String Theory

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Linear Collider Workshop
Amsterdam, April 4, 2003

Two successful theories:

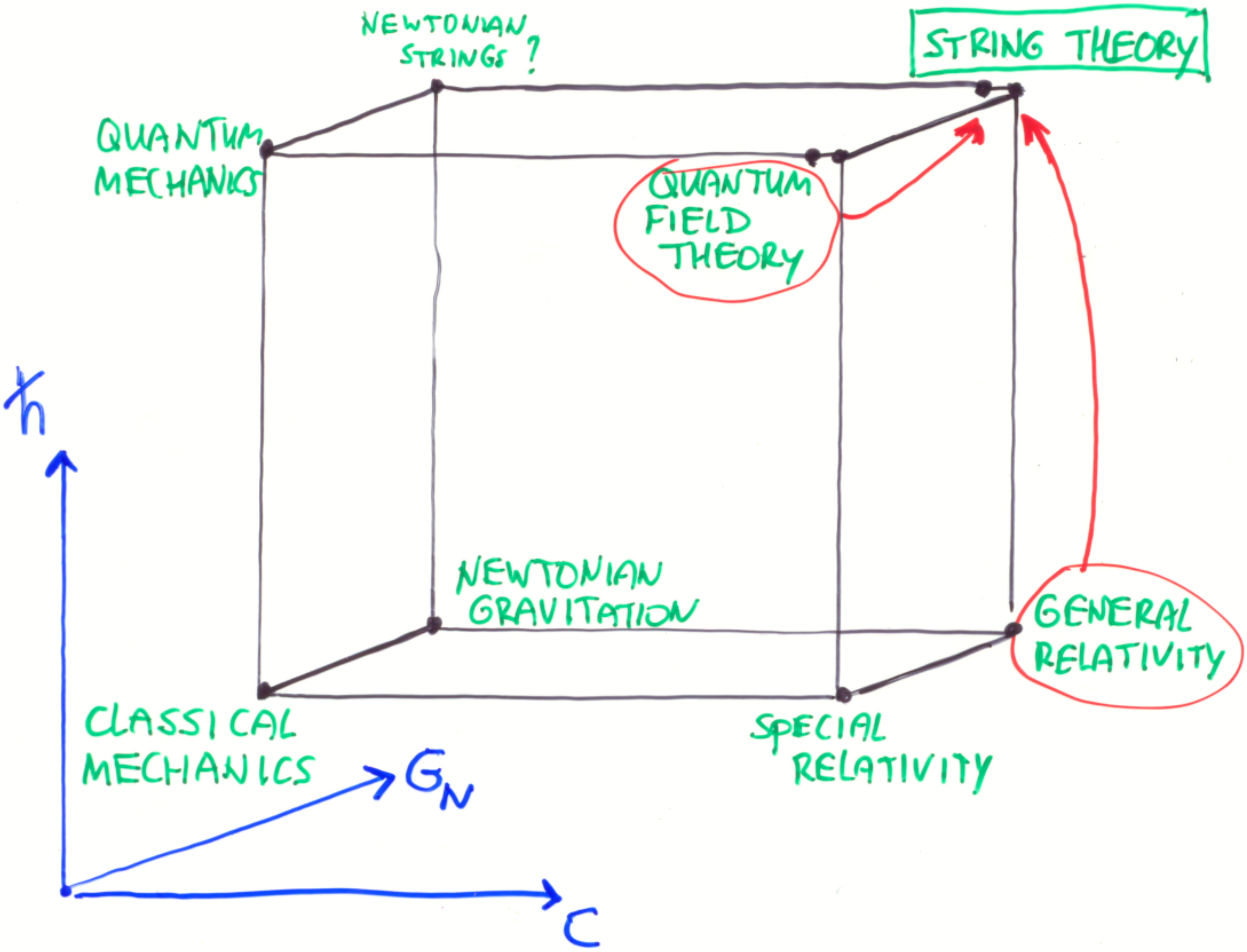
- standard model (strong and weak nuclear forces, electromagnetism)

- general relativity (gravitational forces)

These separate theories cannot, even in principle, describe processes at very high energies $\Rightarrow$ need new theory unifying standard model and general relativity. Only known consistent candidate is

superstring theory

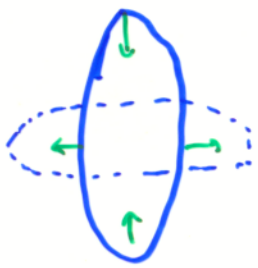
Existence and consistency of such a theory will hopefully constrain the parameters in the standard model, and help explain the origin of the universe, physics of black holes, physics beyond the standard model, etc.



