Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

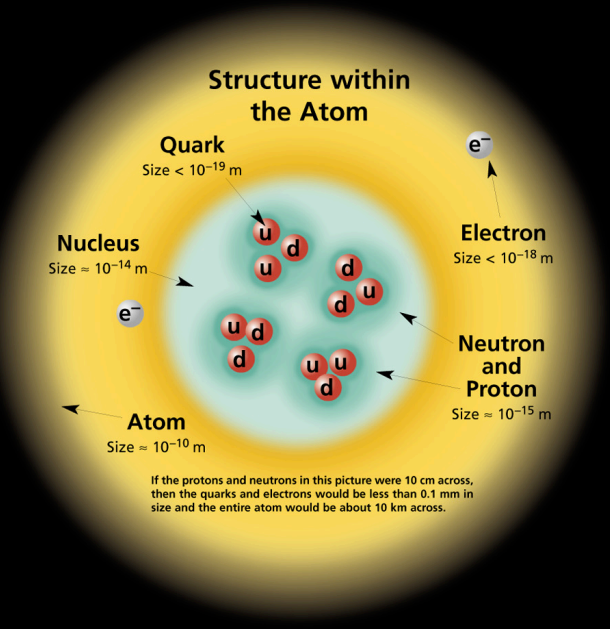
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

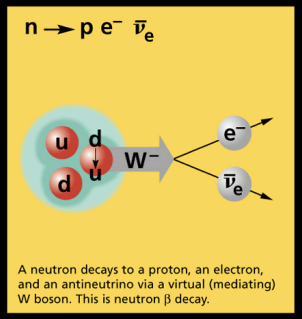
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

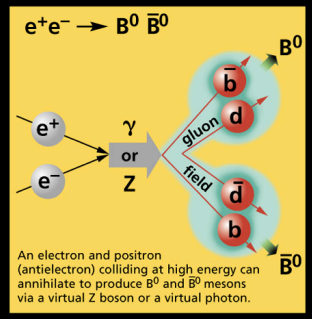
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

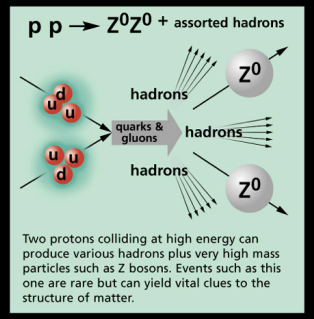
Figures
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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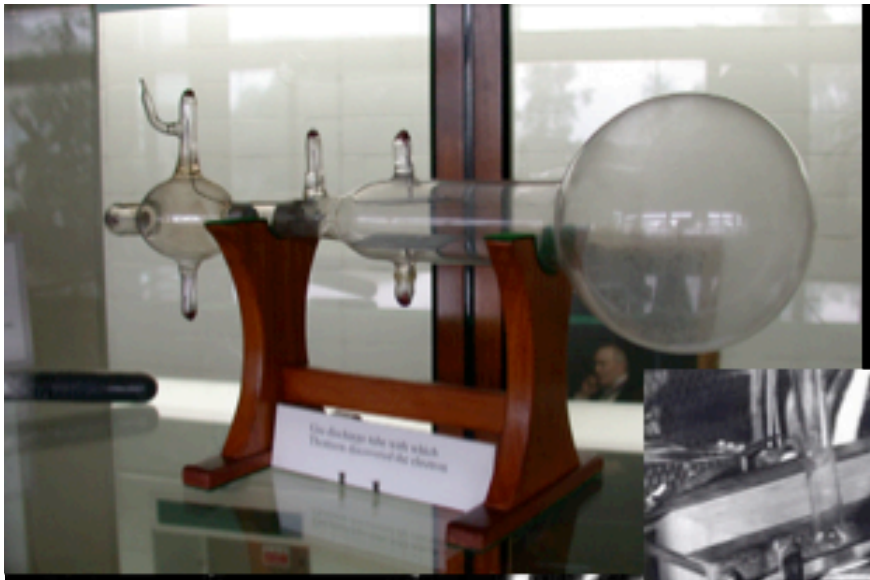
BURLE INDUSTRIES, INC.

Algumas perguntas da *física*

- Como o Universo surgiu? Como ele vai evoluir?
- Por que há muito mais matéria do que antimatéria no Universo?
- Porque temos massa?
- Existem mais de três dimensões espaciais?
- Quais são os elementos básicos que formam a matéria?

Aceleradores de partículas

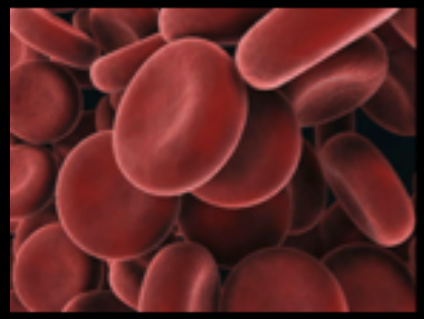


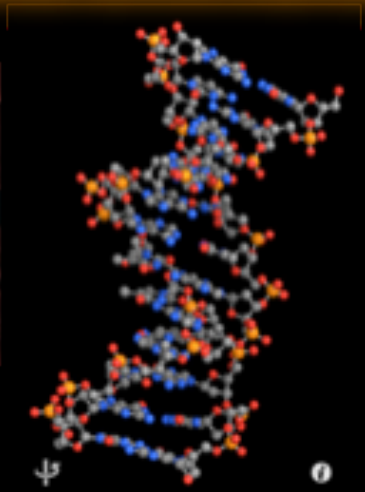
Aceleradores são microscópios

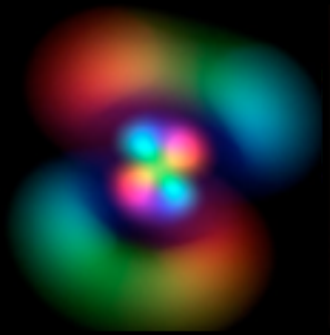
Relação de De Boglie

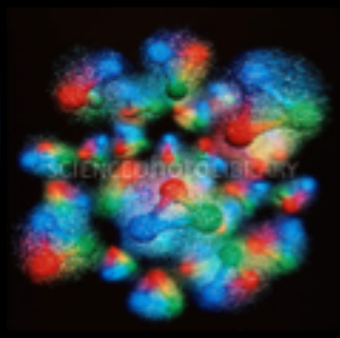
$$\lambda = \frac{h}{p}$$

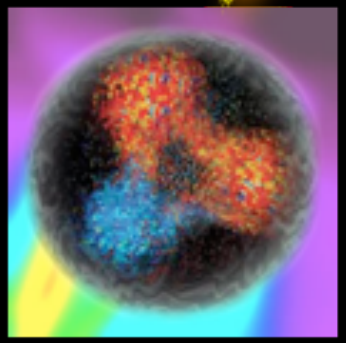
Energia







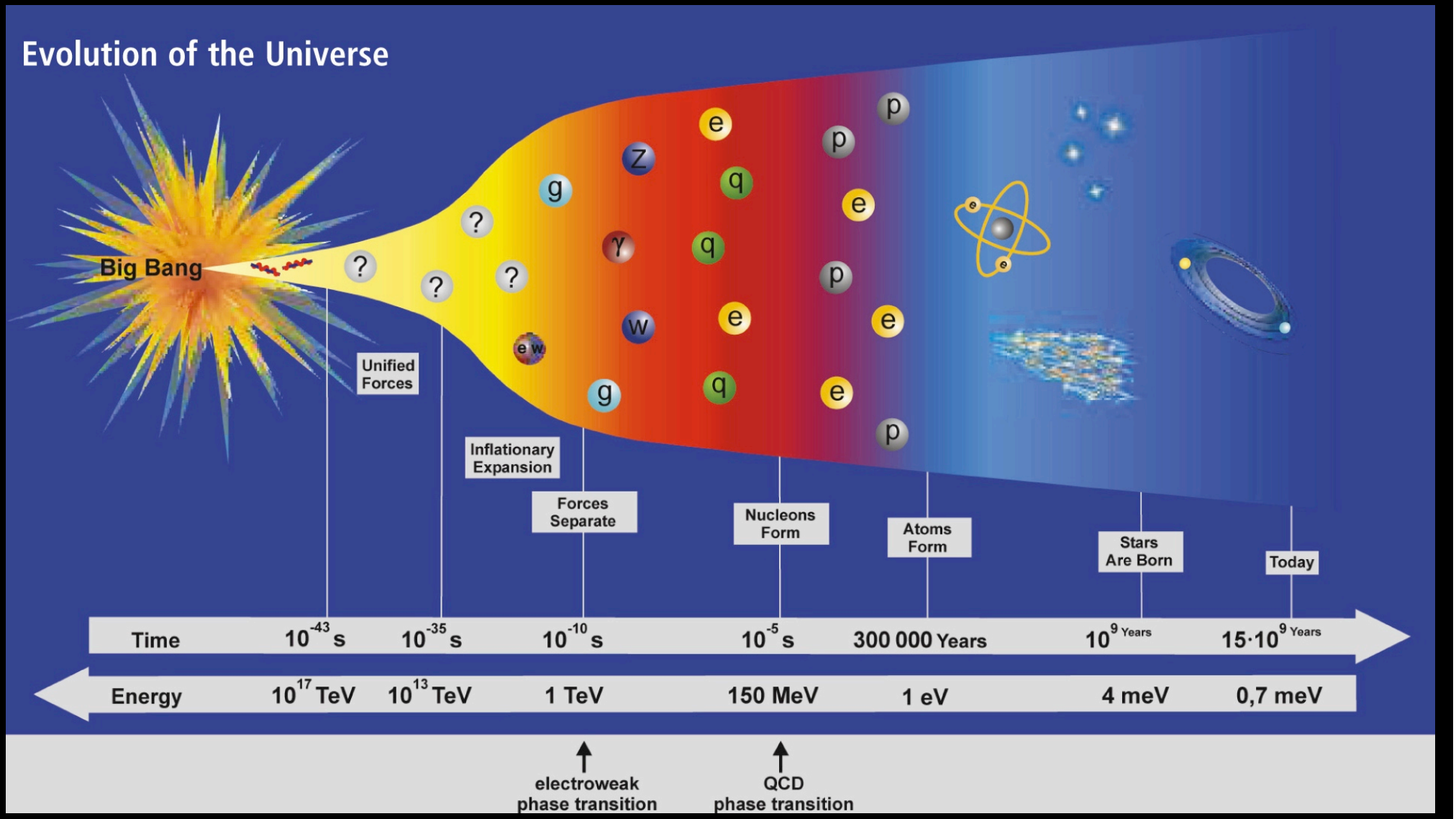




átomos núcleos quarks

Tamanho

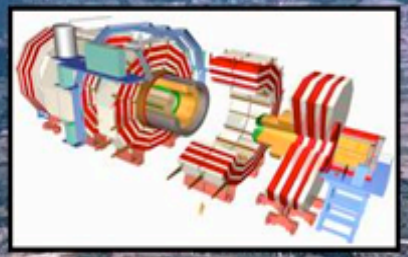
Aceleradores são máquinas do tempo

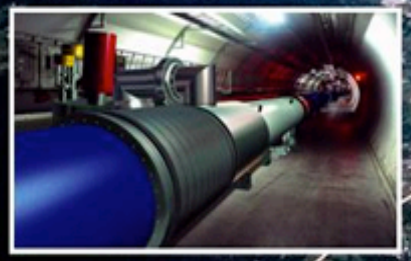
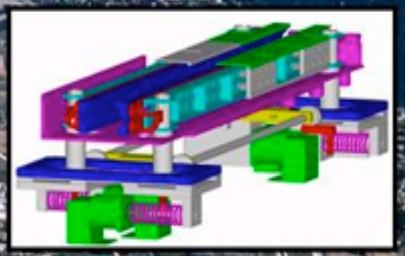
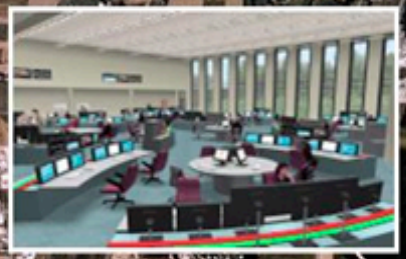


1 eV = energia de um elétron acelerado por uma tensão de 1 V = 1,6 x 10^{-19} J

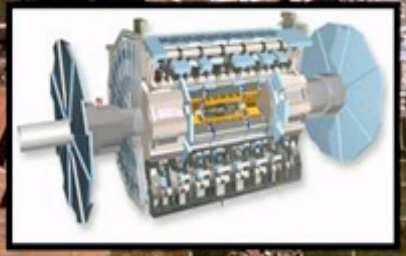
1 MeV = 10^6 eV 1 TeV = 10^{12} eV = 1,6 x 10^{-6} J

