The Higgs Boson
an odyssey in the heart of matter

2nd NPKI Seeds Program

The Physics, the Truth, the Justice

NEW PHYSICS KOREA INSTITUTE

FRONTIERS OF SCIENCE

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CERN

ICREA INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

What is a particle?

A small, quantum and fast moving object

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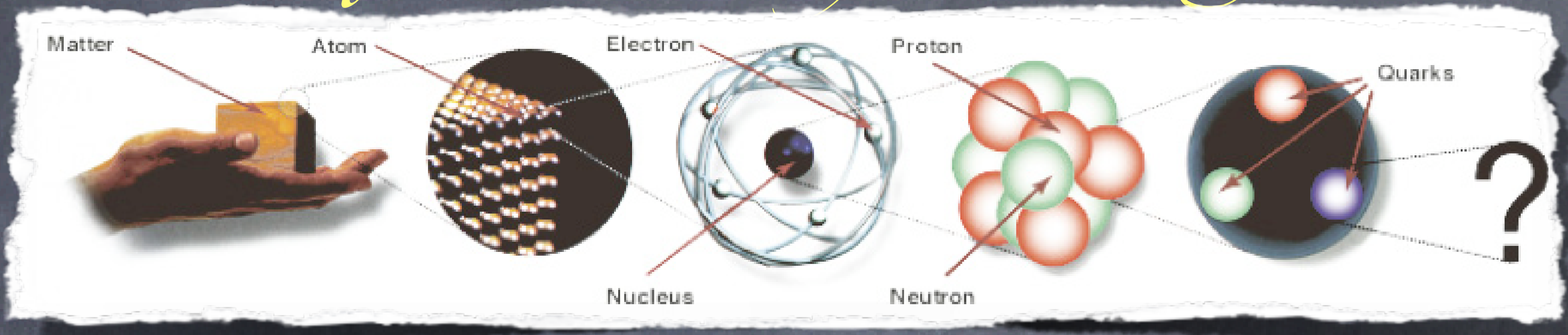


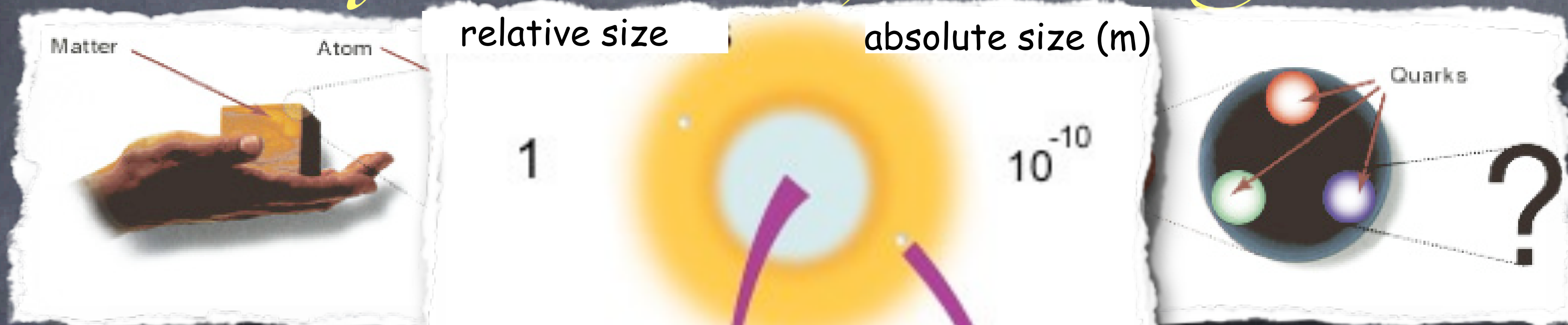
"Small is beautiful"

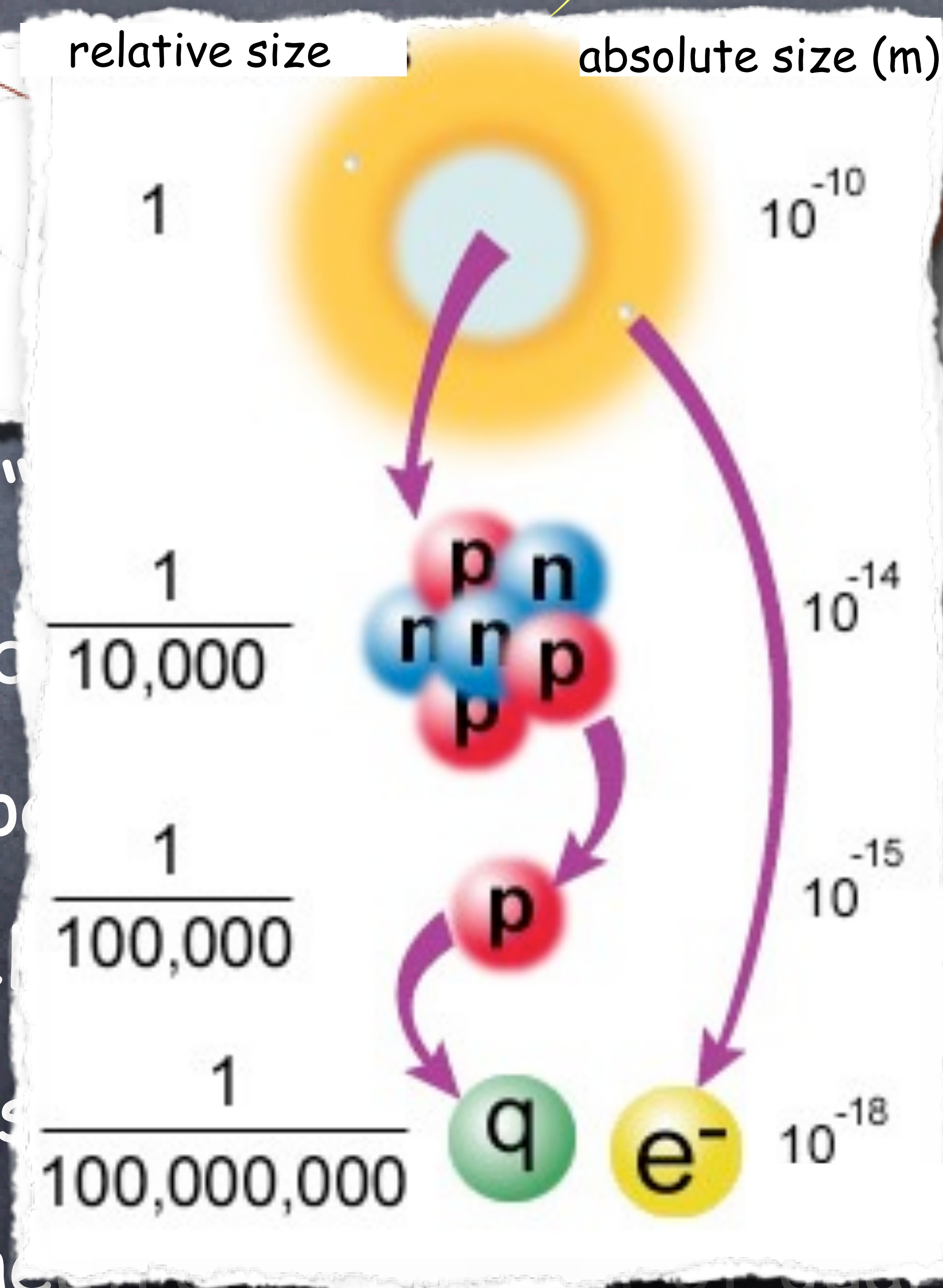
E.F. Schumacher (British economist)

- Matter is made of molecules
- Mocules are packages of atoms...
- Atomes are electrons surrounding a nucleus...
- Nuclei are ensembles of protons and neutrons ...
- Protons and neutrons are built of quarks ...

What is a particle?

A small, quantum and fast moving object





“ … Schumacher (British economist)

- Matter is mac …
- Mocules are p …
- Atomes are el … cleus...
- Nuclei are ens … eutrons ...
- Protons and ne … ks ...

Creating matter from energy

- ***Chemistry : matter reorganization***

  the various consistuants of matter reorganize themselves

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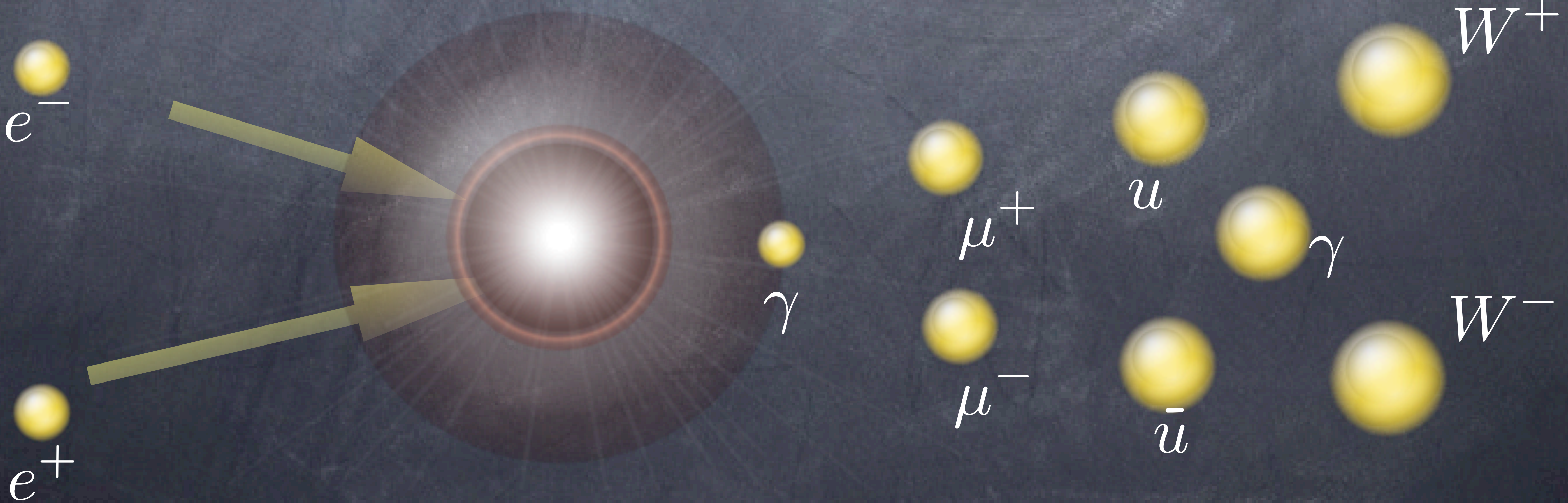

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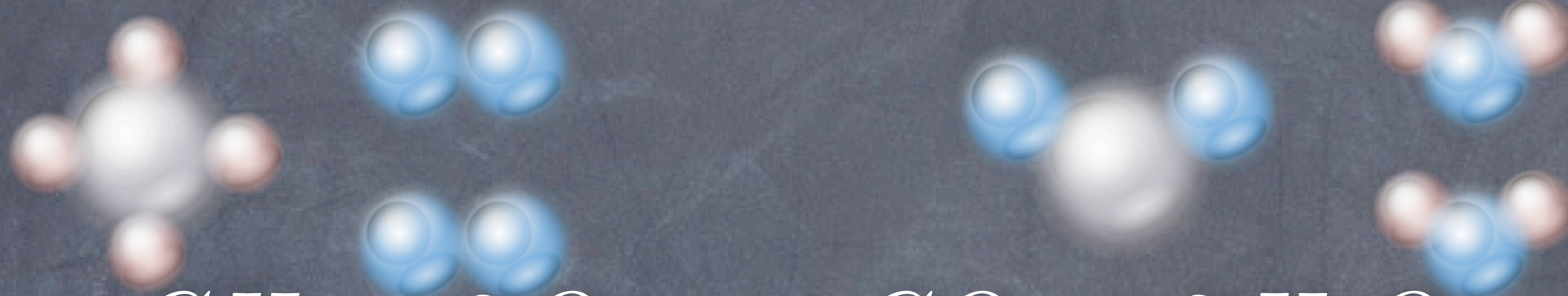

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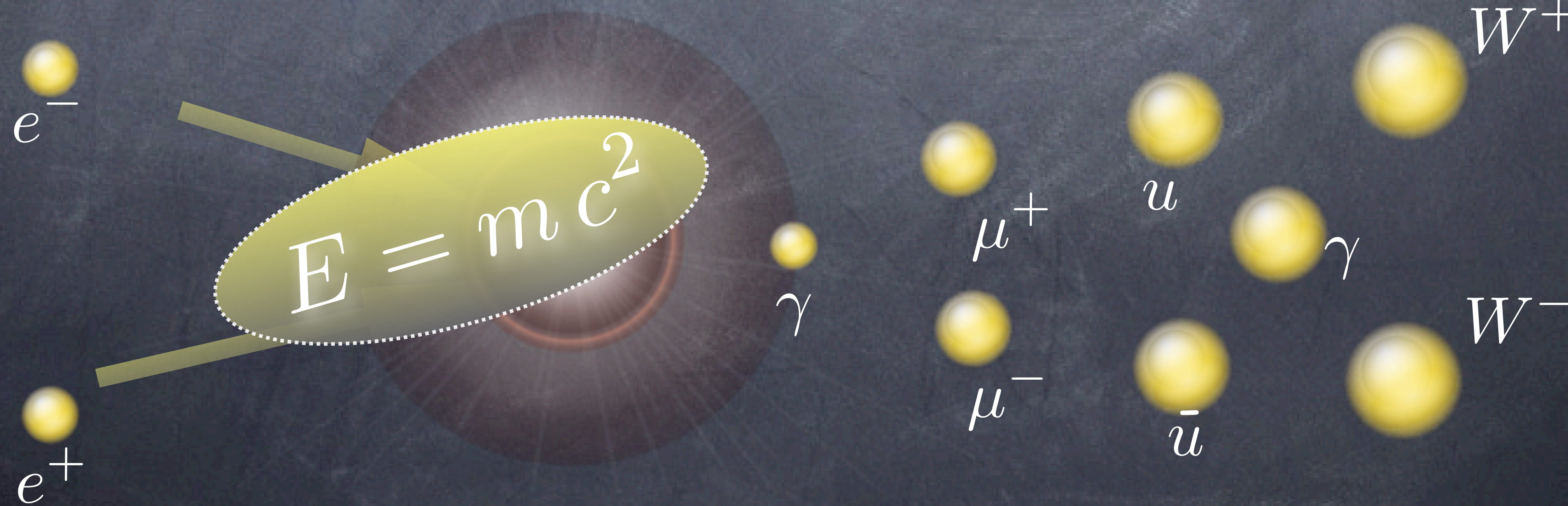

Classical versus quantum collissions

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quantum size
of an object of mass m $\lambda = \frac{h}{mc}$
(Compton wave-length)

h = Planck constant = $6.6\times10^{-34}\ m^2kg/s$

Classical : $\lambda \ll R$

strawberry : $m \sim 30$ g ➡ $\lambda \sim 10^{-40}$ m

quantum : $\lambda \gg R$

e^- : $m \sim 9.1\times10^{-31}$ kg ➡ $\lambda \sim 10^{-12}$ m

p : $m \sim 1.6\times10^{-27}$ kg ➡ $\lambda \sim 10^{-15}$ m

The Standard Model: Matter

The genetic code of matter

The elementary building blocks that everything is made of

LEPTONS	QUARKS

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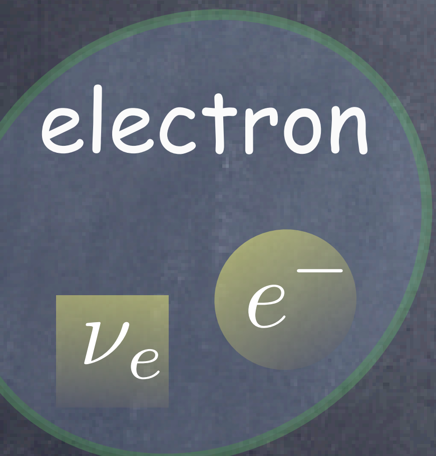

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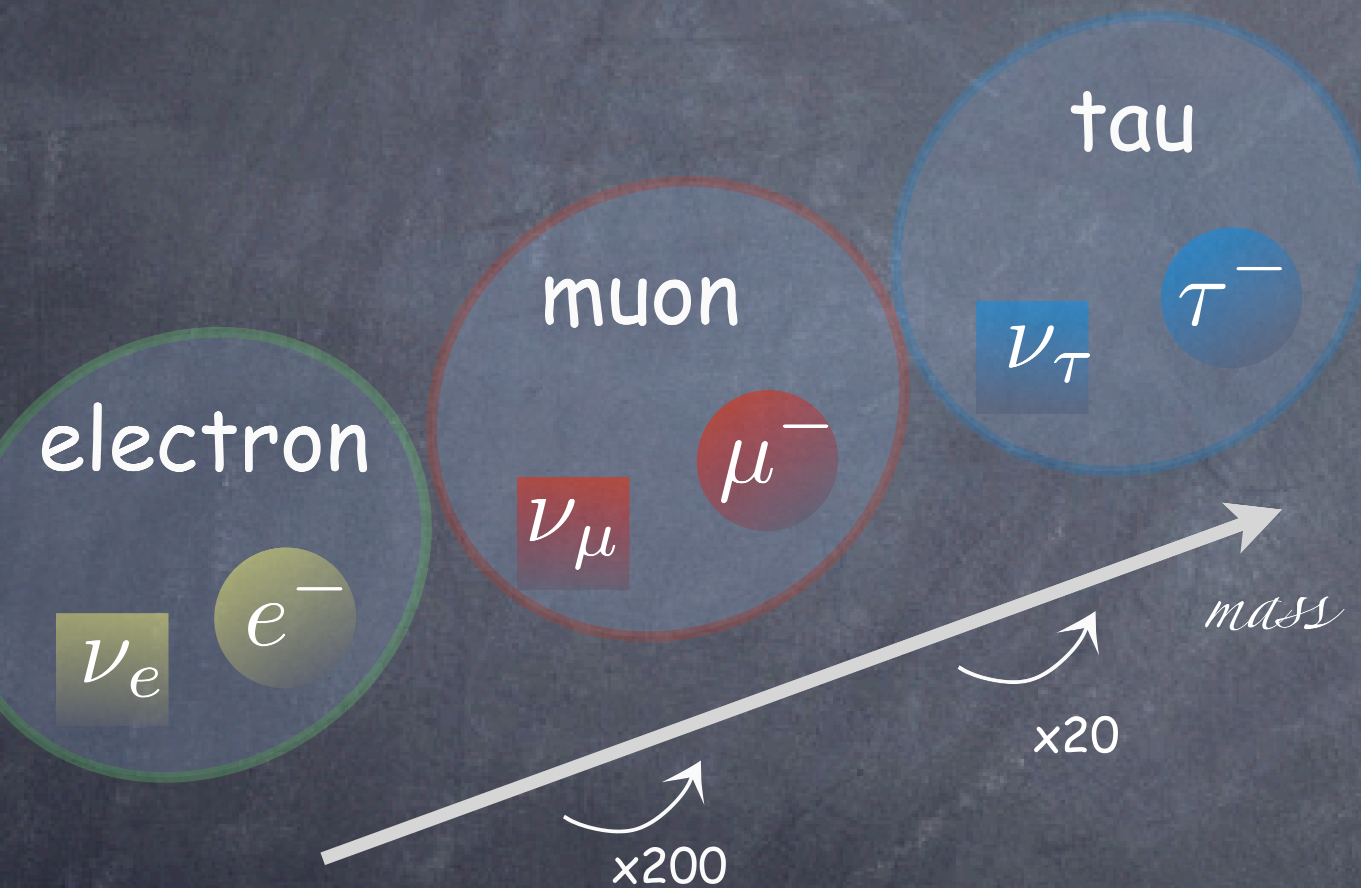

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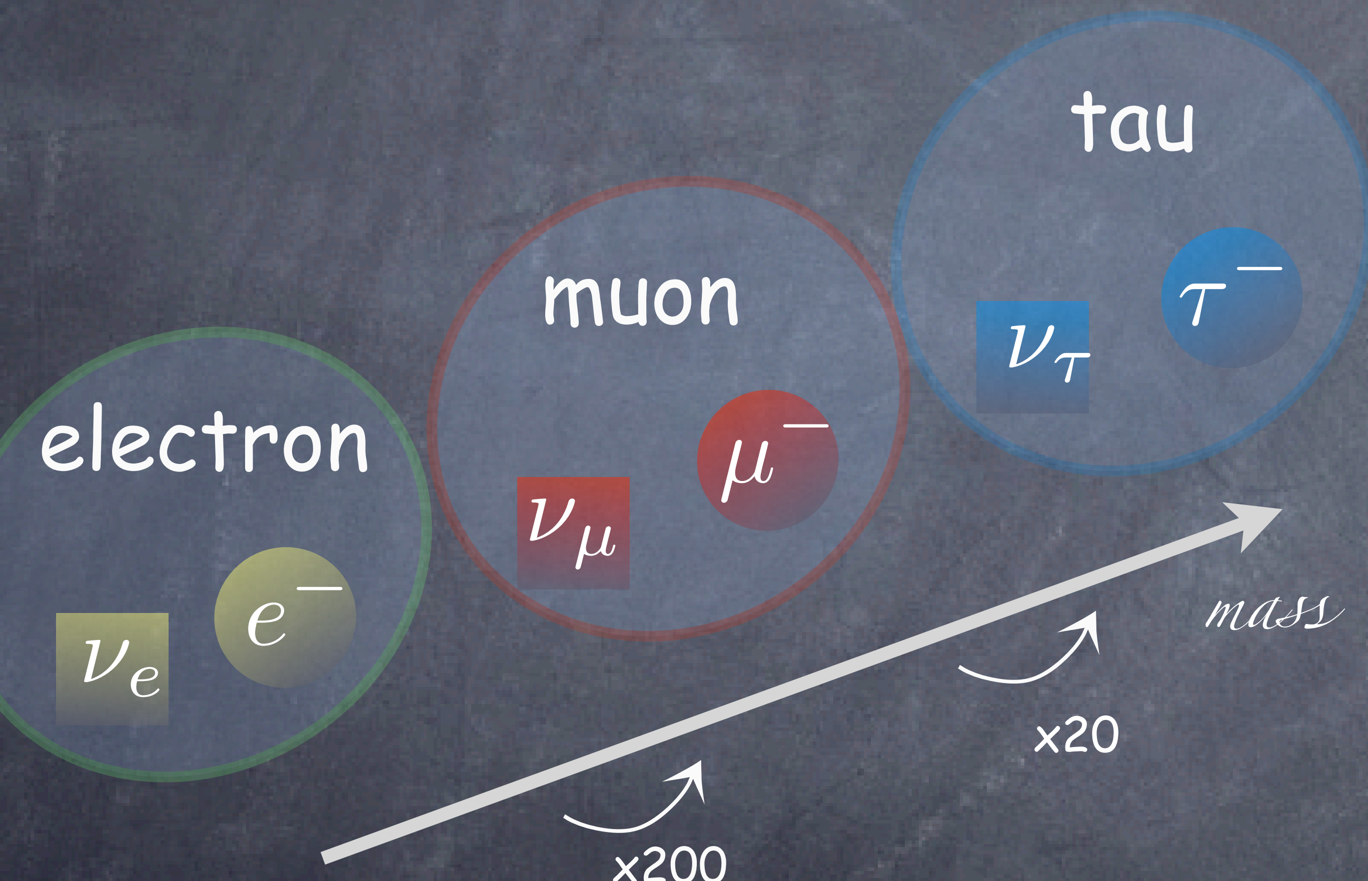

