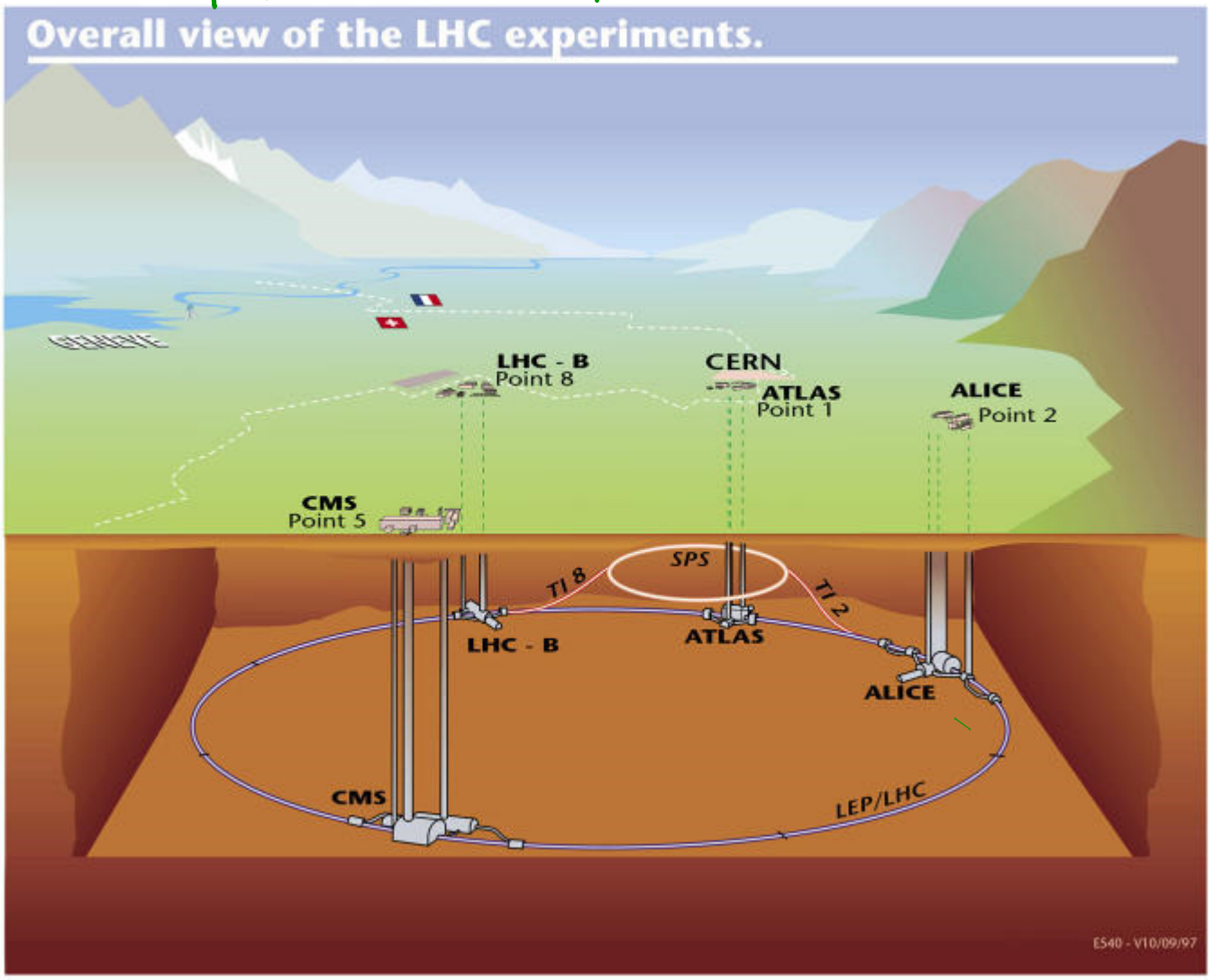
THE QUEST FOR NATURALNESS at the Large Hadron Collider

Raman Sundrum
University of Maryland

THE LHC IS A MULTI-TeV PROTON-PROTON COLLIDER

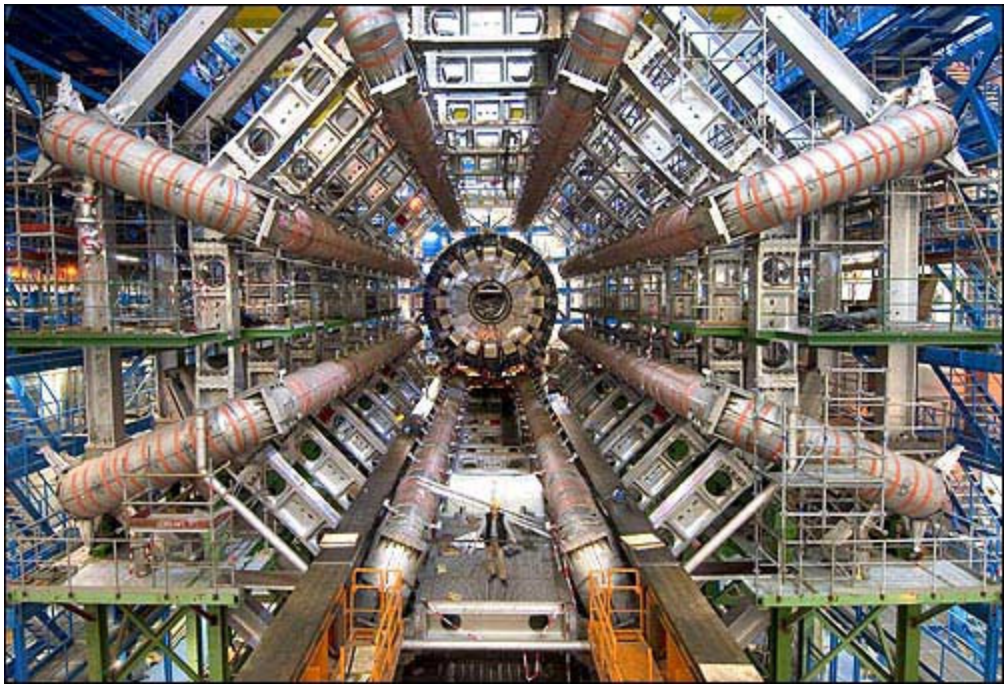


THE HAIL OF EMERGING PARTICLES SCRUTINIZED BY...

BIG, BIG EYES



CMS Detector



Atlas Detector

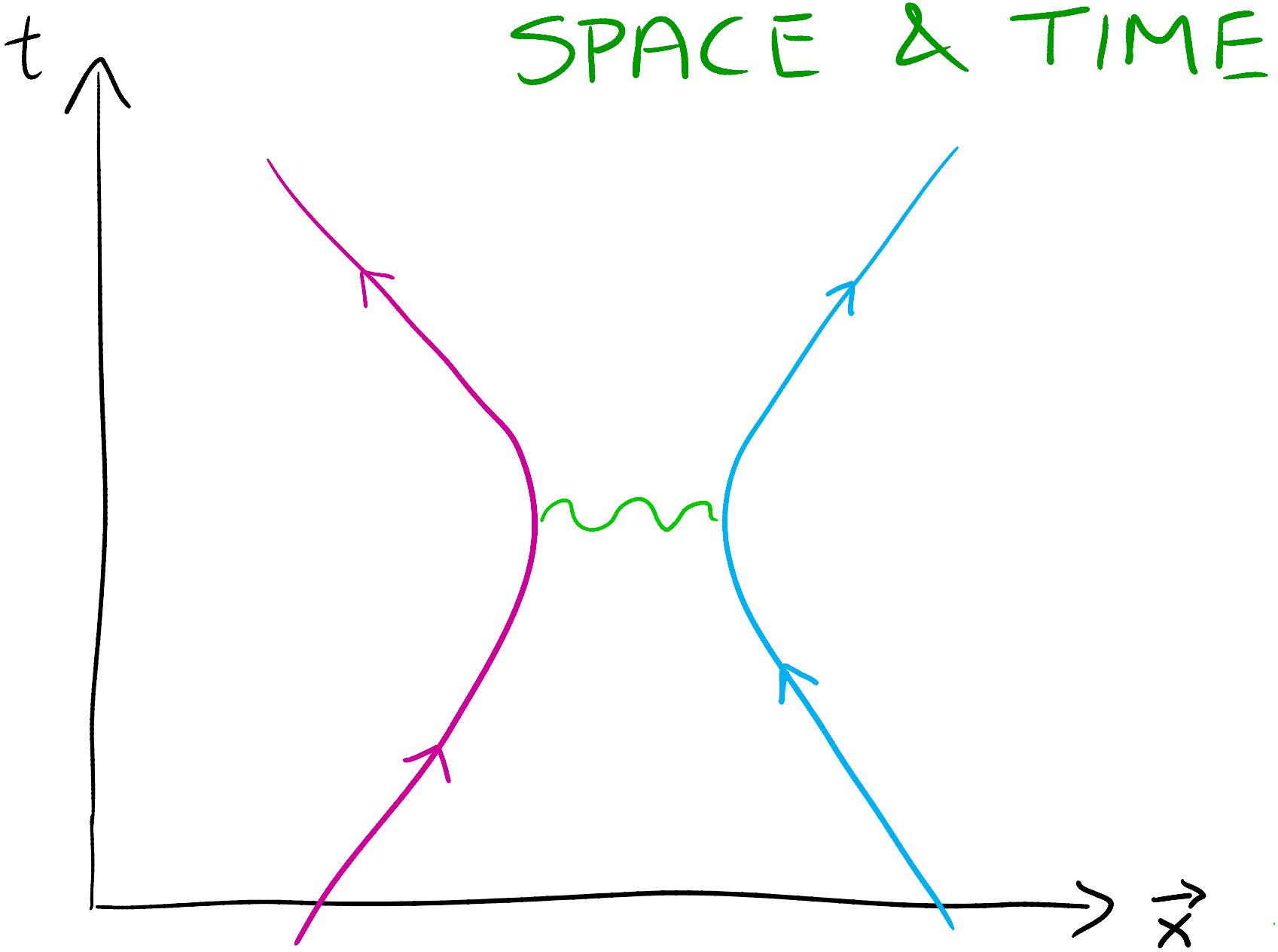
BUT

WHY?

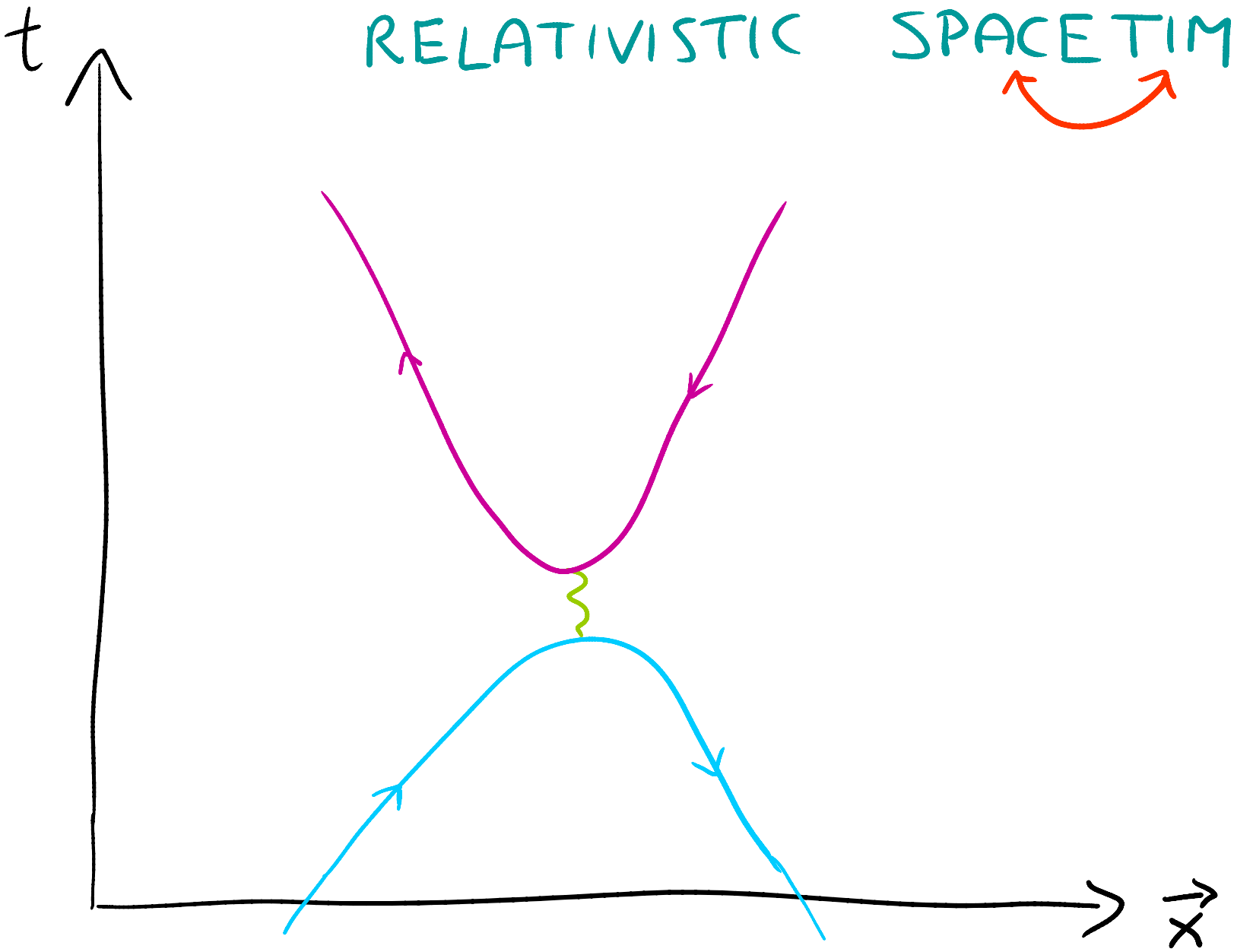
OUTLINE

- Nothing is Something too!
- The Origin of the Masses
- The Grand Principle of Naturalness
- Incarnations of Spacetime —
  - The Multiverse
  - The 5th Dimension
  - Emergent Dimensions
  - SuperSymmetry
- When the going gets tough,
  the tough get going.

