The symmetry and simplicity of the laws of physics and the Higgs boson

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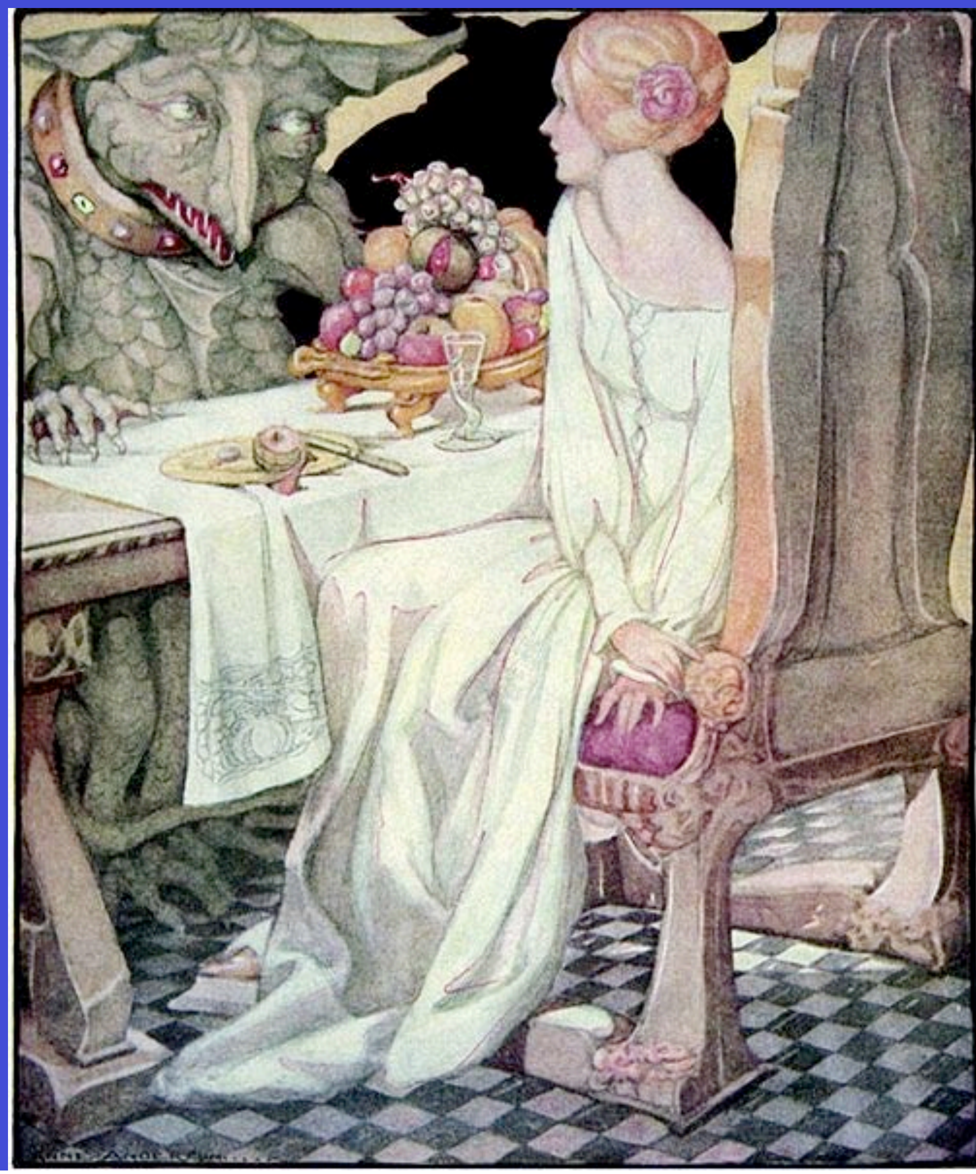
The beauty and the beast



Symmetry
Simplicity
elegance

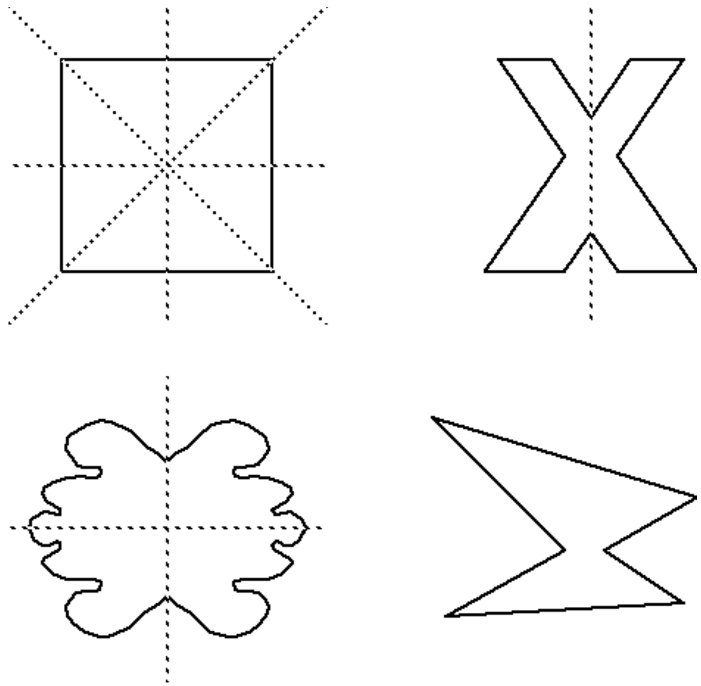
Forces of nature
Electromagnetic
Weak
Strong
Gravity

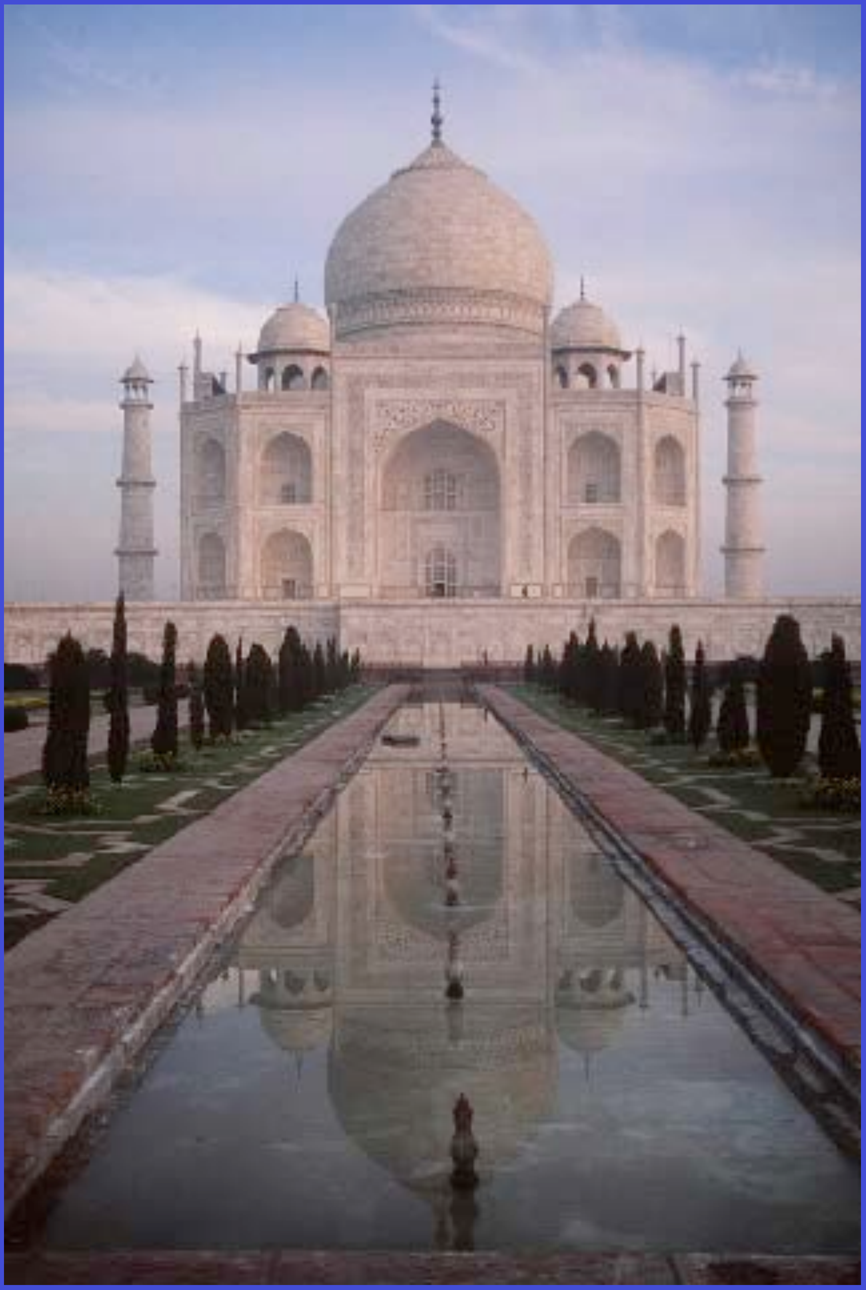
Complicated
Mysterious

Higgs mechanism

We need both to understand nature.
We are the children of this marriage

Symmetry





The symmetries of nature are hidden and it
has taken a long time to uncover them.

They are so hidden that, in some sense, they are not even symmetries!
But just a convenient way to describe the system!

We will try to explain these symmetries, and why
the Higgs mechanism, and the Higgs particle, are necessary.

4 Forces:

Electromagnetic

Weak

Strong

Gravity

Electromagnetism

- Electricity and magnetism
- Dominant force for everyday life: atoms, chemistry, etc
- It was essentially hidden until about 300 years ago, due to the fact that positive and negative charges cancel out almost completely in ordinary matter.
- Understanding it lead to a huge amount of technological progress.

High school electromagnetism

Electric Field

Pushes a charged particle

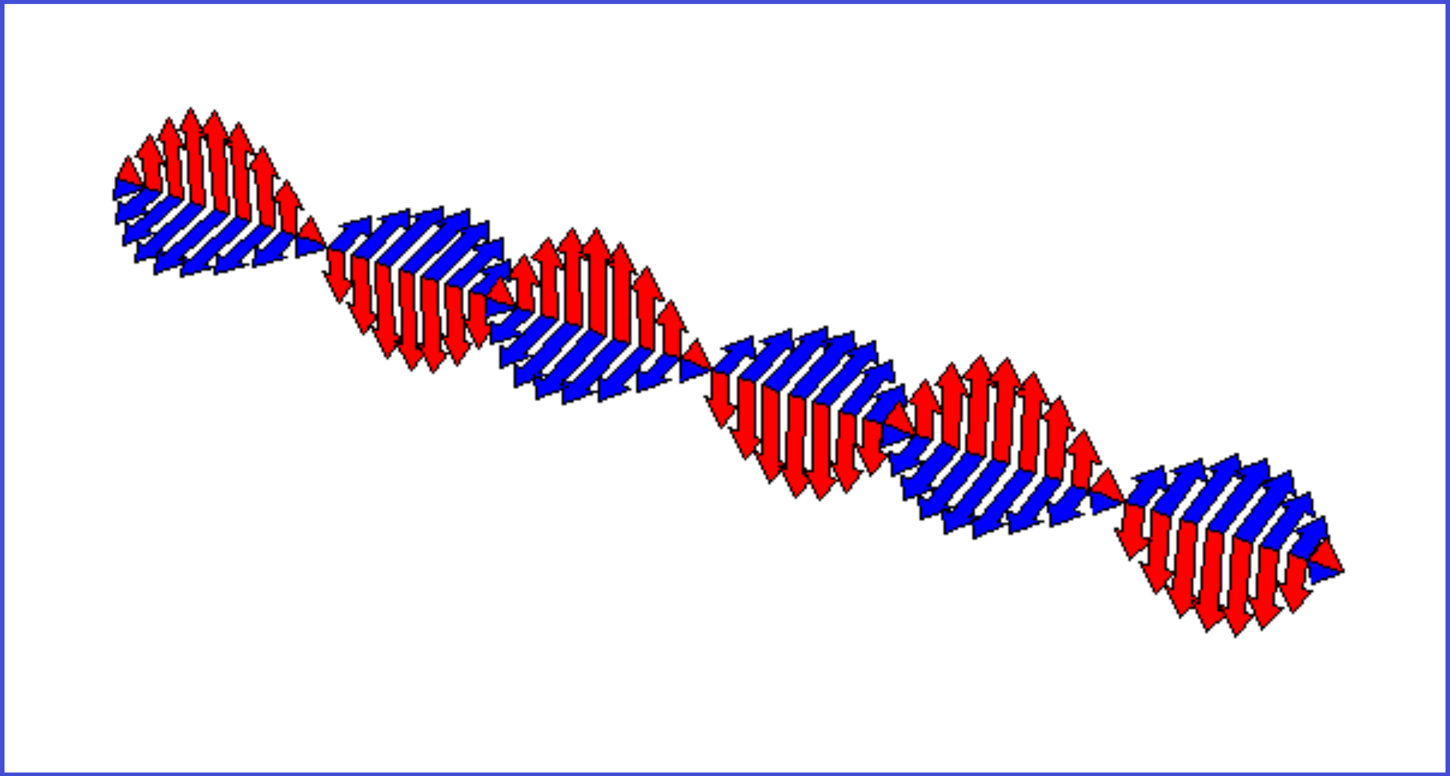
Magnetic Field

Acts on moving charges
and makes them turn

Relativity → relates electric and magnetic fields

Maxwell 1865

The electromagnetic field has its own dynamics. Its oscilations are waves that propagate in empty space:
Light, radio waves, X-rays, gamma rays, etc.



