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La teoria delle stringhe:
l'ultima rivoluzione in fisica?

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Il decennio aureo delle particelle
Il modello standard in un guscio di noce

Preambolo

Quella che vorrei raccontarvi in questo corso è una storia vissuta in prima persona, una storia quasi inverosimile, fatta di un succedersi di rivoluzioni, di vittorie e di sconfitte, di speranze e di frustrazioni. Una storia di cui nessuno ancora conosce la fine, ma alla quale magari qualcuno di voi un giorno contribuirà. È la storia di una teoria che si dice nata per caso, per sbaglio, ma che invece, come vedremo, è piuttosto il frutto di uno strano scherzo che ci ha fatto Madre Natura…

È una storia vecchia di mezzo secolo, eppure ancora agli inizi. Una teoria la cui formulazione attuale è lungi da essere del tutto soddisfacente.
Insegnarla a un pubblico eterogeneo non è facile.
I due estremi, essere troppo discorsivi o troppo tecnici, sono difficili da evitare, ma cercherò di tenere una via di mezzo, evitando un eccessivo formalismo matematico, ma cercando di far passare le principali idee fisiche.
Aggiusterò il tiro, e di conseguenza anche il programma, secondo la risposta del pubblico.

The golden decade of particle physics

Many lucky events have marked my life like having an excellent math. & physics teacher (Prof. Liverani) in high school.

A more professional one is that I embarked in theoretical physics at the University of Florence around 1962-'63 (in my 3rd year of studies in physics).

Around that same time Prof. Raoul Gatto moved from Cagliari to Florence bringing along a bunch of brilliant "Laureati" (Guido Altarelli, Franco Buccella, Giovanni Gallavotti, Luciano Maiani, Giuliano Preparata from Rome, Enrico Celeghini from Cagliari) while the slightly more senior Marco Ademollo, Claudio Chiuderi and Giorgio Longhi were already in place as (very helpful) "Assistenti".

I decided to ask Prof. Gatto for a thesis in theoretical physics and graduated in 1965. With hindsight I can say that Raoul Gatto's group in Florence was a fantastic one for tackling the problems we were facing at the time in the quest for a theory of the elementary particles and their mutual interactions.

And the time was right. Within a decade the paradigm changed completely and, around 1973, the Standard Model would have been born. It is pretty much the same model we are using today (see Prof. Maiani's lectures 2013-2014).

After a year of "perfezionamento" in Florence I went to study at the Weizmann Institute's graduate school (Ph. D. in 1967). But this is part of tomorrow's story…

Status in the mid sixties
(with Michelin-star grading)

1965	FORCE	
*** (QED)	EM	
*(*) (Fermi)	WEAK	
* (Models)	STRONG	
** (GR)	GRAVITY	

Fundamental interactions mid sixties

1. Electromagnetic Interactions

Since the forties there was a successful quantum-relativistic theory: quantum-electrodynamics (QED)

It had impressive successes (predicting the anomalous magnetic moment of the electron, the Lamb shift etc.).

Had been shown to be "renormalizable" i.e. all infinities could be lumped into a finite number of parameters (e.g. α, m_e) to be fitted to the data. The rest is calculable.

One "small" problem at extremely high (small) energies (distances): the Landau pole or triviality problem. Not a practical one, but enough to make people like Landau, Dirac (and others) dissatisfied with QFT.

Even more mistrust came from the other interactions…

2. Weak Interactions

Fermi's theory of β-decay (1933): a 4-fermion interaction describing both neutron and muon decay.

Successful but "phenomenological" since, unlike QED, could not be elevated to a fully consistent quantum theory.

UV divergences were too severe to be able to lump them into a finite number of physical quantities.

3. Strong Interactions

Yukawa's pion theory (1935)... to be continued next week

4. Gravity

Einstein's General Relativity (1915), see below.

La (pen)ultima rivoluzione in fisica?

1965	FORCE	1973
*** (QED)	EM	EW
*(*) (Fermi)	WEAK	*** SM
* (Models)	STRONG	QCD ***
** (GR)	GRAVITY	**

An enormous change of paradigm took place within those 10 years.

1. In spite of their extremely different phenomenology those three interactions are described, at a deeper level, by the same class of theories, based on the principle of gauge-invariance.

2. Their difference stems from the different ways in which the underlying symmetry is realized. A gauge theory can exist in different phases, like a stat. mech. system.

