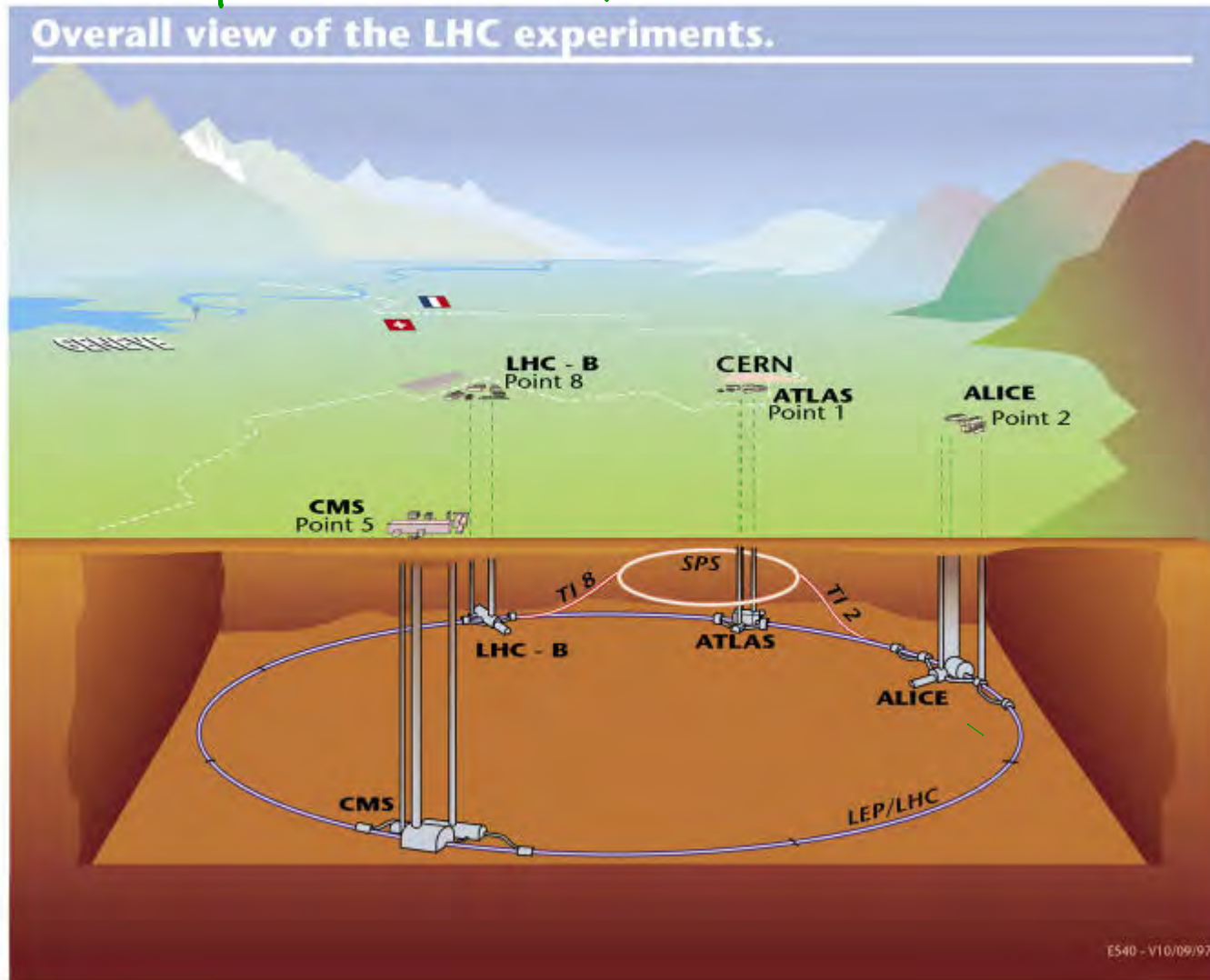


FUNDAMENTAL PHYSICS AND THE FIFTH DIMENSION

Raman Sundrum
University of Maryland

THE LHC IS A MULTI-TeV PROTON-PROTON COLLIDER



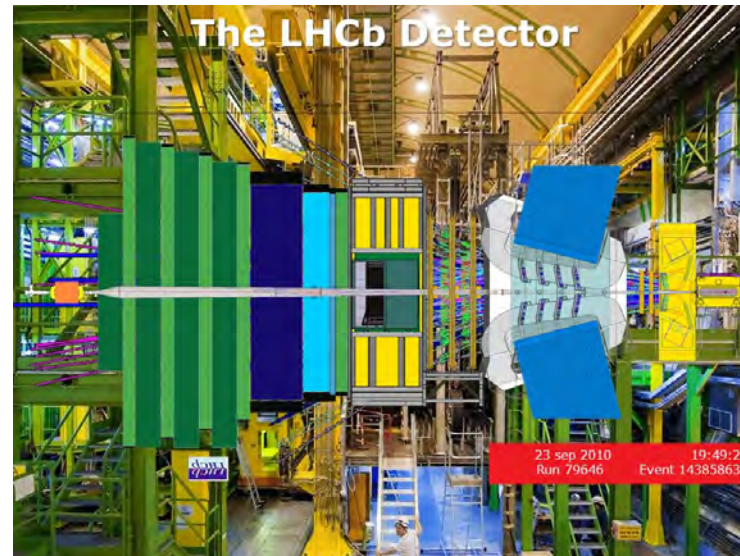
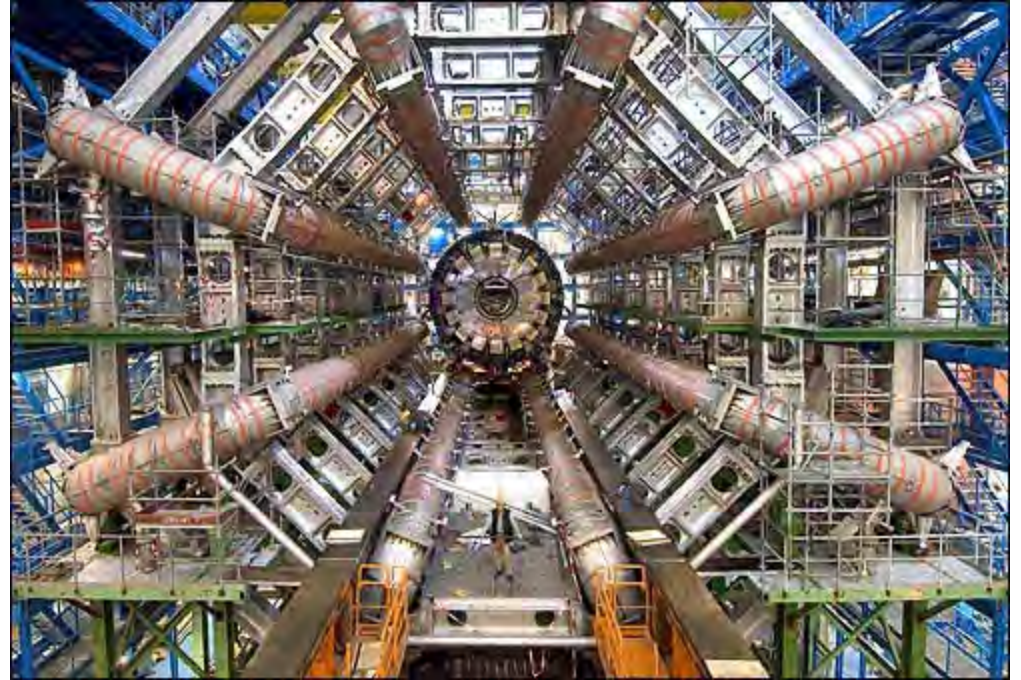
THE HAIL OF EMERGING PARTICLES SCRUTINIZED BY...

BIG, BIG EYES

ATLAS DETECTOR



CMS DETECTOR



The LHCb Detector

LHCb
DETECTOR

BUT

WHY?

OUTLINE

Nothing is Something too!

