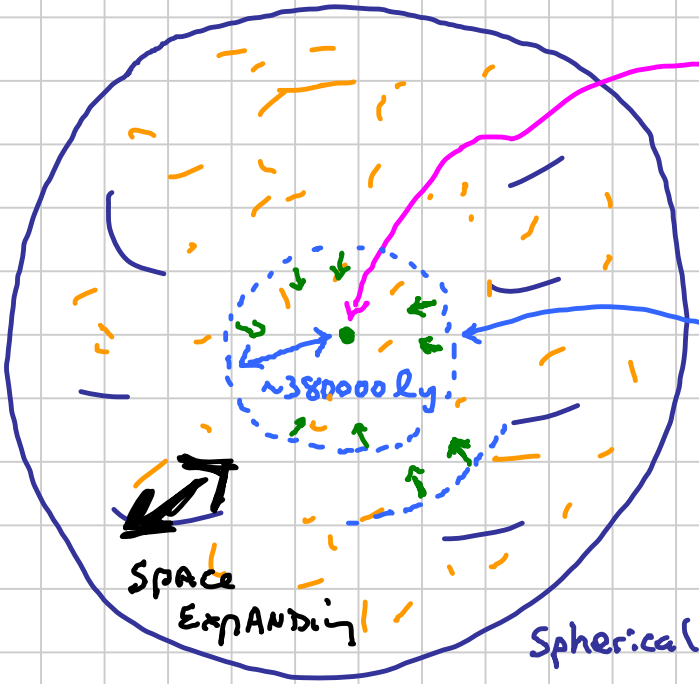
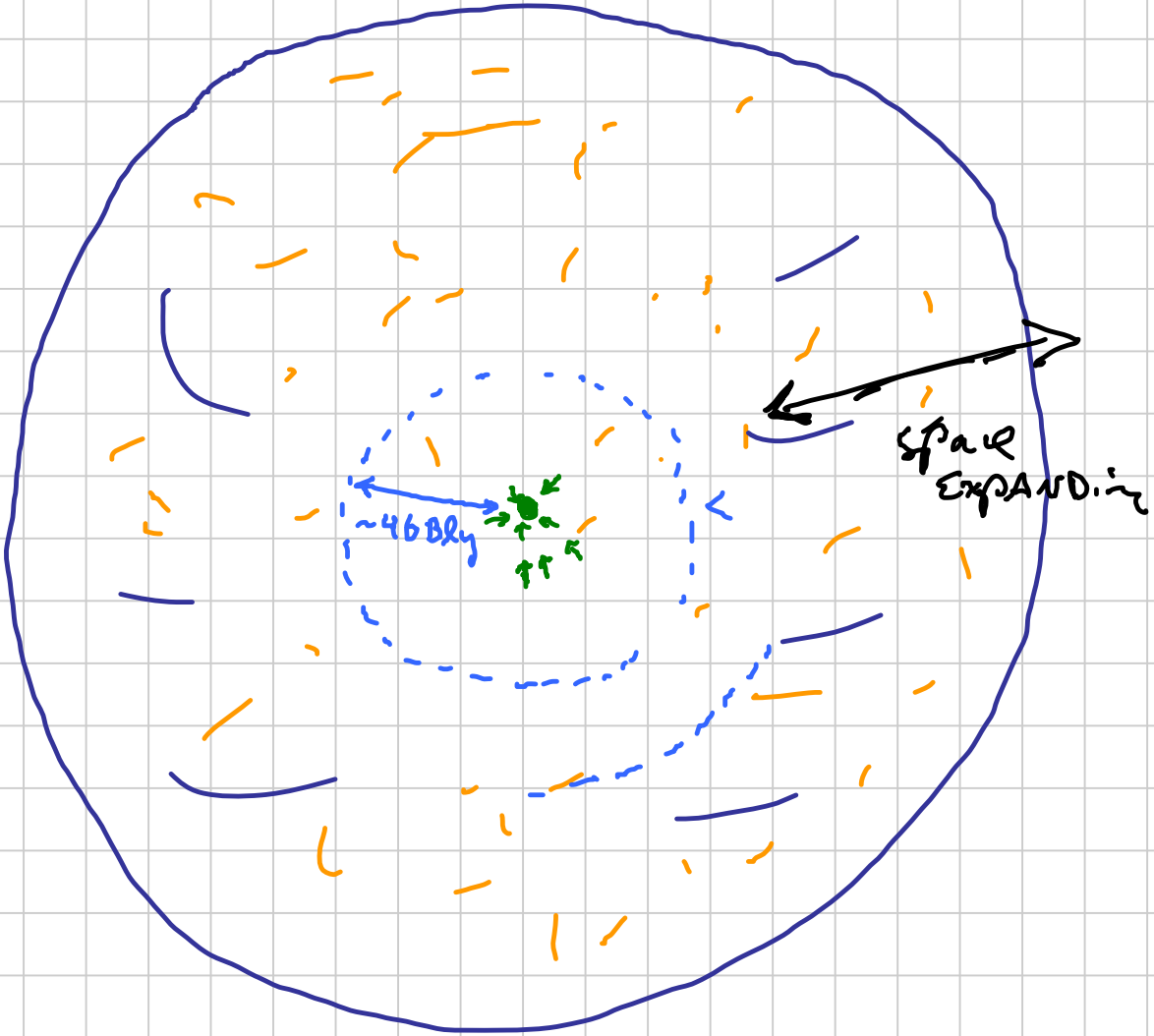
Physics 102 – April 16, 2014



space that eventually is point where Earth exists

surface of last scattering

Spherical volume of Space in post-inflation reality centered on "earth"



Point of space that was origin of CMB photons hitting us now

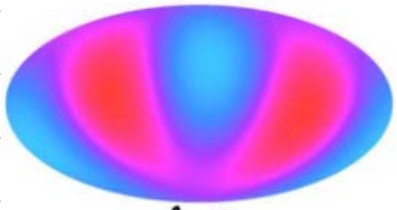
↓

is now 46 Bly Away

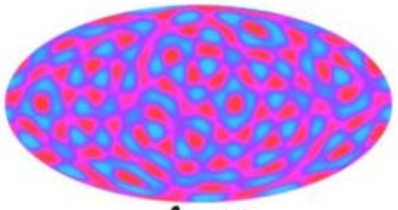
Took the photons 13.8 ish Billion years to travel "expanding 380000 ly"

Big Bang + Inflation + Cold dark Matter + dark energy

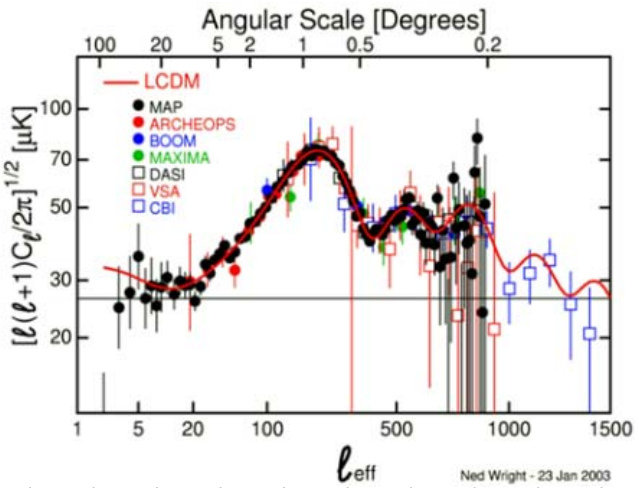
WMAP CMB angular feature size power spectrum – acoustics in the early universe!



$\ell = 2$



$\ell = 16$

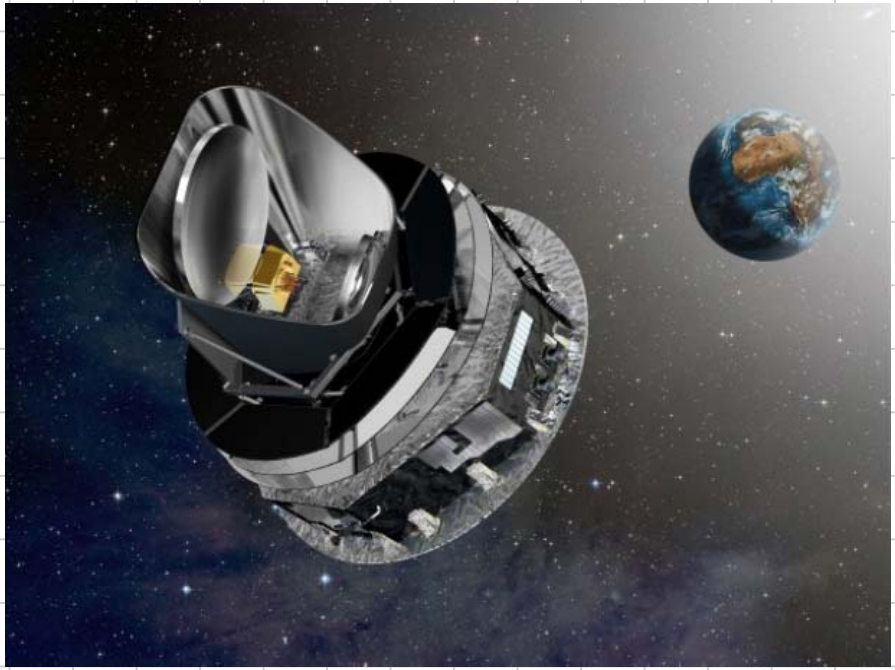


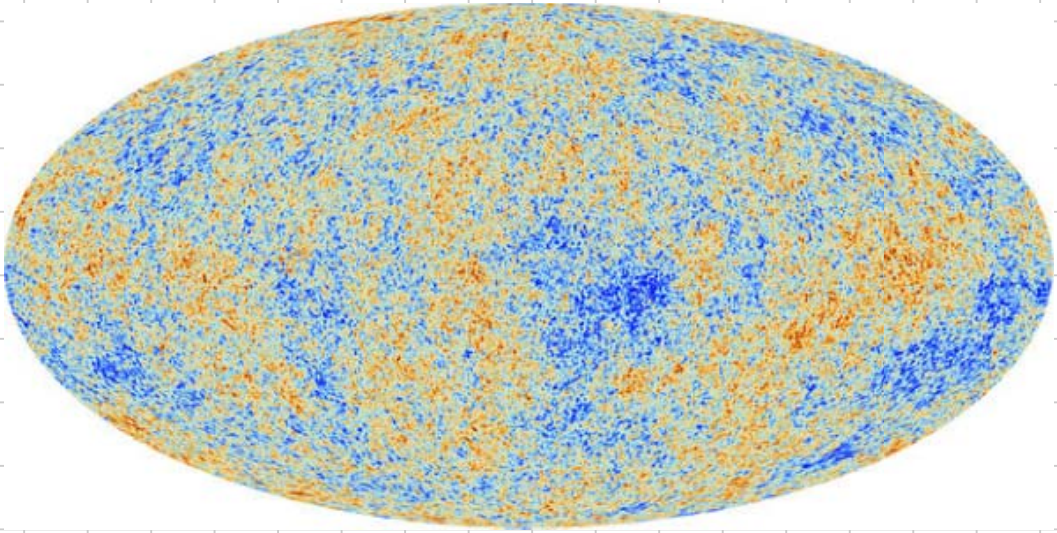
The characteristics of sound waves depend on the medium!

