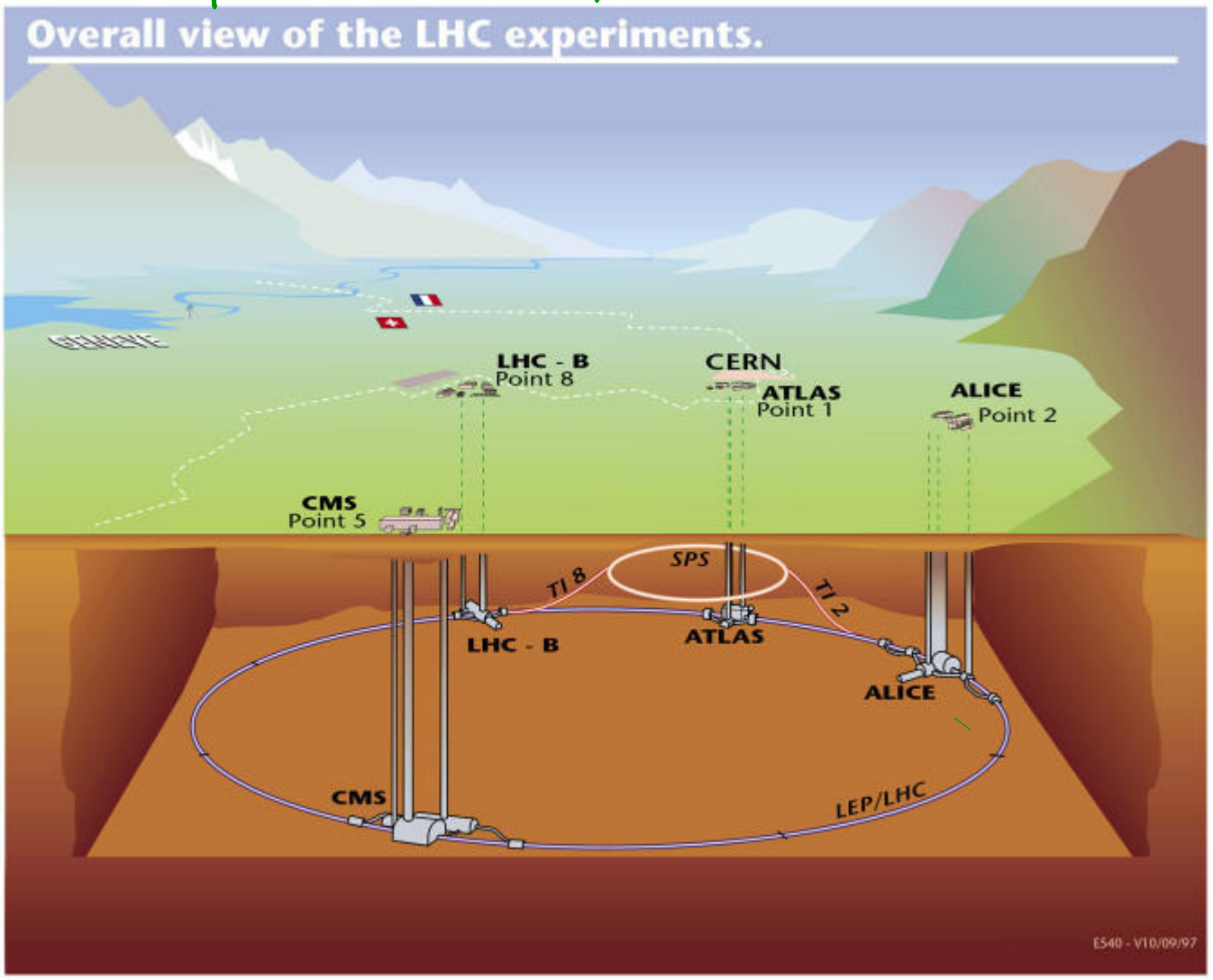
FUNDAMENTAL PHYSICS & THE FIFTH DIMENSION

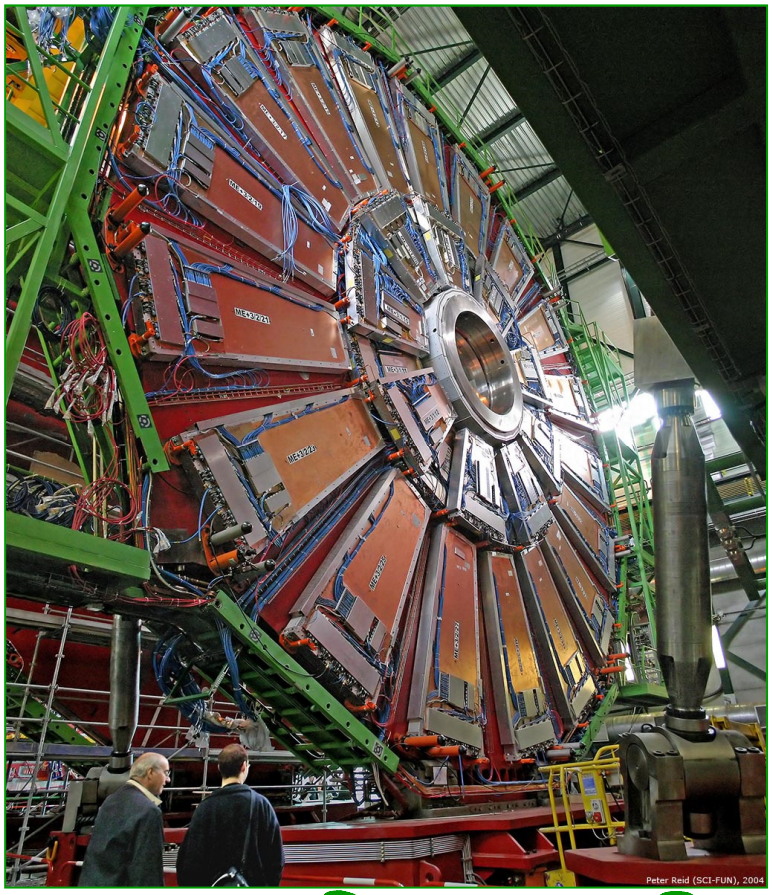
Raman Sundrum
University of Maryland

THE LHC IS A MULTI-TeV PROTON-PROTON COLLIDER



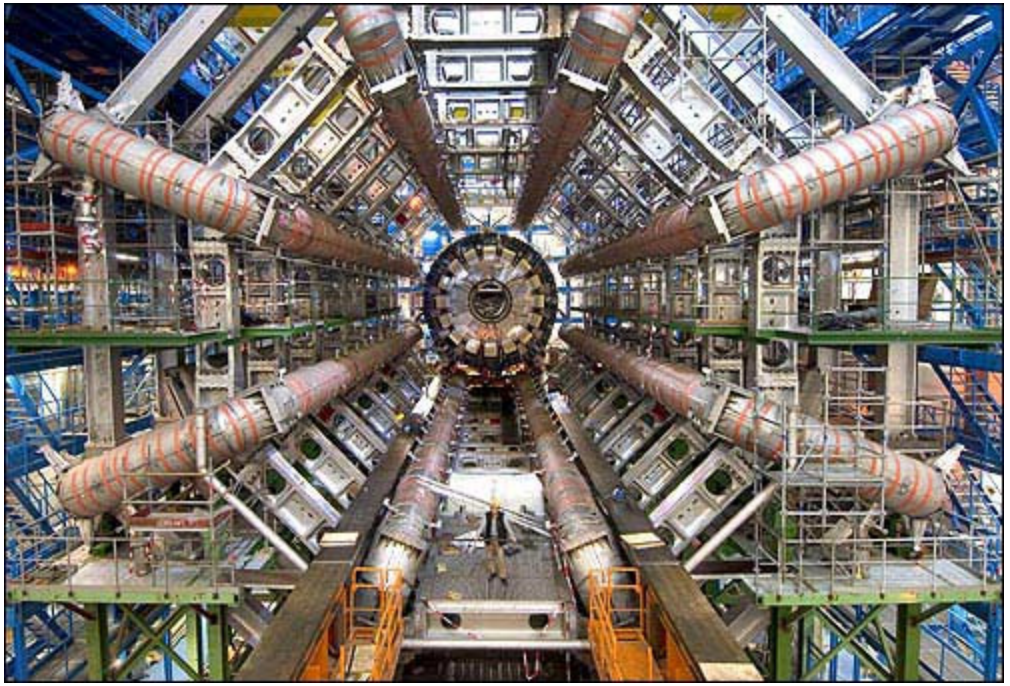
THE HAIL OF EMERGING PARTICLES SCRUTINIZED BY...