Unification & the Geometric Universe

The Origin of the Masses —

LHC, Higgs boson, other matters

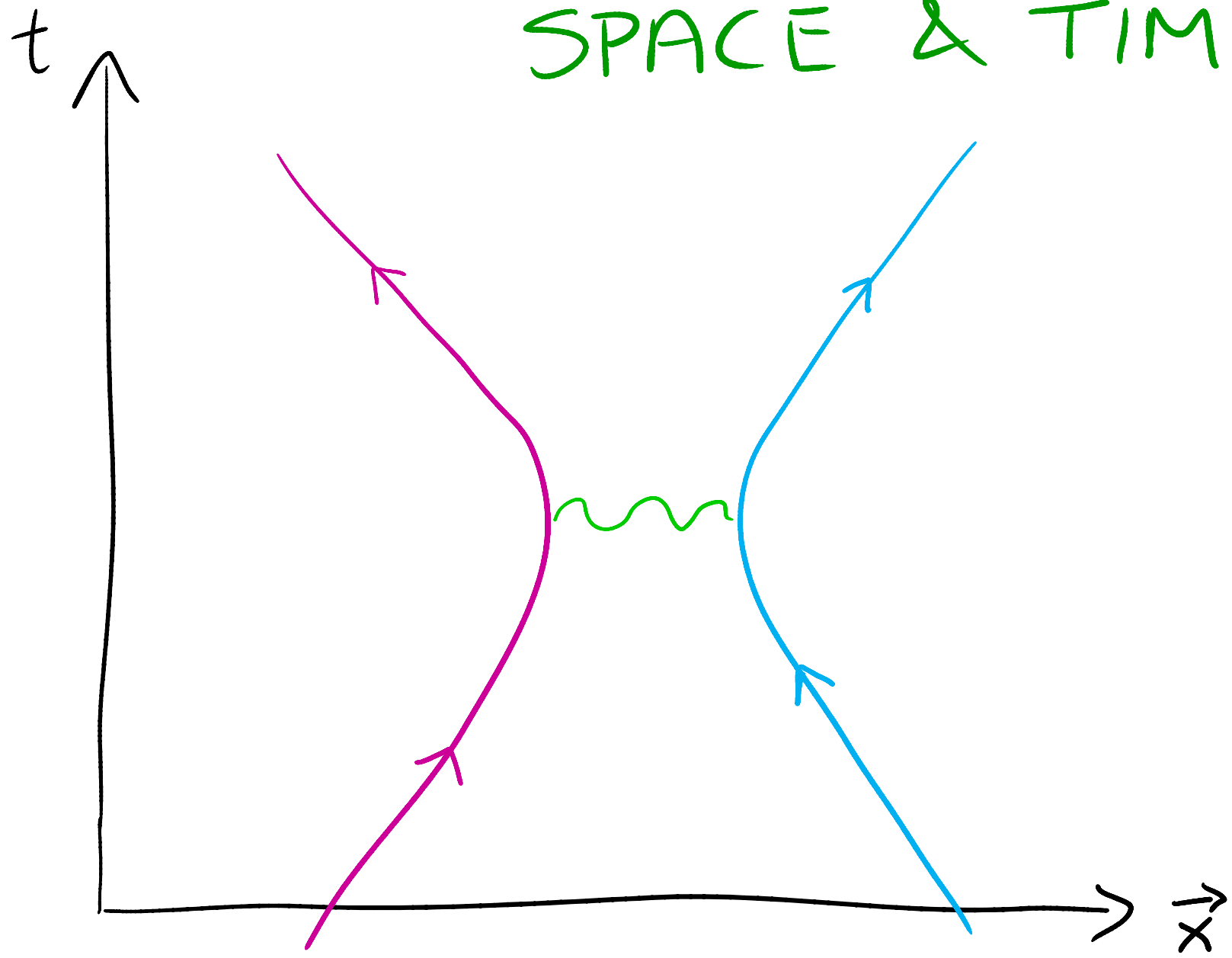
Incarnations of Spacetime —

Multiverse, 5th dimension, Supersymmetry,
curved spacetime, emergent dimensions

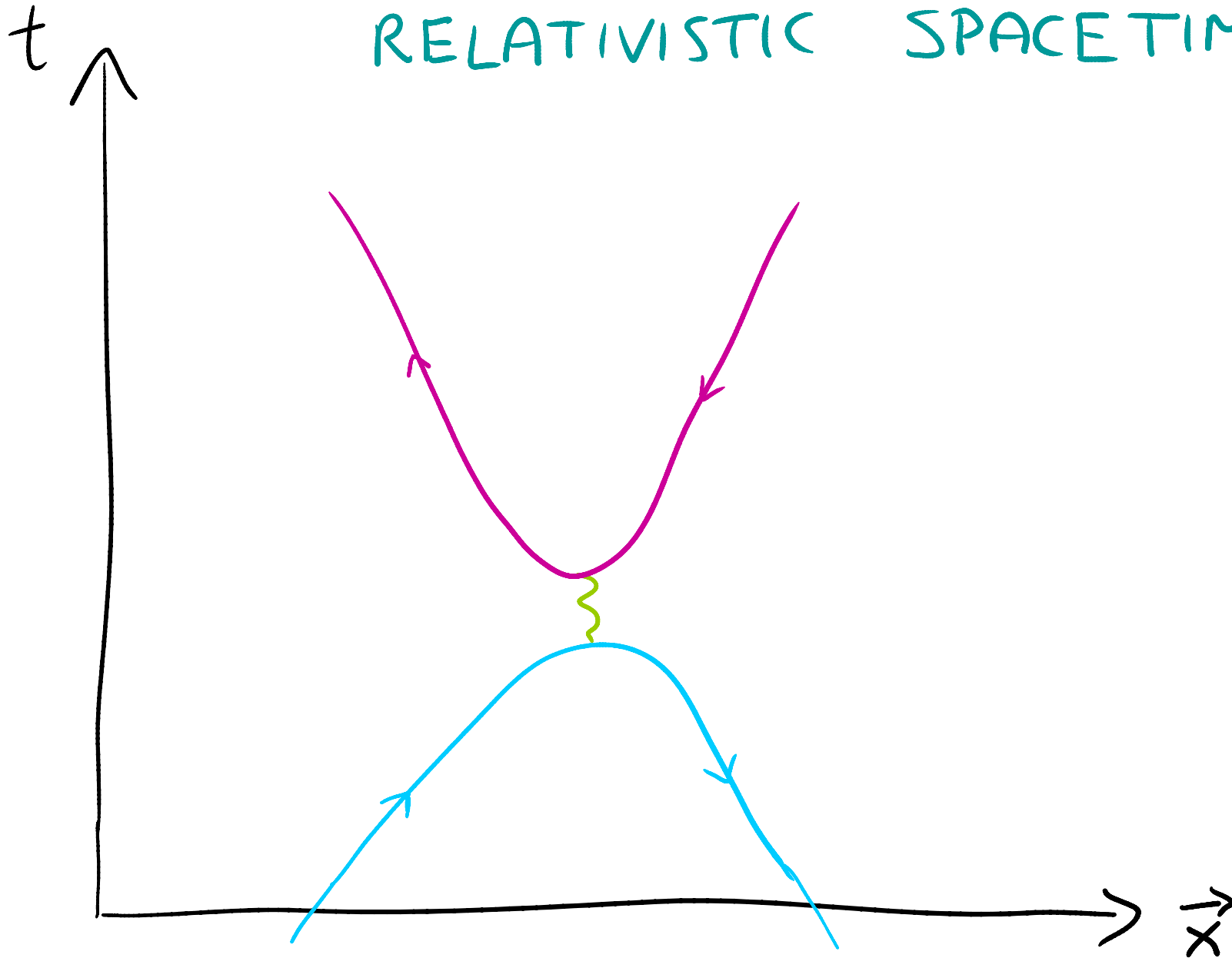
Extra-dimensional Perception —

Collider strategies

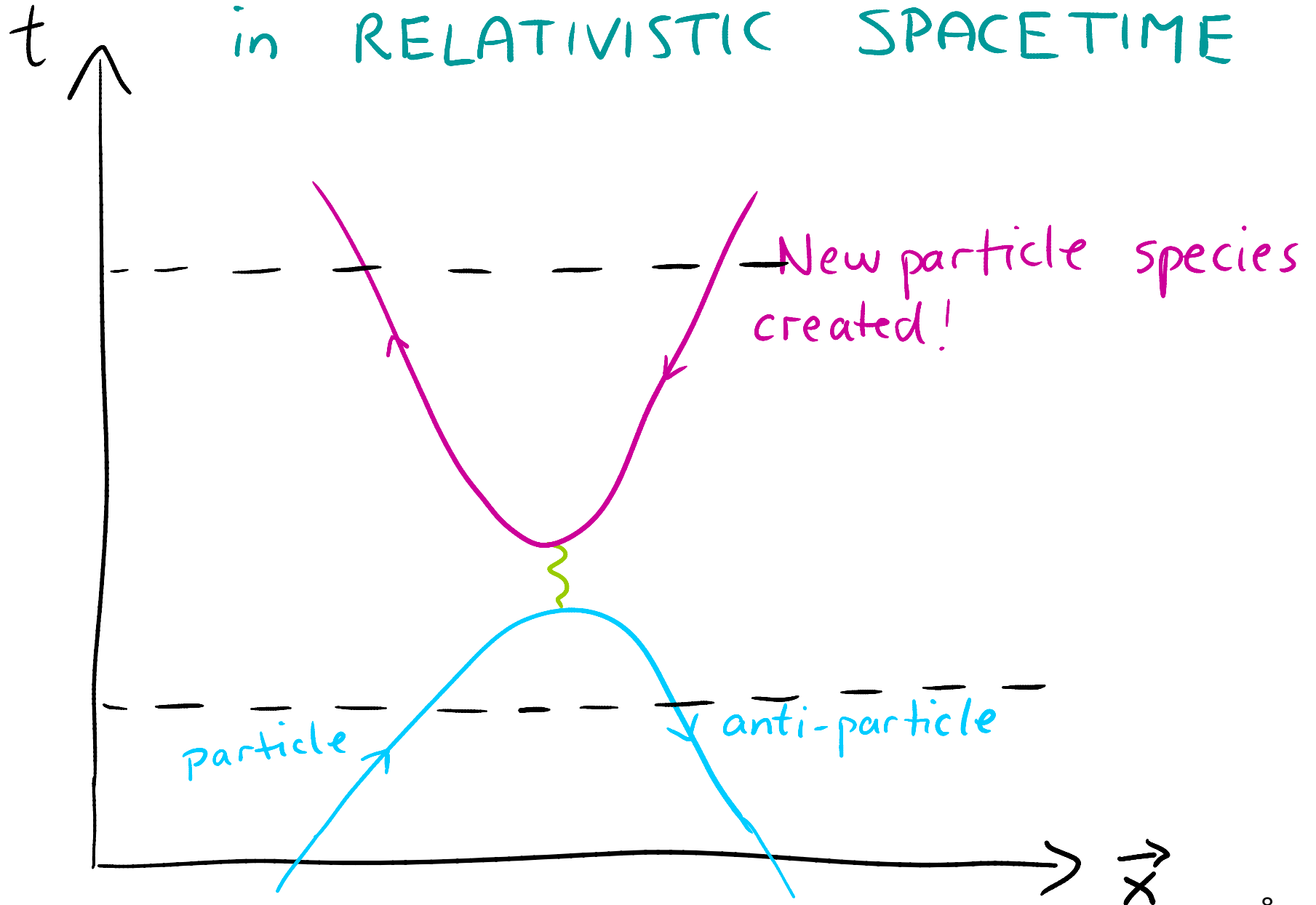
NON-RELATIVISTIC SPACE & TIME



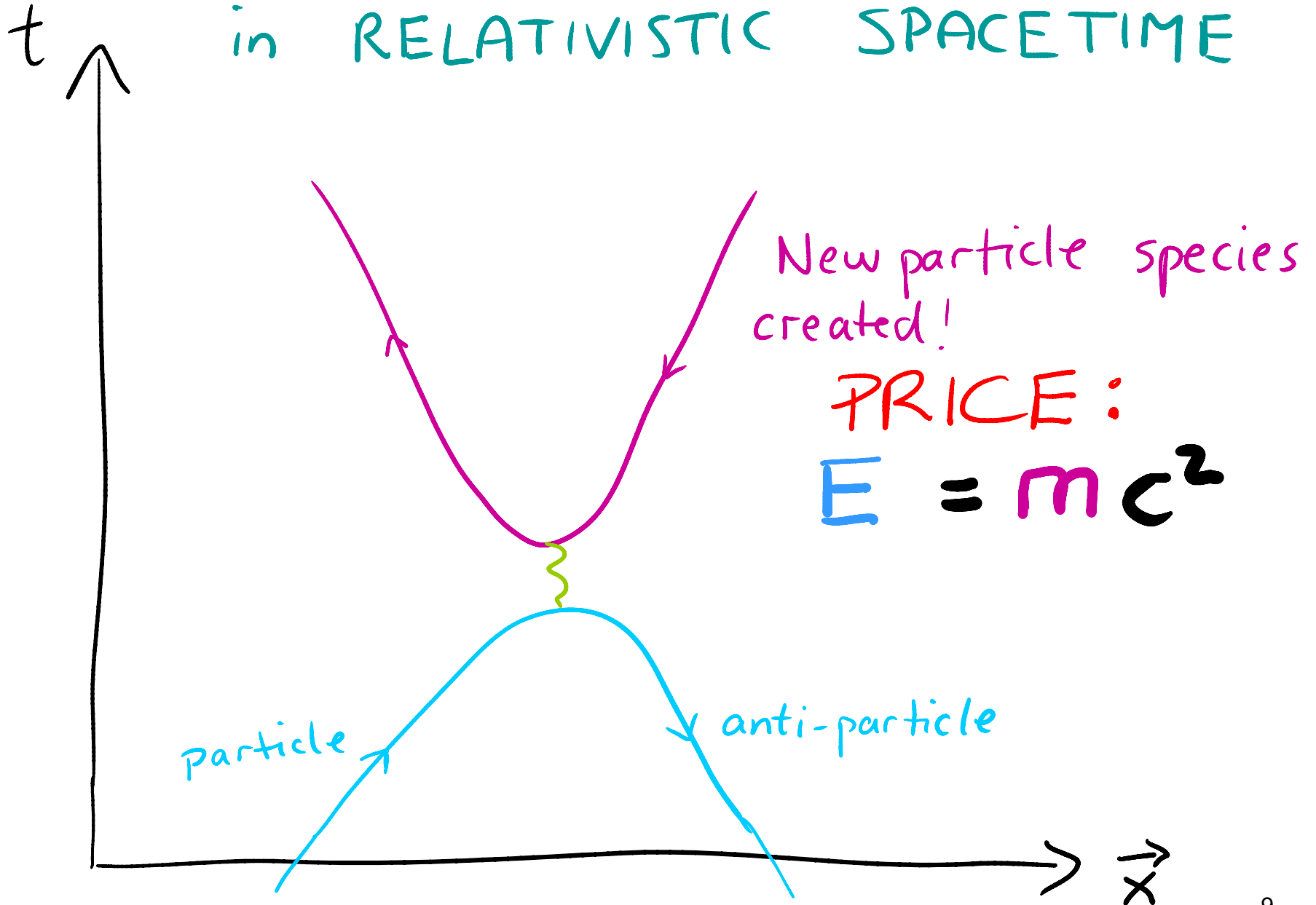
RELATIVISTIC SPACETIME



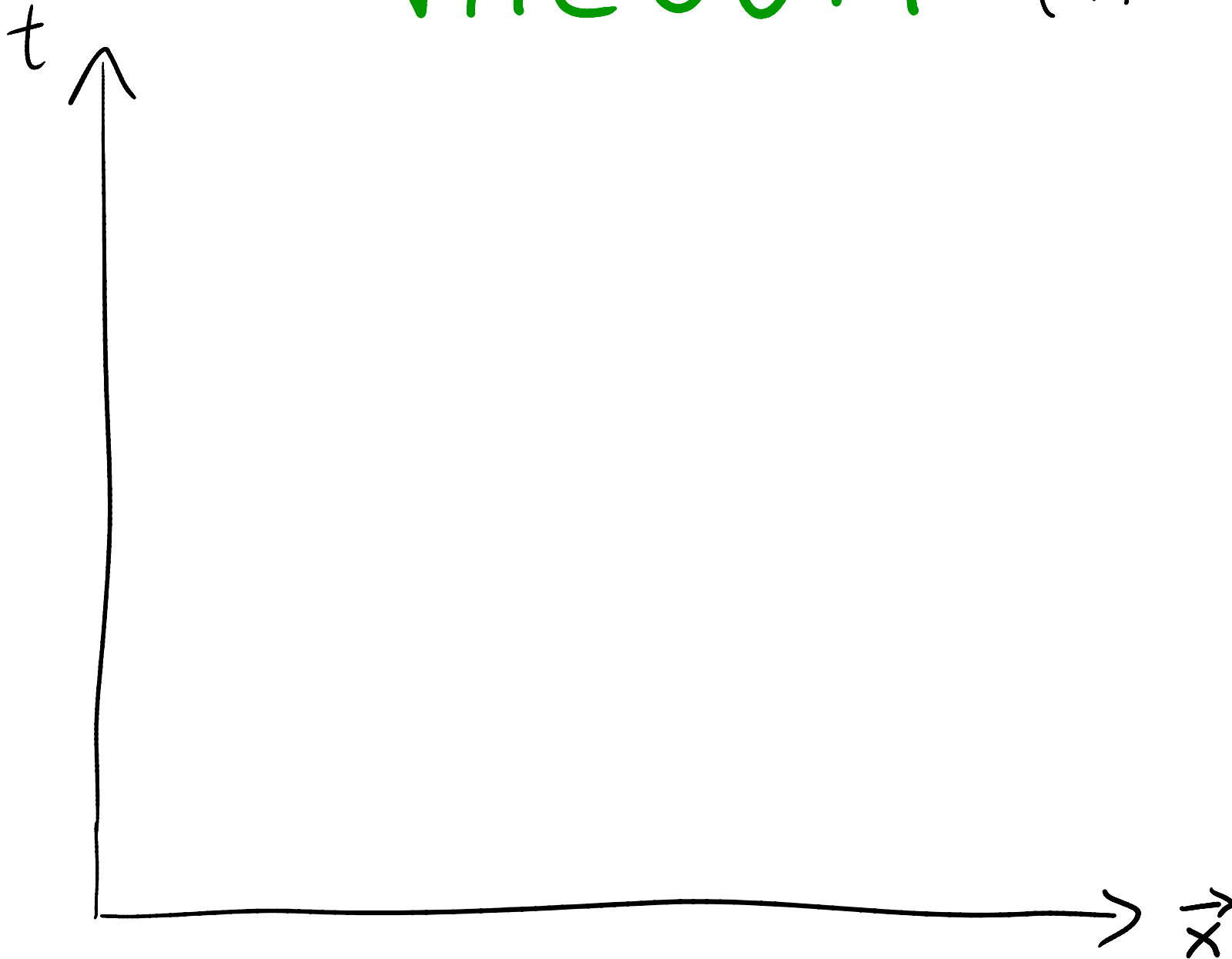
ALCHEMY in RELATIVISTIC SPACETIME



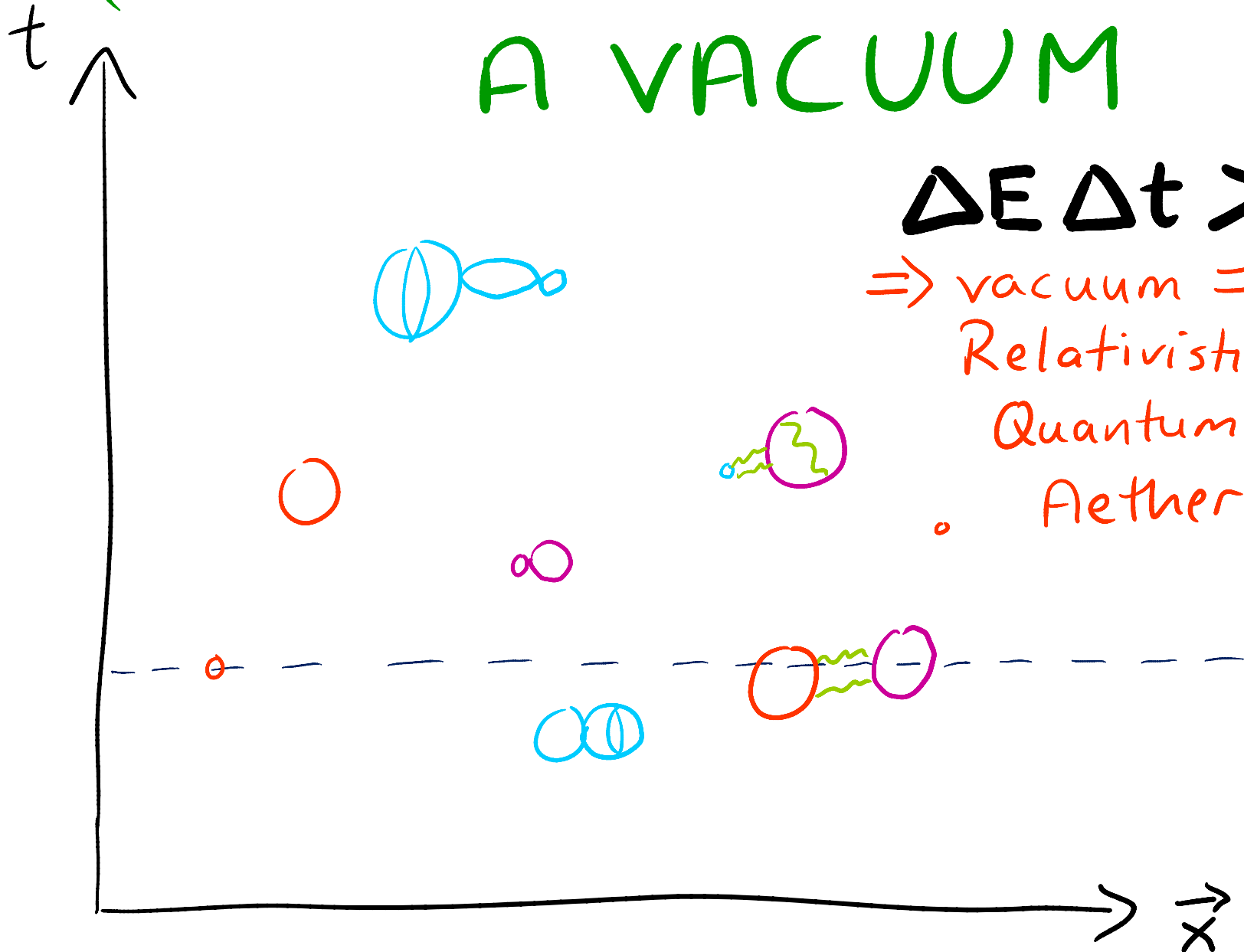
ALCHEMY in RELATIVISTIC SPACETIME



VACUUM ($\hbar = 0$)



(QUANTUM) NATURE ABHORS A VACUUM

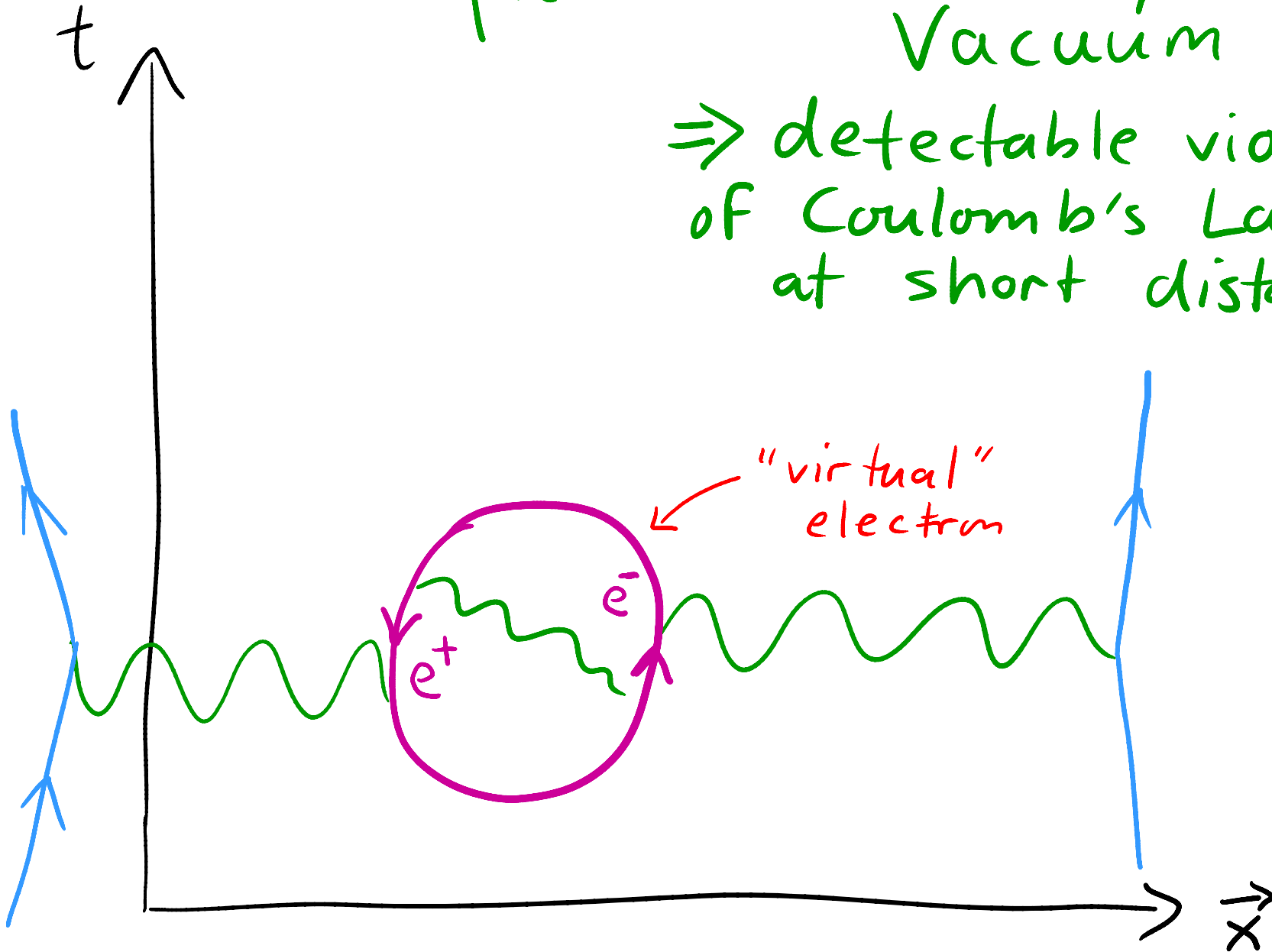


$$\Delta E \Delta t > \hbar$$

\Rightarrow vacuum =
Relativistic
Quantum
Aether

Example: Polarizability of the Vacuum

⇒ detectable violations of Coulomb's Law at short distances



Electro Weak UNIFICATION of PARTICLE INTERACTIONS

Electromagnetism + Weak Nuclear Force

γ photon

Radioactive
decay

W^{\pm}

Neutral
current

Z^0

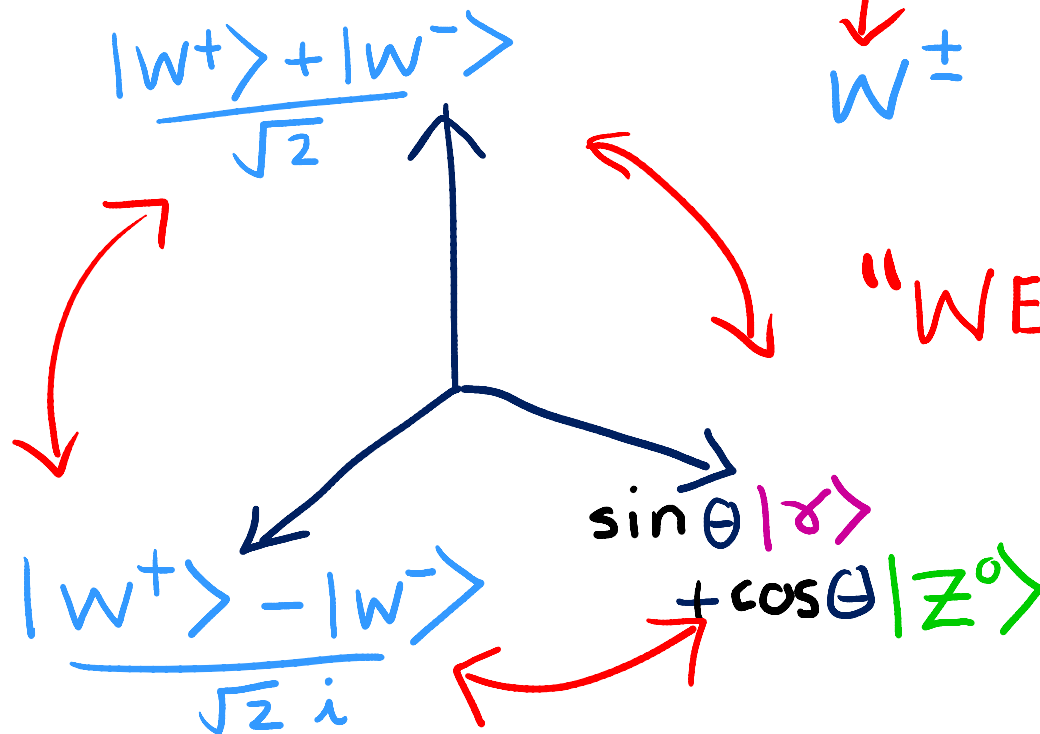
Electro Weak UNIFICATION of PARTICLE INTERACTIONS

Electromagnetism + Weak Nuclear Force

γ photon

Radioactive decay

Neutral current



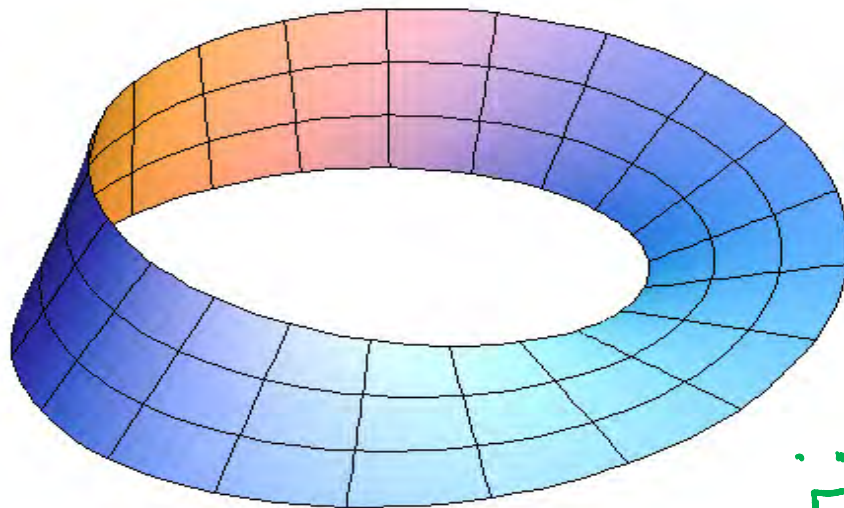
W^\pm

Z^0

"WEAK ISOSPIN"
SYMMETRY

RICH IN MATHEMATICAL
BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists
~ (Quantized) Differential Geometry
of FIBER BUNDLES to mathematicians

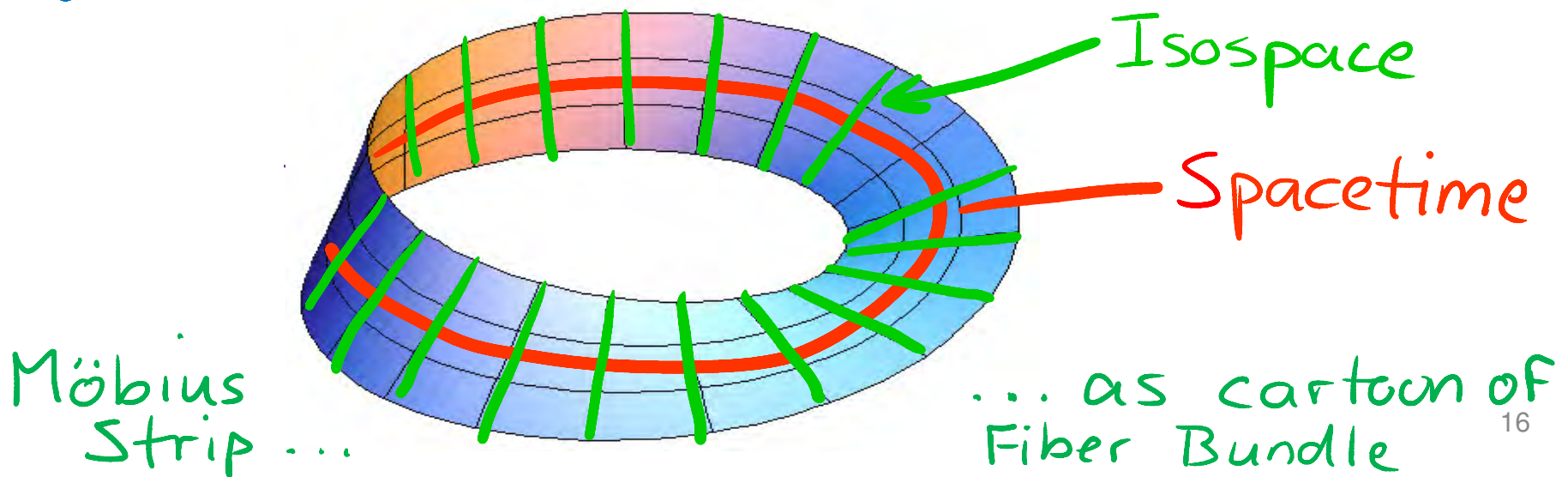


Möbius
Strip ...