3. A crucial construction was that of non-abelian gauge theories generalizing the abelian gauge symmetry of QED.

4. Electromagnetic and weak interactions get unified not only conceptually but also quantitatively inside what is now known as the electroweak theory (Glashow, Salam, Weinberg).

short break?

Classifying particles and fields according to special relativity & quantum mechanics

(normally used units in which $c = h/2\pi = 1$)

1. Point-particles are characterized by their mass (m), spin (J) and various (generalized, see below) charges (Q_i).

2. According to QM, J is an integer or half integer multiple of $h/2\pi$. Besides its "length", we can fix the projection of the vector J along one (say the z)-axis.

3. If $m \neq 0$, J_z can take $(2J+1)$ values from $-J$ to $+J$; if $m = 0$ J_z can take only the values $\pm J$.

4. We can associate fields to particles (cf. wave-particle duality; below x represents, collectively, space & time).

a. $J = 0$: $\Phi(x)$ = Klein-Gordon or scalar (real or complex).

b. $J = 1/2$: $\psi_\alpha(x)$ = Dirac ($\alpha = 1,..4$); Weyl ($\alpha = 1,2$) spinor.

c. $J = 1$: $A_\mu(x)$ = Vector ($\mu = 1, ..4$)

d. $J = 3/2$: Rarita-Schwinger $\psi_{\alpha\mu}(x)$ (supergravity)

e. $J = 2$: symmetric tensor $g_{\mu\nu}$ ($\mu,\nu = 1,..4$) (gravity)

N.B. Add.[al] local conditions needed to remove some d.o.f.

This is particularly true for massless particles because of their smaller number of d.o.f. For massless $J = 1$ particles this is achieved through a (local) symmetry, gauge-invariance.

The SM makes heavy/crucial use of it: it's a gauge theory.

short break?

Quantum field theory: the synthesis of special relativity and quantum mechanics (QFT = SR + QM)

The starting point is the construction of a classical Lagrangian, L, a function of the fields that contains both the information about the individual elementary particles and about the way they interact with each other. One gets field equations in the usual way (Euler-Lagrange eqns.)

L should be invariant under Lorentz and gauge transformations. Strongly restricts its form.

We have to distinguish (integer spin) bosonic fields from (half-integer spin) fermonic fields. They obey, respectively, Bose-Einstein and Fermi-Dirac statistics (=> Pauli's exclusion principle). Implemented at the quantum level via commutation or anti commutation rules of the corresponding fields.

Recipe for a (renormalizable) gauge theory

1. Choose a continuous group G to be identified with the gauge group. It can be Abelian (QED) or non-Abelian (SM).

2. For each generator of the group there is an associated gauge field, a four vector A_μ (and, to start with, a J=1 massless particle). A_μ enters the Lagrangian via its "field strength" $F_{\mu\nu}$ (usual $F_{\mu\nu}$ of EM can be generalized to non-abelian groups). No gauge-field mass term is allowed in L.

The way it enters L is unique up to a coupling for each factor in G.

3. We then add J = 0 bosons and J = 1/2 fermions as Klein-Gordon and Dirac (more generally Weyl) fields. How matter and gauge fields couple in L depends on the representation of G to which they belong.

Irreducible Reps. can be either real or complex.

Generic renormalizable gauge theory lagrangian

$$
\begin{aligned}
L_{RGT} = \quad & -\sum_a \frac{1}{4g_a^2} F^a_{\mu\nu} F^a_{\mu\nu} + \sum_i i\bar{\Psi}_i \gamma^\mu D_\mu \Psi_i + \sum_j D_\mu \Phi_j^* D^\mu \Phi_j \\
- \quad & m_{ij} \Psi_{\alpha i} \Psi_{\beta j} \epsilon_{\alpha\beta} + \lambda^{(Y)}_{ijk} \Phi_k \Psi_{\alpha i} \Psi_{\beta j} \epsilon_{\alpha\beta} + c.c. \\
- \quad & \mu^2_{kl} \Phi_k \Phi_l + \eta_{ijk} \Phi_i \Phi_j \Phi_k + \kappa_{ijkl} \Phi_i \Phi_j \Phi_k \Phi_l
\end{aligned}
$$

In QFT every particle has an associated (but not necessarily distinct) antiparticle. Particle and antiparticle belong to complex-conjugate representations (R and R*) of G (in abelian case they have opposite charge).

A mass term in the Lagrangian is bilinear in the (bosonic or fermonic) fields. It has to be, as always, both Lorentz and gauge invariant. However there is an important distinction:

4a. For scalars we can always write down gauge invariant mass terms since RxR* contains the trivial rep.

