

LHC
& THE WORLD OF
EXTRA
DIMENSIONS

Raman Sundrum
Johns Hopkins University

OUTLINE

At the frontier of experimental
& theoretical particle physics —

LHC, Electro-Weak Unification
and the Hierarchy Problem

An Extra-Dimensional scenario with
some answers

Extra Dimensions at the LHC

Other directions

ORIGIN OF THE MASSES

Past experiments \Rightarrow

Electromagnetism Weak Nuclear Force

Higgs Mechanism

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graph TD; A[Electromagnetism] --- B[Higgs Mechanism]; B --- C[Weak Nuclear Force];
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ElectroWeak Unified Theory

Masses of all known elementary particles must emerge from this bifurcation

LHC poised to explore this revolutionary but mysterious physics

RELATIVITY THEORY

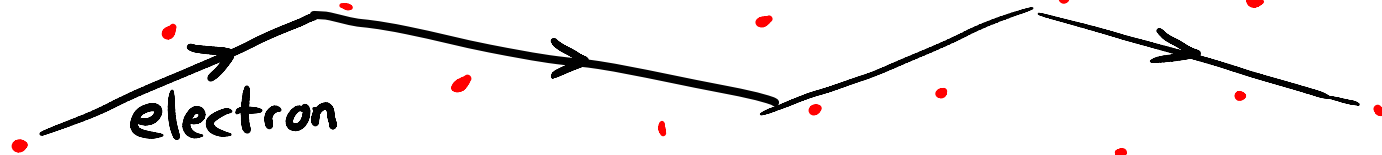
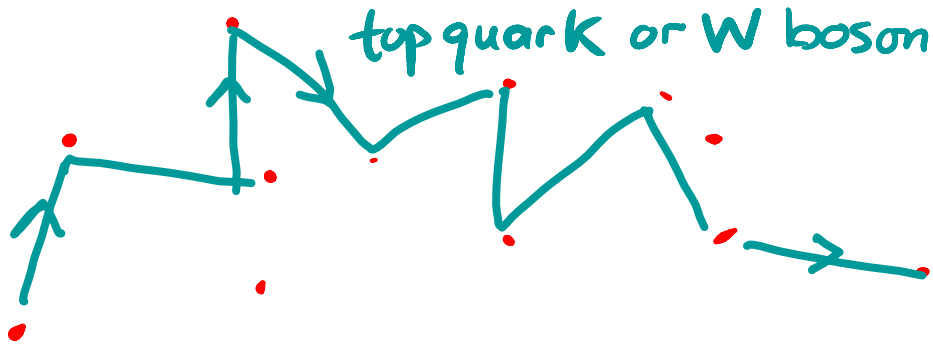
⇒ massless particles must travel at light speed

massive particles must travel below light speed

"STANDARD MODEL"

- ⇒ Elementary particles are fundamentally all massless, but "vacuum" is a rich bath ("condensate") of Higgs Bosons that
- (a) is extremely difficult to detect, evading all tests for an aether etc.
 - (b) slow down elementary particles below light speed (so they acquire mass)

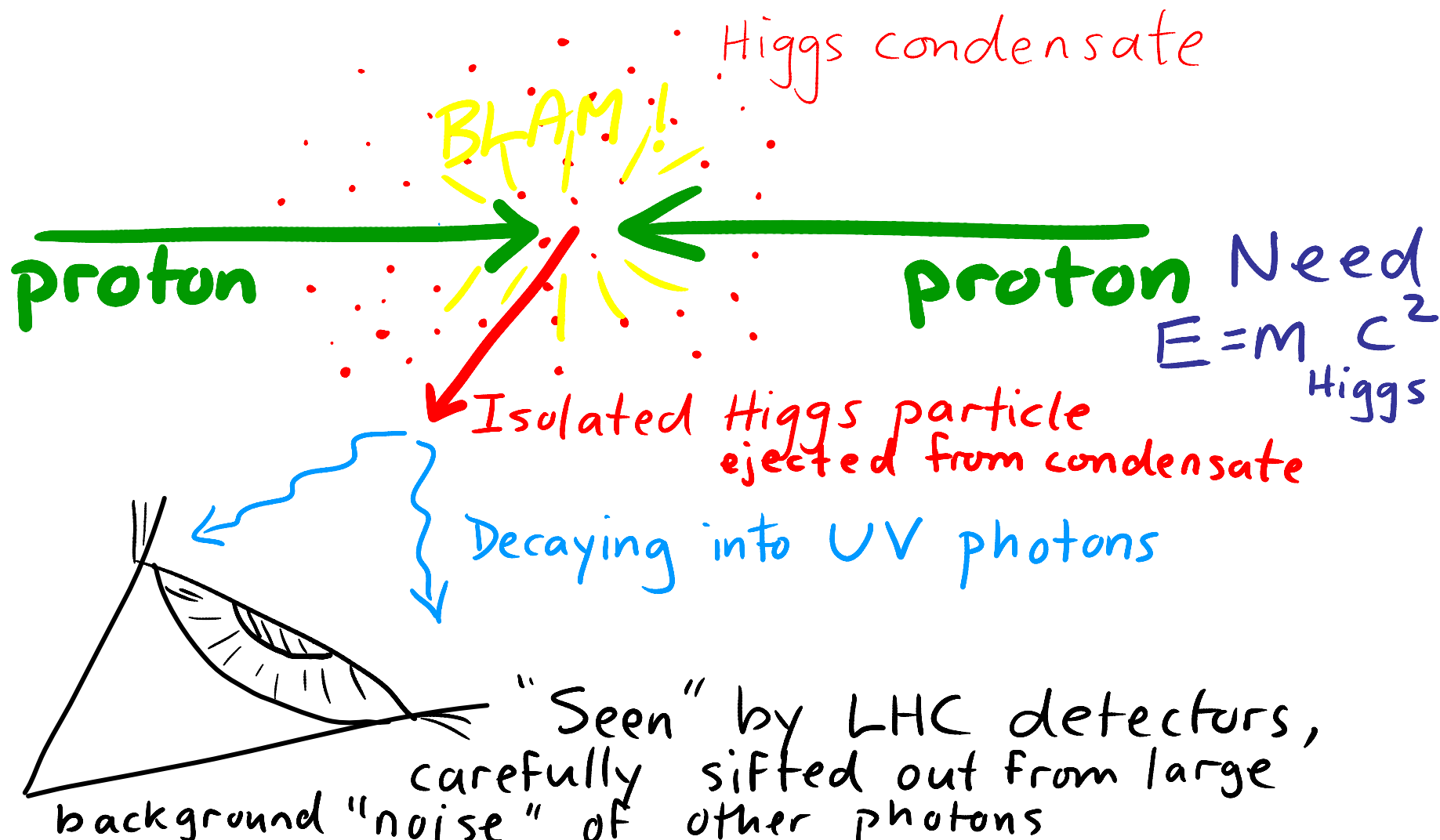
TRAVELS THROUGH THE "VACUUM"



A Higgs Boson
in "vacuum"

A red dot with a red arrow pointing upwards to it. The text "A Higgs Boson in 'vacuum'" is written in red below the dot.

LHC will (very likely)
blast Higgs bosons out of hiding

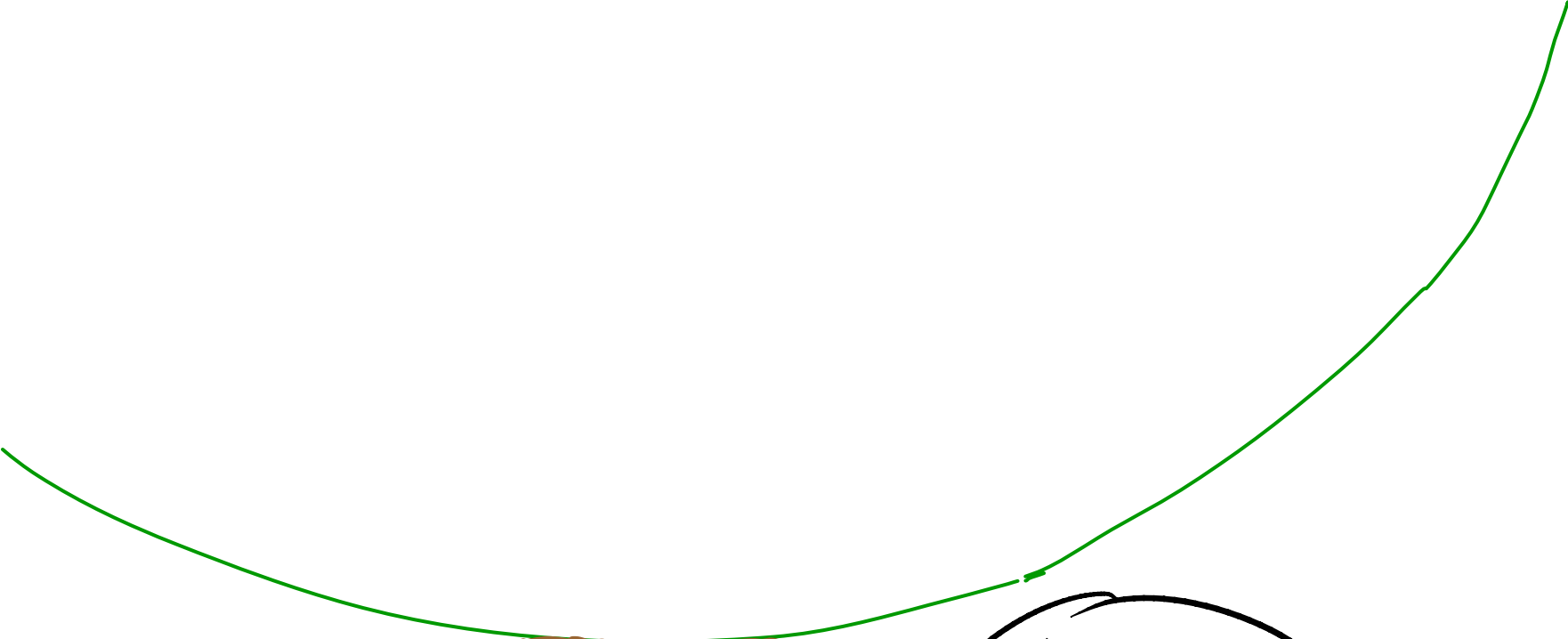


BUT THERE'S A PUZZLE: HIERARCHY PROBLEM

~ Why is gravity so weak?

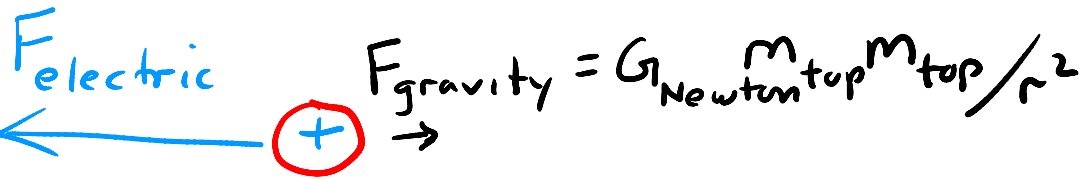


Whew! Gravity
seems pretty
strong to me

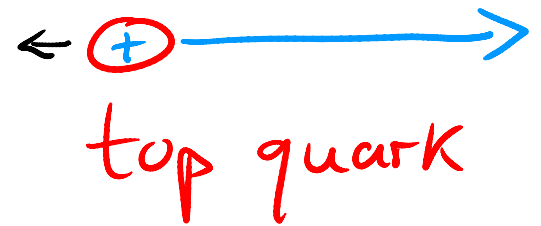


Hey, I
am Atlas!

