

ARIA SULLA QUARTA SUPERCORDA

Massimo BIANCHI

Dip. Fisica & INFN

Università di Roma "Tor Vergata"



8 ottobre 2004

Laboratori Nazionali di Frascati



Istituto Nazionale
di Fisica Nucleare

www.lnf.infn.it/edu/incontri/

TEORIE DI STRINGA

STRINGA CHIUSA $L \{ \bigcirc \} R$

$$\alpha' M_c^2 = (N_L + N_R - 2) \cdot 2: \quad J=2 \quad M=0 \quad (\text{GRAVITA'}) \\ + B_{\mu\nu} + \varphi + \dots$$

• STRINGA APERTA $\rightarrow \leftarrow$

$$\alpha' M_A^2 = (J-1): \quad J=1 \quad M=0 \quad (\text{FOTONI}, \dots) \\ + \dots$$

TRAIETTORIE DI REGGE (VENEZIANO)



TENSIONE

$$T_s = \frac{1}{4\pi\alpha'}$$


STRINGA ADRONICA: $T_s \sim 1 \text{ GeV}^2$

STRINGA "FONDAMENTALE": $T_s \sim 10^{38} \text{ GeV}^2$

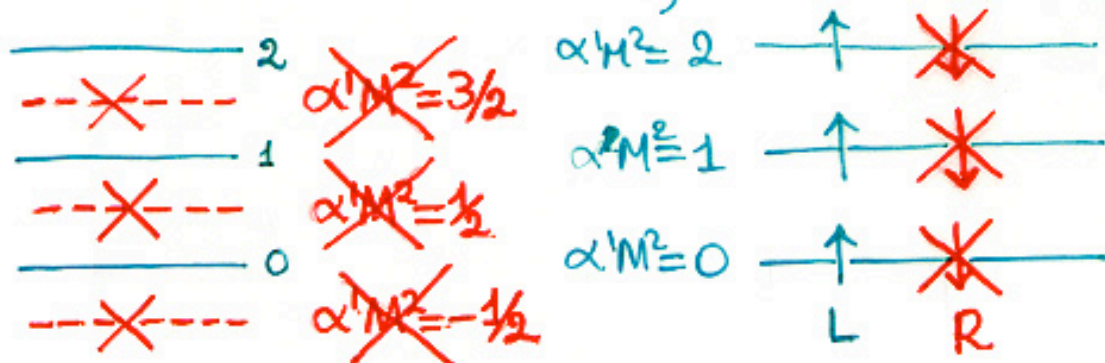
COSTANTE D'ACCOPIAMENTO

$$g_s^{(c)} = e^{2\langle\varphi\rangle} = (g_s^{(A)})^2 \quad \varphi = \text{DILATONE}$$

INSTABILITA' TACHIONICA!

TEORIE DI SUPERSTRINGA

- PROIEZIONE DI GLIOZZI, OLIVE & SCHERK



NEVEU-SCHWARZ

(BOSONI)

$$(-) \psi^\mu(e^{2\pi i} z) = \pm \psi^\mu(z)$$

RAMOND

(+) (FERMIONI)

- MECCANISMO DI GREEN-SCHWARZ

→ SUPERSTRINGA (APERTA) TIPO I

$$N = (1, 0) \text{ SUSY}$$

$$G_{\text{CF}} = SO(32) = G_{\text{SM}}$$

→ STRINGA "ETEROTICA" (CHIUSA)

$$HA: G = E_8 \times E_8 \quad HB: G = SO(32)$$

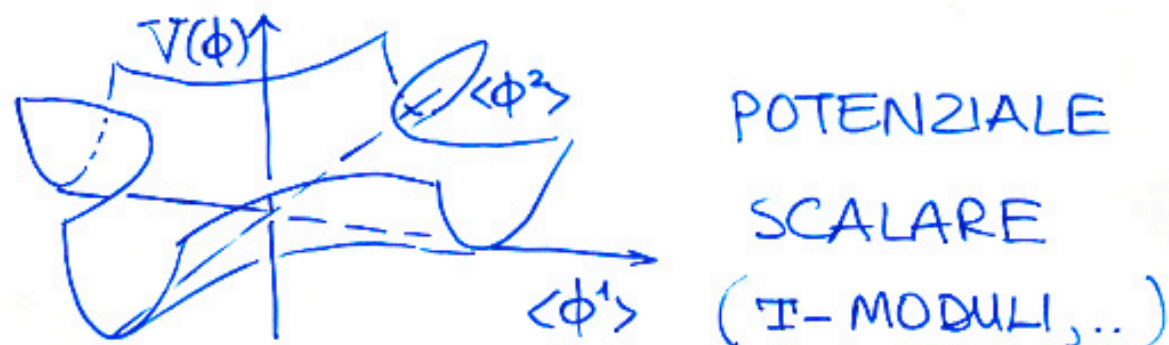
- SUPERSTRINGA (CHIUSA) TIPO II

$$\text{TIPO IIA: } N = 2 = (1, 1) \leftarrow D=11$$

$$\text{TIPO IIB: } N = (2, 0) \text{ CHIRALE}$$

PROBLEMI • 10, 26 $\neq$ 4

- TROPPE TEORIE "CONSISTENTI" ~ 5
- DEGENERAZIONE (∞) DEL "VUOTO"



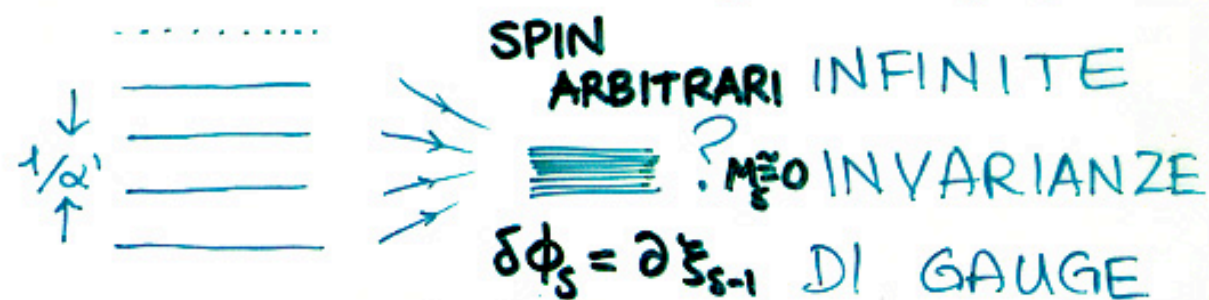
$\leftrightarrow$ DIREZIONI PIATTE DI $V(\phi)$