4b. Fermions come with two helicities h= ± 1/2. But particles and antiparticles have opposite helicities. The set of all h = +1/2 (h = -1/2) particles may belong to a real or to a complex rep of G. In the first case we talk of vector like fermions in the second of chiral fermions.

By Lorentz invariance, a fermonic mass term is bilinear in fermions w/ the same helicity. If these fill by themselves a complex rep. (the case of chiral fermions) it may be impossible to write a gauge-invariant fermonic mass term in L.

5. We finally add interactions among the matter fields (this is where most of the free parameters of the SM come from). Renormalizability restricts them to be tri-linear or quarti-linear in bosons and tri-linear with two fermions and one boson.

Generic renormalizable gauge theory lagrangian

$$
\begin{aligned}
L_{RGT} = & \; -\sum_a \frac{1}{4g_a^2} F^a_{\mu\nu} F^a_{\mu\nu} + \sum_i i\bar{\Psi}_i \gamma^\mu D_\mu \Psi_i + \sum_j D_\mu \Phi_j^* D^\mu \Phi_j \\
- & \; m_{ij} \Psi_{\alpha i} \Psi_{\beta j} \epsilon_{\alpha\beta} + \lambda^{(Y)}_{ijk} \Phi_k \Psi_{\alpha i} \Psi_{\beta j} \epsilon_{\alpha\beta} + c.c. \\
- & \; \mu^2_{kl} \Phi_k \Phi_l + \eta_{ijk} \Phi_i \Phi_j \Phi_k + \kappa_{ijkl} \Phi_i \Phi_j \Phi_k \Phi_l
\end{aligned}
$$

The particular case of the SM

The SM's gauge group is (for unknown reasons):

$$G = SU(3)\times SU(2)\times U(1)$$

It thus contains 8+3+1 = 12 "gauge bosons" one for each generator of G. It also contains 3 gauge couplings, one for each "factor" in G.

With the exception of the Higgs boson, a spin zero particle, the matter fields are all spin-1/2 Weyl fermions, the smallest non-trivial reps. of the Lorentz group.

The l.h. fermions belong to a fully chiral, highly reducible (and somewhat baroque) representation of G.

Furthermore, this rep. is repeated 3 times, giving the famous 3 families of quarks and leptons.

Gauge quantum numbers in theSM
(one family of left-handed fermions)

	SU(3)	SU(2)	U(1)
(u,d) = Q	3	2	1/6
(	1	2	-1/2
u	3*	1	-2/3
d	3*	1	+1/3
e	1	1	+1
(	1	2	1/2

+ the c.c. fields, including $\Phi^{*} = (\phi^{0*}, \phi^{-})$ + two more fermion families + sterile neutrinos?

By a "fully chiral" representation we mean, in physical terms, that we cannot write down any gauge-invariant mass term. Fermion (quark and lepton) masses can only appear as a consequence of the spontaneous breaking of the gauge symmetry à la Brout-Englert-Higgs.

The same mechanism gives mass to the gauge bosons of SU(2)xU(1) leaving behind just a massless photon and 3 massive "intermediate bosons" the $W^{\pm}$ and the Z^0 as well as a single scalar, the Higgs boson recently discovered at the LHC (3 of the 4 particles contained in Φ are "eaten up").

For the SU(3) part a different (non-perturbative) mechanism (confinement) prevents the existence of free quarks and gluons which, instead, form SU(3)-singlet bound states, the hadrons (mesons and baryons).

The Standard Model lagrangian

$$
\begin{aligned}
L_{SMP} \quad = \quad & -\frac{1}{4}\sum_a F^a_{\mu\nu}F^a_{\mu\nu} + \sum_{i=1}^{3} i\bar{\Psi}_i\gamma^\mu D_\mu\Psi_i + D_\mu\Phi^* D^\mu\Phi \\
- \quad & \sum_{i,j=1}^{3} \lambda^{(Y)}_{ij}\Phi\Psi_{\alpha i}\Psi^c_{\beta j}\epsilon_{\alpha\beta} + c.c. \\
+ \quad & \mu^2\Phi^*\Phi - \lambda(\Phi^*\Phi)^2 \\
- \quad & \frac{1}{2}\sum_{i,j=1}^{3} M_{ij}\ \nu^c_{\alpha i}\nu^c_{\beta j}\epsilon_{\alpha\beta} + c.c.
\end{aligned}
$$

New?