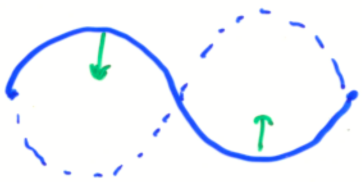
THE THEORY CUBE

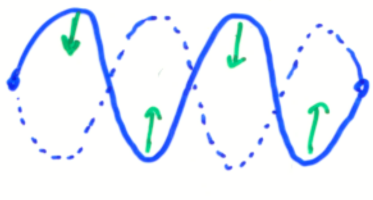
STRINGS

CLOSED

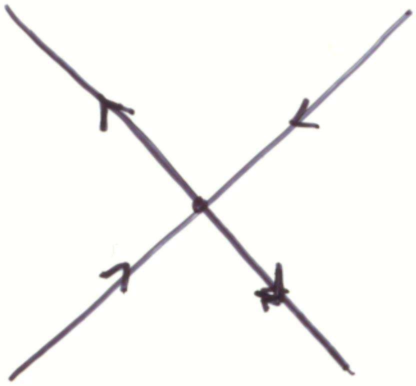


OPEN





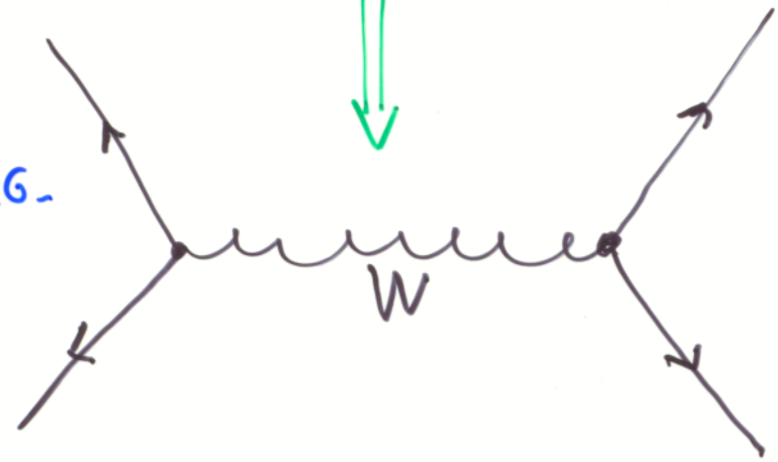
4-FERMI THEORY



4-LEPTON PROCESS

NONRENORMALIZABLE

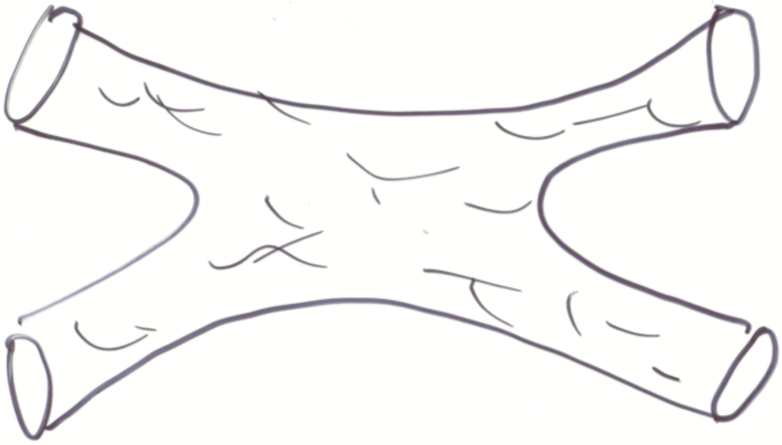
WEINBERG-SALAM THEORY



RENORMALIZABLE

~~GRAVITY~~

STRING THEORY



RENORMALIZABLE

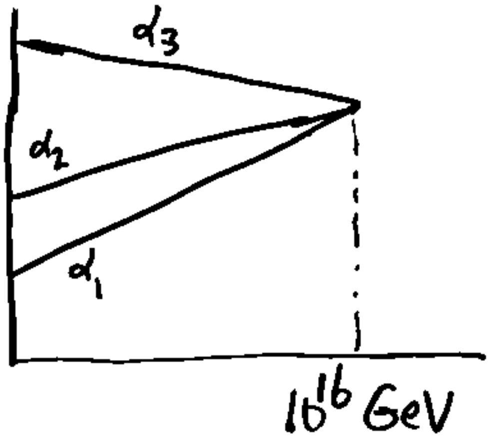
GRAVITY = FINITE

String theory makes three generic predictions (various ifs and buts)

- gauge theory (like standard model)
- general relativity
- supersymmetry

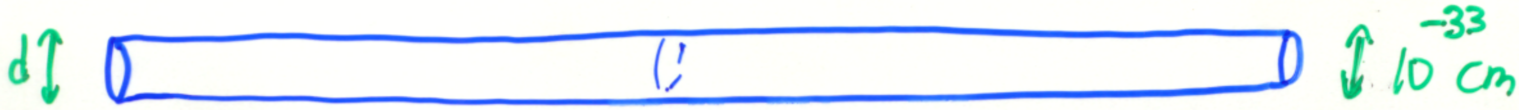
Supersymmetry has not yet been observed in nature (maybe at LHC?). But there are some indications

- gauge coupling unification
- fine tuning problems



Superstrings live in 10 dimensions. We (apparently) in four. ⇒ need for **compactification**.