- TRANSIZIONE DI HAGEDORN

$$Z(\tau) = \sum_E d(E) e^{-E/kT}$$

$$d(E) \sim e^{E/kT_H} \quad T > T_H \sim \frac{1}{\sqrt{\alpha'}} ?$$

- ALTA ENERGIA ($\alpha' \rightarrow \infty, T_s \sim 0$)



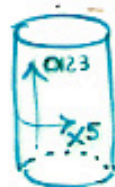
- ROTTURA SUPERSIMMETRIA CON $\Lambda \approx 0, \dots$

COMPATTIFICAZIONI: $D=10(11) \rightarrow D=4$

KALUZA-KLEIN: $D=5 \xrightarrow{S^1} D=4$

$$G_{MN}^{(5)} = \begin{pmatrix} g_{\mu\nu}^{(4)} & A_\mu \\ A_\nu & \phi \end{pmatrix}$$

BPS



$$M_{\text{Pl}} \sim \frac{1}{\sqrt{K}} R$$

$$Q_{\text{EM}} = K$$

• ISOMETRIE CONTINUE $\rightarrow$ SIMMETRIE DI GAUGE

$$G = SU(3)_c \times SU(2)_w \times U(1)_Y \quad M_{\text{min}}^{(7)} = \frac{SU(3) \times SU(2) \times U(1)}{SU(2) \times U(1) \times U(1)}$$

$$\boxed{4+7=11} \leftrightarrow \text{SUPERGRAVITA' } N=1 \quad D=11$$

UNICA, SUSY MAX & SPIN ≤ 2 !

• NON-RINORMALIZZABILE $G_N^{(11)} \sim M_P^{-9}$

• NON CHIRALE: $L=R$ IN $D=2k+1$

- CALABI-YAU: "ANTI" KALUZA-KLEIN

$$\boxed{10-4=2 \times 3} \quad \bullet \text{ OLONOMIA } SU(3) \text{ (SUSY)}$$



K_{CY}

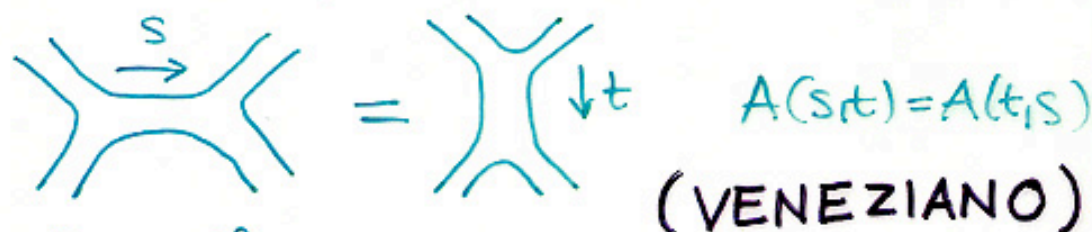
• SENZA ISOMETRIE CONTINUE

• CHIRALITA' $N_{\text{gen}} = \frac{1}{2} |X(K)|$

$\uparrow$ TOPOLOGIA

DUALITA' DI STRINGA

- DUALITA' (NON) - PLANARE



$$A(s,t) = A(t,s)$$

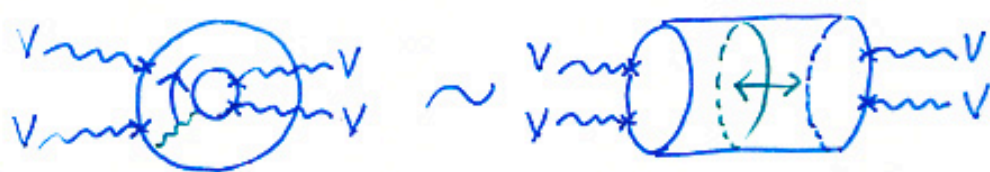
(VENEZIANO)



$$A(s,t,u) = A(s,u,t) = \dots$$

(SHAPIRO-VIRASORO)

- DUALITA' CHIUSA $\leftrightarrow$ APERTA



TIPO I = TIPO IIB / Ω + D9-BRANE

Ω = PARITA' SUL "WORLD SHEET" $L \leftrightarrow R$

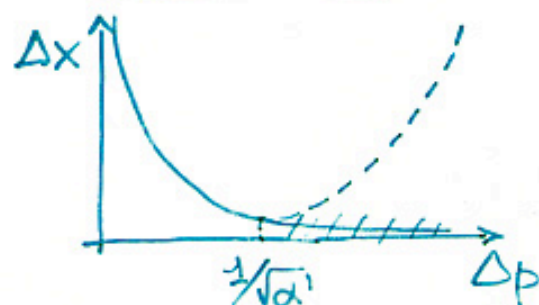
- T-DUALITA': $R \rightarrow \alpha'/R$ $\alpha' \sim T_S^{-1}$



$P = m/R$ MOMENTI KK

$W = nR$ AVVOLGIMENTI

LUNGHEZZA MINIMA



$$\Delta x_{\min} \sim l_s \sim \sqrt{\alpha'}$$

DUALITA' NON-PERTURBATIVE

• DUALITA' ELETTROMAGNETICA

$$\vec{\nabla} \cdot \vec{E} = 4\pi \rho_e$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \frac{1}{c} \frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} \vec{J}_e$$

IN ASSENZA DI CARICHE:

$$(\vec{E}, \vec{B}) \rightarrow (\vec{B}, -\vec{E}) \quad F_{\mu\nu} \leftrightarrow \tilde{F}_{\mu\nu}$$

CARICHE $\longleftrightarrow$ MONOPOLI MAGNETICI

CONDIZIONE* DI QUANTIZZAZIONE DI DIRAC

$$\frac{q_e q_m}{4\pi} = \frac{n}{2} \hbar c$$



(STRINGA DI DIRAC)

$$\{A_\mu, g\}_E \longleftrightarrow \{\tilde{A}_\mu, \tilde{g} = 1/g\}_M$$

$$F_{\mu\nu} \rightarrow \tilde{F}_{\mu\nu} = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} = \partial_\mu \tilde{A}_\nu - \partial_\nu \tilde{A}_\mu$$

ACCOPPIAMENTO FORTE $\longleftrightarrow$ DEBOLE

$$[* \text{ DIONI} \quad q_e^{(1)} q_m^{(2)} - q_e^{(2)} q_m^{(1)} = 2\pi n_{(12)} \hbar c]$$

P-BRANE

p	SORGENTI	-	POTENZIALE
0	PARTICELLE	-	VETTORE A_μ
1	STRINGHE	-	TENSORE $B_{\mu\nu}$
2	MEMBRANE	-	3-FORMA $C_{\mu\nu\rho}$
..	...		
p	P-BRANA	-	$(p+1)$ -FORMA $P_{\mu_1 \dots \mu_{p+1}}$

- SOLITONI ESTESI CARICHI
- CONDIZIONE BPS $M=|Q|$

DUALITÀ GENERALIZZATE

S-DUALITÀ, U-DUALITÀ, ...

