STRING THEORY
Even if not true, it is well conceived and ... worthwhile

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STANDARD MODELS

• Discovery of BEH boson, with $M=125\text{GeV}$ confirmation [after 50 years] of the Standard Model of Particle Physics based on broken/confined gauge symmetry $SU(3)\times SU(2)\times U(1)$

Very little room for new physics:

• neutrino oscillations: masses and mixings ?
• WIMP’s for Cold Dark Matter: LSP?
• Origin of Dark Energy $\Lambda$: ???
Beyond SM?

Future, when?

Present LHC, Planck →

Super-Unification
Strings / M-theory ??

Grand Unification
GUT ??

Quantum
supergravity??

Super-symmetry
SUSY ?

General
Relativity
Λ–CDM ?

Electro-weak
Standard Model

QCD: Quantum
Chromo-dynamics

Relativity

Universal
Gravitation

Strong Nuclear
Interactions

Terrestrial
Gravity

Brout-Englert-Higgs
Mechanism

Weak Nuclear
Interactions

QED: Quantum
Electro-dynamics

Celestial
Gravity

Past

Electricity

Magnetism
Anche se non è vera, è ben trovata

• “Once upon a time ...”

Veneziano amplitude [1968]

\[ A(s,t) = \Gamma(-\alpha's-1) \Gamma(-\alpha't-1) / \Gamma(-\alpha's-\alpha't-2) \]

• Dual resonance models

\[ \alpha' = \frac{1}{2\pi T_s} \] Regge slope = inverse string tension

• Hadronic strings: \( T_s \approx 1 \, \text{GeV}^2 \)

... [by “wild” extrapolation]

• Fundamental strings: \( T_s \approx 10^{38} \, \text{GeV}^2 \)
PLAN

- Open/closed bosonic strings: Pro’s and Con’s
- Superstrings and compactifications
- P-branes and M-theory
- Holography and AdS/CFT correspondence
- Amplitudes, Wilson loops, correlators
- Black Holes in String Theory
- Flux compactifications
- Outlook
CON’s

• D = 26 NOT D = 4
• Tachyons NOT (almost) massless pions
• Massless vector meson NOT massive $\rho$, $\omega$
• Regge behavior in UV NOT hard quarks / asymptotic freedom
• NO baryons / fermions
MESON SPECTRA
PRO’s

• Regge poles = Open String excitations
  \(M^2 = T_s(n - 1)\)  Linear trajectories
• Planar duality  \(A(s,t) = A(t,s)\)
• Chan-Paton factors, flavour symmetry
• Wilson loop, confinement, area law
  \[ W = \exp(-T_s A_\Sigma) \]
• Large N planar limit, topological expansion
  ... strings tantalize
Open string
Closed String
CLOSED STRINGS

• String action

\[ S = - T_s \int_\Sigma g^{ab} \partial_a X^\mu \partial_b X_\mu \sqrt{g} d^2 \sigma = - T_s A_\Sigma \]

• Shapiro-Virasoro amplitude

\[ A(s, t, u) = \frac{\Gamma(-2 - \alpha's/2) \Gamma(-2 - \alpha't/2) \Gamma(-2 - \alpha'u/2)}{\Gamma(-2 - \alpha'(s + t)/2) \Gamma(-2 - \alpha'(t + u)/2) \Gamma(-2 - \alpha'(u + s)/2)} \]

• Non-planar duality

• Massless spin 2 particle

\[ M^2 = 2T_s (2n - 2) \]
FEYNMAN vs POLYAKOV
FERMIONIC STRINGS

- Add world-sheet fermions, get world-sheet Supersymmetry: $\delta X^\mu = \epsilon \Psi^\mu$, $\delta \Psi^\mu = \epsilon \partial X^\mu$
- Two sectors: Ramond and Neveu-Schwarz
- Tachyon (NS) with half-integer mass
- $D=10$

But after GSO projection
- Space-time SUSY
- No tachyon, $L \neq R$
FUNDAMENTAL STRINGS

• Scherk Schwarz 1974 $\alpha' \approx M_{\text{Planck}}^{-2} \approx G_{\text{Newton}}$
• Closed strings: Massless spin 2 boson = graviton
• Open strings: Massless spin 1 boson = photon, gluons
• Geometric interactions: splitting/joining of strings
• Soft UV behavior, finite Quantum Gravity
  Yet ...
• $D = 10$, i.e. 6 extra dimensions
• $g_s = $ string coupling, undetermined dilaton VEV
• Infinite tower of massive Higher Spins: exponential growth of degeneracy, Hagedorn transition $\alpha' (\kappa T_H)^2 \approx 1$
Chiral fermions may lead to quantum anomalies
• Standard Model chiral but NO triangle anomalies
Superstrings in D=10 potential exhagon anomalies
• Type IIA non chiral NO anomaly
• Type IIB chiral yet NO anomaly
• Type I chiral and anomalous
• Green-Schwarz mechanism for anomaly cancellation

\[ \delta C_{\mu
\nu} = \text{Tr}(\alpha F_{\mu
\nu}) \quad \delta A_\mu = D_\mu \alpha \quad \delta S = 0 \]

Reducible anomalies cancel for G=SO(32) ... and E(8)xE(8)
• Heterotic strings: Bosonic Left, Super Right, 16=26-10
COMPACTIFICATIONS

• Tori, flat, trivial holonomy, too much SUSY, NO chirality
• Calabi Yau spaces, SU(3) holonomy, N=1 susy (Type I or Het)
• Chirality, Grand Unification: E(6), SO(10), SU(5) ...
• Number of generations, Yukawa’s/CKM from CY geometry
• T-duality: \( \mathbb{R} \rightarrow \alpha'/\mathbb{R} \), KK vs windings, Mirror symmetry
  Yet
• Many undetermined parameters “moduli” (scalar field VEV’s)

