

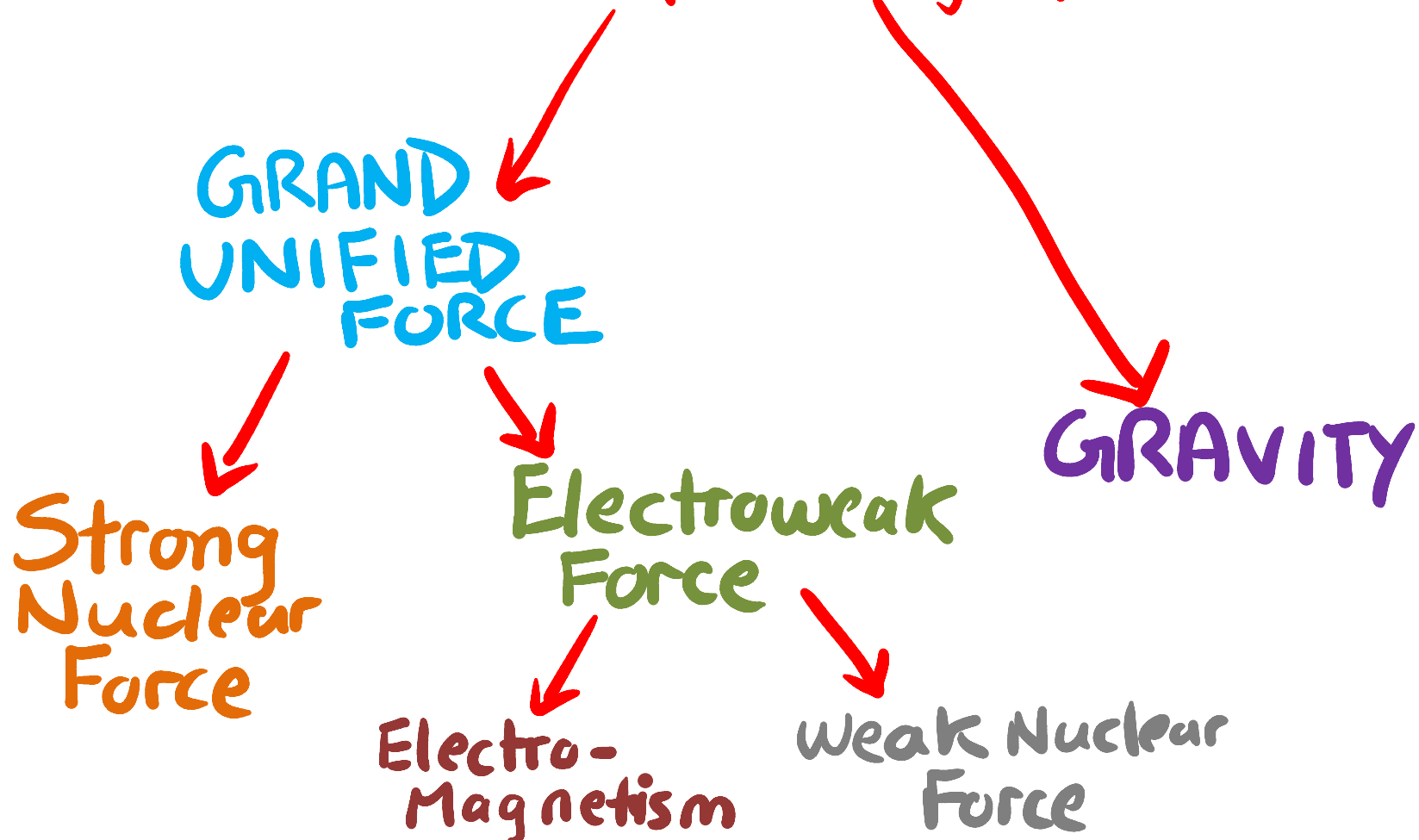
FUNDAMENTAL PHYSICS
AND THE
FIFTH DIMENSION

Raman Sundrum
University of Maryland

ANCESTRY OF FUNDAMENTAL FORCES

MOTHER FORCE

Superstrings?



ANCESTRY OF FUNDAMENTAL FORCES

MOTHER FORCE

Superstrings?

DARK MATTER/
FORCES/ENERGY

GRAND
UNIFIED
FORCE

GRAVITY

Strong
Nuclear
Force

Electroweak
Force

Electro-
Magnetism

Weak Nuclear
Force

GENERAL RELATIVITY

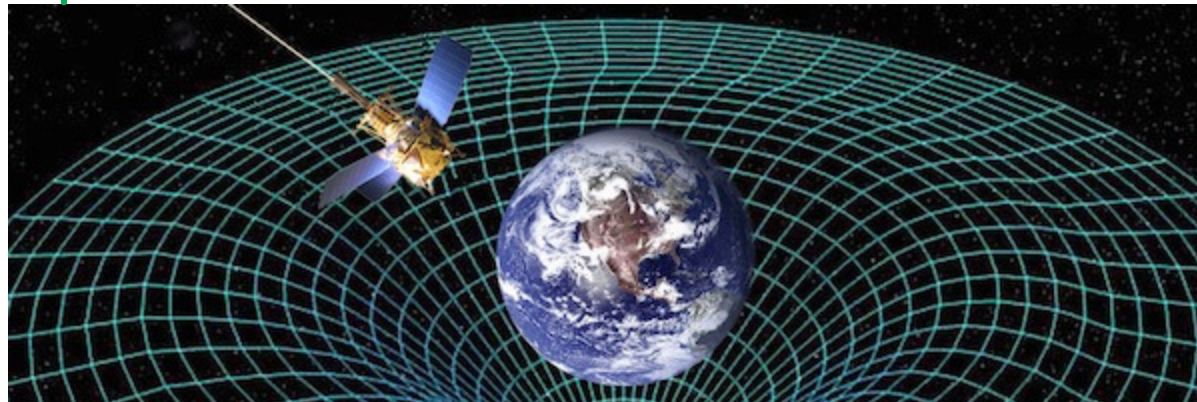
Einstein 1915

Contains Newton's Law of Gravitation.

Consistent with Electromagnetic Laws:

Light Speed is finite & fastest

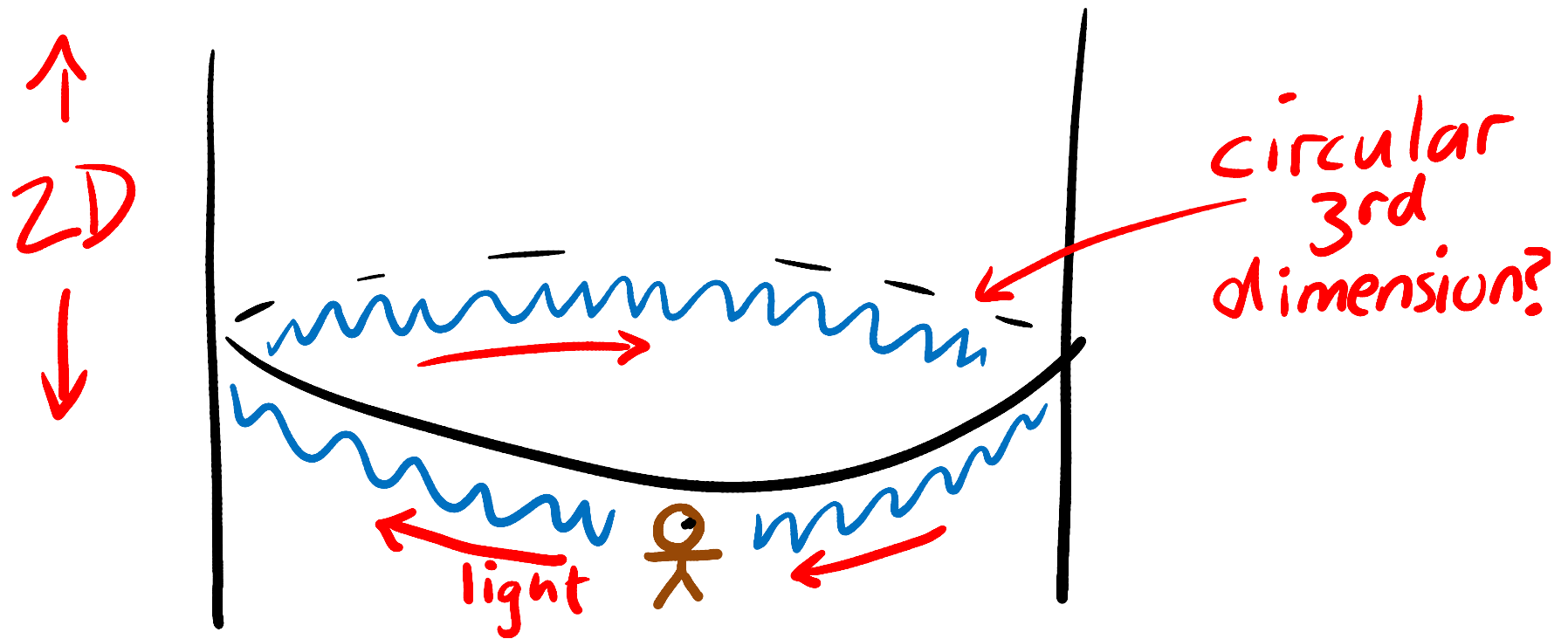
⇒ Spacetime is Curved & Dynamic!



NASA
image

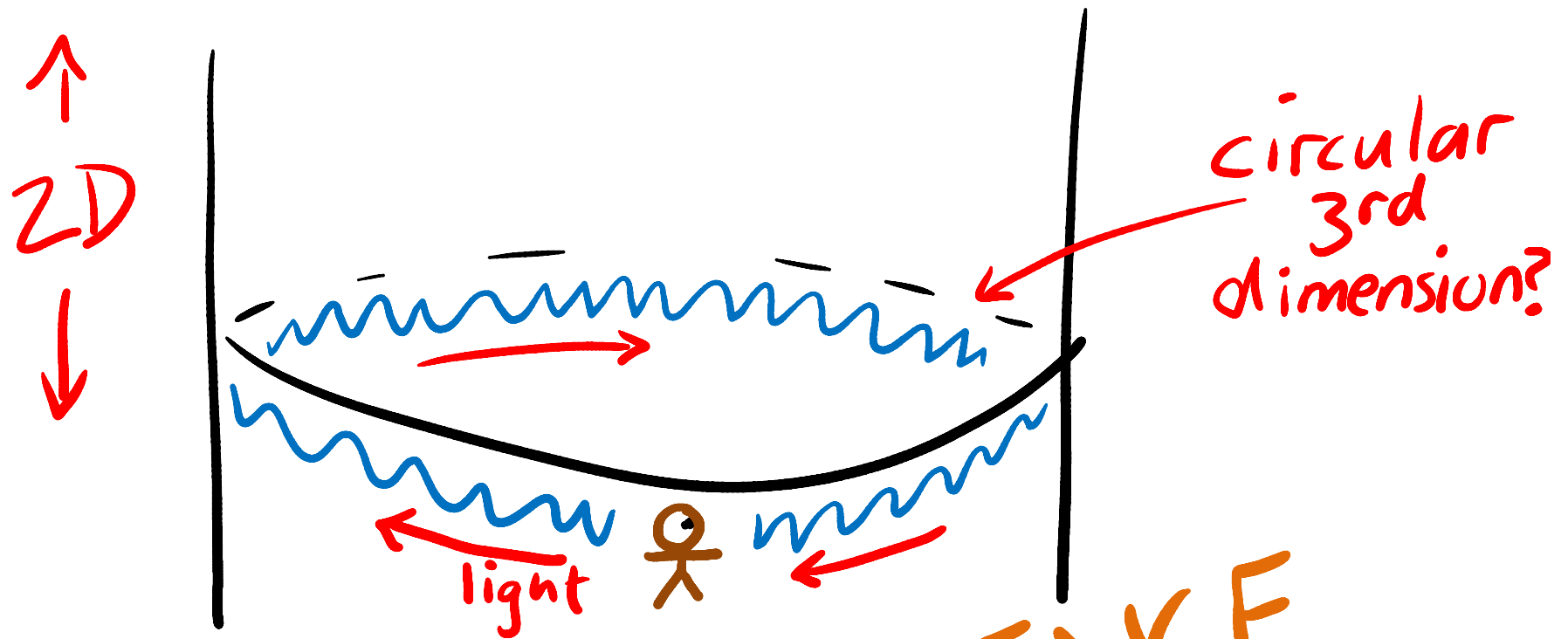
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Can curved space
curl back on itself?



⇒ Seeing the back
of your head!

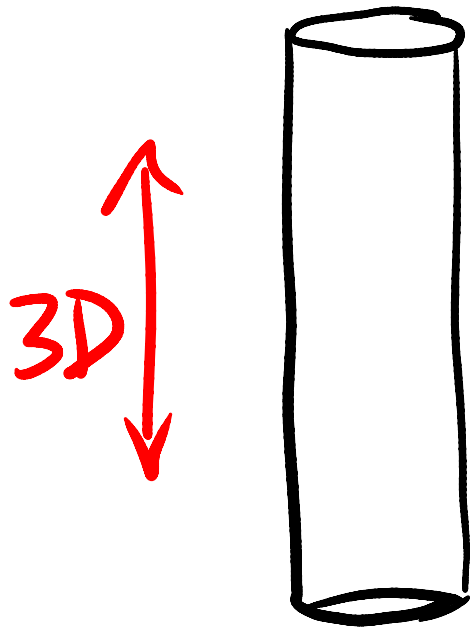
Can curved space
curl back on itself?



⇒ **NO EVIDENCE** Seeing the back
of your head

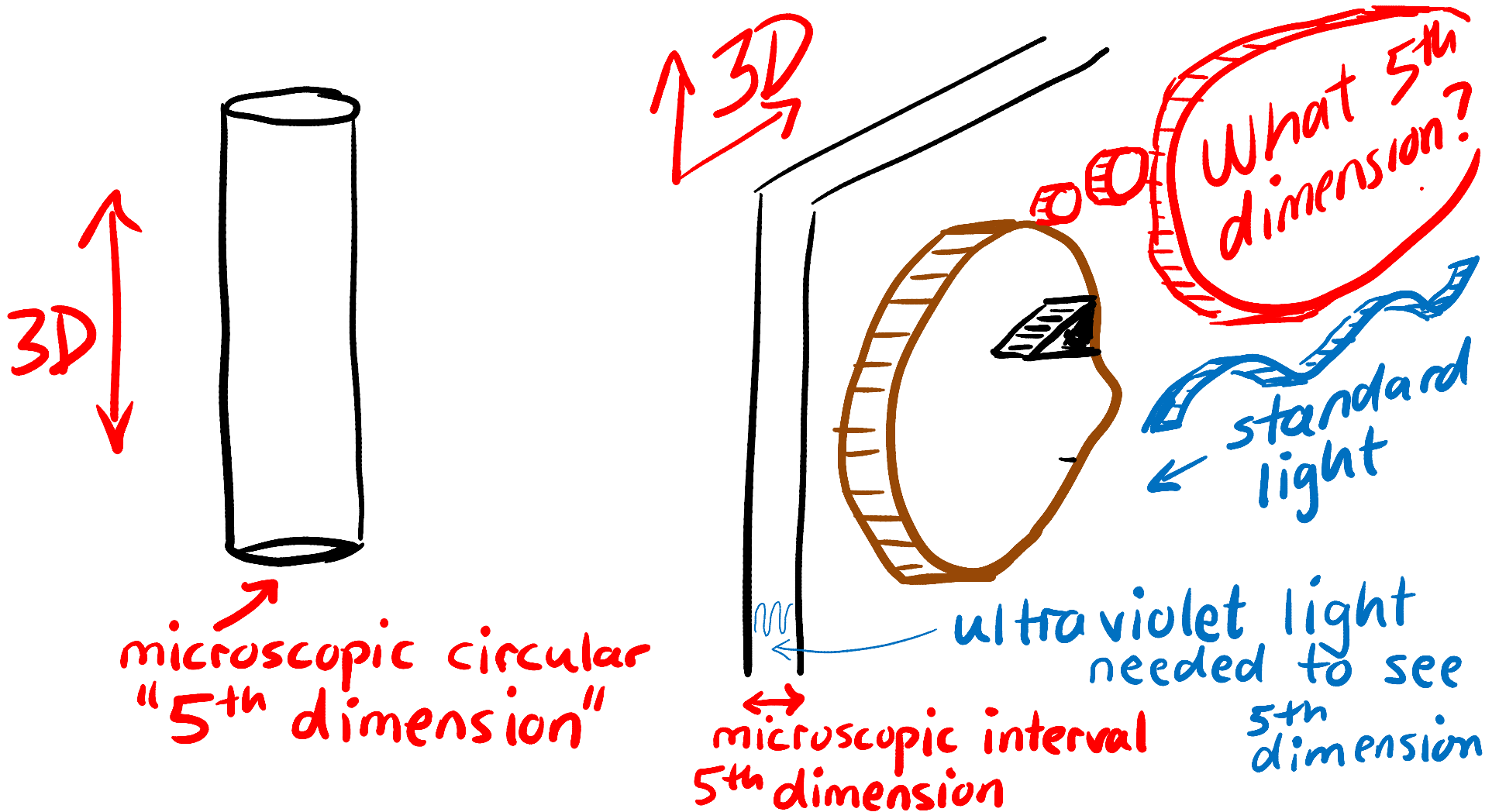
NEW DIMENSIONS MICROSCOPICALLY CURLED?

How to tell in
principle?

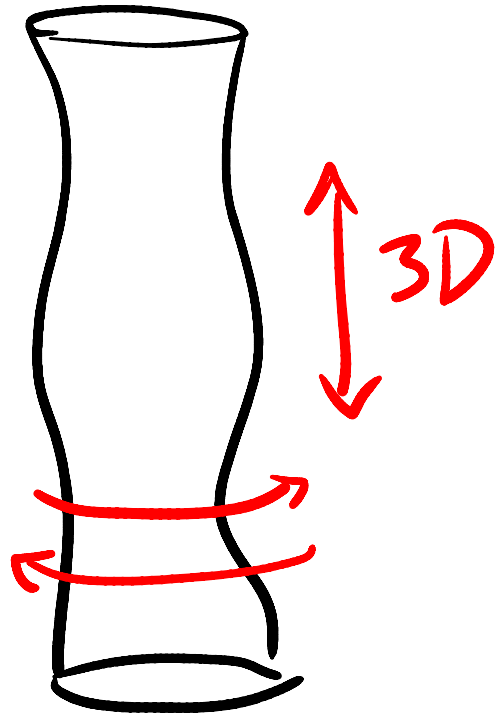


microscopic circular
"5th dimension"

NEW DIMENSIONS MICROSCOPICALLY CURLED?