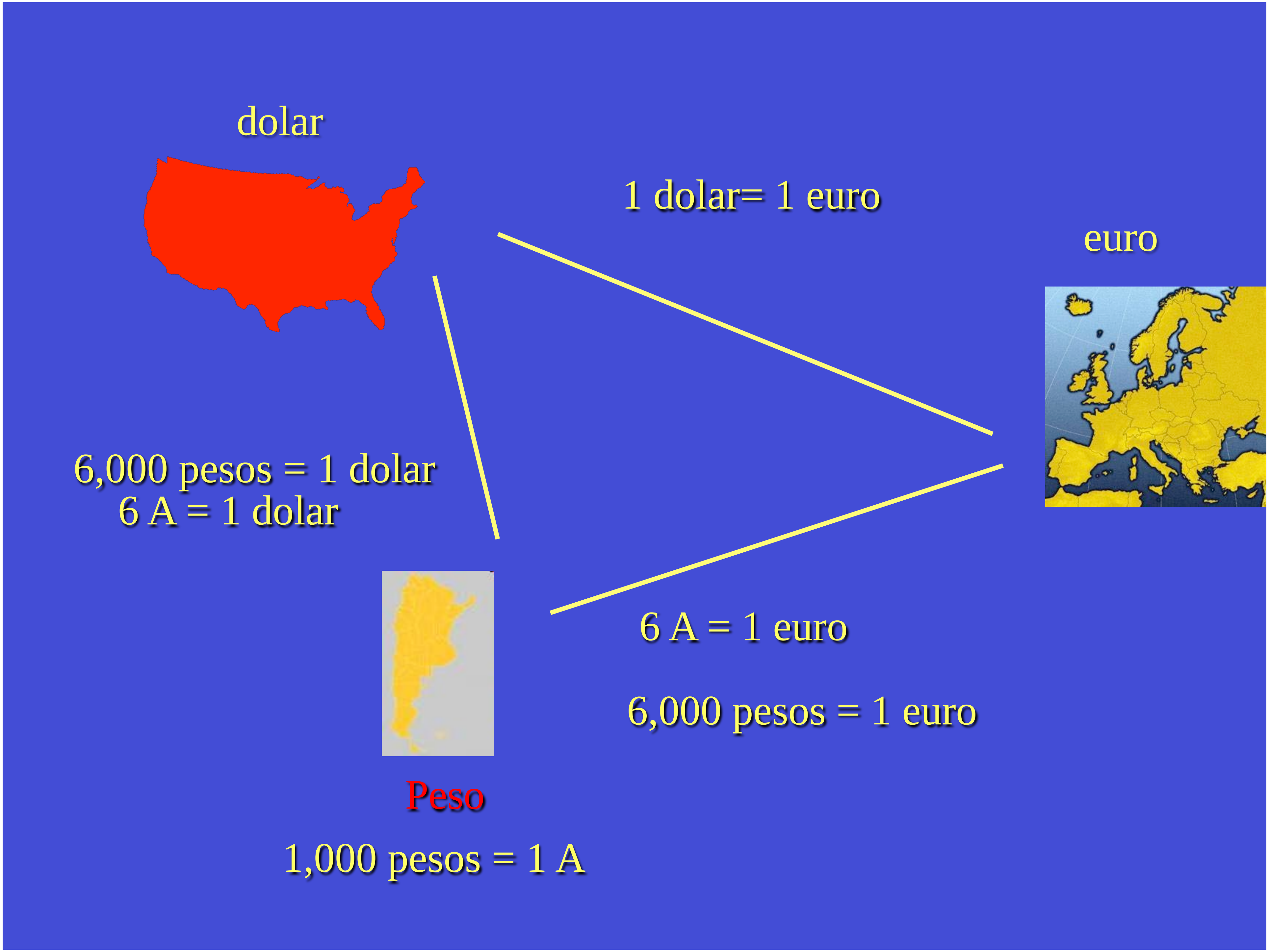
Electromagnetism is based on a ``gauge'' symmetry

H. Weyl, 1918
Based on
Einstein's gravity

Monetary analogy:

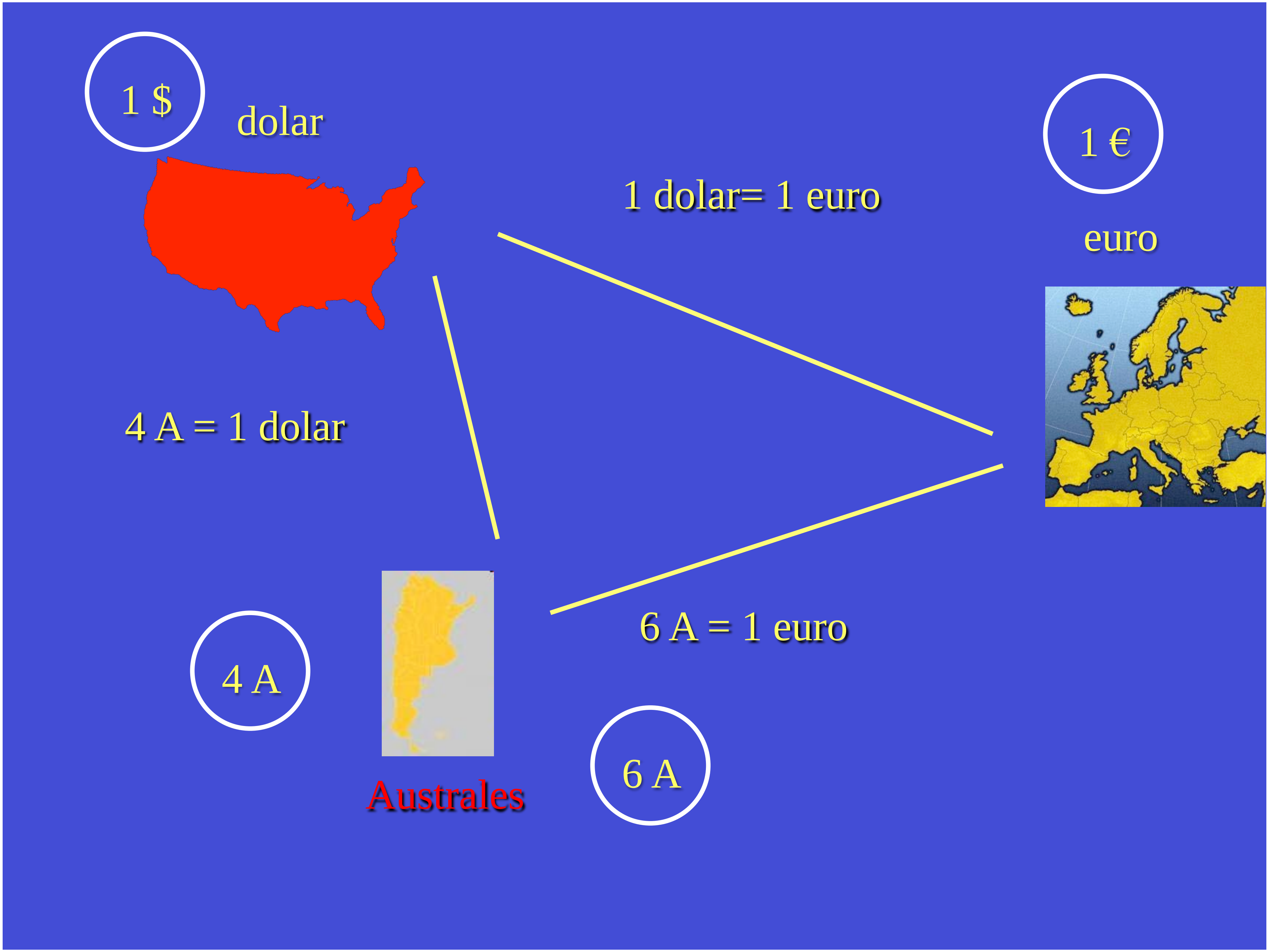
- Countries
- Each country has its own currency
- When you go from one country to the next you need to change all your money to the new currency.
- At the border you have banks that will change your money (no comission) . Each bank fixes the exchange rate it wants.

- There is nothing to buy.


dolar
1 dolar= 1 euro
euro
6,000 pesos = 1 dolar
6 A = 1 dolar
6 A = 1 euro
6,000 pesos = 1 euro
Peso
1,000 pesos = 1 A

1 current peso = 10,000,000,000,000 pesos when I was born

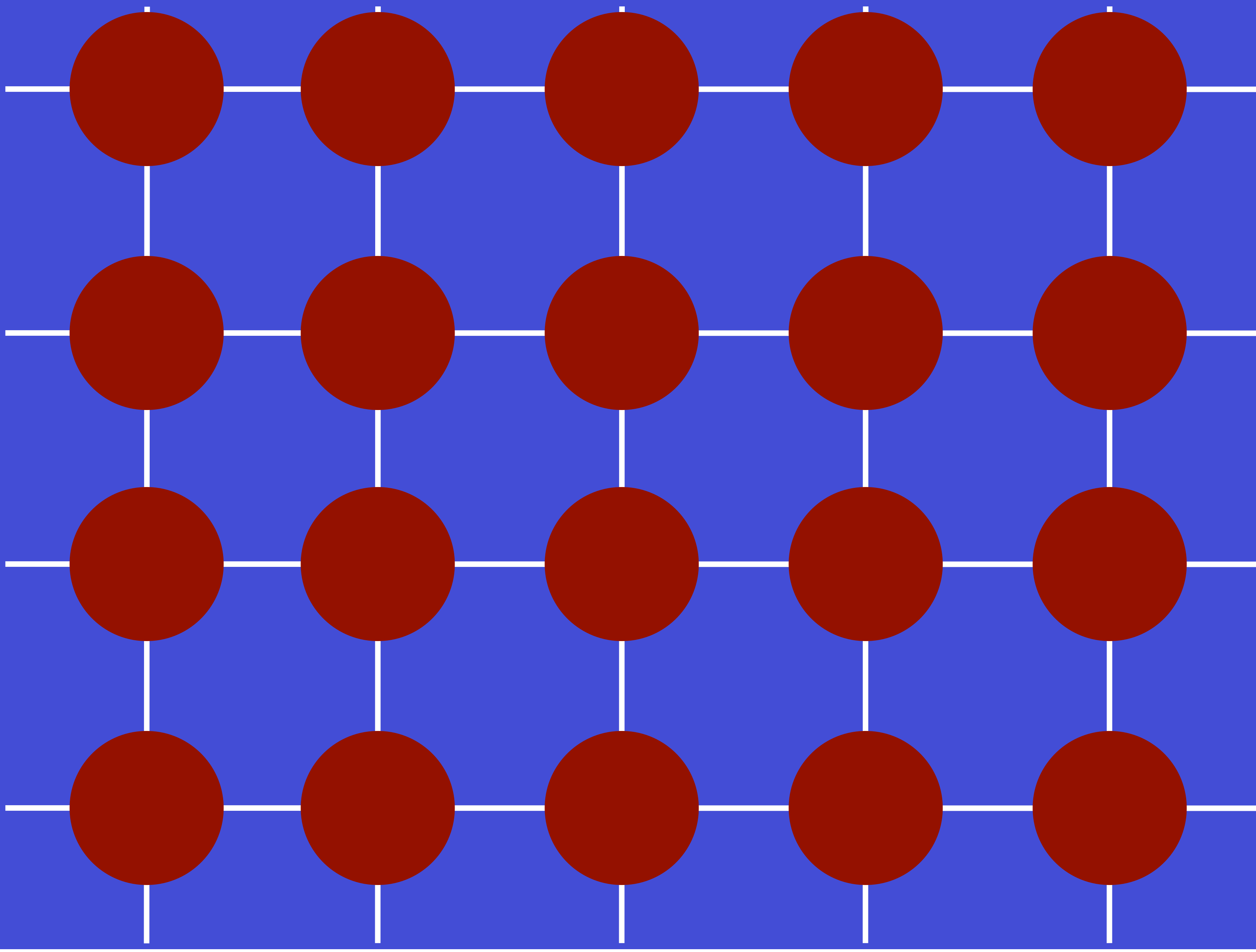
Exchange rates are arbitrary.
Banks do not coordinate them.


