String theory across two centuries

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Summer school and workshop on the standard model and beyond

Corfu
September 2013

First Lecture

FOREWORD

20th century physics emerged from genuine experimental enigmas

- Black-body radiation spectrum: Planck and theory of quanta $\hbar = {}^{h}/_{2\pi} = 1{,}054\,571\,68(18) \times 10^{-34}\ \mathrm{J\,s}$
- Michelson and Morley experiments: Einstein and special relativity $c = 299\,792\,458\ {}^{\mathrm{m}}/_{\mathrm{s}}$

Absence of ether, unsuspected microscopic wonderland, new scientific challenges ...

Culminated with the advent of gauge theories and the standard model (70s - 80s)

- *U(1) × SU(2) × SU(3)*: γ, Z_0, $W_\pm$, g
- leptons: ν_e, e ...
- hadrons - quark bound states: u, d ...
- Higgs - breaking of symmetry: *H*

Z_0,$W_\pm$ observed in 1983 - *H* observed in 2012 at CERN

$$
\begin{aligned}
m_{Z_0} &\approx 91,2\ \mathrm{GeV}/c^2 \\
m_{W_\pm} &\approx 80,4\ \mathrm{GeV}/c^2 \\
m_{\nu_e} &\lesssim \mathrm{O}(1)\ \mathrm{eV}/c^2 \\
m_{\mathrm{e}} &\approx 511\ \mathrm{KeV}/c^2 \\
&\vdots \\
m_\tau &\approx 1,8\ \mathrm{GeV}/c^2 \\
m_{\mathrm{u}} &= \mathrm{O}(1)\ \mathrm{MeV}/c^2 \\
&\vdots \\
m_{\mathrm{t}} &\approx 174,3\ \mathrm{GeV}/c^2 \\
m_H &\approx 125,3\ \mathrm{GeV}/c^2
\end{aligned}
$$

23 adjustable parameters - extraordinary experimental agreement (LEP, Tevatron, LHC)

21st century challenges are of æsthetic nature ...

- Are *all* SM parameters fundamental?
- Why is electric charge *quantised?*
- Why 3 families of quarks and leptons?
- Could electro-weak and strong interactions be «unified»?
- Are there other elementary particles beyond the top quark?
- Are there more fundamental objects?
- Could one explain the SM mass spectrum from first principles?

Quest of a more *fundamental scheme* - experiment largely anticipated by theory (as opposed to the 1900 era)

... or semi-æsthetic: *gravitation*

About gravity ...

- The 4th force - *Newton's law:* $f = G_N {}^{mm'}/_{r^2}$

$$\begin{aligned} G_N &= 6,674\,28(67) \times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2} \\ &= 6,708\,81 \times 10^{-39}\ \left(\mathrm{GeV}/c^2\right)^2 \end{aligned}$$

- Experimentally verified up to 56 μm (2007)
- Relativistic version: *general relativity* - gravity as space-time geometry - successful inside the solar system

... and its caveats

- Cosmological issues: less successful for describing large-scale universe evolution - *ad hoc addenda*
  - *inflation*
  - *dark matter*
  - Λ

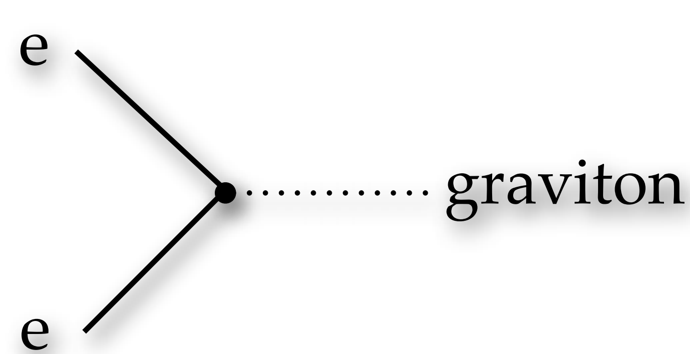
No microscopic understanding

$$\Lambda = \frac{8\pi G_N}{c^2}\varrho_\varnothing$$
$$\varrho_\varnothing \approx 2,5\ \mathrm{KeV}\ c^{-2}\ \mathrm{cm}^{-3}$$

- Relationship with other interactions: *why does gravity look so different?*
  - *Newton's law* $\leftrightarrow$ *space-time geometry*
  - *very weak*

Force between protons at 5 fm
-gravitational: 10^{-37} N
-other: 10^{-2} N to 1000 N

- Quantum properties:
  - quantum scale $L_{\text{Planck}} = \sqrt{G_N \hbar / c^3} \approx 1,6 \times 10^{-25}$ Å
  - lore: interaction mediated by gravitons



Out of experimental reach - Big-Bang?

