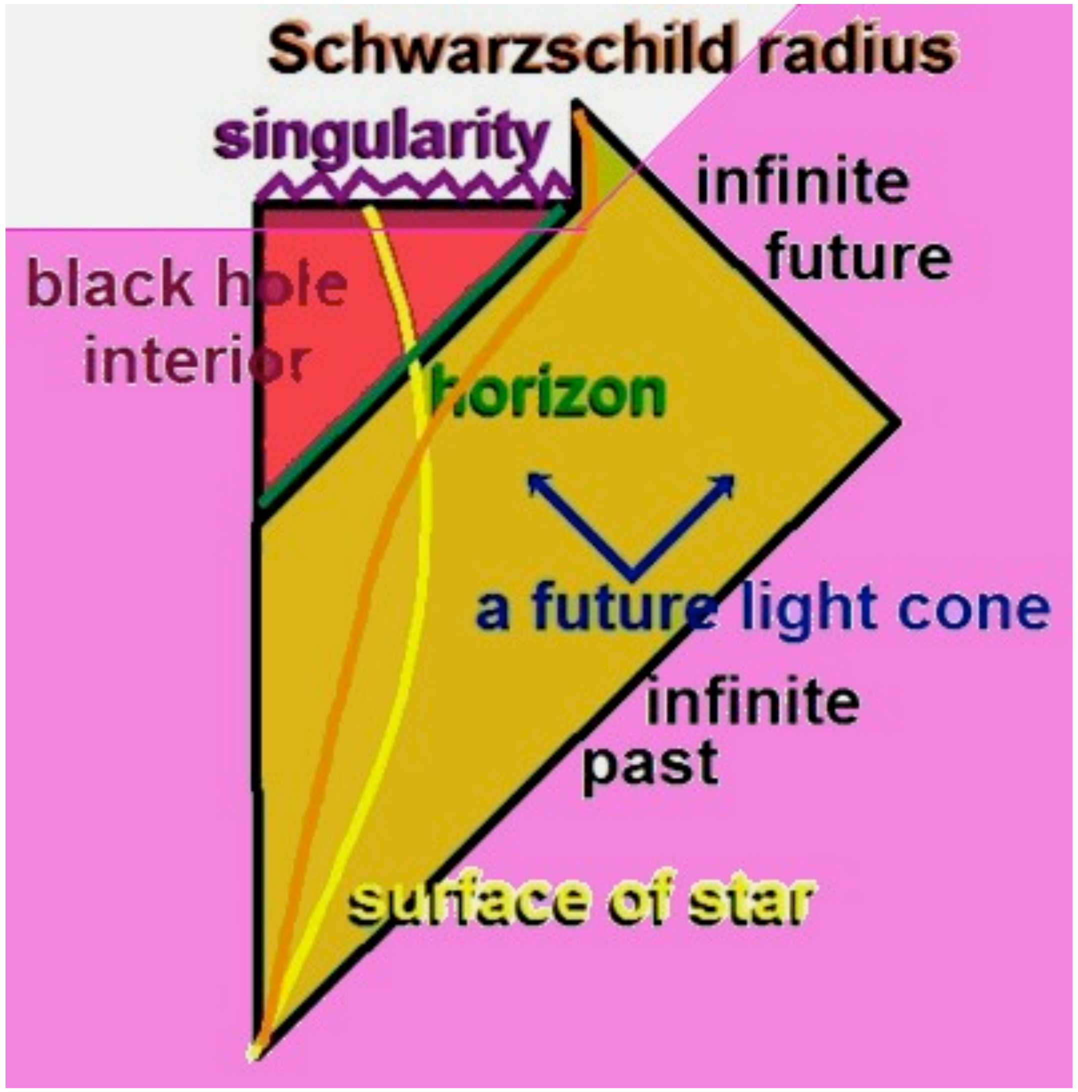
Holography, AdS/CFT

$$T = \frac{\hbar\, c^3}{8\,\pi\, G\, M\, k}$$

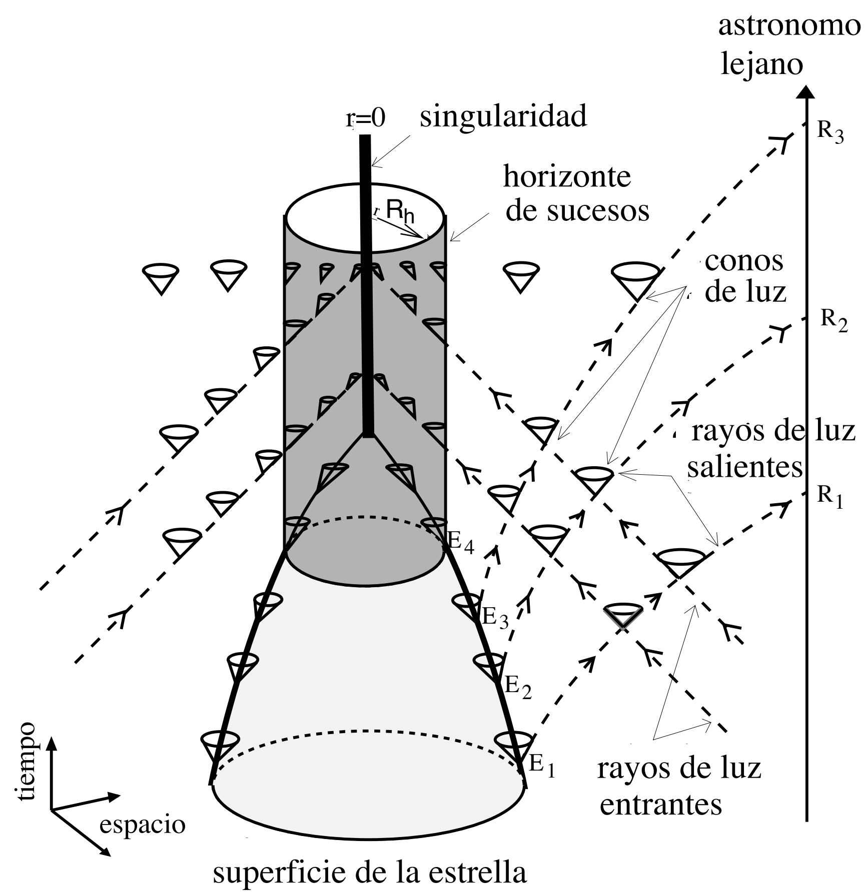
$$S = \frac{1}{4} A \;(\text{in Planck units})$$

One bit of information per Planck unit of surface

Sophisticated theory of BH Thermodynamics and possible problems with Quantum Mechanics



Semiclassical Picture



What is the fate of singularities, inside BHs as well as in the intial BB singularity?

The holographic description should provide us with an answer in terms of a gauge theory, however we do not know how to ask the relevant gauge theory question to get some hint about the fate of the singularity, and the fate of the information swallowed behind the horizon.

It is likely that important progress will be made in this area in the years to come.

Entropy bounds

If we take seriously the BH entropy, ‘t Hooft showed that for a system with a given volume and energy, there is a maximum entropy that is given by the area of the corresponding Schwarschild horizon

$$R = \frac{2\,G\,M}{c^2}$$

A basic violation of extensivity in ordinary thermodynamic systems

In (quantum) gravity there are no local observables. All the information is coded in the boundary as in a hologram.

The amount of information is nevertheless huge

AdS/CFT

One of the more surprising (and deeper) aspects of String Theory is the correspondence discovered by Maldacena. Strongly coupled gauge theories (with a lot of supersymmetry) on a boundary space-time are equivalent to quantum gravity in the bulk

Type IIB in AdS5 x S5

↕

N=4 SYM in Minkowski

Strongly coupled gauge theory is equivalent to weakly coupled gravity and viceversa. Since QFT is unitary, no process taking place in the bulk can violate unitarity. There is no possibility that Hawking evaporation can violate unitary evolution. This is the general picture. Unfortunately, many of the details are still missing...

Hot QCD

RHIC suggests that just above the deconfinement transition the quark-gluon system is described by a nearly ideal, strongly coupled conformal fluid.

For bulk properties, and as a consequence of the universal properties of equilibrium states, any system sharing the same characteristics will have similar values for the response functions.

This is an ideal case where to apply the AdS/CFT correspondence. The strongly coupled, hot N=4 plasma should share many properties with QCD, with the advantage that it has a weakly coupled gravity dual.

