# Beyond General Relativity


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KICP Short Course

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# *Beyond* General Relativity?

- Einstein was right about gravity, wasn't he?

- Yes, in the same sense that Newton was right:

# *Beyond* General Relativity?

- Einstein was right about gravity, wasn't he?
- Yes, in the same sense that Newton was right:
- In a well-defined regime of length scales, time scales, and energy scales, General Relativity is well tested and verified

| | GR |
|---|---|
| Solar system | x |
| Binary pulsar | x |
| BB nucleosynthesis | x |
| Lensing by clusters | x |
| Power spectrum | x |
| CMB (+ $H_0$) | x |
| Supernovae | x |

# *Beyond* General Relativity?

- But why would anyone think that Einstein gravity is the end of the story, any more than Newtonian gravity was the end of the story?

- And there are many outstanding mysteries that hint in the direction that GR is only an approximation…

# Quantum GR?

- GR is a classical theory, but the rest of physics is quantum
- You can try to promote GR to a quantum field theory similar to the Standard Model of particle physics, but a few embarrassing things happen:

# Quantum GR?

- Quantum GR has a built-in energy scale of $10^{19}$ GeV, the "Planck scale", related to the measured value of Newton's gravitational constant
- In quantum GR all hell should break loose (an infinite number of new interactions) as you approach this scale
- Furthermore there should be a gigantic cosmological constant (vacuum energy) from the quantum effects of gravity talking to matter
- So something is too naïve about this picture…

# Why is gravity so weak?

Gravity is in some sense about $10^{39}$ times weaker than electromagnetism – why?

Another way to say it is that (naively) gravity is incredibly weak at observable energies but would appear strong if you could probe the Planck energy scale

$$\frac{e^2}{4\pi\ r^2} \qquad \frac{G m_p m_e}{r^2} \qquad 2.3 \times 10^{39}$$

$$M_{Planck} = \sqrt{\frac{\hbar c}{G}} = 1.22 \times 10^{19}\ \mathrm{GeV}/c^2$$

# Dark Energy

- The observed accelerating expansion of the universe *could* be the result of a cosmological constant

- Or it could be the result of a modification of GR

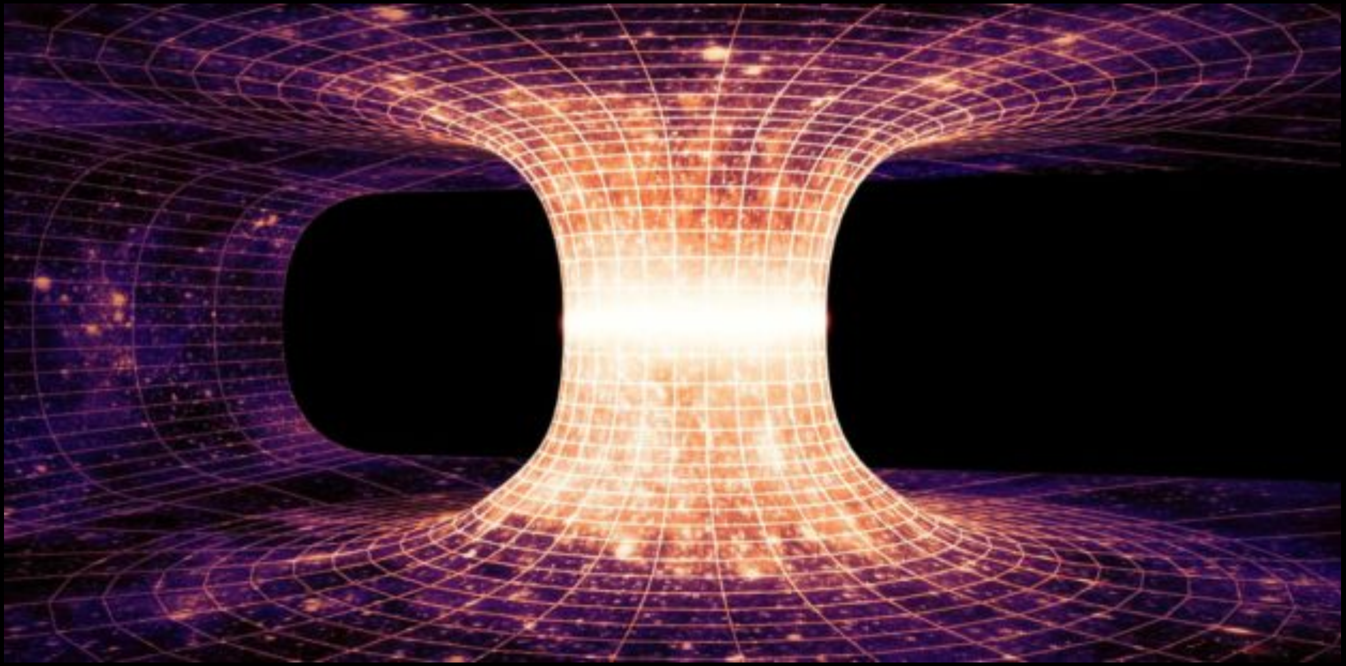
- Or it could be a side effect of a new long range force in addition to gravity

# Dark Matter

- The MOND idea says perhaps the rotation curves of galaxies are explained by mutilating the laws of physics, instead of by the existence of dark matter

# GR singularities

- In GR there are theorems that prove that Black Holes have singularities
- And that the Big Bang came from a singularity
- But singularities are unphysical, so something is wrong…



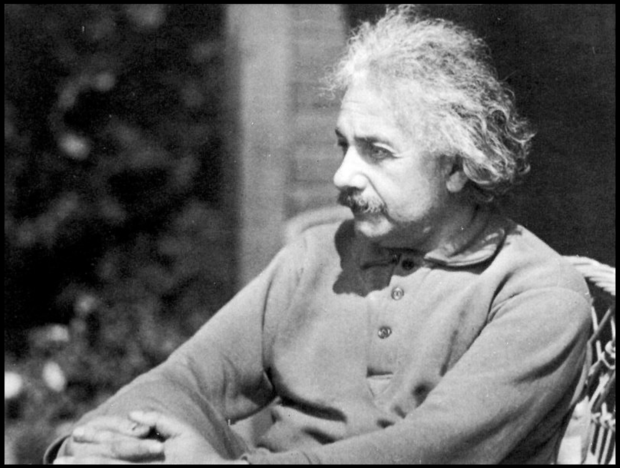
# Beyond GR: scenarios

Some scenarios, in increasing order of radicalism:

- Scalar-tensor gravity, aka Jordan-Brans-Dicke theory
- Extra dimensions
- Holography and the multiverse
- Spacetime emerging from quantum entanglement

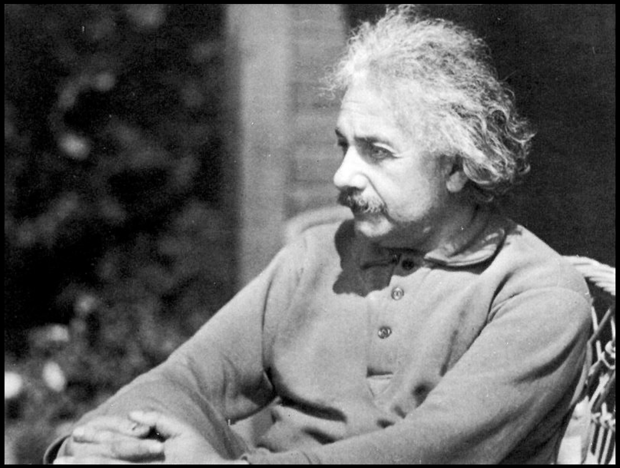
# Scalar-Tensor Gravity

- In 1915 there were two competing relativistic theories of gravity, one from Einstein and the other from the Finnish physicist Gunnar Nordstrom



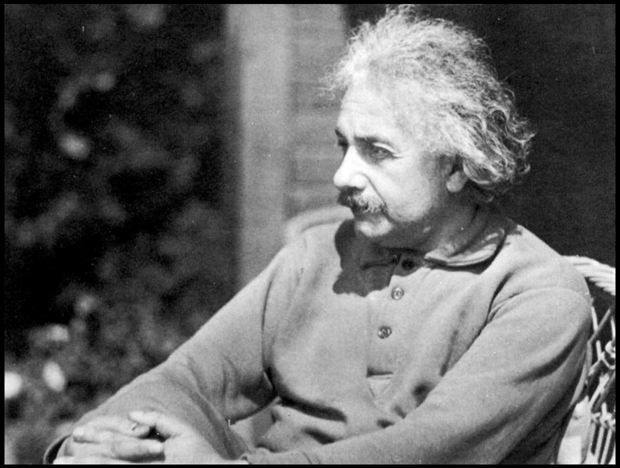
# Scalar-Tensor Gravity

In Einstein's theory gravity is a *tensor* force, related to the curvature *tensor* of spacetime, which is affected by the stress-energy *tensor* induced by matter and radiation



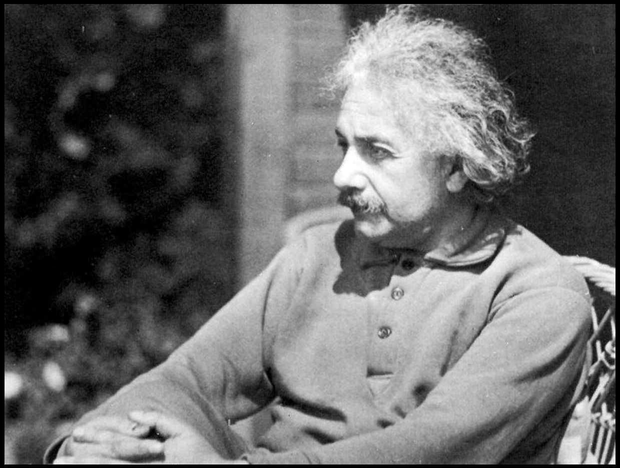
# Scalar-Tensor Gravity

In Nordstrom's theory gravity is a *scalar* force, related to the curvature *scalar* of spacetime, which is affected by the *trace* of the stress-energy tensor induced by matter and radiation