O LHC

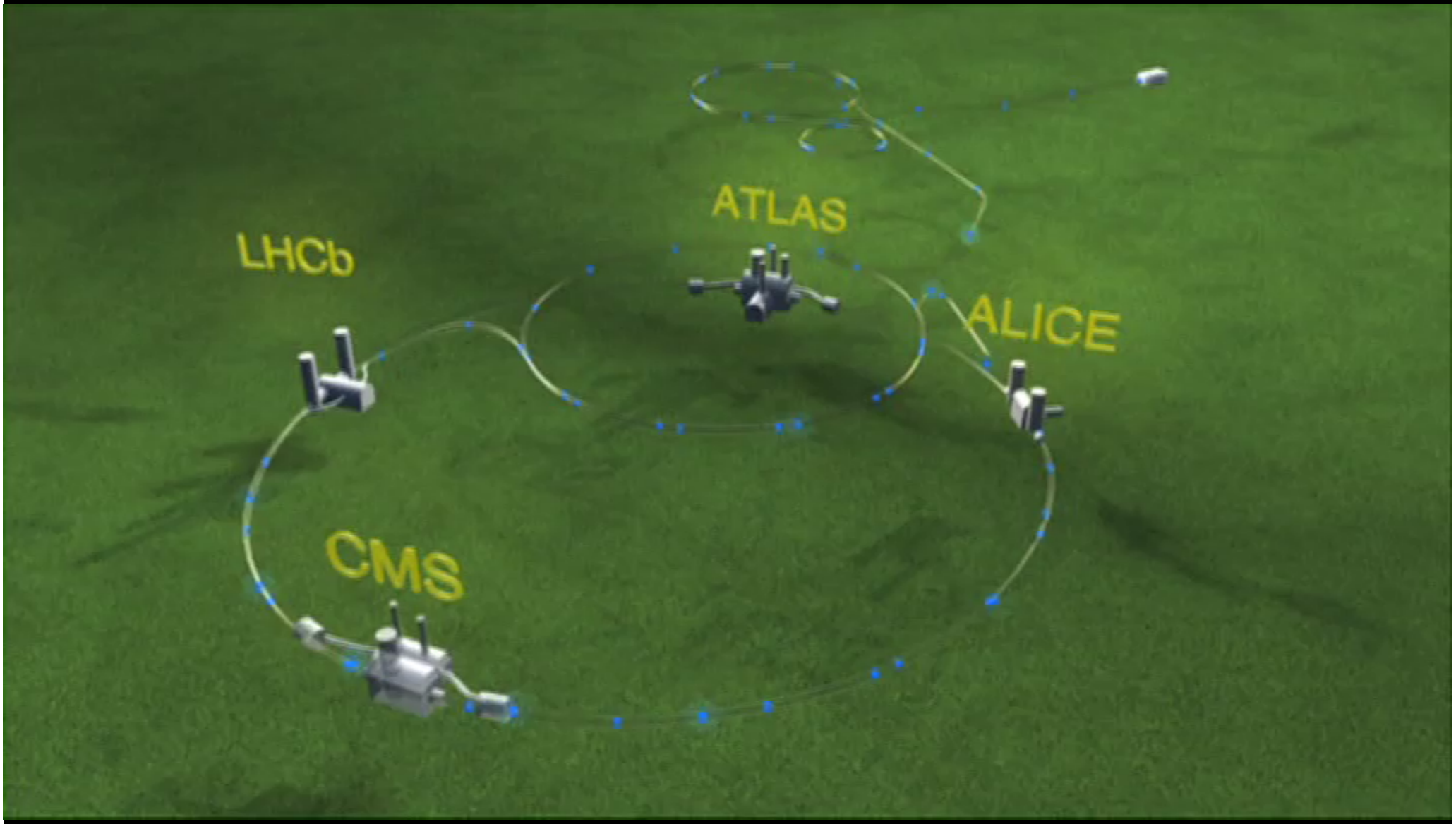






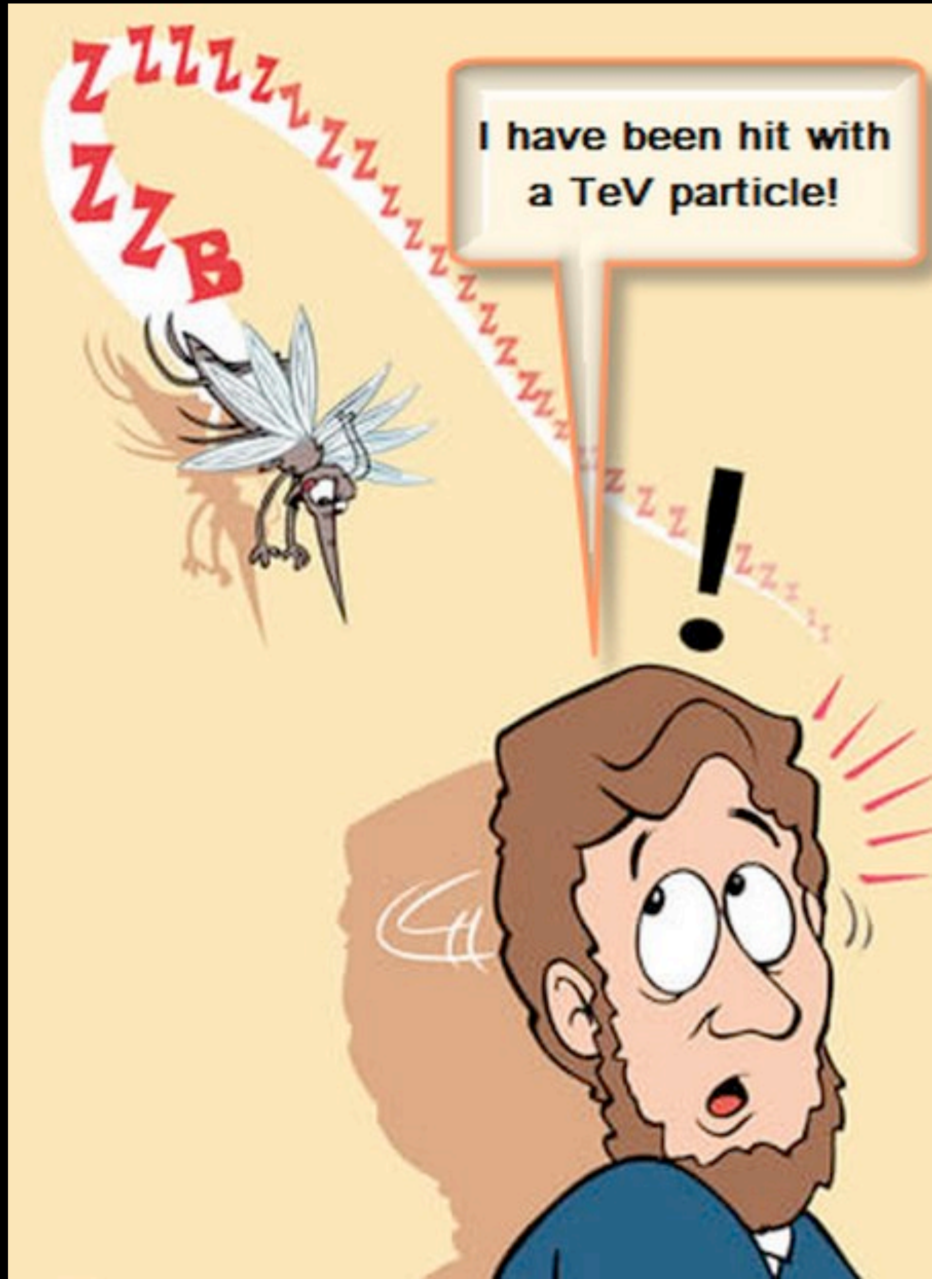
Os experimentos do LHC



Alguns fatos interessantes

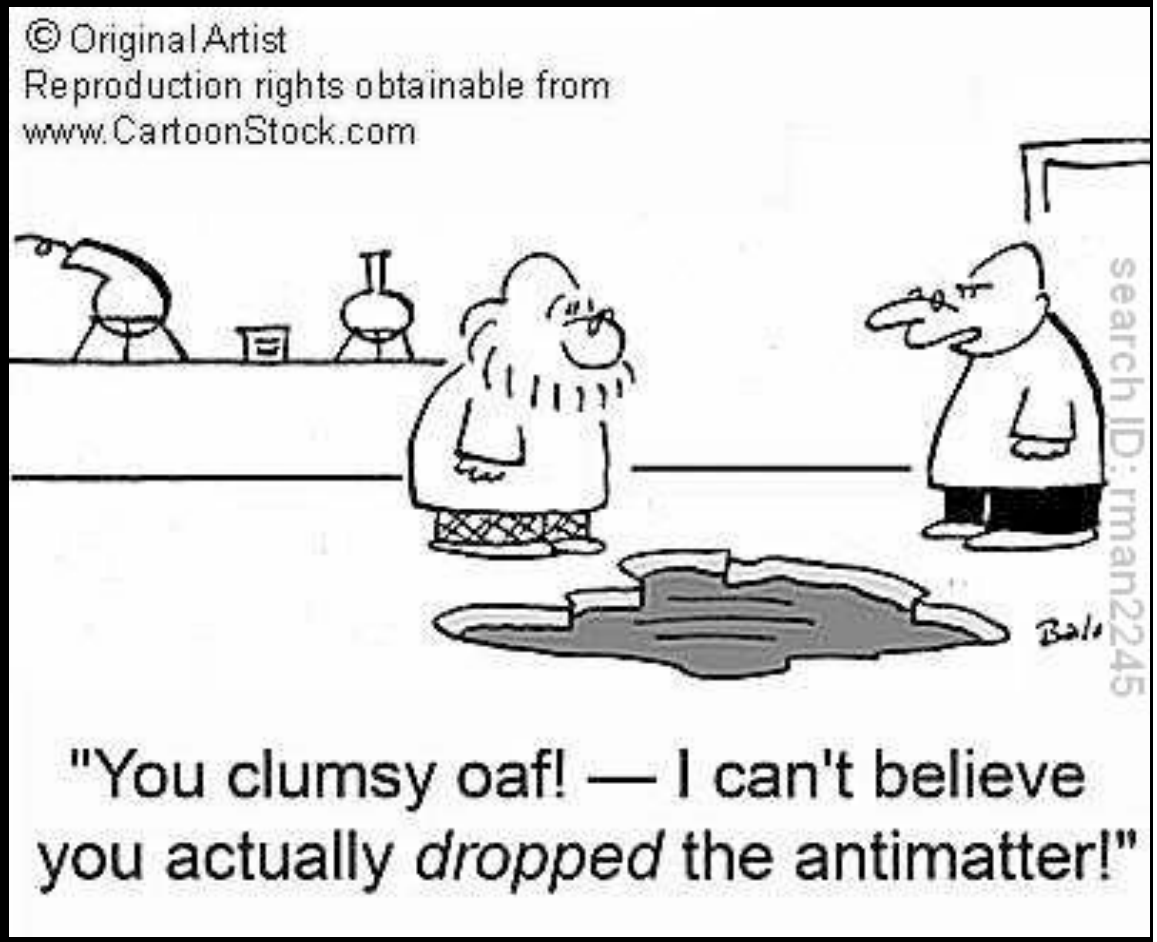
- 27 km de circunferência
  - 99.9999991% c
  - 11 mil voltas por segundo

- Energia 14 TeV
  - 1 TeV – energia de um mosquito voando
  - 1 kg de tijolo caindo de 1 metro de altura tem 4 milhões de TeV