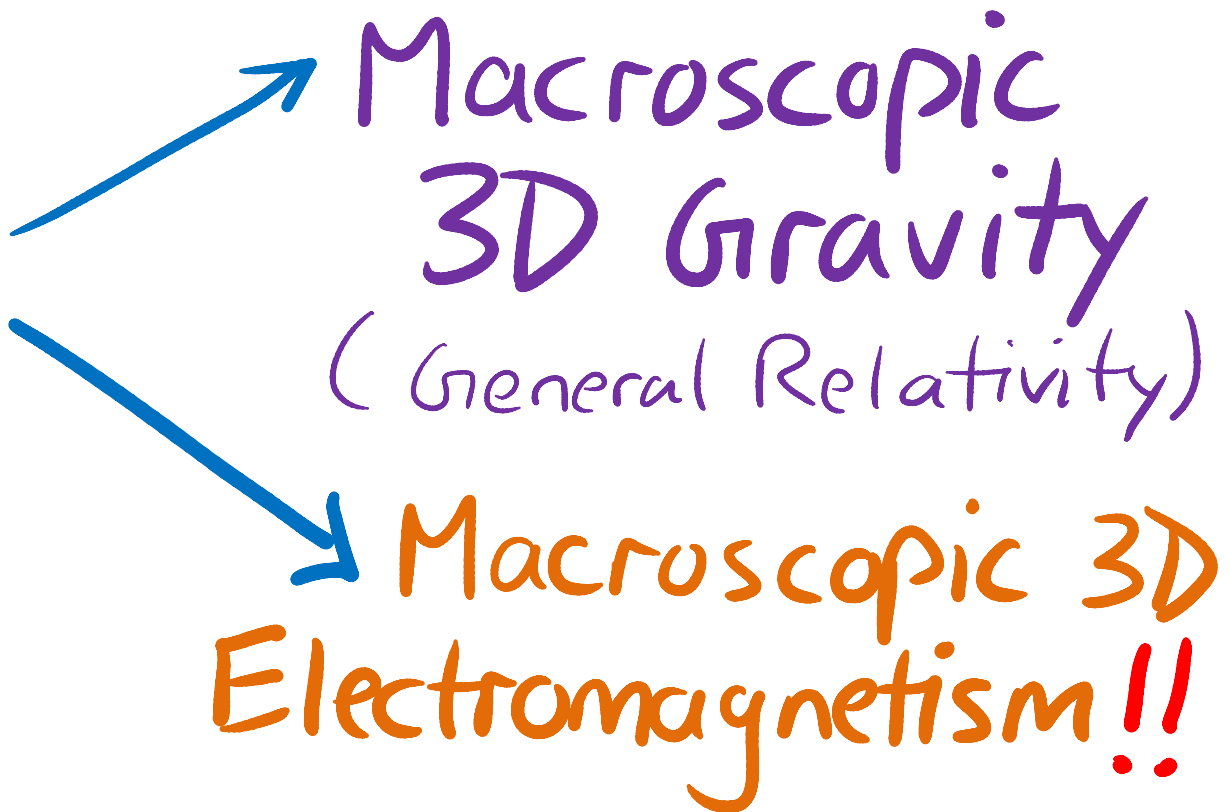


5D Curved Spacetime (5D Gravity)

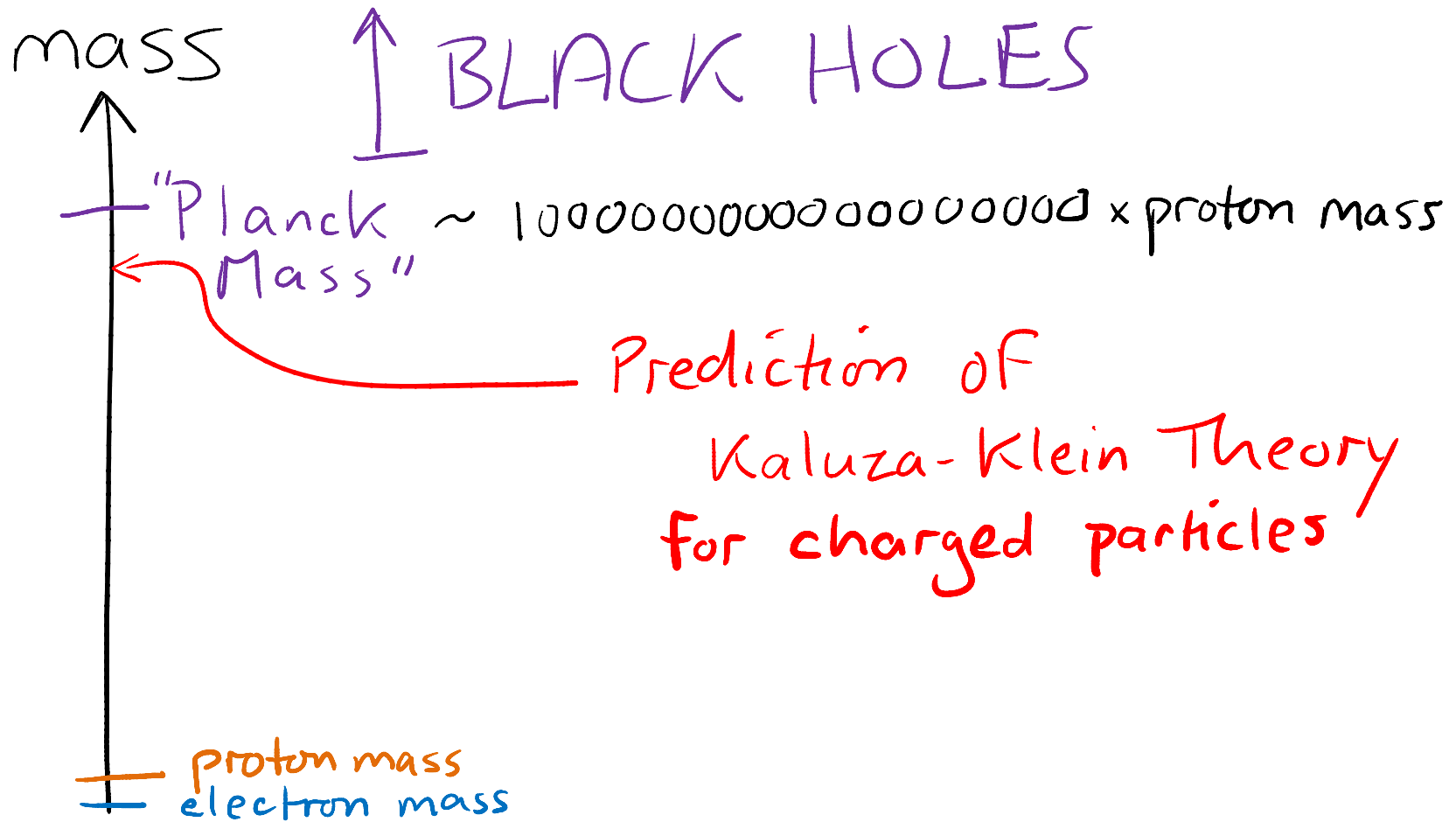


5th
dimension
microscopic
circle

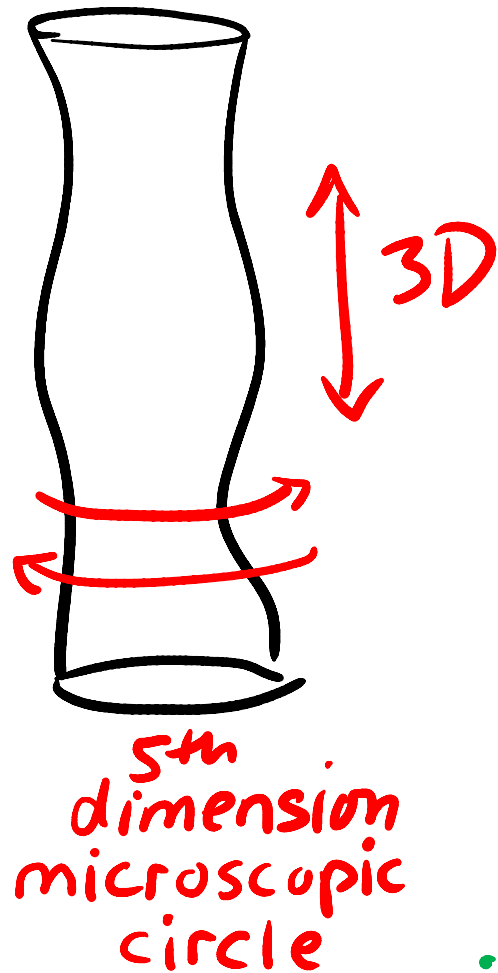
"Kaluza-Klein"
Theory 1930's



BUT UNREALISTIC!



Subtler, but more realistic,
Kaluza-Klein variants ...



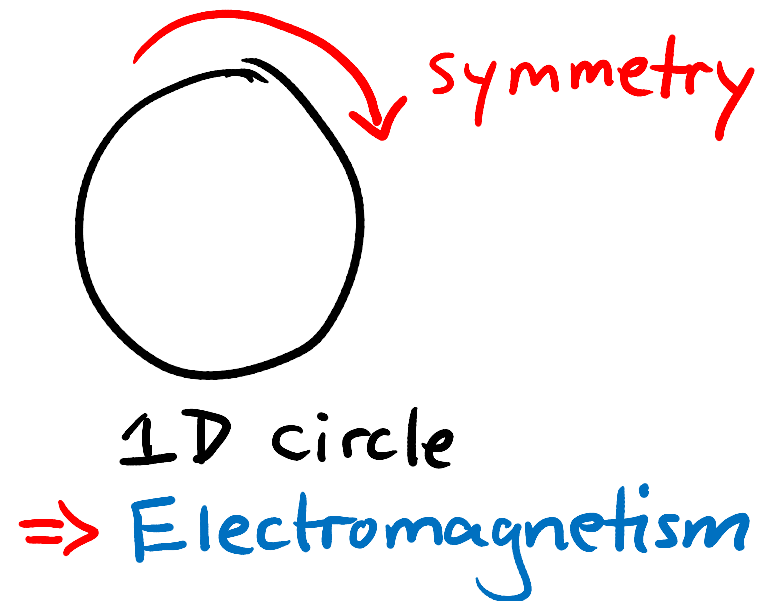
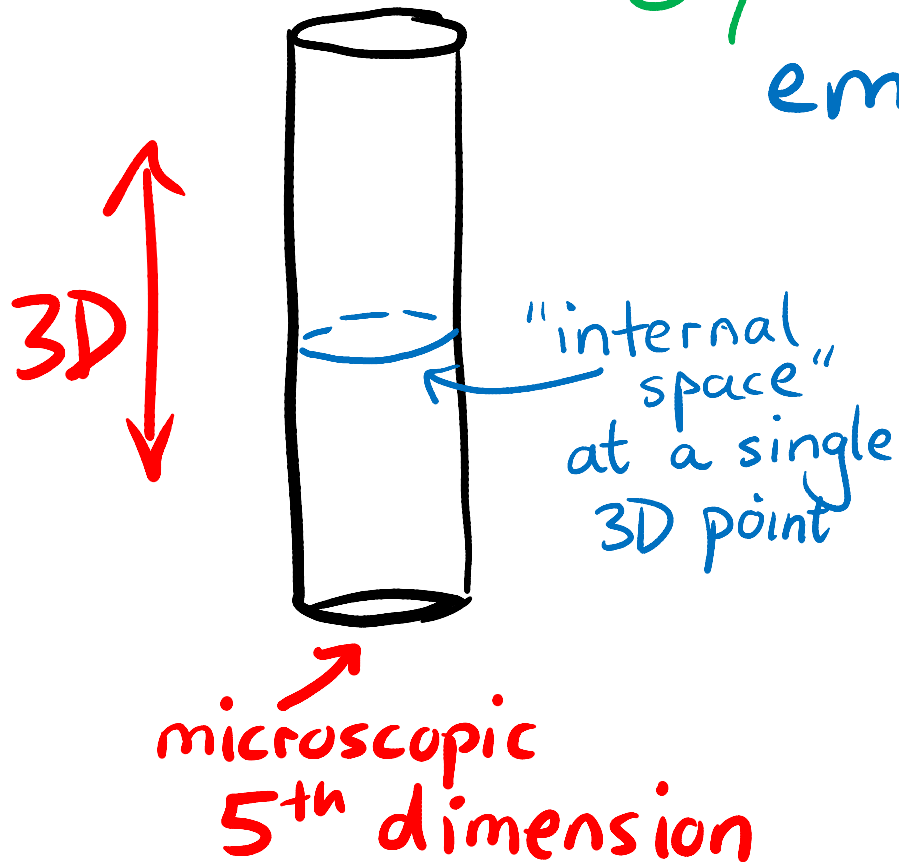
Macroscopic
3D Gravity
(General Relativity)

Macroscopic 3D
Electromagnetism!!

... in modern
SuperString Theories

"INTERNAL SPACES"

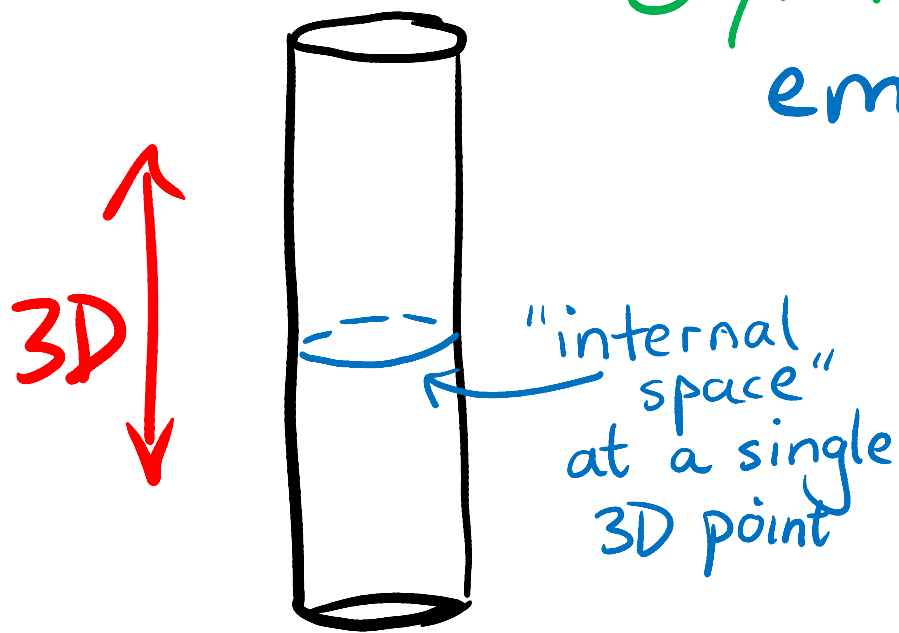
Symmetry determines the emergent macro forces.



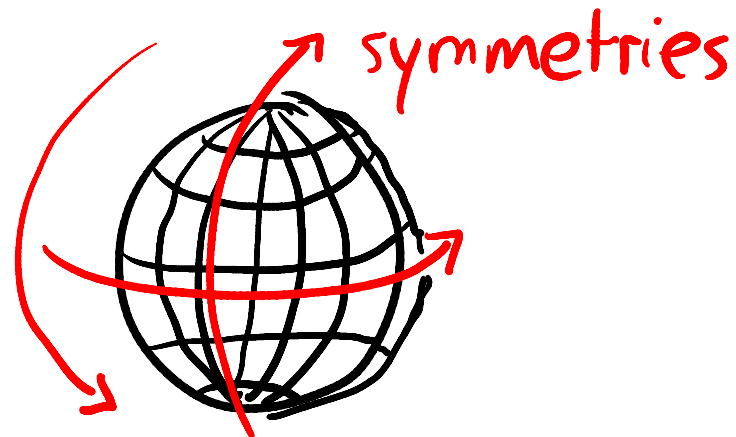
"INTERNAL SPACES"

can be higher-dimensional.

Symmetry determines the emergent macro forces.



microscopic
5th + 6th dimensions



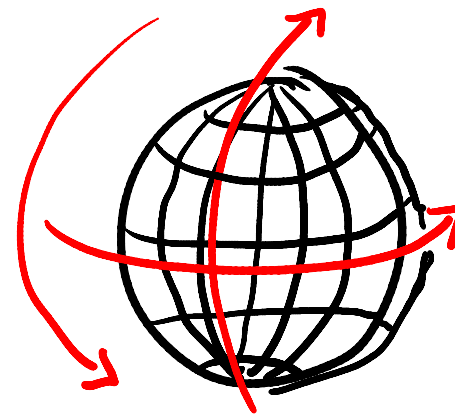
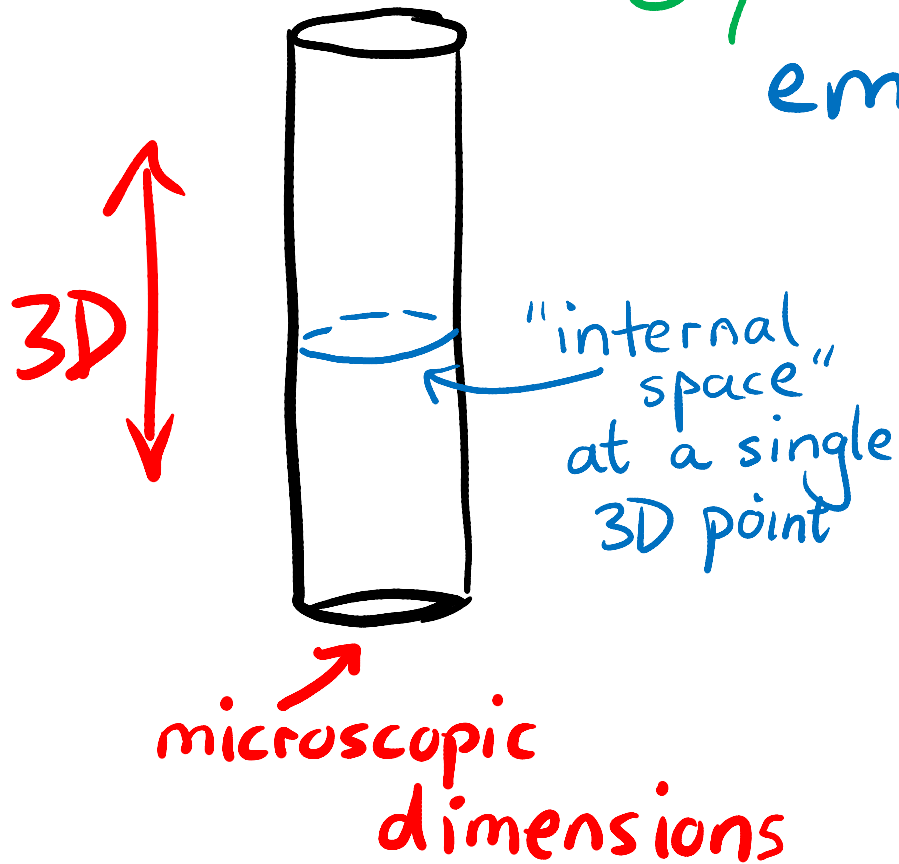
2D sphere

⇒ ElectroWeak
Forces

"INTERNAL SPACES"

can be higher-dimensional.

Symmetry determines the emergent macro forces.

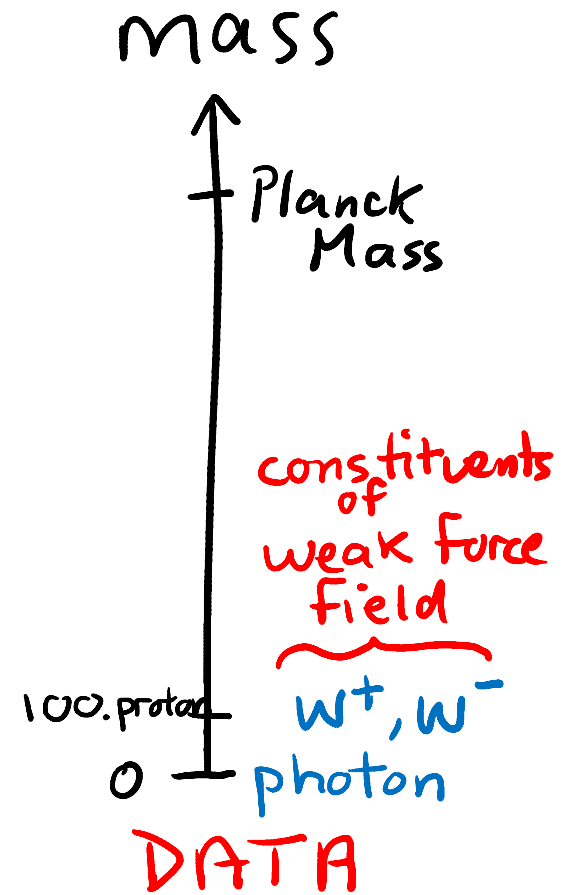
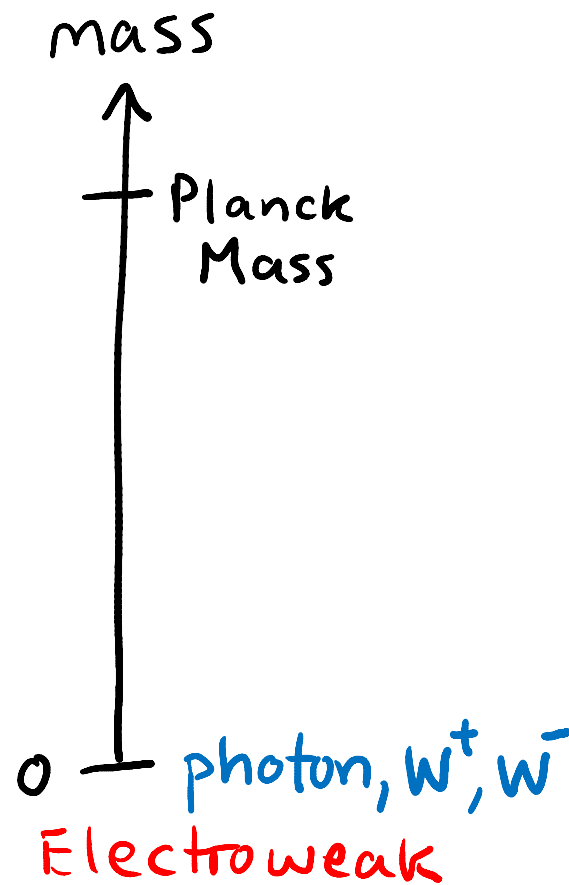
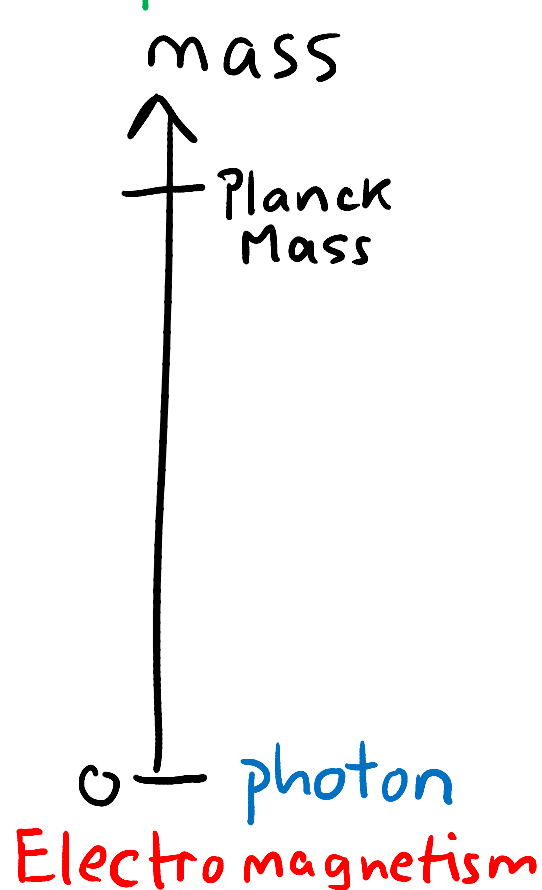