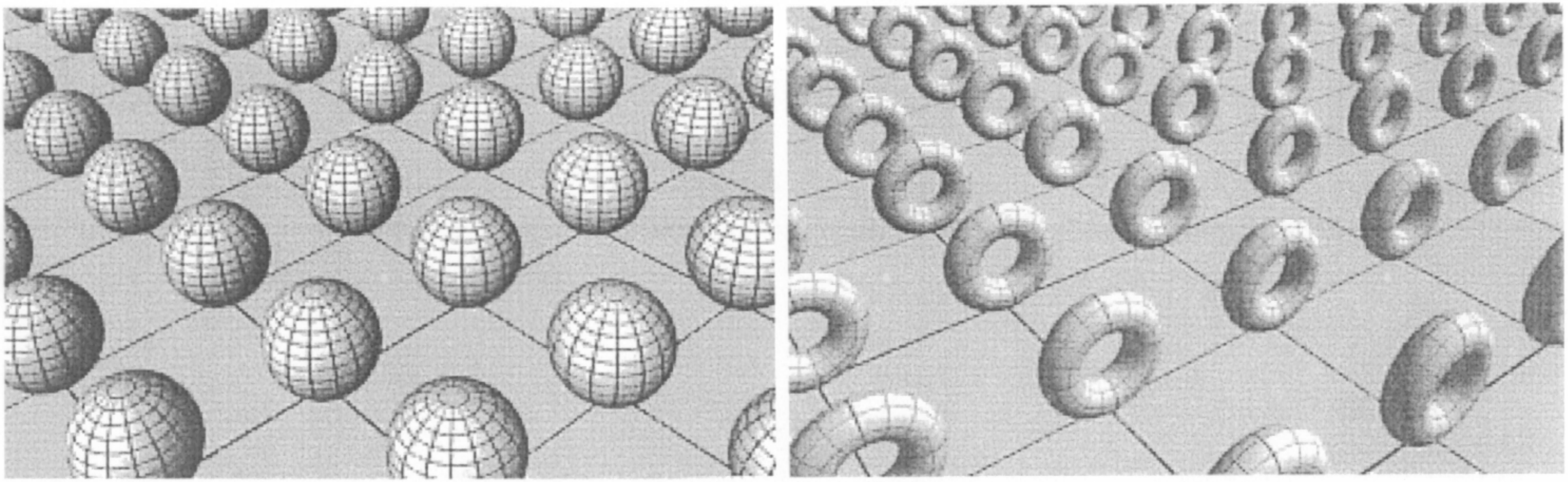
Traditional point of view:



At length scales much larger than d the tube looks like a one-dimensional object

Get reasonable models by compactifying on six-dimensional Calabi-Yau spaces. Problems:

- too many free parameters - recent progress
- difficult to compute things
- how is supersymmetry broken?
- why is the cosmological constant so small?



UNDER A HUGE MICROSCOPE

WHAT DOES SPACE LOOK LIKE ???

Do not yet understand string theory well enough $\Rightarrow$ a lot of effort has been directed at improving the conceptual understanding of string theory.

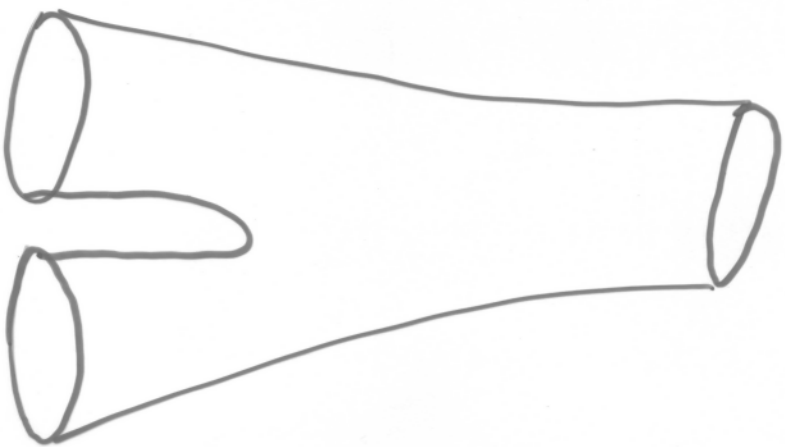
Quantities in string theory are given by an expansion in g_s, the string coupling constant.

$$A = a_0 + a_1 g_s + a_2 g_s^2 + \dots$$

Good for small g_s, but not for large g_s. Also, there are

- non-perturbative effects $\sim e^{-\frac{1}{g_s^2}}$.