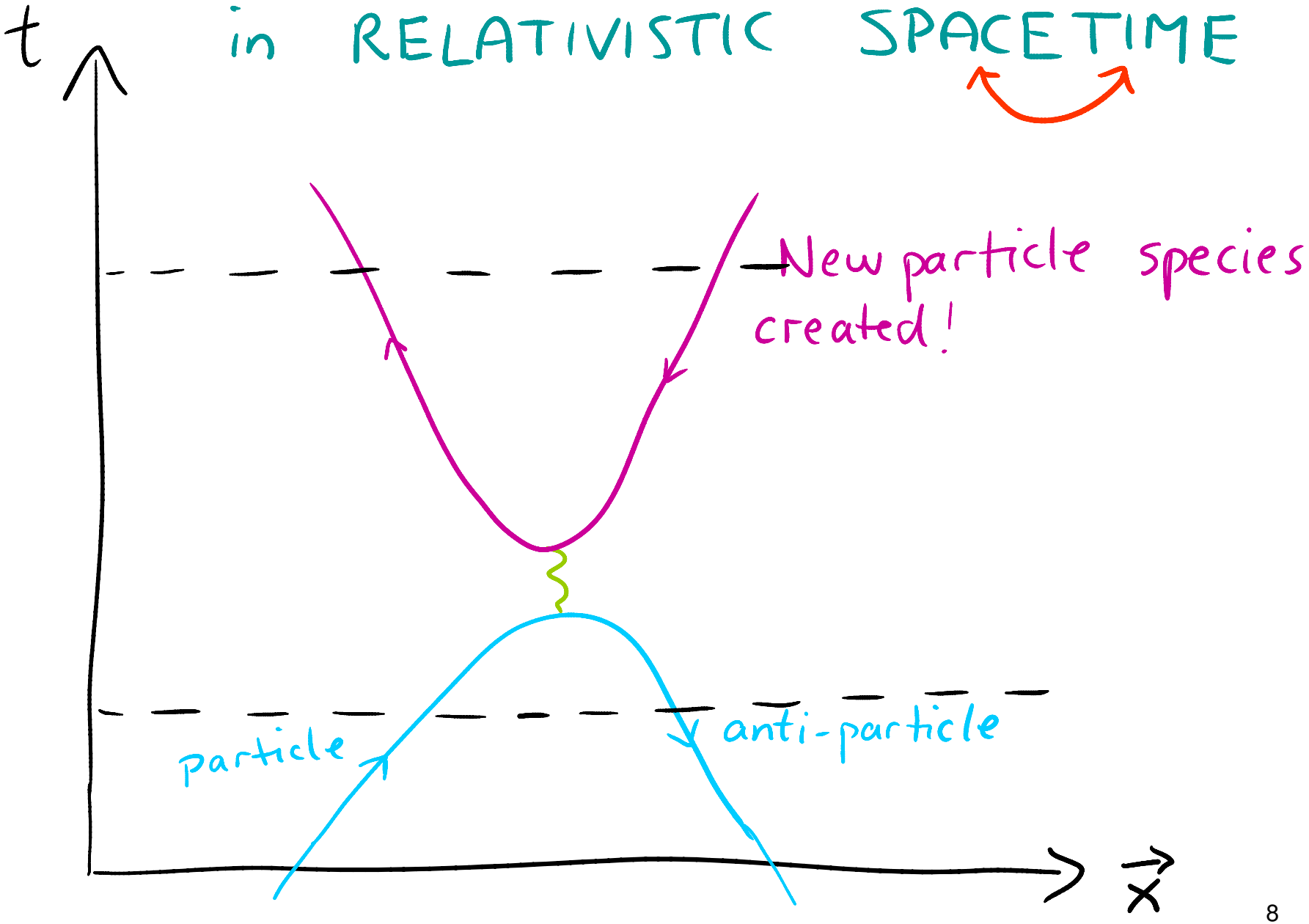
NON-RELATIVISTIC SPACE & TIME



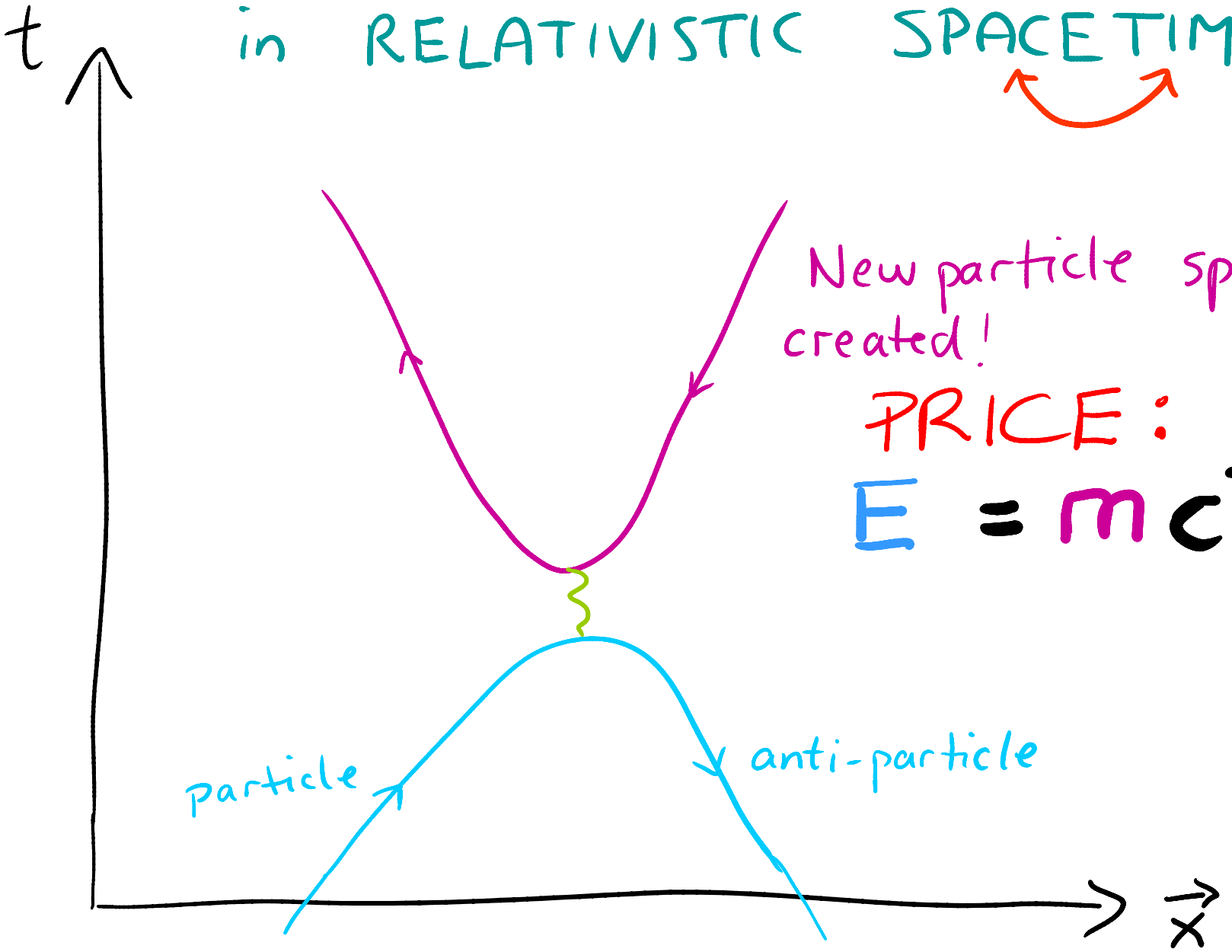
RELATIVISTIC SPACETIME



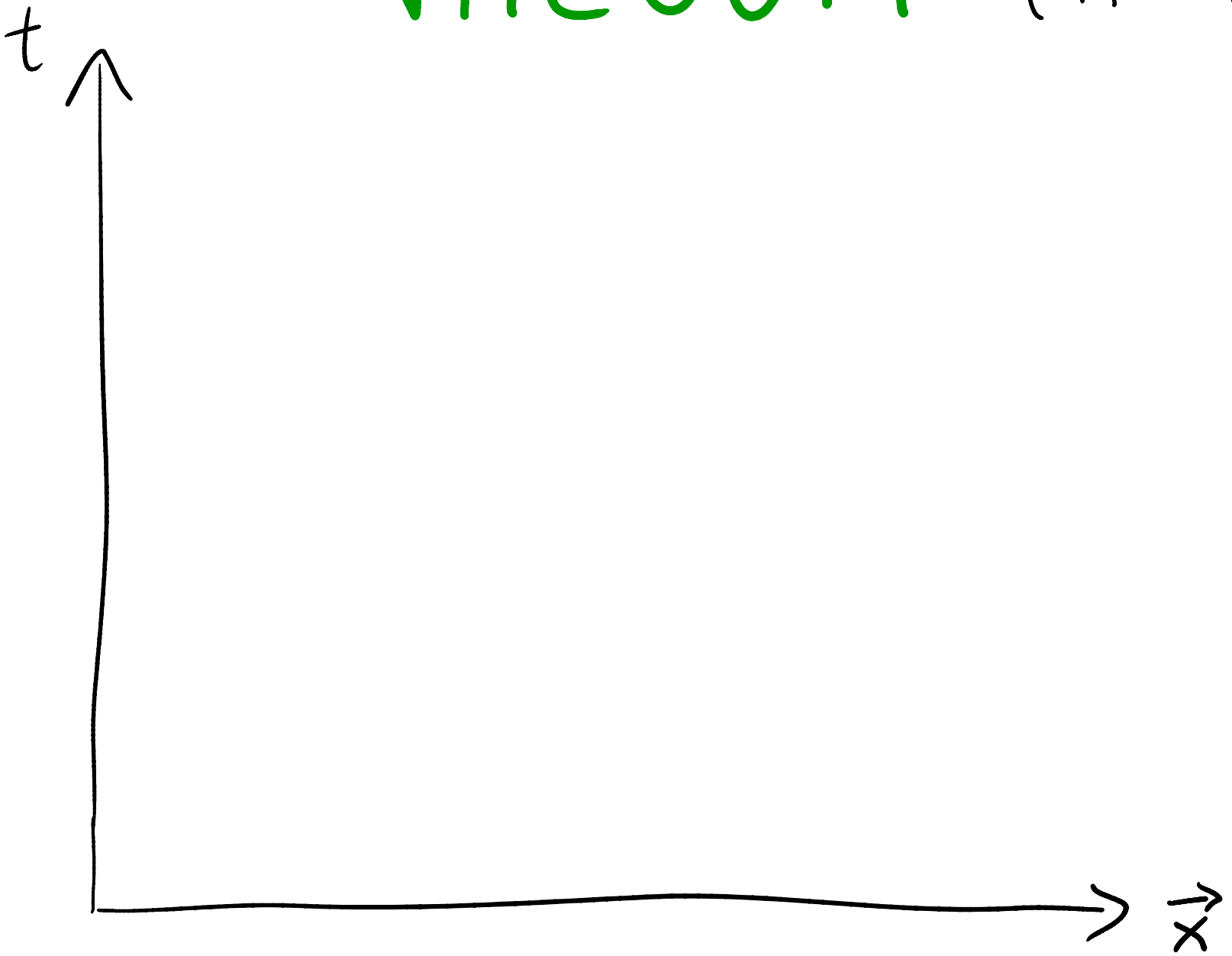
ALCHEMY in RELATIVISTIC SPACETIME



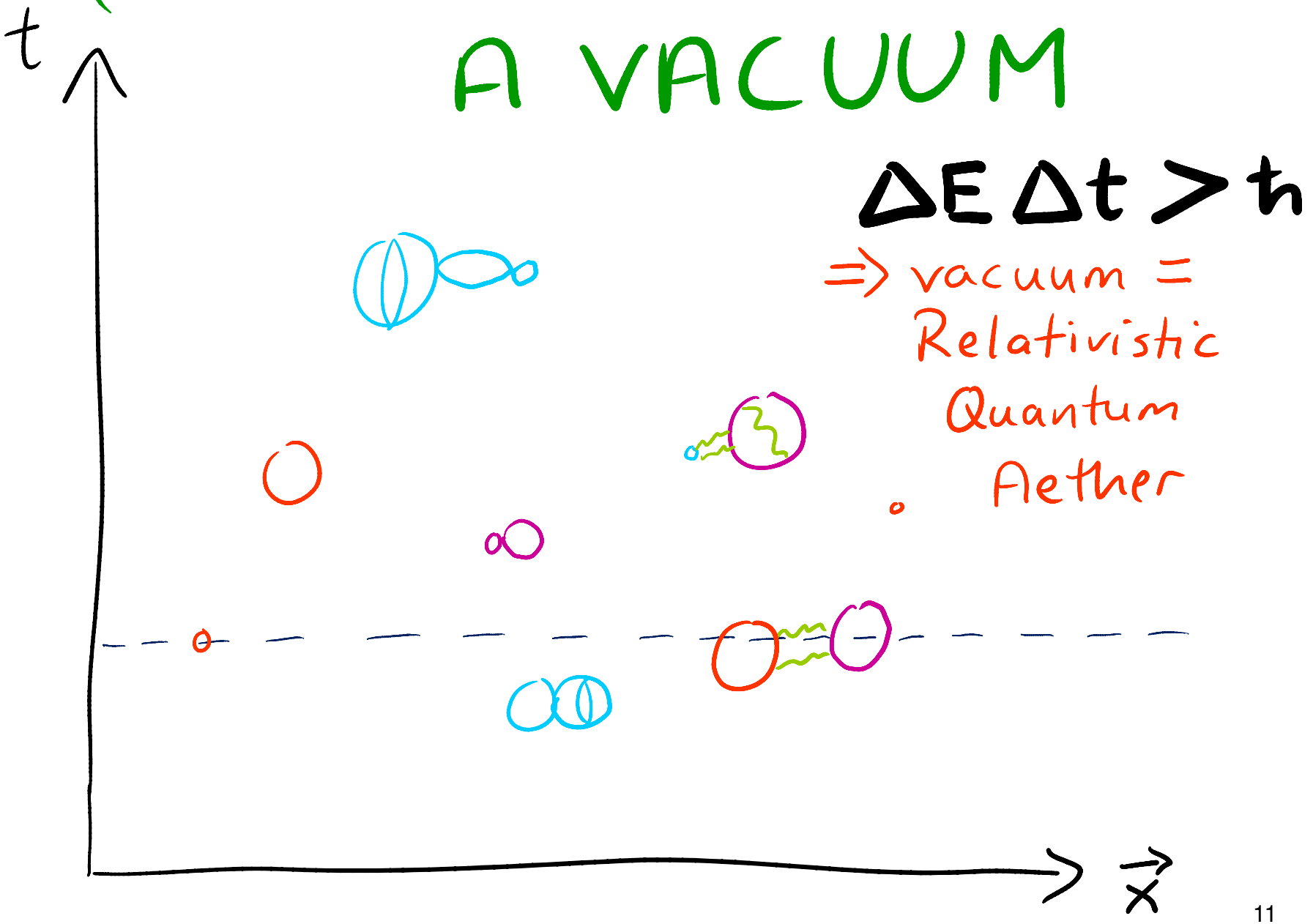
ALCHEMY
in RELATIVISTIC SPACETIME



VACUUM ($\hbar = 0$)



(QUANTUM) NATURE ABHORS A VACUUM

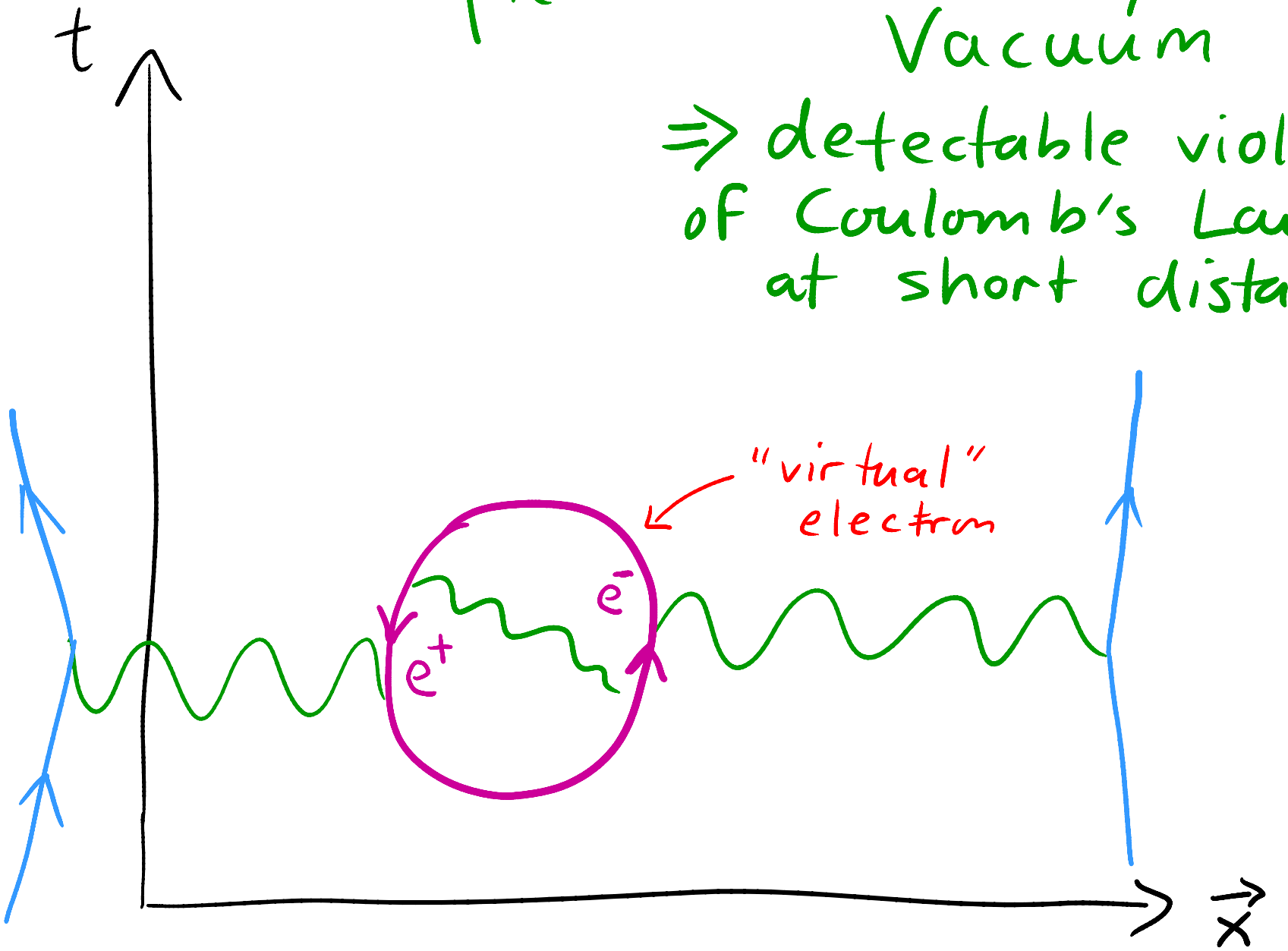


$\Delta E \Delta t > \hbar$

$\Rightarrow$ 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

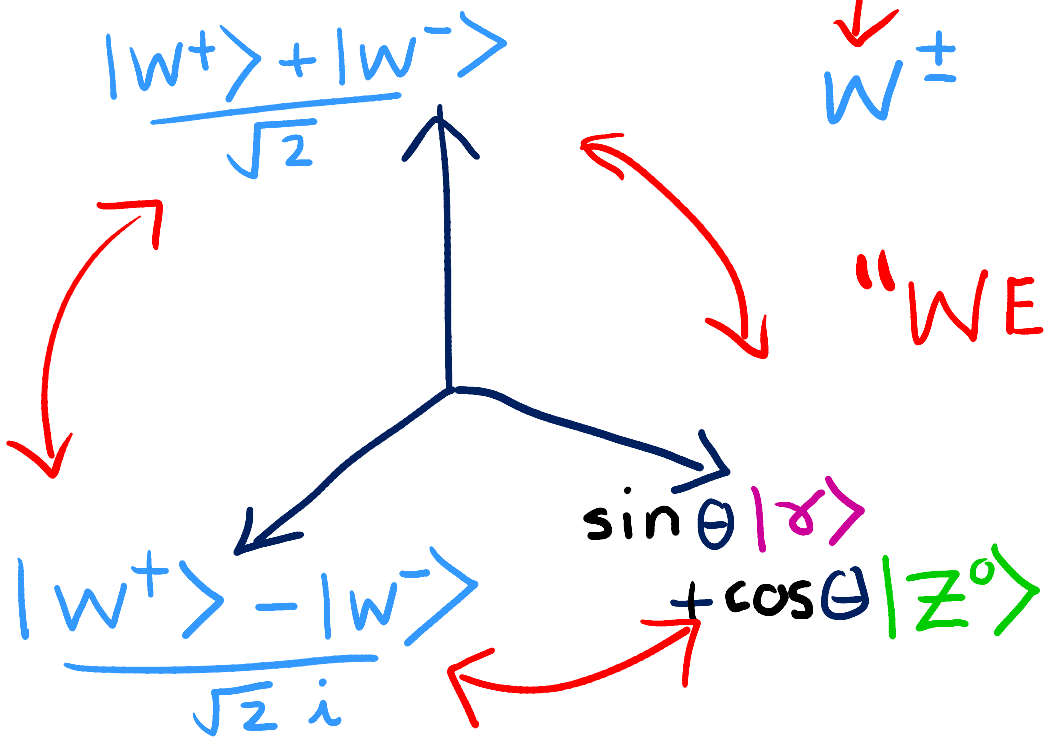
γ photon

Radioactive decay

$W^{\pm}$

Neutral current

Z^0

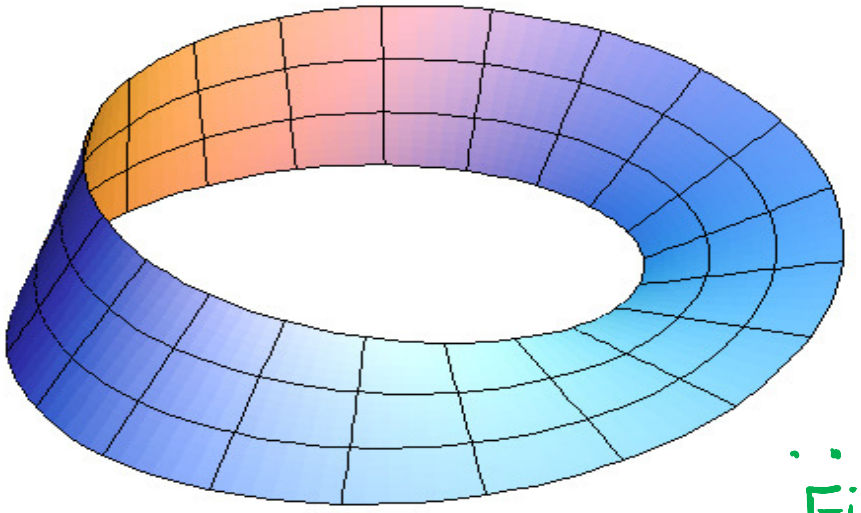


"WEAK ISOSPIN" SYMMETRY

RICH IN MATHEMATICAL BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists

~ (Quantized) Differential Geometry of FIBER BUNDLES to mathematicians



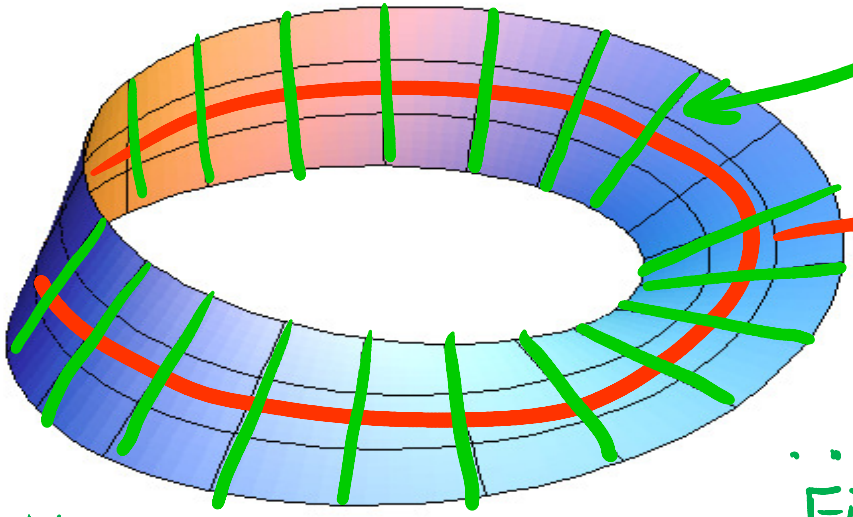
Möbius Strip ...

... as cartoon of Fiber Bundle

RICH IN MATHEMATICAL BEAUTY & SUBTLETY !!