Higher dimensional symmetric internal space

⇒ Strong Nuclear Force,

"Quantum Chromodynamics"

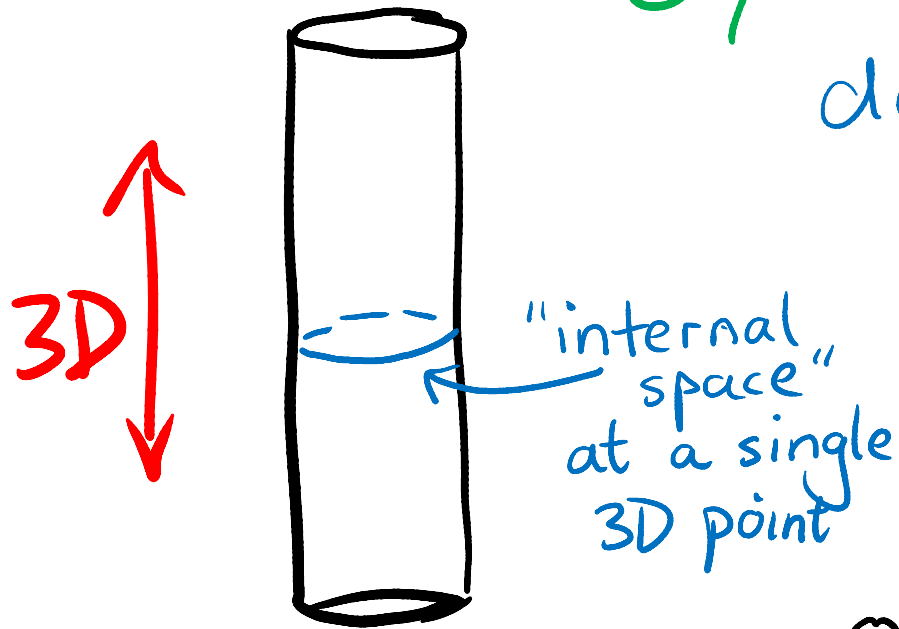
Quantum Mechanics \Rightarrow Force fields comprised of particles



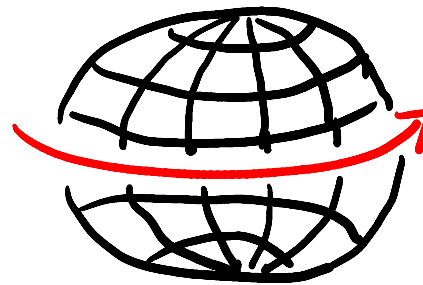
"INTERNAL SPACES"

can be higher-dimensional.

Symmetry & its Breaking
determines emergent
forces



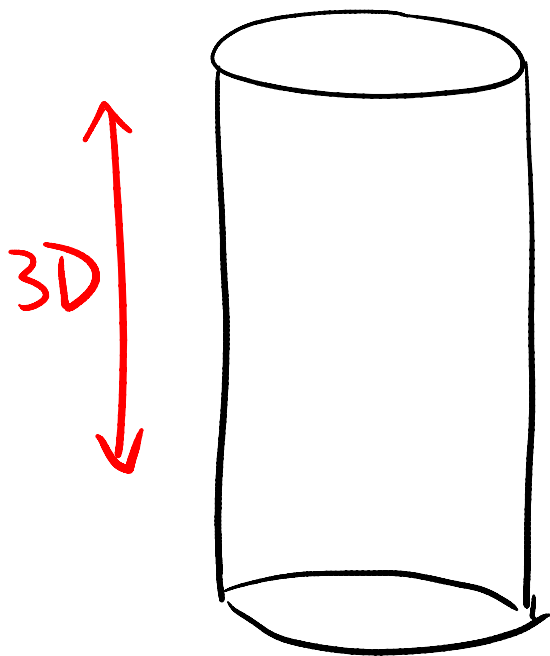
microscopic
5th + 6th dimensions



OBLATE 2D sphere

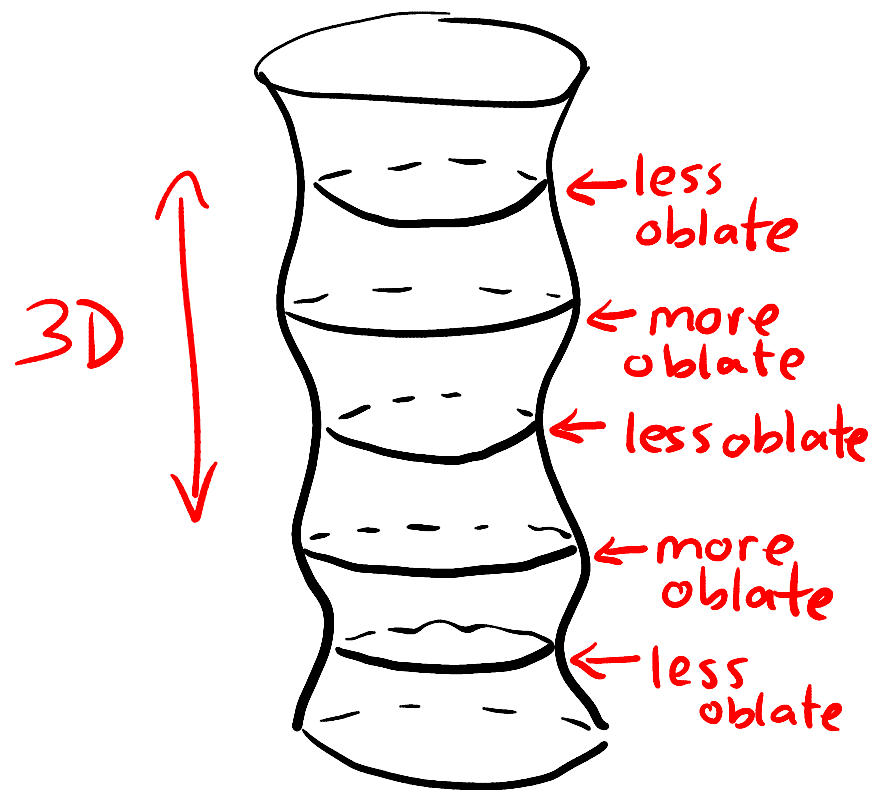
⇒ Electromagnetism
+ (short-range)
Weak Nuclear Force

The Vacuum & the HIGGS FIELD



↗
5th+6th dimensional
oblate sphere

Vacuum \equiv Lowest Energy State



HIGGS FIELD
WAVE

"STANDARD MODEL"

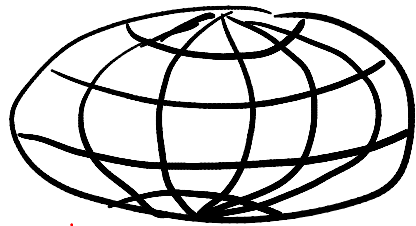
of Gravity, Electromagnetism, Weak
& Strong Nuclear Forces
in full realism

is written in mathematics of
external & internal spaces

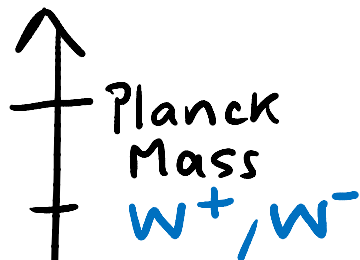
agnostic about whether or not
internal space relates to extra
dimensions or string theory.

It is in fantastic accord with enormous
body of experimental data

The Hierarchy Problem



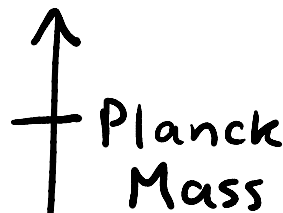
strongly oblate
mass



0 — photon

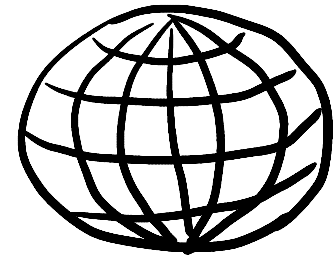


perfect sphere
mass

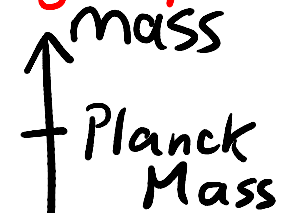


0 — photon, W^+ , W^-

ROBUST



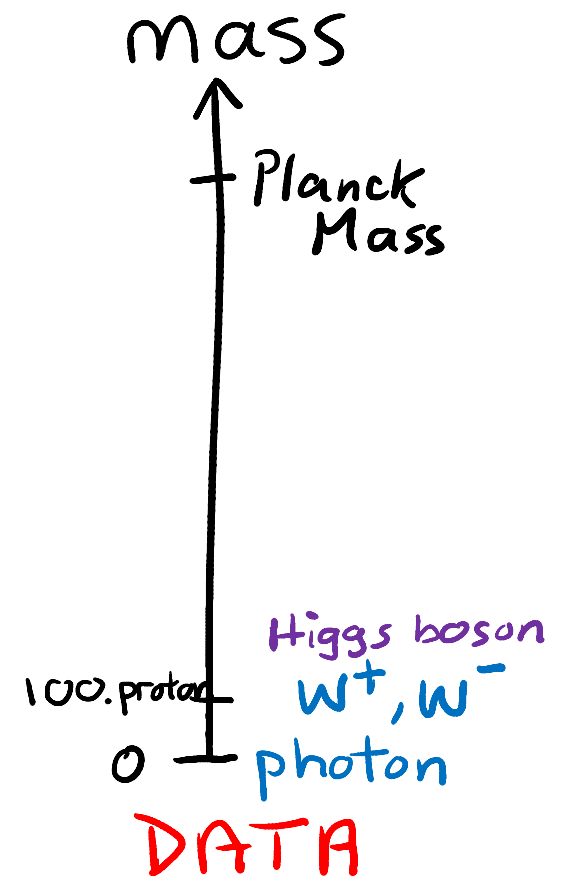
very, very slightly oblate
mass



100. proton — W^+ , W^-
0 — photon

VERY DELICATE

Quantum Mechanics \Rightarrow
Higgs Waves comprised of
particles \equiv Higgs Bosons



Quantum Mechanics + Relativity \Rightarrow

Anything is possible
to create,

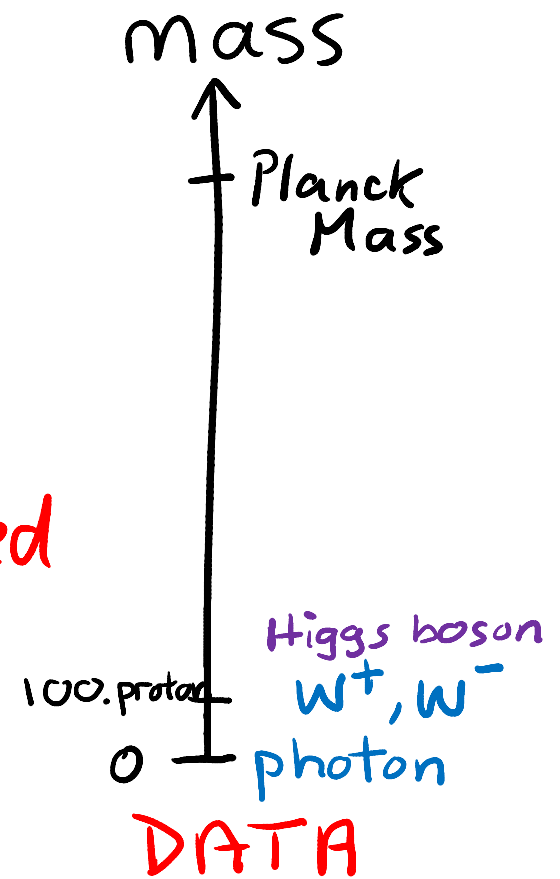
given enough Energy:

$$E = mc^2$$

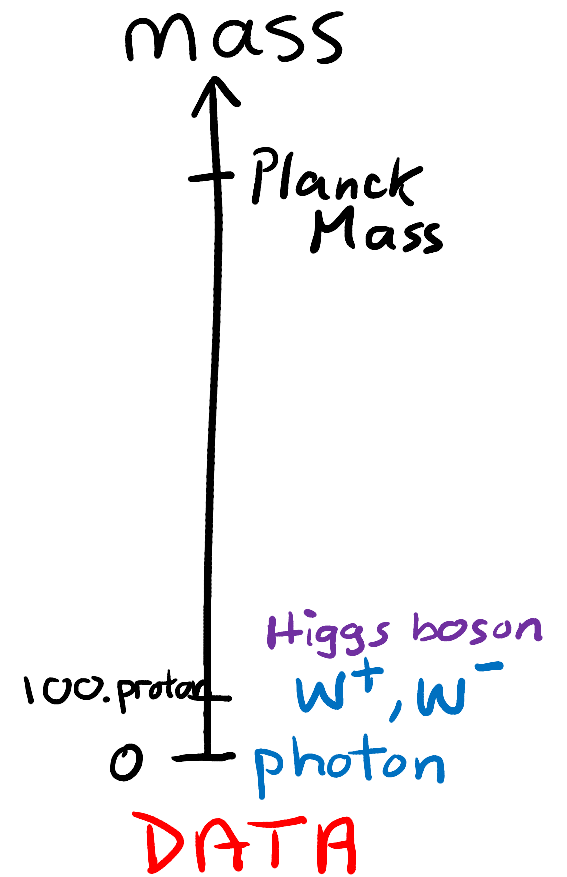
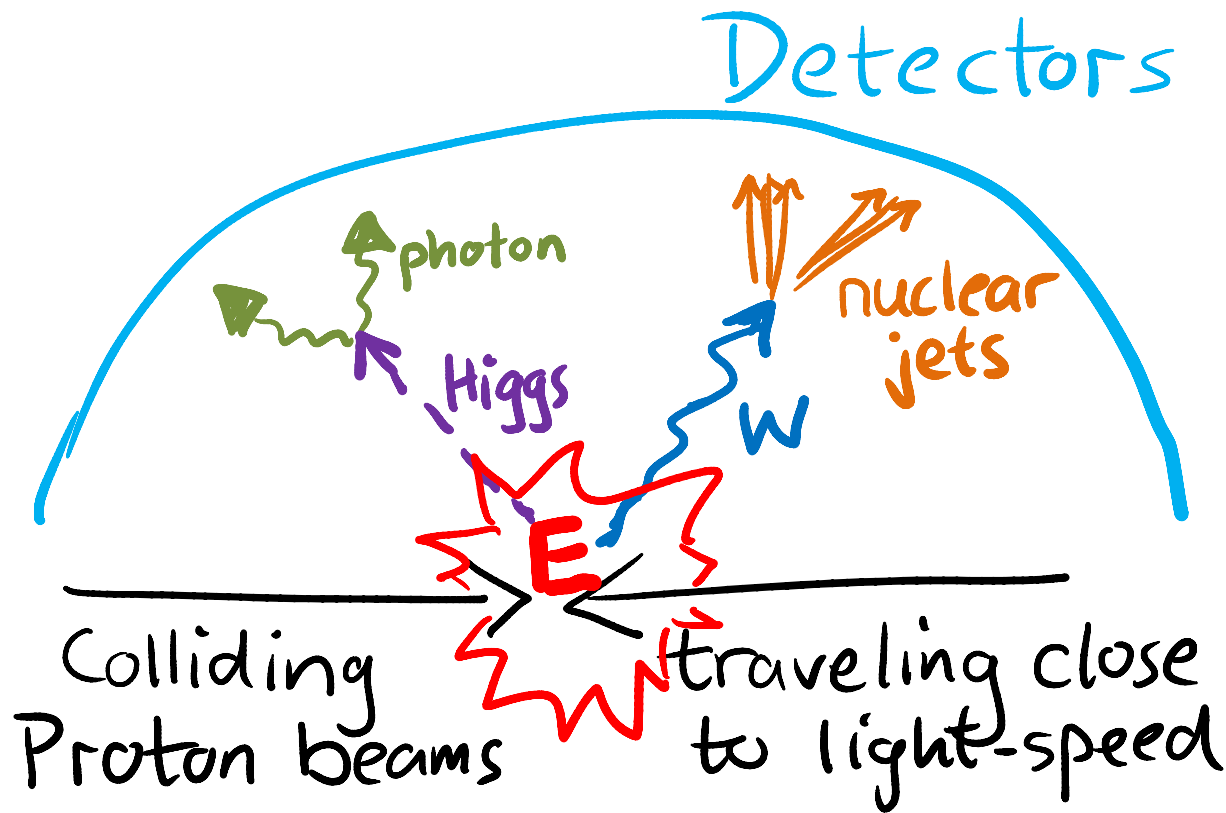
↑
Energy

↑
mass of
thing you
want to create

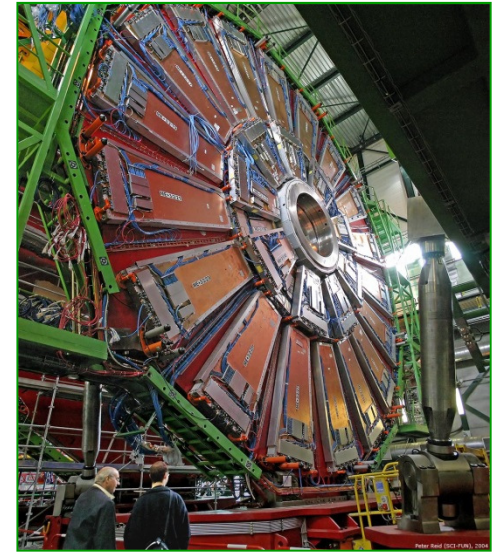
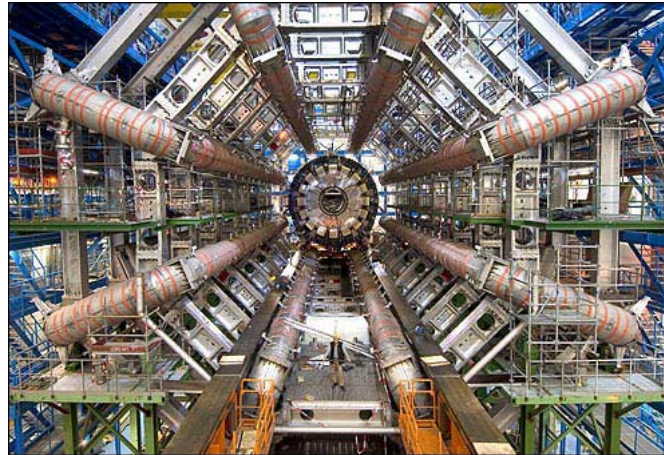
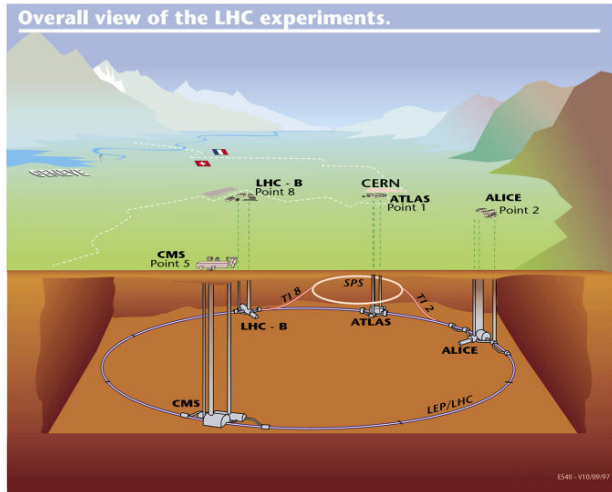
↑
Light-speed
(Big)



PARTICLE COLLIDERS



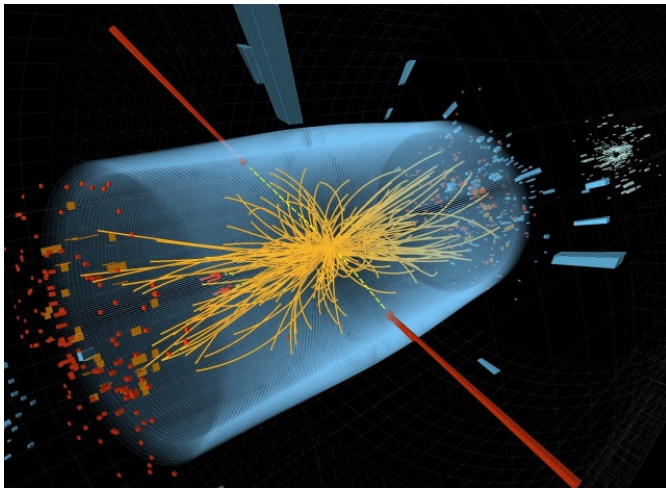
LARGE HADRON COLLIDER



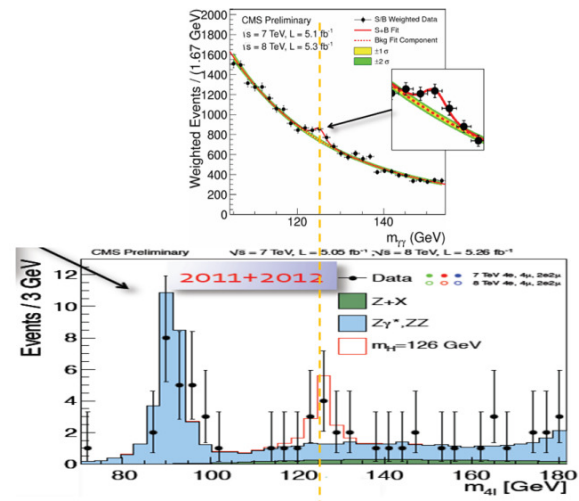
far underground
Franco-Swiss Border

ATLAS & CMS
giant detectors

Higgs
Boson
Discovery
(2012)



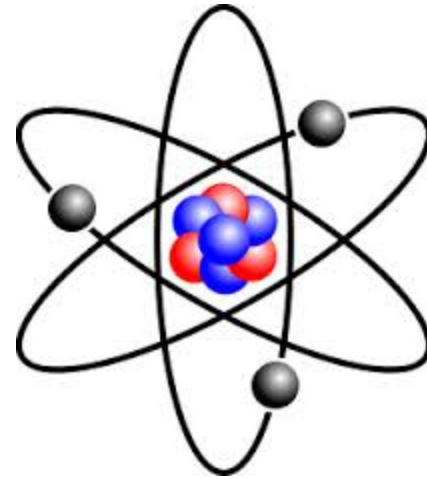
Candidate Higgs event (CMS)



Is newly discovered Higgs boson
truly pointlike ("elementary")
or **COMPOSITE**?