1 $
dolar
1 €
1 dolar= 1 euro
euro
4 A = 1 dolar
4 A
6 A = 1 euro
6 A
Australes

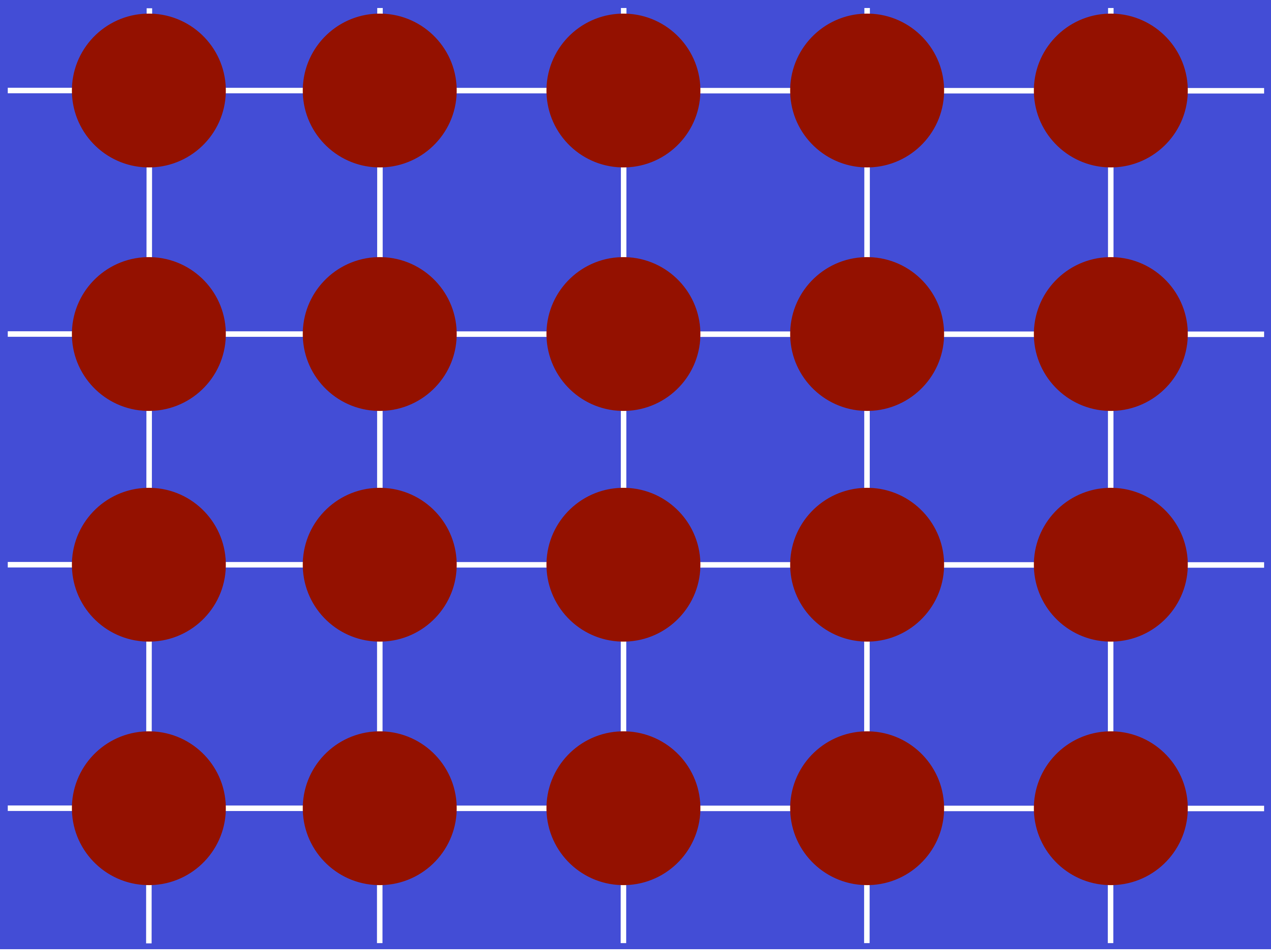

ARCTIC OCEAN
Greenland
Svalbard (Nor.)
ARCTIC OCEAN
United States of America
Canada
Iceland
Norway
Sweden
Finland
Russia
United Kingdom
Denmark
Neth.
Ireland
Estonia
Latvia
Belarus
Ger.
Pol.
Ukraine
France
Kazakhstan
Mongolia
Rom.
Georgia
Italy
Bulgaria
Uzb.
Kyrgyzstan
United States of America
ATLANTIC OCEAN
Portugal
Spain
Turkey
Azer.
Turkm.
Tajikistan
N. Korea
S. Korea
Japan
Greece
Syria
China
Morocco
Tunisia
Lebanon
Iraq
Iran
Afg.
Israel
Kuwait
Pakistan
Nepal
Bhutan
PACIFIC
Algeria
Libya
Jordan
Egypt
Saudi Arabia
U.A.E.
India
Laos
Mexico
Western Sahara
Taiwan
Oman
PACIFIC
Mauritania
Mali
Niger
Chad
Eritrea
Bangl.
Burma
Vietnam
Philippines
OCEAN
Honduras
Guatemala
Nicaragua
Senegal
Sudan
Yemen
Djibouti
Thailand
Costa Rica
Ven.
Guyana
Guinea-Bissau
Nigeria
Cambodia
Panama
French Guiana
Sierra Leone
C.A.R.
Ethiopia
Colombia
Liberia
Ghana
Cam.
Somalia
Sri Lanka
Malaysia
Cote d' Ivoire
Togo
Ecuador
Suriname
Gabon
Dem. Rep. of Congo
Uganda
Kenya
INDIAN
Papua New Guinea
OCEAN
Solomon Islands
Rep. of the Congo
Tanzania
Indonesia
Brazil
Peru
Angola
Zambia
Malawi
Bolivia
Namibia
Zimbabwe
Madagascar
Fiji
Paraguay
Mozambique
Botswana
Australia
ATLANTIC
Swaziland
Chile
Lesotho
OCEAN
South Africa
OCEAN
Argentina
Uruguay
New Zealand

Countries are arranged in a regular pattern

They are all the same. The exchange rates can be all different



You cannot fly. You can only walk from one country to the next, from there to the next and so on



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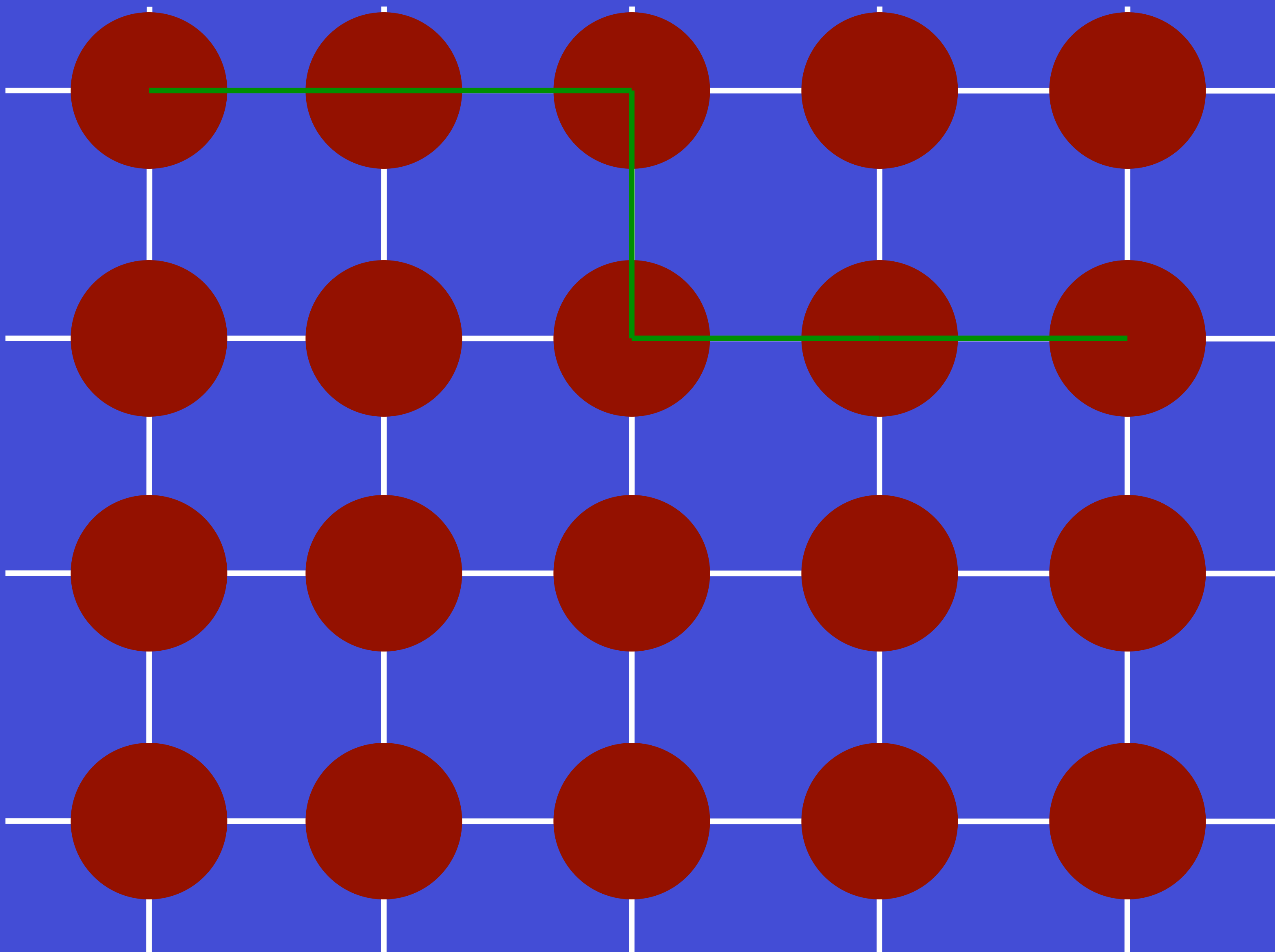
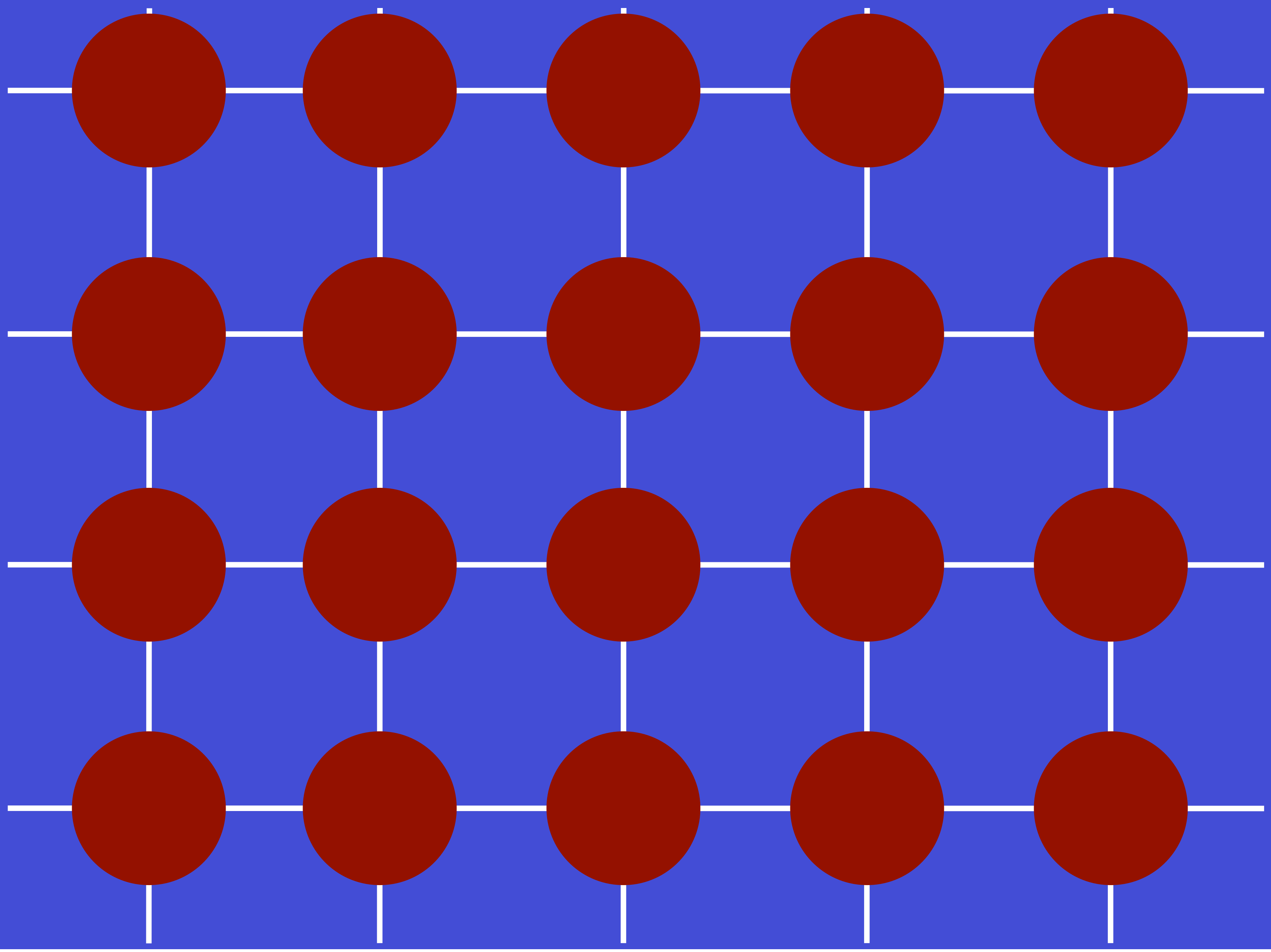


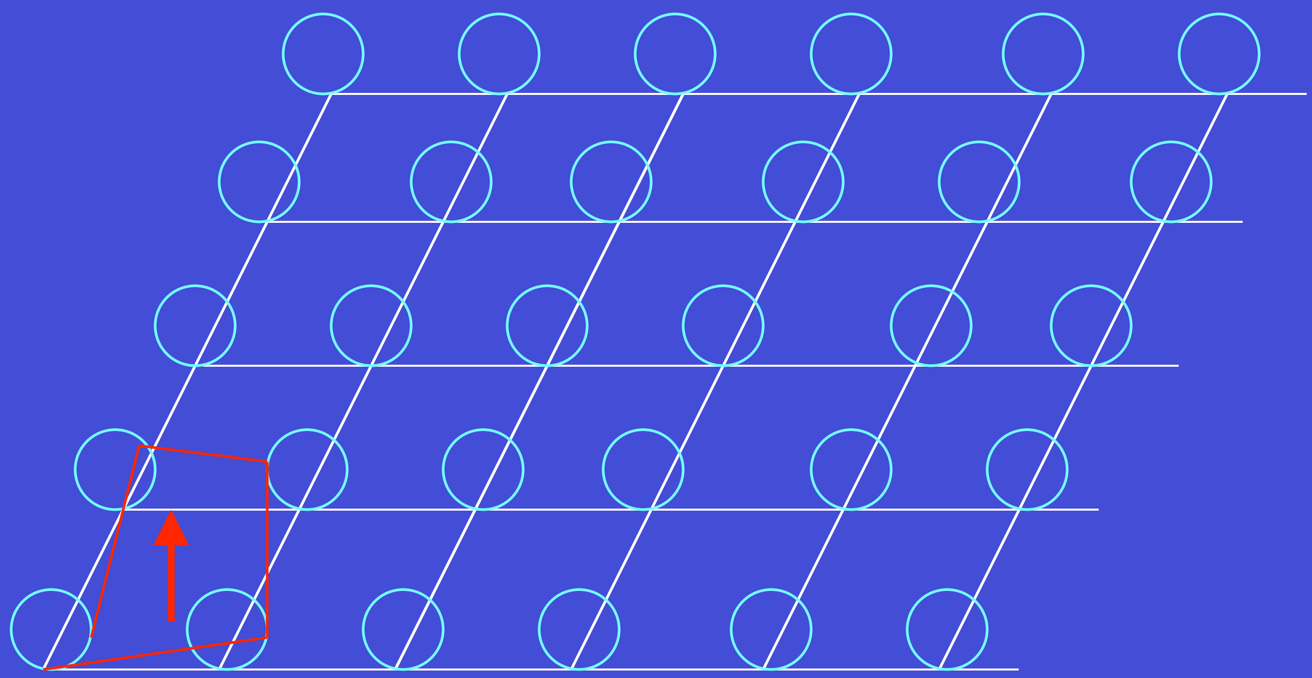
Physics is simpler than economics !



Gauge symmetry of electromagnetism:

Rotations of a circle.

Change in currency → rotations of the circles = gauge transformation
Exchange rates → electromagnetic potential
Speculators → electrons
Opportunities to speculate→ magnetic field



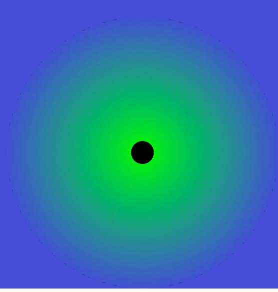
Quantum Mechanics

- At short distances the laws of physics are probabilistic.
- In the analogy: The exchange rates are random with a probability distribution that depends on the opportunity to speculate (magnetic field). Configurations with large opportunities to speculate are less probable. Nature does not like speculation

- Energies of many systems are quantized.
- Electromagnetic waves are quantized.
- Quantum of field excitation = particle.