Yang-Mills Gauge Theory to physicists

~ (Quantized) Differential Geometry of FIBER BUNDLES to mathematicians



Möbius Strip ...

... as cartoon of Fiber Bundle

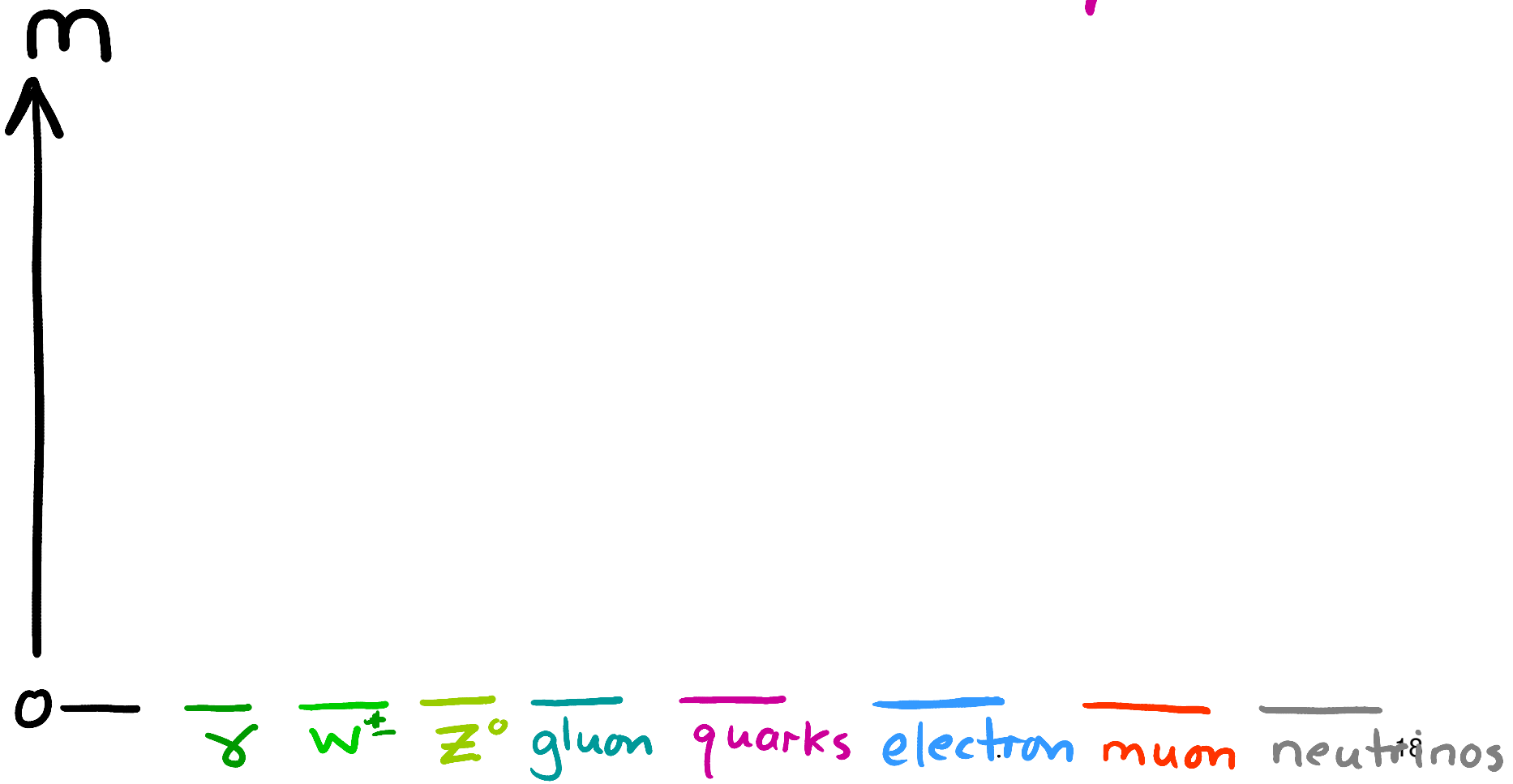
Electro Weak Unification

PREDICTS MASS SPECTRUM of all known elementary particles !

Electro Weak Unification

PREDICTS MASS SPECTRUM

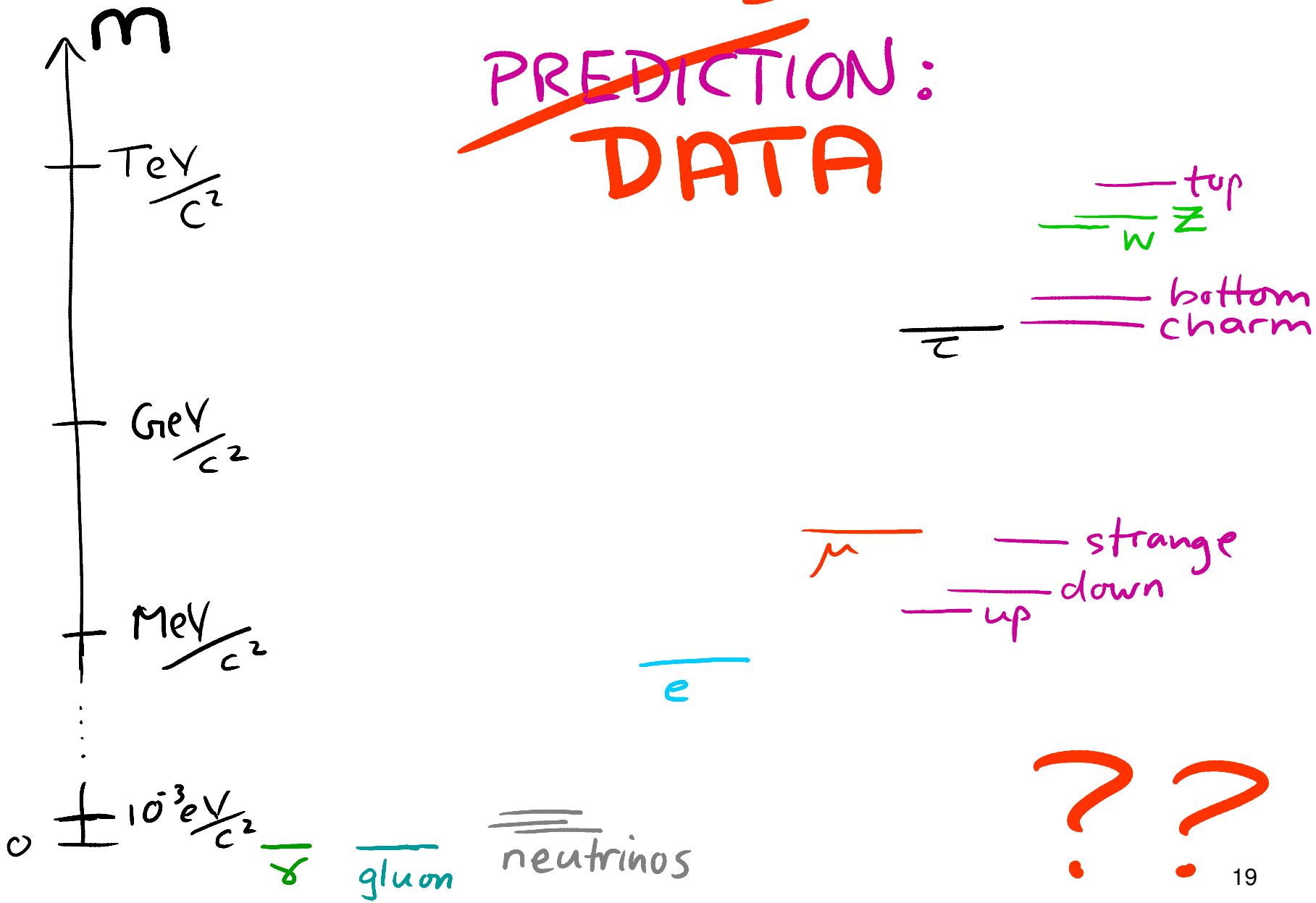
of all known elementary particles



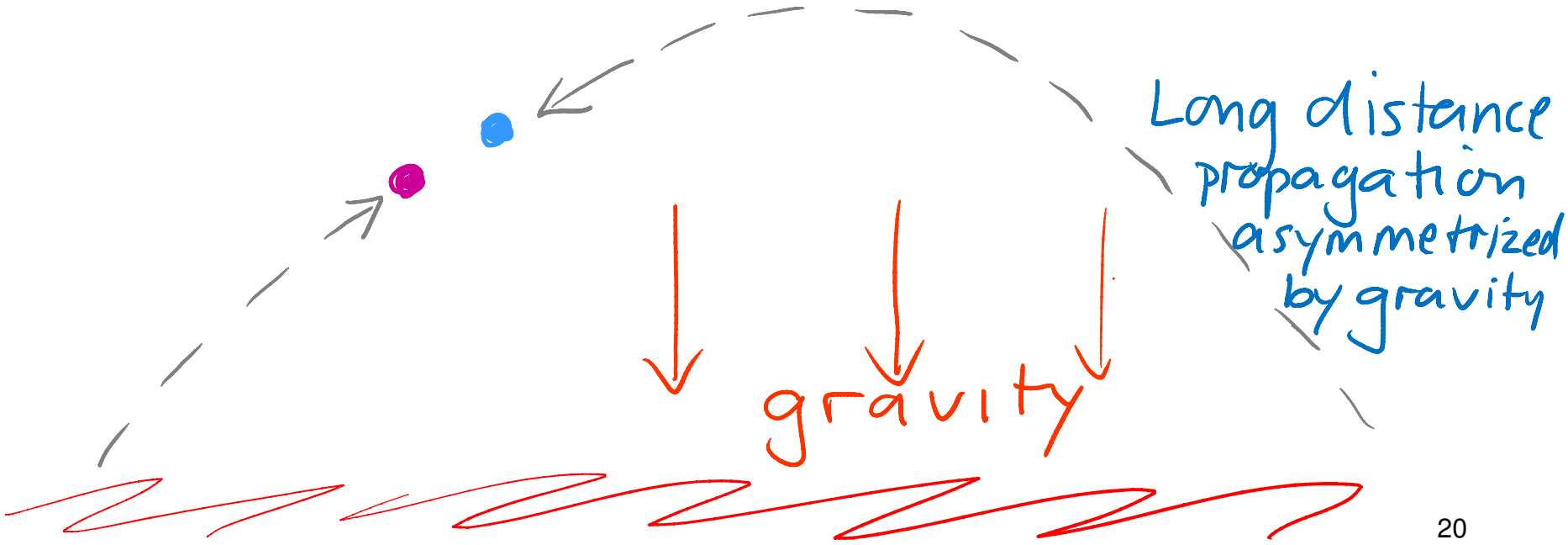
ElectroWeak Unification

PREDICTION:

DATA

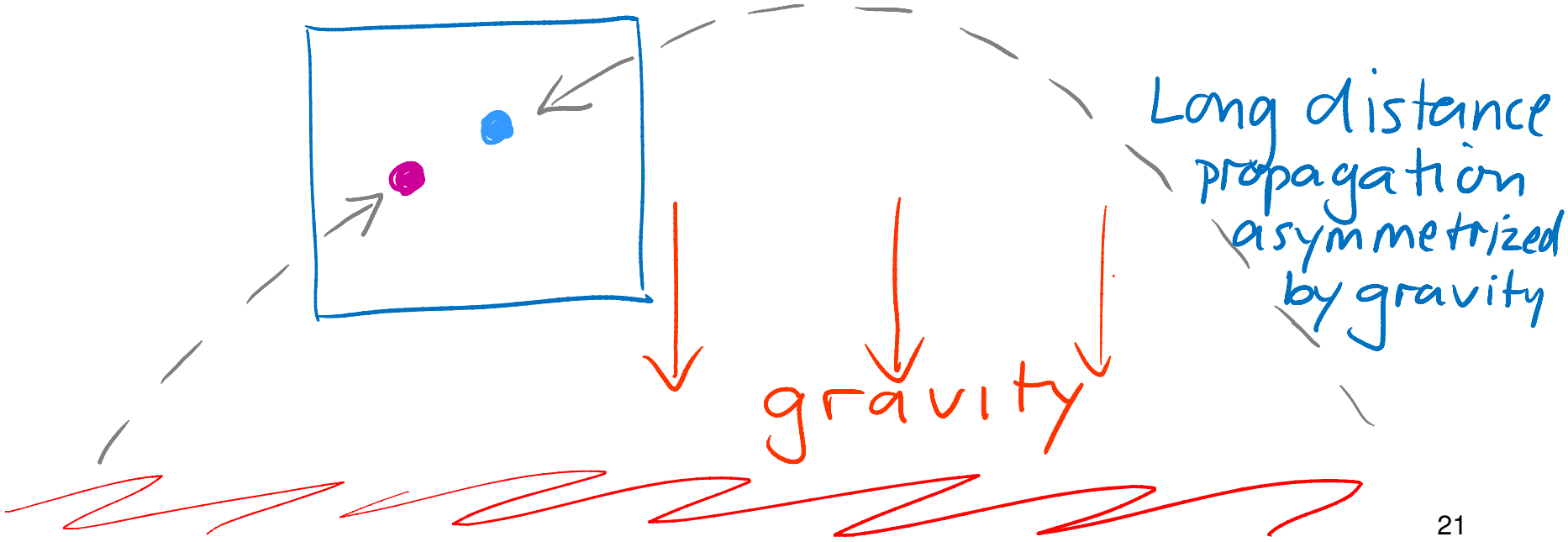


ANALOGY: Rotational ~~symmetry~~ by gravitational force field

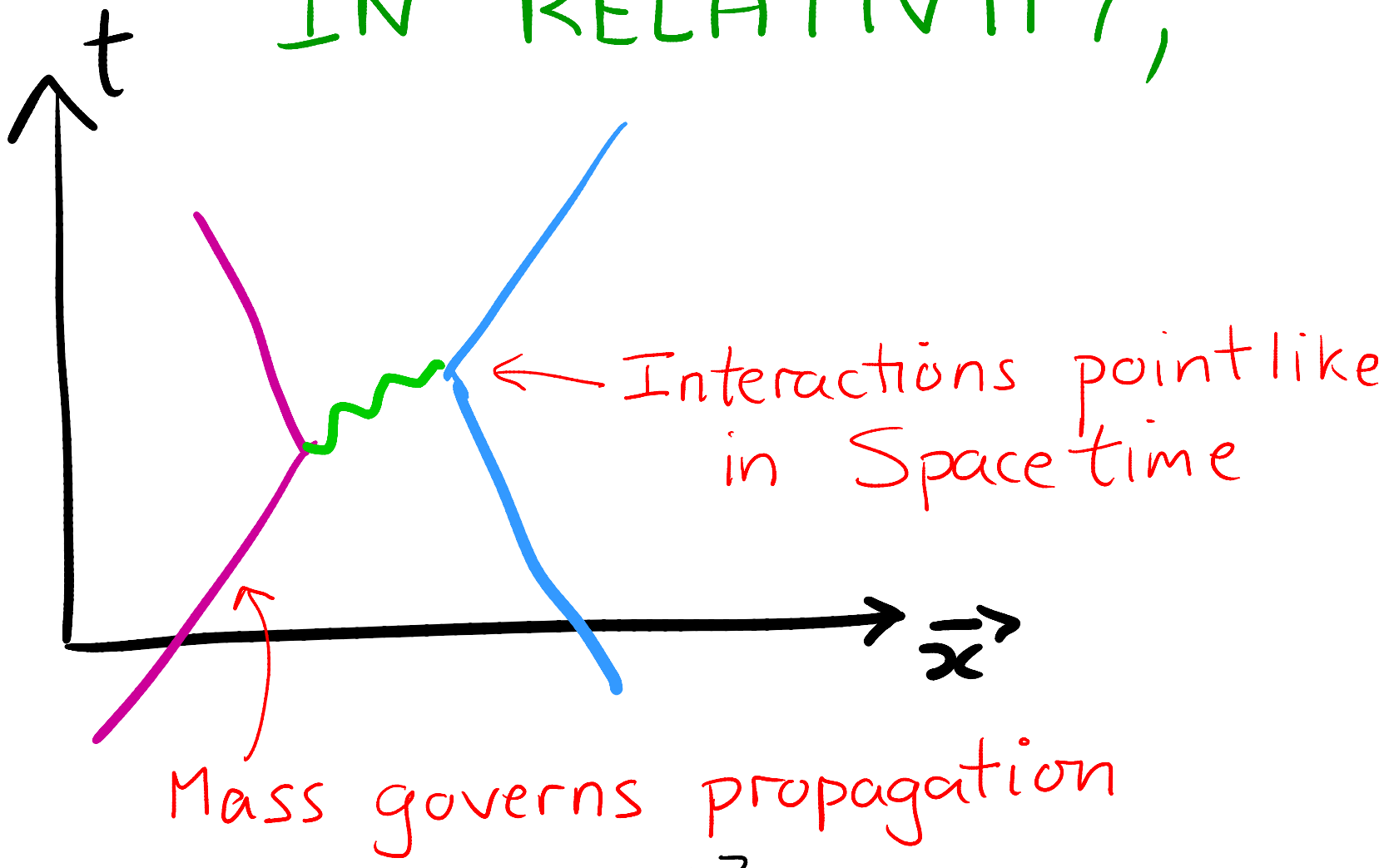


ANALOGY: Rotational ~~symmetry~~ by gravitational force field

Collisions at close quarters
≈ rotationally symmetric



IN RELATIVITY,



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

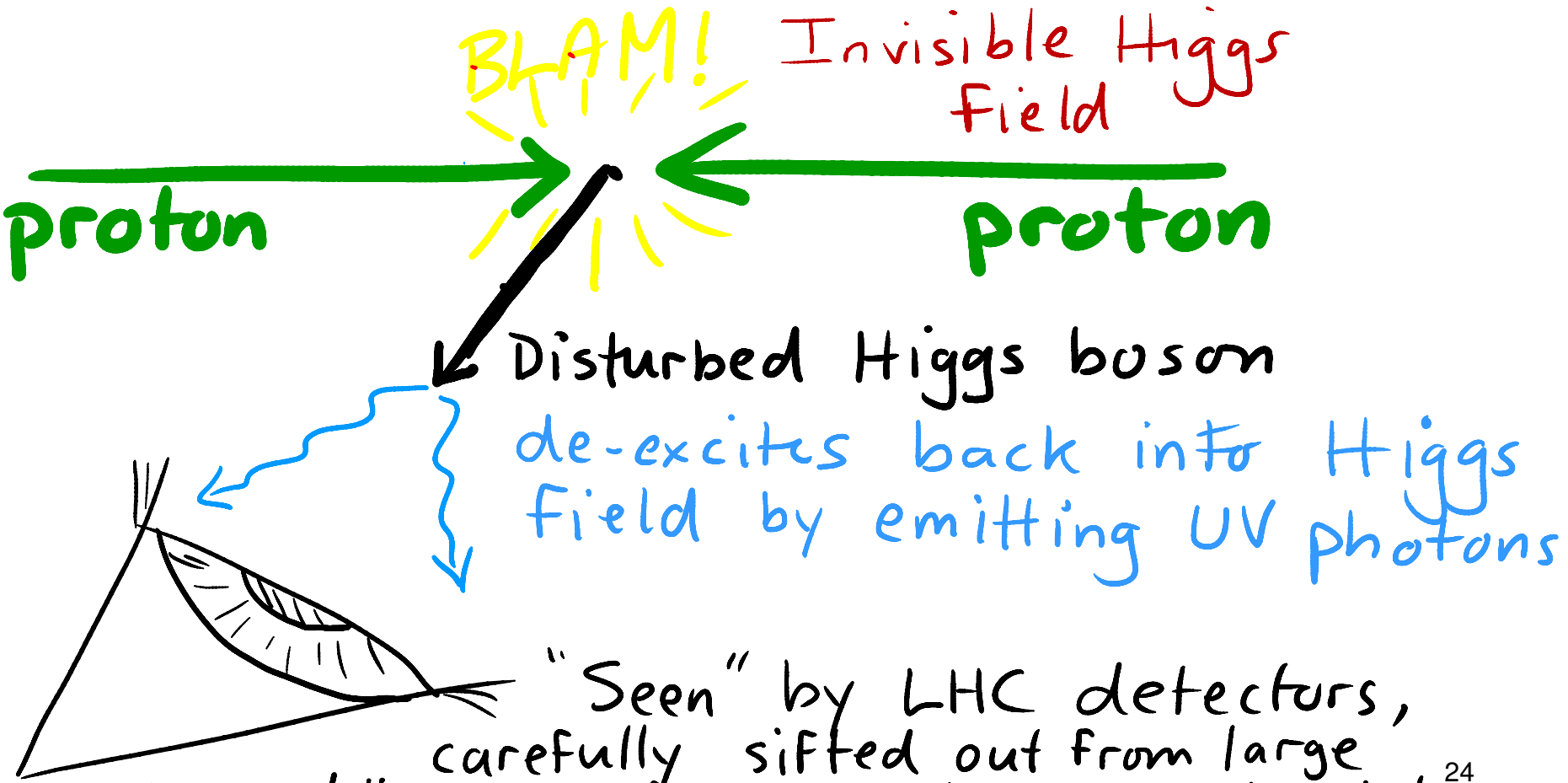
suggests ⟹ space filled by invisible, uniform scalar field "pointing" in "isospace"