Non-perturbative effects are due to **solitons**, certain extended objects.



SPLITTING/JOINING COUPLING: g_s

An example of a soliton is a **monopole**.

Maxwell equations:

$$\vec{\nabla} \cdot \vec{E} = ne \quad \vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$
$$\vec{\nabla} \cdot \vec{B} = m/e \quad \vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = 0$$

Equations have a symmetry $\vec{E} \to \vec{B}, \vec{B} \to -\vec{E}, n \to m, m \to -n, e \to 1/e$. Maxwell theory does not have magnetic monopoles, but if it did, there would be a symmetry

electric charge	$\Longleftrightarrow$	magnetic charge
electric field	$\Longleftrightarrow$	magnetic field
weak coupling	$\Longleftrightarrow$	strong coupling
particle	$\Longleftrightarrow$	soliton

Such symmetries exist in other cases and are called **Dualities**.

For example

for small g_s one has

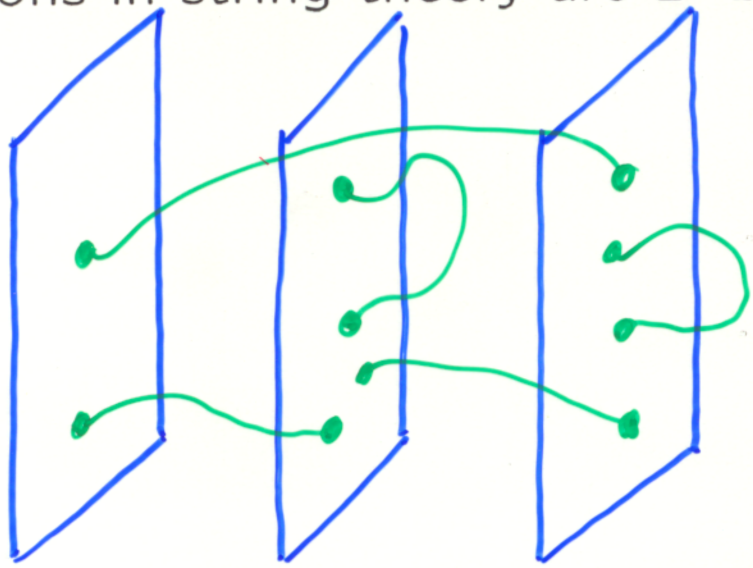
$$\frac{g_s}{g_s + 1} = g_s - g_s^2 + g_s^3 + \dots$$

for large g_s on the other hand

$$\frac{g_s}{g_s + 1} = \frac{1}{1 + g_s^{-1}} = 1 - g_s^{-1} + g_s^{-2} + \dots$$

Two different weak coupling expansions of the same quantity.

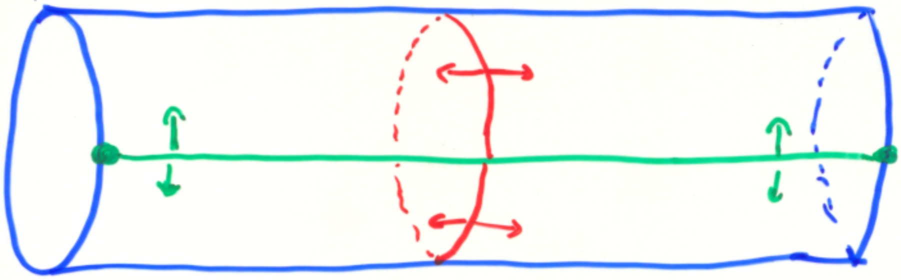
Solitons in string theory are **D-branes**.



A D-brane is a dynamical extended object on which strings can end. A Dp-brane is an object which is p-dimensional. Thus, a D0-brane is a particle, a D1-brane is a string, a D2-brane is a membrane, etc.

Many dualities between string theories have been discovered, in which D-branes play an essential role. Many interesting applications in physics and mathematics.

Duality between open and closed strings:



We can think of a cylinder in two ways: as an open string going around a loop, or as a closed string moving a finite distance.

This gives rise to dualities between theories with open strings and theories with closed strings.