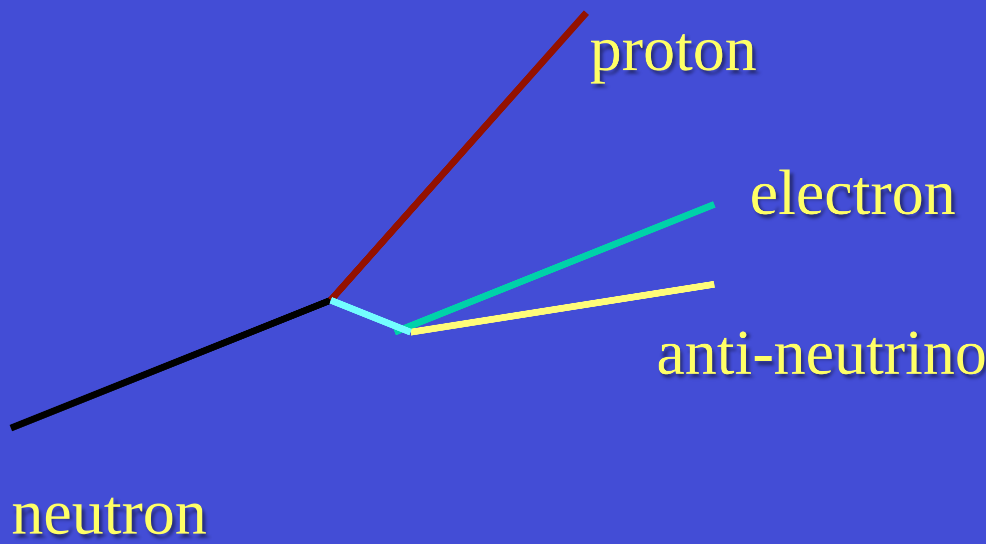
Electrodynamics

- Based on a gauge symmetry.
- Massless photon.
- Electron is massive.
- Nuclei + electrons plus their electromagnetic interactions explains most of what we see in everyday life.



Weak Interactions

It is important for certain radioactive decays.



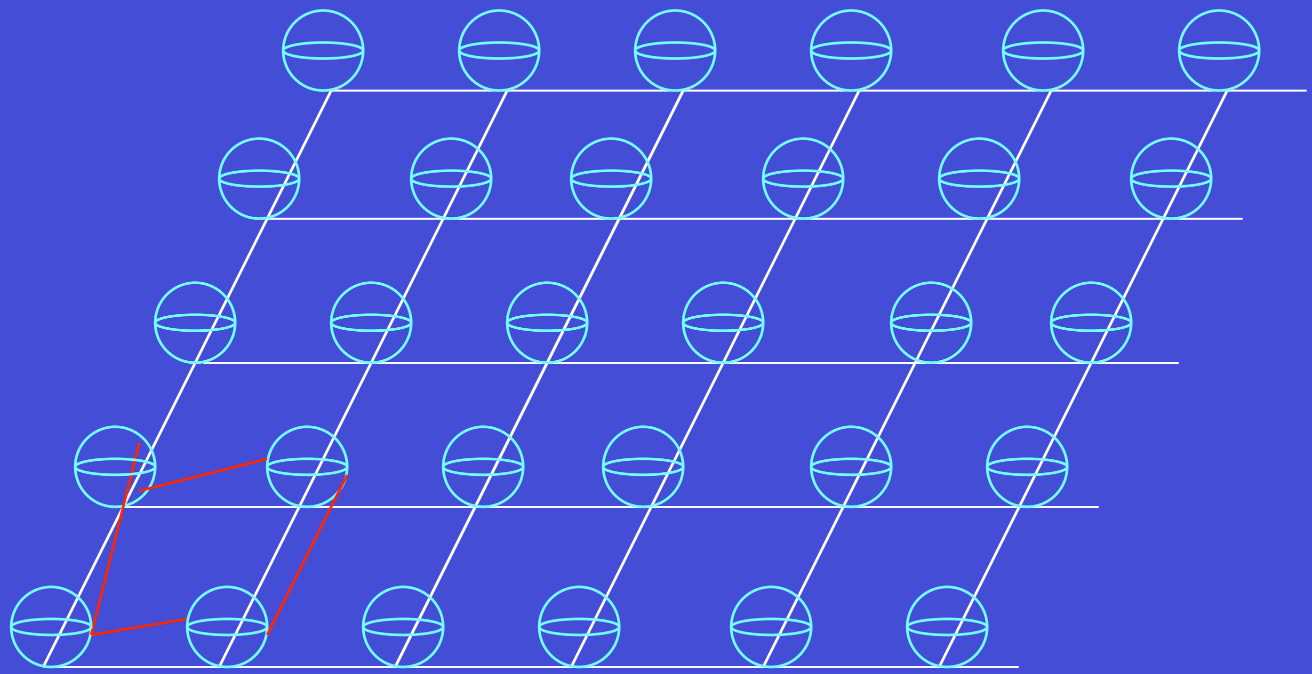
Important for historians → C^{14} dating

Cooked the chemical elements in stars

Can move mountains: Radioactive decays heat the earth, moves continents → forms mountains

The gauge symmetry for weak interactions

- We have the symmetries of a sphere at each point in space.

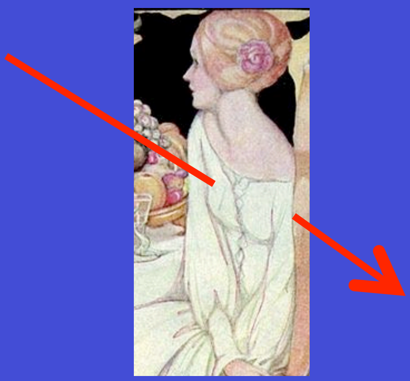


- Rotations: 3 variables → 3 weak "gauge bosons"
- The gauge symmetry determines the interactions among all these particles.

Yang, Mills 54

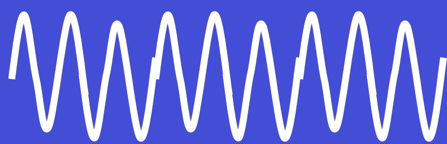
- Pauli’s objection to Yang:
- The gauge bosons would be massless !

- Another beautiful theory killed by an ugly fact ?

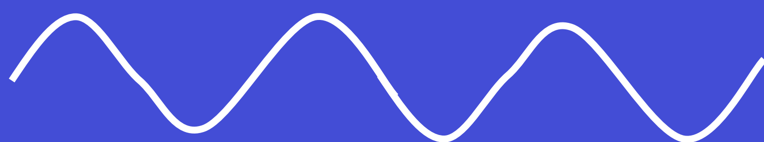


Why massless particles ?

Energy of waves



More energy



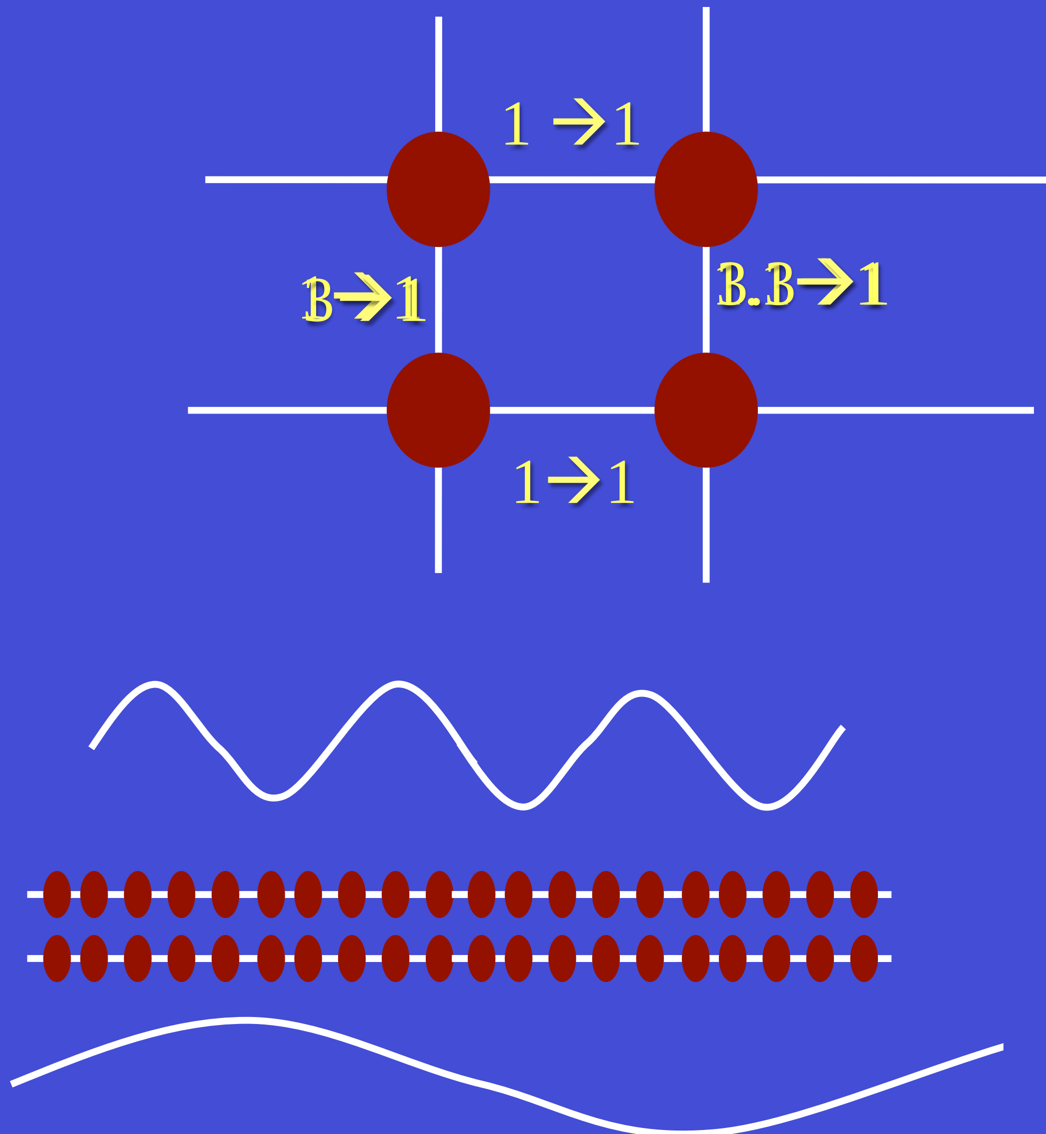
Less energy

Massive particle → $E = m c^2$

Energy → related to the opportunity to speculate

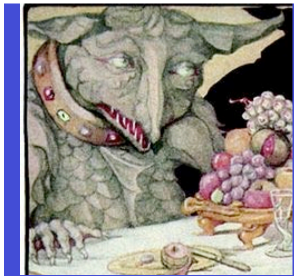
More energy → less probable .

Large opportunities to speculate are less probable



A very long wavelength configuration
gives you little local opportunity to speculate → less energy

How do we solve the mass problem ?

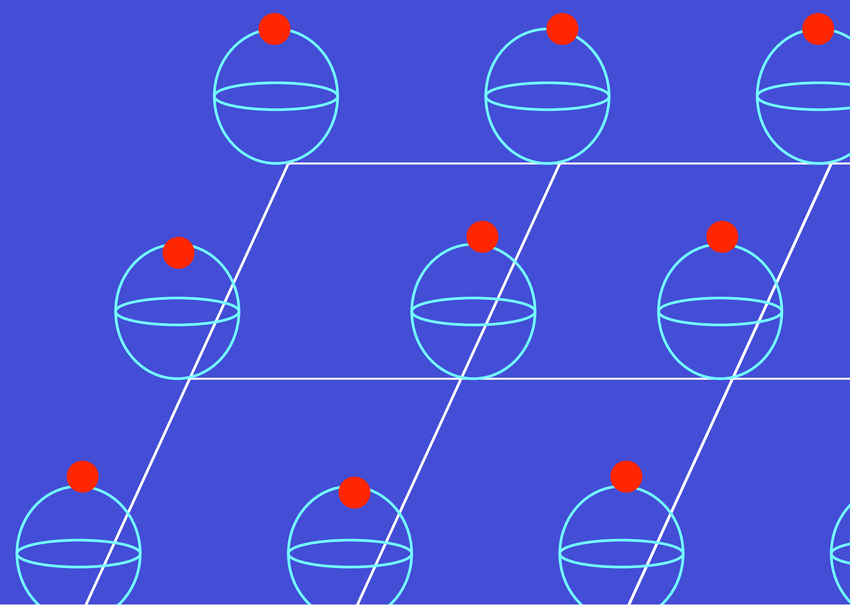


Anderson, Nambu, Goldstone, Higgs,
Brout, Englert, Guralnik, Hagen, Kibble 60's

The Higgs mechanism

There is an object sitting on each of the weak spheres.

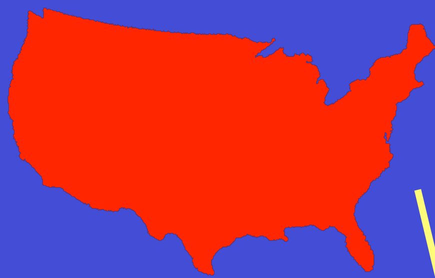
In the vacuum !



Back to the monetary analogy

- Now there is something to buy in each country, say Gold.
- We can take it from one country to its neighbor

 = 1 $

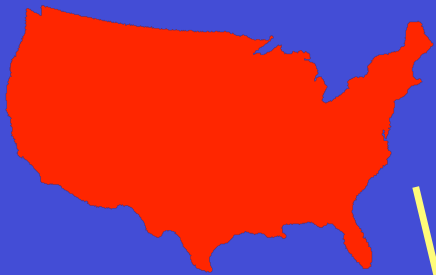


1,000 P = 1 $

New opportunities to speculate!

 = 6,000 P

= 1 $

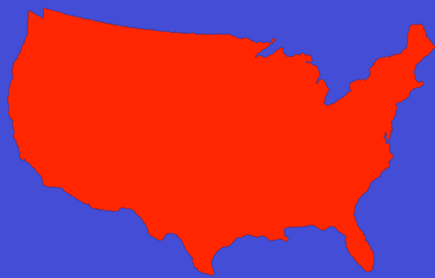


1 A = 1 $

Gauge symmetry still present

= 6 A

= 1 $



1 P = 6 $

Choose the currencies
so that the price of gold is one.

The exchange rates remain.

The opportunities to speculate are
clearer now.