Confirmed by LHC-7?

Why is this not enough?

The SM is extremely successful. So far it has not been seriously challenged experimentally.

Theoretically, however, it also has some unsatisfactory features:

1. A large number of free parameters
2. A non-simple gauge group
3. A highly reducible rep. for the matter fields
4. A large hierarchy problem in fermionic masses
5. A huge hierarchy problem in the Higgs sector
6. Last but not least: gravity is not part of the SM.

It is still the same theory of gravity formulated by Einstein 100 years ago…

General Relativity, is also based on a local symmetry, general covariance, which implements the equivalence principle (universality of free fall) and is naturally associated with a tensor field, the gravitational field. Semiclassically, such a field describes a massless particle of spin 2, the graviton, the analogue of the photon for the electromagnetic field.

Gauge invariance removes the unphysical degrees of freedom of a massless spin-1 particle.

General covariance, likewise, removes the unphysical degrees of freedom,of a massless spin-2 particle.

The analogy unfortunately stops here.

So far, theorists have been unable to extend to gravity the fully quantum framework that led them to the SM: for quantum gravity the UV divergences are too strong!

There are strong indications that, in order to arrive at a fully consistent quantum theory of gravity, one needs to go beyond the framework of local QFT.

At present, string theory (which, as we shall see, predicts the existence of massless J=1 and J=2 particles) is the most promising avenue we have to combine the principles of QM, Gauge Invariance and General Covariance and to arrive at a fully unified quantum theory of all forces and of all elementary particles (but we are not there yet!).

This, however, was not the way historically string theory came about. It came from an attempt, in the sixties, to describe in an unconventional way the strong interactions. That attempt, as such, failed. However, in the process, a beautifully consistent theoretical framework was constructed which, instead, looked perfectly capable of addressing the deeper question of how to reconcile gravity and Quantum Mechanics.

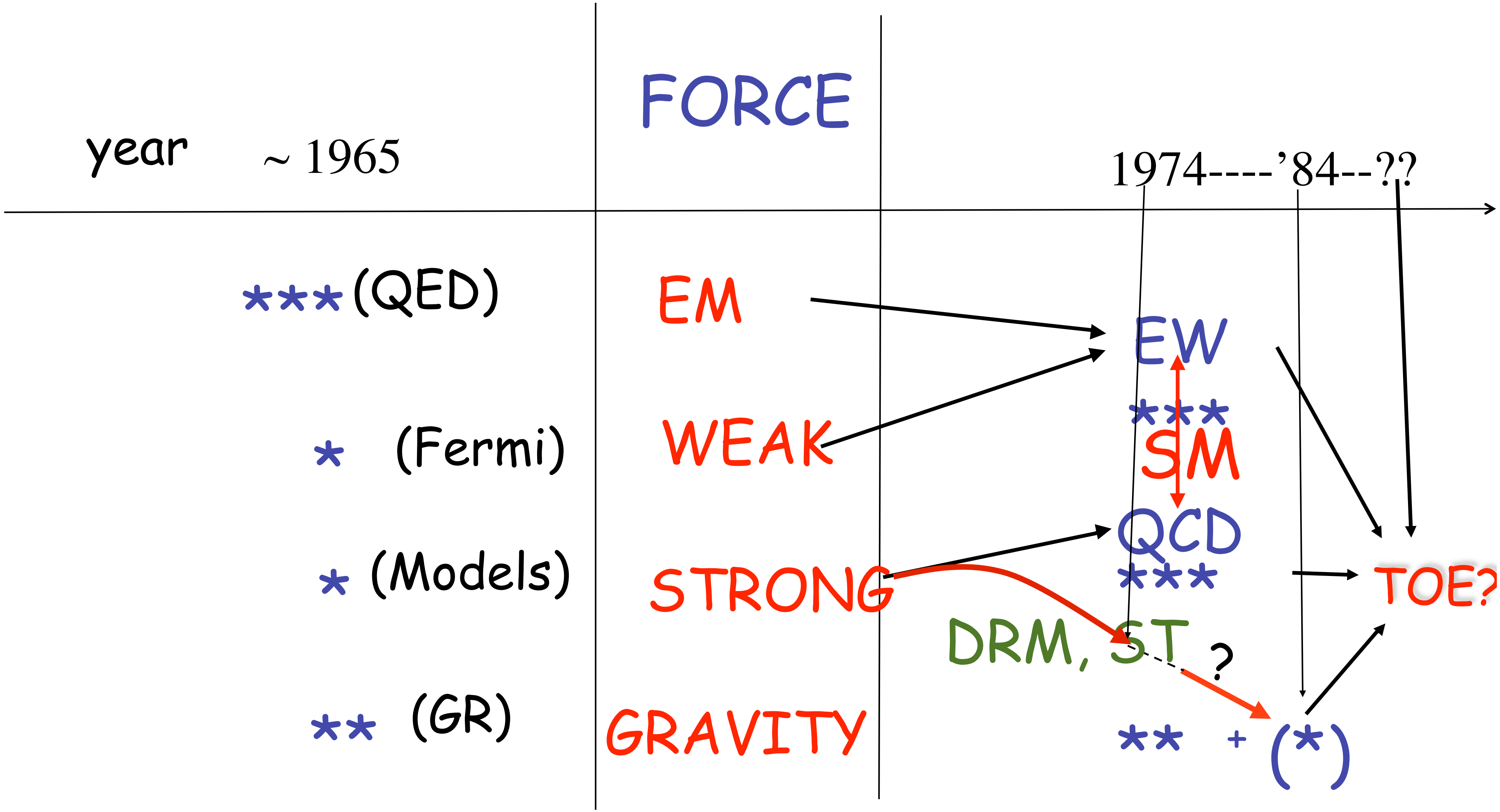
Most courses in string theory start directly from this end (a top-down approach) arriving at the model that historically led to string theory after many pages of non-trivial calculations (see e.g. J. Polchinski's book).