≡ Higgs field,

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

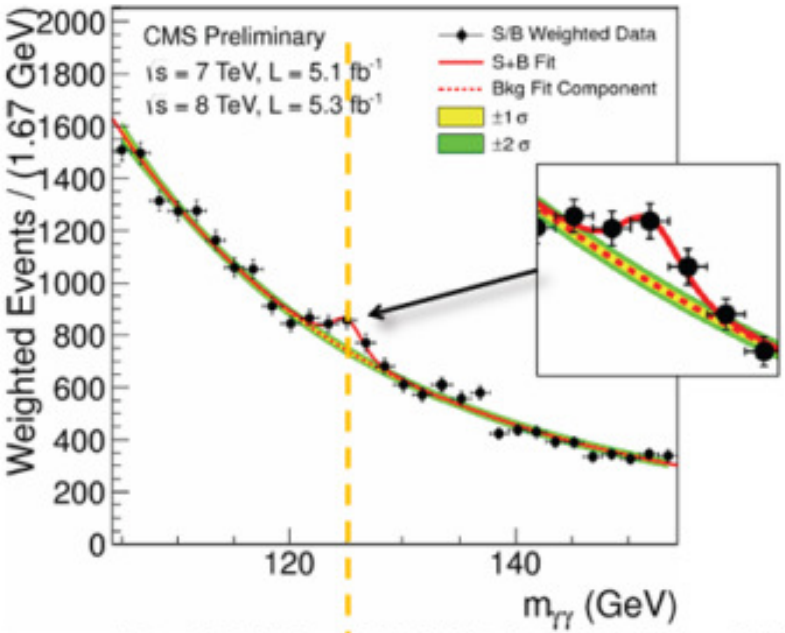
To test this structure we must create & detect such quantum "ripples".

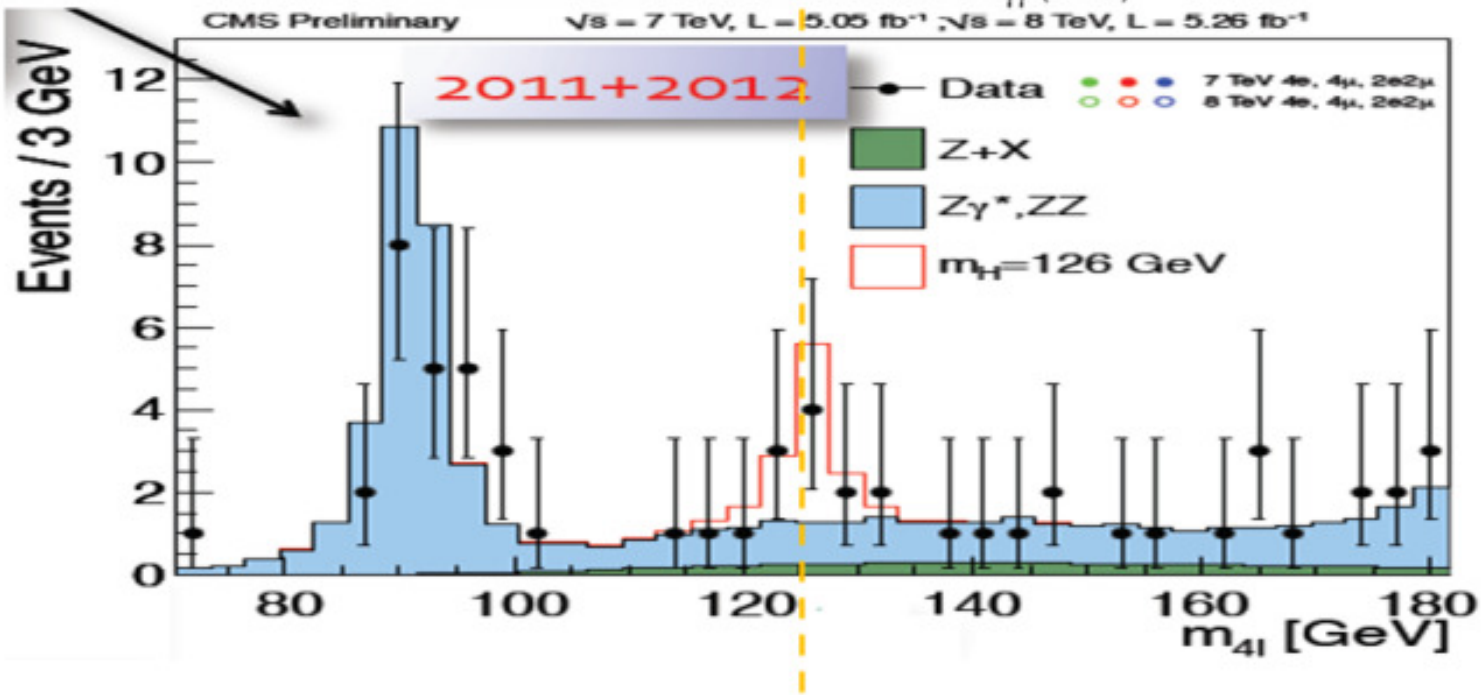
LHC has blasted Higgs bosons out of hiding!



$m_{Higgs} = 126\ GeV$

Early LHC DATA





STANDARD MODEL NOW COMPLETE

Higgs boson discovery wins Nobel prize for theorists.

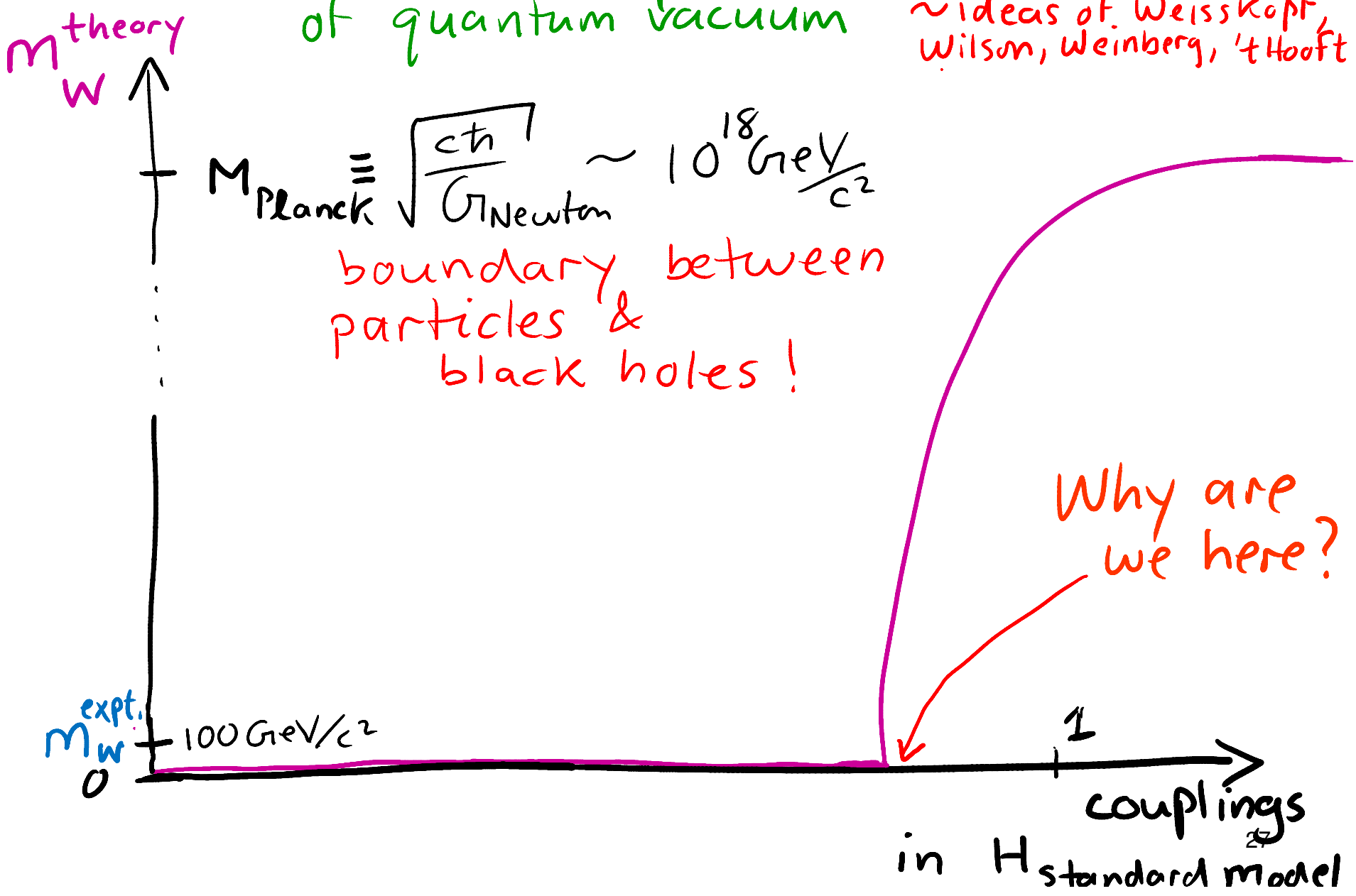
Standard Model brilliant culmination of decades of theory & experiment, deep insights into Nature.

