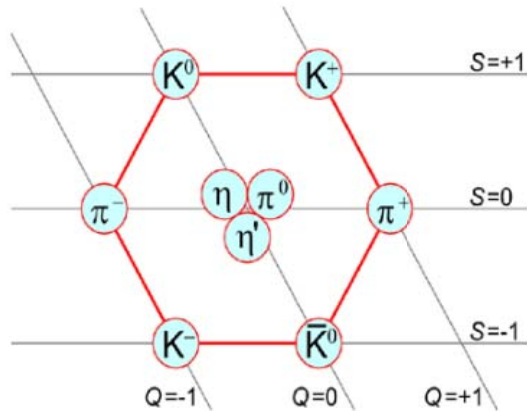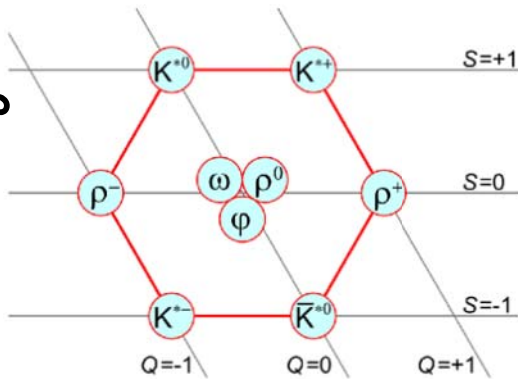# String Theory

Before
   quarks established
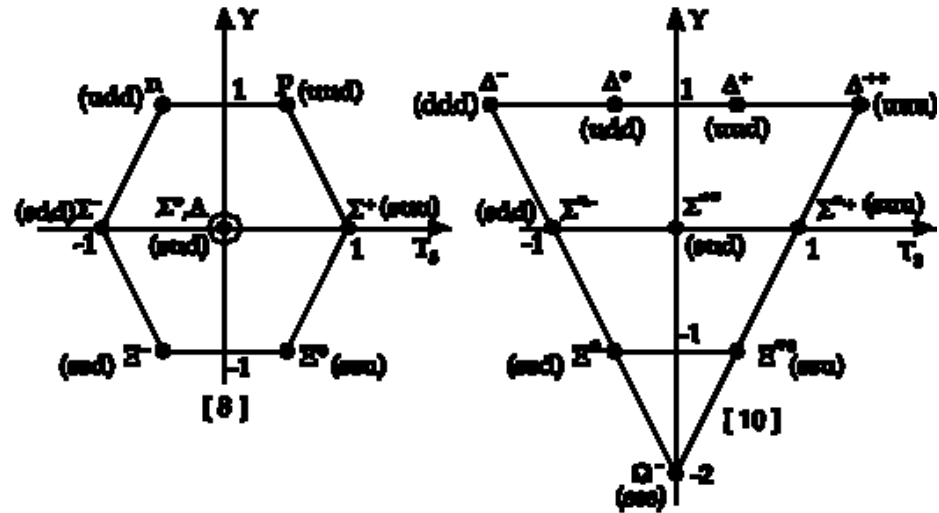Before QCD

Spin 0 Mesons



Spin 1 Mesons

Baryons

| Particle | Rest mass MeV | Average lifetime s | Most frequent type of decay % | |
|---|---|---|---|---|
| **Photon** | | | | |
| $\gamma$ | $0\ (< 2\cdot10^{-22})$ | stable | stable | |
| **Leptons** | | | | |
| $\nu_e$ | $0\ (< 3\cdot10^{-9})$ | stable | stable | |
| $\nu_\mu$ | $0\ (< 0.19)$ | stable | stable | |
| $\nu_\tau$ | $0\ (< 18.2)$ | stable | stable | |
| $e$ | $0.510999890$ | stable $(> 4.2\cdot10^{24}\ a)$ | stable | |
| $\mu$ | $105.658357$ | $2.19703\cdot10^{-6}$ | $e^- \bar{\nu}_e \nu_\mu$ | $98.6$ |
| | | | $e^- \bar{\nu}_e \nu_\mu \gamma$ | $1.4$ |
| $\tau$ | $1777.03$ | $2.906\cdot10^{-13}$ | $e^- \bar{\nu}_e \nu_\tau$ | $17.83$ |
| | | | $\mu^- \bar{\nu}_\mu \nu_\tau$ | $17.37$ |
| **Mesons** | | | | |
| $\pi^0$ | $134.9766$ | $8.4\cdot10^{-17}$ | $\gamma\gamma$ | $98.8$ |
| | | | $\gamma e^+ e^-$ | $1.2$ |
| $\pi^\pm$ | $139.57018$ | $2.6033\cdot10^{-8}$ | (for $\pi^+$) | |
| | | | $\mu^+ \nu_\mu$ | $99.98$ |
| | | | $e^+ \nu_e$ | $0.01$ |
| | | | $\mu^+ \nu_\mu \gamma$ | $0.01$ |
| $\eta$ | $547.305$ | | $\gamma\gamma$ | $389.3$ |
| | | | $\pi^0 \pi^0 \pi^0$ | $312.2$ |
| | | | $\pi^+ \pi^- \pi^0$ | $23.0$ |
| | | | $\pi^+ \pi^- \gamma$ | $4.9$ |
| $K^\pm$ | $493.677$ | $1.2386\cdot10^{-8}$ | (for $K^+$) | |
| | | | $\mu^+ \nu_\mu$ | $63.51$ |
| | | | $\pi^+ \pi^0$ | $21.16$ |
| | | | $\pi^+ \pi^+ \pi^-$ | $5.59$ |
| | | | $e^+ \nu_e \pi^0$ | $4.82$ |
| | | | $\mu^+ \nu_\mu \pi^0$ | $3.18$ |
| | | | $\pi^+ \pi^0 \pi^0$ | $1.73$ |
| $K^0$ | $497.672$ | $K_S\ \ 8.935\cdot10^{-11}$ | $\pi^+ \pi^-$ | $68.61$ |
| | | | $\pi^0 \pi^0$ | $31.39$ |
| | | $K_L\ \ 5.17\cdot10^{-8}$ | $\pi^\pm e^\mp \nu_e$ | $38.78$ |
| | | | $\pi^\pm \mu^\mp \nu_\mu$ | $27.18$ |
| | | | $\pi^0 \pi^0 \pi^0$ | $21.13$ |
| | | | $\pi^+ \pi^- \pi^0$ | $12.55$ |
| | | | $\pi^\pm e^\mp \nu_e \gamma$ | $0.36$ |
| $D^0$ | $1864.6$ | $0.4126\cdot10^{-12}$ | | |
| $D_s^\pm$ | $1968.6$ | $0.496\cdot10^{-12}$ | | |
| $D^\pm$ | $1869.3$ | $1.051\cdot10^{-12}$ | | |
| $B^\pm$ | $5279.0$ | $1.653\cdot10^{-12}$ | | |
| $B^0$ | $5279.4$ | $1.548\cdot10^{-12}$ | | |
| $B_s^0$ | $5369.6$ | $1.493\cdot10^{-12}$ | | |
| **Baryons** | | | | |
| $p$ | $938.27200$ | stable $(> 1.6\ 10^{25}\ a)$ | stable | |
| $n$ | $939.56533$ | $886.7$ | $p\, e^- \bar{\nu}_e$ | $100$ |
| $\Lambda^0$ | $1115.683$ | $2.632\cdot10^{-10}$ | $p\, \pi^-$ | $63.9$ |
| | | | $n\, \pi^0$ | $35.8$ |
| $\Sigma^+$ | $1189.37$ | $8.018\cdot10^{-11}$ | $p\, \pi^0$ | $51.6$ |
| | | | $n\, \pi^+$ | $48.3$ |
| $\Sigma^0$ | $1192.642$ | $7.4\cdot10^{-20}$ | $\Lambda^0 \gamma$ | $100$ |
| $\Sigma^-$ | $1197.449$ | $1.479\cdot10^{-10}$ | $n\, \pi^-$ | $99.9$ |
| $\Xi^0$ | $1314.83$ | $2.90\cdot10^{-10}$ | $\Lambda^0 \pi^0$ | $99.5$ |
| $\Xi^-$ | $1321.31$ | $1.639\cdot10^{-10}$ | $\Lambda^0 \pi^-$ | $99.9$ |
| $\Omega^-$ | $1672.45$ | $8.21\cdot10^{-11}$ | $\Lambda^0 K^-$ | $67.8$ |
| | | | $\Xi^0 \pi^-$ | $23.6$ |
| | | | $\Xi^- \pi^0$ | $8.6$ |

# why Strings ?

Try to understand what is structure of Mesons + barons

Hadrons

Point particles give troubles



$$F \sim \frac{1}{r^2} \Rightarrow \infty$$
as
$r \to 0$

Leonard Susskind



Stanford Univ.

Discovered that
excitations of relativistic
strings have a
correspondance to
particle states



Also publ. recently controv. work about future affecting LHC
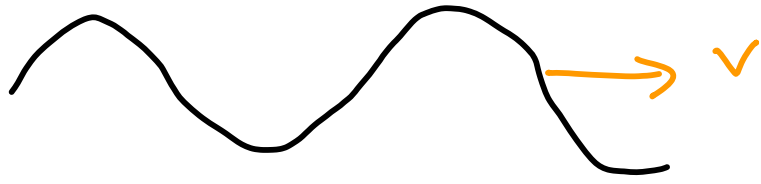
Holger Bech Nielsen

Niels Bohr Inst.