... as cartoon of
Fiber Bundle

RICH IN MATHEMATICAL
BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists
~ (Quantized) Differential Geometry
OF FIBER BUNDLES to mathematicians

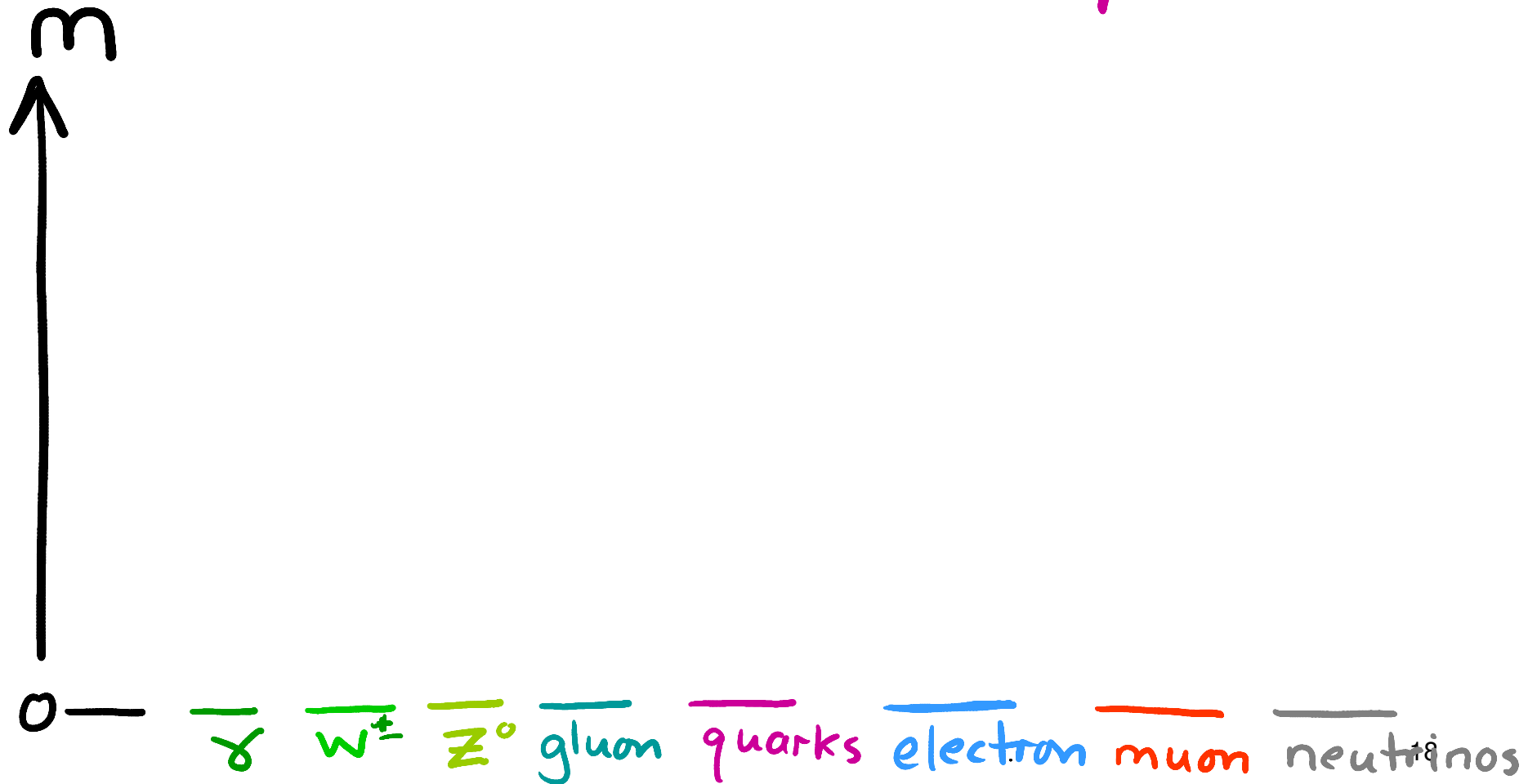


Electro Weak Unification

PREDICTS MASS SPECTRUM
of all known elementary particles!

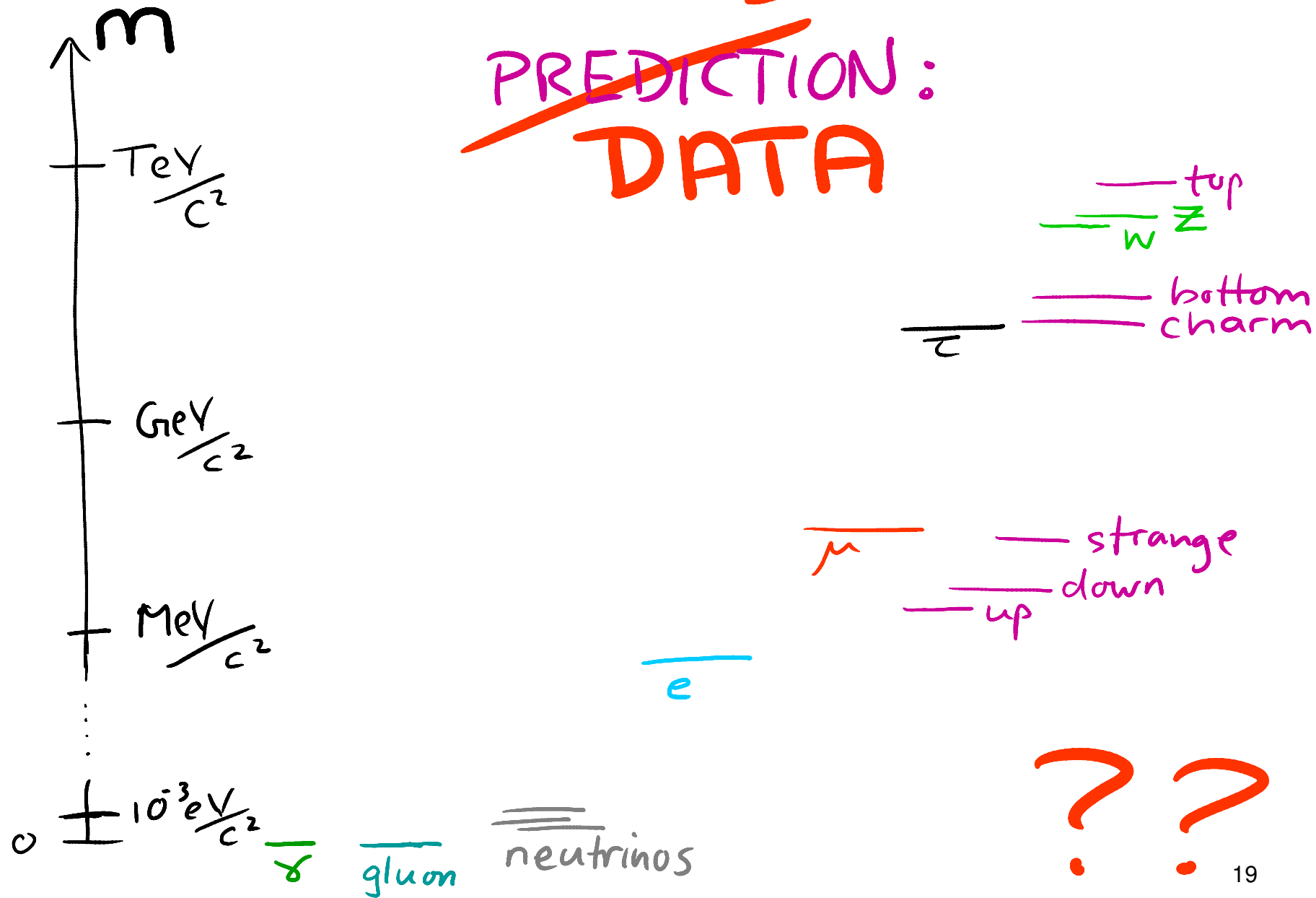
Electro Weak Unification

PREDICTS MASS SPECTRUM
of all known elementary particles

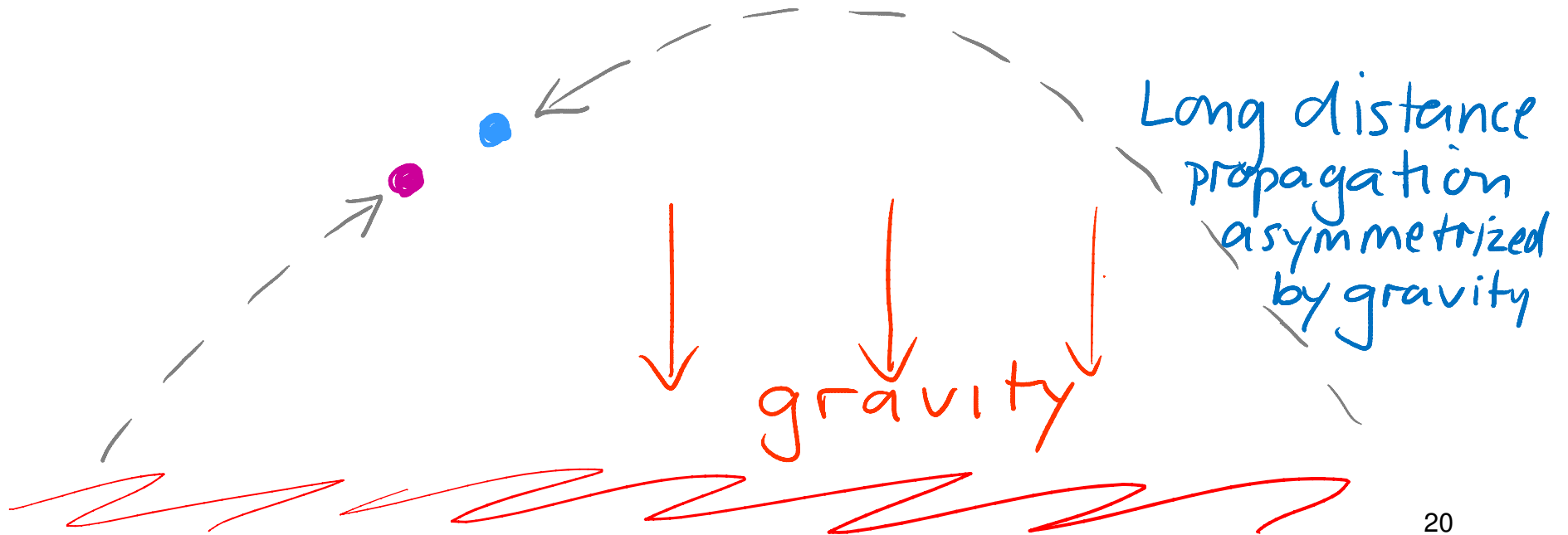


ElectroWeak Unification

~~PREDICTION:~~
DATA

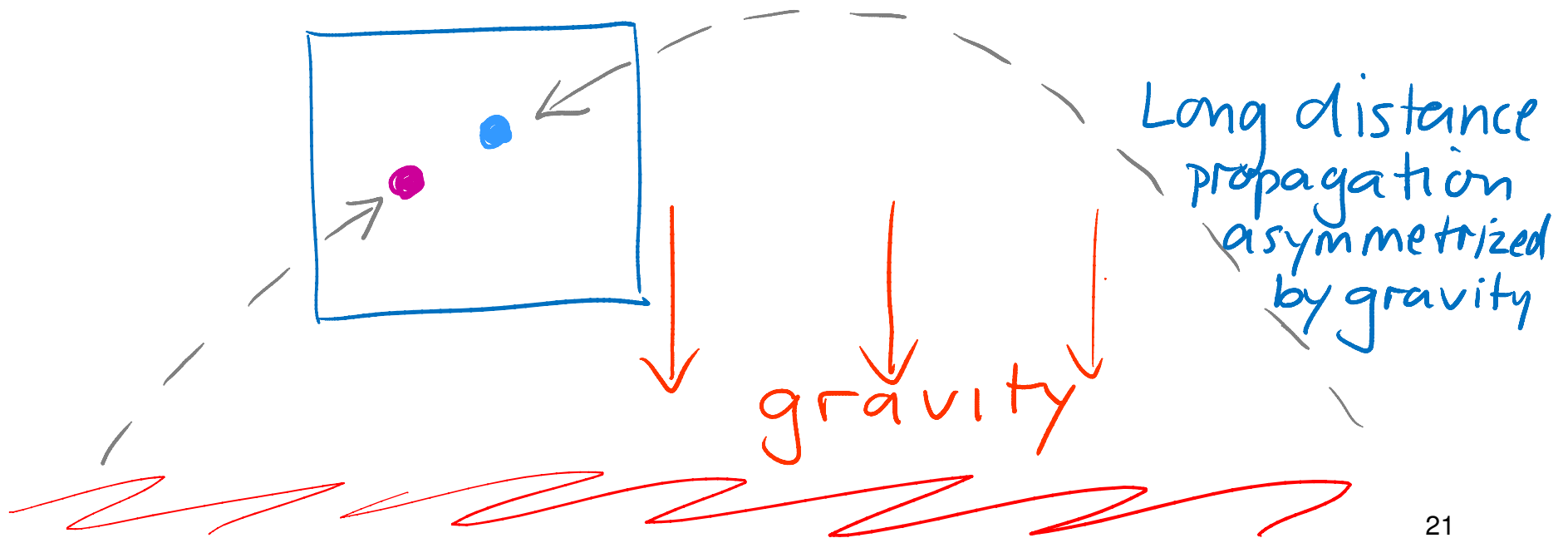


ANALOGY: Rotational ~~symmetry~~
by gravitational force
field

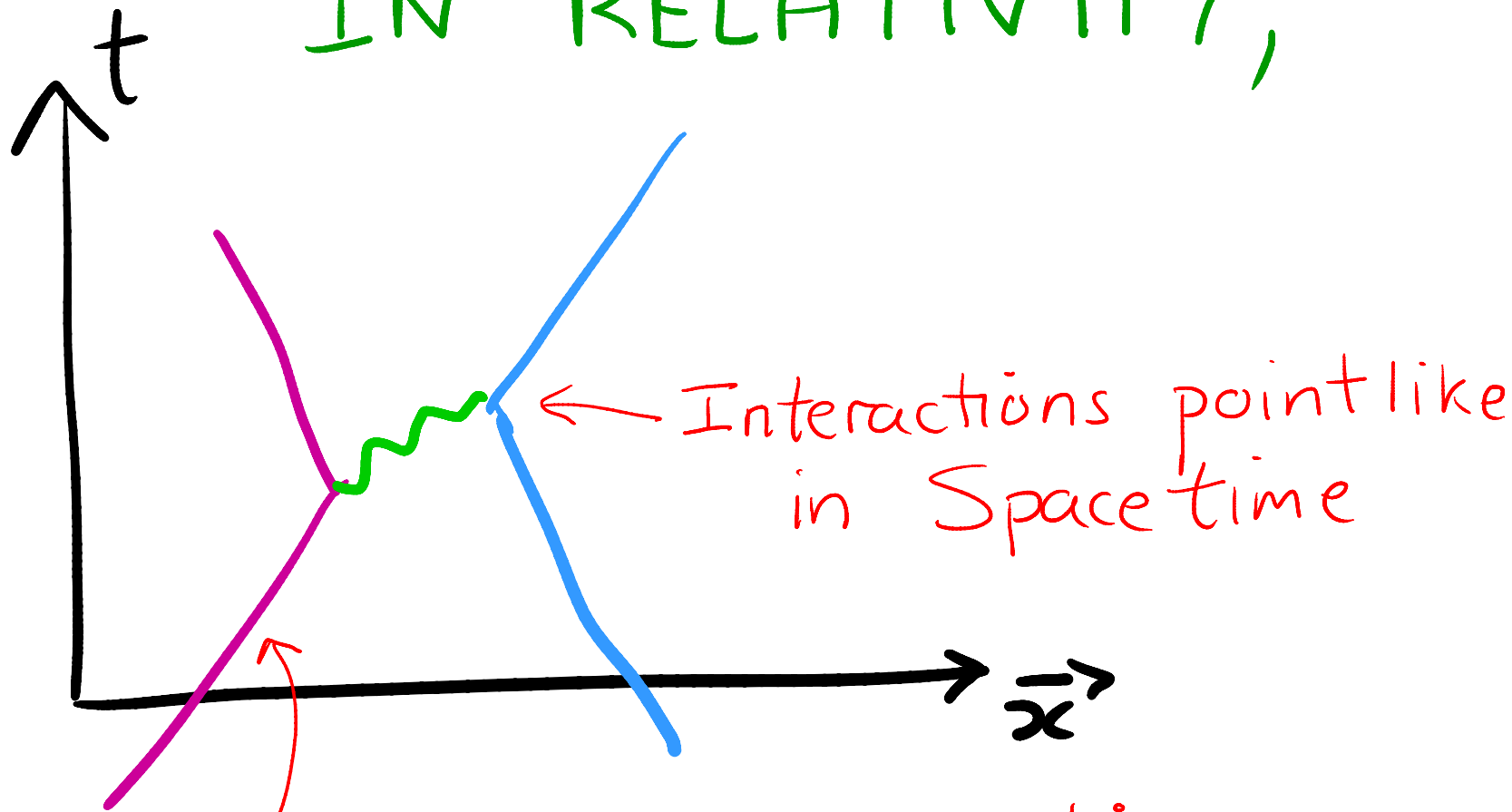


ANALOGY: Rotational ~~symmetry~~
by gravitational force
field

Collisions at close quarters
 \approx rotationally symmetric



IN RELATIVITY,



Mass governs propagation

$$E^2 = \vec{p}^2 c^2 + (mc^2)^2$$



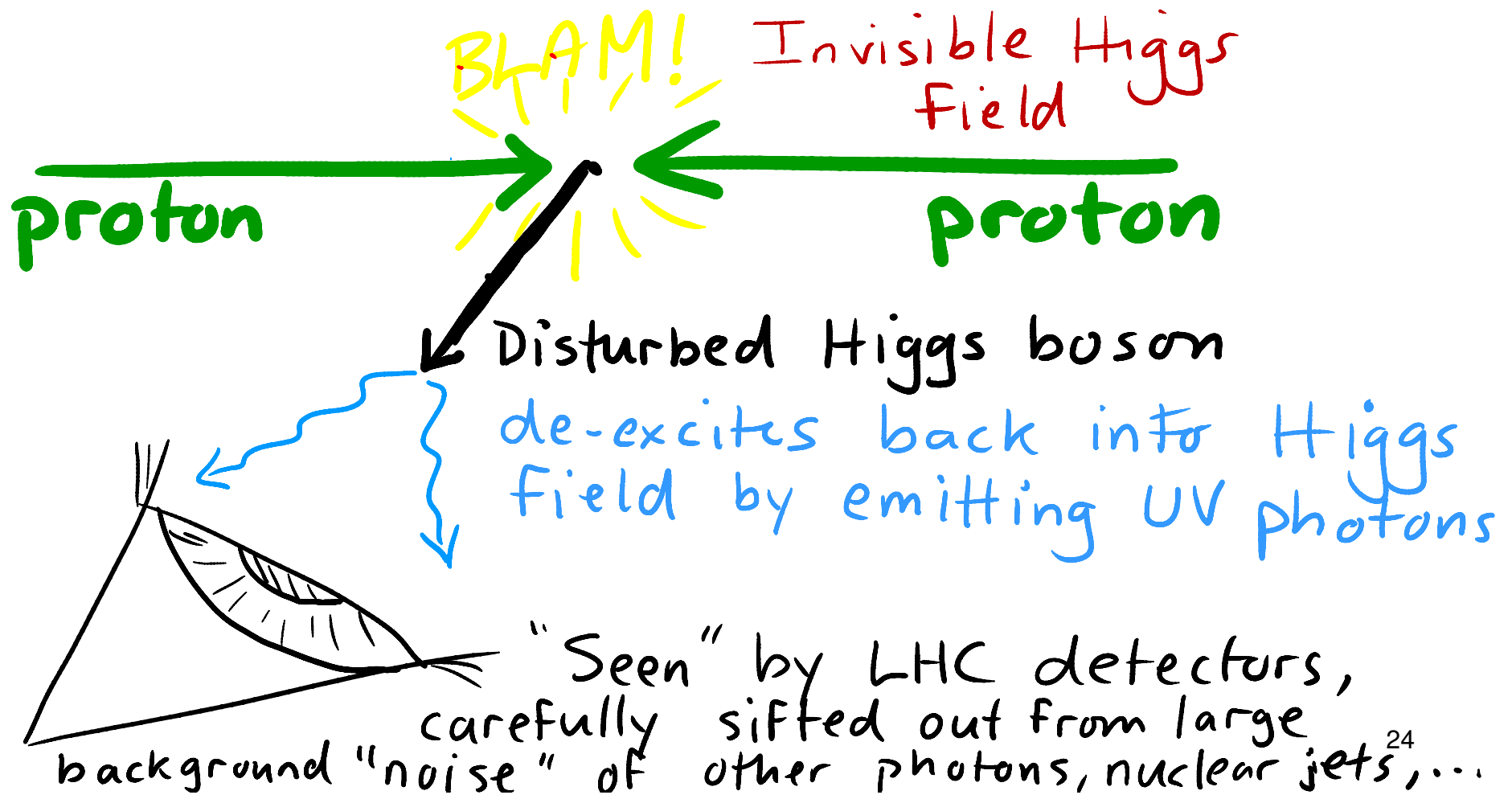
space filled by
invisible, uniform scalar field
"pointing" in "isospace"

