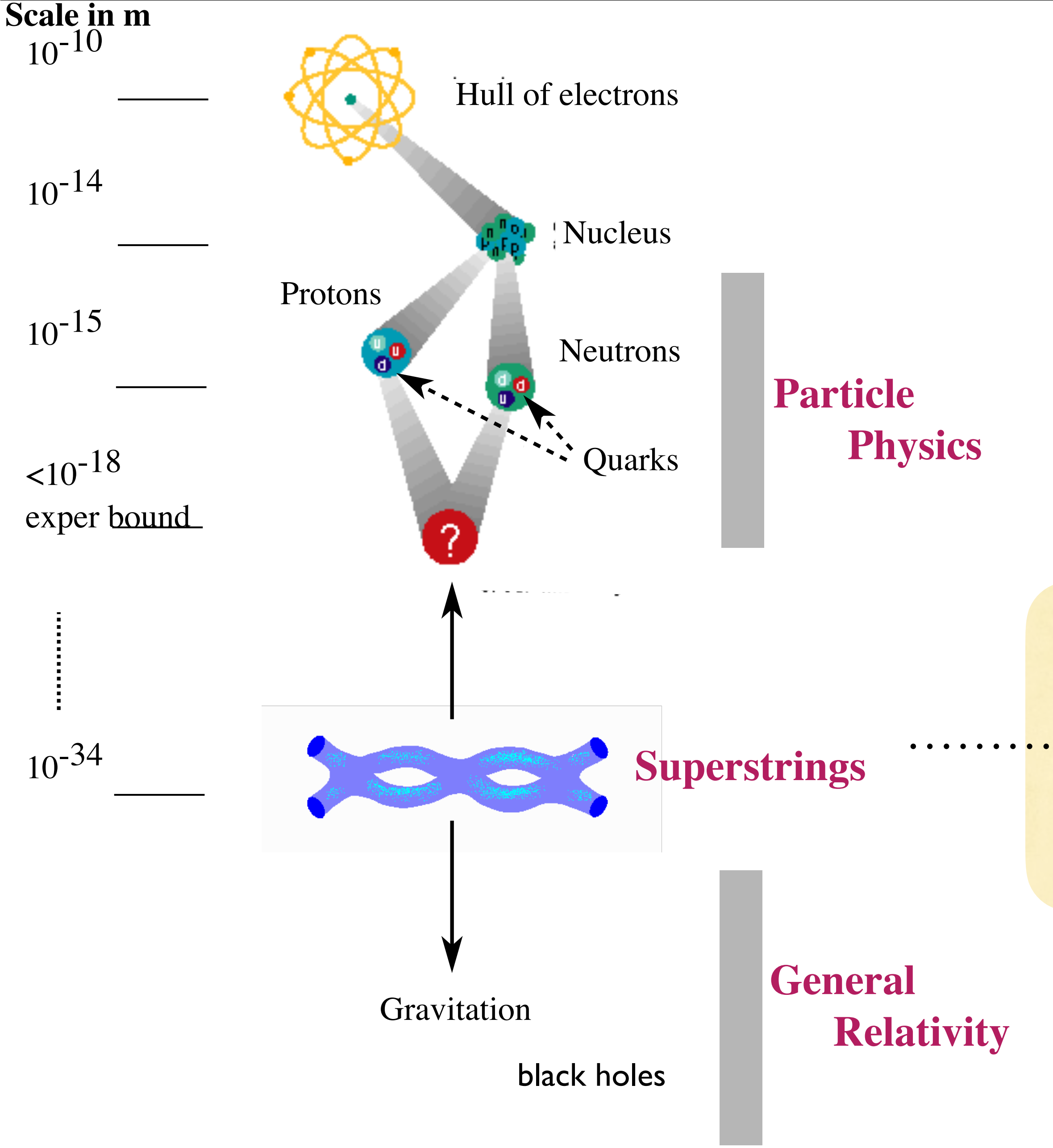
What is String Theory?