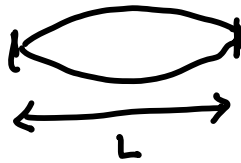2008 Nobel Prize in physics

Yoichiro Nambu

Univ. of Chicago

$$y = A \sin(kx \pm \omega t)$$

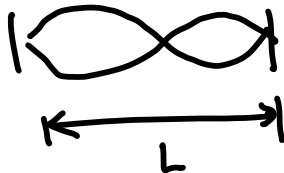Standing waves: non-relativistic string w/ fixed ends
Length L

Music

0 nodes
$$L = \frac{1}{2}\lambda$$

$$v = \lambda \nu$$

$$\lambda = \frac{v}{\nu}$$

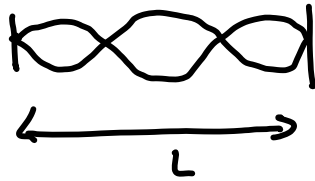$$L = \frac{1}{2}\frac{v}{\nu} \rightsquigarrow \nu = \frac{1}{2}\frac{v}{L}$$

1 node
$$L = \lambda$$

$$L = \frac{v}{\nu}$$

$$\nu = \frac{2}{2}\frac{v}{L}$$

Illustration of how quantized states can come from strings (NOT for you to do on a TEST)

2 nodes

$$L = \frac{3\lambda}{2} \qquad \nu = \frac{3}{2}\frac{V}{L}$$

$$L = \frac{3}{2}\frac{V}{\nu}$$

$\vdots$

$$\boxed{\nu_n = \frac{n}{2}\frac{V}{L}}$$ frequencies that will resonate on string of length L

$n = 1, 2, 3 \ldots$

$V \equiv$ velocity of wave propagation
Depends on string tension
and mass/length

60's , early 70's
Susskind, Nielsen, Nambu independently discovered that
the mathematical Description of relativistic
String vibrations/rotATions

is similar to that for particles
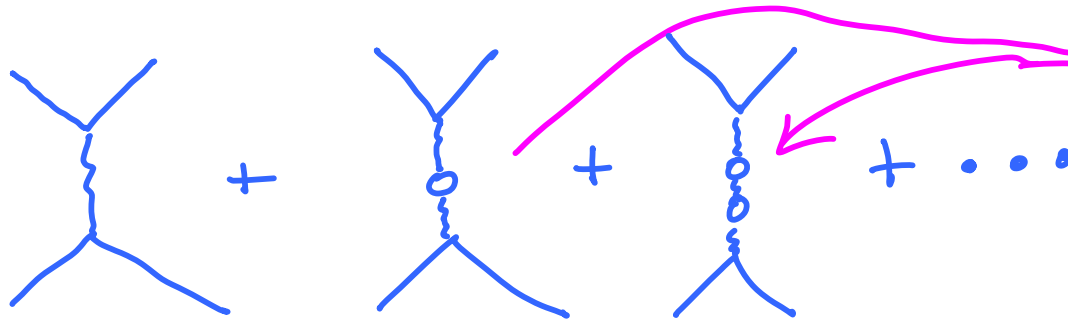with different masses/spins in
quantum field theory

Birth of String theory

# Quantum Mechanics + Gravitation → quantum gravity

Add "graviton" to quantum field theory

Ad hoc Addition (NOT Natural)

two interacting particles (Feynman diagrams)



+    +    + ...

quantum loops of virtual particles
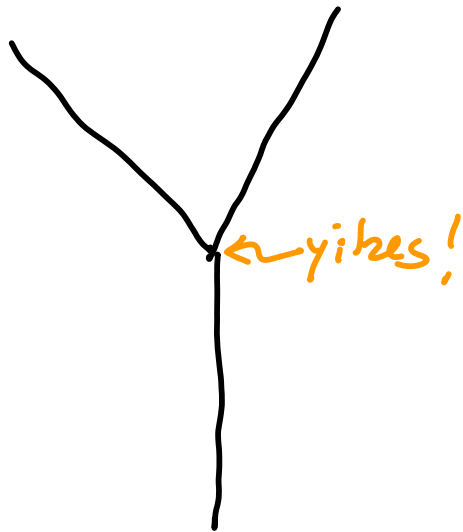
MUST sum over all possibilities at all momenta

graviton at ∞ momentum
  ↳ zero distance

→ Causes calculation to misbehave badly

# Quantum Gravity + String Theory

massless Spin 2 graviton state
unavoidable + Natural in String theory

Short distance behavior problem goes Away

←~yikes!

and well-behaved

Quantum Gravity is natural ∧ in String theory

String theory
Bosons only
   mis behaves
   (ghost particles)
unless done in
26 dimensions Mathematically

Not like the real world

String theory
Bosons + Fermions
   mis behaves
   (ghost particles)
unless done in
10 dimensions Mathematically
   plus
Supersymmetry

like real world ?
   Maybe

Supersymmetry

$$\psi(x_1, x_2) \rightarrow \frac{+}{5} \psi(x_2, x_1)$$

Bosons

Fermions

Supersymmetric matter

normal matter

Spin ½ electron          $\longrightarrow$   Selectron   spin 0
Spin 1 photon            $\longrightarrow$   photino     Spin ½
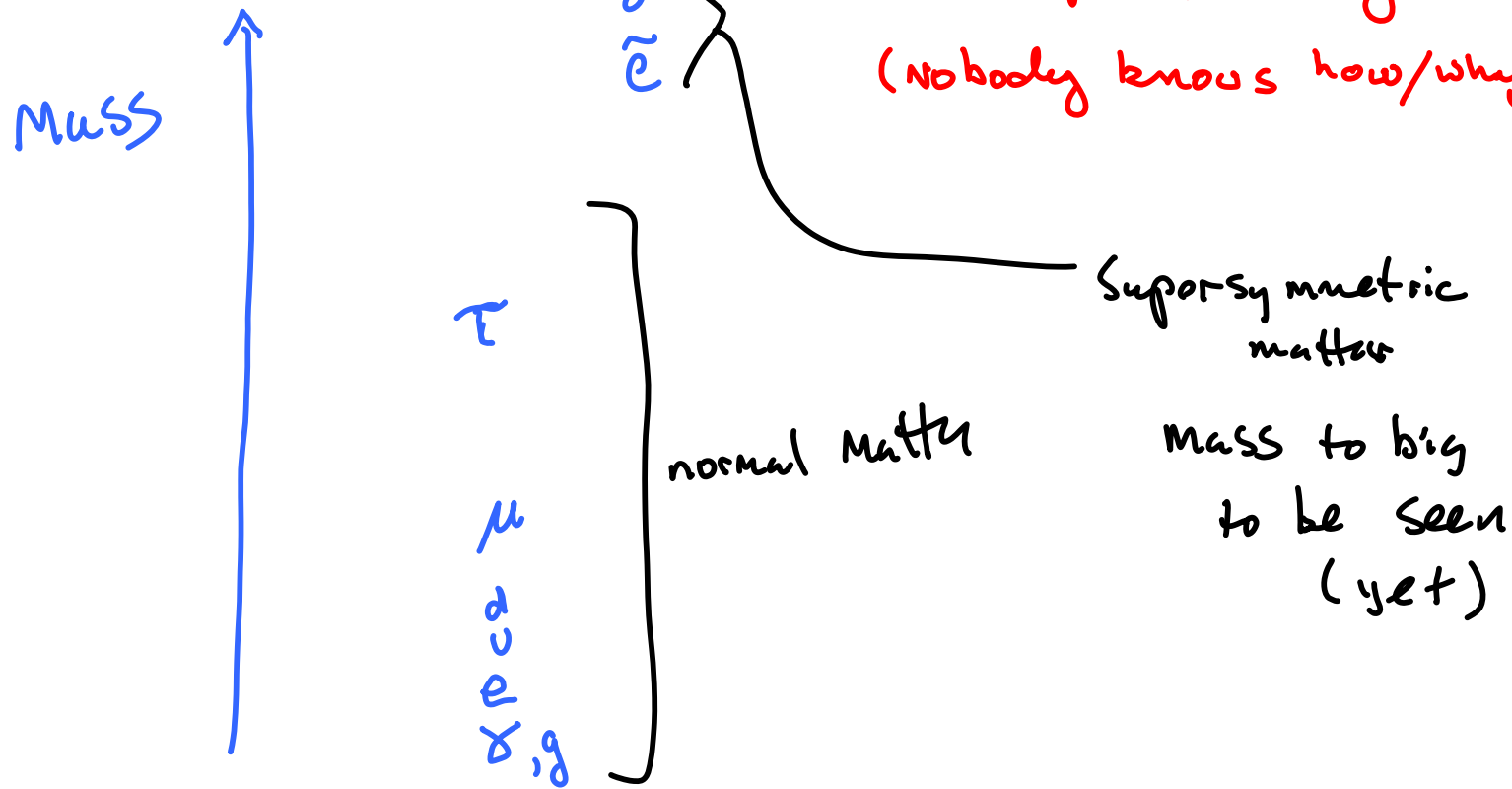
Super symmetry predicts doubling of
particle spectrum

