Particles and Strings –
Probing the Structure of Matter and Space-Time

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Physics in the 20thcentury

Quantum Theory (QT) Planck, Bohr, Heisenberg, ...	General Relativity (GR) Einstein
Physics of small scales	Physics of large scales

QT: asks about origin and structure of matter

GR: asks about structure of space-time and history of our universe

But: so far no unified theory valid at all length scales
– no 'Theory of Everything' – no 'Quantum Gravity'

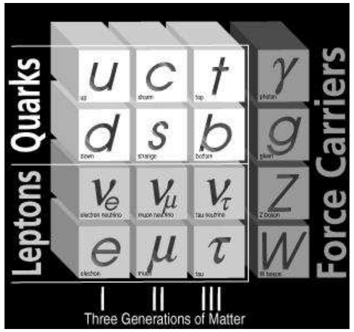
String Theory is possible candidate

Quantum Theory $\rightarrow$ Particle Physics

- 20^{th} century:
  probing nature at increasingly smaller length scales
- led by two questions:
  1. what are the constituents of matter?
  2. which theory governs their interactions?
- answers changed with time/length scale
  1. atoms $\rightarrow$ protons/neutrons/electrons $\rightarrow$ quarks & leptons $\rightarrow$?
  2. quantum mechanics $\rightarrow$ quantum field theory $\rightarrow$?

Particle Physics → Standard Model (SM)

Today both questions are answered by the SM



1. constituents of matter:

   3 families of **quarks & leptons** (spin = 1/2)

2. interactions: governed by

   – local quantum field theory

   – symmetry principle: the non-Abelian gauge symmetry

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

⇒ gauge bosons: **gluons, $W^{\pm}, Z^0$, photon** (spin = 1)

– G is spontaneously broken by Higgs Boson (spin = 0)

⇒ origin of mass

Limits of the Standard Model

➪ experimental situation:

- SM has been fantastically confirmed
- no direct observation of Higgs boson yet $\Rightarrow$ LHC

➪ questions unanswered:

- what determines G and the spectrum of particles ?
  what determines masses and couplings of quarks & leptons ?
- gravitational interaction cannot be consistently turned on !
- origin of dark matter ?

➪ common belief:

SM is only an 'effective theory' above some scale $l \leq 10^{-18} m$

Below this scale: new phenomena and new theory.

Generalization: Supersymmetry

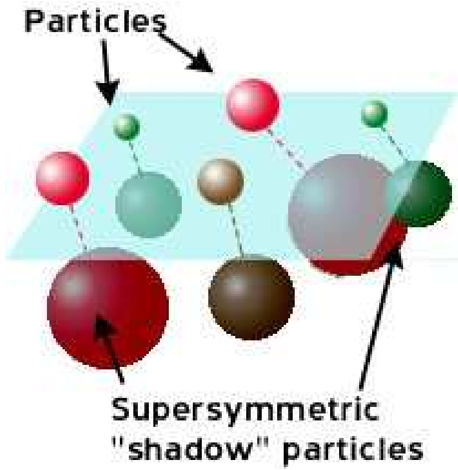
[Wess, Zumino]

enlarge the symmetry principle of the Standard Model:

$$\{Q, Q^\dagger\} \;=\; \gamma^\mu p_\mu$$

extension of the Poincaré-algebra (Q is generator)