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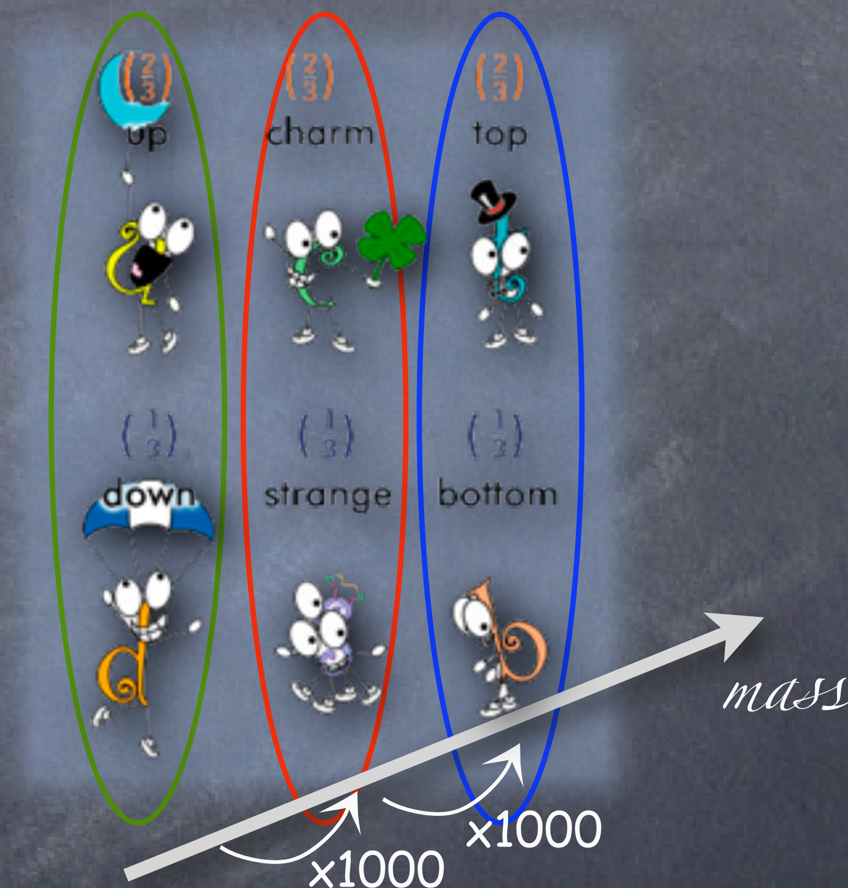

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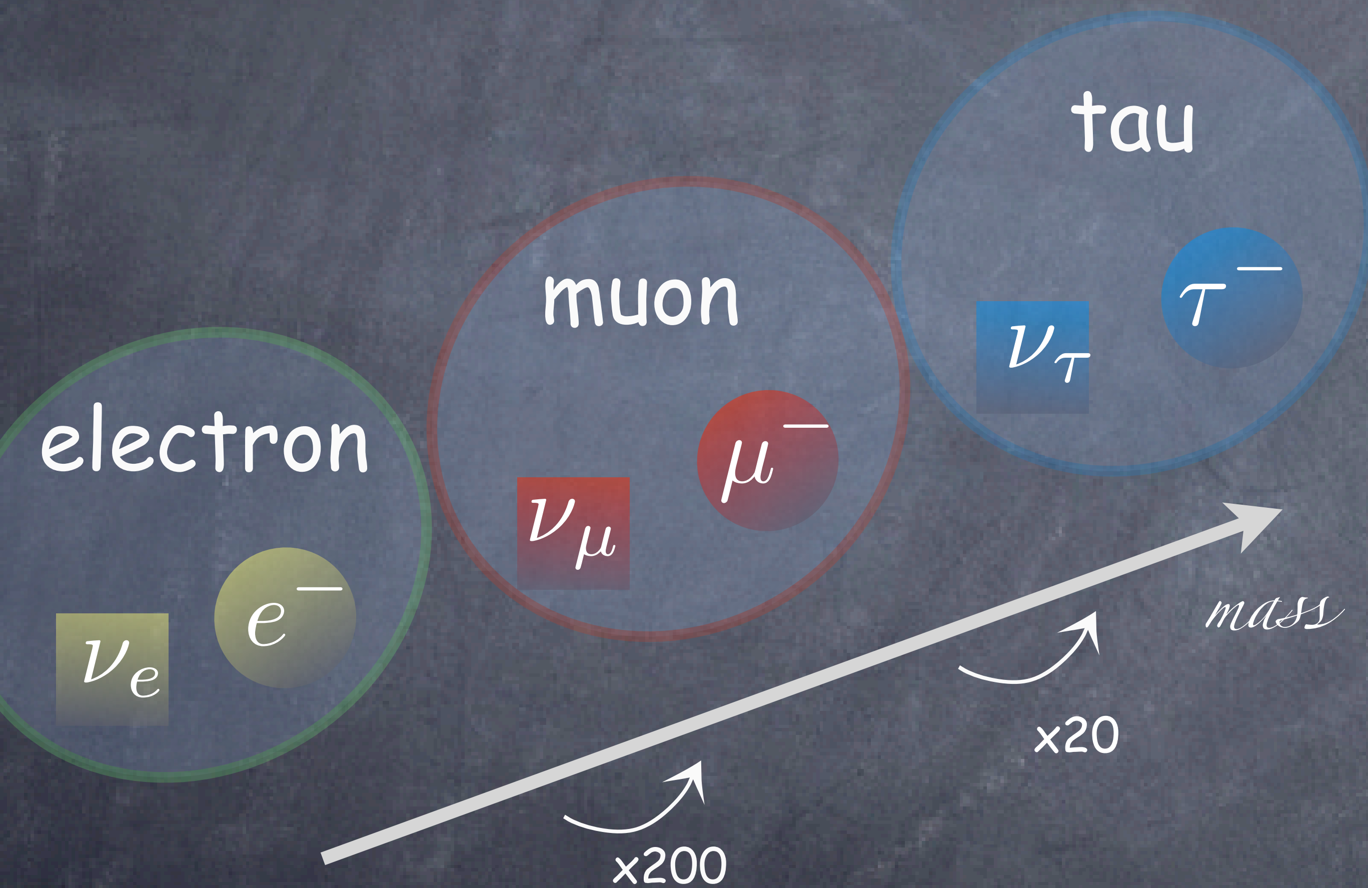

no composite states made of leptons

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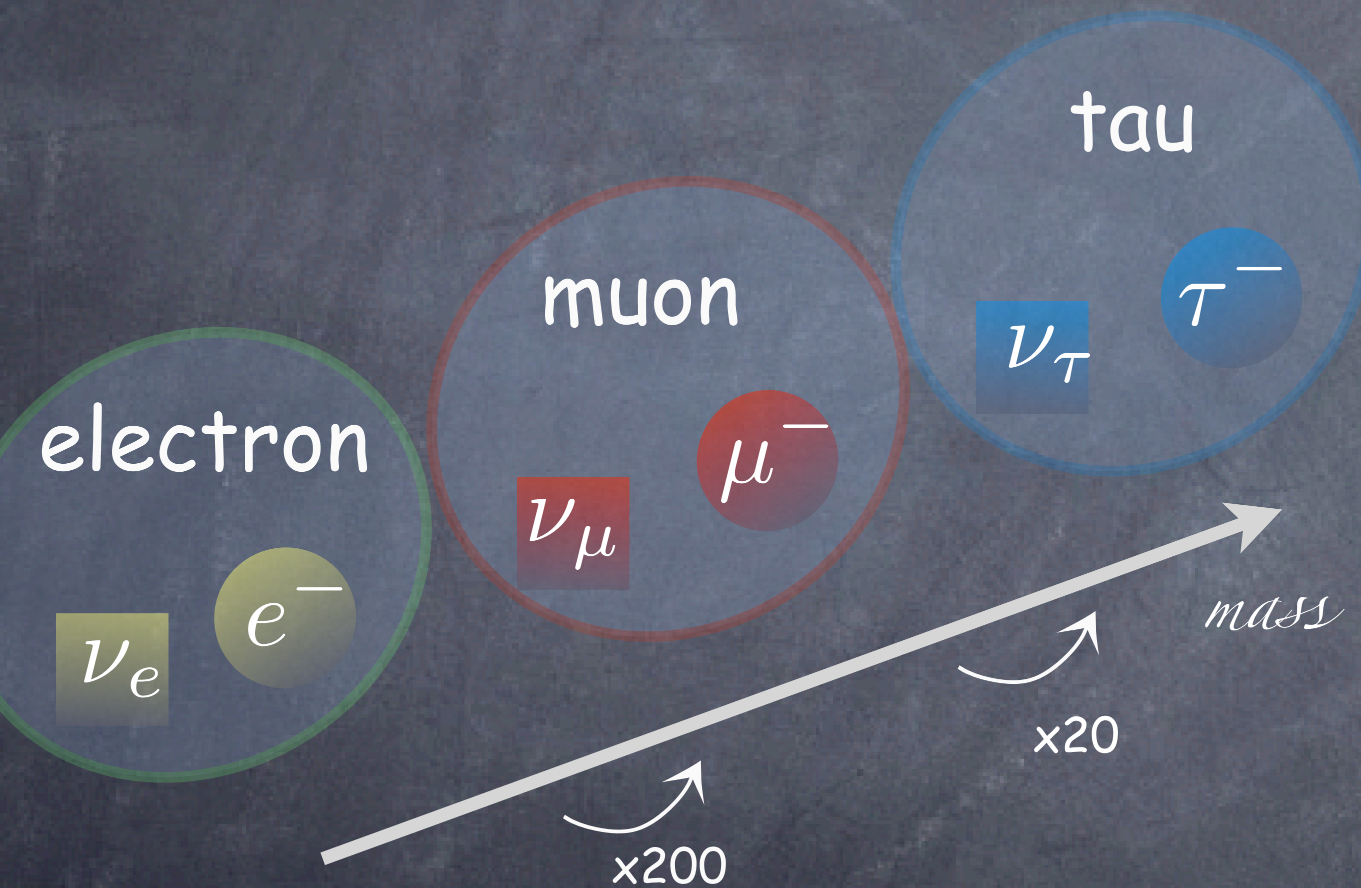

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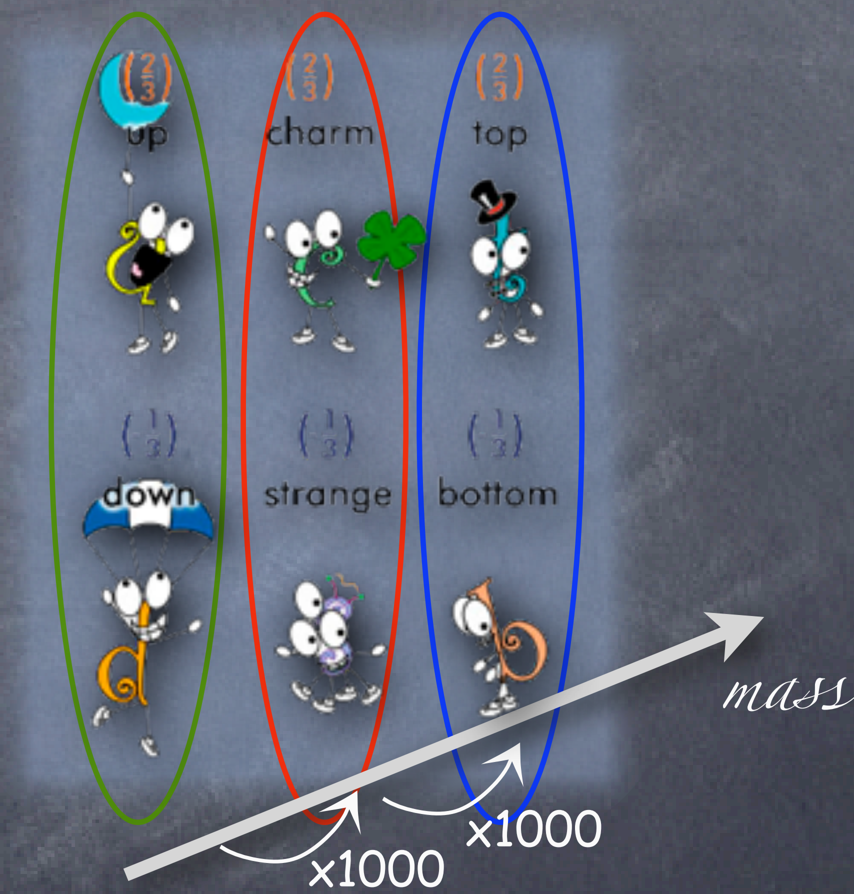


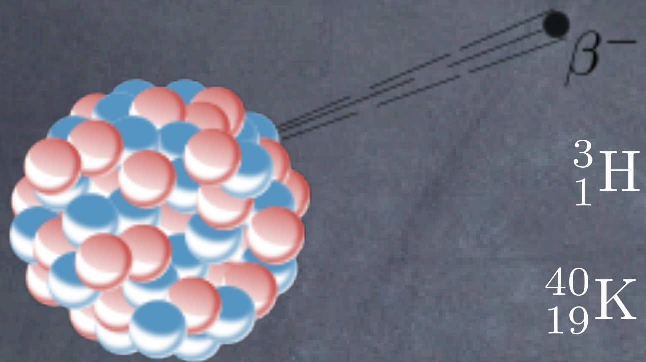
composite states=hadrons

- baryons
  - proton $p = (u, u, d)$
  - neutron $n = (u, d, d)$
- mésons

Fundamental Interactions

How do the elementary particles talk to each other?

β decay



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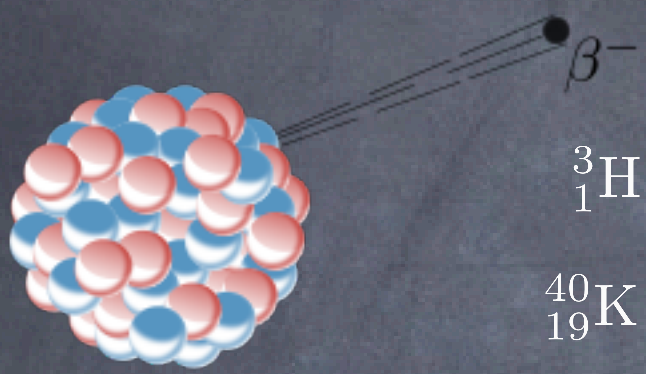

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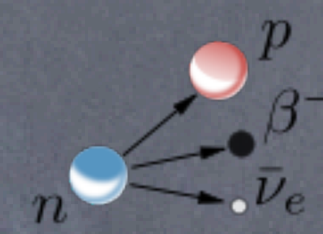

$$n \to p + e^{-} + \bar{\nu}_e$$

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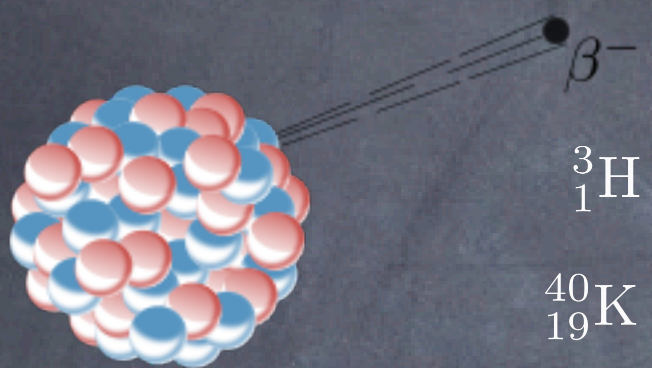

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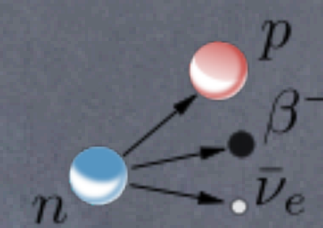

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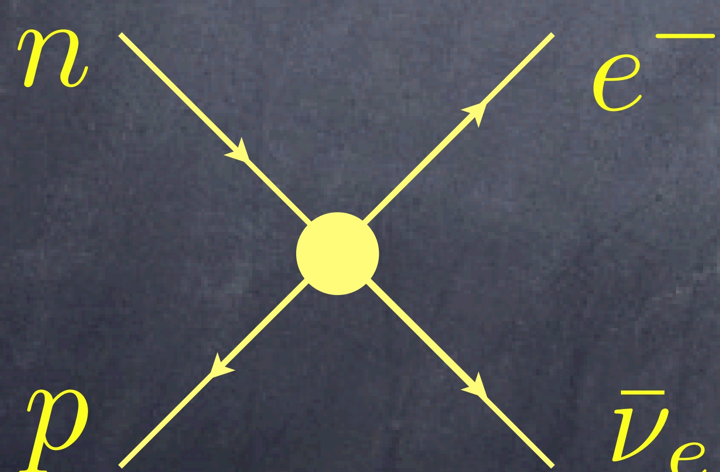
Fermi in the '30 described this interaction by a contact force



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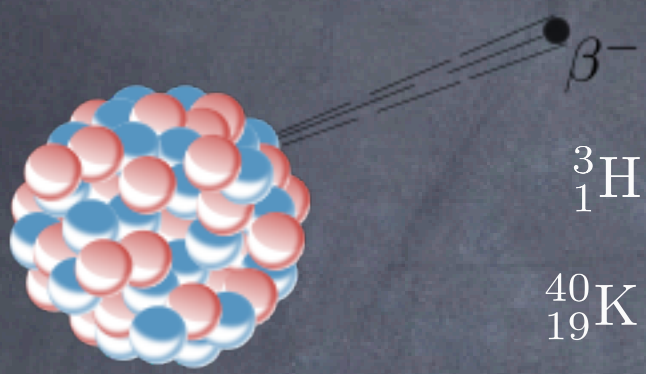

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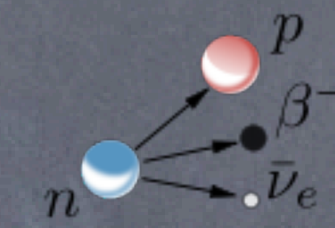

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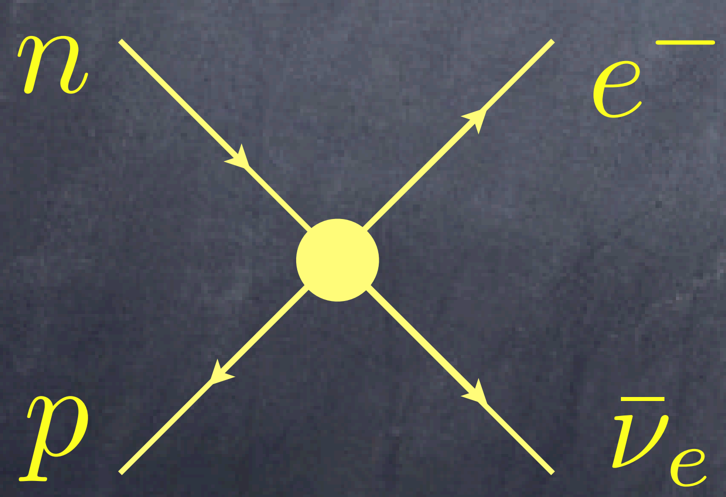

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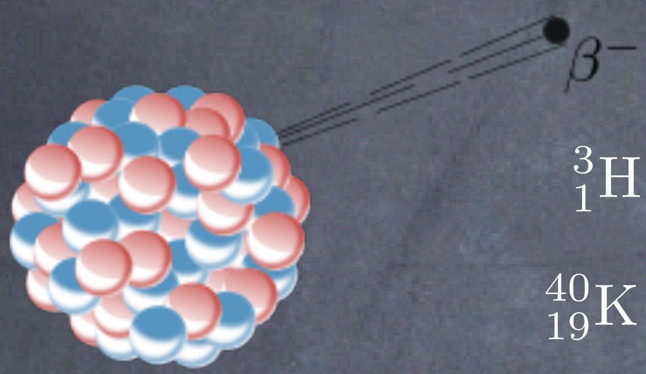

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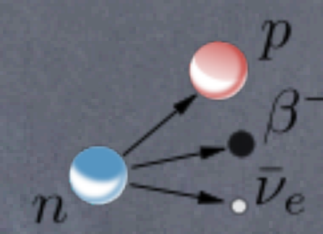

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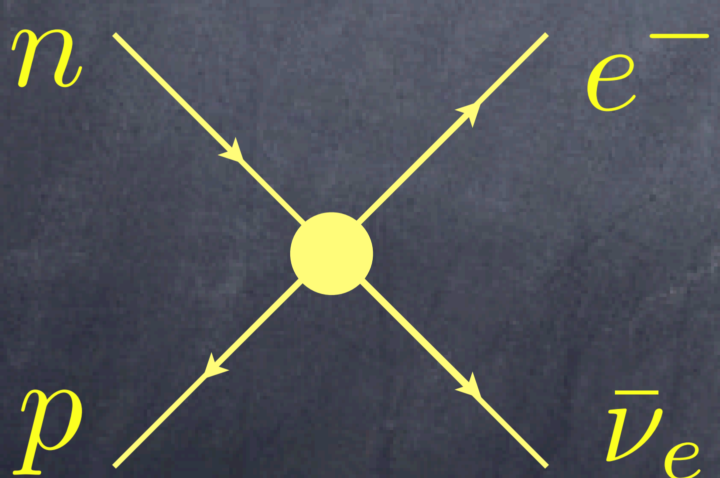