↳ NOT observed

↳ Supersymmetry broken

(Nobody knows how/why yet)

$\tilde{\gamma}$
$\tilde{e}$

Mass ↑

$\tau$

$\mu$

$d$

$u$

$e$

$\gamma, g$

normal Matter

Supersymmetric
matter

Mass to big
to be seen
(yet)

# Extra Dimensions

general Relativity

Einstein 1915
Gemetrical Theory
4 dimensions

Theodor
Kaluza

(German 1885-1954)



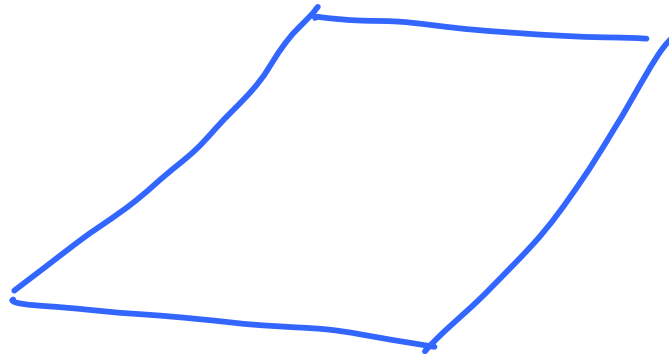Can unify fundamental
forces using
extra
Dimensions

1919-1921    Showed that if you solve
Einsteins GR equations in 5-d
get Electromagnetism
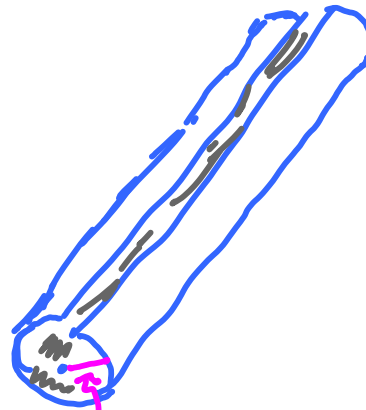+
Gravitation    !

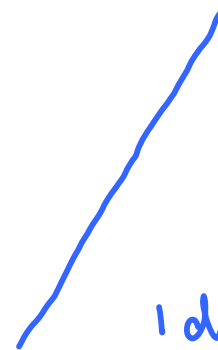# where is this extra dimension?



Oskar Klein
(1894 - 1977)

1926 $\longrightarrow$ Compactification



2d



3d

$R$



1d

Let $R \to$ small

# Superstring Theory in Mid-80's

5 consistent theories known
    hoped <u>one</u> might prove to be the

## Theory of Everything
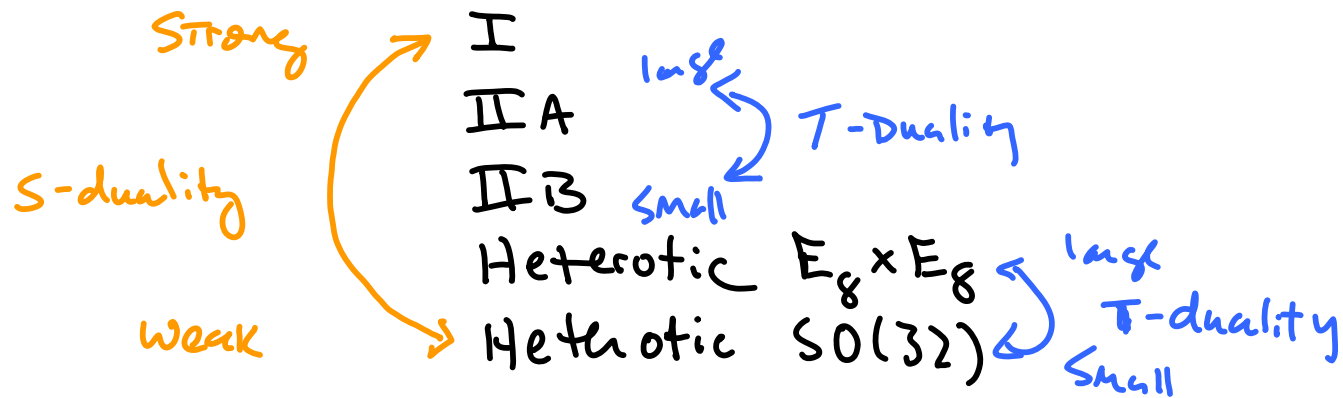
I
II A
II B
Heterotic $E_8 \times E_8$
Heterotic $SO(32)$

Duality discovered – Deep relationships
among the 5 theories

Strong

I

II A    long $\Bigg\}$ T-Duality

S-duality

II B   Small

Heterotic $E_8 \times E_8$   long $\Bigg\}$ T-duality

Weak

Heterotic SO(32)   Small

1995 – All 5 Superstring theories in 10-d
come from single 11-d Theory
M-Theory

Inst. for Advance Study (Princeton)

Edward Witten
(1951 –  )

is This
the
T.O.E.?

# Other structures in String theory

## P-Branes

| | |
|---|---|
| 0-Brane | Point |
| 1-Brane | String |
| 2-Brane | Membrane |
| 3-Brane | |
| ⋮ | |
| 9-Bran | |

D-Brane    (Dai, Leigh Polchinski   + indep by Horava)
                              1989

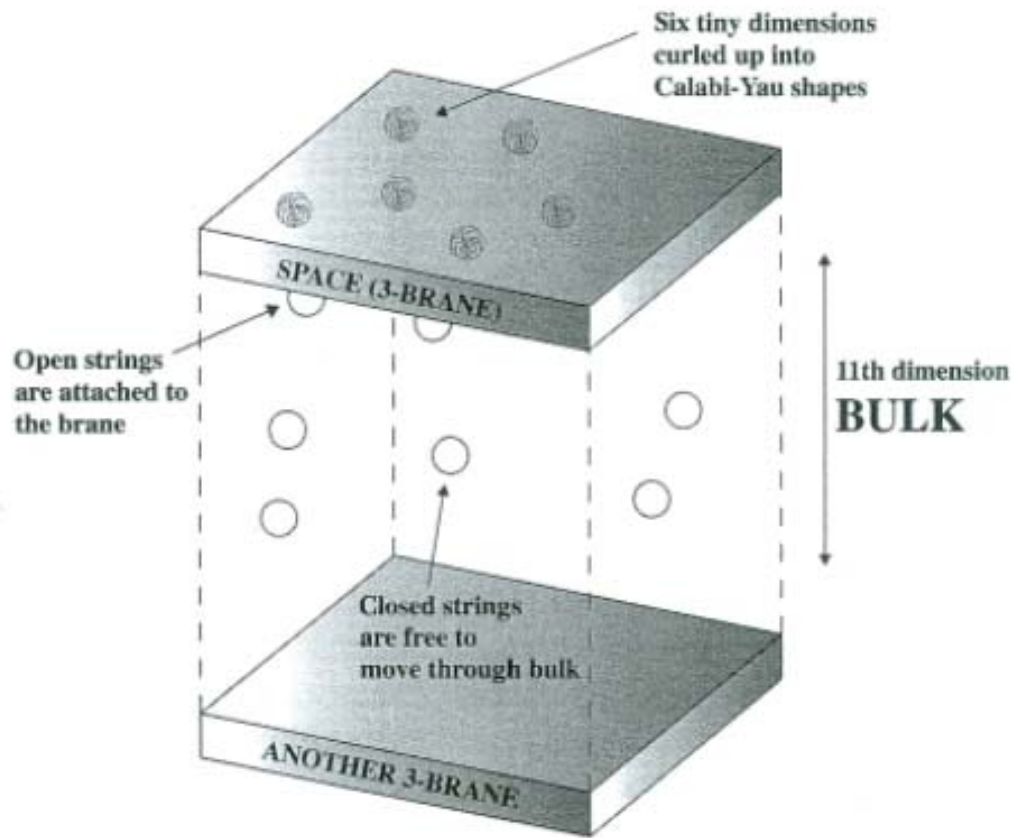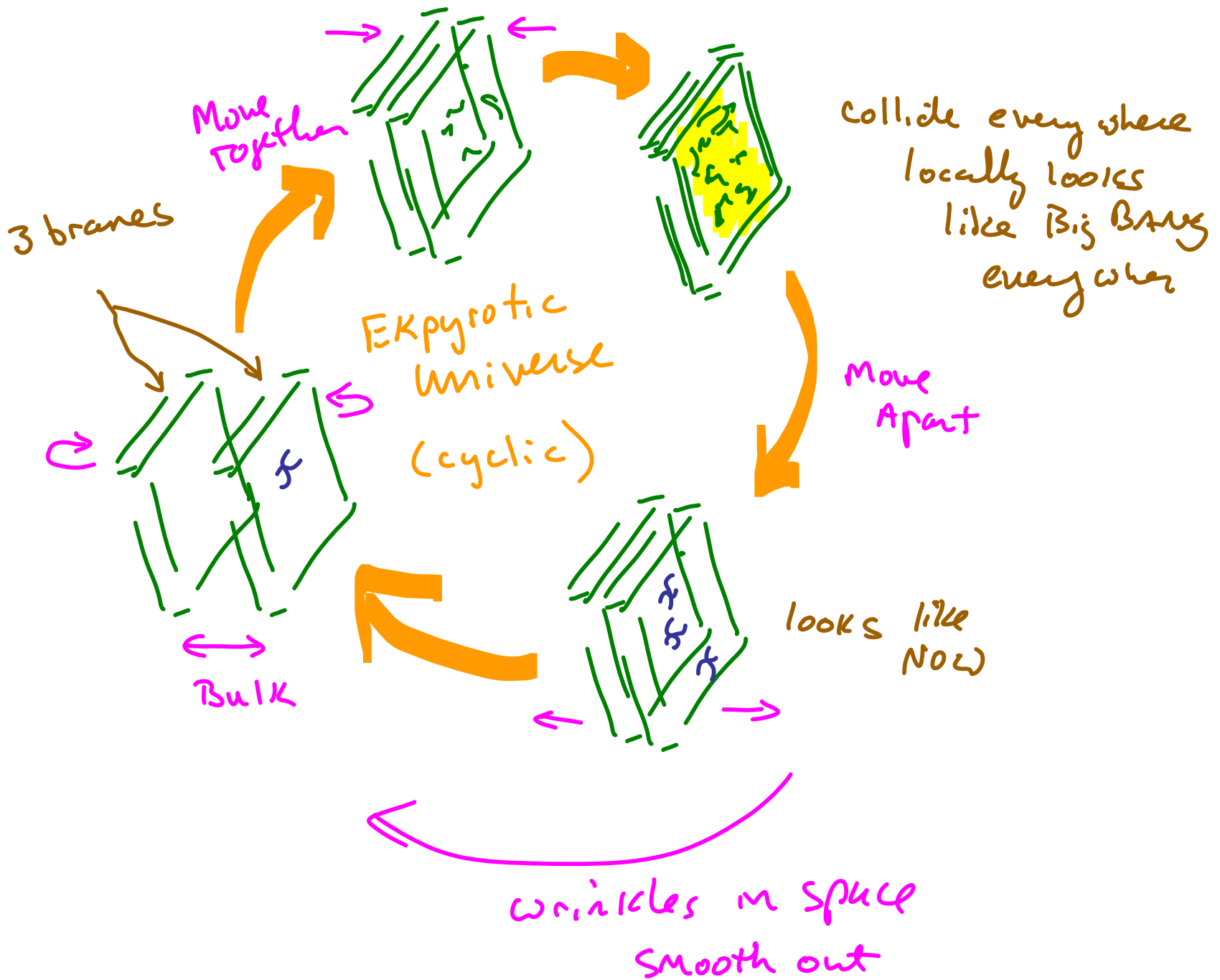P-Brane where on end of an open string
        is attached.