  - bad ultraviolet behaviour: GR is power-counting non-renormalisable

... no experimental sign/need for these issues

Proposals

- Kaluza-Klein theories (1921-1926)
- Extended objects - membranes by Dirac (1962)
- Grand-unified theories (GUTs in ‘70s)
- Supersymmetry (SUSY in ‘70s)

- None fully satisfactory
- All natural ingredients of string theory - at the cost of growing complexity and (sometimes) problems

THE ADVENT OF EXTENDED OBJECTS

Dirac's membrane (1962)

- Electron as a charged membrane of radius r_0
  - finite Coulomb energy

$$E_{\mathrm{Coul}} \propto \int_{r_0}^{\infty} \mathrm{d}r/r^2$$

  - spectrum of vibration → spectrum of leptons

$$m_0 = m_e, \quad m_1 \approx {}^{m_\mu}/4, \quad \ldots$$

- No subsequent developments to this approach
  - absence of spin
  - success of quantum field theory

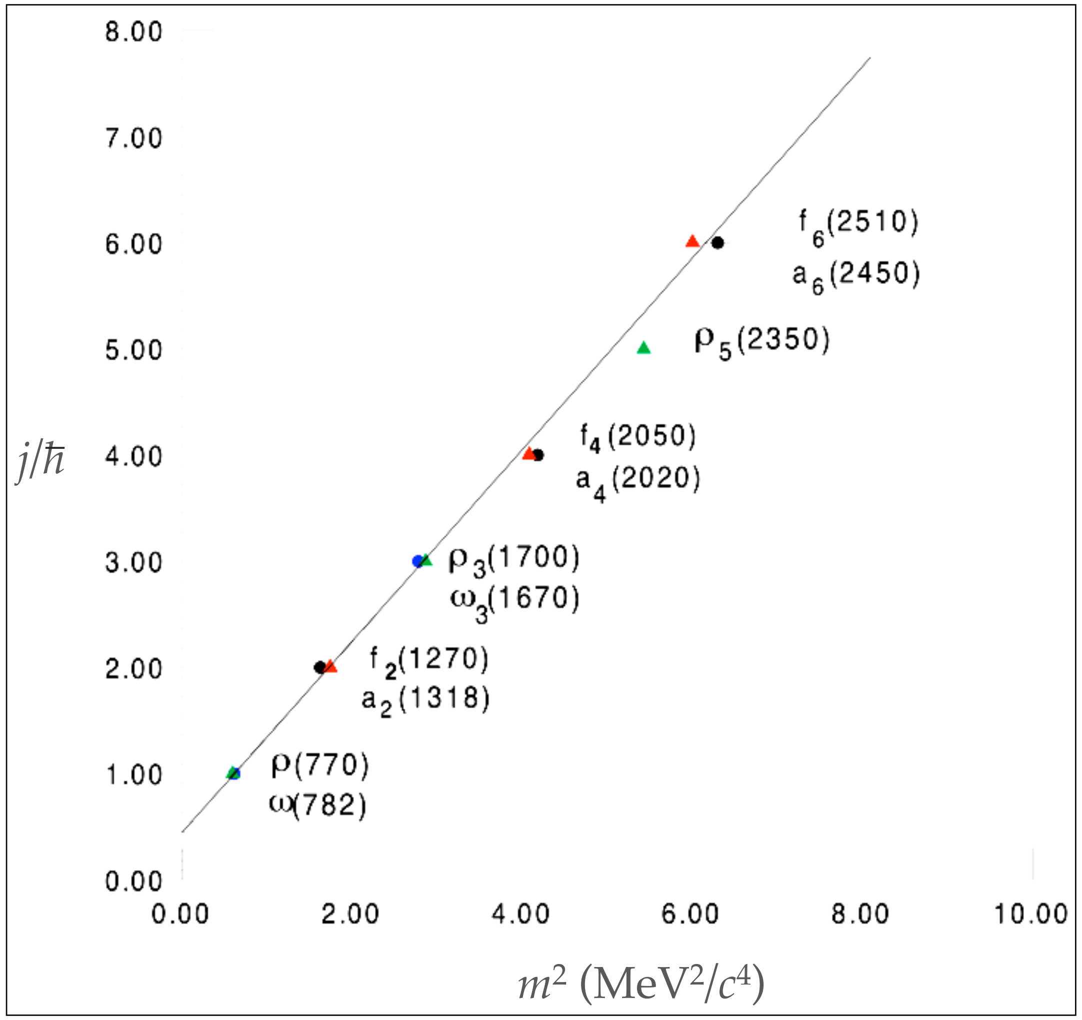
Membranes re-emerged in string theory (1995)

Strings

- Prehistory: *dual models* (1967-1974)
- History: *quantum gravity* (1974-1984)
- Modern times: *theory of everything* (1984-2000)
- Age of maturity: *toolbox* (2000-)

Dual models (1967-1974)

Chew-Frautschi plot



- Meson resonances in hadronic collisions: *Regge trajectories*
- Described as excitations of a relativistic string

Hadronic physics: SLAC experiments (1969)

- No fundamental string but partons
- Quantum Chromo Dynamics: quarks and gluons
- Asymptotic freedom (1972)

Strongly interacting $\rightarrow$ specific computational methods

- in the UV, perturbative QFT
- in the IR
    - lattice methods
    - analytic methods: effective QCD string (stretched chromomagnetic tube fluxes) - explains Regge trajectories and the success of dual models