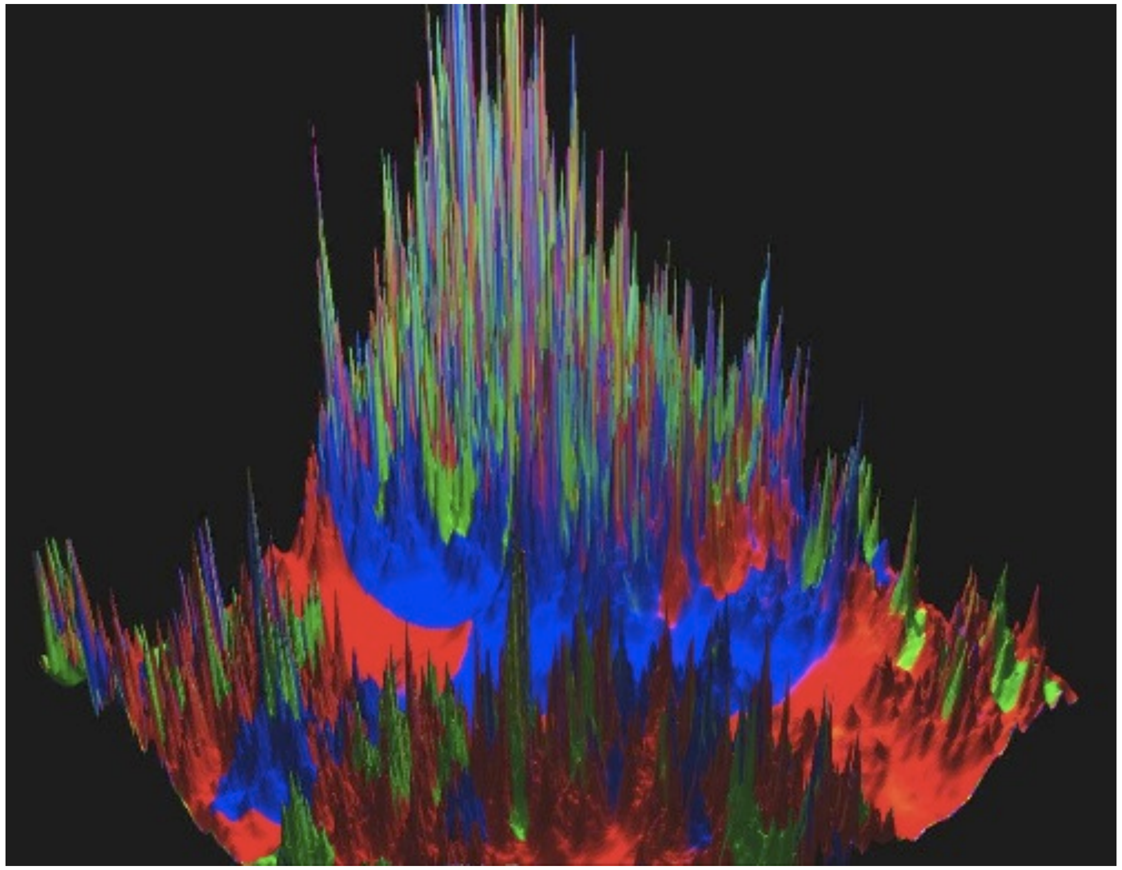
This is to a certain extent the justification for the activity on gravity dual of hot, strongly coupled plasmas and their gravity duals. There seems to be a "theorem" claiming a relation between the shear viscosity and the entropy per unit volume for systems with a gravity dual.

$$\frac{\eta}{s} = \frac{1}{4\,\pi}$$

Landscape and Chaotic Inflation

WARNING!!!

Many people are very critical with these arguments, and think that it is not science. We can perhaps ask the questions in slightly different ways, and applying some common sense.



The non-trivial geometry of the compactifications together with fluxes through topological cycles produce a very large number of possible (meta)stable ground states. In the context of chaotic inflation, one would say that all of them are eventually visited by the universe. We live in the one that makes it possible for us to live.

This is the kind of anthropic reasoning that makes some people mad.

Perhaps there is a more positive way of asking the question:

Our universe comes with its bar code:

What is environmental and what is computable?

Can we assess what will never be known?