PRECEDENTS

The "indivisible"
ATOM is really a
composite of
electrons "orbiting"
a central nucleus.



The nucleus is a composite of protons & neutrons
The proton is a composite of quarks & gluons

HIGGS BOSON COMPOSITENESS
would (help) resolve
the HIERARCHY PROBLEM

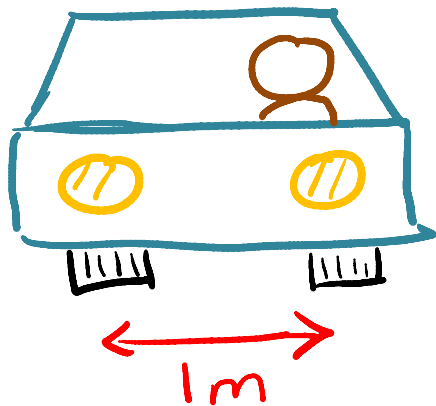
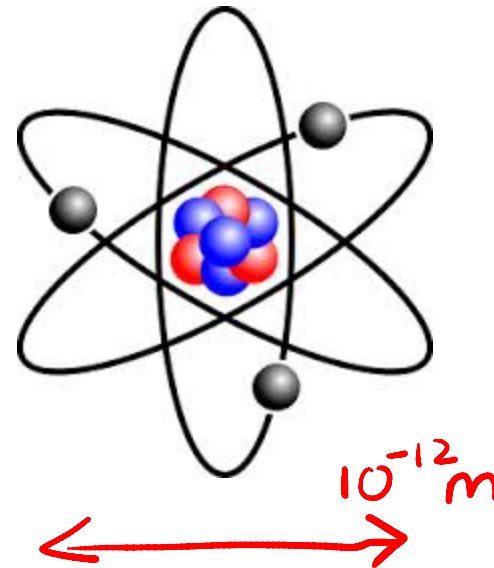
The Higgs constituents would
have to be very tightly bound
in a novel manner

Composite Higgs Theory is
very challenging.

But there is an indirect approach
via an emergent 5th dimension...

CHARACTERISTIC SHAPES & SIZES OF COMPOSITES

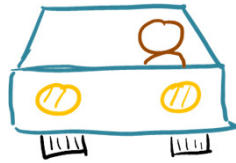
electron



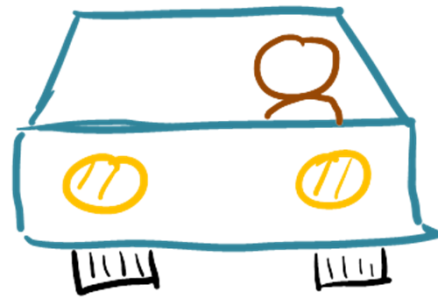
Car

Shapes & Size
can be
correlated.

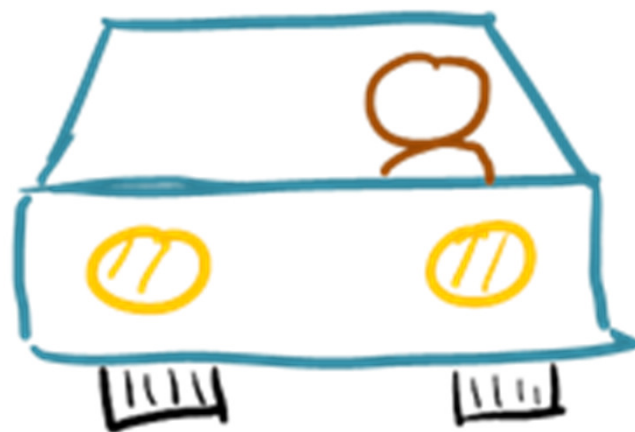
THE ILLUSION OF DEPTH



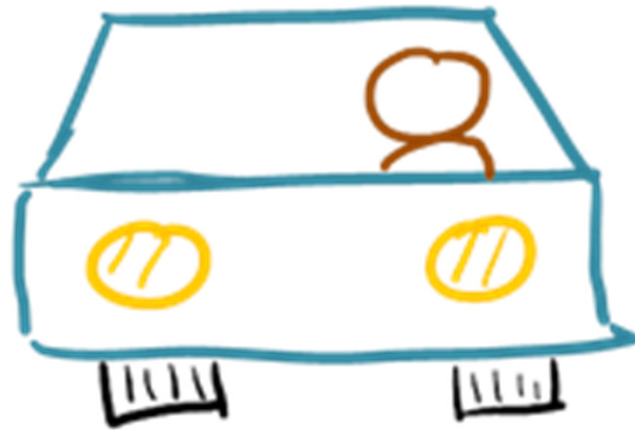
THE ILLUSION OF DEPTH



THE ILLUSION OF DEPTH



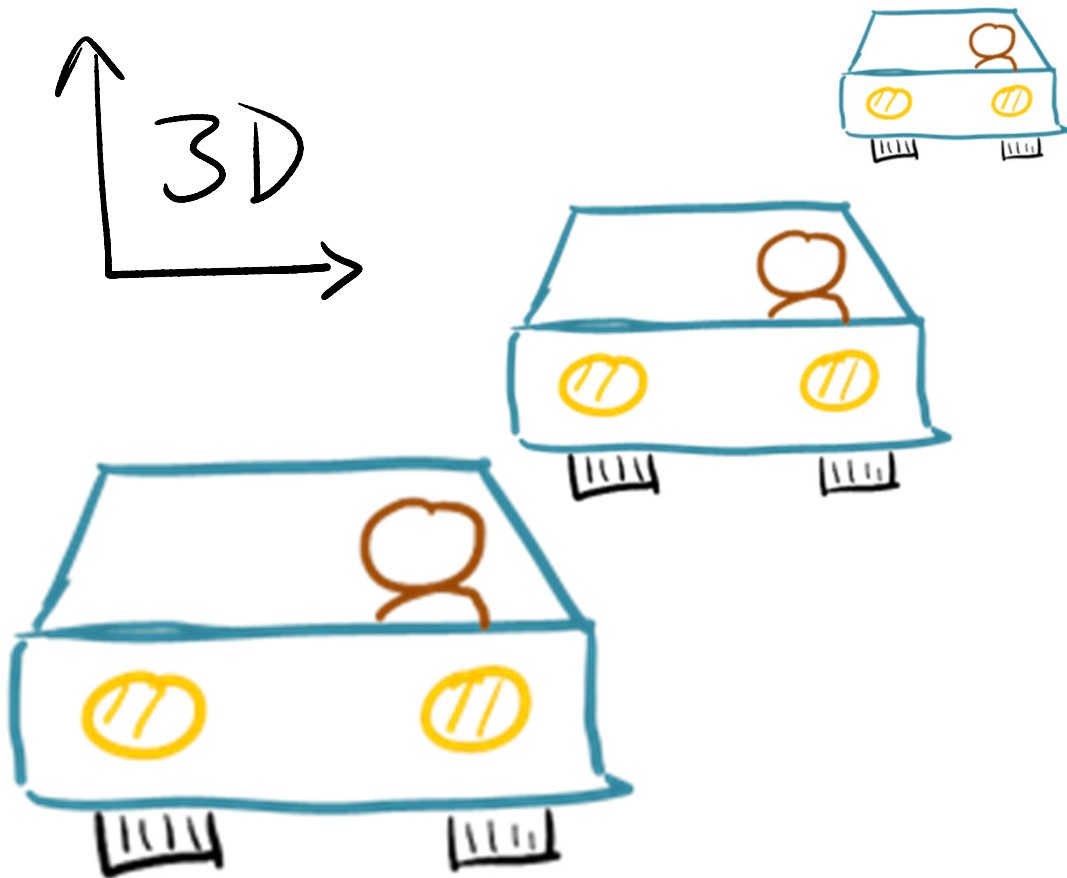
THE ILLUSION OF DEPTH

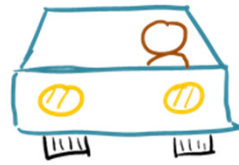
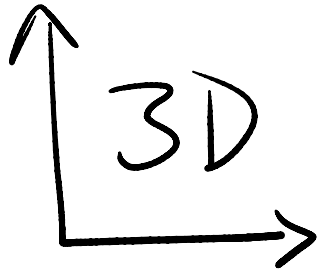


2D → "3D"

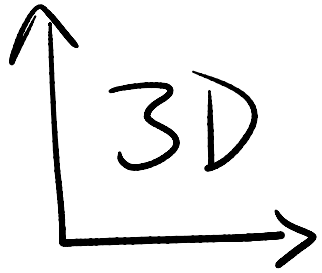
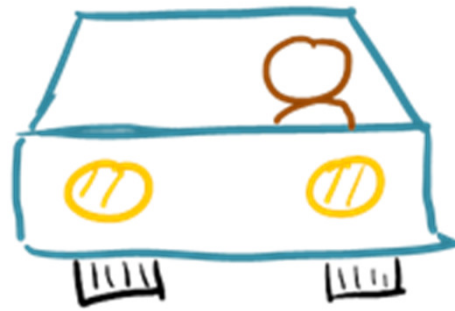
Theoretically, "SCALE-INVARIANT" QUANTUM SYSTEMS

can produce same characteristic shapes
over large range
of sizes ...

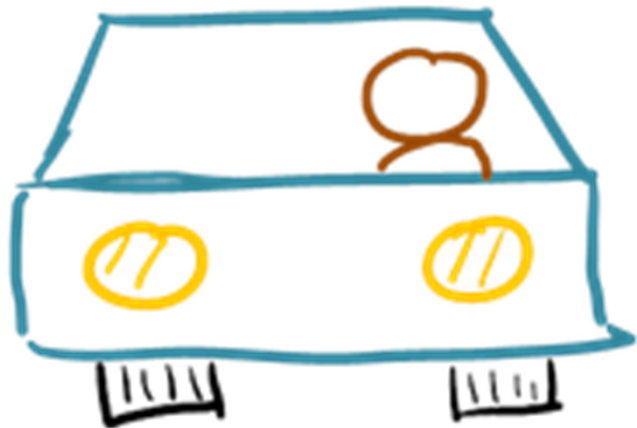
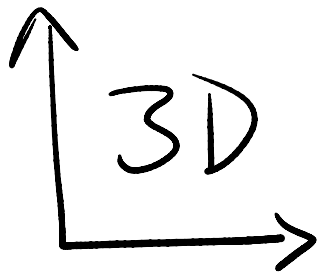




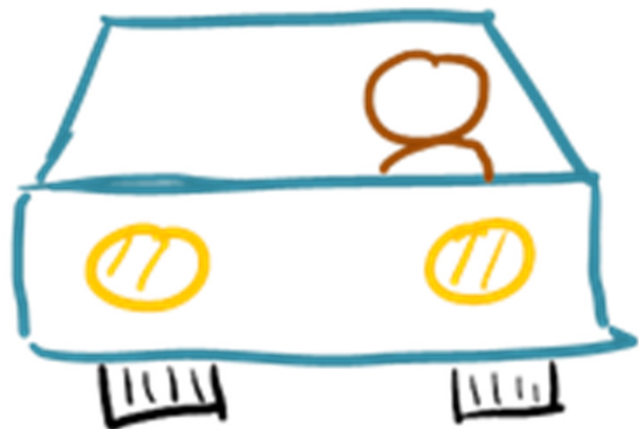
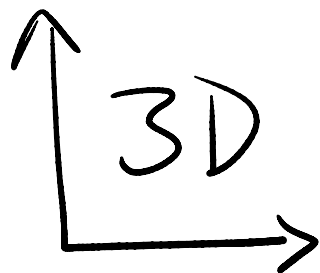
3D

A hand-drawn diagram of a 3D coordinate system. It consists of two perpendicular axes: one pointing vertically upwards and one pointing horizontally to the right. The text "3D" is written in the center of the angle formed by the two axes.

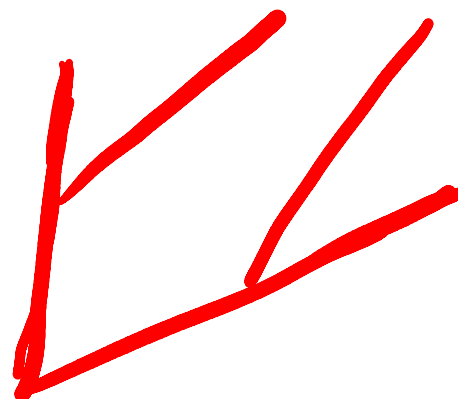
3D



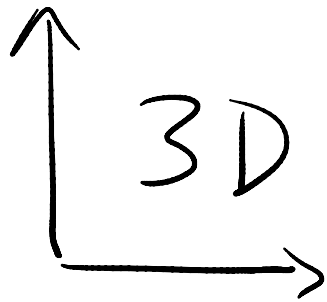
3D $\xrightarrow{\text{"Holography"}}$ "4D Space"



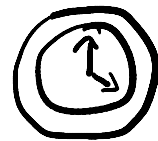
"5th dimension"



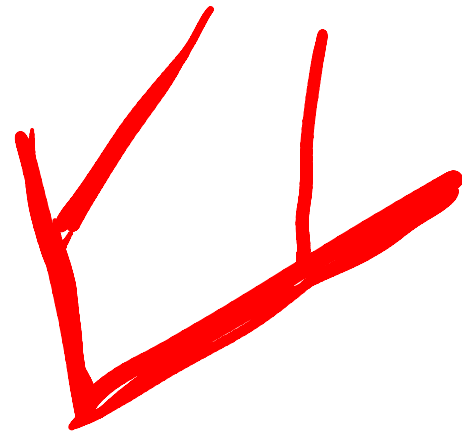
Times rescale with Lengths
like the (mis)behavior of clocks
& aging near a black hole horizon



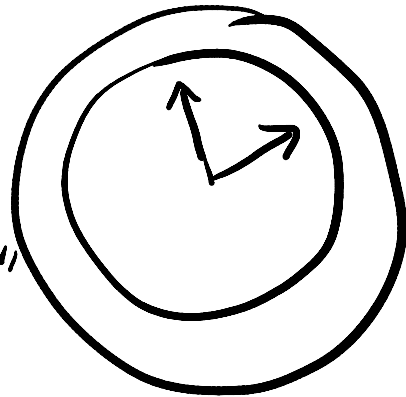
"tick
tick
tick"



"5th dimension"

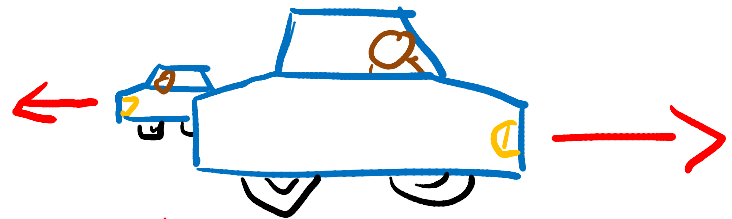
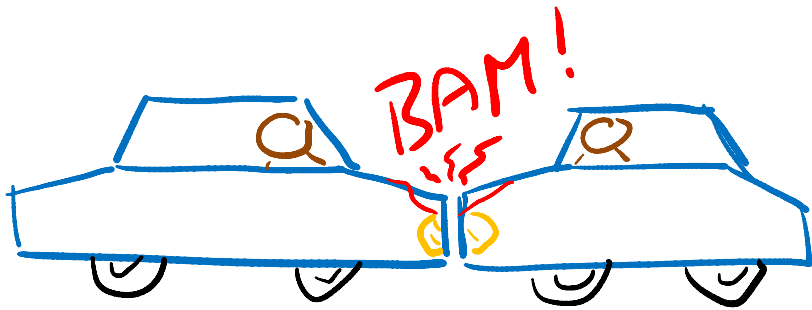
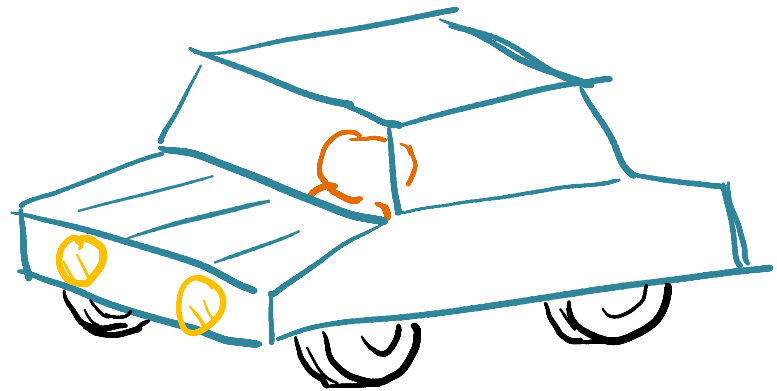
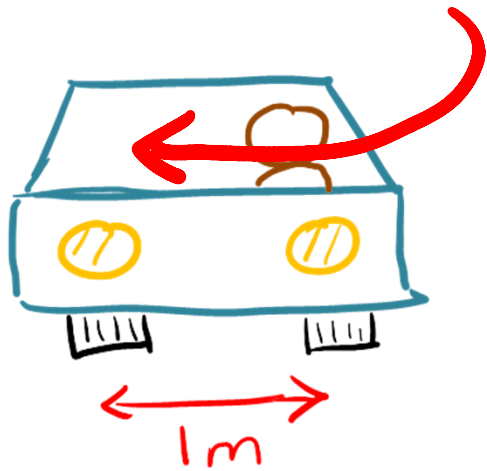


"t-i-c-k
— t-i-c-k
— t-i-c-k"



CONFORMAL SYMMETRY

rotates "5th dimension" with usual real 3D space.