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$$\sigma = \frac{G_F^2\, E^2}{\pi}$$

E > 100 GeV
probability of interaction > 1

Dynamics and Symmetry

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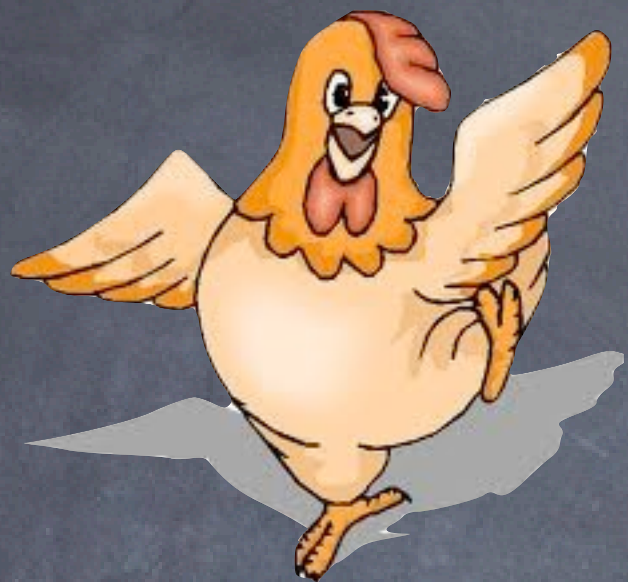

the dynamics
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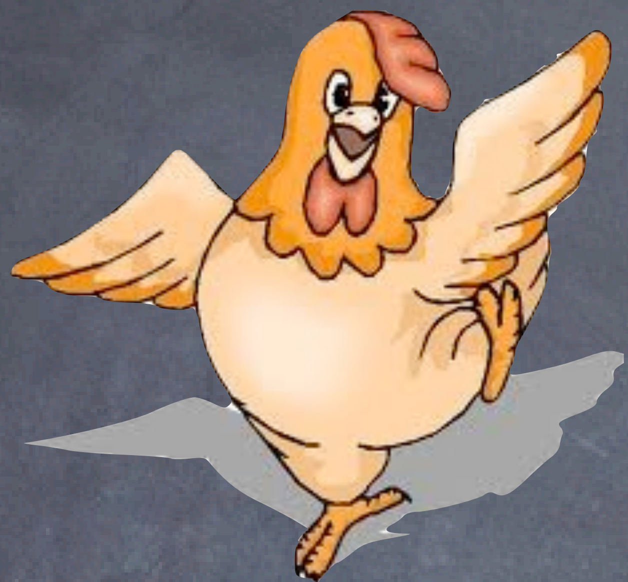

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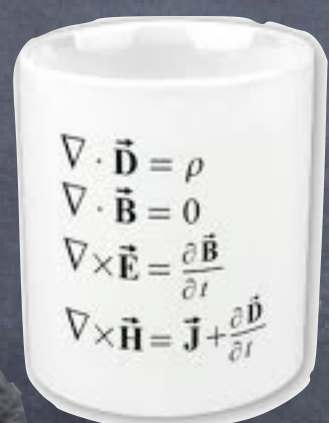

speed of light
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the dynamics
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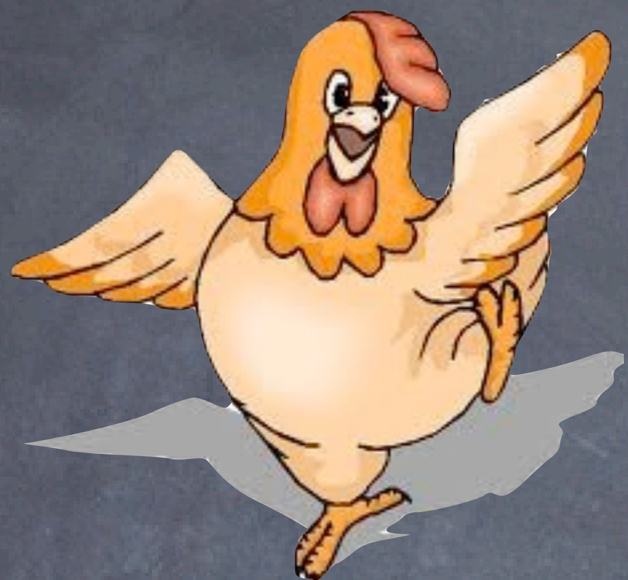

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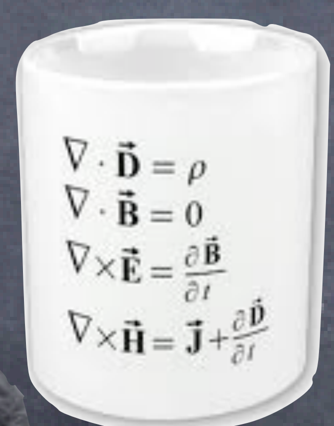

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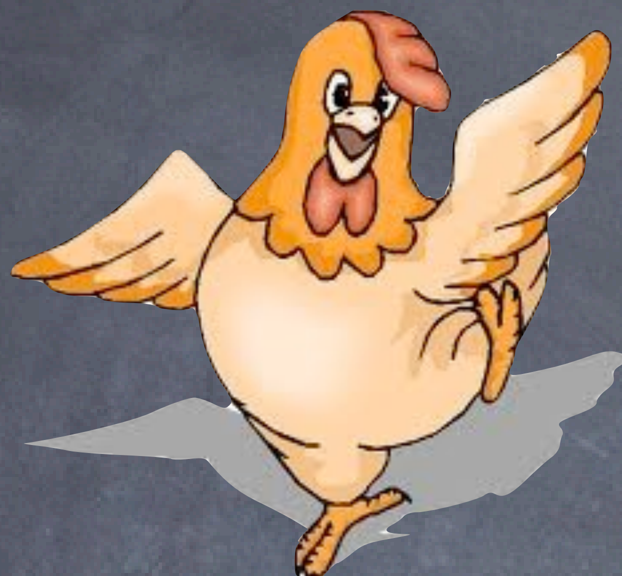

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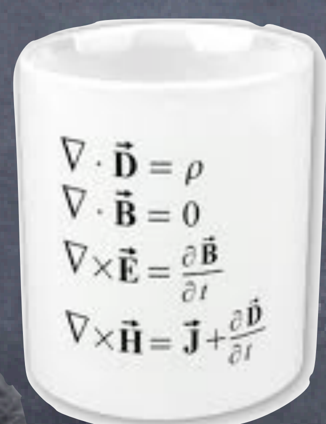

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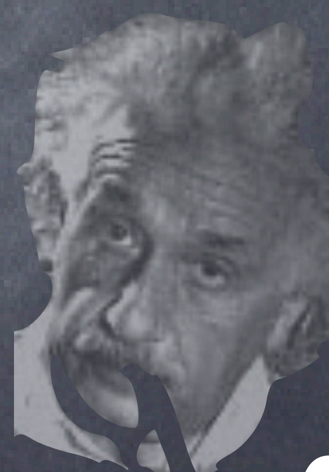

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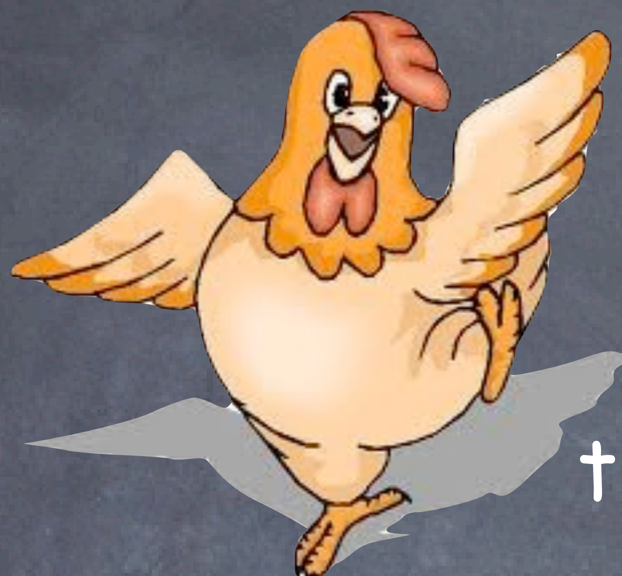

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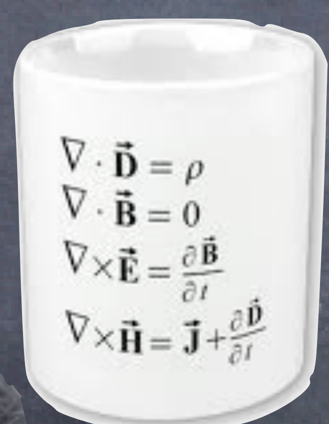

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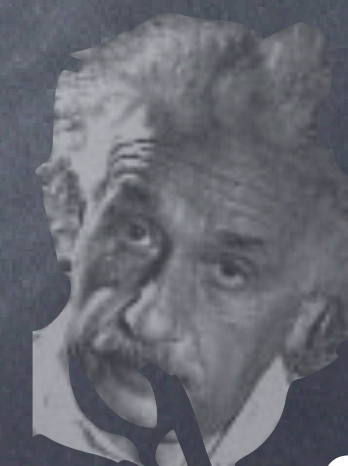

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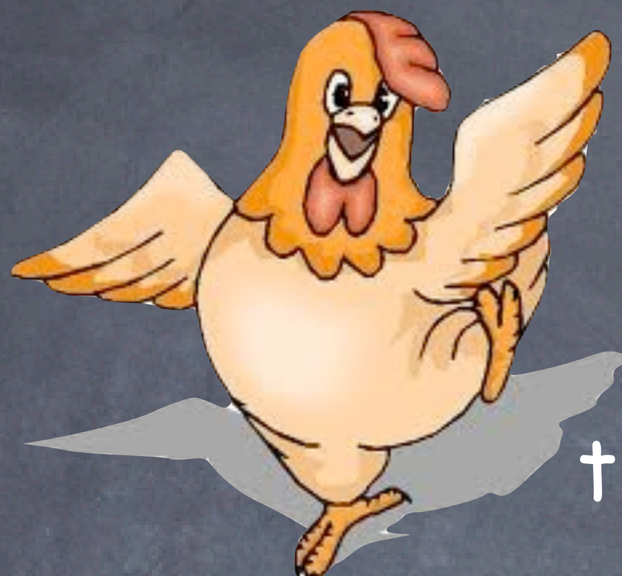

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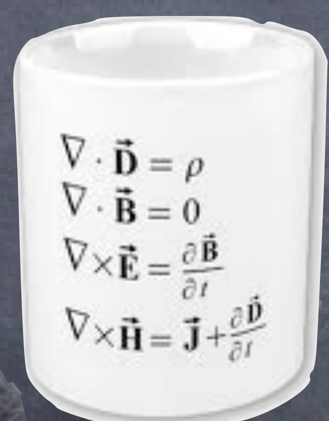

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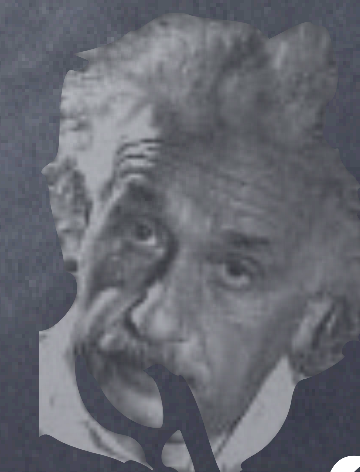

!

the requirement of
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Symmetry and Dynamics

How do the elementary particles talk to each other?

an electron is described by a complex number

Symmetry Principle

the phase of this number can be rotated away

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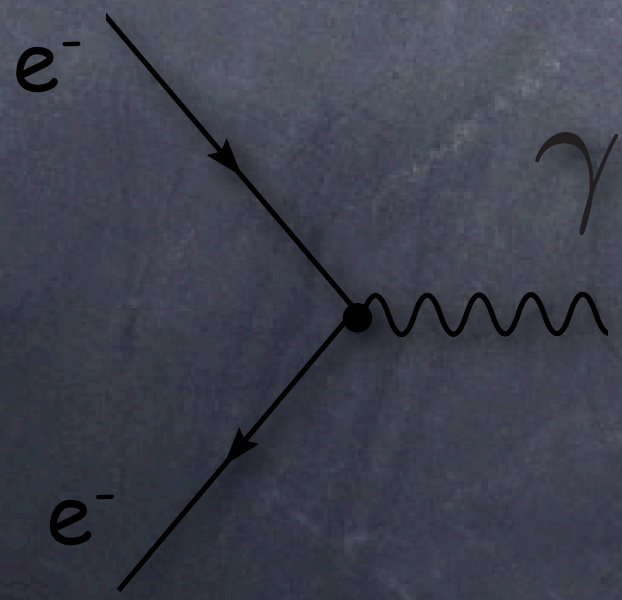


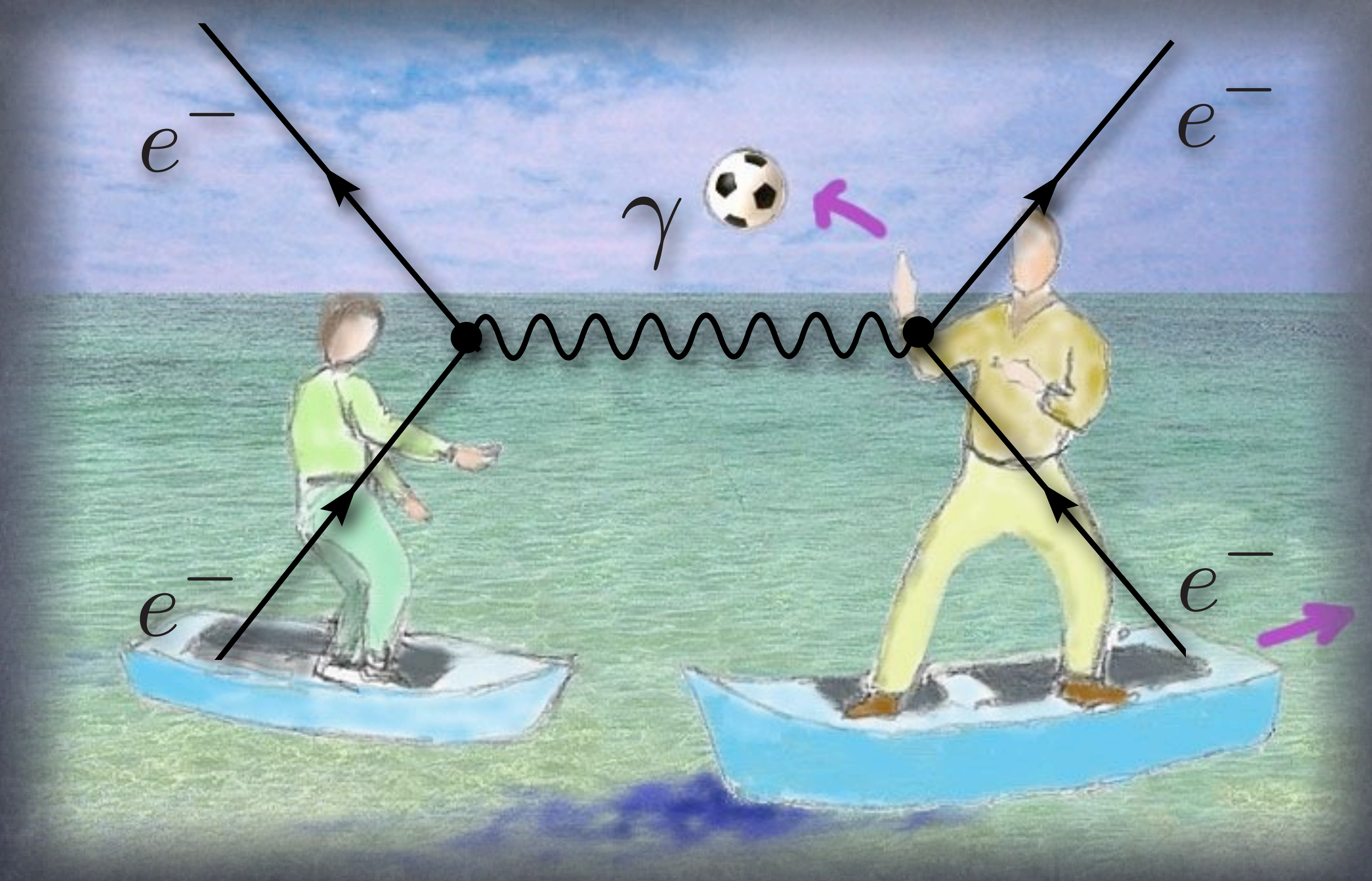
force carrier: photon

"memory" of how the electron phase is changing from one point to another in space-time

Interactions between particles

The elementary particles interact with each other
by exchanging some gauge fields

Interactions between particles



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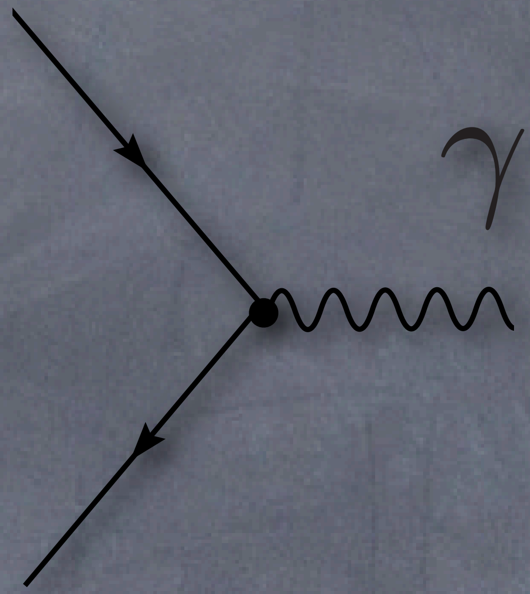
Forces et Symétries

an electron is described by a complex number
the phase of this number can be rotated away



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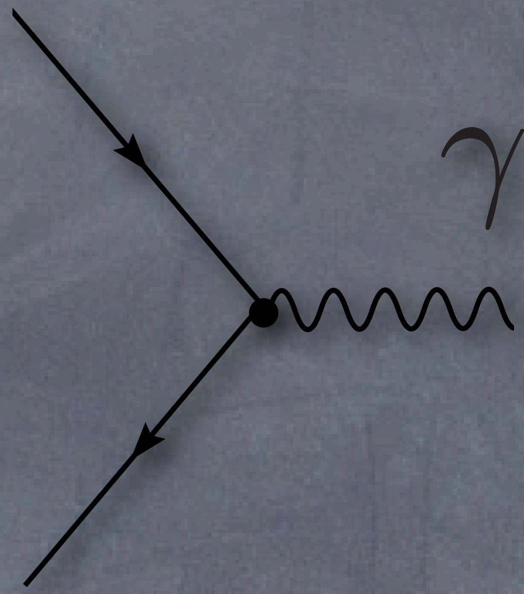

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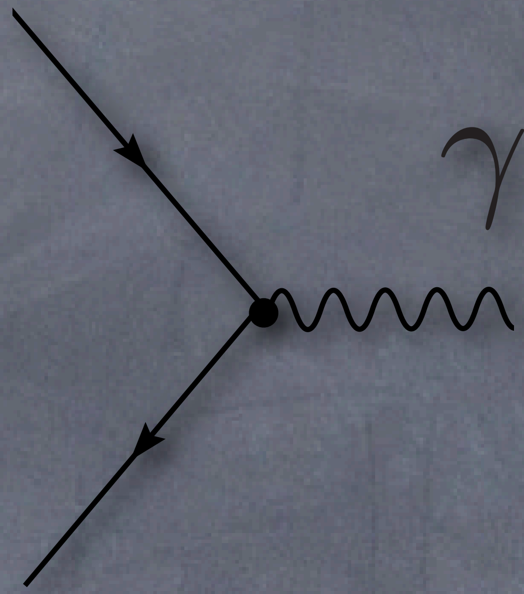

Universality of the interactions

- all the electrons interact with the photons in the same way

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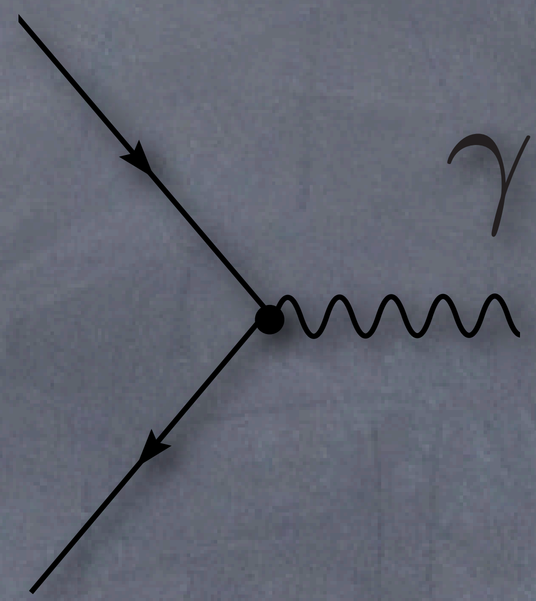

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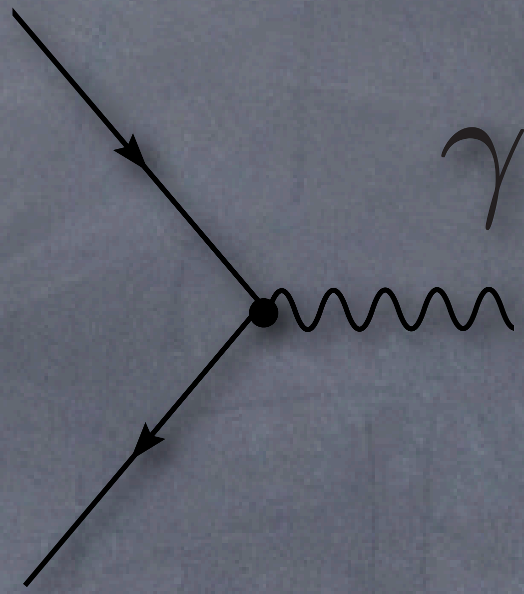

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probabilty for an electron to "produce" a photon

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \sim \frac{1}{137}$$

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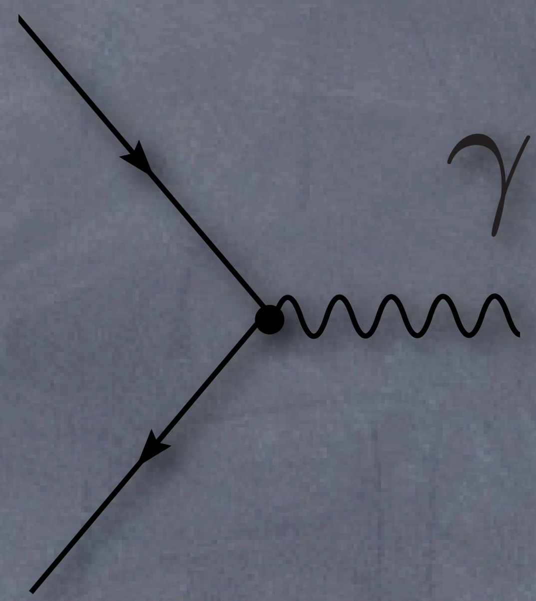

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all fundamental interactions are associated to symmetries

The Standard Model: Interactions

How do the elementary particles talk to each other?