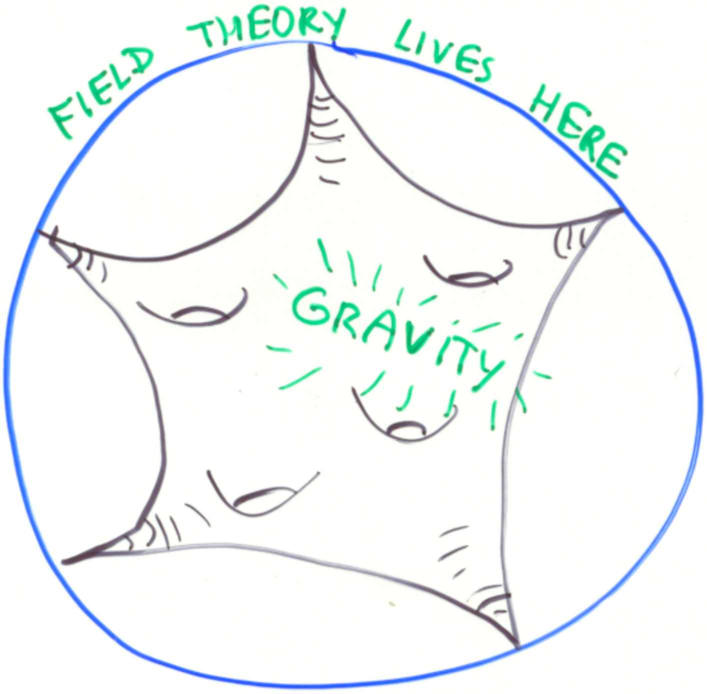
Now

open strings $\Longleftrightarrow$ gauge fields

closed strings $\Longleftrightarrow$ gravity

The duality between open and closed strings gives rise to a duality between theories with gravity and theories without gravity. Example: AdS/CFT correspondence (Maldacena).

Strongly coupled gauge theories are mapped into weakly coupled field theories: use gravity to learn about gauge theory!



General problem: extra states at Λ_{QCD}.

Several important results:

- concrete precise example of holography
- give, for the first time, a microscopic derivation of the entropy of certain black holes (Strominger, Vafa)
- get a new qualitative picture for the confinement-deconfinement transition in gauge theory (Witten)
- compute ratios of glueball masses (Csaki et al)
- get a qualitative picture of deep-inelastic scattering (Polchinksi, Strassler)
- see in examples confinement and chiral symmetry breaking (Klebanov, Strassler)
- inspiration for Randall-Sundrum models

String theory and cosmology

Recent cosmological observations: $\Omega_\Lambda \sim 0.7$ (WMAP data).

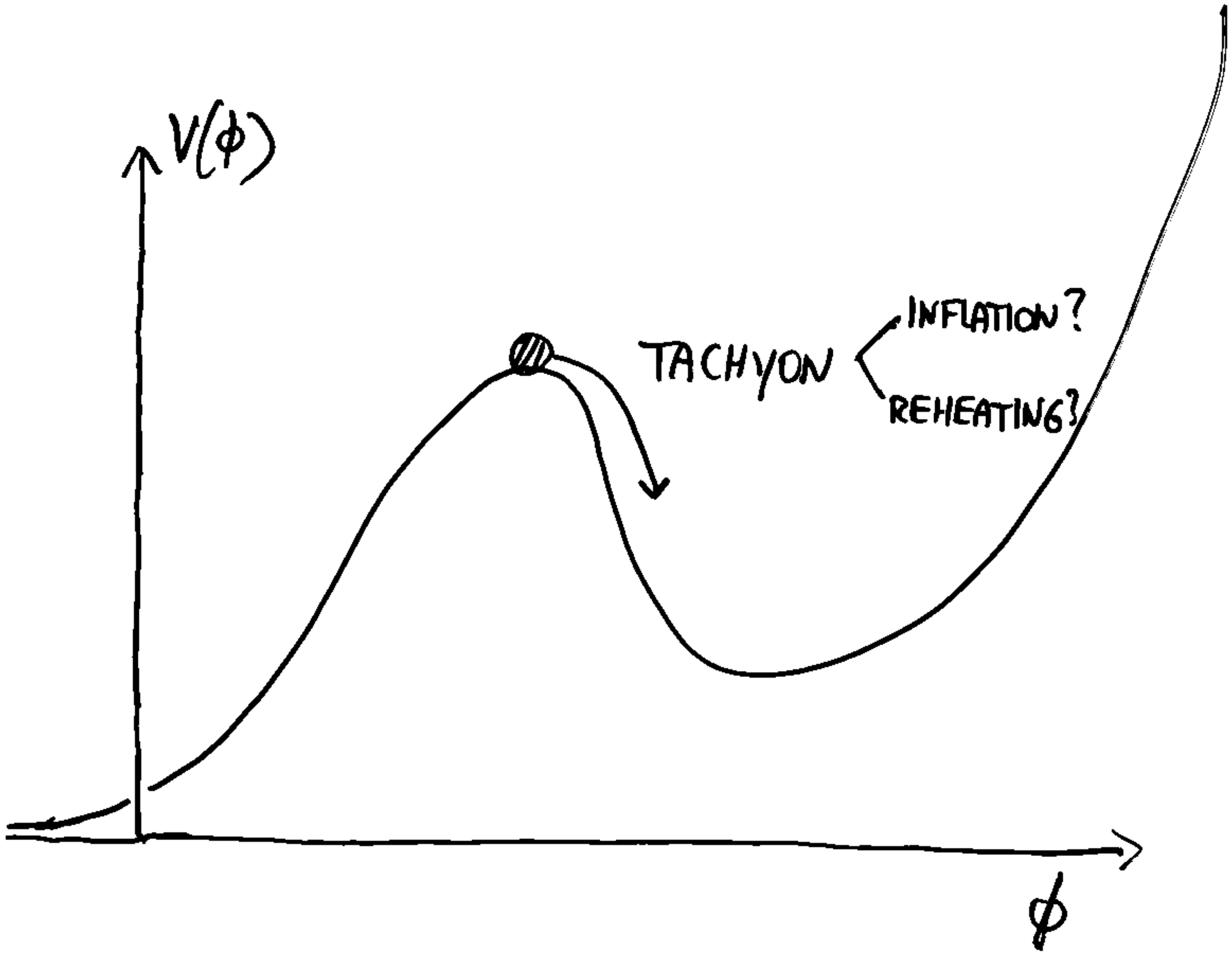
The universe expands at an accelerating rate. Local geometry is that of de Sitter space.