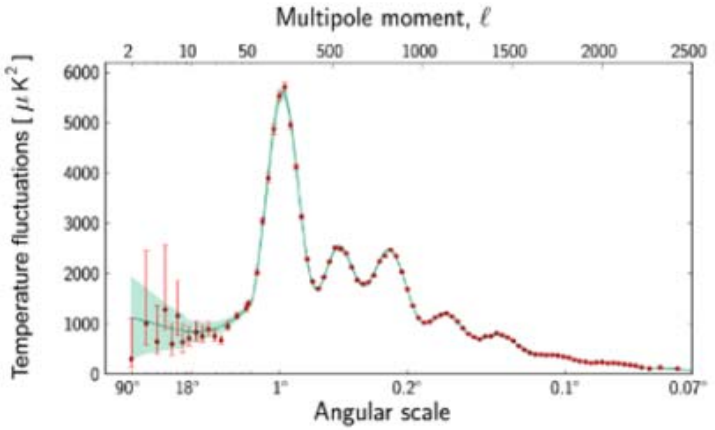
This data is sensitive to amount of
Normal matter, dark matter, dark energy and inflationary model of the early universe

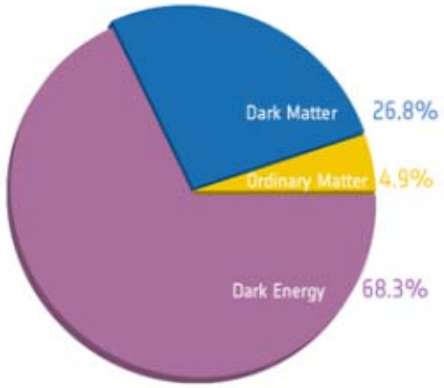
ESA

Planck Mission









After Planck

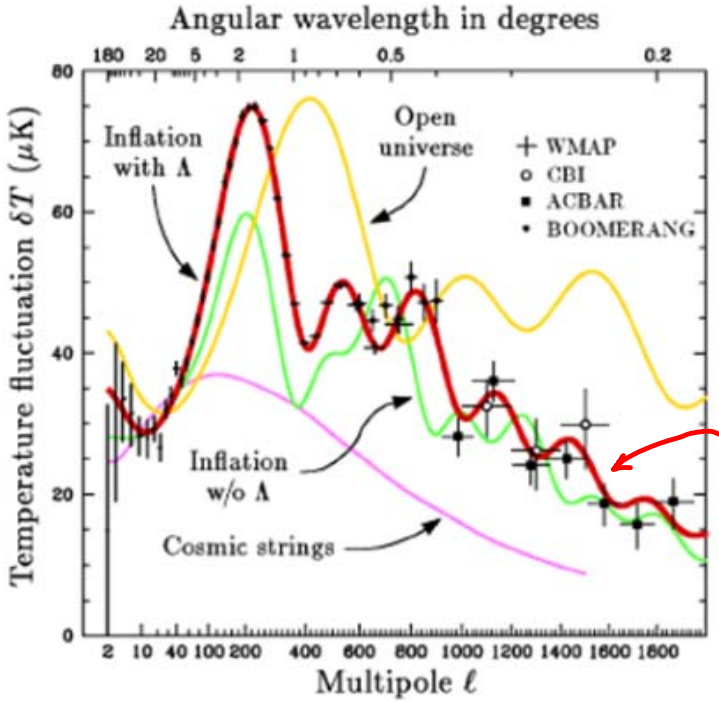
From the Planck collaboration

MIT-CTP#3811 hep-th/0702178

Eternal inflation and its implications‡

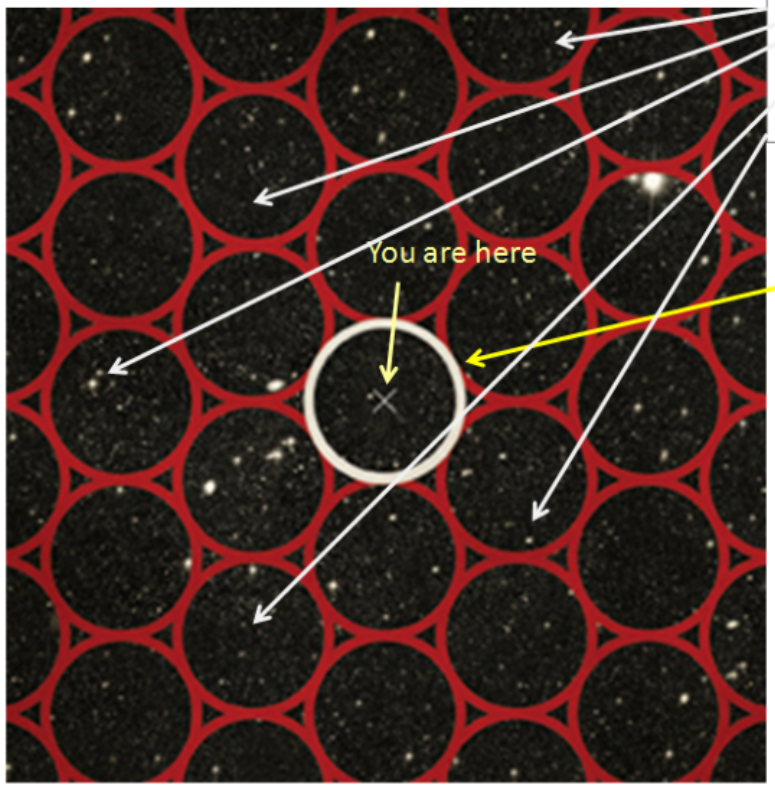
Alan H. Guth
Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

2007



Theory with
Inflation
Dark energy
Cold Dark Matter

If inflation … welcome to the multiverse!



The greater reality which is outside and will always be outside our experience

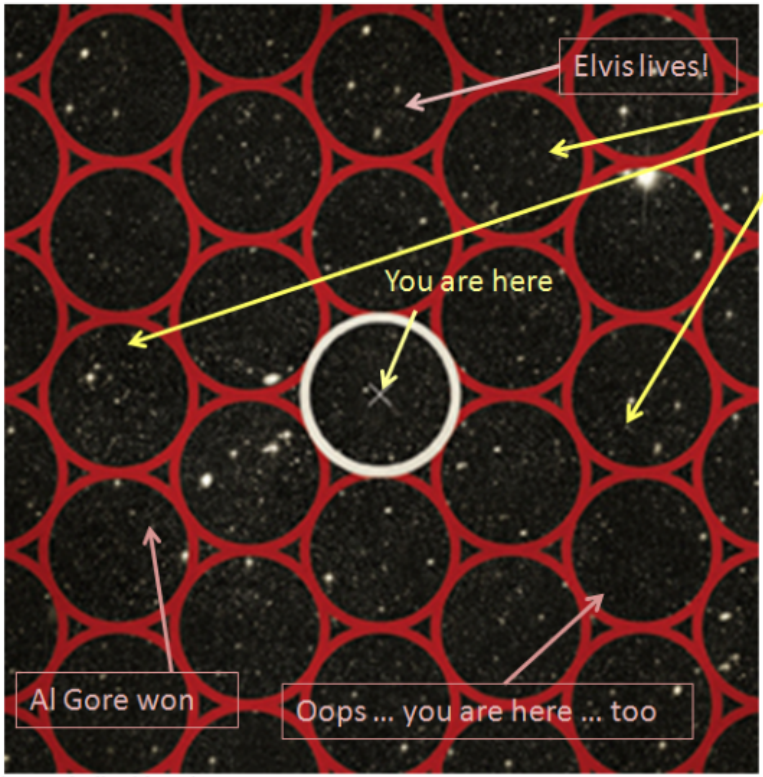
Our cosmic event horizon

SM "beyond-the-horizon" multiverse

Tegmark's Type I multiverse

http://www.scientificamerican.com/article.cfm?id=multiverse-the-case-for-parallel-universe

How big is this reality? How big does it need to be?
How long did inflation last?