⇒ symmetry among fermions and bosons

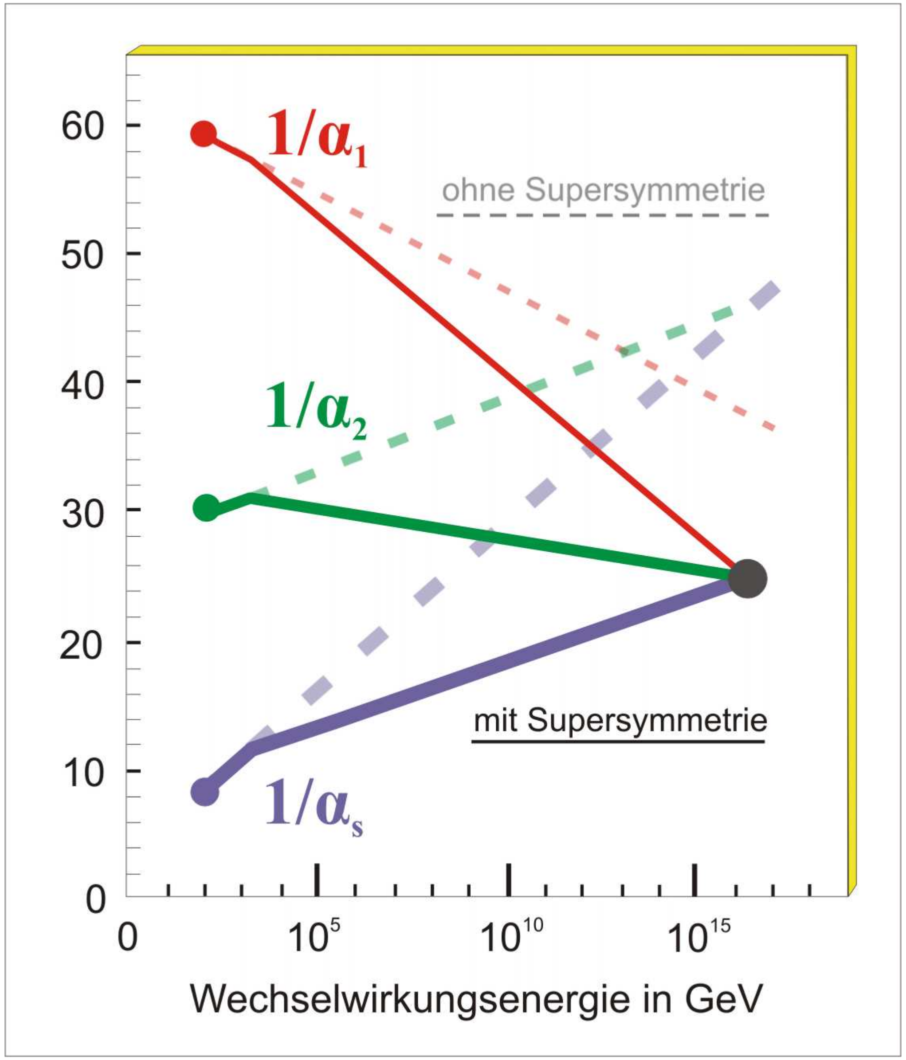


⇒ doubling of the particle spectrum

Properties:

- ➪ quantum corrections are “tamed”
  - ⇒ light Higgs boson is ‘natural’ and predicted
  - ⇒ strongly coupled QFT can be better controlled
- ➪ consistent with electro-weak precision data
- ➪ dark matter candidate: lightest supersymmetric particle (LSP)
- ➪ gauge coupling unification

⇒ Experimental verification: **LHC, ILC**


60
50
40
30
20
10
0
1/α1
1/α2
1/αs
ohne Supersymmetrie
mit Supersymmetrie
0
10^5
10^10
10^15
Wechselwirkungsenergie in GeV

Generalization: Grand Unified Theories

[Georgi, Glashow]

further generalization of the symmetry principle of the SM:

$$G_{\rm GUT} \supset G_{\rm SM} = SU(3) \times SU(2) \times U(1)$$

(e. g.: $G_{\rm GUT} = SU(5), SO(10), E_6$)

necessary condition: unification of the coupling constants

$\Rightarrow$ supersymmetric GUTs at scale $M_{GUT} \sim 3 \cdot 10^{16} {\rm GeV}$

Properties:

- predicts decay of the proton
- suggests light neutrinos $m_\nu \sim \frac{M_{Z^0}^2}{M_{GUT}} \sim \mathcal{O}(10^{-3} {\rm eV})$

  $\Rightarrow$ M_{GUT} is new scale in nature

General Relativity (GR)

[Einstein]

➪ GR is a field theory of the gravitational interaction

Energy & Momentum

$\Downarrow$

Curvature of space-time

$\Downarrow$

Gravitational Interaction

Einstein equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} \;=\; G_N \, T_{\mu\nu}$$

(Λ: cosmological constant, G_N: Newton's gravitational constant)

➪ GR successfully governs cosmology and astrophysics

$\Rightarrow$ Standard Model of Cosmology

Limits of General Relativity

➪ experimental situation: GR has been fantastically confirmed

- correction to Newton law, deviation of light in grav. field
- existence of Black Holes,
- expanding universe, ...