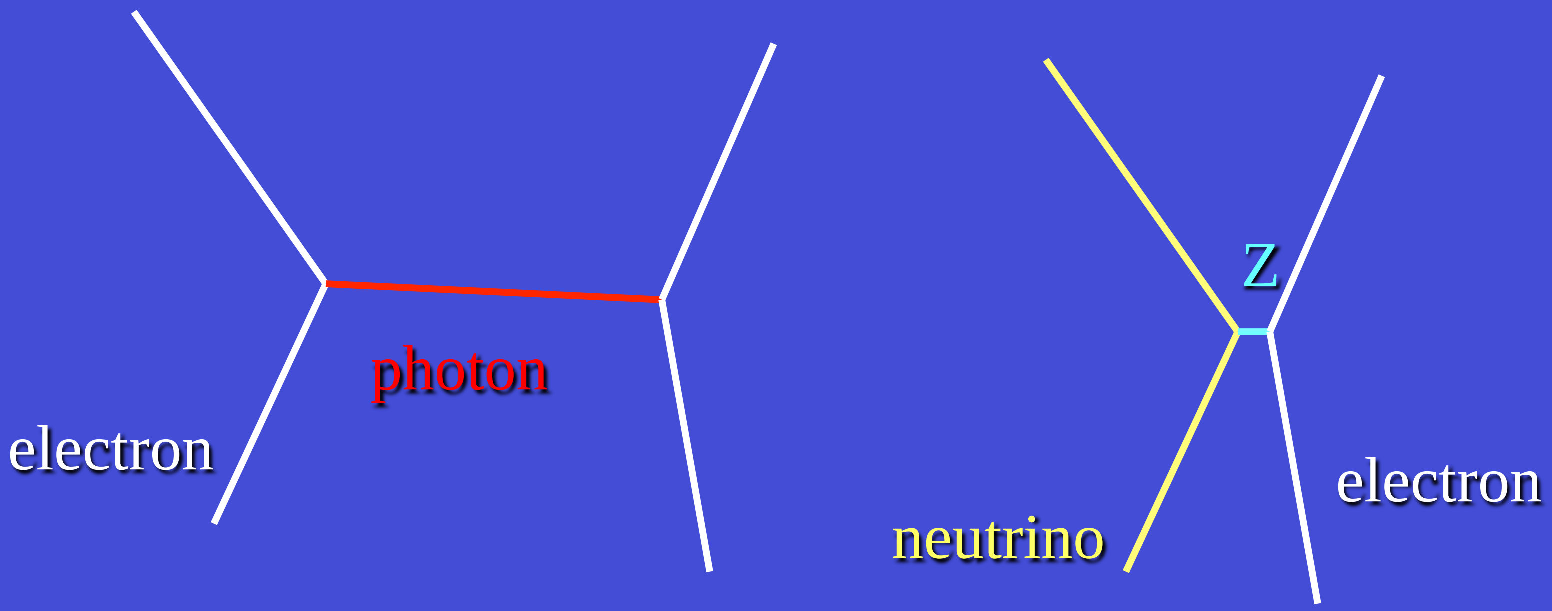
= 1 P

Without Gold: Exchange rates between two countries were arbitrary
Only comparing nearby countries could we speculate

With Gold: The exchange rate between two countries
has a preferred value, the one where you cannot
speculate between two neighboring countries.
Once we fix the price of gold to one everywhere, any fluctuation of
the exchange rate brings opportunity to speculate,
even if it has long wavelength → Mass for gauge bosons

Higgs Field→ The price of gold in each country
Preferential value for the exchange rates→ masses for the
weak gauge bosons (Z & W)

The mass of the weak gauge bosons explains the weakness of the weak force.



Large mass → less probable. Smaller interaction

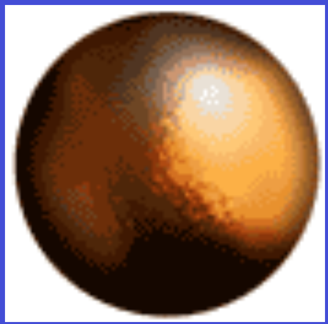
A few percent of the energy of the sun comes out in neutrinos.
These neutrinos, just go through us, the go through the whole earth!

- The weak force has some other strange features…

- Before continuing we need to talk more about rotations

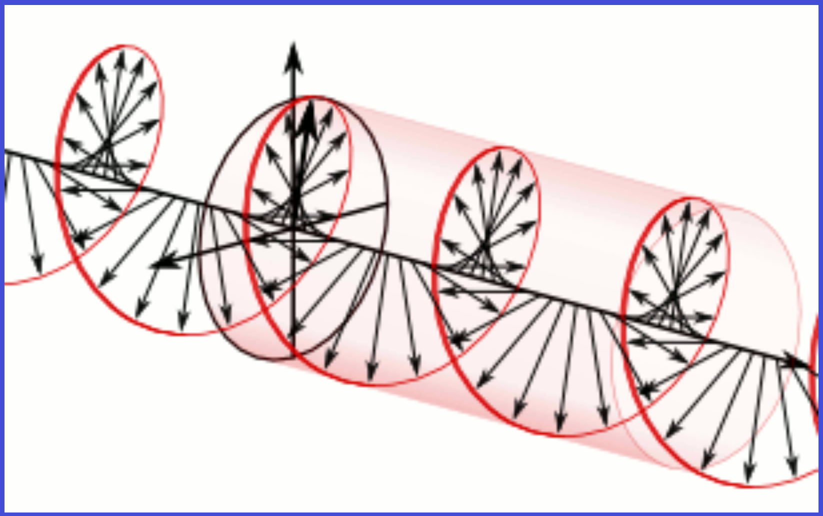
- First start with rotations in space

Rotations in space

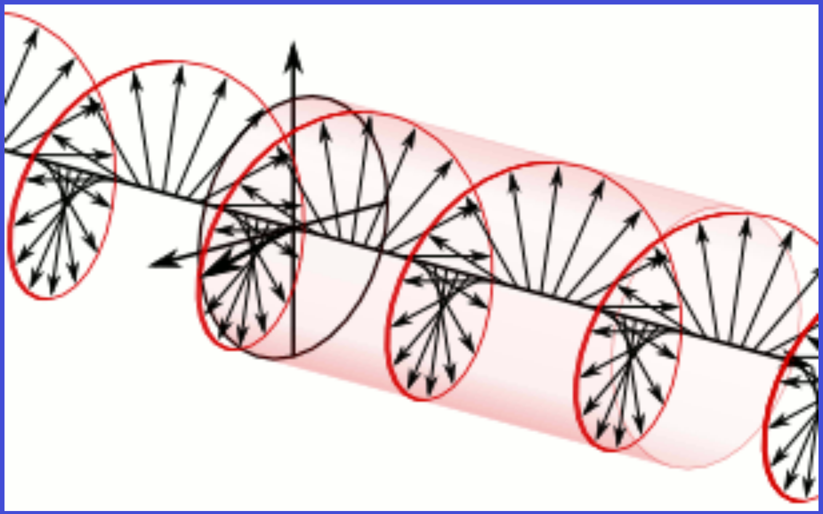


An elementary particle can rotate.
But with a minimal amount of rotation.

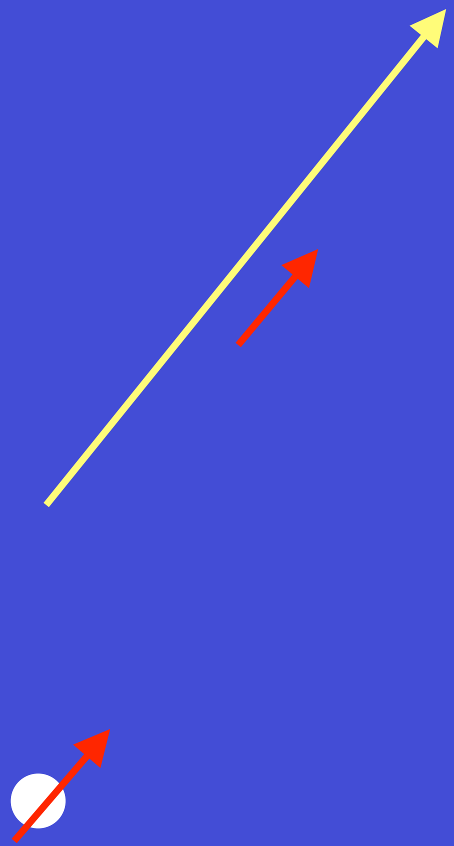
Circularly polarized electromagnetic waves



Direction of motion



Electron



The electron has spin too

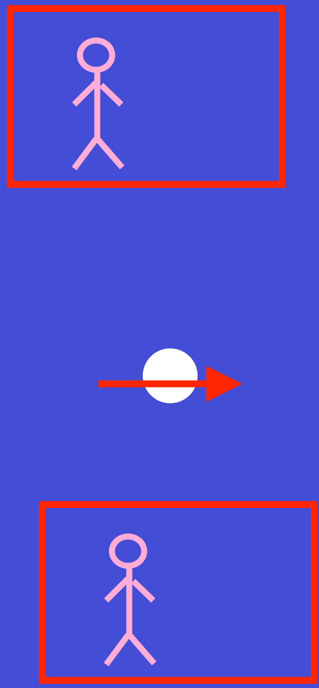
Surprise!

- Weak interactions depend on the spin of the electron.
- They are stronger when the spin is antiparallel to the direction of motion.

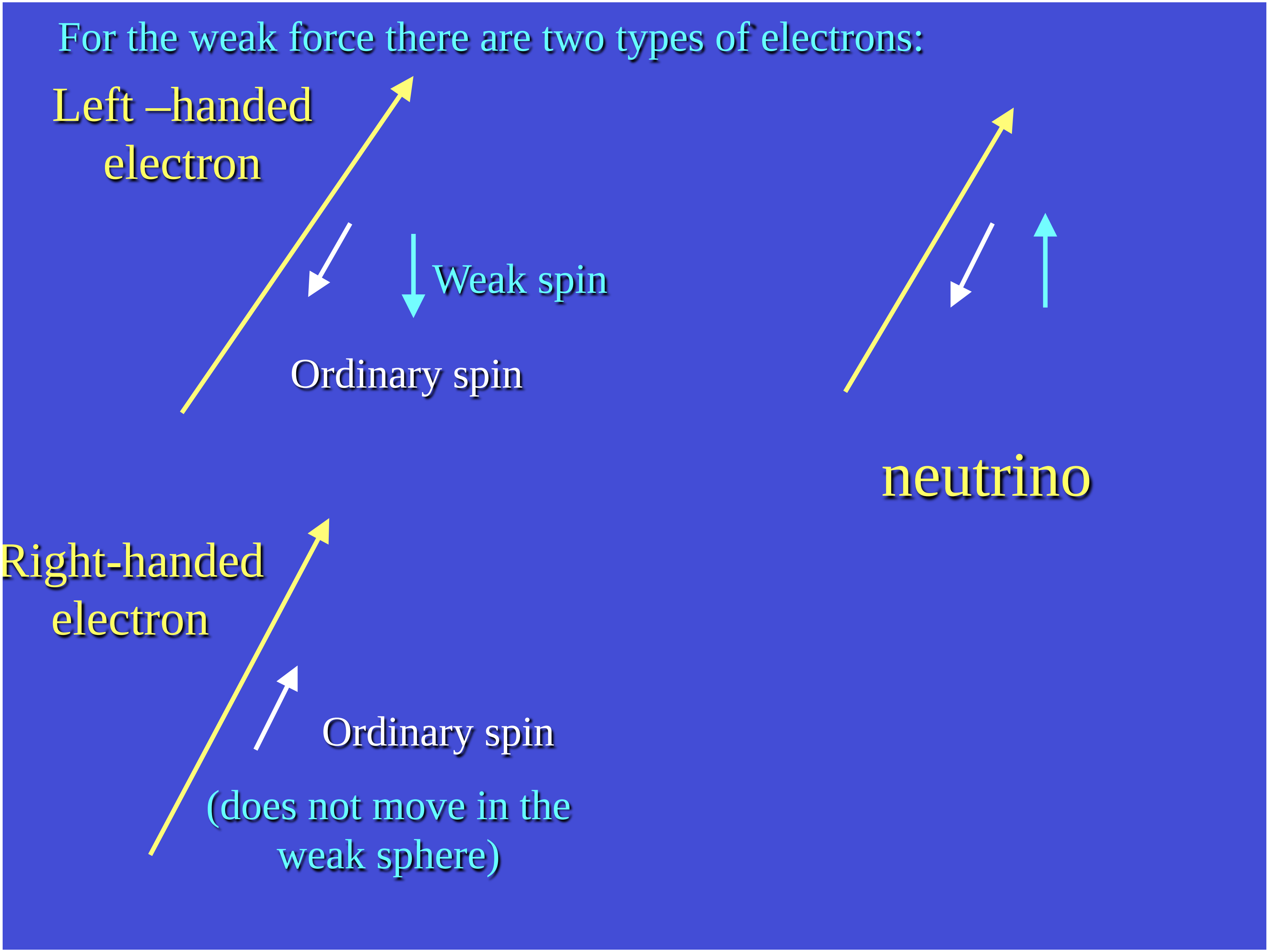
- For massless particles we can distinguish particles depending on whether the spin is in the direction of motion or in the opposite direction.

- For massive particles this is not possible.

Electron at rest ?



- Let us first pretend that the electron is massless.


For the weak force there are two types of electrons:
Left –handed electron
Weak spin
Ordinary spin
neutrino
Right-handed electron
Ordinary spin
(does not move in the weak sphere)

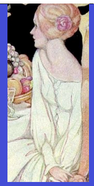
Rotation is reversed when we look at it in a mirror

Lee , Yang 1956

neutrino

Left handed

The laws of nature are not symmetric under a mirror reflection



(with no Higgs field)

Forces	particles
Electromagnetism	Left-handed electron and neutrino
Weak	Right-handed electron
Strong	Quarks (left and right handed)

Very simple

All particles are massless

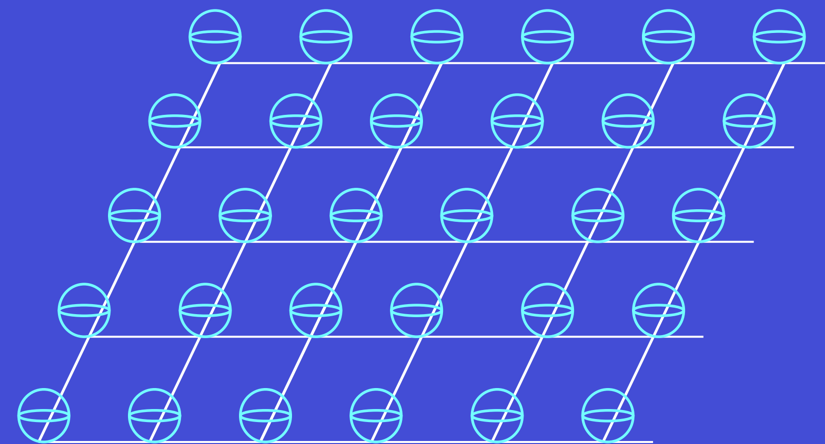
Based on symmetries.