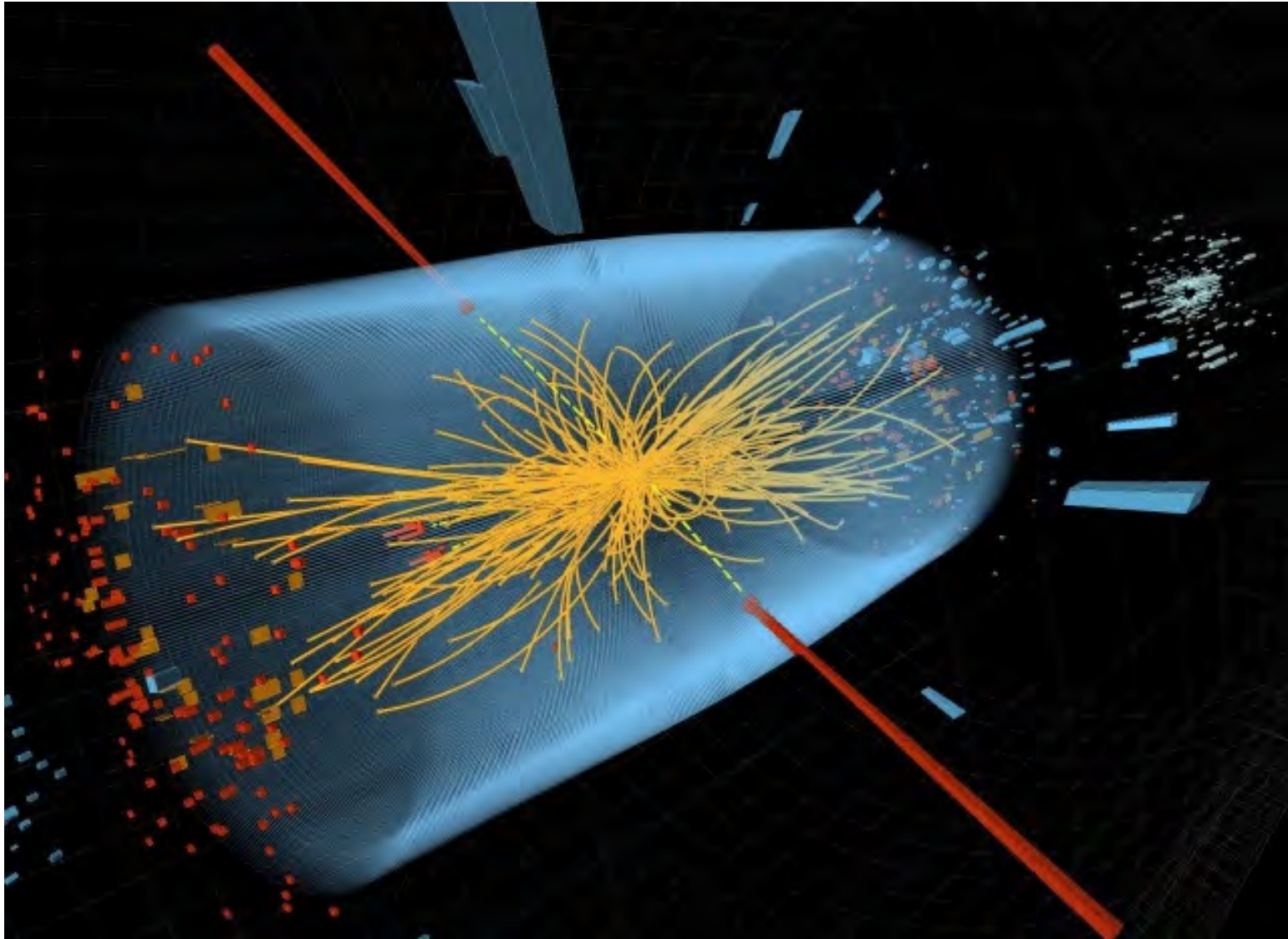
≡ Higgs field,

made of Higgs boson particles,
as EM fields are made of photons.

To test this structure we must
create & detect such quantum
"ripples".

LHC has blasted
Higgs bosons out of hiding!

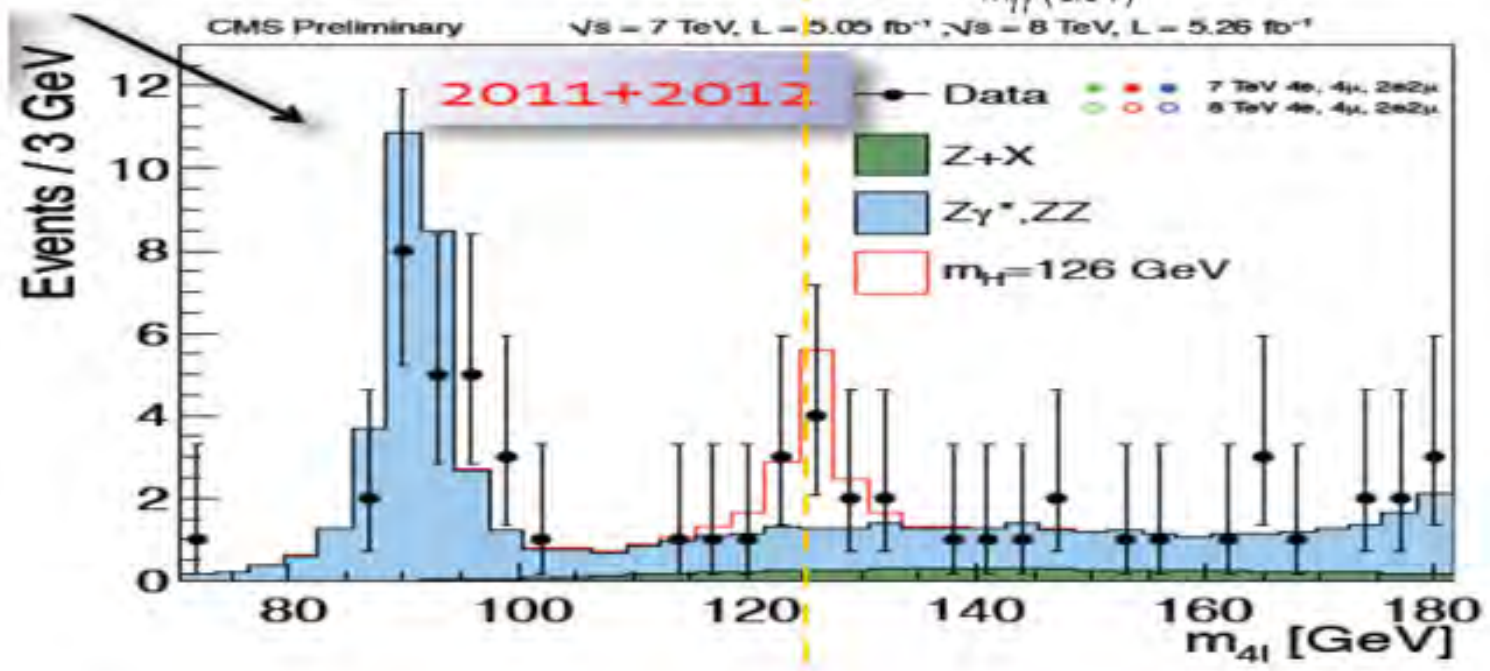
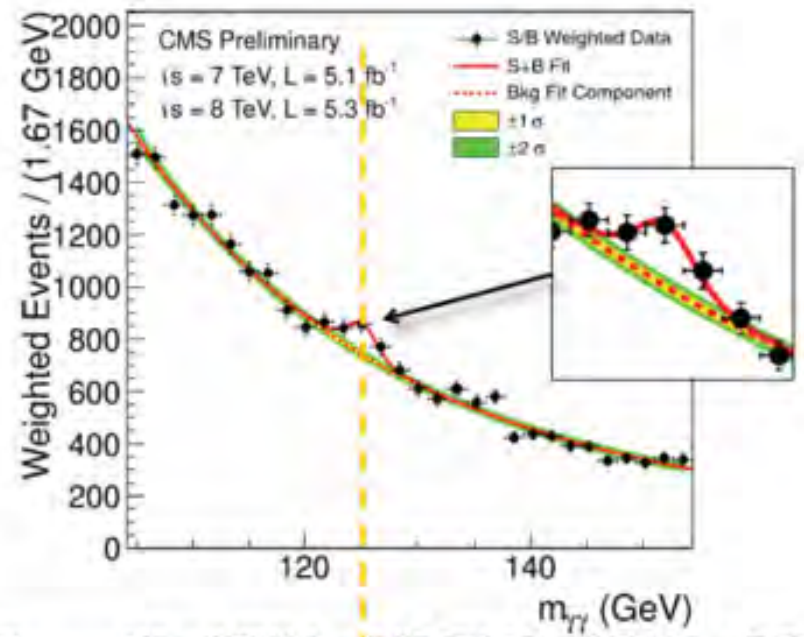




Candidate Higgs \rightarrow 2 photon event in CMS detector

Early
LHC
DATA

m_{Higgs}
= 125 GeV



STANDARD MODEL NOW COMPLETE

Higgs boson discovery wins Nobel
prize for theorists.

Standard Model brilliant
culmination of decades of theory
& experiment, deep insights into
Nature.

It can be extrapolated theoretically to
extremely high energies, BUT...

HIERARCHY PROBLEM

of quantum vacuum

~ ideas of Weisskopf, Wilson, Weinberg, 'tHooft

m_w^{theory}

$$M_{\text{Planck}} \equiv \sqrt{\frac{ct\hbar}{G_{\text{Newton}}}} \sim 10^{18} \text{ GeV}/c^2$$

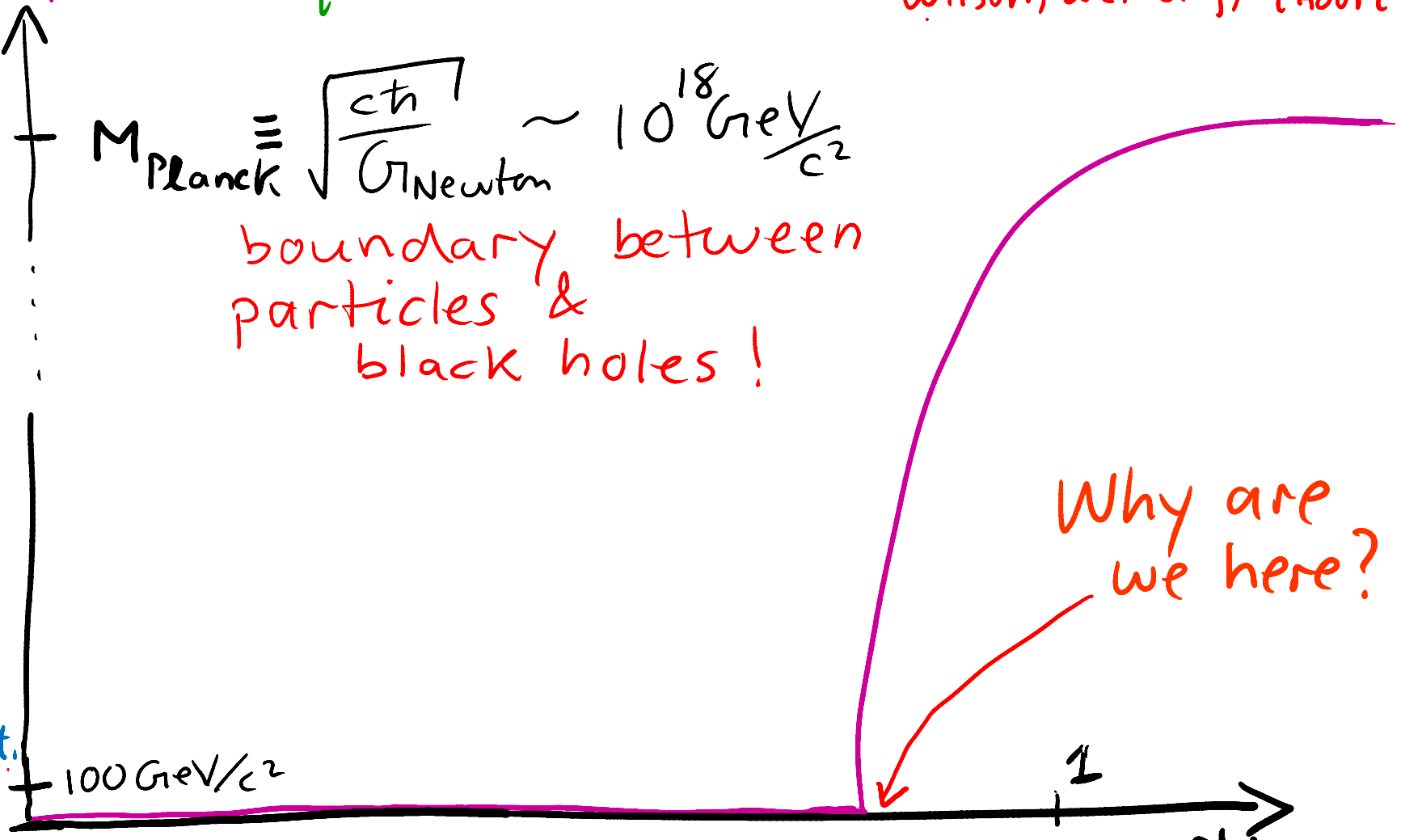
boundary between particles & black holes!

$m_w^{\text{expt.}}$

100 GeV/c²

Why are we here?

couplings
in H standard model



HIERARCHY PROBLEM

of quantum-corrected vacuum

m_w^{theory}

$$M_{\text{Planck}} \equiv \sqrt{\frac{ct\hbar}{G_{\text{Newton}}}} \sim 10^{18} \text{ GeV}/c^2$$

boundary between particles & black holes!

"UNNATURAL!"

Why are we here?