# Scalar-Tensor Gravity

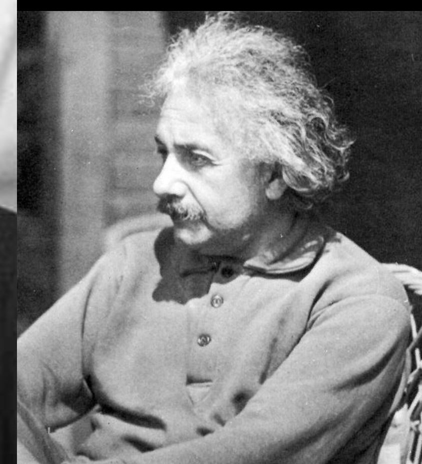
- Nordstrom's theory is simpler than Einstein's
- In particle physics jargon, Einstein gravity is communicated by a massless spin 2 graviton, while Nordstrom gravity is communicated by spin 0 scalar, a massless cousin of the Higgs boson



# Scalar-Tensor Gravity

Nordstrom’s theory was proved wrong in 1915 by a better measurement of the advance of the perihelion of Mercury, and then famously in 1919 when Eddington showed that starlight is bent by the gravity of the Sun

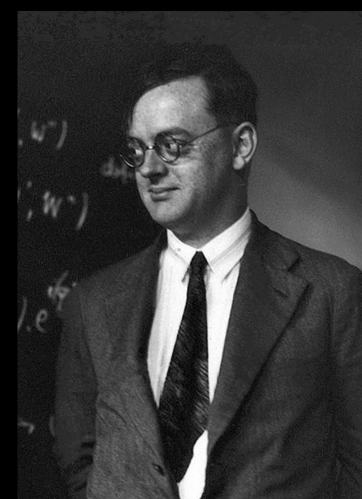




# Scalar-Tensor Gravity

However it is still possible that some kind of scalar gravity exists, as long as it is in addition to, and sufficiently sub-dominant to, tensor gravity

An example is the theory of Carl Brans and Robert Dicke, that built upon the work of Pascual Jordan



# Scalar-Tensor Gravity

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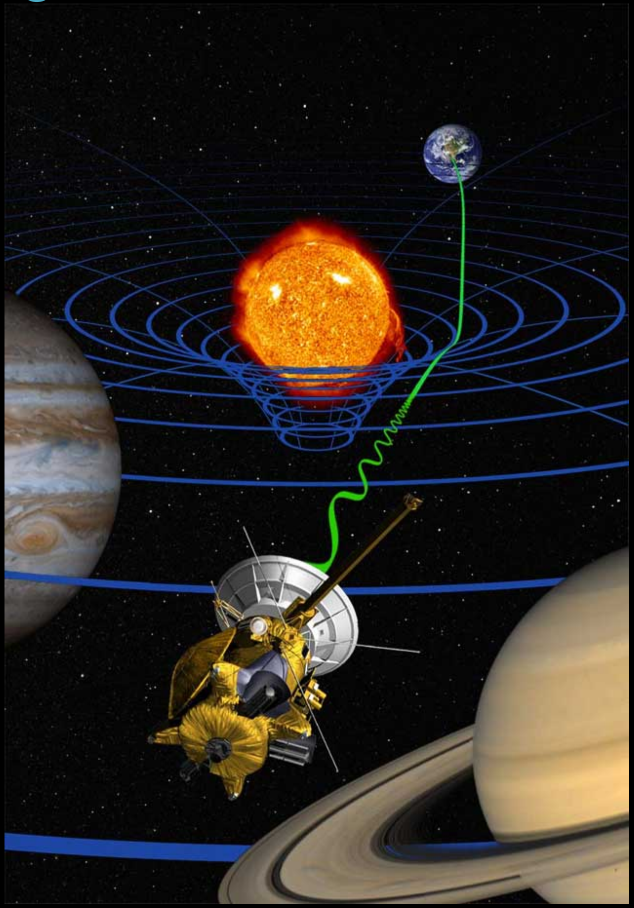
In their theory GR is supplemented by force related to a massless scalar

Newton's gravitational constant G can in principle depend on the scalar field, so GR and the scalar are intertwined

# Scalar-Tensor Gravity

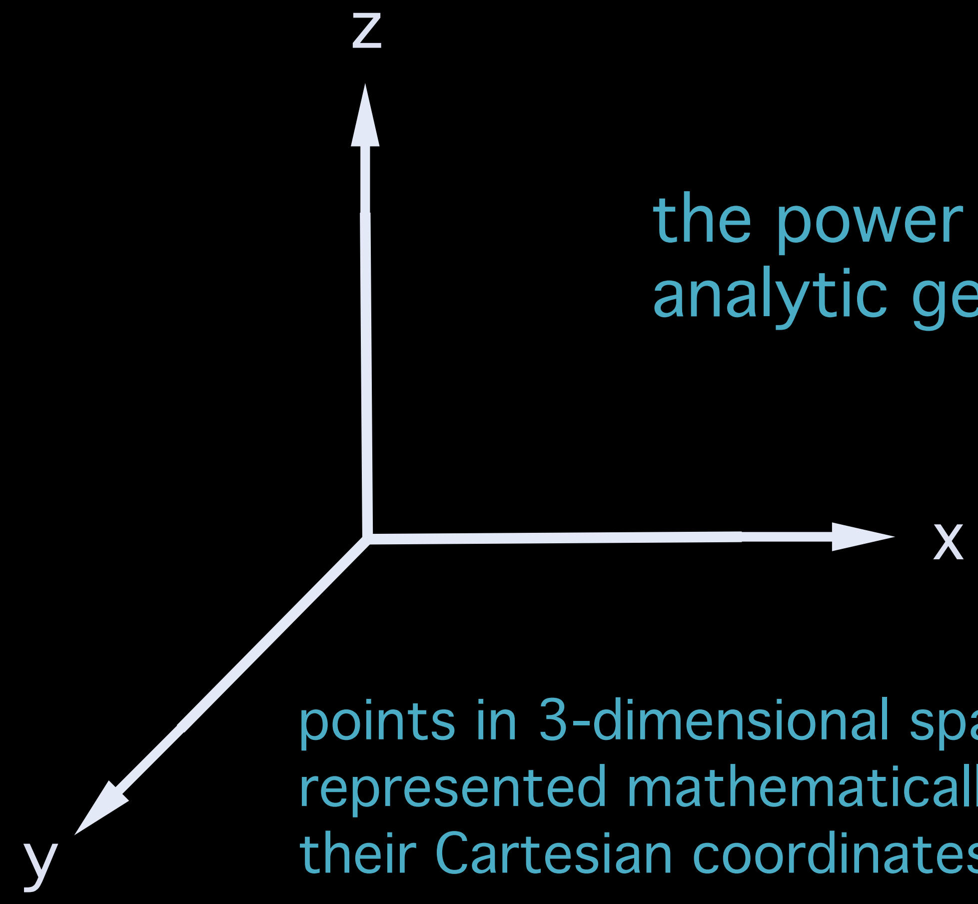
- A dimensionless parameter (i.e. a number) called $\omega$ represents how sub-dominant is the scalar force
- When $\frac{1}{\omega} \to \mathbf{0}$ you get back to regular GR
- Latest data from the Cassini mission requires

$$\frac{1}{\omega} < \mathbf{0.000025}$$



# what is a dimension?

Rene Descartes

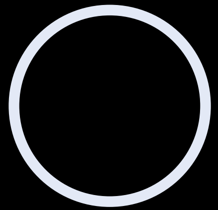



the power of
analytic geometry

points in 3-dimensional space
represented mathematically by
their Cartesian coordinates x,y,z

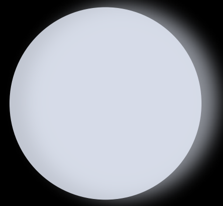
## equations replace pictures:

$$\mathbf{x^2 + y^2 = 1}$$



circle

$$\mathbf{x^2 + y^2 + z^2 = 1}$$



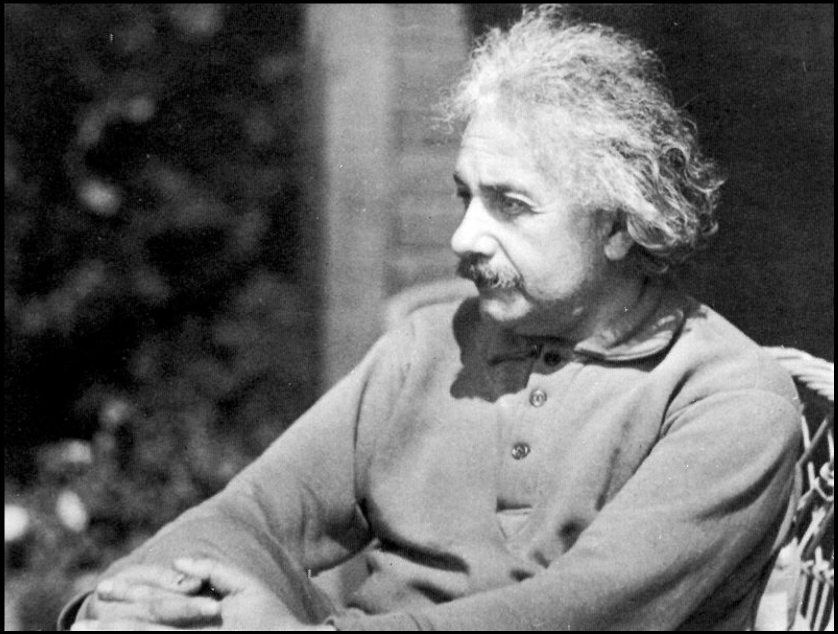
sphere

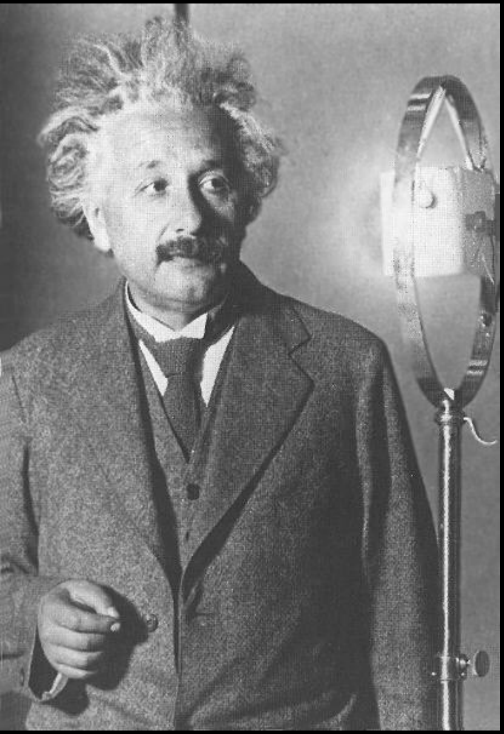
$$\mathbf{x^2 + y^2 + z^2 + w^2 = 1}$$

hypersphere

- extra dimensions make sense in mathematics
- do they also make sense in physics?
- could there be more physical dimensions than the three that we see?
- if so, why are the extra dimensions hidden?
- and what are they good for?

# parents of extra dimensions





# “time is the fourth dimension”

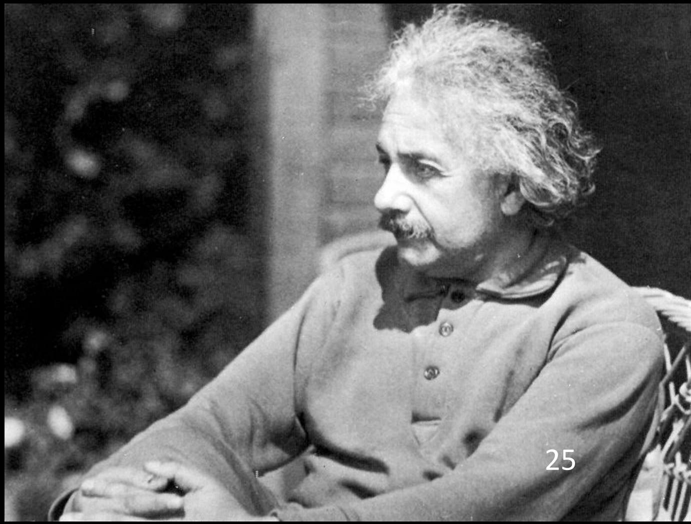
A. Einstein, 1905

- four dimensional space-time: x,y,z, and t
- there is a universal constant, called “c”, which converts measurements of time into measurements of space.
- c = 299,792 kilometers per second

# the fifth dimension

Already in 1914, Gunnar Nordstrom showed that gravity and electromagnetism could be unified as a single force, in a theory with an extra spatial dimension

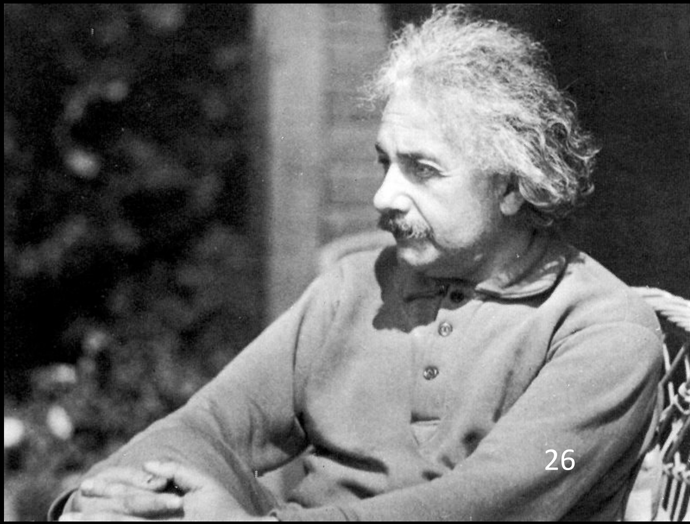
Einstein ignored Nordstrom's idea, probably because it used Nordstrom's own theory of gravity, which was then in competition with Einstein's



# the fifth dimension

in 1919, Polish mathematician Theodor Kaluza again introduced the idea of a fifth dimension, but this time using Einstein's theory of gravity - this made all the difference:

"The idea of achieving [a unified theory] by means of a five-dimensional cylinder world never dawned on me... At first glance I like your idea enormously"

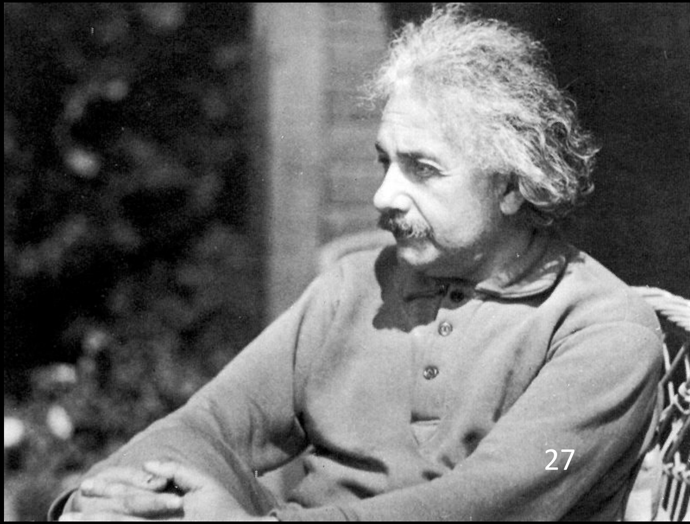


# the fifth dimension is a circle

Nordstrom, Kaluza, and Einstein all assumed that the fifth dimension wasn't real, since otherwise why don't we see it?

in 1926, Swedish physicist Oskar Klein proposed that the fifth dimension was real, but too tiny to see

"Klein's paper is
beautiful and impressive."

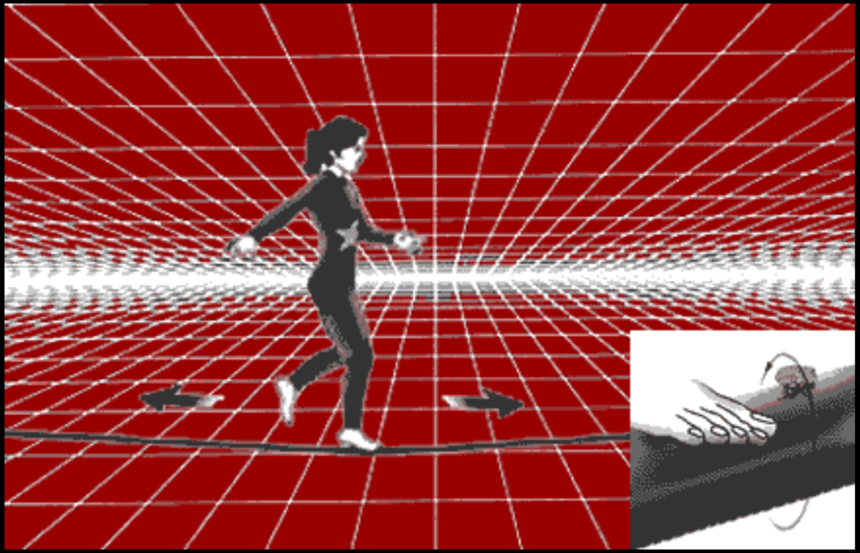


# the fifth dimension is a circle

Klein computed how small the circle of the 5th dimension should be, in order to give a unified theory of gravity and electromagnetism

the answer is:

.00000000000000000000000000000001 centimeters



# nobody thought about extra dimensions for 50 years



# string theory

John
Schwarz

in the 1970s some
visionary physicists began
to construct a
radical new theory

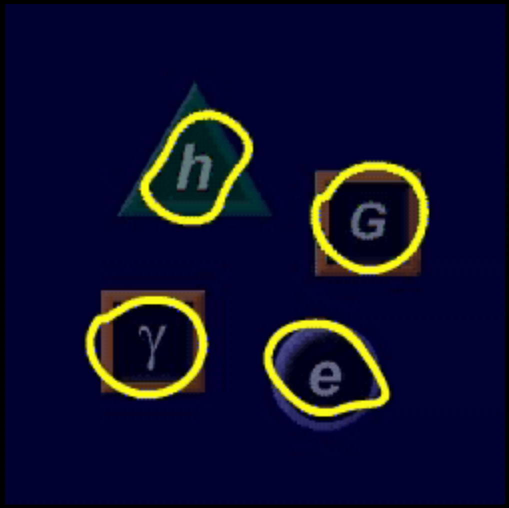
Pierre
Ramond

in this theory all of the
elementary particles are
just different vibrations
of microscopic strings