I thought it would be better, for this audience, to use the opposite, bottom-up approach.

In the first part of the course we will retrace the birth of the so-called Dual Resonance Model (DRM) -and of its interpretation as a string theory- as a candidate theory of strong interactions.

We will then discuss some basic (and apparently unavoidable!) properties of quantum strings and why these properties led to abandoning the original goal when QCD came about. Moreover, QCD even explained, a posteriori, why string theory was invented in an apparently "accidental" way and why it had remarkable success in explaining some strong interaction phenomenology.

An evolving "Michelin guide"



In the second part of the course we will discuss the modern formulation and reinterpretation of string theory (based on its same unavoidable properties) as a unified quantum theory of all interactions, including gravity.

The string theory of the sixties & seventies was so predictive to be easily falsifiable!

Will it be the same for its new incarnation?

Piano preliminare del corso

Prima parte (5 novembre-17 dicembre)

- 1965-1975: Il decennio d'oro delle particelle elementari?
- Elementi essenziali del Modello Standard
- La teoria delle interazioni forti anni sessanta.
- Sopravvento della matrice-S: simmetrie, poli di Regge.
- Dualità di DHS e un bootstrap a buon mercato.
- Il parto faticoso di un modello sorprendente.

- Modello a risonanze duali e il suo spettro inatteso.
- Condizioni di Virasoro e dimensioni dello spazio.
- Il modello di Neveu-Schwarz-Ramond: la supersimmetria.
- La stringa sottostante, azione di Nambu-Goto.
- Difficoltà fenomenologiche della stringa adronica.
- Avvento della QCD: libertà asintotica e confinamento.
- Sviluppo 1/N e la misteriosa stringa della QCD.

Seconda parte (17 marzo-5 maggio) (molto preliminare)

- Stringhe classiche e quantistiche: vive la différence!
- Kaluza-Klein con le stringhe, T-dualità
- La prima rivoluzione (Green-Schwarz, 1984)
- Azione efficace della stringa e il suo duplice significato
- Azione efficace della stringa e il suo duplice sviluppo perturbativo.
- T-dualità per stringhe aperte, D-brane, seconda rivoluzione (Polchinski 1995).
- Unificazione delle teorie di stringa e M-teoria.
- La corrispondenza gauge-gravità (Maldacena 1997)

- Applicazioni cosmologiche: dualità nel fattore di scala e modello del pre-big-bang.
- Conseguenze osservabili della cosmologia di stringa
- Stringhe e buchi neri quantistici: interpretazione dell'entropia di Bekenstein-Hawking
- Il paradosso dell'informazione e lo scattering gravitazionale ad energie estreme.
- Una teoria falsificabile?

per saperne di più sulla prima parte:

The Birth of String Theory

(Eds. A. Cappelli, E. Castellani, F. Colomo, P. Di Vecchia)

Cambridge U. Press 2012

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