

STRING THEORY

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

Massimo Bianchi

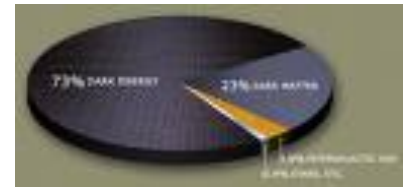
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STANDARD MODELS

- 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:

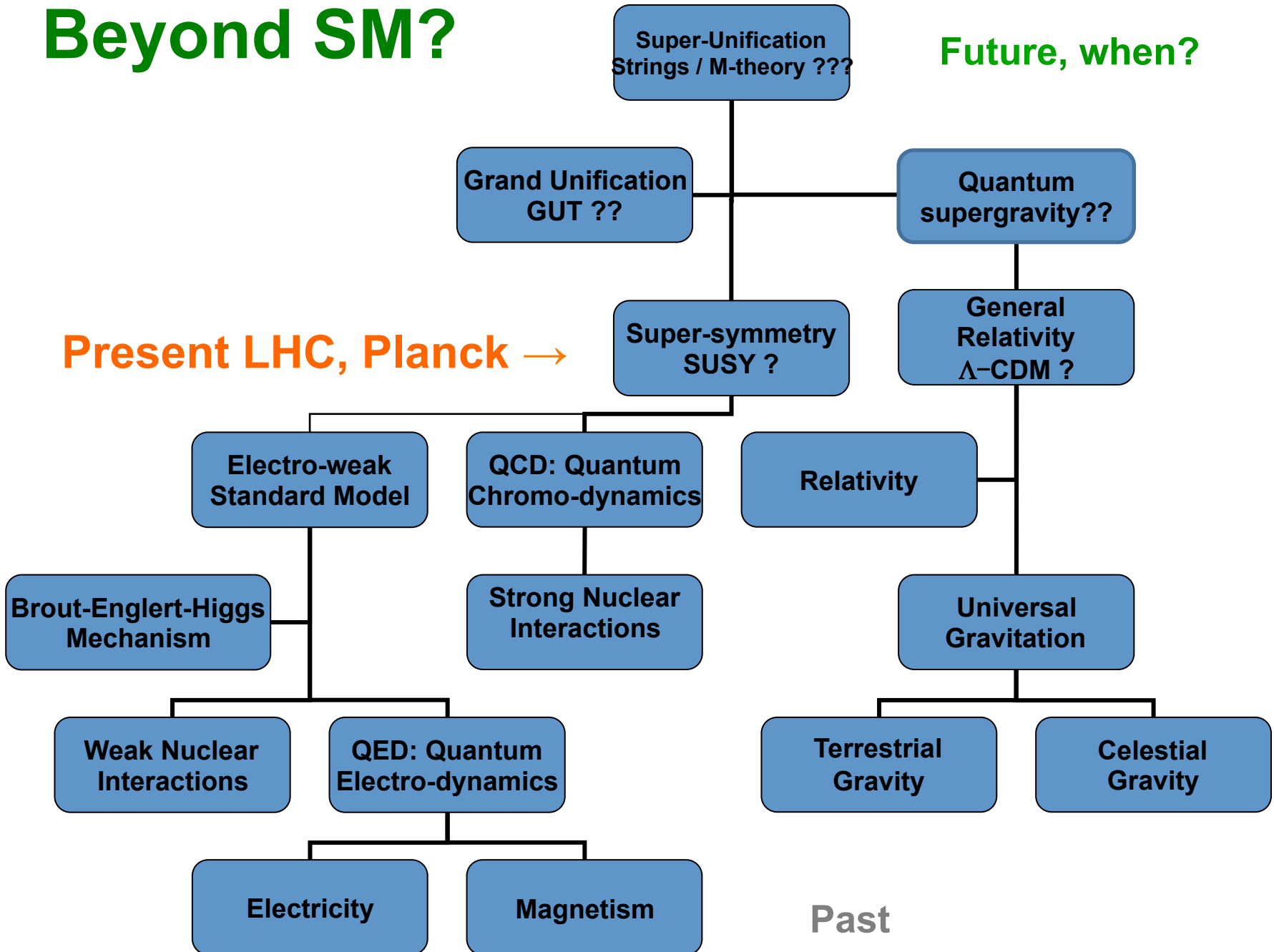
- neutrino oscillations: masses and mixings ?
- WIMP's for Cold Dark Matter: LSP?
- Origin of Dark Energy Λ : ???



Beyond SM?

Future, when?