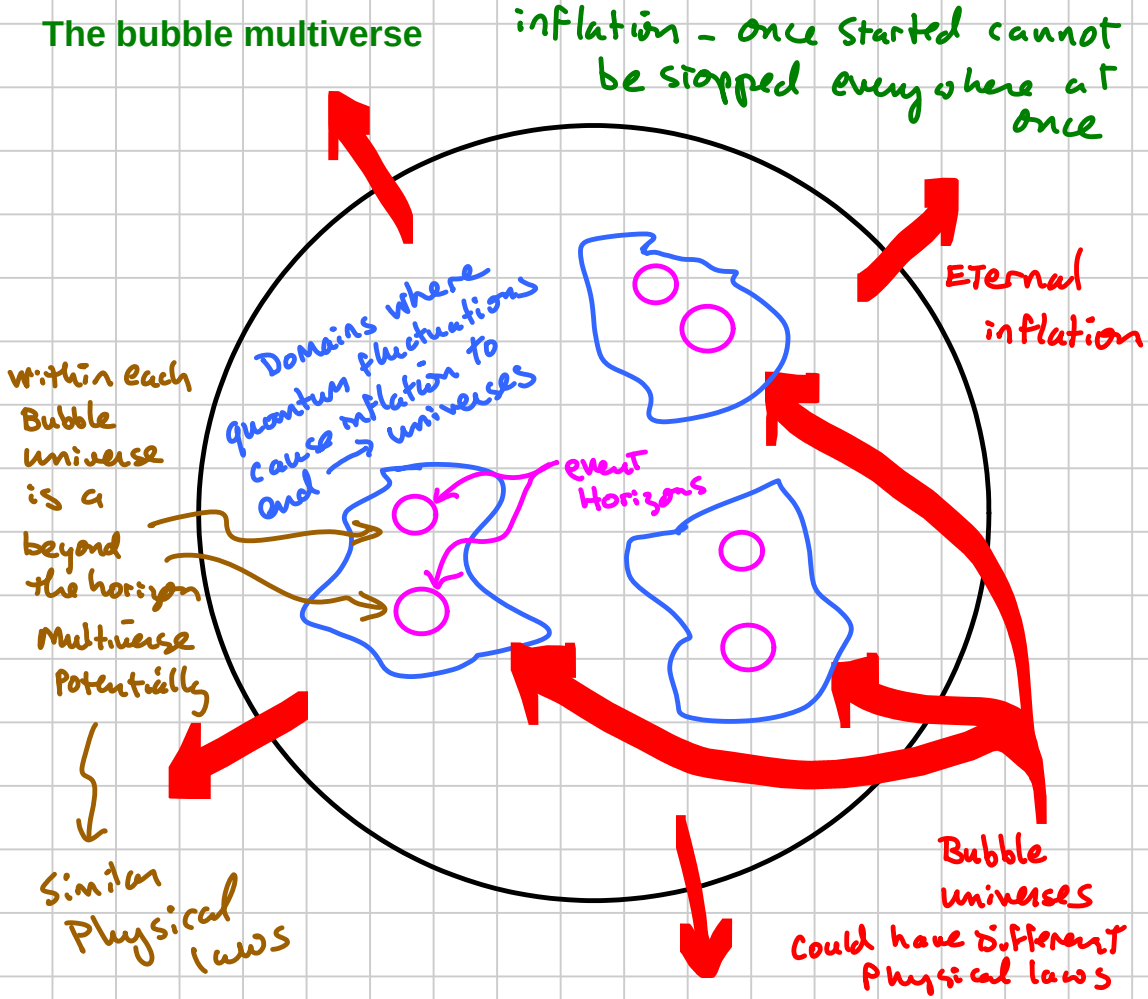
These regions share our physics ... have the same spacetime characteristics.

But each has a different initial condition.

Some serious estimates say there are countless regions of "our universe" size.

All possible initial conditions explored. Anything that could happen does happen.

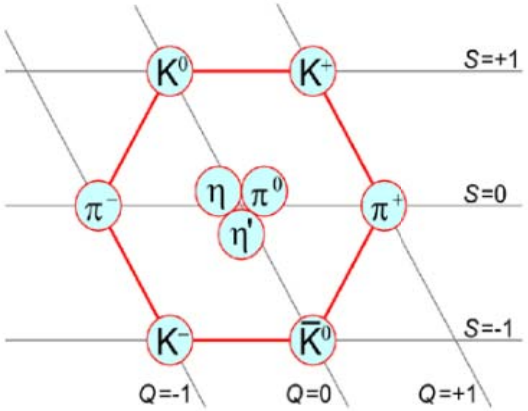
Garriga and Vilenkin, Phys. Rev. D64, 2001, 043511;
Tegmark, Parallel Universes in Science and Ultimate Reality: quantum theory, cosmology and complexity, Ids. Barrow, Davies, Harmper, Cambridge Univ. Press, 2004.


The bubble multiverse
inflation - once started cannot be stopped everywhere at once
Eternal inflation
Domains where quantum fluctuations cause inflation to end → universes
event Horizons
within each Bubble universe is a beyond the horizon Multiverse potentially
Similar Physical laws
Bubble universes could have different Physical laws

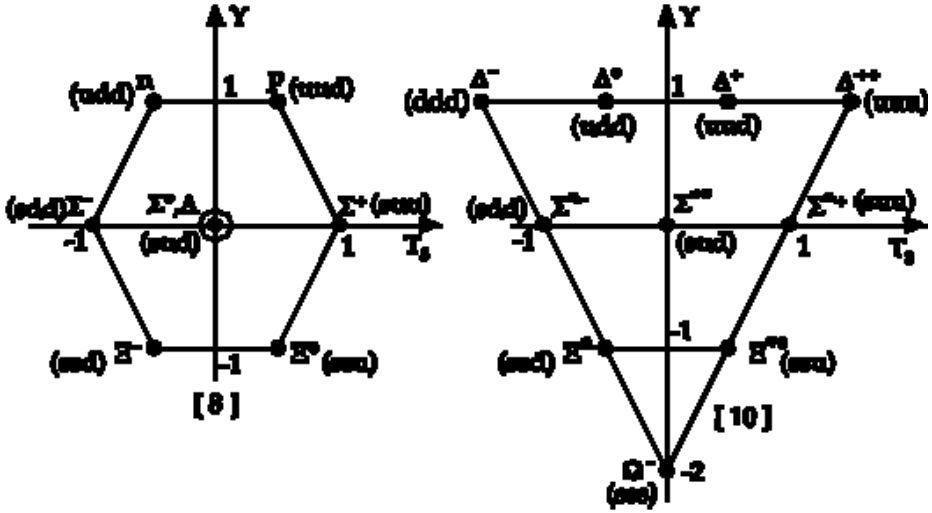
String Theory

Before quarks established
Before QCD

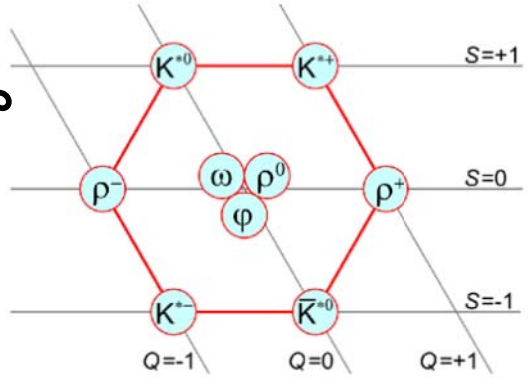
Spin 0 Mesons



Baryons



Spin 1 Mesons



Particle	Rest mass MeV	Average lifetime s	Most frequent type of decay %
Photon			
γ	0 ($< 2\cdot10^{-22}$)	stable	stable
Leptons			
ν_e	0 ($< 3\cdot10^{-6}$)	stable	stable
ν_μ	0 (< 0.19)	stable	stable
ν_τ	0 (< 18.2)	stable	stable
e	0.510999890	stable ($> 4.2\cdot10^{24}$ a)	stable
μ	105.658357	$2.19703\cdot10^{-6}$	$e^- \bar{\nu}_e \nu_\mu$ 98.6 $e^- \bar{\nu}_e \nu_\mu \gamma$ 1.4
τ	1777.03	$2.906\cdot10^{-13}$	$e^- \bar{\nu}_e \nu_\tau$ 17.83 $\mu^- \bar{\nu}_\mu \nu_\tau$ 17.37
Mesons			
π^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 π^+) $\mu^+ \nu_\mu$ 99.98 $e^+ \nu_e$ 0.01 $\mu^+ \nu_\mu \gamma$ 0.01
η	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 $8.935\cdot10^{-11}$ K_L $5.17\cdot10^{-8}$	$\pi^+ \pi^-$ 68.61 $\pi^0 \pi^0$ 31.39 $\pi^\pm e^\mp \nu_e$ 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
Λ^0	1115.683	$2.632\cdot10^{-10}$	$p\ \pi^-$ 63.9 $n\ \pi^0$ 35.8
Σ^+	1189.37	$8.018\cdot10^{-11}$	$p\ \pi^0$ 51.6 $n\ \pi^+$ 48.3
Σ^0	1192.642	$7.4\cdot10^{-20}$	$\Lambda^0 \gamma$ 100
Σ^-	1197.449	$1.479\cdot10^{-10}$	$n\ \pi^-$ 99.9
Ξ^0	1314.83	$2.90\cdot10^{-10}$	$\Lambda^0 \pi^0$ 99.5
Ξ^-	1321.31	$1.639\cdot10^{-10}$	$\Lambda^0 \pi^-$ 99.9
Ω^-	1672.45	$8.21\cdot10^{-11}$	$\Lambda^0 K^-$ 67.8 $\Xi^0 \pi^-$ 23.6 $\Xi^- \pi^0$ 8.6

Why Strings ?

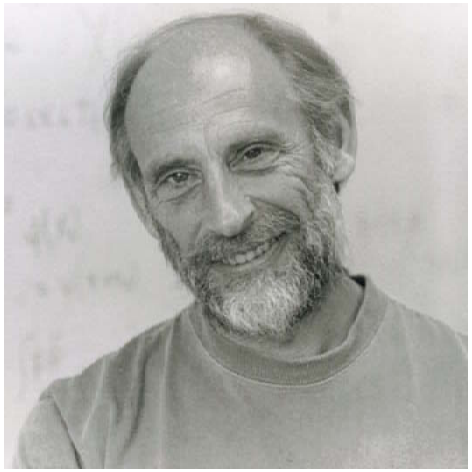
Try to understand what is structure of Mesons + barons

Hadrons

Point particles give troubles

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

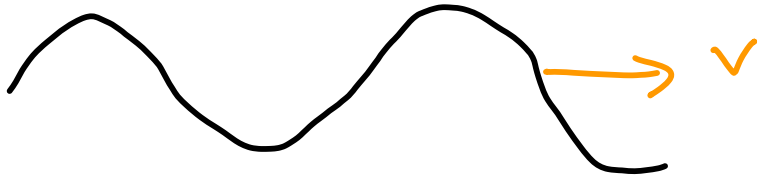
Holger Bech Nielsen

Niels Bohr Inst.