Remarkably difficult to get realistic time-depender geometries in string theory, especially with $\Lambda > 0$.

One reason: positive Λ is not compatible with supersymmetry.

Besides this, there are many conceptual questions that remain unanswered. String theory signatures in cosmology?

Has also triggered a renewed interest in tachyons in string theory.



V(ϕ)
TACHYON
INFLATION?
REHEATING?
ϕ

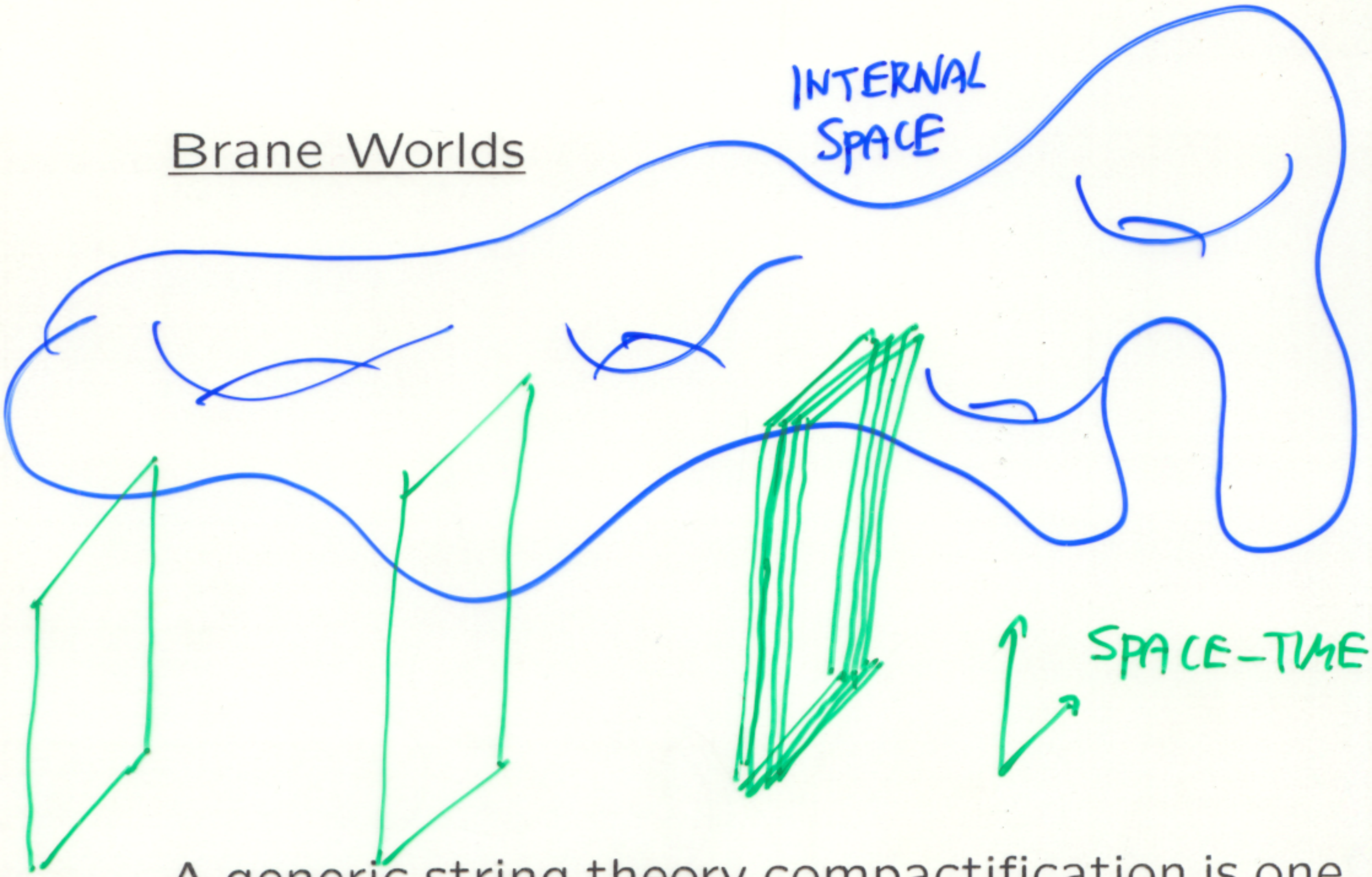
String theory at linear colliders?

