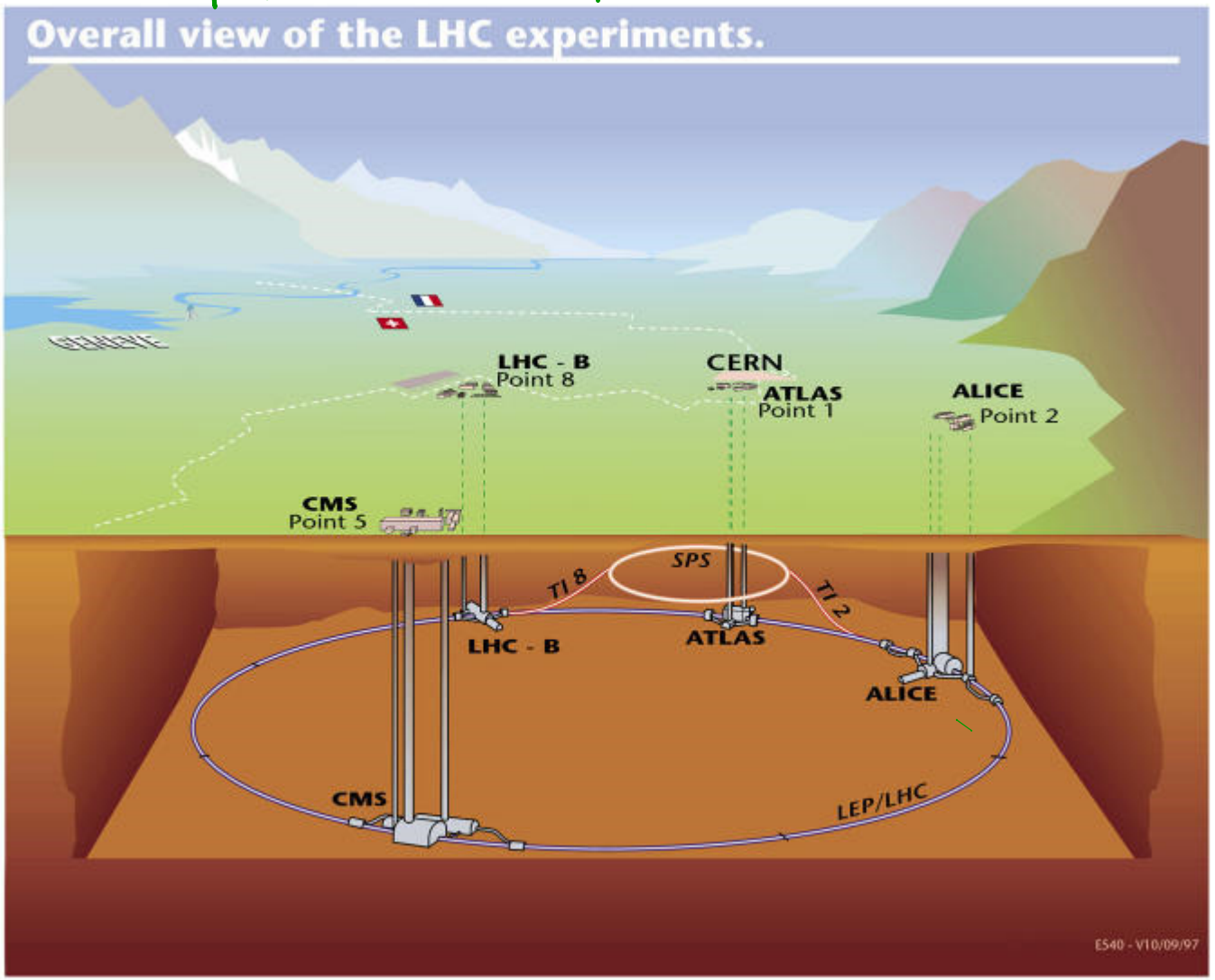
FUNDAMENTAL PHYSICS AND THE FIFTH DIMENSION

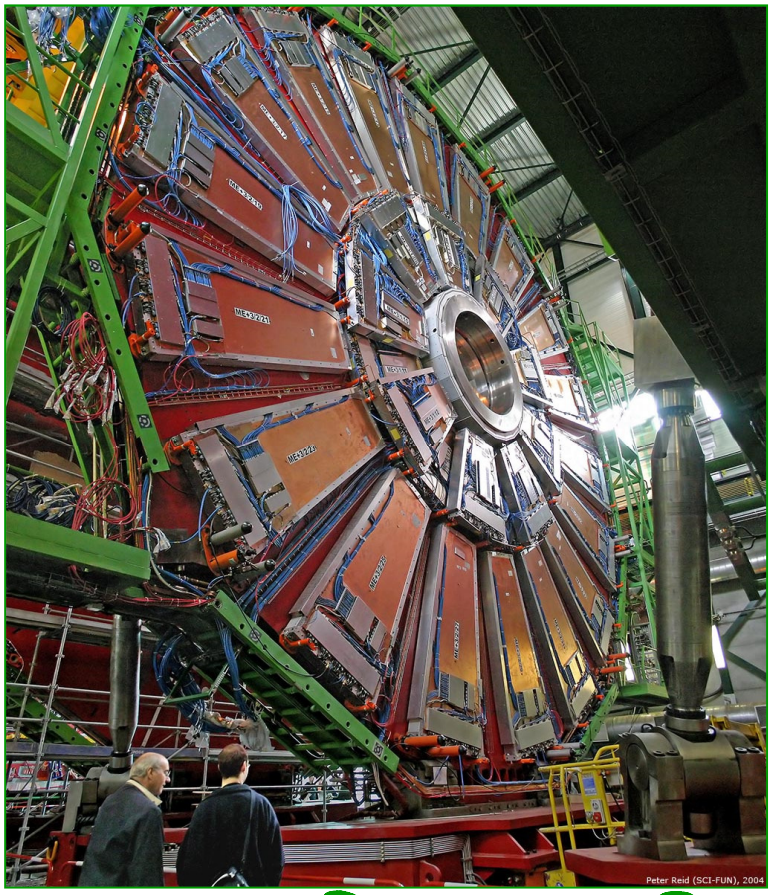
Raman Sundrum
University of Maryland

THE LHC IS A MULTI-TeV PROTON-PROTON COLLIDER



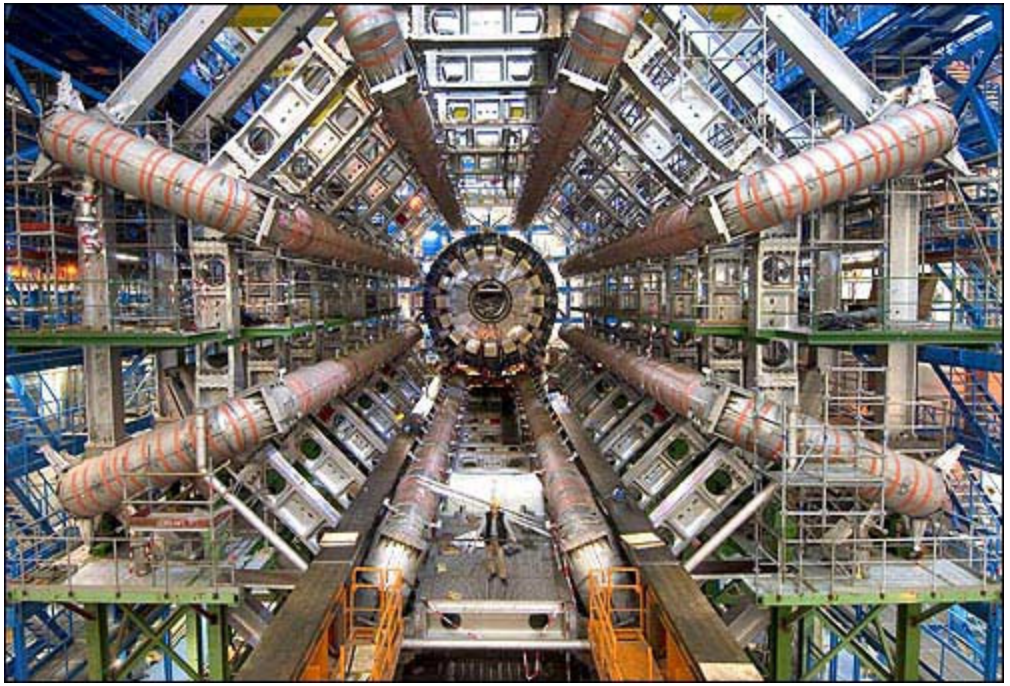
THE HAIL OF EMERGING PARTICLES SCRUTINIZED BY...

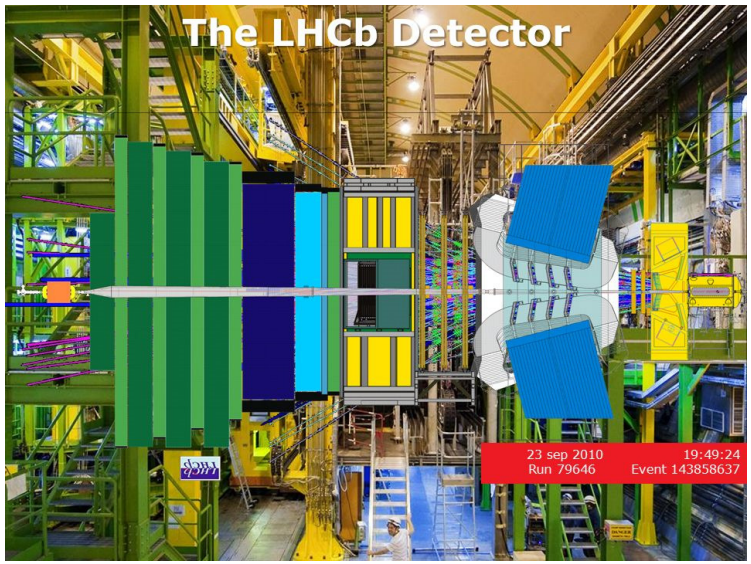
BIG, BIG EYES



CMS DETECTOR

ATLAS DETECTOR





LHCb DETECTOR

BUT

WHY?

OUTLINE

Nothing is Something too!