W.Lerche, Summer Student Lecture, CERN 8/2016

- Motivation
- Basic principles
- Key features: dimensional compactification, landscape….
- Where do we stand: ST as toy model and framework
- "Philosophical" remarks: see discussion session (Thur @ 5:30pm)

Strings: bridge between particle physics and gravitation



Two intertwined branches of string theory:

Grand Unification and Quantum Gravity

Particle Physics: Shortcomings of the Standard Model

- Its **structure** seems ad hoc, are there deeper principles?

$$SU(3) \times SU(2) \times U(1) \ \subset \ ?$$

- Lots of **free parameters:** determined by what? (if at all…)

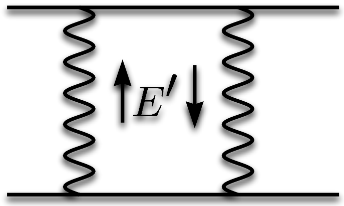
$$\mathcal{L} \ = \ \left(\sum \bar{\psi}\gamma(\partial + g_k A)\psi\right) + \left(\sum m_i \bar{\psi}_i \psi_i + c_{ijk}\phi_i \psi_j \psi_k\right) + \dots$$

gauge field couplings masses Yukawa couplings

- Grand unification?
  Standard Model is not complete: **gravity** is not included

Quantum Gravity: an Unlikely Marriage

- Usual QFT formulation of gravity does not work, due to incurable **divergences**:



$$\frac{1}{m_{\rm pl}^4}\int^{\infty} dE'\,(E')^3 \;\rightarrow\; \infty$$

Unitarity breaks down near Planck scale ~ 10^{19}GeV.

Is GR just an effective low energy approx, like Fermi theory of weak interactions?

- Conceptual problems with quantum **black holes**: Hawking radiation, information loss?

- All these are different aspects of a deeply rooted tension:

Apparent **incompatibility** of Quantum Mechanics and General Relativity (unitarity, locality…)

→ Go beyond standard particle QFT: String Theory

String Theory - naively approached

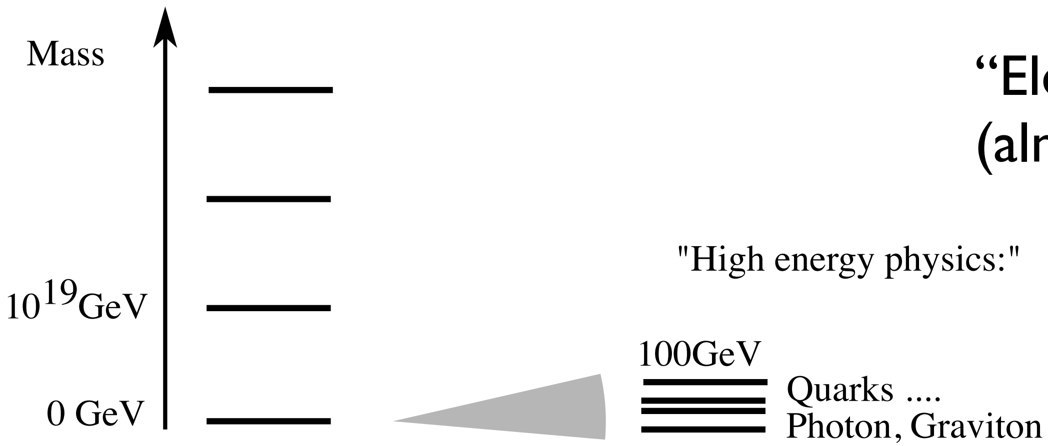
- Small (10^{-34}m), one-dimensional objects:

Scale determined by Newton's constant:

$$G_N = \frac{1}{m^2_{\mathrm{planck}}} \qquad m_{\mathrm{planck}} \sim 10^{19} GeV$$

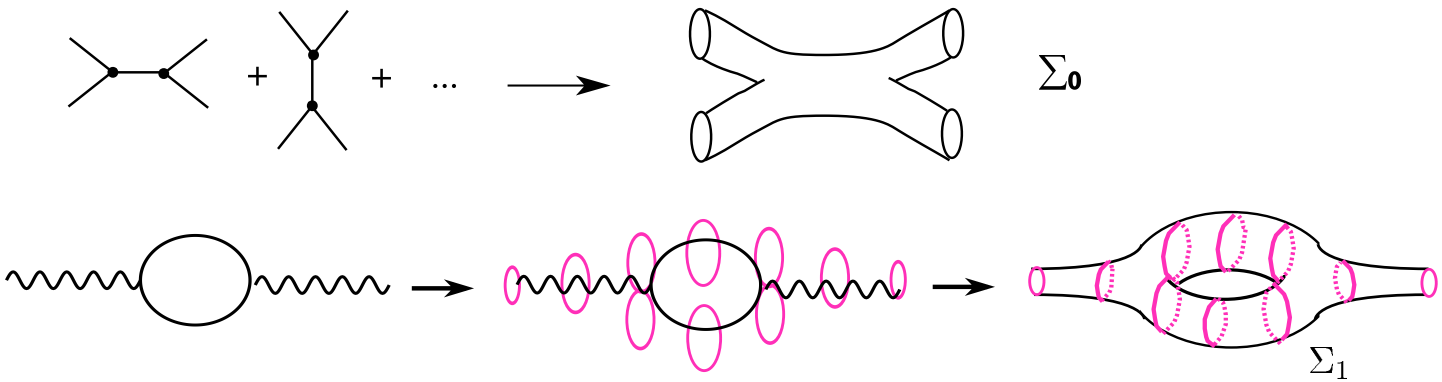
- Resonance spectrum:

“Elementary” particles:
(almost) massless zero modes



String Theory as 2d Field Theory I

- Strings trace out in D-dim space-time 2-dim "world sheets" Σ_g :



- Perturbative string theory = 2d field theory on Riemann surfaces

  Building blocks: can be **free** 2d bosons, playing role of D space-time coo:

$$X_\mu(z) \; : \; \Sigma \to R^D \; , \qquad \mu = 1, ..., D$$

- If also fermions: $(X_\mu, \, \psi_\mu)$ …… "**Superstrings**"

String Theory as 2d Field Theory II

Variety of field operators in D-dimensional space time ⟷ Simple combinatorics of 2-dim field operators

Graviton: $g_{\mu\nu} = \bar{\psi}_\mu(\bar{z})\psi_\nu(z)$

Gauge field: $A_\mu^a = \bar{\psi}_\mu(\bar{z})\psi^a(z)$

Higgs field: $\Phi_{ab} = \bar{\psi}_a(\bar{z})\psi_b(z)$

Intrinsic unification of particles + interactions !

In particular, gravity is automatically built in.

String Theory as 2d Field Theory III

- 2-dim path integral over Riemann surfaces generates a **low-energy effective QFT** in D-dim space-time, consisting of gravity, gauge dynamics, plus matter fields:

$$S_{\text{eff}}^{(D)}(g_{\mu\nu}, A_\mu, ..) = \sum_{\Sigma_g} e^{-\phi\chi(\Sigma_g)} \int_{M(\Sigma_g)} \int d\psi dX..\; e^{\int d^2z\, \mathcal{L}_{2d}(\psi, X, .., g_{\mu\nu}, A_\mu, ..)}$$

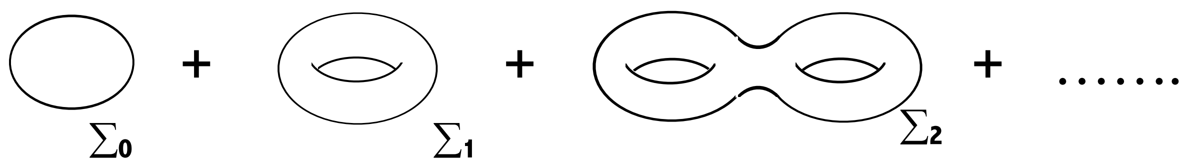
eg free 2d action

$$= \int d^Dx \sqrt{g}\, e^{-2\phi} \left[R + \mathrm{Tr} F_{\mu\nu}F^{\mu\nu} + \ldots\right] + \mathcal{O}({m_{\text{planck}}}^{-1})$$

Einstein Gravity, YM Theory

infinitely many small corrections: “predictions”

“Loop expansion” = sum over 2d topologies



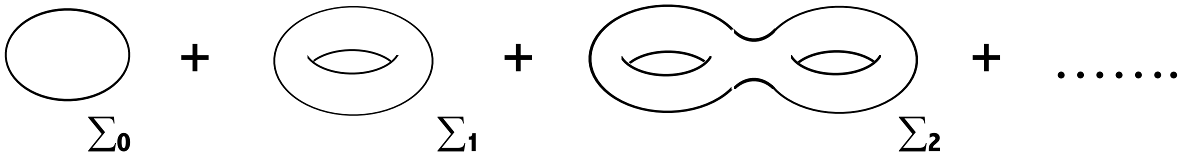
plus integral over shapes of Σ_g

Key Features of String Theory

- Perturbation expansion and UV finiteness
- Supersymmetry?
- Space-time dimension, and compactification
- Geometrization of interactions, moduli, landscape of vacua
- Non-perturbative dualities
- Gauge-gravity correspondence, holographic quantum gravity
- ~~(Spinoff: Susy gauge theories, black holes)~~

Perturbation expansion and UV finiteness

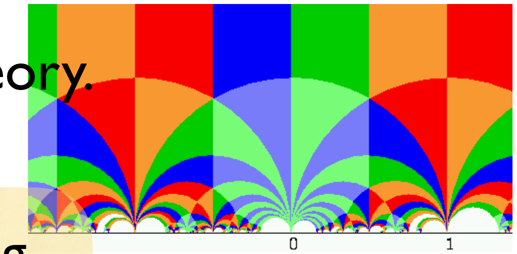
- Perturbative "Loop expansion" = sum over 2d topologies



Only one "diagram" at any given order in perturbation theory

- **Discrete reparametrizations** of Σ_g have **no analog in particle theory**; crucial for UV finiteness, esp. for making sense of graviton scattering.