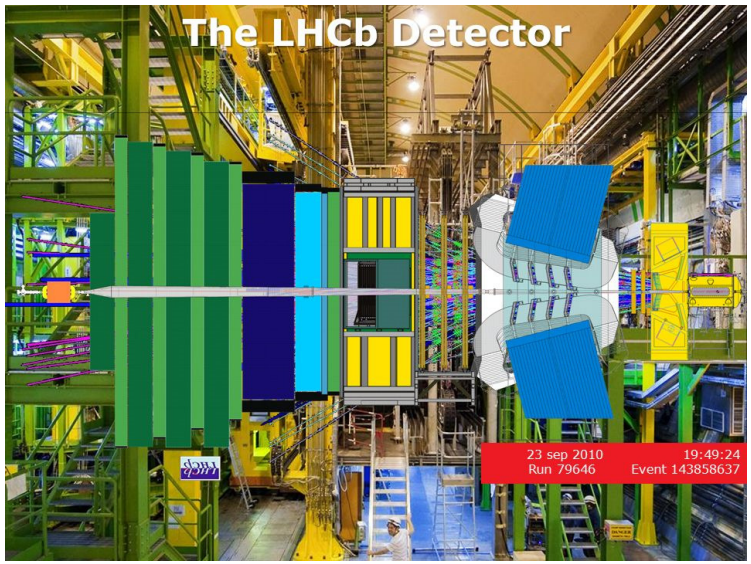
BIG, BIG EYES



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

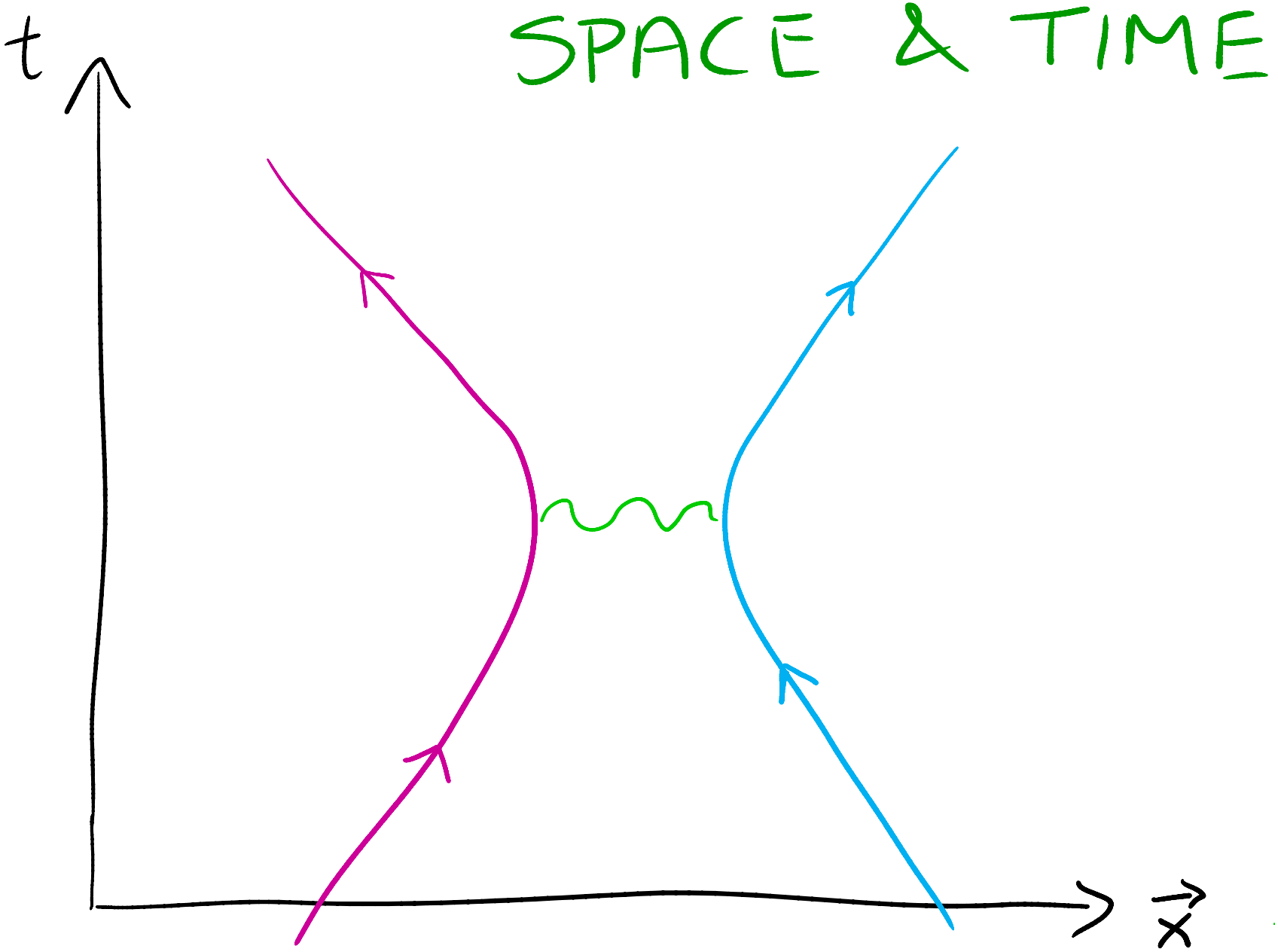
Incarnations of Spacetime —

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

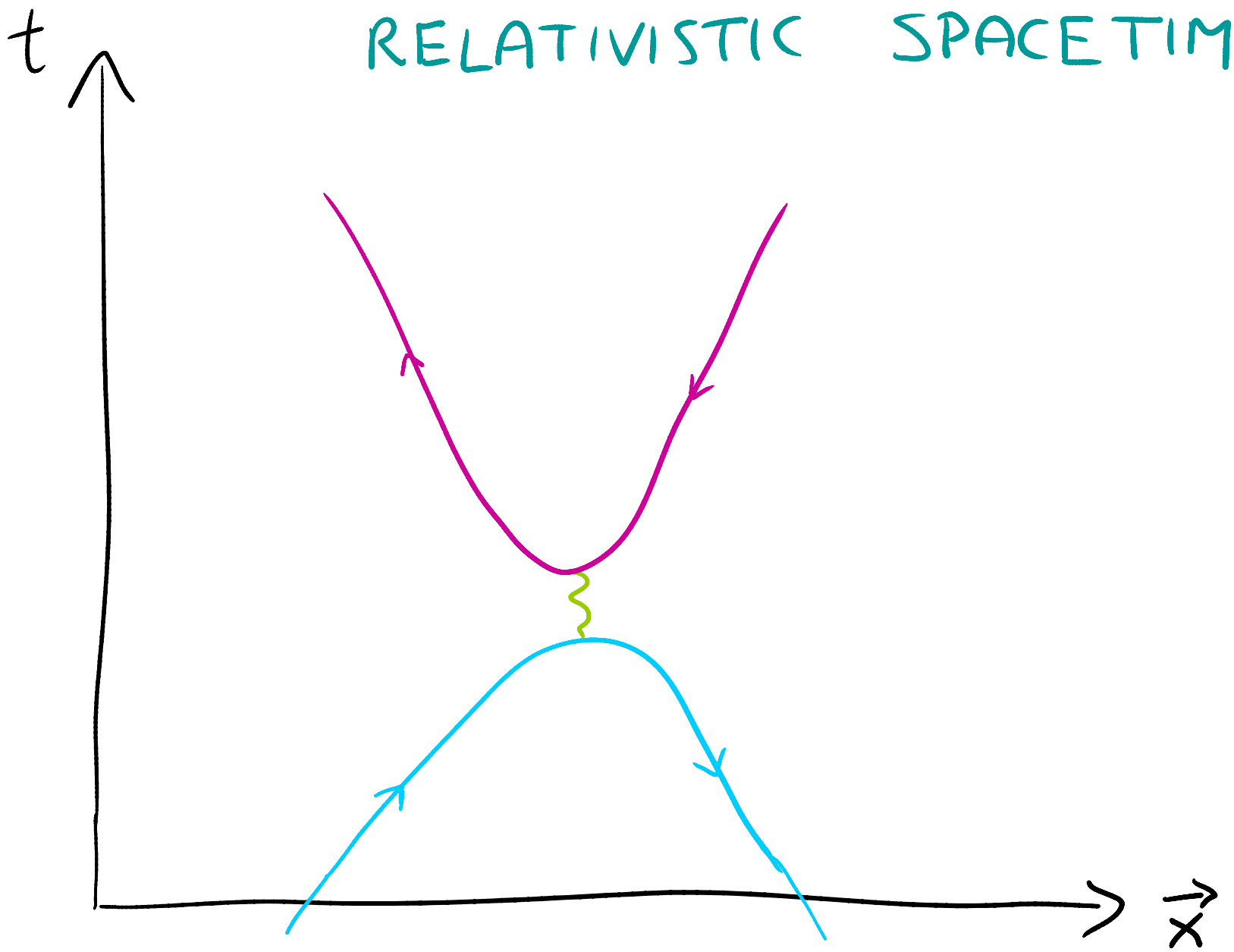
Extra-dimensional Perception —

Collider strategies

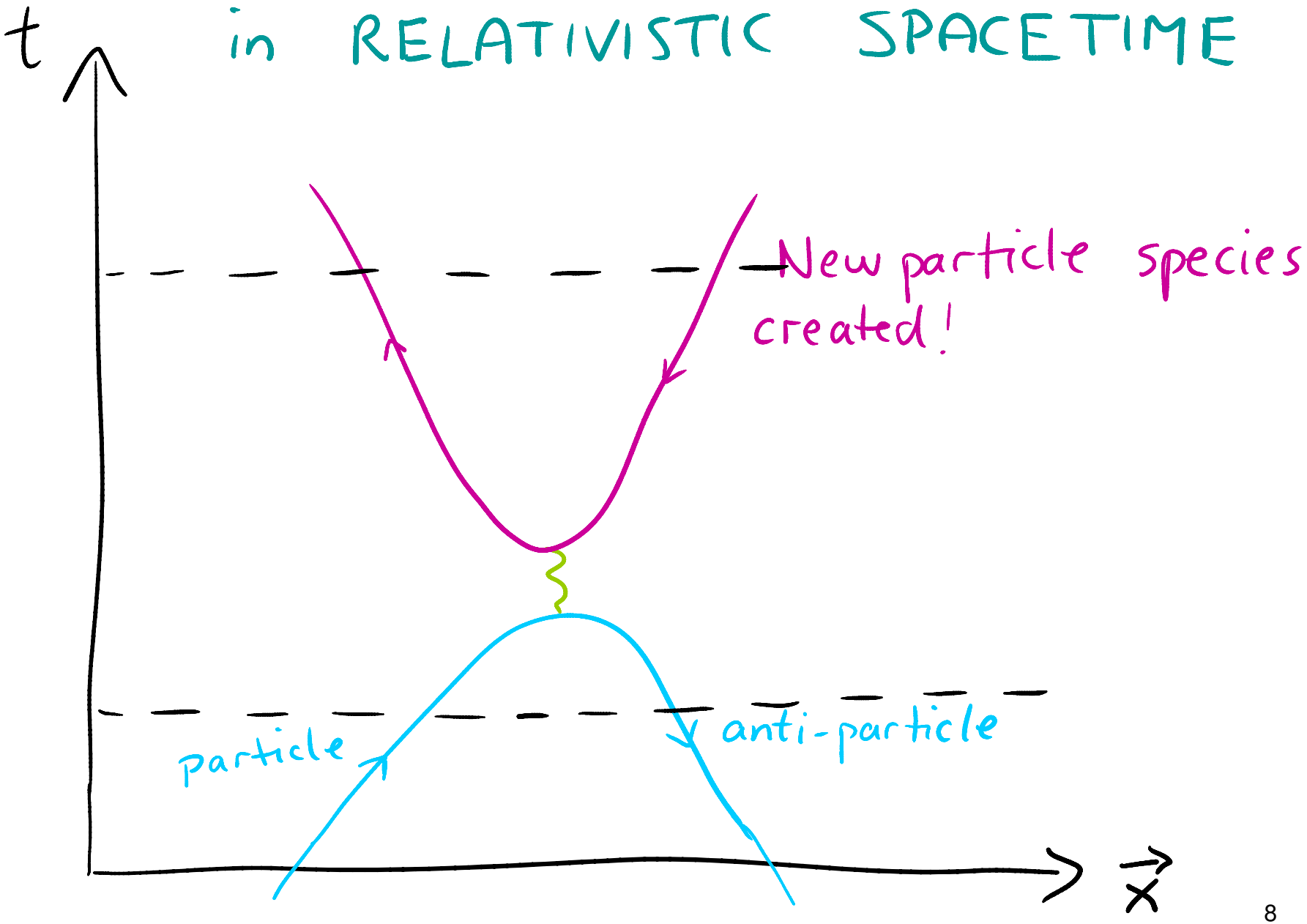
NON-RELATIVISTIC SPACE & TIME



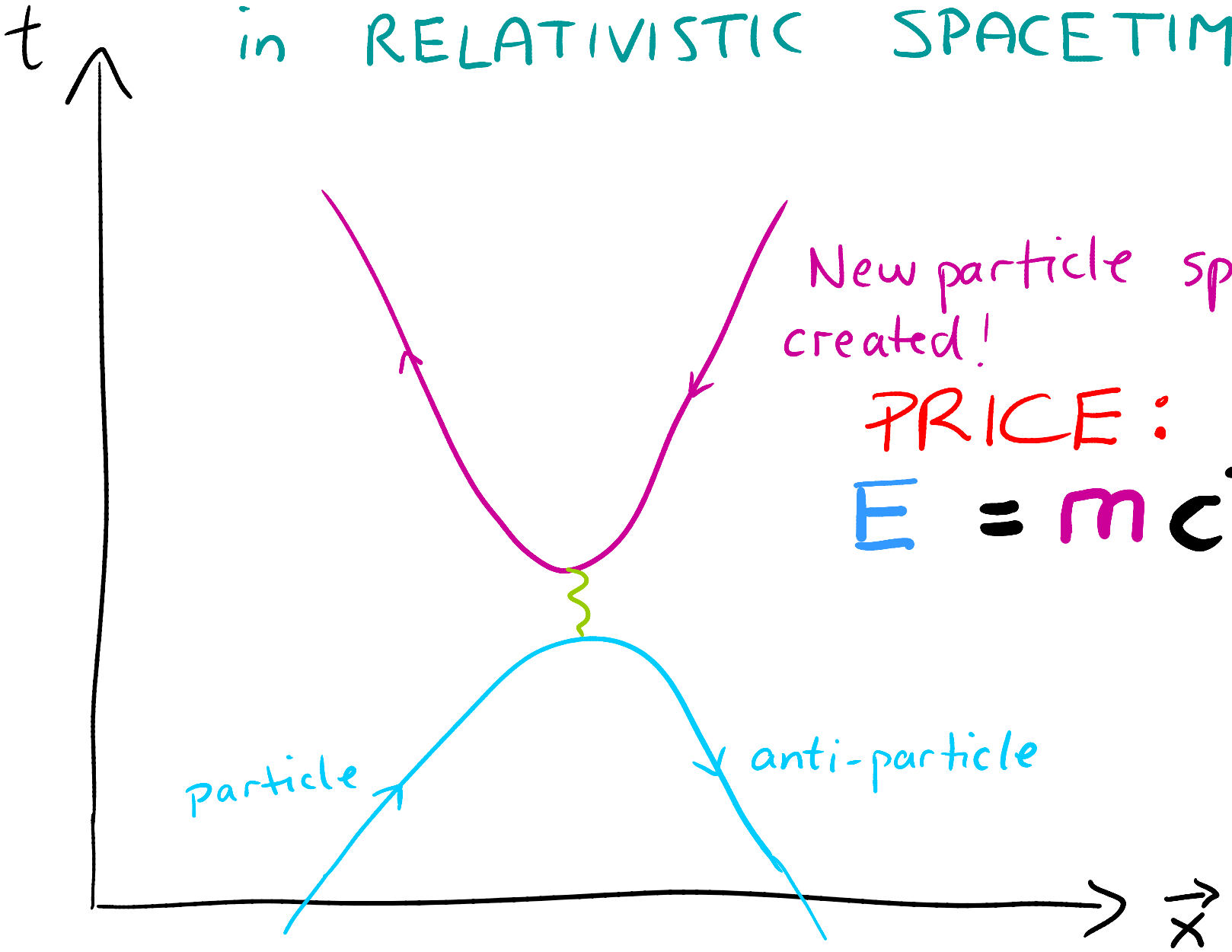
RELATIVISTIC SPACETIME



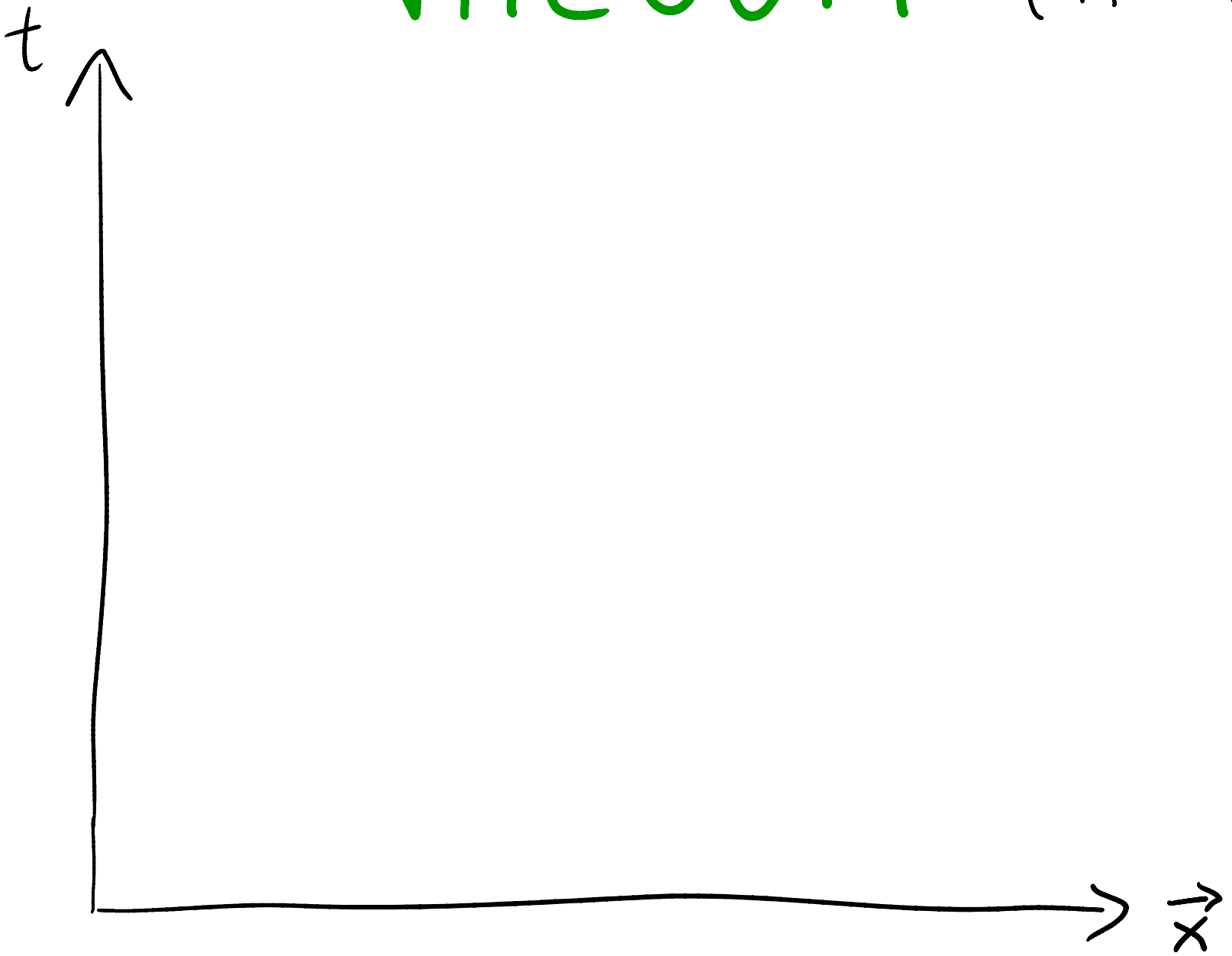
ALCHEMY in RELATIVISTIC SPACETIME



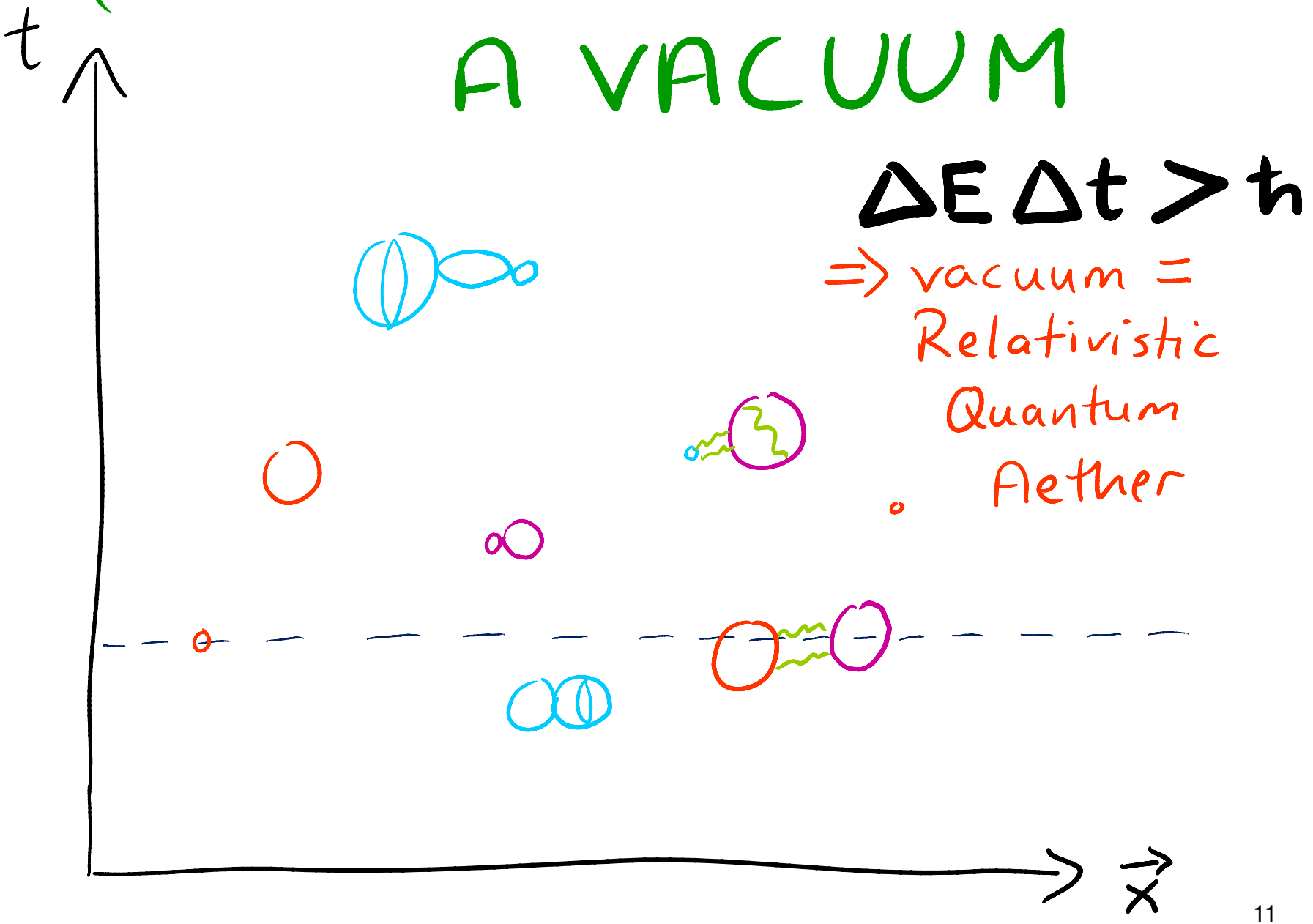
ALCHEMY
in RELATIVISTIC SPACETIME



VACUUM ($\hbar = 0$)



(QUANTUM) NATURE ABHORS A VACUUM

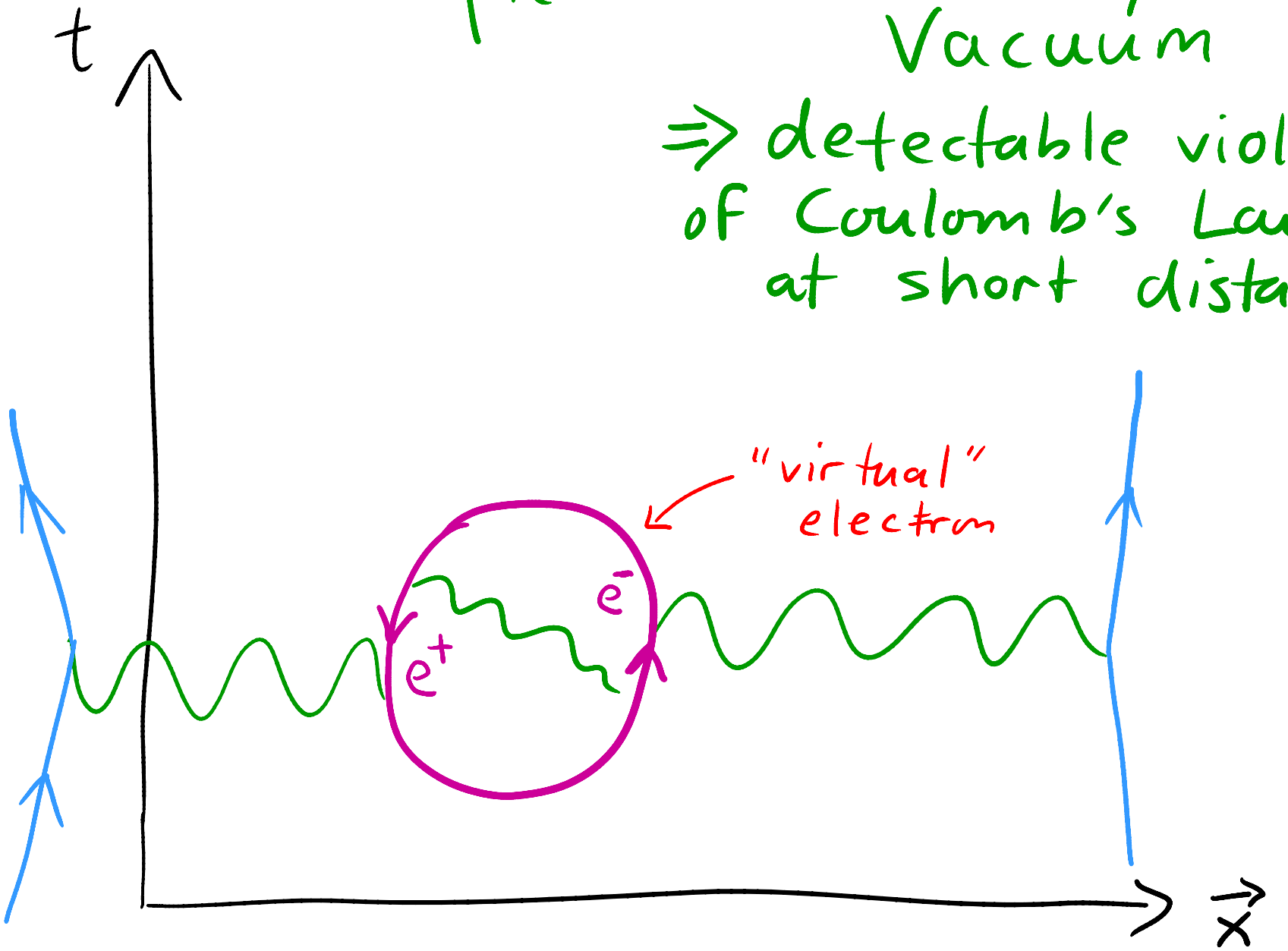


$\Delta E \Delta t > \hbar$

$\Rightarrow$ vacuum = Relativistic Quantum Aether

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

Electromagnetism + Weak Nuclear Force

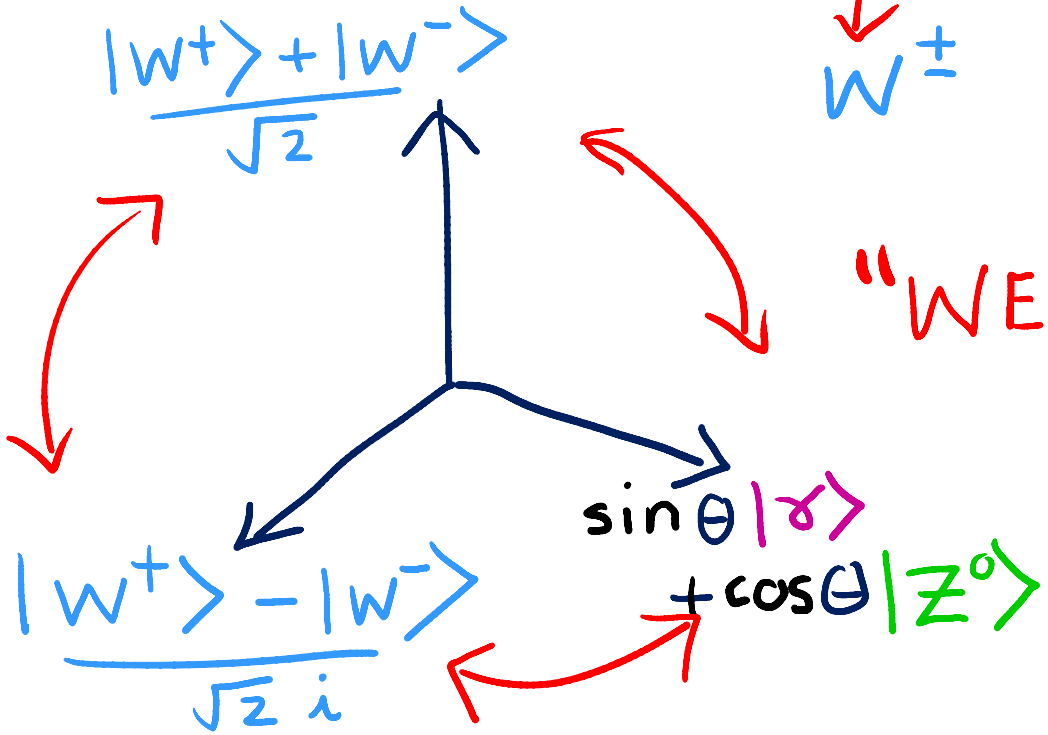
γ photon

Radioactive decay

$W^{\pm}$

Neutral current

Z^0

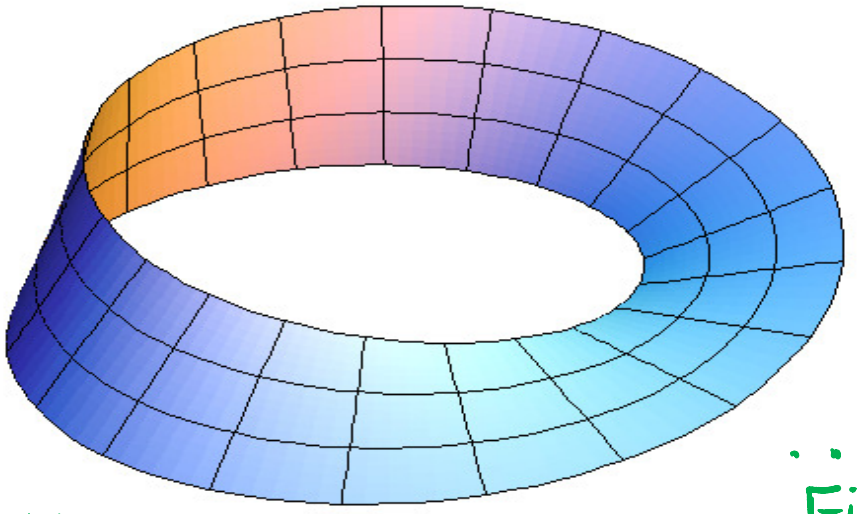


"WEAK ISOSPIN" SYMMETRY

RICH IN MATHEMATICAL BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists

~ (Quantized) Differential Geometry of FIBER BUNDLES to mathematicians



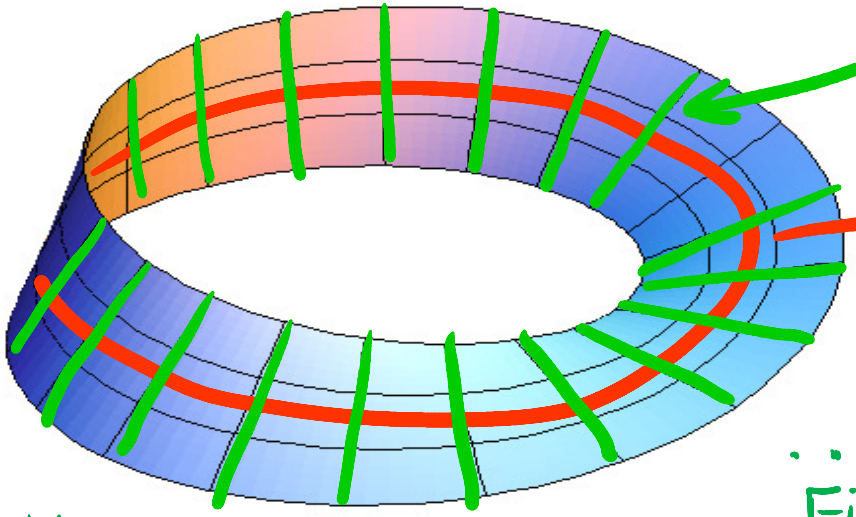
Möbius Strip ...

... as cartoon of Fiber Bundle

RICH IN MATHEMATICAL BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists

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Möbius Strip ...