The strength of interactions is fairly similar

<u>Old</u>

Celestial spheres

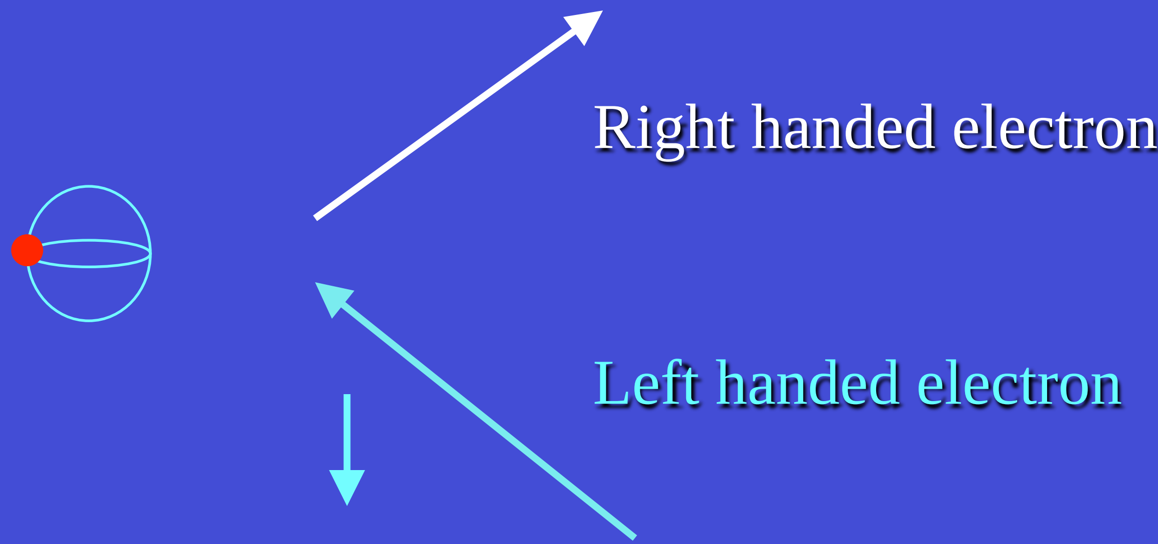
<u>New</u>



One sphere at each point in space

The electron mass

- Due to its interaction with the Higgs field



The left and right handed electrons can interact with the Higgs field.
This interaction gives the electron a mass.

(Mass of neutrinos → Interactions of the neutrino with the anti-neutrino and the Higgs field)

Glashow, Salam, Weinberg 60's

Why ``electro-weak'' ?

- We have the symmetries of the circle plus the symmetries of the sphere.
- The symmetry of electromagnetism is a combination of a rotation on a circle and a rotation on the sphere.
- This is why the neutrino and the electron have different charges.

The Higgs Boson

The mechanism we have just discussed explains the masses of all particles, but does not yet predict the existence of a new one.

In the monetary analogy, the Higgs boson would arise when we have two things we can buy in each country, say Gold and Silver.

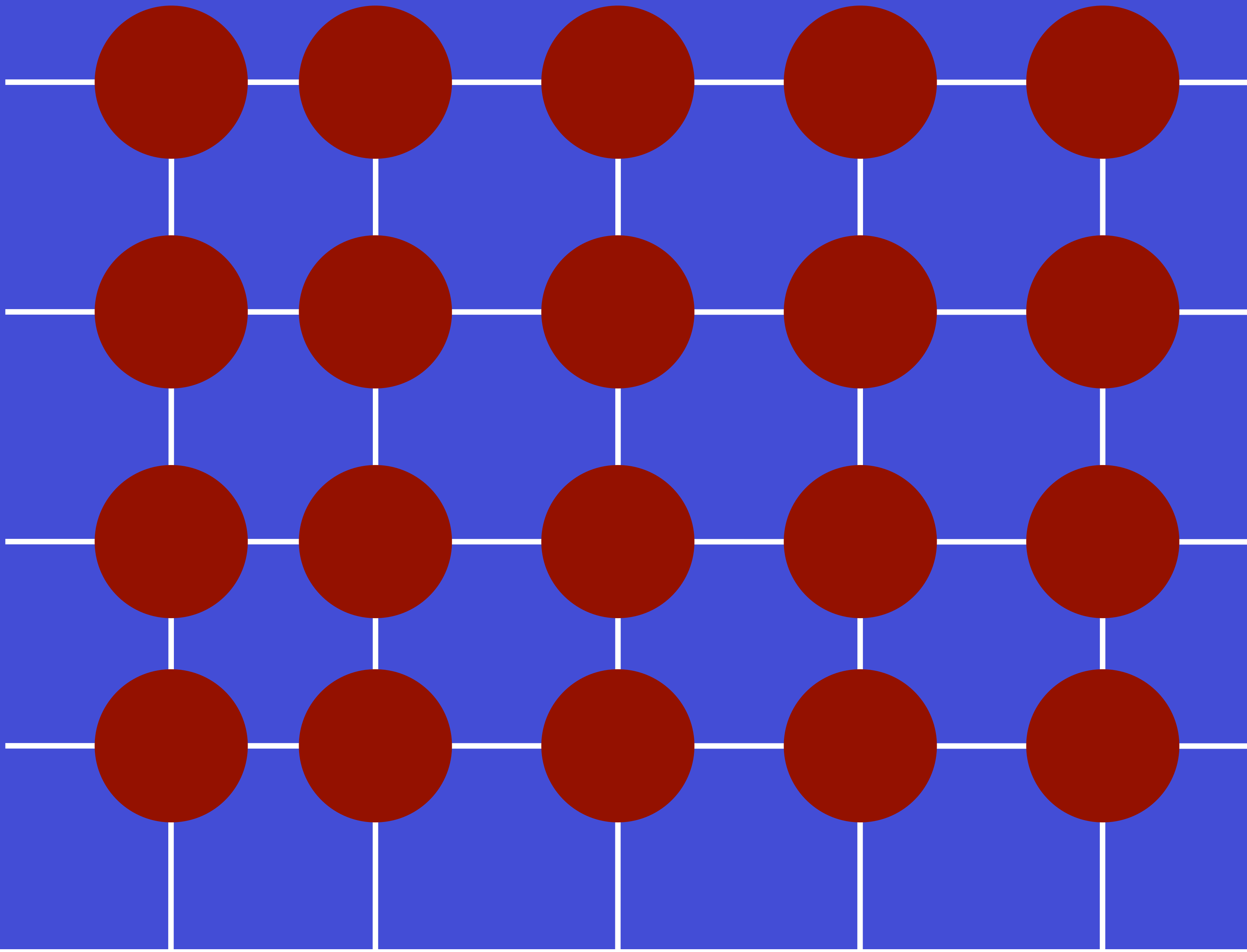
The relative price of Gold and Silver are the Higgs boson.

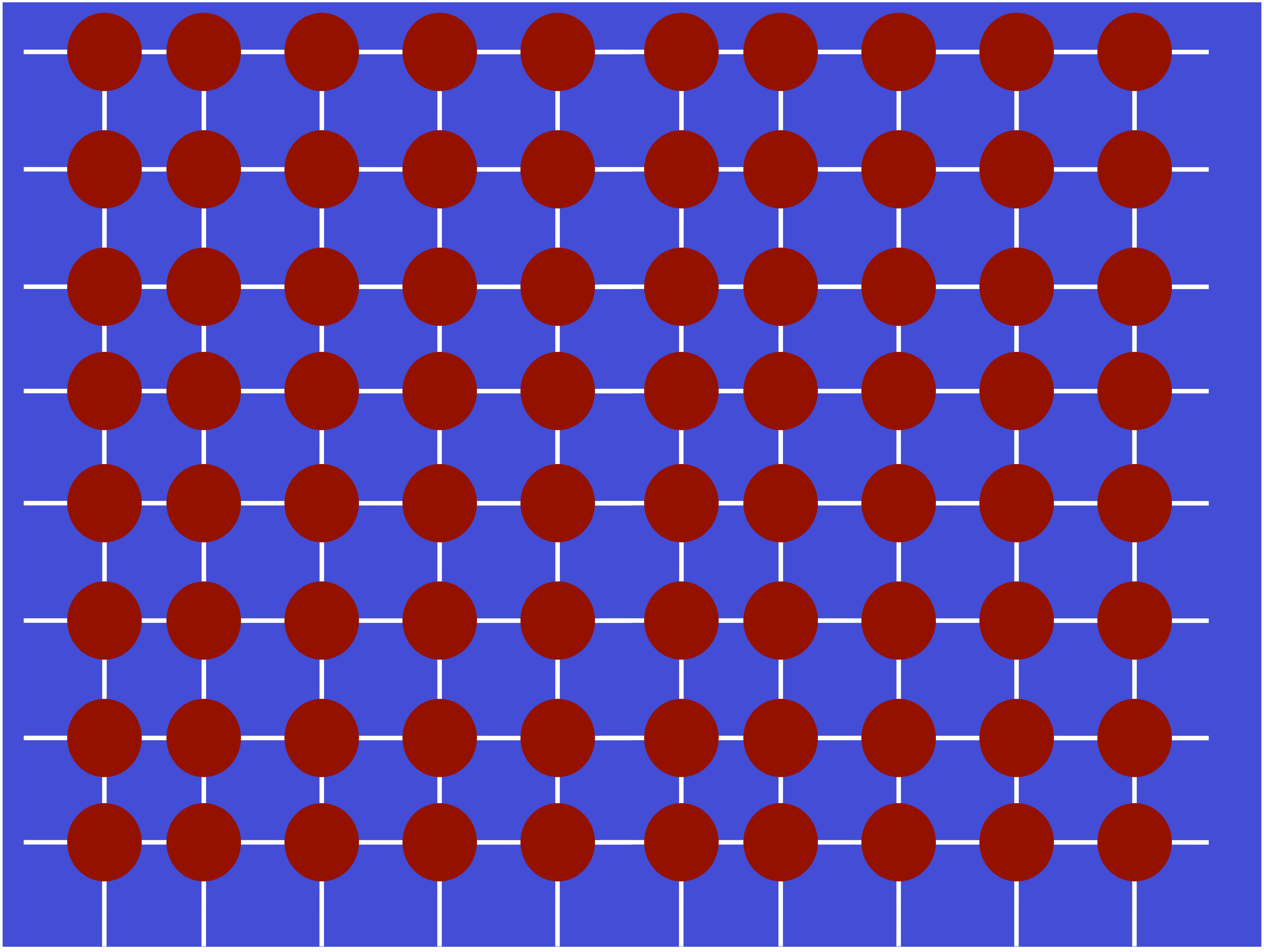
This ratio leads to a new massive particle.

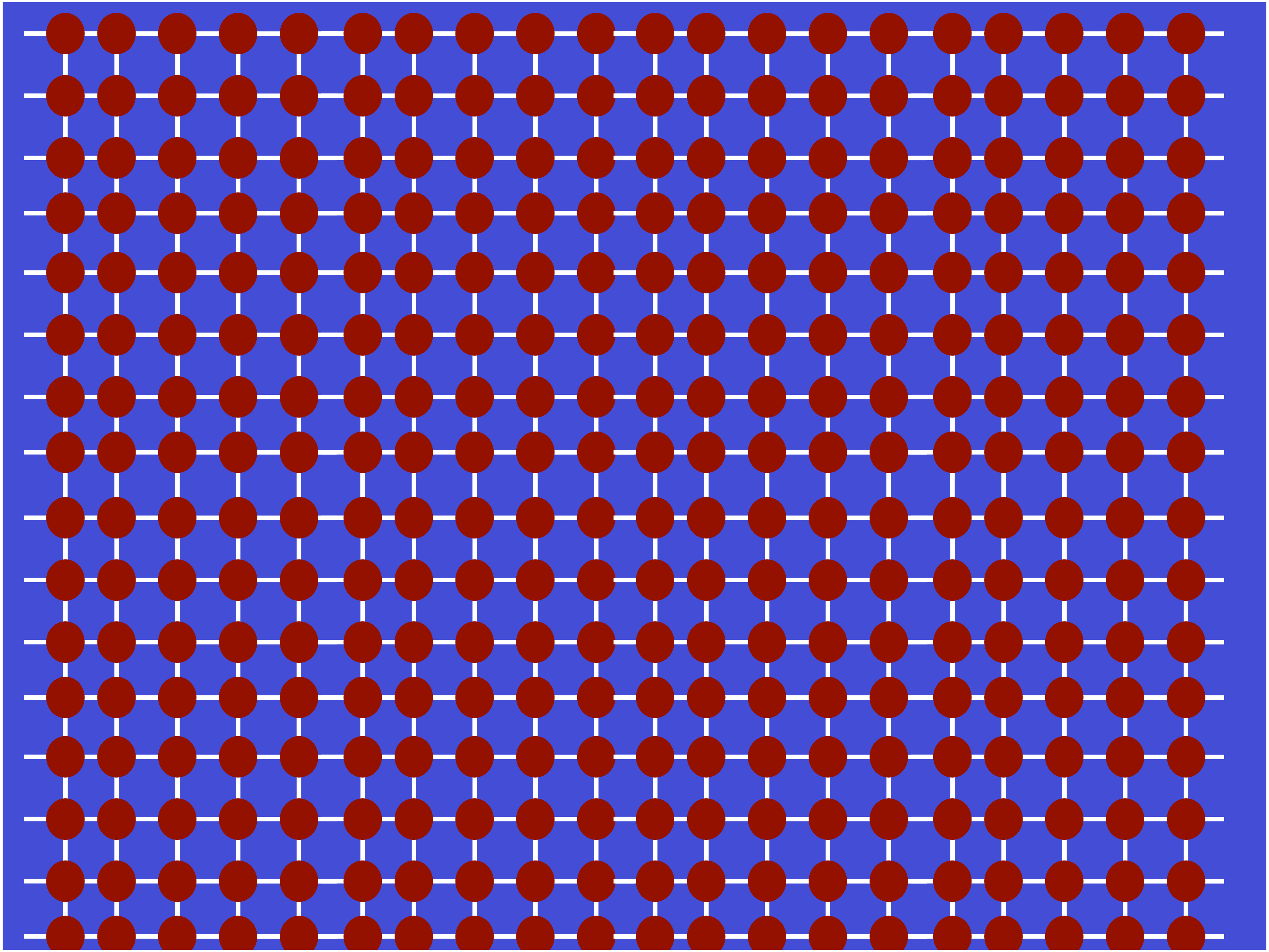
Why do we need at least two?