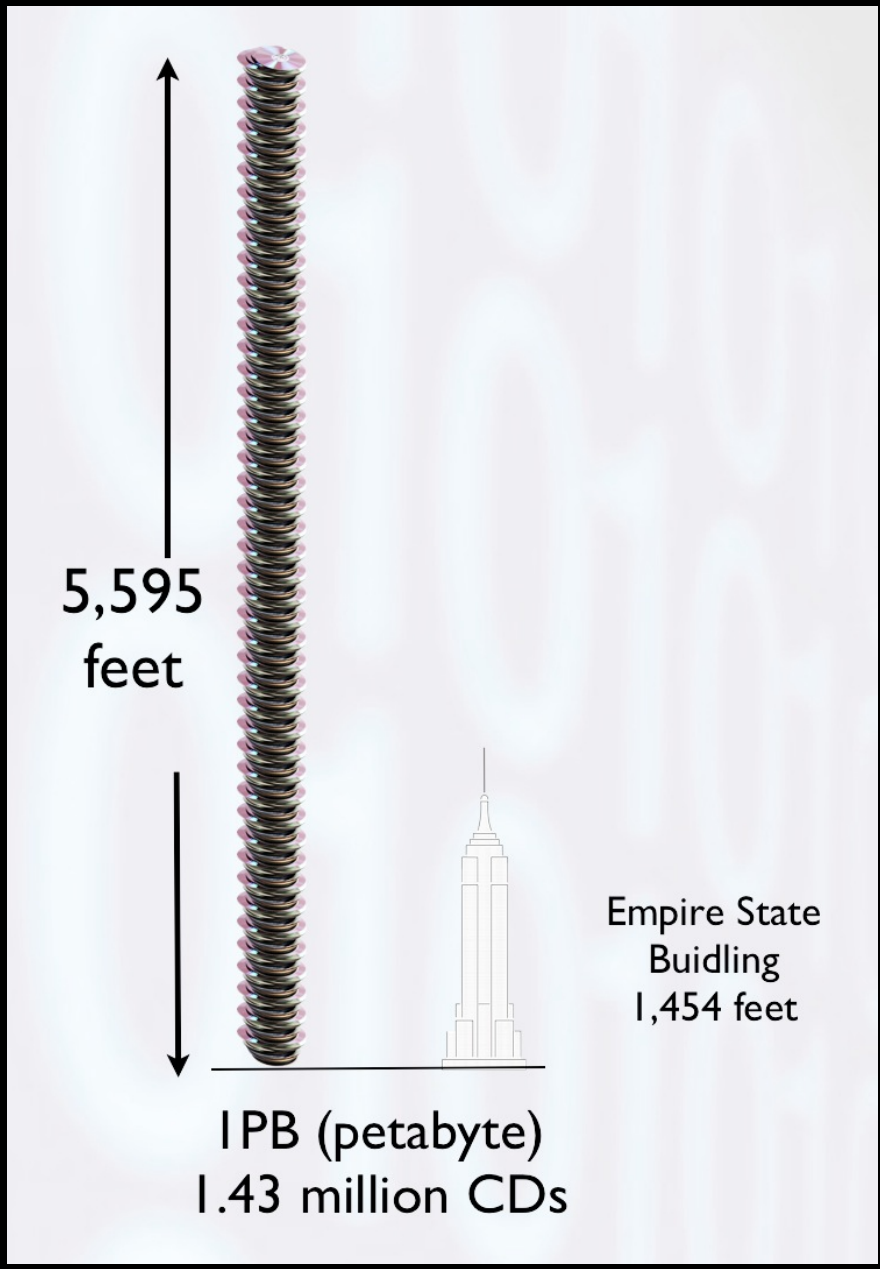
Alguns fatos interessantes

- quente e frio
  - LHC funciona a -271ºC
  - Em uma colisão Pb+Pb produz-se matéria a 1000000000000º C (1000000 x interior do sol)
- Tempo para produzir 1 mg de antimatéria (1/1000 saquinho de sal) > 1 bilhão anos

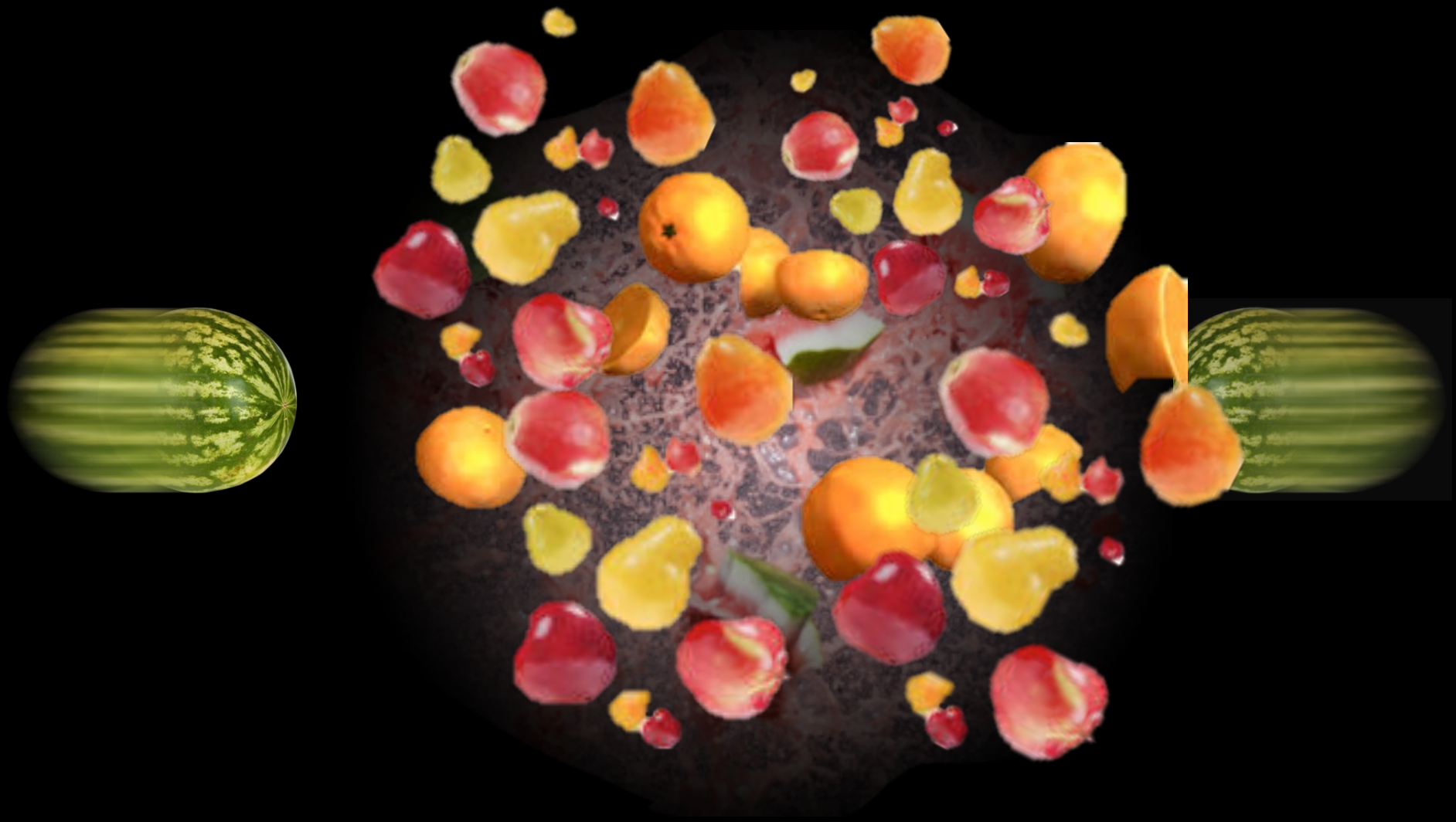


Alguns fatos interessantes

- 1 TB/s de dados (10 mil enciclopédias britânicas por segundo)
  - ~ 10 PB/ano
- 8 bilhões US$ para ser construído em 20 anos
  - Copa do Brasil
    - ~ 20 bilhões US$
  - Guerra no Oriente Médio
    - ~ 2 trilhões US$

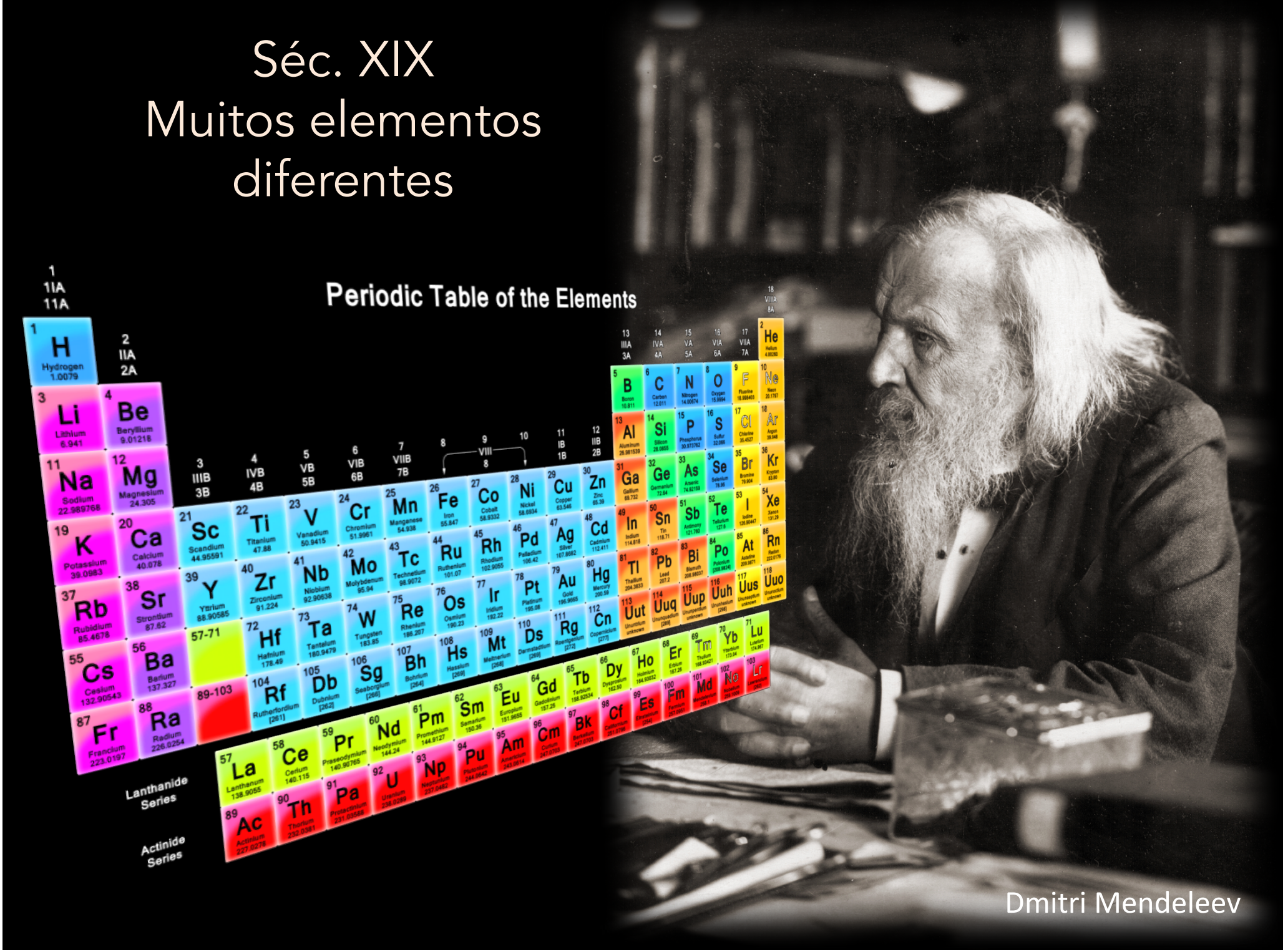


Colisões em aceleradores não são intuitivas



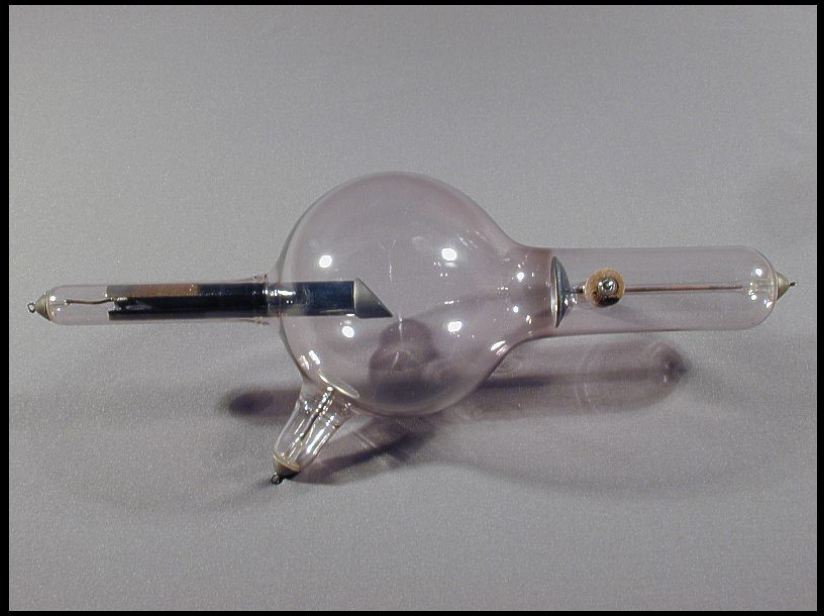
Por que saem laranjas de melancias?