$\Longrightarrow$ Discovery of supersymmetric particles.

To really make any comparison to string theory, need structure of the action and interactions that describe the supersymmetric extension of the standard model.

$\Longrightarrow$ Precision measurements such as those of a linear collider are crucial.

Brane Worlds

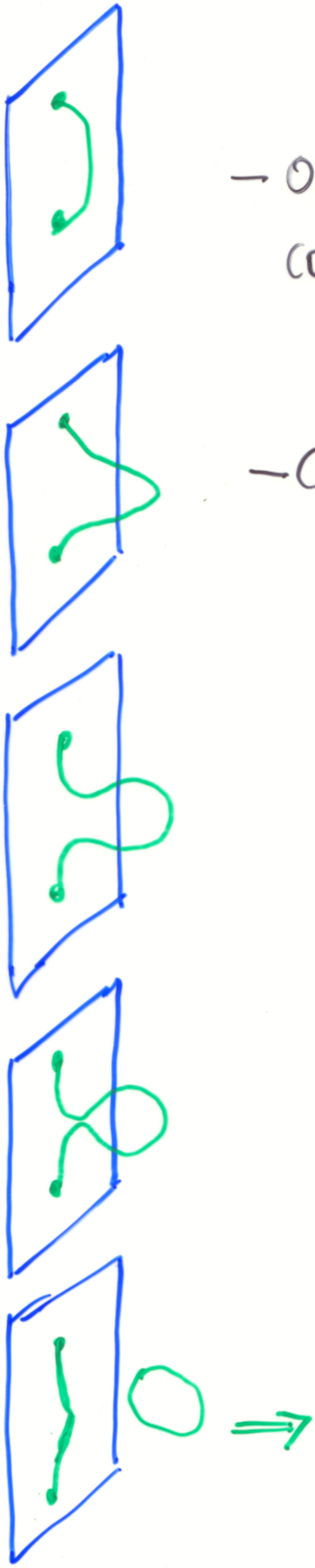


A generic string theory compactification is one that involves branes!

Weakly coupled brane $\equiv$ strongly coupled gravity.

Open strings (standard model fields) are confined to branes, gravity is not.

$\Rightarrow$ We live on a brane ??



— OPEN STRING IS CONFINED TO THE BRANE

— CLOSED STRINGS ARE NOT

features of brane worlds

- provide interesting playgrounds for cosmology (ekpyrosis,...)
- branes appear generically in string theory
- it is very difficult to find stable brane worlds in string theory: tensions and interbrane potentials are determined by string theory and cannot be chosen at will
- supersymmetry breaking?? gauge coupling unification??

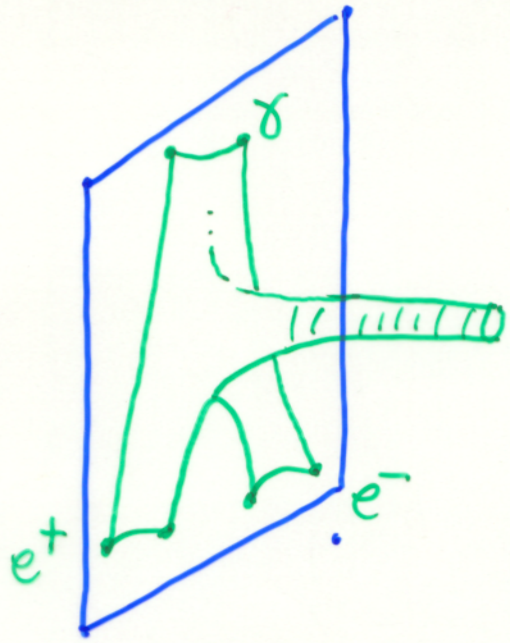
Part of excitement: transverse dimensions can be large due to poor testing of Newton's law. Can be up to $0.2mm$. Higher dimensional Planck mass can be of order ~ 1 TeV!!