Present LHC, Planck →



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

$\alpha' = 1/2\pi T_s$ Regge slope = inverse string tension

- Hadronic strings: $T_s \approx 1 \text{ GeV}^2$

... [by “wild” extrapolation]

- Fundamental strings: $T_s \approx 10^{38} \text{ GeV}^2$

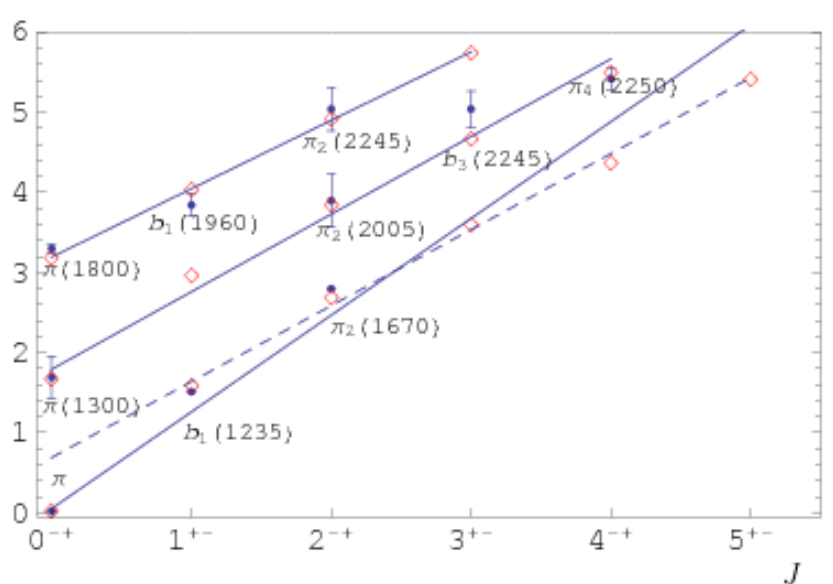
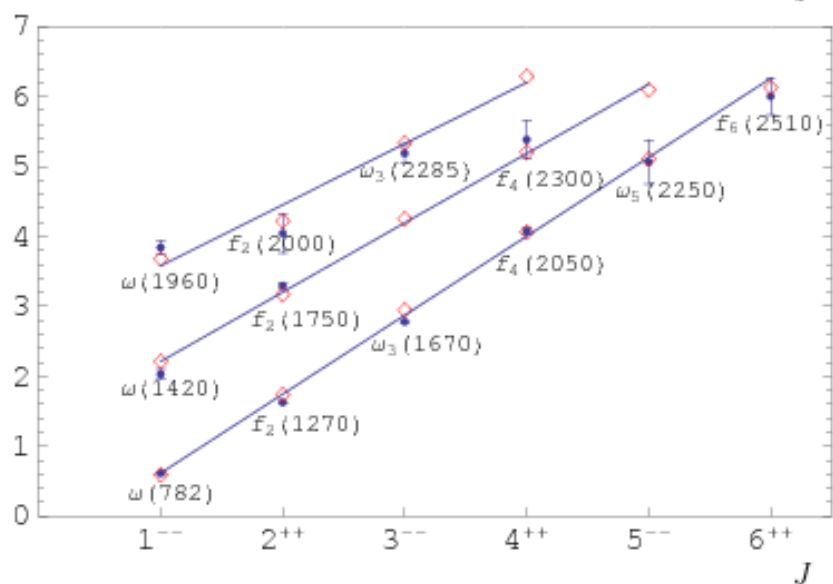
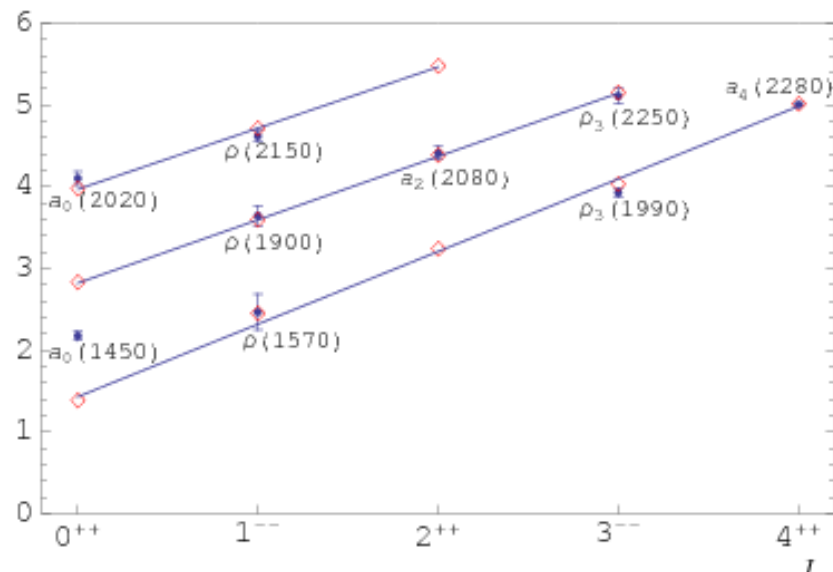
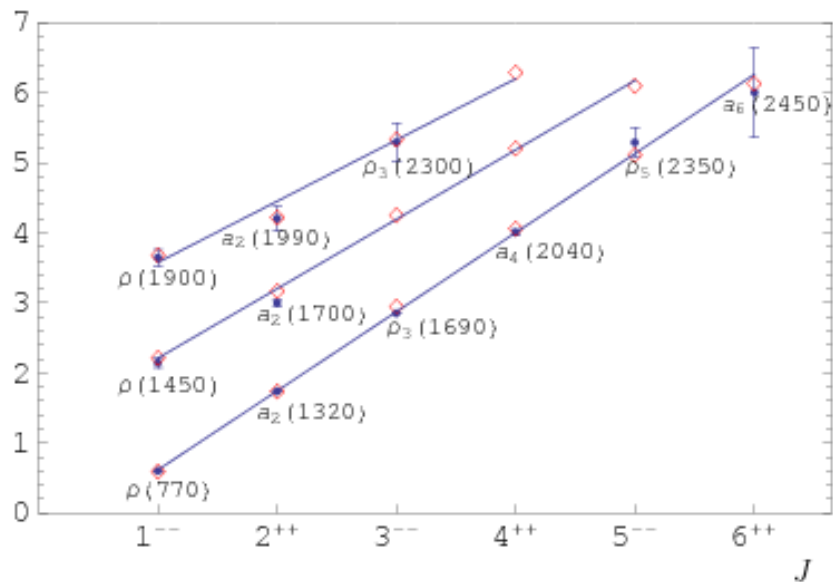
PLAN