Séc. XIX
Muitos elementos diferentes



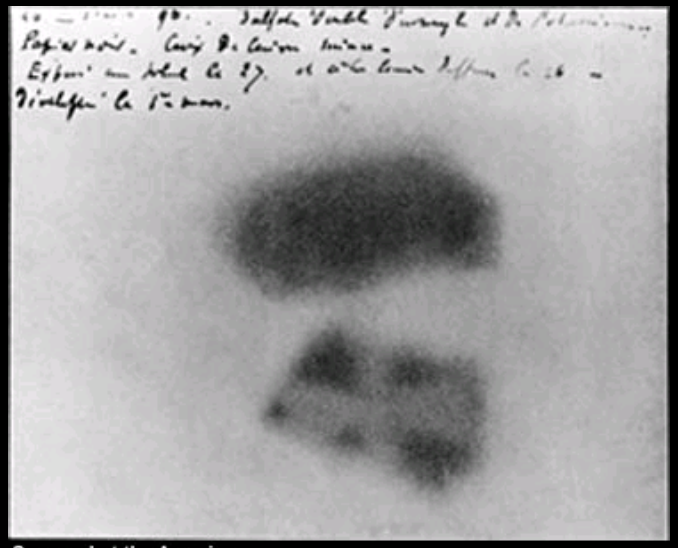
A estrutura básica da matéria

- 1895 – Röntgen descobre o raio-X

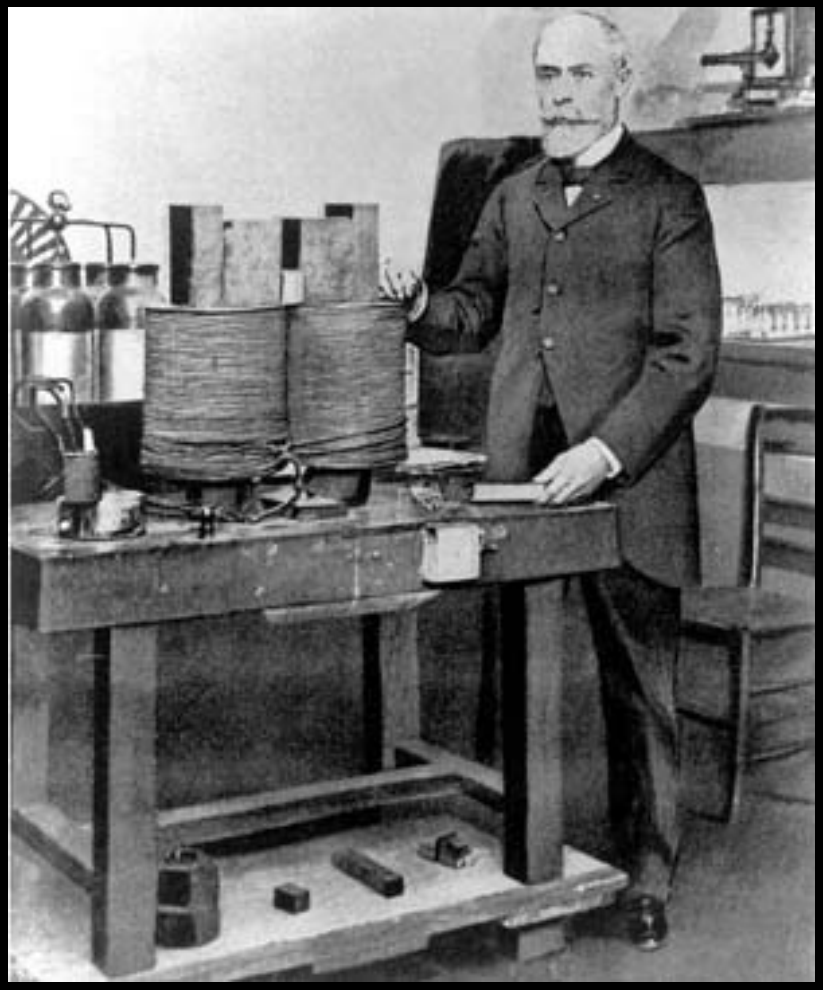


Estudos da radiação

- 1896 – Becquerel
  - Materiais que emitem luz naturalmente
  - Alguns materiais marcam filmes fotográficos, mesmo no escuro

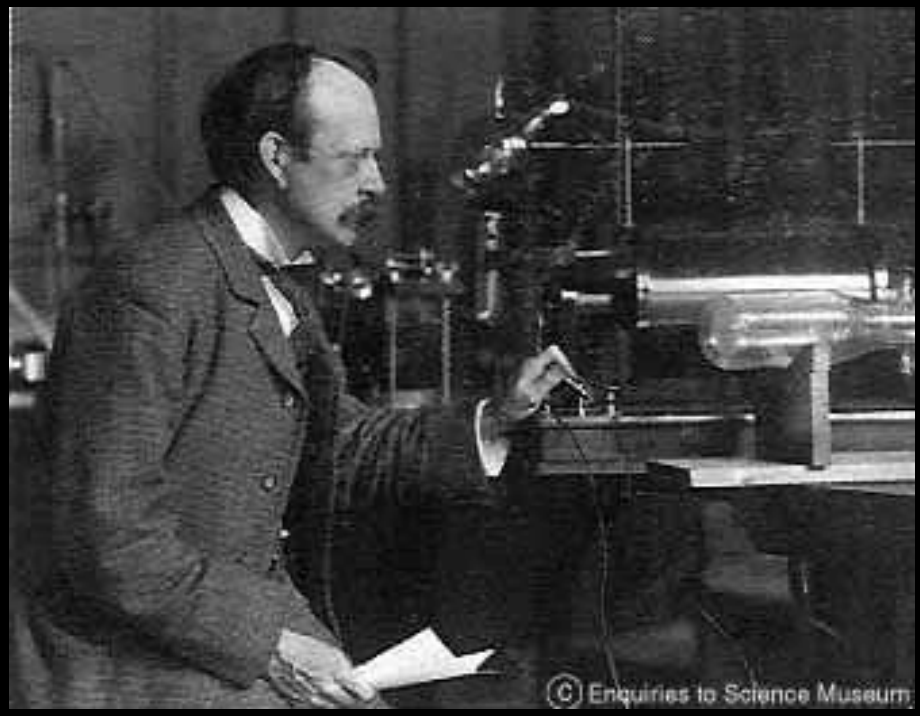


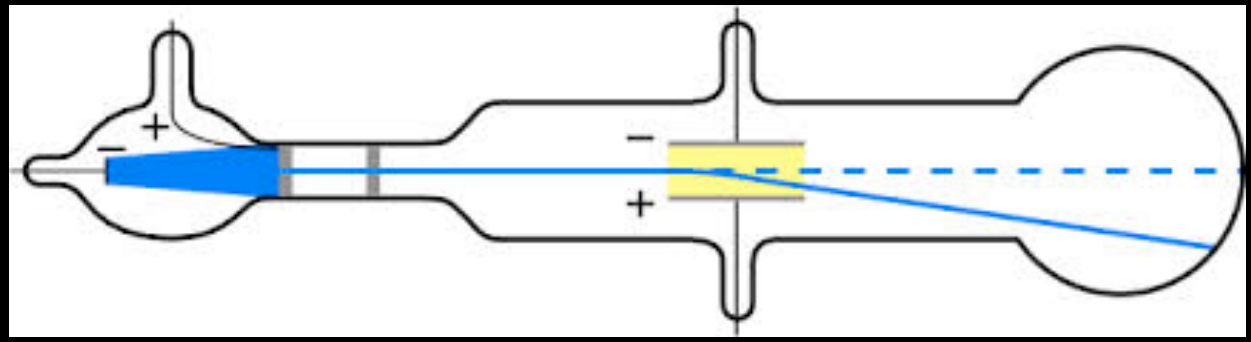
Scanned at the American Institute of Physics



A estrutura básica da matéria

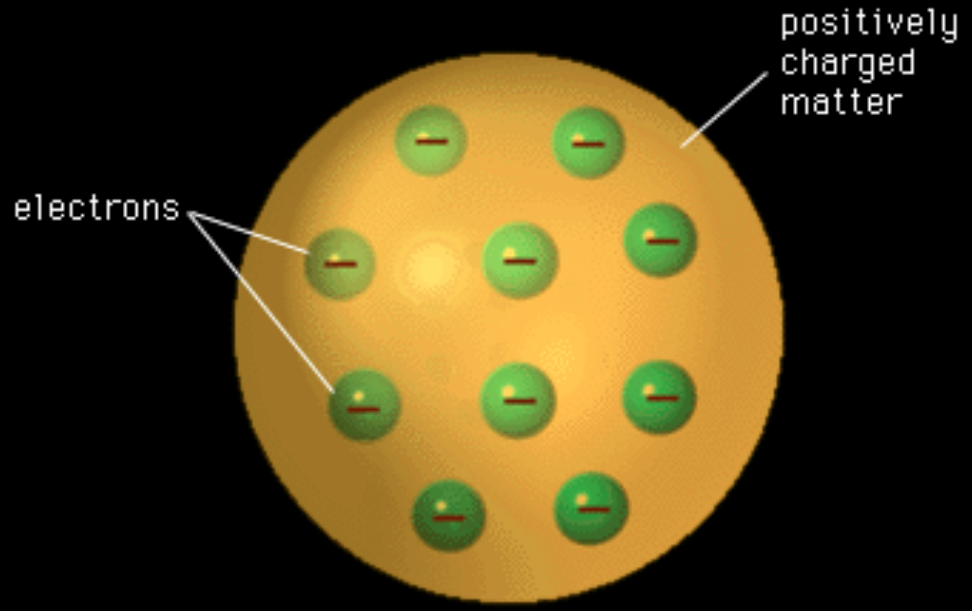
- 1897 – Thomson descobre os elétrons
  - Carga negativa
  - Muito leves





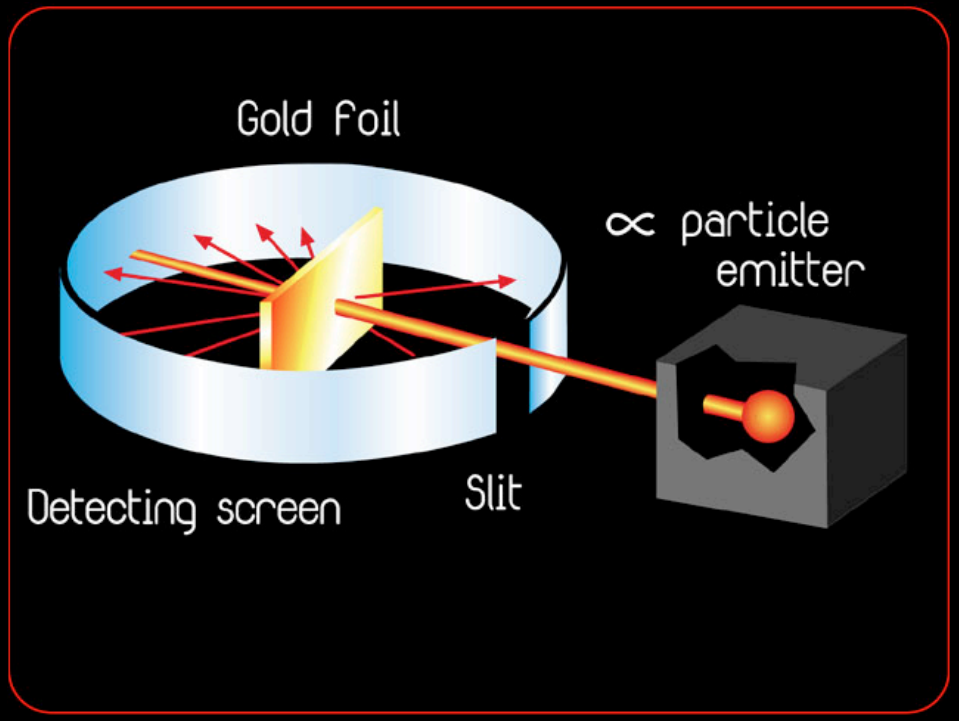
A estrutura básica da matéria

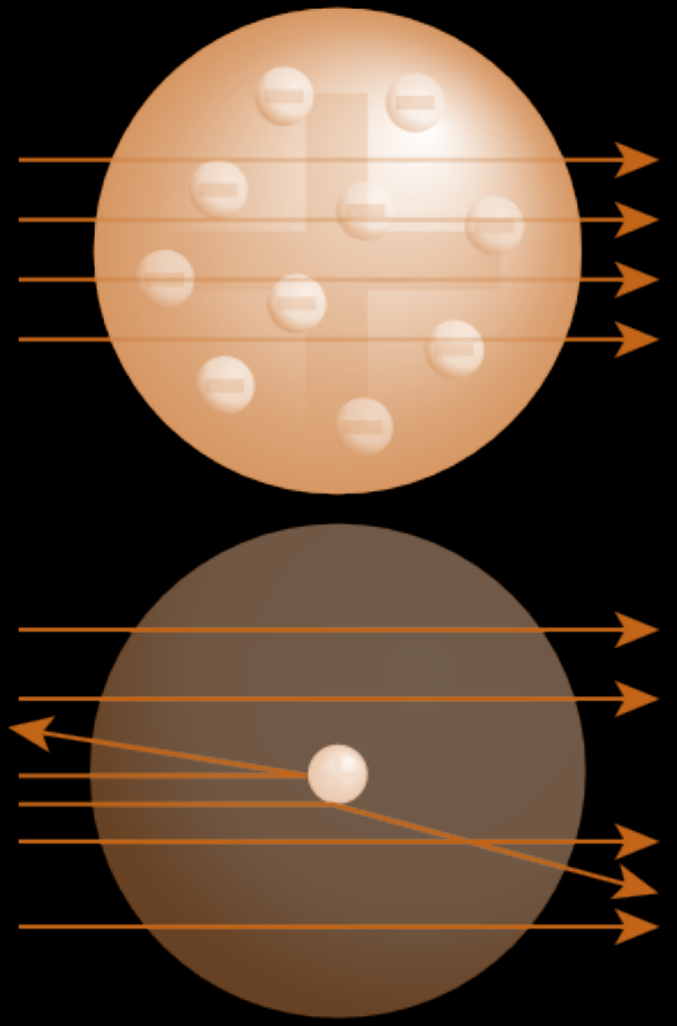
- Por conta disso, Thomson propõe um modelo para o átomo
  - O pudim de passas