ON PER PARTICLE BASIS

$$F_{\text{gravity}} = G_{\text{Newton}} \frac{m_{\text{top}} m_{\text{top}}}{r^2}$$
A diagram showing a red circle with a plus sign inside, representing a top quark. A blue arrow labeled F_{electric} points to the left from the circle. A blue arrow points to the right from the circle, with the equation $F_{\text{gravity}} = G_{\text{Newton}} \frac{m_{\text{top}} m_{\text{top}}}{r^2}$ written above it.

top quark
(heaviest known elementary particle)



top quark

$$\frac{F_{\text{gravity}}}{F_{\text{electric}}} \sim 10^{-30} !$$

Theoretically, in quantum standard model this ratio appears as an implausible cancellation of many order one contributions

EXTRA DIMENSIONS OF SPACETIME

may resolve this puzzle:

Earlier: Supersymmetry, sometimes called "fermionic extra dimensions"

BraneWorld scenarios:

"Large Extra Dimensions" Arkani-Hamed, Dimopoulos, Dvali '98

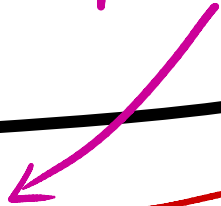
"RS1" Randall, Sundrum '99

Here we discuss Warped Compactification
(or RS) with Bulk Standard Model

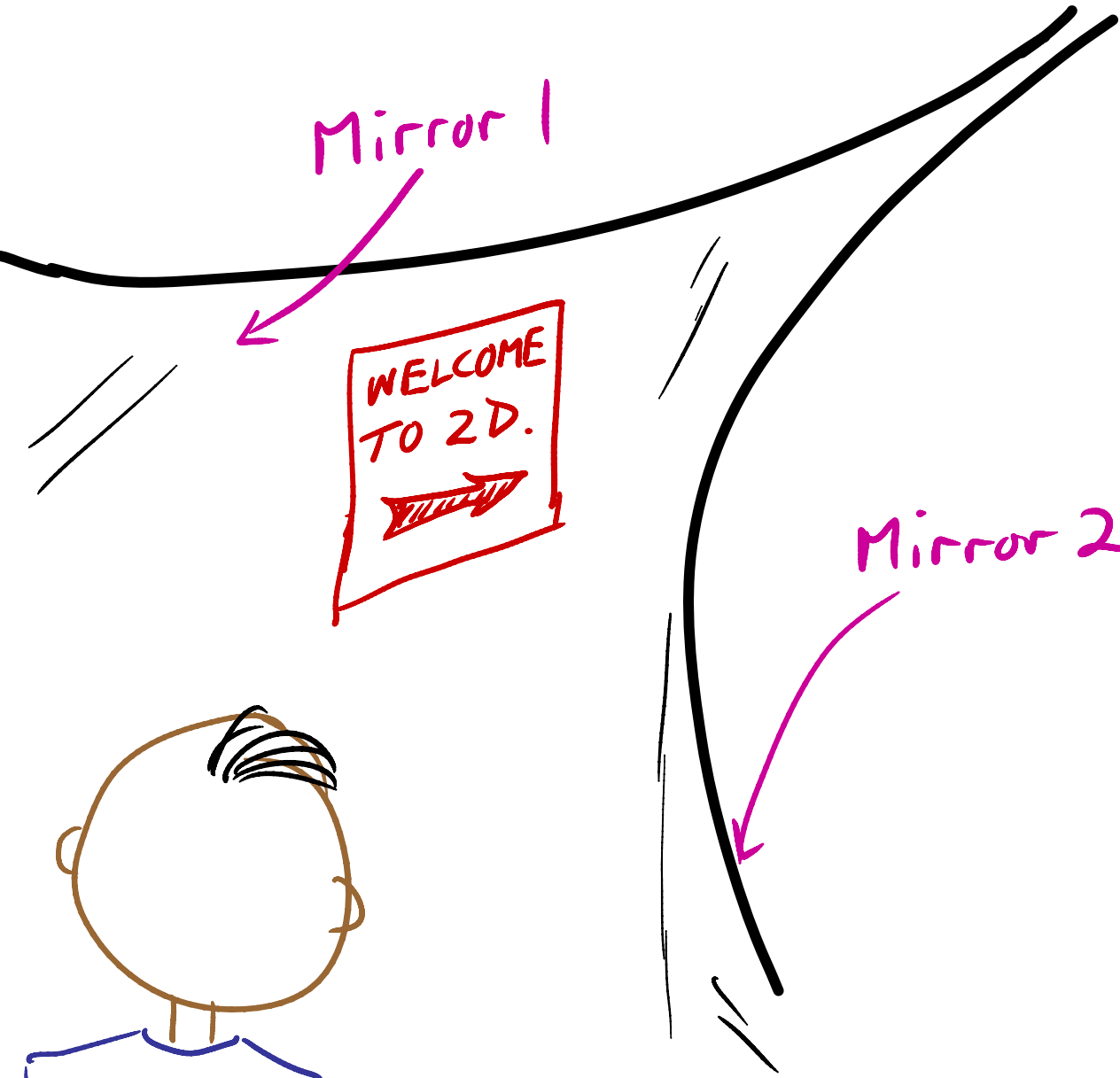
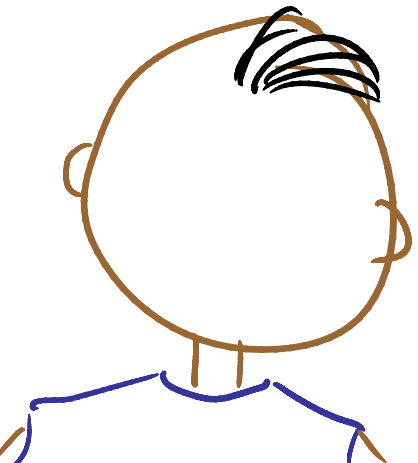
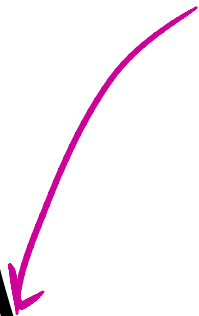
How do we think about Extra Dimensions?

DIMENSION LOST!

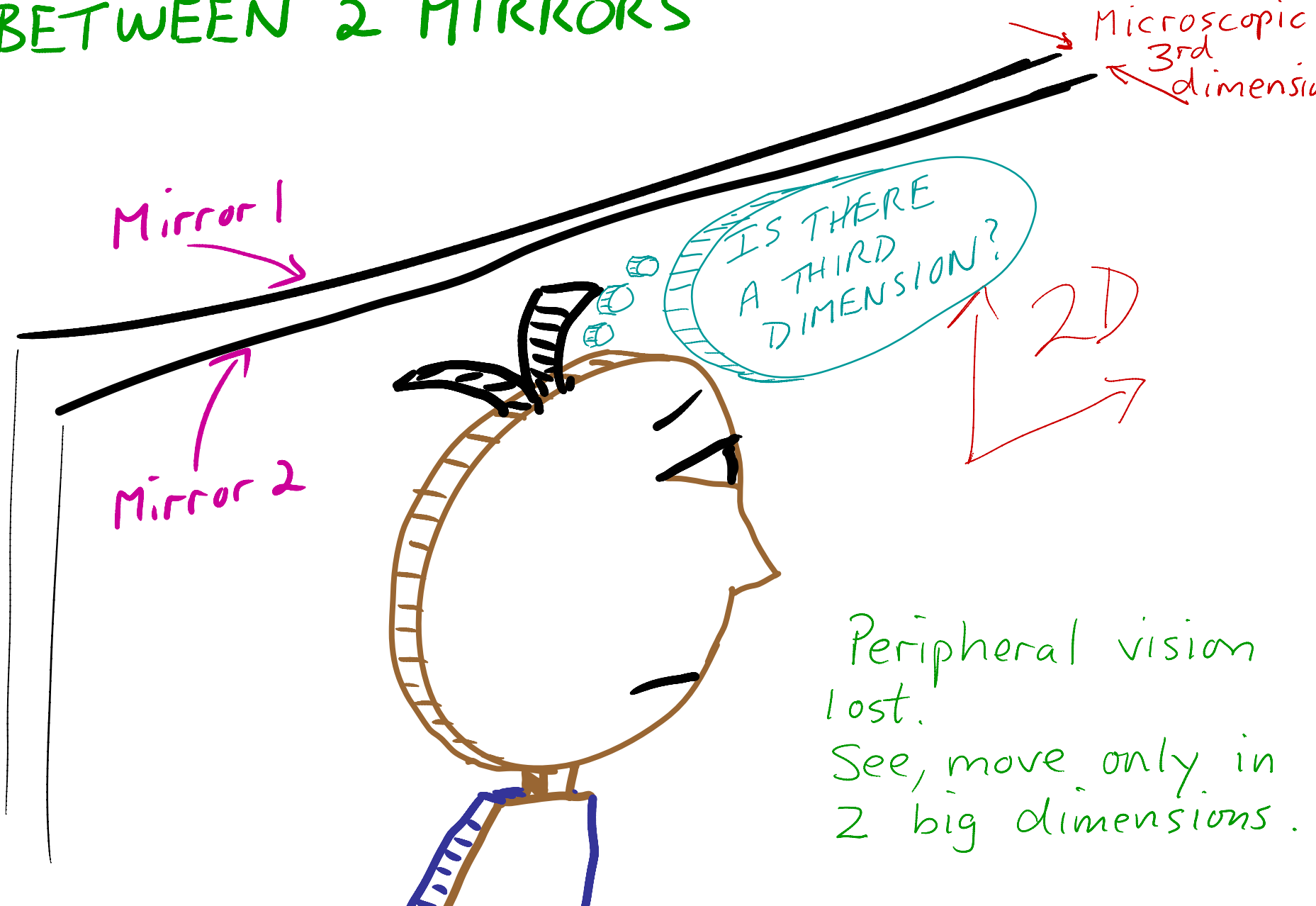
Mirror 1



Mirror 2



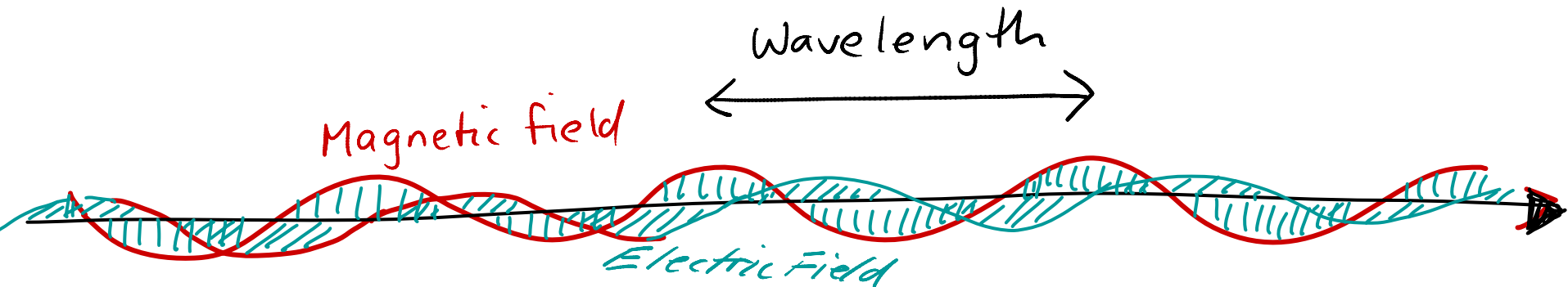
BY BEING SQUASHED FLAT BETWEEN 2 MIRRORS



Peripheral vision lost.
See, move only in 2 big dimensions.

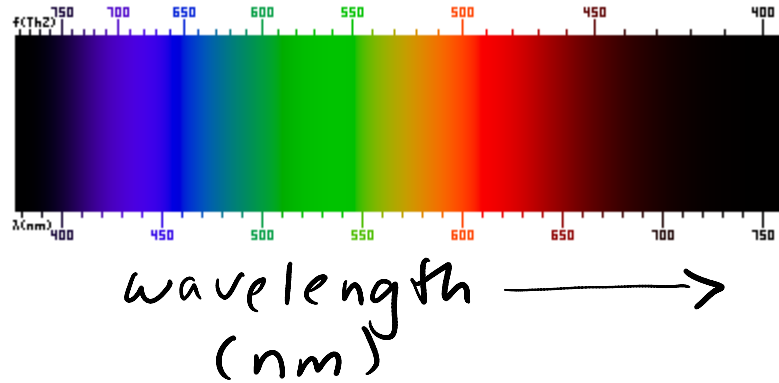
PERIPHERAL VISION

Wave nature of light important
when short distances involved:



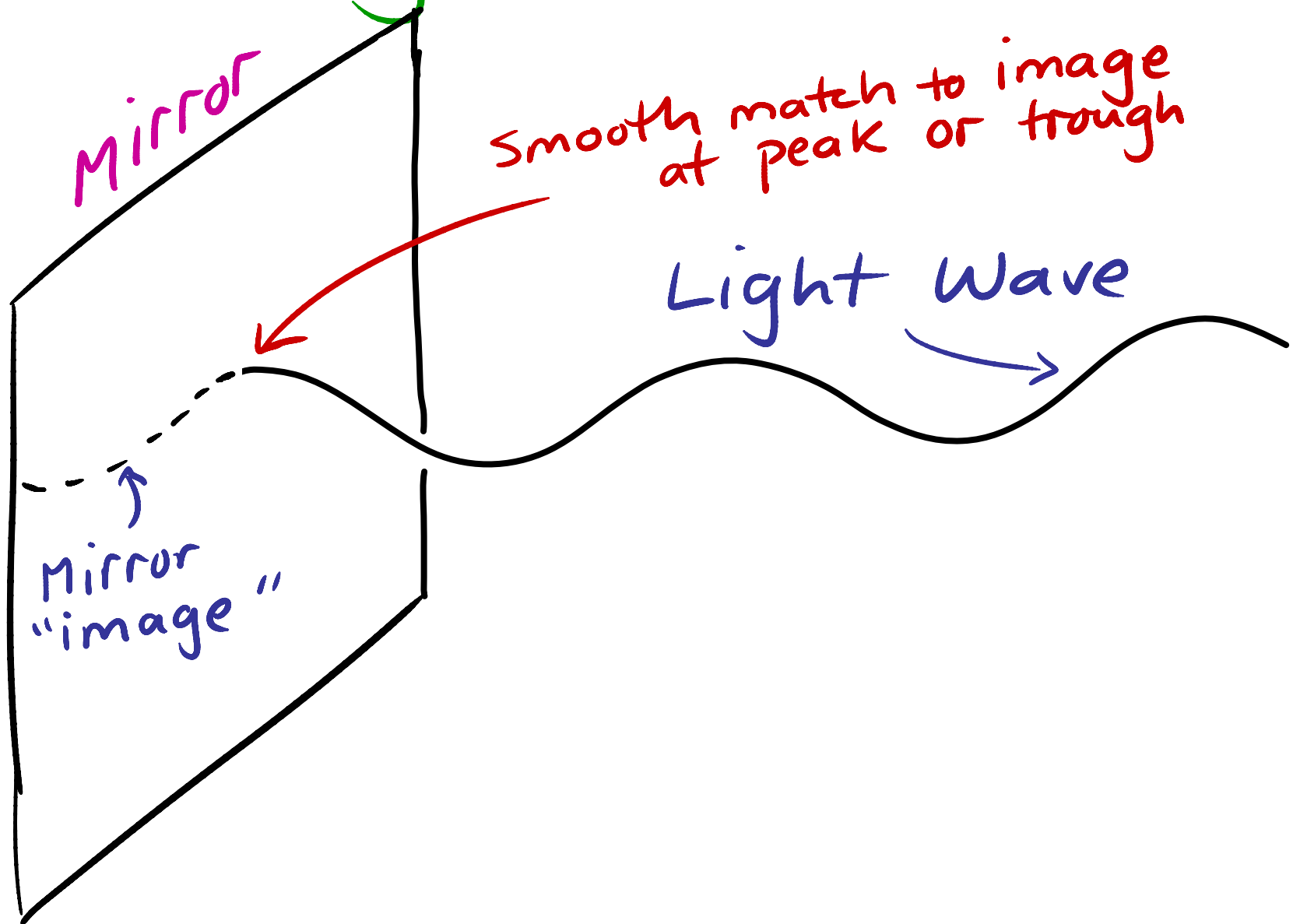
An Electromagnetic Wave

WAVELENGTH \equiv COLOR

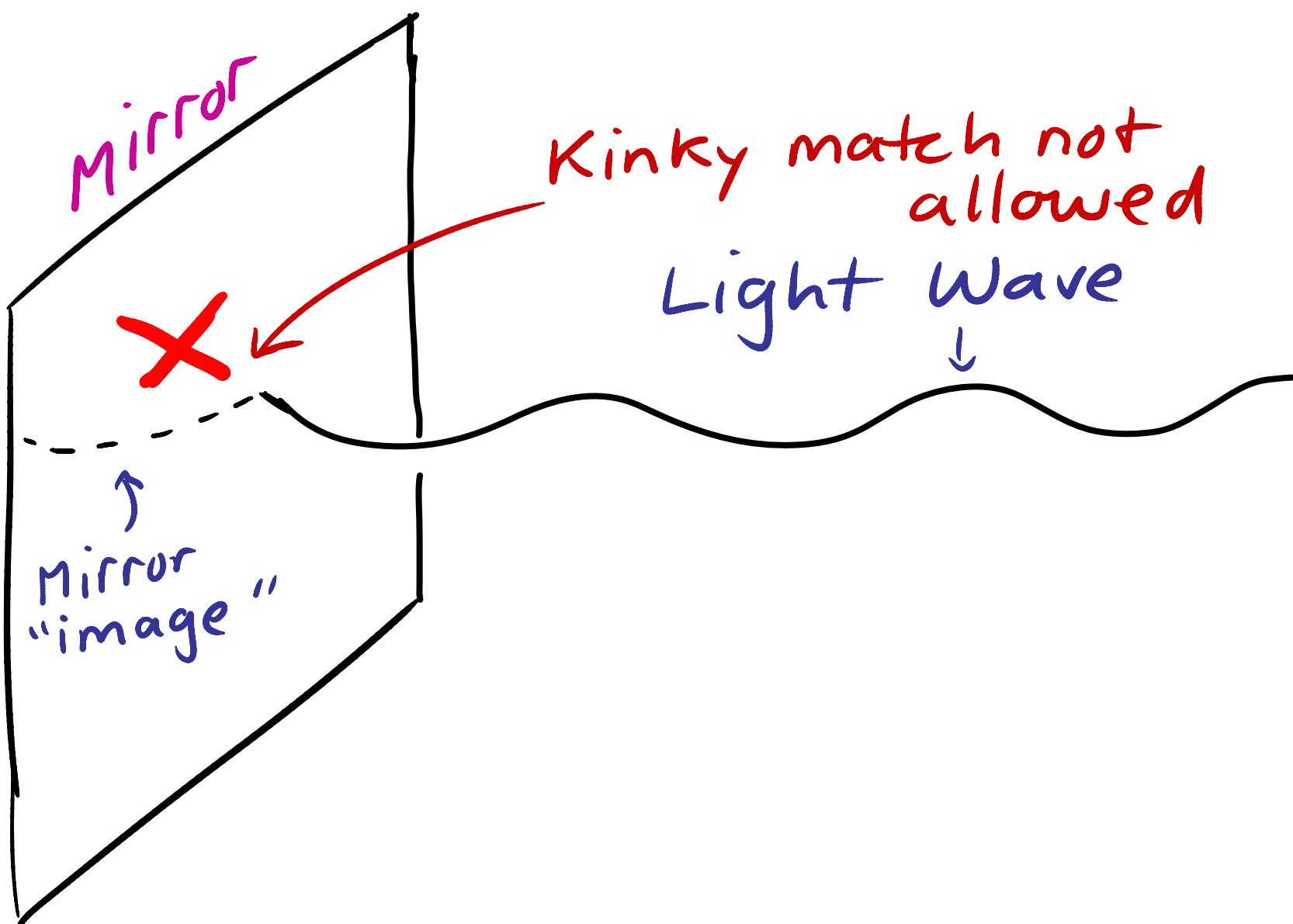


normally continuous, but...