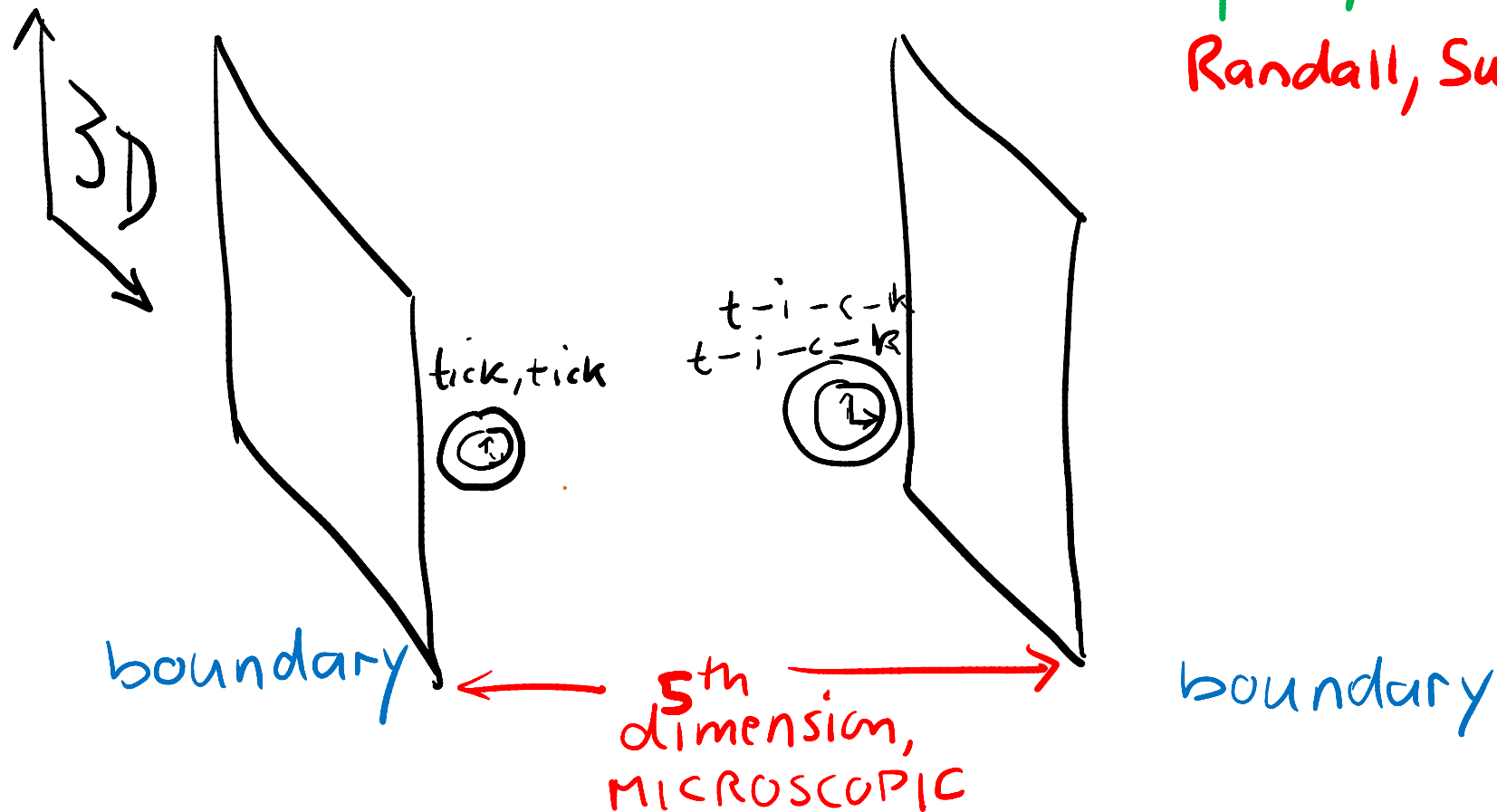


⇒ AdS/CFT Duality

Maldacena '97; Gubser, Klebanov, Polyakov '98; Witten '98

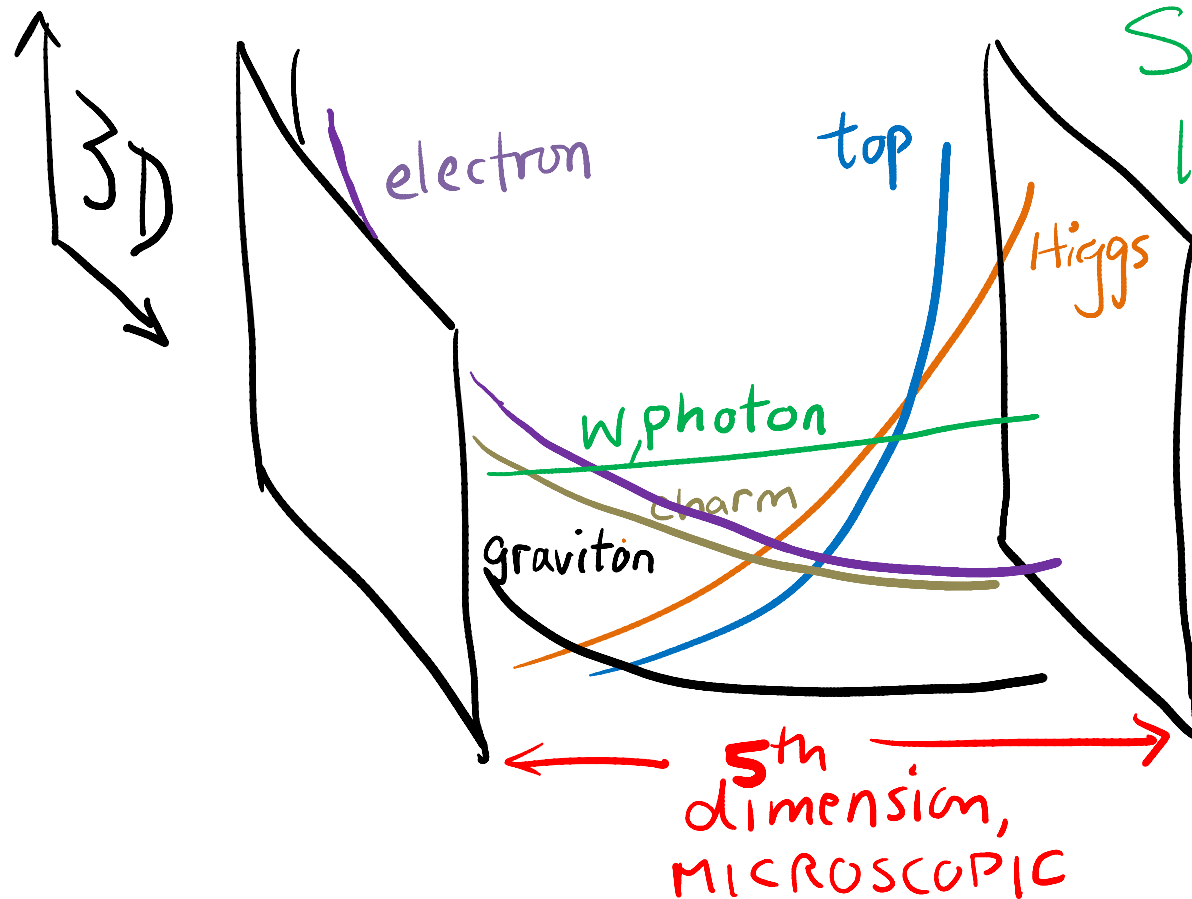
Warped 5D Spacetime is natural "stage" for particle physics

Randall, Sundrum
1999



5D GEOGRAPHY

Quantum fields of different particle species naturally have different characteristic profiles in 5th dimension.



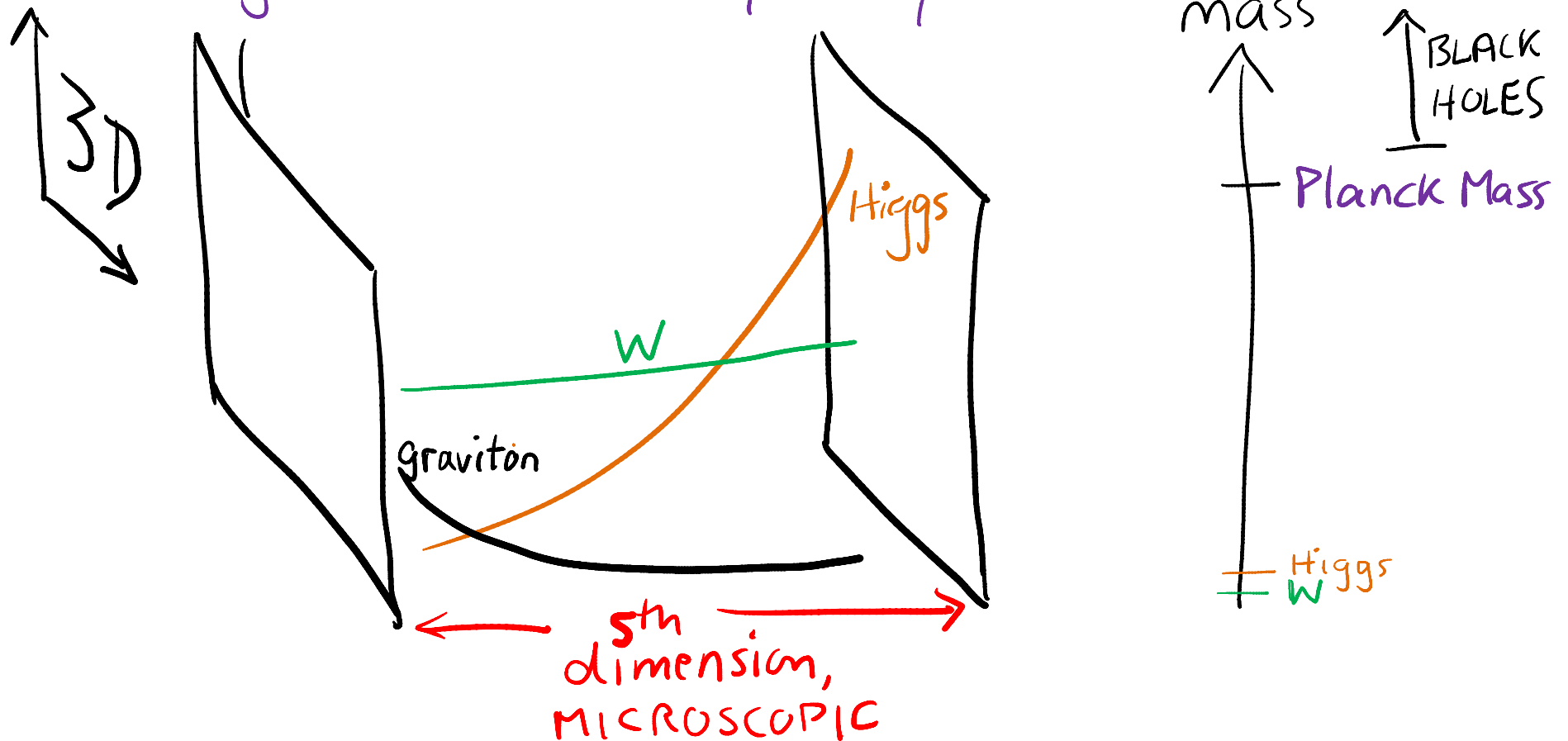
Species with larger overlap are more likely to interact.

This helps explain otherwise mysterious patterns in the observed interaction strengths.

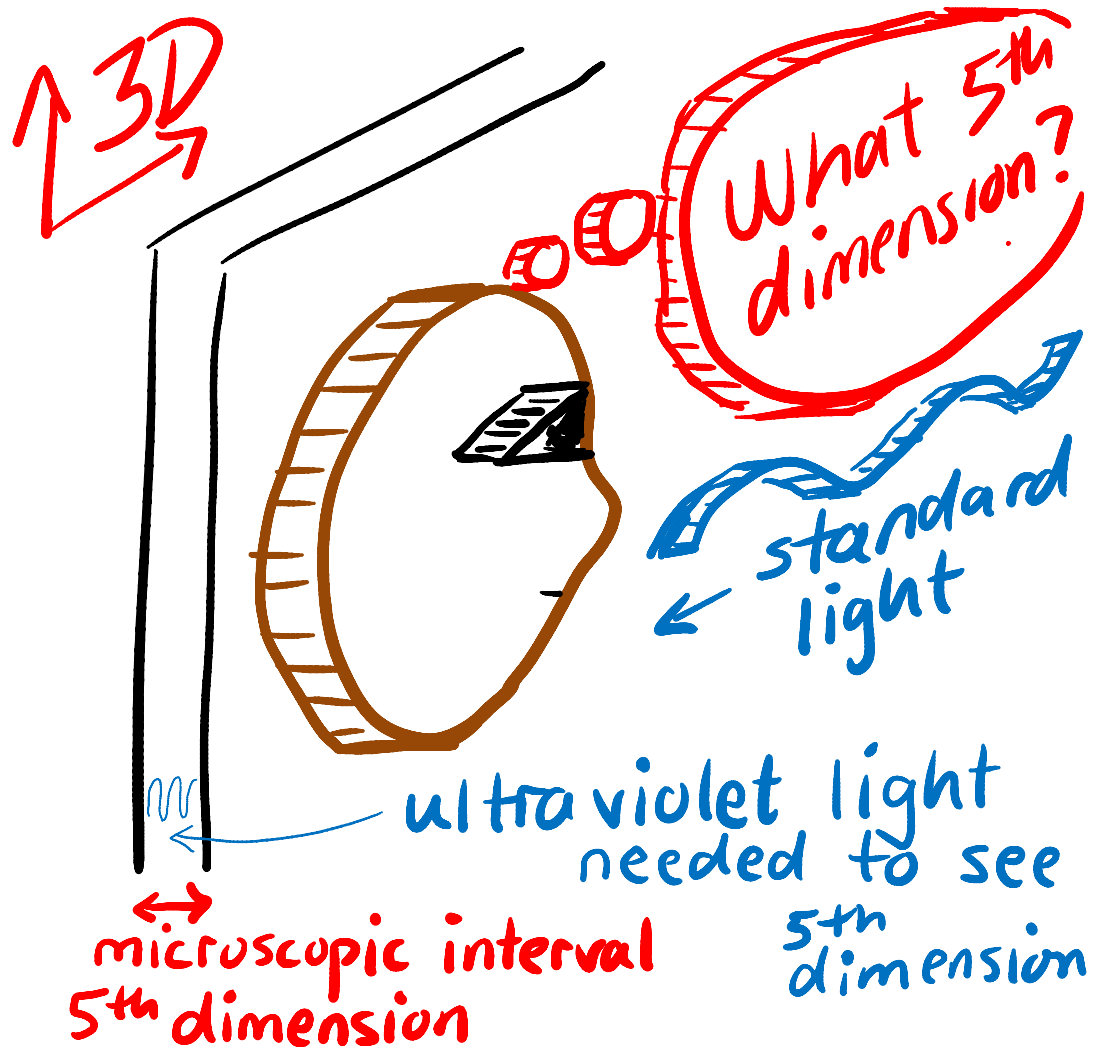
5D GEOGRAPHY

Solves the HIERARCHY PROBLEM!

(W mass from) Higgs mechanism
gravitates only very weakly.