2008 Nobel Prize in physics

Yoichiro Nambu

Univ. of Chicago



Travelling wave on string

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

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

Music

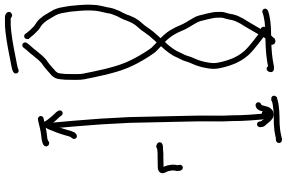
0 nodes

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

$v = \lambda\nu$

$\lambda = v/\nu$

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



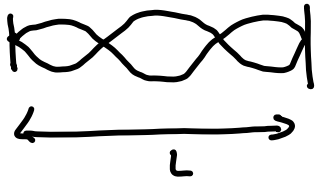
1 node

$L = \lambda$

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

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

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



2 nodes

$L = \frac{3\lambda}{2}$ $\quad \nu = \frac{3}{2}\frac{v}{L}$

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

$\vdots$

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

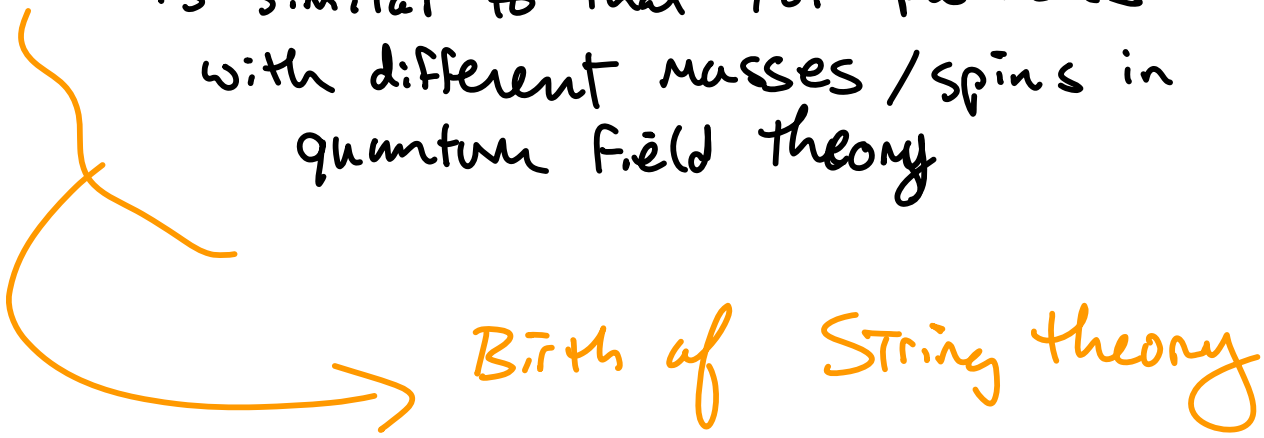
$n = 1, 2, 3 \ldots$

V ≡ 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

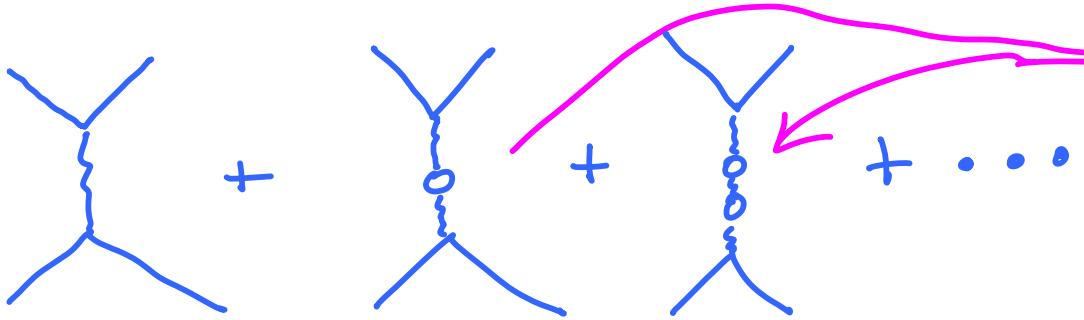


Quantum Mechanics + Gravitation → quantum gravity

Add "graviton" to quantum field theory

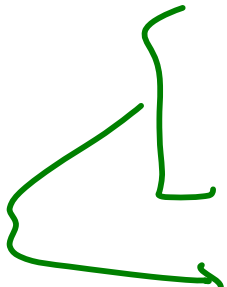
Ad hoc Addition (NOT Natural)

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

and well-behaved
Quantum Gravity is natural in String theory

String theory
Bosons only
misbehaves
(ghost particles)
unless done in
26 dimensions mathematically

NOT like the real world

String theory
Bosons + Fermions
misbehaves
(ghost particles)
unless done in
10 dimensions mathematically
plus
Supersymmetry

like real world?
Maybe

Supersymmetry

$$\psi(x_1, x_2) \rightarrow \underbrace{\pm}_{\substack{\text{Bosons} \\ \text{Fermions}}} \psi(x_2, x_1)$$

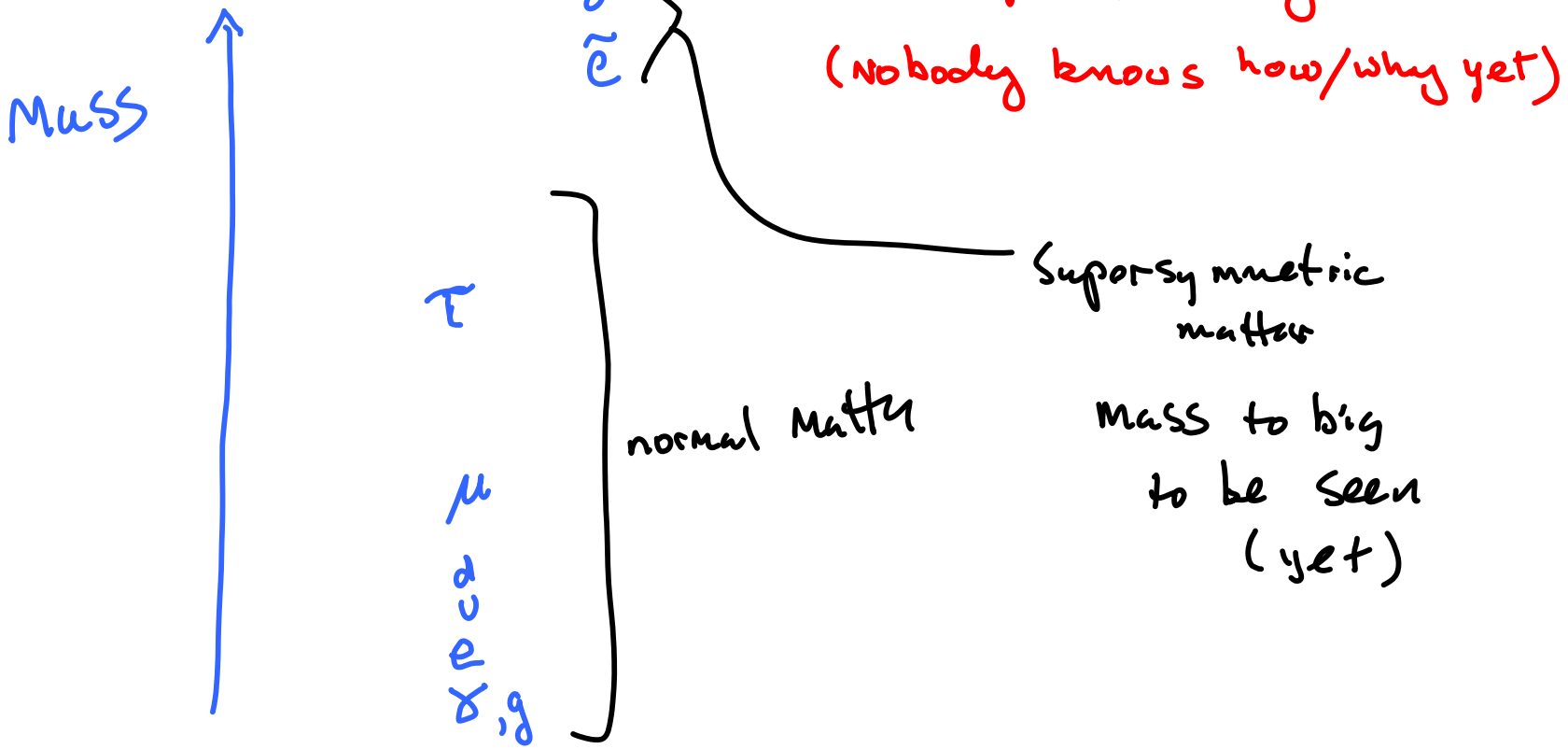
normal matter		supersymmetric matter
Spin ½ electron	⟶	selectron spin 0
Spin 1 photon	⟶	photino spin ½

Super symmetry predicts doubling of particle spectrum

↳ NOT observed

↳ Supersymmetry broken

(nobody knows how/why yet)



Extra Dimensions

General Relativity — Einstein 1915

Geometrical theory

4 dimensions

Theodor Kaluza

(German 1885-1954)

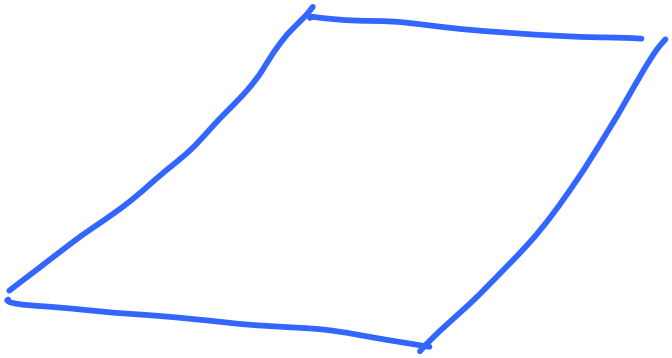
Can unify fundamental forces using extra Dimensions

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

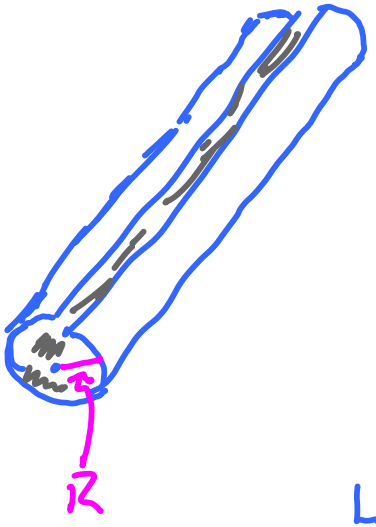
Where is this extra dimension?