Higher dimensional gravity accessible to experiments!

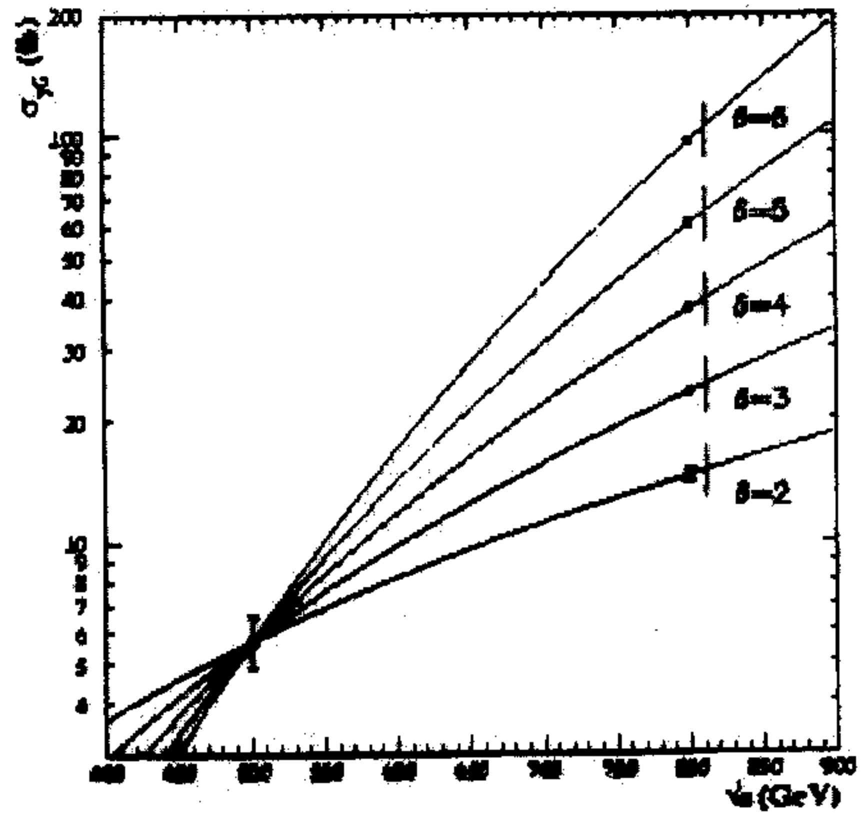
Notice that more stringent (model dependent) bounds on higher dimensional Planck mass come from

- supernova cooling
- neutron star heating
- diffuse γ-ray backgrounds

signature: missing energy



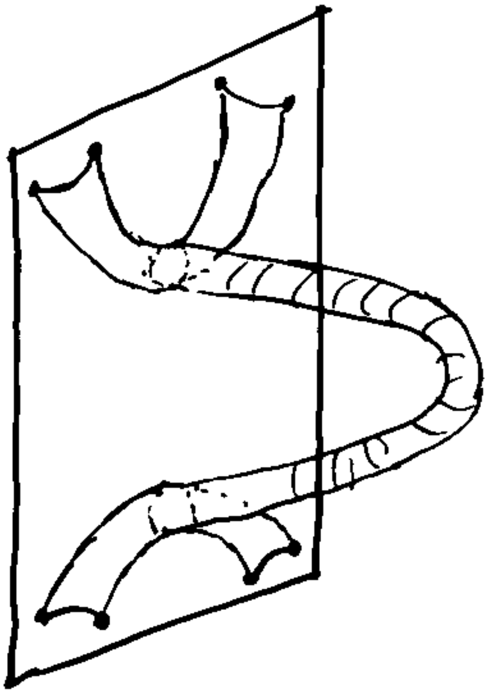
- events with one or two jets
- can measure spin
- can measure angular distribution
- can distinguish from other channels (like gravitino emission)
- can perhaps measure the number of extra dimensions



G. Wilson

LC-PHSM-2001-010

signature: intermediate gravity channels



- see resonances corresponding to spin two particles

- difficult to sum over intermediate states: divergent. Need high-energy completion.

exotic: intermediate black holes

- precise rate still matter of debate, up to one black hole per second (LHC)

- no disaster, black hole Hawking evaporates immediately

- distinct signatures - even test quantum gravity directly?

Exciting times ahead!