Gabriele
Veneziano

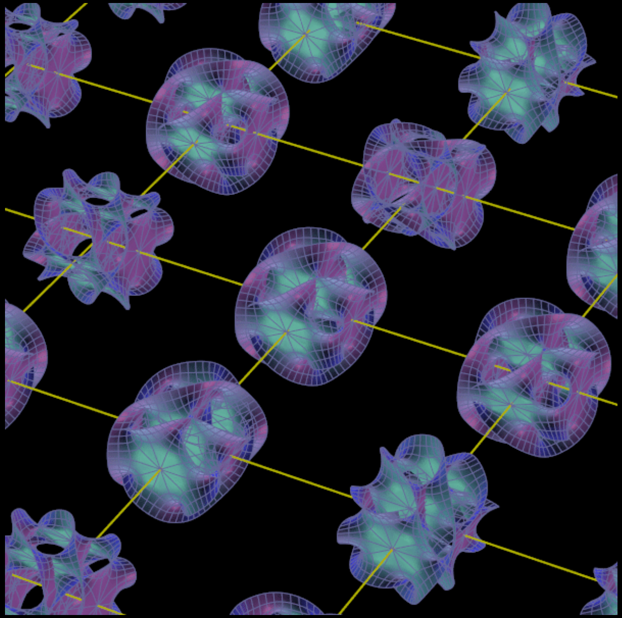
# string theory

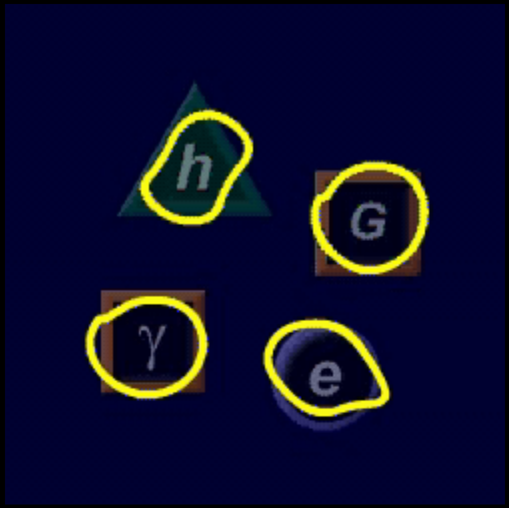
in string theory, all the elementary particles are merely different vibrations of a single substance called strings



physicists have shown that quantum theory only allows one *unique* theory of quantum strings… but there is a catch:

**quantum strings need 9 spatial dimensions to wiggle in!**





# particles from strings

- to us, a microscopic wiggling string looks like a particle, because the string is too small for us to notice either its size or its wiggles

- the momentum of the string vibrations, and the energy of the string stretching, will look to us like the mass of the "particle"

- this mass can be computed from Einstein's famous formula:

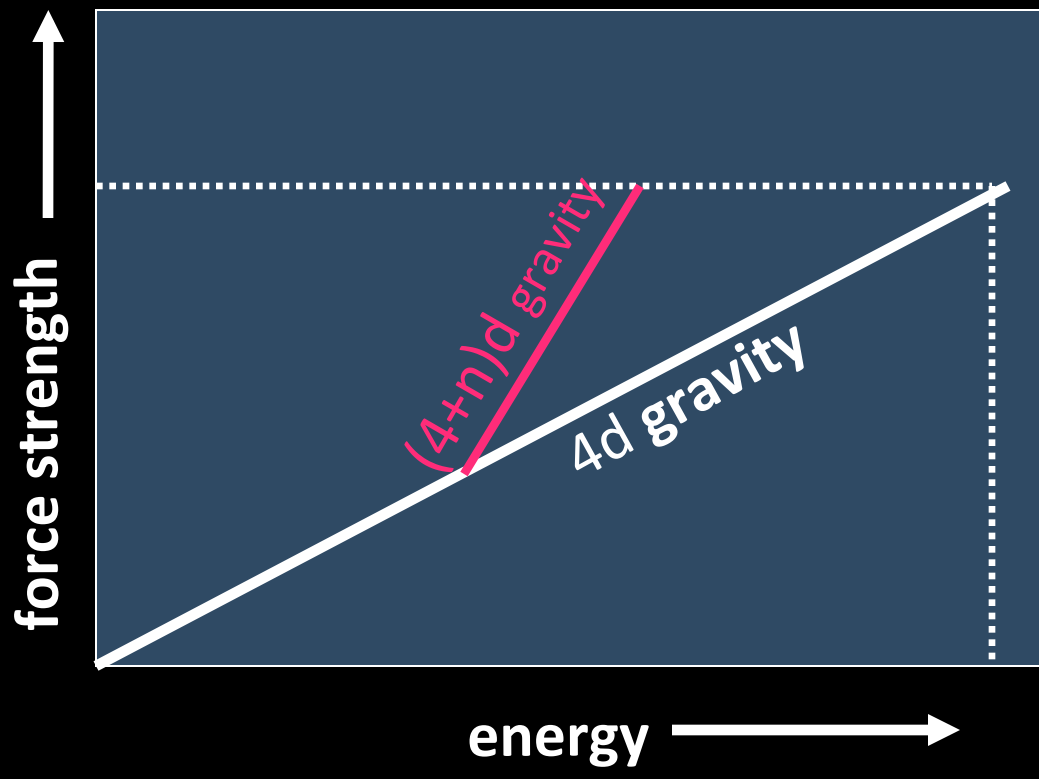
$$\mathbf{E^2 - (p_x c)^2 - (p_y c)^2 - (p_z c)^2 = (mc^2)^2}$$

- string theory is very elegant mathematically
- but if we take string theory seriously, it makes a firm prediction that there are (many) extra dimensions of space
- is this testable?

think_about this:

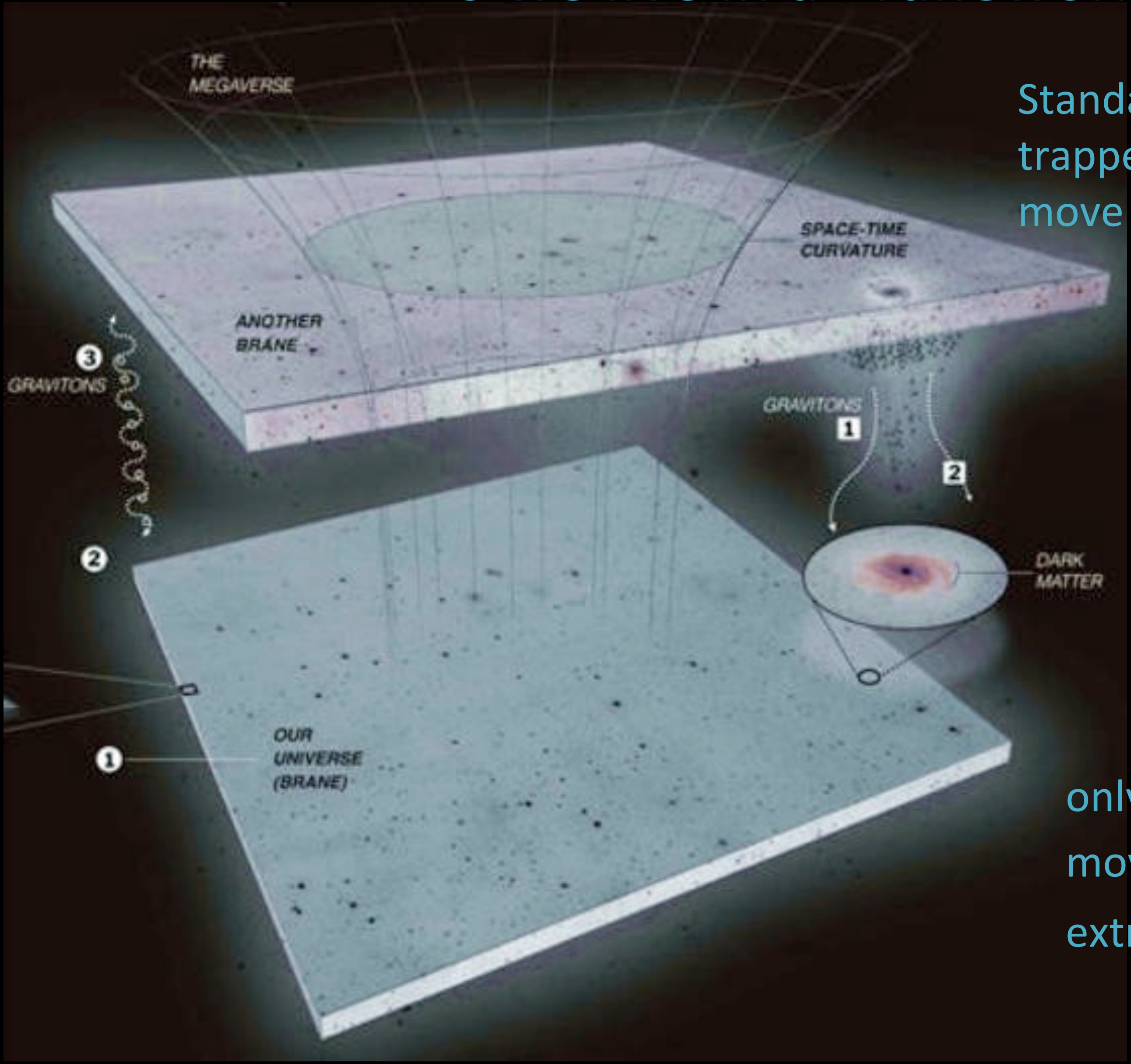
In GR gravity gets stronger at extremely high energies ~ $10^{19}$ GeV (the Planck scale)