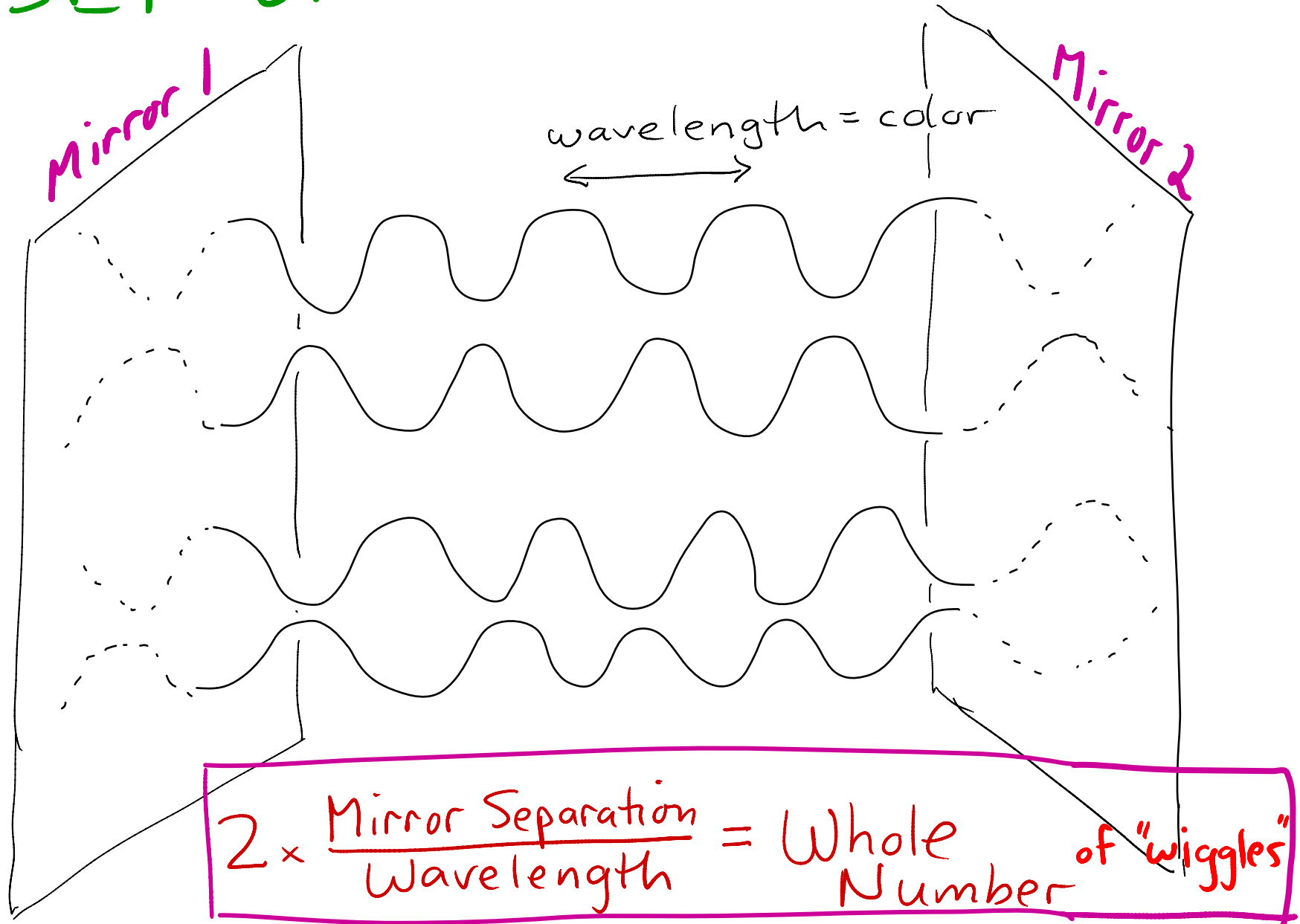
Waving in the Mirror



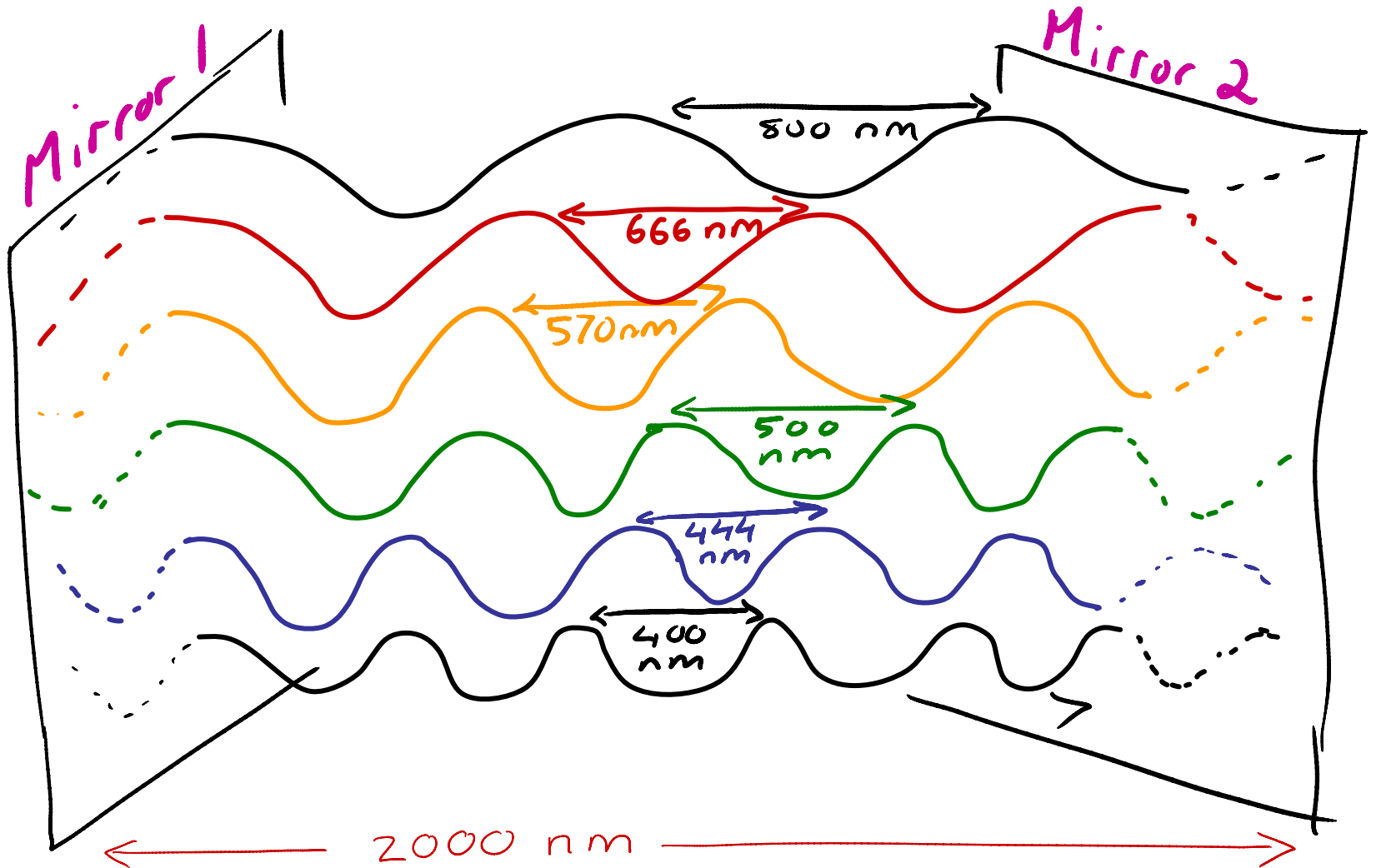
BUT NOT LIKE THIS



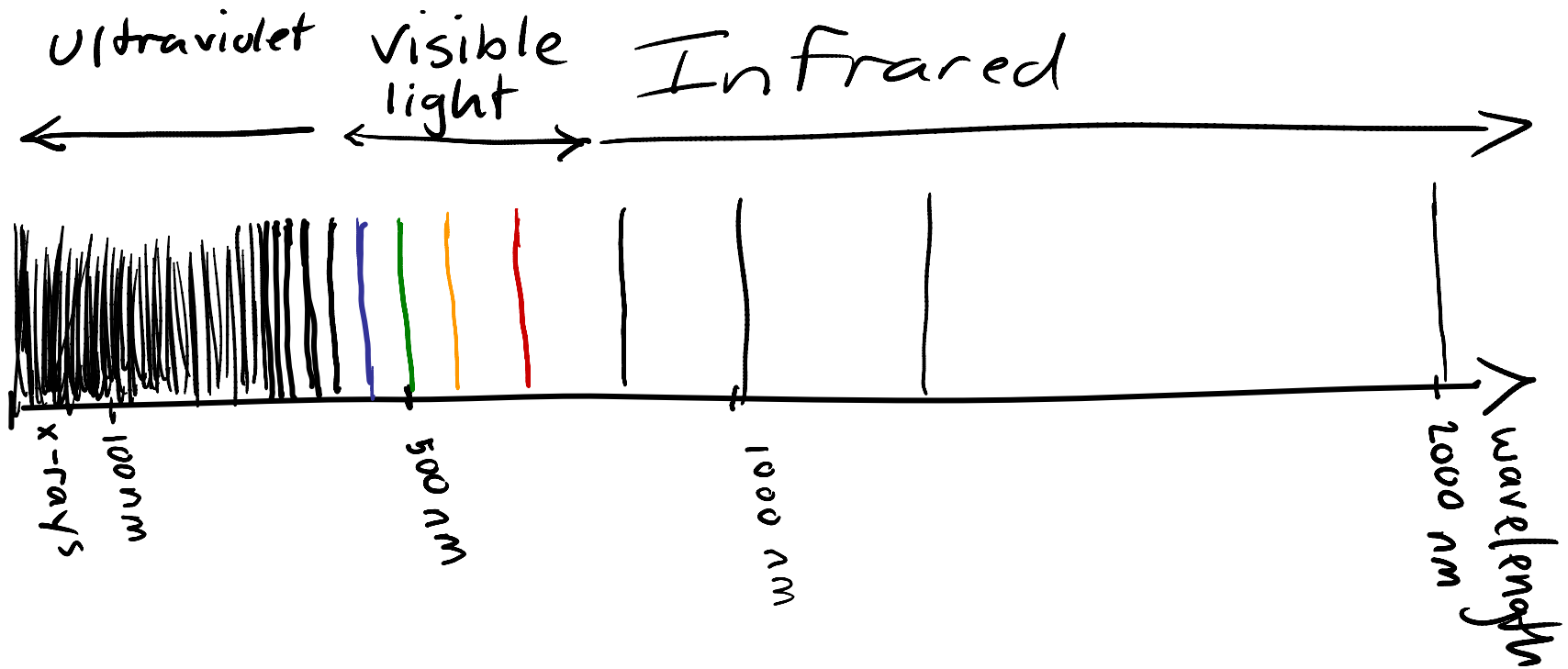
... ALLOWS ONLY DISCRETE SET OF WAVELENGTHS



IMPORTANT FOR MICROSCOPIC MIRROR SEPARATION

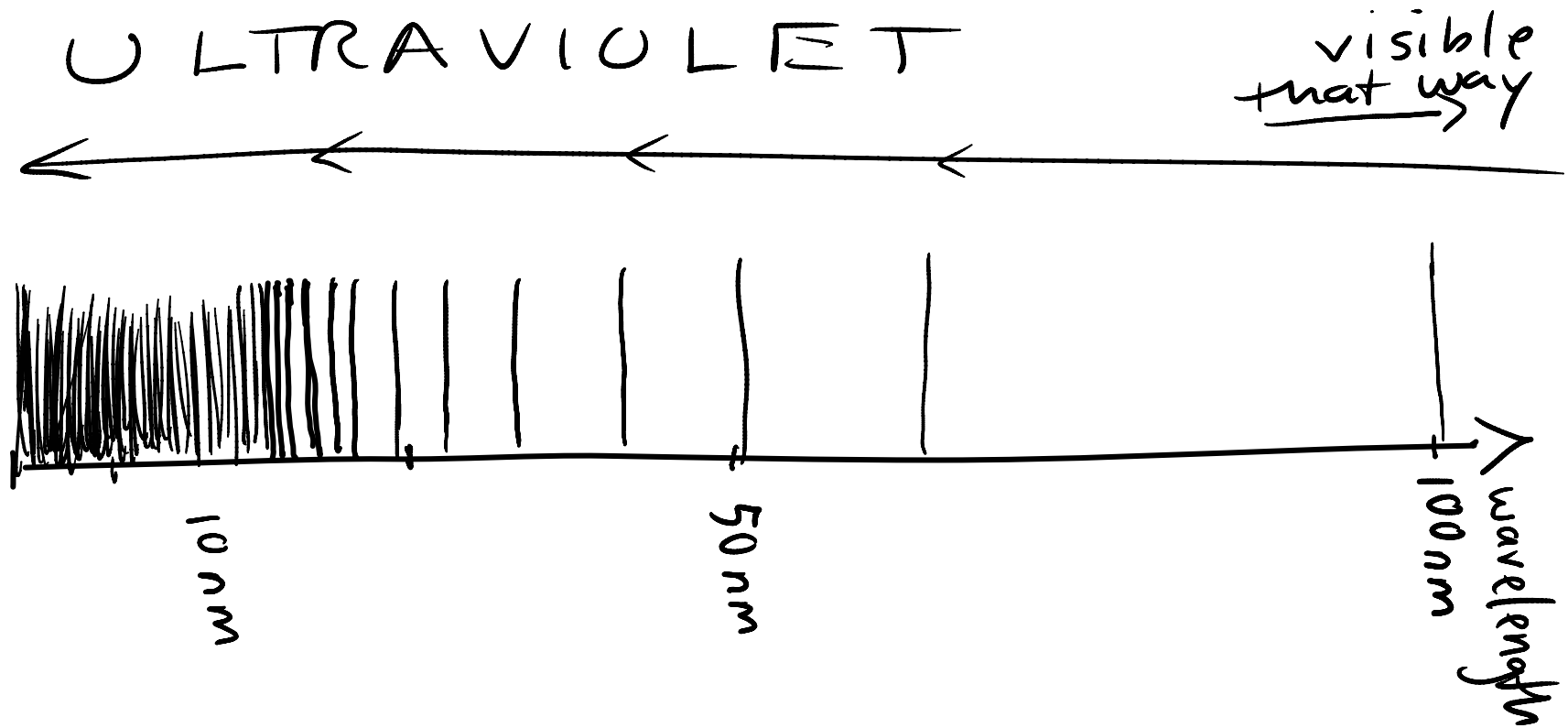


THUMBPRINT OF MICROSCOPIC DIMENSION, 2000 nm WIDE



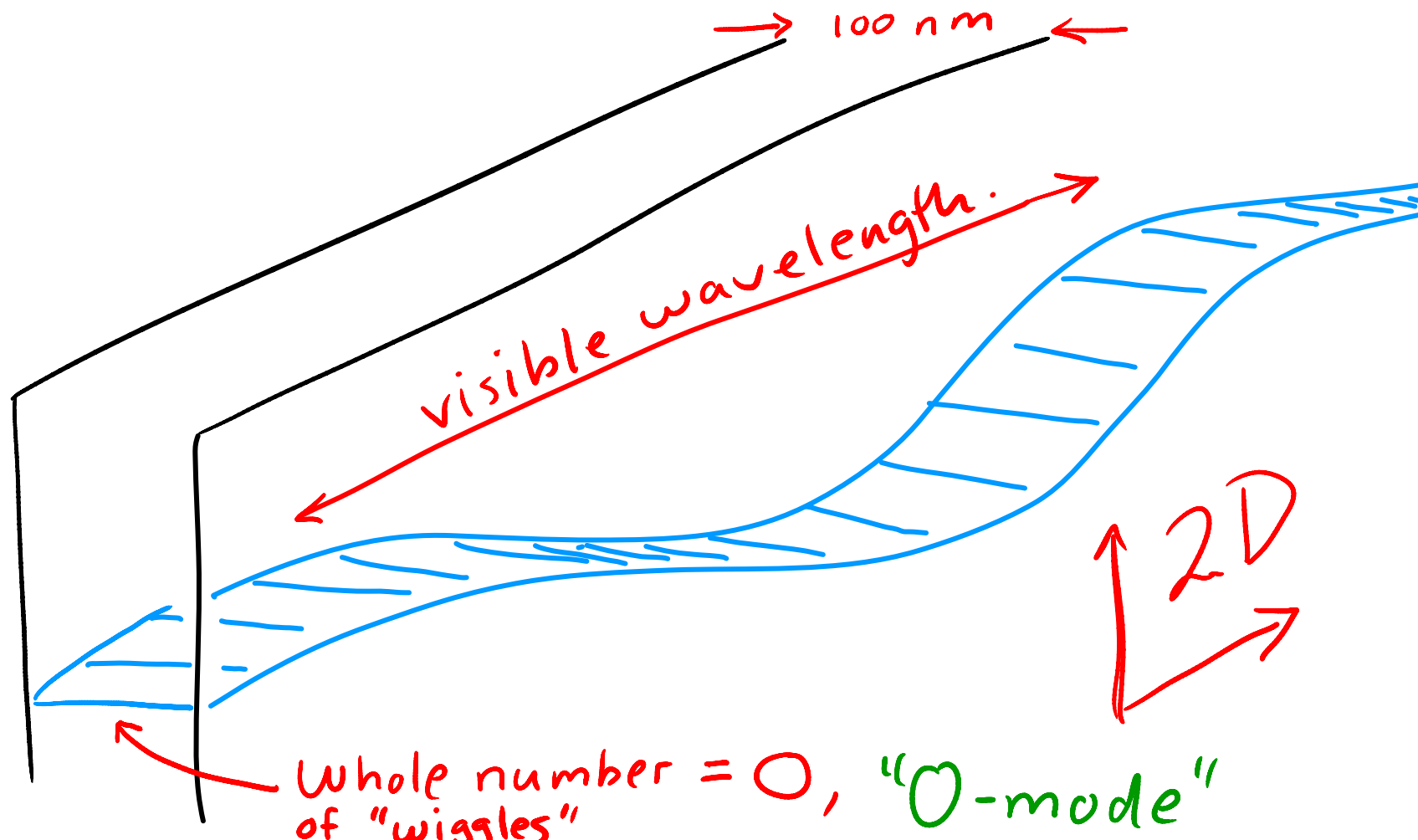
ALSO CALLED "KALUZA-KLEIN SPECTRUM"

KALUZA-KLEIN SPECTRUM FOR
100 nm MIRROR SEPARATION ENTIRELY
ULTRAVIOLET



⇒ NO PERIPHERAL LIGHT
IN VISIBLE RANGE

BUT VISIBLE LIGHT CAN STILL PROPAGATE ALONG LARGE DIMENSIONS



COULD SMALL EXTRA DIMENSIONS BE HIDDEN THIS WAY?