Modern reincarnation of dual models via QCD string: AdS/CFT correspondance

DYNAMICS OF RELATIVISTIC STRINGS

Nambu-Gotto action: worldsheet area

- Worldsheet: $x^\mu = x^\mu(\zeta^a),\ \zeta^a = \{\tau, \sigma\}$
- Induced metric: $h_{ab} = \partial_a x^\mu \partial_b x^\nu \eta_{\mu\nu} = \partial_a x \cdot \partial_b x$

$$S_{\rm NG} = \frac{1}{2\pi\alpha'} \int \mathrm{d}\tau \mathrm{d}\sigma \sqrt{(\partial_\tau x \cdot \partial_\sigma x)^2 - (\partial_\tau x)^2 (\partial_\sigma x)^2}$$

- Lorentz-invariant
- Reparameterization-invariant
- Not unique (1st term in derivative expansion involving extrinsic/intrinsic curvature)
- A single parameter: the string tension $T = {}^1\!/_{2\pi\alpha'}\ \ [T] = 2$

Reparameterization invariance

- Relativistic strings support only
  - transverse waves
  - propagating at the speed of light
- Special parameterizations:
  - static: $x^0 = \tau,\ x^1 = \sigma$
  - conformal: $h = |\partial_\tau x|^2 \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$
    - free wave equations in 2 dim: $\left(\partial_\tau^2 - \partial_\sigma^2\right) x^\mu = 0$
    - subject to the conformal constraints

- General solution: $x^\mu = f^\mu(\tau-\sigma) + \tilde{f}^\mu(\tau+\sigma)$
  - closed strings: independent $f^\mu, \tilde{f}^\mu$
  - open strings: standing waves

$$f^\mu = \pm\tilde{f}^\mu \begin{cases} \text{free endpoints (Neumann)} \\ \text{fixed endpoints (Dirichlet)} \end{cases}$$

- Conformal-gauge conditions (on initial data)

$$f' \cdot f' = \tilde{f}' \cdot \tilde{f}' = 0$$

$$\begin{cases} f^\mu(\tau-\sigma) = \frac{1}{2}x_0^\mu + \frac{\alpha'}{2}p^\mu(\tau-\sigma) + i\sqrt{\alpha'/2}\sum_{n\neq 0}\frac{1}{n}\alpha_n^\mu \mathrm{e}^{in(\tau-\sigma)} & \text{(R)} \\ \tilde{f}^\mu(\tau+\sigma) = \frac{1}{2}x_0^\mu + \frac{\alpha'}{2}p^\mu(\tau+\sigma) + i\sqrt{\alpha'/2}\sum_{n\neq 0}\frac{1}{n}\tilde{\alpha}_n^\mu \mathrm{e}^{in(\tau+\sigma)} & \text{(L)} \end{cases}$$

$$\alpha_{-n}^\mu = \left(\alpha_n^\mu\right)^* \qquad \tilde{\alpha}_{-n}^\mu = \left(\tilde{\alpha}_n^\mu\right)^*$$

- Solving the conformal constraints
  - light-cone coordinates: $x^{\pm} = x^0 \pm x^1$
  - light-cone gauge: $x^+ = \alpha' p^+ \tau \Rightarrow f^{+\prime} = \tilde{f}^{+\prime} = {}^1\!/_2 \alpha' p^+$
- Conformal-gauge conditions (on initial data)

  $f^-, \tilde{f}^-$ eliminated $\Rightarrow$ *only* $D-2$ transverse modes

  - closed strings

    $$m^2 \equiv -p_\mu p^\mu = \frac{4}{\alpha'} \sum_{n=1}^{\infty} \alpha^i_{-n} \alpha^j_n \delta_{ij} = \frac{4}{\alpha'} \sum_{n=1}^{\infty} \tilde{\alpha}^i_{-n} \tilde{\alpha}^j_n \delta_{ij}$$
  - open strings

    $$m^2 \equiv -p_\mu p^\mu = \frac{1}{\alpha'} \sum_{n=1}^{\infty} \alpha^i_{-n} \alpha^j_n \delta_{ij}$$
- Positive and continuous mass spectrum
- Angular momentum $j \leq \alpha' m^2$

Quantization

- Center of mass: $[x^\mu, p^\nu] = i\eta^{\mu\nu}$
- Creation operators: $\alpha^{\dagger\mu}_{n>0}, \tilde{\alpha}^{\dagger\mu}_{n>0}$
- States: $|\mathbf{p}, i_r, m_r, \ldots, j_s, n_s, \ldots\rangle = \left(\alpha^{\dagger i_r}_{m_r} \ldots\right) \left(\tilde{\alpha}^{\dagger j_s}_{n_s} \ldots\right) |\mathbf{p}\rangle$
- Levels: $N = \sum_r m_r \quad \tilde{N} = \sum_s n_s$
- String spectrum:
  - closed: $N = \tilde{N}$
$$-p^2 = m^2 = \frac{4}{\alpha'}\left(N - \frac{D-2}{24}\right)$$
  - open: ignore right
$$-p^2 = m^2 = \frac{1}{\alpha'}\left(N - \frac{D-2}{24}\right)$$

Note: regularization $\sum_{n=1}^{\infty} {}^{n}\!/_{2} = {}^{1}\!/_{2}\,\zeta(-1) = {}^{-1}\!/_{24}$

String coupling and string amplitudes

- 1st quantized string: each state in a different Poincaré representation - no multiparticle states
- Method: similar to relativistic quantum mechanics
  - asymptotic states & propagators
  - diagramatic rules for computing order by order

$$\mathcal{A}(1,\ldots,N) = \sum_{\gamma=0}^{\infty} g_s^{2\gamma+N-2} \mathcal{A}_\gamma(1,\ldots,N)$$

- String coupling $g_s = \exp \Phi$

At large g_s the worldsheet has no meaning

The tachyon

- Level zero: a scalar χ with $m^2 \propto -\frac{D-2}{24}$

➡ false vacuum

Perturbative instability of Minkowski space-time: ultimate fate - $V(\chi)$? Supersymmetry at rescue!