Unification & the Geometric Universe

The Origin of the Masses —

LHC, Higgs boson, other matters

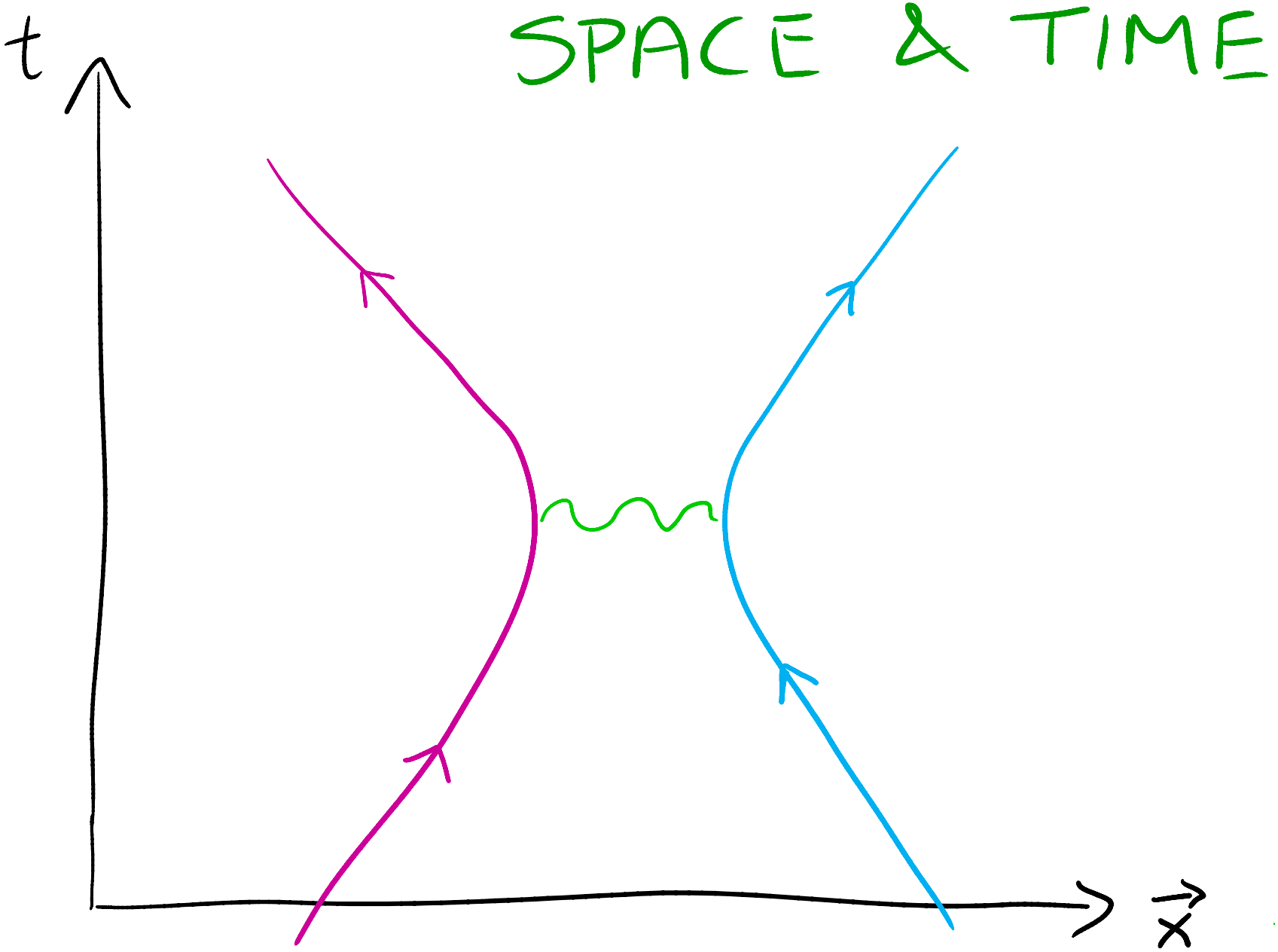
Incarnations of Spacetime —

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

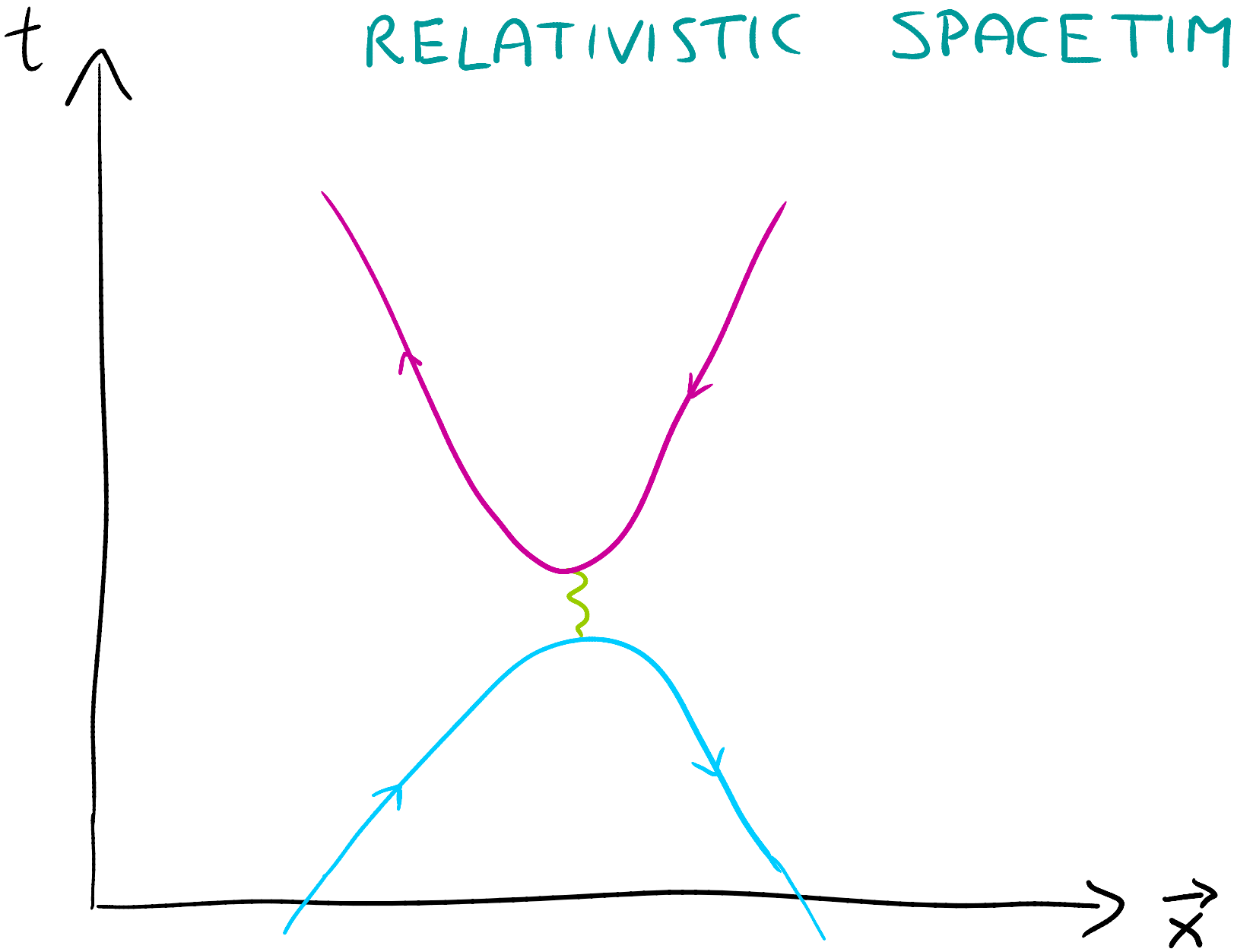
Extra-dimensional Perception —

Collider strategies

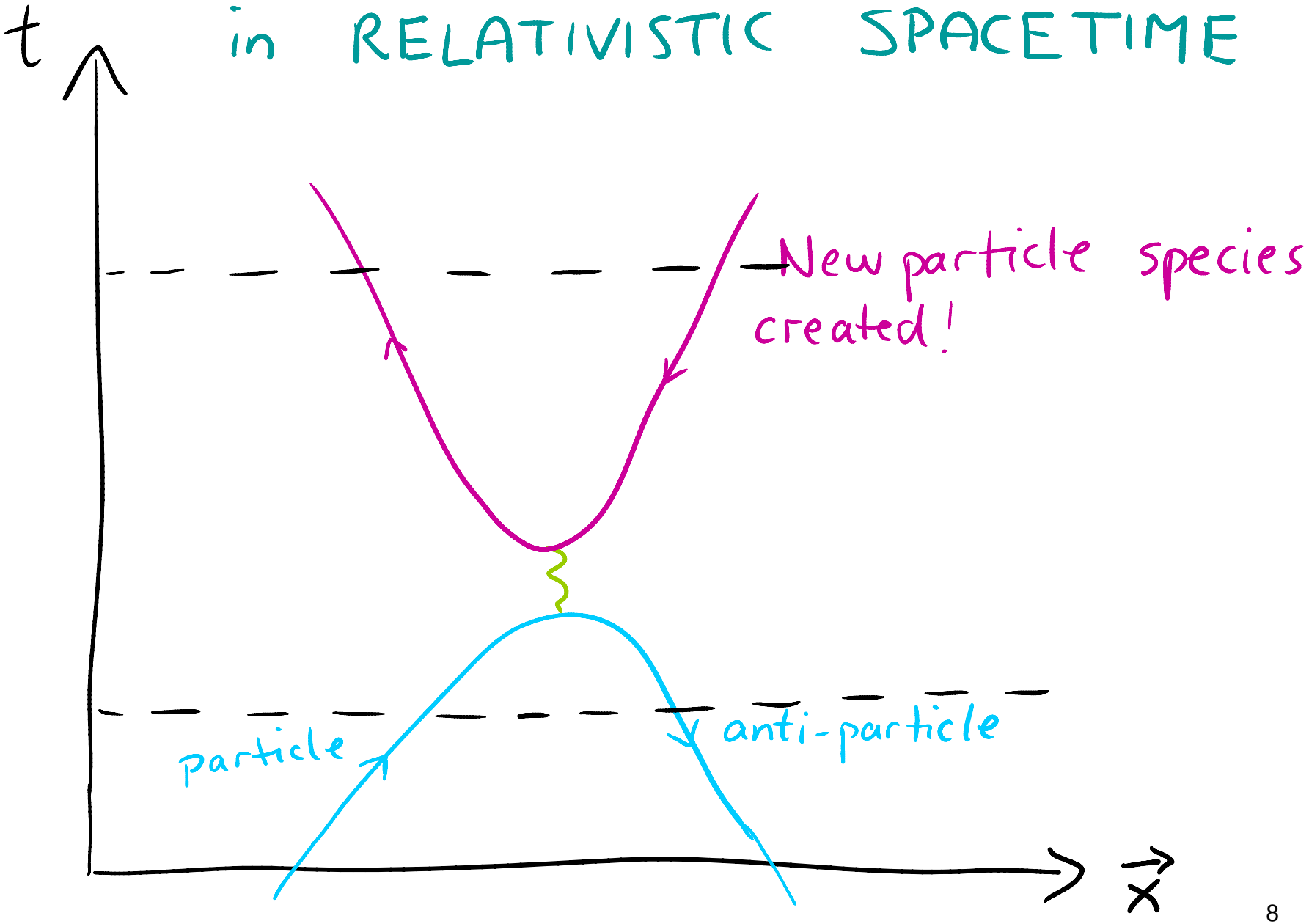
NON-RELATIVISTIC SPACE & TIME



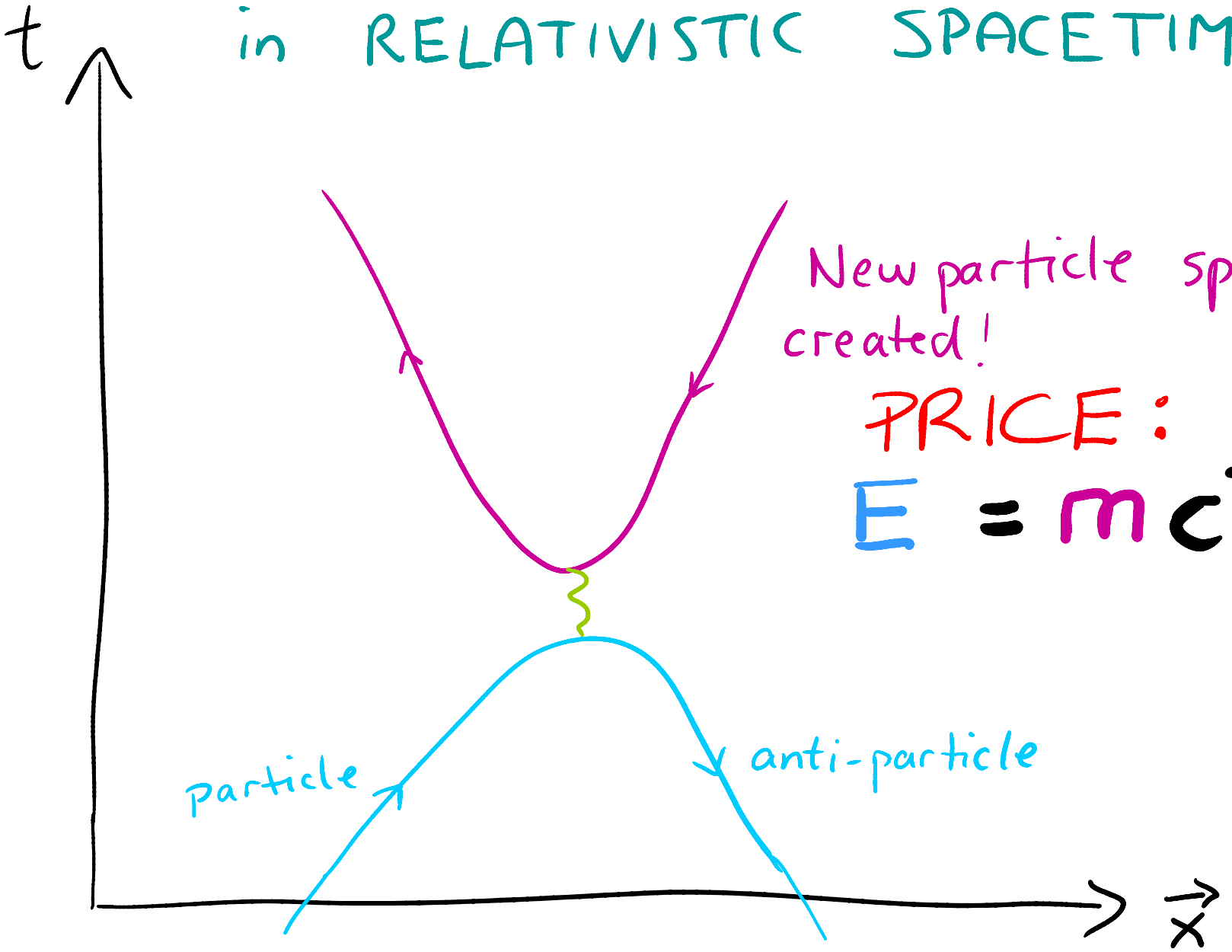
RELATIVISTIC SPACETIME



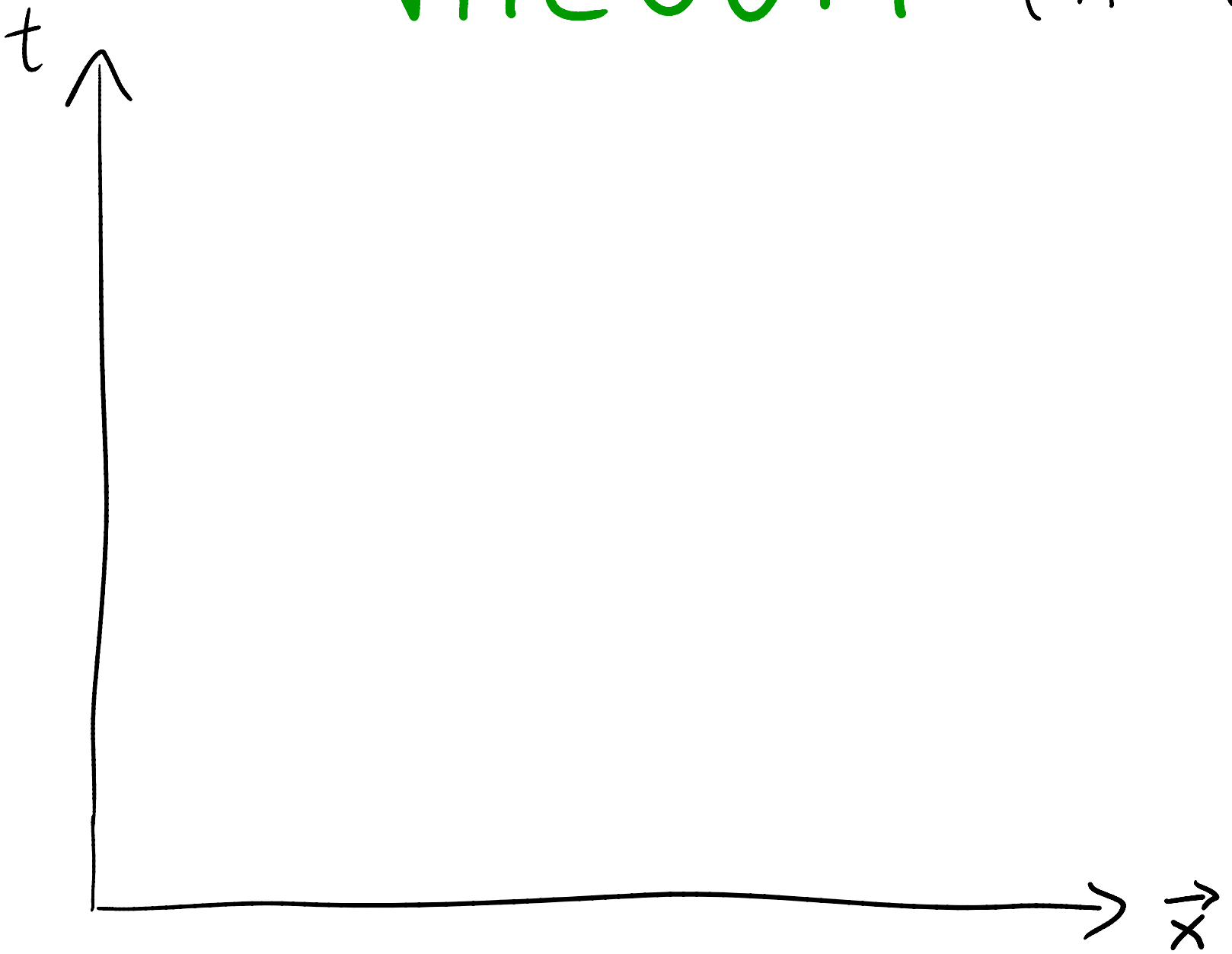
ALCHEMY in RELATIVISTIC SPACETIME



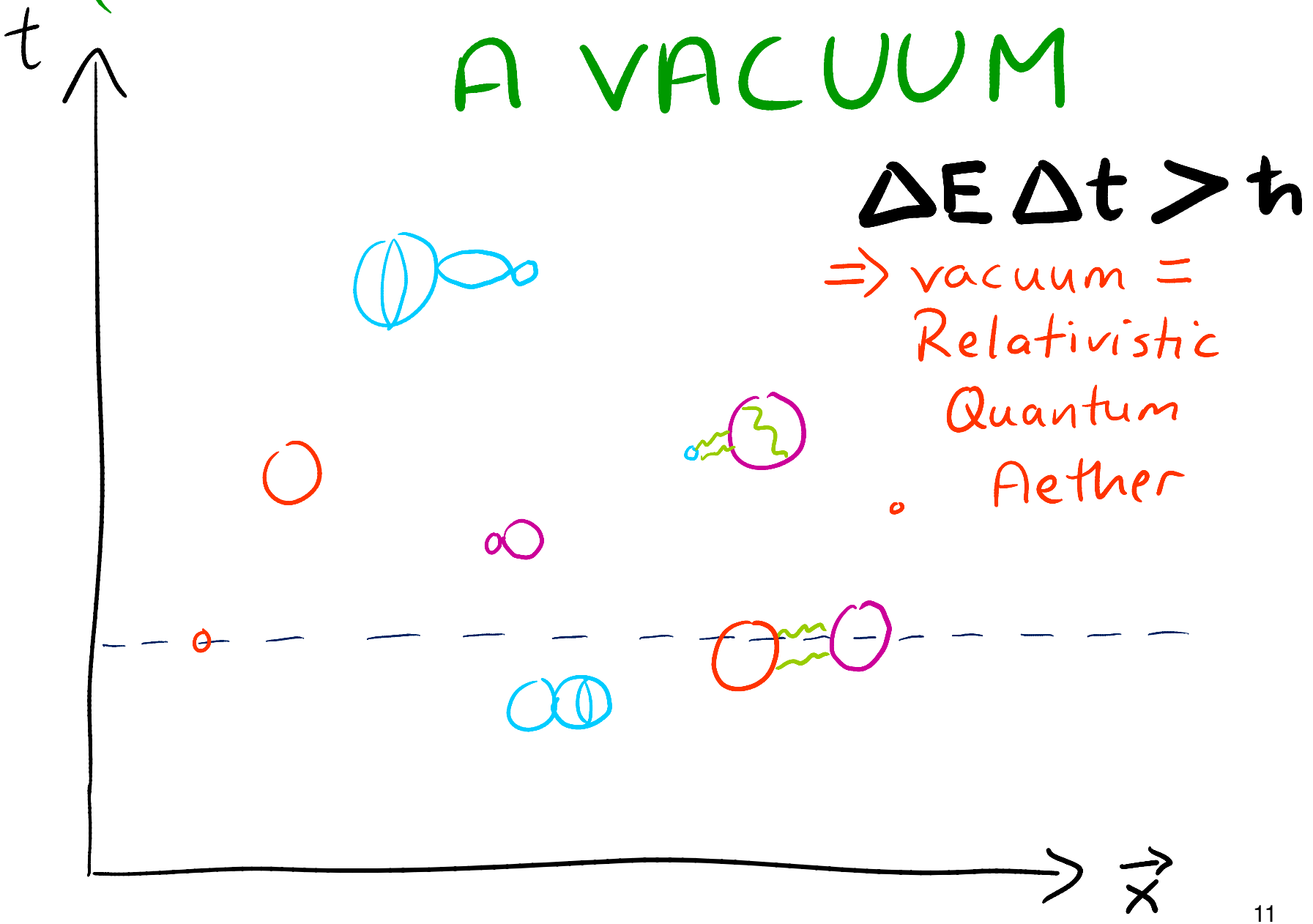
ALCHEMY
in RELATIVISTIC SPACETIME



VACUUM ($\hbar = 0$)

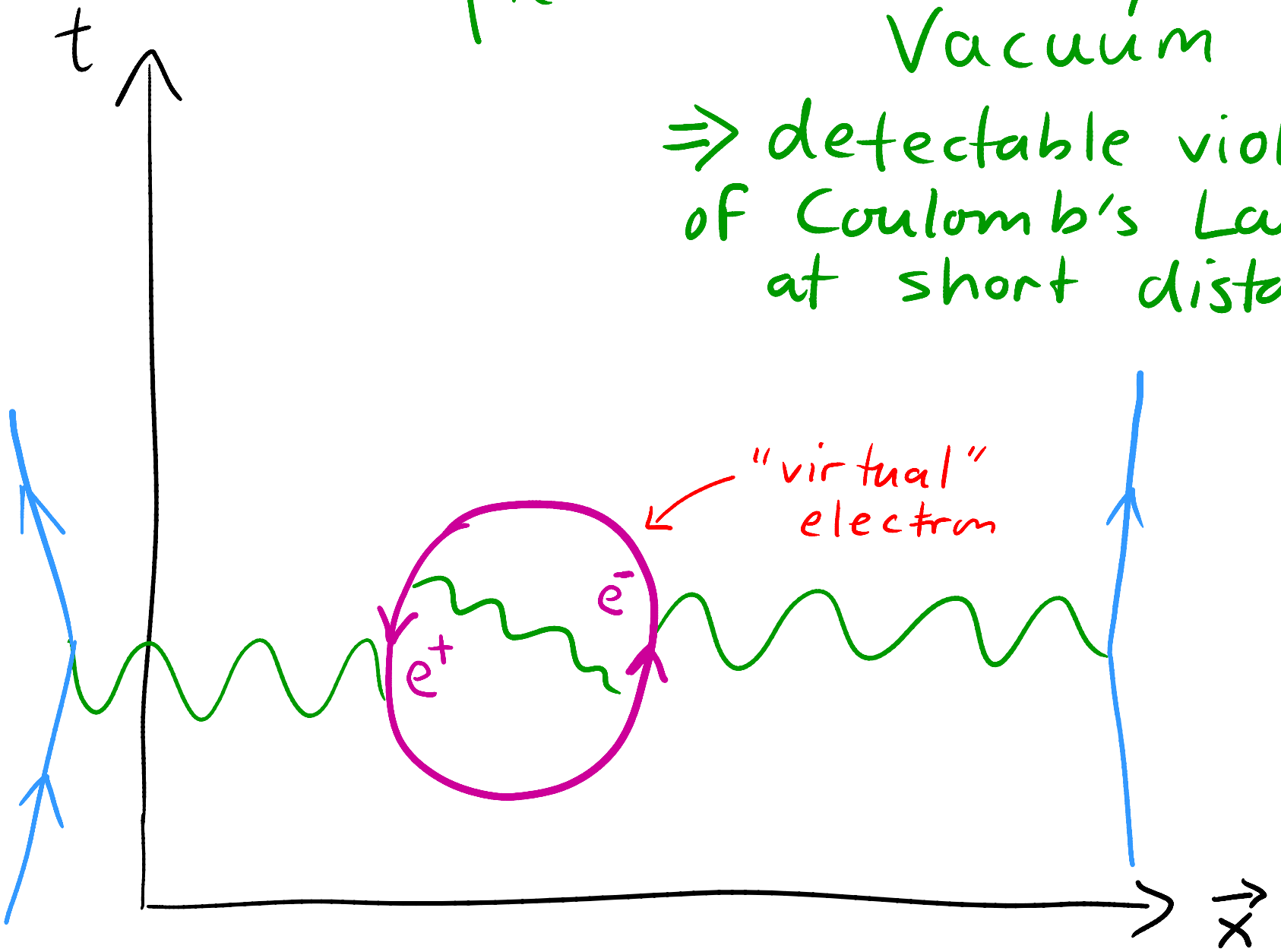


(QUANTUM) NATURE ABHORS A VACUUM



Example: Polarizability of the Vacuum

$\Rightarrow$ 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

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$W^{\pm}$

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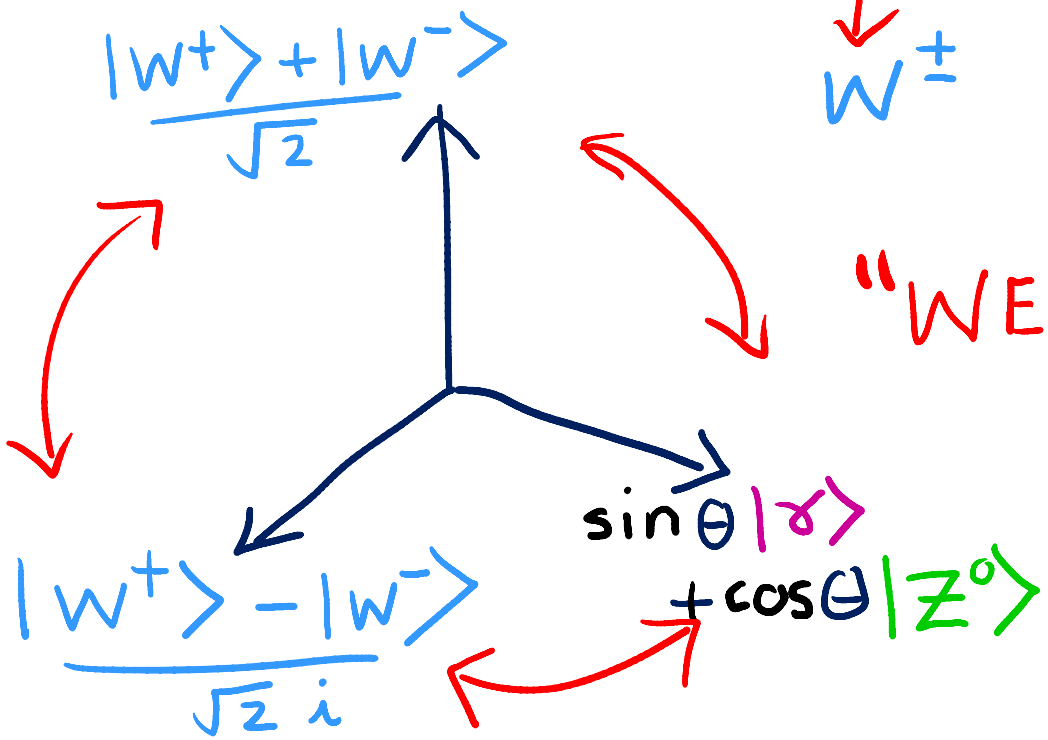
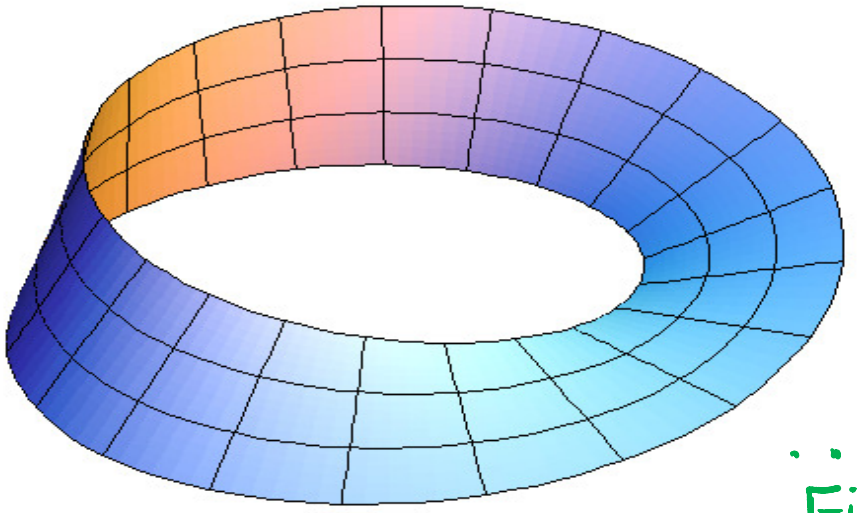


"WEAK ISOSPIN" SYMMETRY

RICH IN MATHEMATICAL BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists

$\sim$ (Quantized) Differential Geometry of FIBER BUNDLES to mathematicians



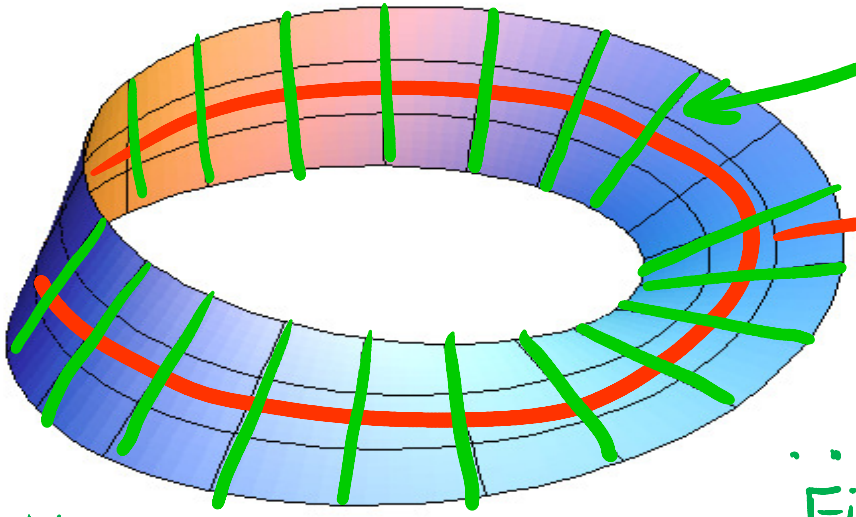
Möbius Strip ...