A estrutura básica da matéria

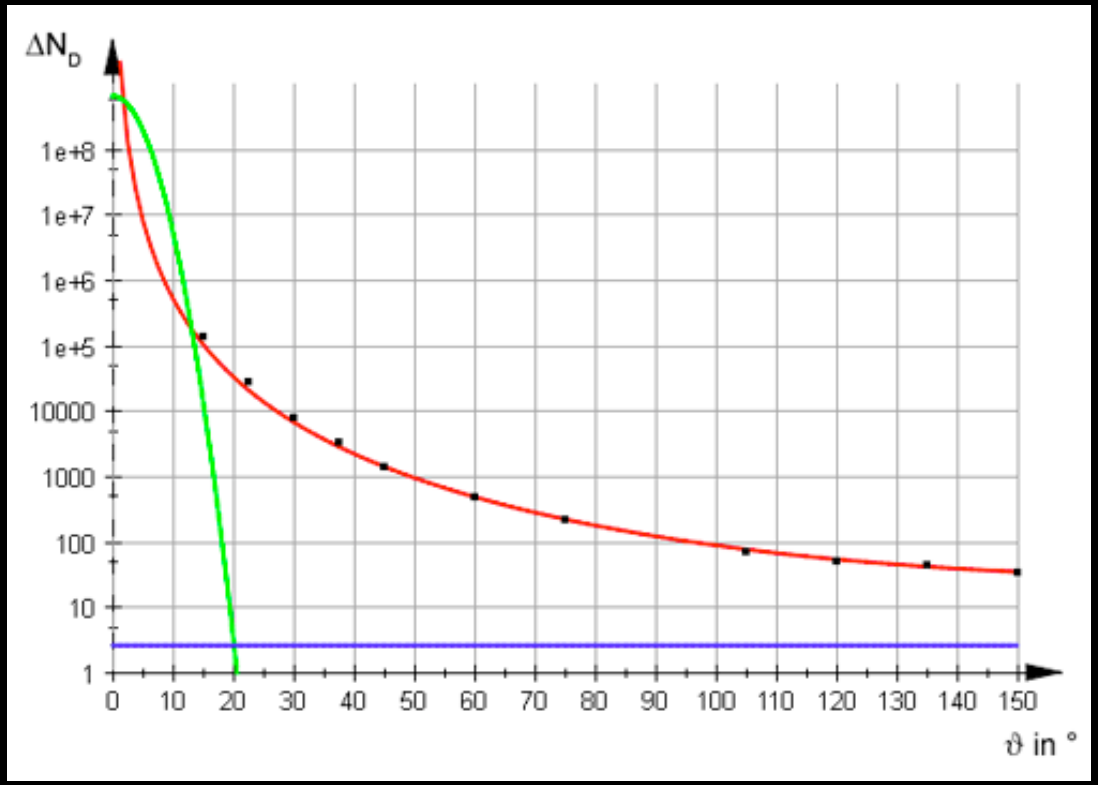
- Rutherford, Geiger e Marsden
  - Descobrem o núcleo atômico

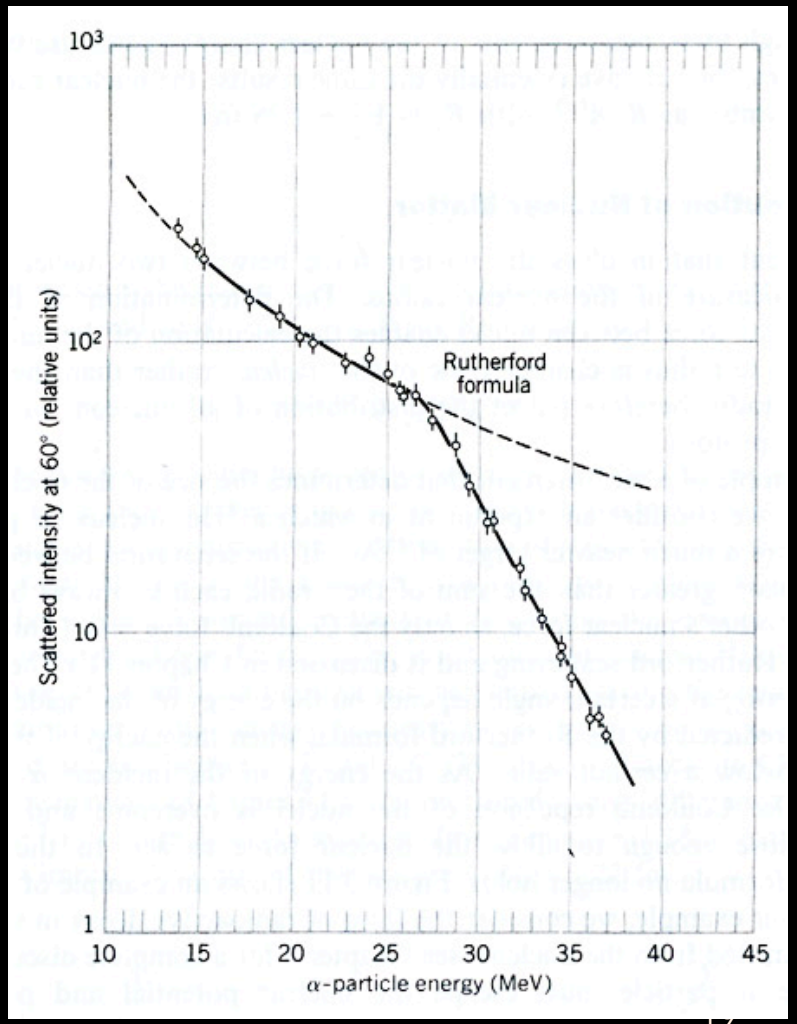




O núcleo atômico

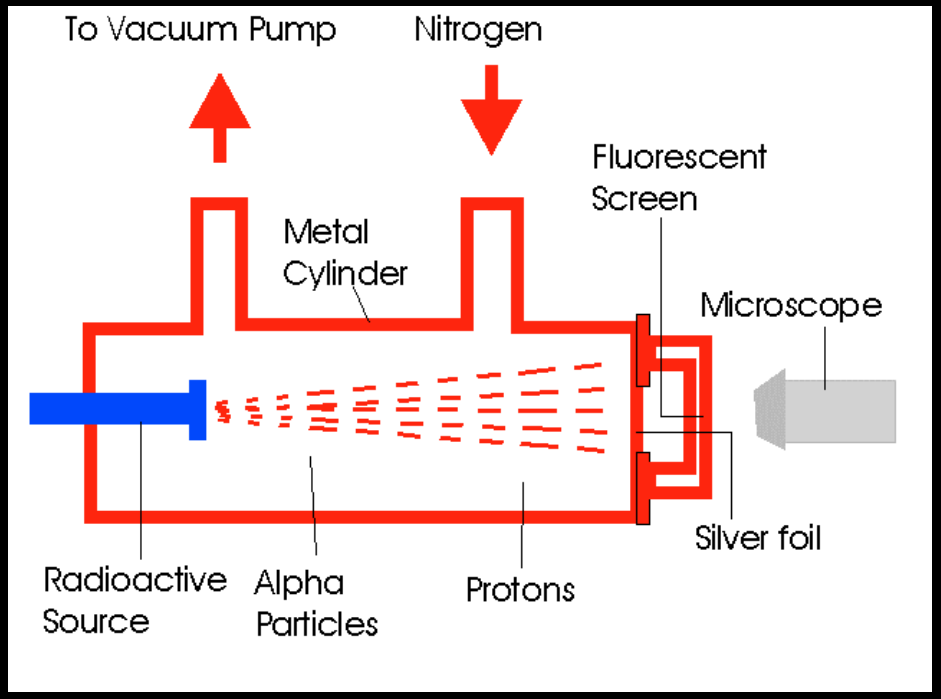
- Rutherford, Geiger e Marsden

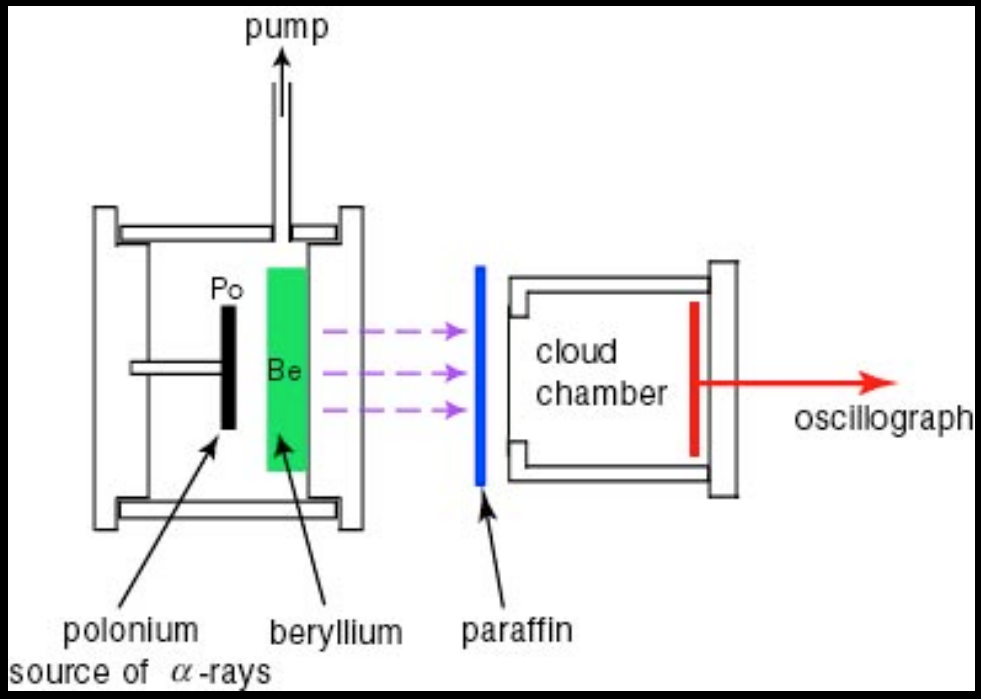




O próton e o nêutron

- 1919 – Próton (Rutherford)
- 1931 – nêutron (Chadwick)





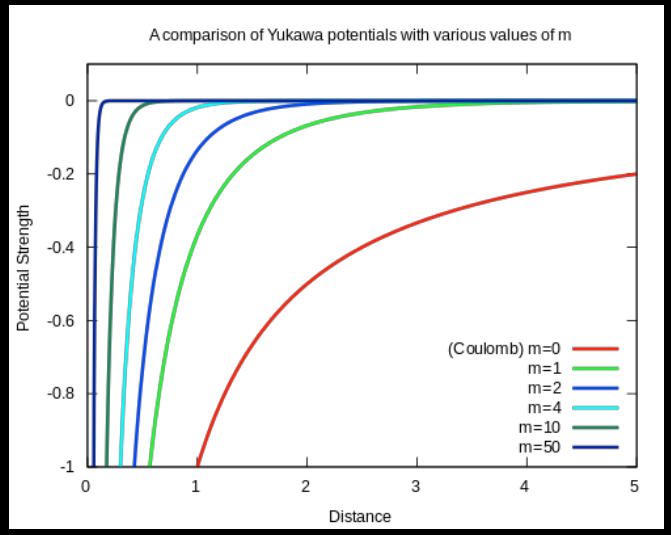
$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}p$$