The photon and critical dimension

- Open-string level one: a vector $|\mathbf{p}, 1, i\rangle = \alpha^i_{-1}|\mathbf{p}\rangle$

with mass $m^2 = \frac{1}{\alpha'}\left(1 - \frac{D-2}{24}\right)$

➡ $D-2$ dof $\Rightarrow m = 0 \Rightarrow \boldsymbol{D = 26}$

photon in 26 dim

The graviton *et al*

- Closed-string level one: a rank-two tensor

$|\mathbf{p}, 1, i, 1, j\rangle = \alpha^i_{-1}\tilde{\alpha}^j_{-1}\,|\mathbf{p}\rangle$

with mass $m^2 = \frac{4}{\alpha'}\left(1 - \frac{D-2}{24}\right)$

traceless symmetric: graviton
antisymmetric: axion
trace: dilaton

➡ $(D-2)^2$ dof $\Rightarrow m = 0 \Rightarrow \boldsymbol{D = 26}$

h^{ij}, b^{ij}, Φ

➡ string theory as quantum gravity [Scherck, Schwarz; Yoneya '74]

- Higher levels: higher-rank tensors

with mass $m \gtrsim 1/\sqrt{\alpha'}$

higher spins

➡ Regge trajectories

Main features

- Rigid spectrum
  - tachyon
  - no fermions
- Extra dimensions

Note: the original KK method for $D > 4$

- Fundamental idea of *dimensional reduction 5 → 4*
- Unification of e and G_N assuming $R \sim 100\, L_{\text{Planck}}$
- No solution to the specific problems of gravity
- Worse ultra-violet behaviour

$$E_{\text{Coul}} \propto \int_0^\infty \frac{\mathrm{d}r}{r^3} \text{ versus } \int_0^\infty \frac{\mathrm{d}r}{r^2}$$

Must be embedded in a more adequate framework: *string theory*

The superstring

- Eliminate the tachyon
- Introduce fermions in the spectrum
- A little freedom on the spectrum (GSO)

Neveu–Schwarz–Ramond: $(x^\mu, \psi^\mu, \tilde{\psi}^\mu)$

L & R worldsheet
real fermions

- $N = (1,1)$ local superconformal invariance (closed)
- Critical dimension $D = 10$
- 2 main differences wrt the bosonic string

1^{st} difference

- Fermions on the worldsheet (closed string)
  - periodic, integer frequence: Ramond
  - antiperiodic, half-integer: Neveu-Schwarz
- Ramond sector: anticommuting zero-modes

$$\left\{b_0^\mu, b_0^\nu\right\} = \eta^{\mu\nu}$$

  - Dirac matrices
  - spinorial ground states (wrt spacetime)

(open strings at each end: $\psi^\mu = \tilde{\psi}^\mu,\ \psi^\mu = \pm\tilde{\psi}^\mu$)

2^{nd} difference

Consistency requires definite worldsheet parity:

GSO projection $(-1)^{F \text{ or } \tilde{F}}$ [Gliozzi, Scherk, Olive '76]

- separately for left and right sectors
- removes sectors, acts as a chirality projection on Ramond states

Second Lecture

Summary of first lecture

Fermionic string

- $D = 10$ & Poincaré invariance
- Ground states
  - space-time scalar $|\mathbf{p}\rangle_{\mathrm{NS}}$
  - space-time spinor $|\mathbf{p}\rangle_{\mathrm{R}}$
- Oscillator modes $\alpha_n^\mu, b_n^\mu, b_{n+1/2}^\mu$
- L-R duplication for closed string with $N = \tilde{N}$
- Mass-shell condition and GSO projection

Open fermionic string massless spectrum

- Level-0: tachyon projected out $|\mathbf{p}\rangle_{\text{NS}}, \; m^2 = -1/2\alpha'$
- Level-1: massless
  - vector (**8**): $b^j_{-1/2}|\mathbf{p}\rangle_{\text{NS}}$
  - Majorana-Weyl spinor (**8**): $|\mathbf{p}, -\rangle_{\text{R}}$
  - Majorana-Weyl spinor (**8**) projected out: $|\mathbf{p}, +\rangle_{\text{R}}$