``Feynman rules" are substantially different from particle theory.



> String perturbation theory involves **more** than just having infinitely many particles plus a cutoff !

Supersymmetry

- If one wants to have fermions ("quarks, leptons") in spacetime, one necessarily needs supersymmetry in the 2dim field theory on Σ_g: $(X_\mu,\ \psi_\mu)$

This is the origin of the name "Superstrings".

- Does this imply supersymmetry also in D-dimensional space-time?

Answer: not really. Supersymmetry in space-time helps to stabilize the ground state (absence of "tachyons"), and to make the perturbation series better behaved, and to render many quantities explicitly computable.

In practice it is very difficult to build consistent theories without Susy, but this does not logically imply the need of Susy in Nature.

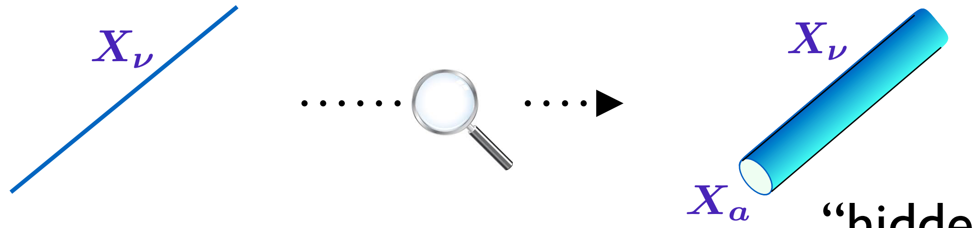
I use to view Susy as providing simplified toy models not to be taken too literally. Others may disagree….

Dimensional Compactification I

- Consistent quantization requires D=26 for bosonic and D=10 for Superstrings
  Traditional viewpoint: 10-4=6 "superfluous" dimensions can be "compactified":

$$X_\mu \longrightarrow (X_\nu,\, X_a) \quad \nu = 1...4, \;\; a = 5...10.$$

- Analogy of garden hose:
  from a distance (~low energies) it looks 1dim, while from close it looks 2dim:

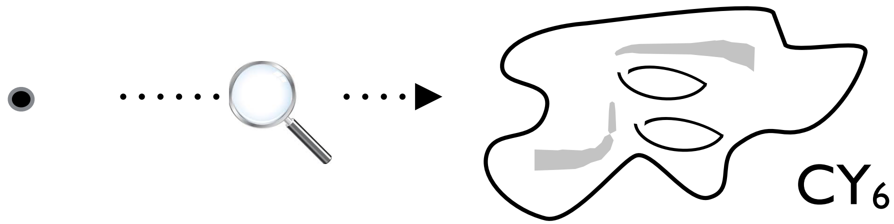


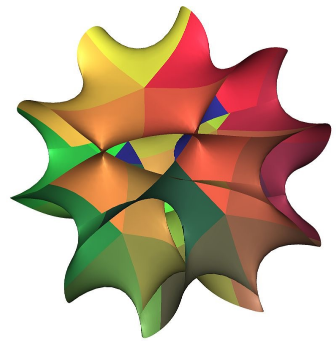
"hidden" periodic bosonic coo

$$X_a \sim X_a + 2\pi R_a$$

Dimensional Compactification II

- Circles yield too many supersymmetries in D=4.
  This is why often more complicated, 6dim “Calabi-Yau” spaces are considered.