- 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

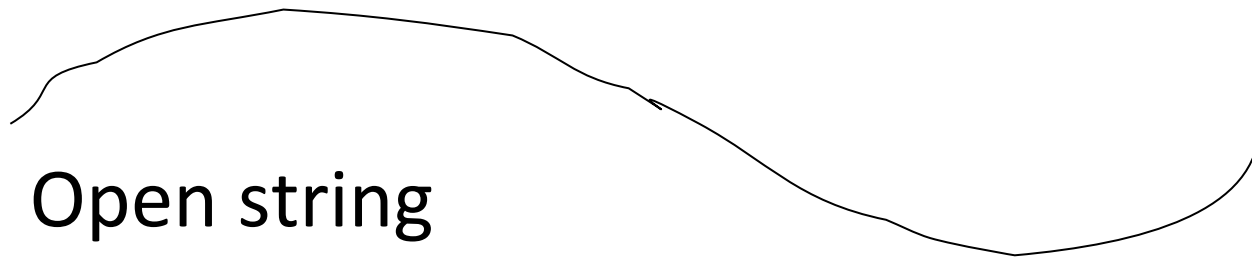
- $D = 26$ NOT $D = 4$
- Tachyons NOT (almost) massless pions
- Massless vector meson NOT massive ρ, ω
- Regge behavior in UV NOT hard quarks / asymptotic freedom
- NO baryons / fermions