EXTRA-DIMENSIONAL PERCEPTION

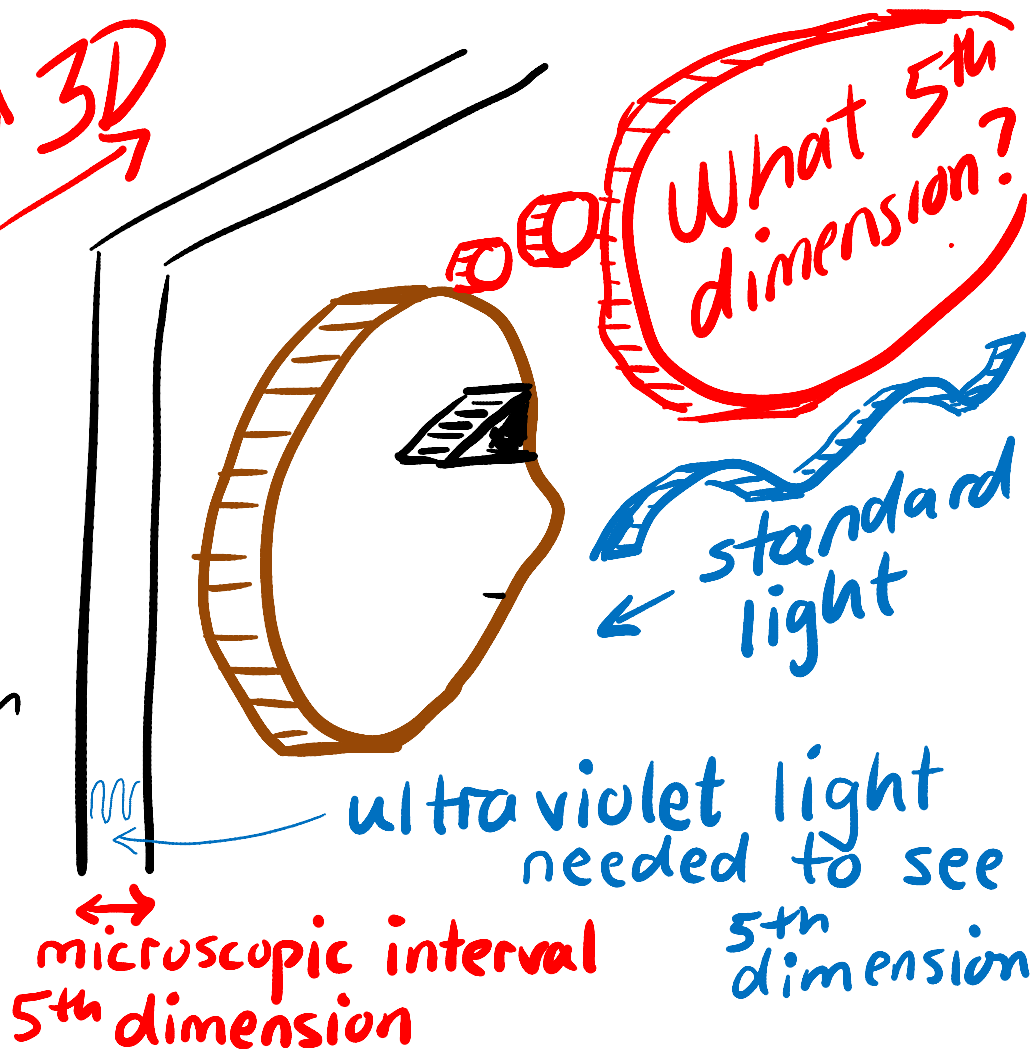


EXTRA-DIMENSIONAL PERCEPTION

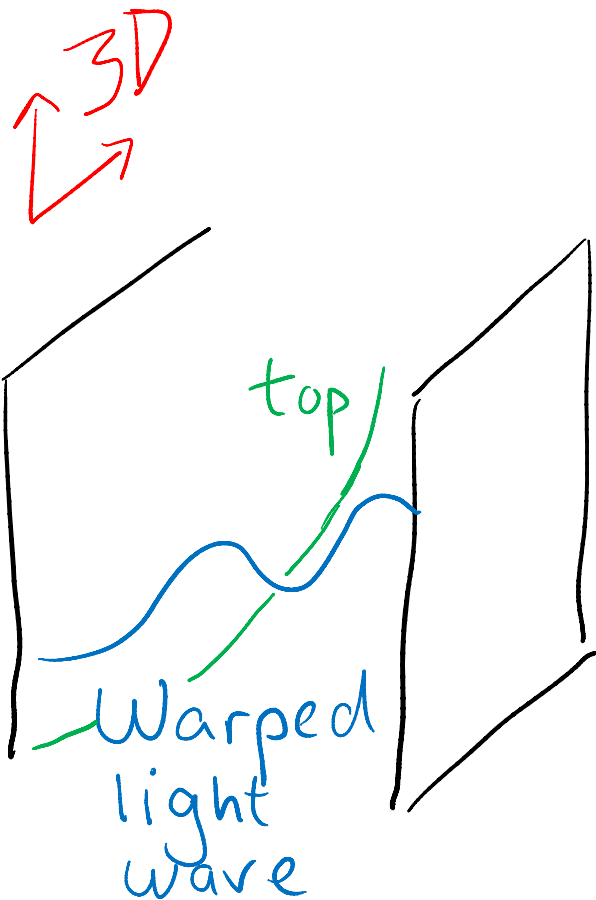
Quantum Energy

$$E_{\text{photon}} \sim \frac{1}{\text{wavelength}}$$

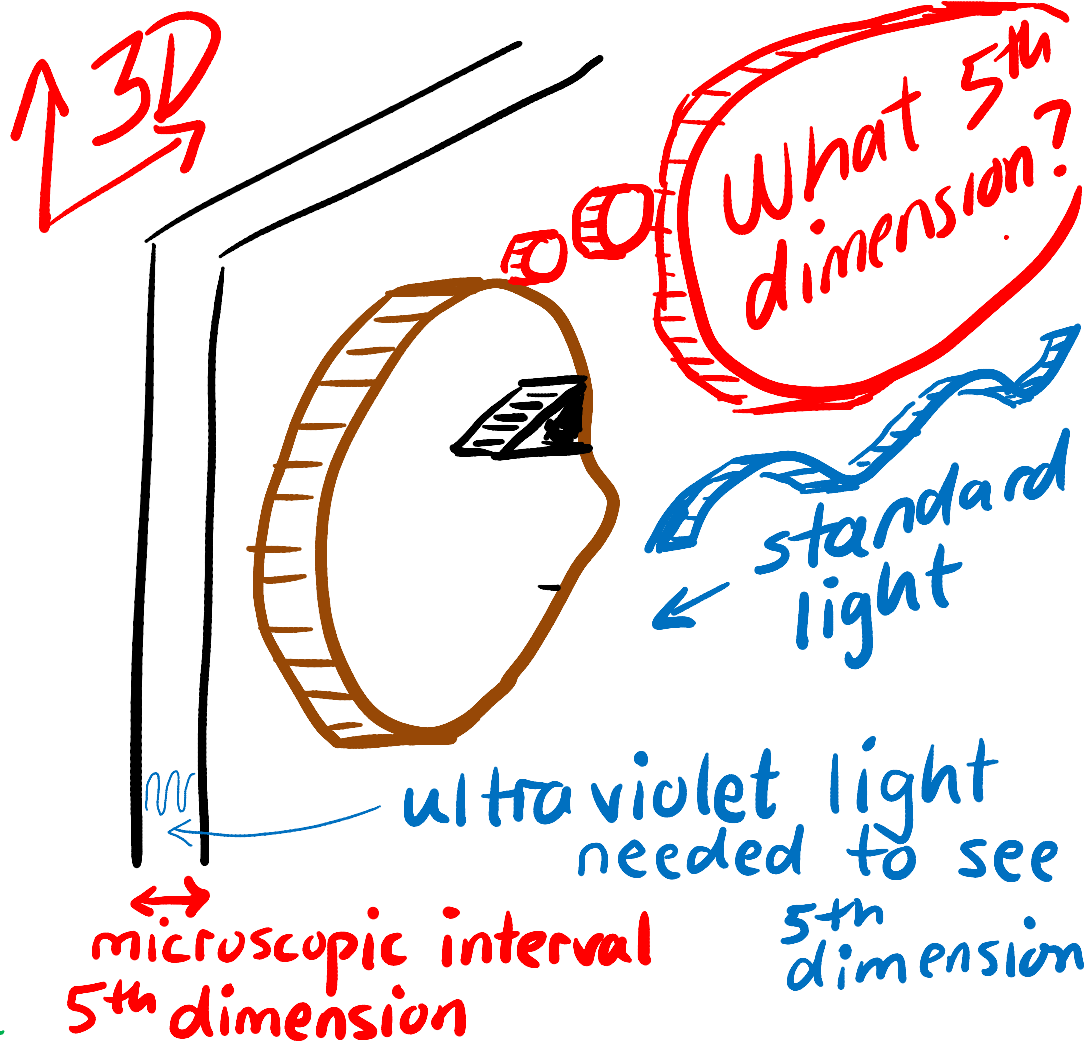
↑ 3D



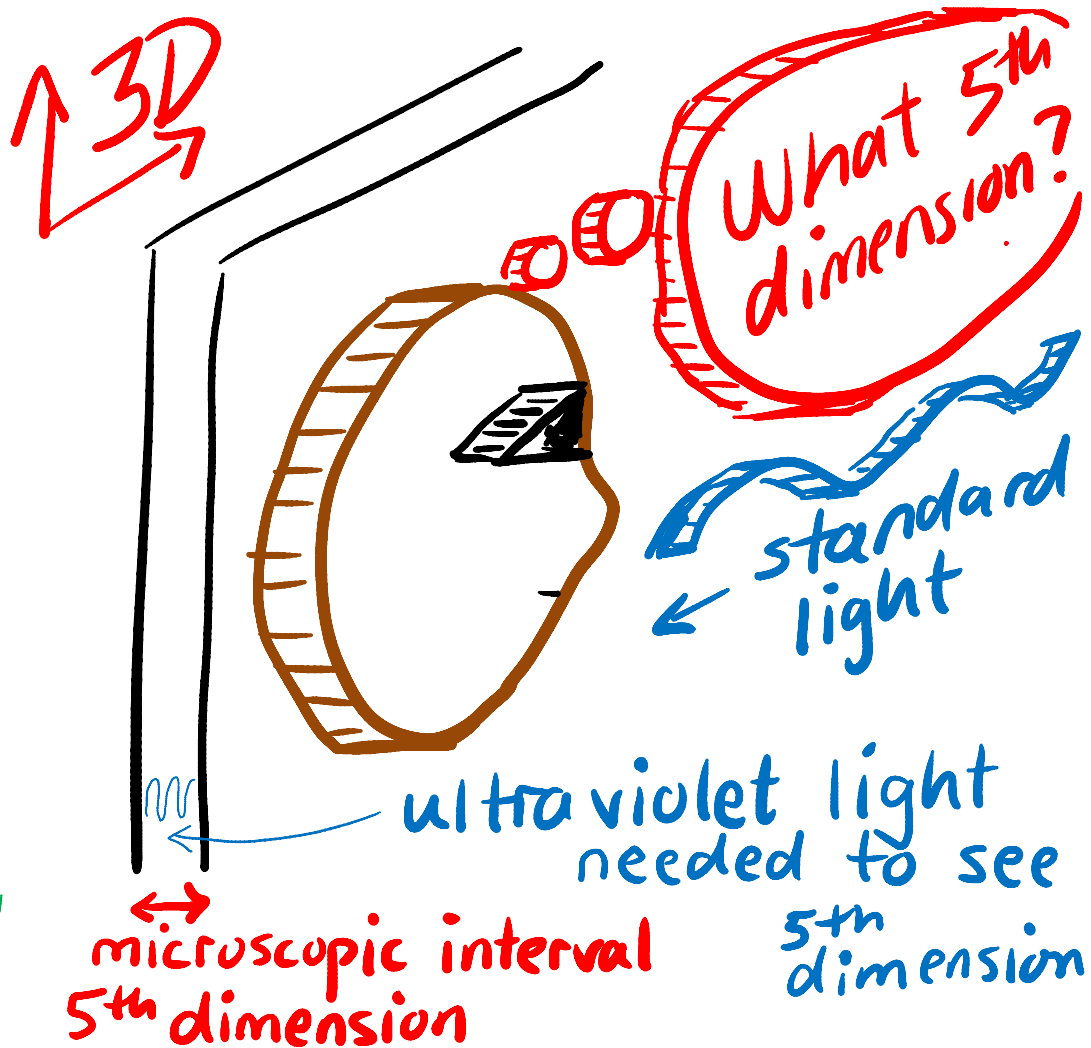
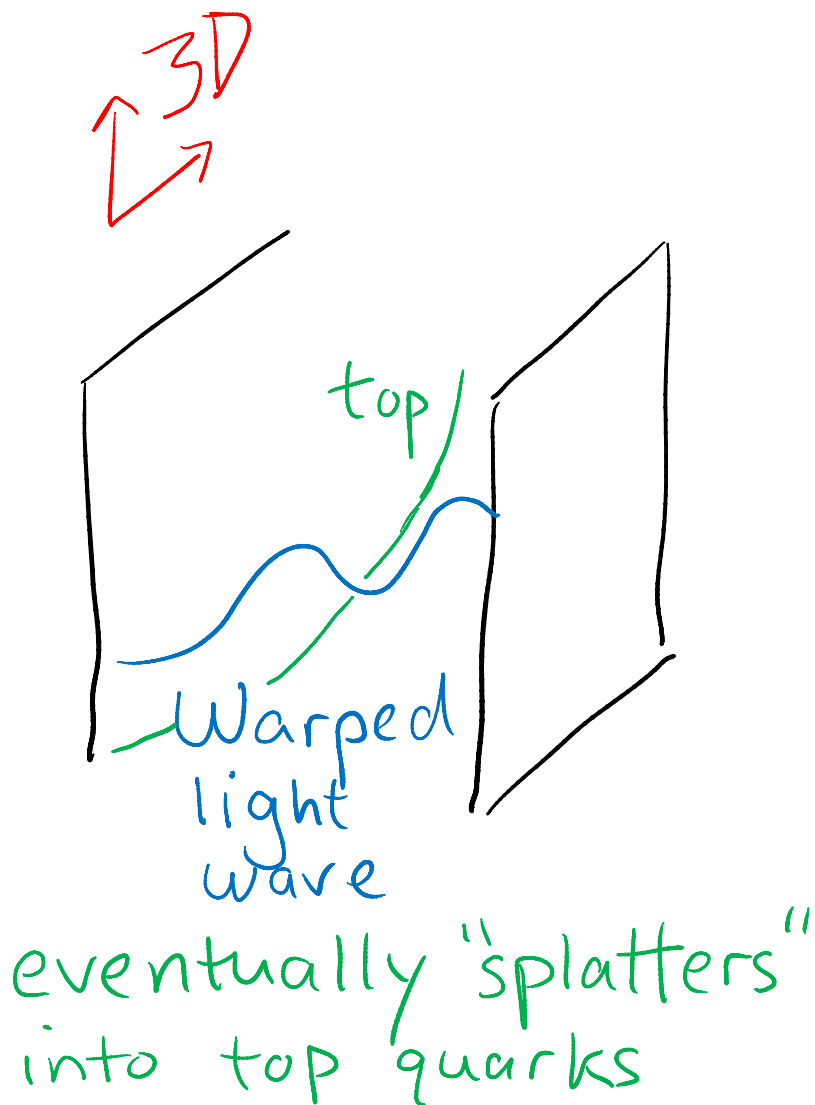
EXTRA-DIMENSIONAL PERCEPTION



E_{photon} requires
Large Hadron Collider

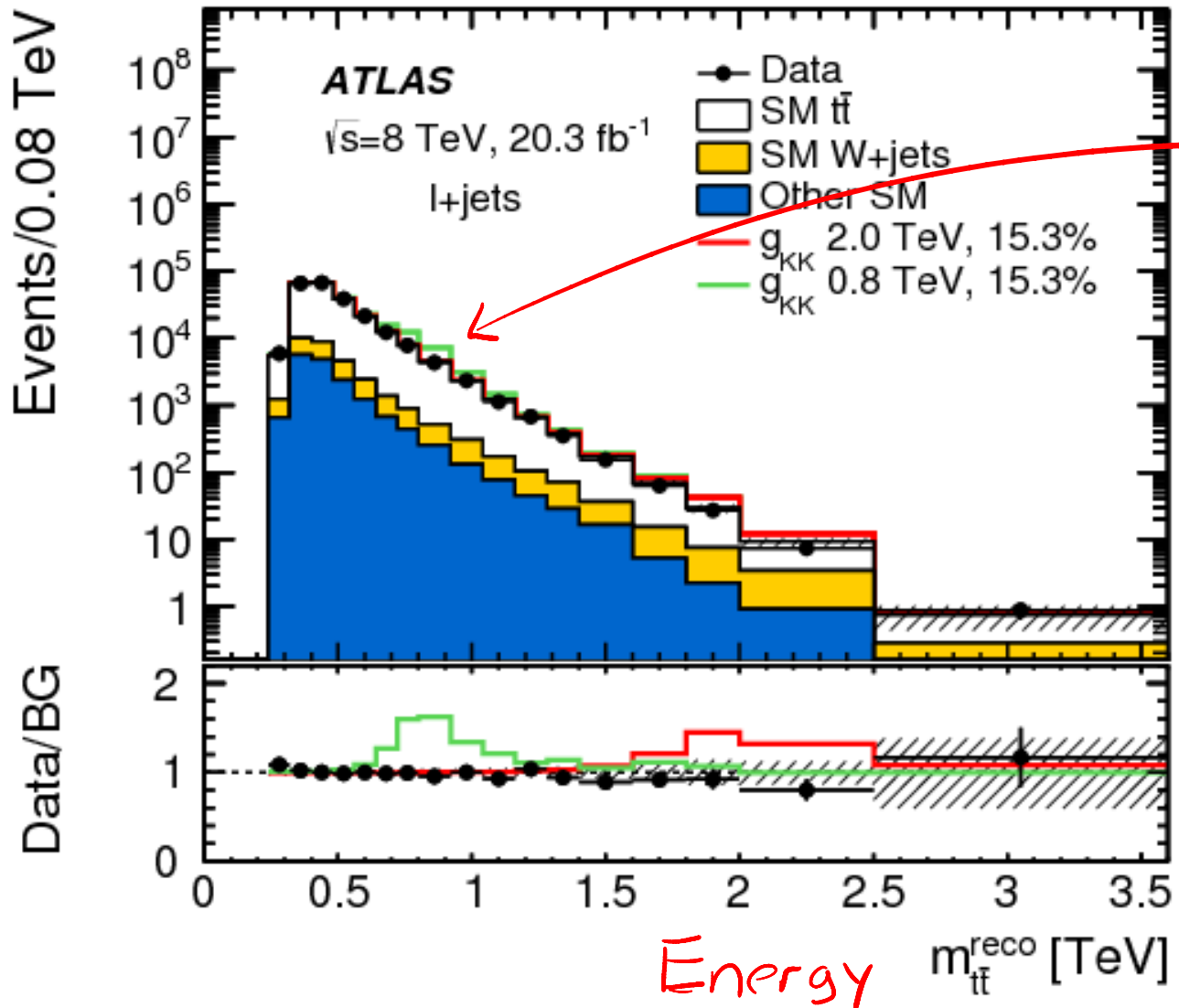


EXTRA-DIMENSIONAL PERCEPTION



BUT COMPETES WITH STANDARD TOP QUARK PRODUCTION

Top quark production



top quark excess from "splatter" of extra-dimensional photons, gravitons, gluons. not yet seen

PRECISION TESTS OF STANDARD PROCESSES

- Higgs boson properties
- species-changing processes
- time-reversal asymmetric processes

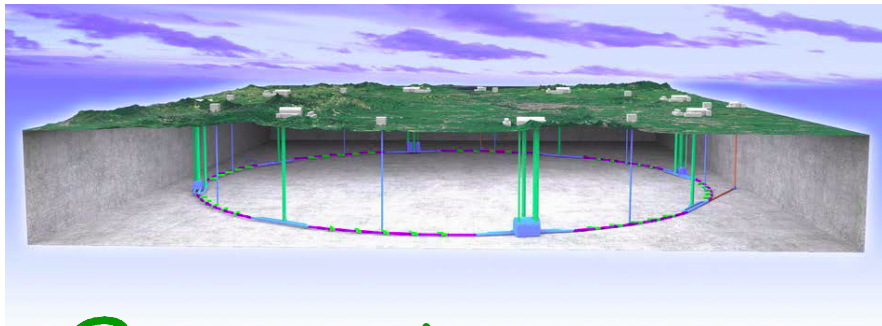
also provide powerful but
indirect probes of 5th dimension

sensitive to
details of theoretical model

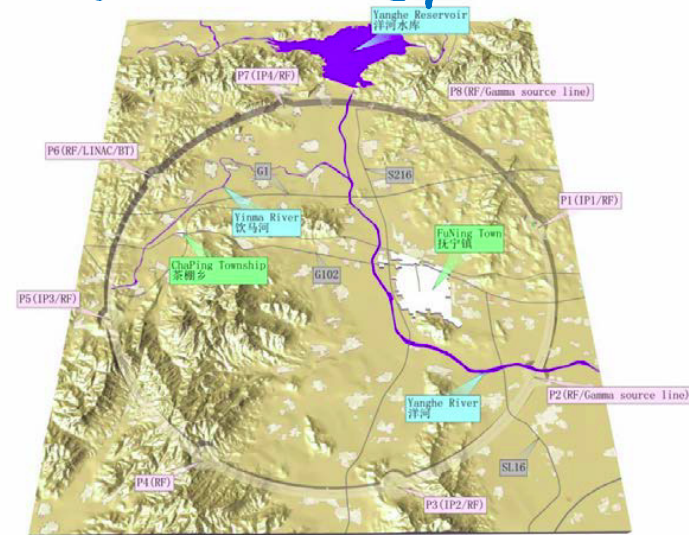
Also yet to make a discovery...

FUTURE COLLIDERS ?

at high precision & high energy frontiers



Proposed in China...



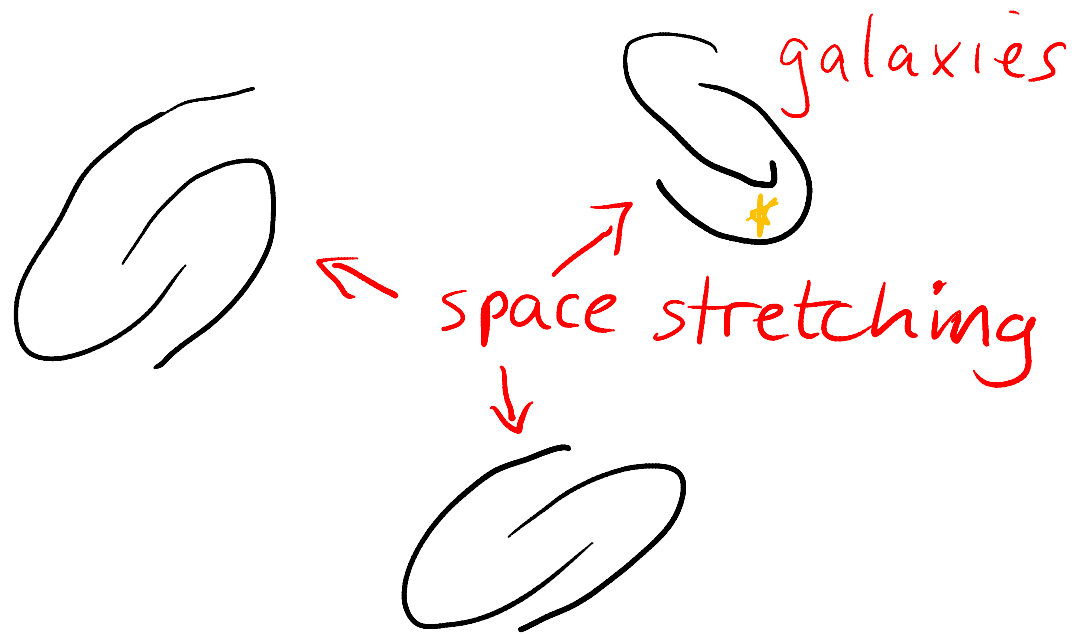
...And in Europe
(environs of CERN)



$O(10)$ improvements in E
& Higgs precision!

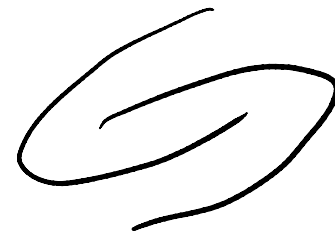
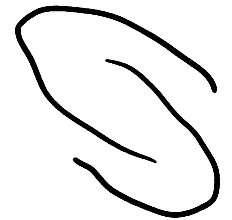
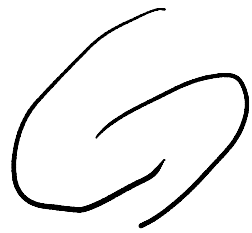
VERY EARLY UNIVERSE

The Universe is expanding:



VERY EARLY UNIVERSE

The Universe is expanding:



VERY EARLY UNIVERSE

The Universe is expanding

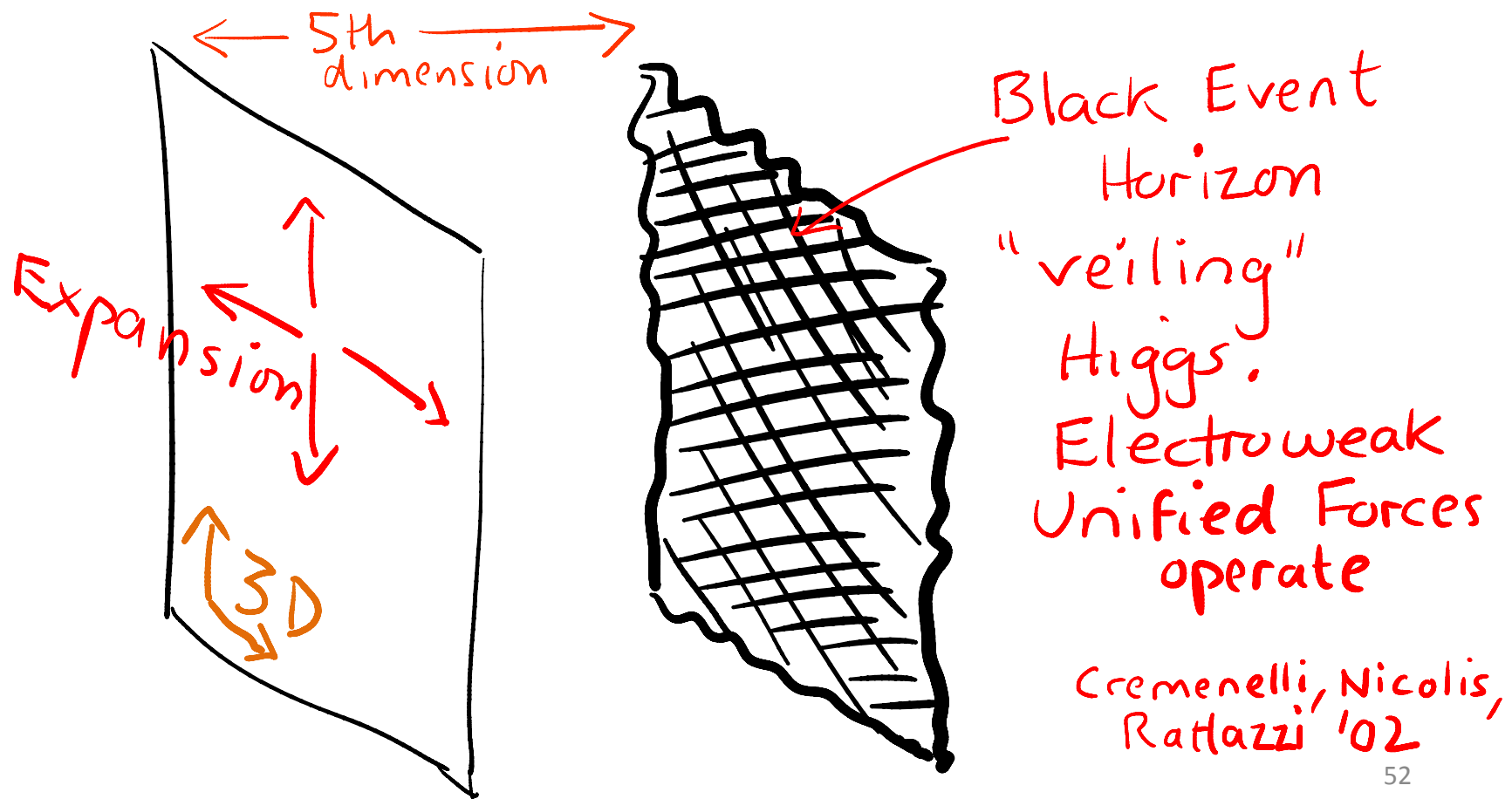
Just after Big Bang it was
far denser, hotter