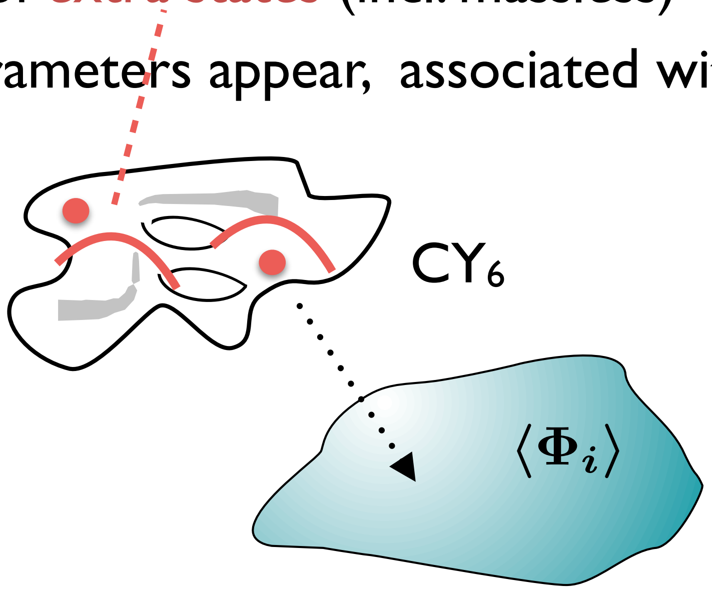
By judiciously choosing these,
the resulting effective theories with D=4 at low-energies,
are typically like what is considered in particle QFT!

They naturally exhibit: N=1 Susy, chiral fermions,
Higgs fields, gauge fields, family replication

… and this in a consistent manner together with gravity, at quantum level!

Geometrization of Particle Physics in 4D

- After compactification to D=4, string theories become **much more complex**:
  - Proliferation of extra states (incl. massless)
  - Many new parameters appear, associated with the shape of CY_6



String parameter space = deformation space of compactification manifold CY6

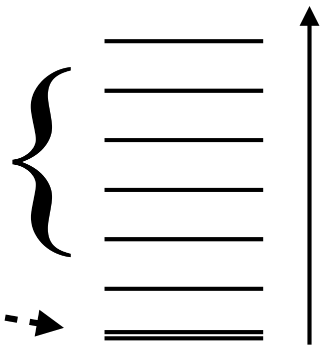
- The geometrical parameters ("moduli") that govern the shape of CY_6 become free physical vacuum VEV's, which are not determined by the 10d theory.
- Many couplings of the effective 4 dimensional theory have a geometric interpretation rooted in the properties of CY_6 and depend on these VEVs.

Predictivity?

- Are there more than **generic** predictions of string theory?

In principle: infinitely many predictions!
(massive spectrum and interactions very tightly constrained)

In practice: almost no predictions in zero mode sector!

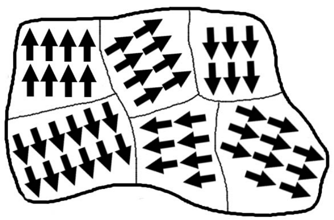


Properties of low-energy sector ⟷ Properties of compactification space = choice vacuum state

.. are not much determined by 10dim string theories !

- Analogous to spontaneously chosen direction of magnetization in a ferro-magnet, or to snowflakes, whose precise shapes are also not fixed by fundamental principles....

  Nevertheless, the underlying laws of electromagnetism and QM are far from arbitrary!

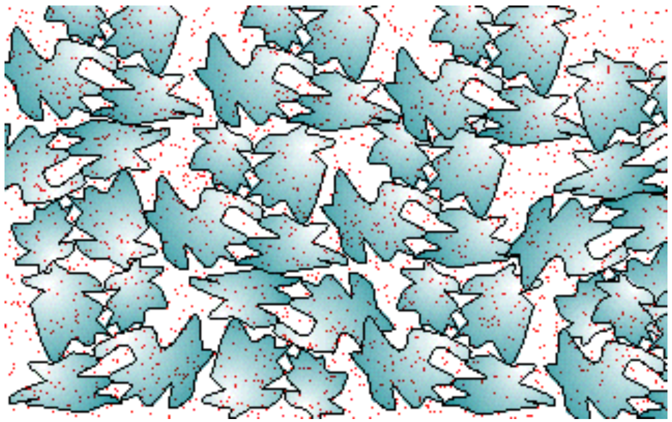


Weiss Magnetic Domains

Vacuum Selection Problem, and Landscape

- The lack of predictivity at low energies is the most serious challenge for the credibility of string theory!
- There are plenty of Calabi-Yau spaces, and it is not clear why any one should be singled out. Nor why D=4 would be preferred at all ....
- Each Calabi-Yau space leads in general to a different spectrum in D=4, and, even worse, has a huge parameter space by itself… plus "fluxes"

Alltogether this forms a huge **landscape of possible vacua**, each with different particle spectrum and coupling parameter space

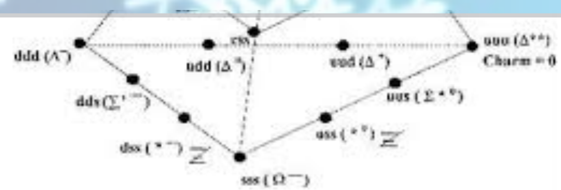


Possible selection mechanisms among such vacua?
….beyond current formulation of theory

The Anthropic Principle

- Fundamental question:
  is vacuum selection deterministic or …. just accidental?