**it gets stronger at not-so-high energies if there are extra dimensions….**



think way different

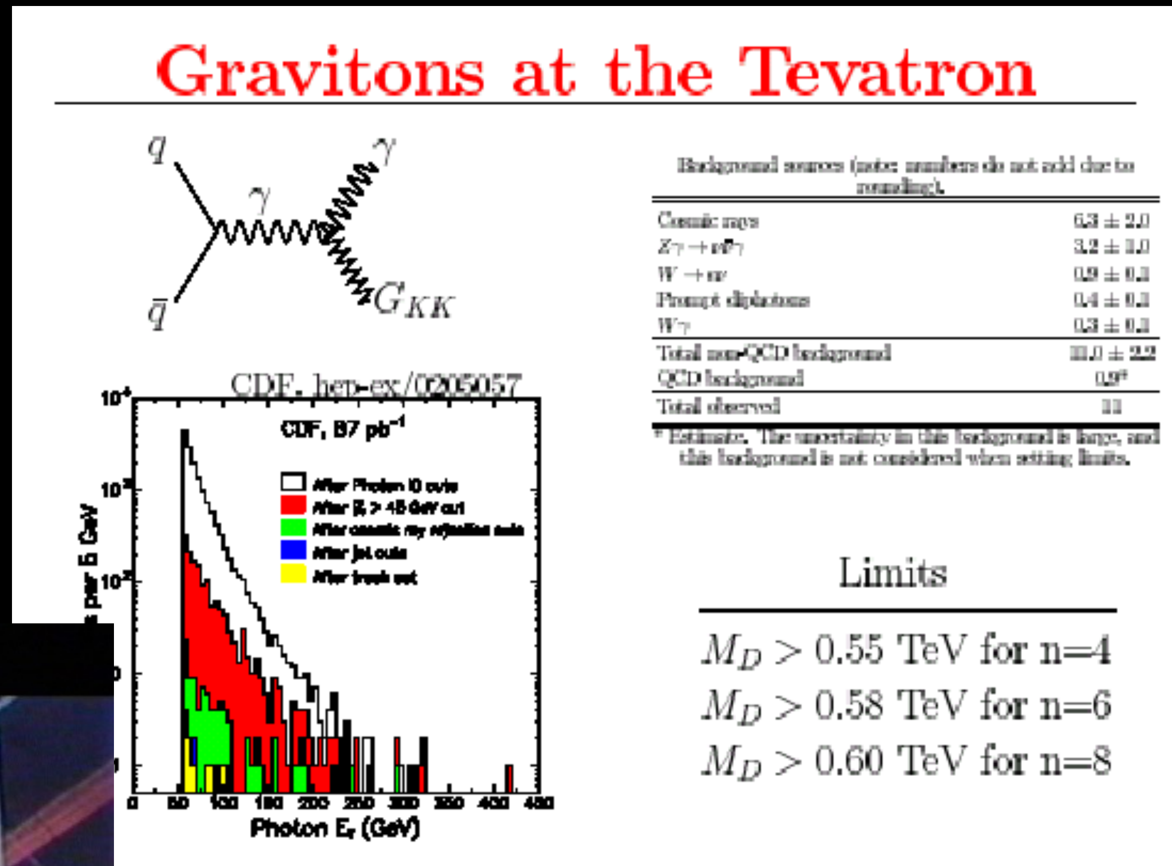
# Do we live in a Braneworld?




Standard Model particles are trapped on a brane and can't move in the extra dimensions

only gravitons and exotics move in the "bulk" of the extra dimensional universe

# What happens if gravity becomes strong at energies accessible to the LHC?



# Gravitons at the Tevatron



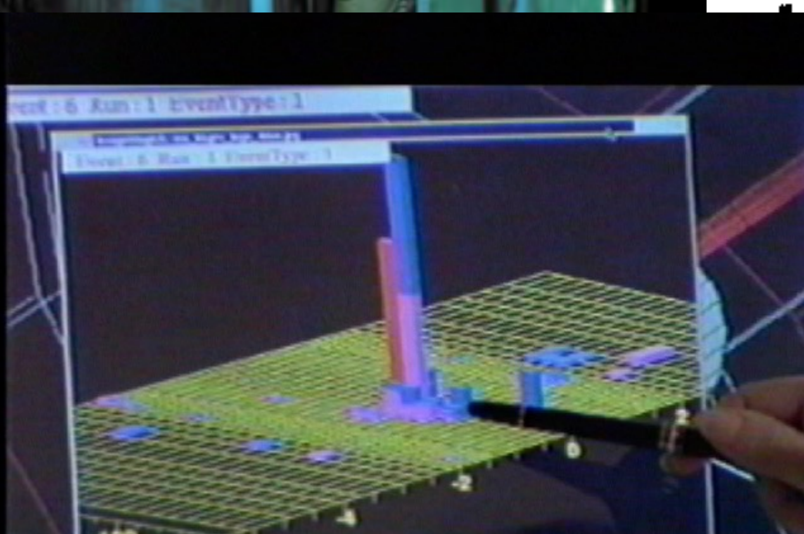
Background sources (note: numbers do not add due to rounding).

| | |
|---|---|
| Cosmic rays | $6.3 \pm 2.0$ |
| $Z\gamma \to \nu\bar{\nu}\gamma$ | $3.2 \pm 1.0$ |
| $W \to e\nu$ | $0.9 \pm 0.1$ |
| Prompt diphotons | $0.4 \pm 0.1$ |
| $W\gamma$ | $0.3 \pm 0.1$ |
| Total non-QCD background | $11.0 \pm 2.2$ |
| QCD background | $0.9^*$ |
| Total observed | 11 |

* Estimate. The uncertainty in this background is large, and this background is not considered when setting limits.

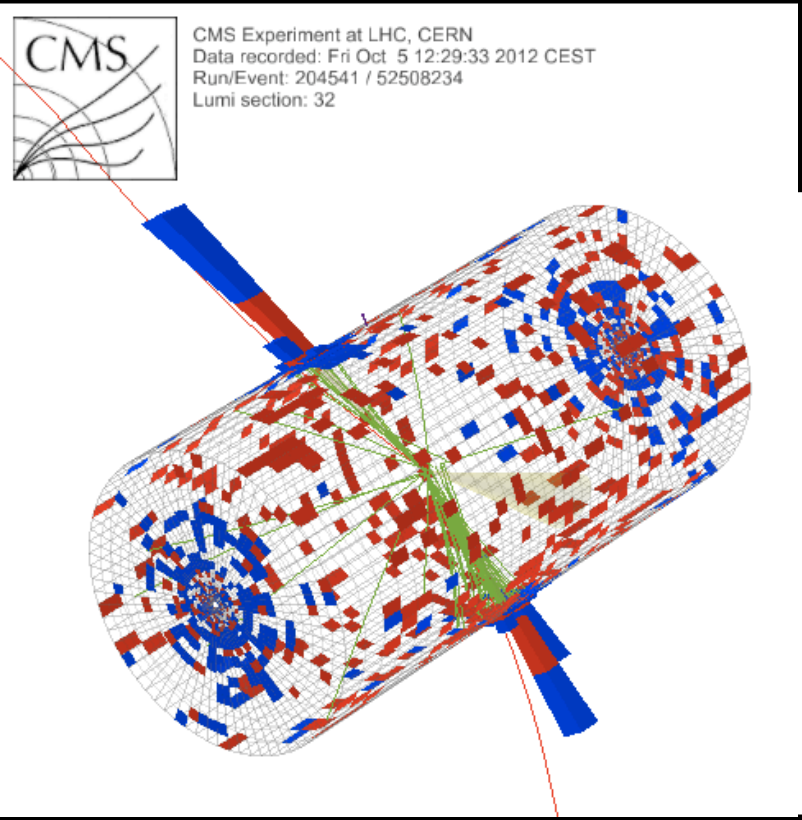
Limits

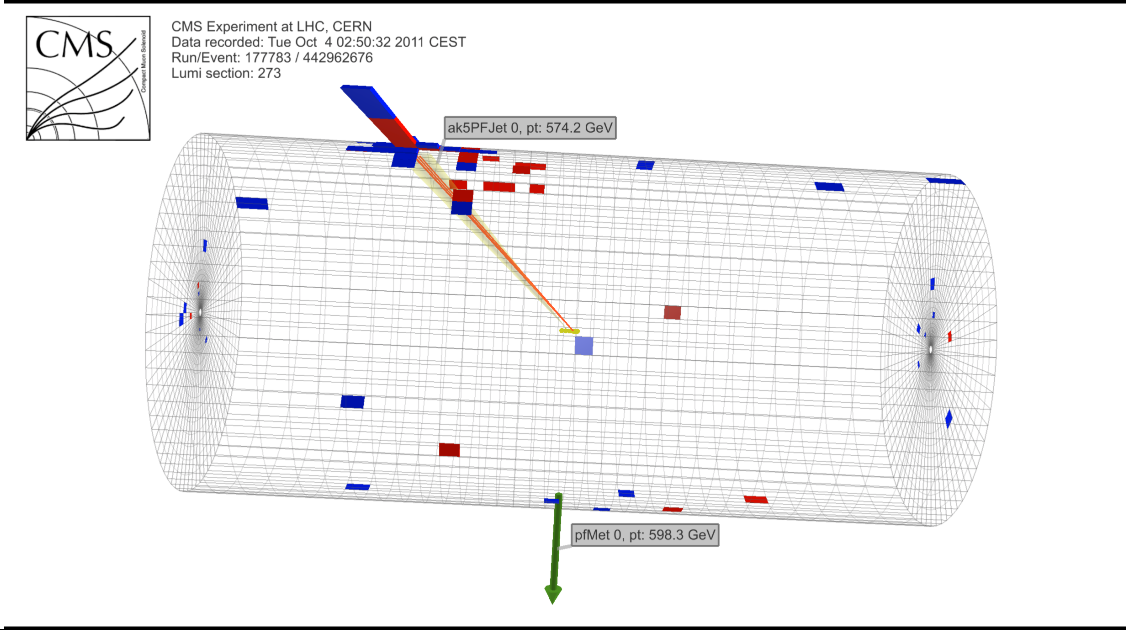
$M_D > 0.55$ TeV for n=4
$M_D > 0.58$ TeV for n=6
$M_D > 0.60$ TeV for n=8