- ***electromagnetic interactions***

  (1873, Maxwell)

  tested with an accuracy of 10^{-8}

  light, atoms, molecules

- ***weak interactions***

  (1933, Fermi)

  tested with an accuracy of 10^{-3}

  β decay

  $$n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e$$

  $$e^+ + e^- \xrightarrow{Z^0} D^+ + D^-$$

- ***strong interactions***

  tested with an accuracy of 10^{-1}

  atomic nuclei

  α decay

  $${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

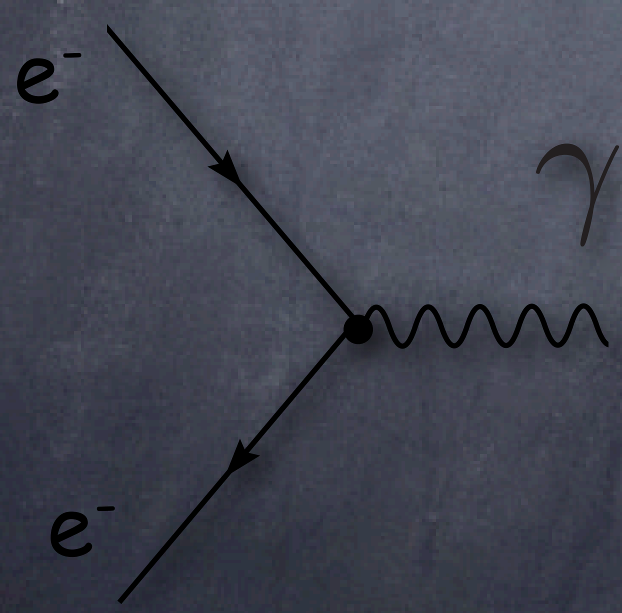
(1911, Rutherford ; 1921, Chadwick et Biesler)

Electroweak Symmetry

all fundamental interactions are associated to symmetries

electromagnetism

change of electron phase



weak interactions

exchanging electron ⇄ neutrino

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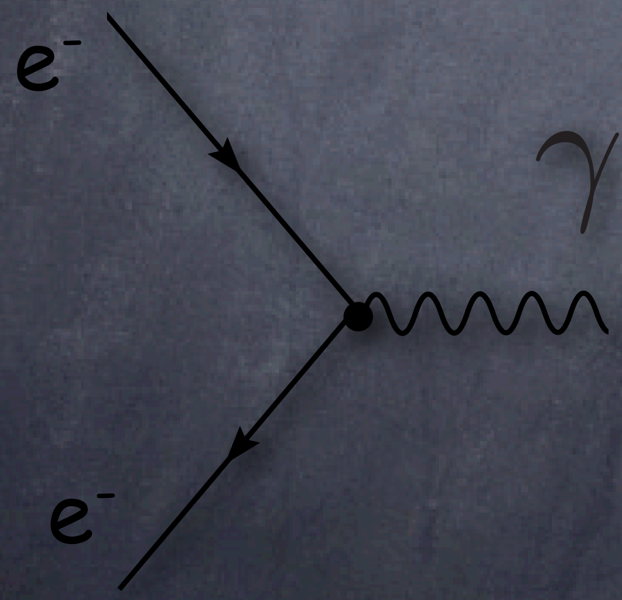
electromagnetism

change of electron phase



weak interactions

exchanging electron ⇄ neutrino

challenging hypothesis formulated in '68
by Glashow, Salam, Weinberg

Prix Nobel '79

Electroweak Symmetry

all fundamental interactions are associated to symmetries

electromagnetism

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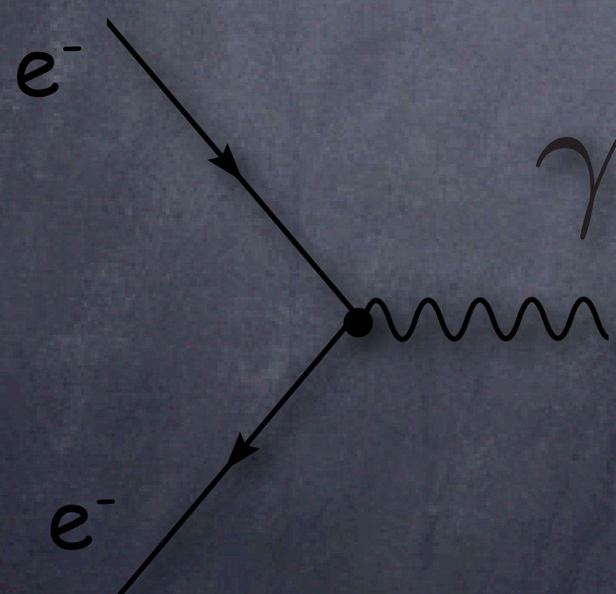

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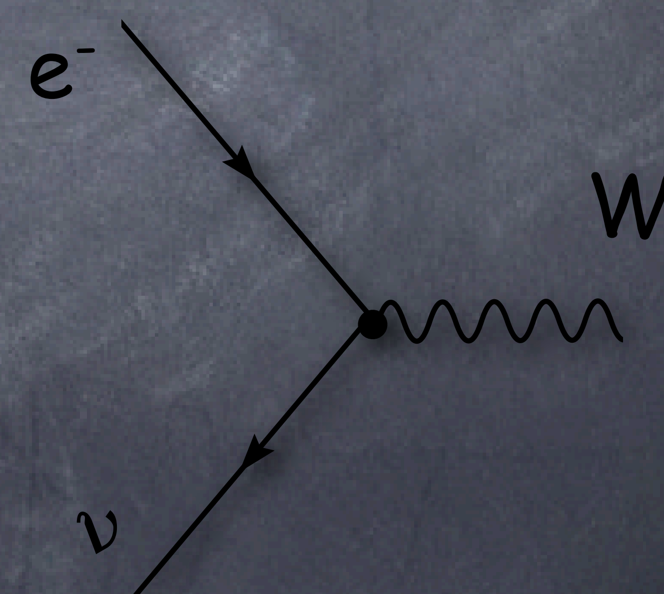

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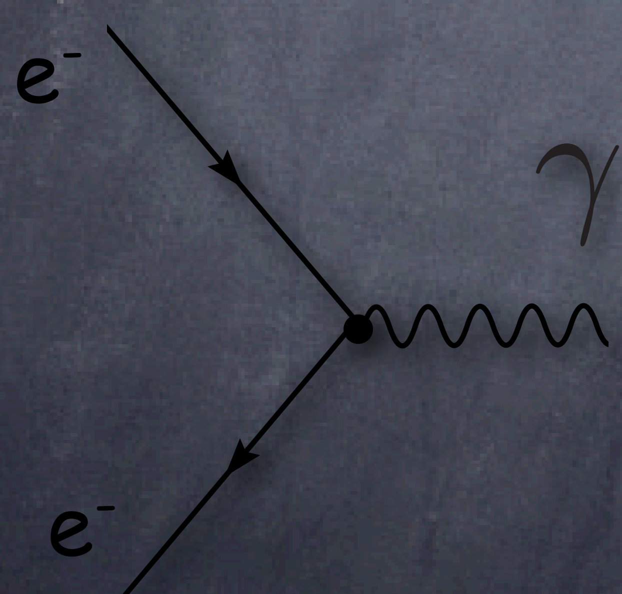

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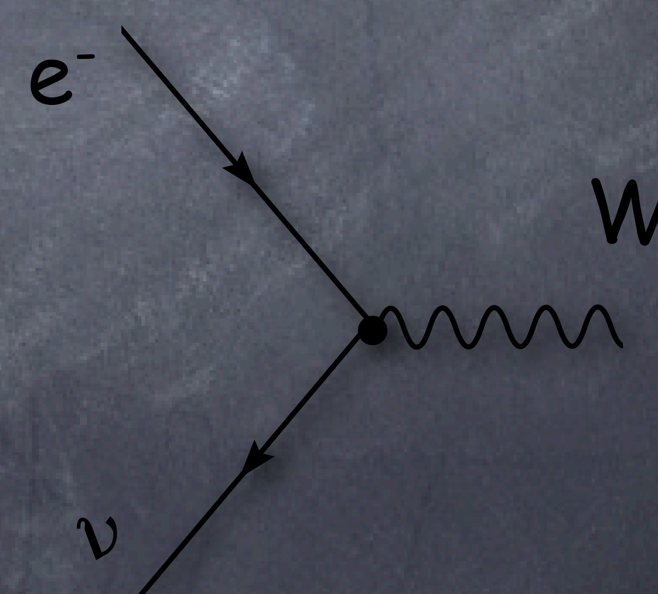


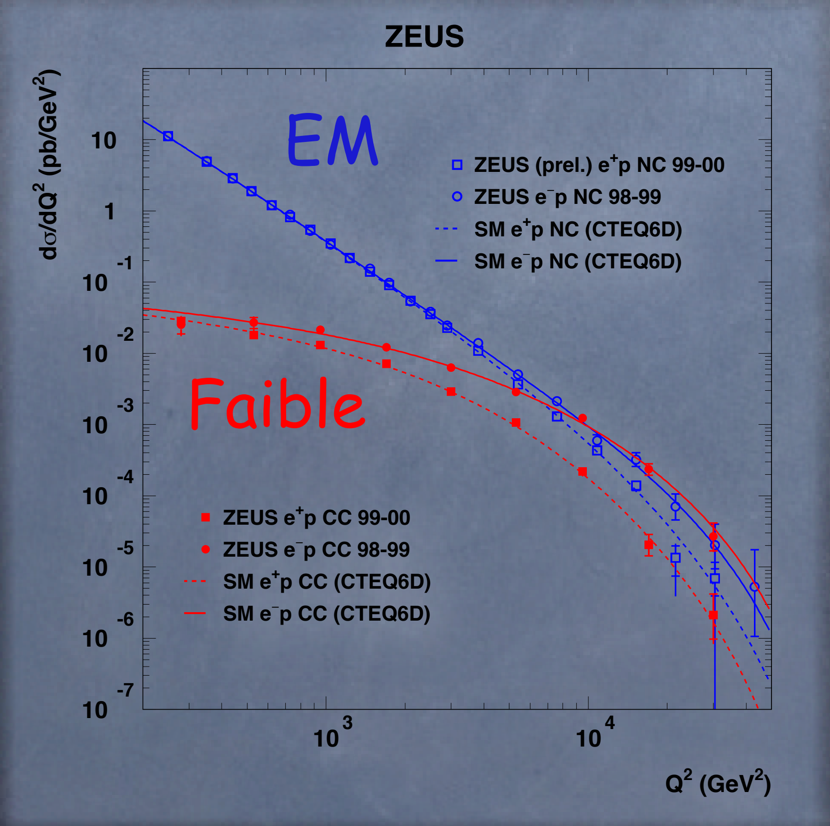
W boson discovered @ CERN in '83

Symmetry Breaking

mathematically, all fundamental interactions are described by symmetries
however they look very different from eath other

High Energy (> 100 GeV)

Low Energy



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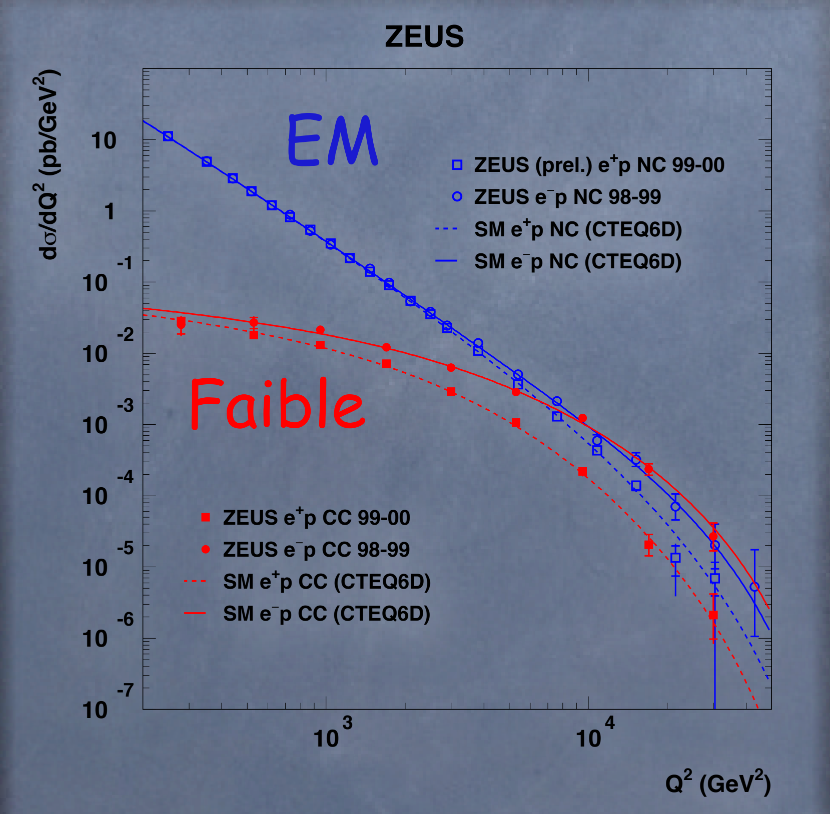
electromagnetic and weak interactions
are physically equivalent



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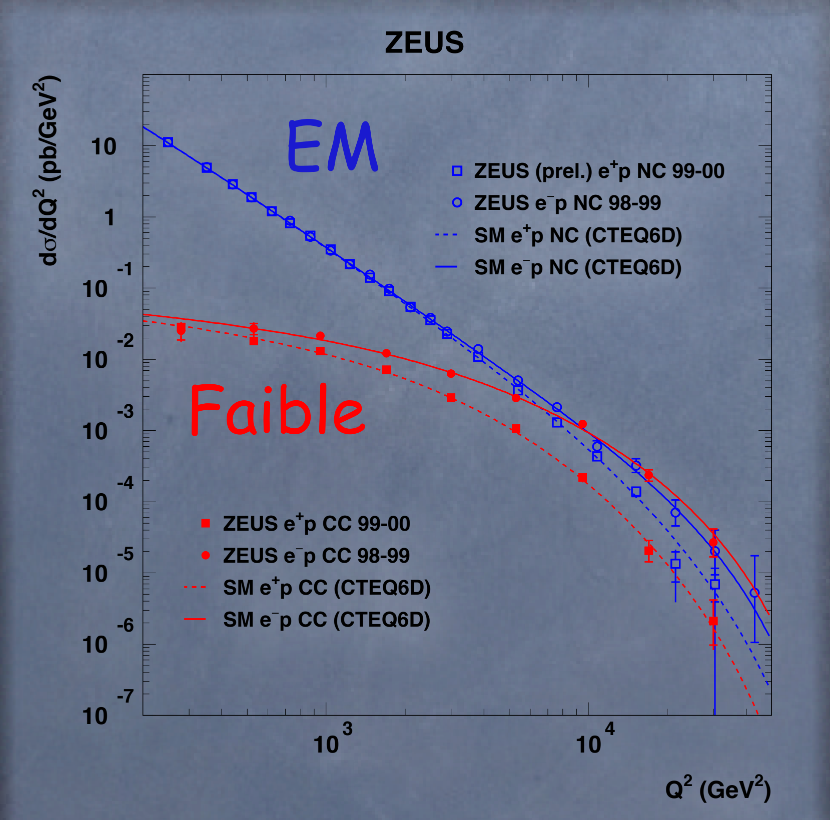
Low Energy

This room is full of photonsbut not W nor Z
The e^- are quite different from the neutrinos
The EW symmetry is broken at large distances



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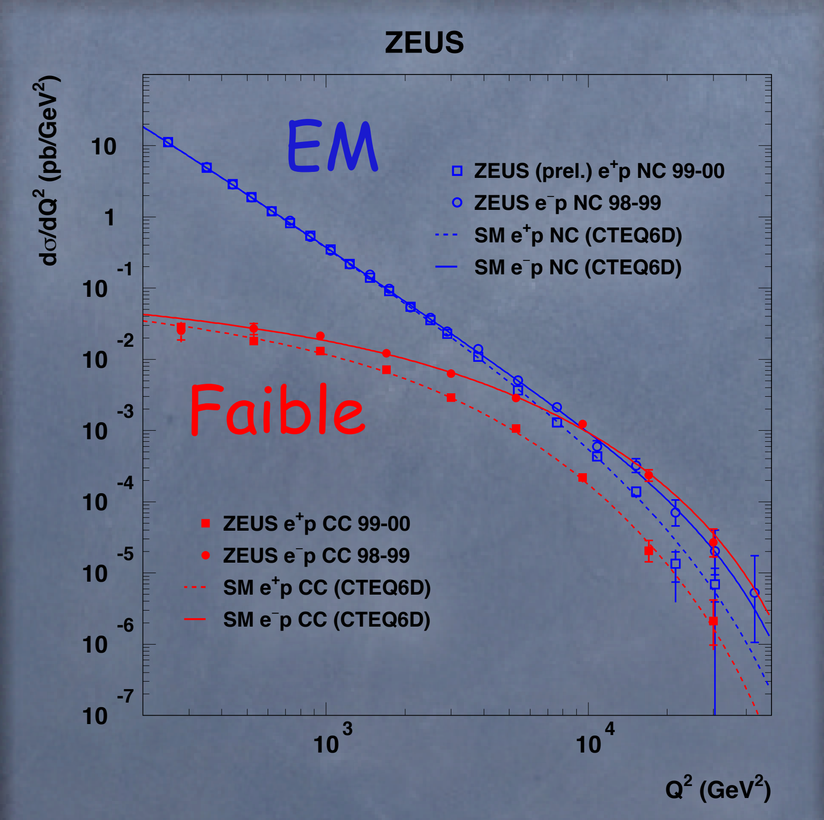

the photons are massless
(em is a long range force)
the W & Z's have a mass ~ 100 GeV
(weak interactions are short range forces
$1/(100 \text{ GeV}) \sim 10^{-18}$ m)

Spontaneous Symmetry Breaking

Isotropy in
the 3 spatial directions

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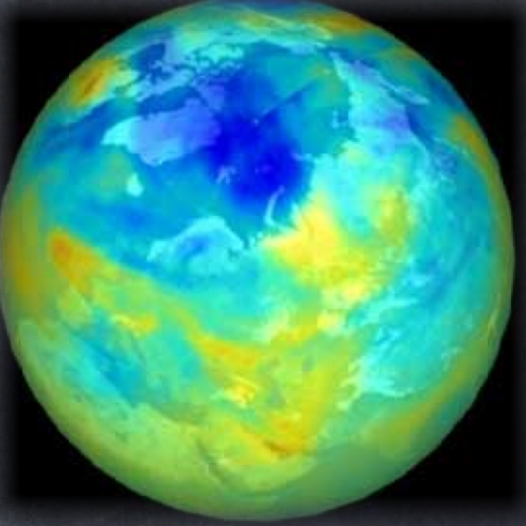
Isotropy in
the 3 spatial directions



On Earth:
isotropy in the 2 horizontal
directions only

Spontaneous Symmetry Breaking

Isotropy in
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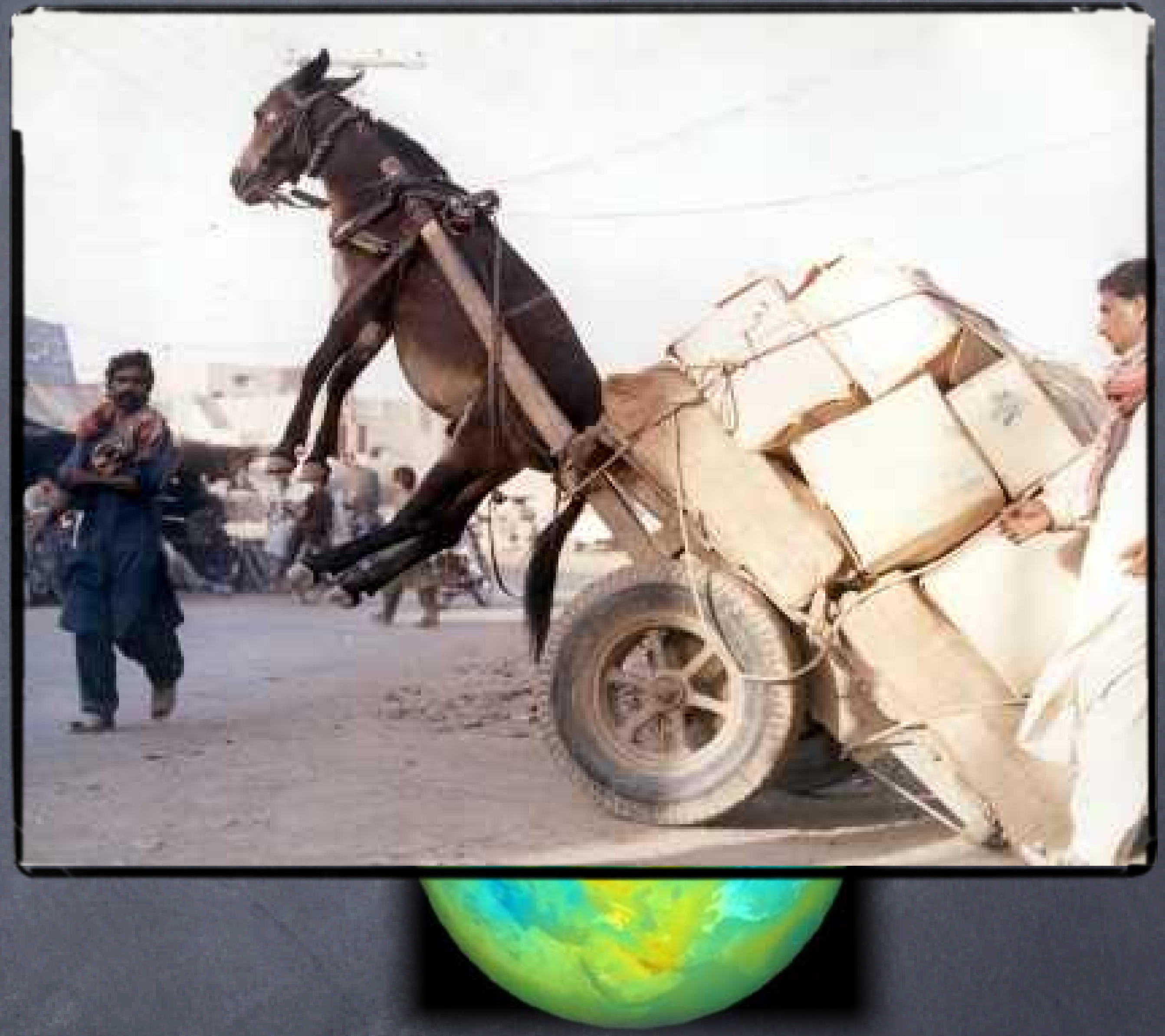