Six tiny dimensions curled up into Calabi-Yau shapes

SPACE (3-BRANE)

Open strings are attached to the brane

11th dimension
**BULK**

Closed strings are free to move through bulk

ANOTHER 3-BRANE

image from  http://abyss.uoregon.edu/~js/qc/qc.html

# Ekpyrotic multiverse  (cyclic Brane collisions)

Move
Together

3 branes

Ekpyrotic
Universe

(cyclic)

Bulk

Collide everywhere
locally looks
like Big Bang
everywhere

Move
Apart

looks like
Now

wrinkles in space
smooth out

# The Cosmic Landscape

In String Theory —
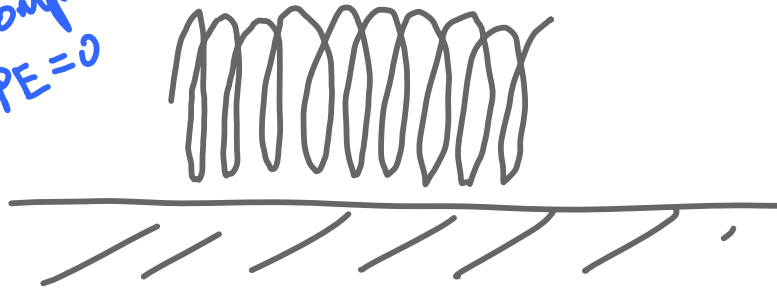
Laws of Physics
Particle Spectrum
Nature of forces
} dictated by

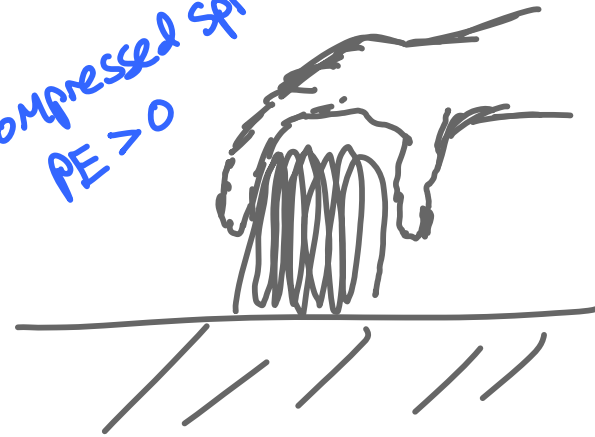Shades of the Ancient Greeks!