Maria Spiropulu figured out how to do this first at the Fermilab Tevatron

# Gravitons at the LHC?




Typical high energy LHC collision producing two balanced jets of high energy particles

Unbalanced "monojet" recoiling against something undetected: could be a graviton (or neutrinos)

# Was Friedmann Wrong?

Cosmology in GR mostly boils down to one equation, the Friedmann (-Lemaitre-Robertson-Walker) Equation:

$$\mathbf{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{\rho_0^{\mathrm{mat}}}{a^3} + \frac{\rho_0^{\mathrm{rad}}}{a^4}\right) - \frac{kc^2}{a^2} + \frac{1}{3}\Lambda c^2}$$

This equation makes lots of things obvious like:

- A radiation-dominated expansion eventually becomes matter-dominated
- A matter-dominated expansion slows down
- Any cosmological constant will eventually dominate the expansion and cause it to speed up

# Was Friedmann Wrong?

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If GR is modified in a way that affects cosmology, you would expect it show up as a modification of this equation

You can also turn this around and ask what kinds of modifications are interesting and observable

# Was Friedmann Wrong?

Extra dimensions with braneworlds can modify the left-hand side of the Friedmann equation

$$\mathbf{H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left(\frac{\rho_0^{\rm mat}}{a^3} + \frac{\rho_0^{\rm rad}}{a^4}\right) - \frac{kc^2}{a^2} + \frac{1}{3}\Lambda c^2}$$

$$\mathbf{H^2 \to H^2 - m_0\, H}$$

In that case dark energy could be replaced by a "self-accelerating" solution with braneworlds

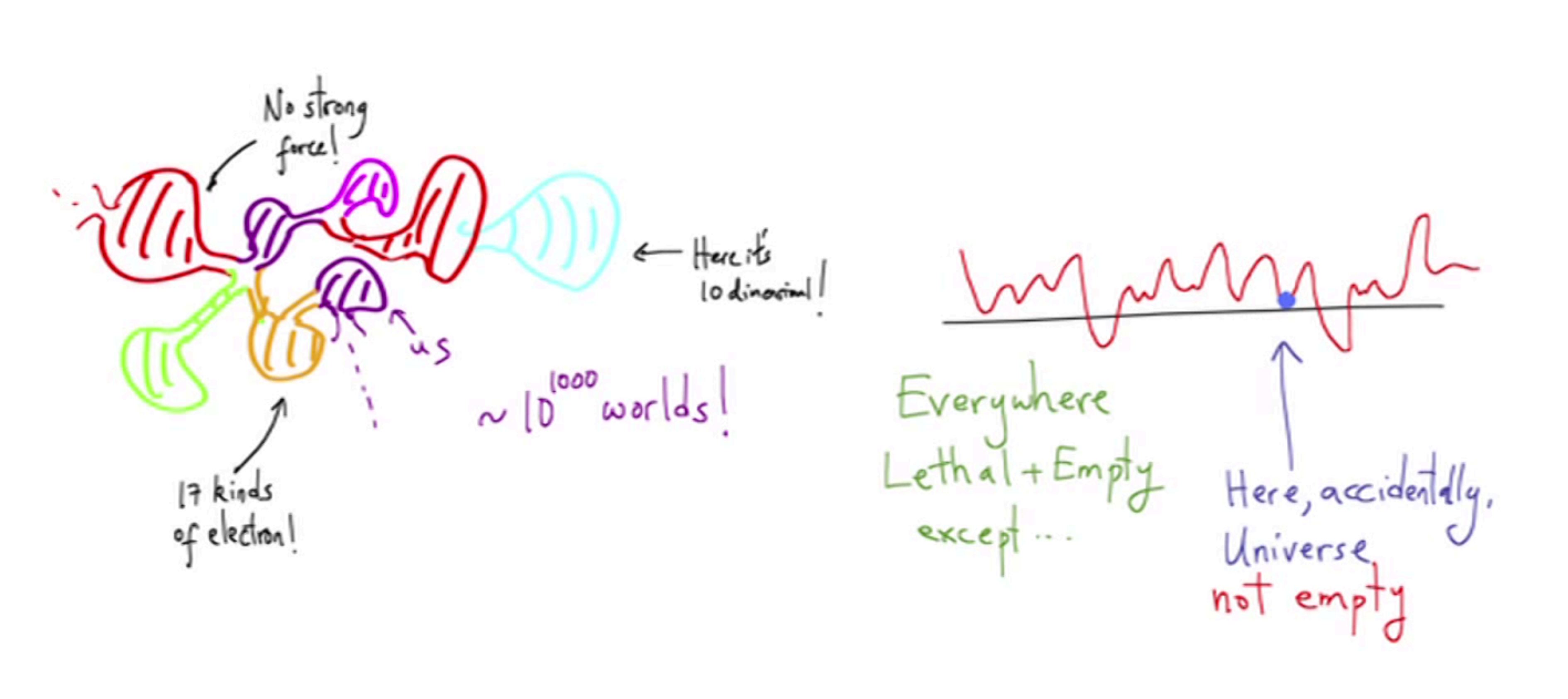
$$\mathbf{H^2 = \frac{1}{3}\Lambda c^2 \quad \to \quad H^2 - m_0\, H = 0}$$

# Multiverse cosmology

- The multiverse is a possible byproduct of the idea of primordial cosmic inflation
- This idea implies that the entire observed universe is contained in a single inflated bubble of space
- It is at least plausible that the mechanism that produced this inflating bubble also produced many other bubbles (perhaps due to quantum fluctuations) and may even be producing new bubbles today

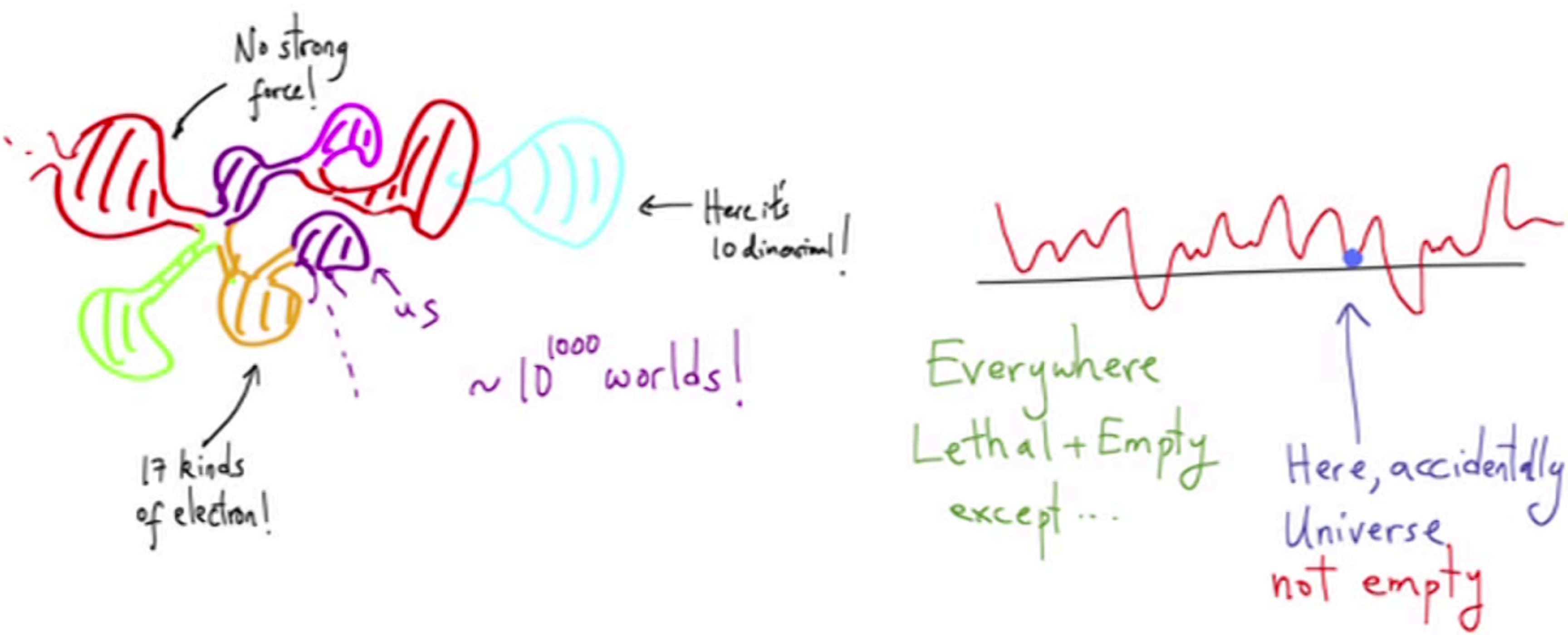
# Multiverse cosmology

As illustrated here by Nima Arkani-Hamed, physics as seen in each bubble may look very different