Explicit constructions
• Orbifolds eg \( \mathbb{Z}_2 : X = -X + 2\pi R \), with/without fixed points
• Non-geometric compactifications: asymmetric orbifolds, free fermions, Gepner models, T-folds ... double tori
OPEN & UNORIENTED STRINGS

- Largely unexplored in the CY decade
- Systematic construction circa 1990 (pre D-branes / $\Omega$-planes)
- New (non susy) theories in $D=10$
- Generalized GS mechanism in $D=6$ and $D=4$
- Rank reduction when $B_{NSNS} = \frac{1}{2}$ in $D=8$ and below
- Chiral models in $D=4$ with 3 generations
**P-BRANES**

- p-branes = extended objects, BPS bound:
  \[ T_p = |Q_p| \]
- Macroscopic description = solitonic solutions of low-energy supergravity
  \[
  ds^2 = B(r) dx \, dr + A(r) dy \, dy \\
  \phi = \phi(r) \\
  C_{p+1} = C(r) \, dx^0 \, dx^1 \ldots \, dx^p
  \]
- Microscopic description (D[irichelet]-branes) = hypersurfaces where open strings can end
- Natural interaction on the world-volume
  \[
  S_{\text{int}} = - Q_p \int_{W_p} C_{01\ldots p}(X) \, dx^0 \, dx^1 \ldots \, dx^p
  \]
D-BRANES
M-THEORY

• Generalized electric-magnetic duality:
  \[ p\text{-brane} \rightarrow C_{p+1} \rightarrow F_{p+2} \rightarrow F'_{D-p-2} \rightarrow C'_{D-p-3} \rightarrow p'\text{-brane} \]
  \[ p' = D-4-p \]

Dirac quantization: \( Q_p Q_{p'} = n \ h \ c \)

• p-brane democracy, “U-duality”

• M-theory: 11-d Supergravity + M2’s/M5’s + ...

• All descriptions related by generalized duality
HOLOGRAPHY

• Black Hole entropy, Bekenstein-Hawking area law,
  \[ S_{\text{BH}} = \frac{1}{4} A_H \]
  
• True degrees of freedom in quantum gravity localized on the boundary / horizon

• AdS/CFT correspondence from D3 near horizon

• Gravity (closed strings) in Anti De Sitter space \( \Lambda < 0 \)
  Dual to

• Conformal theory (open strings) on the boundary
  \[
  \langle \exp \int f(x) O_\Delta(x) d^4x \rangle_{\text{CFT}} = Z_s[\Phi_M(\rho,x) \approx f(x)]
  
  M^2 L^2 = \Delta (\Delta - 4)
  \]
BRANE WORLDS / HOLOGRAMS
THE HARMONIC OSCILLATOR OF QFT

- N=4 SYM with G = SU(N) in D=4 (superconformal + ...)
  Dual to
- Type II B superstrings in AdS$_5 \times S^5$ with $\int F_5 = N$
- Classical strings = large N, planar limit
- Small curvature, supergravity = strong ‘t Hooft coupling
- RG flows and Holographic Renormalization
- Dilatation operator = integrable super spin chain
- OPE’s, Correlators, Wilson loops, Amplitudes
- Finite temperature and density: $\eta/s = 1/4\pi$ !!! RHIC
- Holographic QCD, QG plasma ... AdS/CMT
s-MATRIX RELOADED

• Remarkable simplification for colour-ordered MHV amplitudes (Maximally Helicity Violating)

\[
A (+++ ... −i ...−j ... +) = u_1 u_2^4 / u_1 u_2 u_2 u_3 ... u_n u_1 \\
a_\mu (p,+) = \bar{e} \gamma_\mu u_p / \bar{e} u_p \quad \text{with} \quad \gamma^\mu p_\mu u_p = 0, \quad \gamma^5 u_p = u_p
\]

• Any gauge theory is susy at tree level
• String theory helps organizing diagramatic expansion
• Loops, IR divergences, exponentiation
• Cusp anomalous dimension
• Holography: Correlators / Wilson-loops / Amplitudes
BLACK HOLES

• Bound states of (wrapped) strings and p-branes, eg D1-D5-F1-N5
• Use $d(E) = \exp(E/\kappa T_H)$ to reproduce $S_{BH}$ or $\sigma_{BH}$
• BH microstate counting
• Perfect agreement for BPS BH’s
• Hawking radiation from near extremal BH’s
• Fuzzball proposal, non-singular geometries
FLUX COMPACTIFICATIONS

• Use internal fluxes to stabilize moduli ≈ supergravity gaugings
• Include Dp-branes, instantons [ADHM for free]
• No fully satisfactory model:
  “The devil is in the details”
• No concrete predictions: large extra dimensions, new anomalous U(1)’s, discrete symmetries, small BH’s, higher spins, inflat(i)on ... ??????
OUTLOOK

• NO string landscape
• In fact NOT a single string model reproducing SM or beyond
• NO experimental evidence ... except for gravity
• In fact, given the success of the SM’s, it is very hard to conceive any viable extension
• Yet ...
• Consistent framework where quantum gravity can be quantitatively tackled
• Many insights into (SUSY) gauge theories
• New algebro-geometric structures
• Dualities ... M-theory
• Holography

and
Anche se non è vera, 
è ben trovata e ... 
ricompensa gli sforzi:

Congratulations, Mike