geometry

Shape + size of
Extra dimensions

Depends on details of the Compactification

Vacuum "potential energy" depends on
the details of the configuration of
the different dimensions
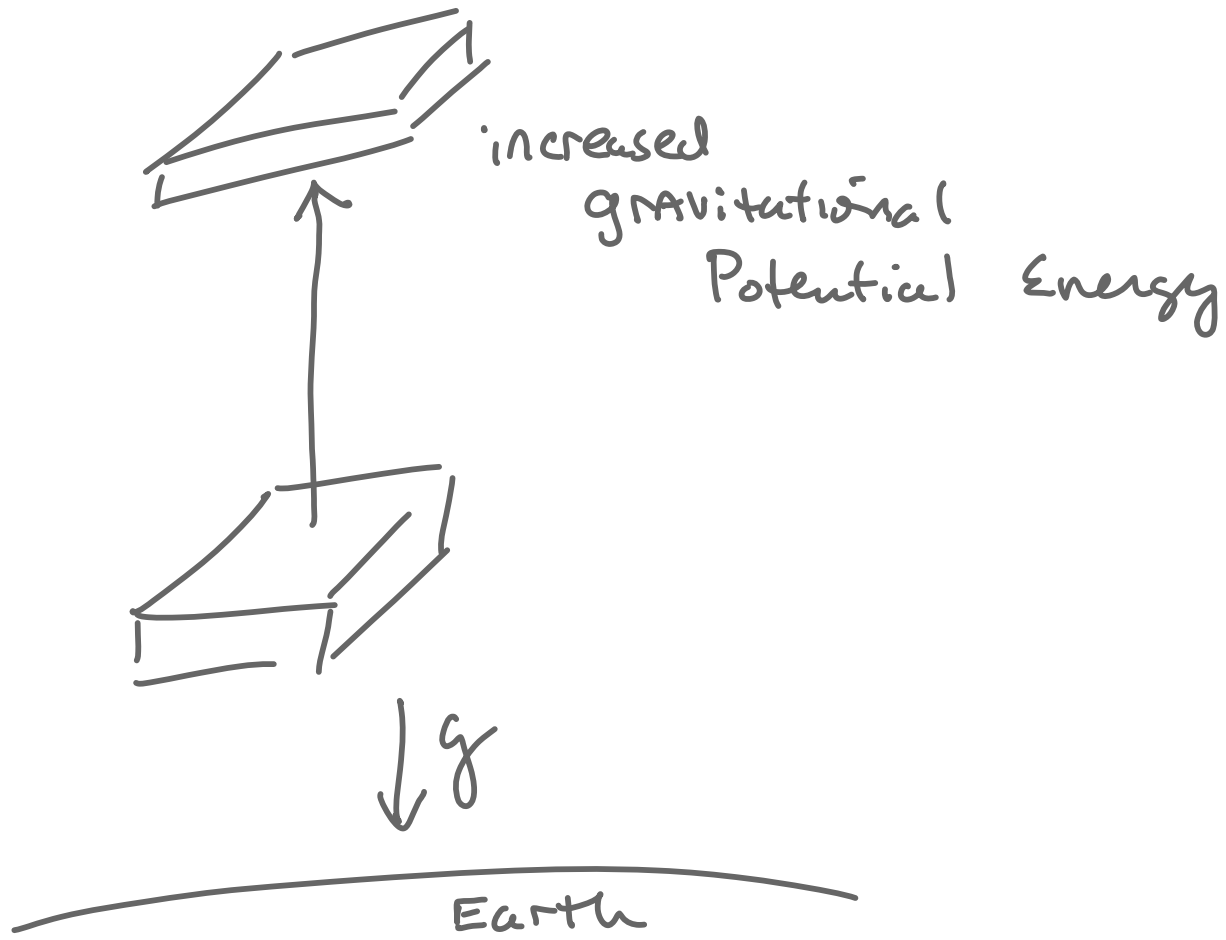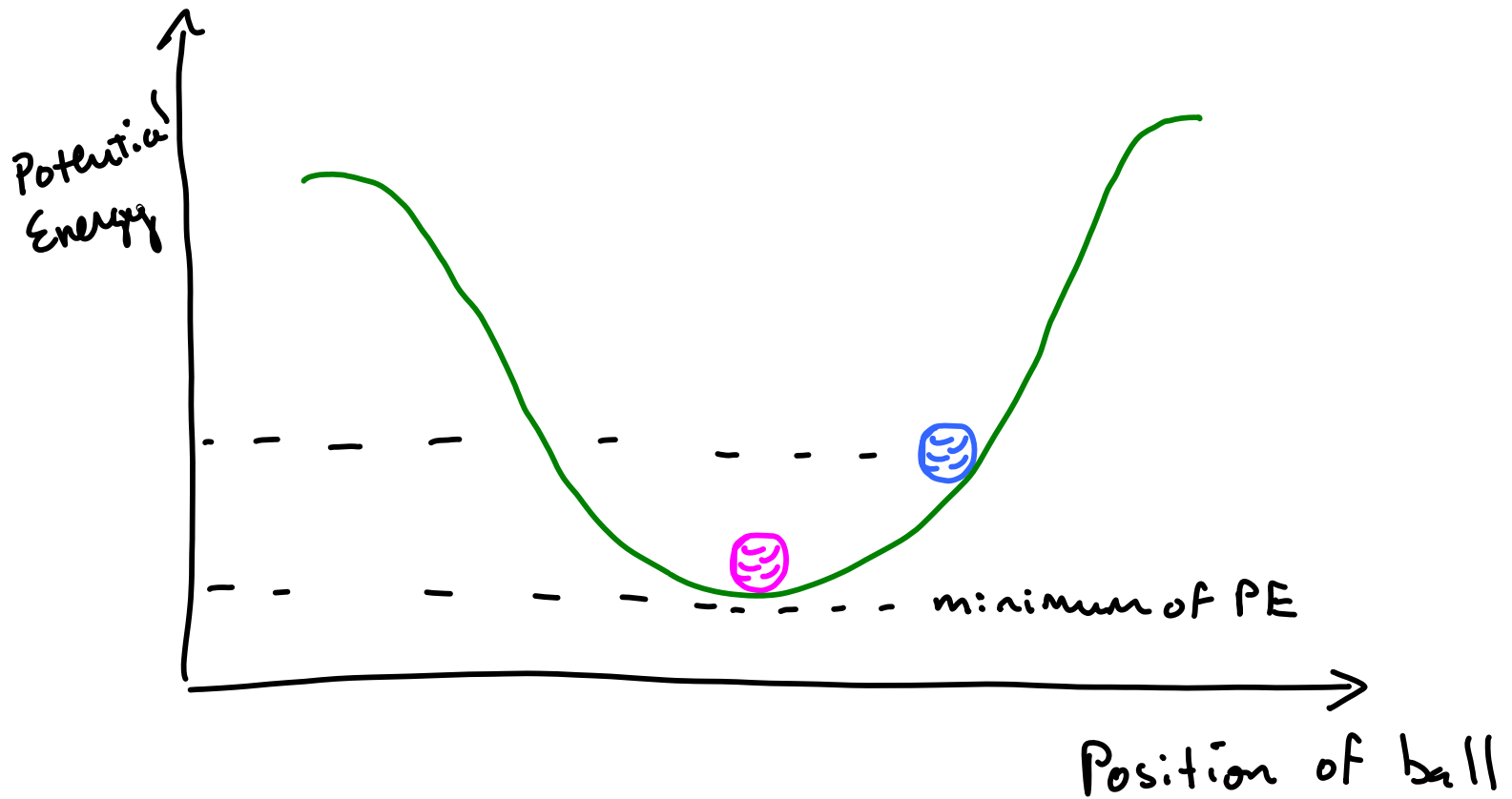
uncompressed spring
PE = 0

compressed spring
PE > 0

Springs and Potential energy

# gravitational Potential Energy

increased
gravitational
Potential Energy

$\downarrow g$

Earth

Potential Energy
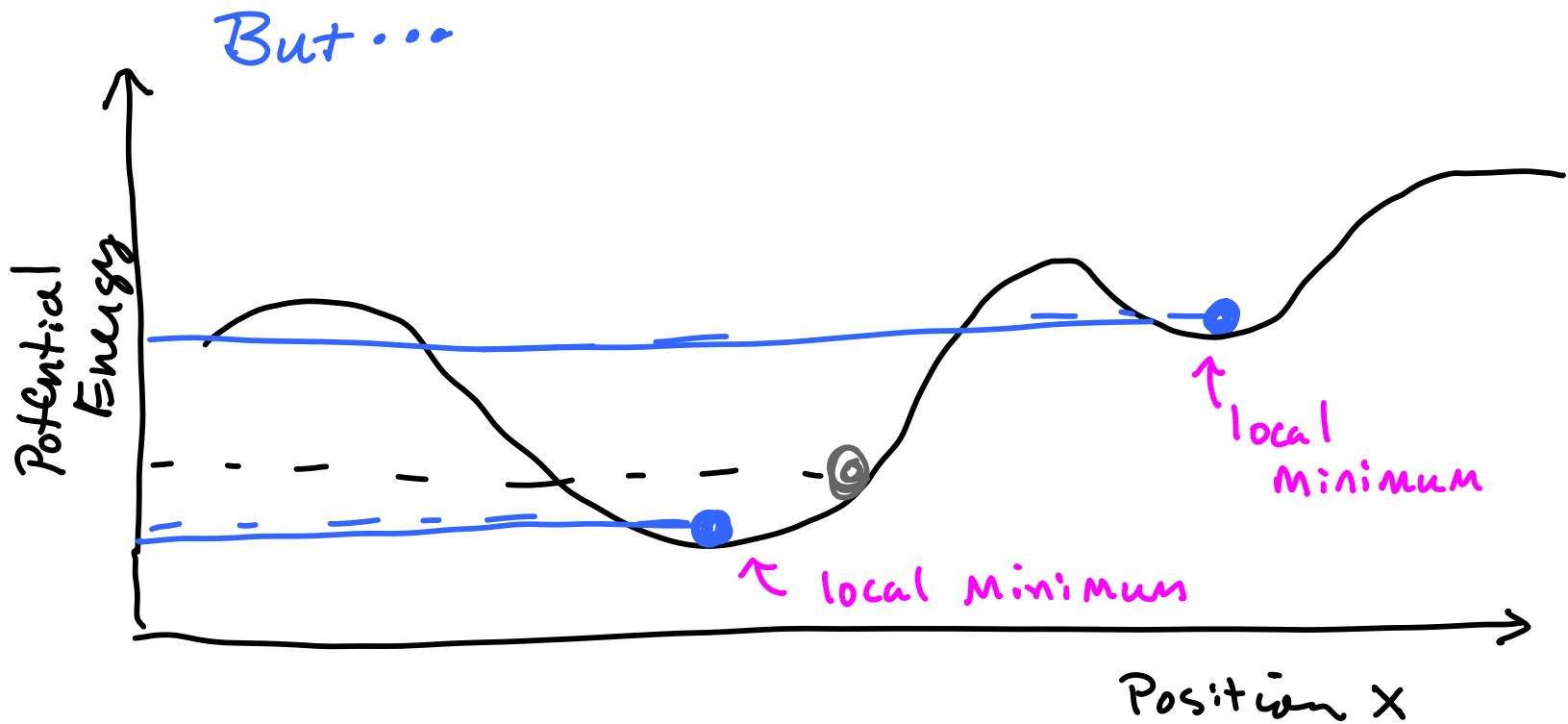
minimum of PE

Position of ball

Different compactification schemes
involve different degrees of
Potential energy stored in the "Vacuum"

The String theorist's fantasy:
   There is a Single, Particular Model
Compactification that leads to a
Minimum in the total energy of the
System ... Corresponds to the particle
Spectrum, Cosmological constant, forces we see
   $\longrightarrow$ The Theory of Everything!!

But...