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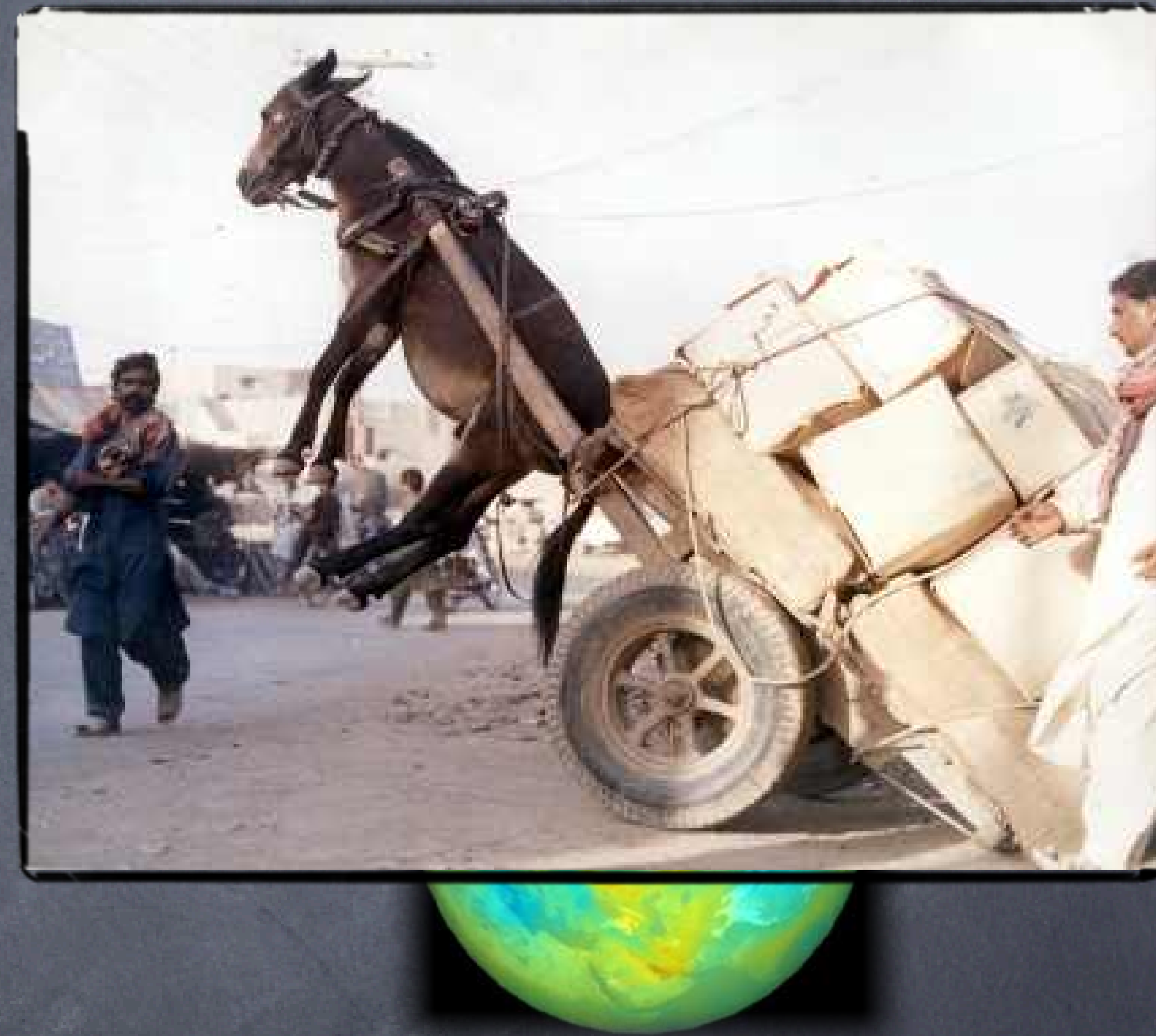

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SO(3) → SO(2)

Electroweak Symmetry Breaking

~ 10^{-10}s after Big-Bang, space-time crystallized into a new form
Nature filled vacuum with Higgs substance because it saved energy

(courtesy @ G. Giudice)

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Imagine Tokyo station

in the early morning (5h30), it is empty

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Imagine Tokyo station
in the early morning (5h30), it is empty
at rush hour, it is awfully pack-crowded

no difference no matter
which direction you are looking into

Electroweak Symmetry Breaking

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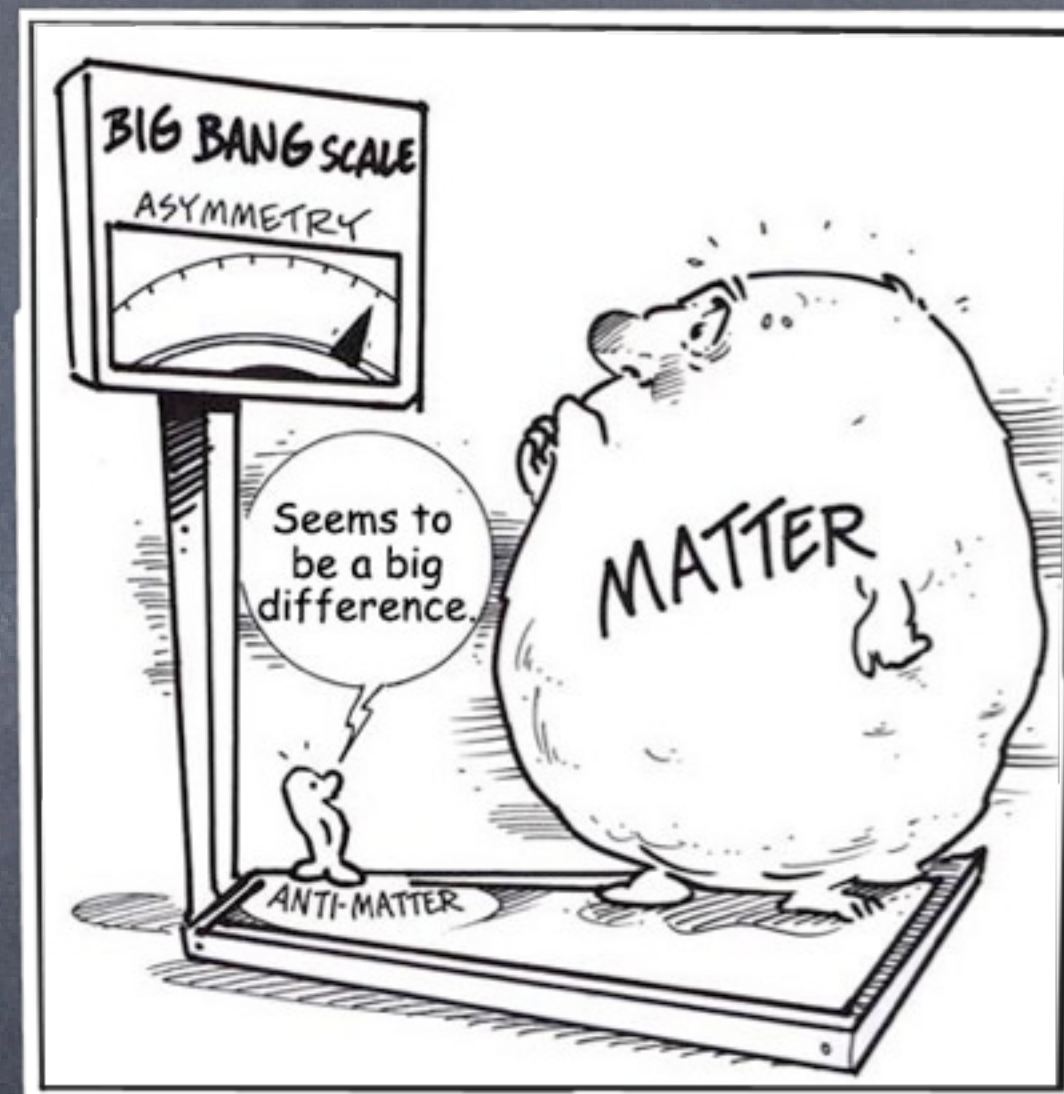
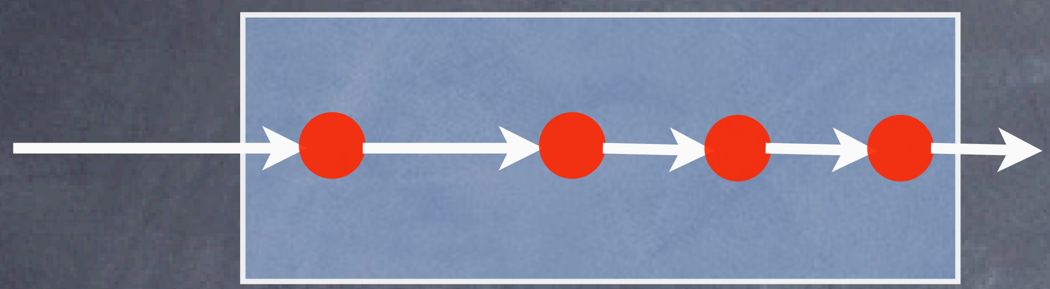


Cosmologists think that it is during this phase transition that matter could have taken over antimatter

Massive particles & Higgs field

light propagating in a medium is slow down
"photons acquired a mass"



c=299792 km/s in the vacuum
~3/4 c in water
~2/3 c in ordinary glass
~125000 km/s in diamond

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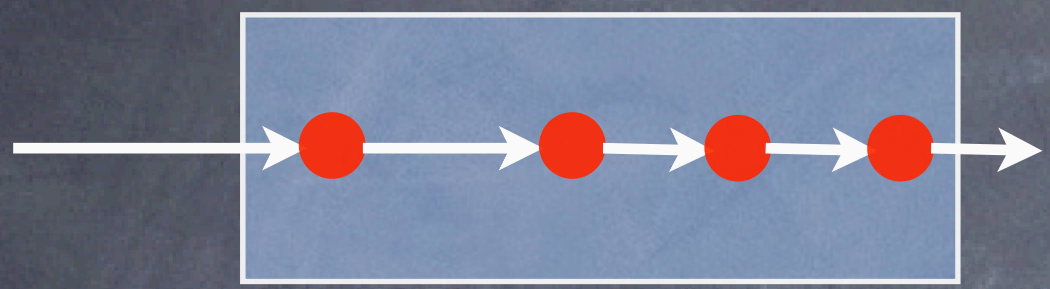

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Higgs = substance/field filling out the Universe (Lorentz invariance)
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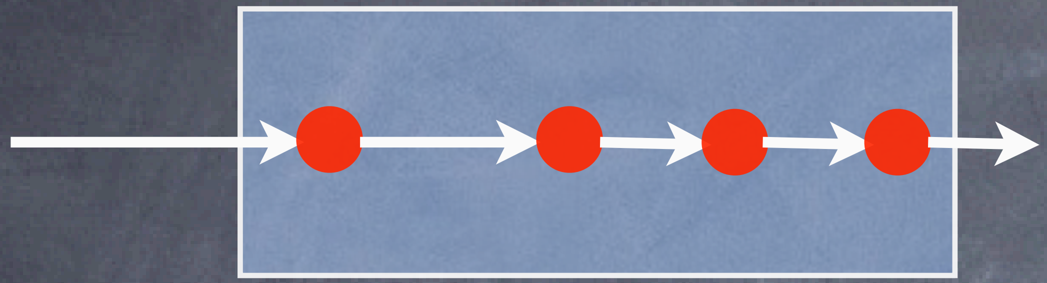

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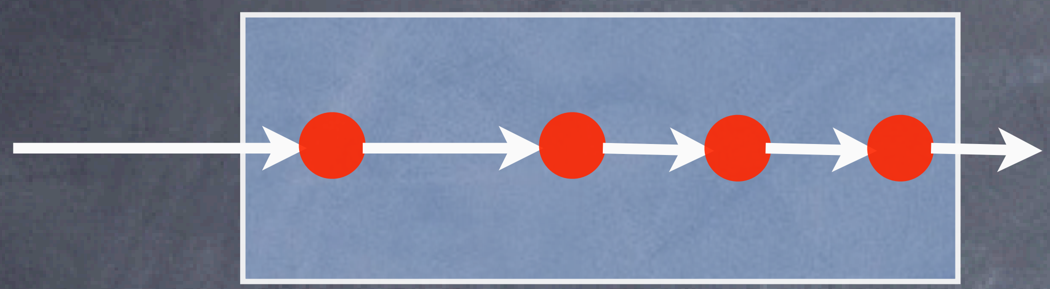

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Higgs boson = ripple on the Higgs substance

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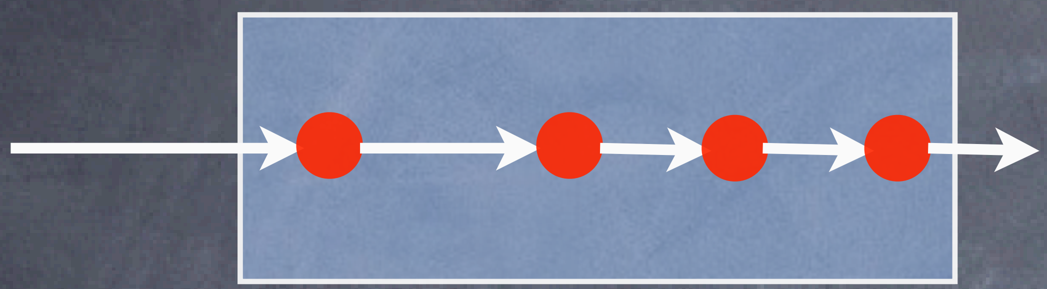

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Higgs boson = ripple on the Higgs substance

LHC = machine to produce ripples on the Higgs substance

Higgs boson at the LHC

producing a Higgs boson is a rare phenomenon
since its interactions with particles are proportional to masses
and ordinary matter is made of light elementary particles

NB: the proton is not an elementary particle,
its mass doesn't measure its interaction with the Higgs substance

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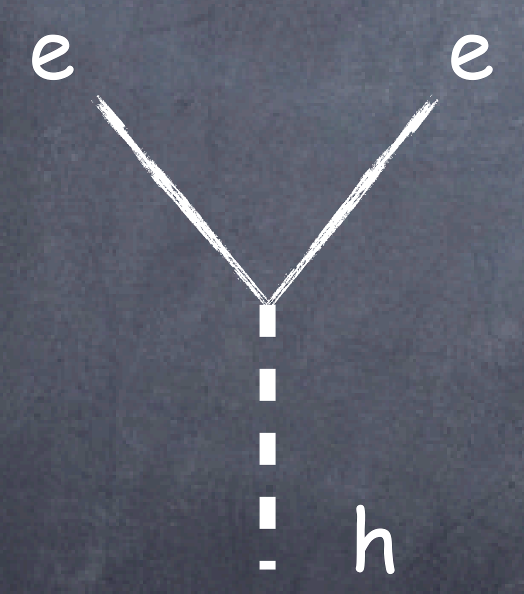
From electrons



probability ~ 10^{-11}

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From electrons

probability ~ 10^{-11}

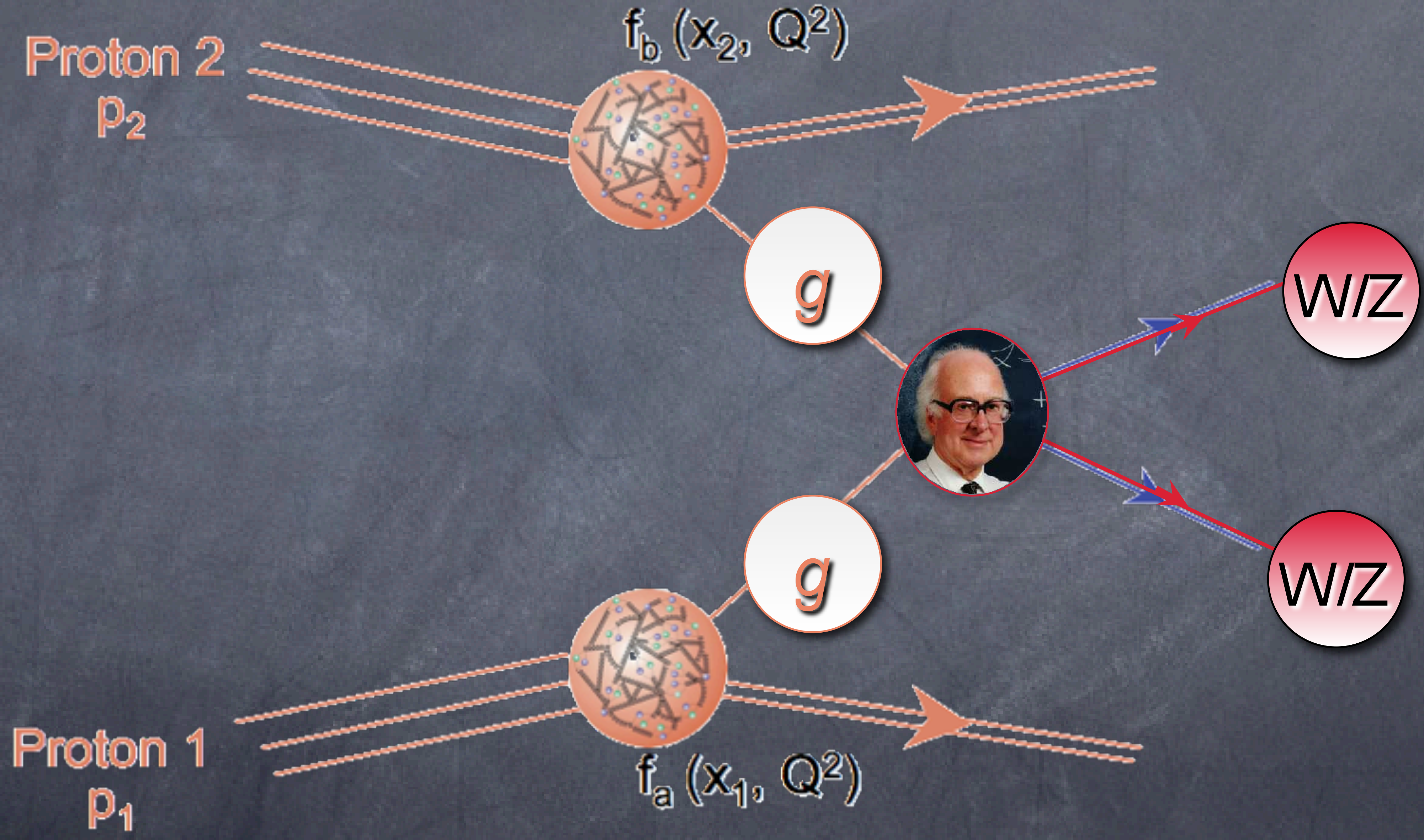
From top quarks

probability ~ 1

but no top quark at our disposal

Higgs boson at the LHC

Higgs boson at the LHC



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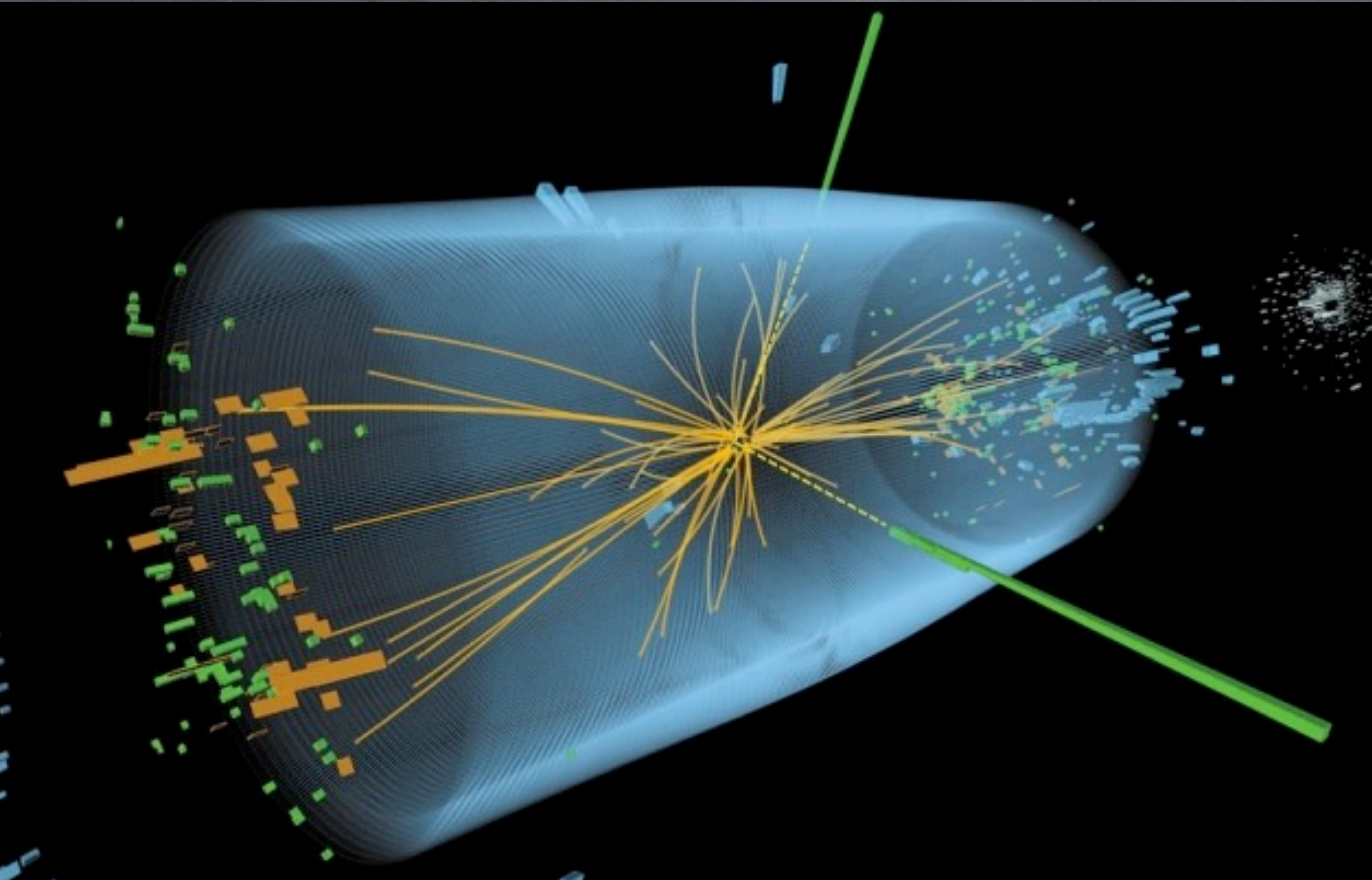