MESON SPECTRA

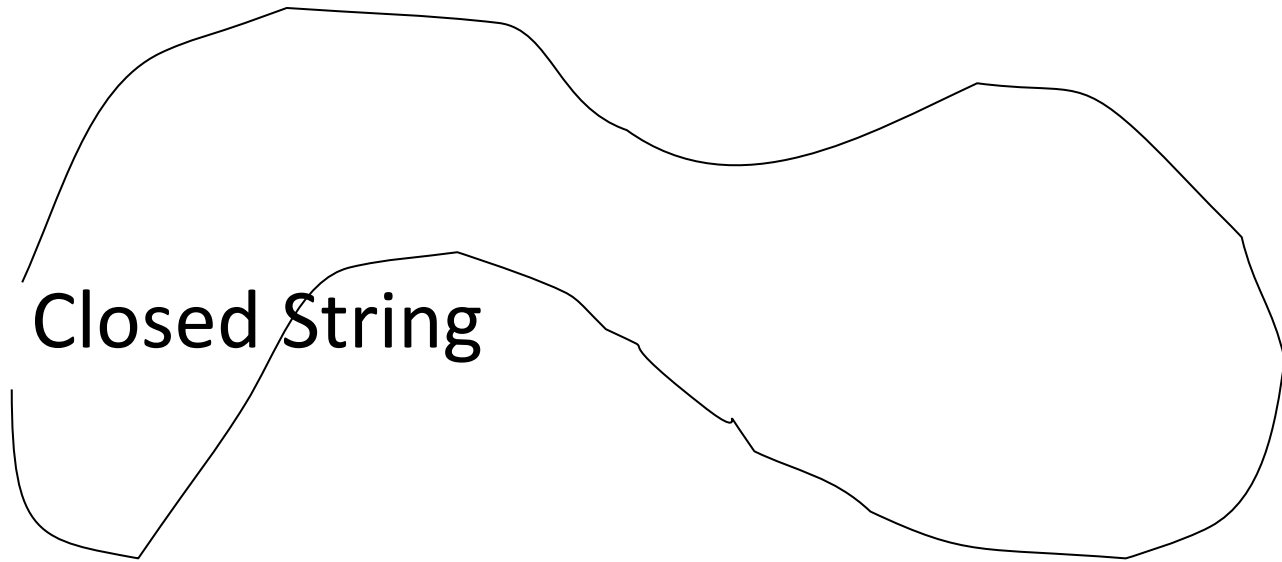


PRO's

- 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 STRINGS

- String action

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

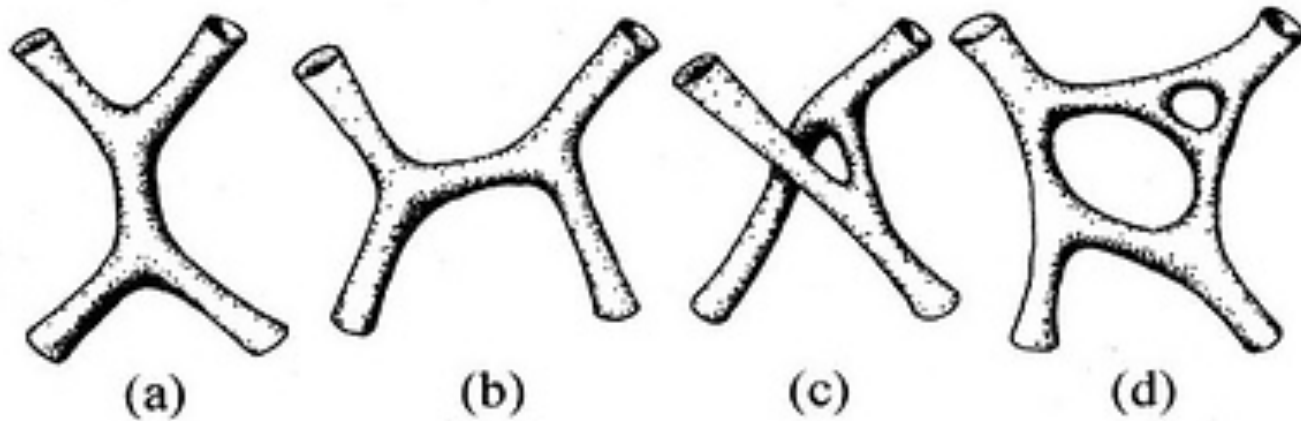
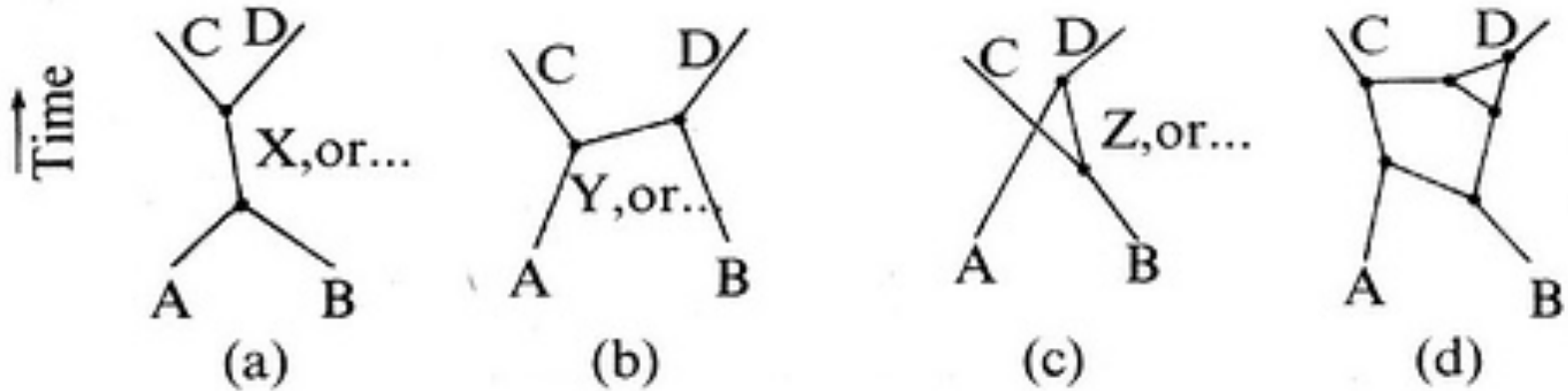
- Shapiro-Virasoro amplitude