> Some or all specific properties of the standard model may not have any fundamental reason at all …
> They simply might be "frozen historical accidents"

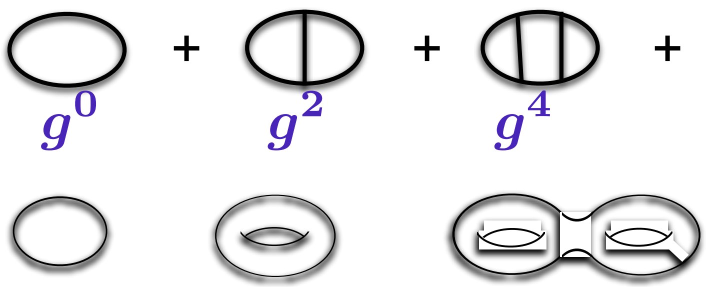


- This may help to understand the apparent miracle why our world seems fine-tuned precisely such we can exist….

  Very speculative and controversial…… more about this in the discussion session!

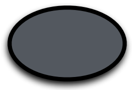
Beyond Perturbation Theory

- So far all discussion was in terms of perturbation theory:



$$\mathcal{A} \sim \sum a_k g^{2k}, \quad g << 1$$

But QFT is by far more than just Feynman diagrams!



$$\mathcal{A}_{\text{inst}} \sim e^{-\frac{1}{g^2}}$$

eg, instantons

- Many important features cannot be captured in p.t. at all, or by writing naive lagrangians and quantizing them.

- Prime feature: "Duality"

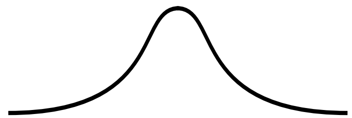
  Typically associated with relating weak and strong coupling limits

  Intrinsic quantum phenomenon!

$$g \longrightarrow \frac{1}{g}$$

Dualities: Non-Perturbative Equivalences

- Map map solitonic (non-perturbative, extended) degrees of freedom to elementary (perturbative, local) ones, and vice versa

$\bullet\ \Phi(x)$ $\qquad g \longleftrightarrow \frac{1}{g}$ 

local "electric"
elementary field

non-local "magnetic"
collective excitation, "soliton"

> These are two ways to describe one and the same physical degree of freedom

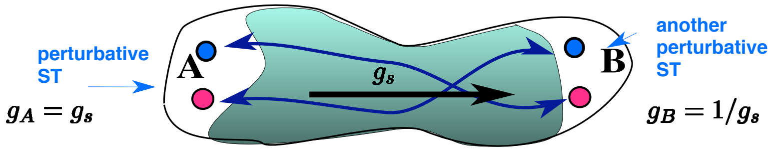
- Simple example: bosonization in 2d

$$\text{fermion} \quad \Psi(z) \quad \longleftrightarrow \quad :e^{i\Phi(z)}: \quad \text{soliton}$$

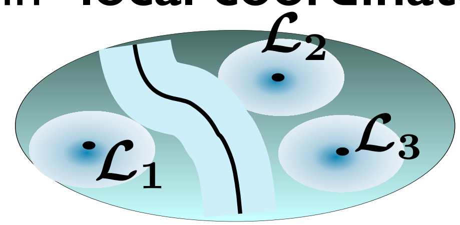
- Teaches another lesson: view $\Phi \sim \Phi + 2\pi$ as compactified spacetime coo. We see that the notion of a compactified dimension is **ambiguous**
  … special case of some abstract "internal" degree of freedom!

Duality in Parameter Spaces

- We have similar phenomena also for coupling parameters other than g.



Lagrangian descriptions make sense only in "**local coordinate patches**" covering the parameter space:



These describe different local approximations of the same theory in terms of different weakly coupled local physical degrees of freedom.