Potential Energy

↑ local Minimum

↑ local Minimum

Position X

Expect a huge # of compactification schemes
to lie at local minima of the
"potential energy" function
→ should be quasi stable or stable

Brane

Flux line

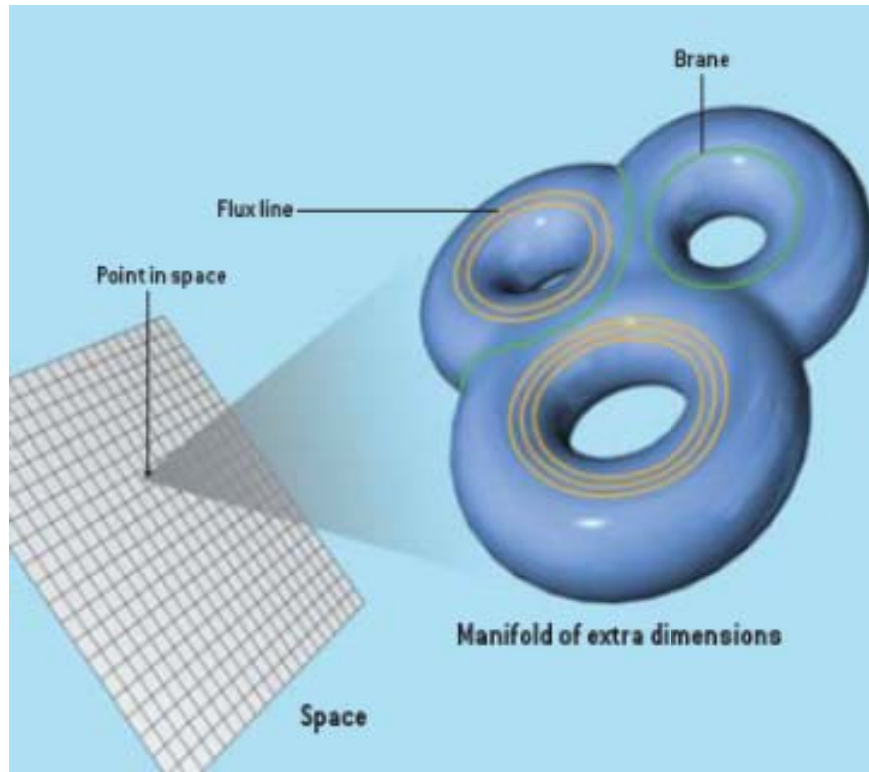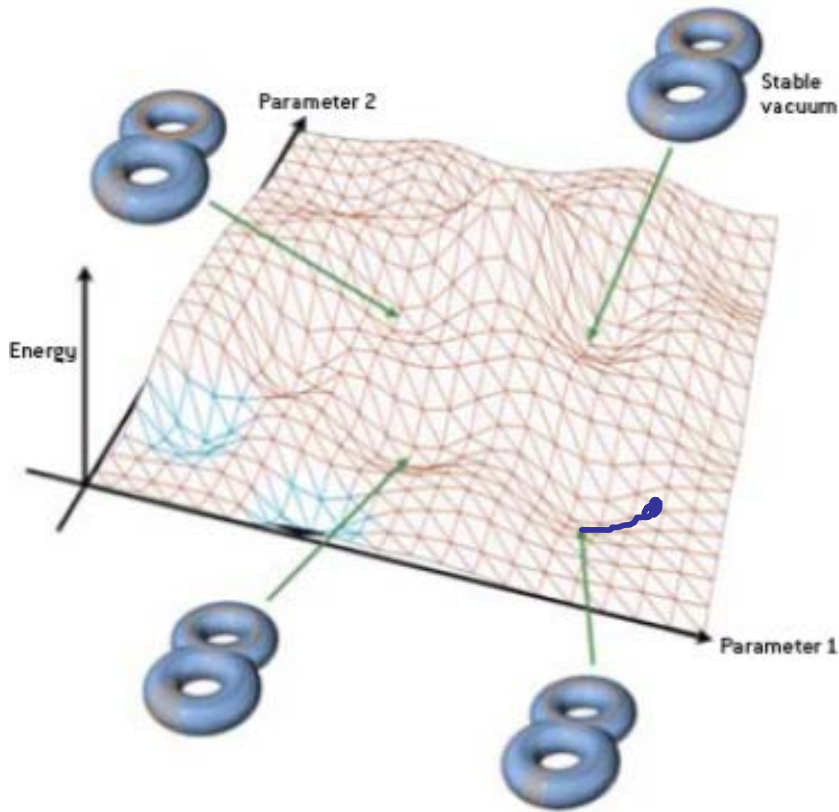Point in space

Manifold of extra dimensions

Space

Fig from —
Bousso + Polchinski:
The String Theory Landscape
Sci. Am. 2004

What does the space
look like on a
very small
scale?

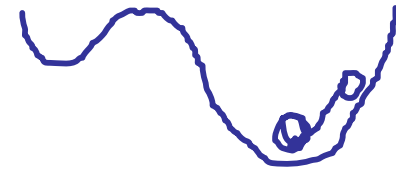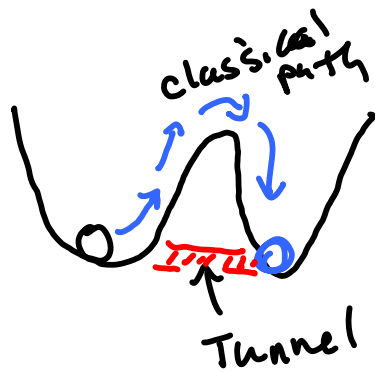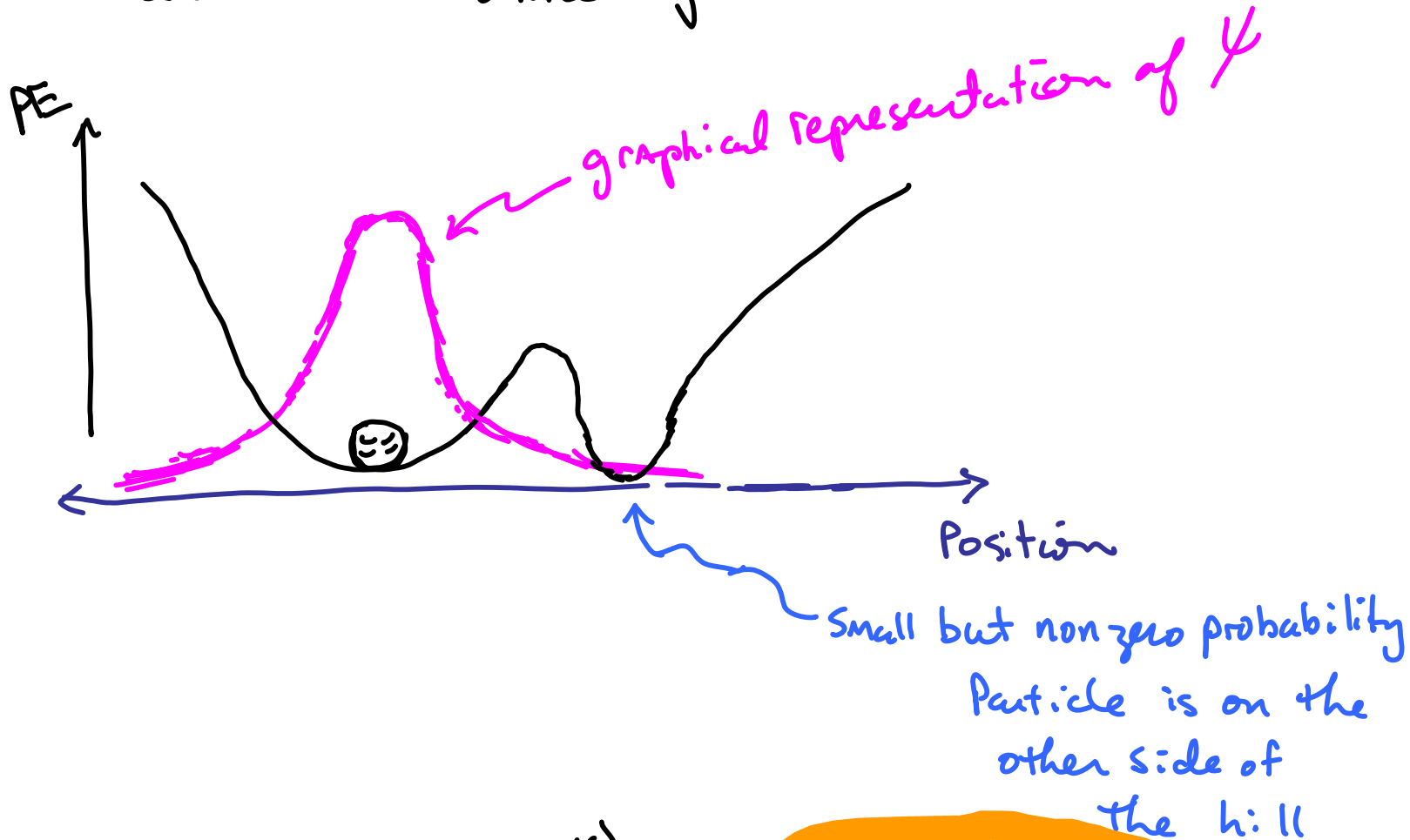The "vacuum energy" depends on this.