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

- Non-planar duality
- Massless spin 2 particle

$$M^2 = 2T_s(2n - 2)$$

FEYNMAN vs POLYAKOV



FERMIONIC STRINGS

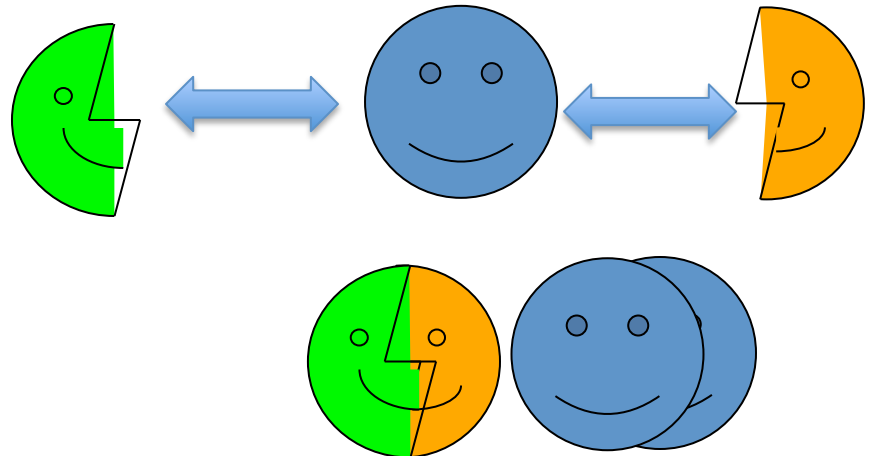
- Add world-sheet fermions, get world-sheet Supersymmetry: $\delta X^\mu = \varepsilon \Psi^\mu$, $\delta \Psi^\mu = \varepsilon \partial X^\mu$
- Two sectors: Ramond and Neveu-Schwarz

Yet

- Tachyon (NS) with half-integer mass
- $D=10$

But after GSO projection

- Space-time SUSY
- No tachyon, $L \neq R$

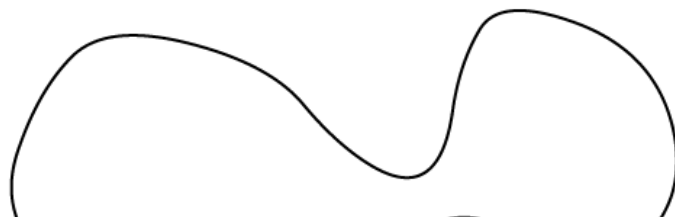
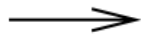
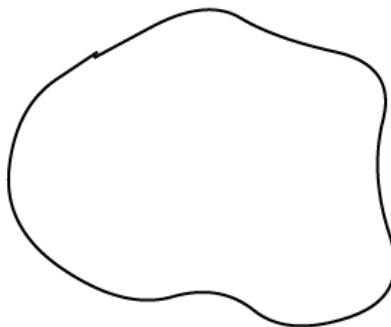
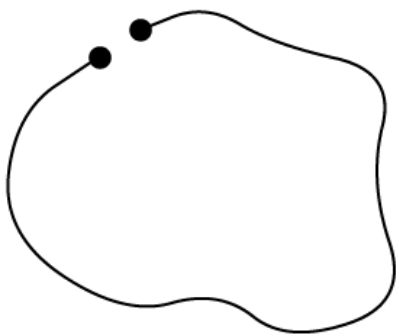
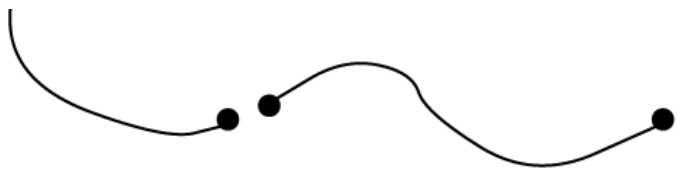


FUNDAMENTAL STRINGS

- 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 $\alpha'(\kappa T_H)^2 \approx 1$



1984

Chiral fermions may lead to quantum anomalies

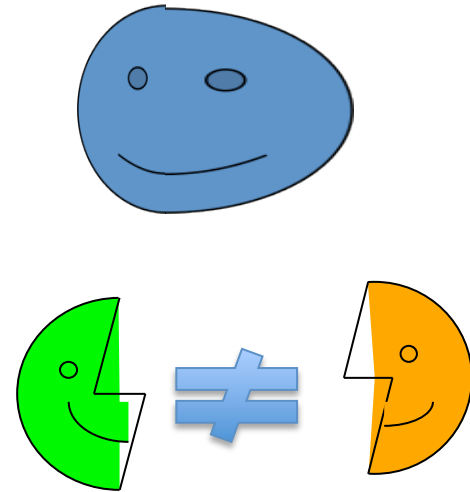
- Standard Model chiral but NO triangle anomalies