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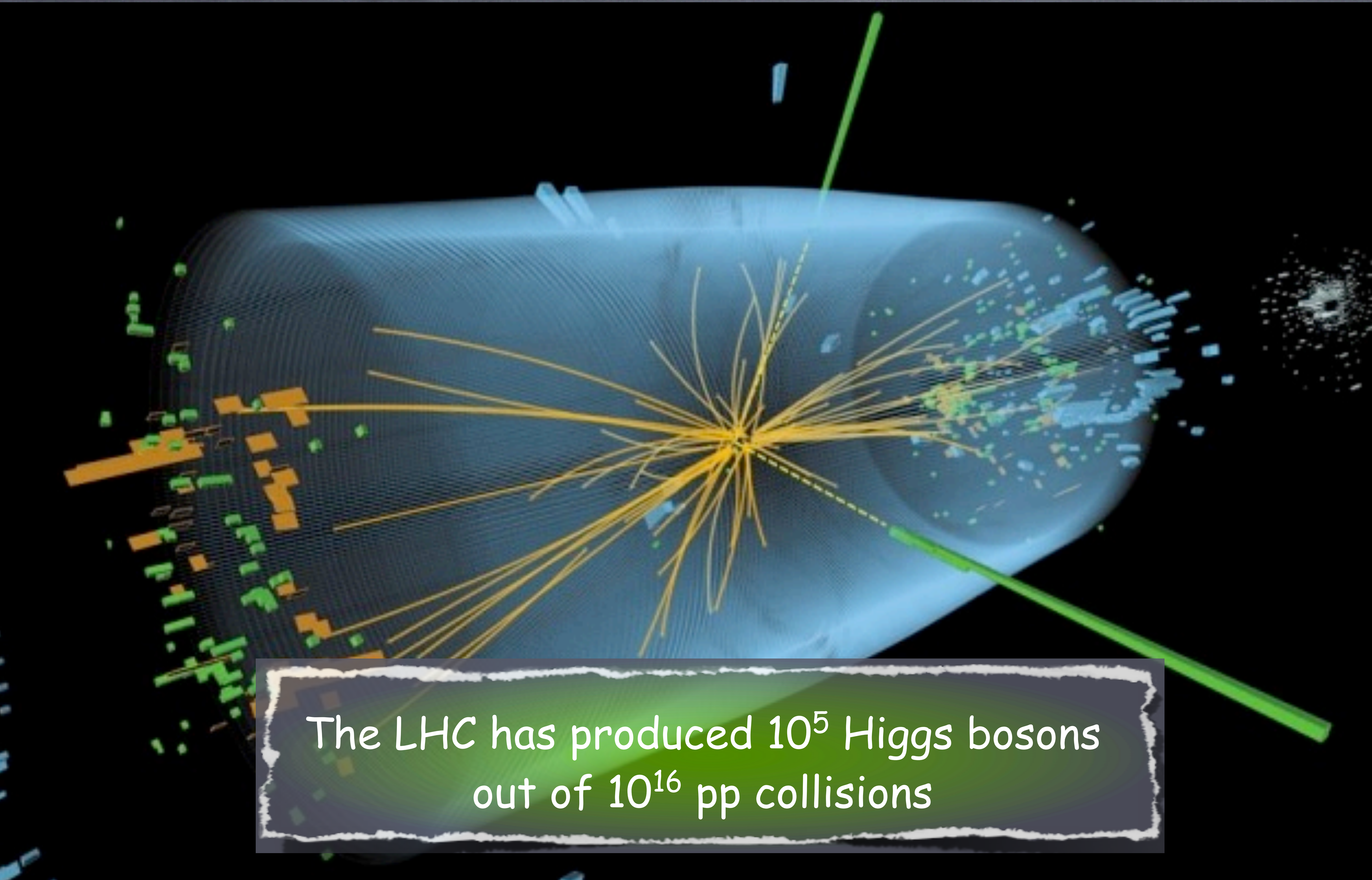
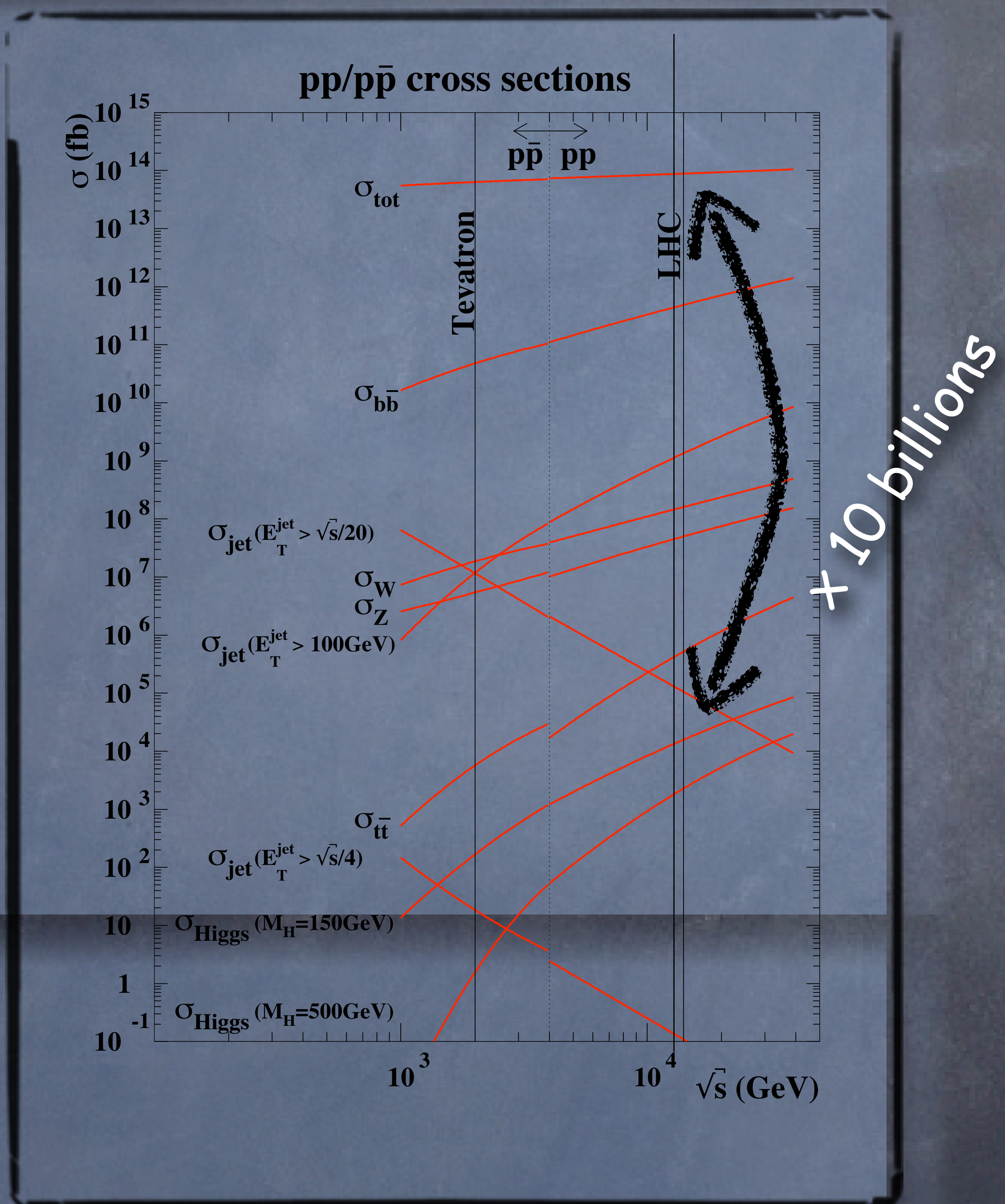


The LHC has produced 10^5 Higgs bosons out of 10^{16} pp collisions

The search for the Higgs boson



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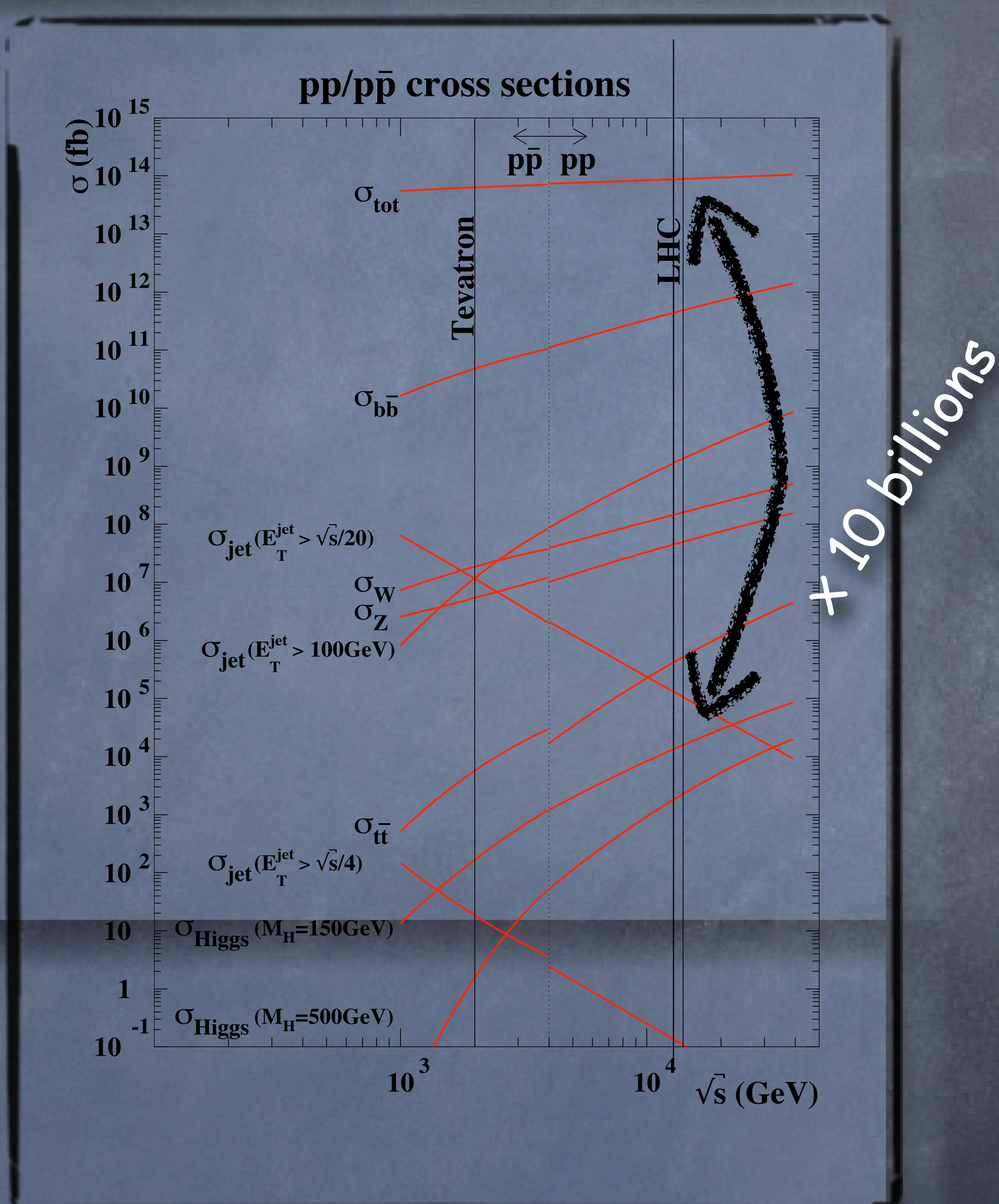

only
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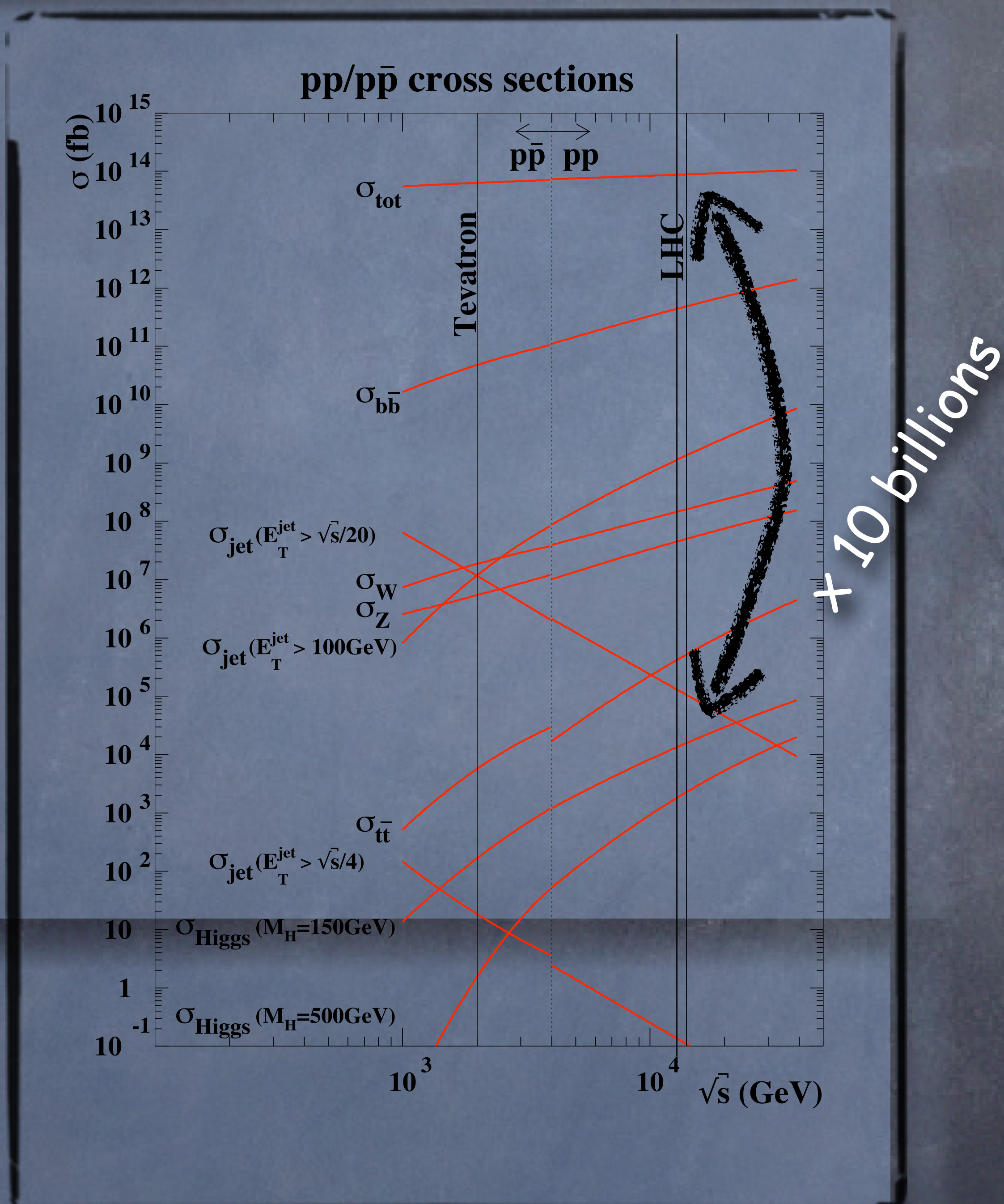

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... finding the interesting paper
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1 collision out of 10 billons
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finding a Higgs boson is like...

... finding the interesting paper
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... finding a book in a library 1000 times
as large as the French Library
while all the books have the same size,
the same color...

Where are we?

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The Higgs discovery is a triumph of human endeavor

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We have a consistent description of
i) the elementary building blocks of matter
ii) their interactions

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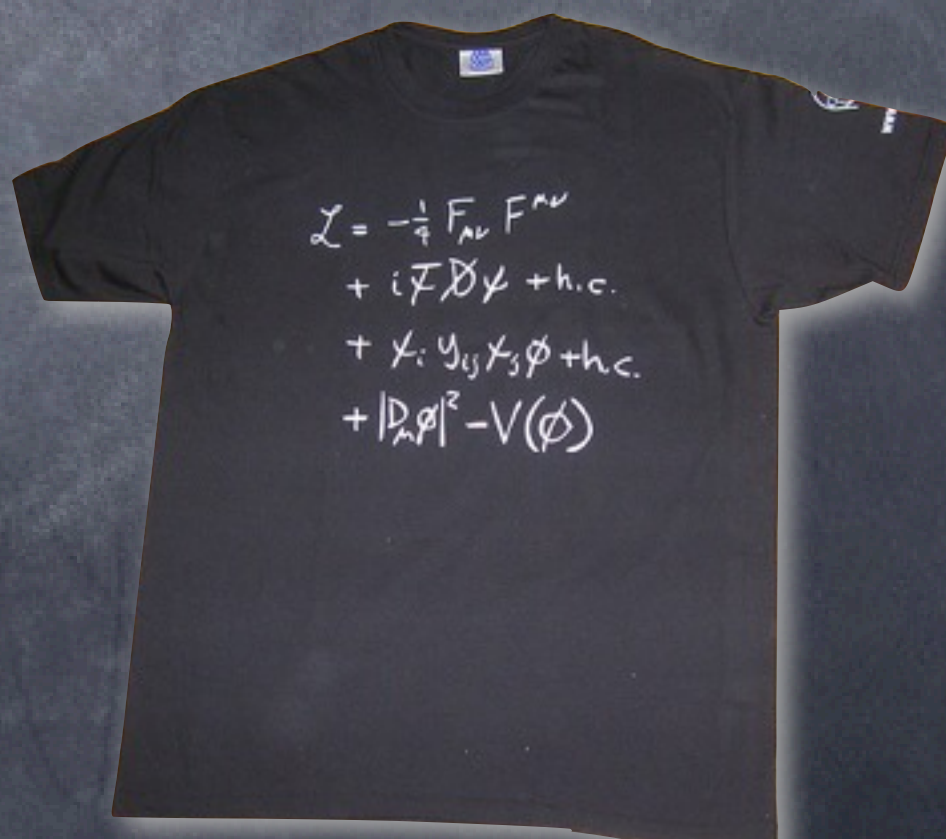

Where are we?