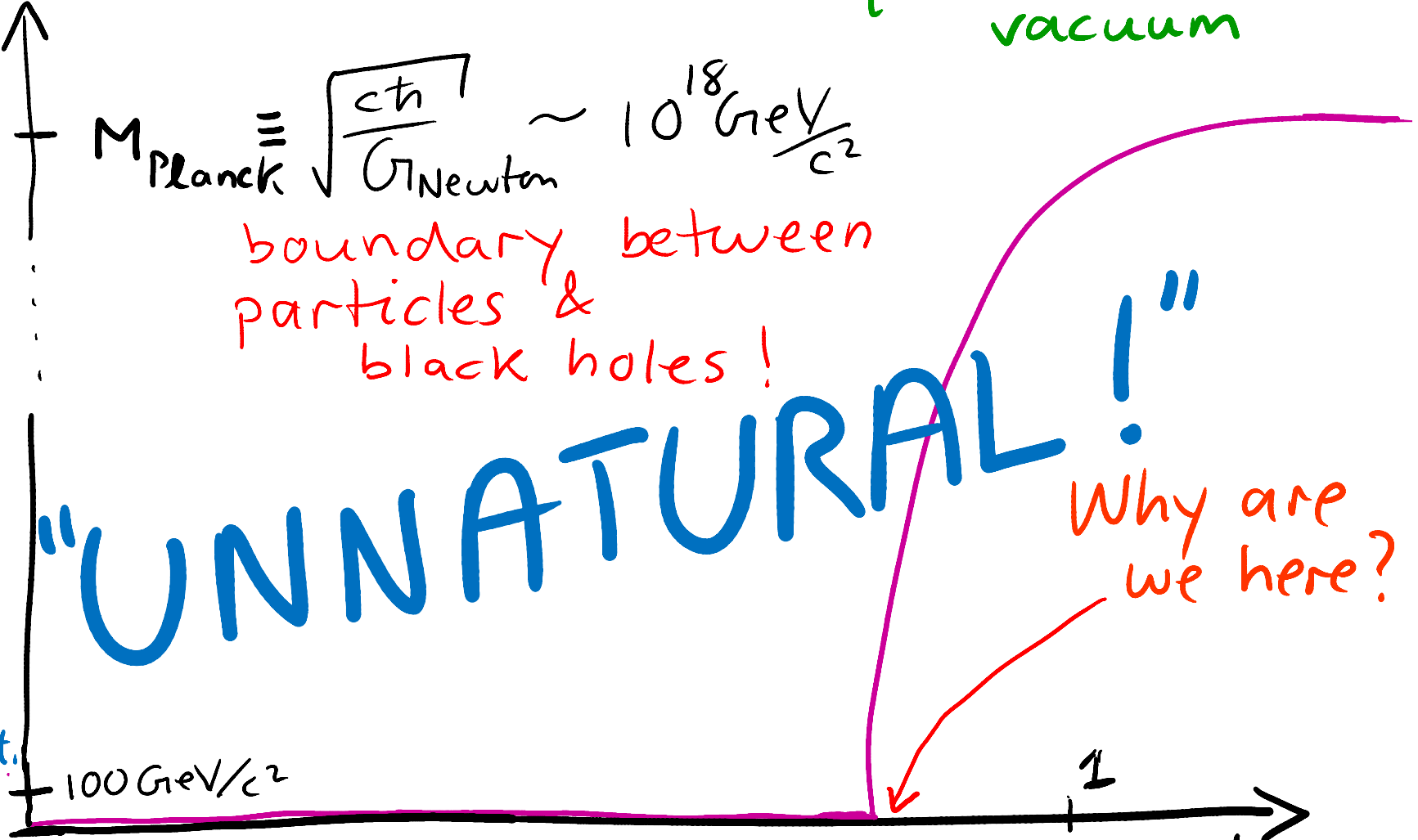
$m_w^{\text{expt.}}$
0

100 GeV/c²

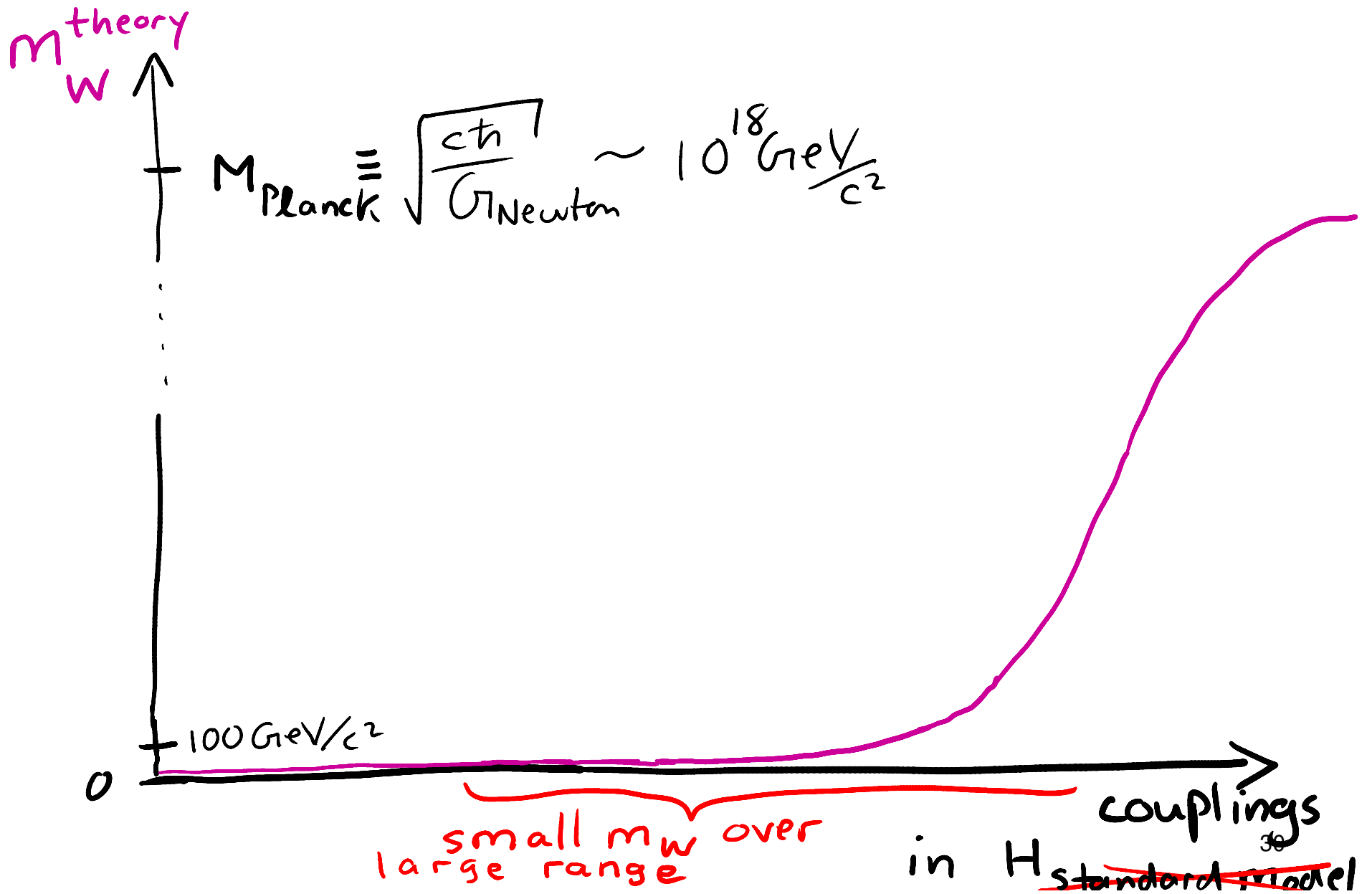
1

couplings

in $H_{\text{standard model}}$



A DIFFERENT VACUUM?



A DIFFERENT VACUUM?

m_W^{theory}

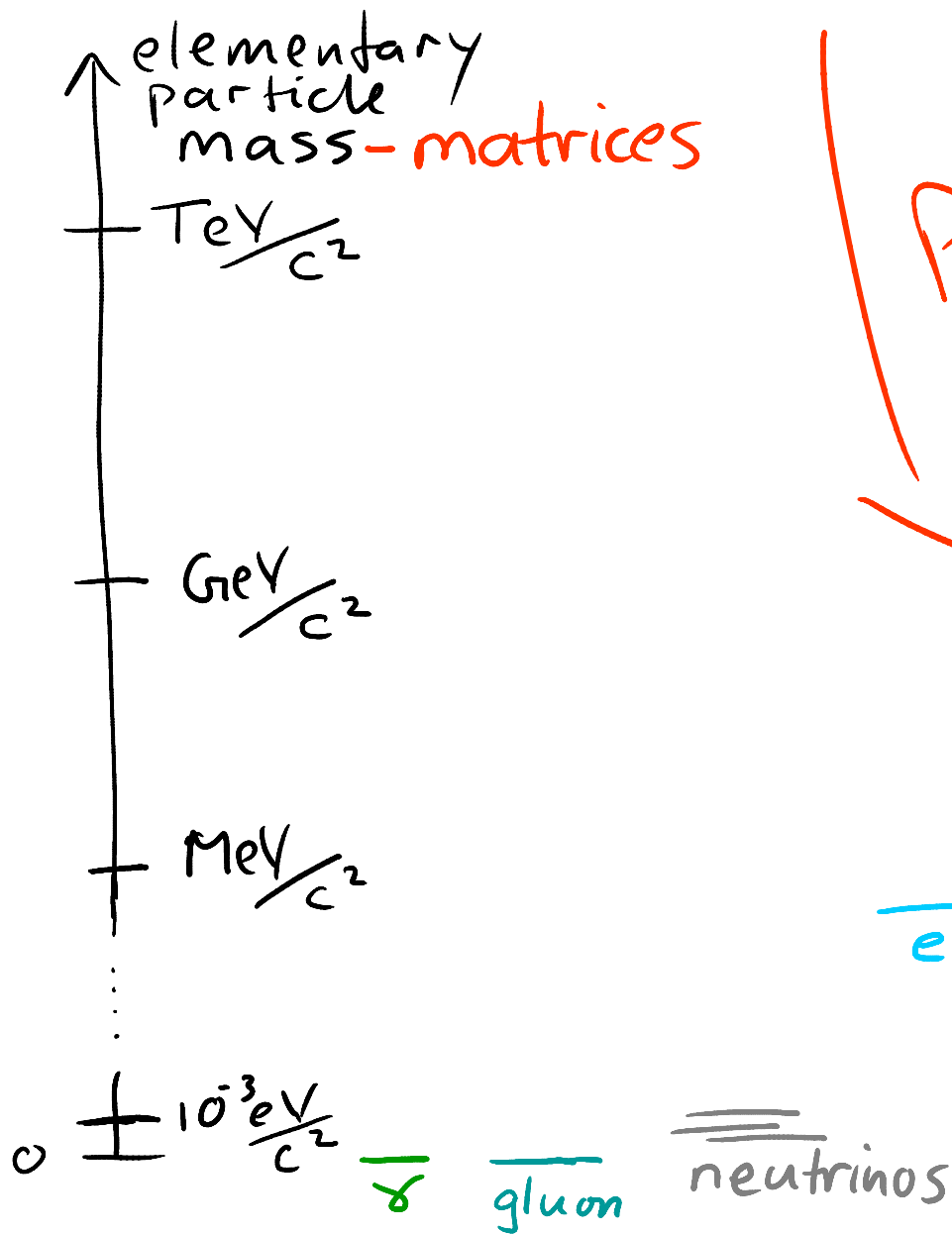
$$M_{\text{Planck}} \equiv \sqrt{\frac{ct\hbar}{G_{\text{Newton}}}} \sim 10^{18} \text{ GeV}/c^2$$

"NATURAL"

0 $100 \text{ GeV}/c^2$

couplings
in $H_{\text{standard model}}$
small m_W over large range

Flavor Puzzle



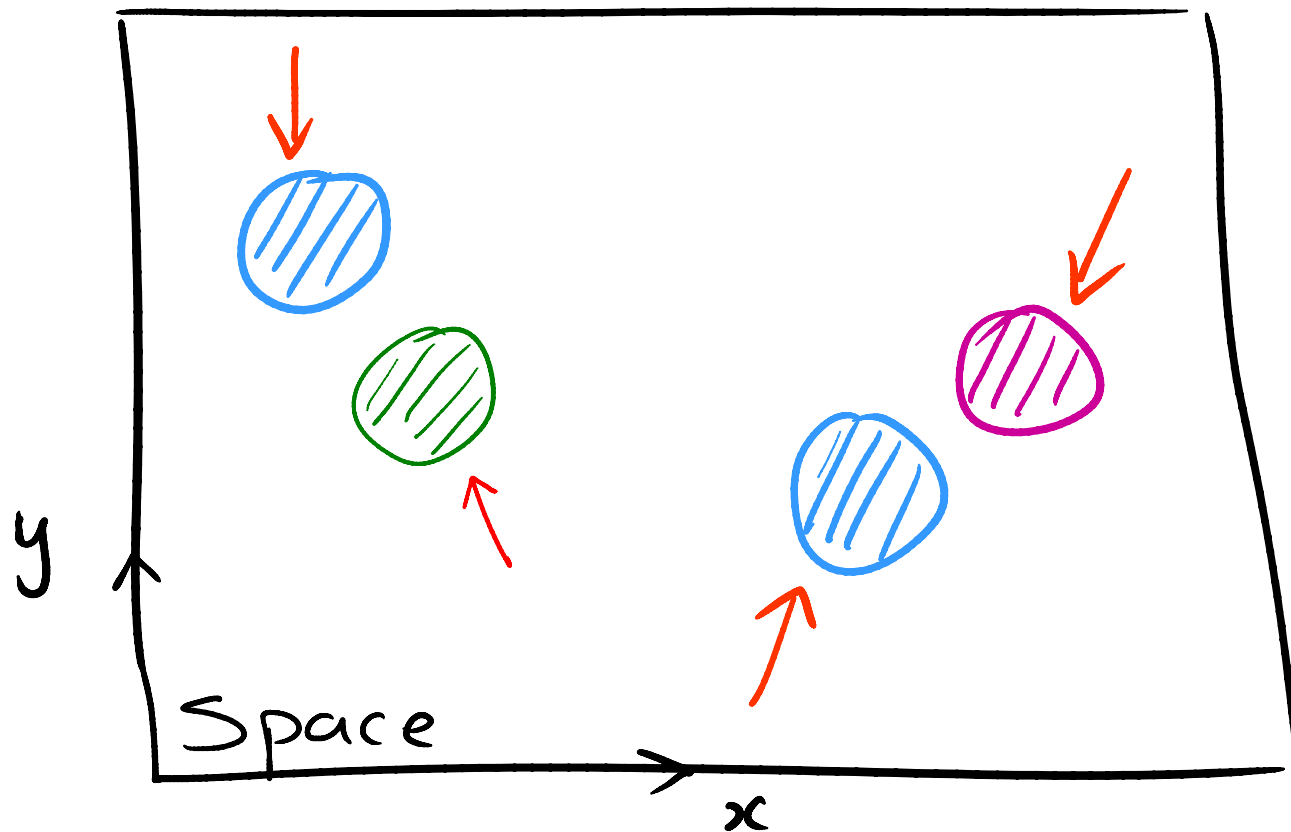
Pattern?

— top
 — W Z
 — bottom
 — charm

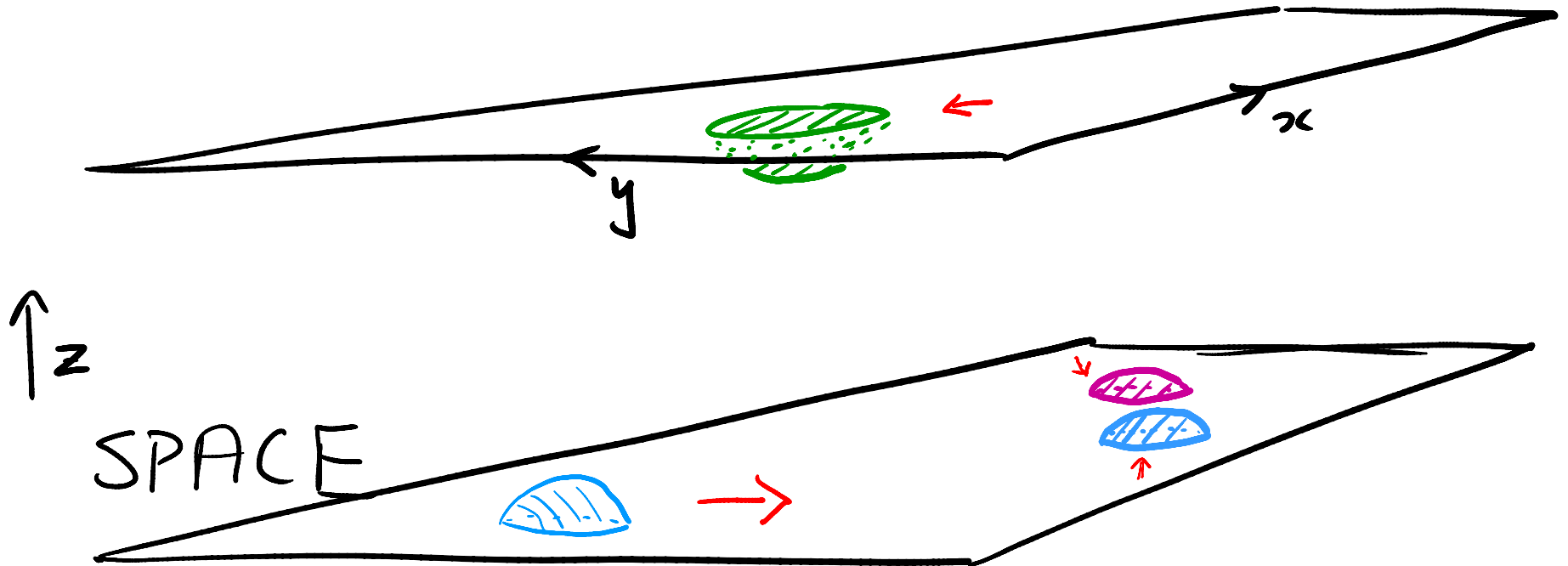
— strange
 — down
 — up

≡ couplings to Higgs Boson.

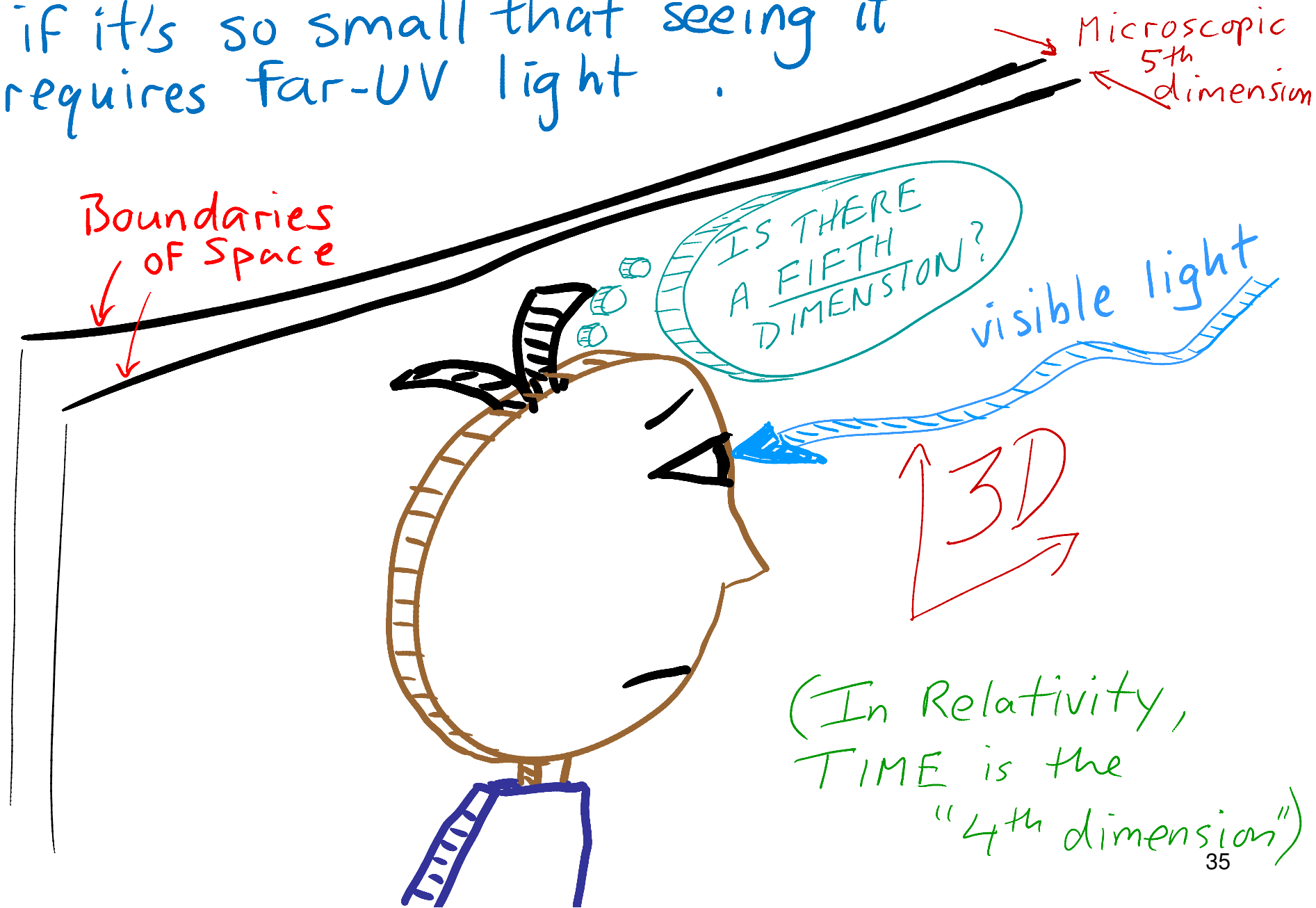
THE ANSWERS TO
THESE PUZZLES
MAY BE HIDDEN...



IN NEW DIMENSIONS!



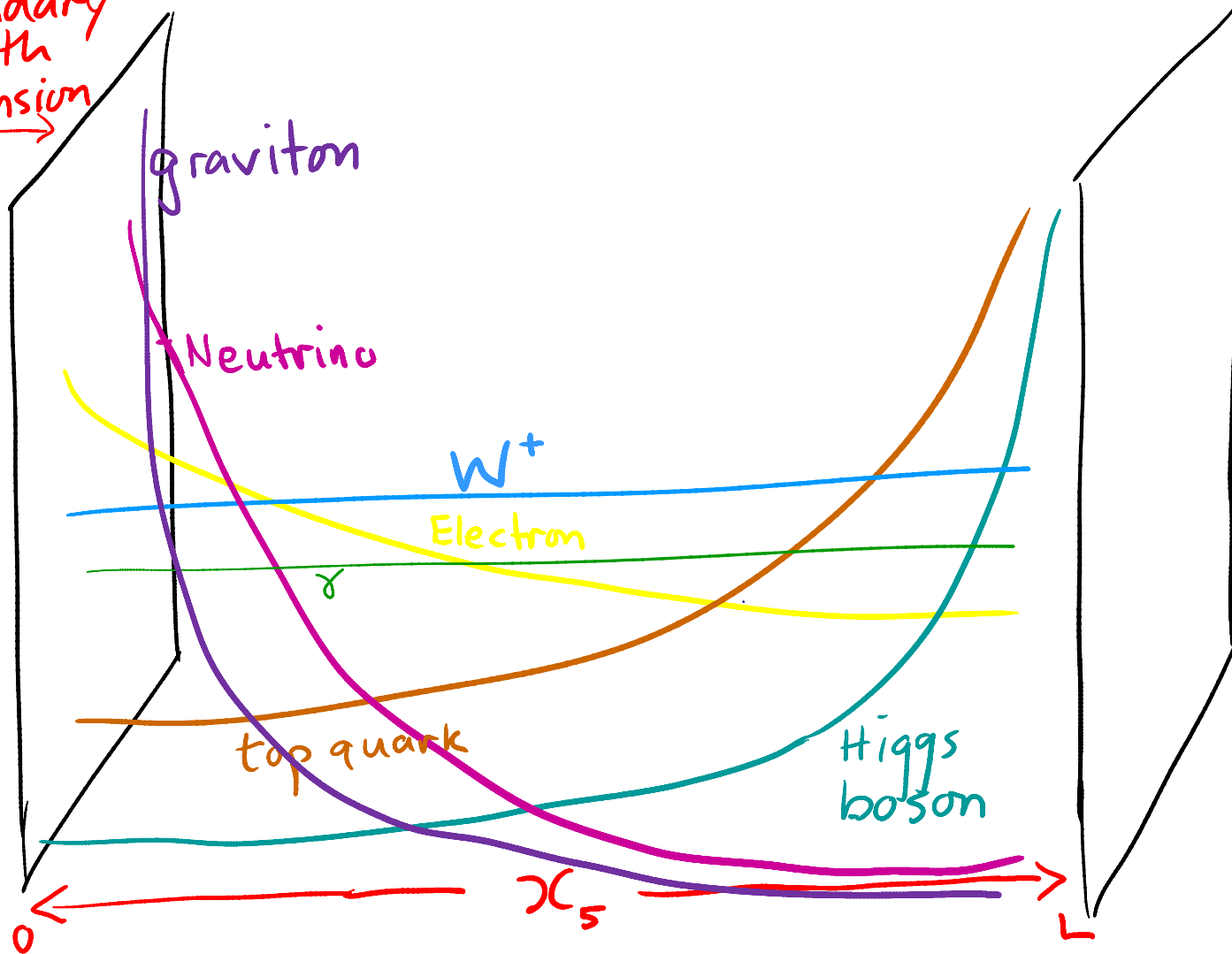
A NEW DIMENSION COULD HIDE
if it's so small that seeing it
requires far-UV light .