1926 → Compactification

Oskar Klein
(1894-1977)

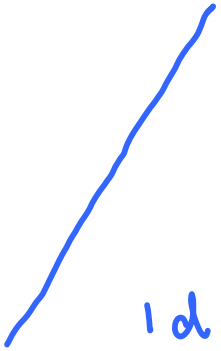


2d



R

3d



1d

Let R → small

Superstring Theory in Mid-80's

5 consistent theories known

hoped one might prove to be the

Theory of Everything

I

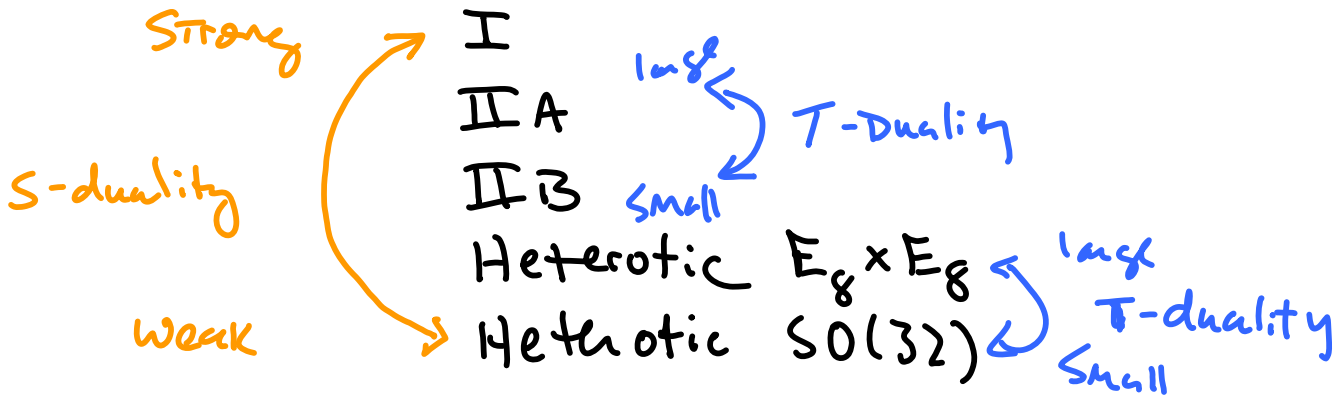
IIA

IIB

Heterotic $E_8 \times E_8$

Hetrotic $SO(32)$

Duality discovered – Deep relationships among the 5 theories



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-Brane	

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

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

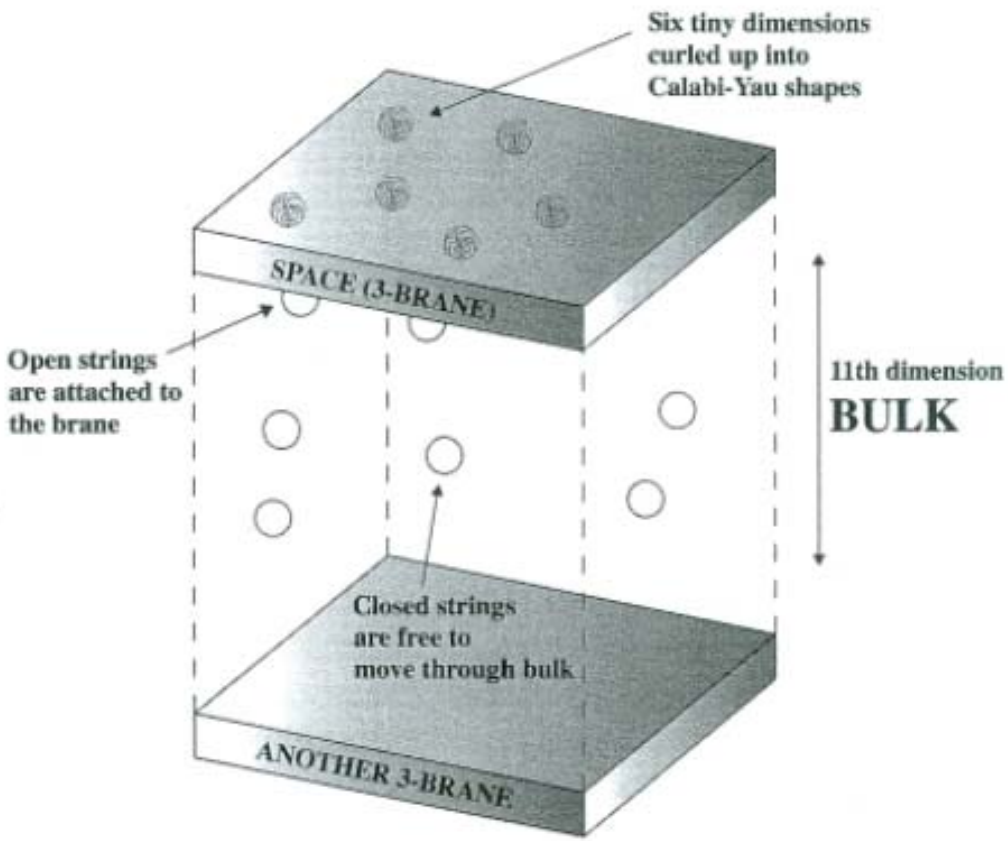
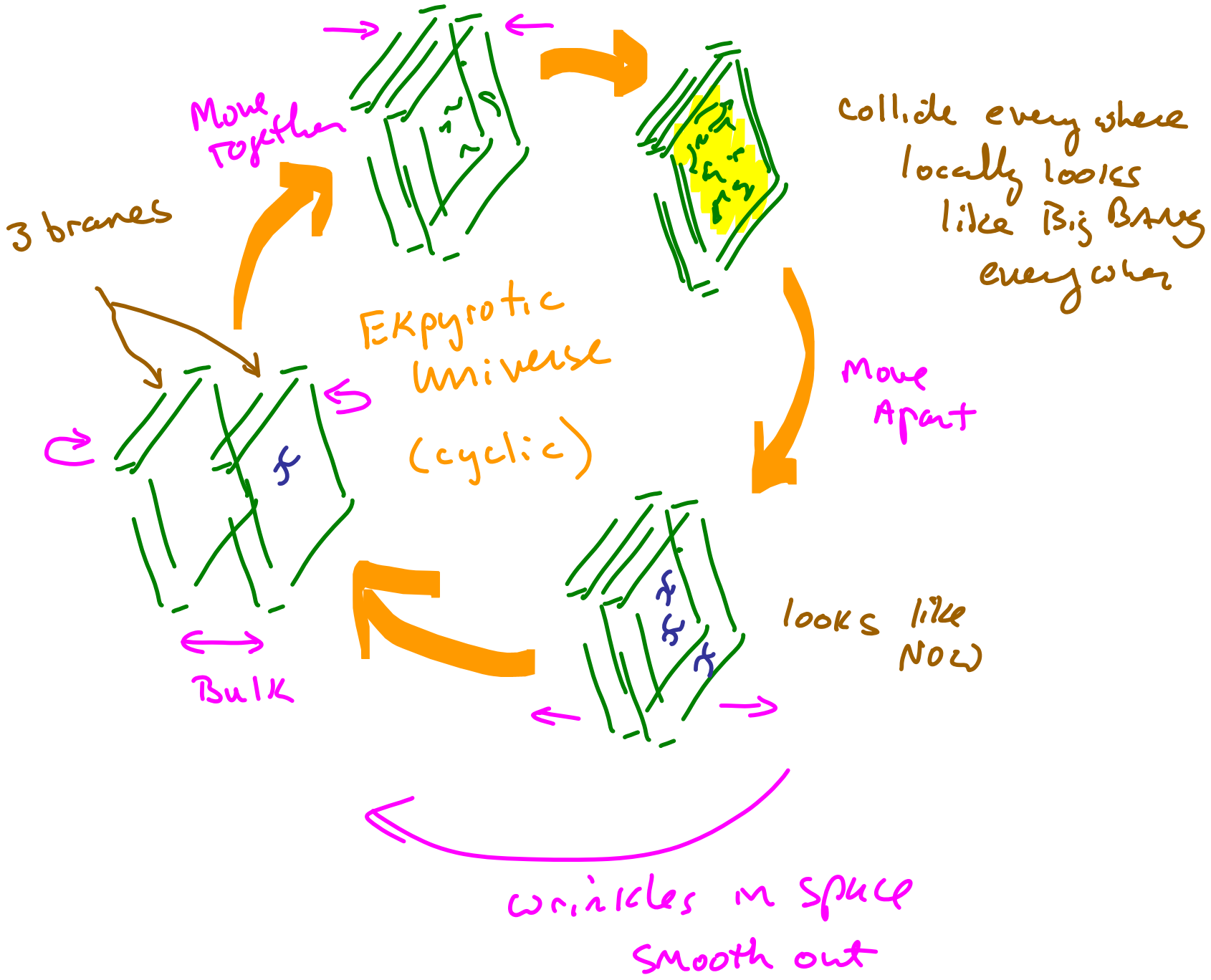


image From http://abyss.uoregon.edu/~js/qc/qc.html

Ekpyrotic multiverse (cyclic Brane collisions)


Move Together
Collide everywhere locally looks like Big Bang everywhere
3 branes
Ekpyrotic Universe (cyclic)
Move Apart
Bulk
looks like NOW
wrinkles in space smooth out

The Cosmic Landscape

In String theory –

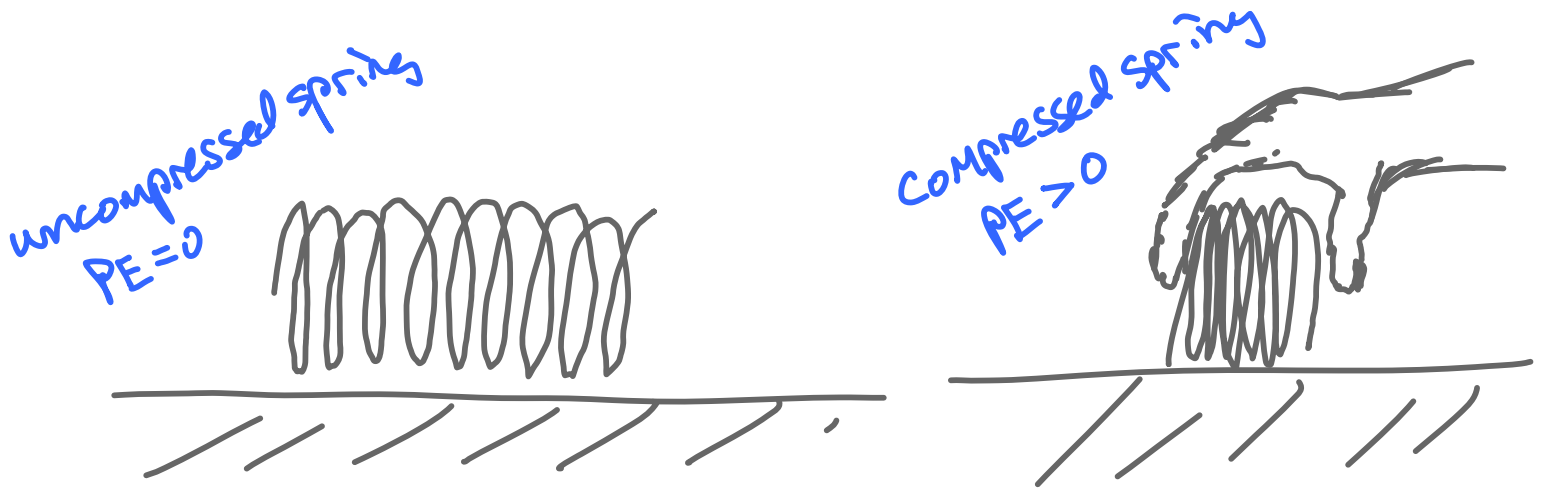
Laws of Physics
Particle spectrum
Nature of forces