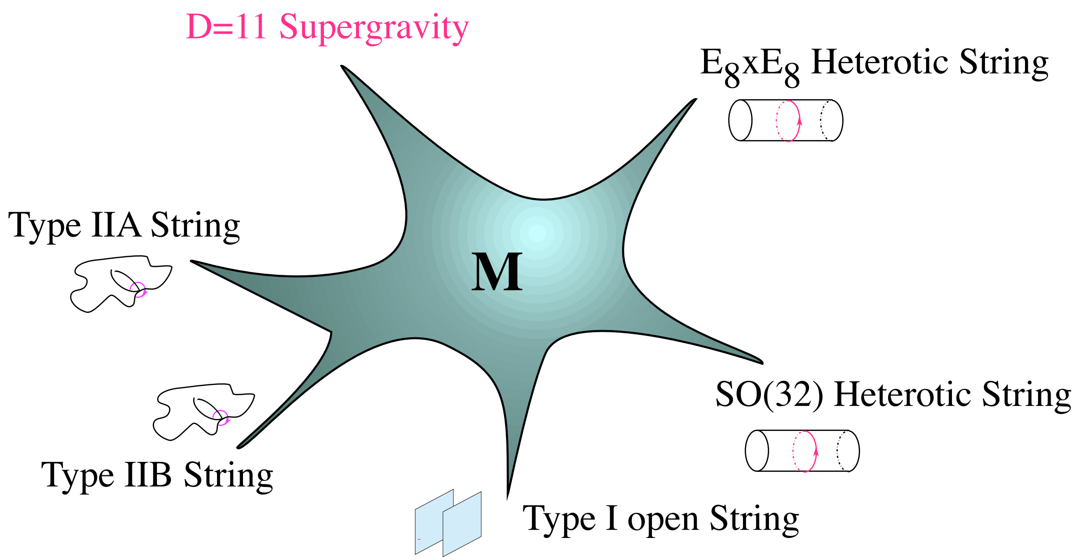
The perturbative physics (local QFT) may look completely different in the various local patches (eg, different gauge groups and matter fields)

- In general, there is no global description that would be valid throughout the whole parameter space!

Concept of "fundamental degrees of freedom" is ambiguous

Unity of Strings and Membranes

- In particular all 5 string theories in 10dim can be seem as particular perturbative limits .. of … what?



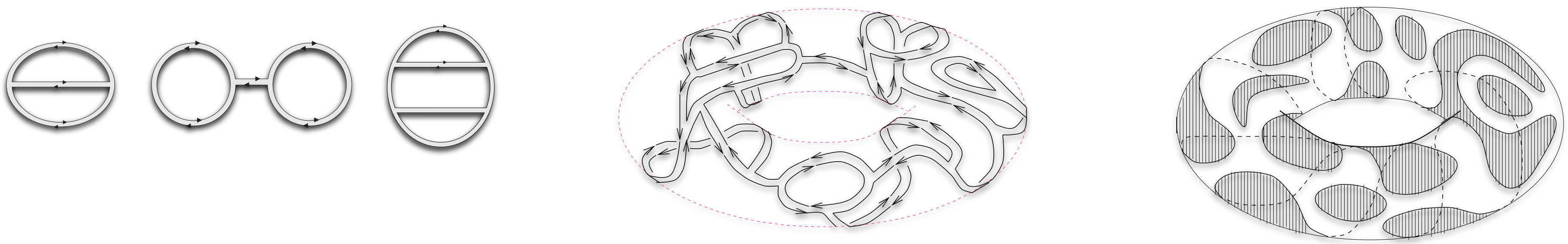
Surprise: taking the strong coupling limit in the Type IIA string, non-perturbative states ("D0-branes") generate an 11th dimension !

D=11 supergravity in not related to a string theory, but rather to supersymmetric membranes.....

Dualities take us beyond string theory !

The Gauge-Gravity Correspondence

- Consider N=4 supersymmetric gauge theory for SU(n) for $n \to \infty$:
  Only "planar" Feynman diagrams dominate, and build up Riemann surfaces!



- At large n, the gauge theory is best described by a string theory, namely Type IIB Strings compactified on $S^5 \times AdS_5$

$$\sum_{i=1}^{6} {x_i}^2 = R^2 \qquad\qquad {y_0}^2 + {y_1}^2 - \sum_{i=1}^{4} {x_i}^2 = R^2$$

String theory weakly coupled for:		Gauge theory weakly coupled for:	
$g^2 n$	large	$g^2 n$	small
g	small	g	small