5D CHAOS \rightarrow 4D COSMOS

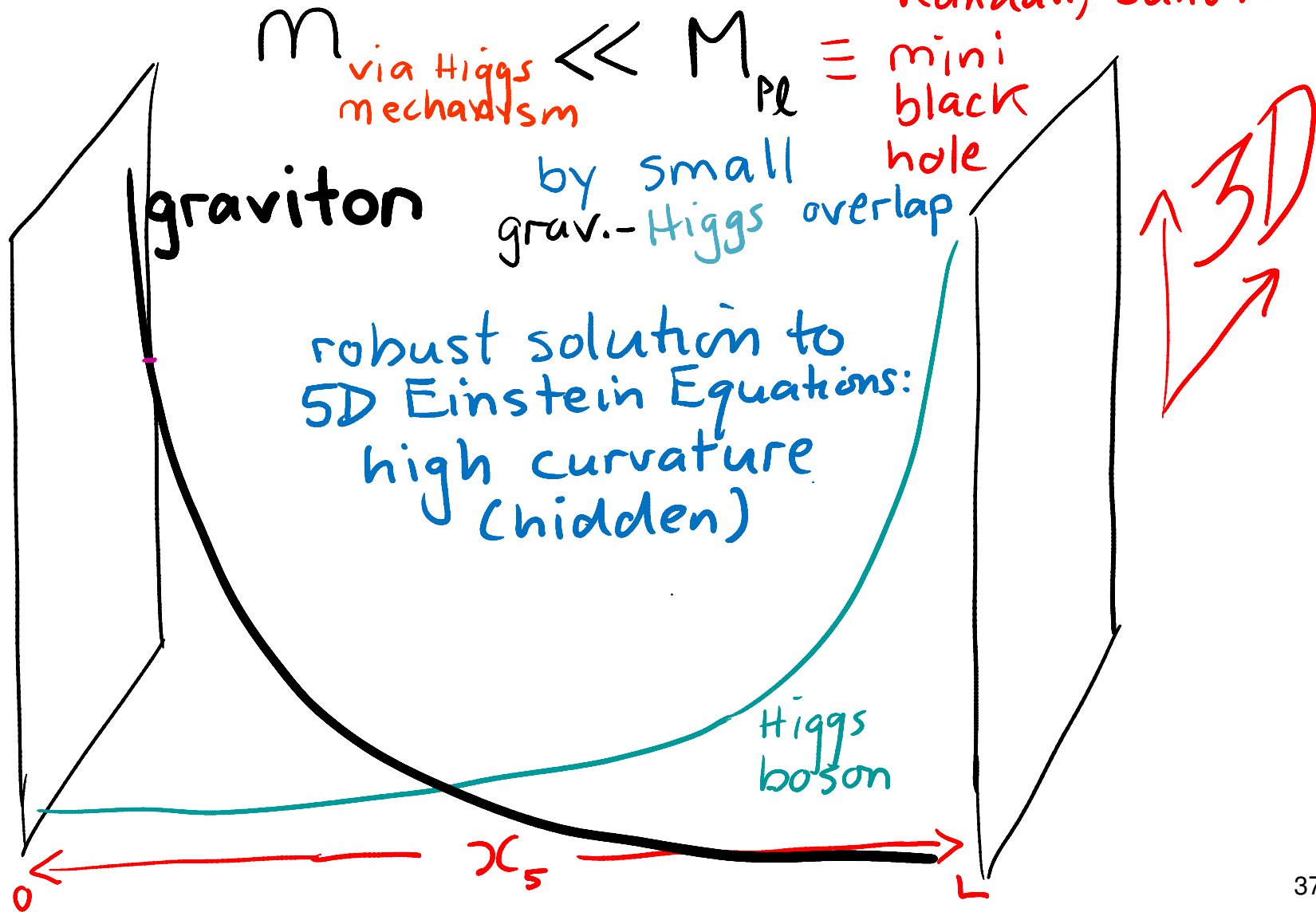
Different species have different wavefunction solutions to their wave equations

Boundary of 5th dimension \rightarrow



Warped Compactification solves the Hierarchy Problem...

Randall, Sundrum '99



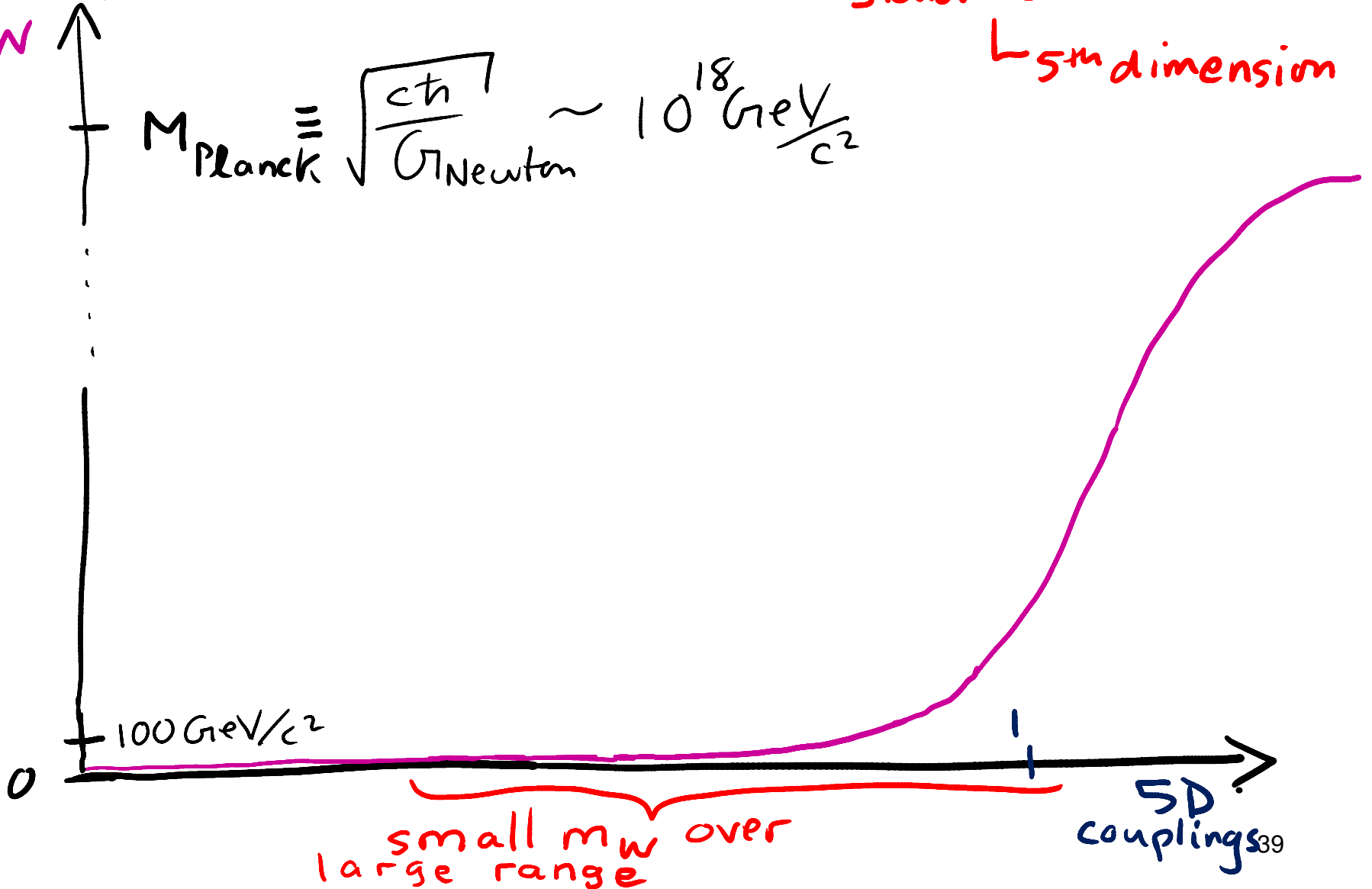


Some of the physics inspiration behind "Interstellar"³⁸

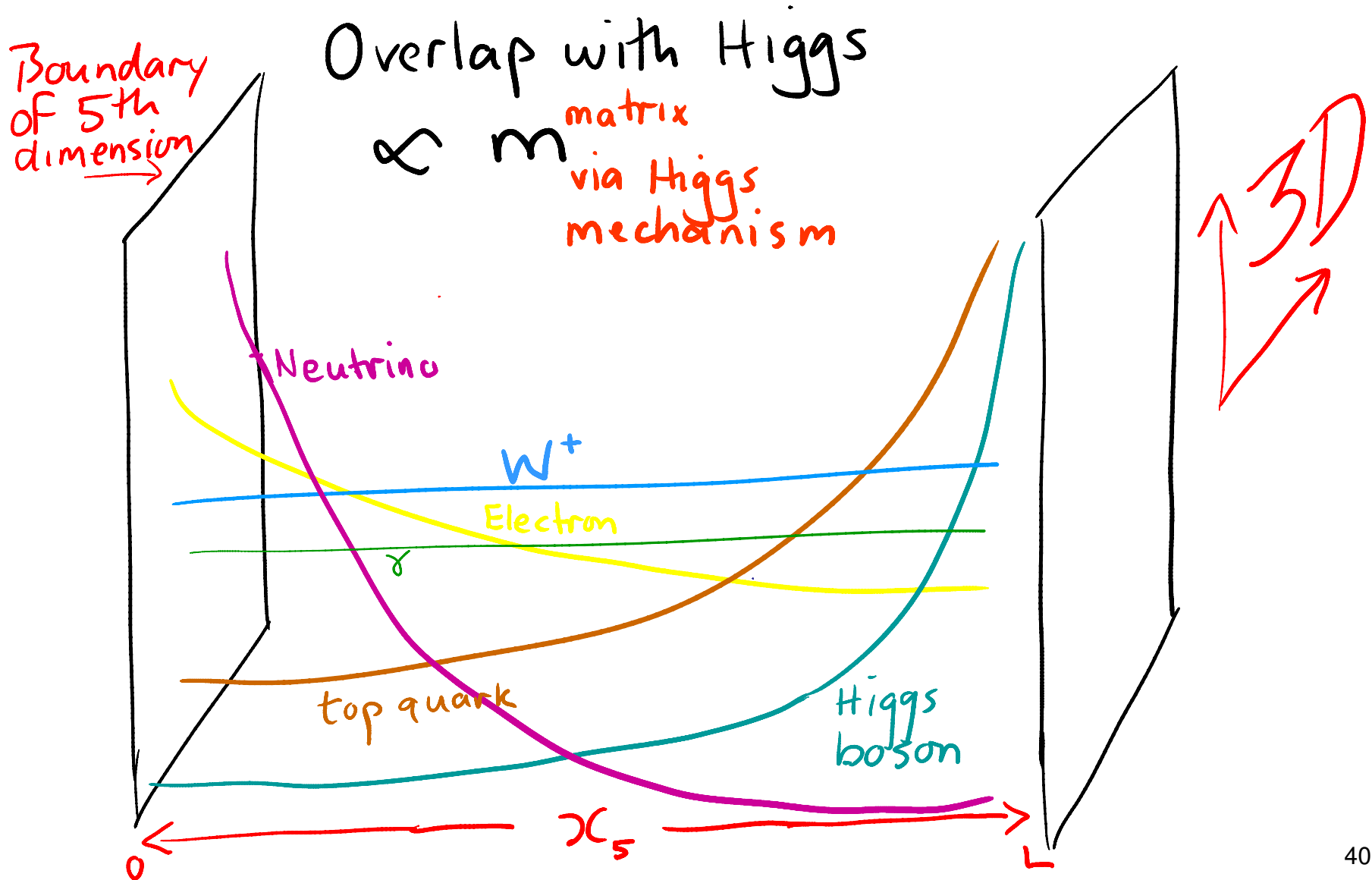
...NATURALLY

Goldberger, Wise '99
stabilization of
5th dimension

m_W^{theory}



Satisfying answer to FLAVOR PUZZLE



Work of many hands
to discover this story

⋮

Goldberger, Wise '00

Arkani-Hamed, Schmaltz '00

Davoudiasl, Hewett, Rizzo '00

Grossman, Neubert '00

Chang, Hisano, Nakano, Okada, Yamaguchi '00

Gherghetta, Pomarol '00

Agashe, Delgado, May, Sundrum '03

Contino, Namura, Pomarol '03

Agashe, Contino, Pomarol '05

Agashe, Okui, Sundrum '08

& test & constrain it by
high-precision
pre-LHC data

Davoudiasl, Hewett, Rizzo '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

Agashe, Perez, Soni '04 '05 '06

Fitzpatrick, Perez, Randall '07

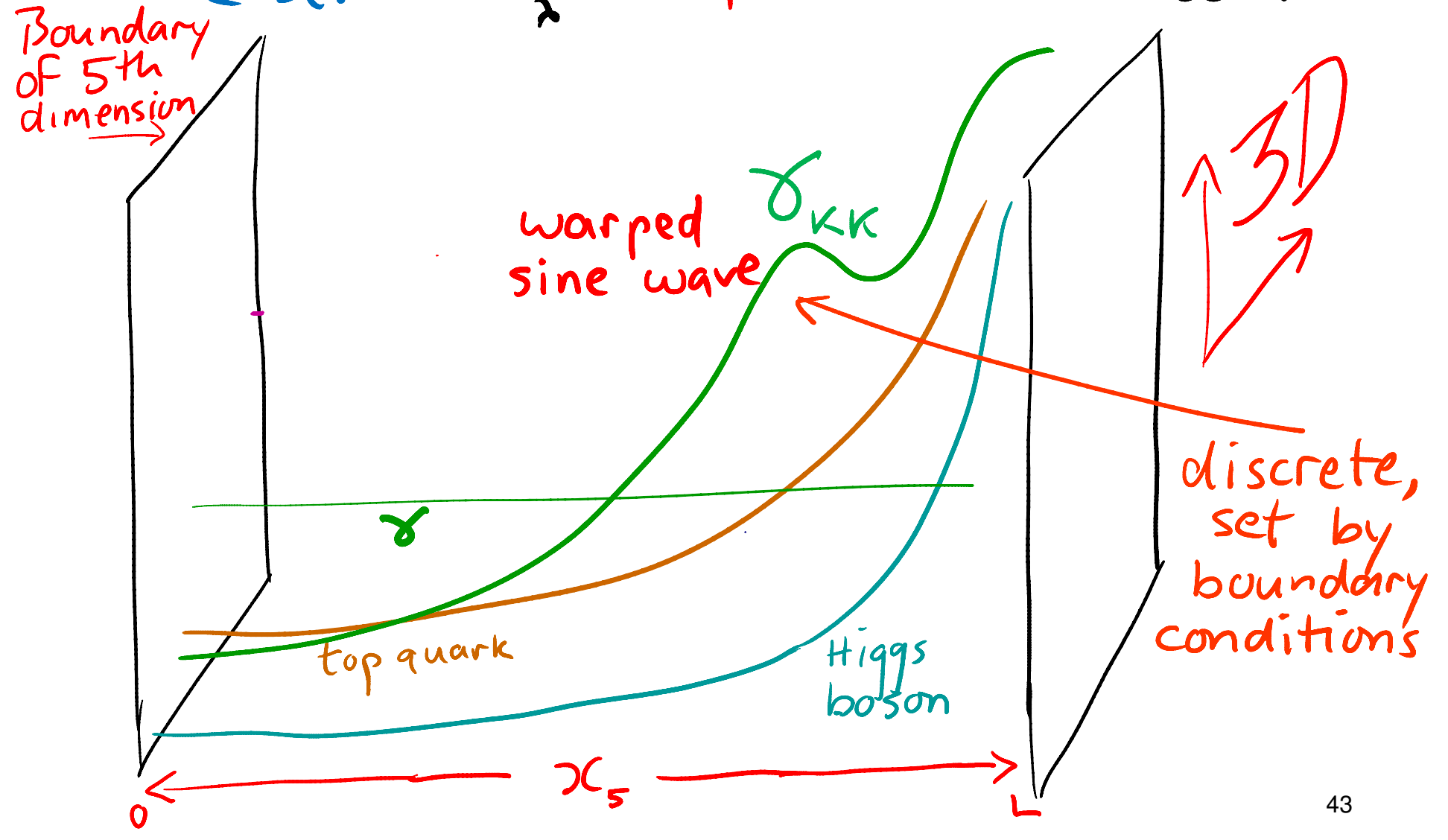
Csaki, Falkowski, Weiler '08

Agashe, Azatov, Zhu '08 . . .