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

HIERARCHY PROBLEM

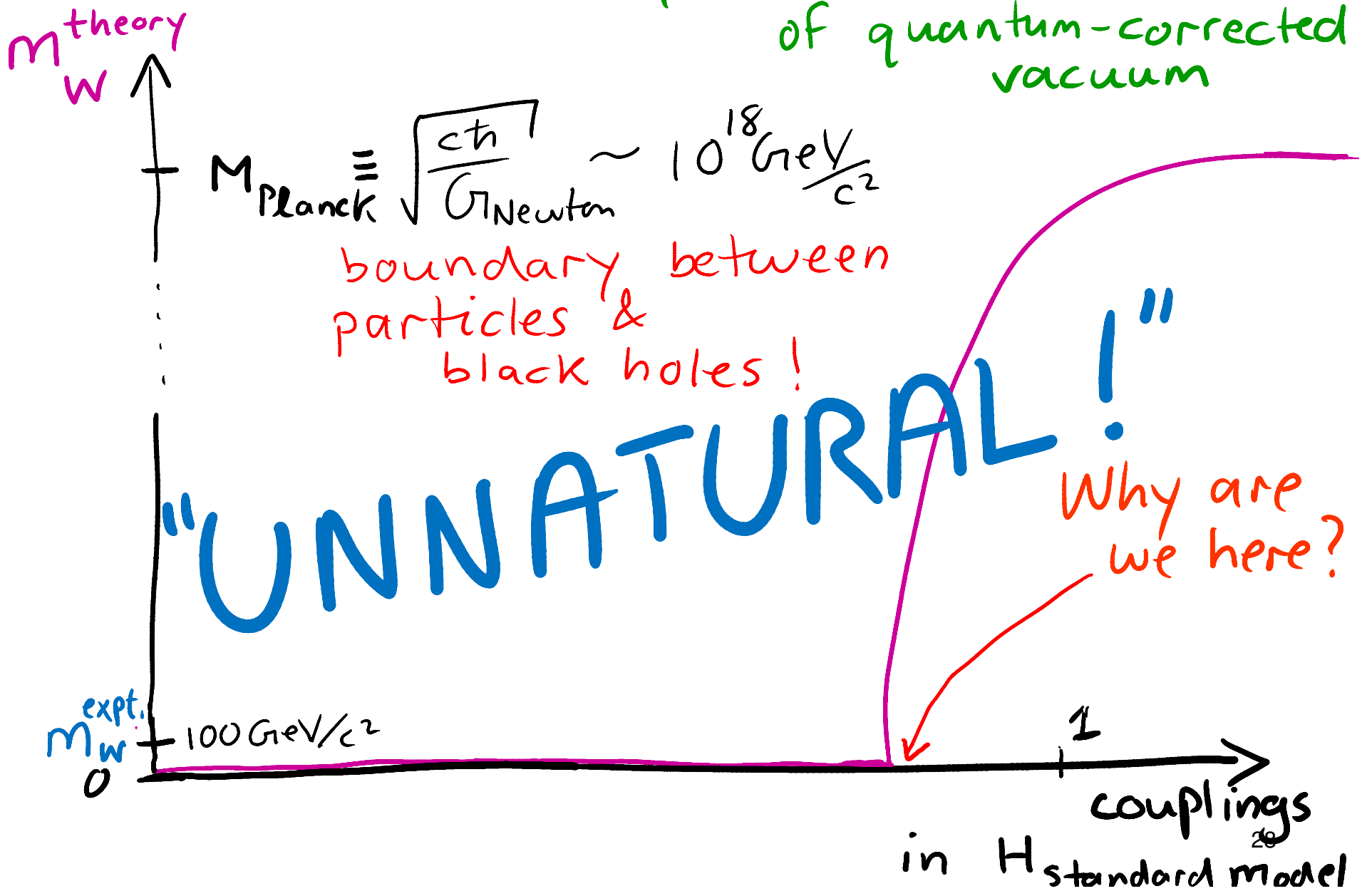
of quantum vacuum

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

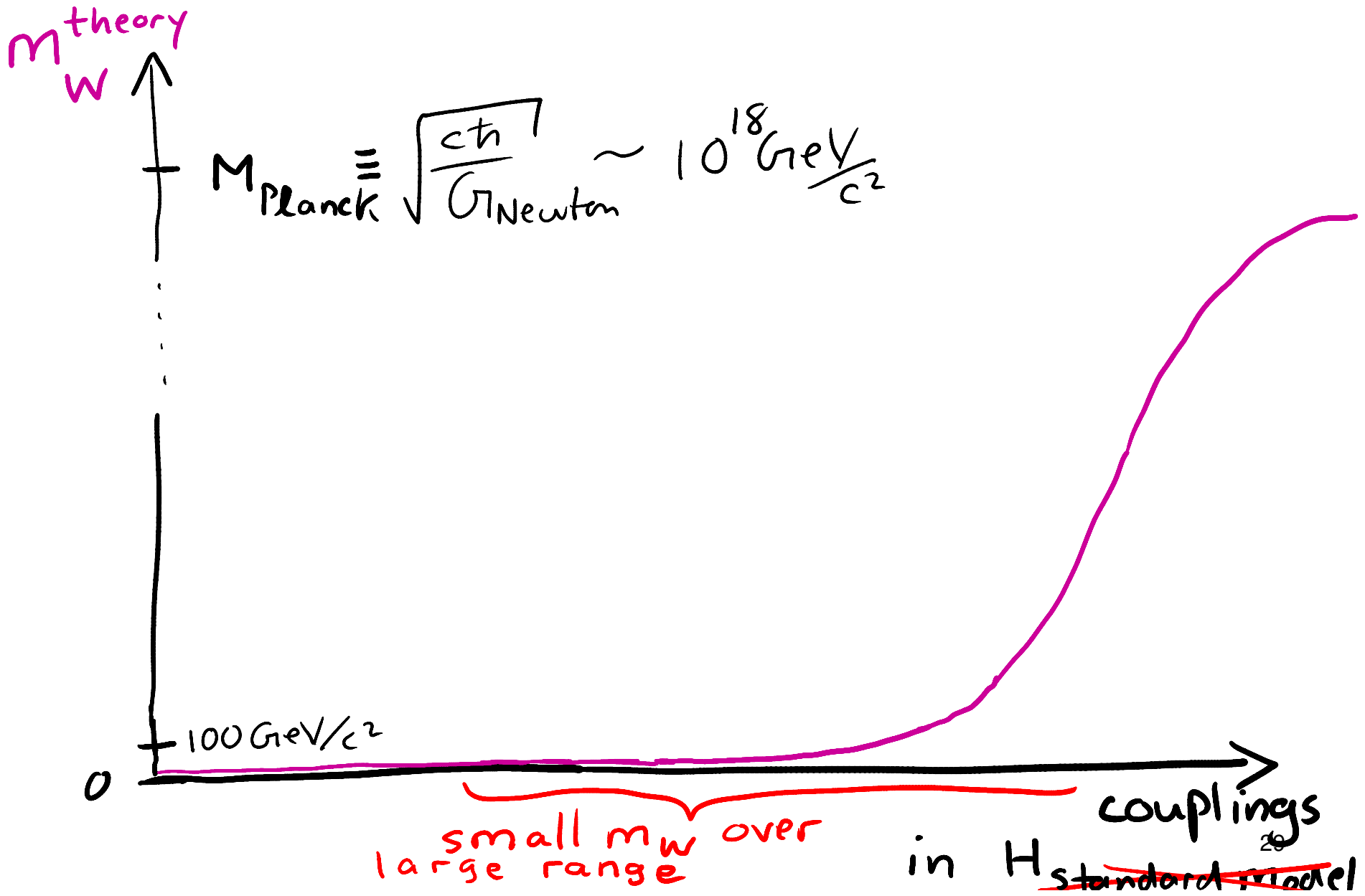


HIERARCHY PROBLEM

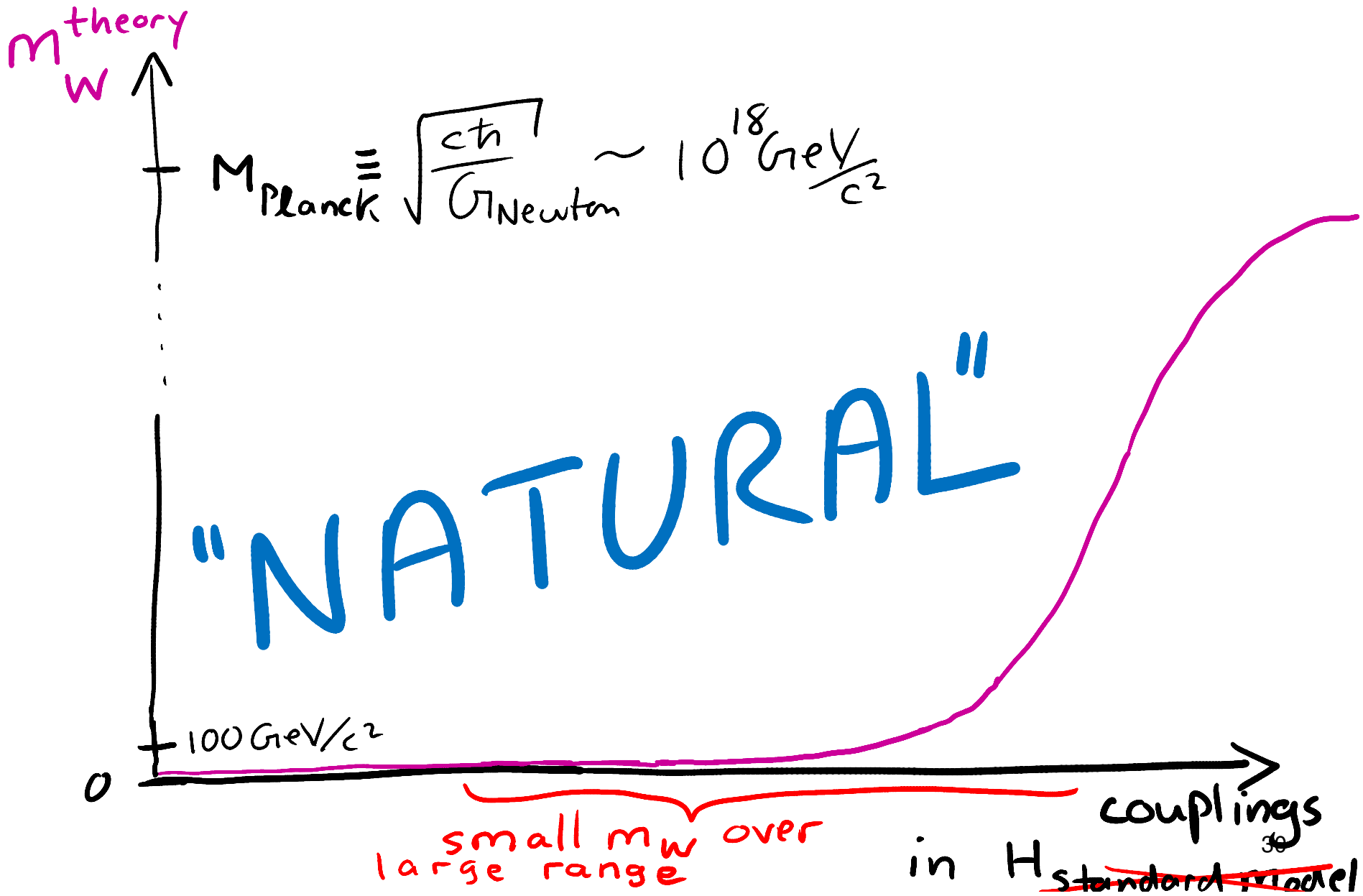
of quantum-corrected vacuum



A DIFFERENT VACUUM?



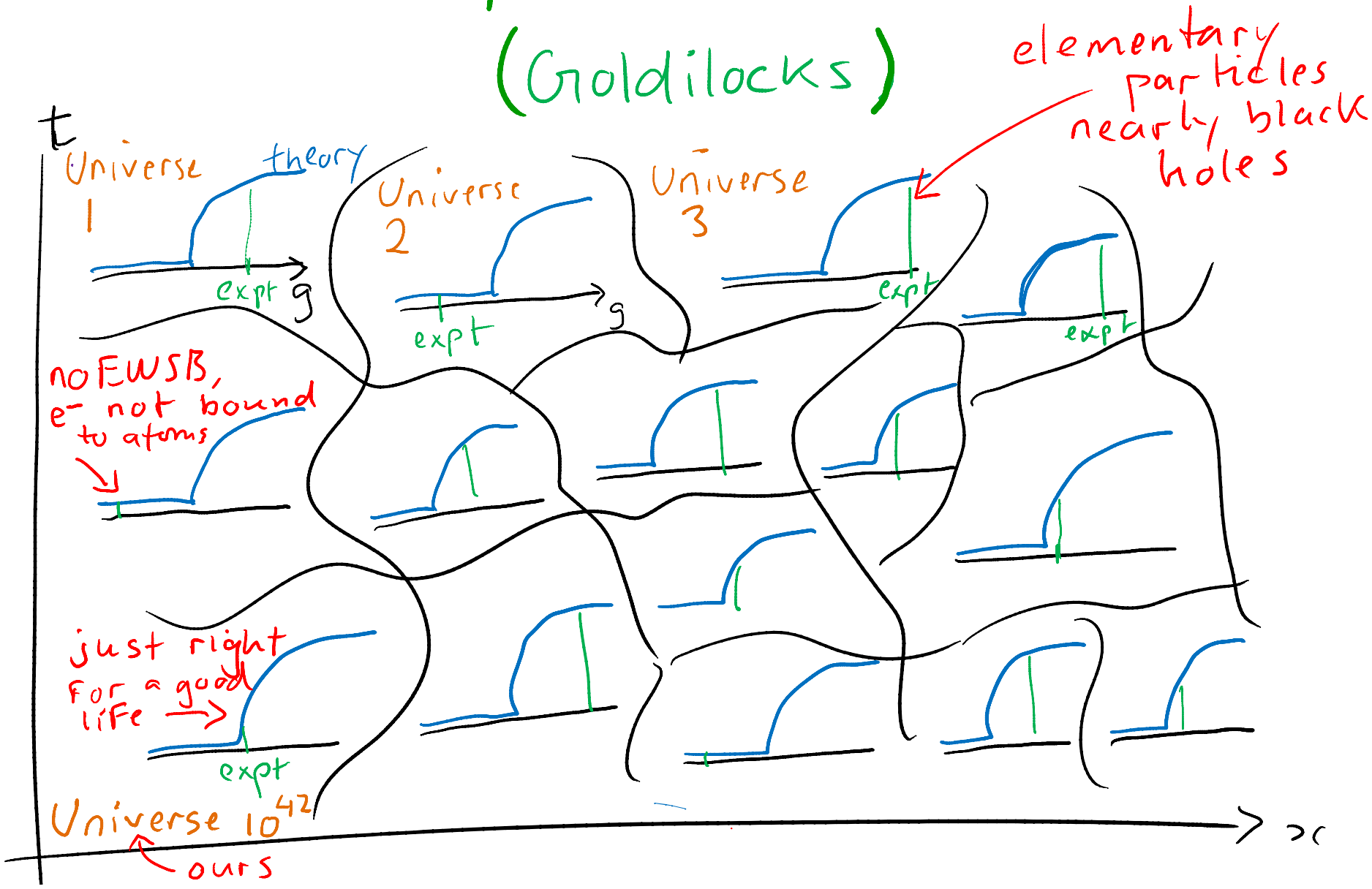
A DIFFERENT VACUUM?



OR A MULTI-VERSE ?

with Anthropic Selection

(Goldilocks)



OR A MULTI-VERSE ?
with Anthropic Selection

The end of Science?

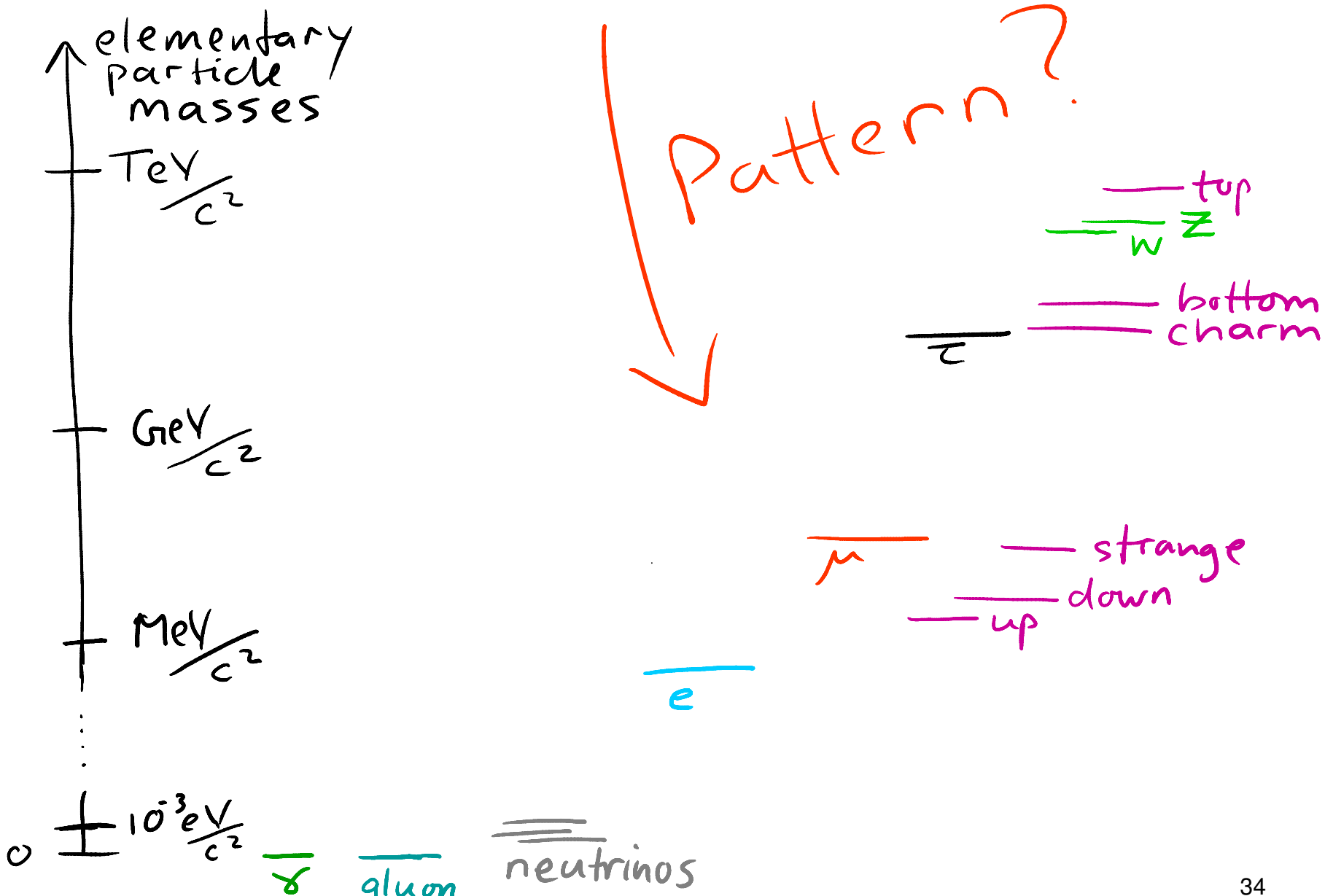
OR A MULTI-VERSE ?
with Anthropic Selection

The end of Science?

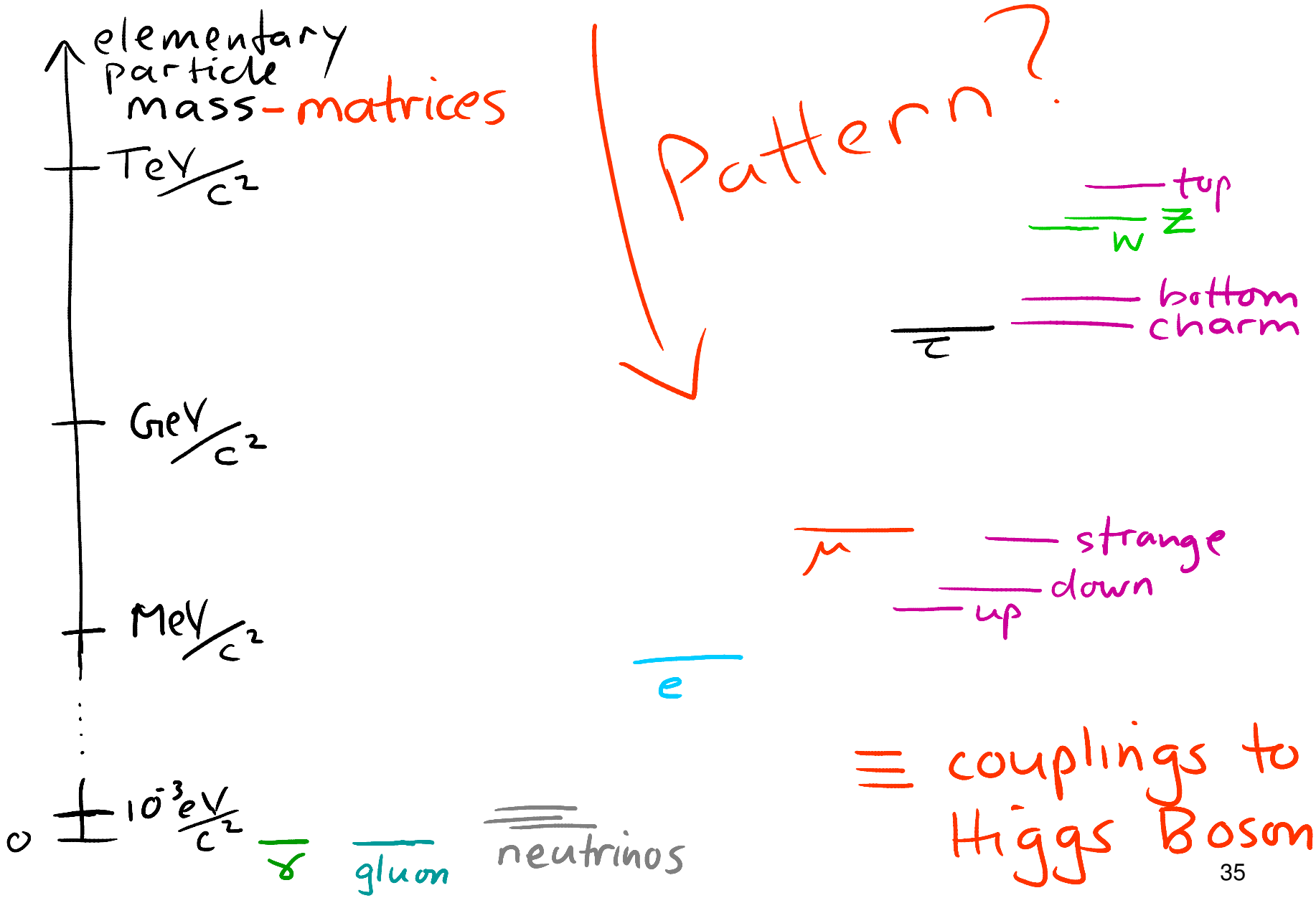
Most famous prediction
(rough order of magnitude)
when applied to UNNATURAL
COSMOLOGICAL CONSTANT
& ACCELERATION OF UNIVERSE