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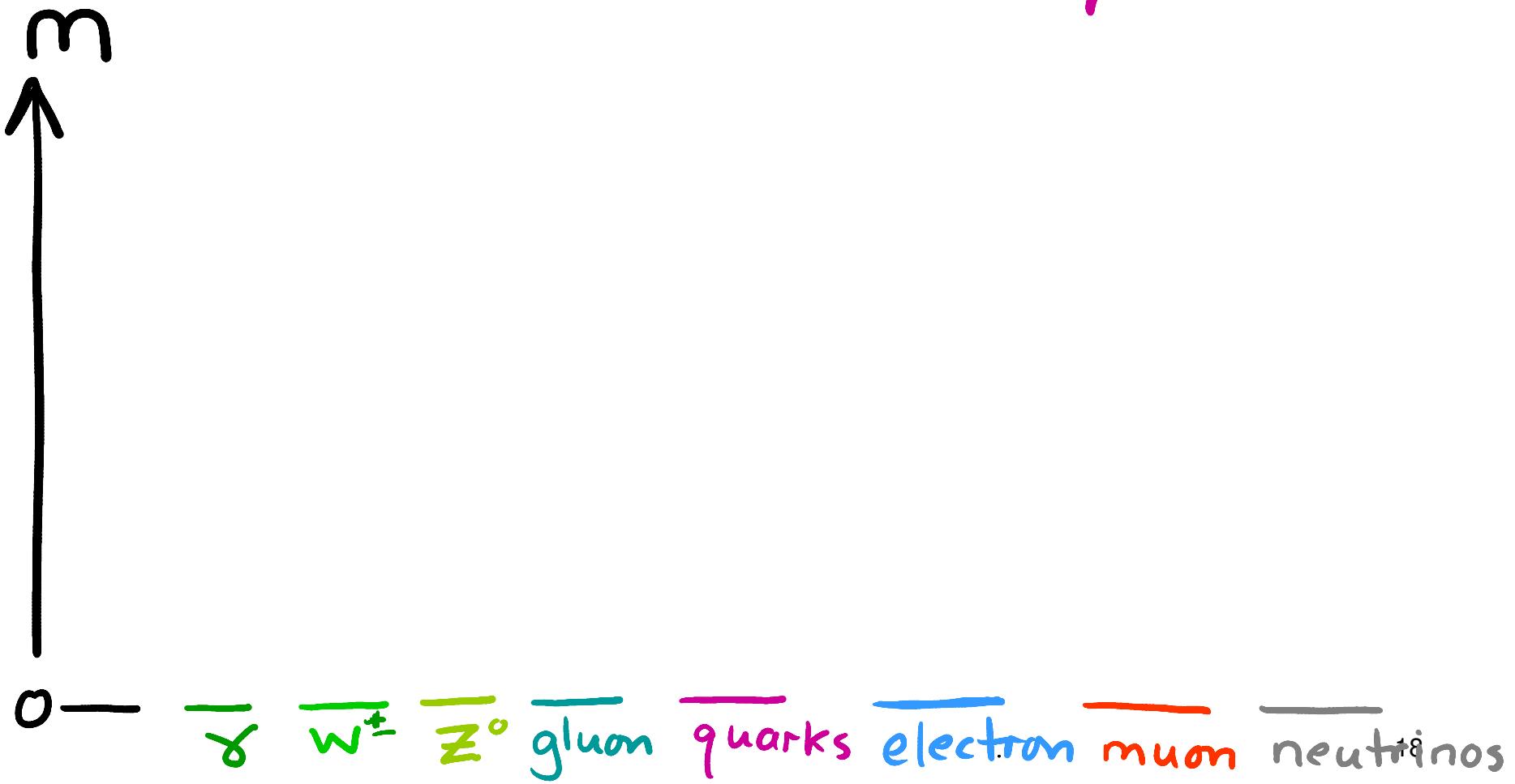
Electro Weak Unification

PREDICTS MASS SPECTRUM of all known elementary particles !

Electro Weak Unification

PREDICTS MASS SPECTRUM

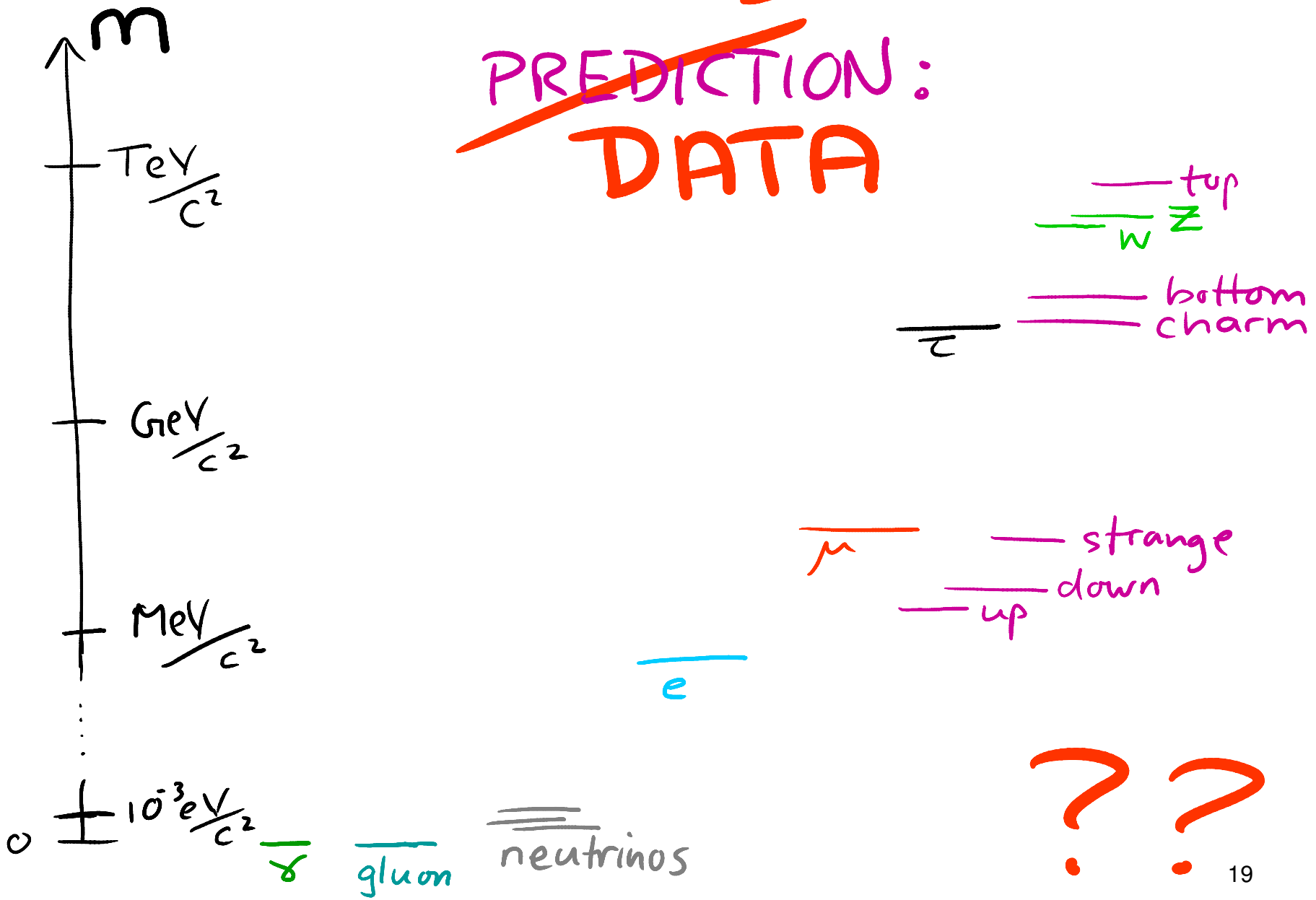
of all known elementary particles



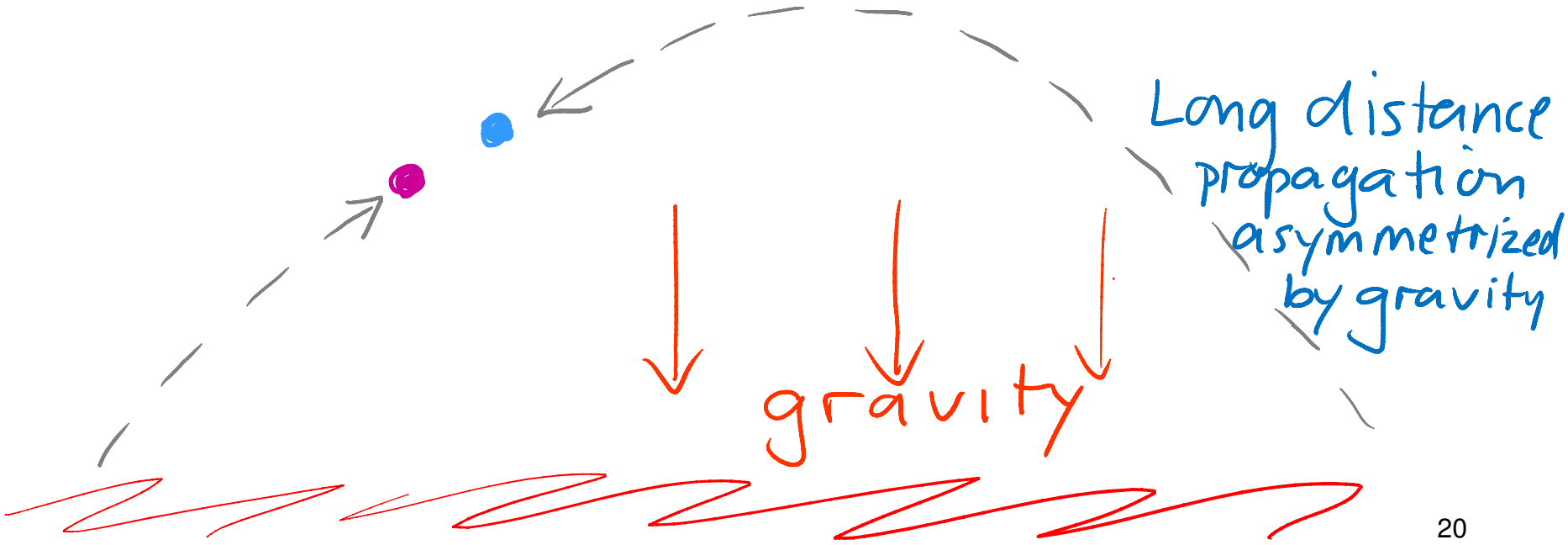
Electro Weak Unification

PREDICTION:

DATA

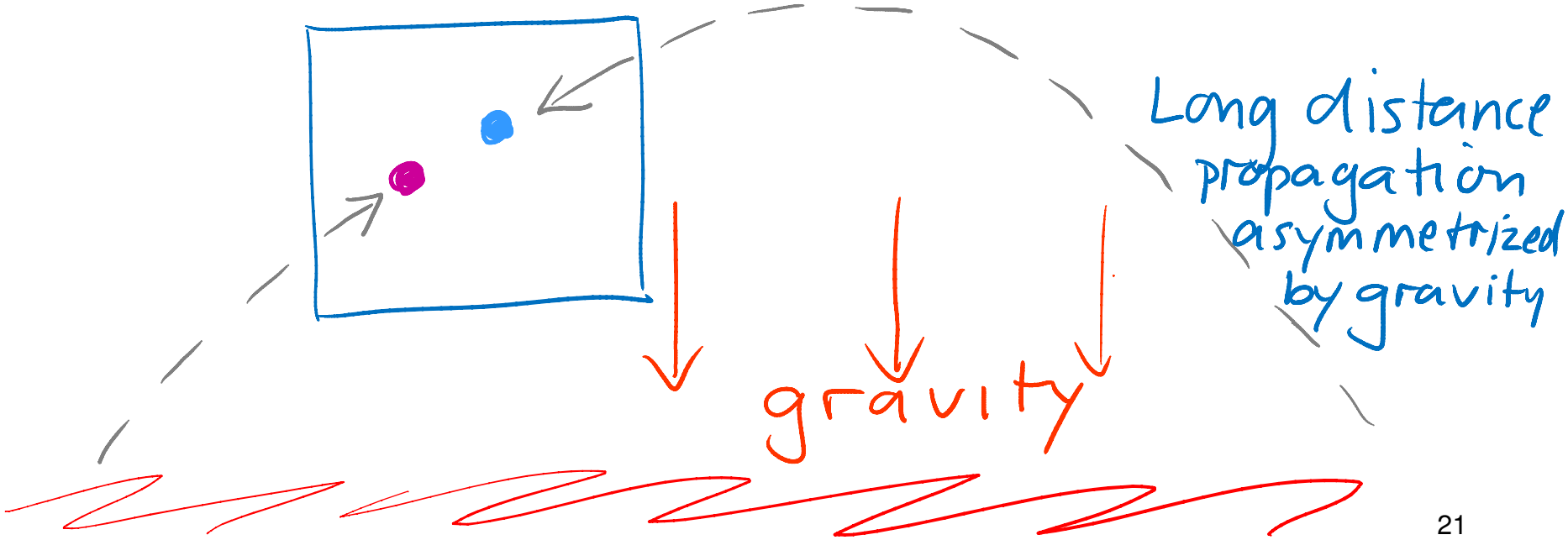


ANALOGY: Rotational ~~symmetry~~ by gravitational force field

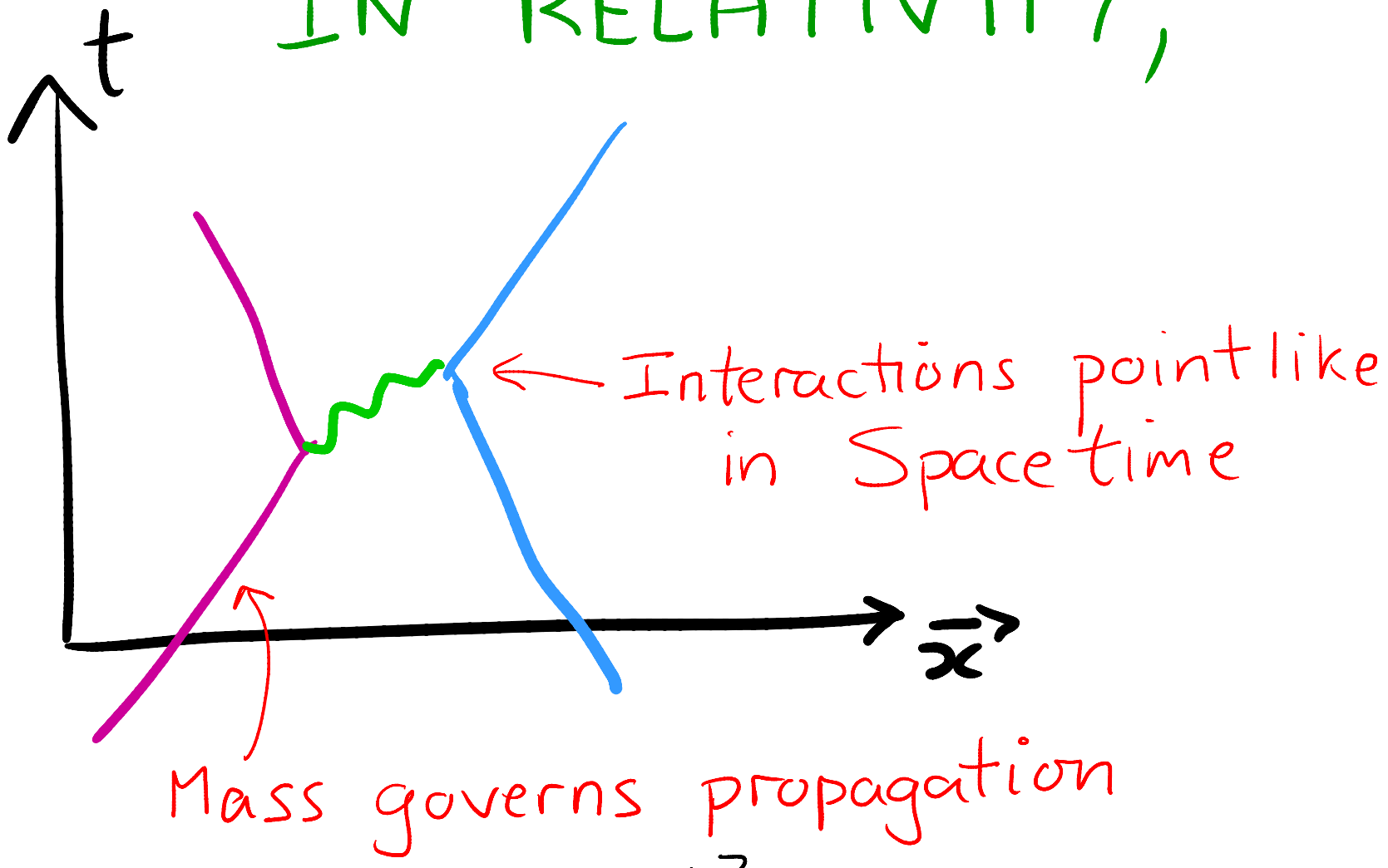


ANALOGY: Rotational ~~symmetry~~ by gravitational force field

Collisions at close quarters
≈ rotationally symmetric



IN RELATIVITY,



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

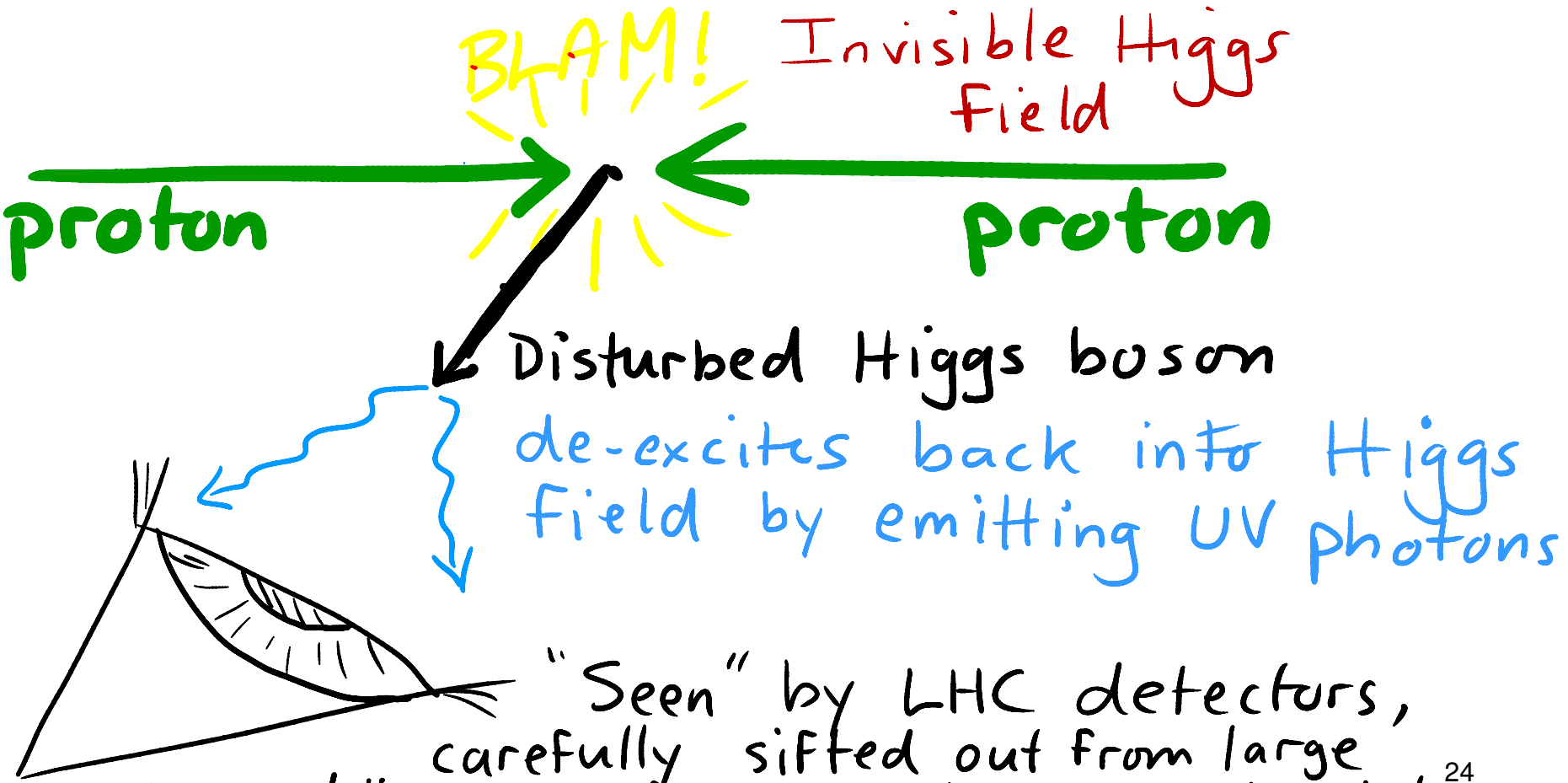
suggests ⟹ space filled by invisible, uniform scalar field "pointing" in "isospace"

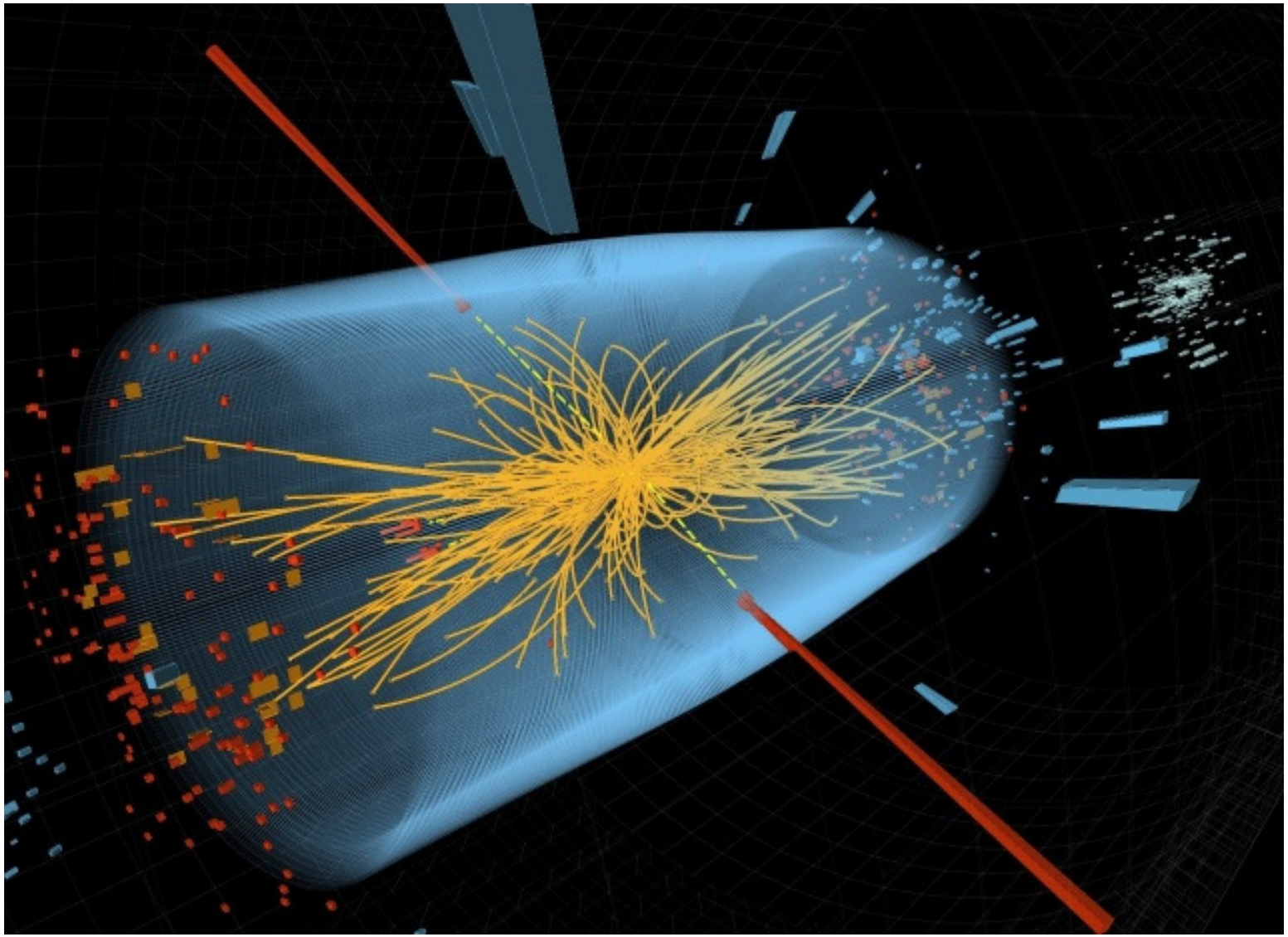
≡ Higgs field,

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!