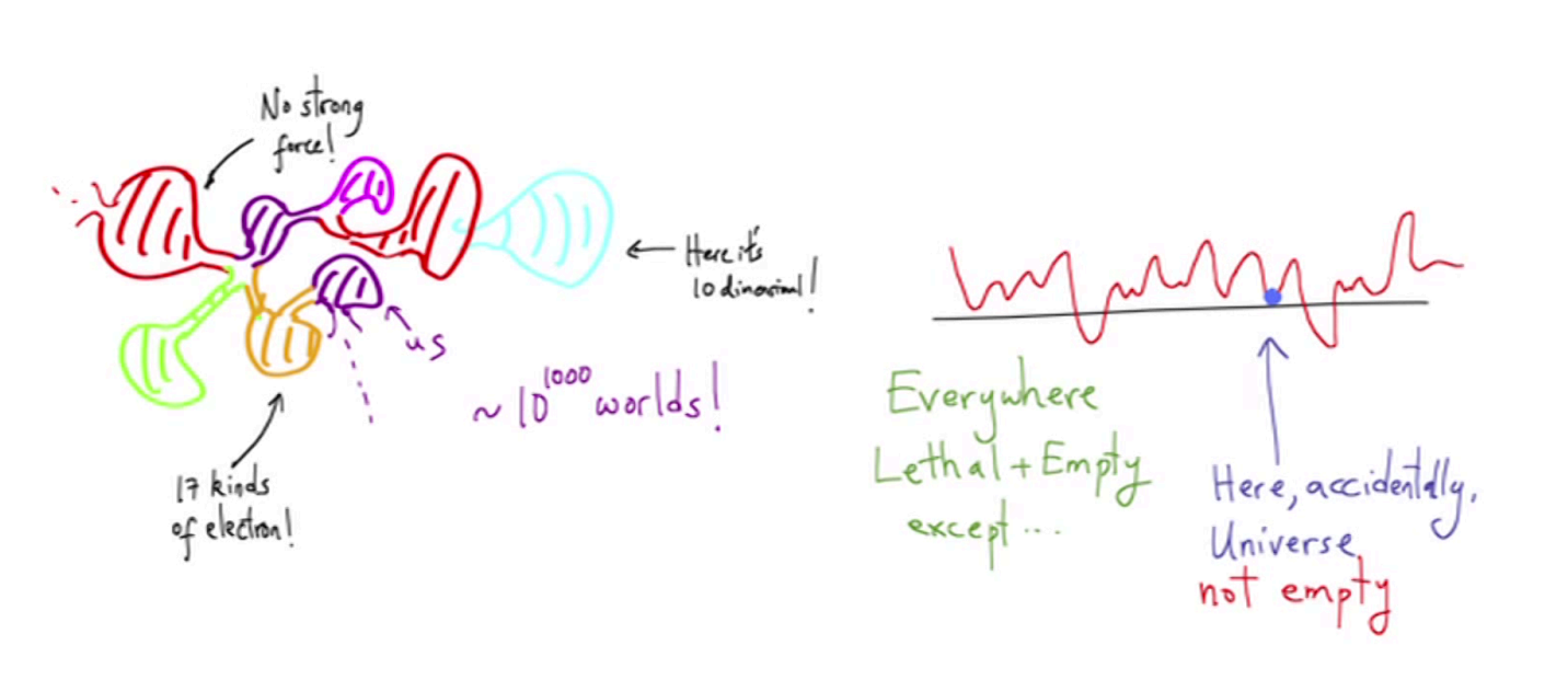
# Multiverse cosmology

This expanded but speculative view of cosmology is called the multiverse



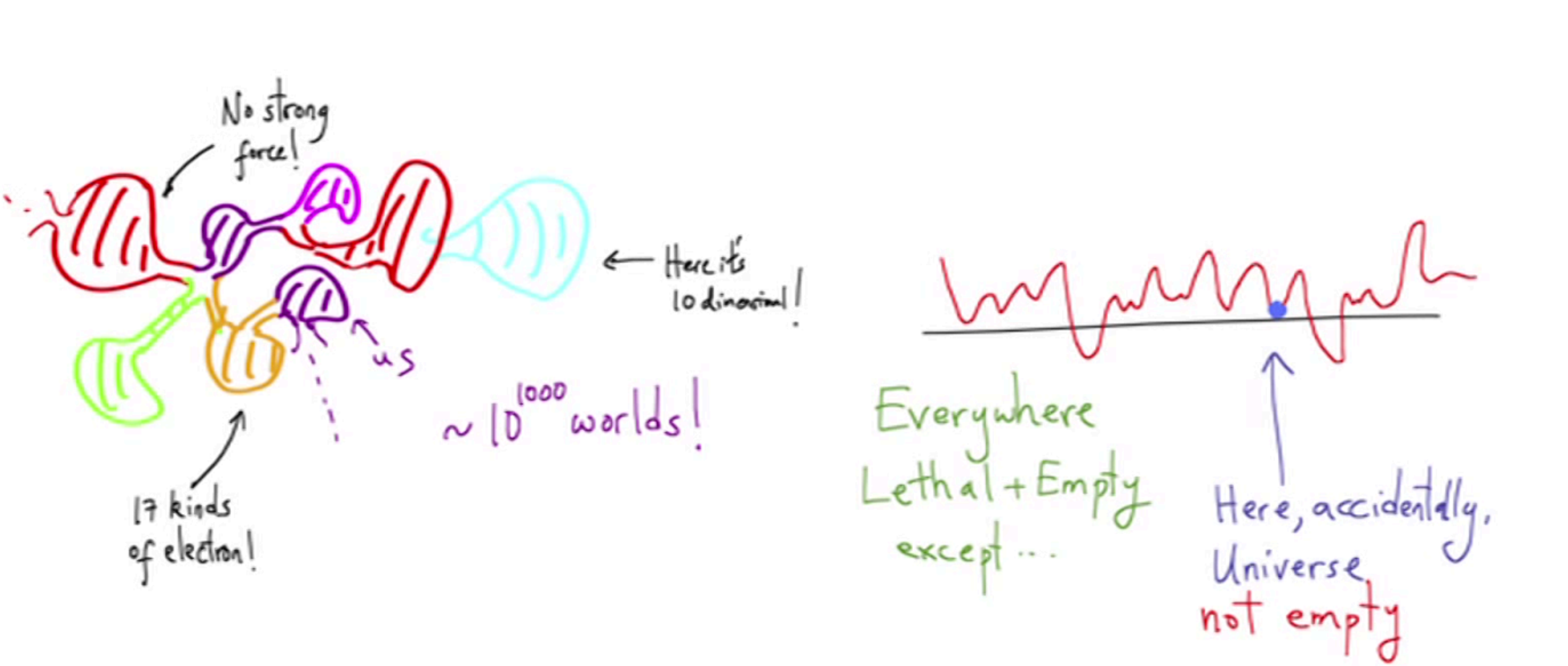
# Multiverse cosmology

It looks especially interesting in string theory, where the $10^{1000}$ bubbles can all have different particles, forces, dimensionalities, and vacuum energies



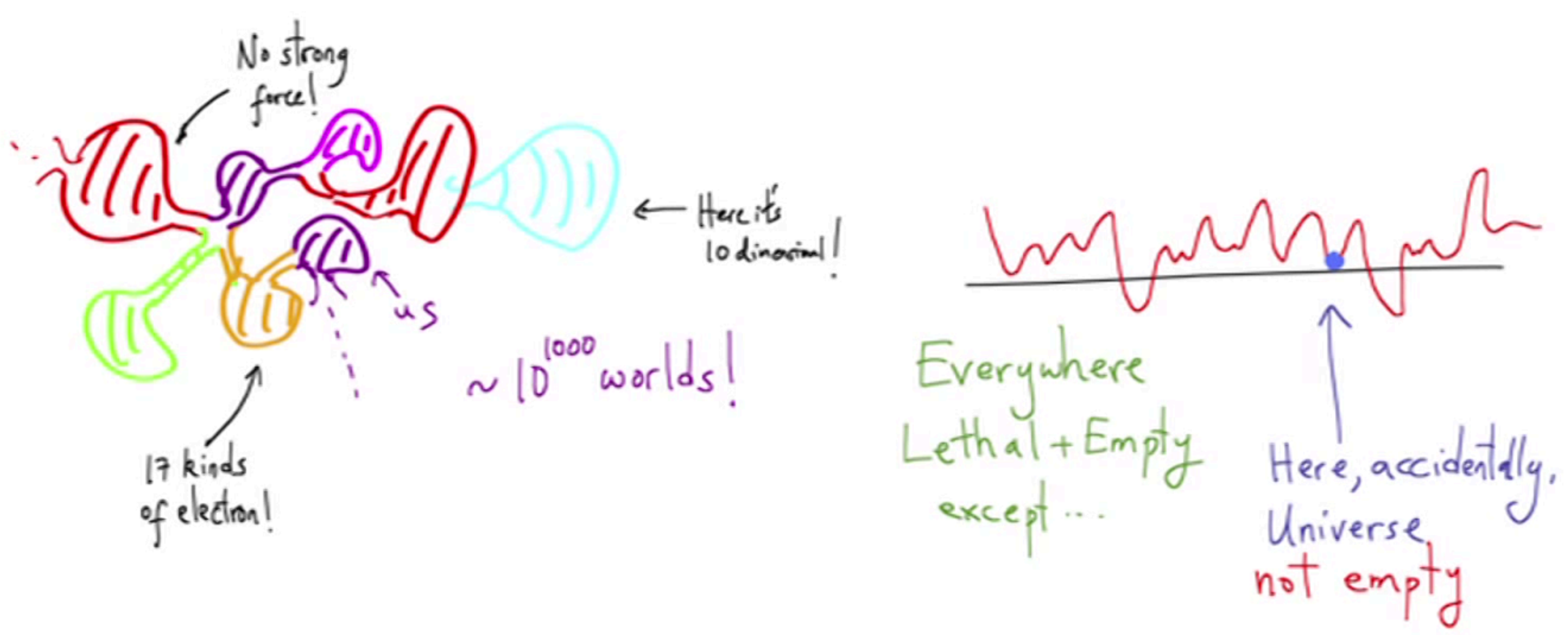
# Multiverse cosmology

If this idea is correct, many seemingly fundamental properties of particle physics may be local conditions of our bubble