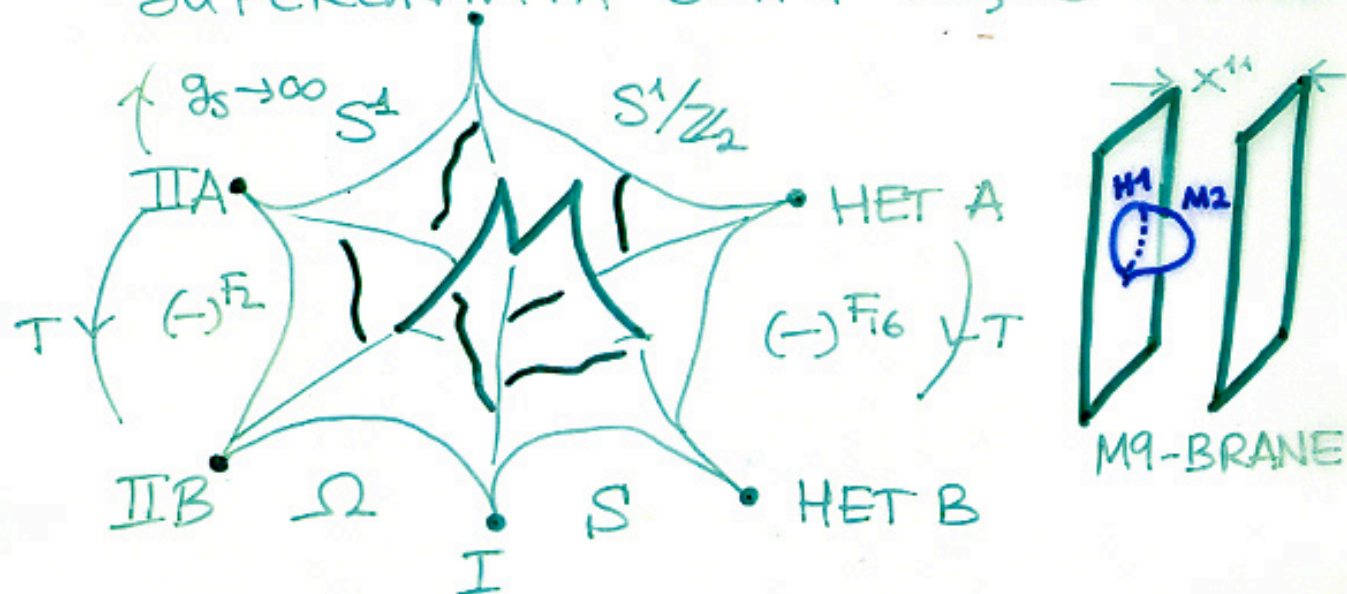
IN GENERALE: $\tilde{p} = D - p - 4$

$D=4$	C O S T - T H E O R Y	$p=0 \longleftrightarrow \tilde{p}=0$	S O L - I T O N
$D=10$		$p=1 \longleftrightarrow \tilde{p}=5$	
$D=6$		$p=1 \longleftrightarrow \tilde{p}=1$	
$D=11$		$p=2 \longleftrightarrow \tilde{p}=5$	
$D=12$			
		F-TEORIA ?	M-TEORIA ?

DEMOCRAZIA DELLE P-BRANE

M-TEORIA

SUPERGRAVITA' D=11 + M2, M5-BRANE



FORMULAZIONI NON-PERTURBATIVE

- TEORIA DI MATRICI $N \times N$, $N \rightarrow \infty$

$$\mathcal{L} = \int dt (DX \cdot DX + \lambda \not{D} \lambda + X [\lambda_i, \lambda_j] + [X, X]^2)$$

(~ MECCANICA QUANTISTICA SUPERSIMMETRICA)

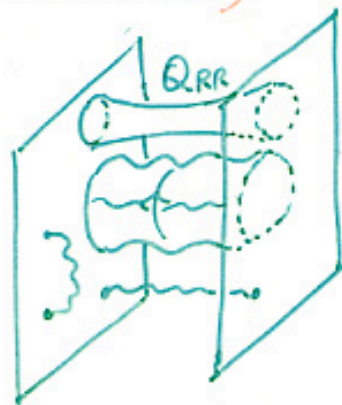
- PENTABRANE M5, D5, NS5,



$$p=5 \leftrightarrow \tilde{p}=1 \quad D=10$$

$$p=5 \leftrightarrow \tilde{p}=2 \quad D=11$$

Dp-BRANE (ARISTOCRAZIA DELLE (D=DIRICHLET) STRINGHE APERTE)



Q_{RR} = CARICA RAMOND-RAMONI

$$M_p^2 \sim |Q_{RR}|^2 \sim \frac{1}{g_s} \quad \text{BPS}$$

$$M_V^2 \sim \frac{1}{\alpha'} |y_1 - y_2|^2 \quad \text{"HIGGS"}$$

$$\mathcal{L}_{\text{eff}}^{(S.Y.M.)} = \int d^p x \{ F^2 + (DX)^2 + \bar{\lambda} \not{D} \lambda + [X, X]^2 + X [X, X] \}$$

TIPO IIA $p = 0, 2, 4, 6, 8$

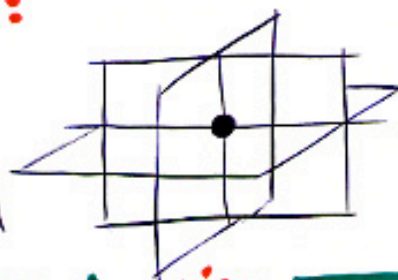
TIPO IIB $p = -1, 1, 3, 5, 7, 9$

TIPO I

HET p_1, n_5

STATI LEGATI:

- BUCHI NERI
- CARICHI ESTREMI



ORIZZONTE
REGOLARE

- ENTROPIA

$$S_{\text{BH}} = \frac{A^{\text{macro}}}{4G_N} = \sqrt{N_1 N_5 N_k}^{\text{micro}} \quad !$$

$\uparrow$ $D=5$



- RADIAZIONE DI HAWKING

- CONFIGURAZIONI CHIRALI ($N_{\text{gen}}=3$ $G > G_{\text{SM}}$)

SVILUPPI RECENTI

CORRISPONDENZA AdS/SCFT:

GEOMETRIA DELL'ORIZZONTE DI D3-BRANE

$$ds^2 = \left(1 + \frac{L^4}{r^4}\right)^{-\frac{1}{2}} (dx \cdot dx) + \left(1 + \frac{L^4}{r^4}\right)^{\frac{1}{2}} (d\vec{y} \cdot d\vec{y})$$

$r/L \ll 1$ $r = \vec{y} \cdot \vec{y}$ **OLOGRAFIA**

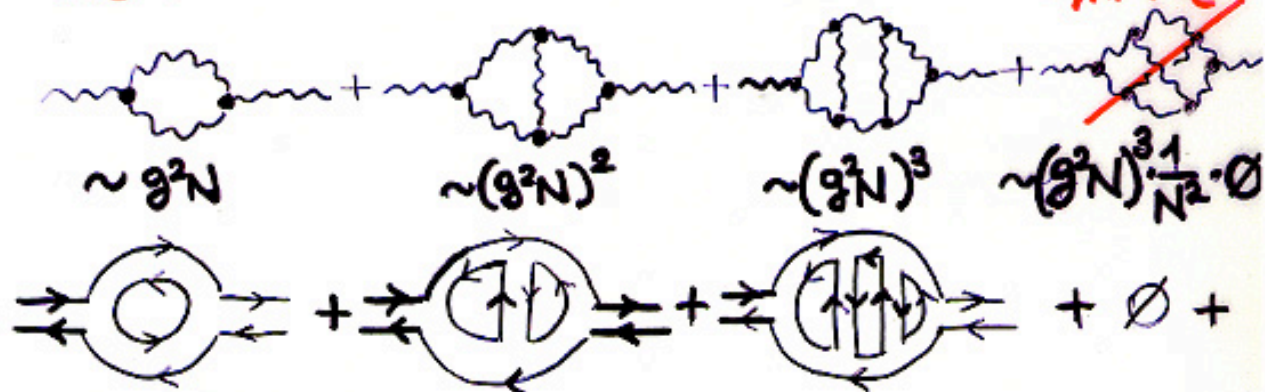


SUPERGRAVITÀ su $AdS_5 \times S^5 \sim$

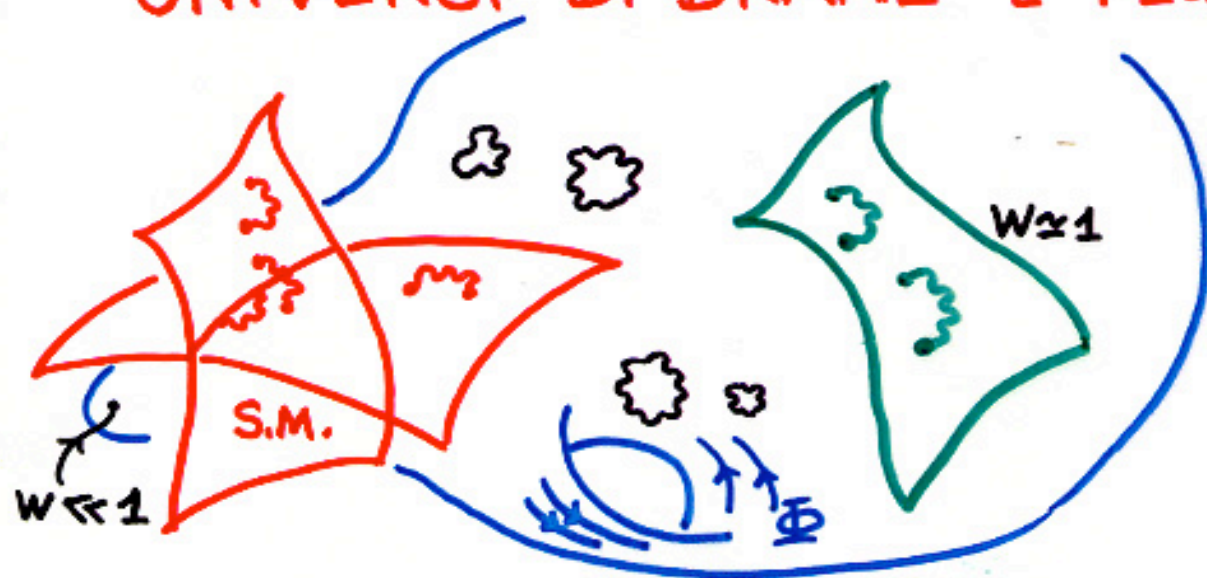
TEORIA SYM $N=4$ $SU(N_c)$ $g_m^2 N_c = \frac{L^4}{(\alpha')^2}$

• STRINGA DELLA QCD?

$N_c \rightarrow \infty$ LIMITE PLANARE $g_m^2 \sim \frac{1}{N_c}$



UNIVERSI DI BRANE E FLUSSI



GEOMETRIE "ORDITE" ("WARPED")

$$ds^2 = W(y) dx \cdot dx + g_{ij}(y) dy^i dy^j$$

GRANDI DIMENSIONI EXTRA

$$\frac{M_{Pl}}{M_{4+\delta}} = M_{4+\delta}^\delta R^\delta$$

$$M_{4+\delta} \simeq 1 \text{ TeV}$$

$$\cancel{d=1} \quad R \simeq 10^8 \text{ km} \quad ; \quad \cancel{d=2} \quad R \simeq 0.1 \text{ mm} \quad \text{EötW}$$

DEVIAZIONI DALLA LEGGE DI NEWTON

$$V(r) = \frac{m}{M_{4+\delta}^{2+\delta} r^{1+\delta}} \quad r \gg R \quad \approx \quad \frac{m}{M_{Pl}^2} \frac{1}{r} (1 + \alpha e^{-M_{4+\delta} r})$$