... as cartoon of Fiber Bundle

RICH IN MATHEMATICAL BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists

~ (Quantized) Differential Geometry of FIBER BUNDLES to mathematicians



Möbius Strip ...

... as cartoon of Fiber Bundle

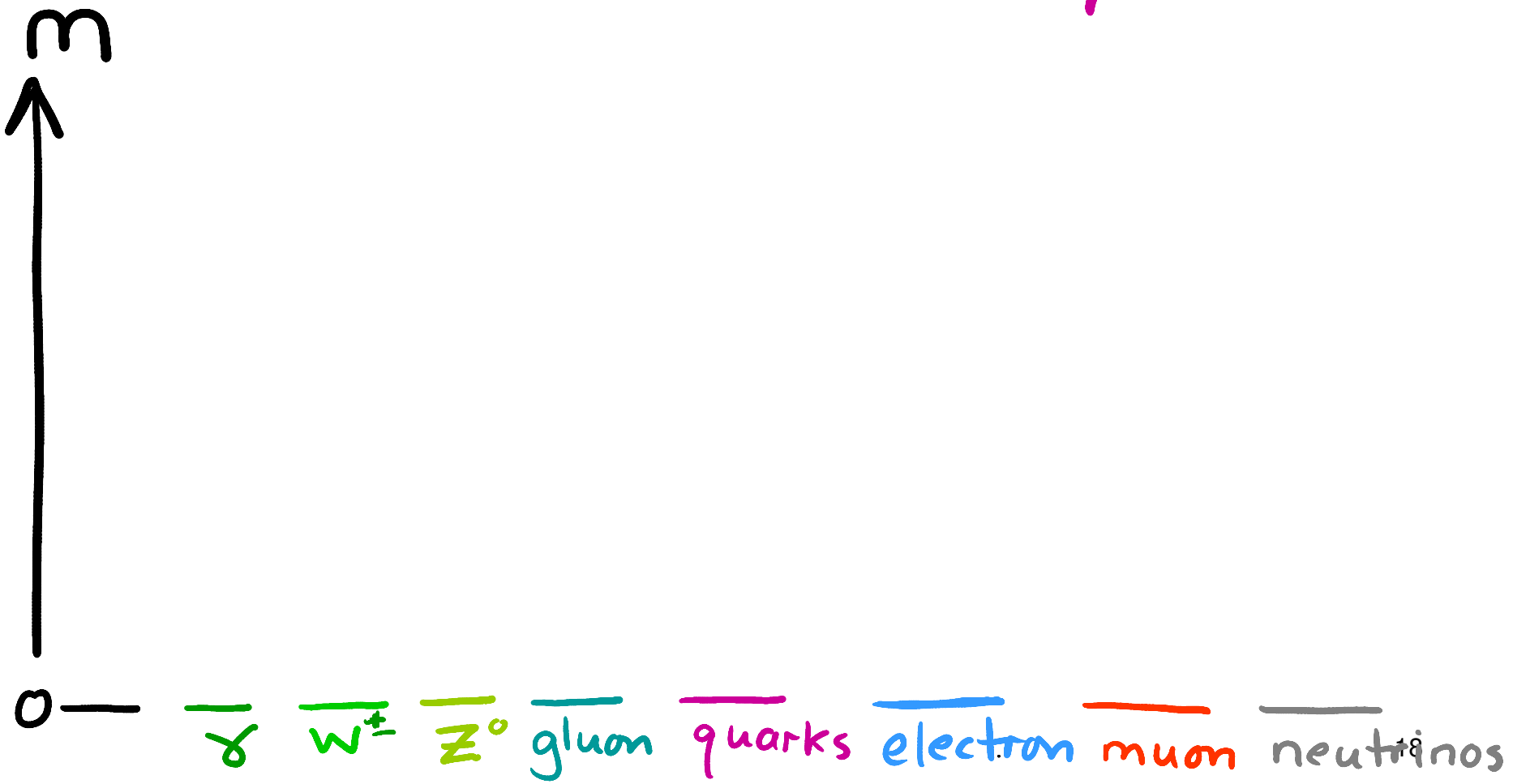
Electro Weak Unification

PREDICTS MASS SPECTRUM of all known elementary particles !

Electro Weak Unification

PREDICTS MASS SPECTRUM

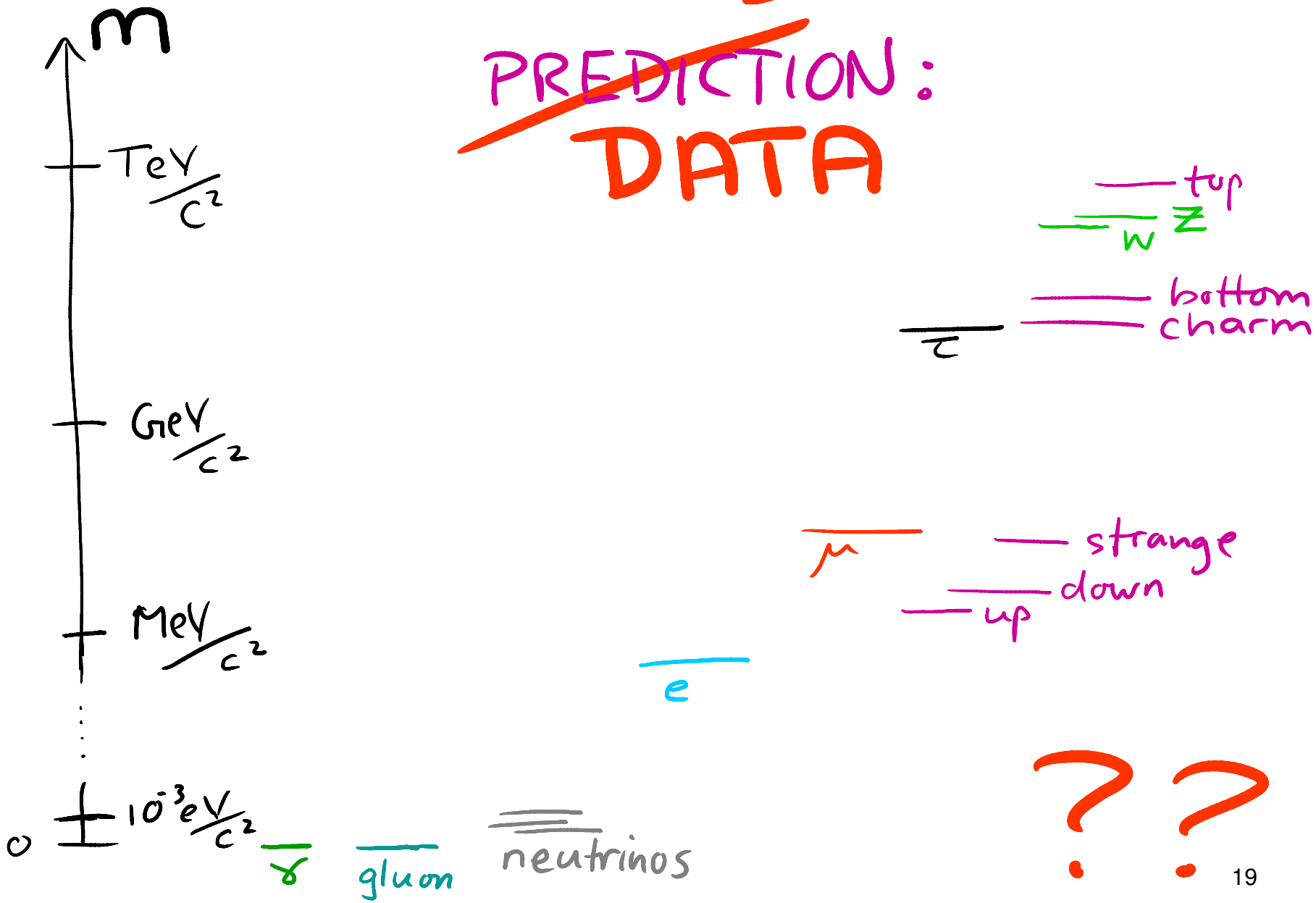
of all known elementary particles



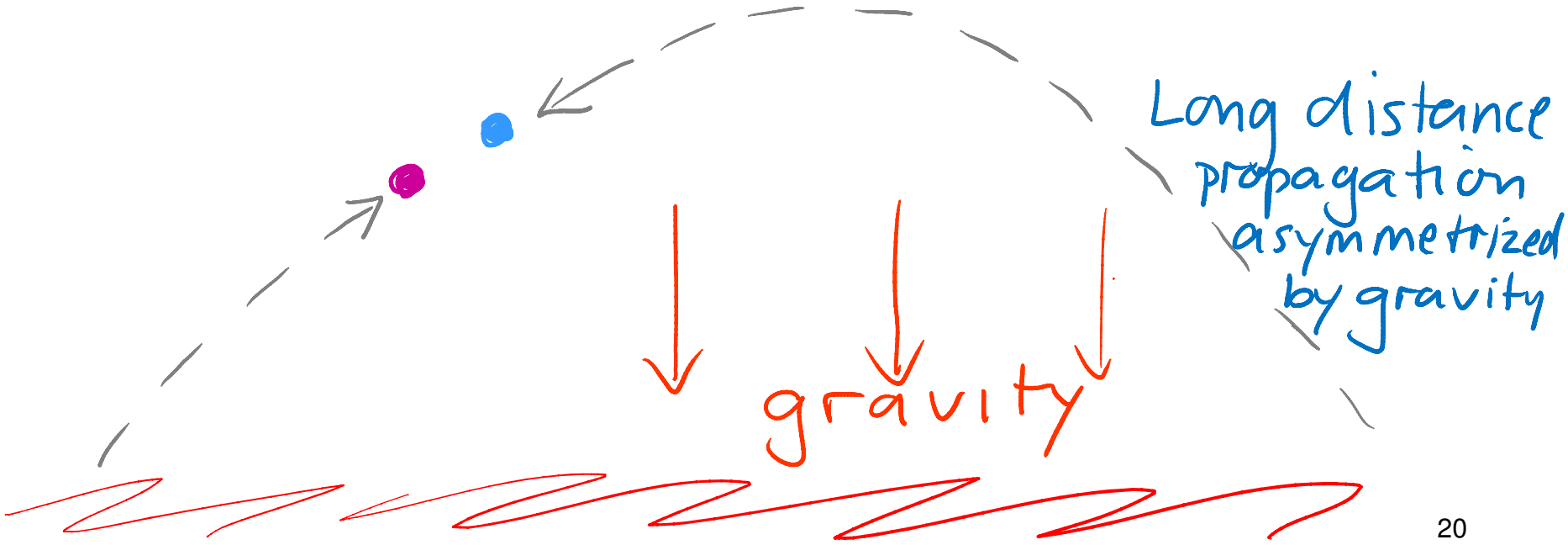
ElectroWeak Unification

PREDICTION:

DATA

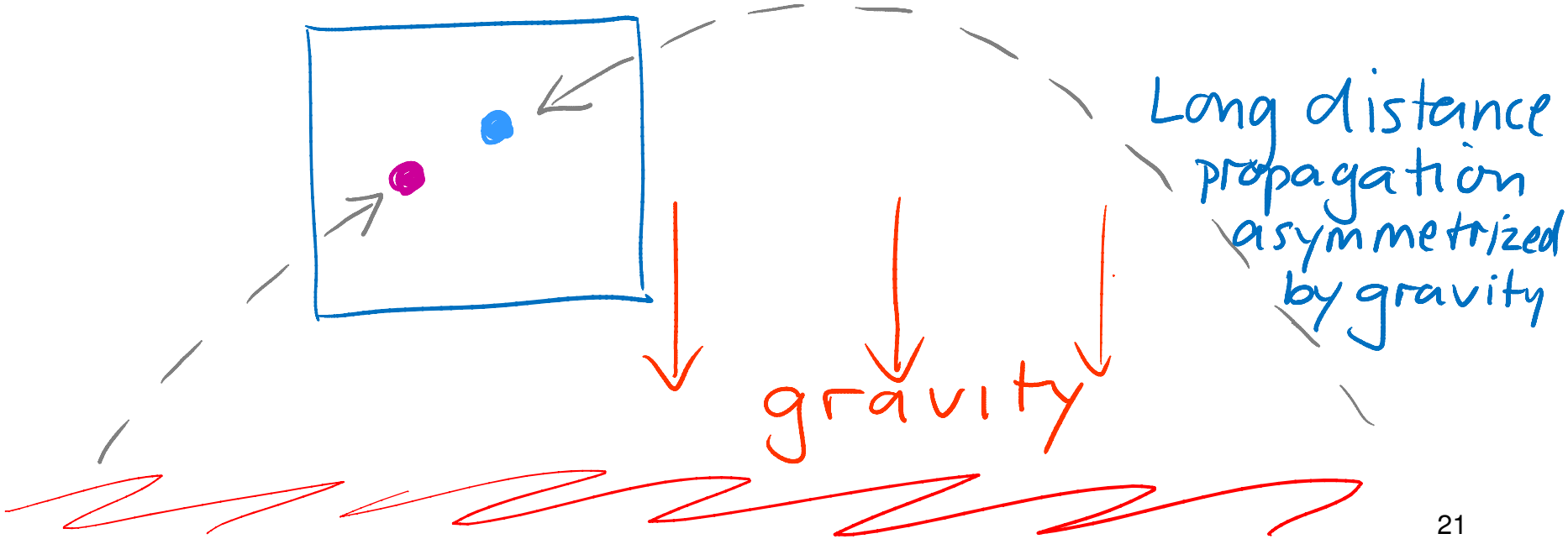


ANALOGY: Rotational ~~symmetry~~ by gravitational force field

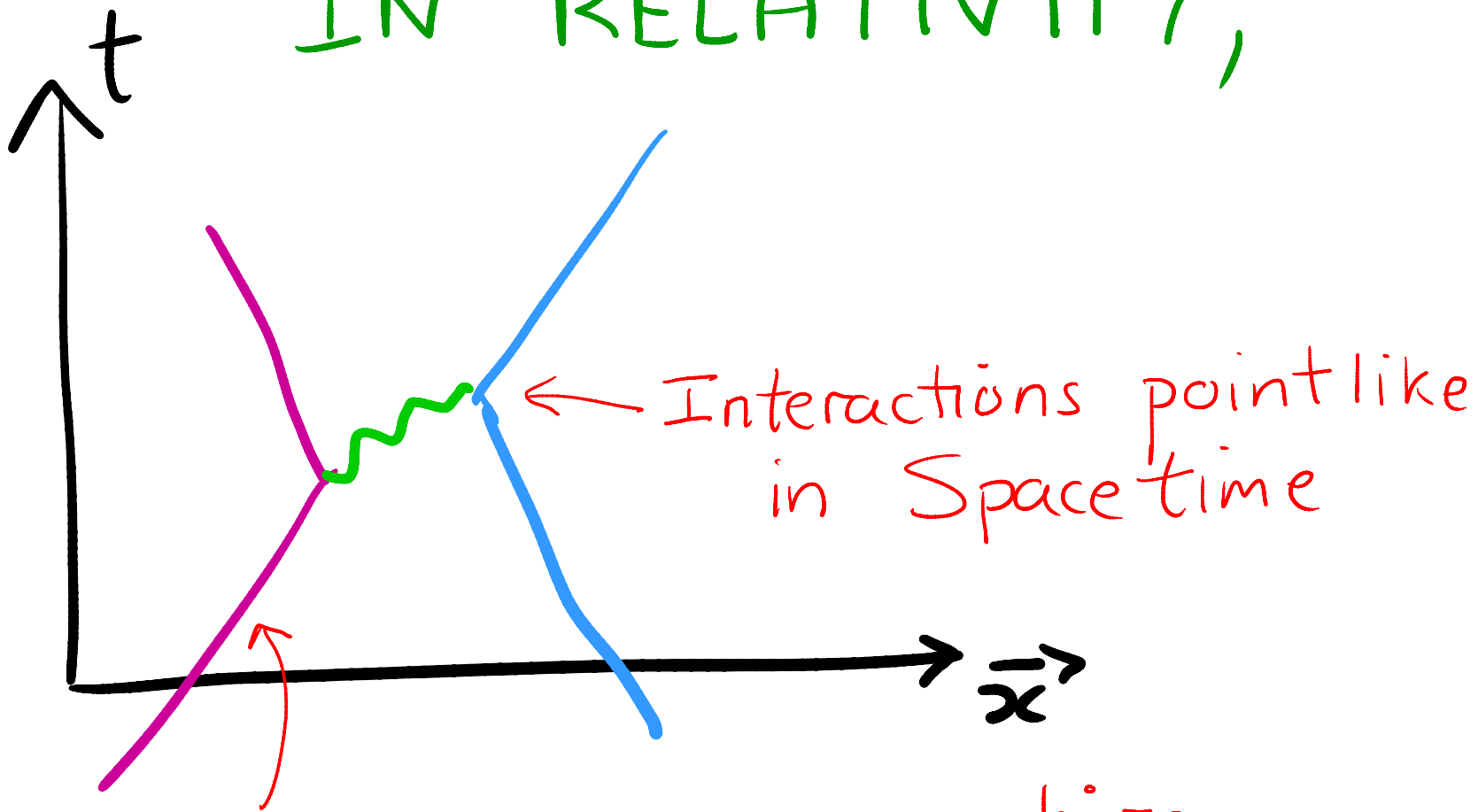


ANALOGY: Rotational ~~symmetry~~ by gravitational force field

Collisions at close quarters
≈ rotationally symmetric



IN RELATIVITY,



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

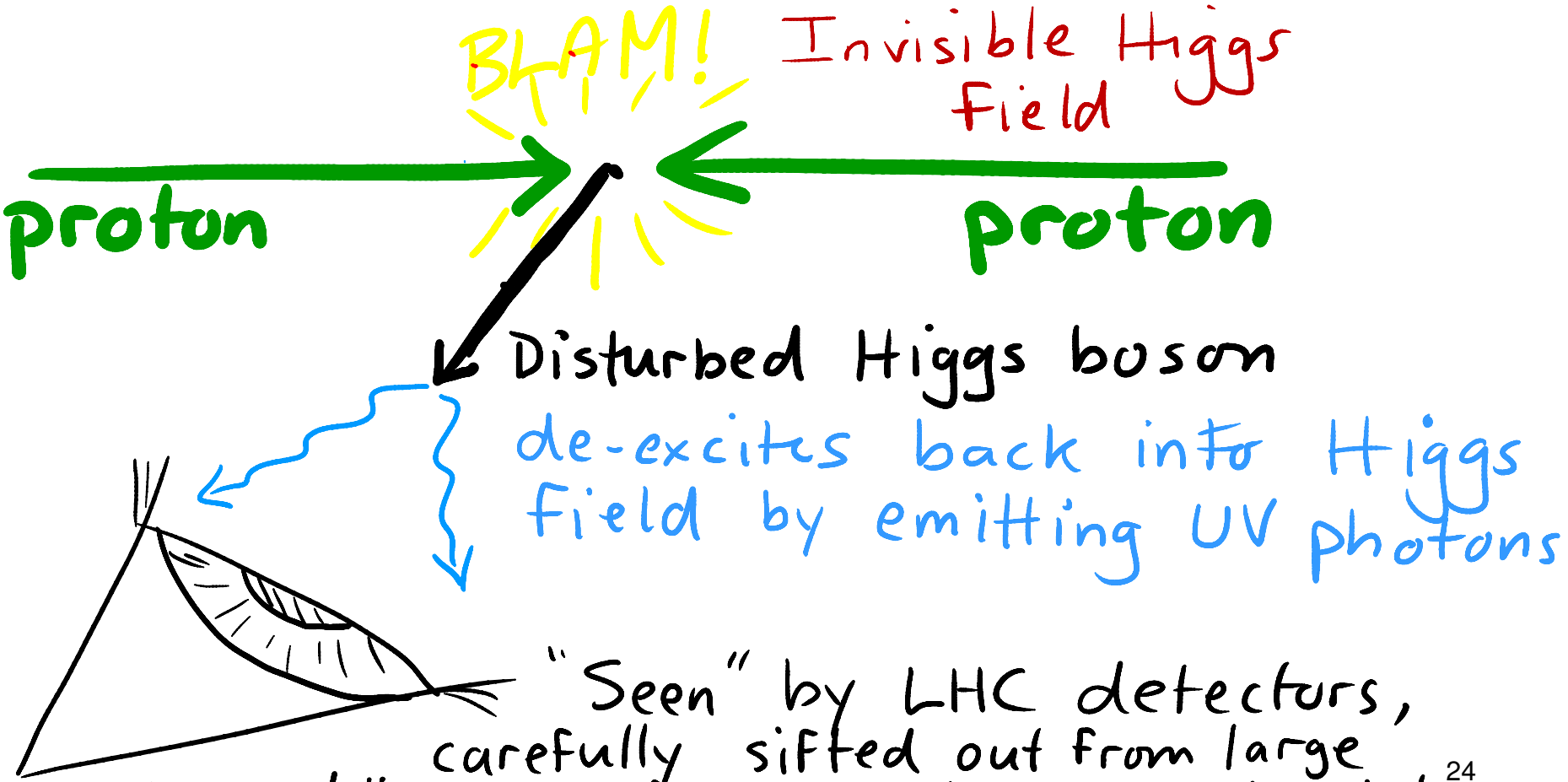
suggests ⟹ space filled by invisible, uniform scalar field "pointing" in "isospace"