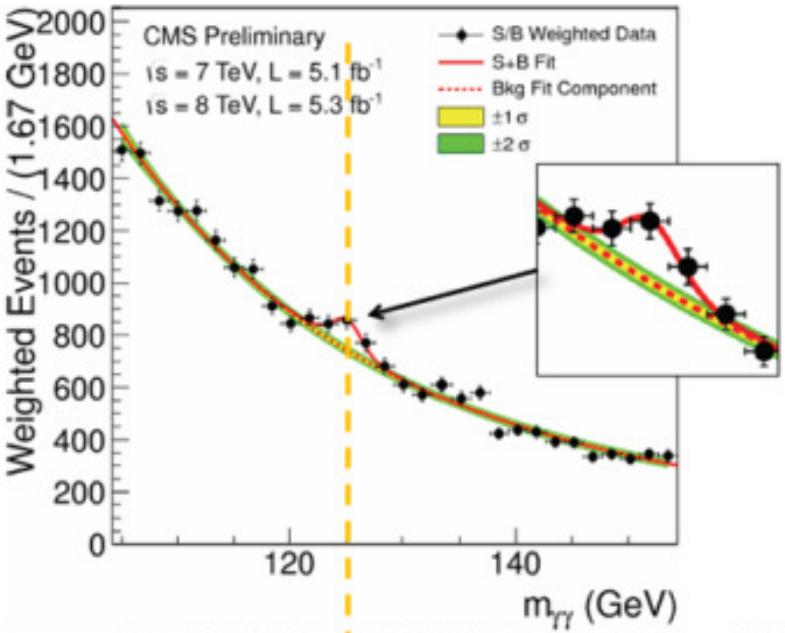


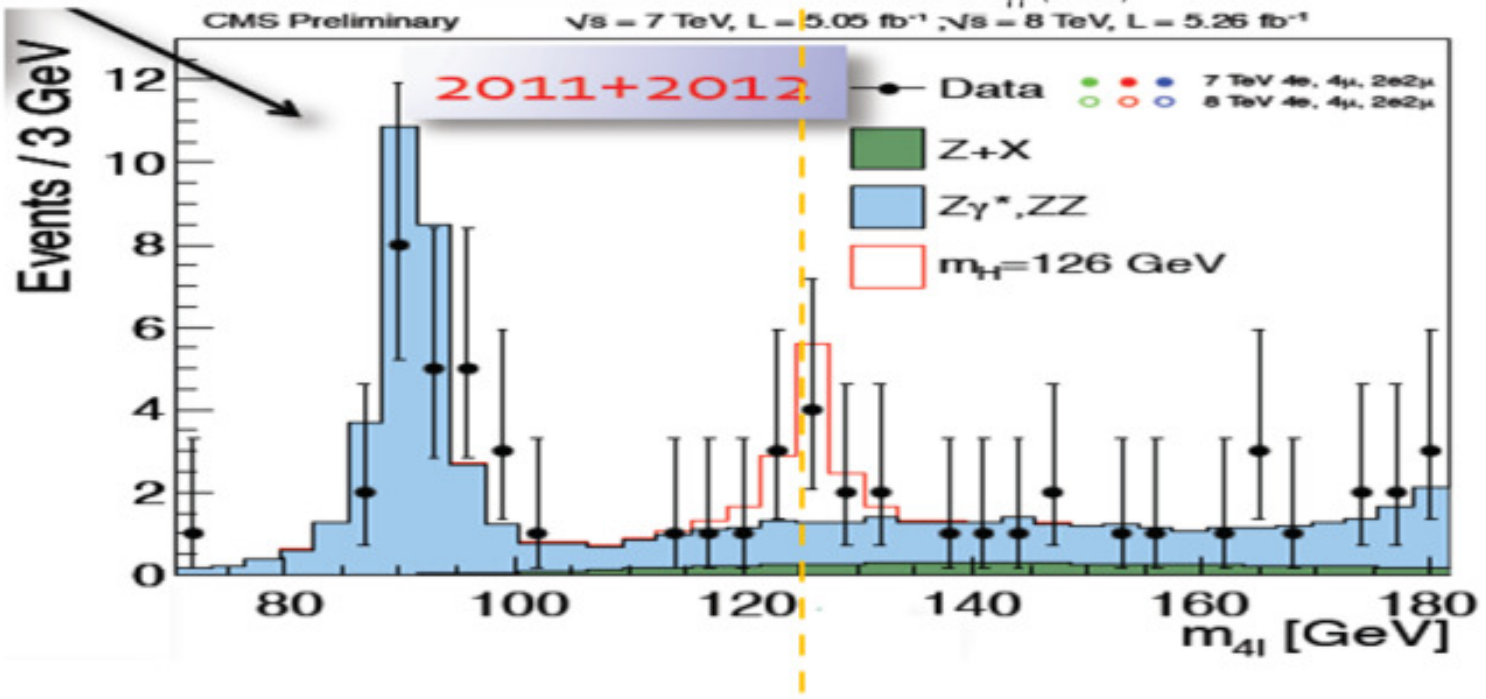


Candidate Higgs → 2 photon event in CMS detector

$m_{Higgs} = 125\ GeV$

Early LHC DATA





STANDARD MODEL NOW COMPLETE

Higgs boson discovery wins Nobel prize for theorists.

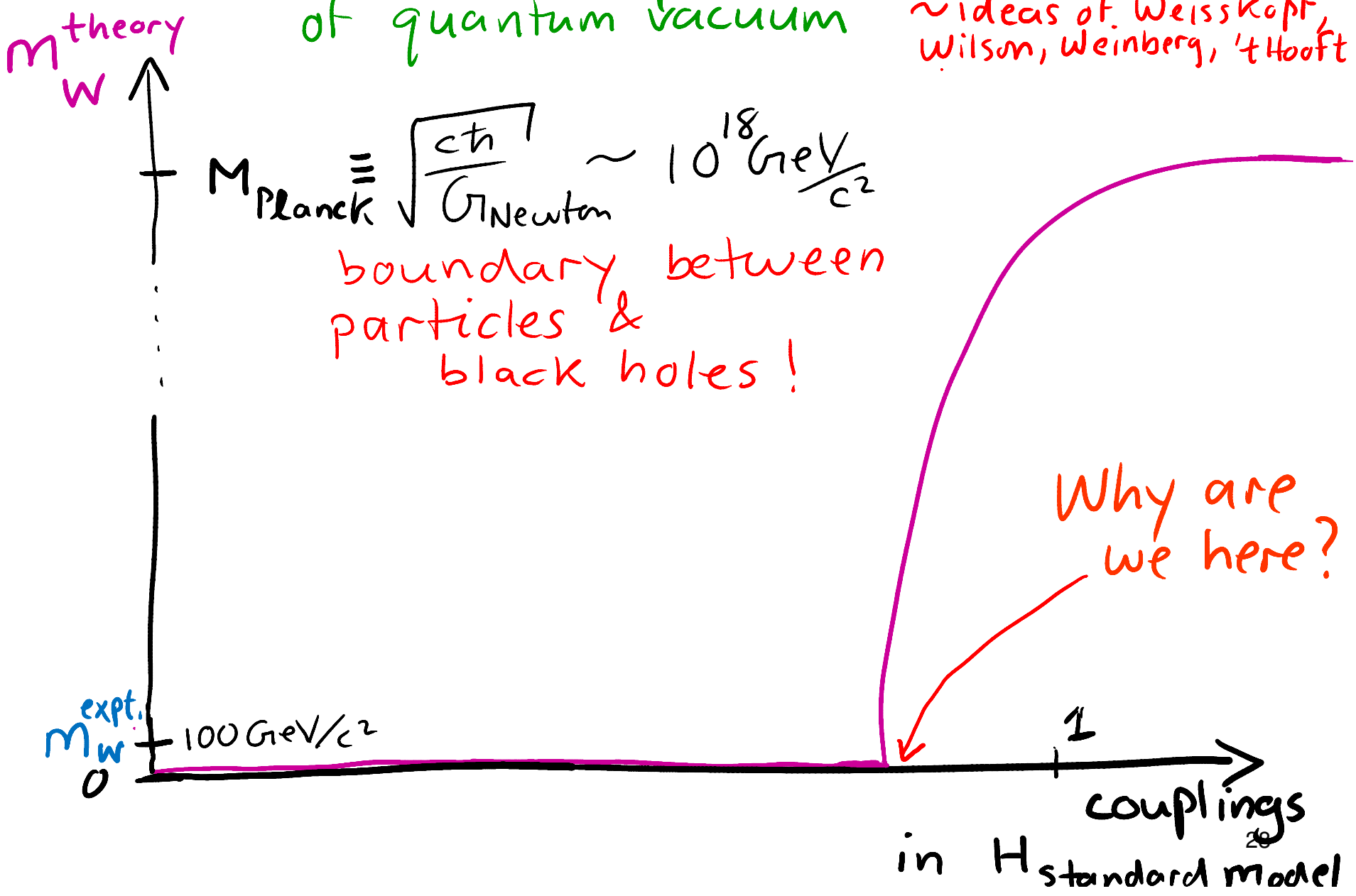
Standard Model brilliant culmination of decades of theory & experiment, deep insights into Nature.

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

HIERARCHY PROBLEM

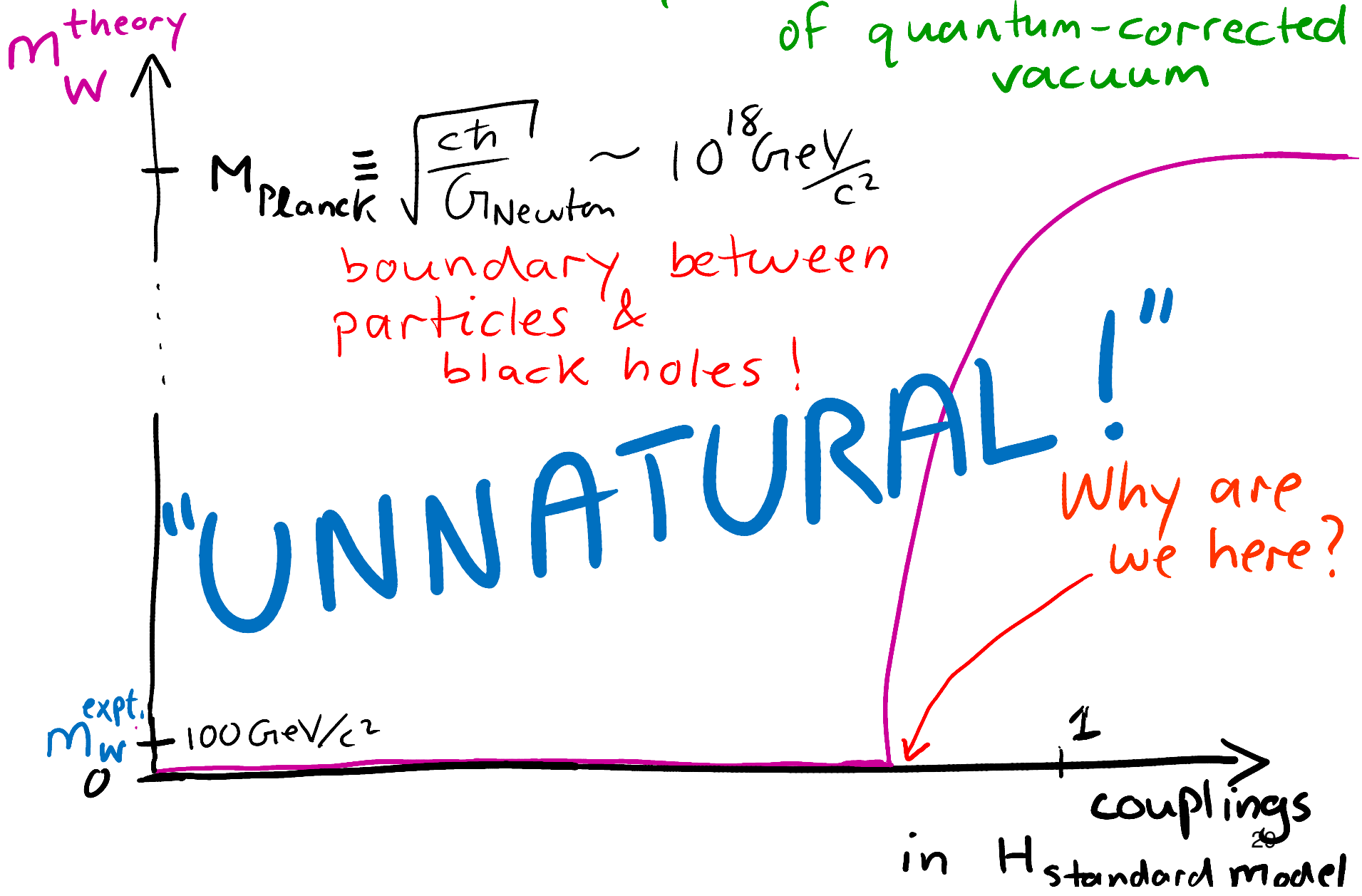
of quantum vacuum

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

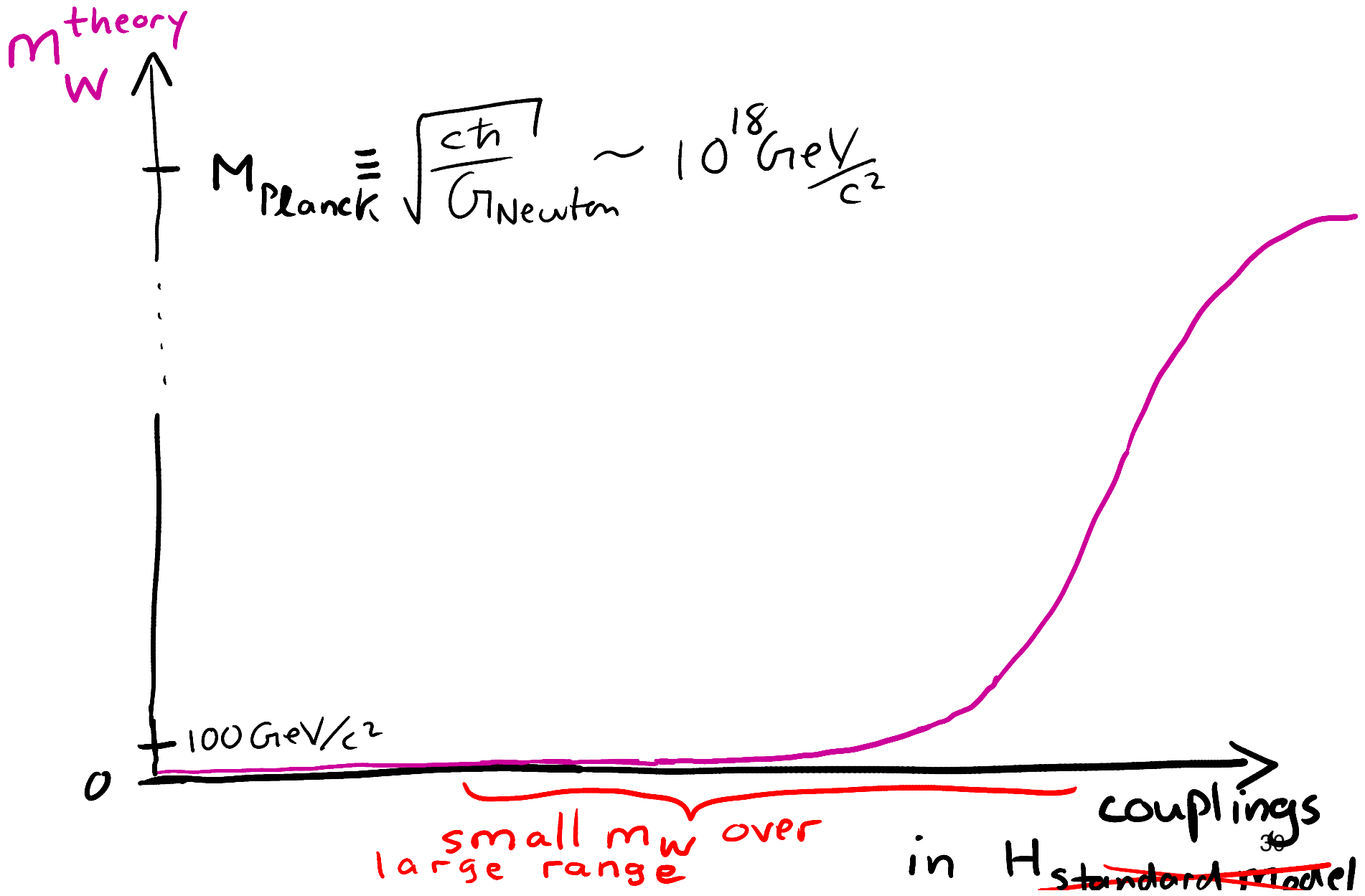


HIERARCHY PROBLEM

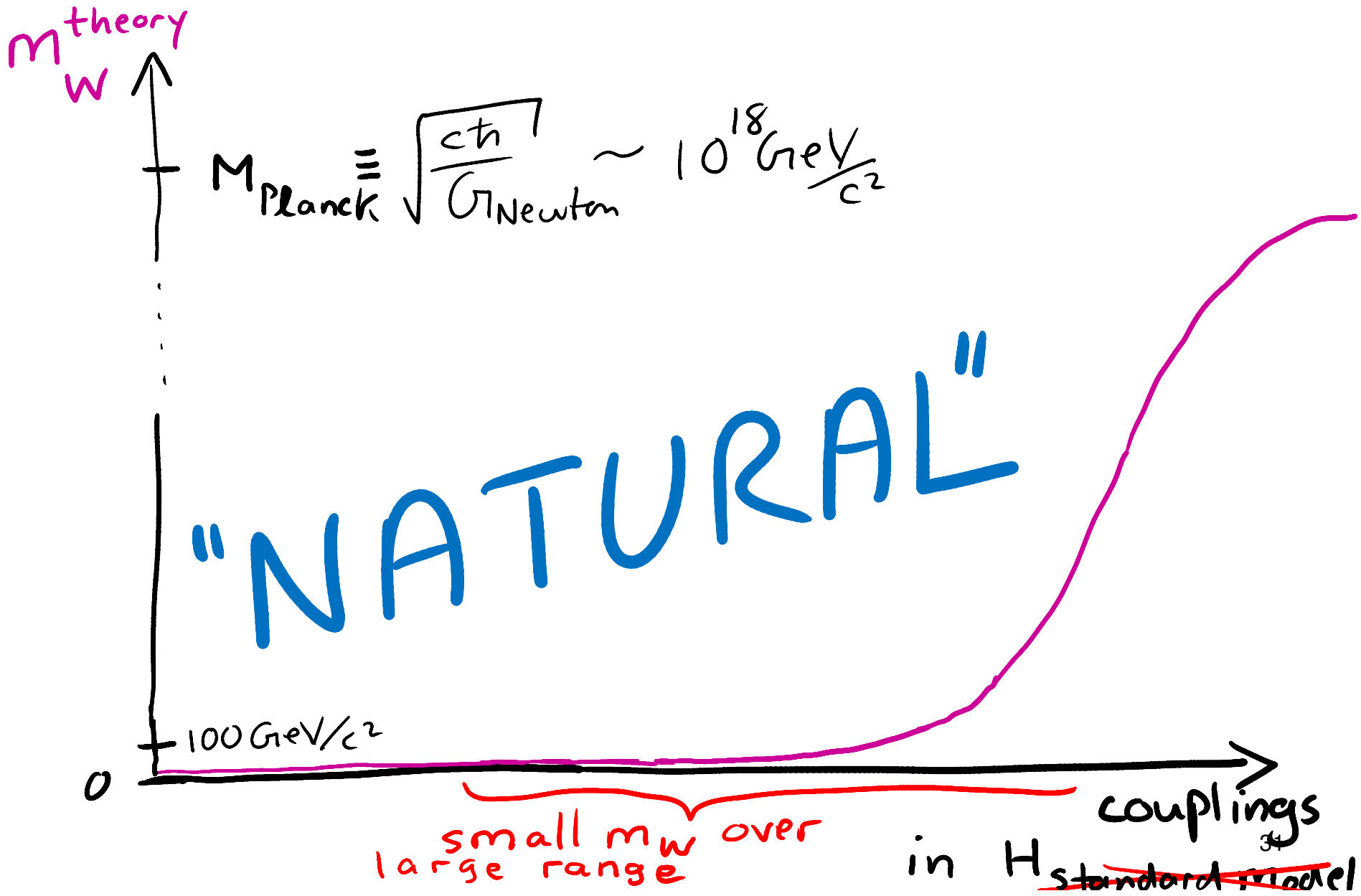
of quantum-corrected vacuum



A DIFFERENT VACUUM?