Cosmic Hyper Mirror 1
Cosmic Hyper Mirror 2

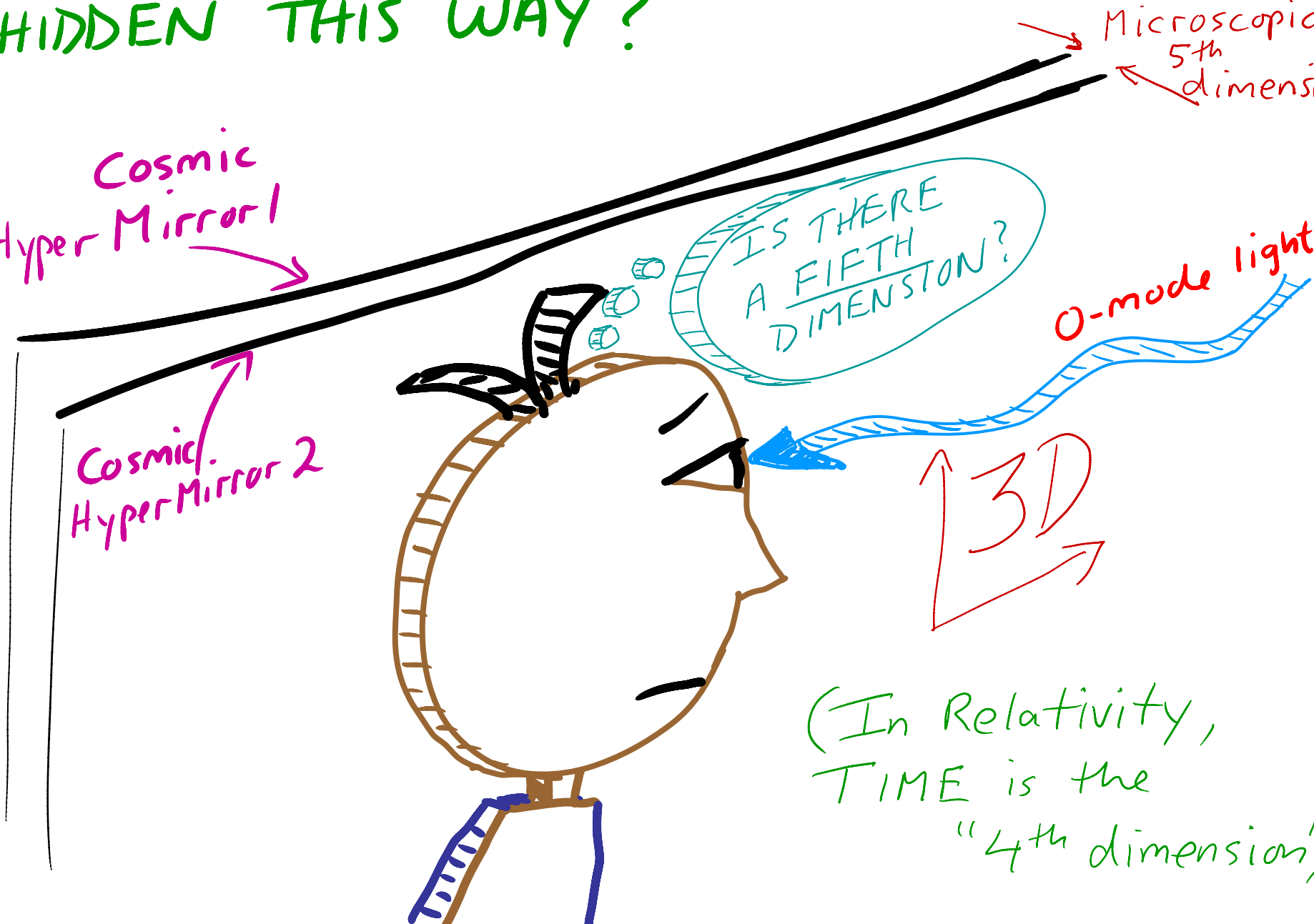
Microscopic 5th dimension

IS THERE A FIFTH DIMENSION?

0-mode light

3D

(In Relativity, TIME is the "4th dimension")



QUANTUM MECHANICS

⇒ LIGHT WAVES MADE OF
PHOTONS

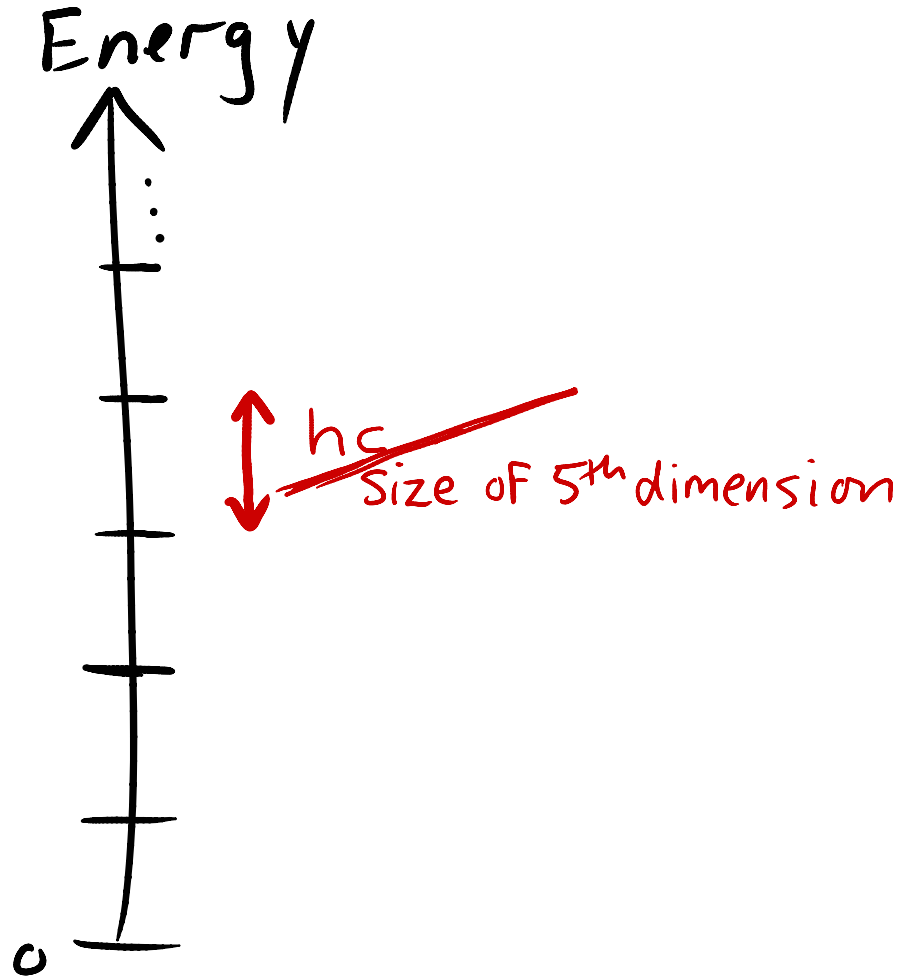
Energy per photon =

$h \times \text{frequency} =$

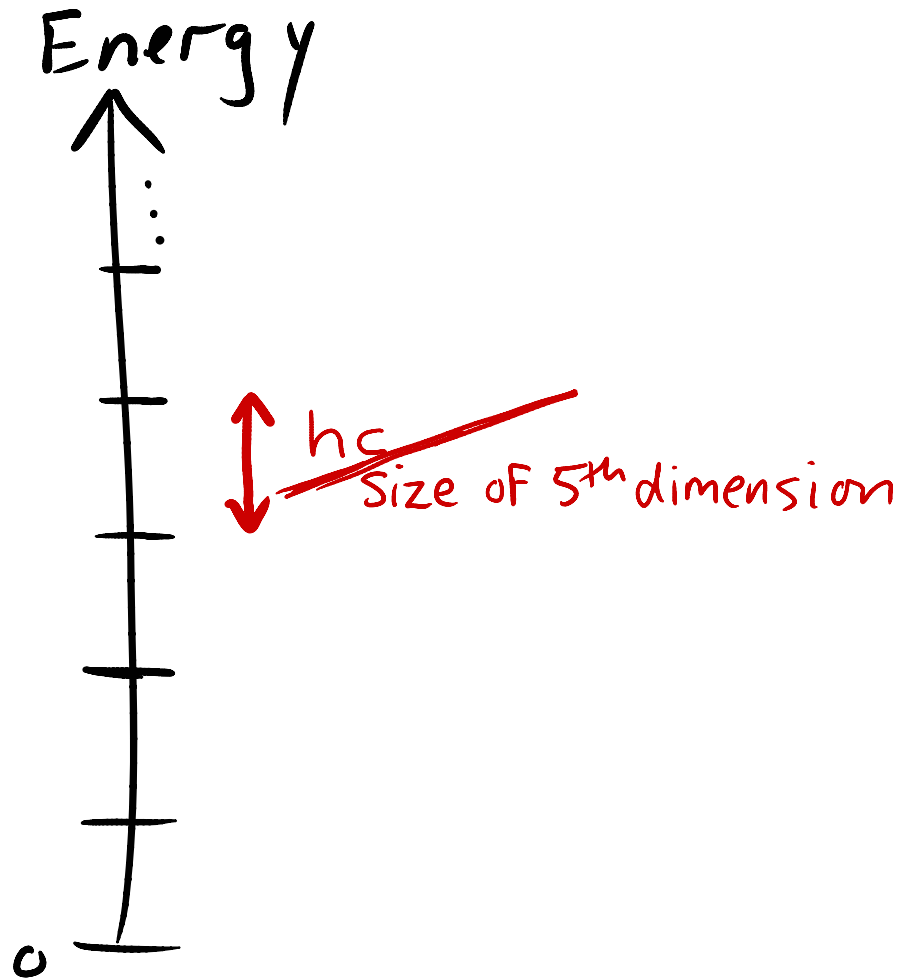
↑ Planck's Constant

$\frac{hc}{\text{Wavelength}}$ ← speed of light

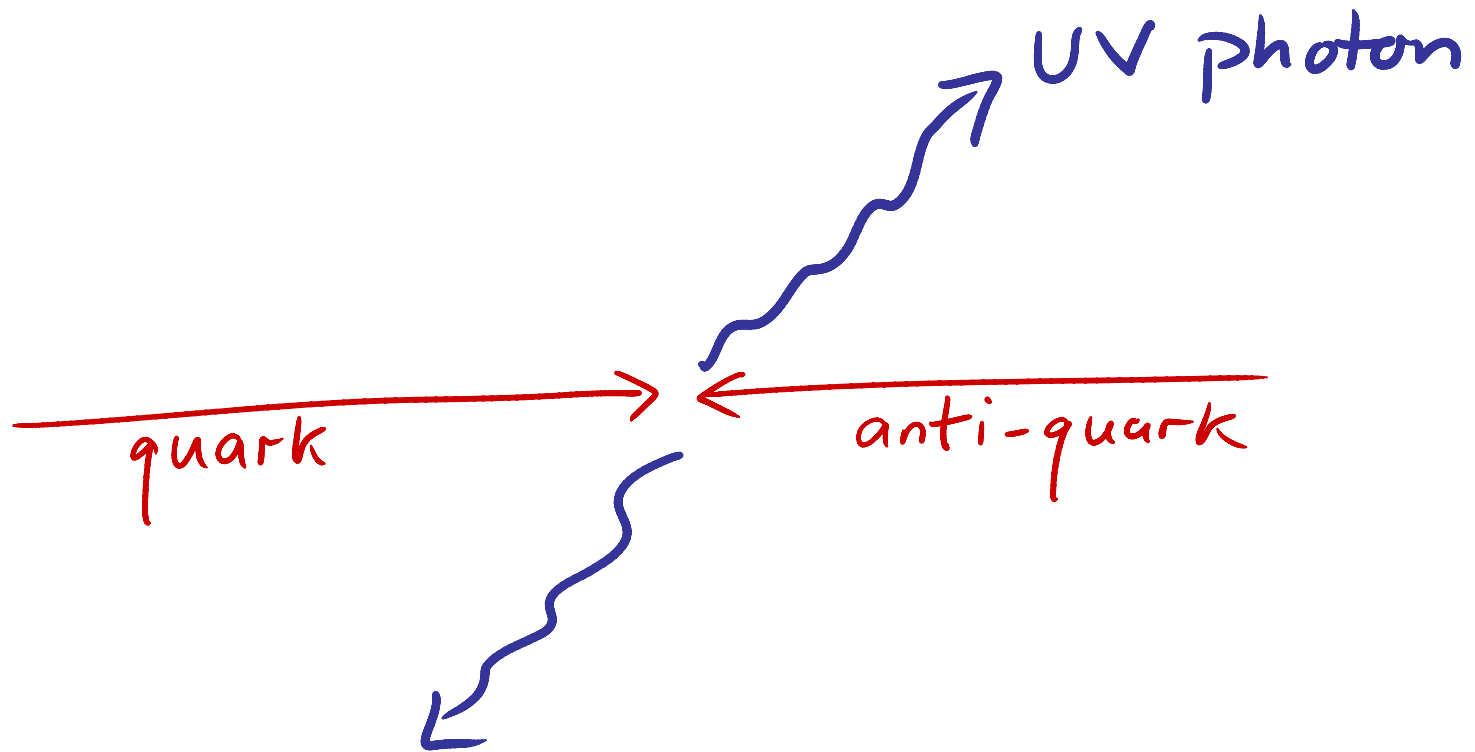
⇒ KALUZA-KLEIN EXCITATIONS OF PHOTONS



AND PARTICLES HAVE PROBABILITY
WAVES \Rightarrow KK EXCITATIONS OF
ELECTRONS, QUARKS, ...