EXTRA-DIMENSIONAL PERCEPTION

requires shorter wavelengths

Cost: " $E = \frac{hc}{\lambda}$ " warped version \sim few TeV

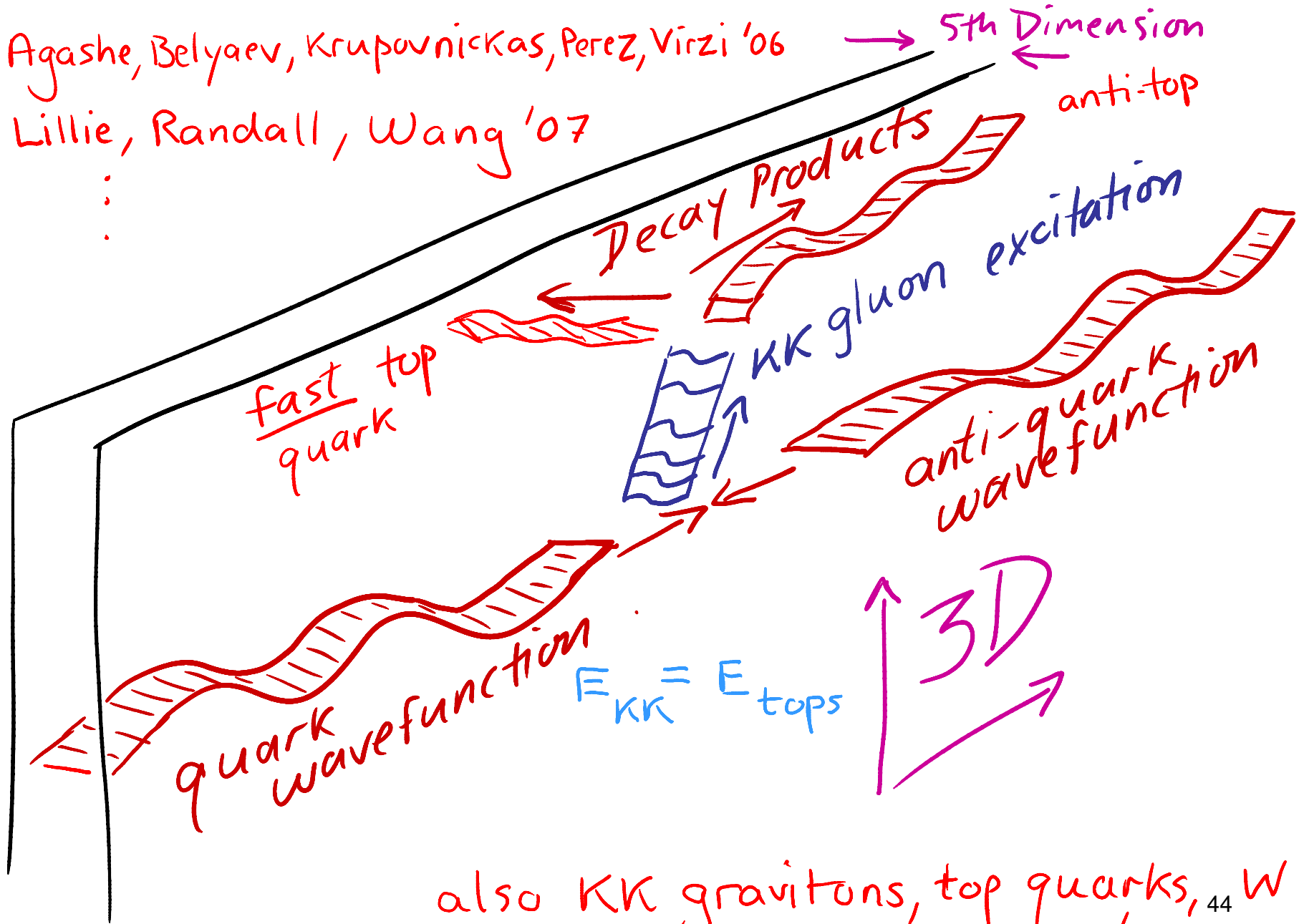


EXTRA-DIMENSIONAL PERCEPTION

Agashe, Belyaev, Krupovnickas, Perez, Virzi '06

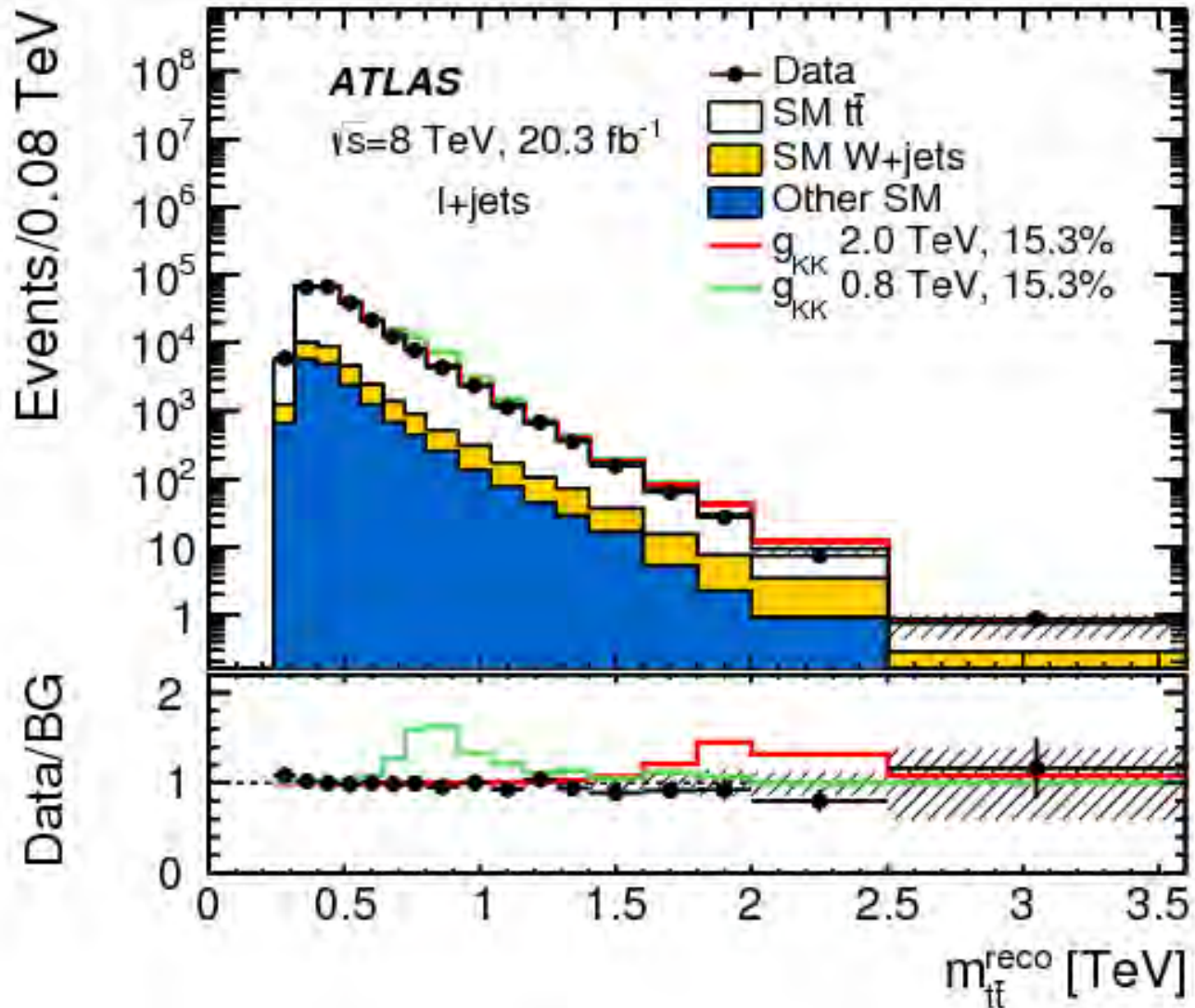
Lillie, Randall, Wang '07

⋮



also KK gravitons, top quarks, ⁴⁴W etc.

COMPETES WITH STANDARD MODEL BACKGROUNDS



EMERGENT DIMENSIONS

Warped extra dimension
is an emergent phenomenon!
Not put into fundamental Hamiltonian
"by hand", created by strong quantum
interactions

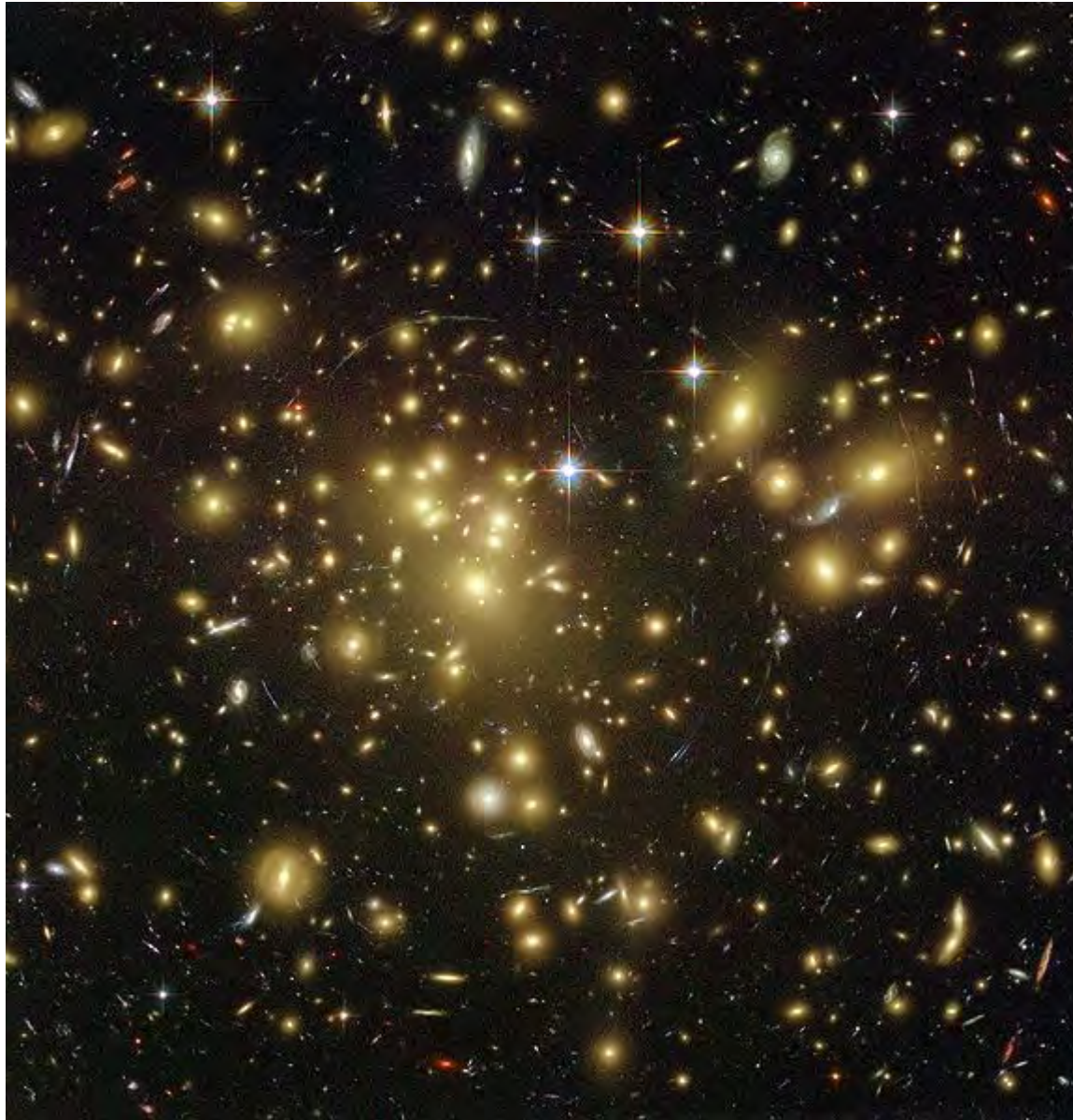
"AdS/CFT duality"

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

related to compositeness of Higgs degrees
of freedom

Weinberg '79; Susskind '79;
Georgi, Kaplan '84

WHAT IS DARK MATTER?

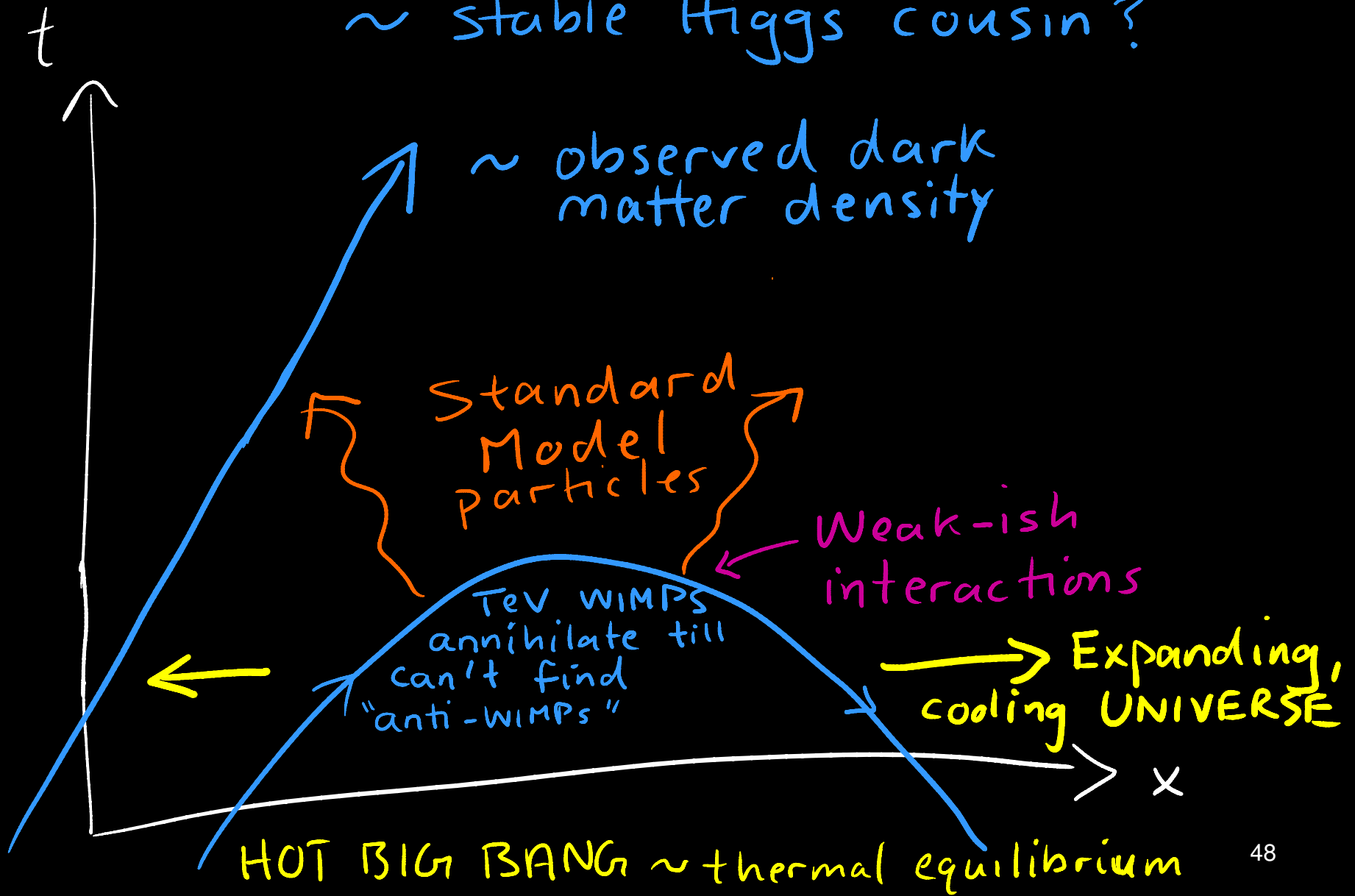


Galaxies distorted by gravitational lensing due to (otherwise) invisible Dark Matter.

Hubble Space
Telescope
Abell Cluster⁴⁷

"WIMP" DARK MATTER

~ stable Higgs cousin?



Supersymmetry (SUSY)

= " $\sqrt{-1}$ "

of Quantum Spacetime

Gervais, Sakita '71;
Golfand, Likhthman '71;
Volkov, Akulov '72;
Ramond, Schwartz, Neveu '71; Wess, Zumino '74

SUSY CARTOON

$$i\partial_t \equiv H = Q^2$$

↑ "supercharge"
operator

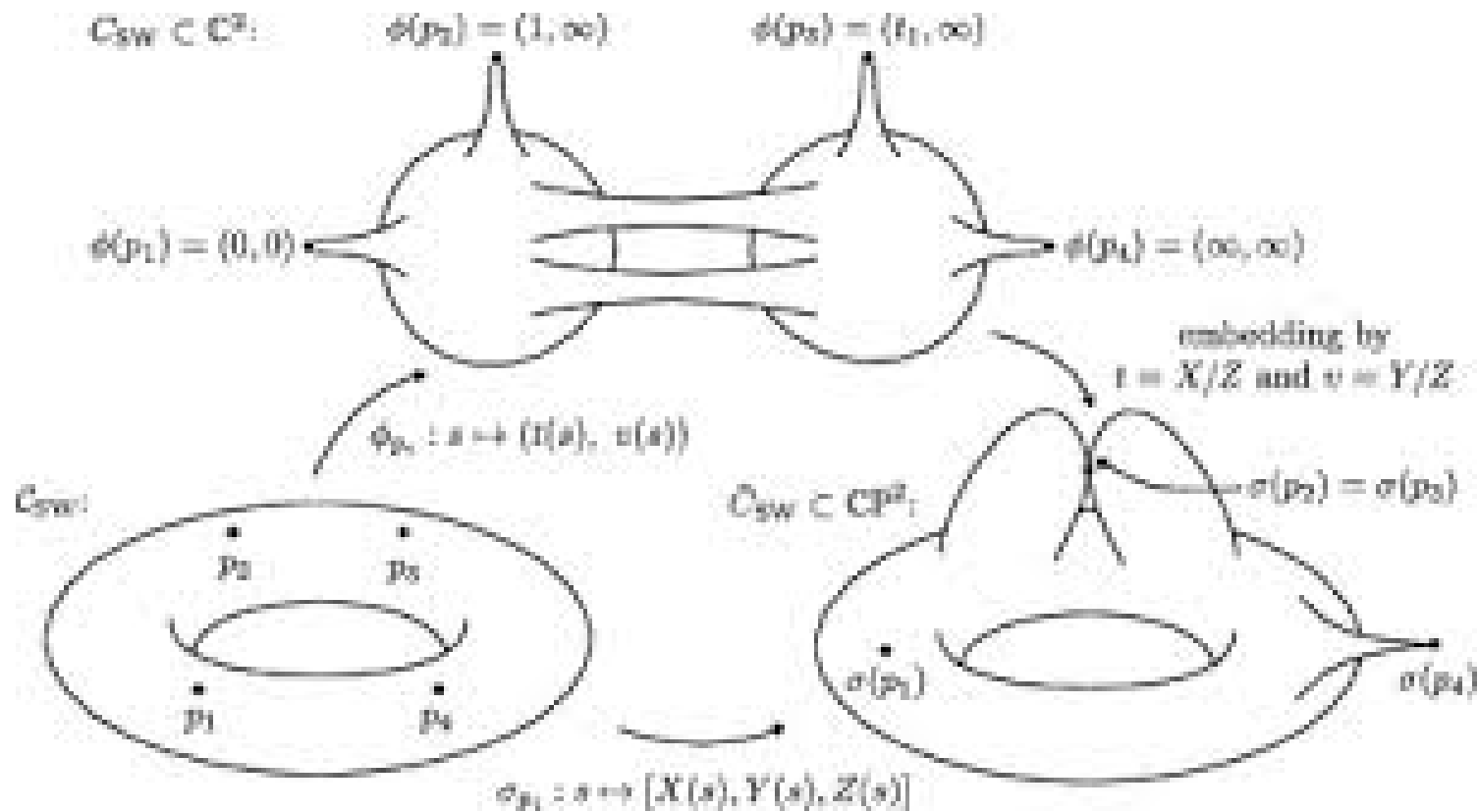
$$Q | \text{boson} \rangle = | \text{fermion} \rangle$$

$$Q | \text{fermion} \rangle = | \text{boson} \rangle$$

$$Q | \text{vacuum} \rangle = 0$$

Many quantum corrections to vacuum
(related to Hierarchy Problem) MUST cancel
by SUSY algebra. Eg. $H | \text{vacuum} \rangle = 0$
clearly.