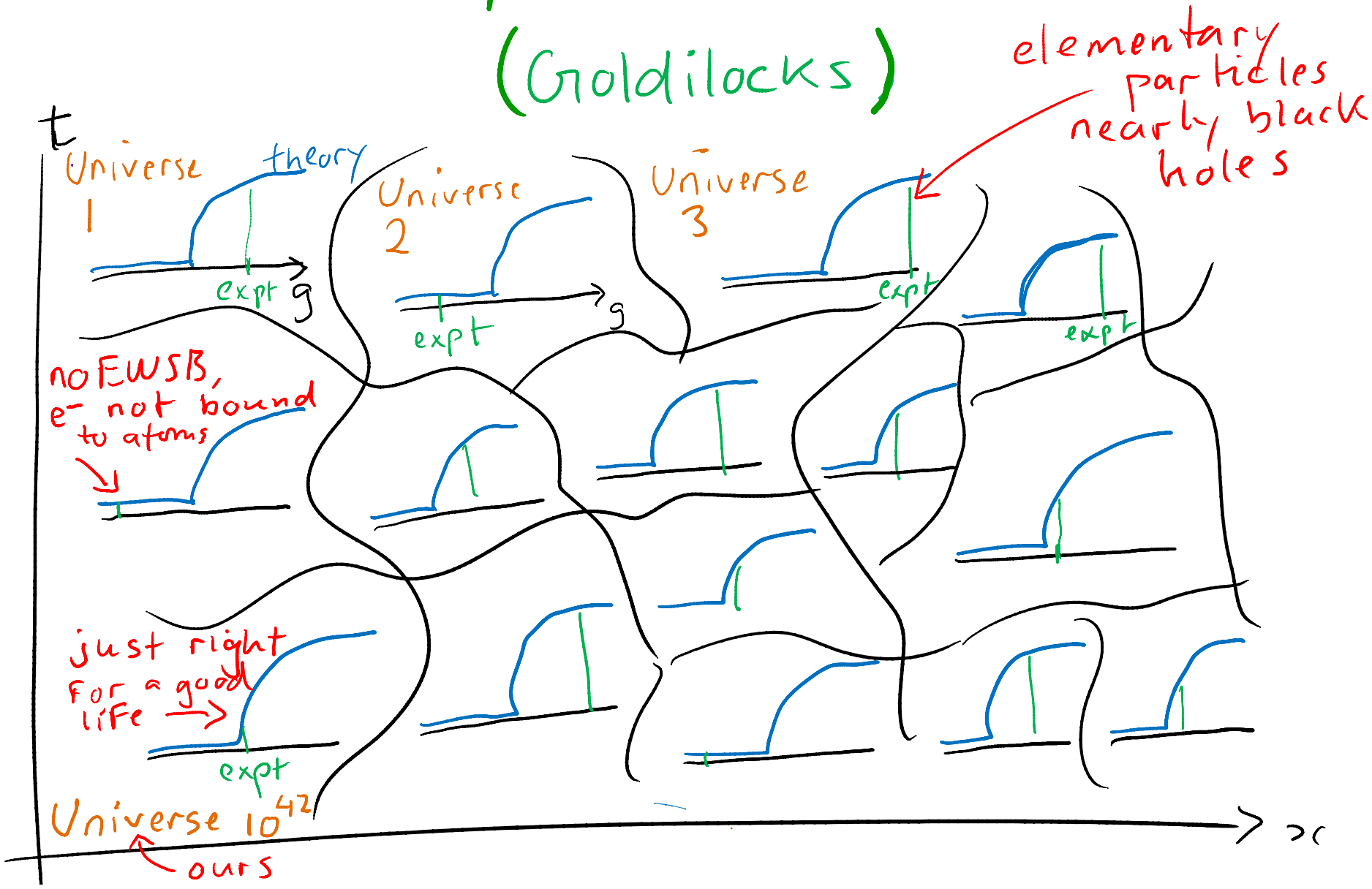
A DIFFERENT VACUUM?



OR A MULTI-VERSE ?

with Anthropic Selection

(Goldilocks)



OR A MULTI-VERSE ?
with Anthropic Selection

The end of Science?

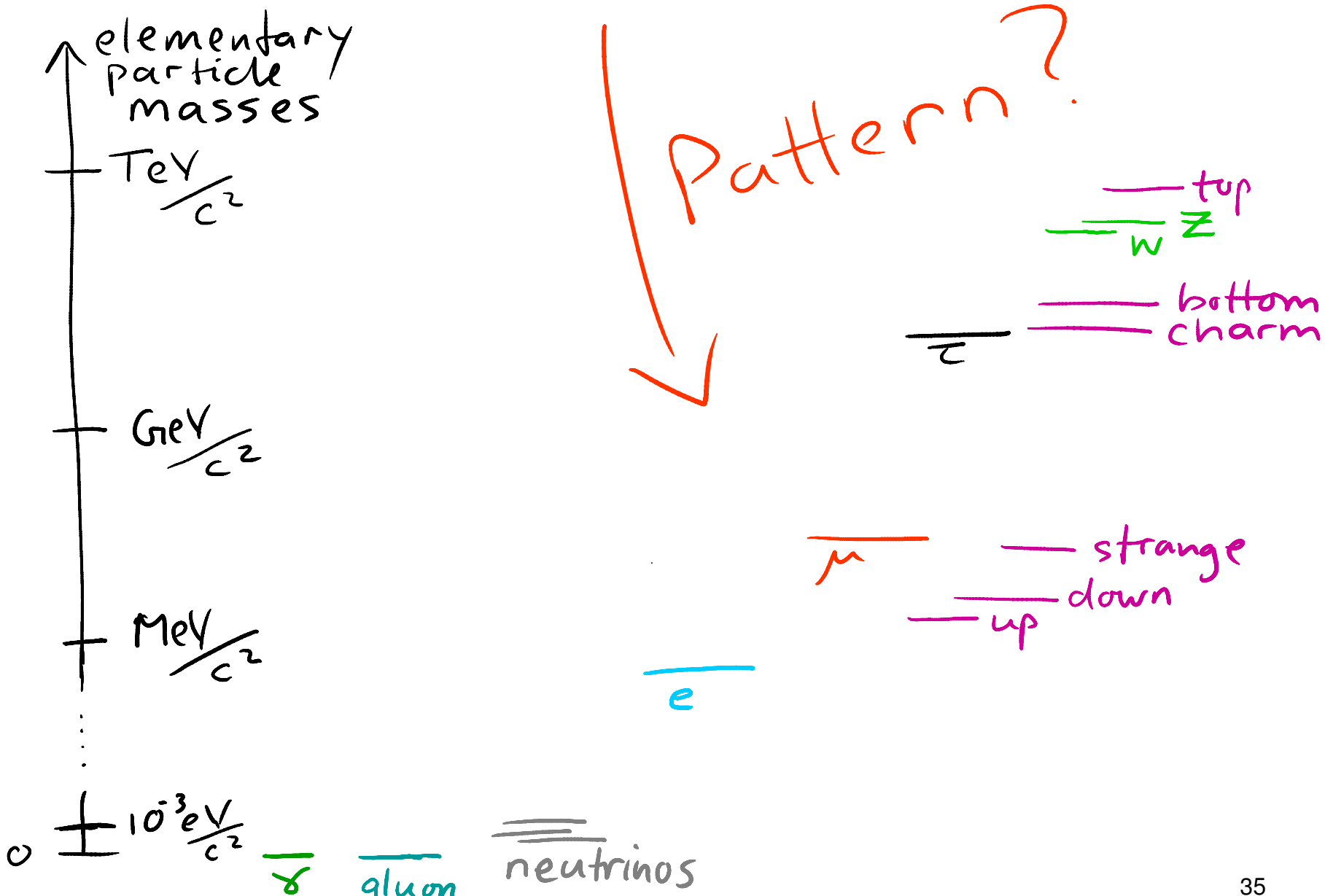
OR A MULTI-VERSE ?
with Anthropic Selection

The end of Science?

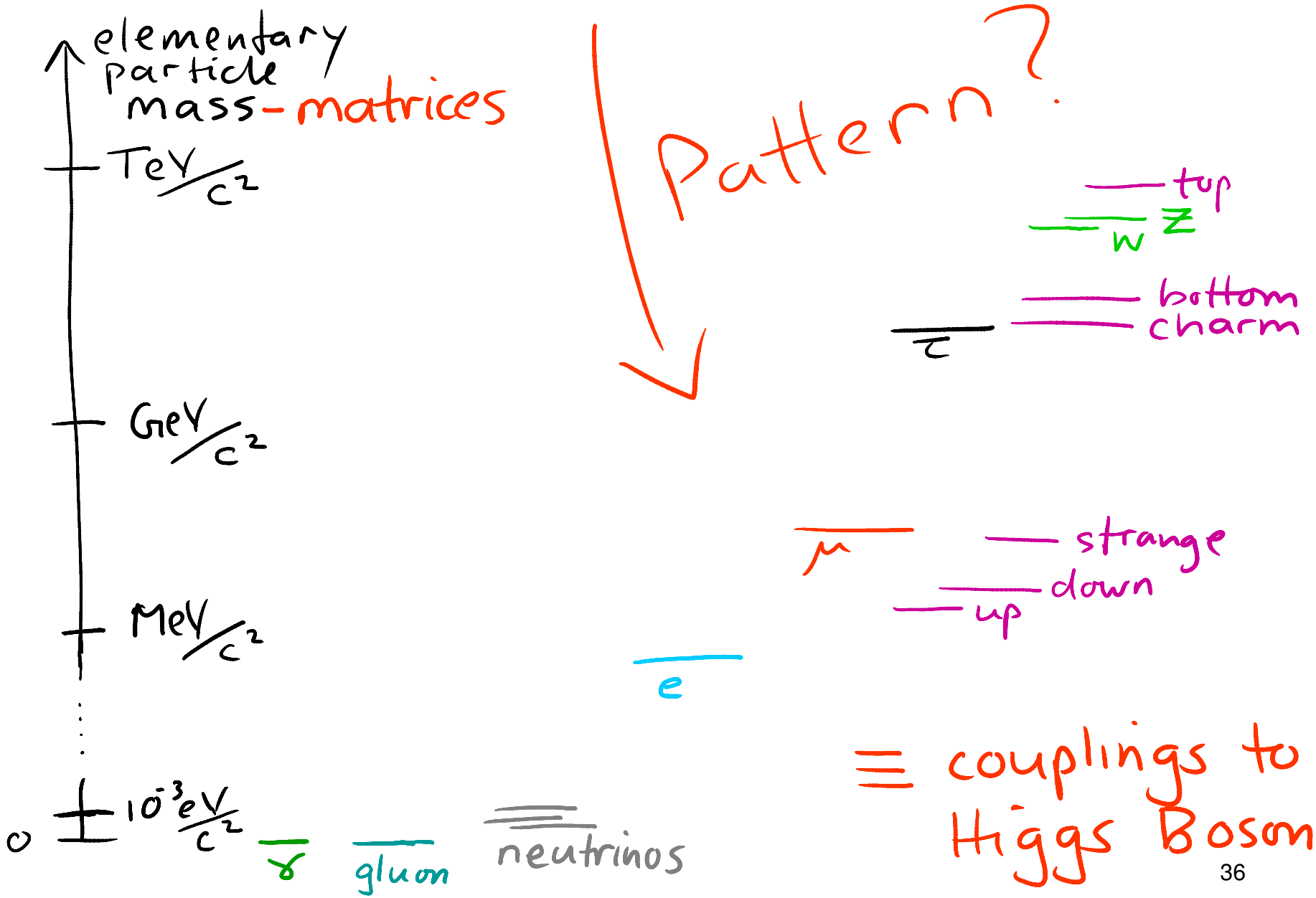
Most famous prediction
(rough order of magnitude)
when applied to UNNATURAL
COSMOLOGICAL CONSTANT
& ACCELERATION OF UNIVERSE

Weinberg '87

Flavor Puzzle

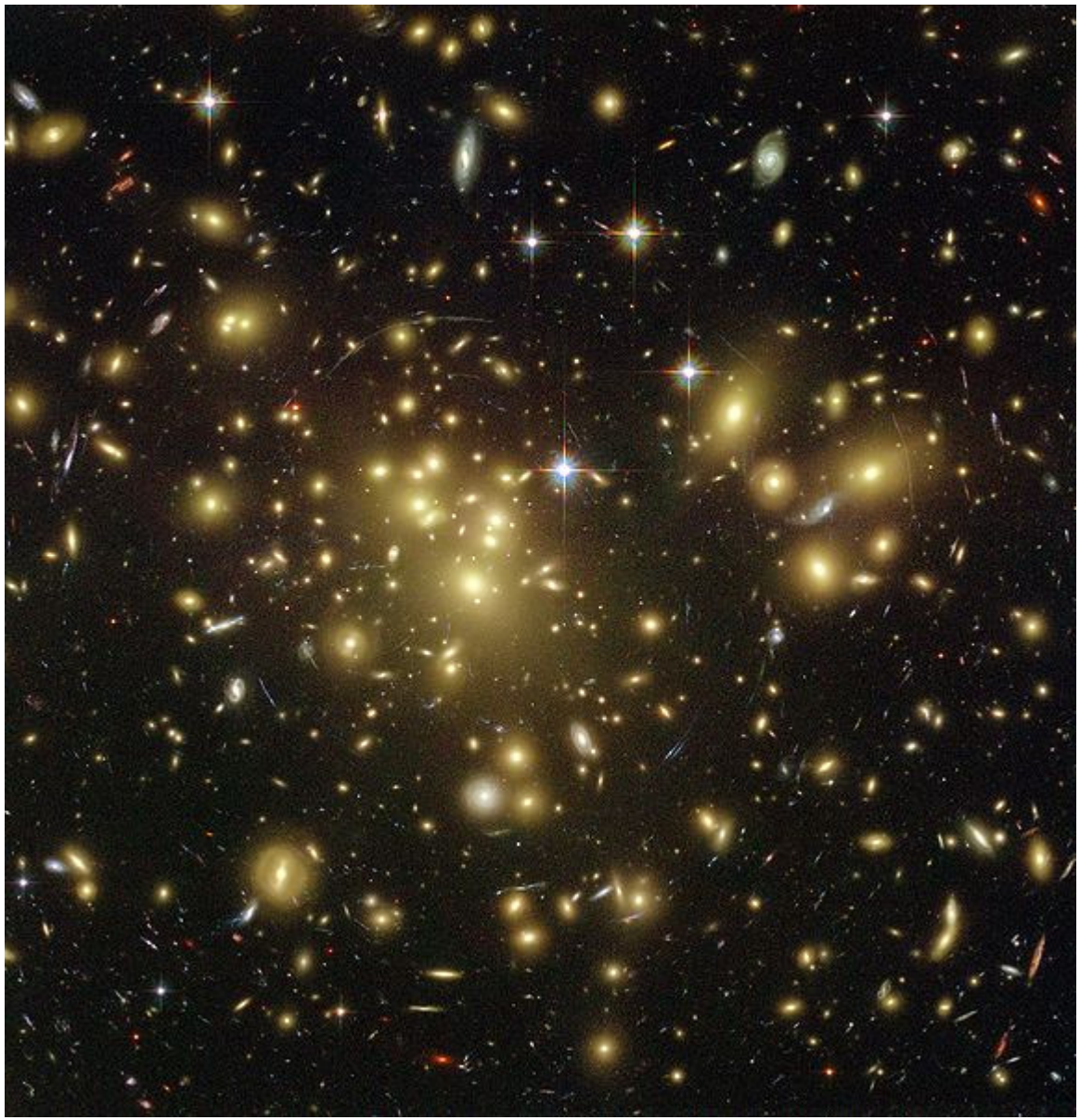


Flavor Puzzle



≡ couplings to Higgs Boson.

WHAT IS DARK MATTER?

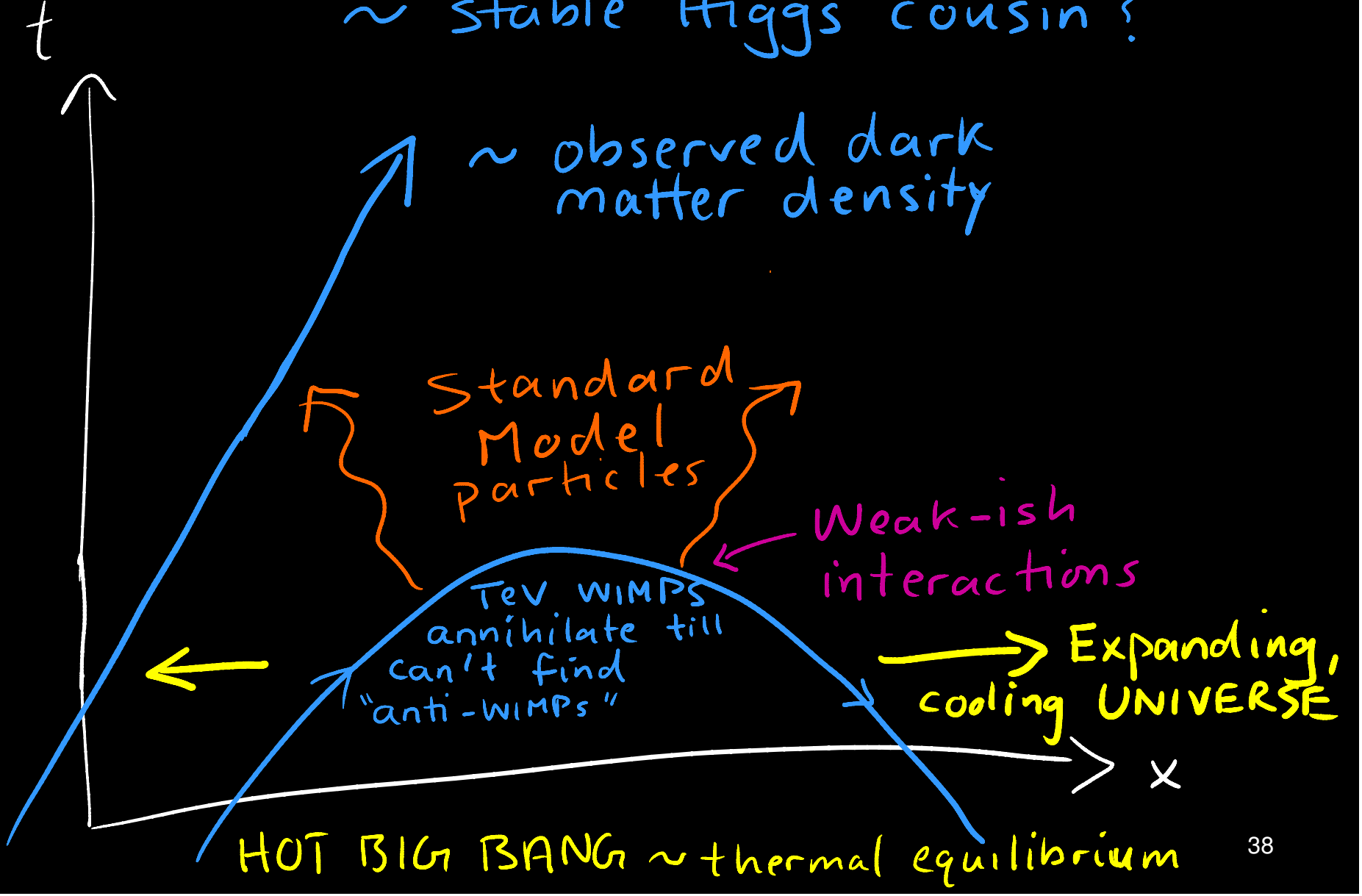


Galaxies distorted by gravitational lensing due to (otherwise) invisible Dark Matter.