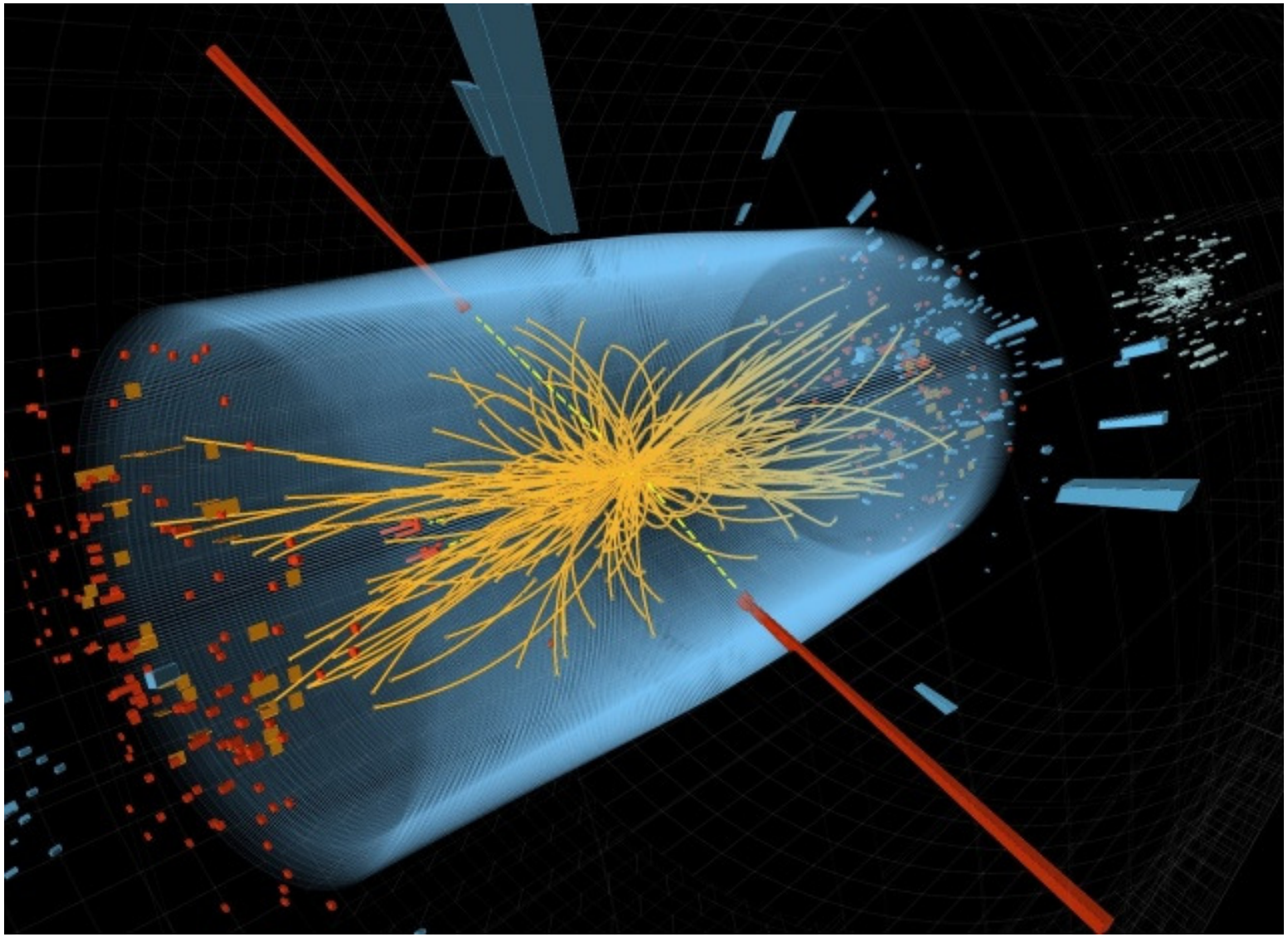
≡ Higgs field,

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!

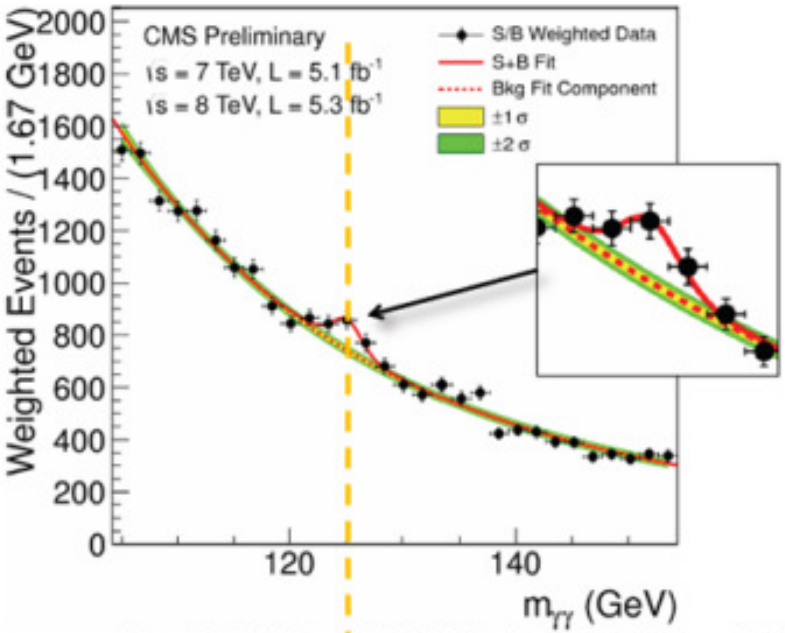


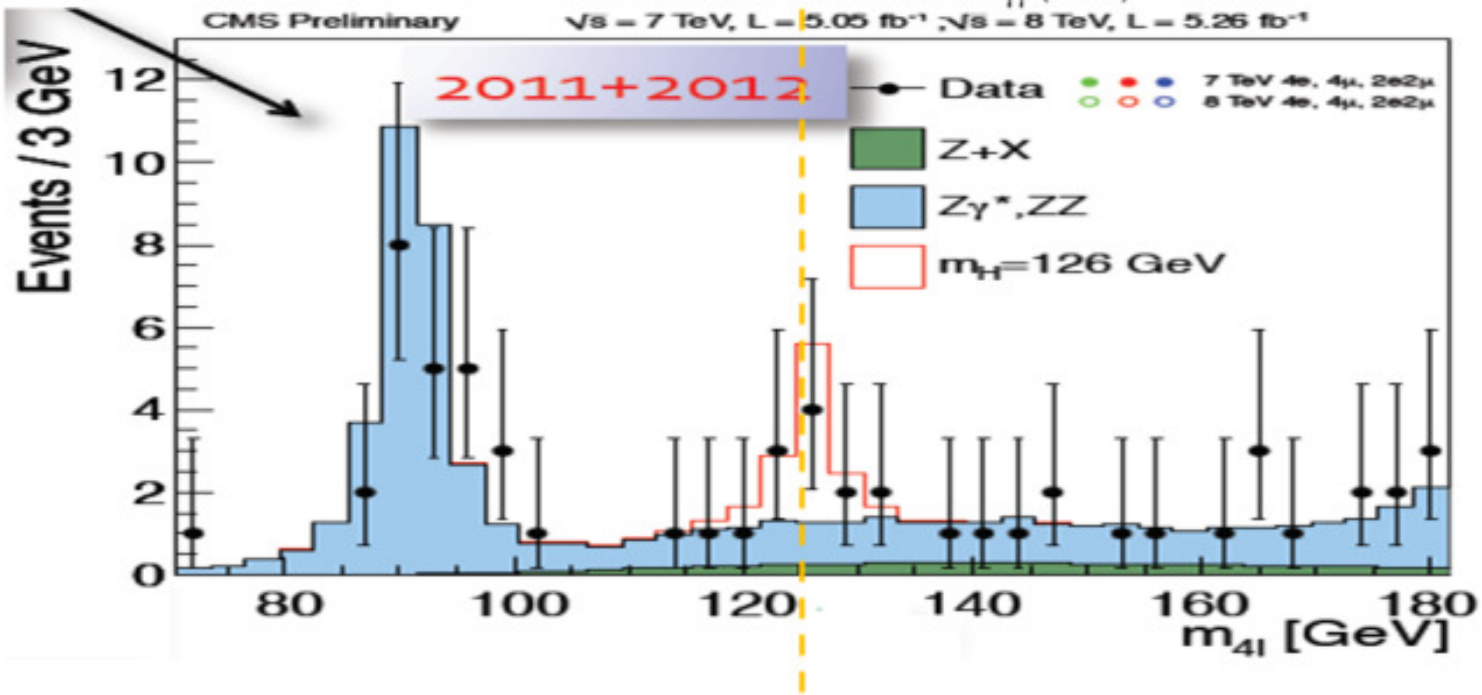


Candidate Higgs → 2 photon event in CMS detector

$m_{Higgs} = 125\ GeV$

Early LHC DATA





STANDARD MODEL NOW COMPLETE

Higgs boson discovery wins Nobel prize for theorists.

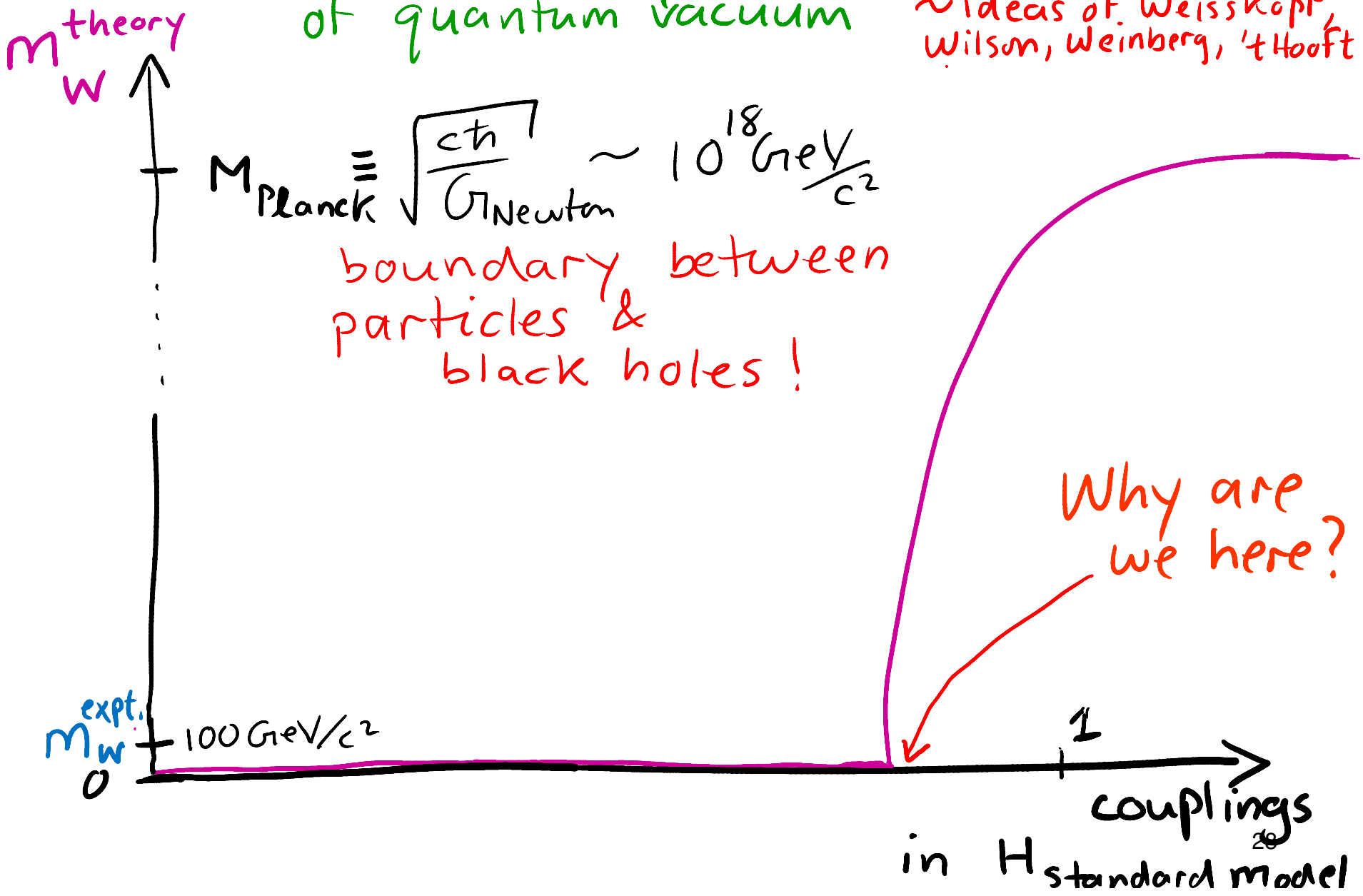
Standard Model brilliant culmination of decades of theory & experiment, deep insights into Nature.

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

HIERARCHY PROBLEM

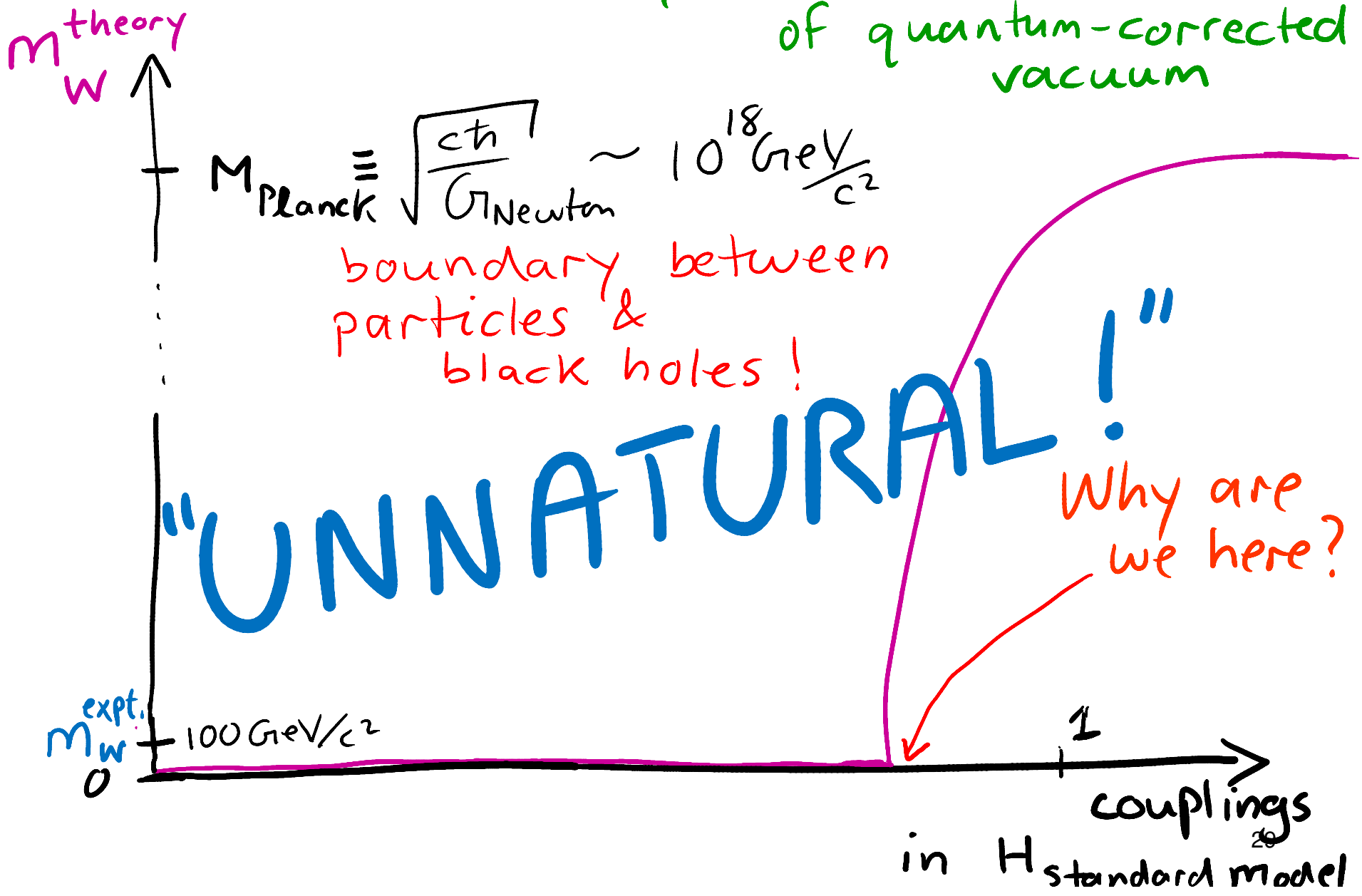
of quantum vacuum

~ideas of Weisskopf, Wilson, Weinberg, 't Hooft

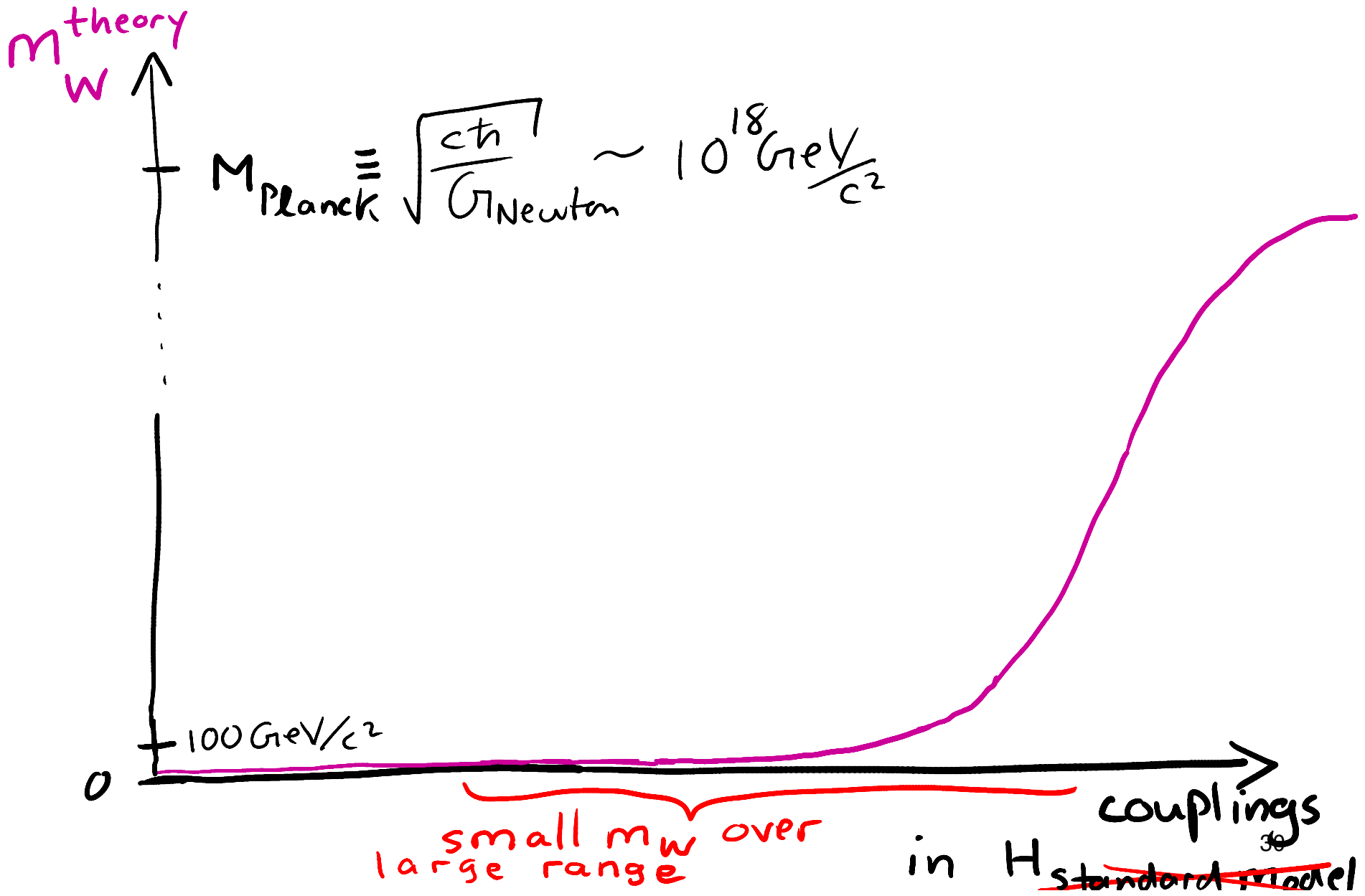


HIERARCHY PROBLEM

of quantum-corrected vacuum



A DIFFERENT VACUUM?