The Higgs discovery is a triumph of human endeavor

We have a consistent description of
i) the elementary building blocks of matter
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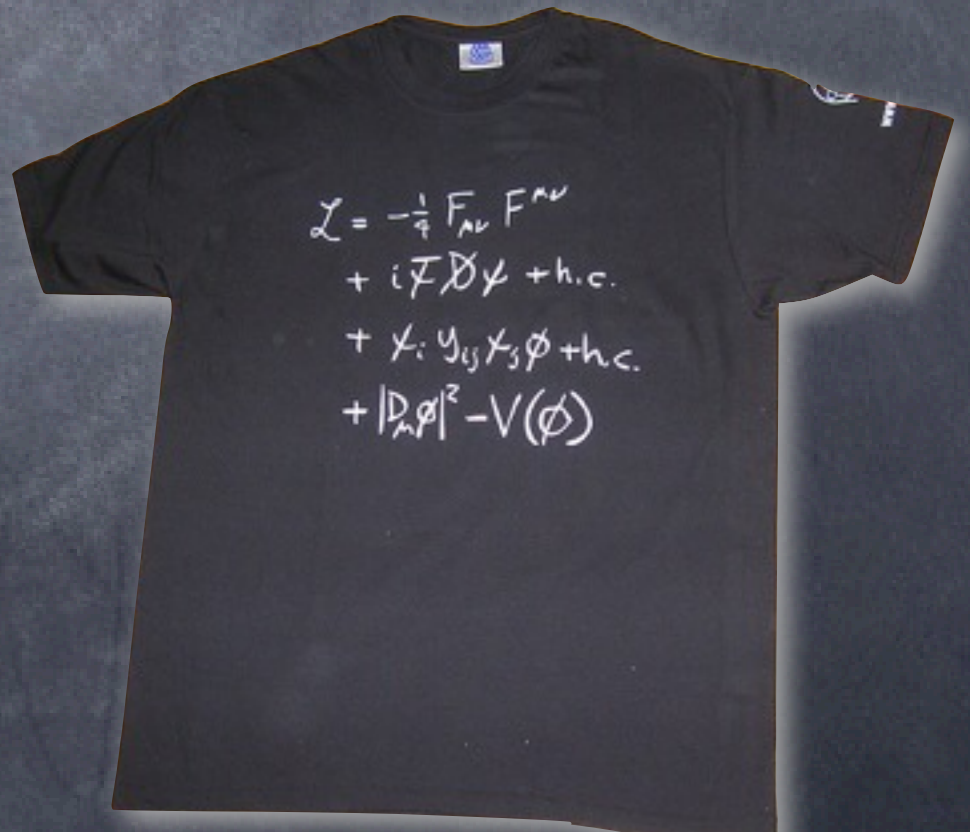
In principle, from what is written on this T-shirt we can describe/compute how the Universe as we see it today has emerged from the Big-Bang



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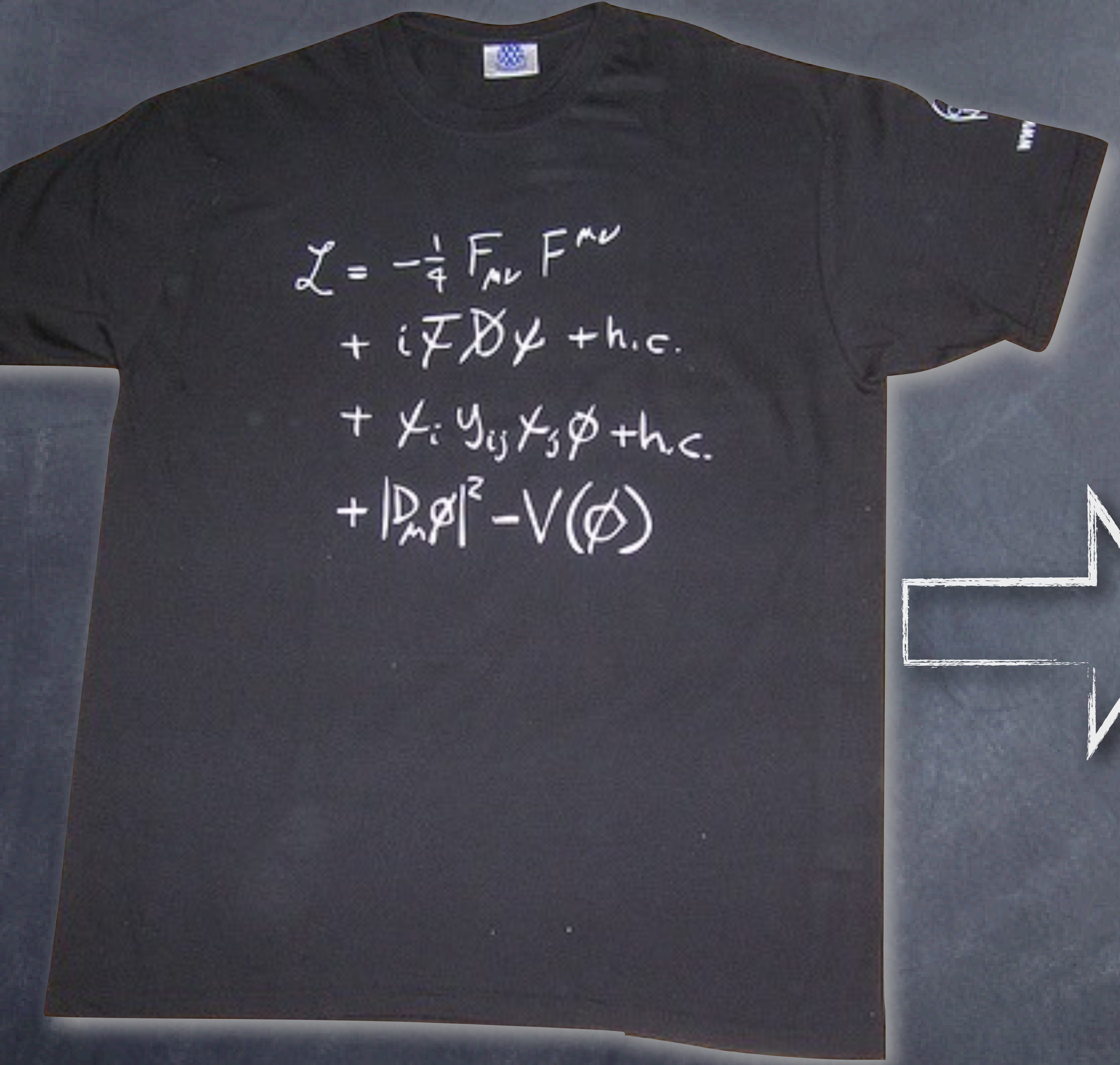
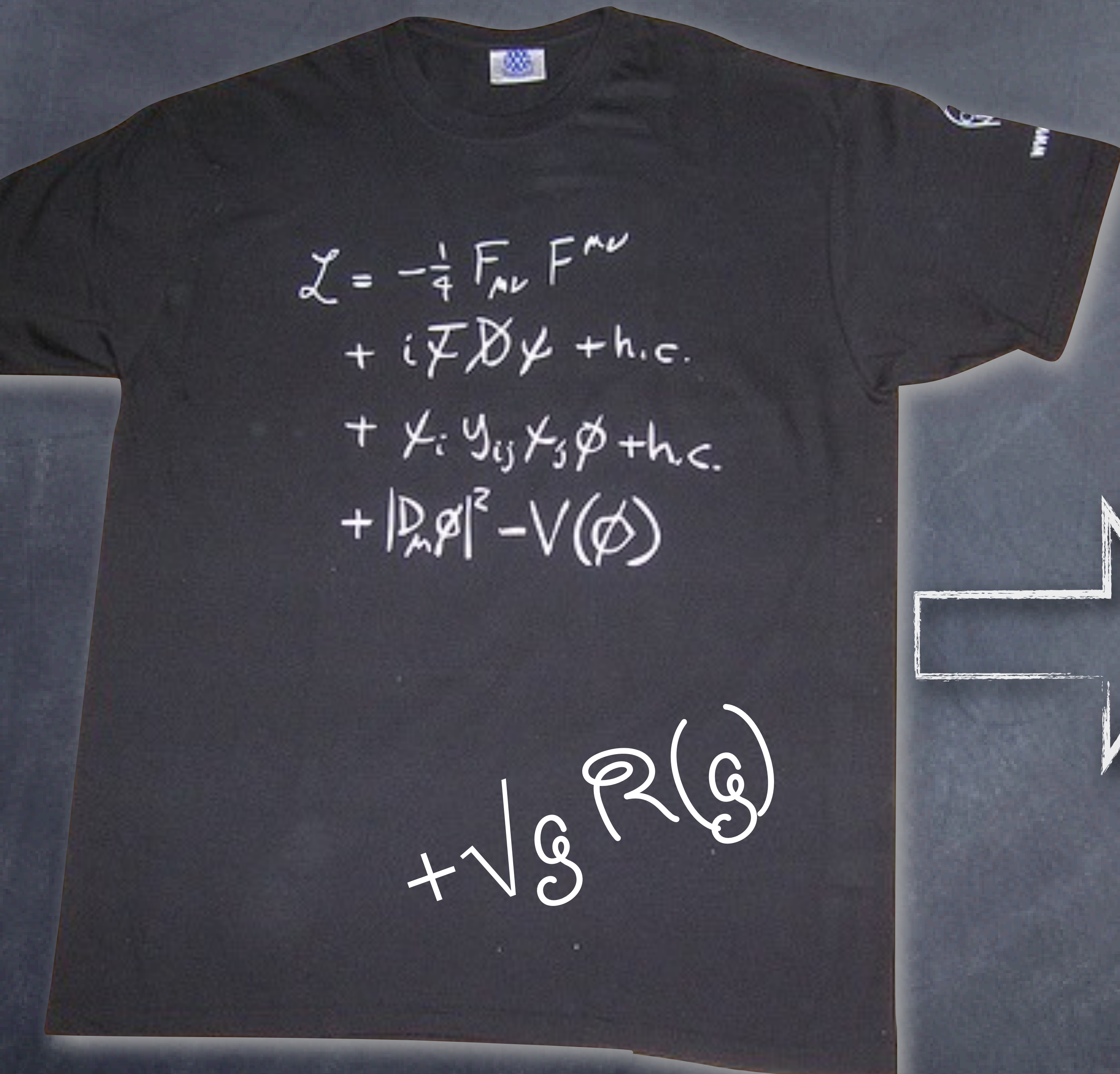


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Where are we?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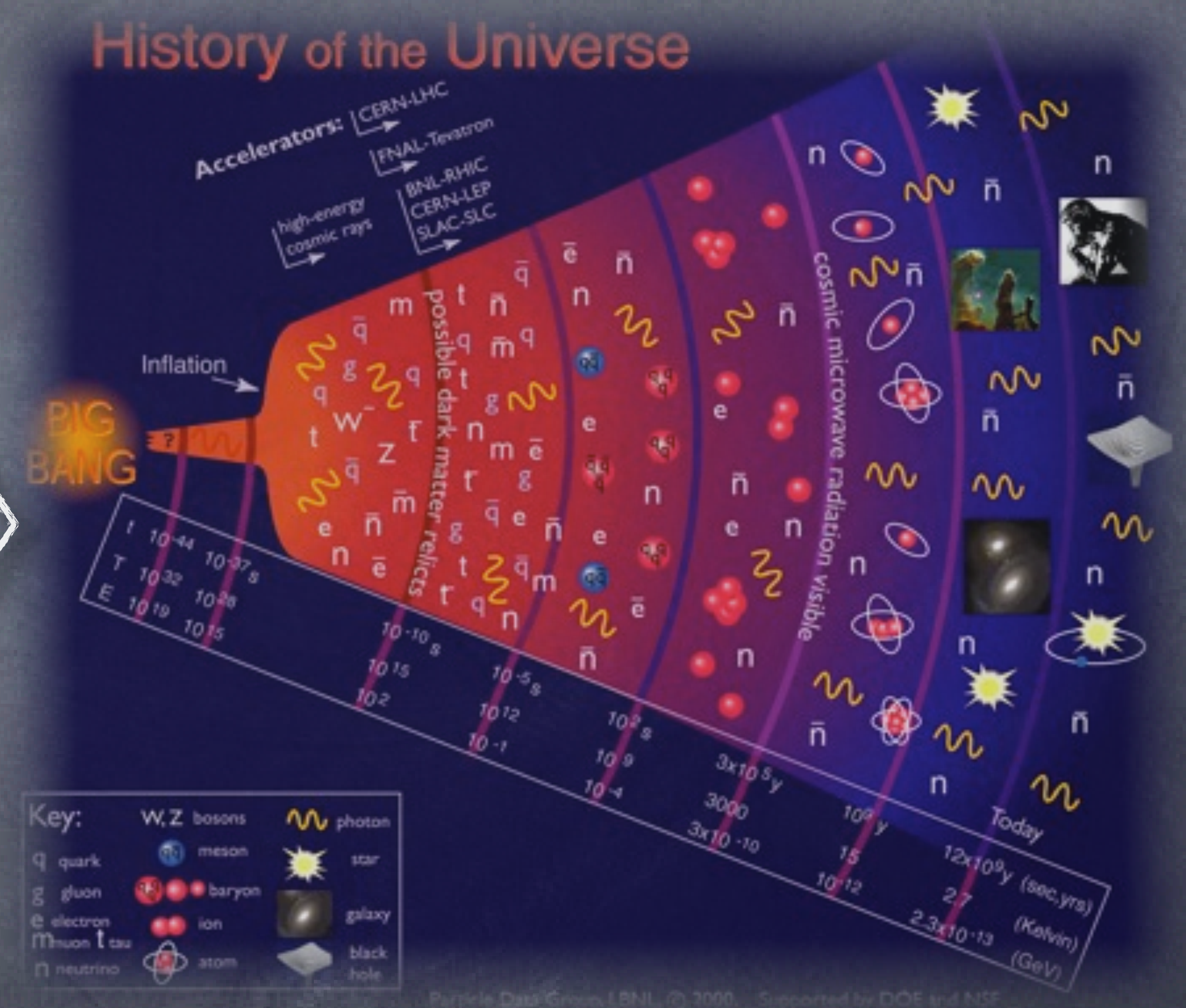
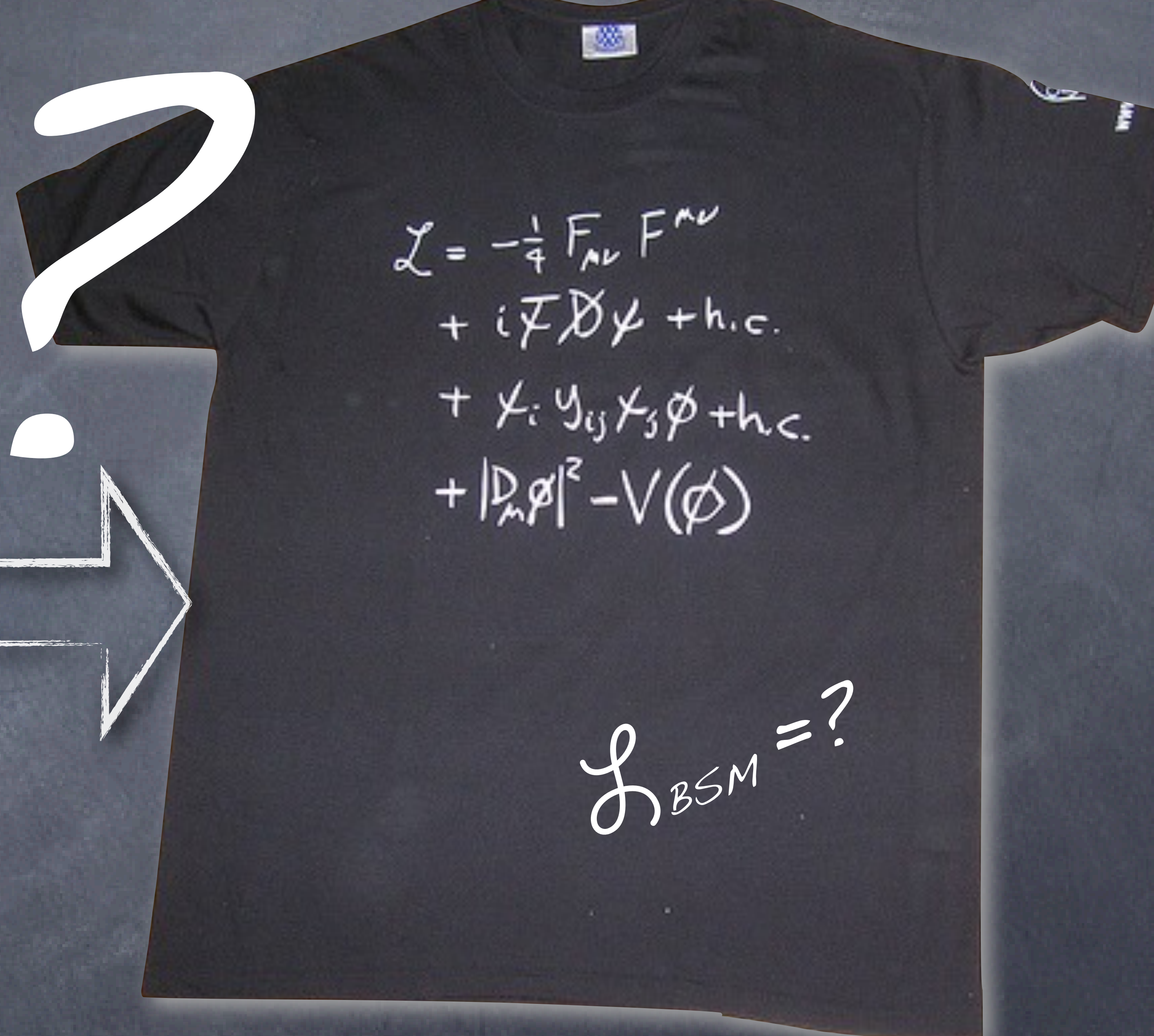
$+ \sqrt{g} R(g)$


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
W, Z bosons
photon
quark
meson
star
gluon
baryon
electron
ion
galaxy
muon
tau
atom
black hole
neutrino

What's next?



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$\mathcal{L}_{BSM} = ?$

What's next?

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only a few eletrons are enough to lift your hair (~ 10^{25} mass of e^-)

the electric force between 2 e^- is 10^{43} times larger than their gravitational interaction

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ie we don't know why the masses of particles are so small?

Several theoretical hypothesis

new space-time structure?

modification of special relativity? of quantum mechanics?

To continue the discussions...

Running of gauge couplings

Even if the intensity of the elctric bulb remains the same
the amount of light reaching us depends on the depth of the fog

The intenisty of the electric charge depends on the density of virtual particles

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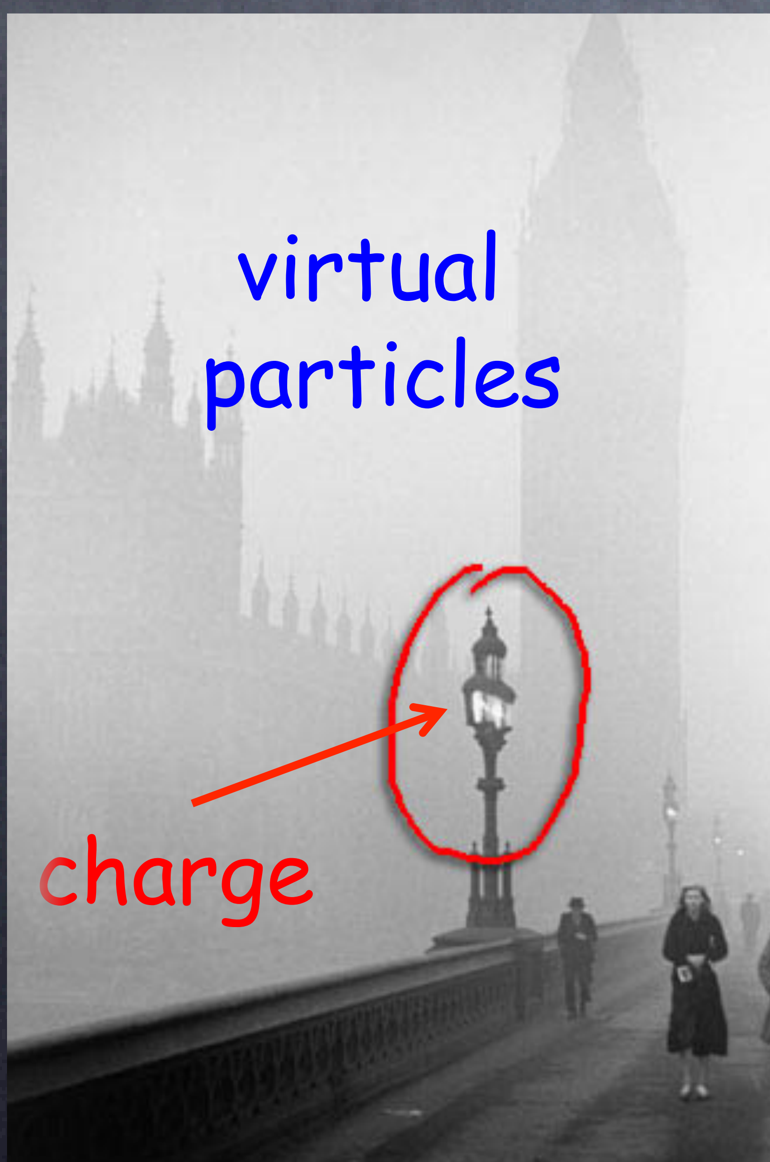

(pictures: courtesy of G. Giudice)

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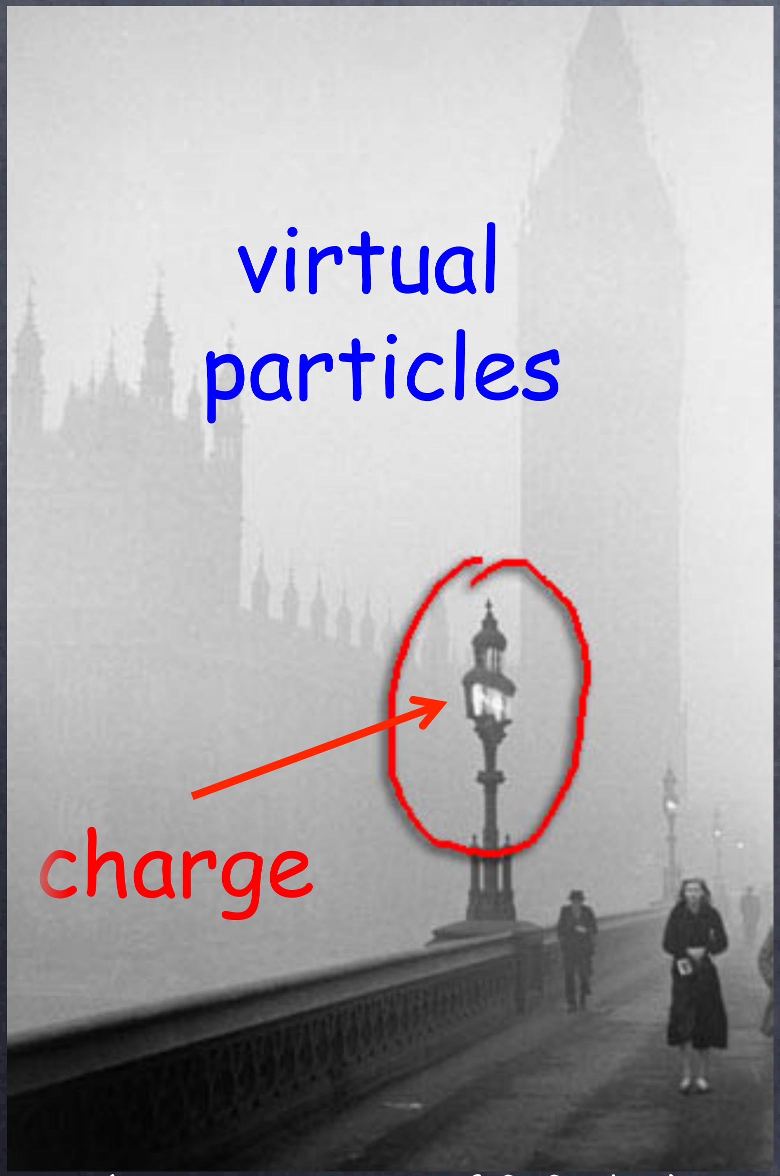

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QED: virtual particles screen the electric charge: $\alpha \searrow$ when d $\nearrow$