Hubble Space Telescope Abell Cluster

"WIMP" DARK MATTER

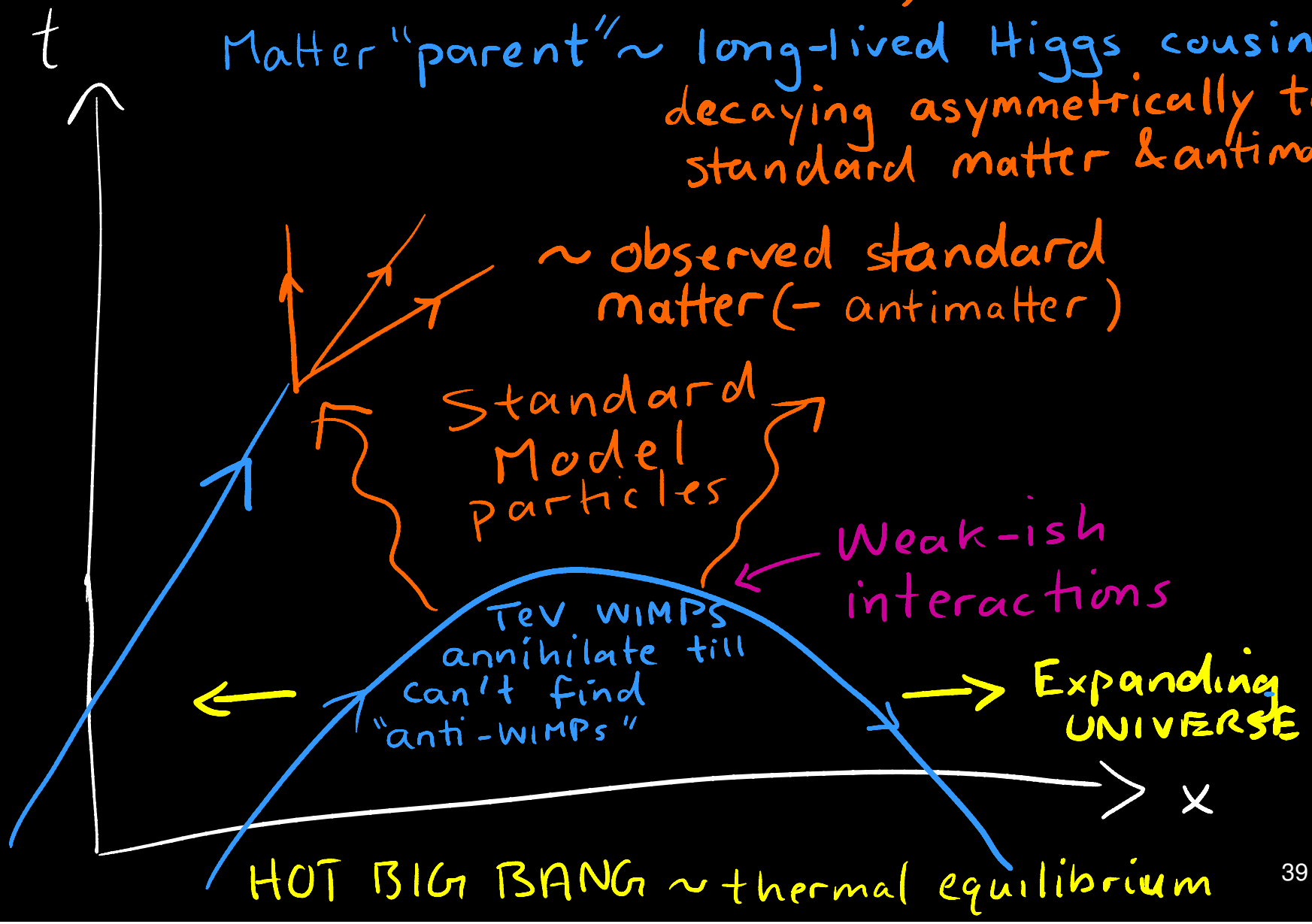
~ stable Higgs cousin?



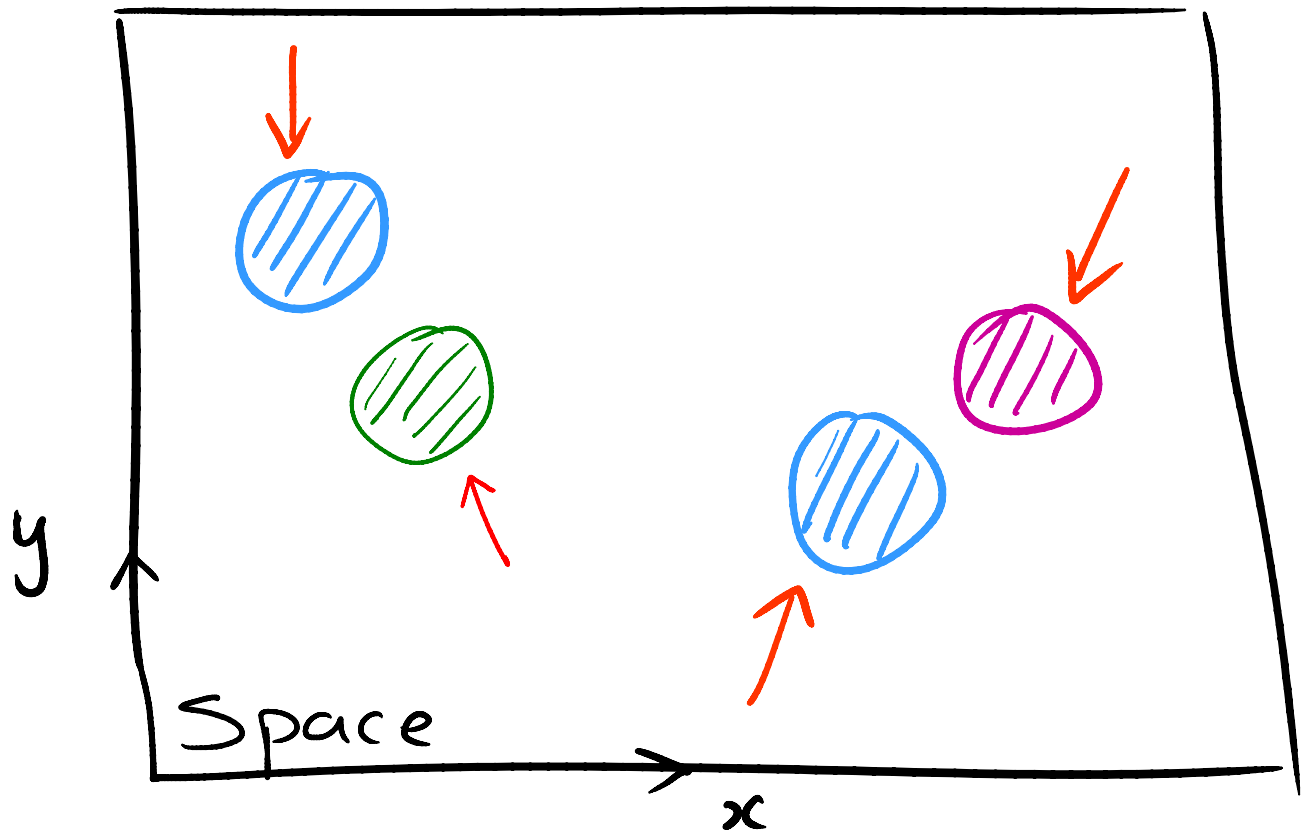
THE MATTER/ANTIMATTER ASYMMETRY FOR WIMPS

Cui, Sundrum '13

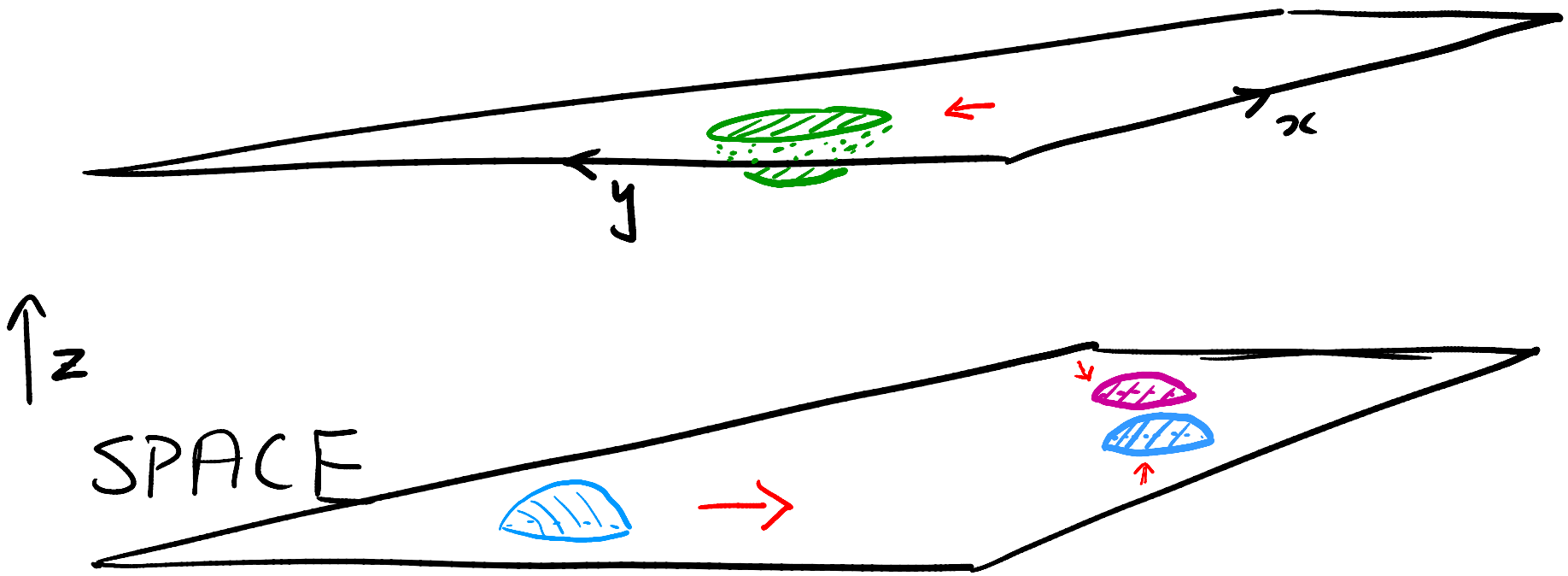
Matter "parent" ~ long-lived Higgs cousin ? decaying asymmetrically to standard matter & antimatter



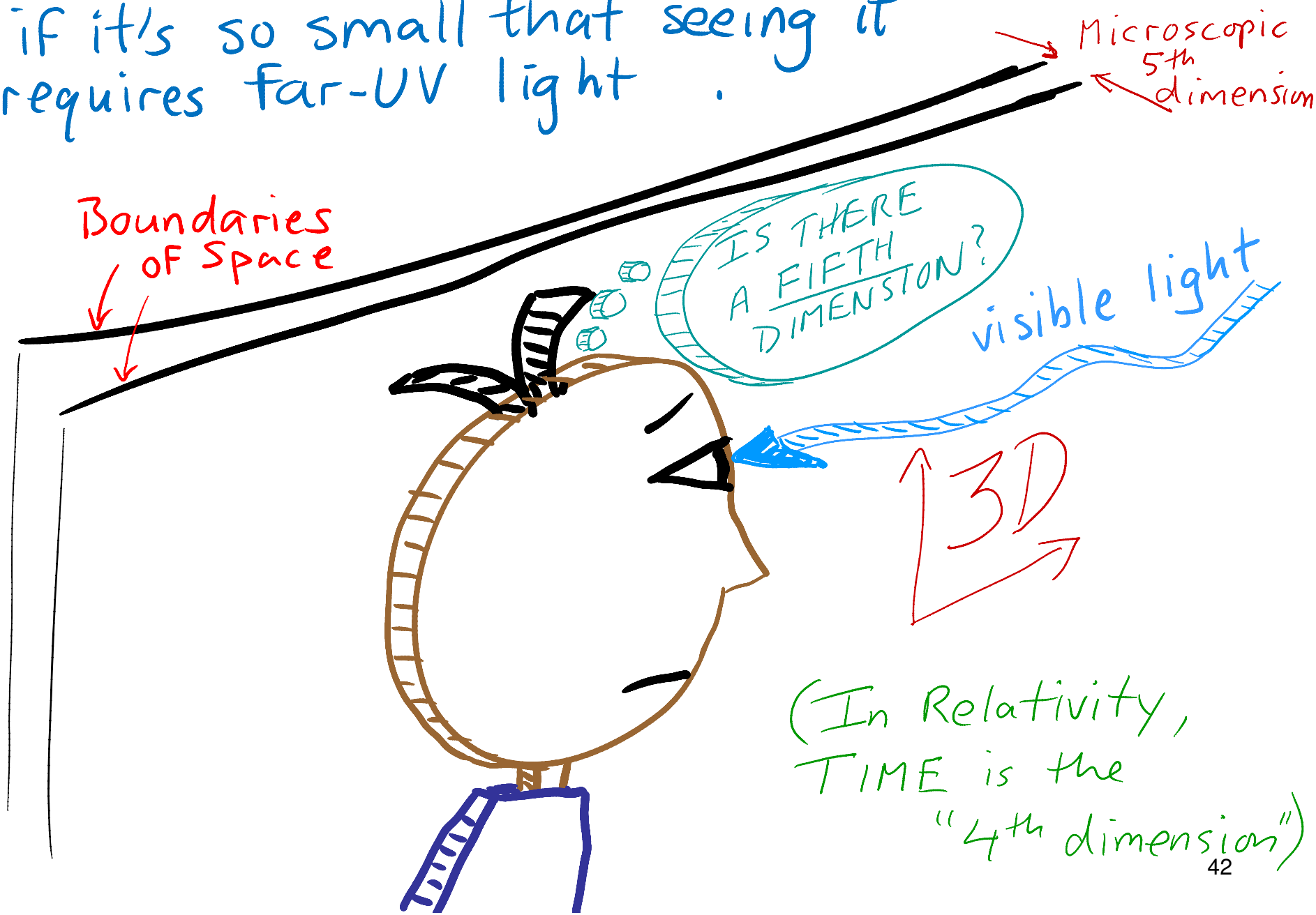
THE ANSWERS TO THESE PUZZLES MAY BE HIDDEN...



IN NEW DIMENSIONS!



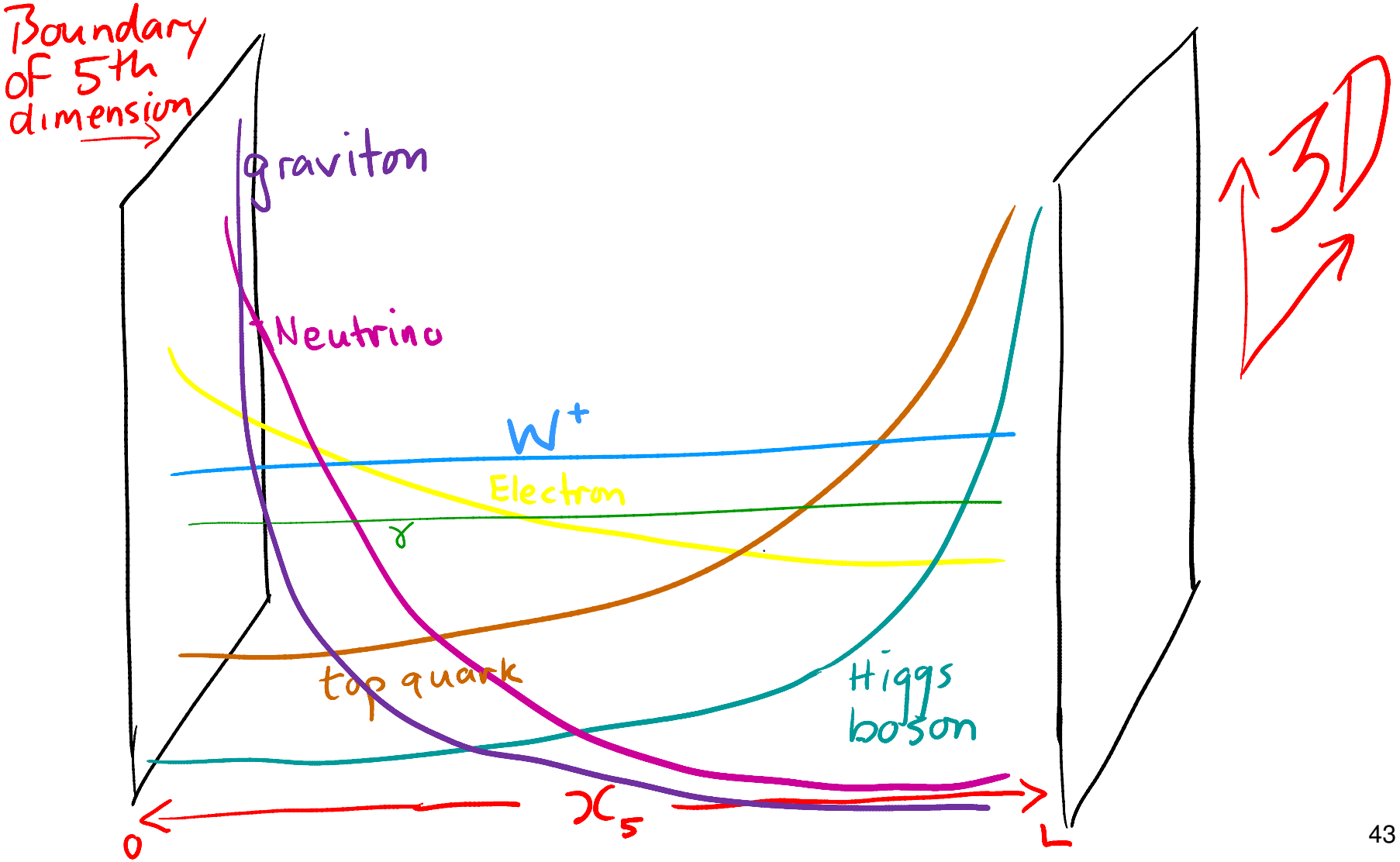
A NEW DIMENSION COULD HIDE if it's so small that seeing it requires far-UV light .



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

5D CHAOS ⟶ 4D COSMOS

Different species have different wavefunction solutions to their wave equations



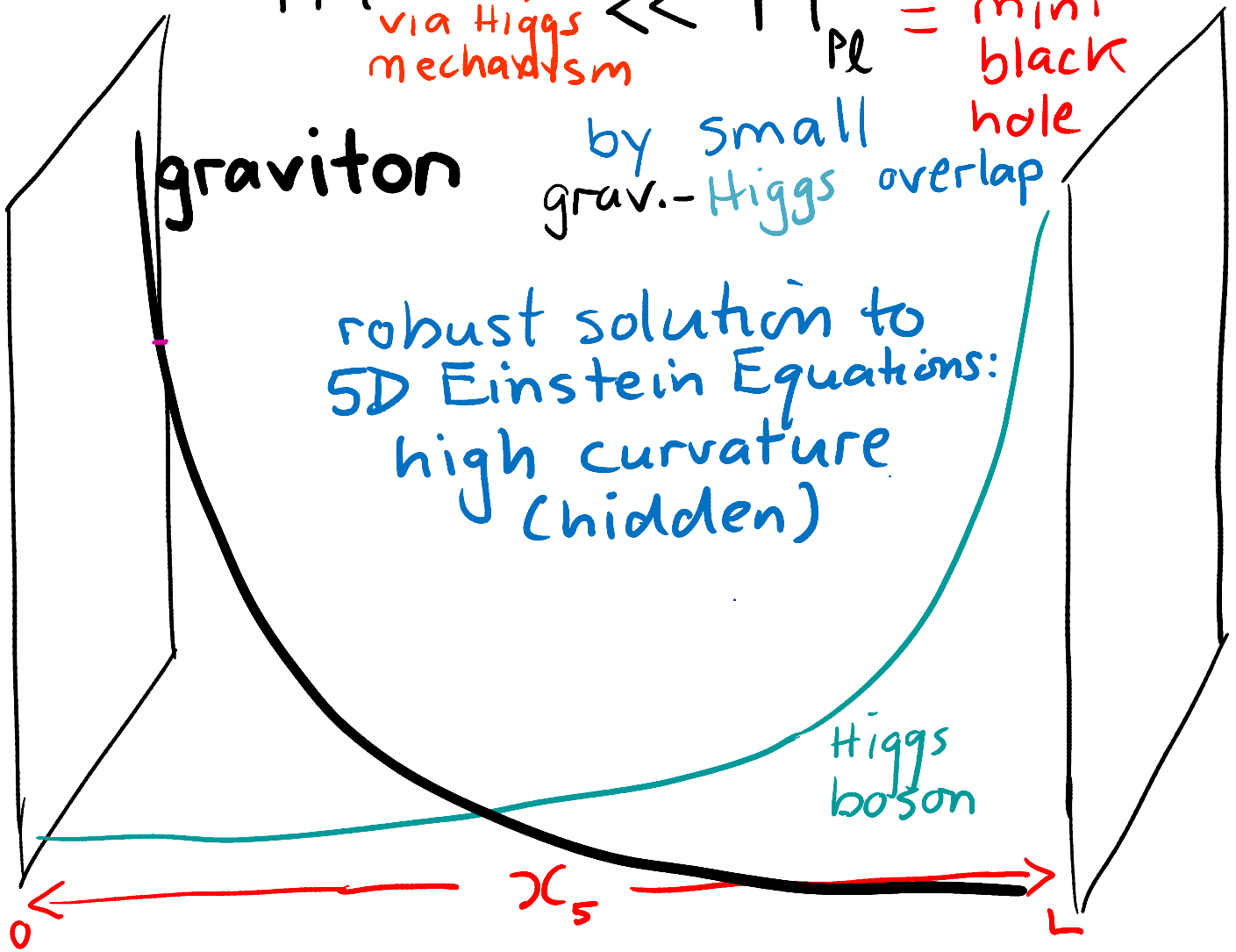
Warped Compactification solves the Hierarchy Problem...