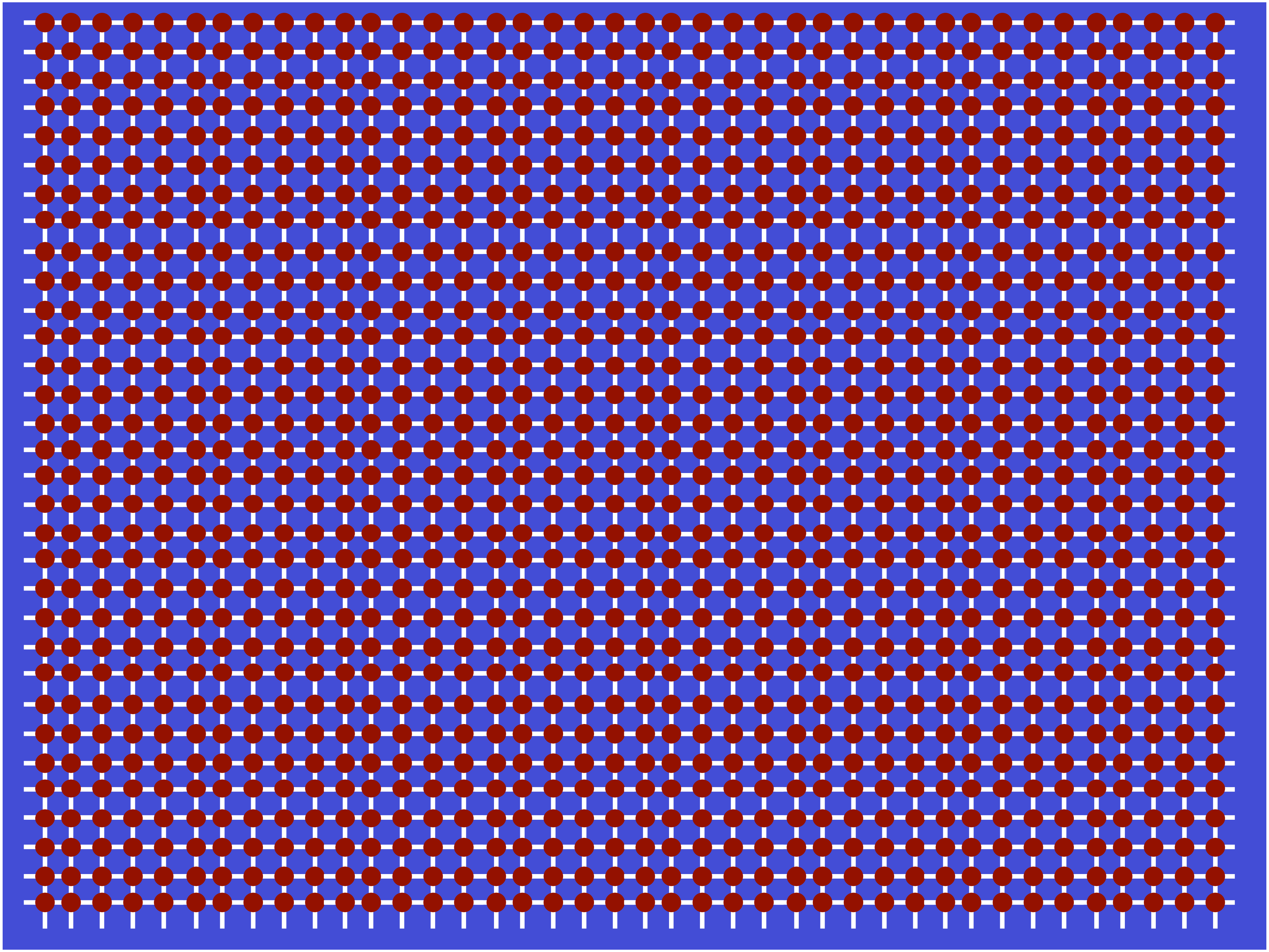
- It is a subtle reason related to the possibility of taking the limit when the distances between countries become very small, while retaining interesting interactions at long distances.

Continuum limit: In physics all of this is happening at very, very short distances









With no extra particles →

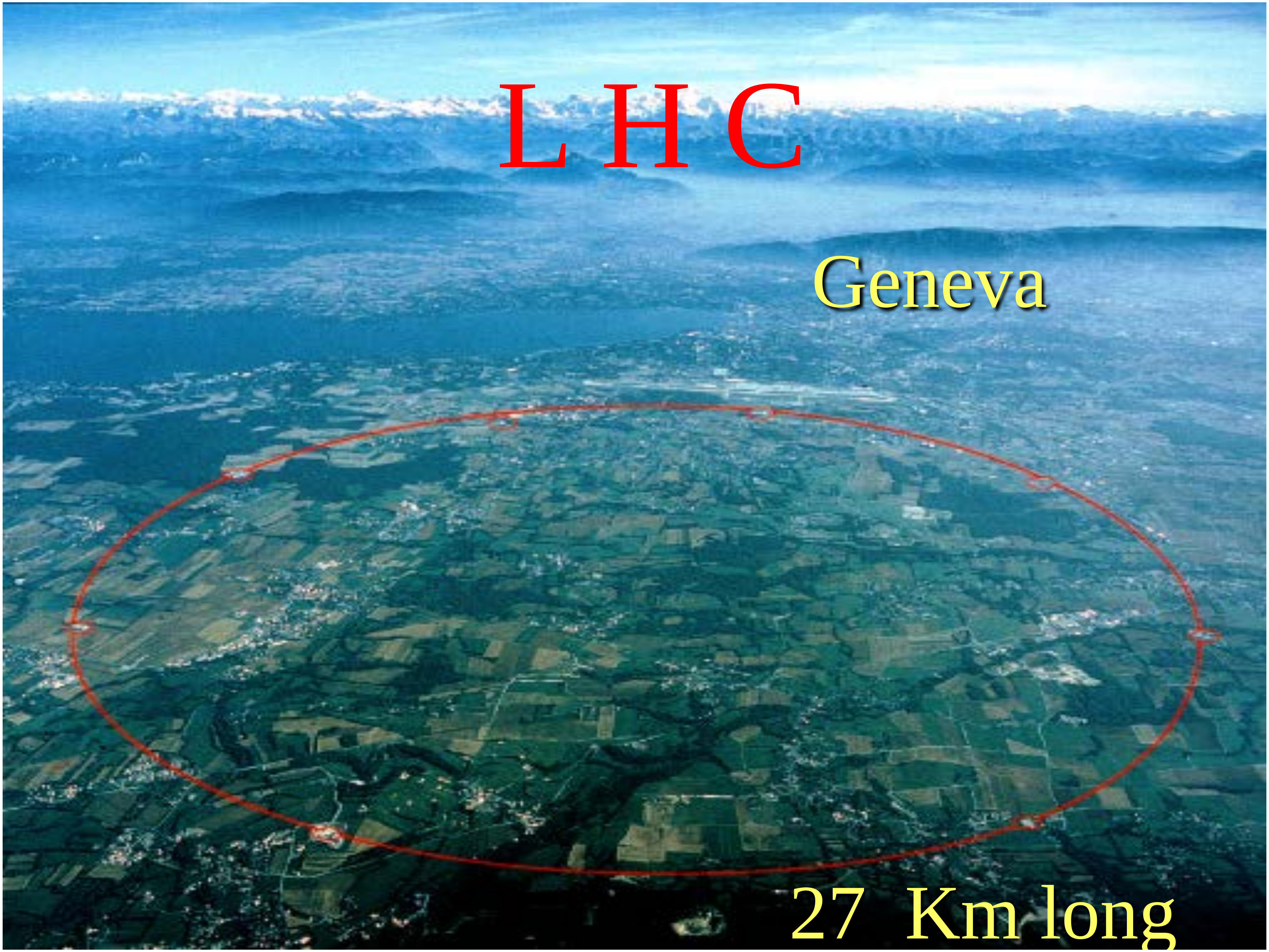
masses of the W and Z would go to infinity in this limit

Before July 2012

- We new that there HAD to be new particles with masses below 1,000 Gev. (proton ~ 1 Gev)
- The Higgs boson was the simplest possibility.
- There were many others, thanks to the prolific imagination of theorists…
- July 2012, 1 particle, mass = 125 Gev (proton ~ 1 Gev)

How are we exploring the origin of mass for the weak partícles ?

- Collide particles at high energies to produce the Higgs boson.


L H C
Geneva
27 Km long

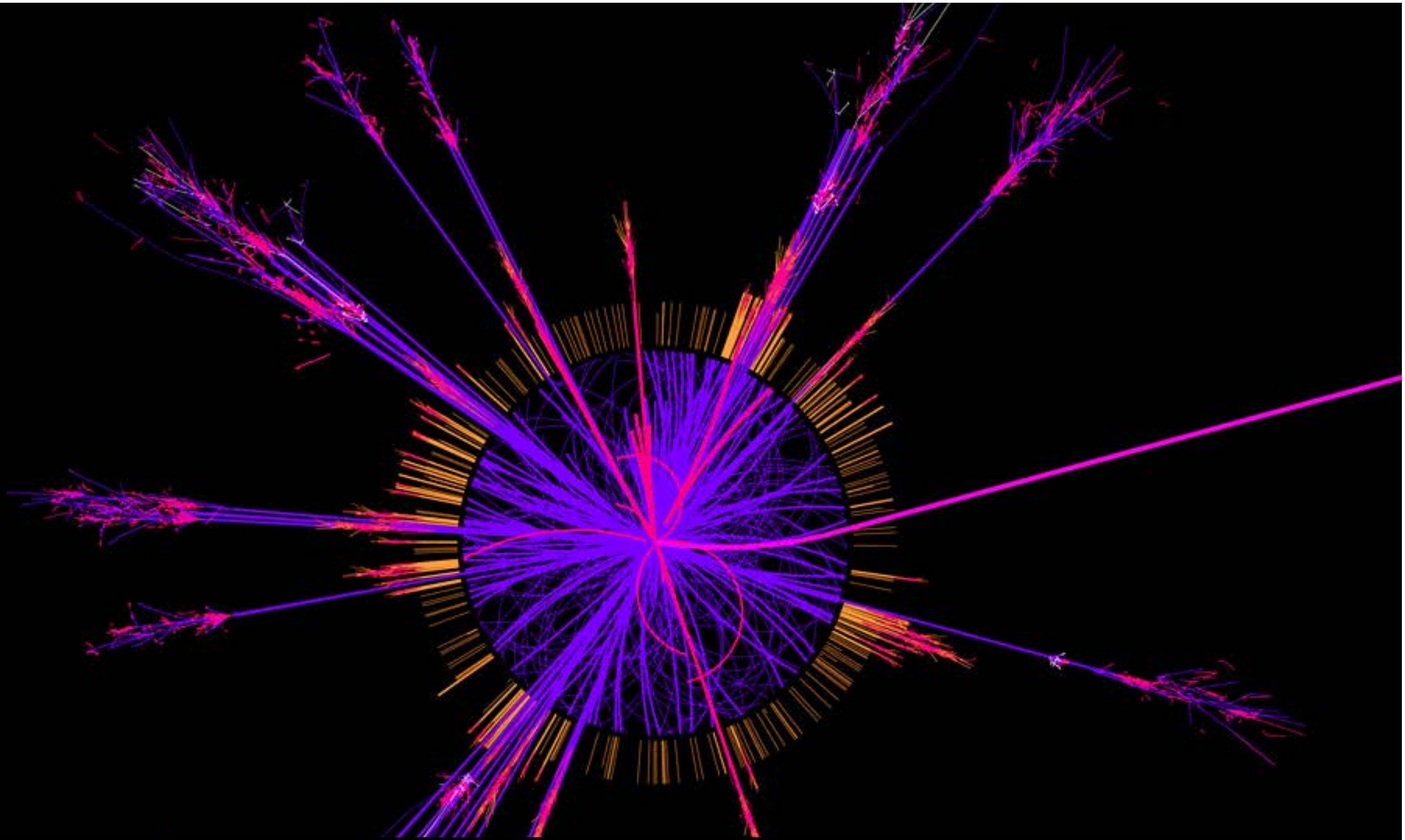
Small electron collider

TV vs LHC

Energy given to the particles

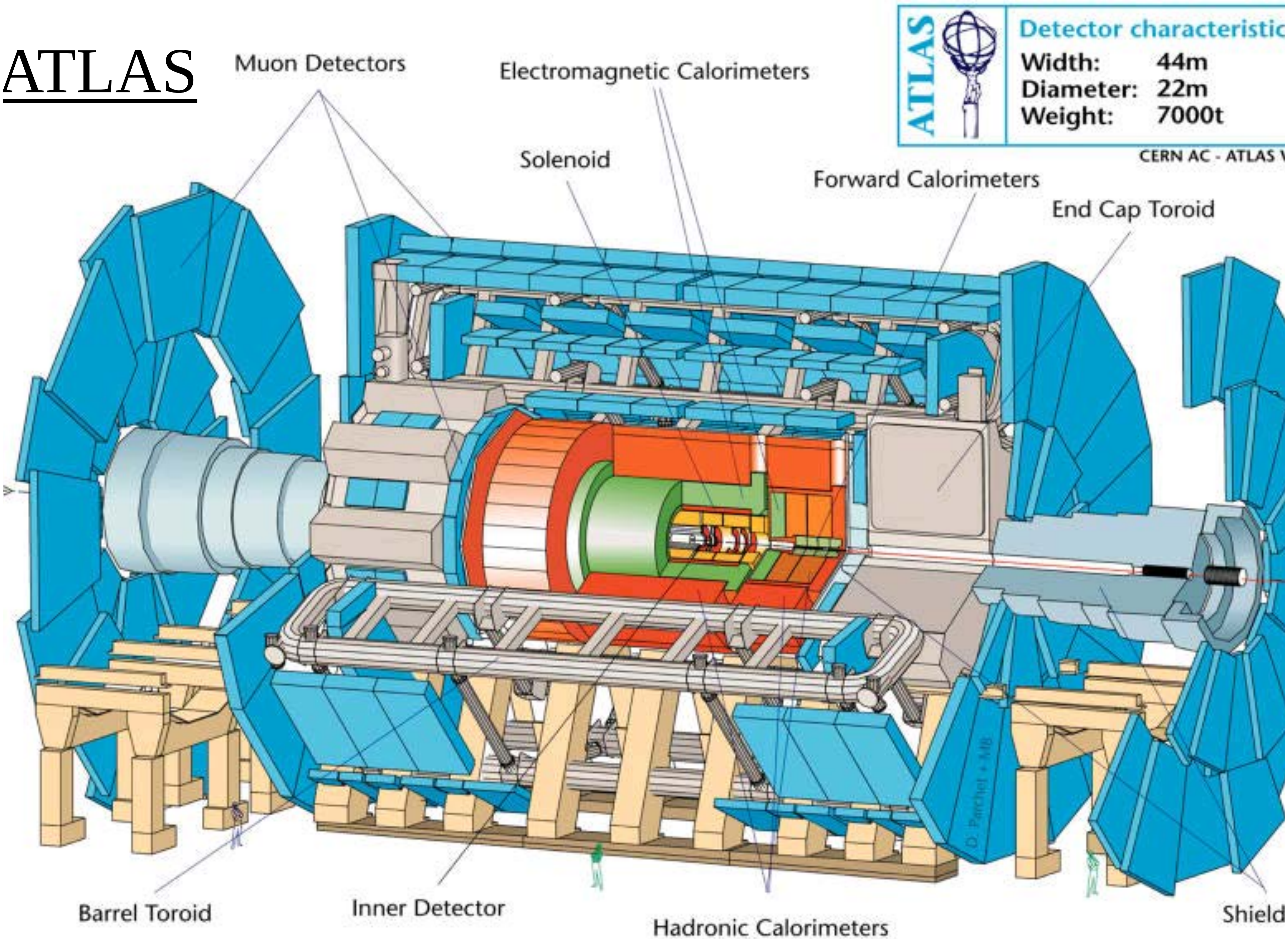
TV:	8,000	Volts
LHC	8,000,000,000,000	Volts

The LHC gives them a billion times more energy than a TV.