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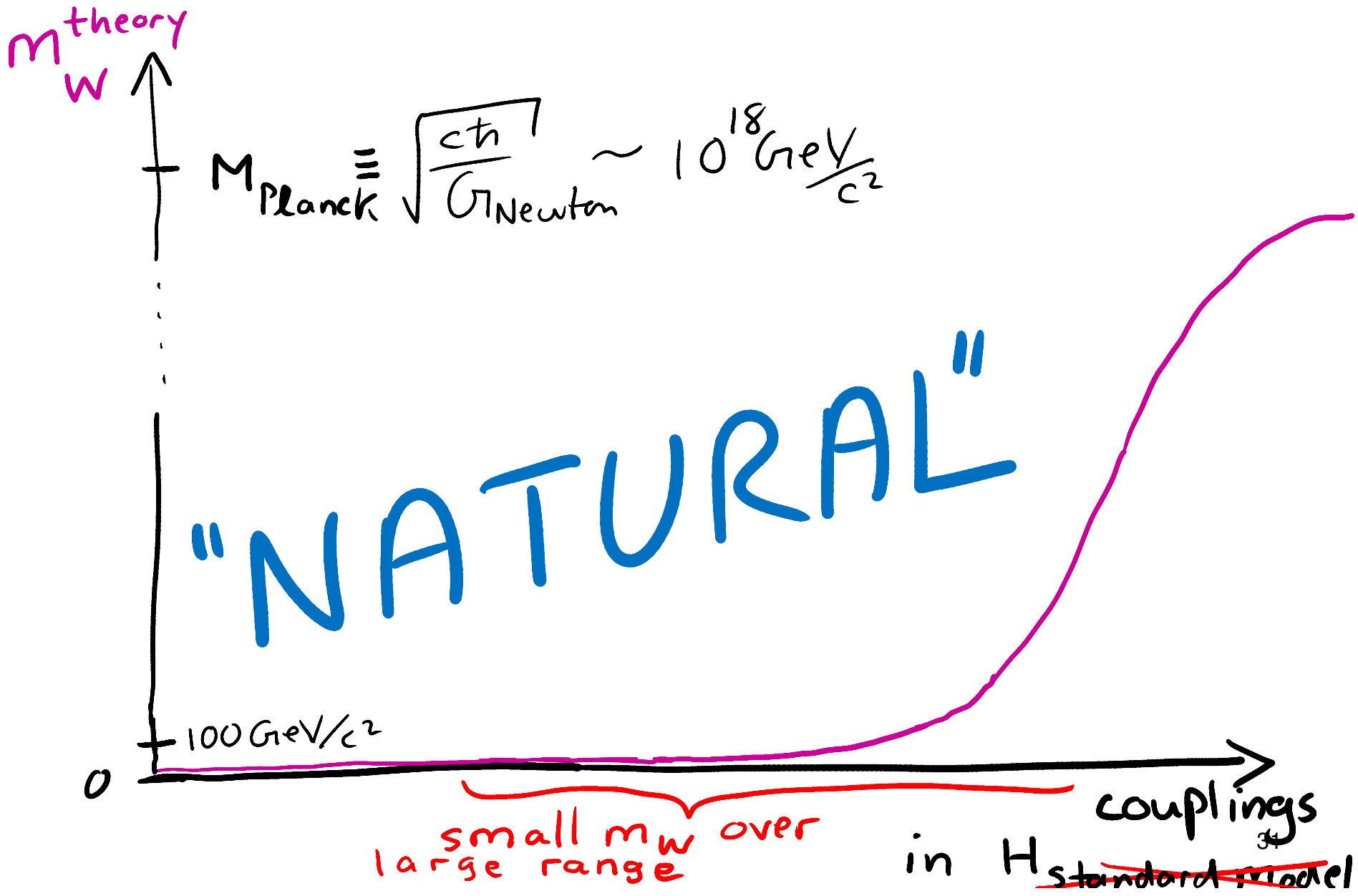
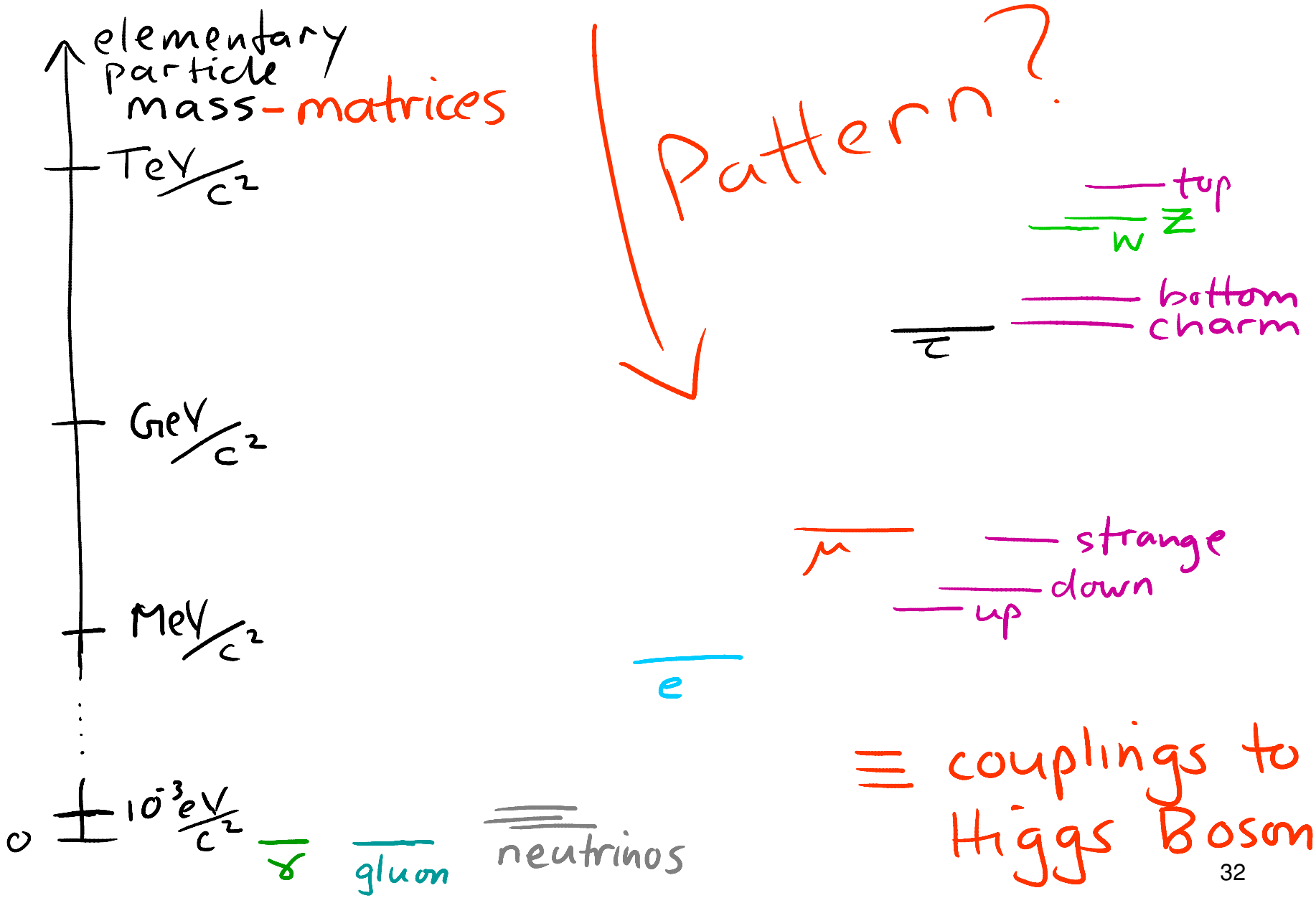
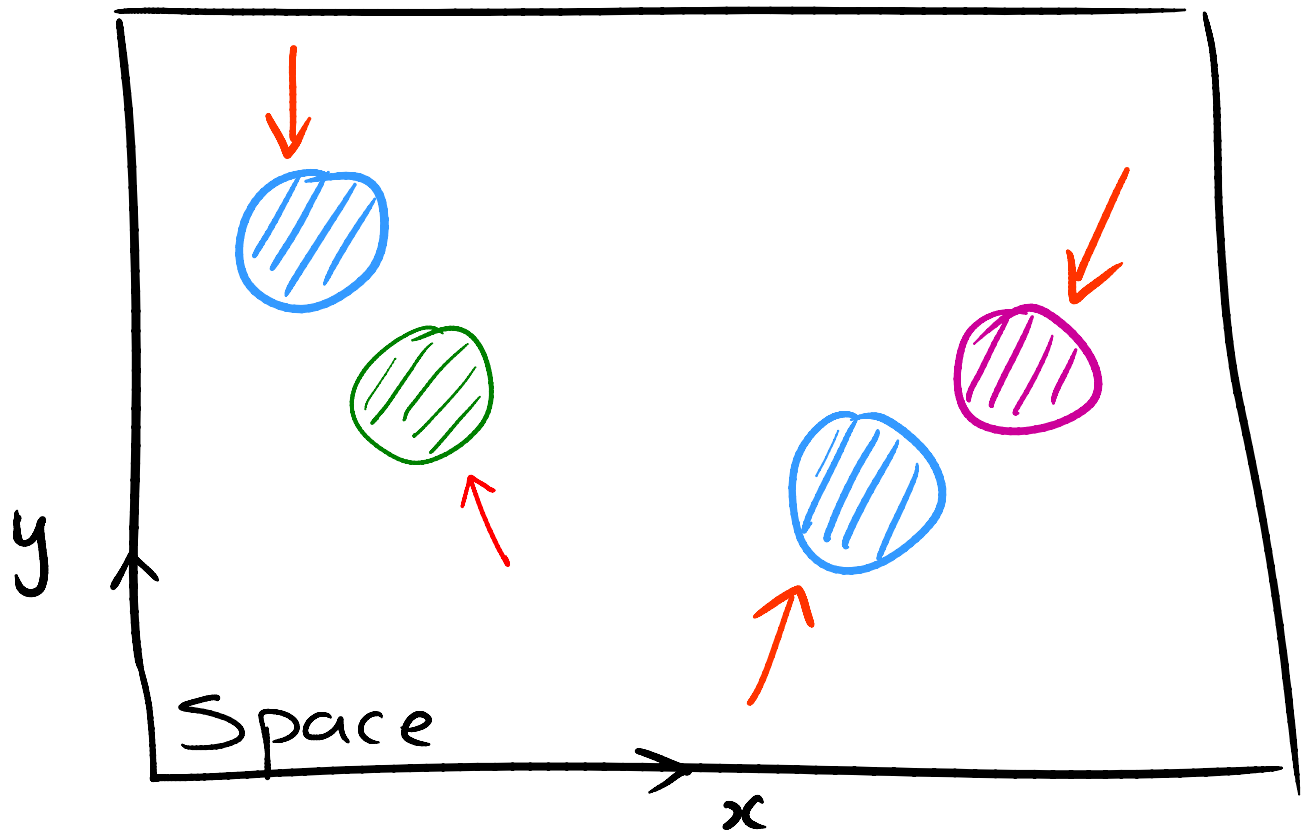


Flavor Puzzle

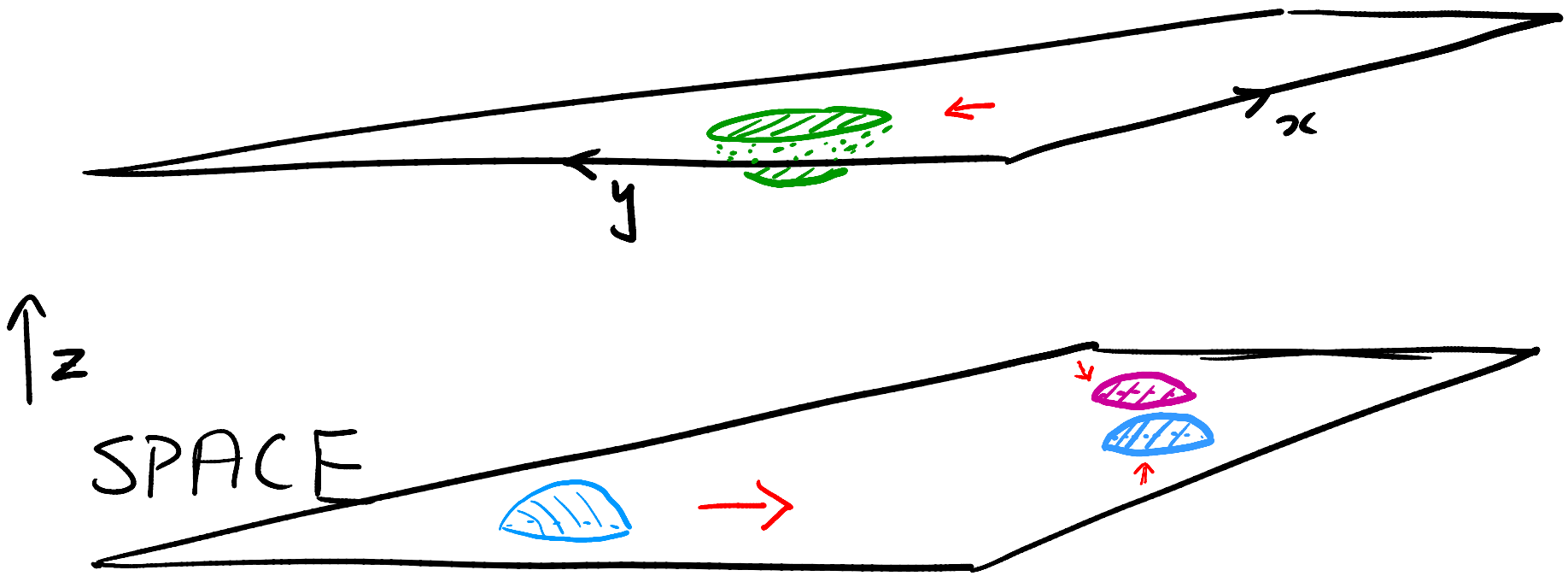


≡ couplings to Higgs Boson.

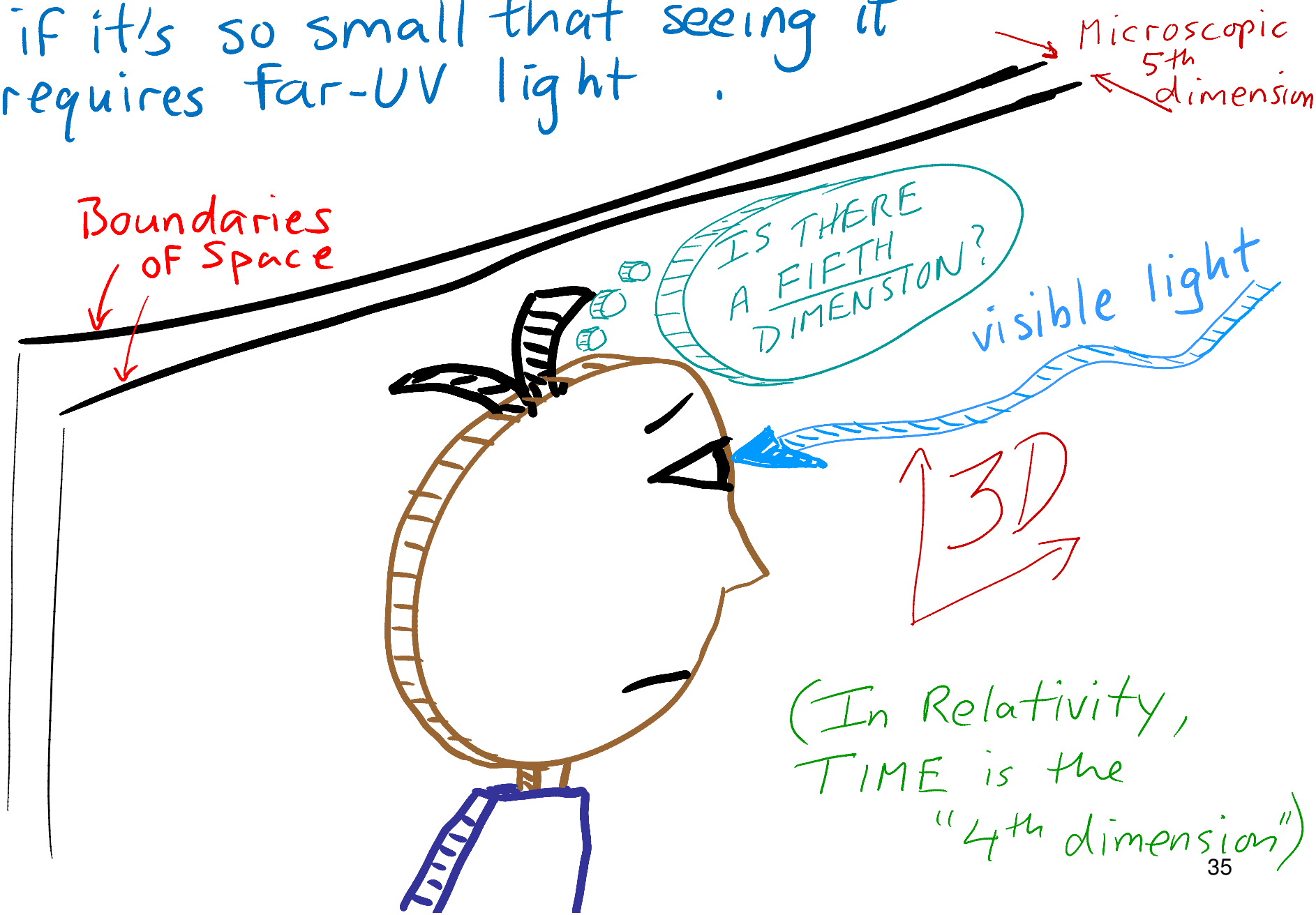
THE ANSWERS TO THESE PUZZLES MAY BE HIDDEN...



IN NEW DIMENSIONS!