Parameter 2

Energy

Stable vacuum

Parameter 1

Different configurations → Different energies
→ Different locations in the landscape of Possibilities

# Quantum Tunneling
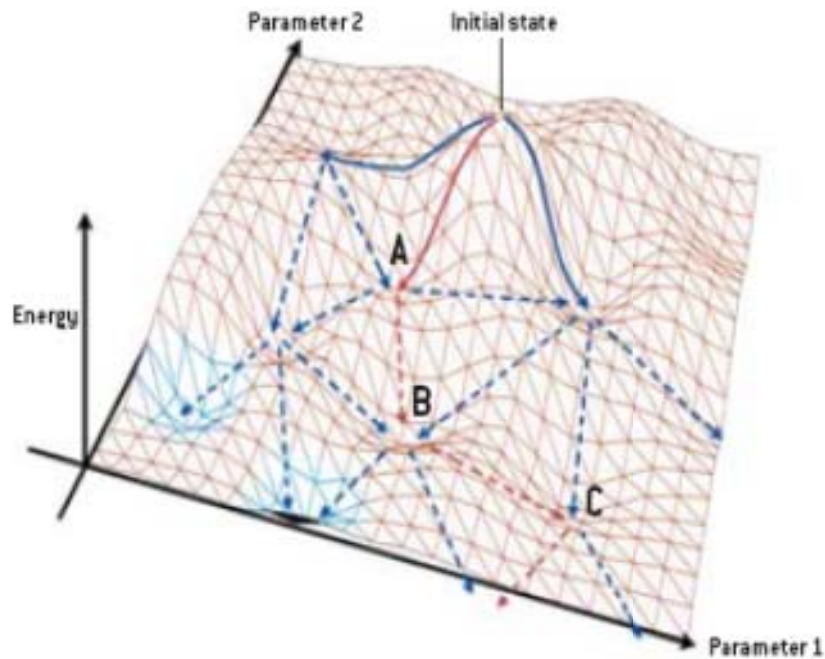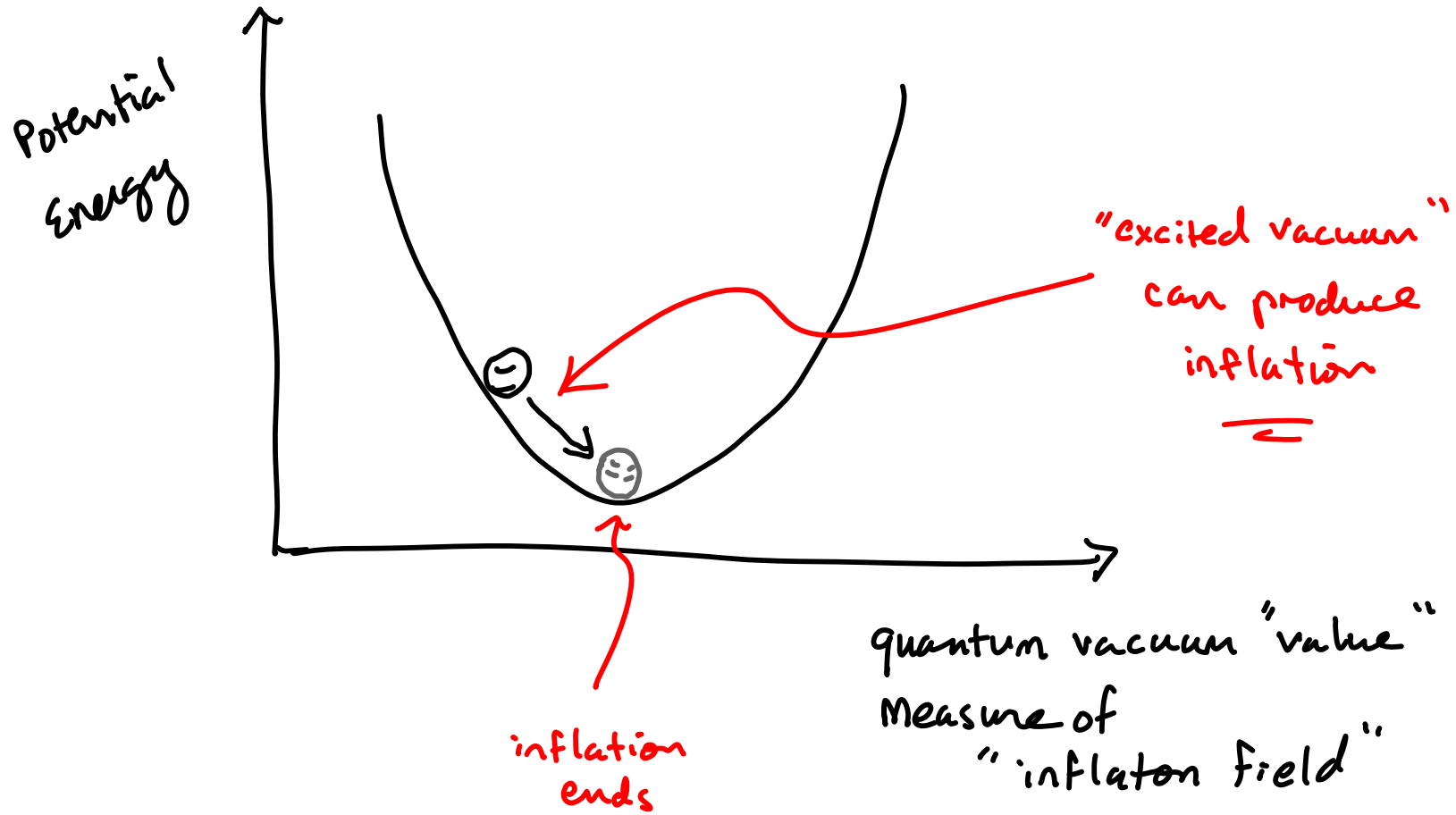
PE

*graphical representation of $\psi$*

Position

Small but non zero probability Particle is on the other side of the hill

classical path

Tunnel

quantum Tunneling Model of $\alpha$-decay

nucleus

$\alpha$-Particle

Fig from —
Bousso + Polchinski:
The String Theory Landscape
Sci. Am. 2004

Parameter 2    Initial state
Energy
A
B
C
Parameter 1

▌Different configurations of the String Theory vacuum
      are    ~ Stable

▌Quantum mechanics allows one configuration to
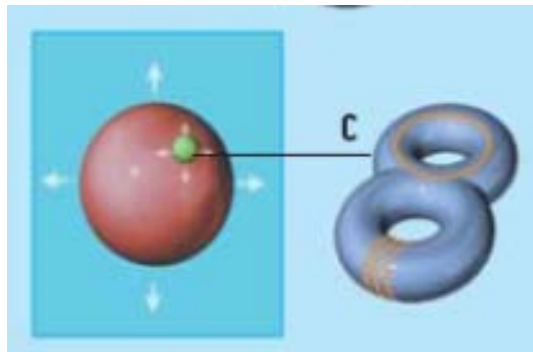      decay/fluctuate/Tunnel   to another
      configuration locally

# "False vacuum" and inflation

Potential Energy

"excited vacuum" can produce inflation

inflation ends

quantum vacuum "value"
Measure of
"inflaton field"

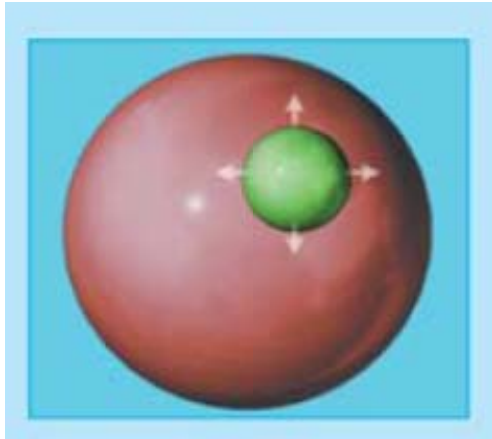# The cosmic Landscape of the Multiverse in String Theory



Tunneling from one stable vacuum to another would not occur everywhere in the universe at once. Instead it would occur at one random location, producing an expanding bubble of space (arrows) having the new vacuum. In this example, the blue region of space has vacuum A, whose manifold of small extra dimensions consists of a two-handled doughnut with groups of two and four flux lines wrapped around the handles. The red region, which has vacuum B, emerges when one of the four flux lines decays. Corresponding to their different manifolds, the two regions will have different kinds of particles and forces and thus different laws of physics.
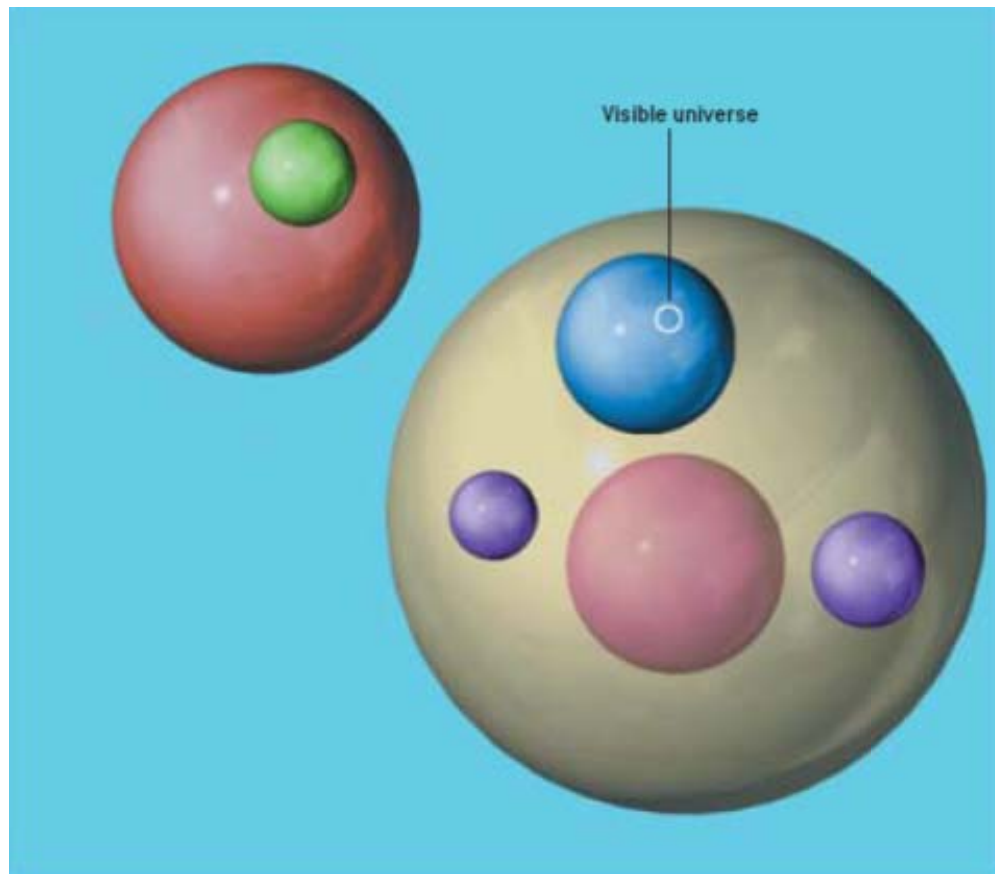