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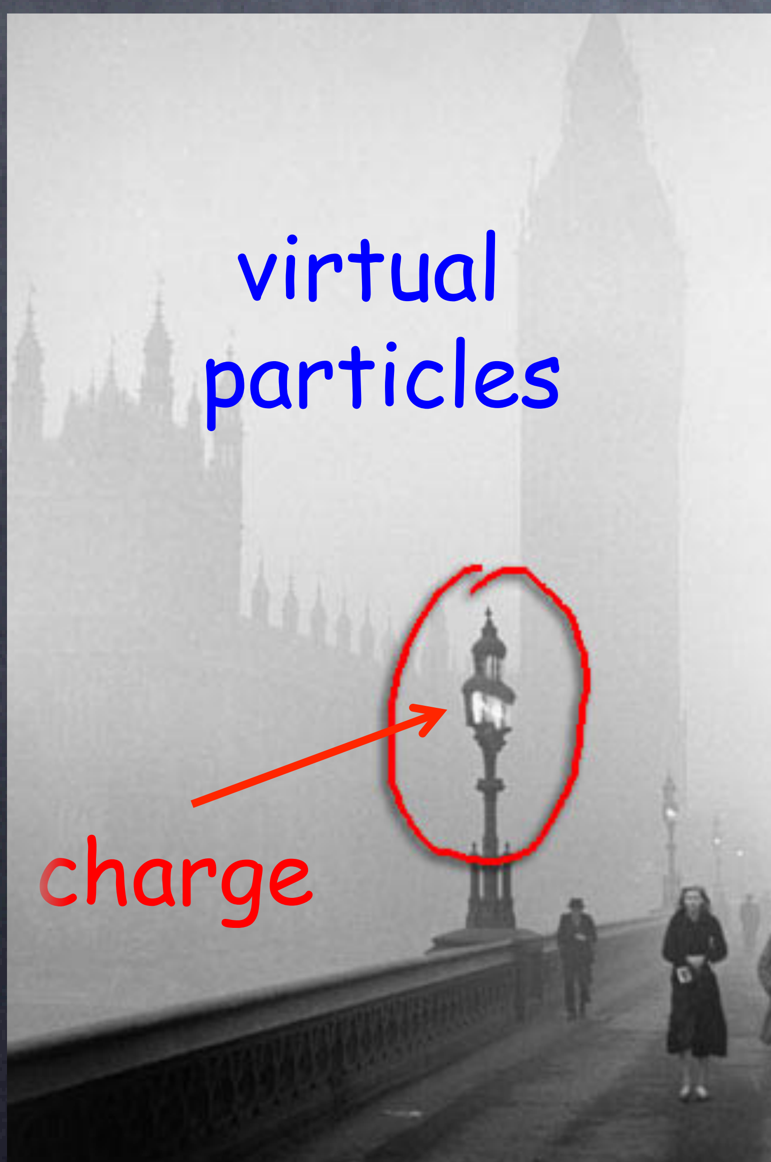

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QCD: virtual particles (quarks & *gluons*) screen the strong charge: $\alpha_s \nearrow$ when d $\nearrow$

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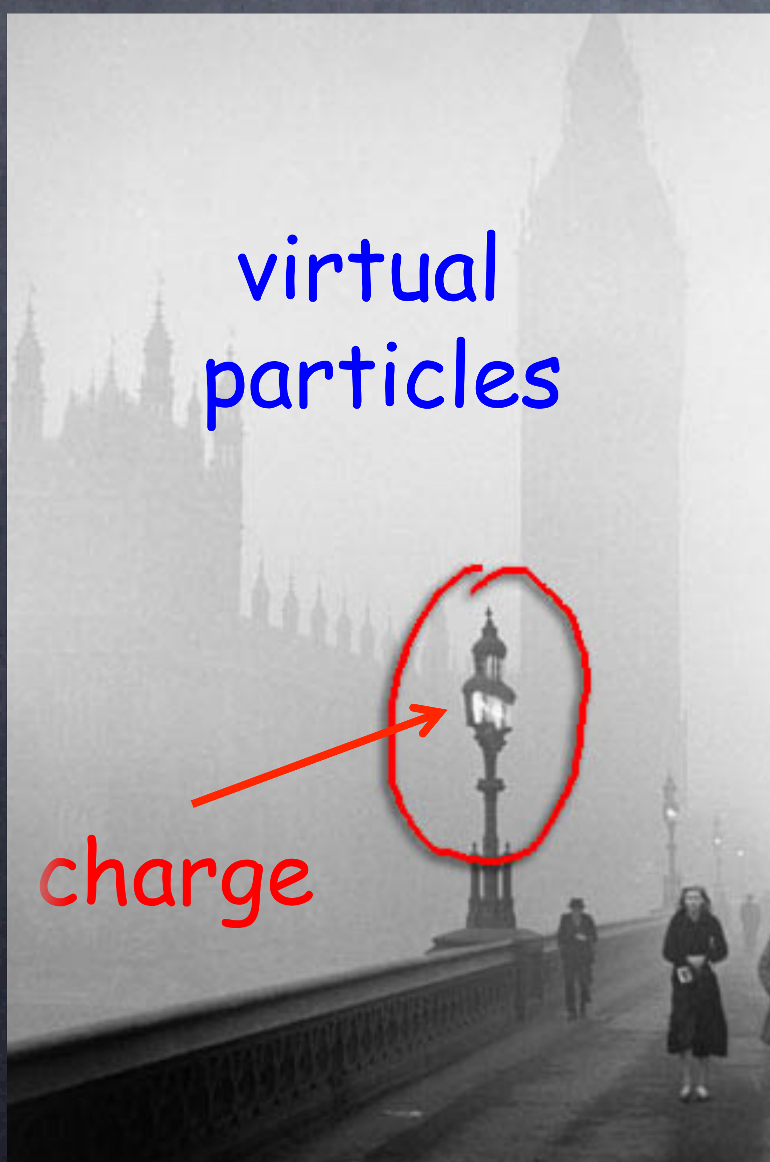

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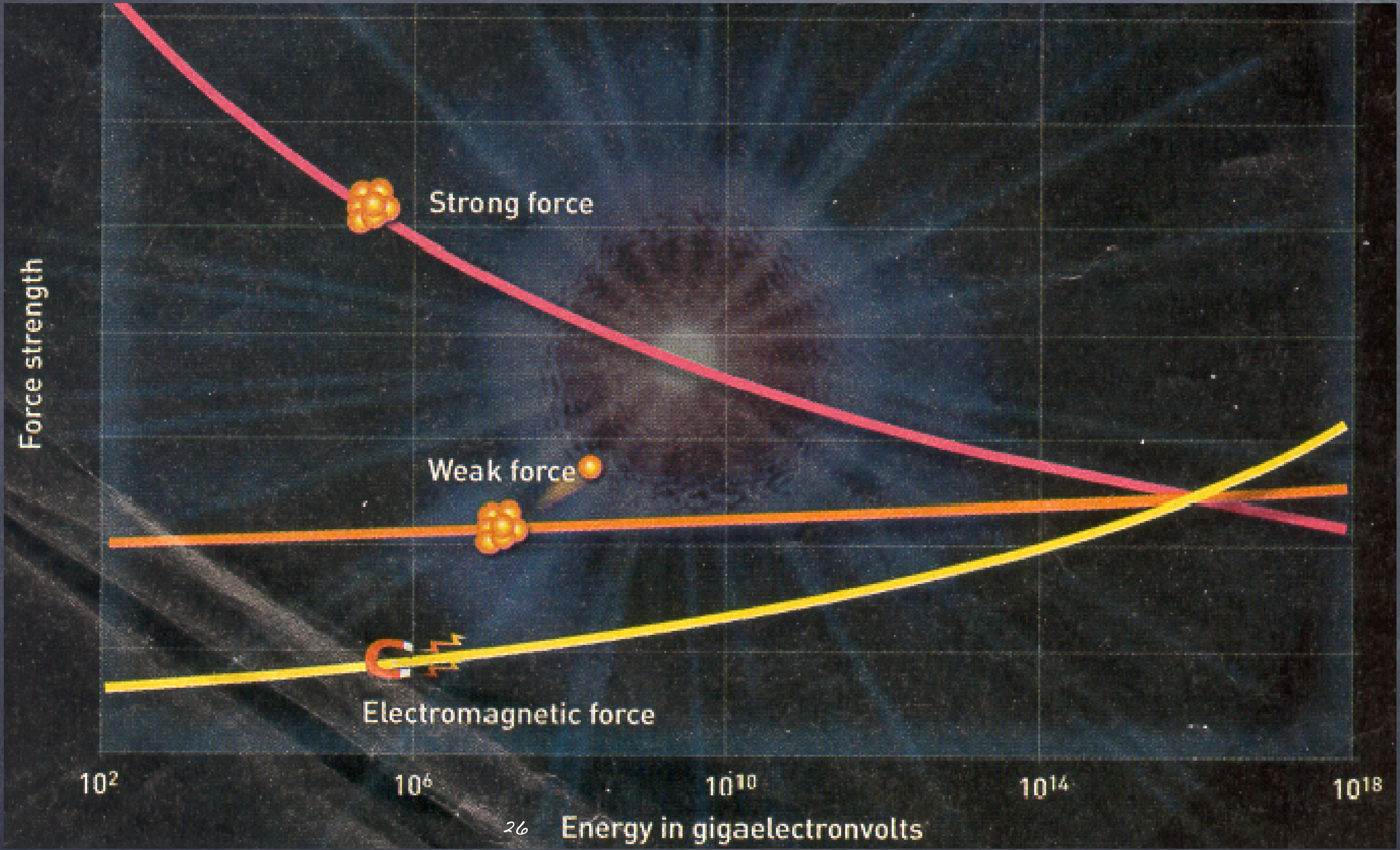
QCD: virtual particles (quarks & *gluons*) screen the strong charge: $\alpha_s \nearrow$ when d $\nearrow$

'asymptotic freedom'

$$\frac{\partial \alpha_s}{\partial \log \mu} = \beta(\alpha_s) = \frac{\alpha_s^2}{\pi}\left(-\frac{11 N_c}{6} + \frac{N_f}{3}\right)$$

Unification of Interactions



Only one time of matter
Only one fundamental interactions

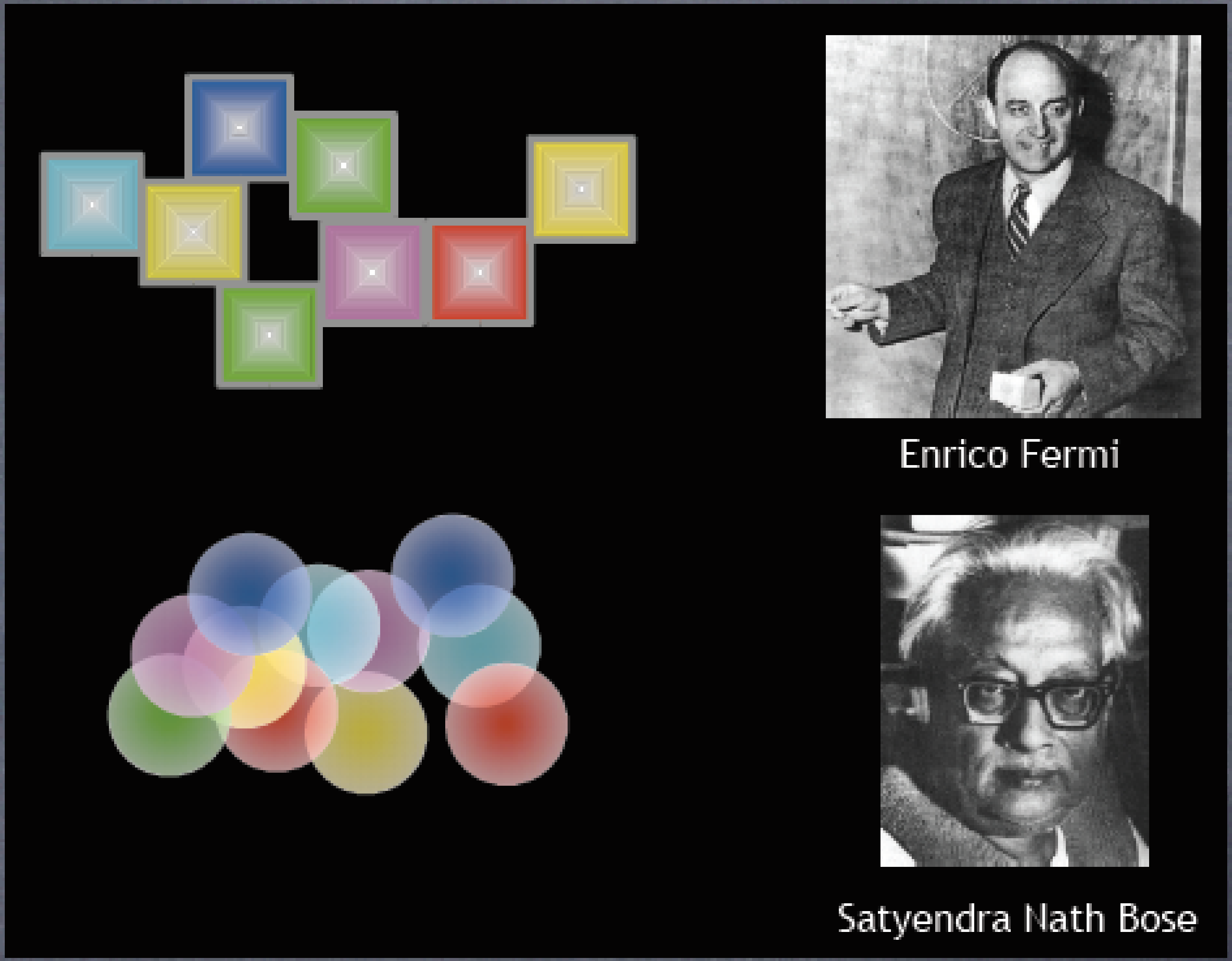
Supersymmetry

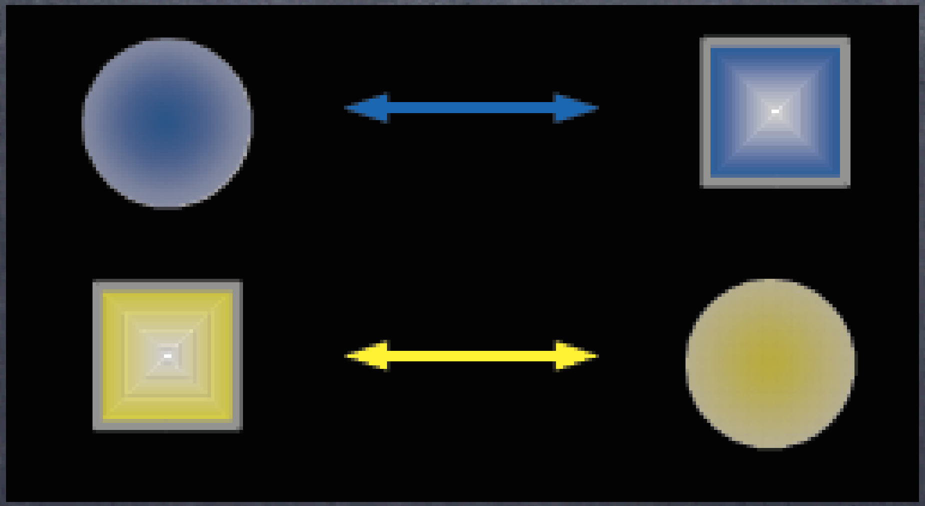
Fermions *matter particles*

the fermions are repelling each other

Bosons *force carriers*

the bosons can be pilled up





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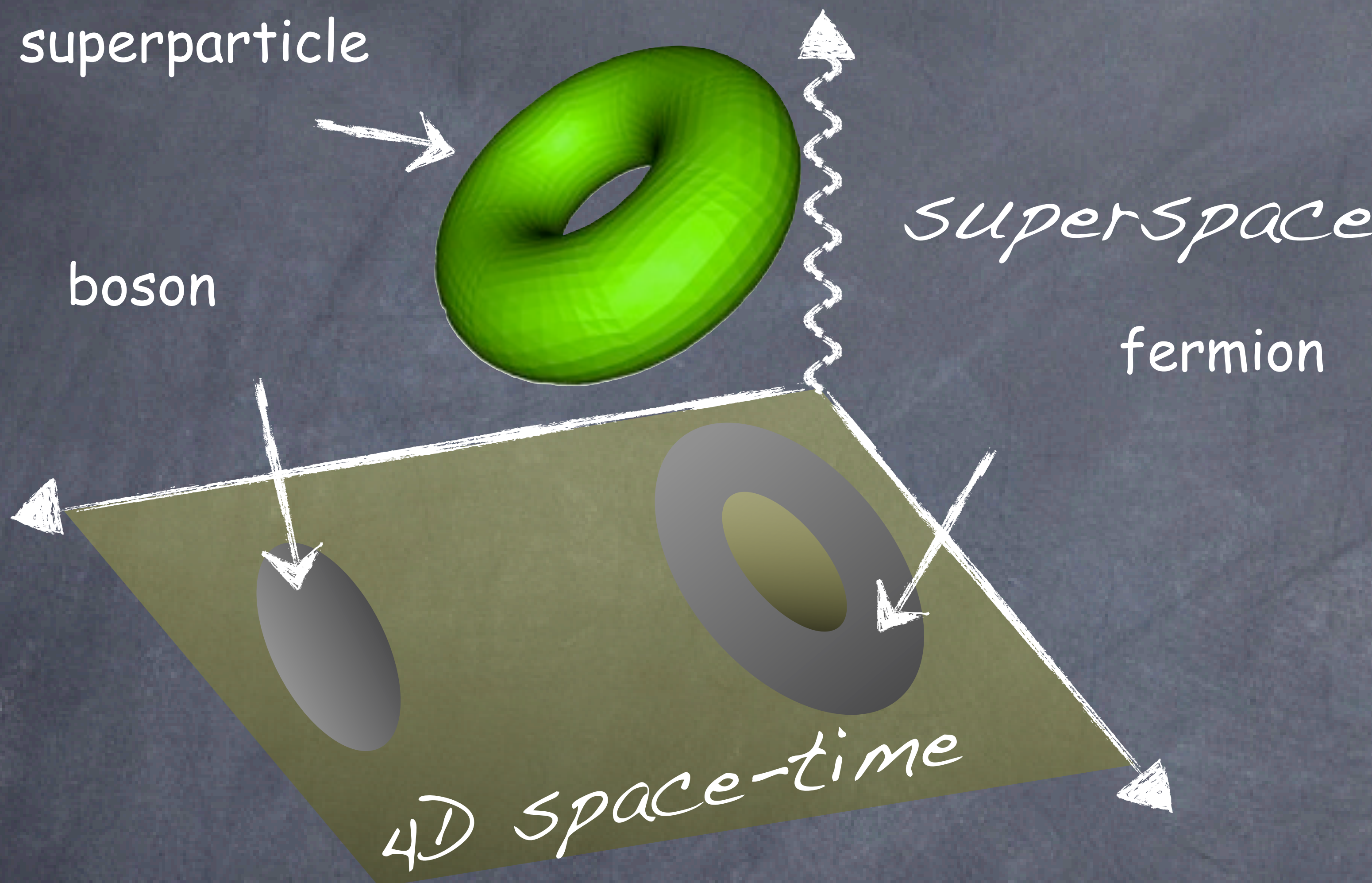
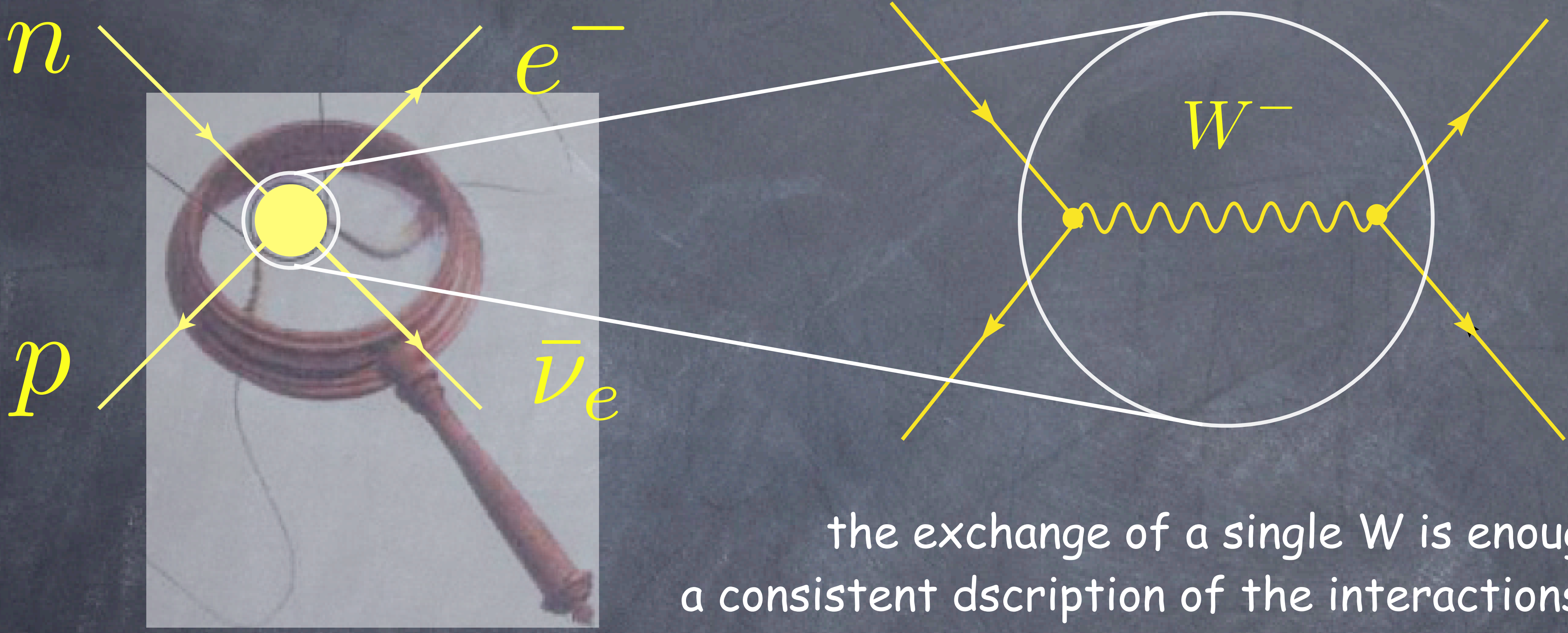


$x^2=1$ ➡ matter and antimatter

$x^2=-1$ ➡ matter and supermatter

Towards Quantum Gravity



the exchange of a single W is enough to get
a consistent dscription of the interactions at high energy

How to get a consistent description of gravity at high energy?

$$\mathcal{L} = \frac{1}{M_{Pl}} h_{\mu\nu} T^{\mu\nu}$$

exchange of an infinity of particles
of more and more massive particles
with larger and larger spins
= spectrum of an extended object (a "string")

Extra dimensions

String theories are well-defined only in space-times
with 10 or 11 dimensions

These extra dimensions are curved and compactified