http://www.nature.com/physics/looking-back/chadwick/chadwick.pdf

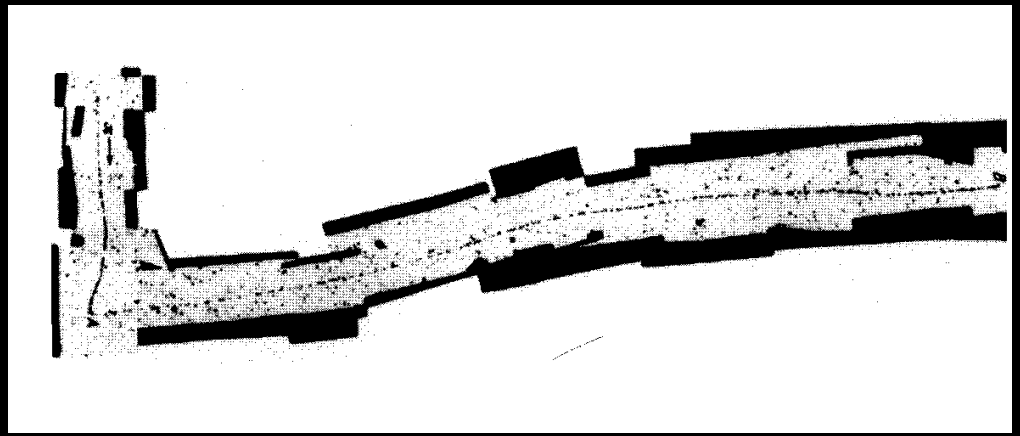
O píon

- Yukawa 1934
  - Interação forte entre nucleons devida a troca de partículas

$$V(r) = -g^2 \frac{e^{-mr}}{r}$$



- Lattes, Occhialini, Powell, 1947



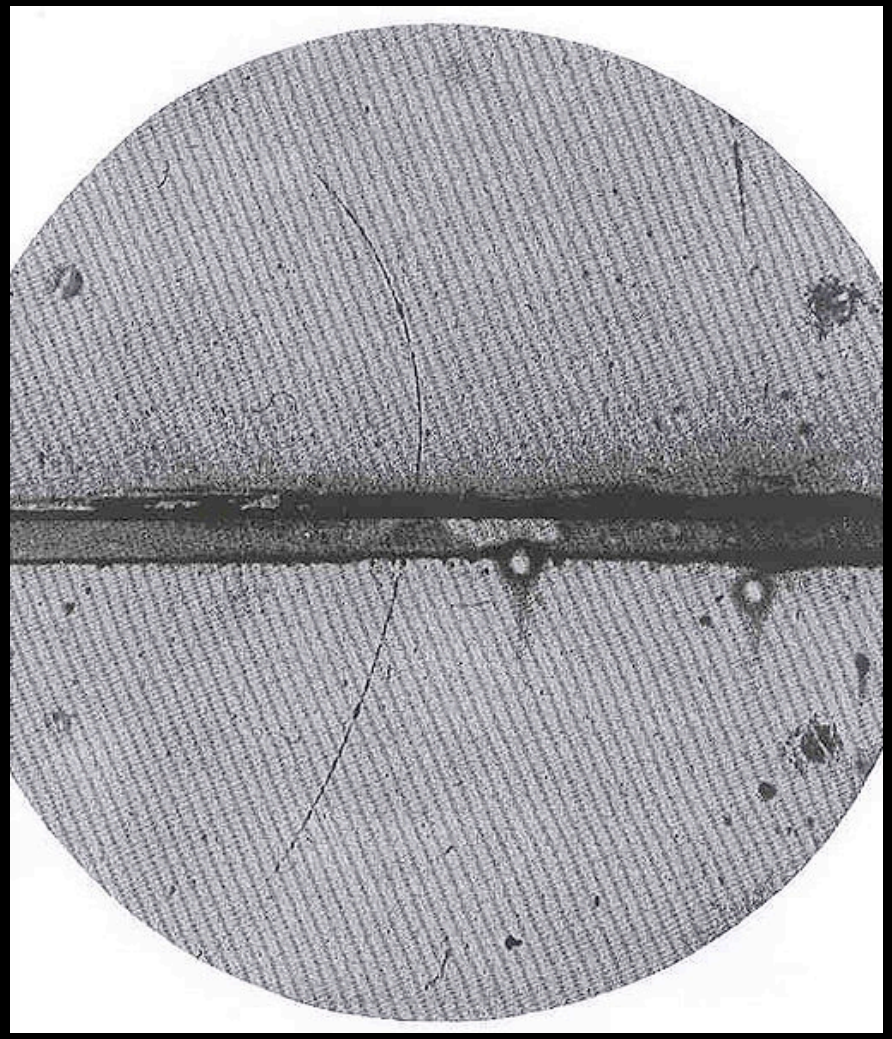
Todos pareciam contentes

- Todos os elementos da natureza eram compostos de 4 elementos básicos
  - Prótons
  - Nêutrons
  - Elétrons
  - Fótons – luz e interação eletromagnética
  - Píon – interação forte
- Até que...

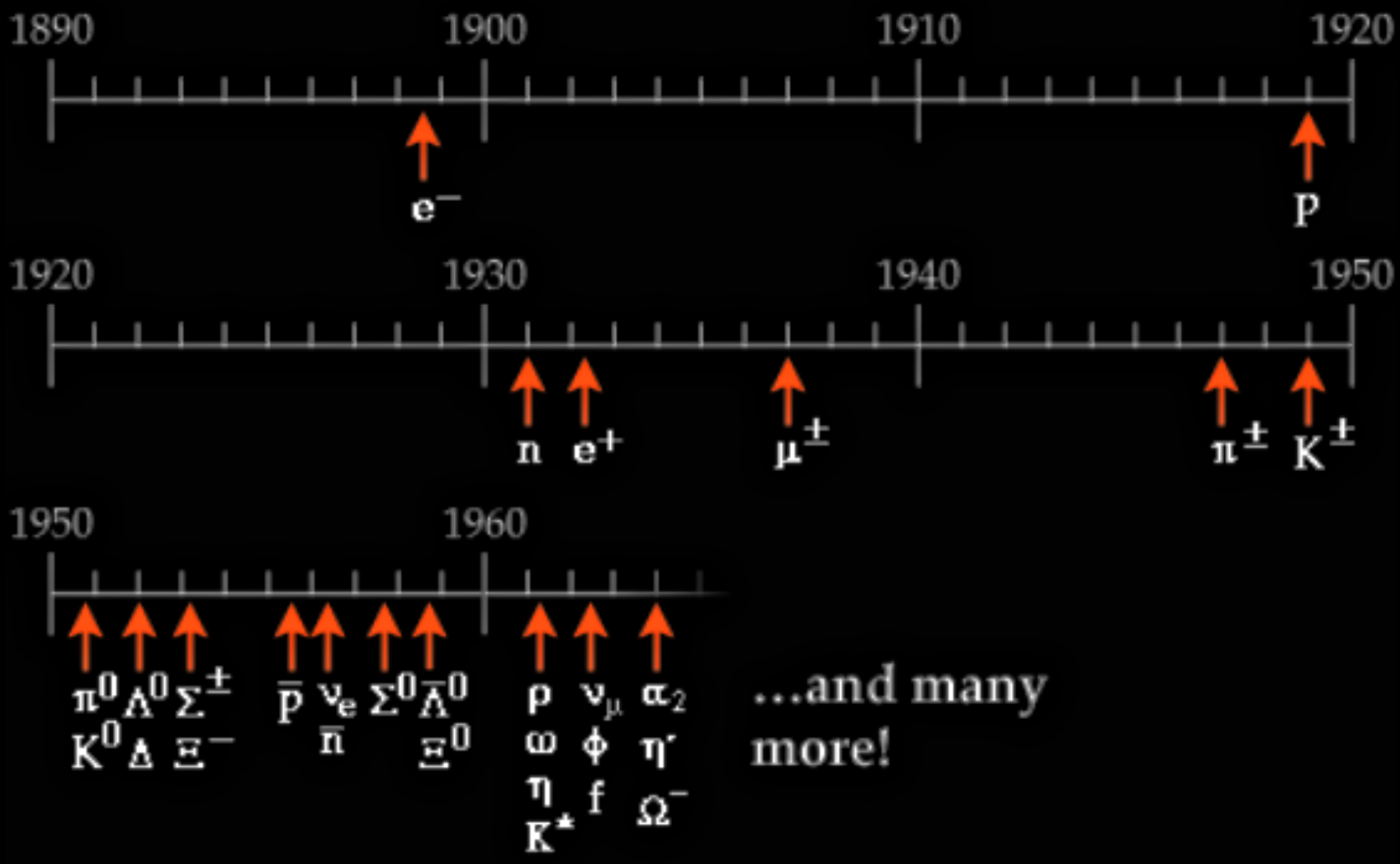
Antimatéria

- Dirac achou estranho o resultado de uma conta, em 1930, e postulou que o resultado seria devido à existência de antimatéria