& expanding much faster

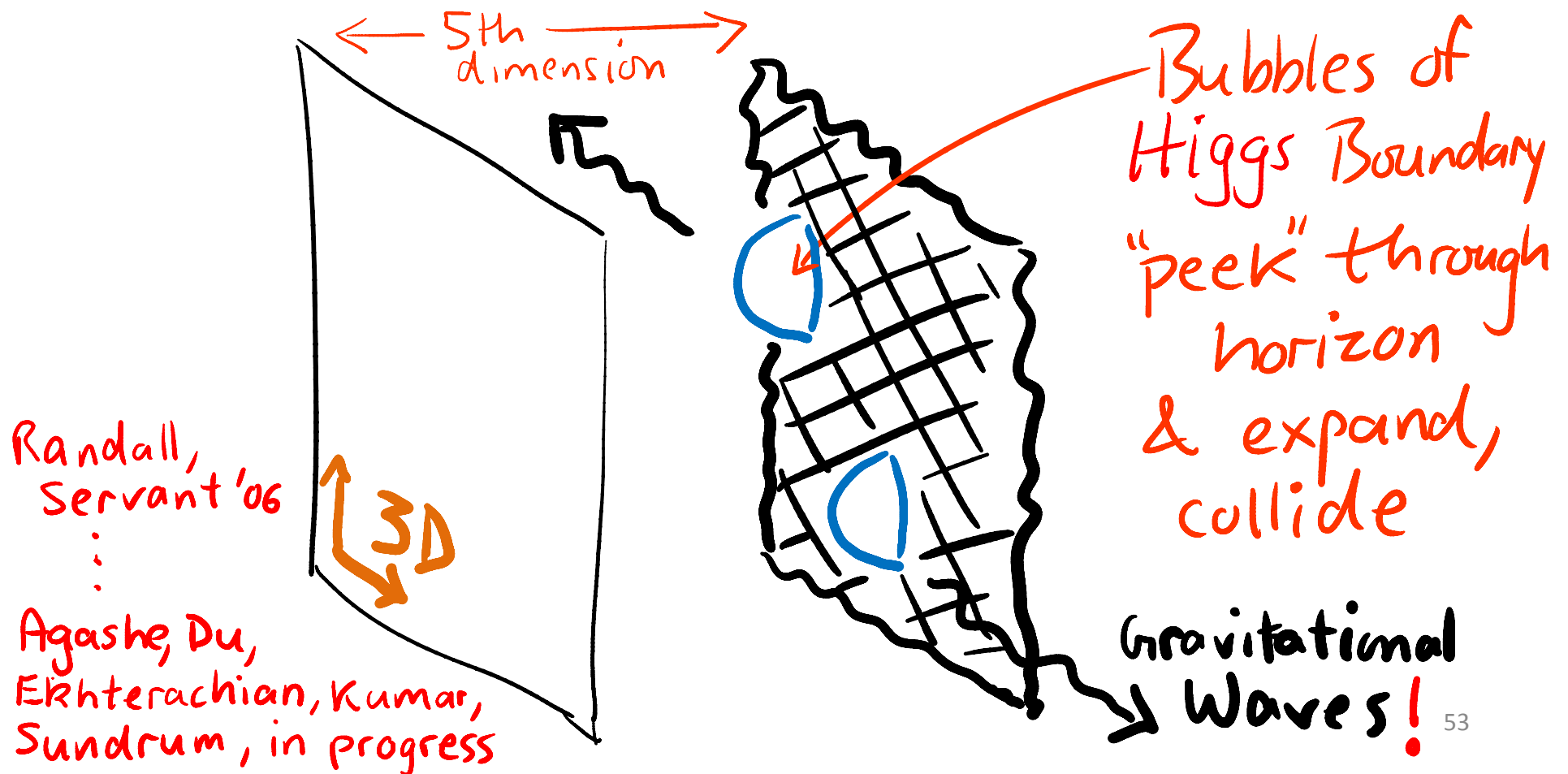
No galaxies, stars, atoms then.
Just thick opaque hot cosmic soup
of subatomic particles & antiparticles.

EARLY UNIVERSE: WARPED 5D PHASE TRANSITION

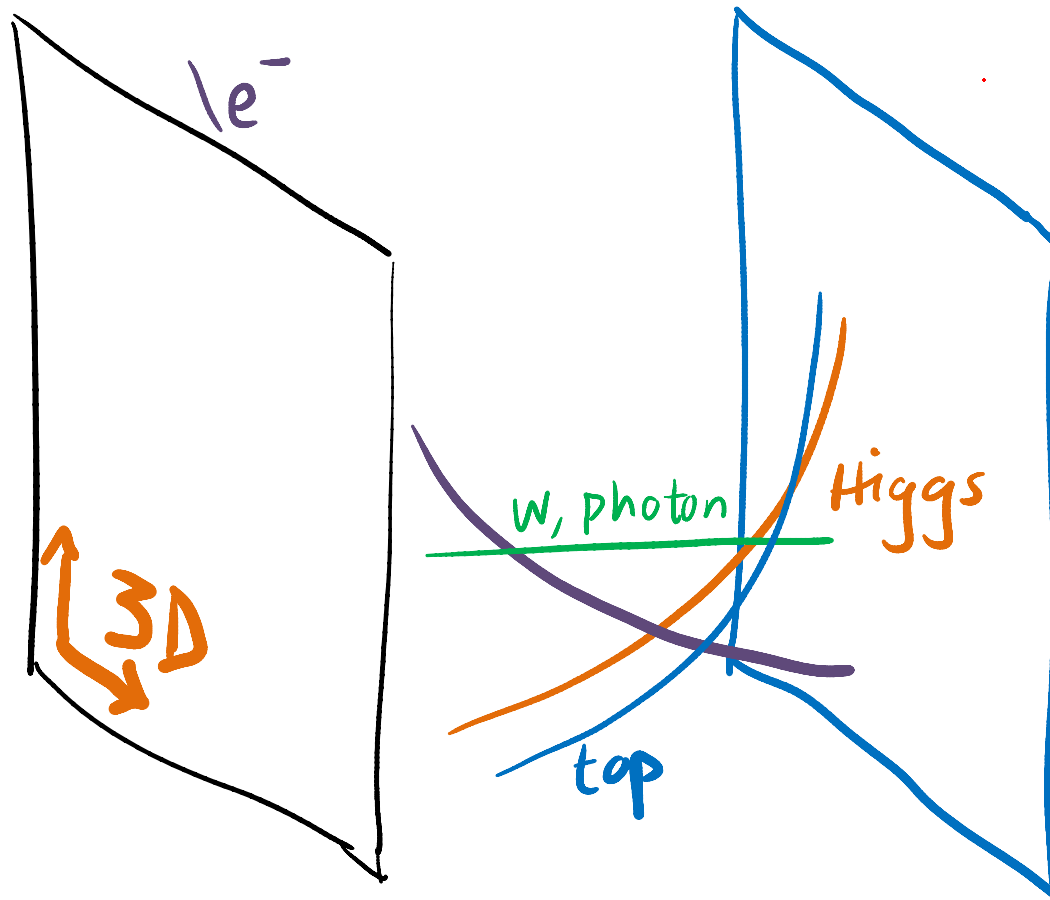
High Temperature after Big Bang



Later, Universe cools a bit
until...