} dictated by Shape + Size of Extra dimensions

Shades of the Ancient Greeks! geometry

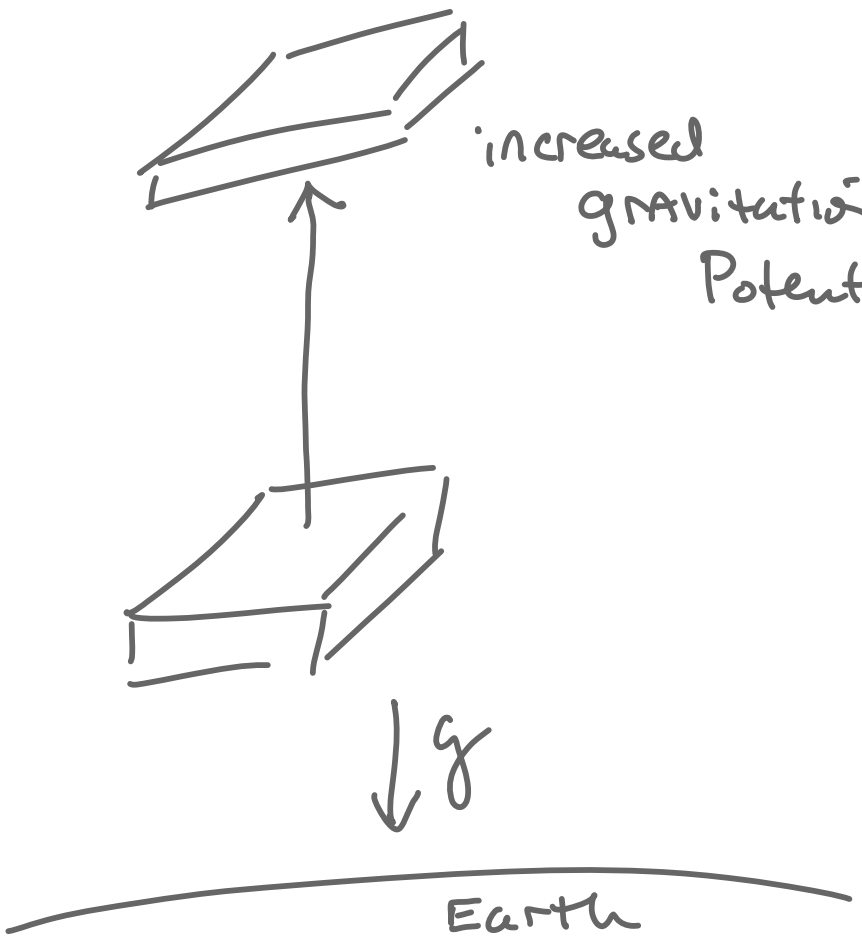
Depends on details of the compactification

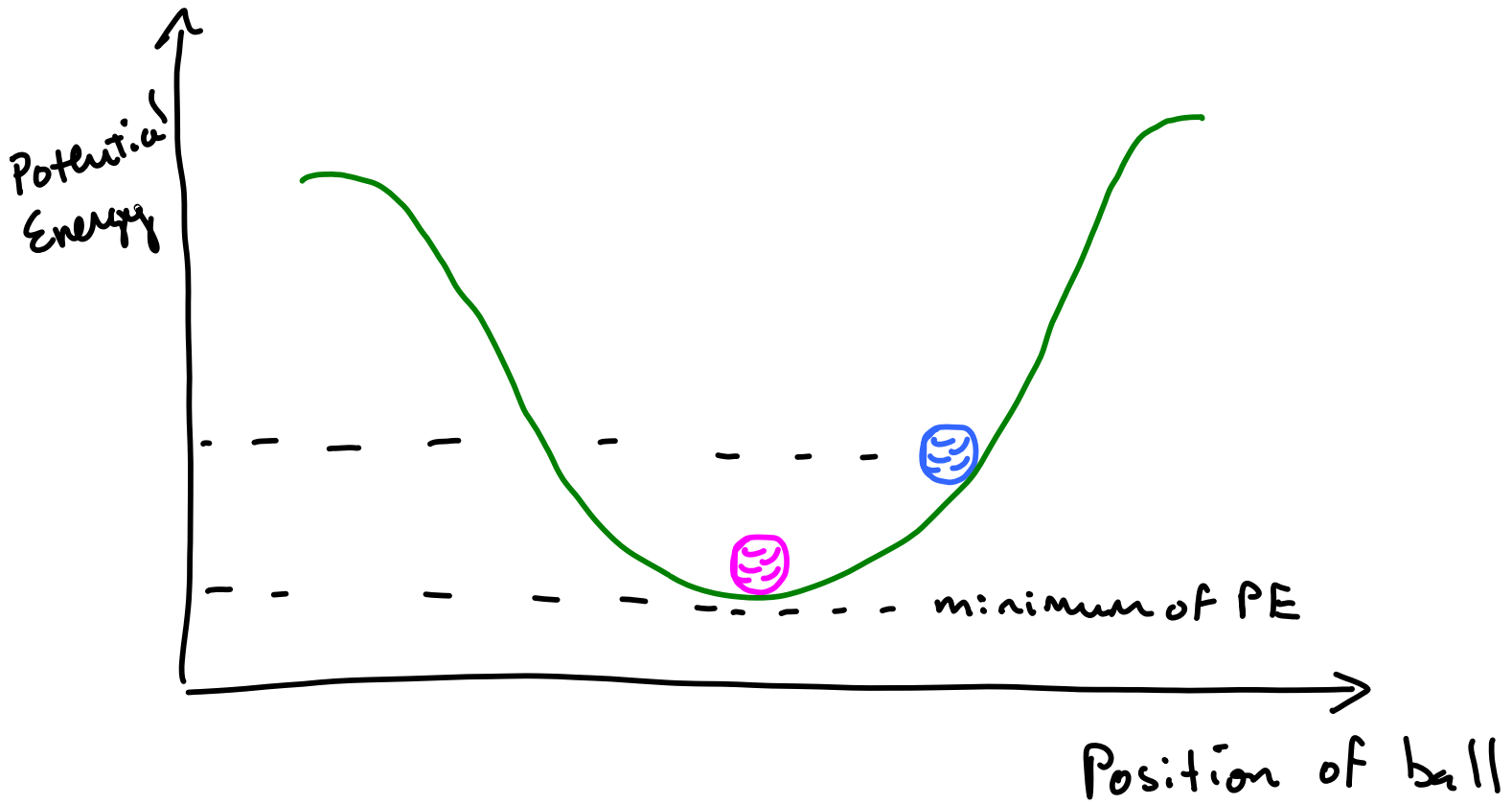
Vacuum "potential energy" depends on the details of the configuration of the different dimensions



Springs and Potential energy

gravitational Potential Energy



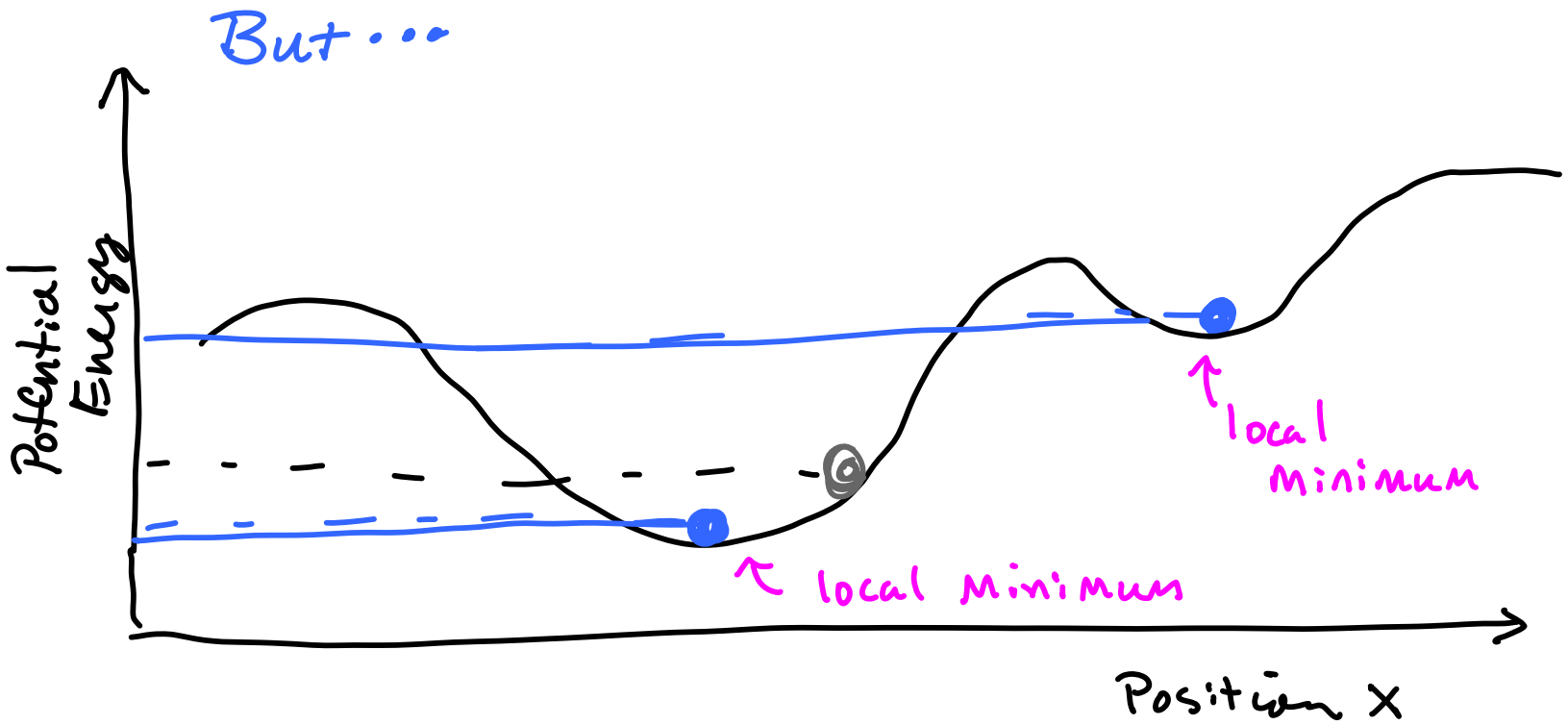


Different compactification schemes involve different degrees of potential energy stored in the "vacuum"

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

→ The Theory of Everything!!