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 $E(8) \times E(8)$

- 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: $R \rightarrow \alpha'/R$, KK vs windings, Mirror symmetry

Yet

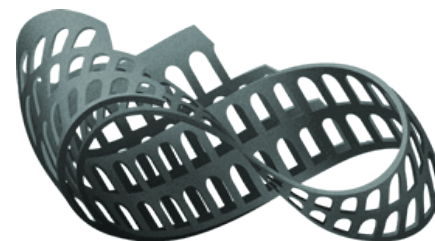
- Many undetermined parameters “moduli” (scalar field VEV's)

Explicit constructions

- Orbifolds eg 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 / Ω -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

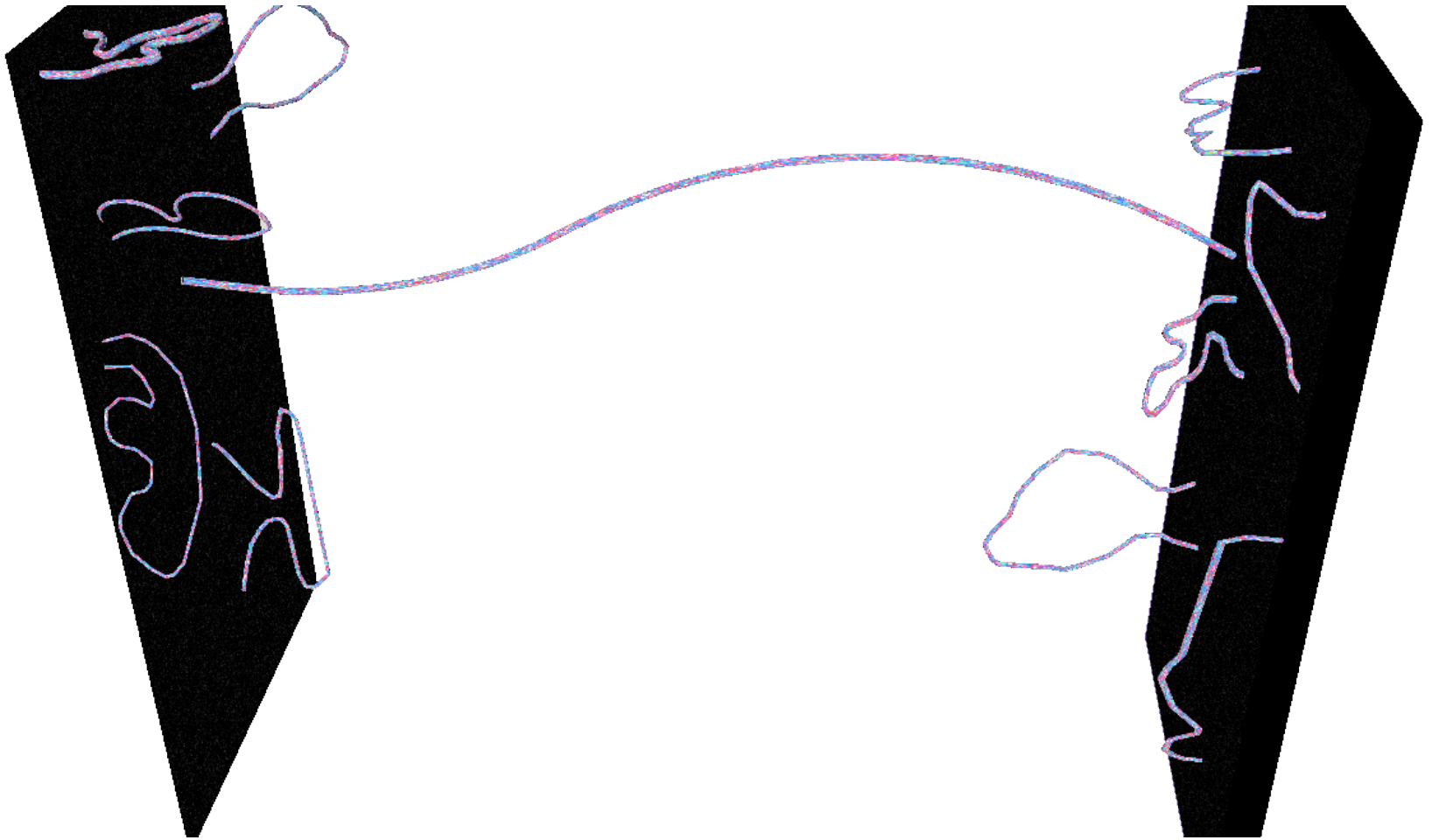
$$ds^2 = B(r) dx dx + A(r) dy dy$$

$$\phi = \phi(r) \quad C_{p+1} = C(r) dx^0 dx^1 \dots dx^p$$

- Microscopic description (D[irichelet]-branes) = hypersurfaces where open strings can end
- Natural interaction on the world-volume