$D = 10$, $N = 1$ vector multiplet
supersymmetric Maxwell spectrum

Closed fermionic string massless spectrum

- Level-0: tachyon projected out $|\mathbf{p}\rangle_{\mathrm{NSNS}}$, $m^2 = -2/\alpha'$
- Level-1: massless
  - rank-two tensor ($\mathbf{1} + \mathbf{28} + \mathbf{35}$): graviton, dilaton, antisymmetric NSNS $b^i_{-1/2}\tilde{b}^j_{-1/2}|\mathbf{p}\rangle_{\mathrm{NSNS}}$
  - vector-spinors ($2 \times (\mathbf{8} + \mathbf{56})$): 2 dila-gravitinos of opposite or equal chirality $b^i_{-1/2}|\mathbf{p}\rangle_{\mathrm{NSR}}$, $\tilde{b}^j_{-1/2}|\mathbf{p}\rangle_{\mathrm{RNS}}$
  - bispinors ($\mathbf{8} + \mathbf{56}$ or $\mathbf{1} + \mathbf{28} + \mathbf{35}$): antisymmetric RR tensors $|\mathbf{p}\rangle_{\mathrm{RR}}$

$D = 10$, $N = 2$ IIA or IIB supergravity spectrum

Finally superstring in $D = 10$

Combining open and closed superstrings

- Type I: closed & open strings
- Type II A & B: closed string
- Heterotic $SO(32)$ or $E_8 \times E_8$: closed string

Good and bad...

- Are elementary particle masses following arithmetic sequences?
  - no! but the zero-mass string sector is intriguing
- Existence of an helicity-2 mode: graviton?
  - requirement: introduce G_N in $T = c/2\pi\alpha'$

$$T \sim \hbar c / 2\pi L_{\text{Planck}}^2 = c^4 / 2\pi G_N \approx 1,9 \times 10^{43}\ \text{N}$$

  - recover general relativity (supergravity) at large length scales $\ell \gg L_{\text{Planck}}$
- Massive spectrum basically unobservable ($m > M_{\text{Planck}}$)

- Massless spectrum: spin 0, ½, 1, ³⁄₂, 2
  - is it reminiscent of the SM spectrum or of any of its extensions SUSY / GU?
  - if yes
    - how to lift mass degeneracy?
    - how to reproduce the correct interactions?
    - How to break SUSY?
- How to go from $D = 10$ to $D = 4$? Contact with KK?
- Contact with Dirac-like membranes?

...in a natural way!

Wide programme launched around 1985 ...

String phenomenology

Yes! massless spectrum & interactions are SUGRA-like at low energies - not so suprising

Crucial: non-Abelian gauge group

- 1985-1995: heterotic string
- 1996-2009: orientifolds - discovery of D-branes
- 2009- : heterotic/orientifolds/F-theory

- Some facts are surprisingly natural
- The actual implementation is Ptolemaic

Is the spectrum complete?

D-BRANES

Emergence

Two intriguing observations

- Open strings allow for Dirichlet boundary conditions
- Strings are electric sources for the NSNS form

$$\int_{\text{worldsheet}} B_{\mu\nu}\, \mathrm{d}x^{\mu} \wedge \mathrm{d}x^{\nu}$$

For a charged particle coupled to a gauge field: $\int_{\text{worldline}} A_{\mu}\, \mathrm{d}x^{\mu}$

- What are the sources of RR forms?
- Are these sources part of the perturbative string spectrum?

Interpretation [Polchinski '96]

String theory allows for excitations of domain-wall type:
D-branes

D: Dirichlet

- Open strings can be attached to these D-p-branes
- The D-p-branes are electric sources for $(p+1)$-forms

$$\int_{\text{worldvolume}} A_{\mu_1 \ldots \mu_{p+1}} \, \mathrm{d}x^{\mu_1} \wedge \ldots \wedge \mathrm{d}x^{\mu_{p+1}}$$

and magnetic sources for $(D-p-3)$-forms


D 2-brane

D-branes

- carry RR charge and tension (mass density)

$$T_p = \frac{1}{g_s (2\pi)^p \alpha'^{\frac{p+1}{2}}}$$

- are not elementary string modes but *solitonic* objects of type II string - analogous to magnetic monopoles
- create RR fields which alter the gravitational background
- alter the string spectrum: closed-string plus open-string brane-localized modes with $m^2 \ll 1/\alpha'$

How to study? BCFT or semi-classically - guide: kink paradigm in the two-scalar field theory

The kink solution in field theory

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial\chi)^2 + \frac{g}{8}\left(\phi^2 + \chi^2 - \frac{m^2}{g}\right)^2 + \frac{g'}{8}\chi^4$$

- 2 translation-invariant vacua: $(\phi,\chi) = \left(\pm\frac{m}{\sqrt{g}}, 0\right)$
- 2 interpolating kinks: $(\phi_{\mathrm{K}},\chi_{\mathrm{K}}) = \left(\pm\frac{m}{\sqrt{g}}\tanh\frac{m(x_\perp - a)}{2}, 0\right)$
  - thick membranes of width $1/m$
  - the spectrum in the background of a kink: massless χ and long-wavelength transverse modes

expanding around the kink solution one finds the effective action for the low-energy modes

$$\phi(x) \approx \phi_{\mathrm{K}}(x_\perp) + \psi(y)\partial_\perp\phi_{\mathrm{K}}(x_\perp)$$

$$S_{\mathrm{eff}} = \int d^4x\left(\frac{1}{2}(\partial\chi)^2 + \frac{g+g'}{8}\chi^4\right) + \int_{\mathrm{membrane}} d^3y\left(\frac{1}{2}(\partial\psi)^2 + V(\psi,\chi)\right)$$

D-branes in string theory

- No action available for the description of strings
- D-branes do not appear as translation-breaking extrema
- No direct way to obtain the D-brane-modes effective action

How to describe the string spectrum in the background of a D-brane and its dynamics?