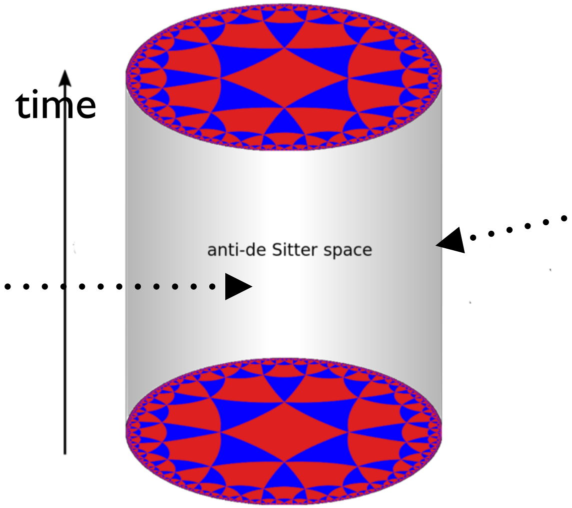
- Correlators of gauge invariant operators in the N=4 gauge theory are 1:1 to the Green's functions of the type IIB string on $S^5 \times AdS_5$

…. many non-trivial tests and results !

The Holographic Principle

- Geometry of Anti-de-Sitter space AdS_5:

String theory/
Gravity in the "bulk" ....



N=4 gauge theory on the
3+1 dimensional boundary
= Minkowski space

- How can a theory be equivalent to "another" theory on the boundary ? It seems to have far too many degrees of freedom !

The "Holographic Principle" posits:

A theory of quantum gravity is non-local and carries the same number of degrees of freedom as a theory on the boundary !
(...very relevant for quantum information in black holes)

So…what, finally, is String Theory? I

- An fruitful **toy model** for grand unification and for studying quantum gravity in simplified but consistent settings

- A **framework** for answering non-trivial questions about gauge theories, black holes, math.

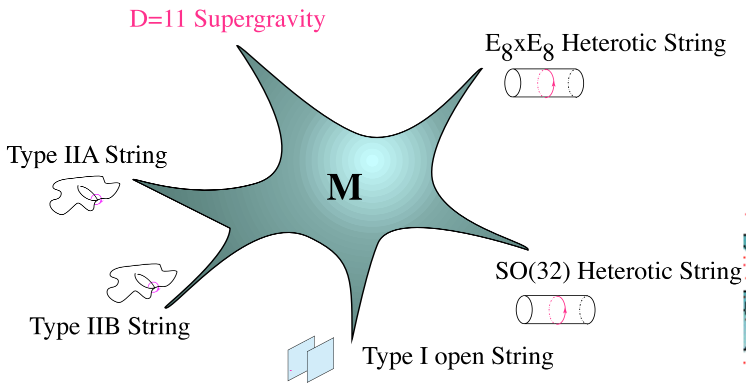
- "Theoretical experiments" pass all conceivable **consistency tests**, including highly non-trivial ones such as precision counts of micro states in black holes.

- There cannot be any doubt that the theory "works" but to what extent it applies to nature is another question.

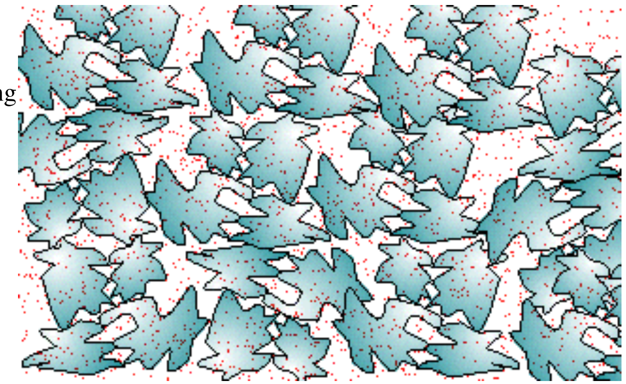
….still in search for a realistic application!

So…what, finally, is String Theory? II

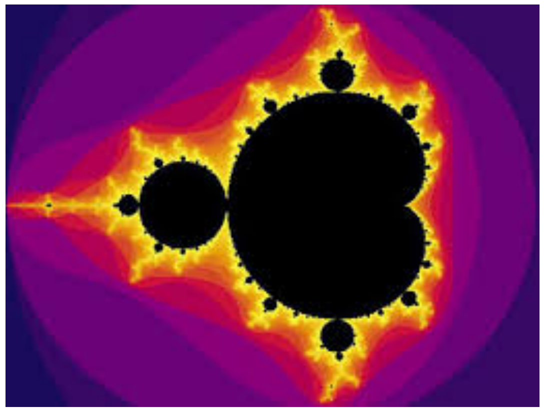
- Perhaps strings should simply be viewed as a preferred choice of “coordinates” on the **set of all consistent quantum theories** that include gravity, relevant at least in certain regions.



N=8,4 SUSY, 10/11dim



N=2,1 SUSY 4dim



N=0 SUSY?