➪ questions unanswered:

- what sets the value of G_N – why is it so small?
  what sets the value of Λ – why is it so small and positive ?
- physics of singularities (Big Bang and Black Holes) ?
  quantum theory of gravity ?

➪ common belief:

GR is only an 'effective' theory valid on macroscopic scales

Where is the Problem?

At what scale is a quantum gravity necessary?

$$\lambda_{\text{Compton}} = \frac{\hbar}{Mc} \approx R_{Schwarz} = \frac{MG}{c^2}$$

$\Rightarrow$ Planck mass: $M_{\text{PL}} = \sqrt{\frac{\hbar c}{G}}\,, \qquad E_{\text{PL}} = c^2 M_{\text{PL}} \approx 10^{19} GeV$

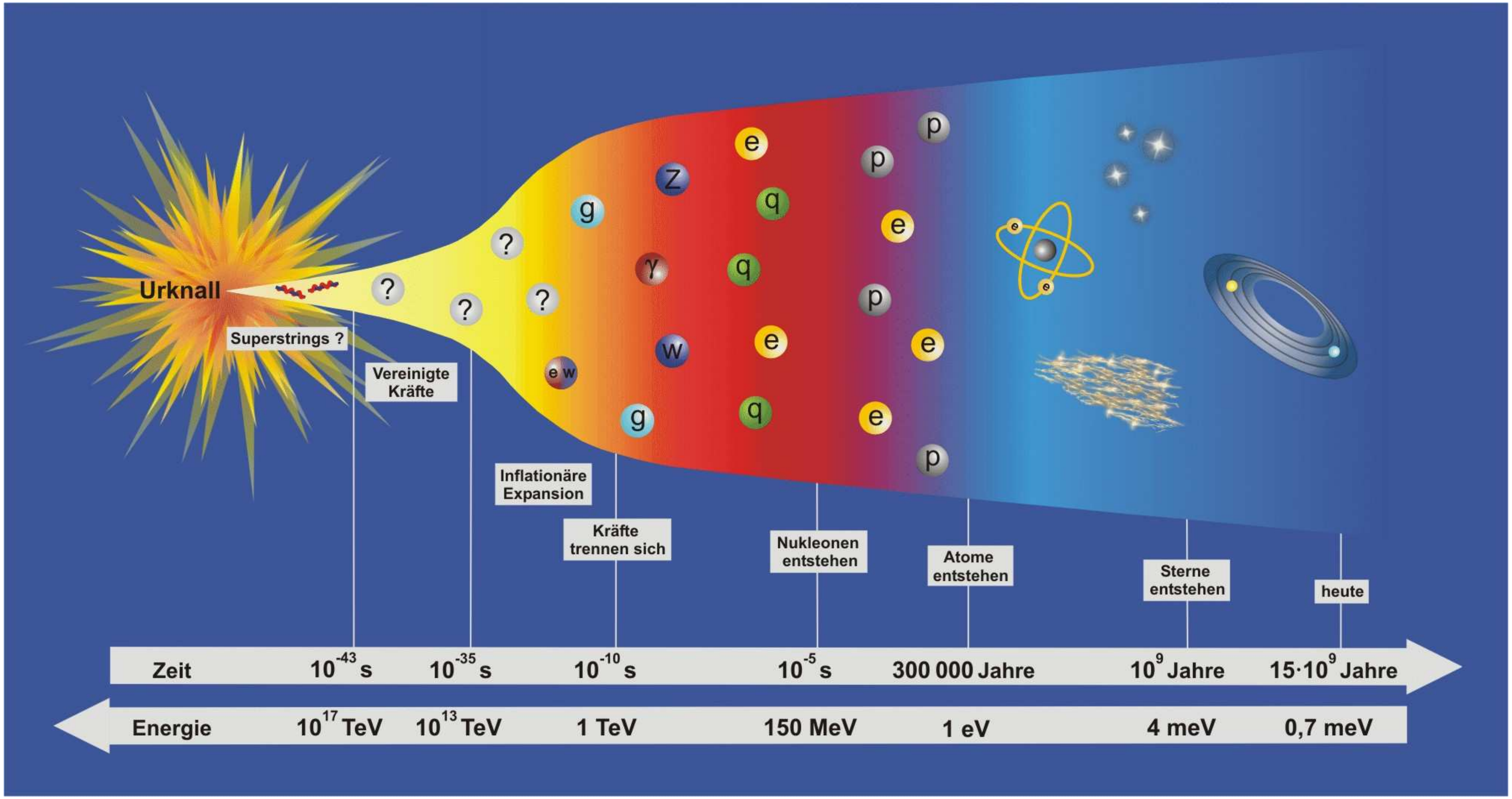
Planck length: $l_{\text{PL}} = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-35} m$