SEGNATURA A LHC $pp \rightarrow \text{jets} + \cancel{E}_T$

PROSPETTIVE

- UNIFICAZIONE DELLA GRAVITA' CON LE INTERAZIONI DI GAUGE ... + ALTRO
- SUPERSIMMETRIA MOLTO UTILE MA NON STRETTAMENTE NECESSARIA
- STABILIZZAZIONE DEL VUOTO ($\langle \phi_i \rangle$) POSSIBILE CON BRANE E FLUSSI
- DESCRIZIONE OLOGRAFICA :
DUALITA' STRINGHE / CAMPI DI GAUGE
- BUCHI NERI, SINGOLARITA', ...
- GRANDI DIMENSIONI EXTRA $d \geq 3$ $M_{4+d} \approx 10^{17}$

* 1 MILIONE DI BUONE RAGIONI (\$)

"MASS GAP" (CLAY MATHEMATICS INSTITUTE)

SCHEMA

- COSTITUENTI FONDAMENTALI & SPETTROSCOPI
- MODELLO STANDARD & UNIFICAZIONE
- MUSICA PER SUPERSTRINGHE
- P-BRANE & M-TEORIA
- OLOGRAFIA, UNIVERSI DI BRANE, ...

BIBLIOGRAFIA

- B. GREENE "L'universo elegante" Einaudi 2000
- A. SAGNOTTI "Teoria delle stringhe"
Contributo a "Storia della Scienza" Vol. IX
"La Grande Scienza" Sez. Fisica
Istituto dell'Enciclopedia Italiana, 2003
- www.roma2.infn.it/stringaperta