- Determine the open-string modes localized on the brane
- Recast conformal-invariance requirement as an effective action

$$S_{\mathrm{DBI}} = \int \mathrm{d}^{p+1}y \sqrt{-\det\left(\hat{g} + \hat{F}\right)}$$

Back to Dirac's membrane … '62

Open string on a D-p-brane: $p+1$ dimensionally reduced Maxwell field (photon & $9-p$ massless scalars & gauginos)

What can N D-branes do?

- Open strings can be attached between them
  - low-energy effective field theory: $U(N)$ Yang-Mills (spontaneously broken to $U(1)^N$ if separated)
  - novel expectations in string phenomenology
- If N is macroscopic: emergence of RR expectation values
  - new gravitational/RR backgrounds - example: D-3-branes in IIB $\rightarrow$ $\mathrm{AdS}_5 \times S^5$ plus self-dual $F_{[5]}$
  - advent of AdS/CFT holographic duality

LET'S PAUSE: UNIFICATION, STANDARD MODEL AND BEYOND

Remember: original questions

- Are *all* SM parameters fundamental?
- Why is electric charge *quantised?*
- Why 3 families of quarks and leptons?
- Could electro-weak and strong interactions be «unified»?
- Are there other elementary particles beyond the top quark?
- Are there more fundamental objects?
- Could one explain the SM mass spectrum from first principles?

String theory does not provide definite and direct answers - some and only via GUTs and SUSY

Grand unification (70s)

Paradigm of electro-weak unification: extension of gauge symmetry group → GUT

- $SU(3)_C \times SU(2)_L \times U(1)_Y \subset$ min-rank-4 semi-simple group with complex representations
  - no U(1) factor ⇒ charge quantization
  - extra gauge bosons X (besides of Z and W)
  - Higgs sector: two-stage BEH mechanism with $M_X > M_Z$ by 12 orders of magnitude

- Quarks & leptons $\subset$ appropriate multiplets
  - Y and T_3 embedded to reproduce Q
  - fermion assignments s.t. anomaly-free couplings to all gauge bosons
  - potentially new matter: leptoquarks

▸ Archetype - simplest: $SU(5)$ [Georgi, Glashow '74]

▸ More general: $SO(10)$, E_6 [Georgi '74; Fritzsch, Minkowski; Gursey *et al* '75]

$SU(5)$

Rational basis for understanding particle charges and weak hypercharge assignments in the SM

rank 4, dimension 24

- 12 extra gauge bosons
- Fermion family $(\mathbf{1}, \mathbf{2}) + (\mathbf{1}, \mathbf{1}) + (\mathbf{3}, \mathbf{2}) + (\mathbf{3}^*, \mathbf{1}) + (\mathbf{3}^*, \mathbf{1})$ fits *exactly* in $\mathbf{5}^* + \mathbf{10}$ of $SU(5)$ and *reproduces* electric charges *without anomalies*
- Scalar sector: adjoint plus vector

Some prominent features of GUTs

- Majorana neutrino masses via effective dimension-5 operators
- Prediction for Weinberg angle
- No explanation for family replication, uncertainty on mixing angles
- Arbitriness in the choice of representations and in the Yukawa couplings
- Large uncertainty on the BEH symmetry breaking sector
- Extra ultra-massive gauge bosons $\Rightarrow$ baryon-number non-conservation: effective 4-fermion interaction $\Rightarrow$ proton decay (and baryon asymmetry - good cosmological feature)