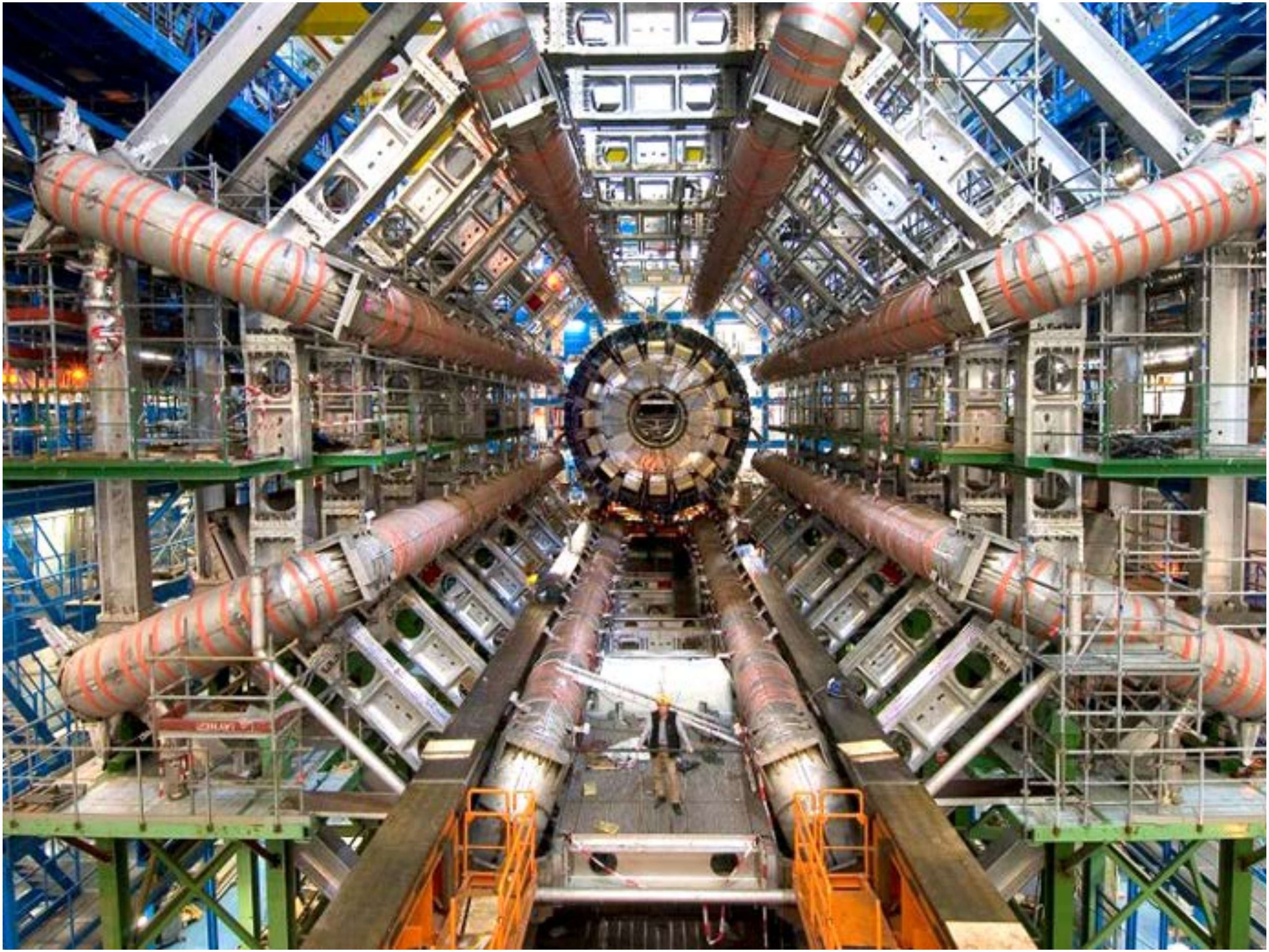


There is a lot of energy, which can produce many particles.
This shower of particles is determined by these simple gauge symmetries.

ATLAS



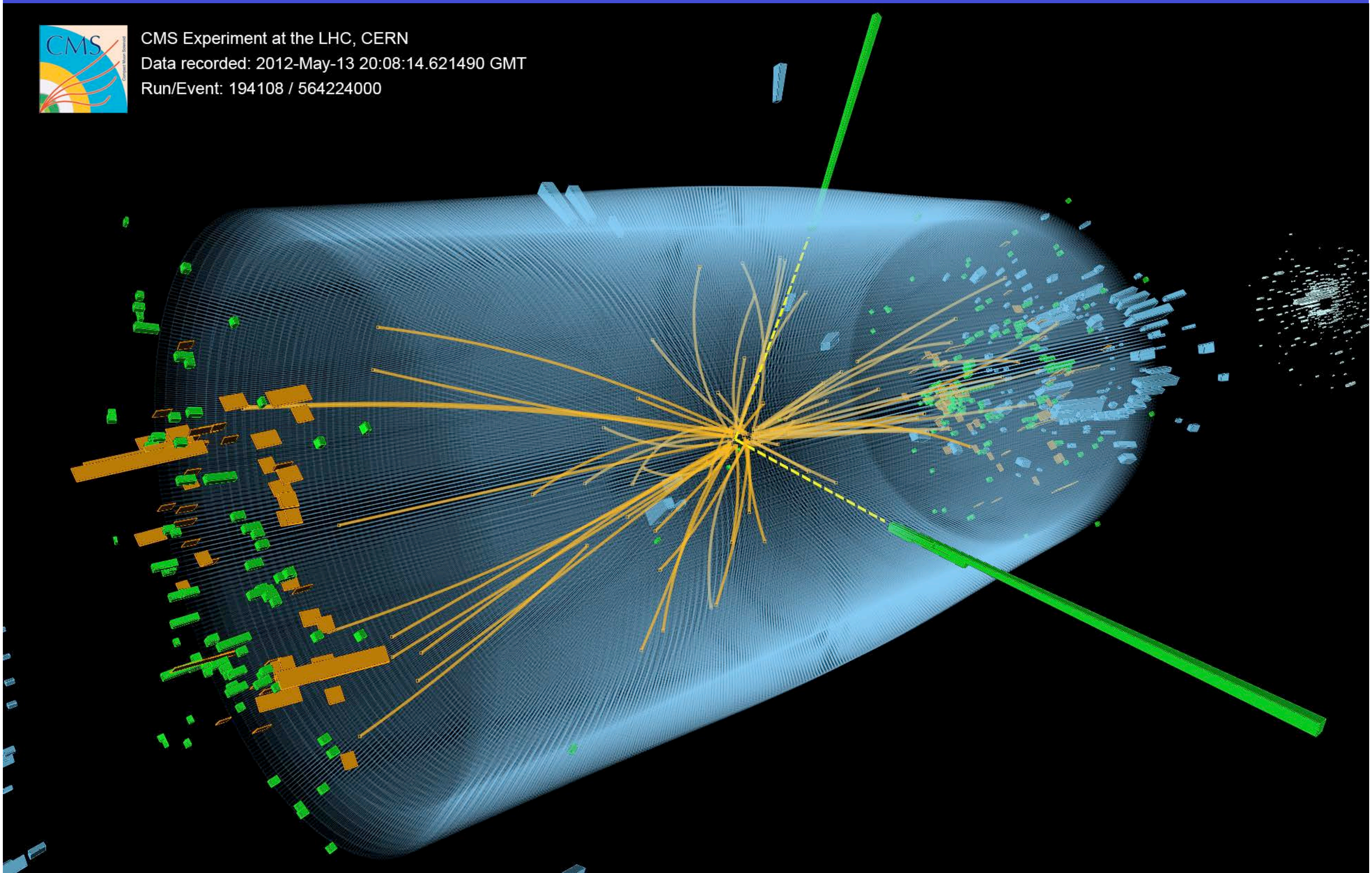
Muon Detectors
Electromagnetic Calorimeters
Detector characteristic
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shield

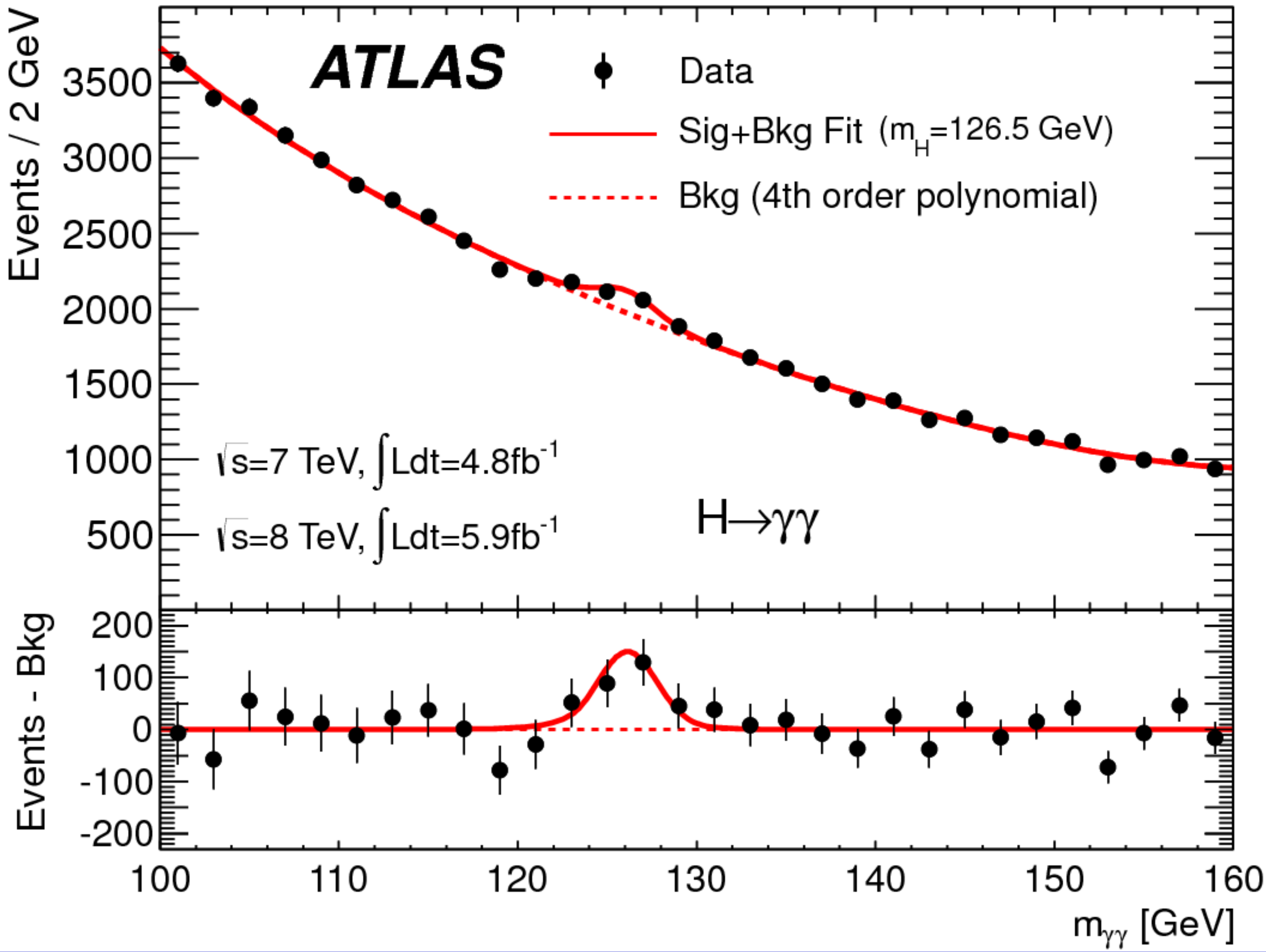


Protons collide and produce many particles

Very rarely they produce Higgs bosons.

These Higgs bosons decay very quickly into other known particles leaving a special imprint


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb^-1
√s=8 TeV, ∫Ldt=5.9fb^-1
H→γγ
Events / 2 GeV
3500
3000
2500
2000
1500
1000
500
Events - Bkg
200
100
0
-100
-200
100
110
120
130
140
150
160
m_γγ [GeV]

What is it useful for?

I do not know of any possible technological application

It is helping us understand what happens in nature at very short distances. We are finally understanding how the electro-weak force works at short distances.

Why is the Higgs Ugly?

- Introduces lots of new parameters in the Standard Model.
- It is not based on any symmetry.
- Why is its mass so much smaller than the mass scale of gravity?

And now what?

- There are reasons to think that there will be new particles.
- Theoretical: Higgs is Ugly.
- Experimental: Dark Matter.

Dark Matter

- There is more matter than what we see. This other matter is different from ours.

The particles of dark matter might or might not be produced at the LHC.

Other experiments are looking for dark matter in other ways.

We will probably have more exciting experimental discoveries in particle physics in the next few years.

And we will understand how:

… they lived happily ever after

A written version can be found in:

http://arxiv.org/abs/1410.6753