relevant in

- (very) early universe $t = t_{PL} = l_{PL}/c \approx 10^{-43} s$ after big bang
- physics of black holes

belief:

at length scales $l \approx l_{PL} = \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-35} m$
a completely new concept is necessary to describe nature.



Urknall
Superstrings ?
Vereinigte Kräfte
Inflationäre Expansion
Kräfte trennen sich
Nukleonen entstehen
Atome entstehen
Sterne entstehen
heute
Zeit
10^-43 s
10^-35 s
10^-10 s
10^-5 s
300 000 Jahre
10^9 Jahre
15·10^9 Jahre
Energie
10^17 TeV
10^13 TeV
1 TeV
150 MeV
1 eV
4 meV
0,7 meV

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DISCOVERY

SCIENCE'S NEXT FRONTIERS

Some experts believe they are on track to achieve the great quest of modern physics: the theory of everything

Pulling the right strings

BY DAN FALK

Physicists have always been driven by an urge to simplify. Confronted with myriad observations from the natural world, they try to explain what they see with the fewest possible laws and equations. Now, some are hunting for one single theory to explain all of physics — the long-sought theory of everything. So far, that achievement remains elusive — but a field known as string theory seems to offer at least a glimpse of this Holy Grail.

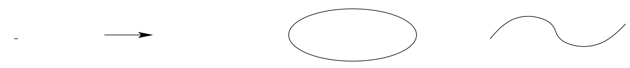
If the string theorists are right, we are on the way to realizing the dream of a final theory. For some areas, such as cosmology and particle physics, the impact would be

fundamental particles — one massive "superparticle" corresponding to each of the known particles. No such superparticles have ever been observed, but the next generation of giant particle accelerators could settle the matter. The Large Hadron Collider (LHC), now under construction at the CERN facility near Geneva, should be powerful enough to detect superparticles — if they in fact exist. "If they turn on the LHC and discover the supersymmetric partner of the electron, that would be terribly exciting," Peet says. If that happens, "a lot of people would think that string theory was likely to be the right theory of the world."

The ultimate hurdle for any new theory is experimental testing. But even before that — when a theory is still on the drawing