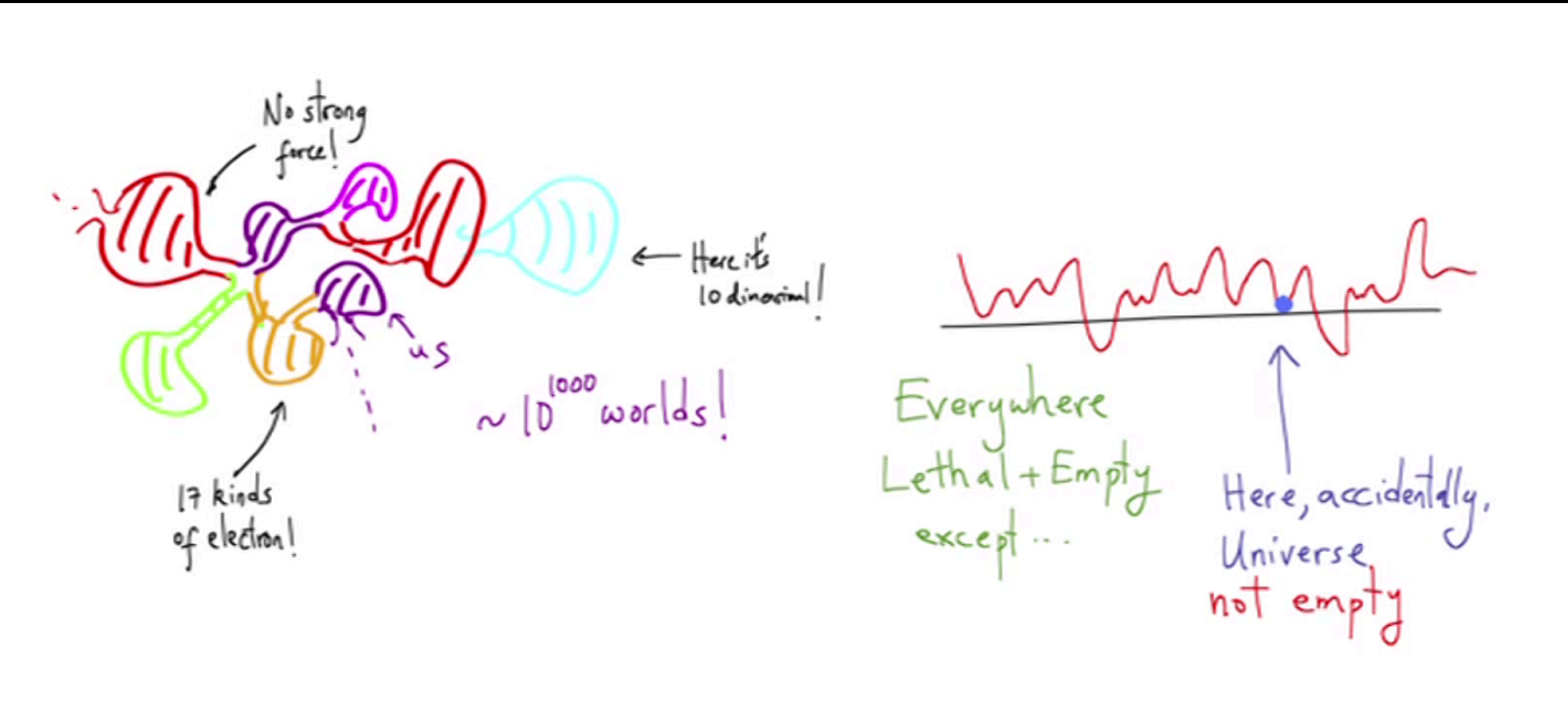


# Anthropic reasoning

Since we are here to observe them, these local conditions are not random; in fact they must be rather special; this idea is called Anthropic selection



For example, as Steve Weinberg observed many years ago, the cosmological constant cannot be more than a factor of ~10 bigger than what we measure, otherwise stars and galaxies would not exist and we would be here



# Multiverse cosmology

I consider this idea to be vastly over-hyped, and agree with two objections expressed by Frank Wilczek:

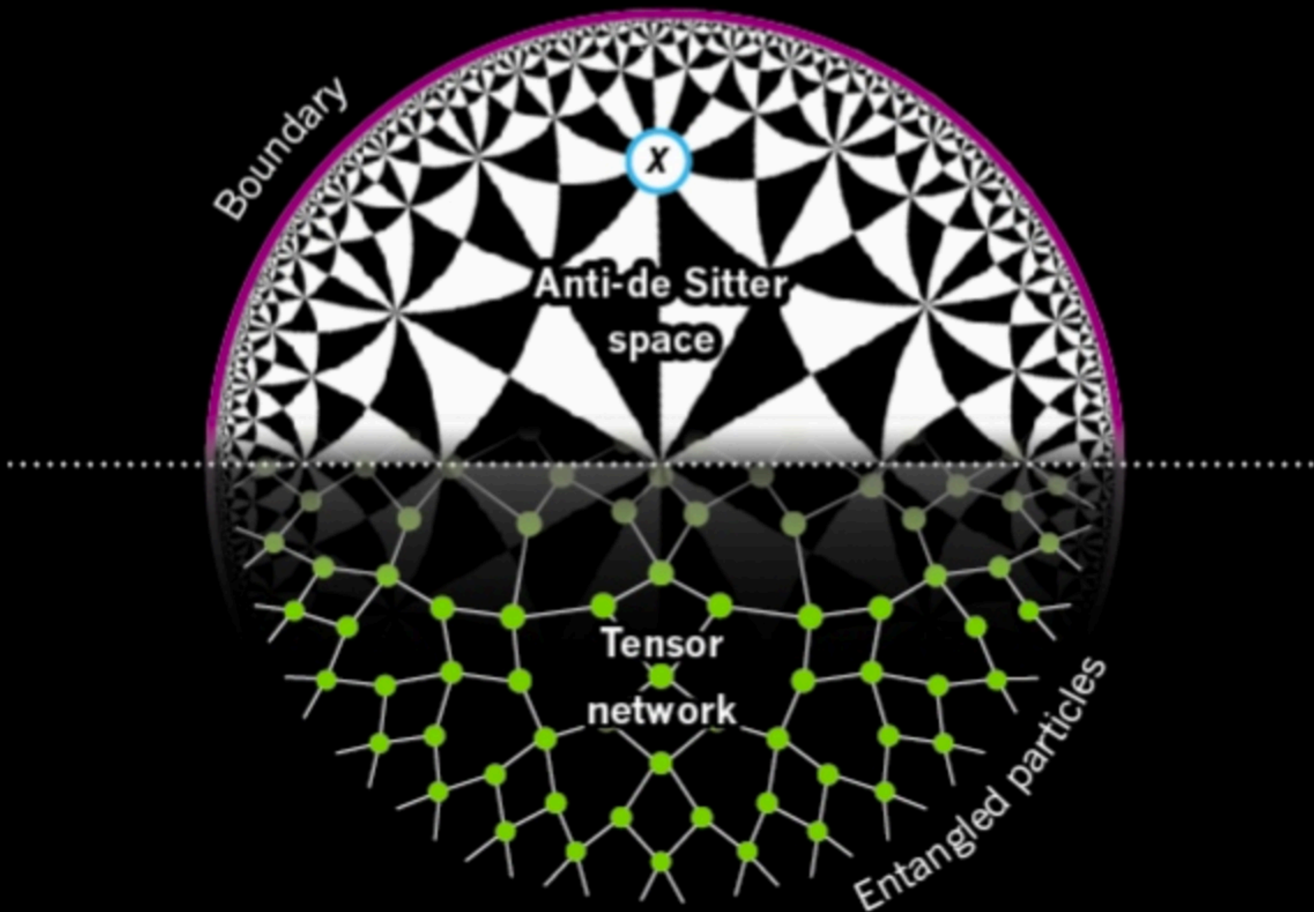
#1: Warning: There is a danger that selection effects will be invoked prematurely or inappropriately, and choke off the search for deeper, more consequential explanations of observed phenomena. To put it crudely, theorists can be tempted to think along the lines "If people as clever as us haven't explained it, that's because it can't be explained – it's just an accident."

# Multiverse cosmology

I consider this idea to be vastly over-hyped, and agree with two objections expressed by Frank Wilczek:

#2: Lamentation: I don't see any realistic prospect that anthropic or statistical selection arguments – applied to a single sample! – will ever lead to anything comparable in intellectual depth or numerical precision to the greatest and most characteristic achievements of theoretical physics and astrophysics, such as (for example) the prediction of electron and muon anomalous magnetic moments, the calculation of the hadron spectrum, or the enabling of GPS… In that sense, intrusion of selection arguments into foundational physics and cosmology really does, to me, represent a lowering of expectations

# Spacetime emerging from quantum entanglement




I don't actually know how to explain this…

# Thank You