Weinberg '87

Flavor Puzzle

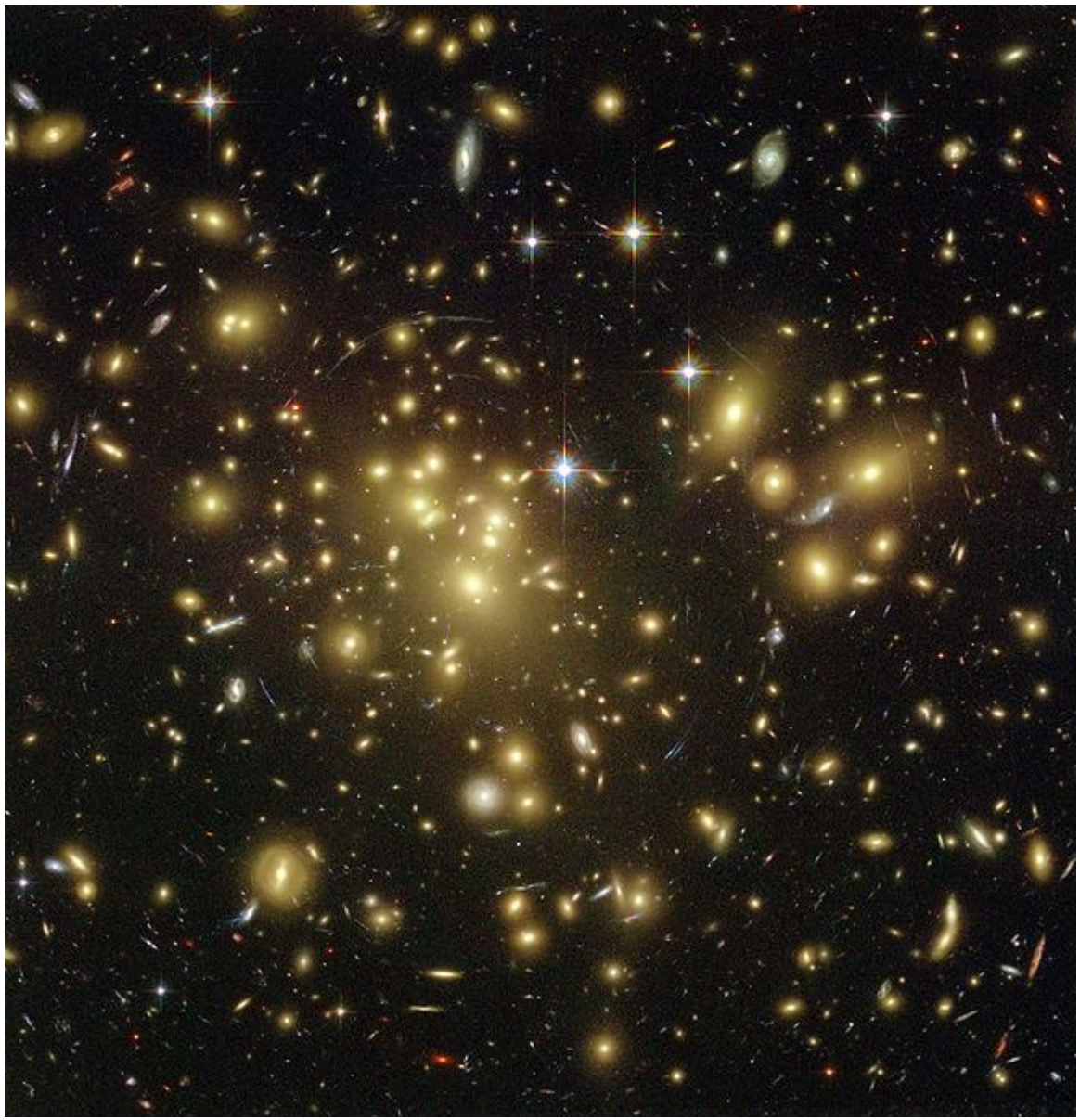


Flavor Puzzle



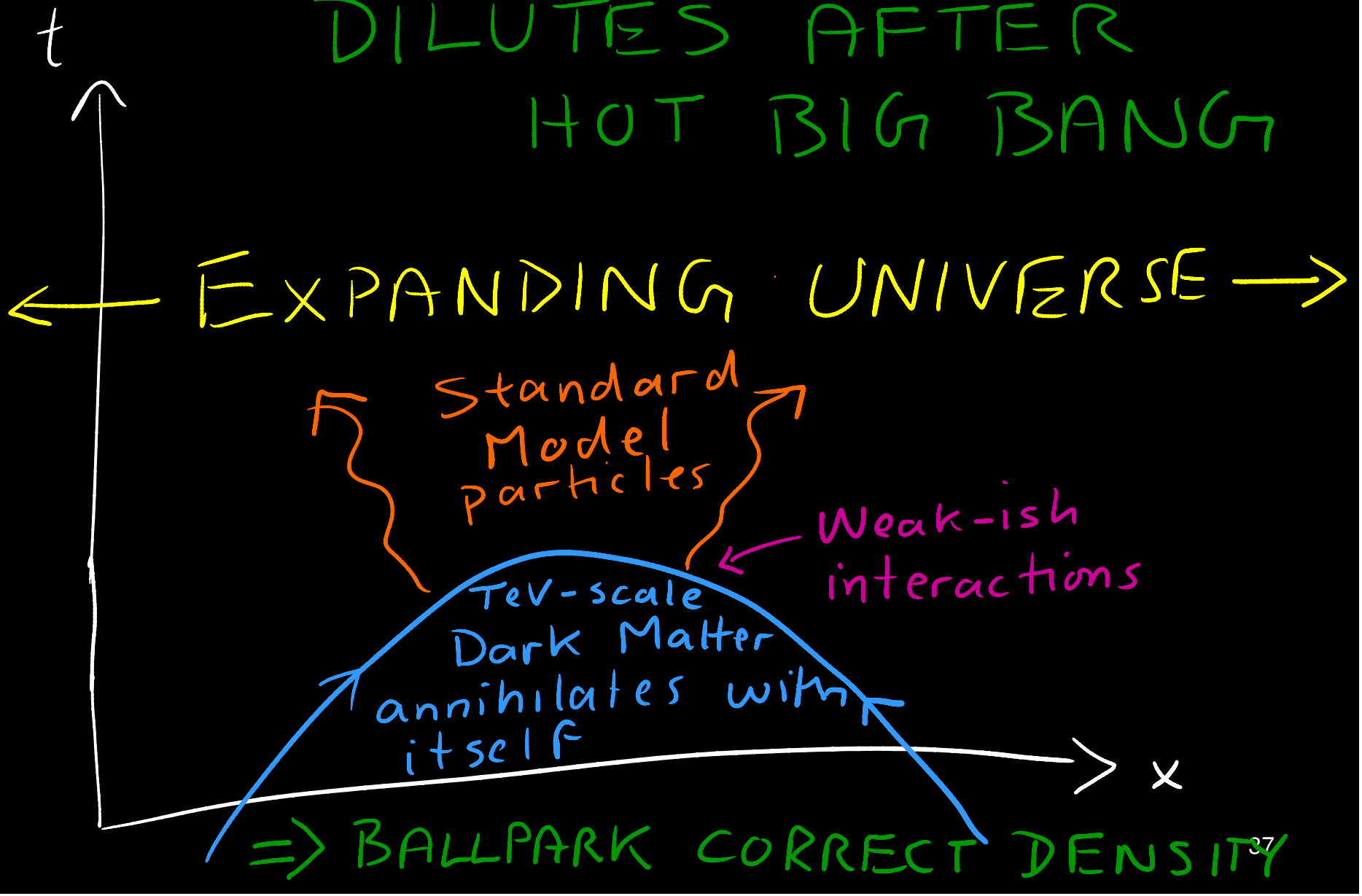
≡ couplings to Higgs Boson.

WHAT IS DARK MATTER?

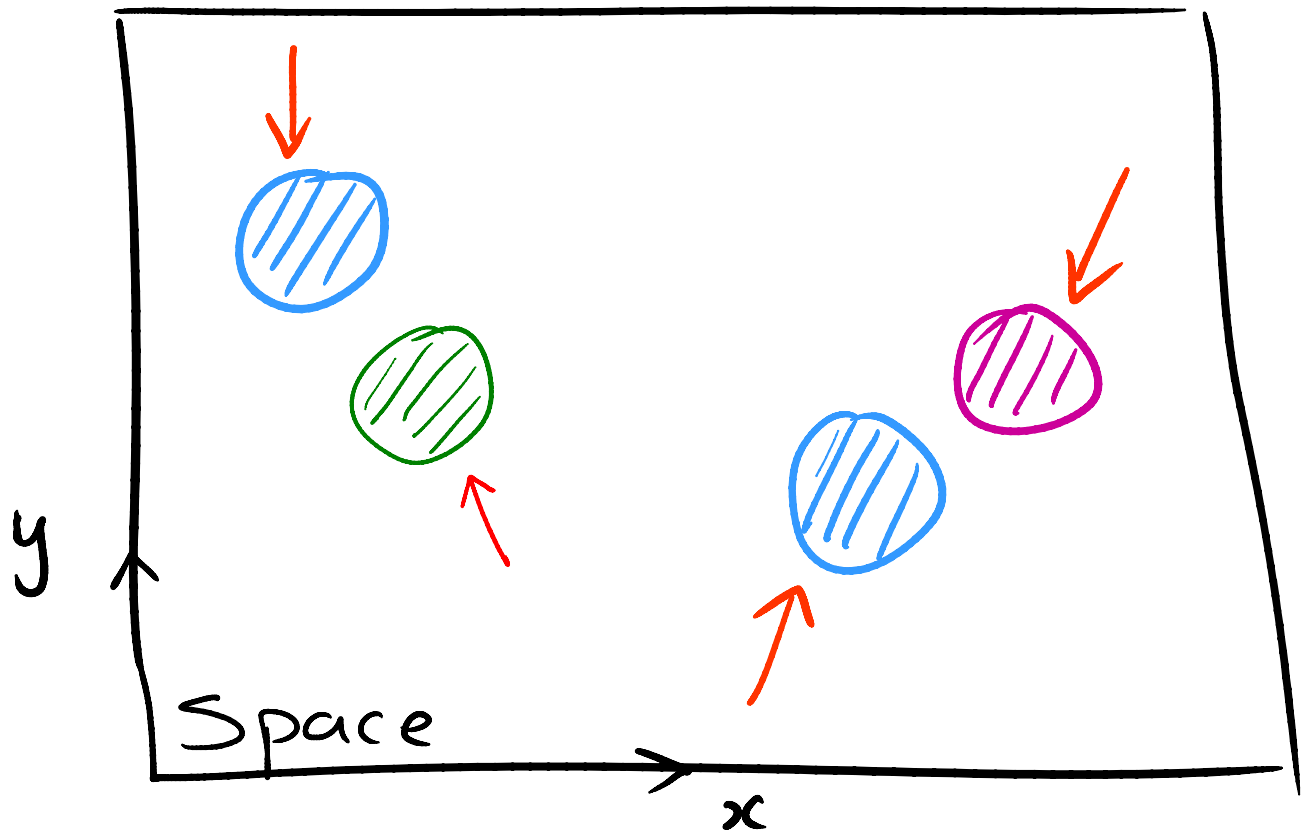


Galaxies distorted by gravitational lensing due to (otherwise) invisible Dark Matter.

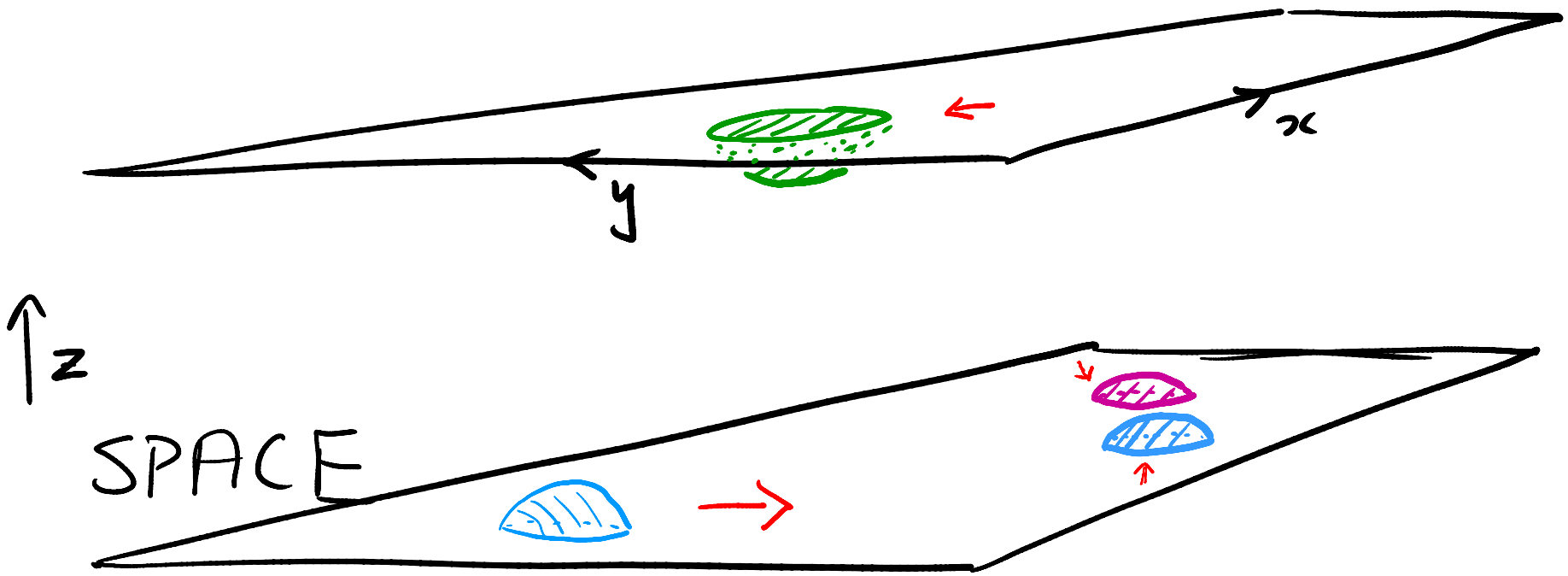
"WIMP" DARK MATTER DILUTES AFTER HOT BIG BANG



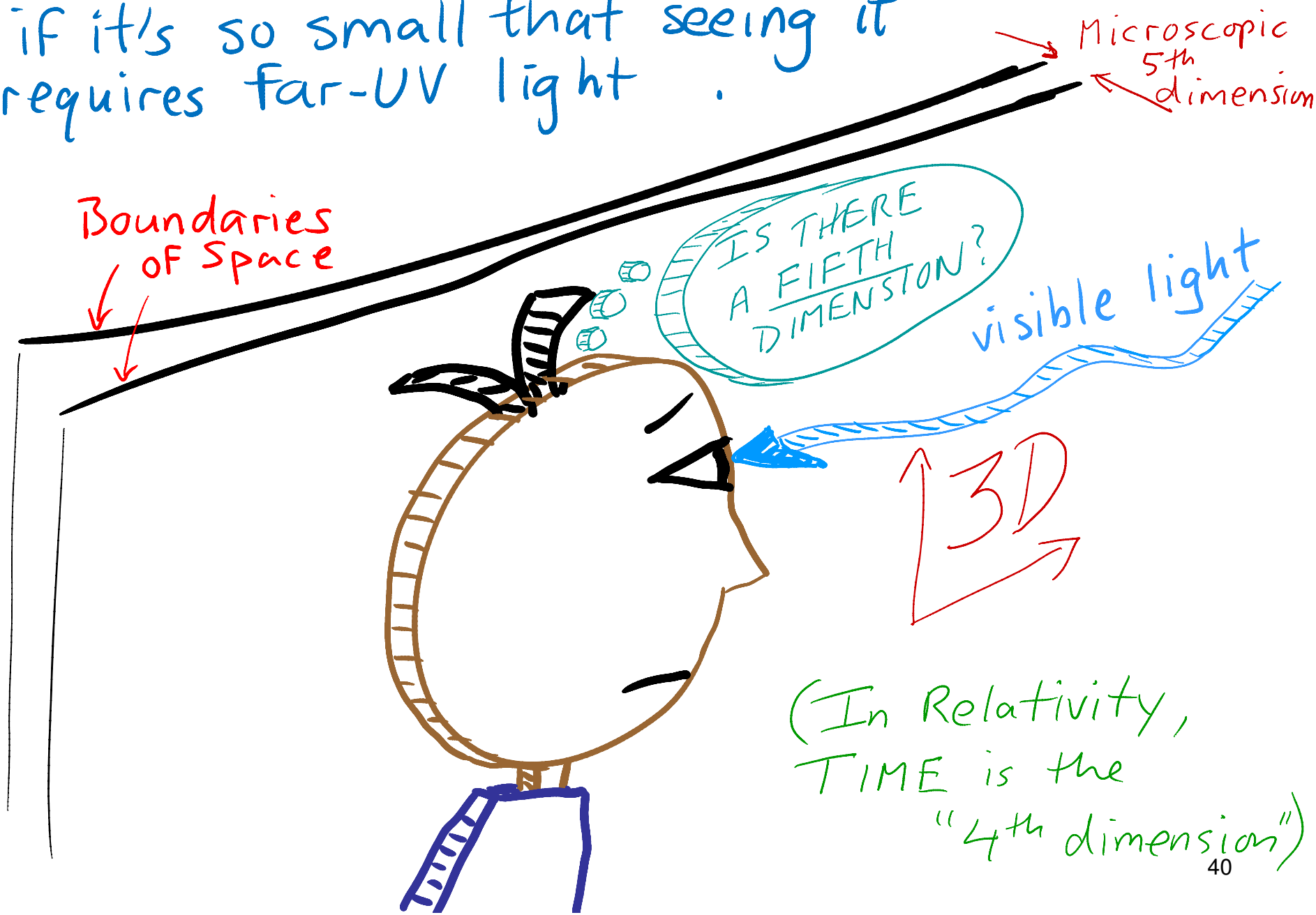
THE ANSWERS TO THESE PUZZLES MAY BE HIDDEN...



IN NEW DIMENSIONS!



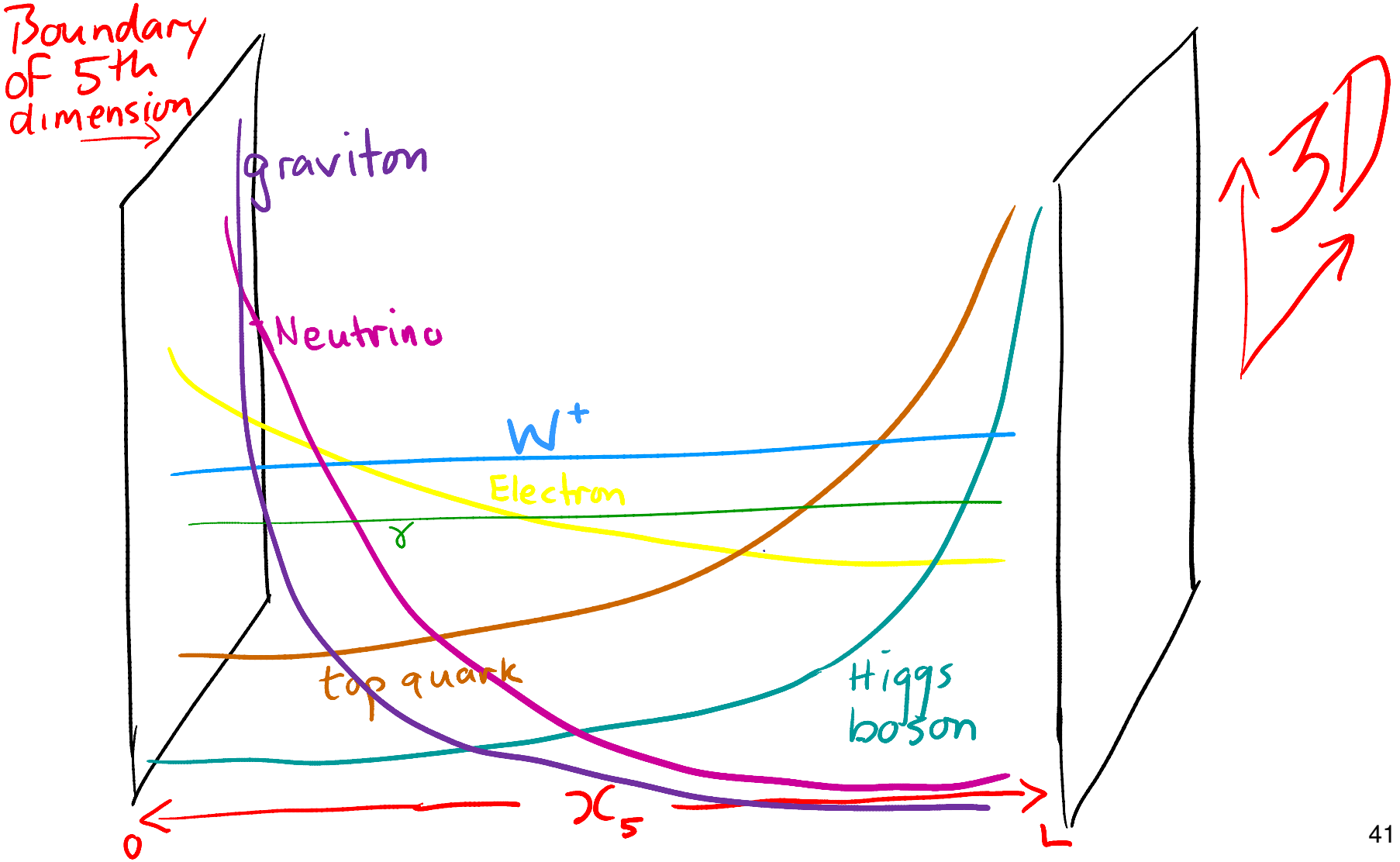
A NEW DIMENSION COULD HIDE if it's so small that seeing it requires far-UV light .



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

5D CHAOS → 4D COSMOS

Different species have different wavefunction solutions to their wave equations



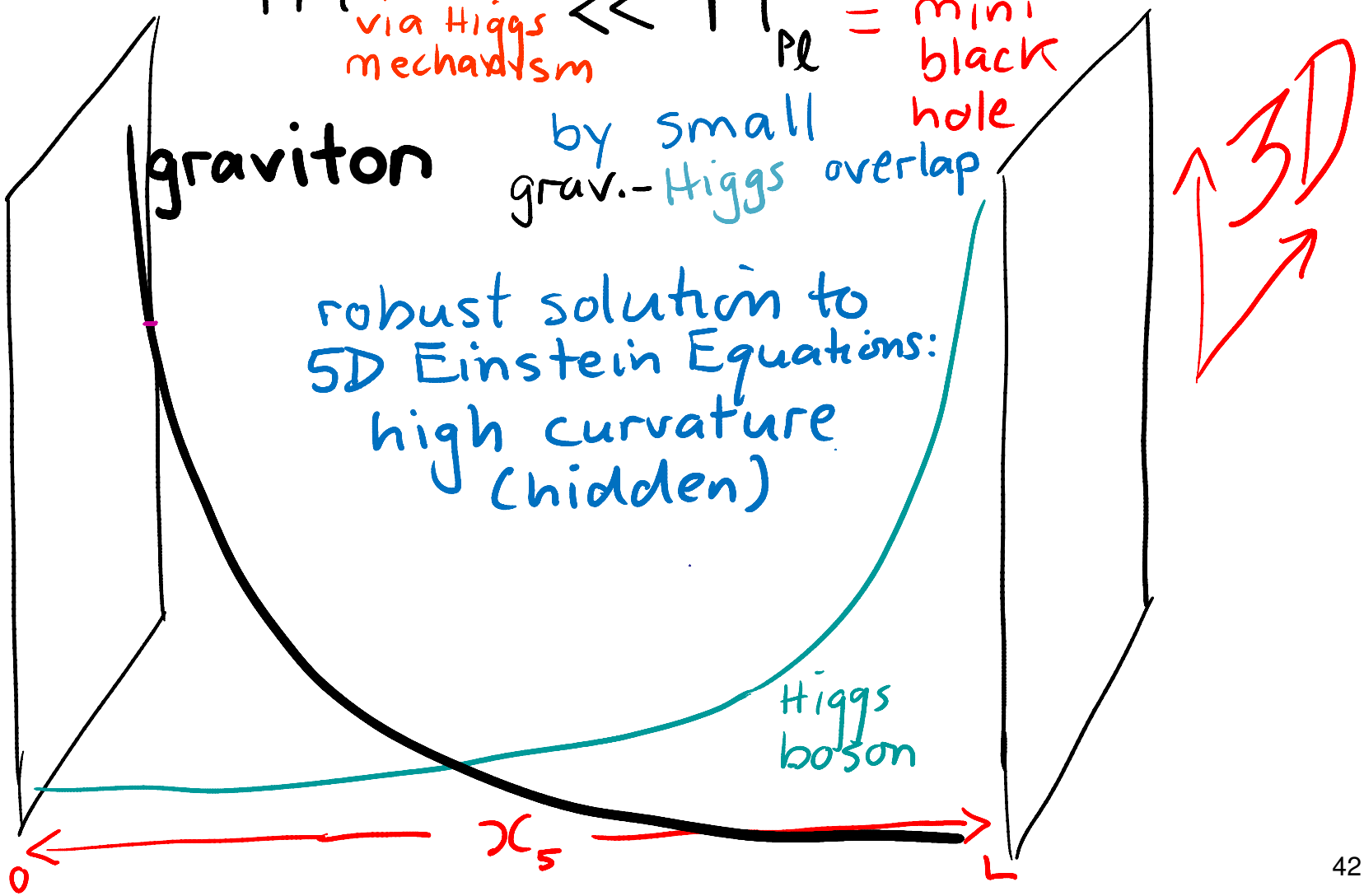
Warped Compactification solves the Hierarchy Problem...