Expect a huge # of compactification schemes to lie at local minima of the "potential energy" function

→ should be quasi stable or stable

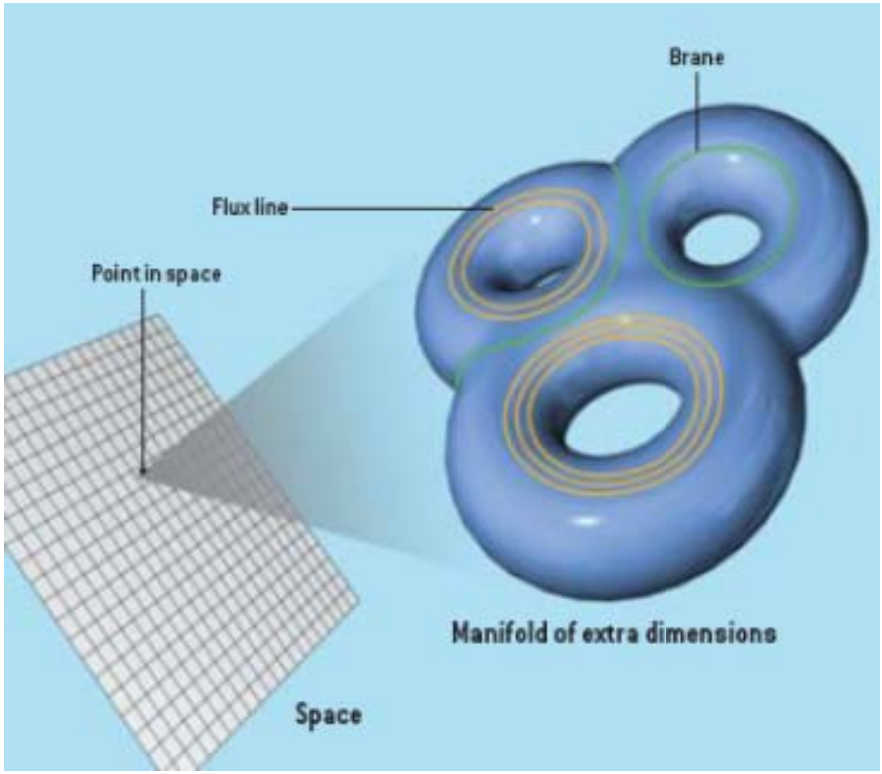
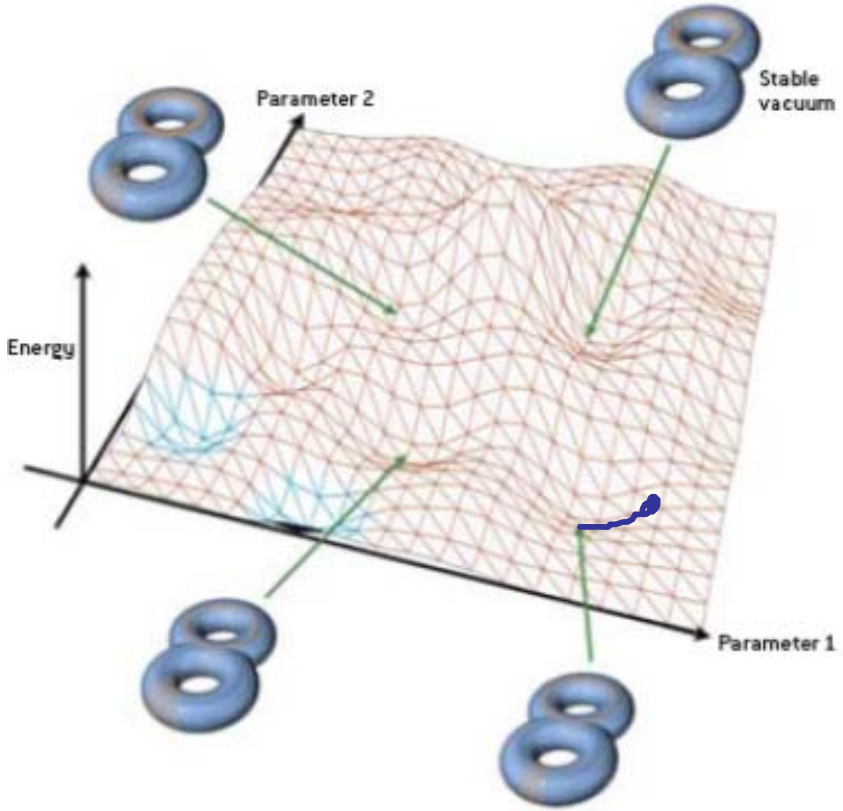


Fig from —
Bousso + Polchinski:
The String Theory Landscape
Sci. Am. 2004

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

The "vacuum energy" depends on This.



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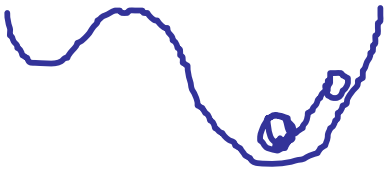
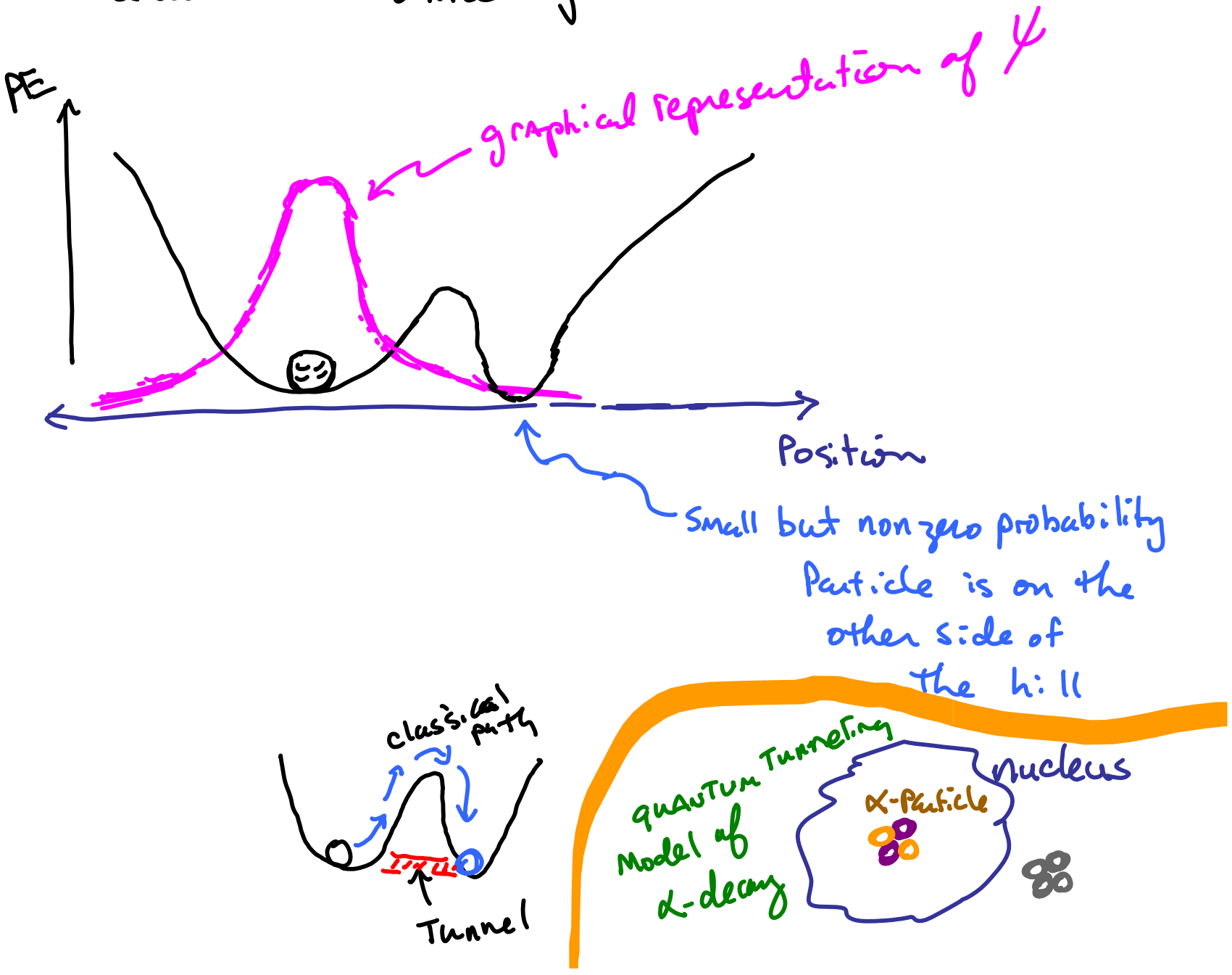


Different configurations → Different energies
→ Different locations in
the landscape of
Possibilities