(Perturbative) String Theory

Idea: point-like objects → strings

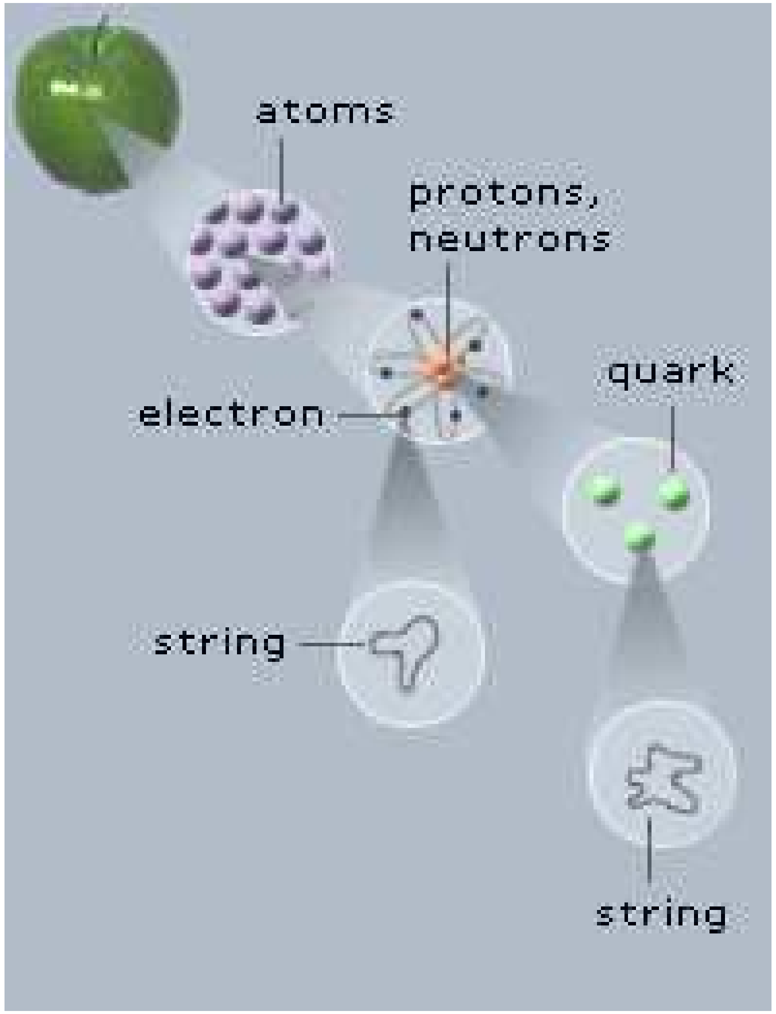


Strings move in D-dimensional Minkowskian background.

(pert.) string theory is quantum theory of extended objects (strings).

Proposal:

fundamental constituents of matter and space-time are strings



Quantum excitations:

- finitely many massless excitations:

s = 2	$\longrightarrow$	graviton	$\Rightarrow$ gravity cannot be turned off
s = 3/2	$\longrightarrow$	gravitino	$\Rightarrow$ supersymmetric spectrum
s = 1	$\longrightarrow$	gauge bosons	
s = 1/2	$\longrightarrow$	fermions (quarks & leptons)	
s = 0	$\longrightarrow$	Higgs, ...	

- infinitely many massive excitations

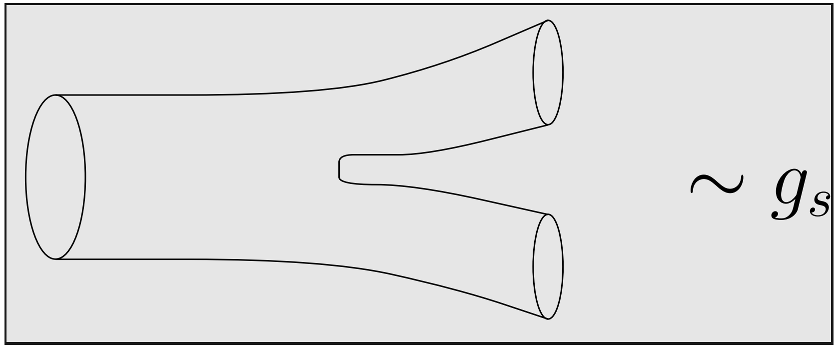
$$M \sim n \cdot M_S \ ,$$

$M_{\rm S}$ = characteristic scale of string theory (tension of the string)

$M_{\rm S} \sim M_{\rm Pl}$ (from coupling of graviton)

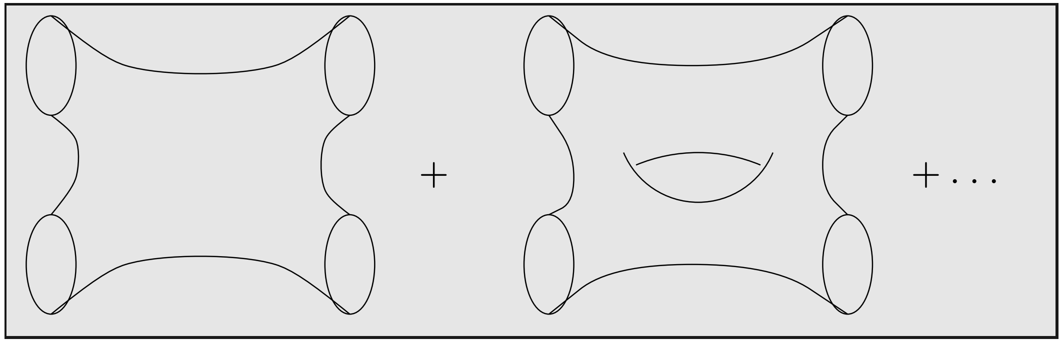
$\Rightarrow$ soft UV behavior

Back to Strings: Interactions



$g_s = e^{-\langle \phi \rangle}$ is coupling constant, ϕ is scalar field (dilaton)

scattering amplitudes:



quantization via "Feynman-diagrams"

$$\text{scattering amplitude:} \qquad A = \sum_{n=0}^{\infty} A^{(n)} g_s^{2+2n} \ .$$