$$S_{\text{int}} = - Q_p \int_{W_p} C_{01\dots p}(X) dX^0 dX^1 \dots dX^p$$

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,

$$S_{\text{BH}} = \frac{1}{4}A_{\text{H}}$$

- 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 $\Lambda < 0$

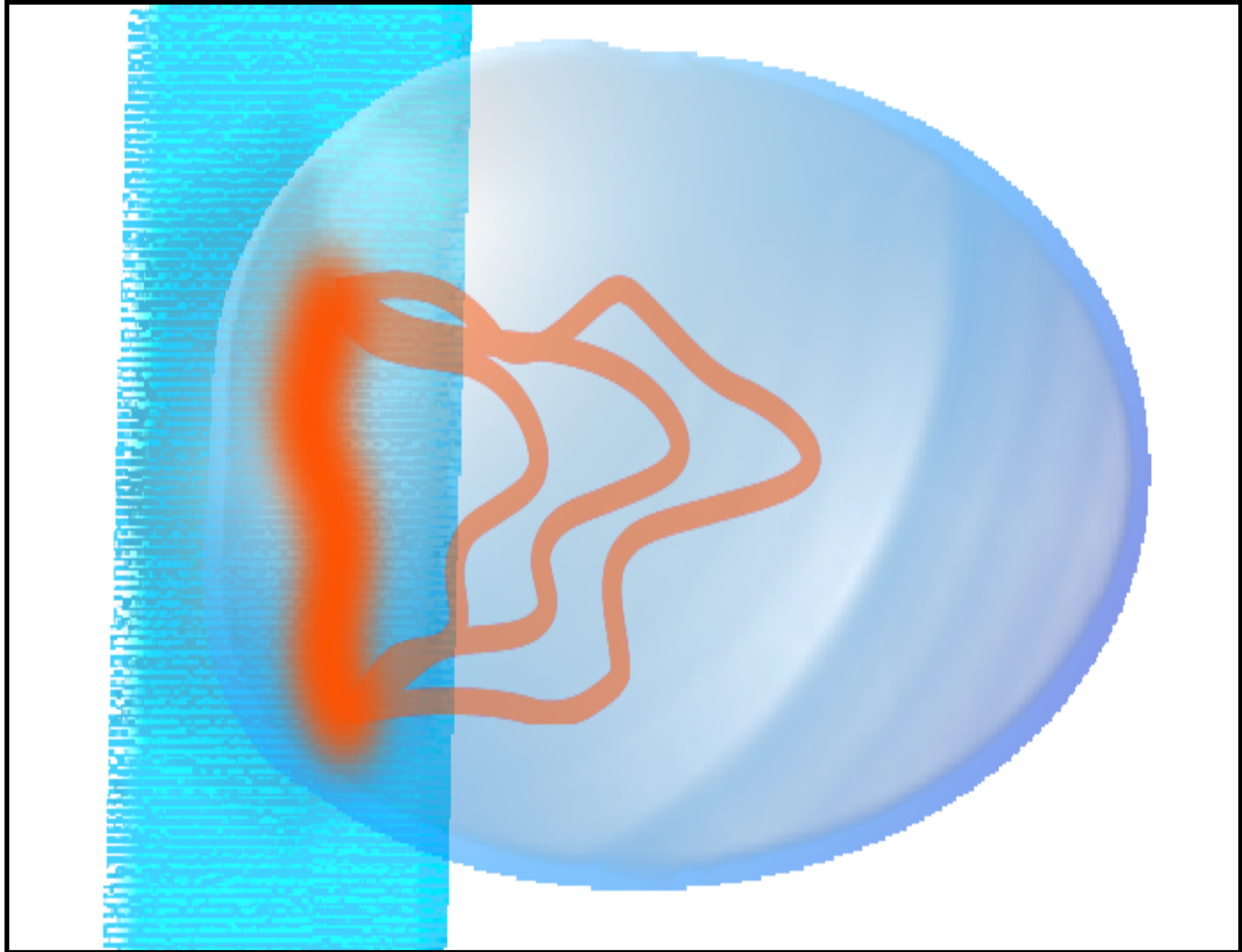
Dual to

- 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

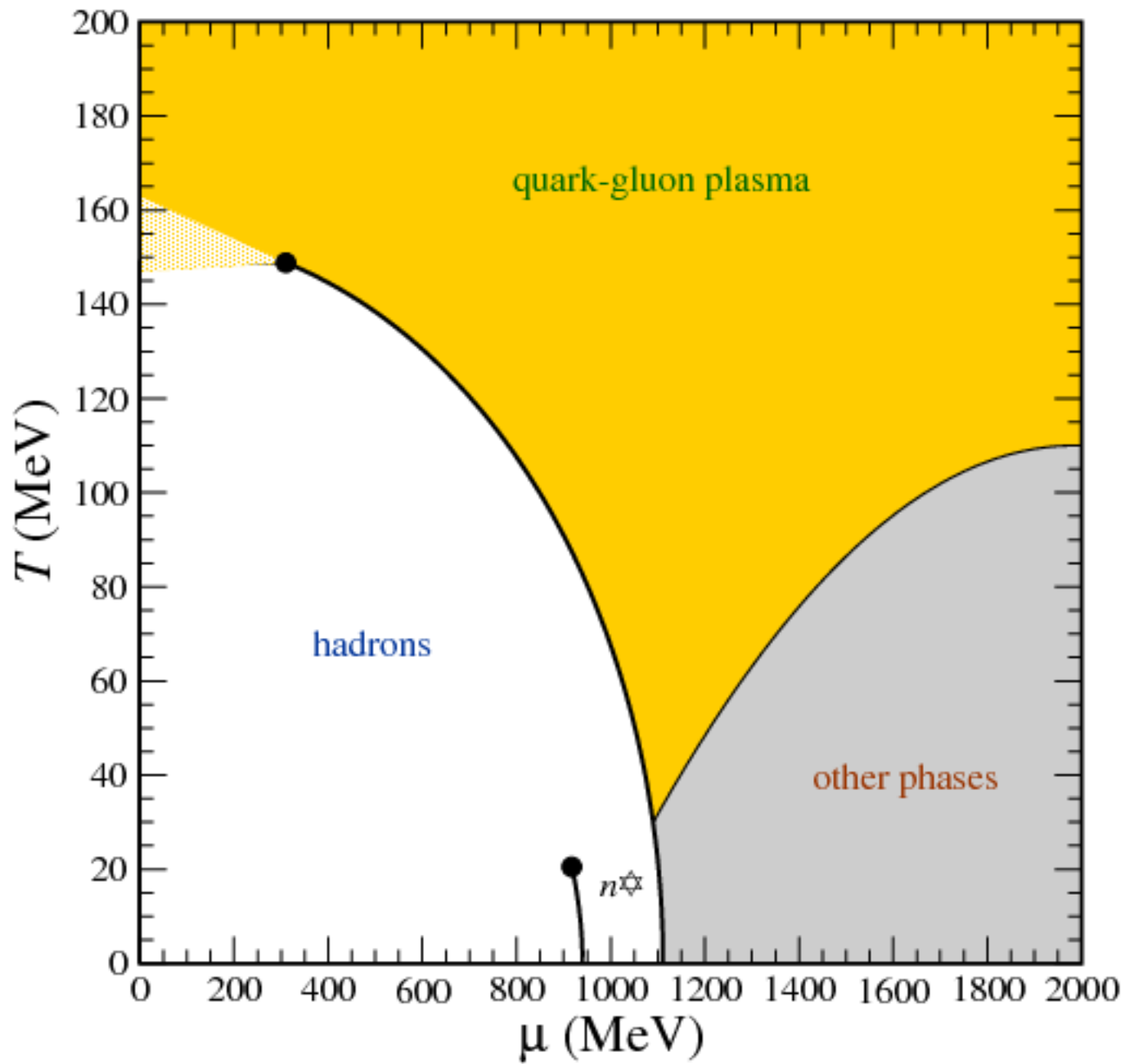


THE HARMONIC OSCILLATOR OF QFT

- **N=4 SYM** with **G = SU(N)** in **D=4** (superconformal + ...)

Dual to

- **Type II B** superstrings in **AdS₅ x S⁵** 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)

$$A(+++ \dots -_i \dots -_j \dots +) = u_1 u_2^4 / u_1 u_2 u_2 u_3 \dots u_n u_1$$

$$a_\mu(p, +) = \bar{e} \gamma_\mu u_p / \bar{e} \bar{u}_p \quad \text{with} \quad \gamma^\mu p_\mu u_p = 0, \gamma^5 u_p = u_p$$

- Any gauge theory is susy at tree level
- String theory helps organizing diagrammatic 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 σ_{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 \approx 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, inflation ... ??????

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