RICH IN MATHEMATICAL BEAUTY & SUBTLETY



from Seiberg-Witten '94 theory

BOSON-FERMION SUPERPARTNERS

electron (spin- $\frac{1}{2}$)

selectron (spin-0)

photon (spin-1)

photino (spin- $\frac{1}{2}$)

top squark (spin- $\frac{1}{2}$)

top squark (spin-0)

Higgs (spin-0)

("stop")
Higgsino (spin- $\frac{1}{2}$)



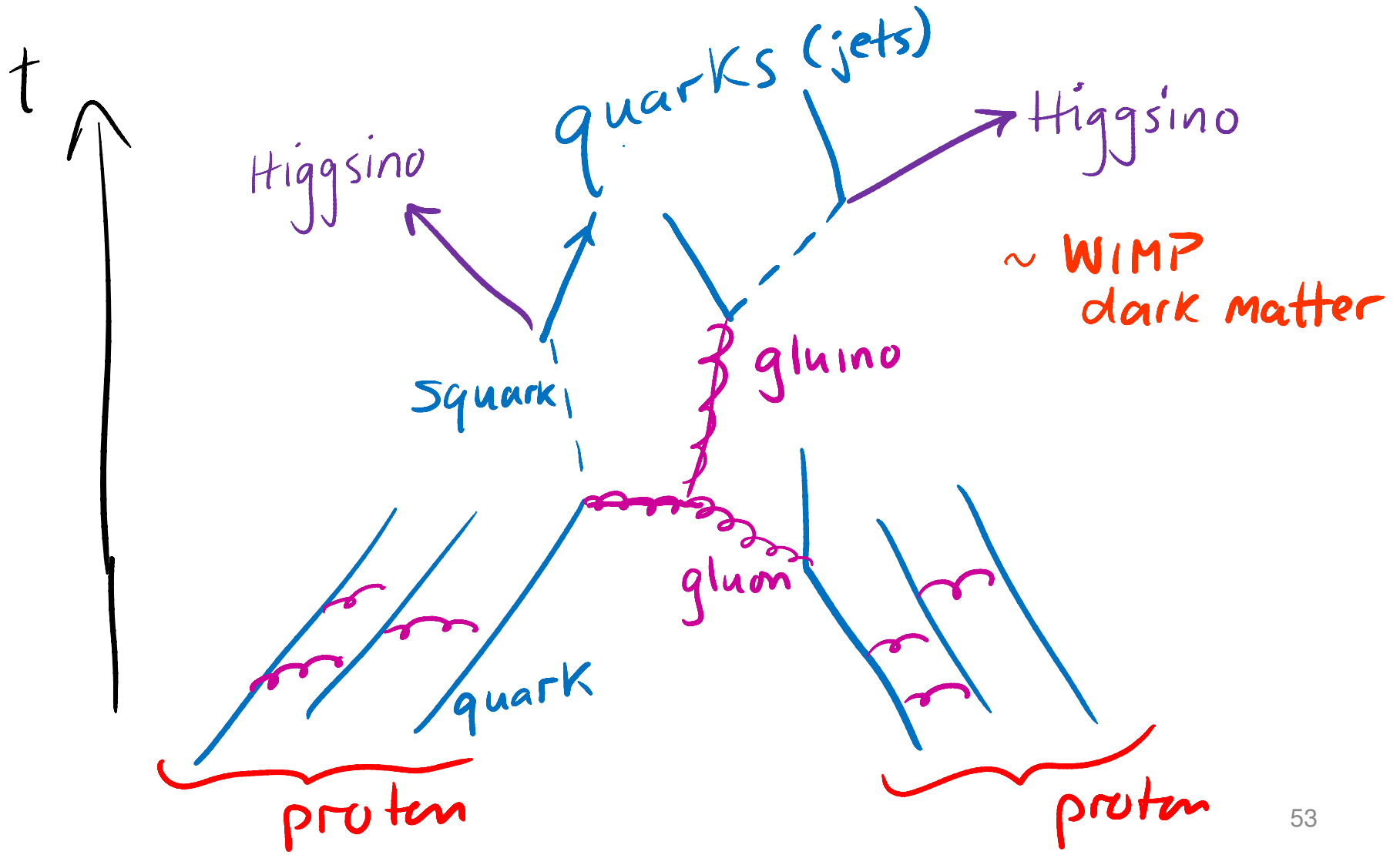
A "Mirror" in Quantum Statistics

Minimal Supersymmetric Standard

Model (MSSM) Dimopoulos, Georgi '81

But a Mirror cracked...

What LHC sought but hasn't found (so far)

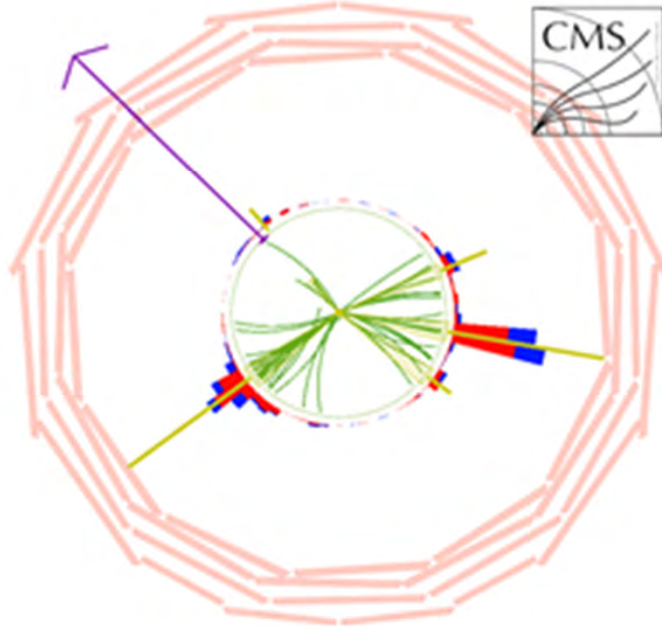


HUNTING THE INVISIBLE



Energy imbalance perpendicular to beams due to

"Higgsino" ("neutralino", generally)
readily escaping detectors



But there are
backgrounds,
famously neutrinos

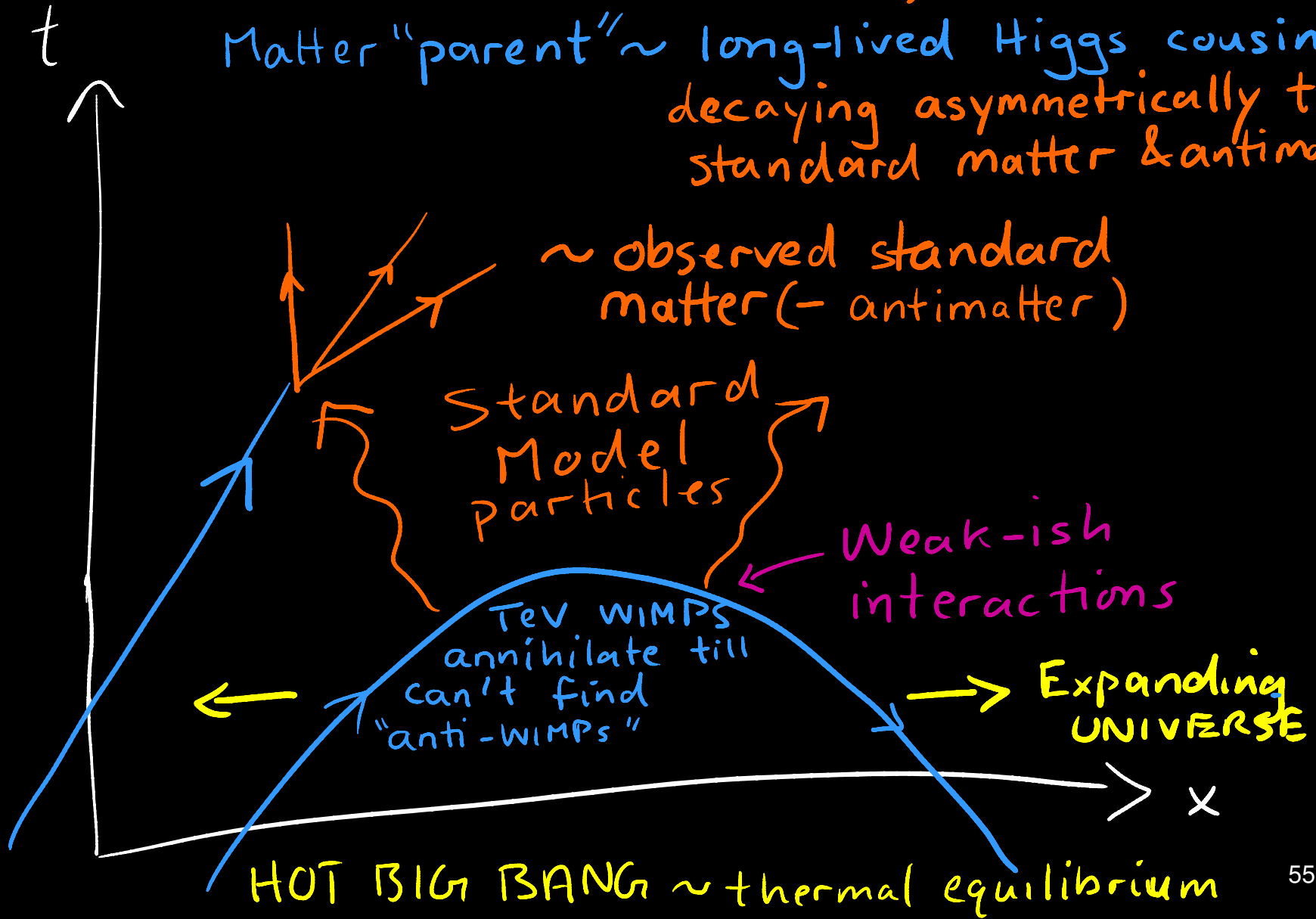
Simulated SUSY
event in CMS

Several variants of SUSY & their large
parameter spaces are being pursued

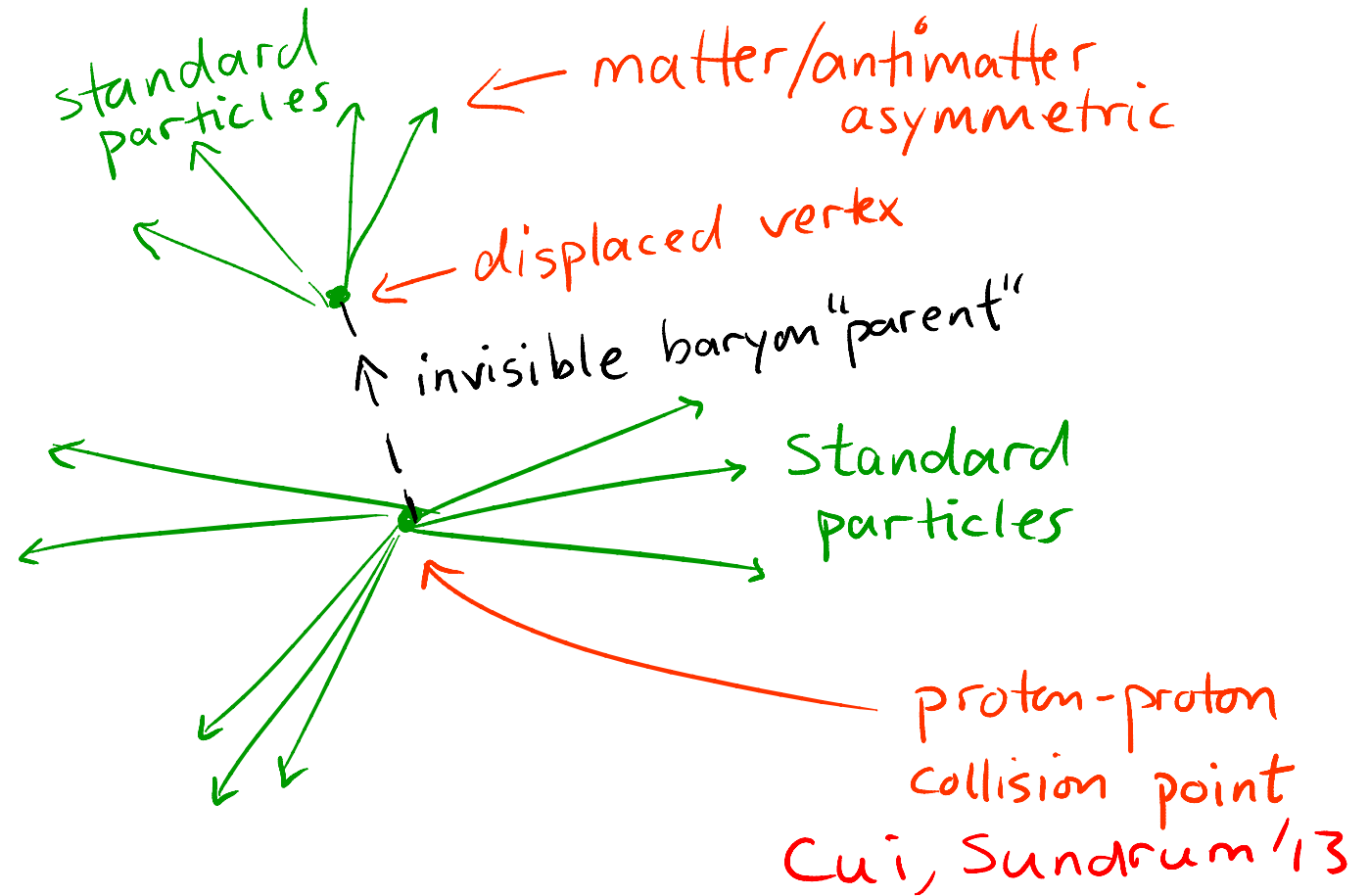
THE MATTER/ANTIMATTER ASYMMETRY FOR WIMPS

Cui, Sundrum '13

Matter "parent" \sim long-lived Higgs cousin?
decaying asymmetrically to
standard matter & antimatter



MATTER "PARENT" produced at LHC
must live long enough to decay out of equilibrium
in early Universe



⇒ DISPLACED VERTEX DECAYS
(v. low backgrounds)

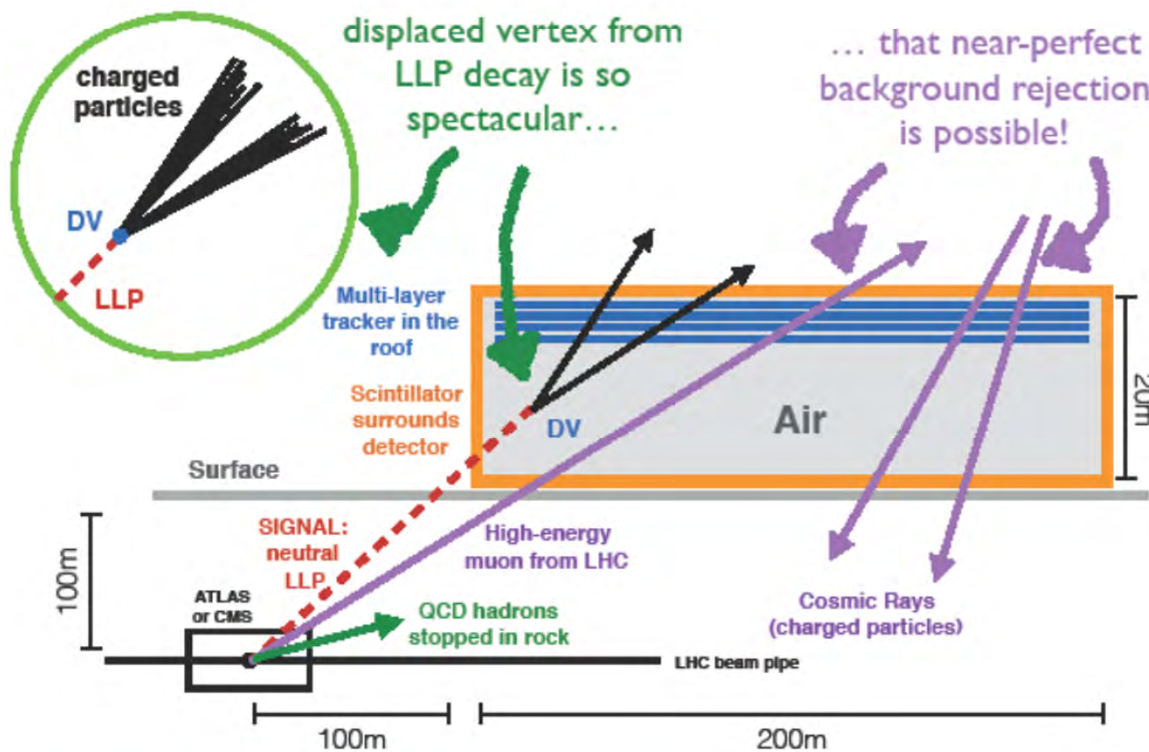
New Displaced Vertex Detector Proposal

MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti
1606.06298



MAssive Timing Hodoscope for Ultra-Stable Neutral PArticles



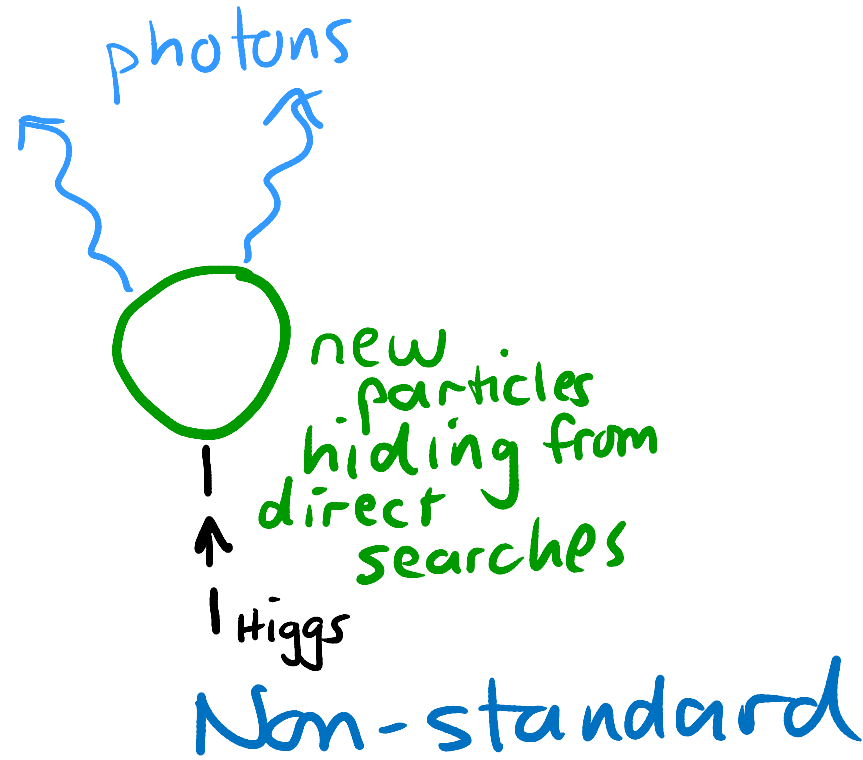
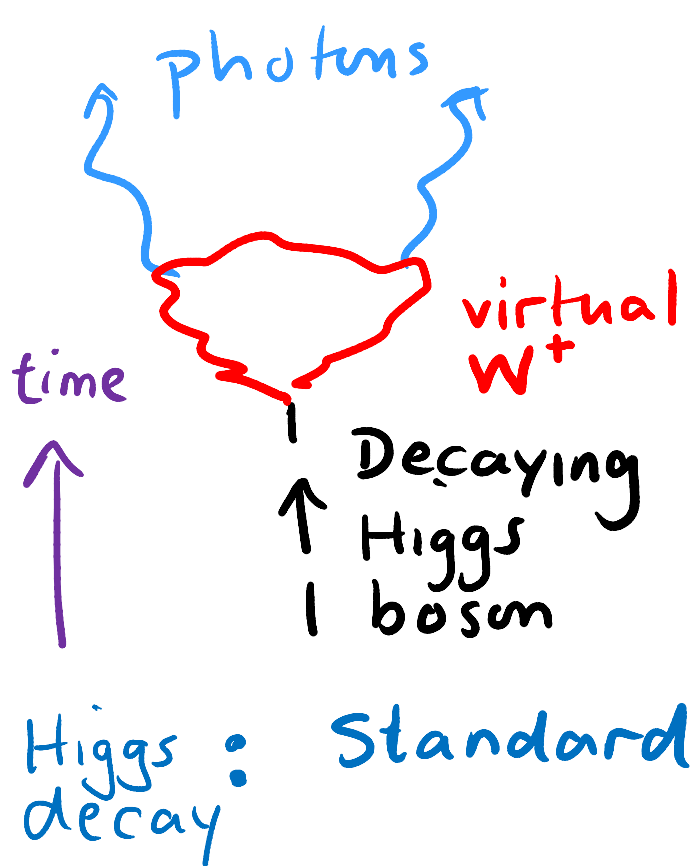
On schedule for

prototype
mid 2017
letter of intent
end 2017

theory
white paper
mid 2017

Figure Credit: Curtin, Sundrum, submitted to Physics Today

PRECISION HIGGS PHYSICS is underway



LHC is very powerful
& may make dramatic discoveries,
perhaps requiring considerable ingenuity.
But unable to VERY DEFINITELY &
strongly test Naturalness
or very precisely test Higgs.

To do this, & to fully
understand LHC findings,

New colliders, more
powerful/precise, will be needed

On Theory side,

all roads seem to lead to

Extensions of

Relativistic Spacetime

in some form or another

& connects to a host of experiments
in Cosmology, Astrophysics, Cosmic Rays,
Dark Matter detection, ...

My sense is our journey
into Spacetime is just at

The Beginning ...