Results:

- ➪ spectrum contains non-Abelian gauge theory with families of chiral fermions coupled to gravity
- ➪ for scattering processes with $p \ll M_S$:

  string theory $\stackrel{p \ll M_S}{\longrightarrow}$ QFT & GR $\qquad (A_{string} \longrightarrow A_{QFT,GR})$

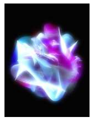
  $\Rightarrow$ QFT & GR are low energy limit of string theory.
- ➪ g_s is free parameter and one can choose $g_s \ll 1$

  $\Rightarrow$ perturbative evaluation of A possible
- ➪ amplitudes $A^{(n)}$ are UV-finite ?

  $\Rightarrow$ pert. quantum corrections to GR can be sensibly computed
- ➪ string theory provides perturbative quantum gravity and unifies all interactions

Problems of perturbative String Theory

- spectrum is supersymmetric $\Rightarrow$ necessary for consistency?
- quarks, leptons and Higgs massless
  - $\Rightarrow$ what generates small masses ?
  - $\Rightarrow$ what generates the hierarchy $\frac{M_Z}{M_{\rm Pl}} \approx 10^{-17}$
- unitarity of scattering amplitudes $\Rightarrow$ $\boxed{D \leq 10}$
  - $D = 10$: 5 different string theories:
    IIA, IIB, I, Het. $E_8 \times E_8$, Het. $SO(32)$
  - $D < 10$: families of theories
    geometrical compactification: $\mathcal{M}^{(10)} = \mathcal{M}^{(D)} \times K^{(10-D)}$
  - $\Rightarrow$ what chooses D ? $\Rightarrow$ what chooses K ?

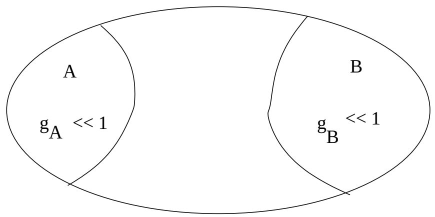


hope: cured by non-perturbative effects.

Non-perturbative Aspects of String Theory

conjecture:

different string theories are dual description of one quantum theory:



perturbative spectrum A $\Leftrightarrow$ non-perturbative spectrum B

perturbative spectrum B $\Leftrightarrow$ non-perturbative spectrum A

difficult to prove but successful checks on 'protected' couplings

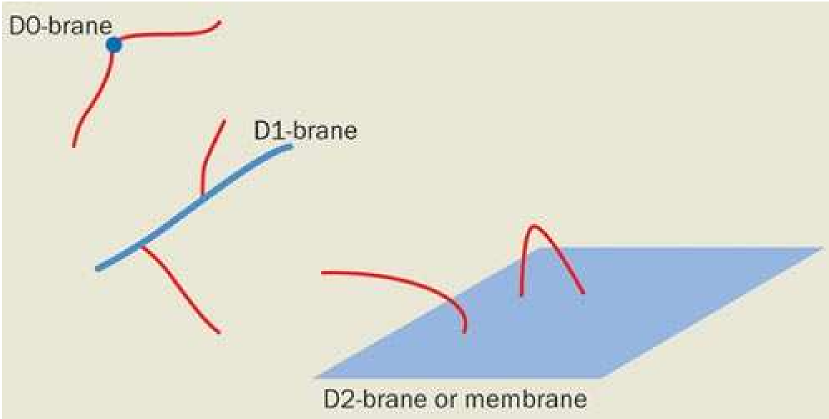
(such couplings do exist in supersymmetric theories)

Non-perturbative states of string theory: D-branes

D-Branes

[Polchinski]