COSTITUENTI ELEMENTARI & SPETTROSCOPI

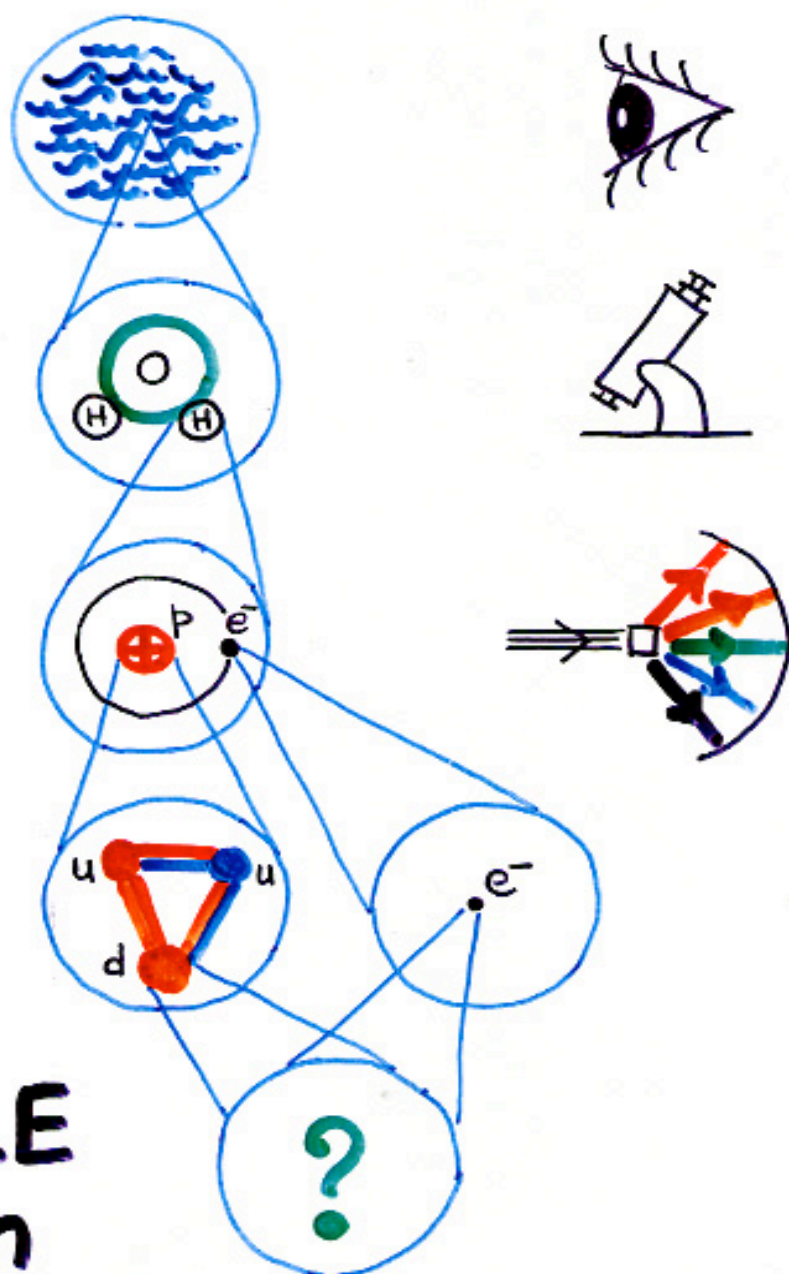
ELEMENTI
 $L \sim 1\text{m}$

MOLECOLE
 $L \sim 10^{-6}\text{m}$

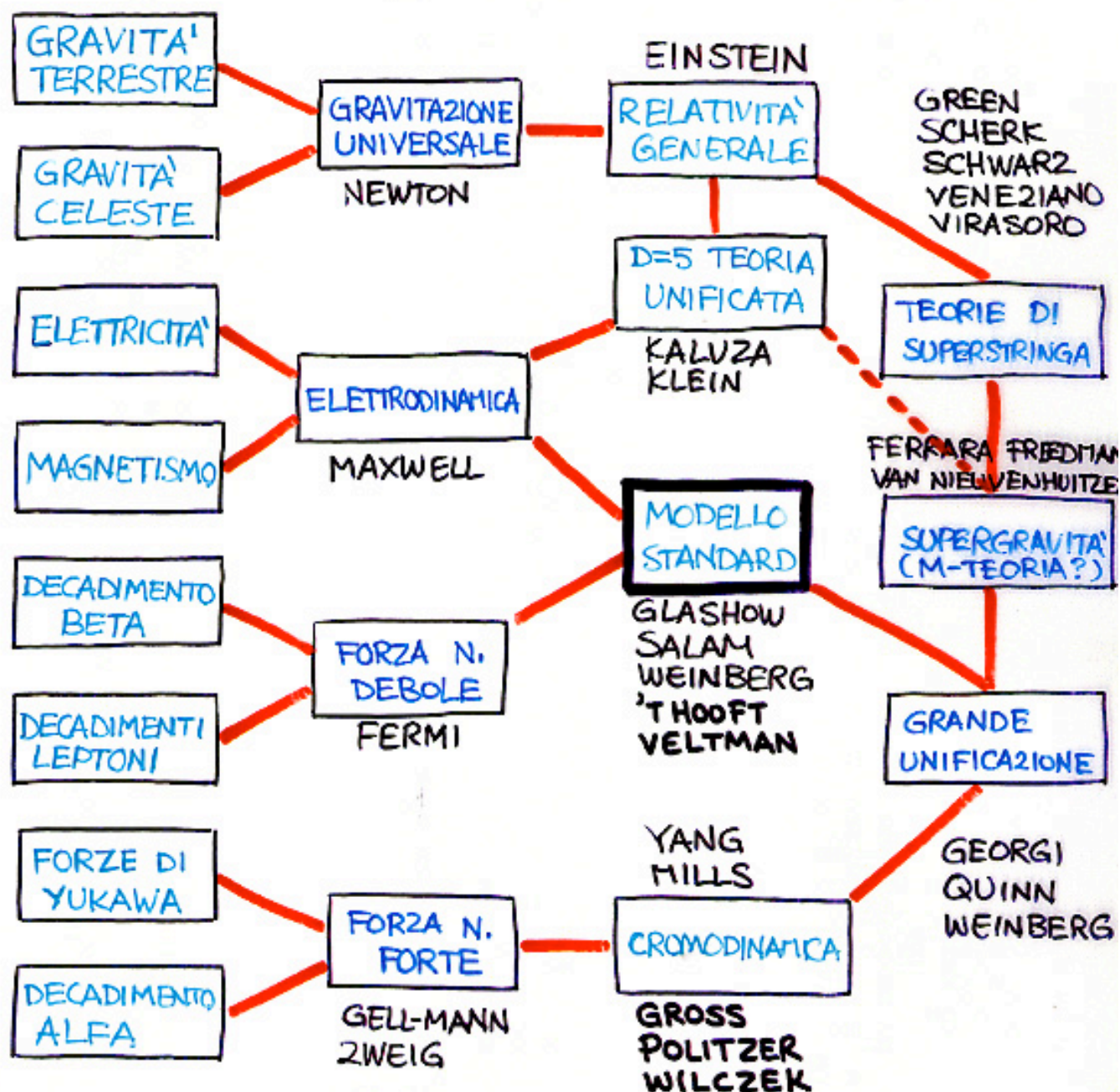
ATOMI
 $L \sim 10^{-10}\text{m}$

NUCLEI
 $L \sim 10^{-15}\text{m}$

PARTICELLE
 $L \sim 10^{-18}\text{m}$



FORZE (INTERAZIONI) FONDAMENTALI



PARTICELLE ELEMENTARI

ECCITAZIONI "PUNTI FORMI" / QUANTI

DI CAMPI RELATIVISTICI $\Psi_S^f(x^\mu)$

BOSONI



$S=1$ (VETTORI) $A_\mu = \cos\theta_w B_\mu - \sin\theta_w W_\mu^3$

G_μ^a (8)

W_μ^i (3)

B_μ $U(1)_Y$

$S=0$ (SCALARI)

$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

$\nwarrow$ GOLDSTONE + HIGGS

$S=\frac{1}{2}$ FERMIONI



$L \neq R$

• LEPTONI

$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

e_R ν_R $\cancel{?}$

• QUARK

$\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix}_L$

$(u \ u \ u)_R$

$(d \ d \ d)_R$

$\times$ 3 GENERAZIONI ! ?

DESCRIZIONE MICROSCOPICA MODELLO STANDARD

IDEA BASE

SIMMETRIA DI GAUGE

TRASFORMAZIONI LOCALI DI
"ORIENTAZIONE" INTERNA



GENERAZIONE DELLE MASSE
MECCANISMO DI HIGGS

$$M=0 \quad \text{[circle with dot]} + \text{[orange triangle]} = \text{[circle with dot and orange triangle]} \quad M \neq 0$$

INTERPRETAZIONE

PROBABILISTICA (BORN)