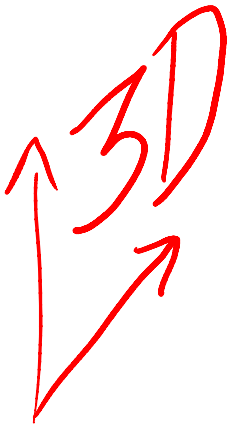
Randall, Sundrum '99

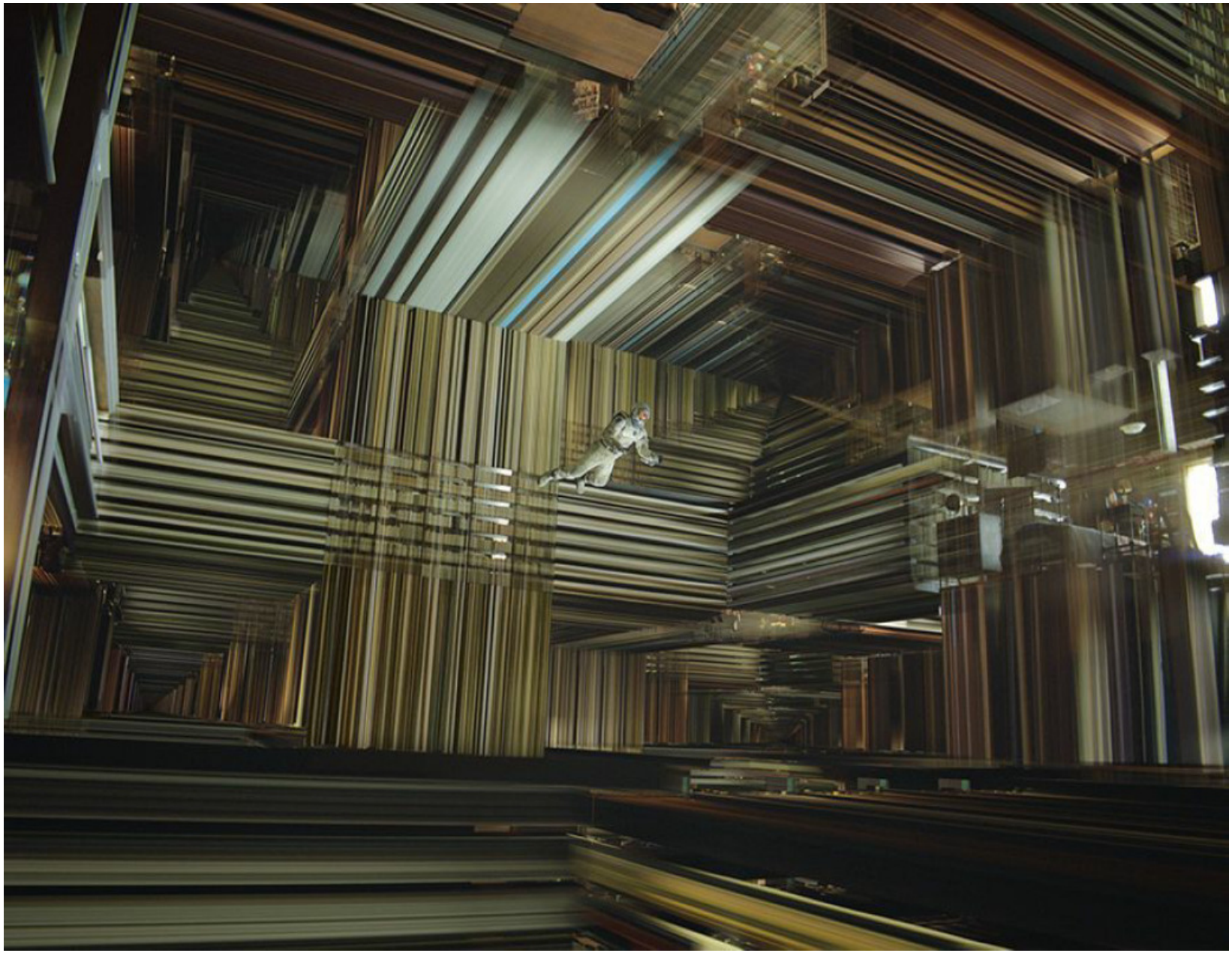
m via Higgs mechanism $\ll M_{Pl} \equiv$ mini black hole

graviton

by small grav.-Higgs overlap



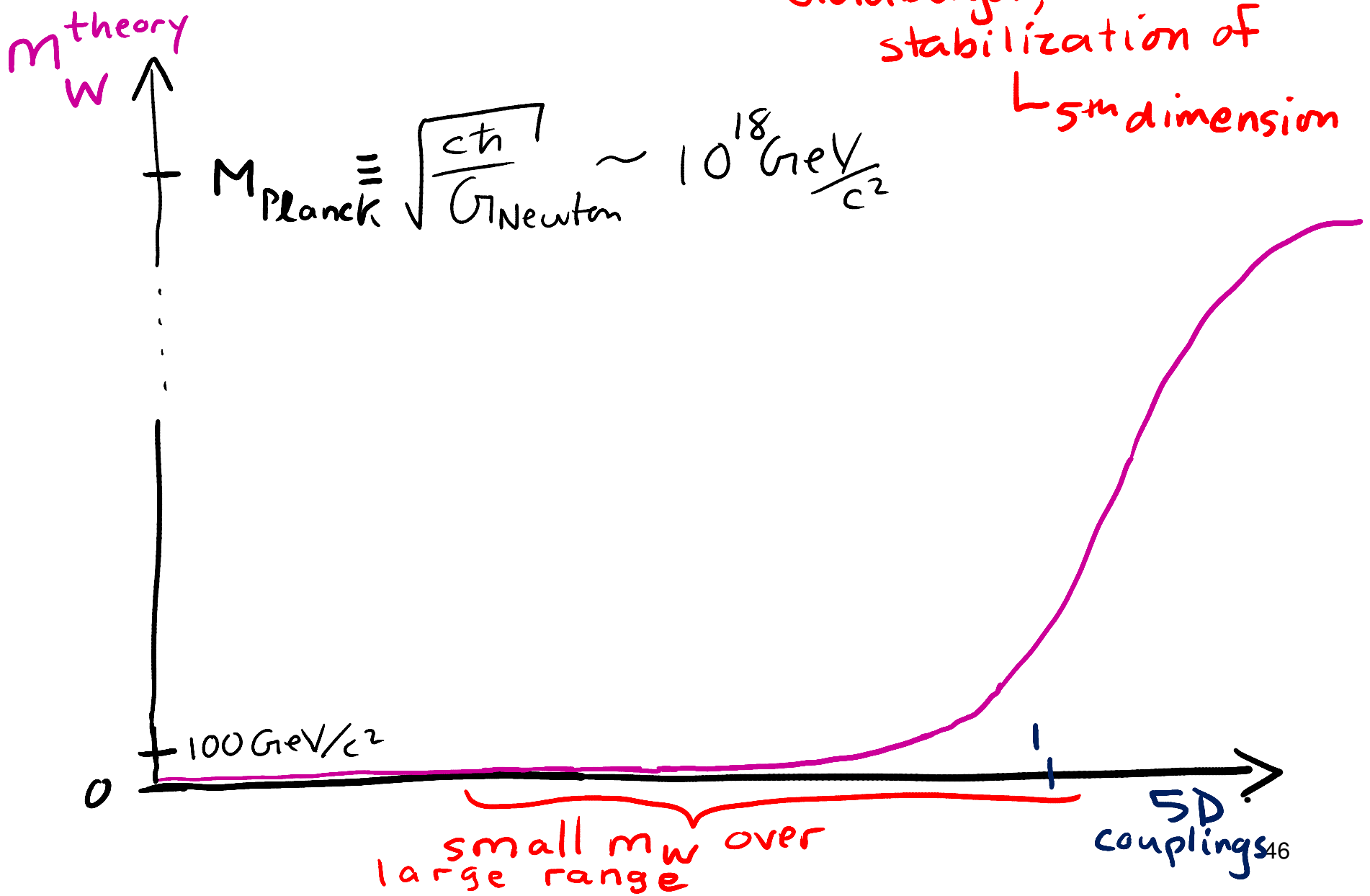




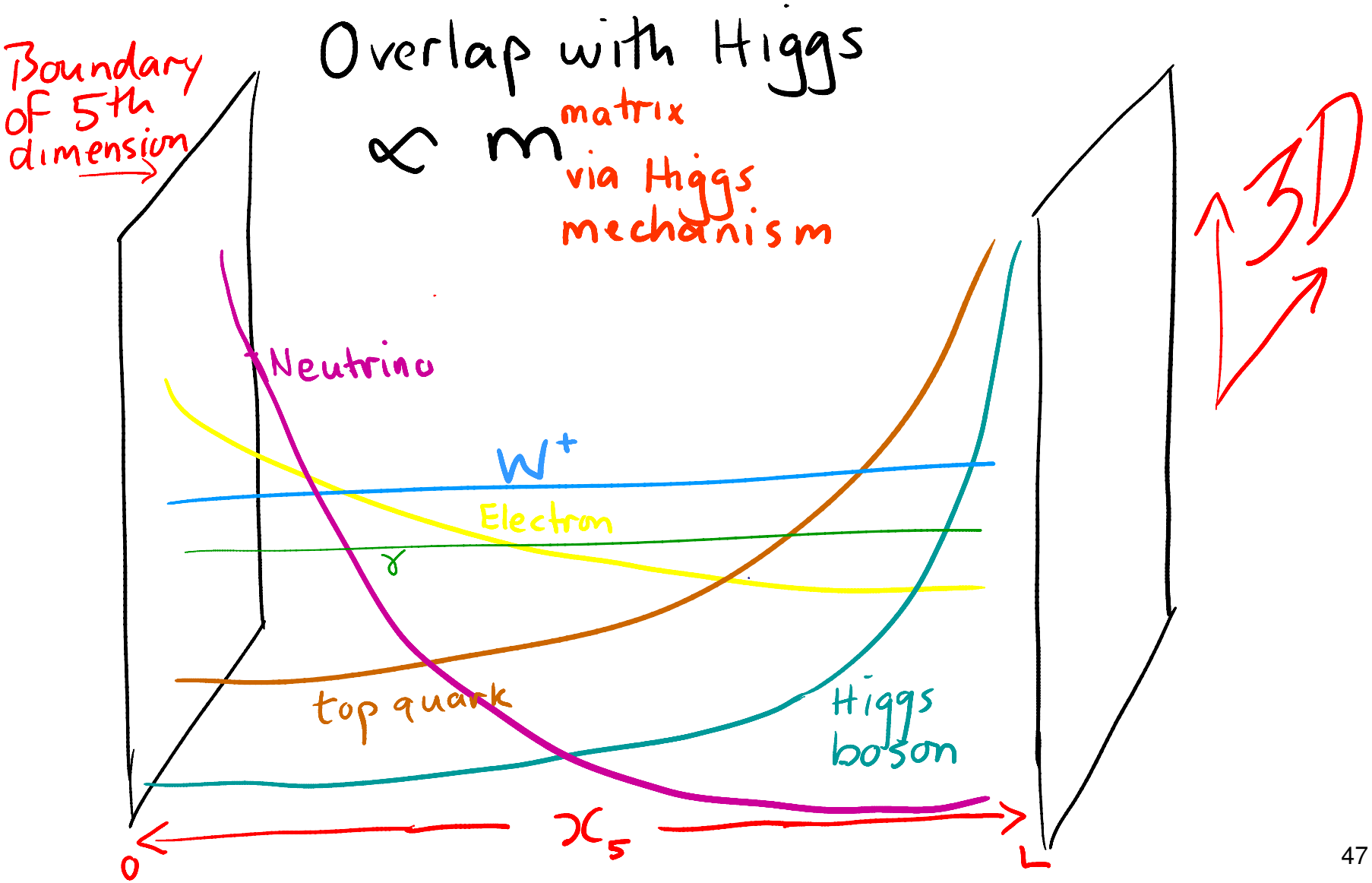
Some of the physics inspiration behind "Interstellar"

...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

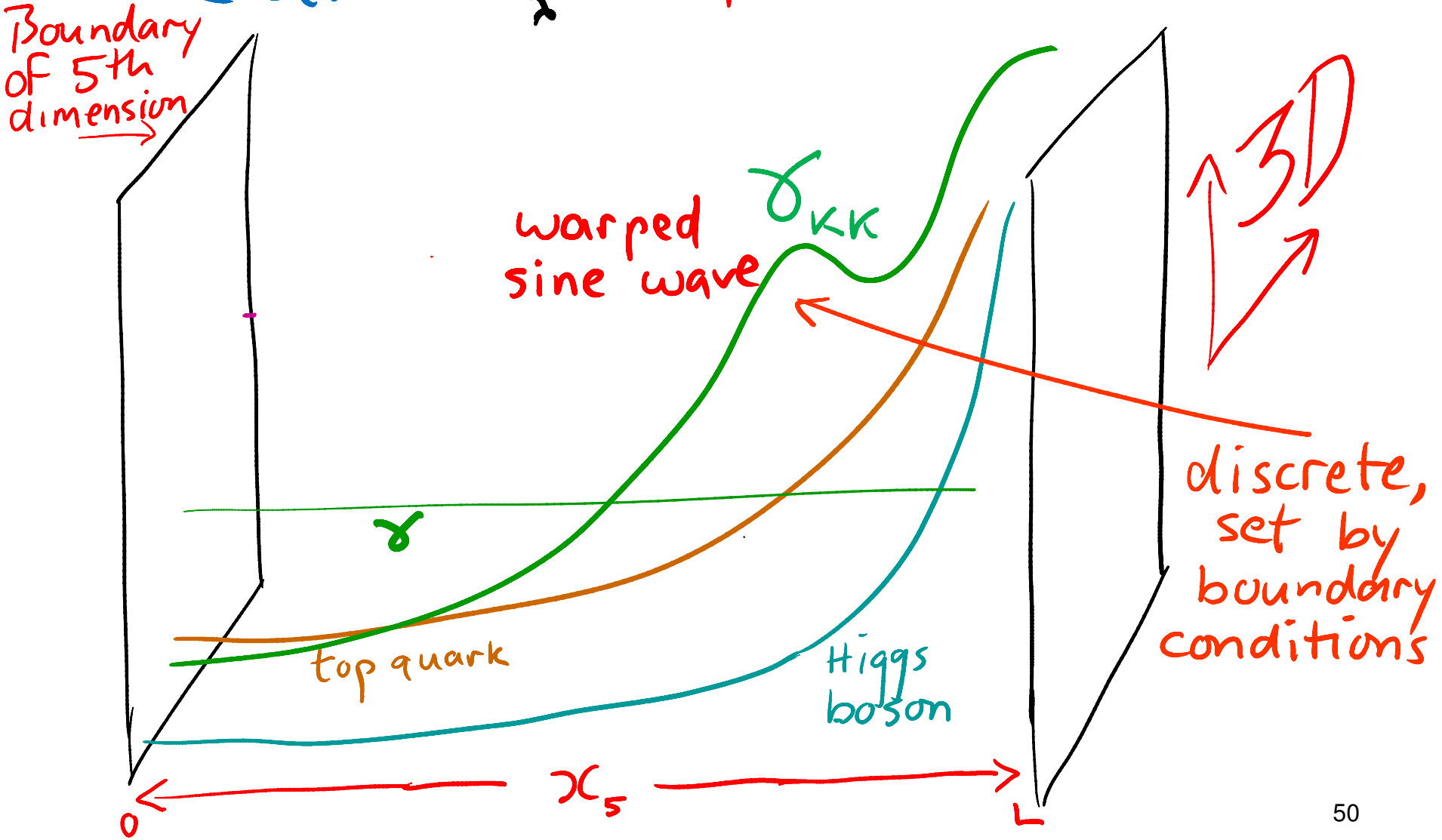
& test & constrain it by high-precision pre-LHC data

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 . . .