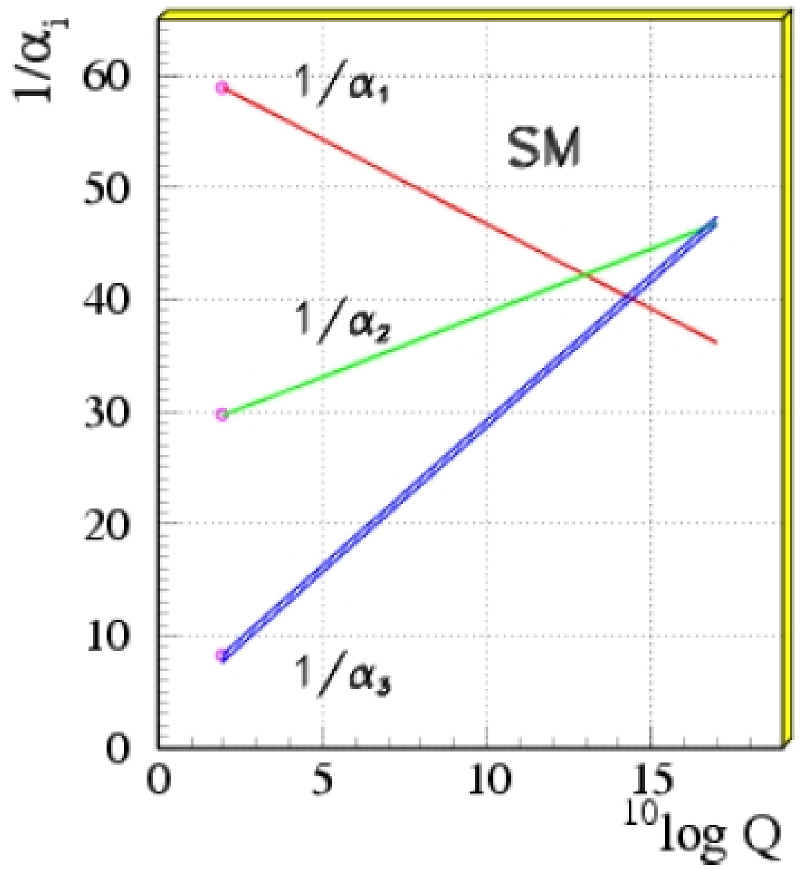
$$\boxed{\text{Super-Kamiokande: } \tau_{\text{proton}} > 5 \times 10^{33} \text{ years}}$$

Other often quoted *bad* features of GUTs

$$\alpha_i^{-1}(M_Z) = \alpha_{\mathrm{GUT}}^{-1}(M_U) + \frac{b_i}{2\pi}\log\left(M_Z/M_U\right) + \delta_i$$

- b_i: beta-function running parameters («massless» spectrum)
- δ_i: threshold corrections («massive» spectrum)

$M_Z \approx 100$ GeV
$M_X \approx 10^{14}$ GeV
$M_U \approx 10^{16}$ GeV



- Couplings do not meet: is this a problem?

- What does unification mean?
- What is the degree of confidence of such a plot?
    - assumptions on the spectrum over > 10 orders of magnitude
    - large uncertainties on threshold corrections

- 12 orders of magnitude in $M_X > M_Z$: is this a problem?

Hierarchy problem: fine tunning order by order

- particle physics *is* fine-tuned (over 11 orders of magnitude) - not number theory!
- strictly: absent in the SM - only one scale M_Z

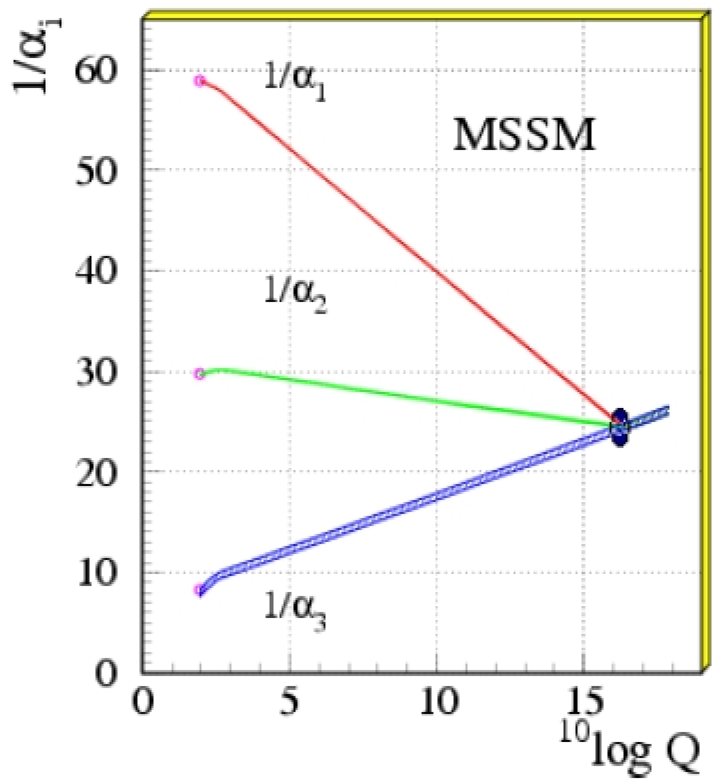
Supersymmetry (70s)

Paradigm of electric- and magnetic-field unification:
extension of space-time symmetry → supersymmetry
[Gervais-Sakita 1971, Gol'fand-Likhtman-Volkov-Akulov 1971, Wess-Zumino 1974]

- Conceptually appealing
- Practically: many shortcomings/drawbacks

Natural embedding of SUSY in *string theory*

Some features of SUSY theories



- Couplings seem to meet *simultaneously*
  - impressionistic (as the non-SUSY)
  - not required from first principles
- Hierarchy is stabilized - *not explained*
- Supermultiplets cannot contain more that 1 known particle
  - inflation of superpartners - *yet to be discovered*
  - Achilles'heel: supersymetry breaking - *with sociologically determined scale*

MSSM: *more than 110 parameters*

BACK TO STRINGS

Heterotic string [Gross, Harvey, Martinec, Rohm '84]