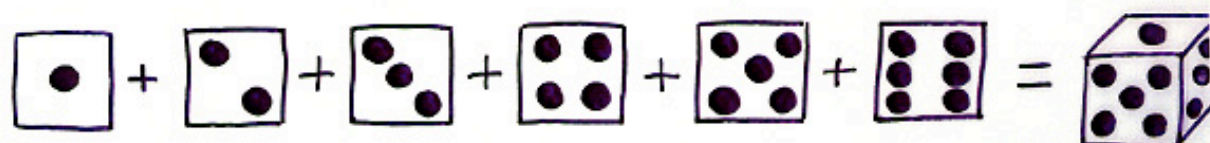
AMPIEZZE DI TRANSIZIONE

MATRICE S $q = \text{CARICA (PICCOLA)}$

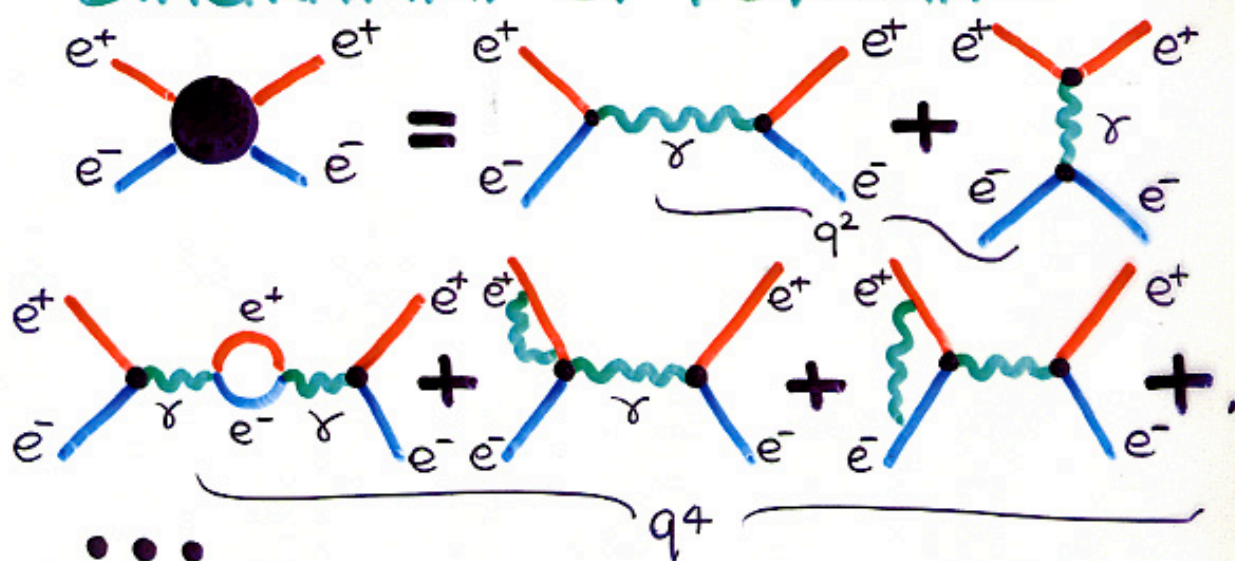
CALCOLO PERTURBATIVO

$$S(q) = 1 + q + q^2 + \dots = 1/(1-q)$$

UNITARIETA' $P_{\text{TOT}} = 1 = SS^\dagger$



DIAGRAMMI DI FEYNMAN



MODELLO STANDARD $(\hbar=c=1)$

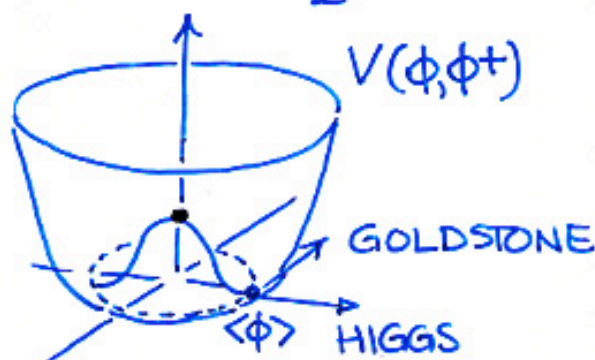
- SIMMETRIA DI GAUGE: $SU(3)_C \times SU(2)_W \times U(1)_Y$

$$\delta A_\mu^A = \partial_\mu \theta^A(x) + \dots \quad \delta \mathcal{L} = 0$$

- ROTTURA SPONTANEA

$$SU(2)_W \times U(1)_Y \rightarrow U(1)_{EM} \quad \delta \langle \phi \rangle \neq 0$$

$$Q_E = T_3 + \frac{Y}{2} \quad \phi = \langle \phi \rangle e^{i\gamma(x)} + \eta_H(x)$$



$$M_{W,Z} \sim g \langle \phi \rangle$$

$$M_F \sim y \langle \phi \rangle$$

$$M_H \sim \sqrt{\lambda} \langle \phi \rangle$$

- RINORMALIZZABILITA'

$$-\mathcal{L}_{int}^{(\Delta=4)} = g A_\mu J^\mu + y \phi \bar{\psi} \psi + \lambda \phi^4 + \cancel{\phi \Box^2} + \cancel{\bar{\psi} \Box \psi}$$

- ASSENZA DI ANOMALIE CHIRALI

$$\partial_\mu J_A^\mu = 0$$

$$\text{Triangle diagram with } J_L - \text{Triangle diagram with } J_R = 0$$

PROBLEMI

- TROPPI PARAMETRI

$[M]^0: g_3, g_2, g_1, y_{ff'}^H, \lambda, \theta_3, \theta_2, \theta_1$

$[M]^1: \Lambda_{QCD}, M_W, M_Z, M_F, \theta_{CKM}, M_H,$

- INSTABILITA' DEL MECCANISMO DI HIGGS

TRIVIALITA': $\lambda_{eff}(\mu) \rightarrow \infty \quad \mu \rightarrow \infty$

GERARCHIA: $\Delta m_\phi^2 \sim \int \frac{d^4 p}{(p^2 + m^2)} \sim M_x^2 \gg M_W^2$



- CONFINAMENTO DEL COLORE



BARIONI

(ADRONI)

MESONI

GLUEBALL

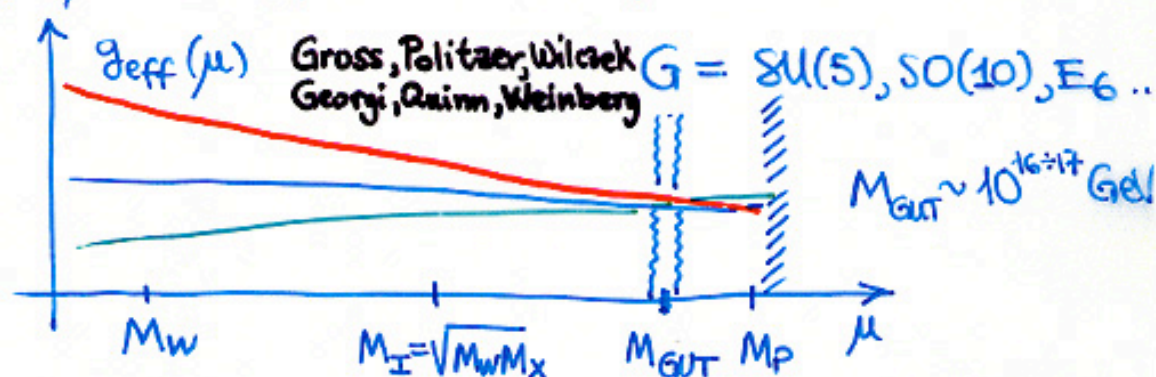


"MASS GAP" Λ_{QCD}

SOLUZIONI

GRANDE UNIFICAZIONE GUT

$$\frac{4\pi}{g_i^2(\mu)} = \frac{4\pi}{g_i^2(\mu_0)} + \frac{b_i}{4\pi} \ln \frac{\mu^2}{\mu_0^2} \quad g_i(M_{\text{GUT}}) = g_{\text{GUT}}$$



SUPERSIMMETRIA : $\{Q, \bar{Q}\}_+ = P$

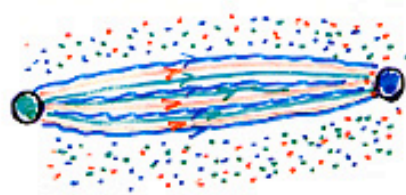
$$\delta\phi = \psi\epsilon \quad \delta\psi = \partial\phi\epsilon \quad \text{😊} \xleftrightarrow{Q} \text{☺}$$

$$\mathcal{L}_{\text{WZ}} = \partial\phi\partial\phi^\dagger + i\bar{\psi}\not{\partial}\psi - |m\phi + g\phi^2|^2 + \left(\frac{1}{2}m + g\phi\right)\psi^\dagger\psi + h.c.$$

$$m_B^2 = m_F^+ m_F \quad \Delta m_\phi^2 \sim \Delta m_\psi^2 \sim m^2 \ln M_X^2/m^2$$