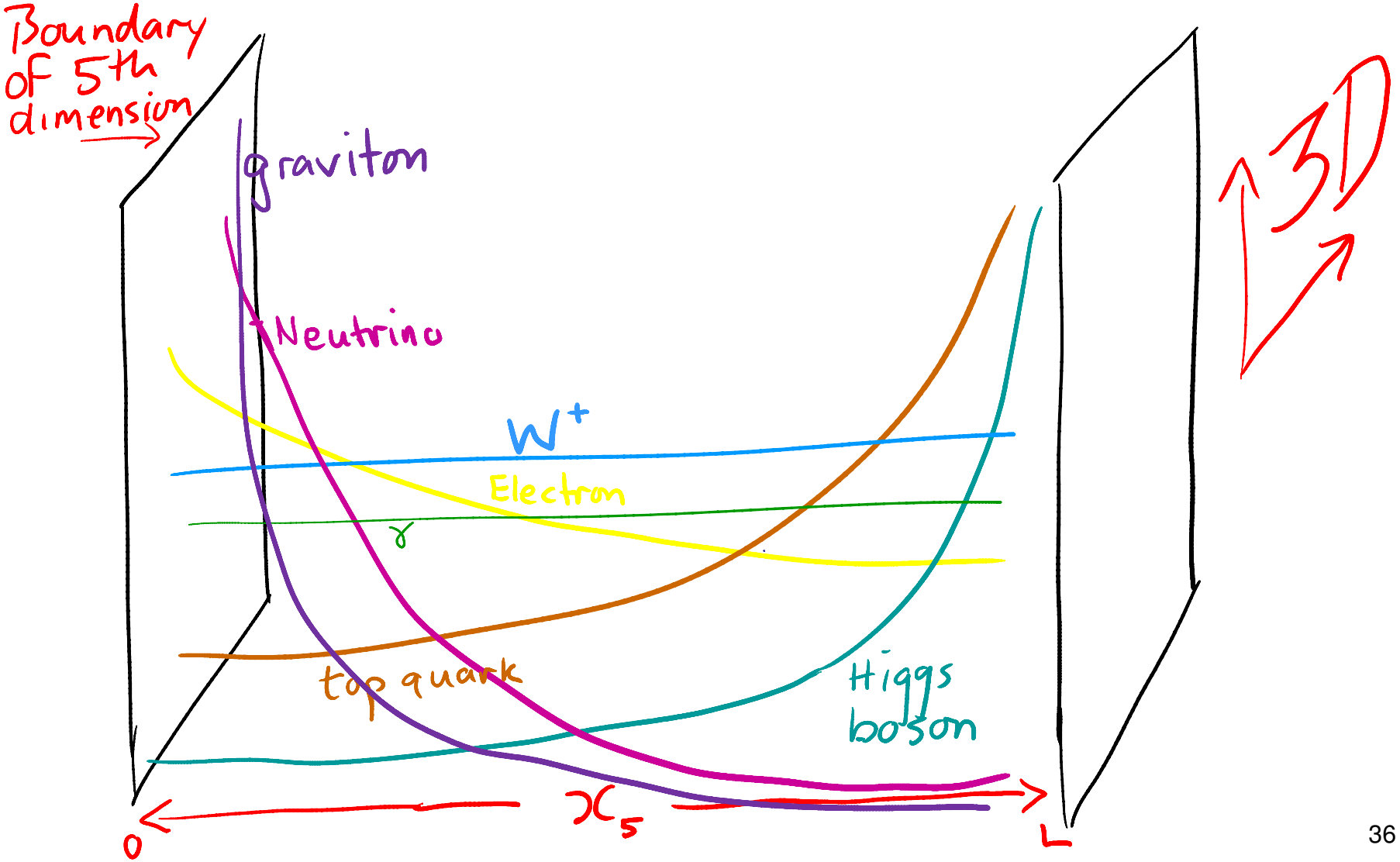
A NEW DIMENSION COULD HIDE if it's so small that seeing it requires far-UV light .



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

5D CHAOS → 4D COSMOS

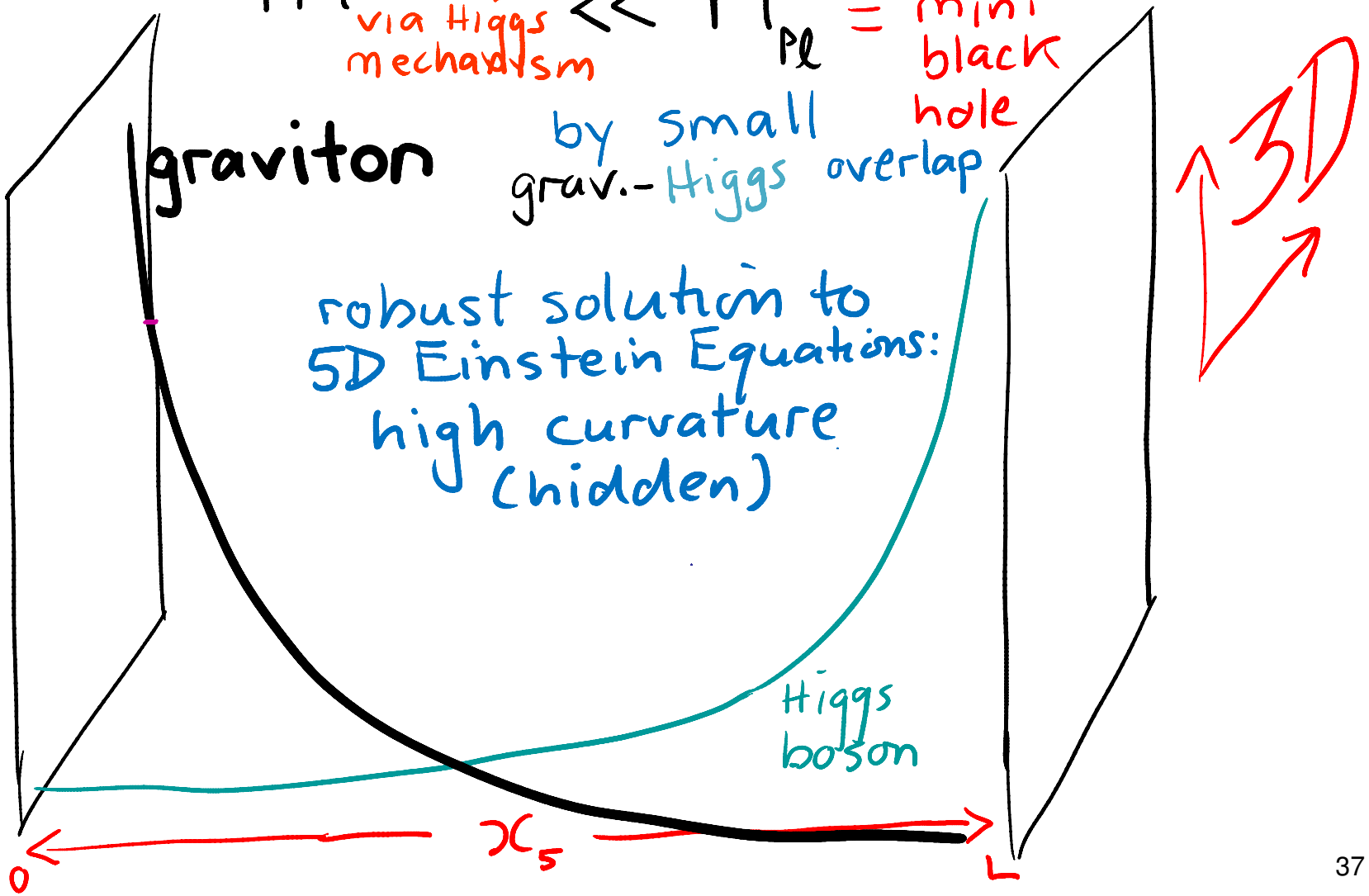
Different species have different wavefunction solutions to their wave equations

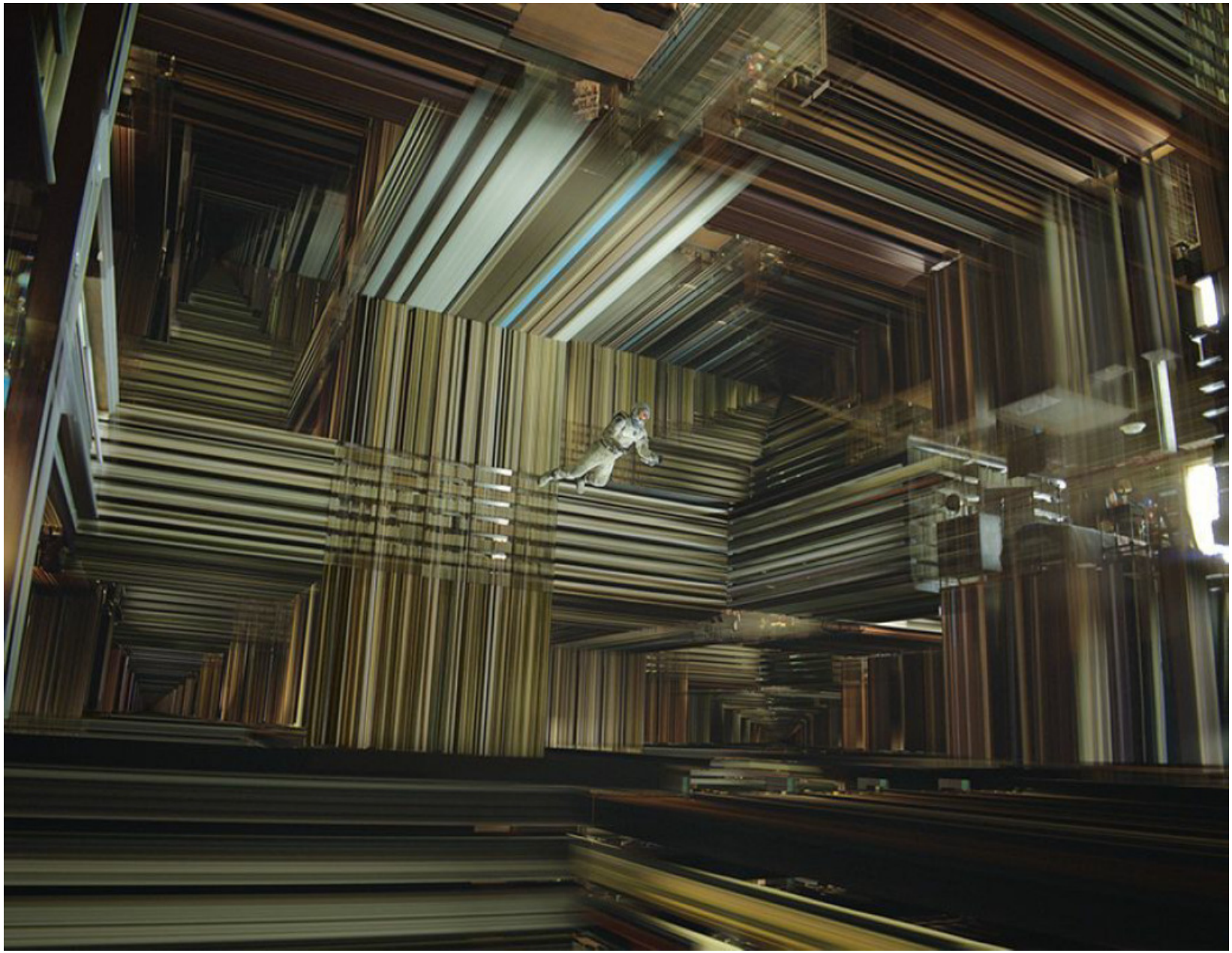


Warped Compactification solves the Hierarchy Problem...

Randall, Sundrum '99

$m_{\text{via Higgs mechanism}} \ll M_{Pl} \equiv$ mini black hole

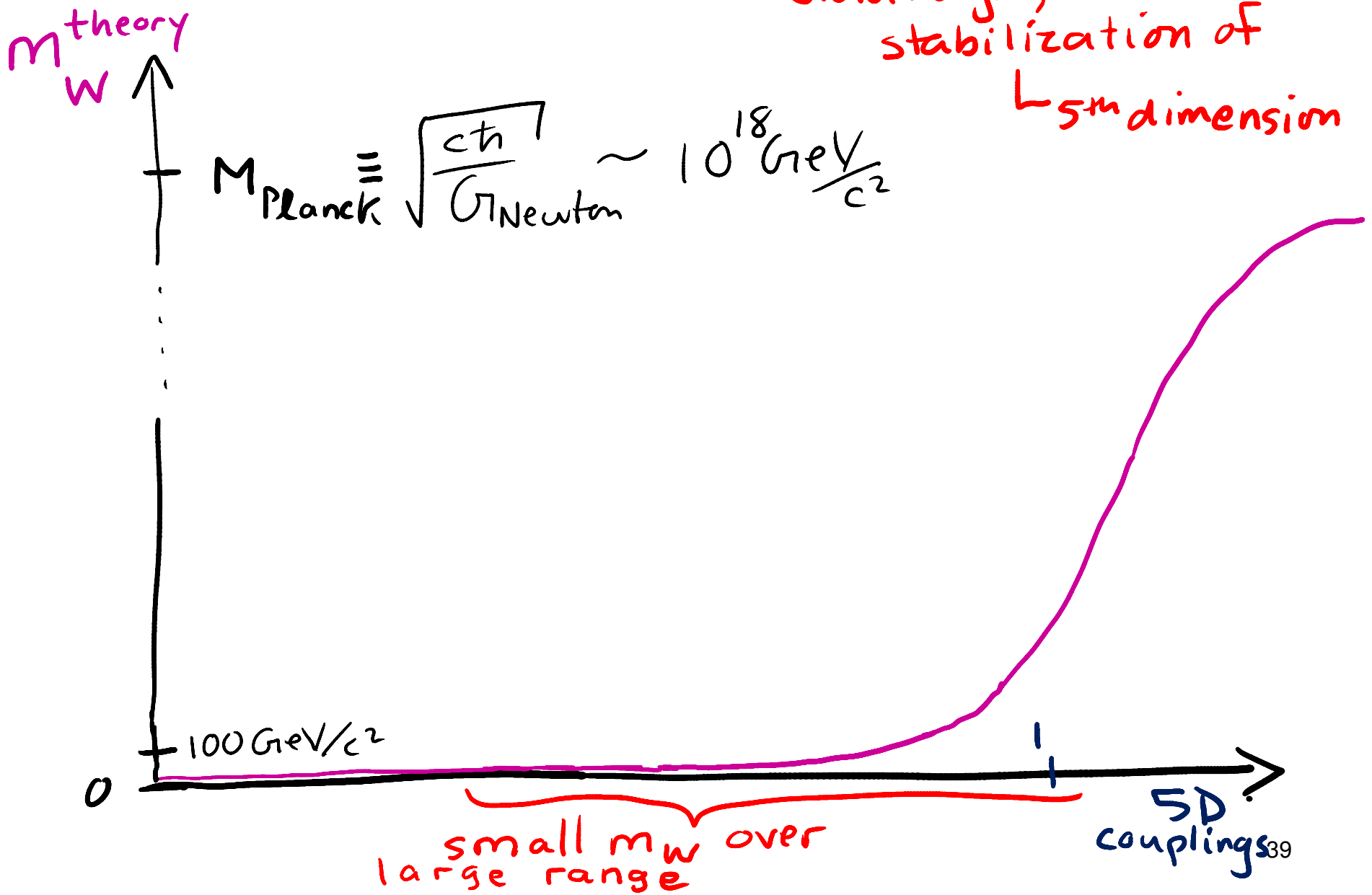




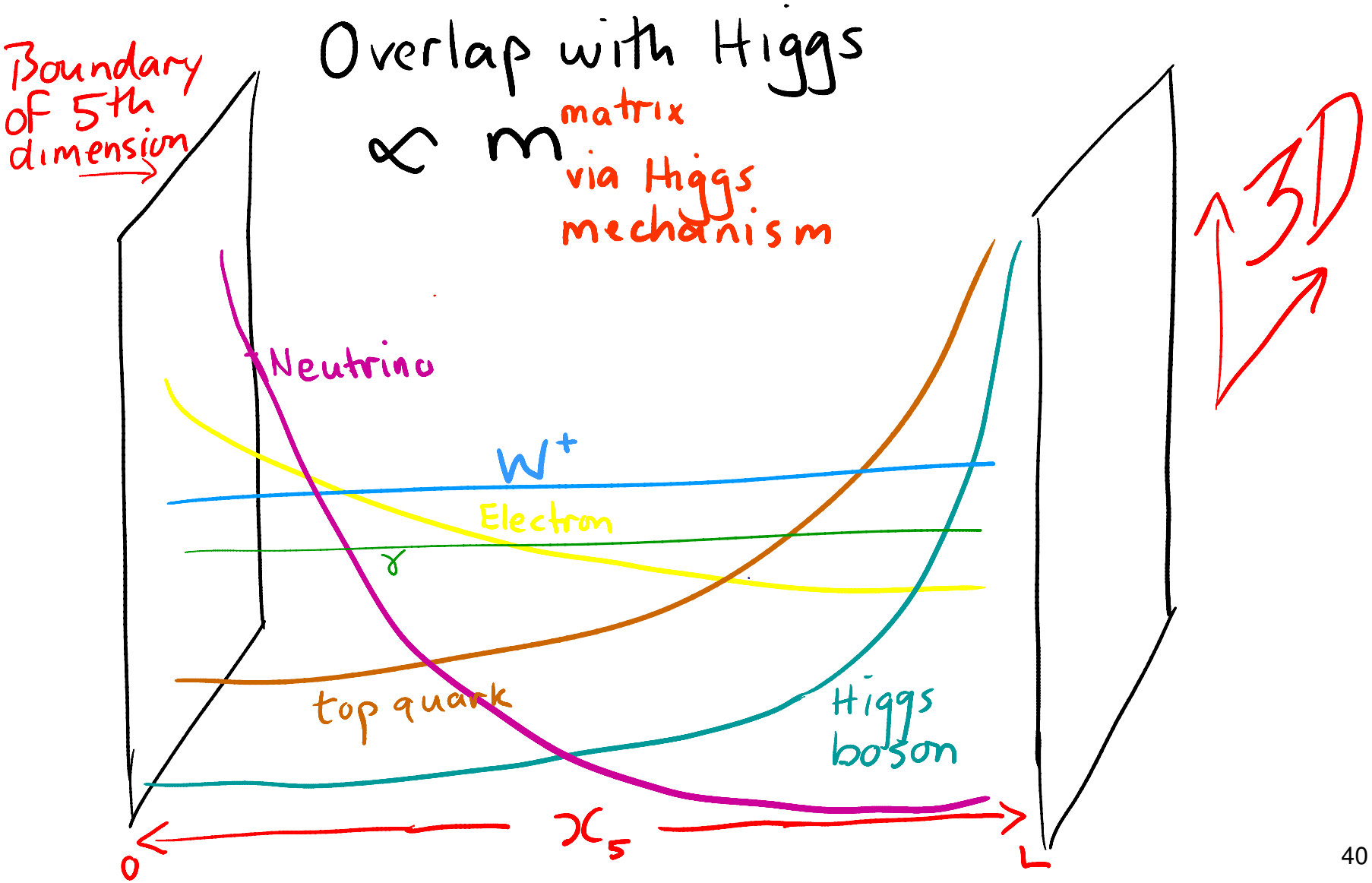
Some of the physics inspiration behind "Interstellar"

...NATURALLY

Goldberger, Wise '99
stabilization of
$L_{5^{th}\,dimension}$



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

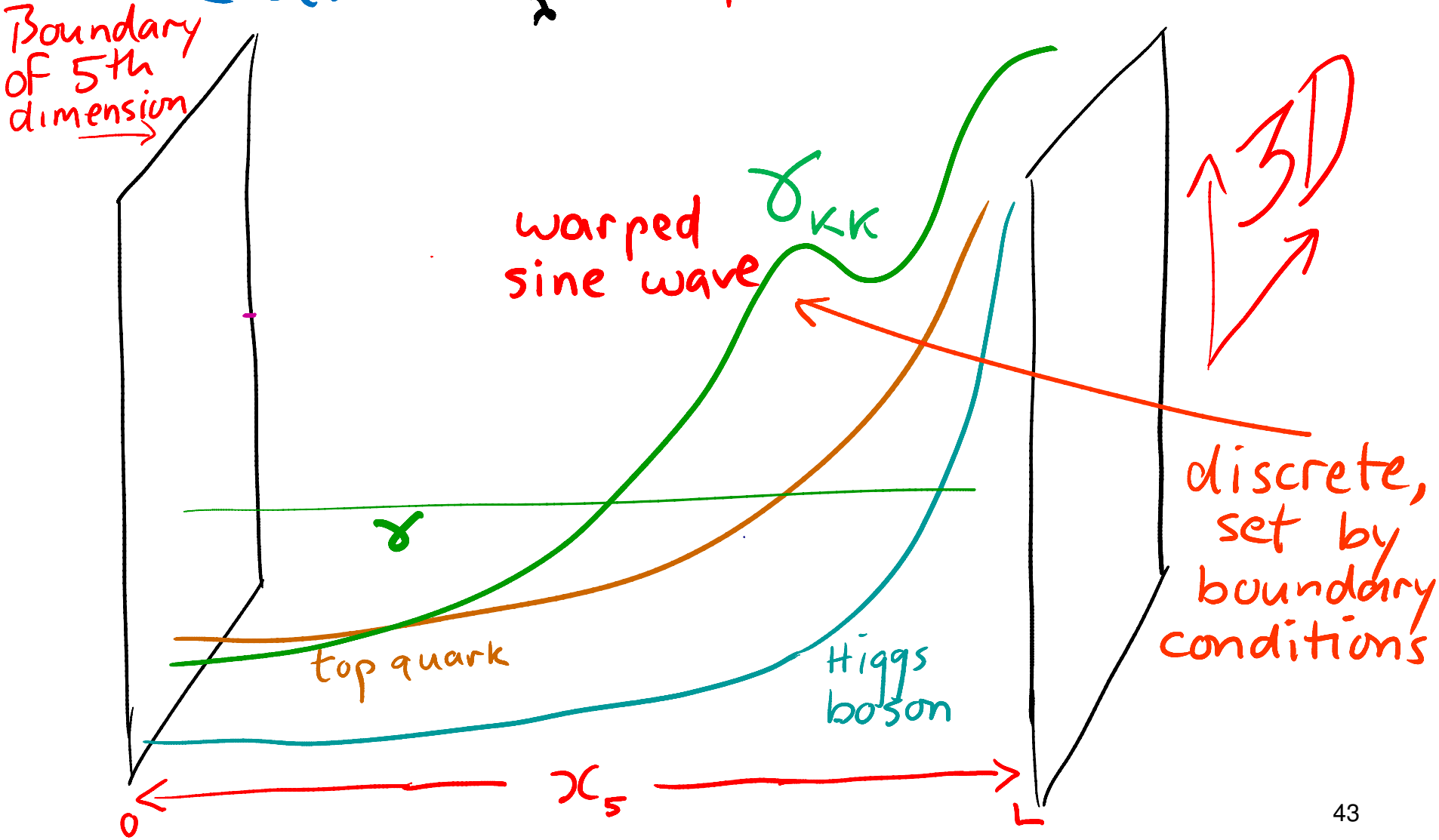
& test & constrain it by high-precision pre-LHC data

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 . . .