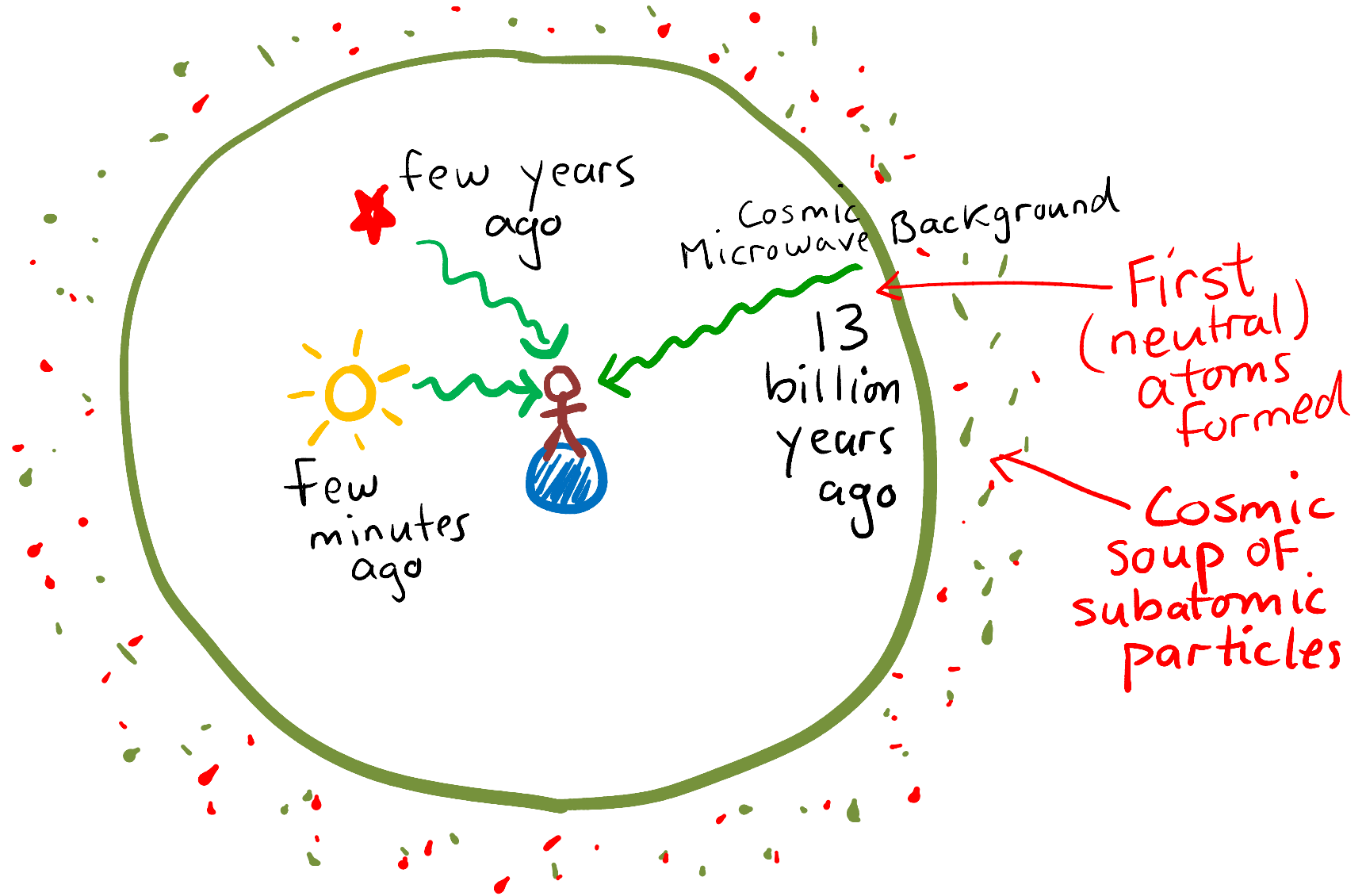


TODAY the Universe is
very cold

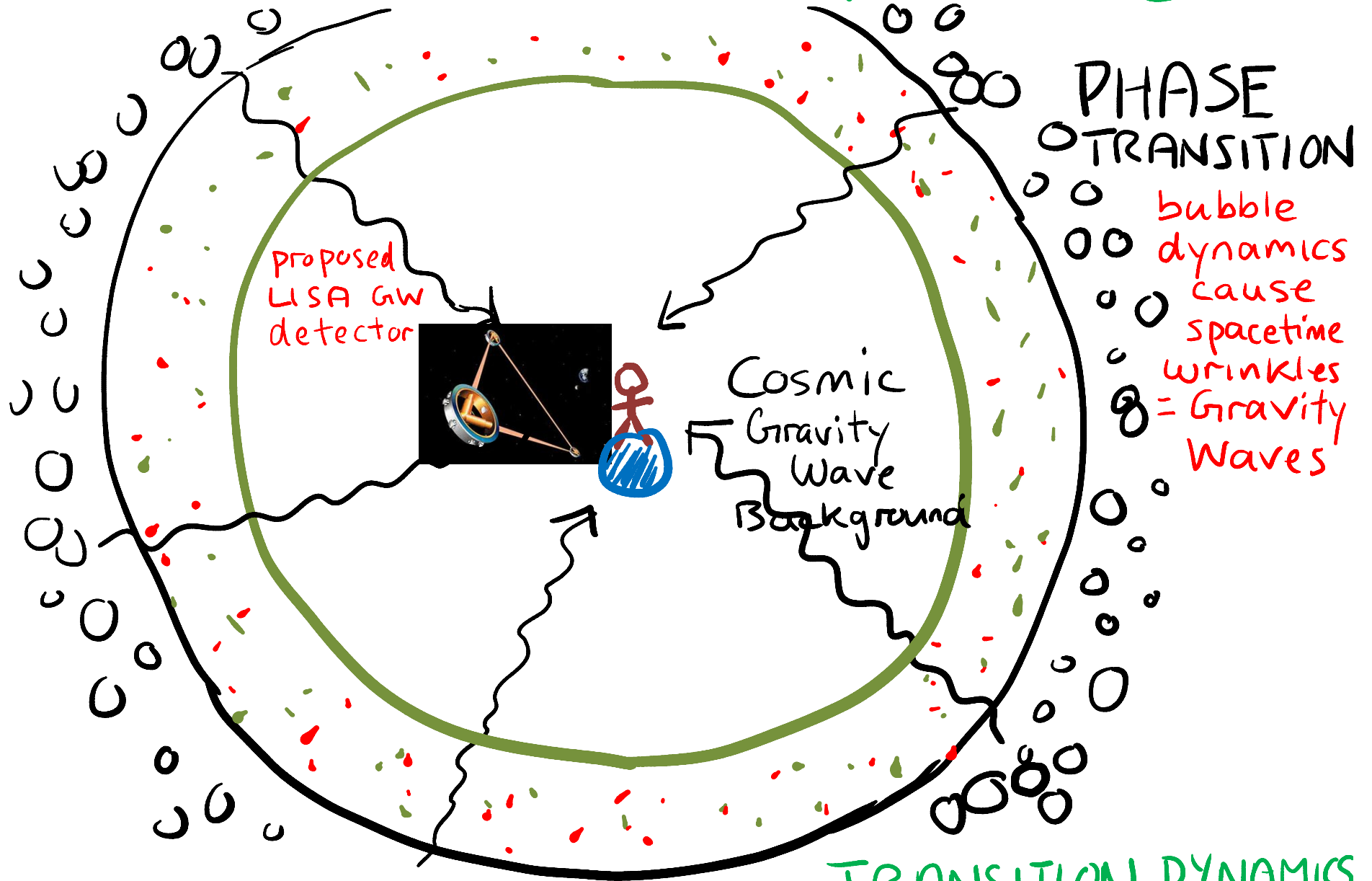


Bubbles have
coalesced &
"taken over"
Electromagnetism
& Weak Force
are distinct

LOOKING BACK IN TIME



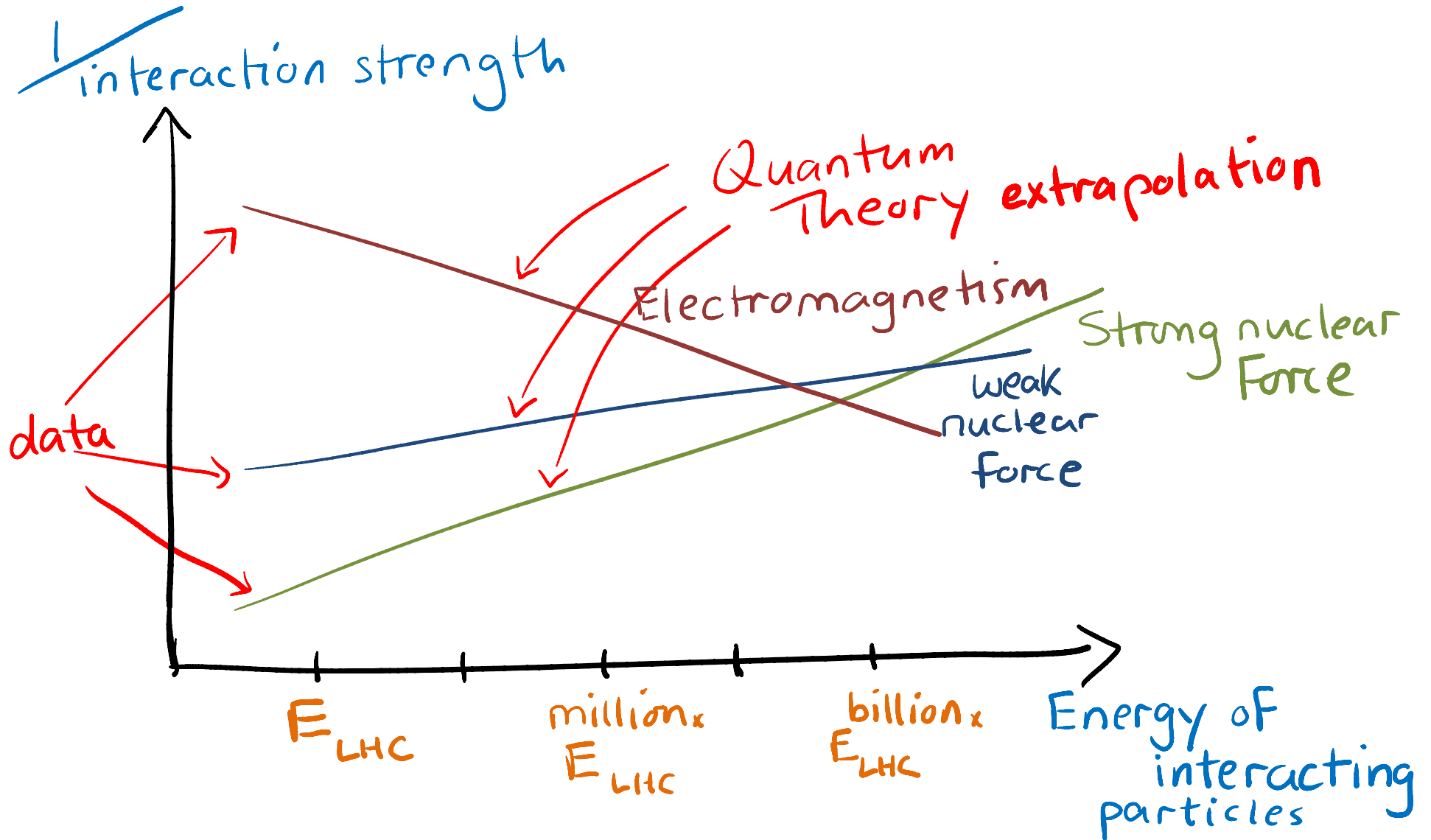
WRINKLES IN SPACETIME



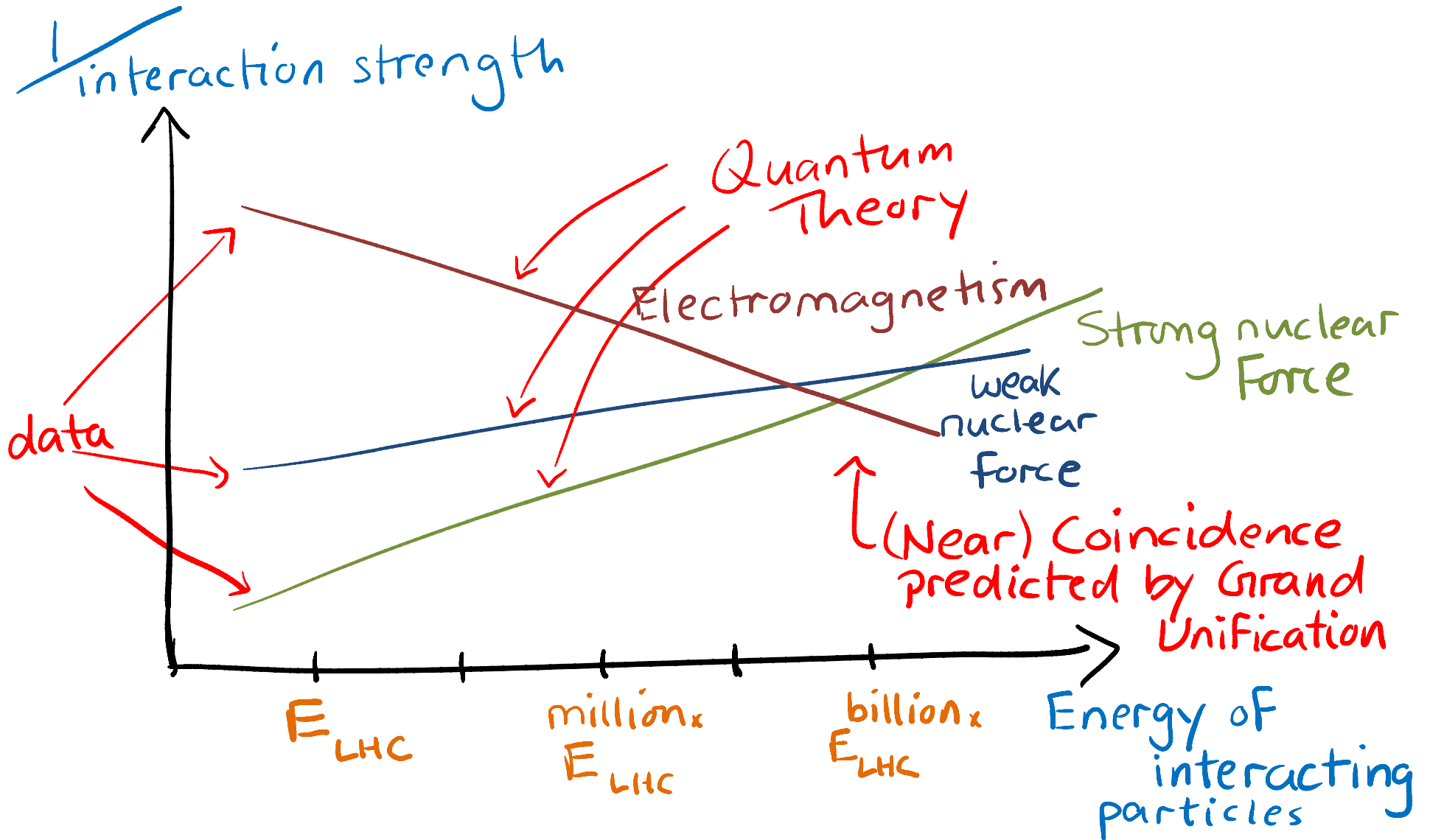
GRAND UNIFICATION

There is circumstantial evidence that the Electroweak Force & Strong nuclear Force emerge from a highly symmetric internal space (symmetry of 9D sphere!) again somewhat "oblate".

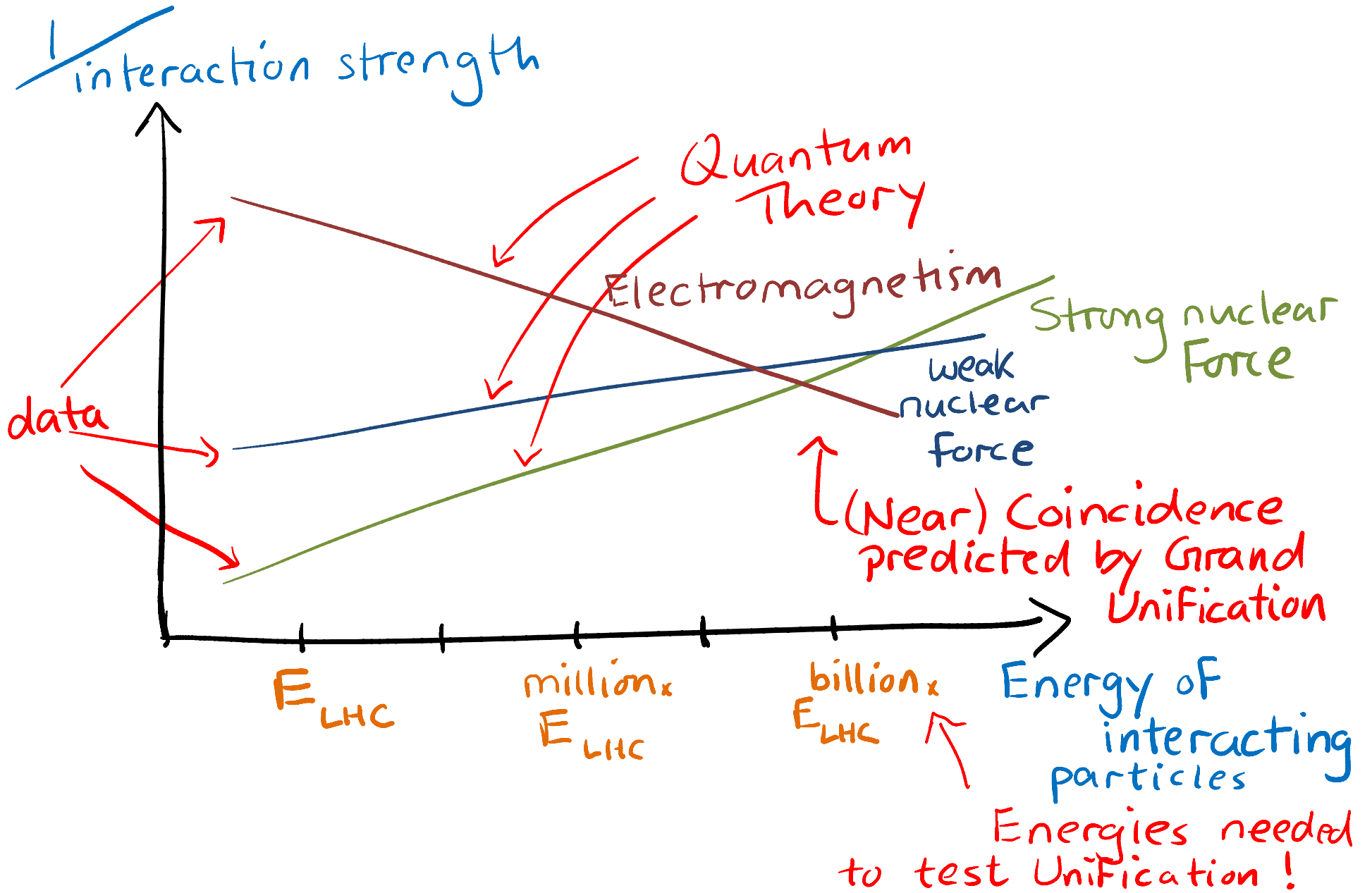
GRAND UNIFICATION



GRAND UNIFICATION



GRAND UNIFICATION



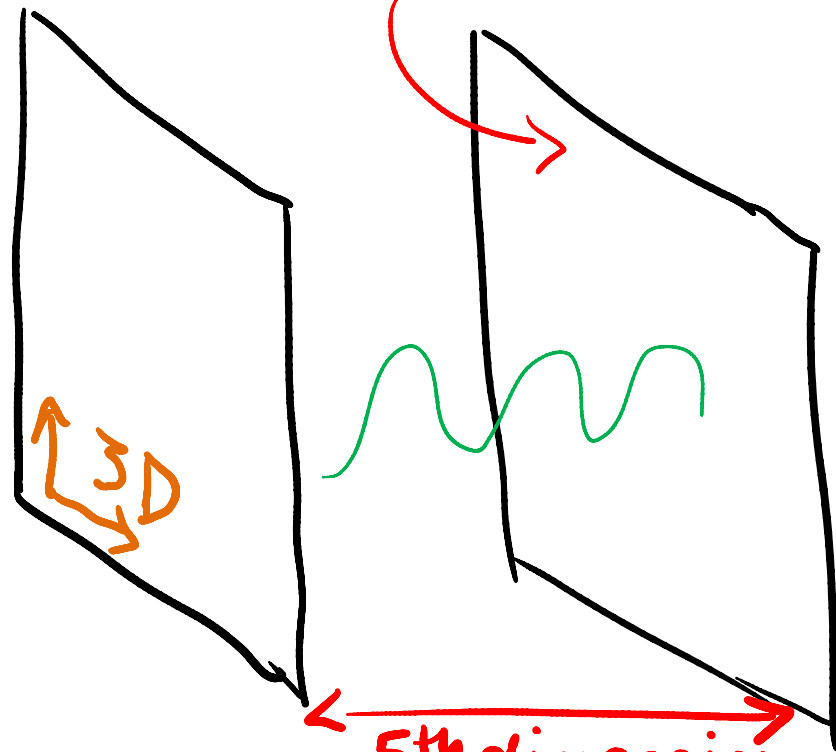
"Orbifold"

Grand Unification

of EM + Weak + Strong interactions

Grand Unification Higgs

Analogous
to Electroweak
Higgs
mechanism...



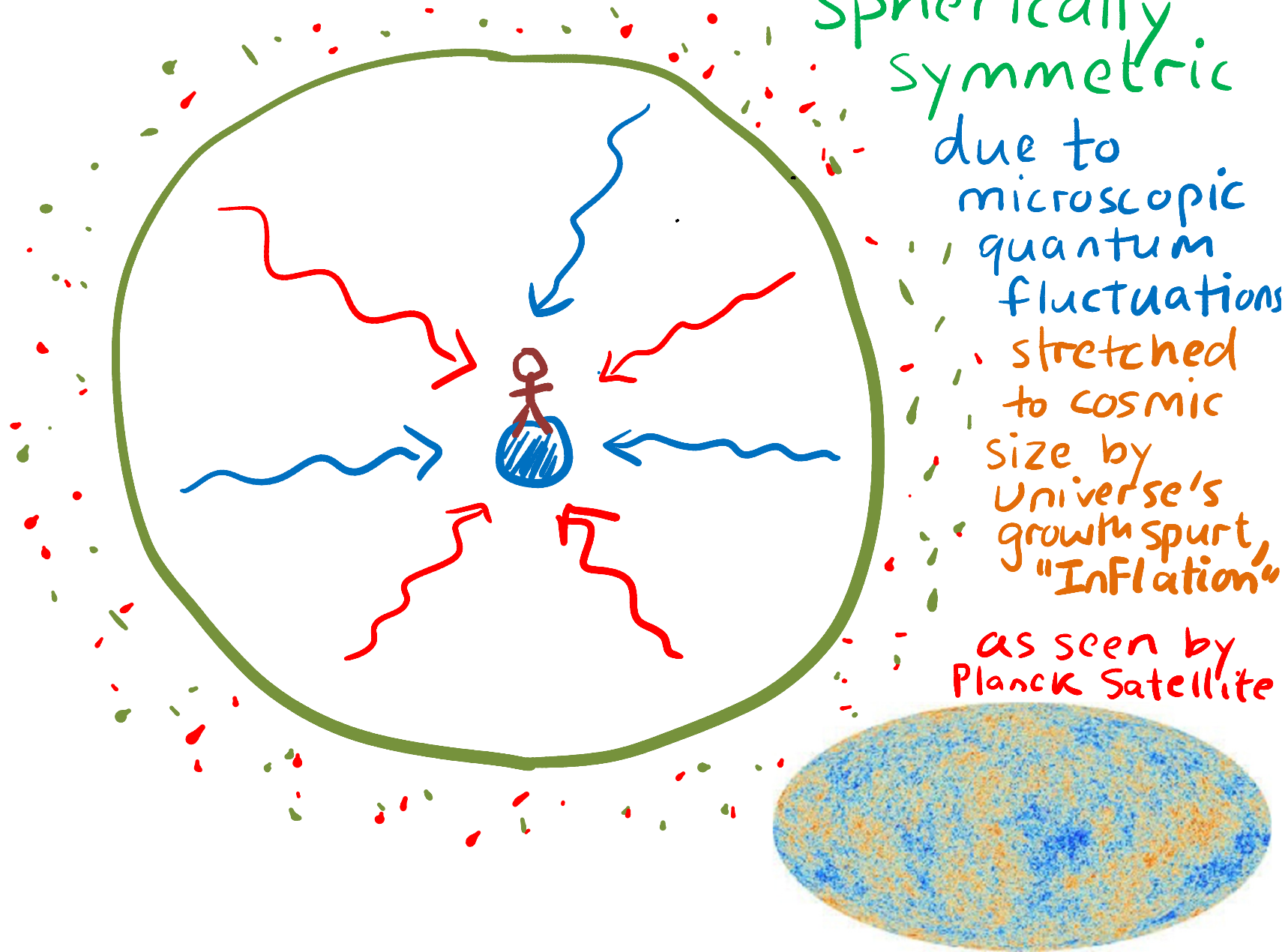
5th dimensional
unified fields
& gravitons
orders of
magnitude
beyond
terrestrial
colliders!

5th dimension
 $\sim \frac{1}{1000000000000}$ proton size

CMB is almost, but not perfectly
spherically
symmetric

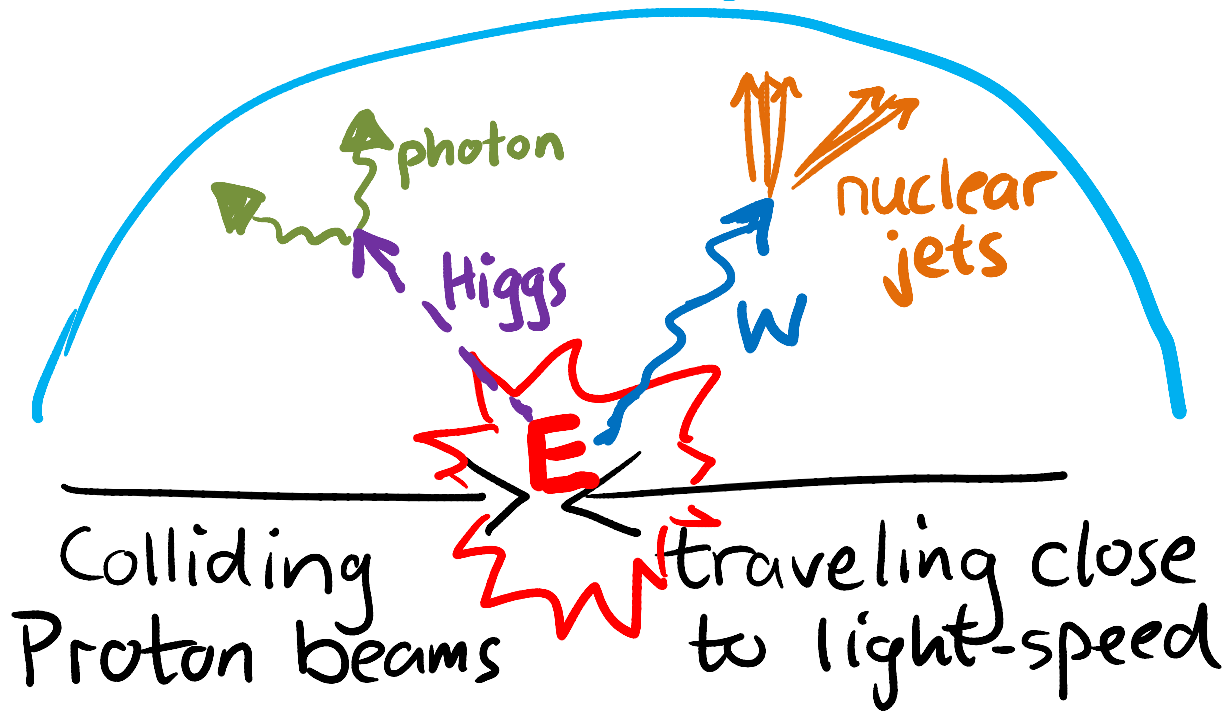
due to
microscopic
quantum
fluctuations
stretched
to cosmic
size by
Universe's
growth spurt,
"Inflation"

as seen by
Planck Satellite



RECALL
PARTICLE COLLIDERS

Detectors



COSMOLOGICAL COLLIDER

PHYSICS

Chen, Wang '10

Arkani-Hamed, Maldacena '15

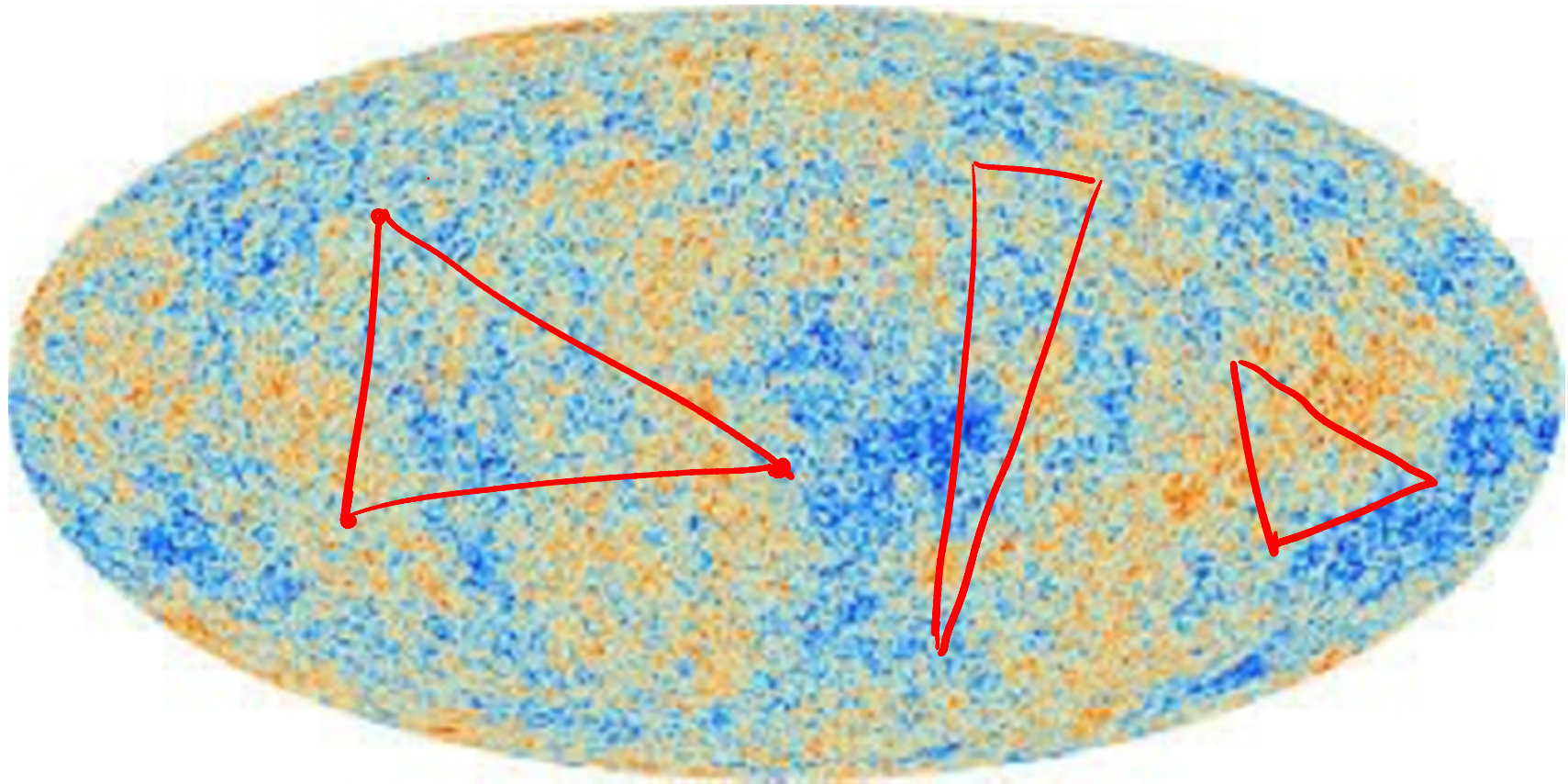
Recall we need $E \sim \frac{1}{\text{wavelength}}$
to create waves to look inside
5th dimension.

The expansion of space itself
during cosmic inflation can supply
this energy!

The CMB (& its future successors)
act as detectors of the "splatler" of
the 5th dimensional
gravitational & unified waves

Kumar, Sundrum '18

DECODED BY STATISTICS
OF QUANTUM FLUCTUATIONS



TO SEE THE 5D WAVES

CONCLUSION

Fundamental Physics is strangely beautiful, driven by geometric & symmetry principles.

Fundamental forces are members of a family, descended from unified ancestors at the dawn of time.

Extra-dimensional spacetime structure can play a central role in this physics.

A diverse range of ambitious, titanic experiments will probe this physics this century.