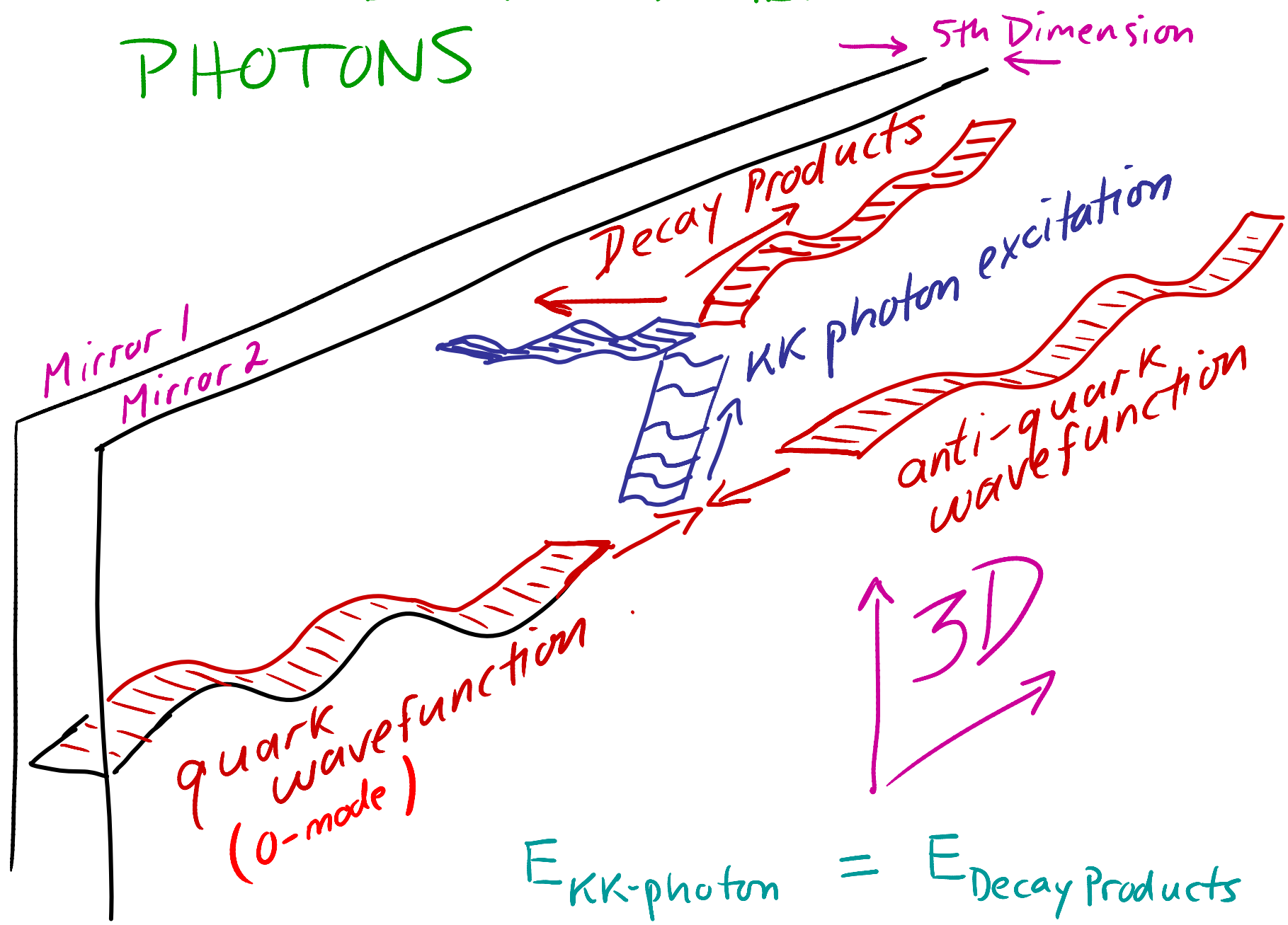


FAR ULTRAVIOLET PHOTONS CAN BE CREATED IN PARTICLE COLLIDERS



from energy of colliding particles.

INCLUDING EXTRA-DIMENSIONAL PHOTONS



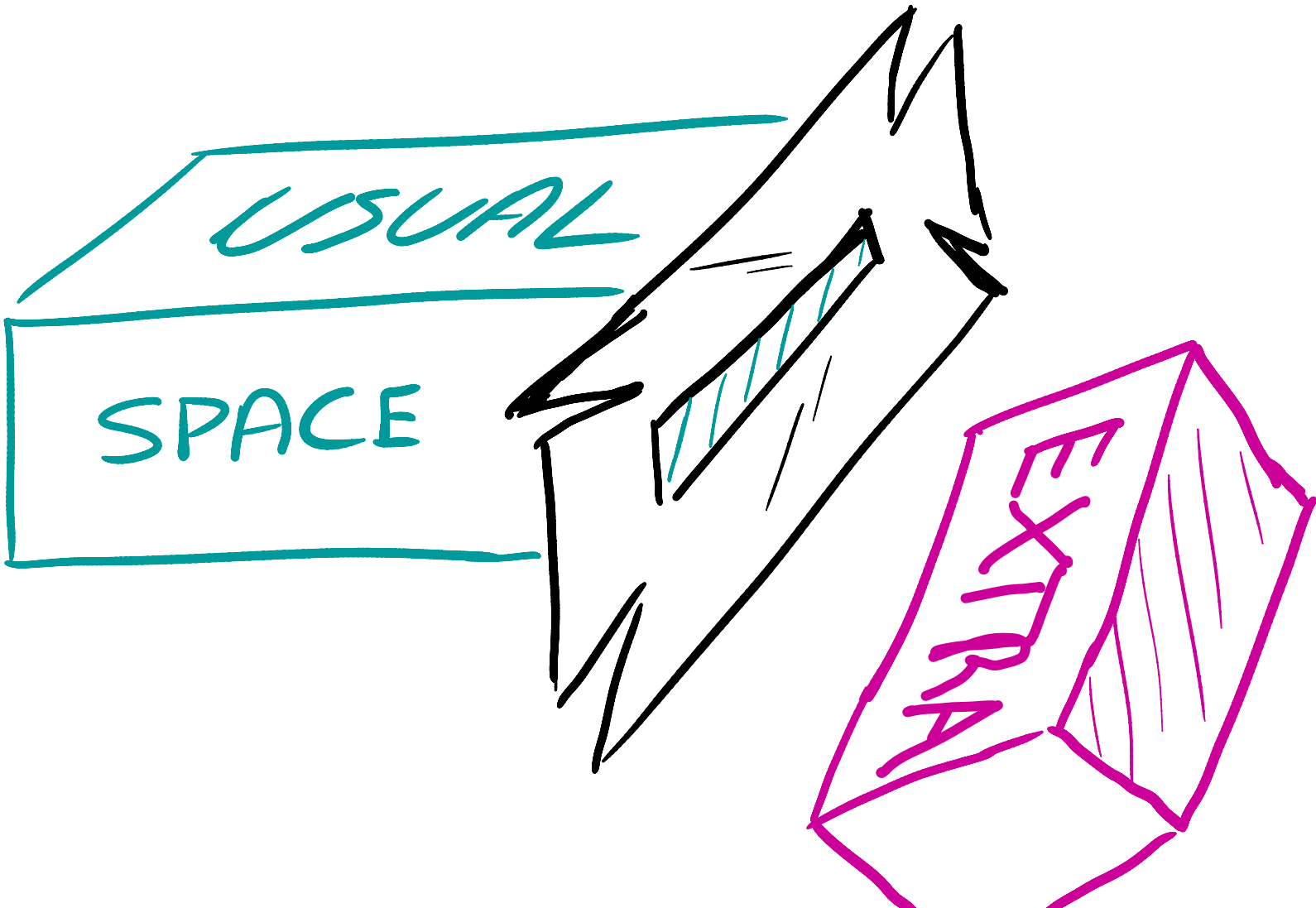
BUT NO KK EXCITATIONS
FOUND THUSFAR

⇒ Size of 5th Dimension

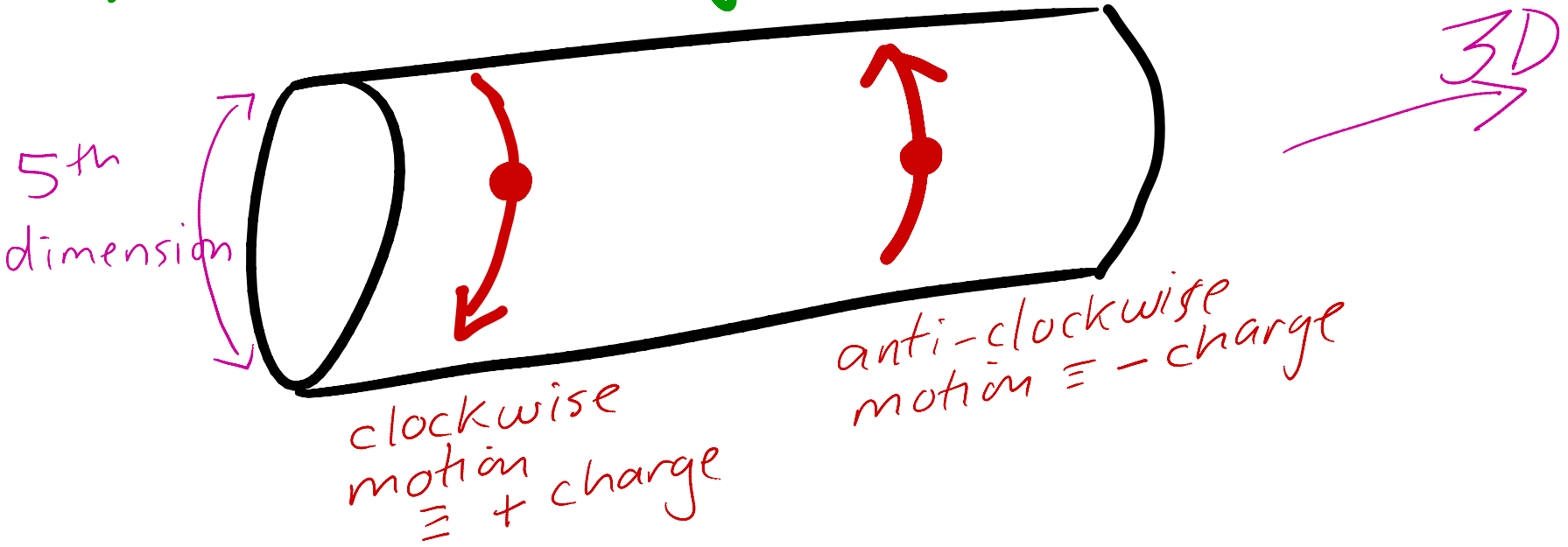
$$< 10^{-18} \text{ m}$$

LHC WILL ZOOM IN
ANOTHER $\times 10$, BUT . . .

OCCAM'S RAZOR?



GENERAL RELATIVITY with
microscopic 5th dimensional circle
→ macroscopic general relativity



+ macroscopic ELECTROMAGNETISM

Kaluza 1921, Klein 1926

BEAUTIFUL, but some crucial features
of Nature fail to emerge from theory.