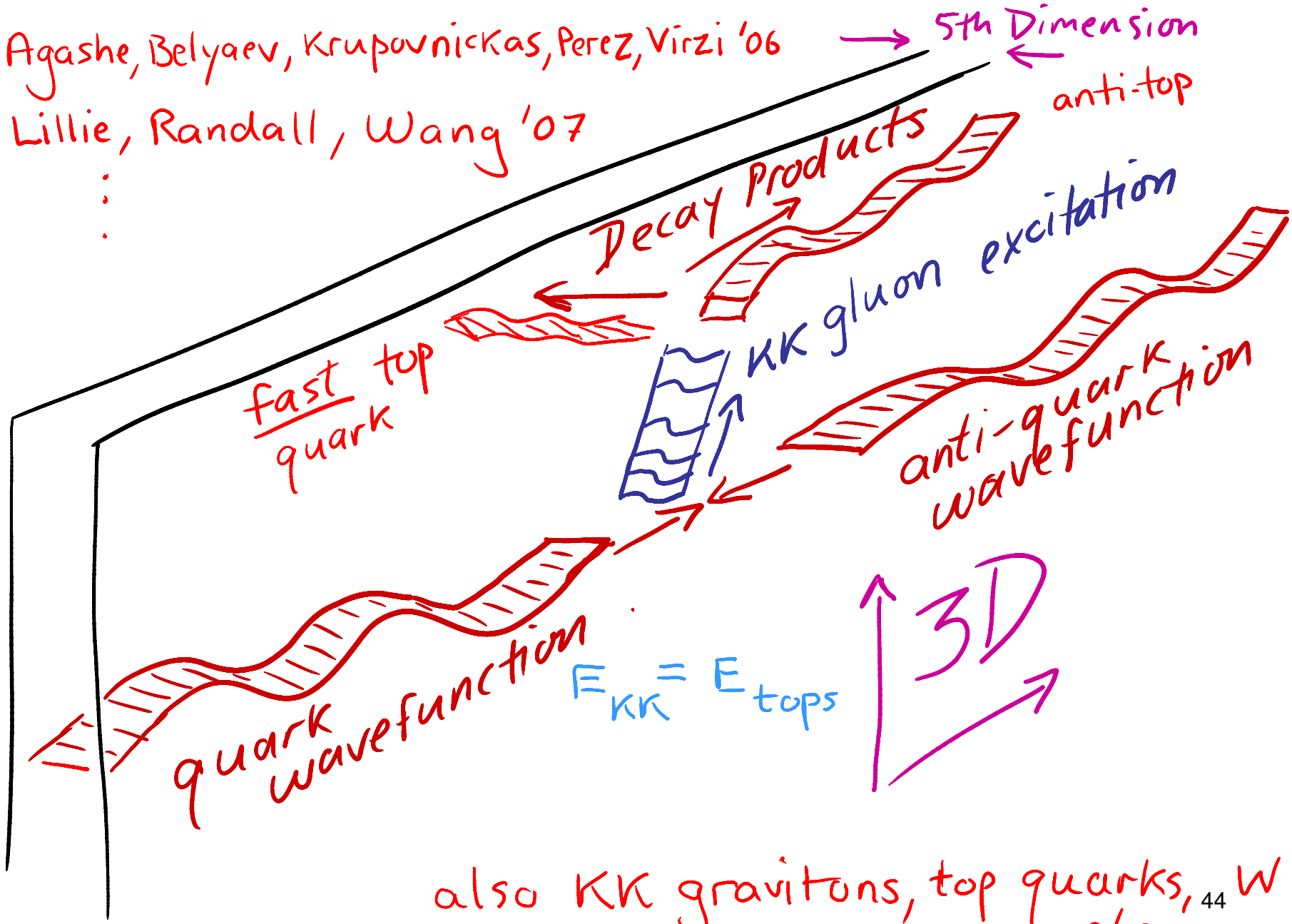
EXTRA-DIMENSIONAL PERCEPTION

requires shorter wavelengths

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

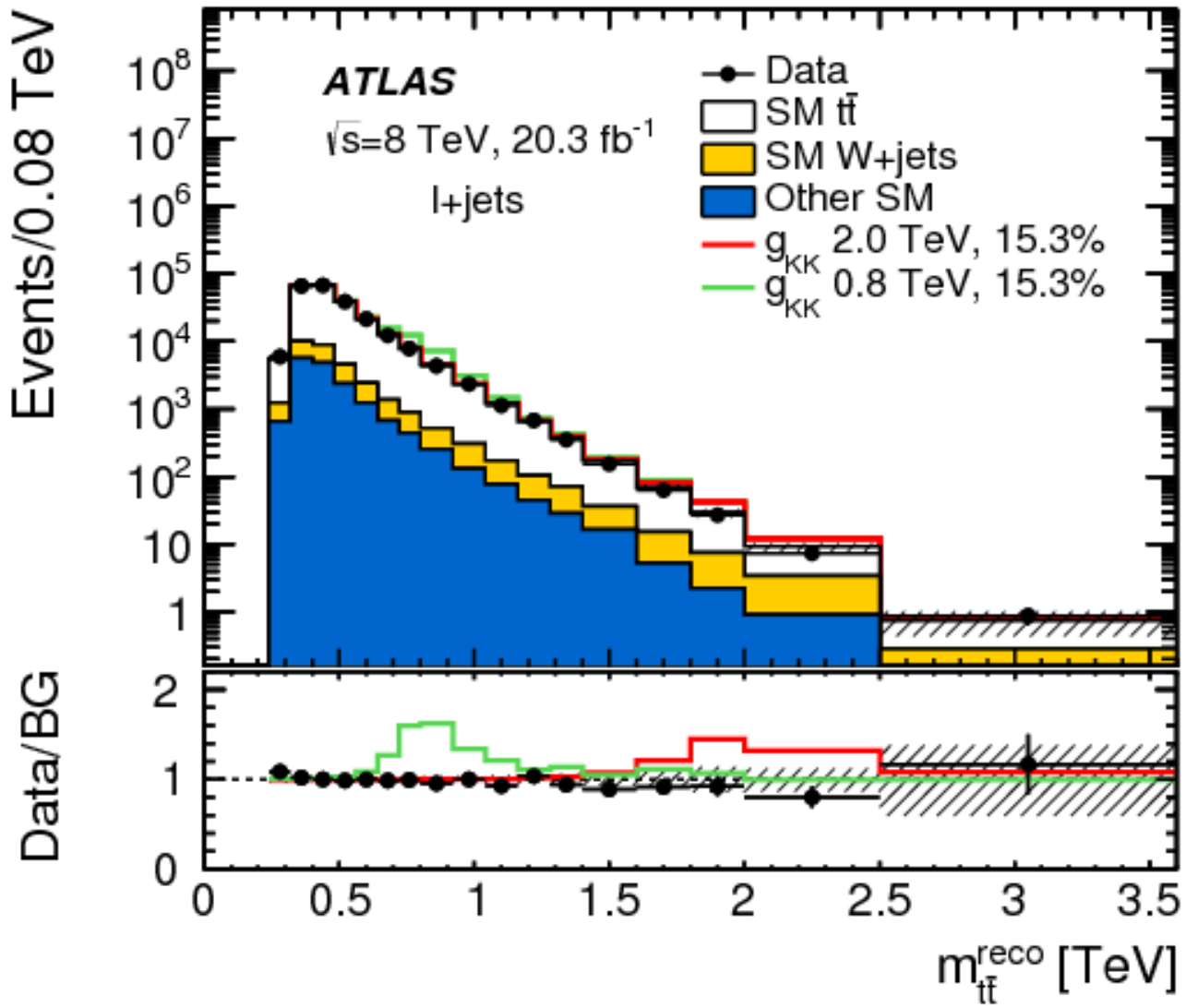


EXTRA-DIMENSIONAL PERCEPTION



also KK gravitons, top quarks, W etc.

COMPETES WITH STANDARD MODEL BACKGROUNDS



EMERGENT DIMENSIONS

Warped extra dimension is an emergent phenomenon!

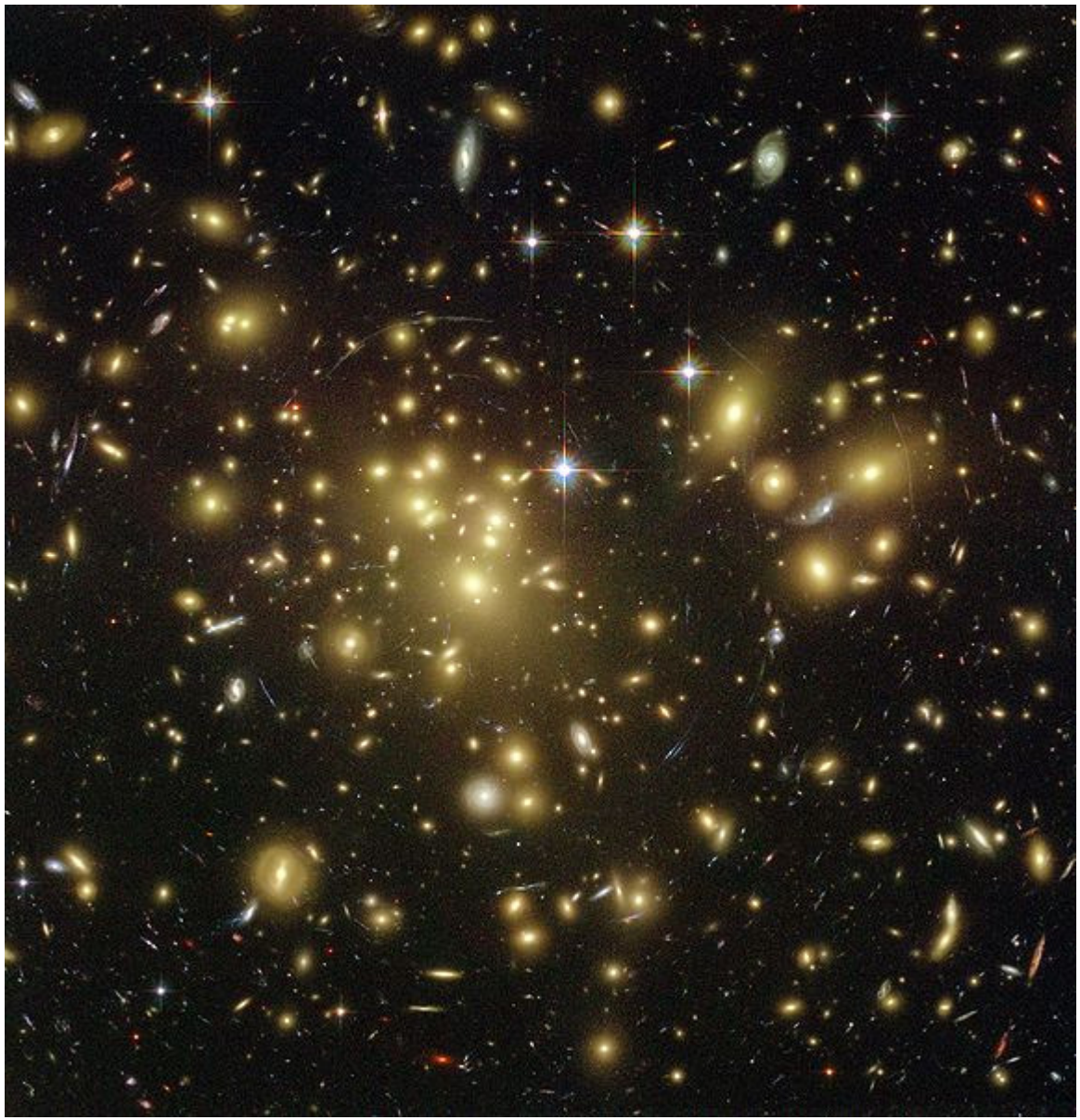
Not put into fundamental Hamiltonian "by hand", created by strong quantum interactions

"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?

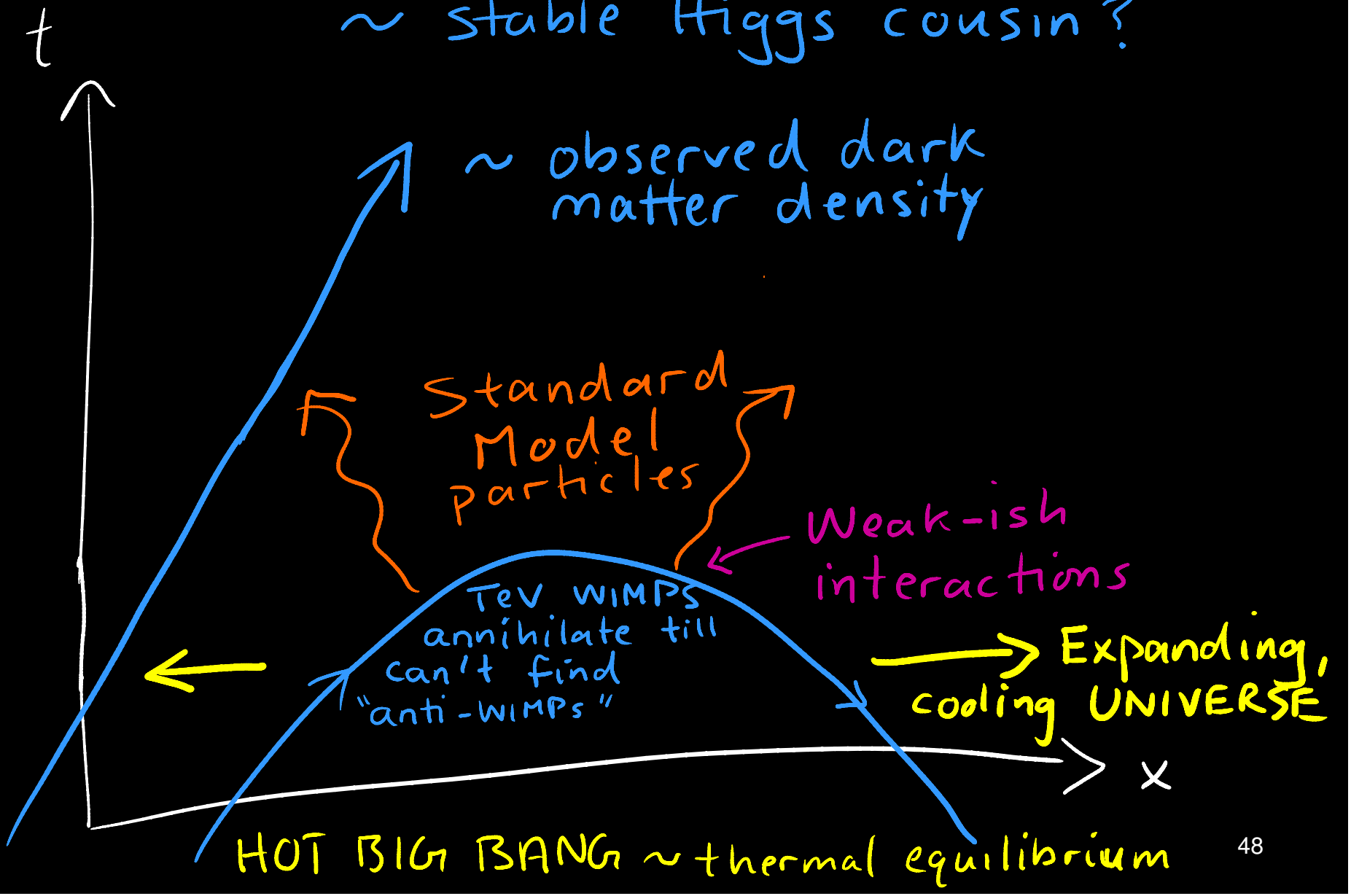


Galaxies distorted by gravitational lensing due to (otherwise) invisible Dark Matter.

Hubble Space Telescope Abell Cluster

"WIMP" DARK MATTER

~ stable Higgs cousin?