- Anderson, em 1932, descobre o pósitron

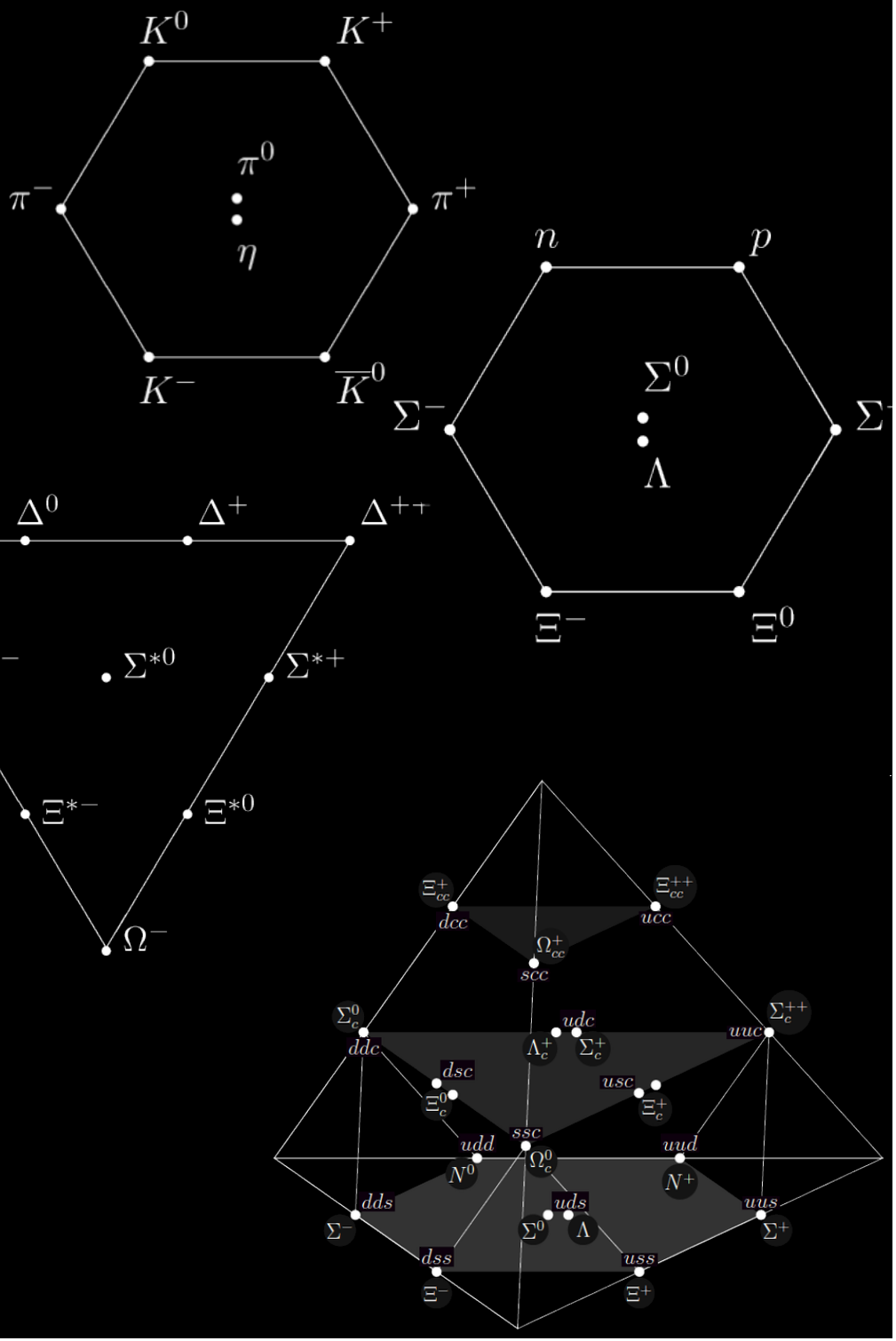


Novas partículas



Anos 60
Muitas partículas novas
> 500 atualmente

Murray Gell-Mann

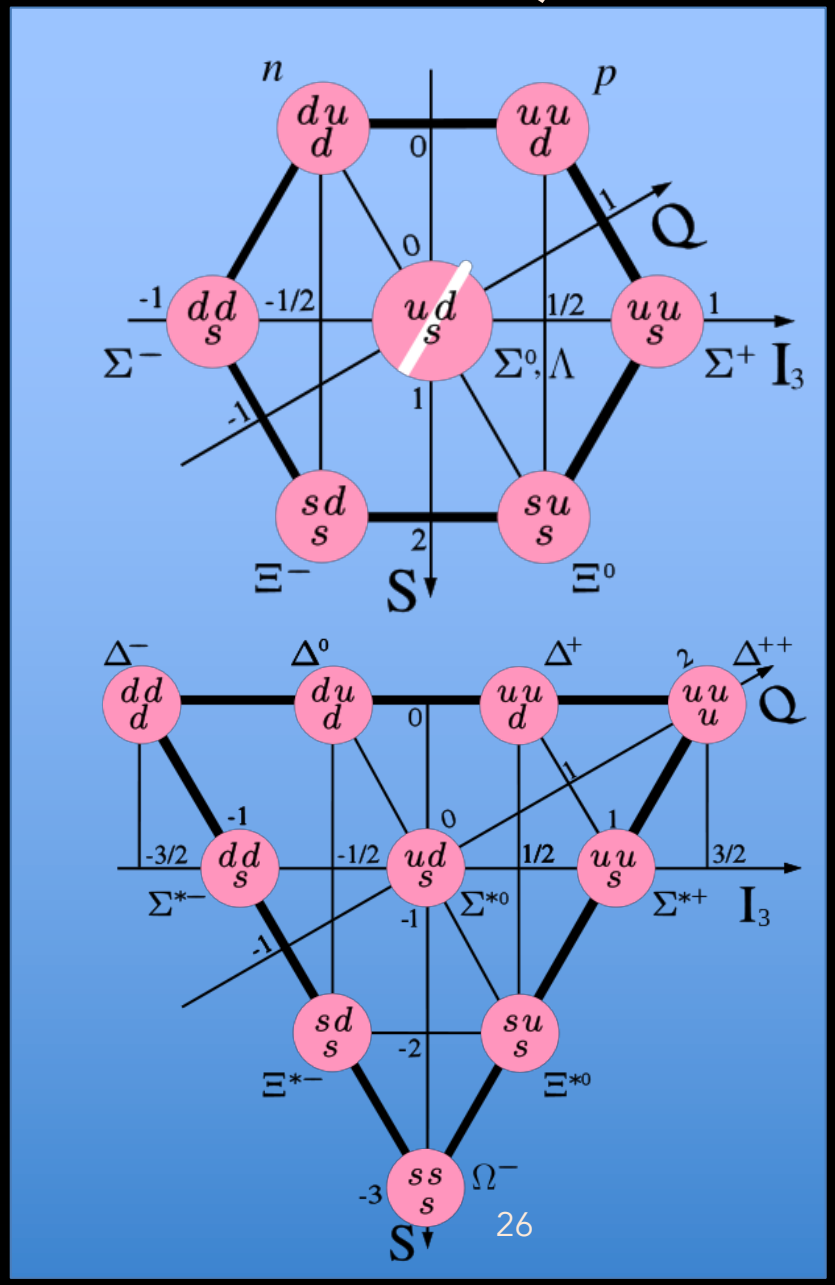


Eightfold Way (Gell-Mann)

- Todas essas partículas podem ser compostas de três outras mais fundamentais (e antipartículas)
  - u (q = 2/3, s = 0, spin = ½)
  - d (q = -1/3, s = 0, spin = ½)
  - s (q = -1/3, s = -1, spin = ½)

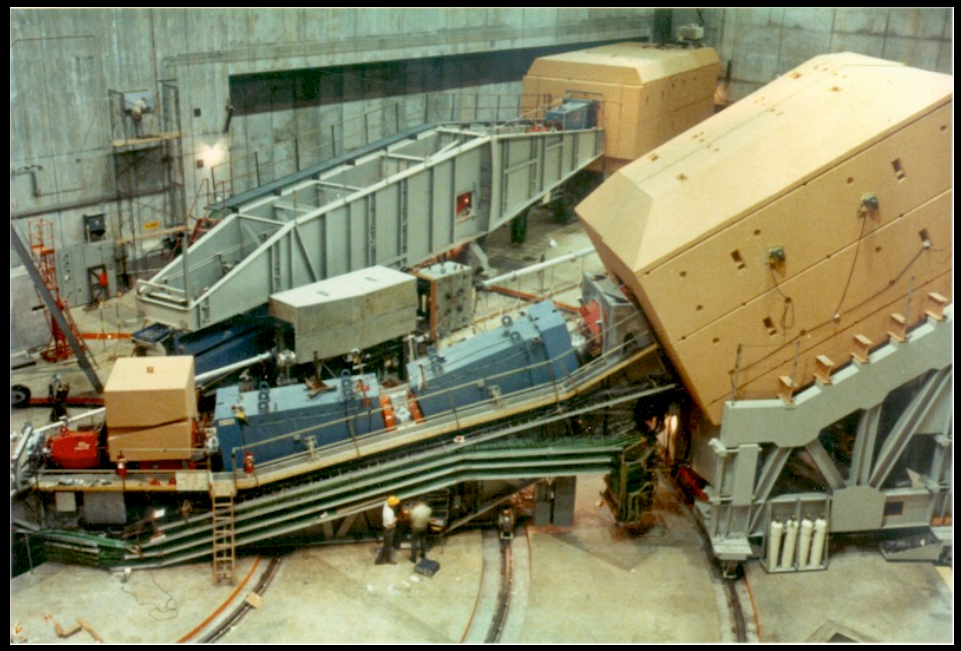
- Da Wikipedia: "*For some time, Gell-Mann was undecided on an actual spelling for the term he intended to coin, until he found the word quark in James Joyce's book Finnegans Wake:*

  - *Three quarks for Muster Mark!*
    Sure he has not got much of a bark
    And sure any he has it's all beside the mark.
    - *—James Joyce, Finnegans Wake"*



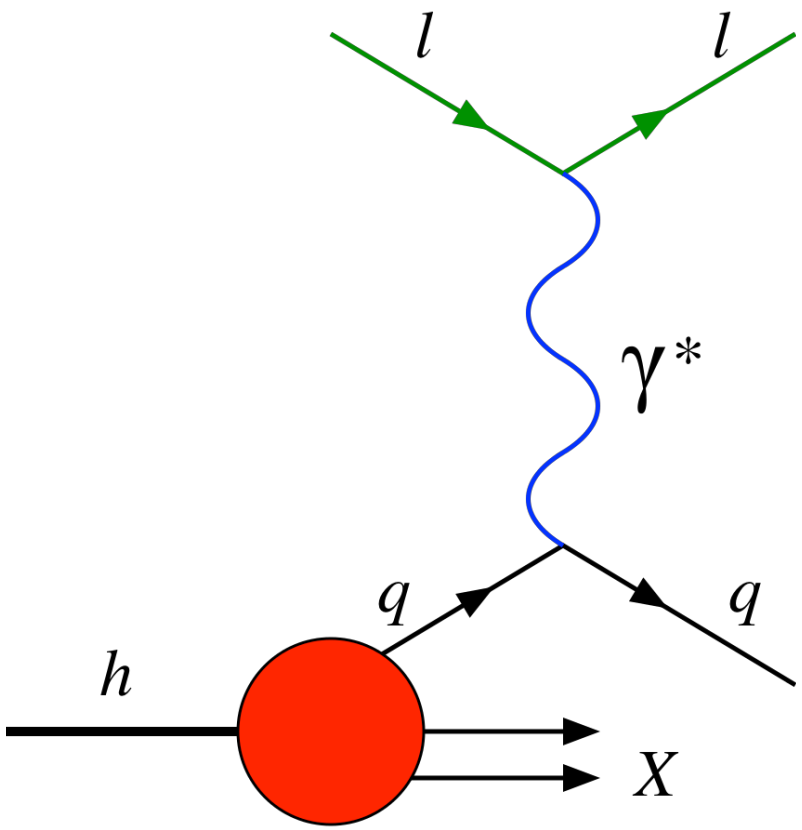
Os quarks

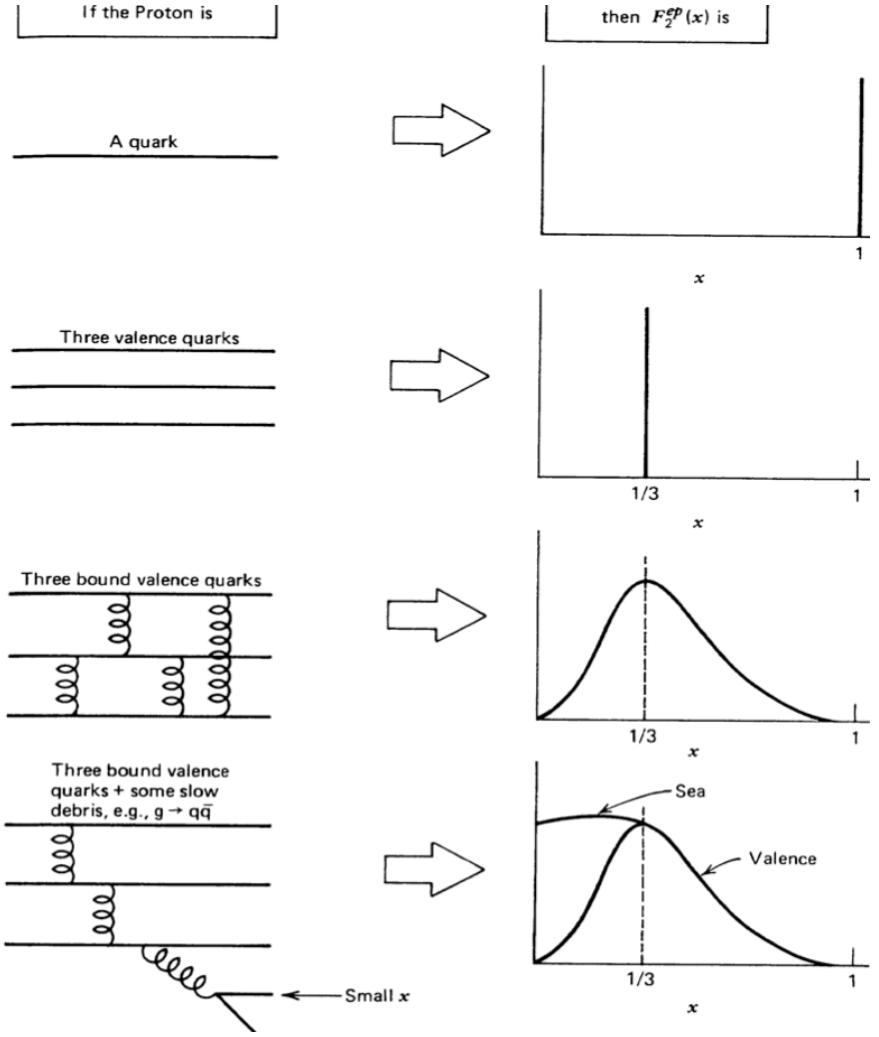
- Gell-Mann, nos anos de 1960, postula que todas os hádrons (os que não são léptons) seriam formados de duas ou três partículas mais elementares, os quarks
  - *Three quarks for Muster Mark! - James Joyce, Finnegans Wake"*