Randall, Sundrum '99

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

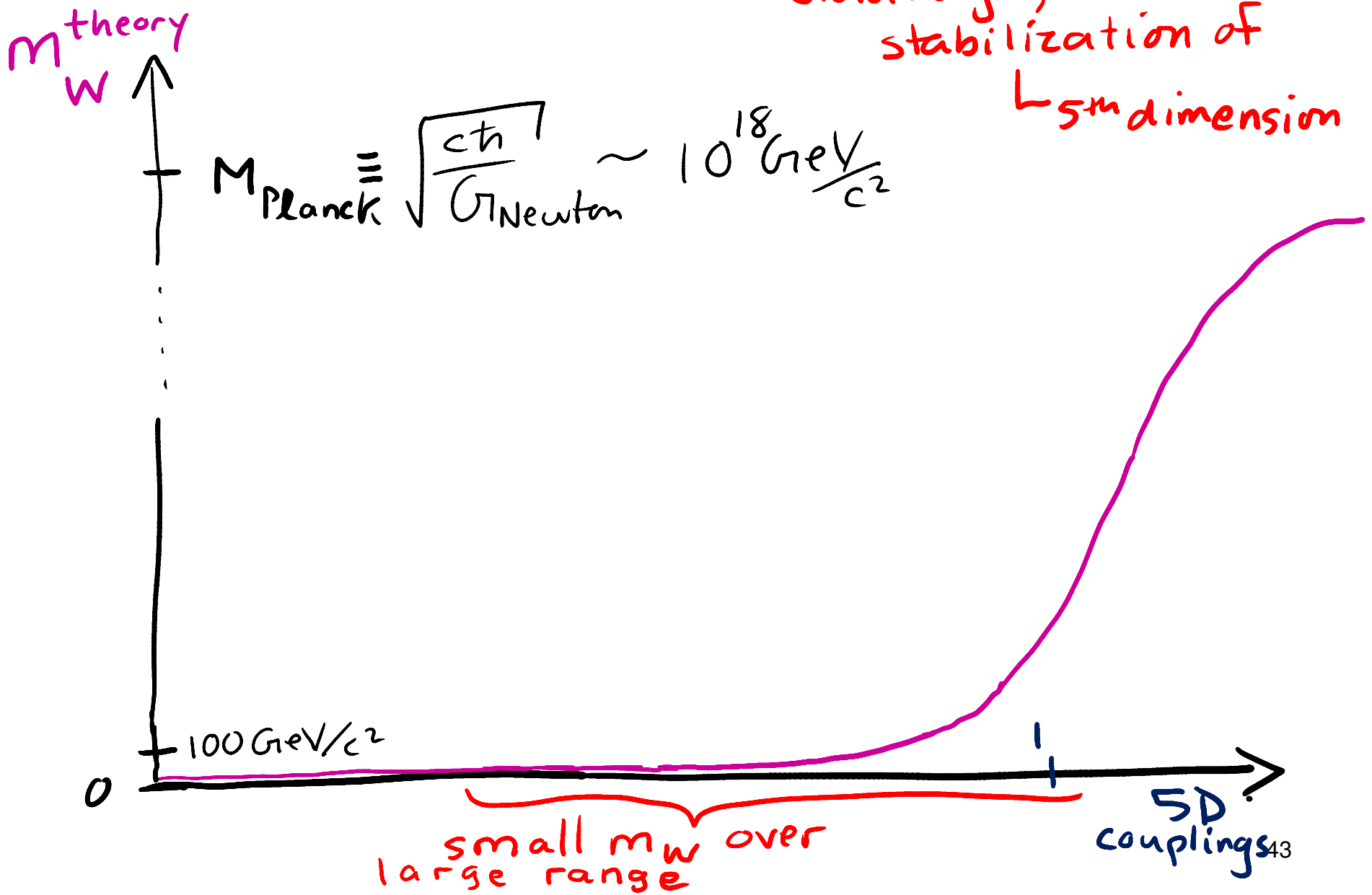
graviton

by small grav.-Higgs overlap

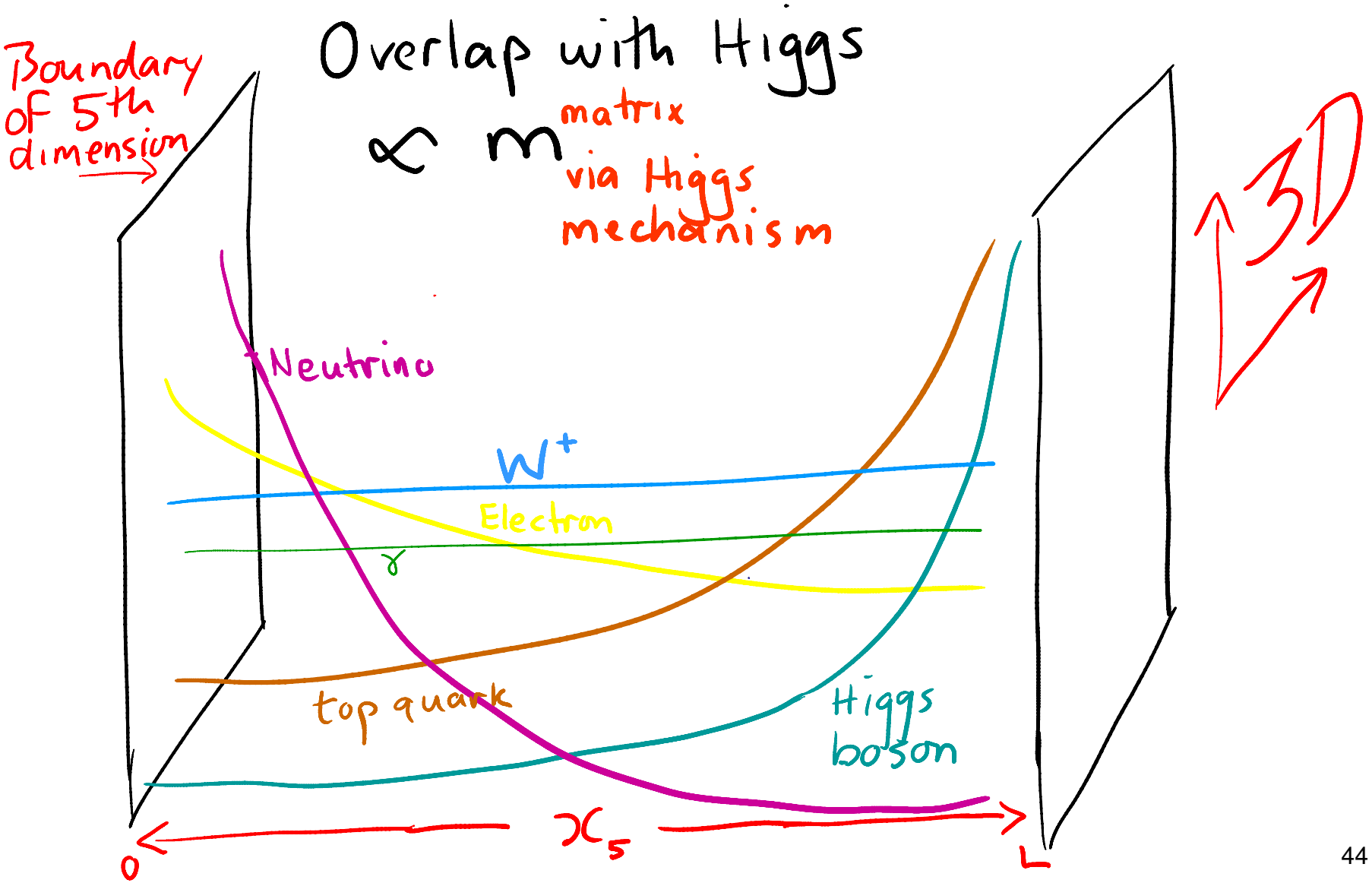


. . . NATURALLY

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

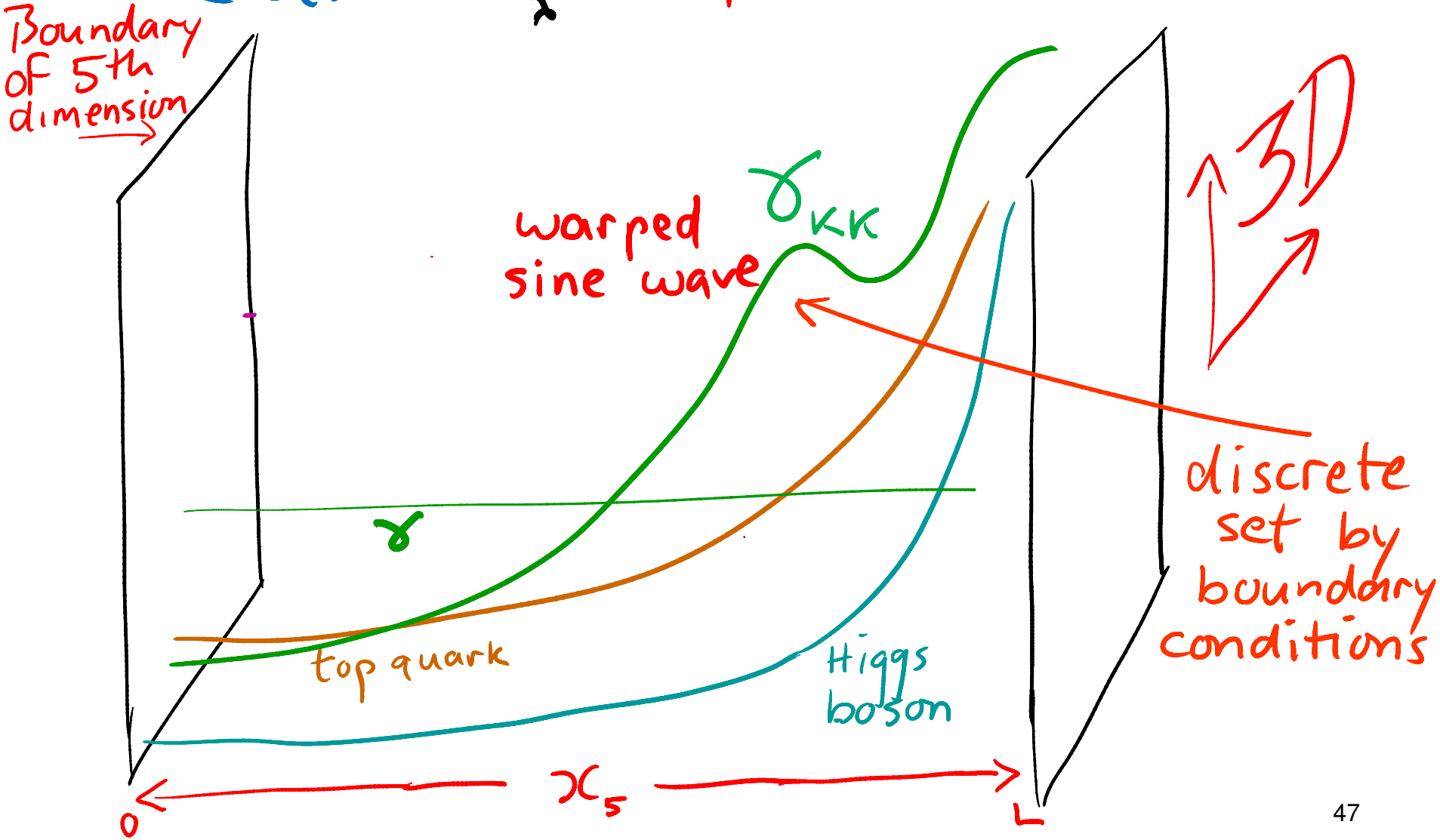
& test & constrain it by high-precision pre-LHC data

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

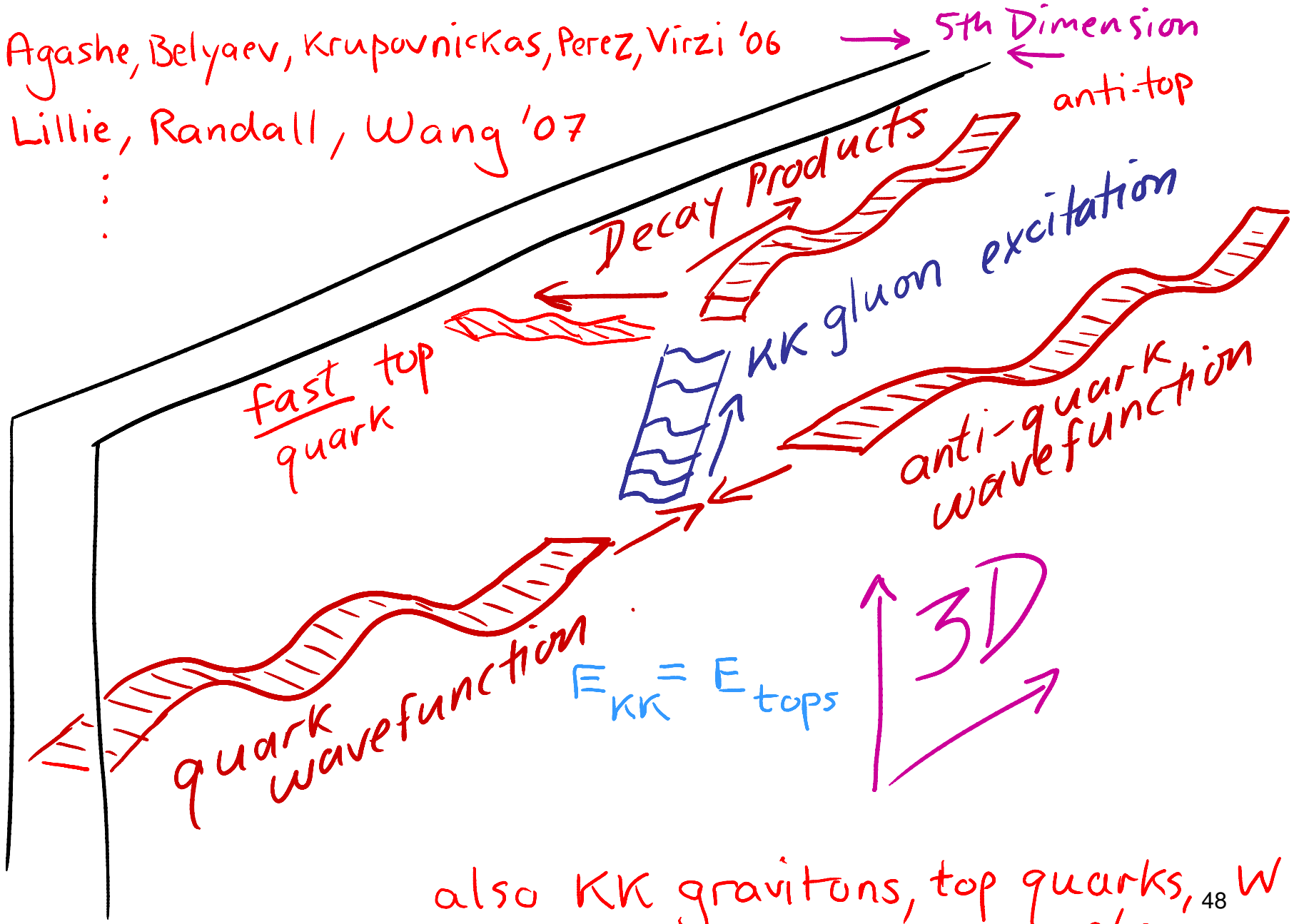
EXTRA-DIMENSIONAL PERCEPTION

requires shorter wavelengths

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

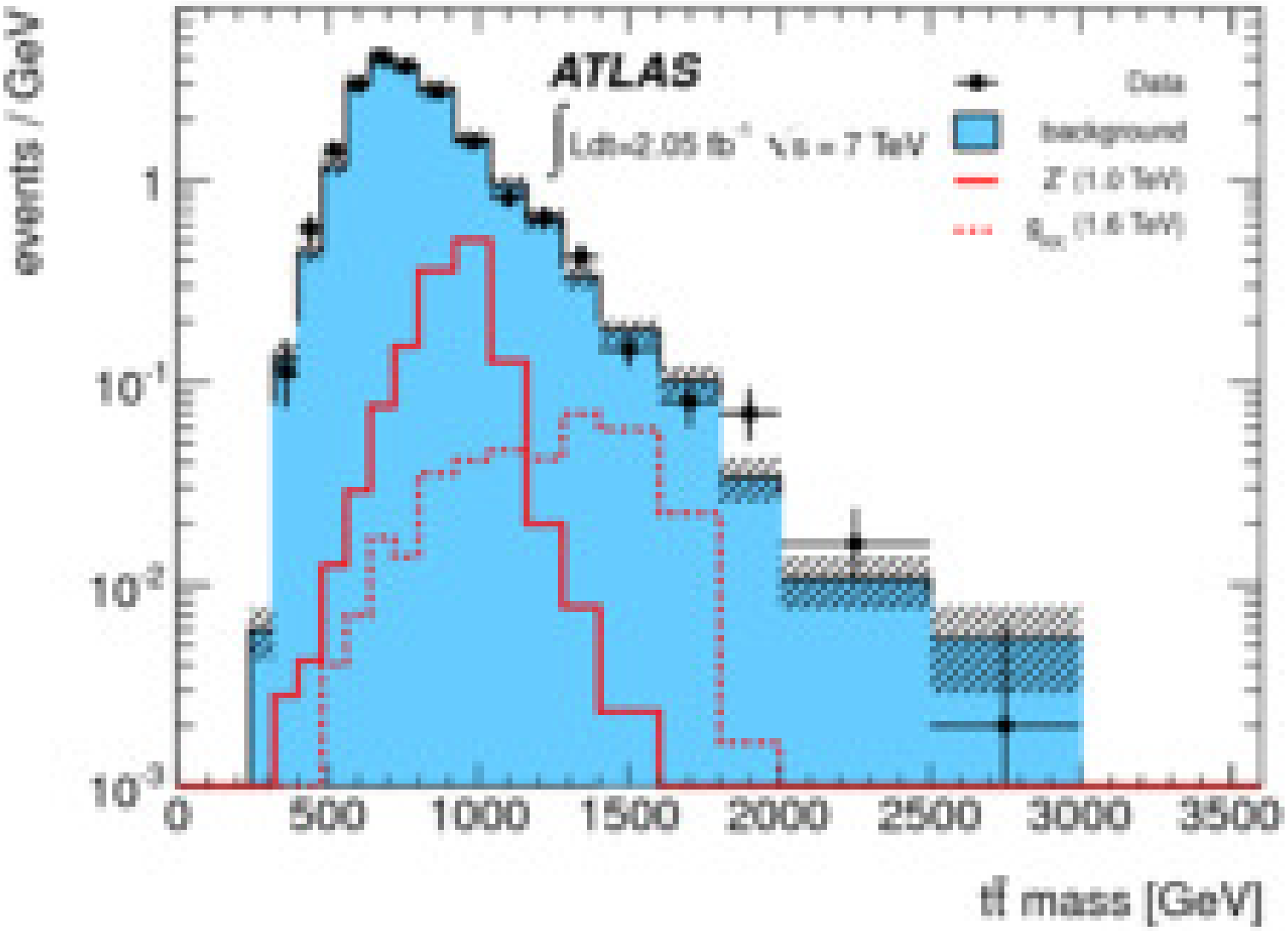


EXTRA-DIMENSIONAL PERCEPTION



also KK gravitons, top quarks, W etc.