STRING THEORY

is the best developed approach
to the unification of

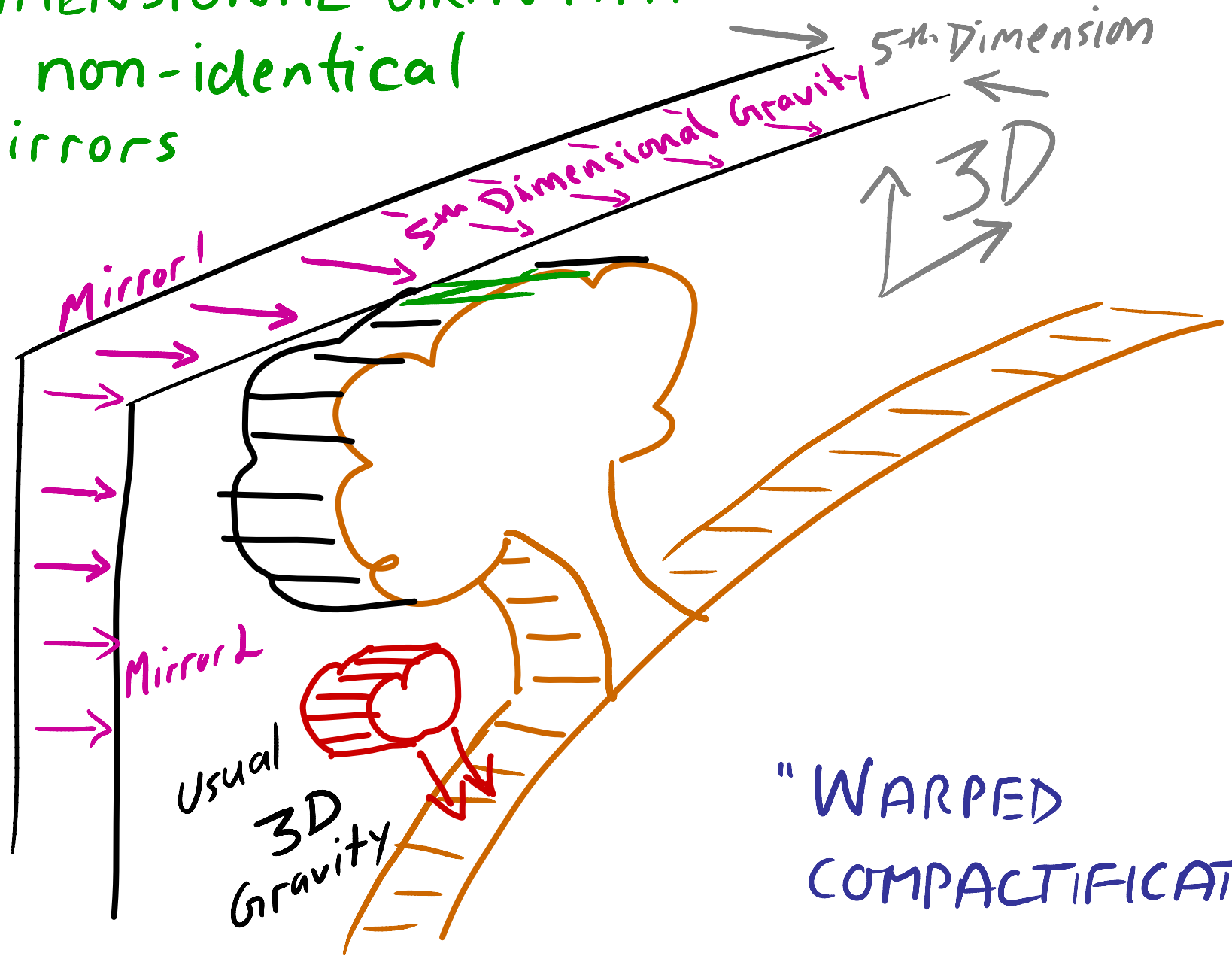
General Relativity + Quantum Mechanics

replacing fundamental particles by
fundamental STRINGS

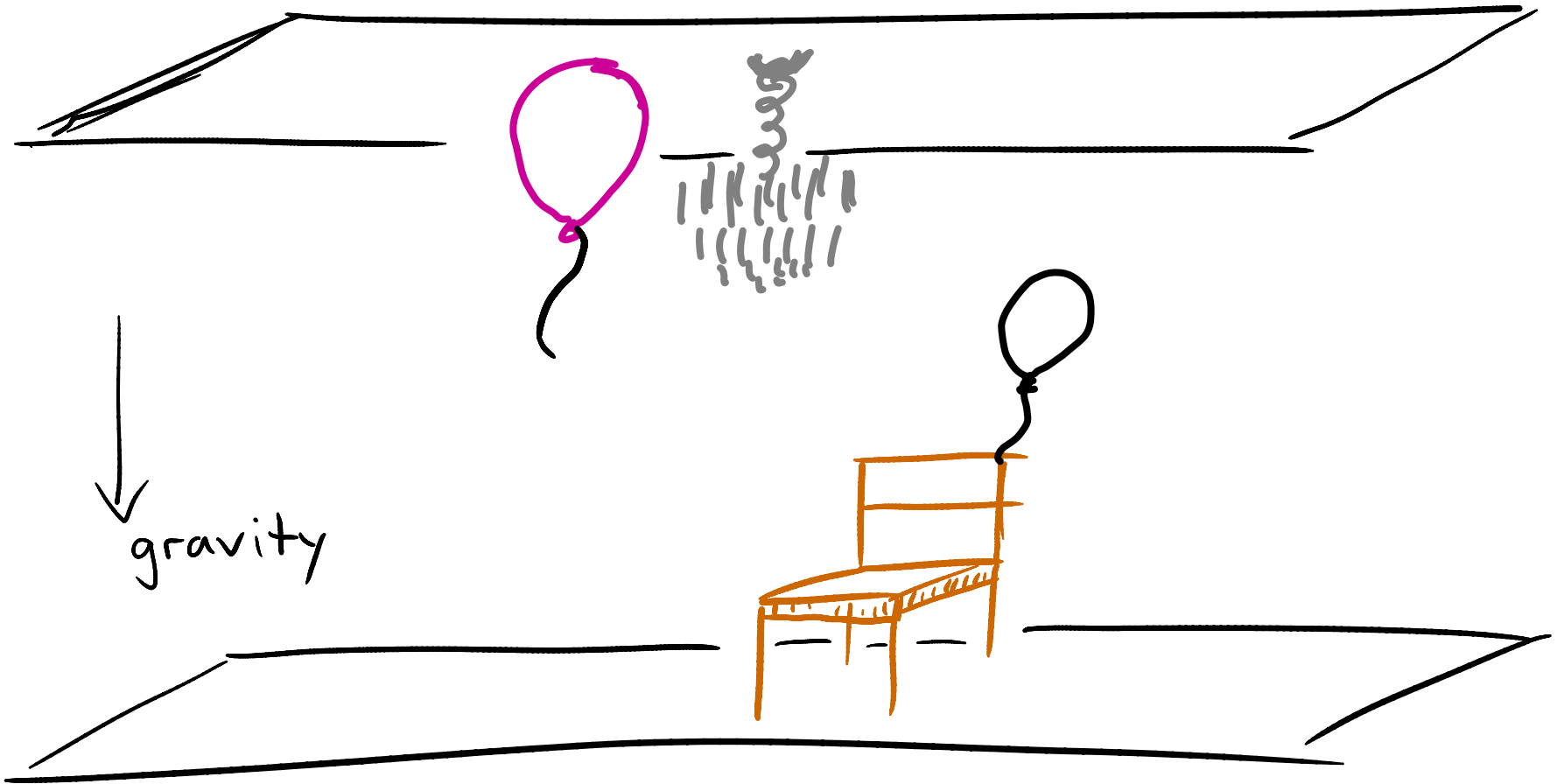
and contains extra dimensions
and contains Cosmic HyperMirrors.

and more successful stringy
generalizations of Kaluza & Klein's
unification of forces

HIDDEN 5th DIMENSION CAN HIDE A
5th DIMENSIONAL GRAVITATIONAL FIELD
For non-identical
mirrors