Supersymmetry (SUSY)

$= \text{“}\sqrt{-1}\text{”}$

of Quantum Spacetime

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

SUSY CARTOON

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

↑ "supercharge" operator

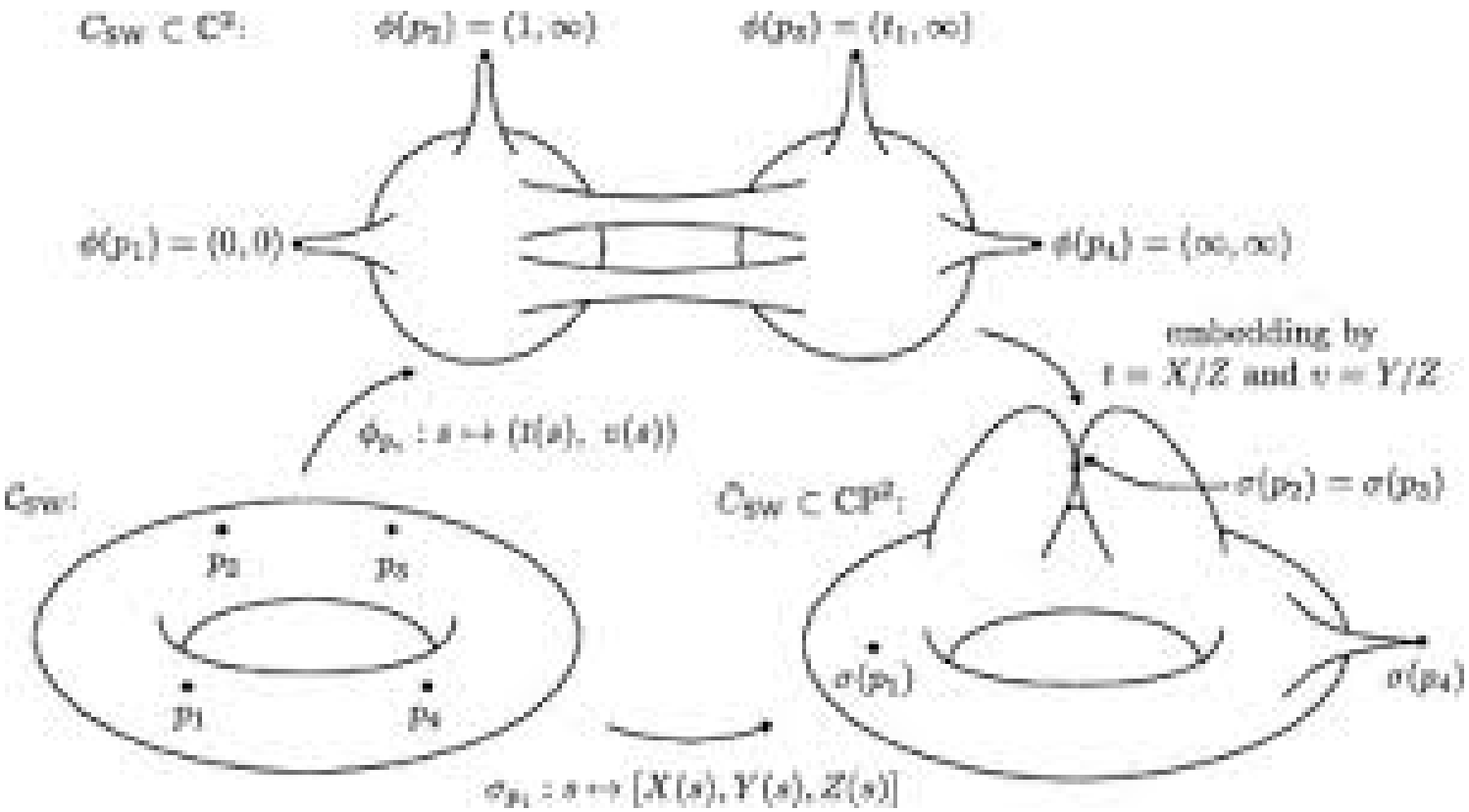
$$Q\,|\,\text{boson}\rangle = |\,\text{fermion}\rangle$$

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

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

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

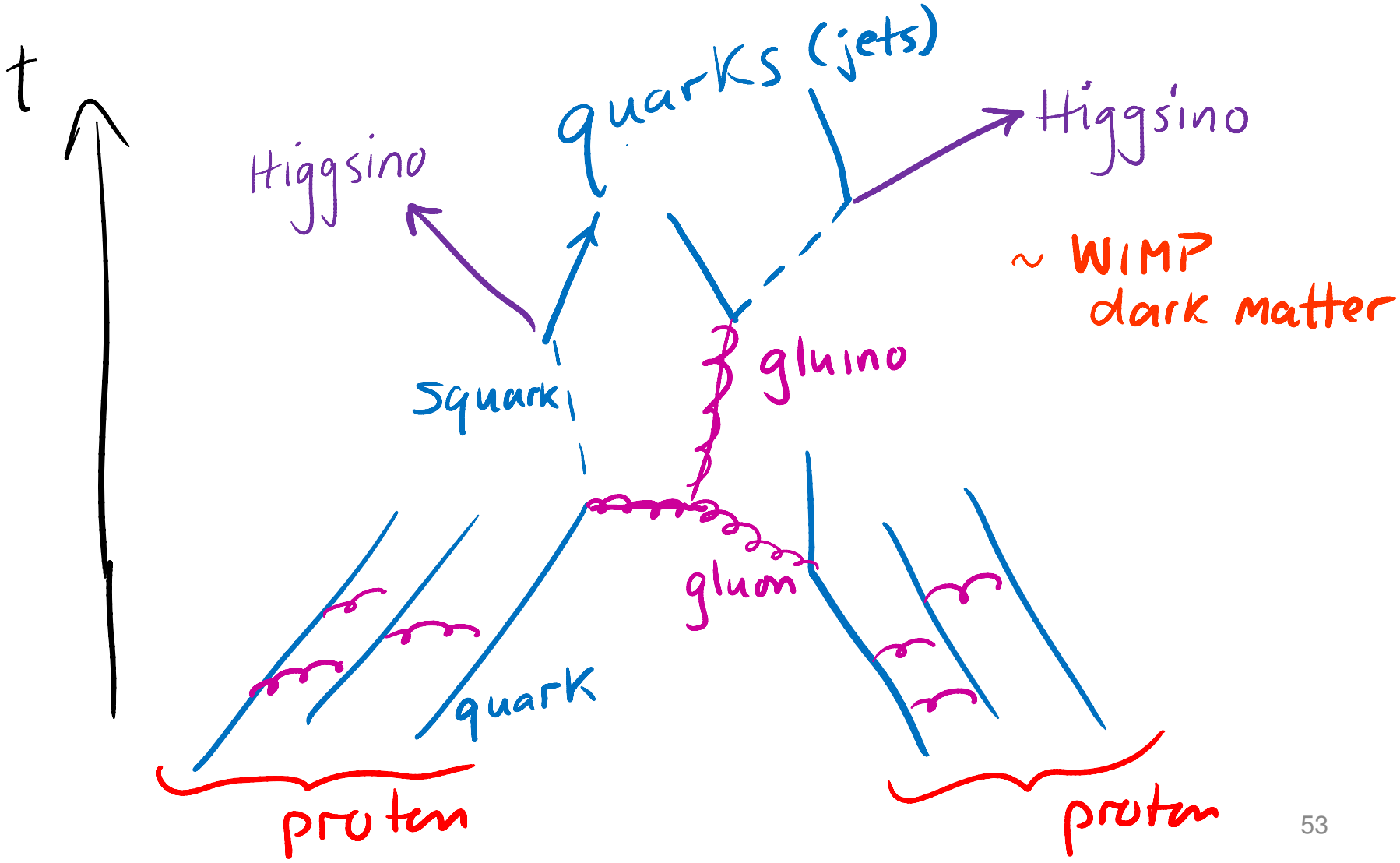
electron (spin-$\frac{1}{2}$)	selectron (spin-0)
photon (spin-1)	photino (spin-$\frac{1}{2}$)
top squark (spin $\frac{1}{2}$)	top squark (spin-0) ("stop")
Higgs (spin-0)	Higgsino (spin-$\frac{1}{2}$)

A "Mirror" in Quantum Statistics

Minimal Supersymmetric Standard Model (MSSM) Dimopoulos, Georgi '81

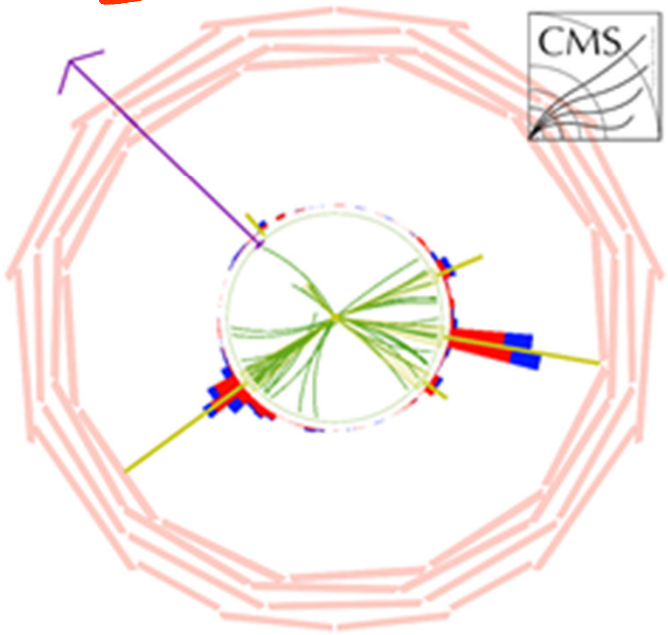
But a Mirror cracked ...

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



Simulated SUSY event in CMS

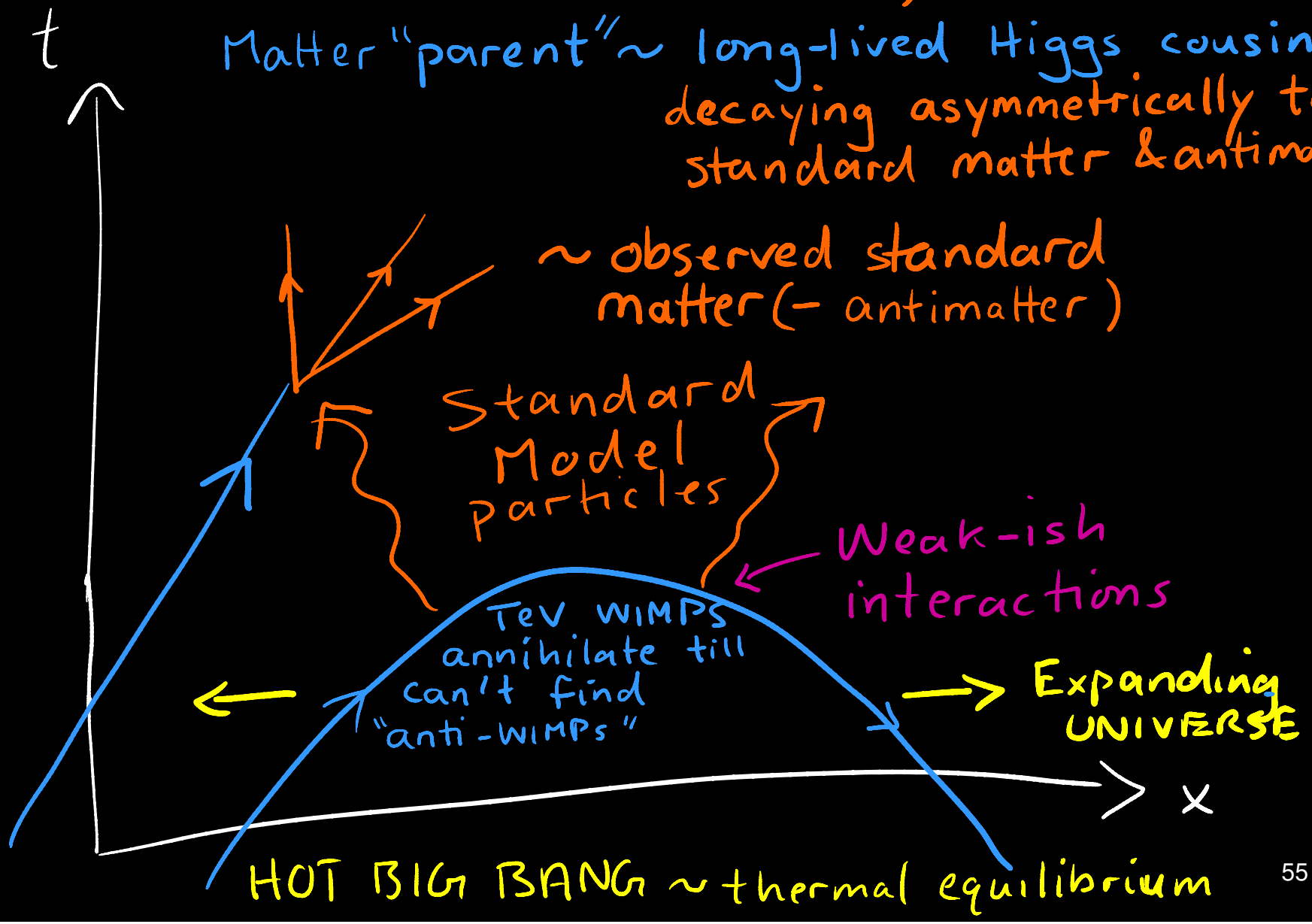
But there are backgrounds, famously neutrinos

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

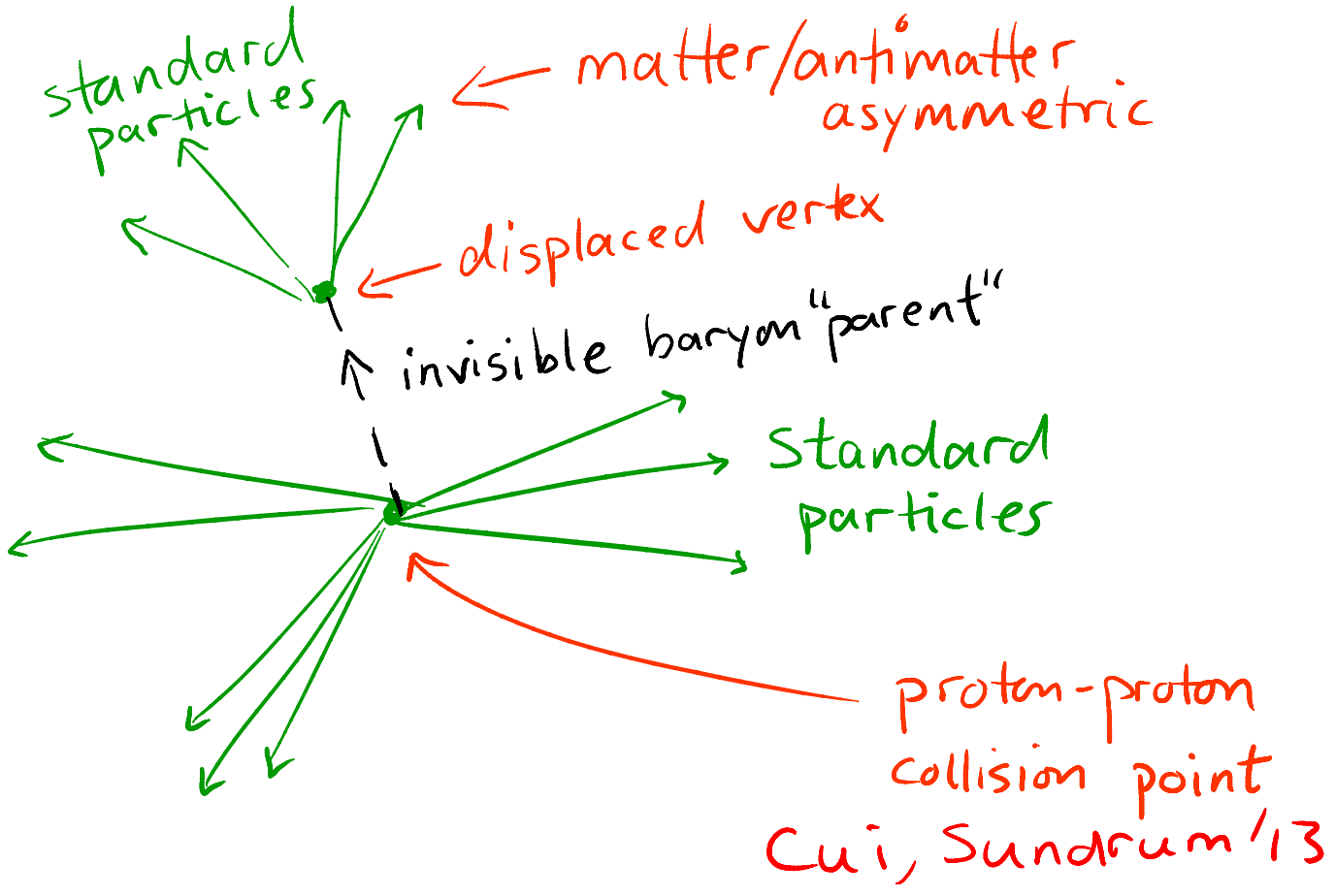
THE MATTER/ANTIMATTER ASYMMETRY FOR WIMPS

Cui, Sundrum '13

Matter "parent" ~ 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

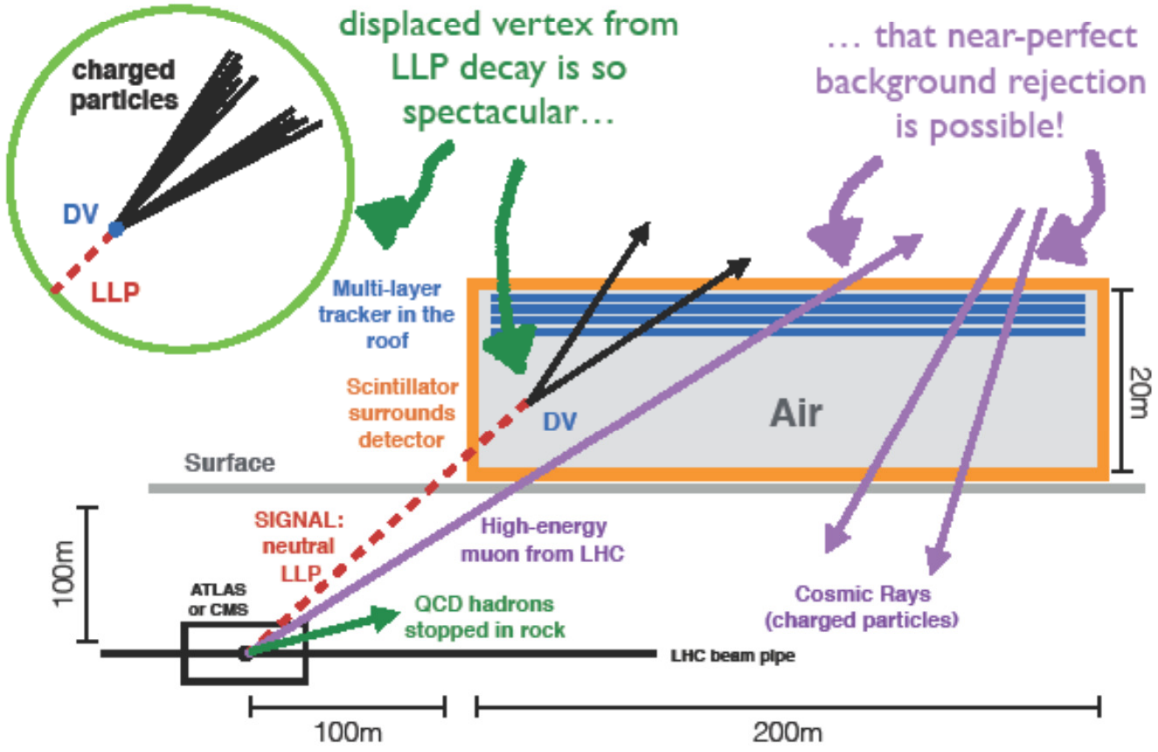


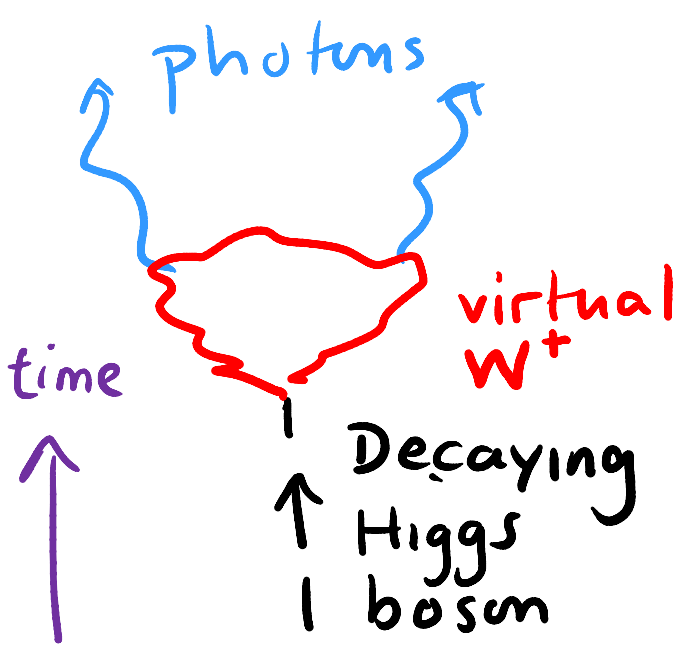
Figure Credit: Curtin, Sundrum, submitted to Physics Today

On schedule for

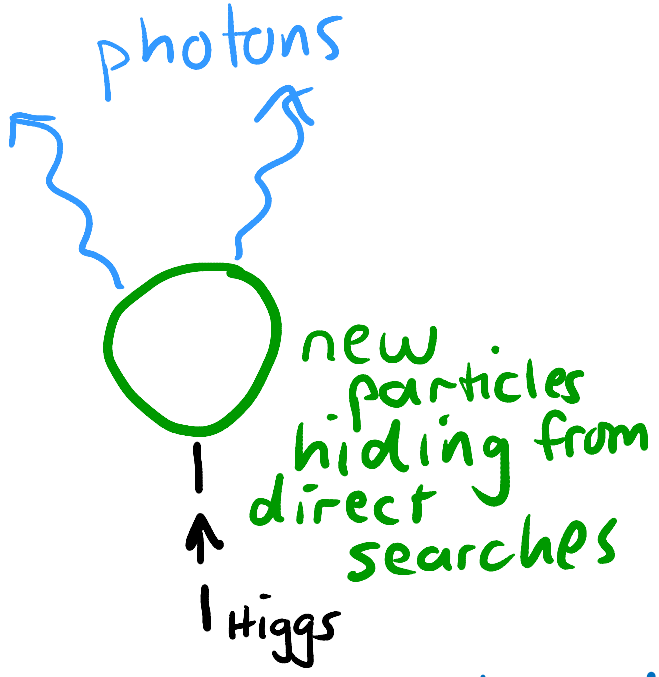
prototype
mid 2017
letter of intent
end 2017

theory
white paper
mid 2017

PRECISION HIGGS PHYSICS is underway



Higgs decay: Standard



Non-standard

LHC is very powerful & may make dramatic discoveries, perhaps requiring considerable ingenuity. But unable to VERY DEFINITIVELY & 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 . . .