The red region grows rapidly, potentially becoming billions of light-years in diameter. Eventually another transition occurs within the red region, this time a decay of one of the two flux lines. This decay generates the green region, which has vacuum C and still another set of particles and forces.

Figures + Text From

The green region also grows rapidly, but it never catches up with the red region. Similarly, the red region never completely replaces the original blue vacuum.



Visible universe

Because the quantum tunneling is a random process, widely separated locations in the universe will decay through different sequences of vacua. In this way, the entire landscape is explored; every stable vacuum occurs in many different places in the universe.

The whole universe is therefore a foam of expanding bubbles within bubbles, each with its own laws of physics. Extremely few of the bubbles are suitable for the formation of complex structures such as galaxies and life. Our entire visible universe (more than 20 billion light-years in diameter) is a relatively small region within one of these bubbles.

Many $\left(10^{500}\right)$ ways to compactify the extra dimensions $\longrightarrow$ many Different Potential energies and Characteristics of the vacuum ↖ particles forces

All are possible ?

So — it is certainly true that a universe like ours — seemingly fine-tuned and suitable for life as we know it - Should exist

Scientific ?

What does this mean for the Theory of Everything ?
How does this relate to intelligent design ?

# The Mathematical Universe Hypothesis



Max Tegmark
ArXiv: 0704.0646
gr-gc

**External Reality Hypothesis:**

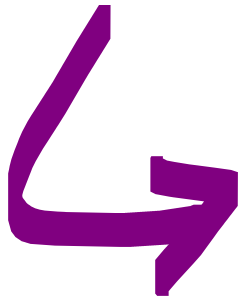There Exists an external reality
Completely independent of us humans.

ERH reasonable to most folks but
NOT universally accepted
— even among Scientists ...
extreme Copenhagenists for example.

Ultimate goal of theoretical physics

Develop/Discover Theory that completely
describes this External Reality
Theory of Everything ≡ TOE

TOE MUST NOT have Ambiguities
or human-related "baggage"

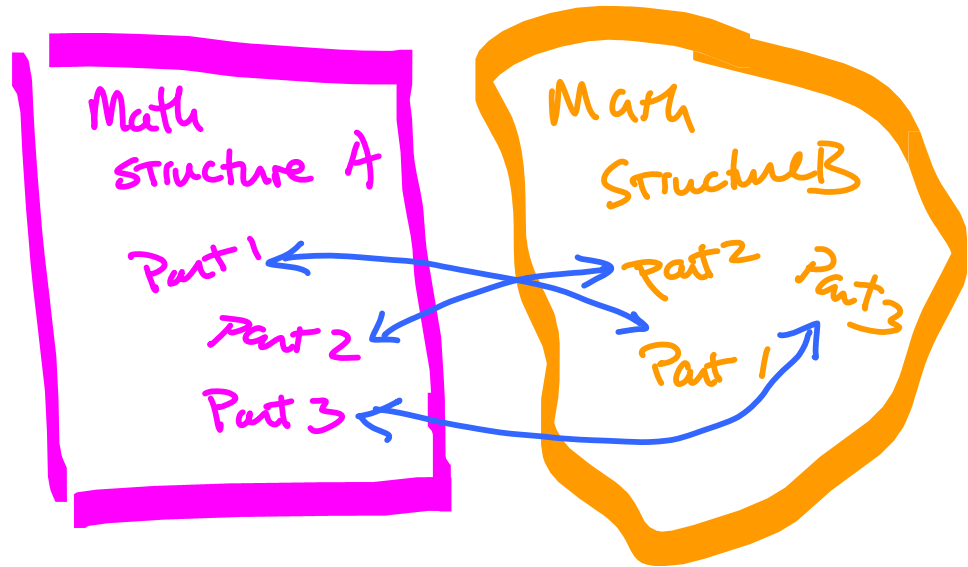↳ Mathematical Structure

In Mathematics

If {
Part 1 same as Part 1
Part 2 same as Part 2
Part 3 same as Part 3
}

Then
Math Structure A and Math Structure B
are one and the same

Math structure A

Part 1
Part 2
Part 3

Math Structure B

Part 2
Part 3
Part 1

Mathematical Structure that is The TOE $=$ External Reality

The External Reality $=$ is a Mathematical Structure

→ Mathematical Universe Hypothesis

Could Have Many Different complete and Self-consistent and independent irreducible Mathematical Structures

⇄

Does each correspond to a Different Universe? → Multiverse

↖ NOT quite the same as "Anything goes".

If discover TOE

Why these equations

and NOT others?

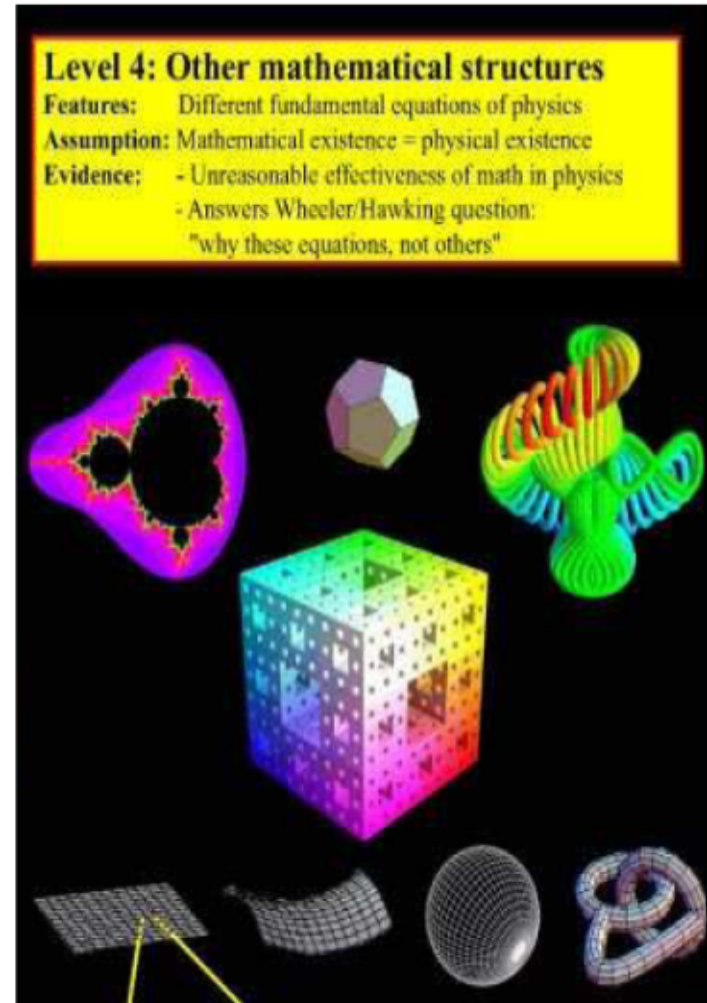(Wheeler / Hawking)

MUH $\longrightarrow$ why NOT others?

Multiverse

Extreme Copernican Revolution ...

# The ultimate Copernican revolution – The Mathematical Universe

## Tegmark's idea:

➢ Assume there is an external reality independent of humans
➢ There exists a TOE (theory of everything)
➢ TOE must be well-defined and unambiguous (no human language, etc.)
➢ TOE must be mathematics
➢ TOE must be a self-contained mathematical theory
➢ The TOE must be perfect and must have parts that correspond to every aspect of reality … isomorphic mapping
➢ The TOE is reality
➢ If this self-contained, self-consistent mathematical framework corresponds to our reality, why not others?



> **Level 4: Other mathematical structures**
> **Features:** Different fundamental equations of physics
> **Assumption:** Mathematical existence = physical existence
> **Evidence:** - Unreasonable effectiveness of math in physics
> - Answers Wheeler/Hawking question:
> "why these equations, not others"

*SM "mathematical" multiverse*