- Soon after Green-Schwarz anomaly cancellation in '84
- Closed oriented string: supersymmetric on the left and bosonic on the right
  - no tachyon
  - $D = 10$ & $N = 1$
  - massless spectrum & effective theory: $D = 10$, $N = 1$ supergravity with vector multiplets
  - rank-16 gauge groups: $E_8 \times E_8$ or $SO(32)$
- As opposed to SUSY GUTs
  - much less freedom for the gauge groups and representations
  - huge freedom for compactifications

Interesting feature

- Effective low-energy Lagrangian

$$\mathcal{L} = \frac{M_s^8 V_6}{g_s^2} R_{(4)} + \frac{k M_s^6 V_6}{8 g_s^2} F^2 + \cdots = \frac{1}{2\kappa^2} R_{(4)} + \frac{1}{2 g_{\mathrm{YM}}^2} F^2 + \cdots$$

$$M_s = 1/\sqrt{\alpha'} \quad \kappa^2 = 8\pi G_{\mathrm{N}} \quad g_{\mathrm{YM}}^2 = 4\pi\alpha_{\mathrm{YM}}$$

$$\boxed{\kappa^2 = \alpha_{\mathrm{YM}} \frac{k\pi\alpha'}{2}}$$

- If $M_U \approx M_s \approx 10^{16}$ GeV and if α_{YM} results from the SM

$$\boxed{1/\kappa \approx 10^{17} \text{ instead of } 10^{18} \text{ GeV}}$$

Appealing but not exact

- No way to do much better (thresholds, higher-order corrections ...)
- Simple argument to rule out heterotic string (?)

Orientifolds [precursor: Sagnotti '84, review and book by Blumenhagen *et al*]

Closed and open strings plus D-branes and orientifold planes in type II theories

- Intersecting / magnetized D-brane models
  - chiral matter on intersections
  - unbroben gauge symmetry from coincident branes
  - broken - from distant branes
- Generic features
  - large freedom for matter representation: less restrictive than heterotic

- extra $U(1)$s - some massive via anomalous couplings but some massless: way to rule out orientifold models

- no prediction for Newton's constant

$$\frac{1}{2\kappa^2} = \frac{M_s^8 V_6}{g_s^2} \qquad \frac{1}{2g_{\rm YM}^2} = \frac{M_s^{p-3} V_{p-3}}{n_p g_s}$$

- exotic possibility (consistency?) [ADD; AADD '98]

$$M_s \approx 1\,\text{TeV} \quad p = 7 \quad V_\perp = {}^{V_6}/{}_{V_{p-3}} \approx 100\,\mu\text{m}^2$$

Ruled out by microgravity experiments?

- Weakness of gravity: flux lines spread in the transverse space
- Gauge hierarchy under the large transverse carpet

What does betray the presence of a compact dimension?

- Mass spectrum: *Kaluza-Klein* pattern

$$m^2 = m_0^2 + n^2 \left(\frac{\hbar}{Rc}\right)^2$$

$$\Delta m^2 = 1 \ \left(\mathrm{TeV}/c^2\right)^2 \Leftrightarrow R = 1,9 \times 10^{-19} \ \mathrm{m}$$

- Deviations with respect to Newton's law

$$r \gg R \to f = \mathrm{G_N}\frac{mm'}{r^2} \qquad r \ll R \to f = 4\pi R \mathrm{G_N}\frac{mm'}{r^3}$$

Exact law:

$$f = \mathrm{G_N}\frac{mm'}{r^2}\left(\coth\frac{r}{2\pi R} + \frac{r}{2\pi R}\sinh^{-2}\frac{r}{2\pi R}\right)$$

Common 30-year caveats

- Vacuum selection & stability
  - absence of guiding principle (such as symmetry and renormalisability in field theory)
  - presence of numerous massless scalar fields: moduli
    - ruled out e.g. by micrograviy experiments
    - potentially stabilized by fluxes (vevs of NS, R, geometric, ... antisymmetric tensors)? [review by Graña ’05]
- At the end the treatment is phenomenological (e.g. for the (super)symmetry-breaking sector)
  - no accurate predictions
  - no exclusive signatures

IN SUMMARY

String theory: ™ for unification since 1984

- Contains a theory of quantum gravity: *true*
- Unifies gauge & gravity: *true*
- Is UV finite / controllable: *probably*
- Gives a handle on Λ: *not really*
- Is better than GUTS & SUSY: *debatable*
  - same weakness: (super)symmetry-breaking sectors
  - freedom in representation / gauge group & hierarchy
    $\to$ freedom in compactification / intersection
  - unnaturalness of the SM «realizations», hidden sectors

Are we addressing the right questions?

Conceptual advantages damped by the plethora of options, parameters and new particles - we should maybe

- disentangle gravity quantization and gravity unification
- abandon supersymmetry - reconsider dark matter
- come back to 4 space-time dimensions

reconsider what is a «more fundamental theory» - *should it provide all SM parameters plus Λ out of a single one - too much pythagorean perspective?*

Unification / strings: (anesthetic) ether of 20th century?

A first step has been taken: holography

String theory

- gives a handle on black-hole degrees of freedom
- puts on firm ground gauge/gravity duality
- sorts perturbative expansions in field theory

  - New perspectives on gravitational phenomena
  - New areas of application beyond high-energy
  - New relations with quantum fields

String/holography: magic tool of 21st century?