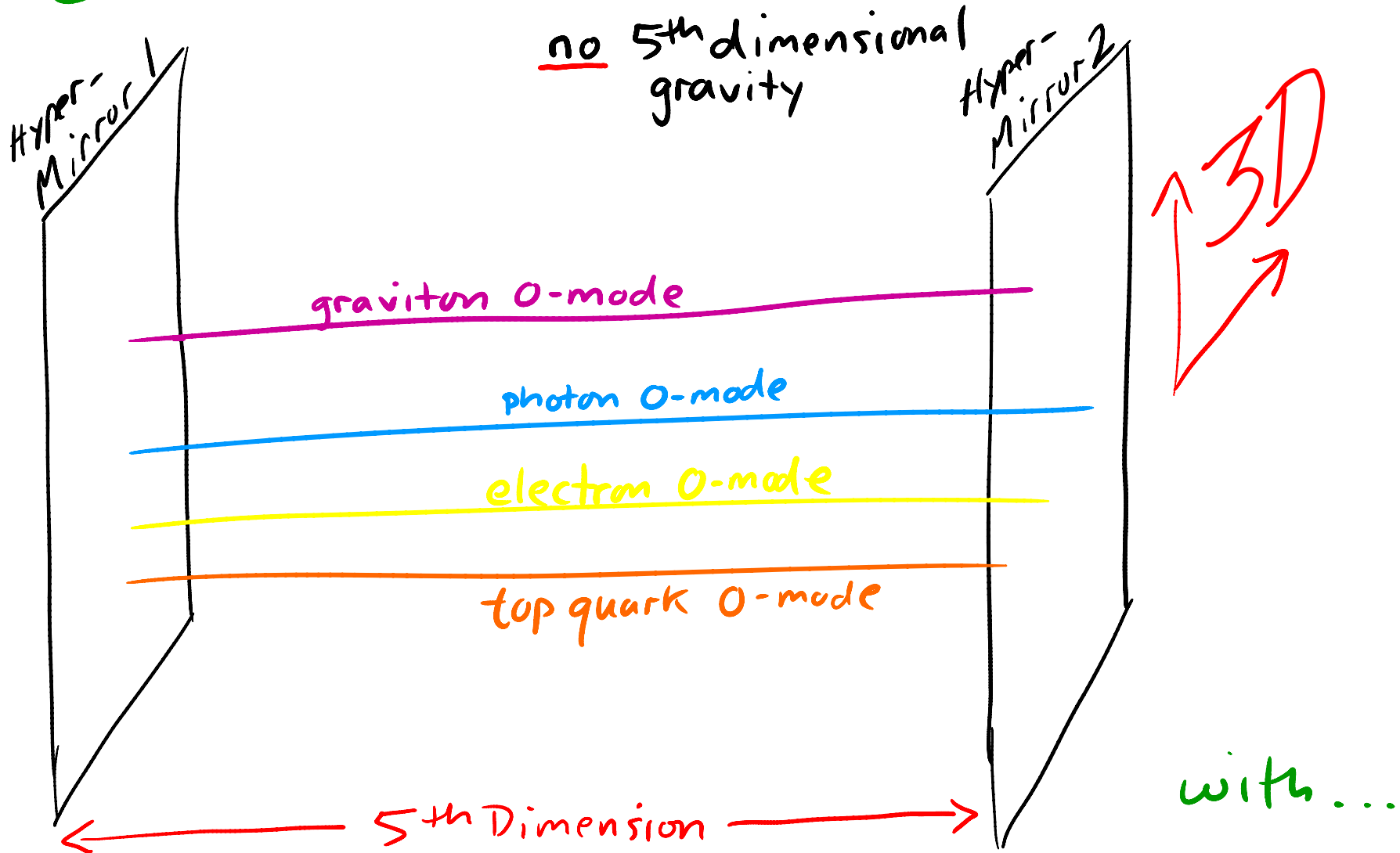


IN A GRAVITATIONAL FIELD
DIFFERENT THINGS LOCALIZE IN
DIFFERENT PLACES

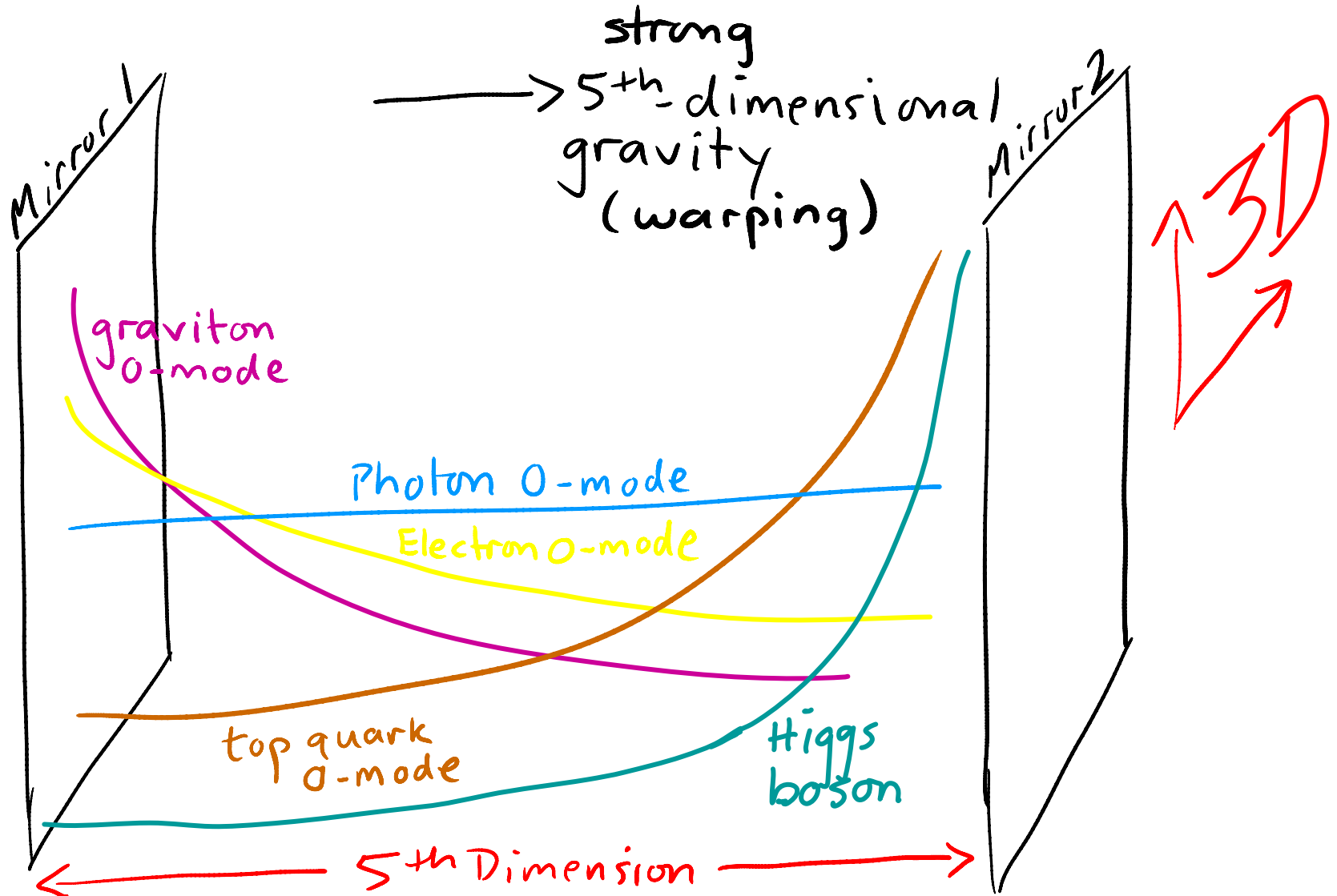


INCLUDING 0-MODES

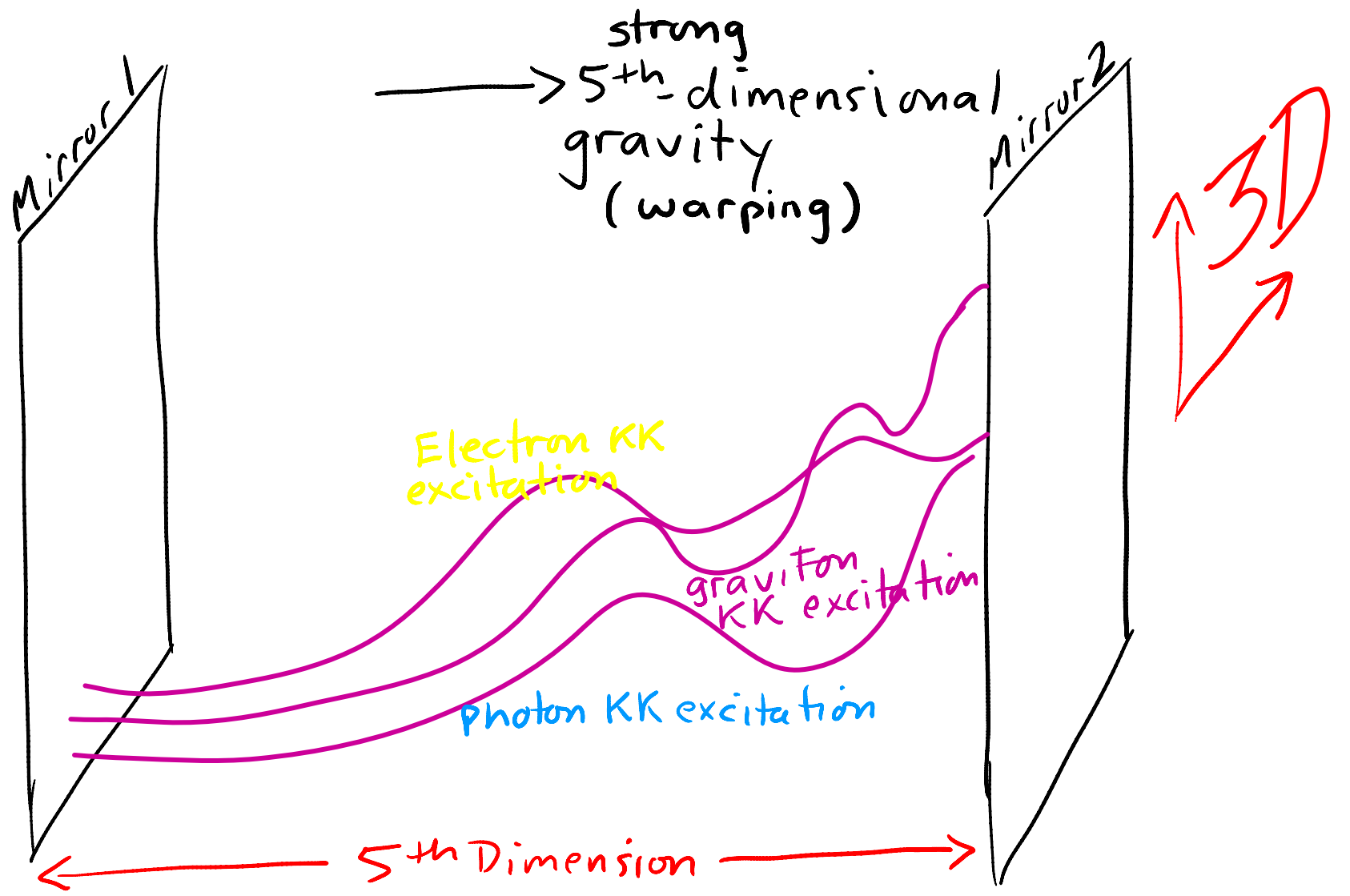
Contrast



INCLUDING 0-MODES



KK EXCITATIONS DISTORTED TOO



SECRET OF 5th DIMENSIONAL

REAL ESTATE:

LOCATION, LOCATION, LOCATION!

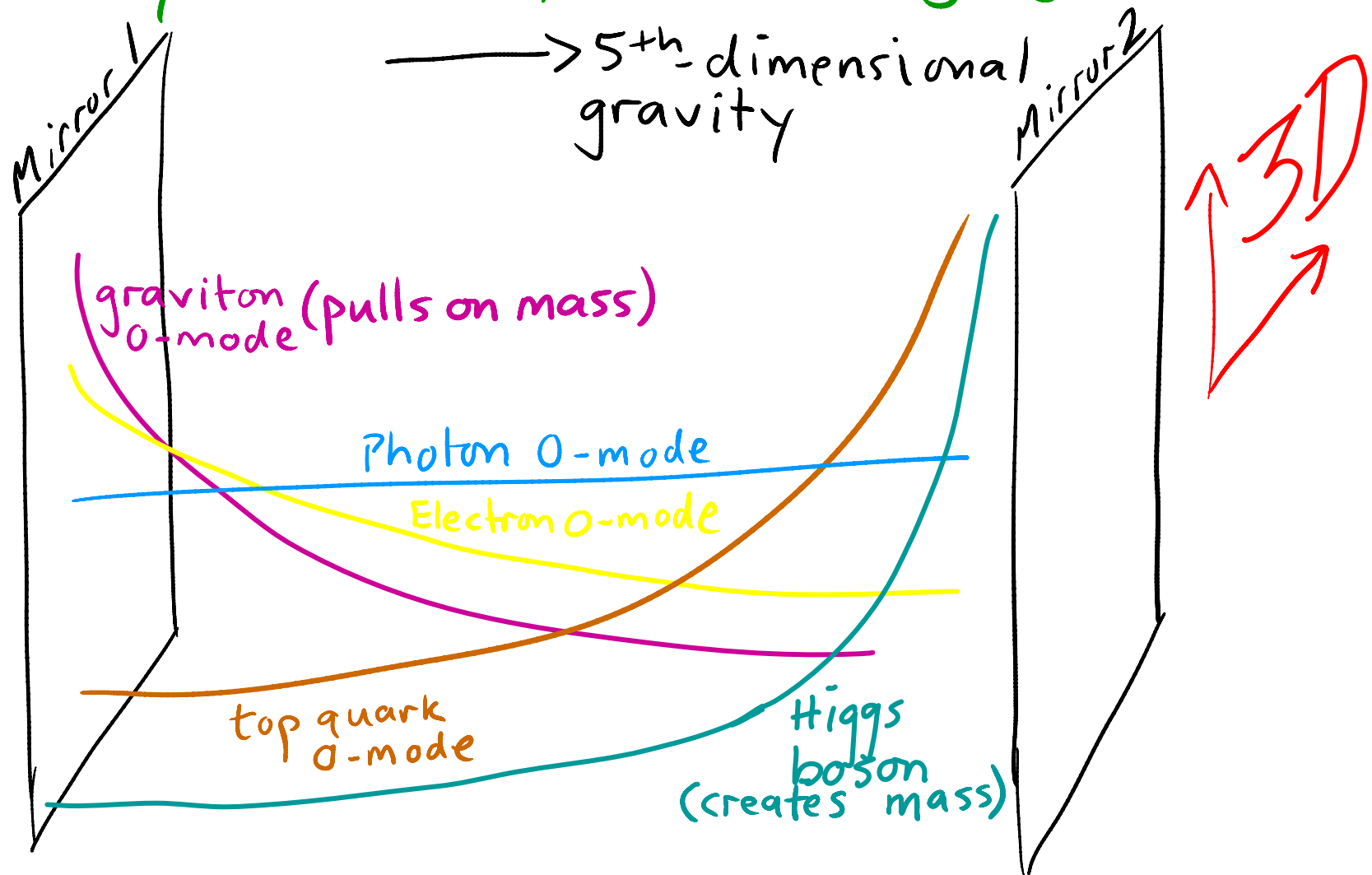
Particles interact most with their neighbours, less with particles with v. different extra-dimensional profiles

Localizing tendencies in 5D can naturally account for several puzzling features of interaction strengths among different particle species

In particular . . .

WARPED EXTRA DIMENSION

naturally separates graviton from Higgs, thereby drastically weakening gravity.



ONE OF FEW KNOWN SOLUTIONS TO HIERARCHY PROBLEM!

PREDICTION of this resolution of Hierarchy Problem

$$E_{\text{KK-excitations}} \gtrsim m_{\text{max.}} c^2$$

maximum mass that Higgs
mechanism can generate, $\sim m_{\text{top quark}}$

\Rightarrow KK excitations at LHC!

But this should be viewed as an
order-of-magnitude prediction for E_{KK} ,
not a sharp prediction.

HIDING IN THE QUANTUM SHADOWS?

Heisenberg Uncertainty Principle

$$\Delta E \Delta t \sim h$$

Energy conservation can be violated, but only briefly

\Rightarrow KK would wink in & out of existence, should affect past particle experiments where $E < E_{KK}$

Absence of such "virtual" KK effects

puts bounds $E_{KK} > \text{few TeV}$

close to LHC limits

\Rightarrow KK hunting at LHC will be challenging

WARPED VIEW OF HIERARCHY PROBLEM & IMPLICATIONS

Randall, Sundrum '99

Goldberger, Wise '99

Davoudiasl, Hewett, Rizzo '00

Chang, Hisano, Nakano, Okada, Yamaguchi '00

Grossman, Neubert '00

Gherghetta, Pomarol '00

Huber, Shafi '01

Huber, Lee Shafi '02

Csaki, Erlich, Terning '02

Burdman '02

Hewett, Petriello, Rizzo '02

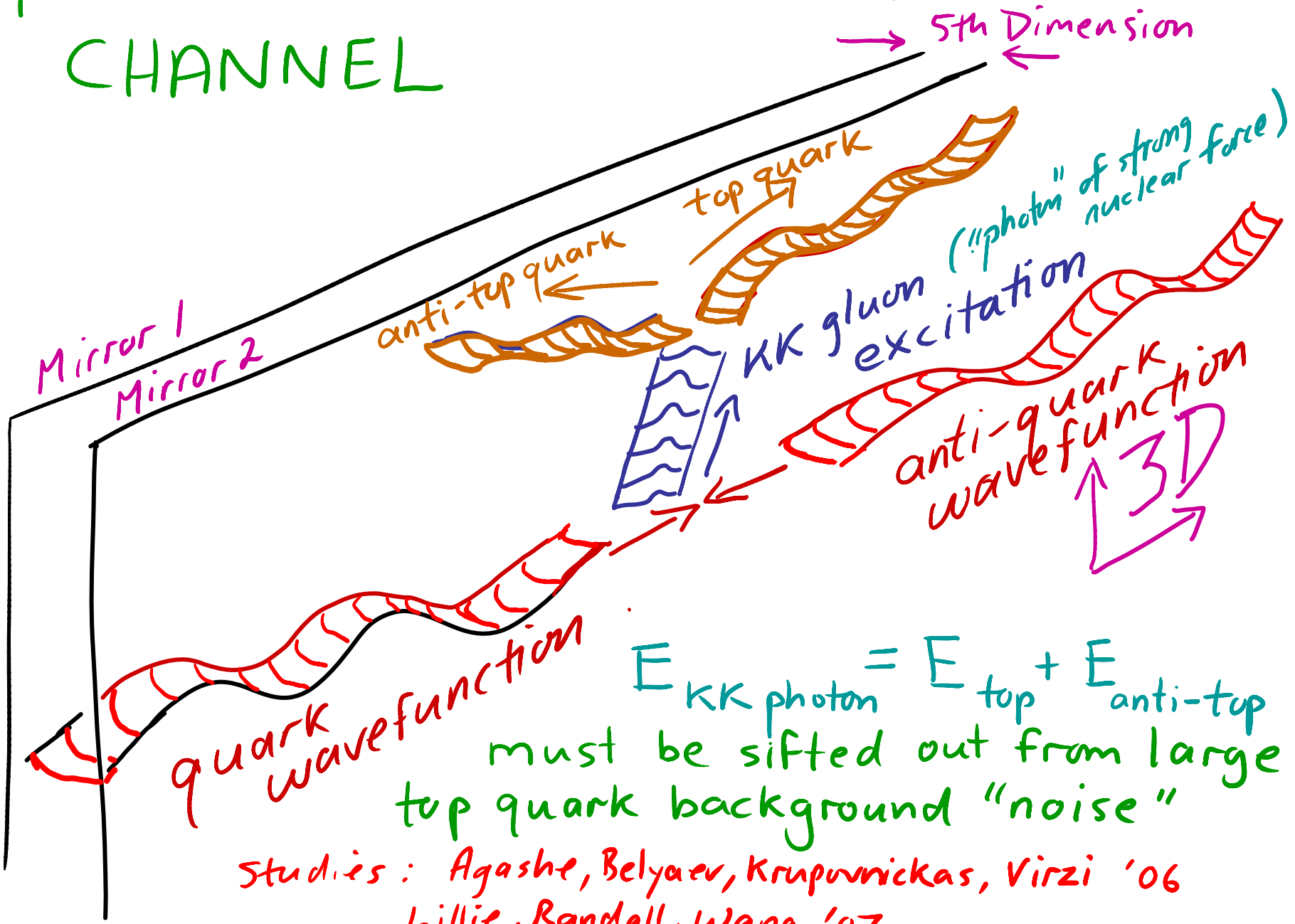
Agashe, Delgado, May, Sundrum '03

Contino, Nomura, Pomarol '03

Agashe, Contino, Pomarol '05

+ . . .

A POSSIBLE DISCOVERY CHANNEL



OTHER DIRECTIONS