COMPETES WITH STANDARD MODEL BACKGROUND



EMERGENT DIMENSIONS

Warped extra dimension is an emergent phenomenon of underlying new strongly coupled force in 3+1 dimensions!

"AdS/CFT duality"

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

EMERGENT DIMENSIONS

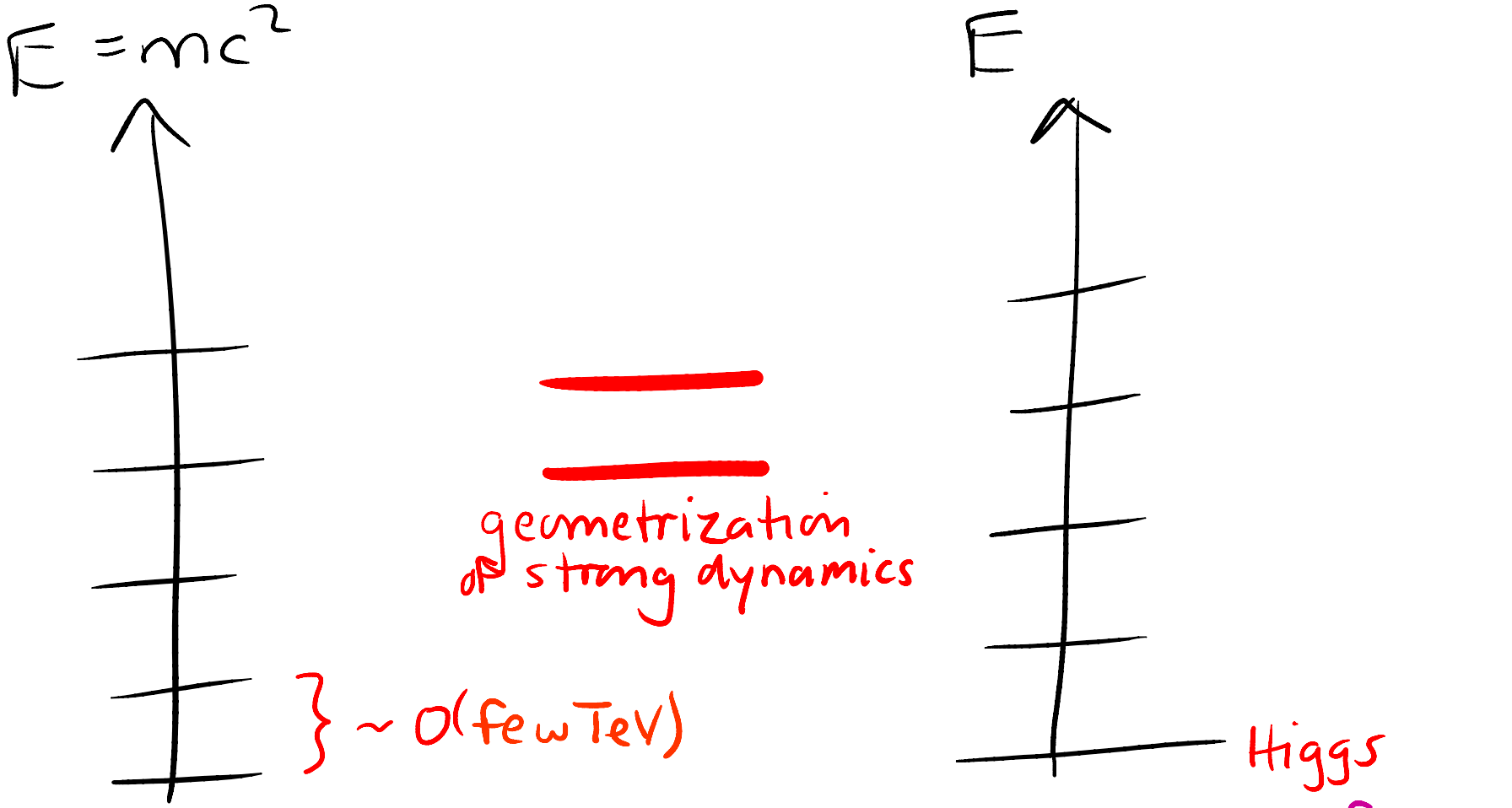
Warped extra dimension is an emergent phenomenon of underlying new strongly coupled force in 3+1 dimensions!

"AdS/CFT duality"

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

~ related to older "Technicolor", Weinberg '79 Susskind '79
"Composite Higgs" Georgi, Kaplan '84 approaches to Naturalness

EMERGENT DIMENSIONS



Kaluza-Klein spectrum in extra-dimensional "wave guide"

Bound states of new strong TeV scale force

Supersymmetry (SUSY)

= "$\sqrt{-1}$"

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

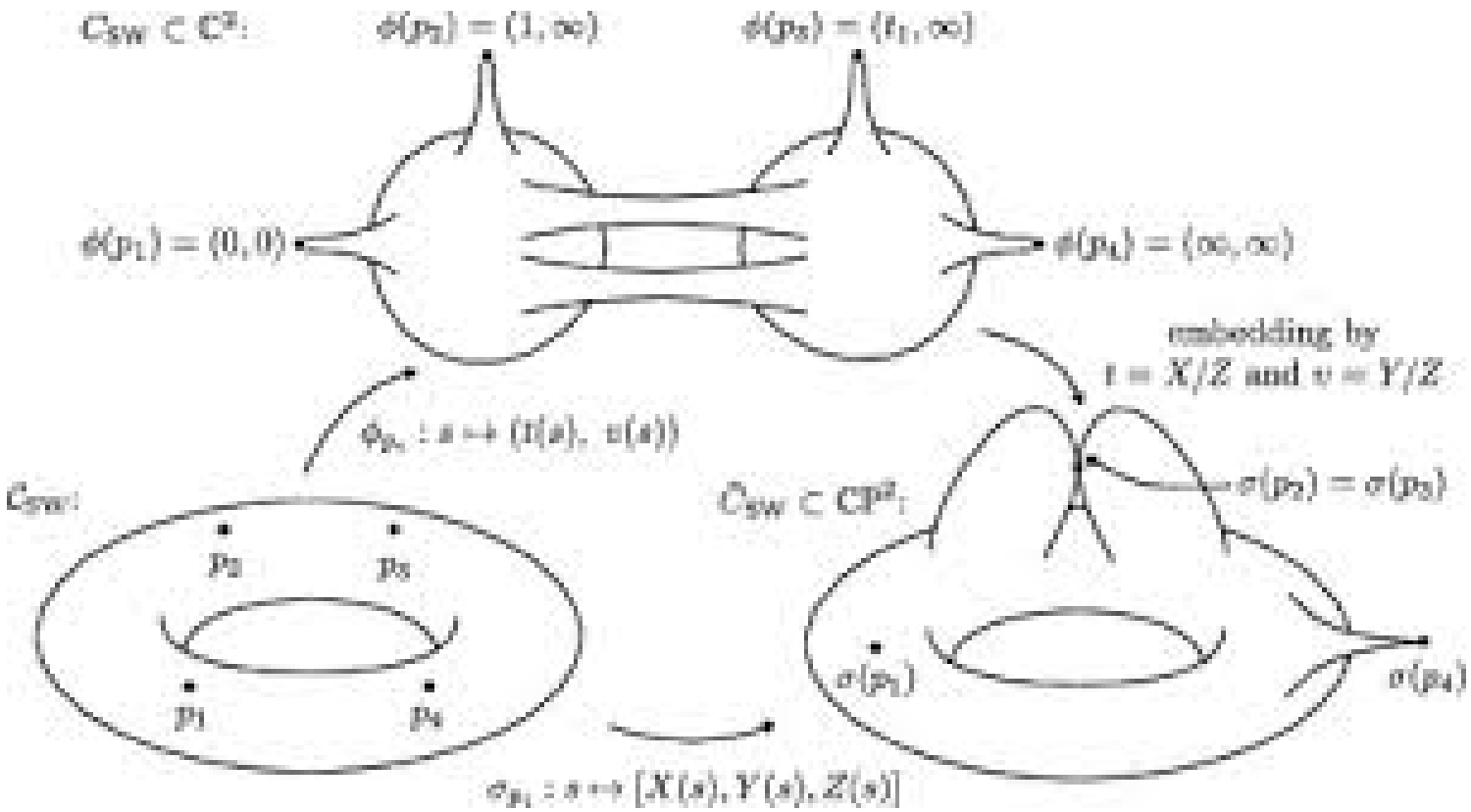
$$Q\,|\,\text{boson}\rangle = |\,\text{fermion}\rangle$$

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

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

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

$\equiv$ Minimal Supersymmetric Standard Model Georgi, Dimopoulos '81

BOSON-FERMION SUPERPARTNERS

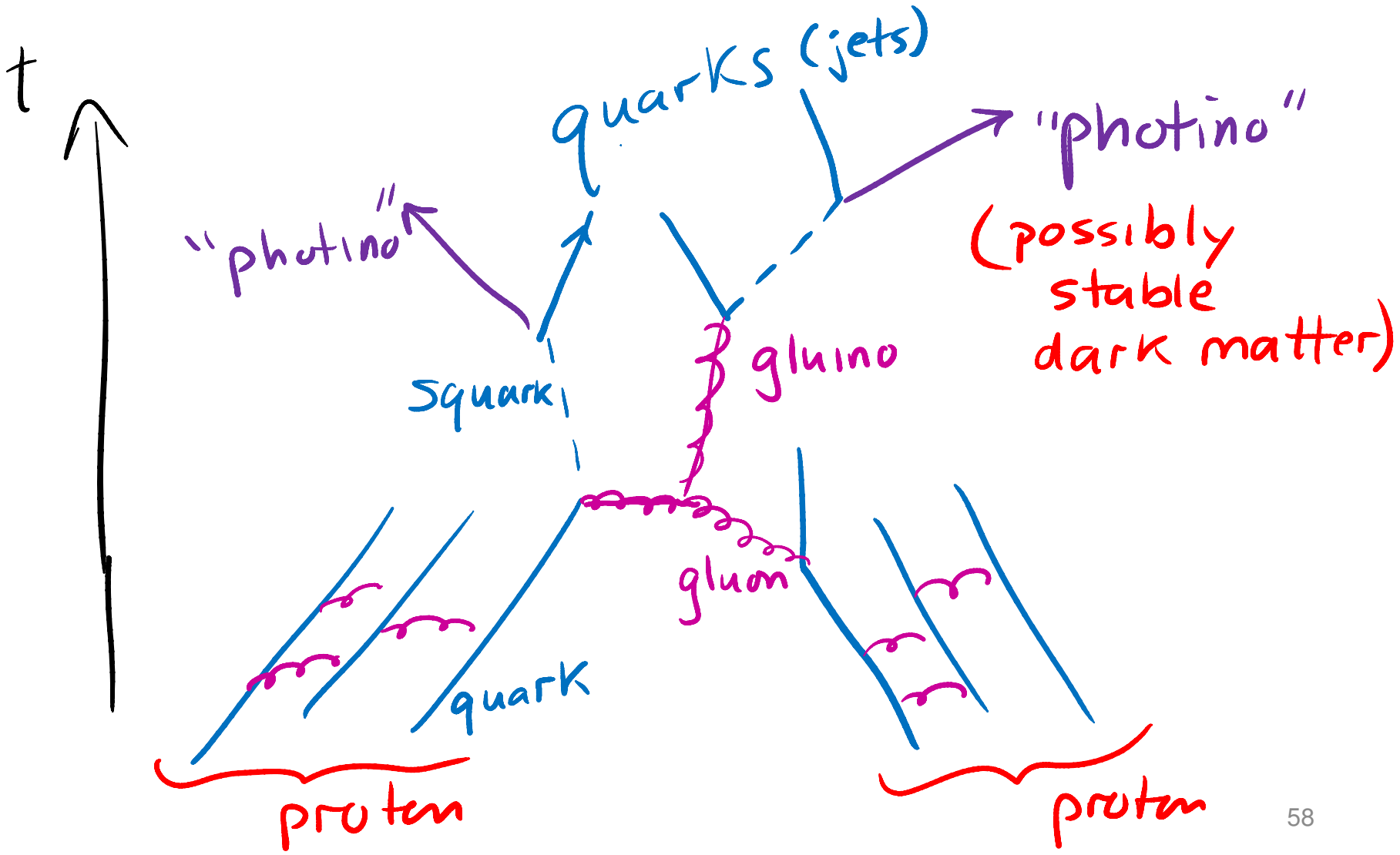
electron (spin-$\frac{1}{2}$)	selectron (spin-0)
photon (spin-1)	photino (spin-$\frac{1}{2}$)
top squark (spin $\frac{1}{2}$)	top squark (spin-0) ("stop")
Higgs (spin-0)	Higgsino (spin-$\frac{1}{2}$)

SUSY breaking via "natural" super-Higgs mechanism

$\Rightarrow \sim O(\text{TeV})$ scale masses for superpartners.

but highly model-dependent

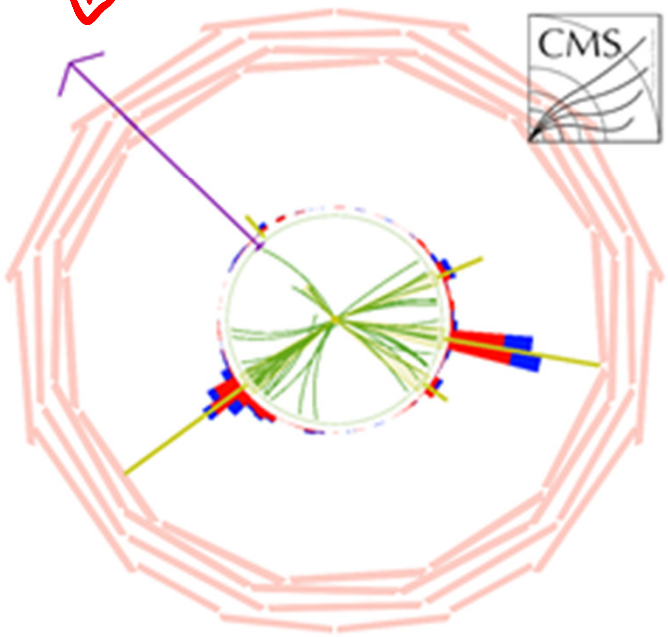
What LHC sought but hasn't found (so far)



HUNTING THE INVISIBLE



Energy imbalance perpendicular to beams due to neutral "photino" ("neutralino") 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

NO GUARANTEES

Next phase much more data ~13-14 TeV

Principle of NATURALNESS IS ON TRIAL

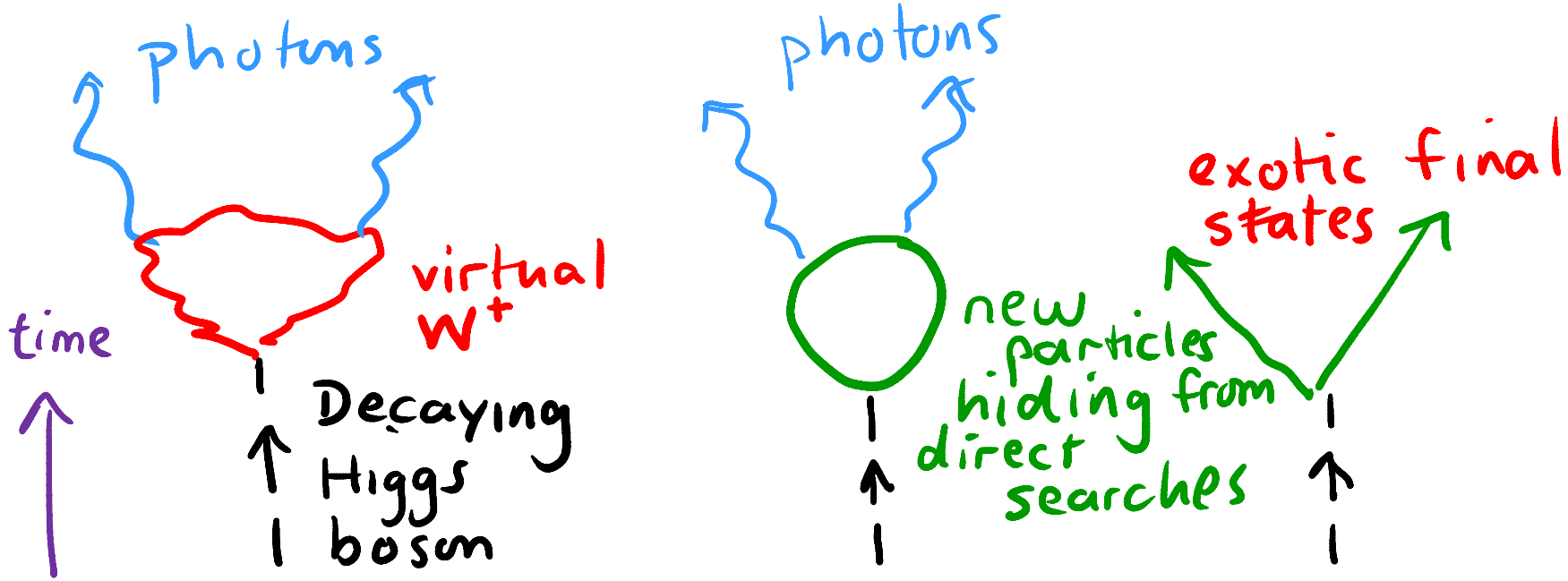
There are beautiful, natural Higgs mechanisms

$\Rightarrow$ new TeV-scale particles on general grounds

Ingenuity is required to hunt them thoroughly in complex collider environment & to provide theoretical templates.

General purpose (agnostic) searches essential

PRECISION HIGGS PHYSICS is underway



Standard

Non-standard

contributions to Higgs decay

LHC is very powerful
& may make dramatic discoveries

But unable to very
strongly test Naturalness
or very precisely test Higgs.

To do this, & to fully
understand LHC findings

New colliders, more
powerful/precise, will be needed

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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

My sense is the
journey is just at

The Beginning . . .