Conclusions

Those aspects where we have learned the most, are those which do not have a simple field theory analogue. There is no clear result at low energy, as in QFT: the CPT theorem for example

If we try to obtain low-energy properties from String Theory, it is difficult (if not impossible) to disentangle them from ordinary constructions based on supersymmetric field theories

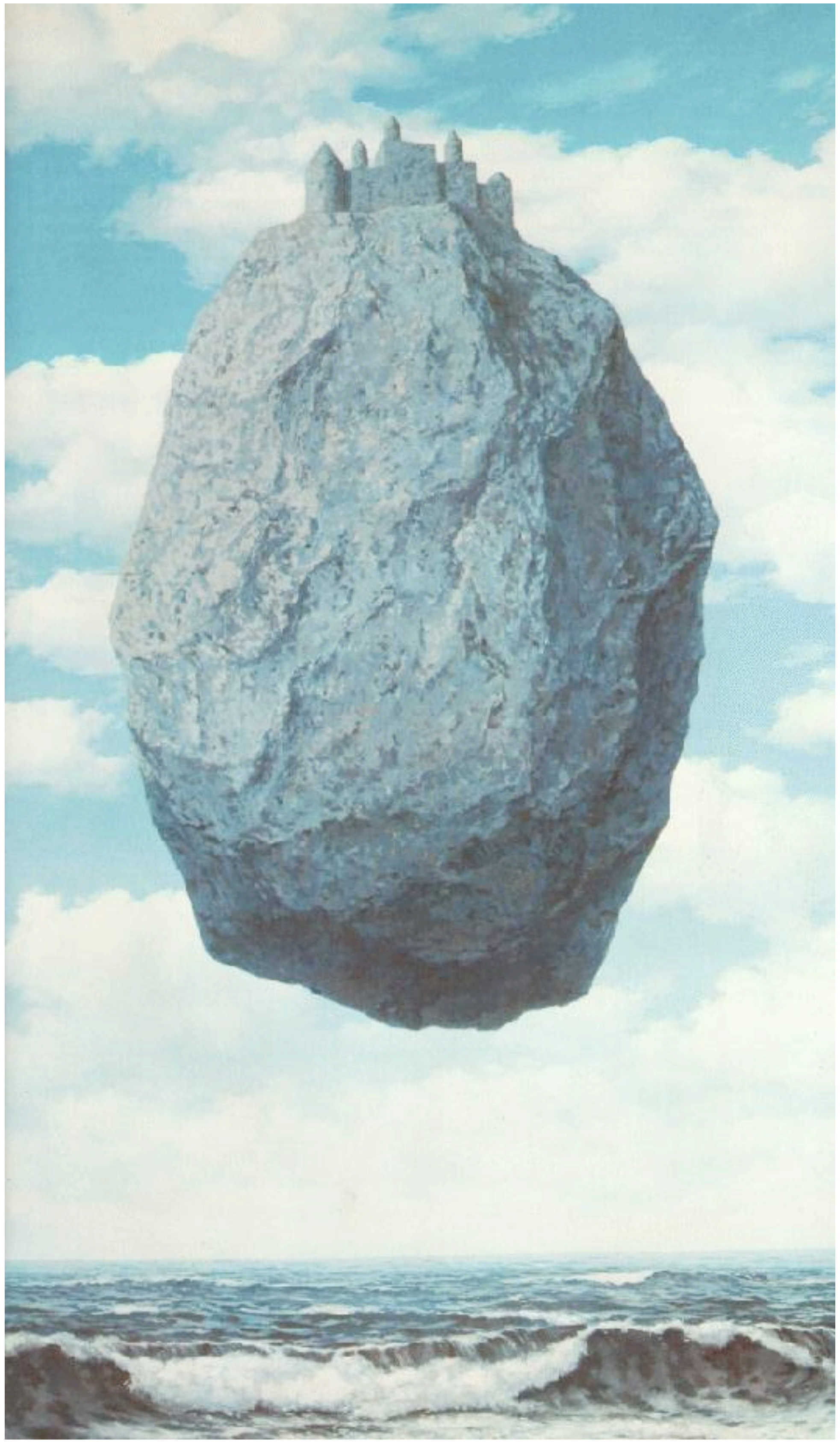
To this day there is no compelling theoretical reason implying that String Theory leads to a low energy version of the MSSM or its variations

If supersymmetry is indeed discovered, it will provide strong evidence that the underlying theory is based on some form of String Theory

String Theory seems to be the only theoretical arena where some of the deep BH puzzles could find an answer

A lot of model building, low energy predictions, cosmology.... not yet compelling

Supersymmetry is at the same time the blessing and the curse of String Theory



String Theory is rock solid,
but still up in the air!!

Thank you!