Quantum Tunneling



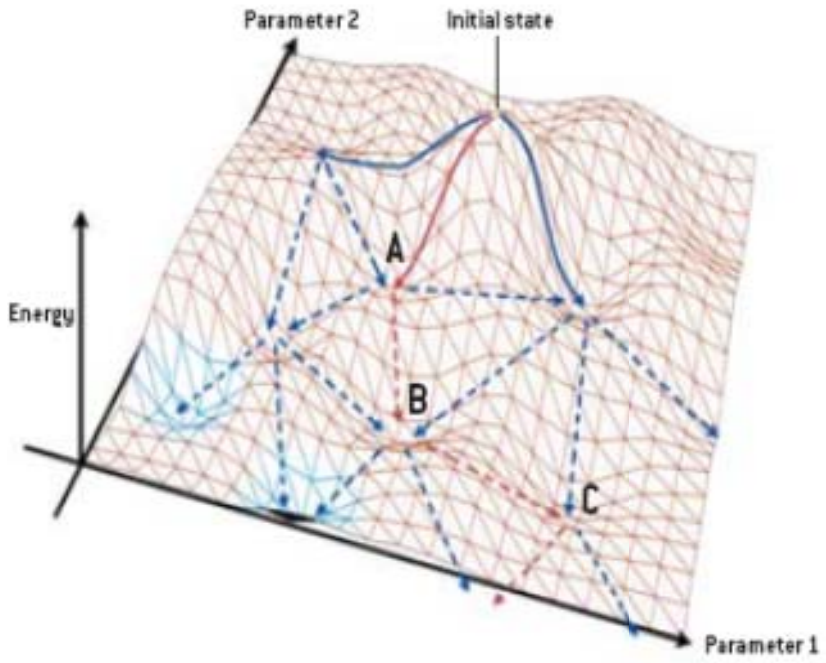
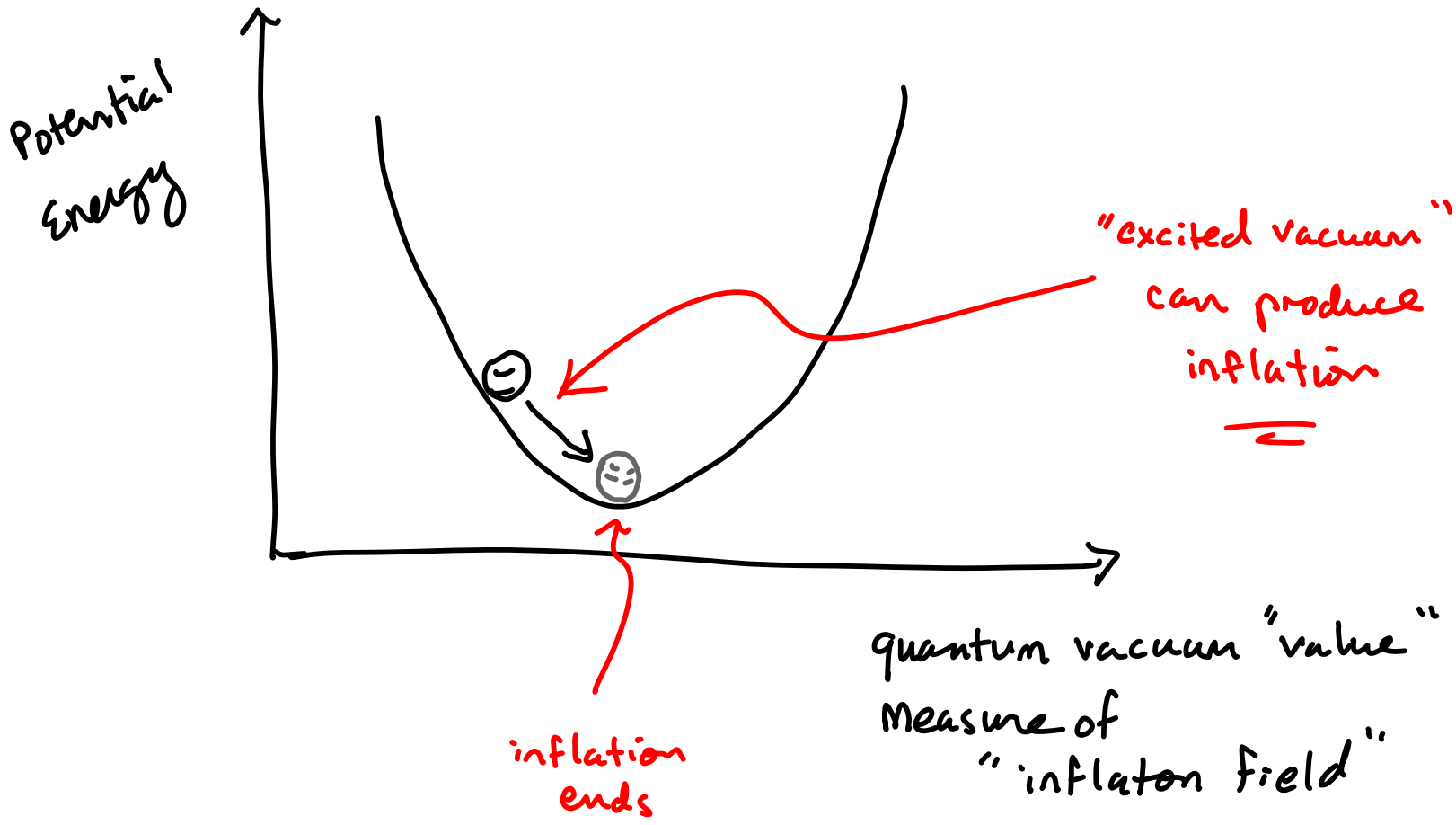


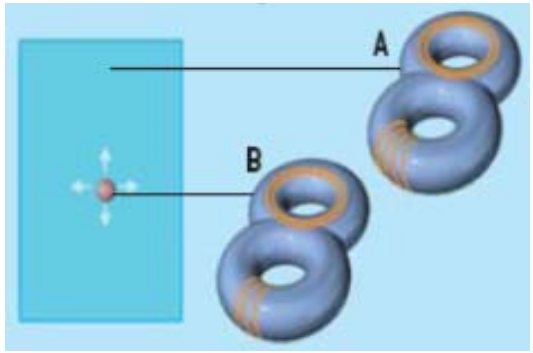
Fig from —
Bousso + Polchinski:
The String Theory Landscape
Sci. Am. 2004

- Different configurations of the String Theory vacuum are ~ stable
- Quantum mechanics allows one configuration to decay / fluctuate / tunnel to another configuration locally

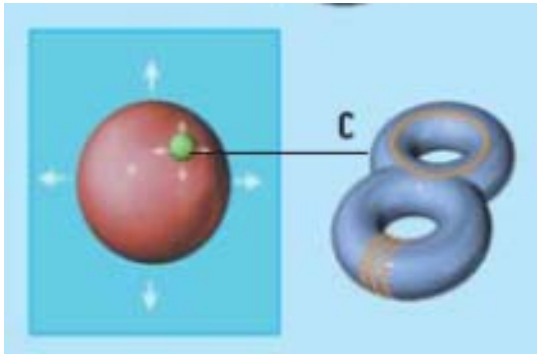
"False vacuum" and inflation



The cosmic Landscape of the Multiverse in String Theory



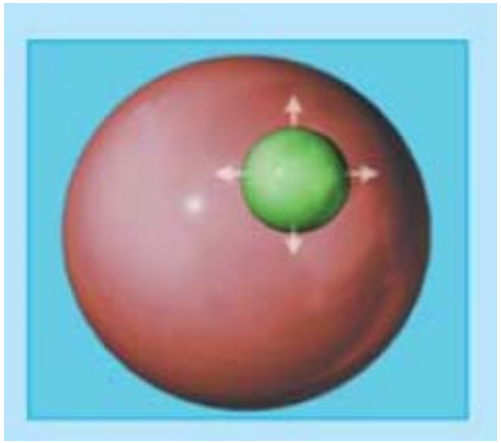
Tunneling from one stable vacuum to another would not occur everywhere in the universe at once. Instead it would occur at one random location, producing an expanding bubble of space (*arrows*) having the new vacuum. In this example, the blue region of space has vacuum A, whose manifold of small extra 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.



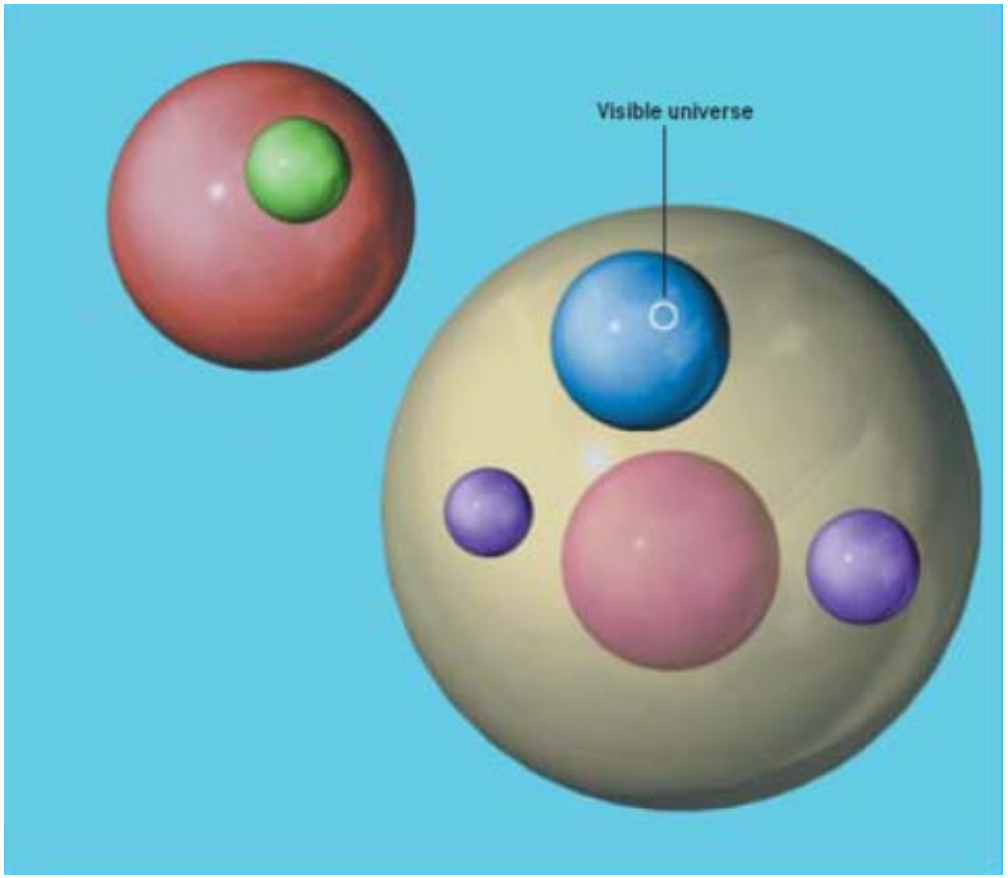
The red region grows rapidly, potentially becoming billions of light-years in diameter. Eventually another transition occurs within the red region, this time a decay of one of the two flux lines. This decay generates the green region, which has vacuum C and still another set of particles and forces.

Figures + text from

Bousso + Polchinski, "The String Theory Landscape", Sci. Amer. 2004



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.



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.

The cosmic landscape

Many (10^{500}) ways to compactify the extra dimensions → 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?