EFFETTO MEISSNER "DUALE"

CONDENSAZIONE DI MONOPOLI



$$V(R) \sim T_s R$$



STRINGA ! [CORDA]

INCLUSIONE DELLA GRAVITA'

$$R_{\mu\nu}(g) - \frac{1}{2} g_{\mu\nu} R(g) = 8\pi G_N T_{\mu\nu}$$



- COVARIANZA GENERALE: $\delta g_{\mu\nu} = \nabla_\mu \xi_\nu + \nabla_\nu \xi_\mu$

$$S_{EH} = \frac{1}{16\pi G_N} \int d^4x \sqrt{|g|} \underbrace{g^{-1} (g^{\mu\nu} \partial_\mu \partial_\nu g + (g^{\mu\nu} \partial_\mu g)^2)}_R$$

- NON POLINOMIALE: $g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_P} h_{\mu\nu}$, $S=2$

- NON-RINORMALIZZABILE ($S_{EH}^{(E)} \leq 0!$)

$$M_P = \left(\frac{\hbar c}{G_N} \right)^{1/2} \sim 10^{19} \text{ GeV}/c^2 \quad G_N \sim 10^{-34} G_F$$

$$\mathcal{L}_{int} = \sum_{n=4}^{\infty} \frac{C_n}{M_P^{n-4}} \mathcal{L}_{int}^{(\Delta=n)} \quad \Delta_q C_n = \infty!$$

- SINGOLARITA' (BIG-BANG, BUCHI NERI, ...)

- COSTANTE COSMOLOGICA (!?)

$$S_\Lambda = \Lambda \int \sqrt{|g|} d^4x \quad \Lambda \sim M_{(P, X, \dots)}^4$$

$$\Lambda^{exp} \sim 1 \text{ g/cm}^3 \sim 10^{-95} M_P^4 \sim 10^{-35} M_{W}^4$$

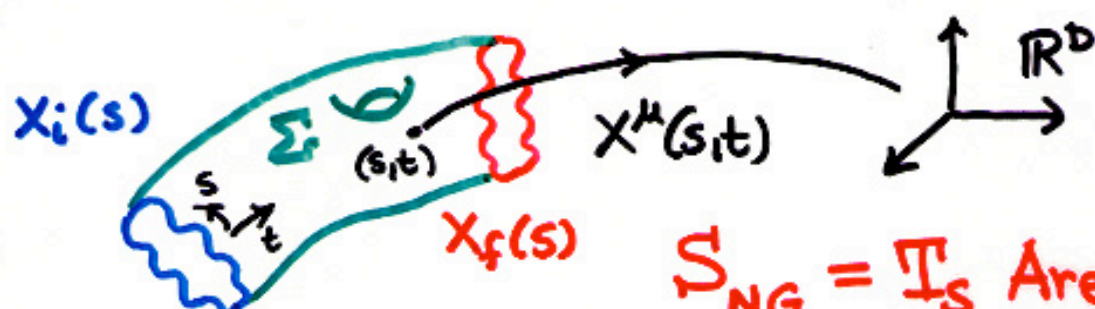
DALE PARTICELLE ALLE CORDE / STRINGHE

INTEGRALE SUI CAMMINI DI FEYNMAN

$$\langle x_f, t_f | x_i, t_i \rangle = \int [Dx]_i^f e^{\frac{i}{\hbar} S[x(t)]}$$


 $S_{rel} = -mc^2 \int_{t_i}^{t_f} dt \sqrt{1 - v^2/c^2}$

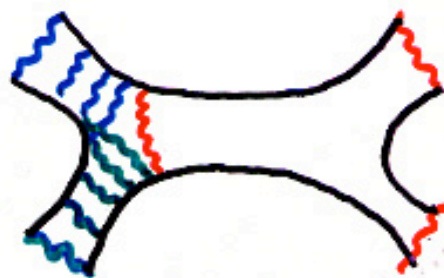
INTEGRALE SULLE SUPERFICI DI POLYAKOV


 $S_{NG} = T_s \text{Area}(\Sigma)$

FORMULAZIONE GEOMETRICA (BRINK, DI VECCHIA HOWE)

$$S_{BDH} = \frac{1}{4\pi\alpha'} \int \sqrt{|g|} g^{\alpha\beta} \partial_\alpha X^\mu \partial_\beta X^\nu G_{\mu\nu}(X) d^2\sigma$$

- INVARIANZA "CONFORME" $g_{\alpha\beta} \rightarrow \Omega^2(\sigma) g_{\alpha\beta}$
- INTERAZIONI "DELOCALIZZATE" $\rightarrow$ FINITEZZA UV



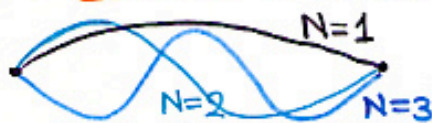
MUSICA PER SUPERSTRINGHE

COMPORTAMENTO "SOFFICE"

AD ALTA ENERGIA $\sim e^{-\alpha' p^2}$

SPETTRO DELLE ECCITAZIONI

$$M_N^2 = (N-1)T_s$$



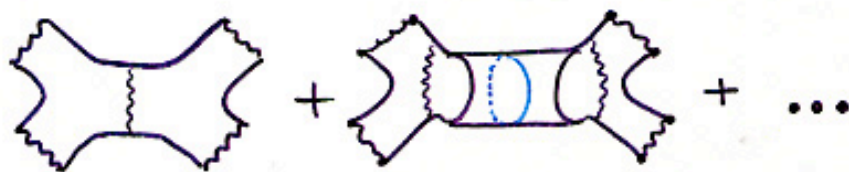
$T = \text{TENSIONE DI STRINGA} = \frac{E}{L}$

FORMULAZIONE PERTURBATIVA (POLYAKOV)

STRINGA CHIUSA $\sim$ INTERAZIONI GRAVITAZIONALI



STRINGA APERTA $\sim$ INTERAZIONI DI GAUGE



STRINGA BOSONICA $D=26$

SUPERSTRINGA $D=10$