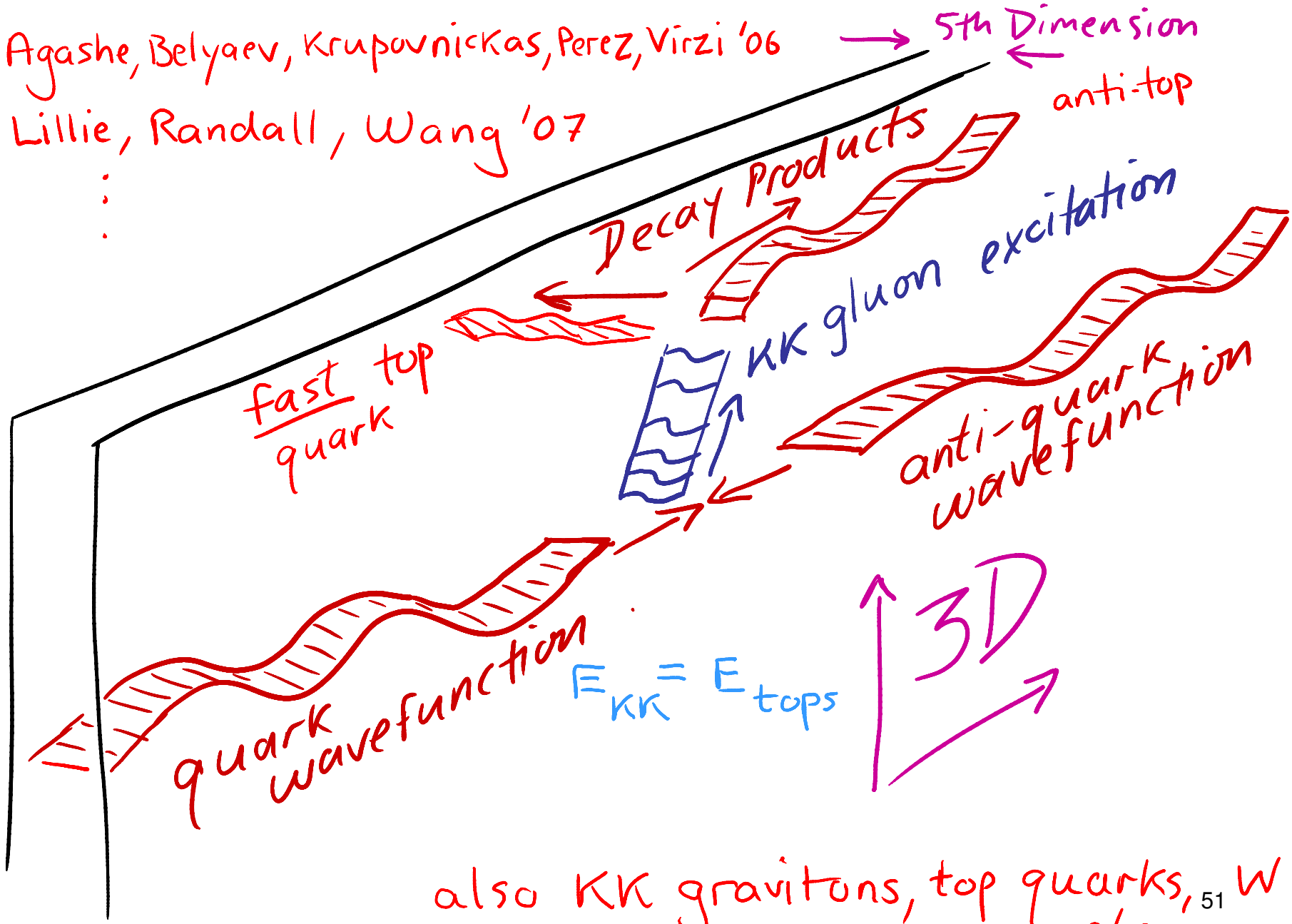
EXTRA-DIMENSIONAL PERCEPTION

requires shorter wavelengths

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

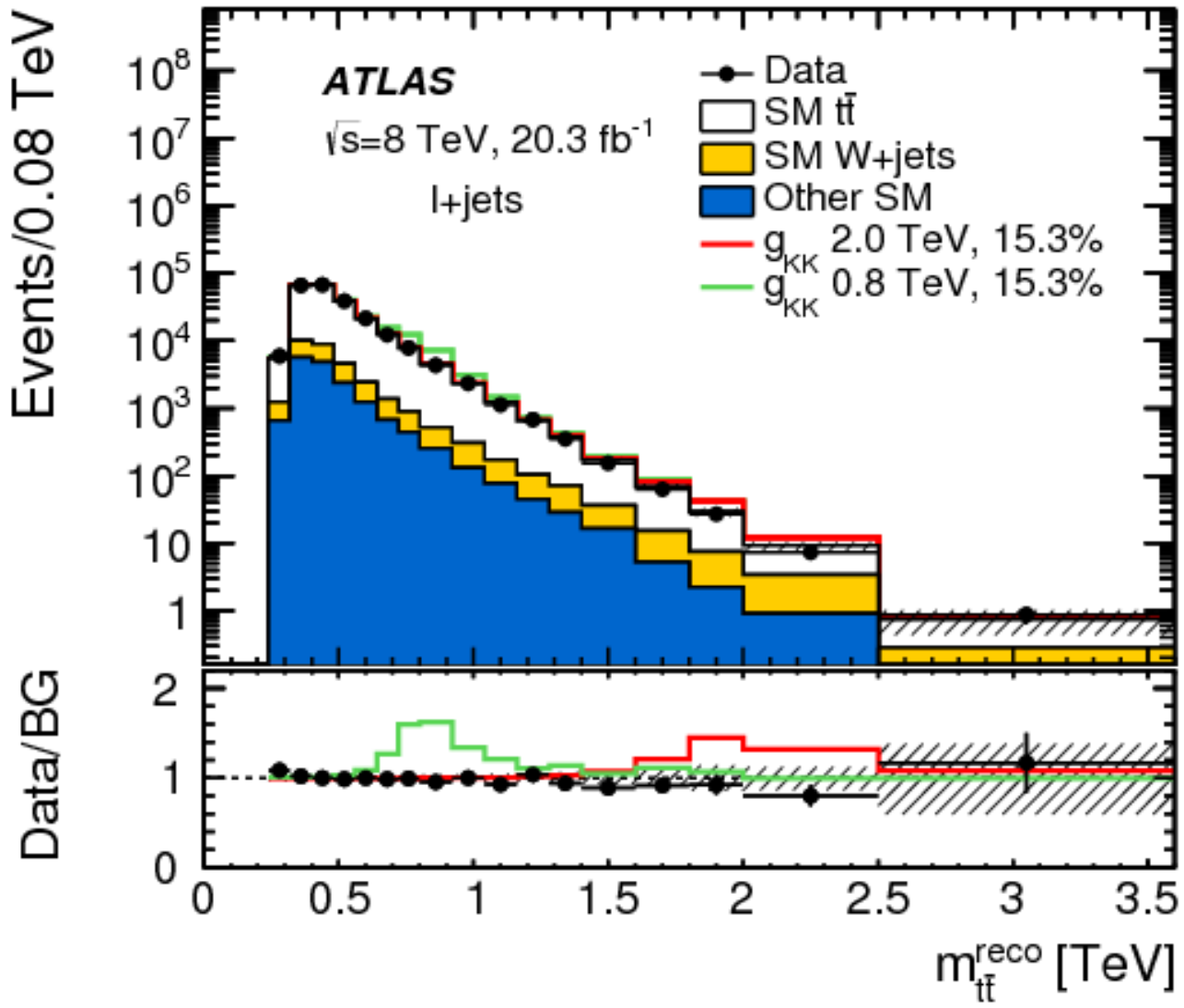


EXTRA-DIMENSIONAL PERCEPTION



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

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

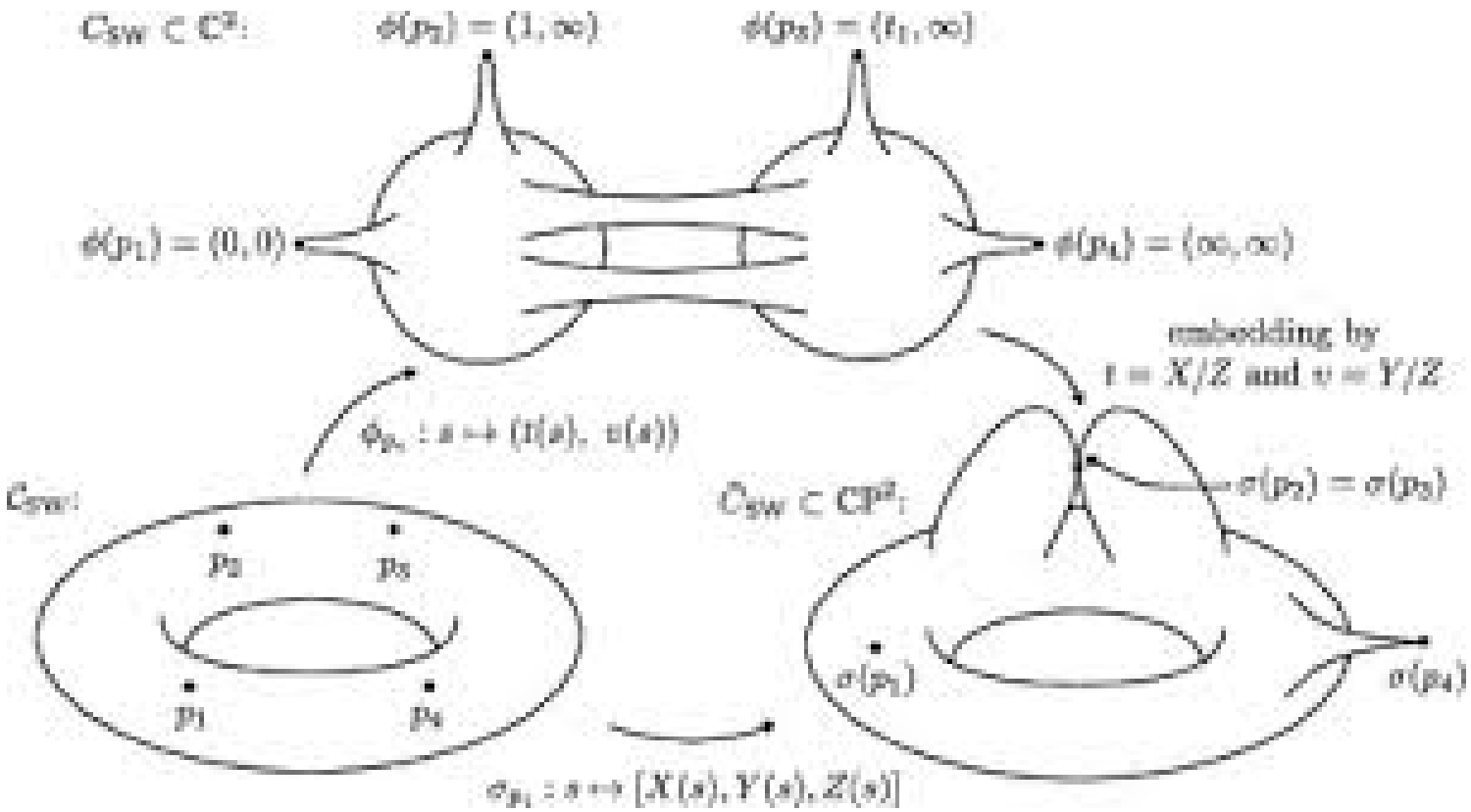
$$Q\,|\,\text{boson}\rangle = |\,\text{fermion}\rangle$$

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

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

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-$\frac{1}{2}$)

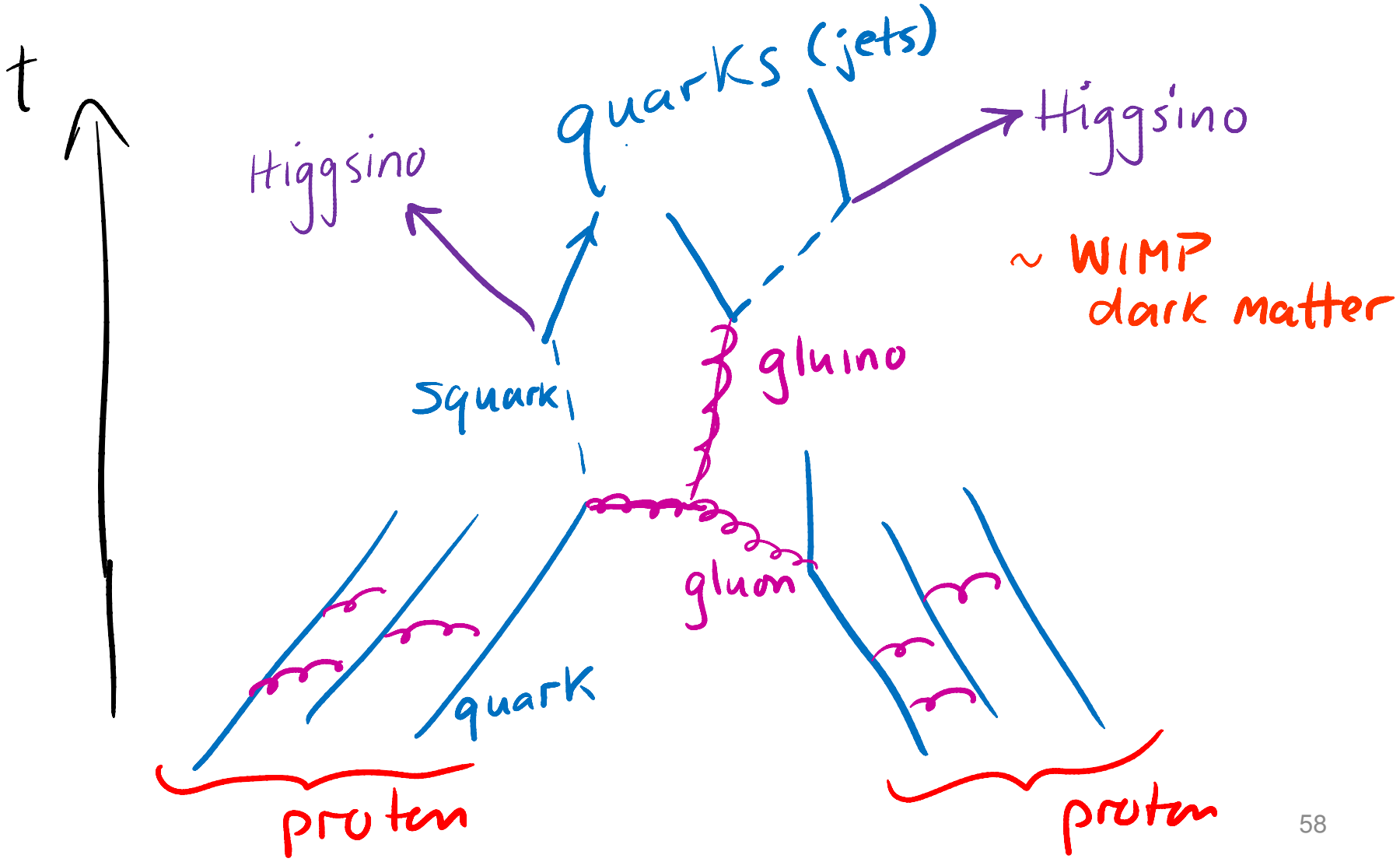


A "Mirror" in Quantum Statistics

≡ Minimal Supersymmetric Standard Model Georgi, Dimopoulos '81

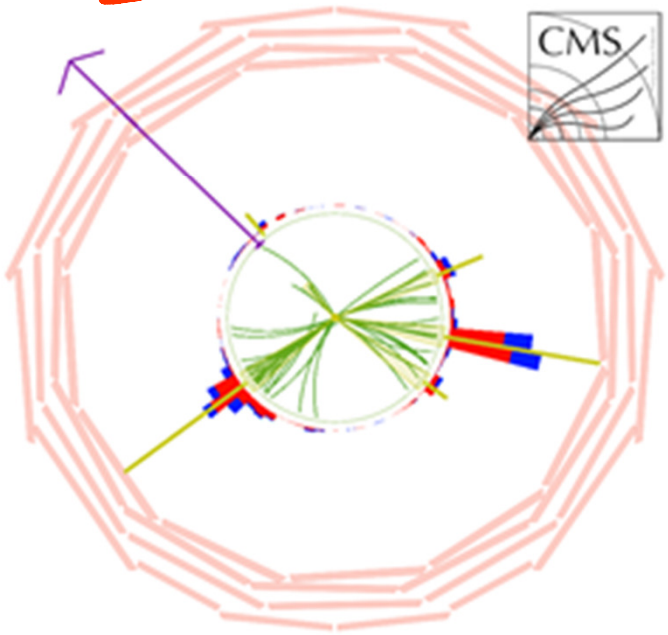
But a Mirror cracked ...

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

MINIMAL CONSEQUENCES

Top down:

SUSY (breaking) + Gravity (supergravity)

$\Longrightarrow$ "Anomaly-Mediation"

Equivalence Principle

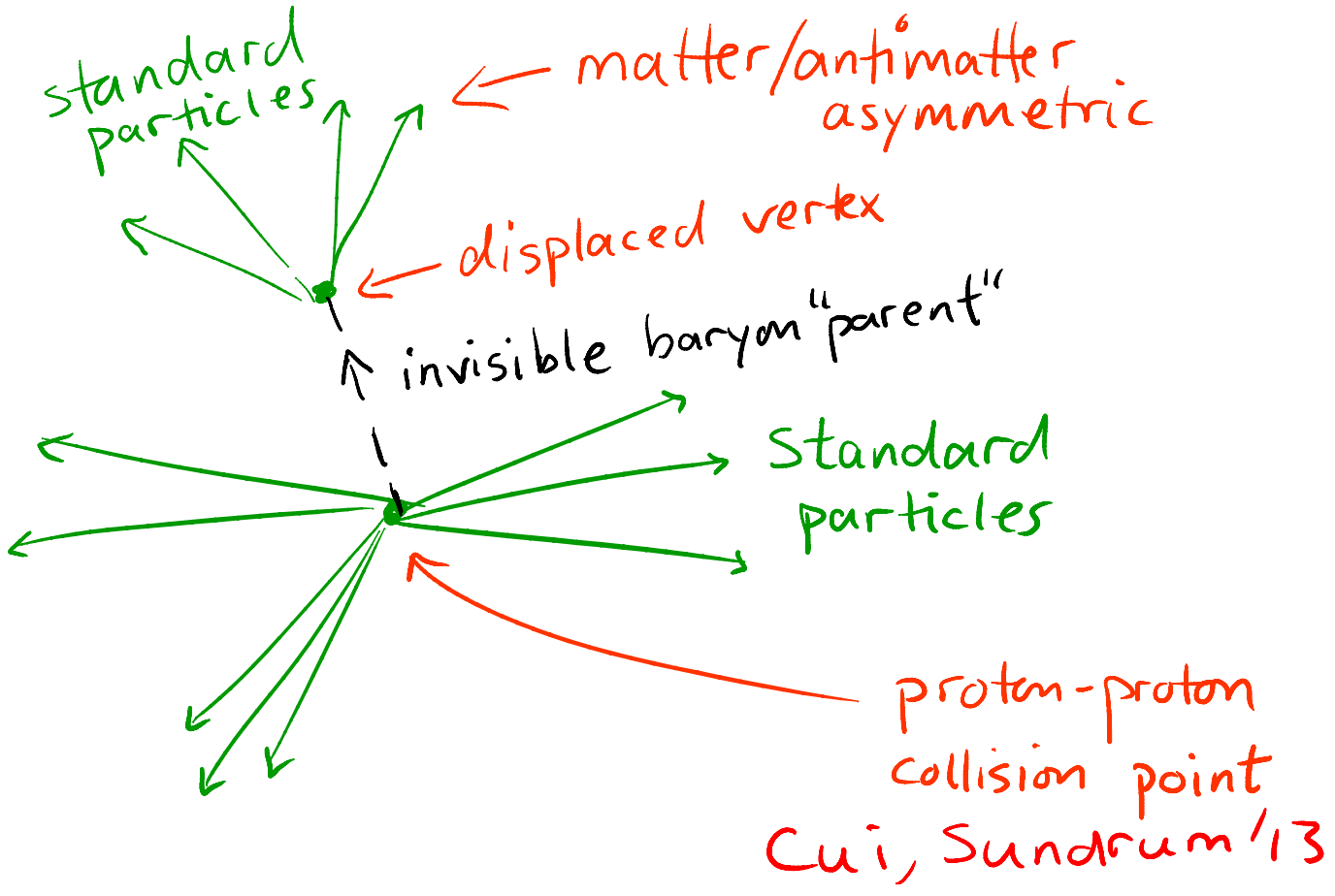
Randall, Sundrum '99
Giudice, Luty, Murayama, Rattazzi '99
Luty, Sundrum '00
⋮

$\Rightarrow$ subtle Wino phenomenology

Bottom up: Flexible "agnostic" framework for LHC searches for SUSY

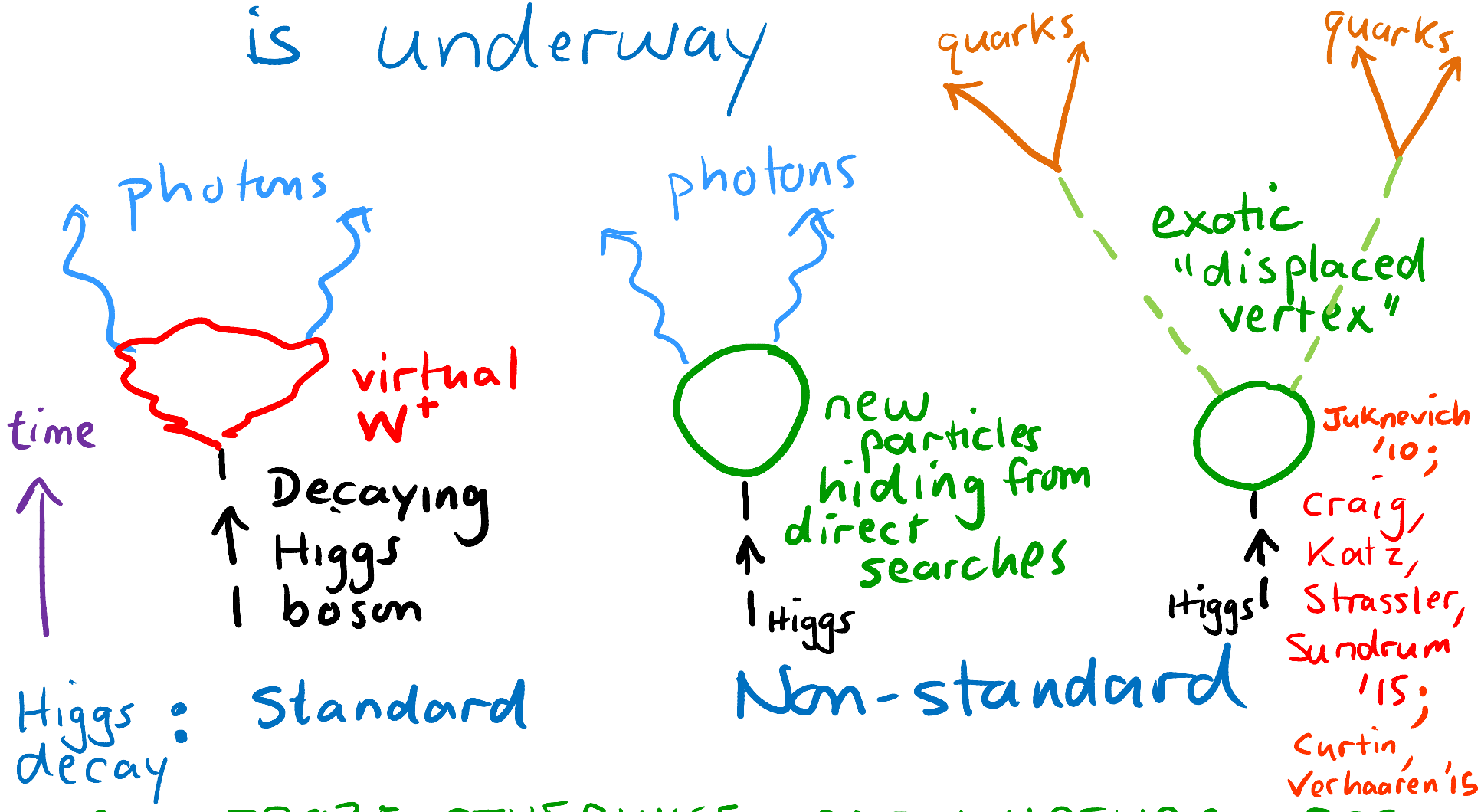
Brust, Katz, Lawrence, Sundrum '11

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



⇒ DISPLACED VERTEX DECAYS
(v. low backgrounds)

PRECISION HIGGS PHYSICS is underway



CAN PROBE OTHERWISE HIDDEN NATURALNESS

Chacko, Goh, Harnik '06; Burdman, Chacko, Goh, Harnik '07

New Displaced Vertex Detector Proposal

MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti
1606.06298



MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

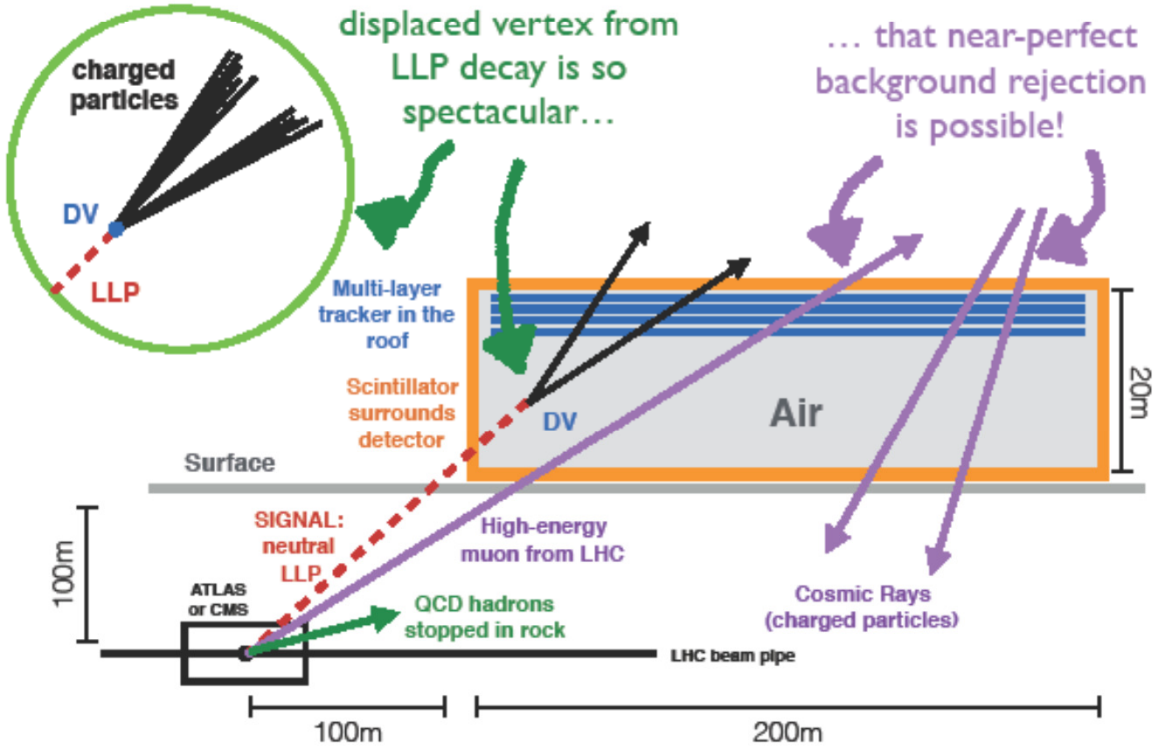


Figure Credit: Curtin, Sundrum, submitted to Physics Today

On schedule for

prototype
mid 2017
letter of intent
end 2017

theory
white paper
mid 2017

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,

emergent Relativity in Condensed Matter. . .

My sense is our journey into Spacetime is just at

The Beginning . . .