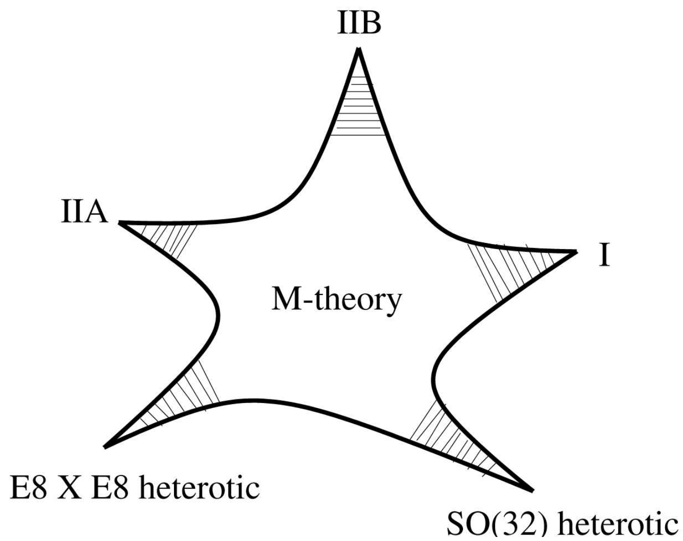
open string with Dirichlet boundary condition define hyperplane



- D-Branes are dynamical objects of string theory
- D-Branes are non-perturbative states of string theory (tension $\sim g_s^{-1}$)
- string theory is not a theory of only strings but also describes higher-dimensional objects: Branes

M-Theory

Proposal: all string theories are pert. limits of one quantum theory



What is M-theory ?

Suggestion: theory of D-particles [Banks, Fischler, Shenker, Susskind].

$\Rightarrow$ space-time becomes non-commutative

The Standard Model on a D3-brane

$\Rightarrow$ gauge interaction is localized on the D3-branes

$\Rightarrow$ transverse dimension only feel gravitational interaction

$\Rightarrow$ how big can they be?

$$V(r) \sim \frac{1}{r} \qquad \begin{cases} \text{Coulomb} \quad \text{valid down to } \sim 10^{-16} cm \\ \\ \text{Newton} \quad \text{valid down to } \sim 10^{-1} cm \end{cases}$$

$\Rightarrow$ large extra dimension possible

$\Rightarrow$ signal at LHC ?

Cosmology in String Theory

so far only little known about cosmological solutions in ST

⇒ no convincing picture of the Big Bang

- early universe: inflationary phase

  ST: has many scalar fields ! with right couplings ?

- late universe: $\Lambda > 0$ ST: problematic asymptotically

  options:

  - time-dependent scalar field can 'simulate'

    $T_{\mu\nu} = -\Lambda g_{\mu\nu}$ (quintessence)

  - only local de-Sitter vacuum (string landscape)

Black Holes in String Theory

With help of duality one can study black holes

- so far only supersymmetric black holes studied
  (extreme Reissner-Nordstrøm BH: $M = Q$)

- Bekenstein–Hawking entropy

$$S = \frac{A}{4G_N}\ , \qquad\qquad A = \text{ Area of Horizon}$$

  can be computed as sum over micro-states [Strominger, Vafa]

  micro-states = excitations of D-branes

- Hawking radiation (temperature und decay rate) is reproduced

String theory as a technical tool

➪ use string theory to organize QCD amplitudes

[Bern, Dixon, Kosower, Witten]

➪ use string theory as regulator ⇒ lessons for supersym. QFT

➪ learn about strongly coupled (supersym.) QFTs ⇒ (s)QCD

- AdS/CFT correspondence ($N = 4$)
- Seiberg/Witten ($N = 2$)
- Dijkgraaf/Vafa ($N = 1$)

and develop new tools

String Theory and Mathematics

➪ point-like particle $\equiv$ probe of continuous space-time geometry

$\Rightarrow$ relation with Riemannian geometry [Einstein,Hilbert]

➪ string as probe: sees coarser structure

$\Rightarrow$ development of quantum geometry [Kontsevich, Manin, . . .]

surprising results:

- mirror symmetry in Calabi-Yau manifolds
- computation of number of holomorphic curves on Calabi-Yau manifolds
- development of quantum cohomology

Summary

- ➪ GR and QFT are the foundations of contemporary physics
- ➪ GR/cosmology successfully describes the universe
  QFT/particle physics successfully describes small length scales
- ➪ supersymmetric theories have remarkable properties:
  - consistency with electro-weak precision experiments
  - unification of the gauge couplings
  - candidates for dark matter
  - light neutrinos
- ➪ string theory unifies all interactions
  - provides perturbative quantum gravity
  - qualitative agreement with generalizations of the SM
  - non-perturbative definition of string theory not yet achieved