- *Experimentos no SLAC confirmam esta hipótese*

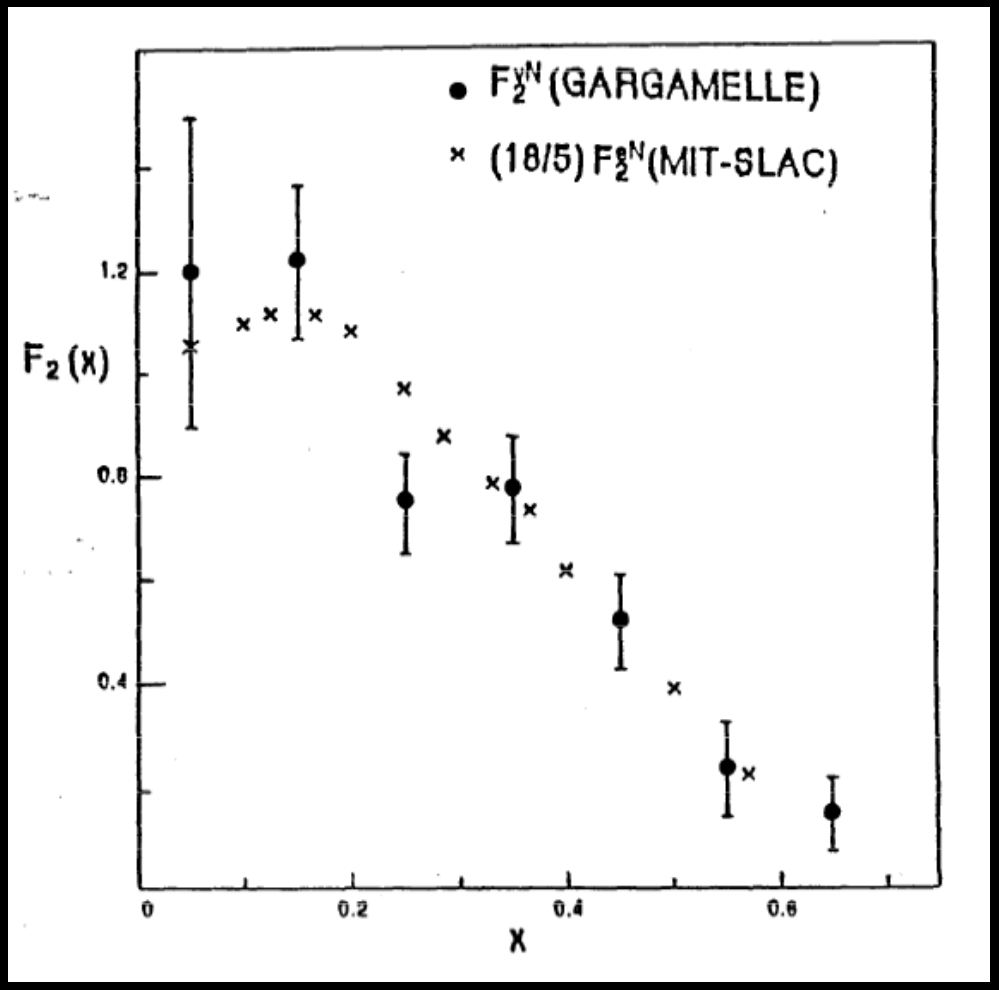
A existência do quark

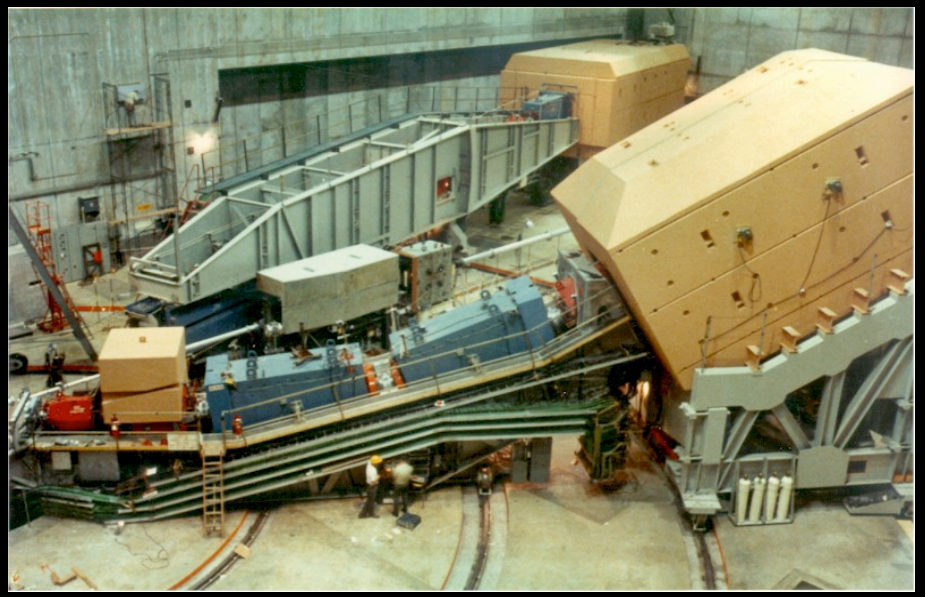




SLAC DIS 1960

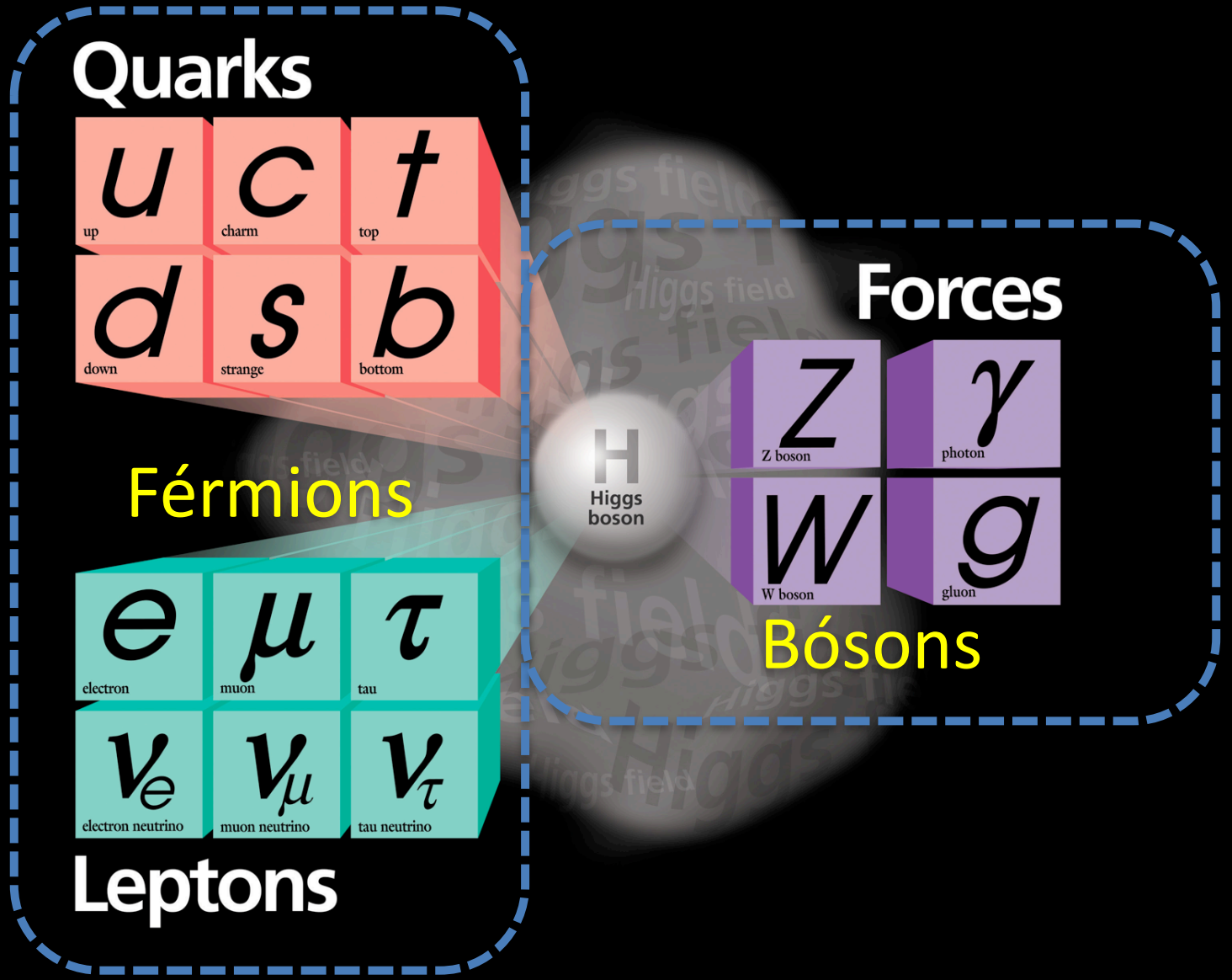
- Existência dos quarks





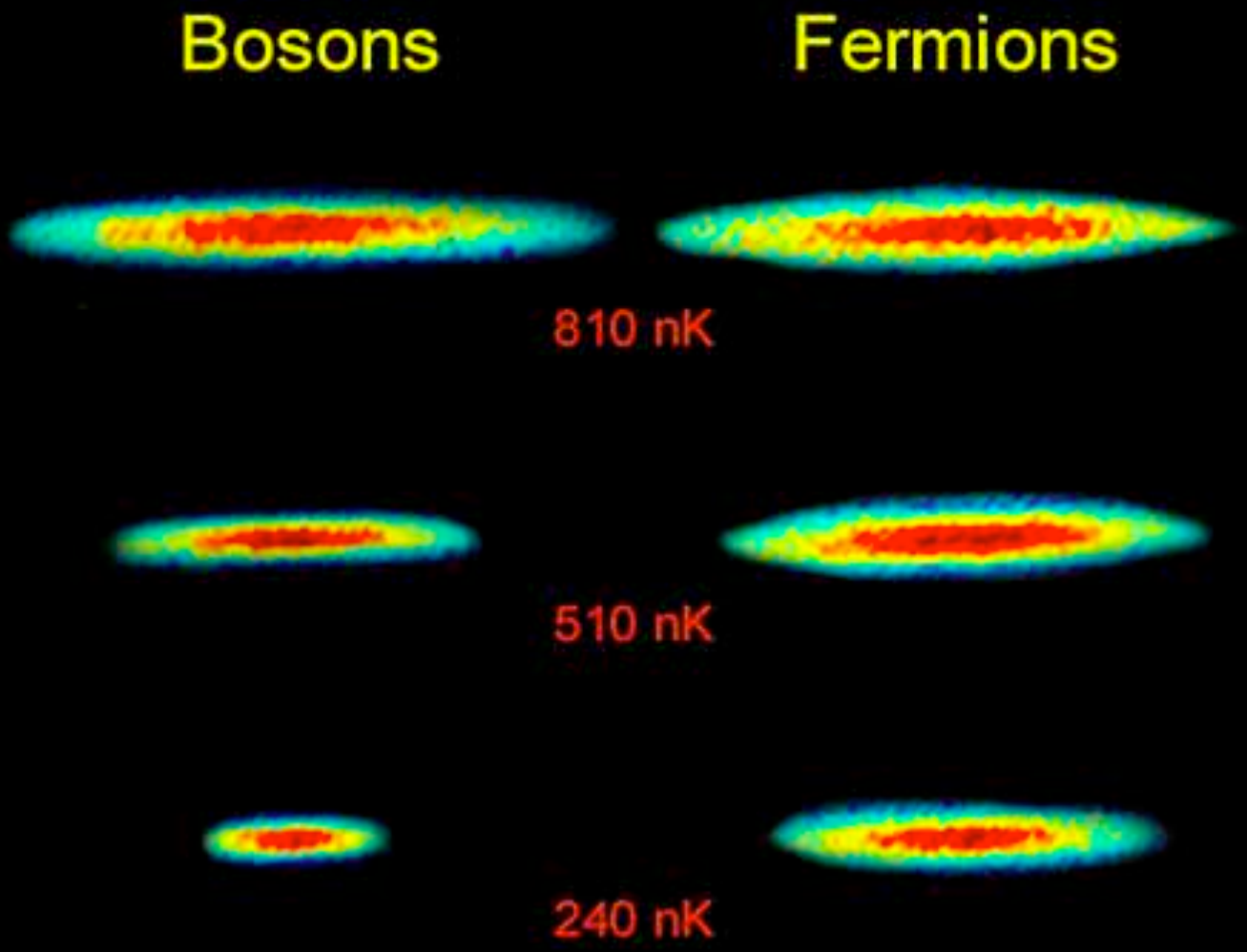
http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-5724.pdf

O Modelo Padrão



Férmions e bósons

Princípio de exclusão de Pauli



O que somos?

- Somos feitos de átomos
  - Núcleos (prótons + nêutrons)
    - Feitos de quarks
  - Elétrons
- Uma pessoa de 50 kg
  - 25 g de elétrons
  - 1,5 kg de quarks
  - Onde estão os outros 48,5 kg?

O que somos?

- Se colocássemos quarks e elétrons juntinhos, seríamos menor que um grão de areia

- Somos “vazio” e neste “vazio” está quase toda nossa massa!

Para entender o que somos precisamos entender

- Energia
- Campo
- Força
- Massa
- Matéria

Energia

uma grandeza que se conserva

- Energia é substância?

- Cinética

$$\frac{1}{2}mv^2$$

$$\frac{1}{2}Mv^2$$

$$\frac{1}{2}Mv^2 \neq \frac{1}{2}mv^2$$

Energia
uma grandeza que se conserva

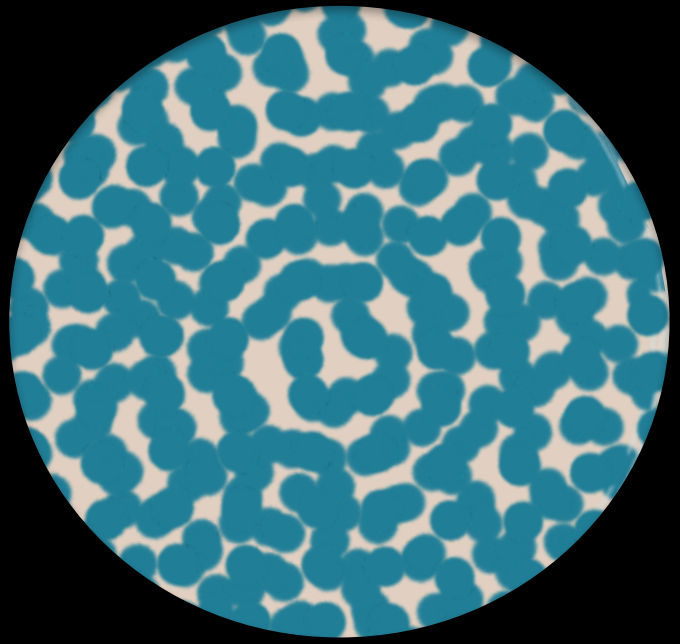
- Energia é substância?
  - Não é substância
- Cinética

Energia
uma grandeza que se conserva

- Energia é substância?
  - Não é substância
- Cinética
- Potencial

Energia
uma grandeza que se conserva

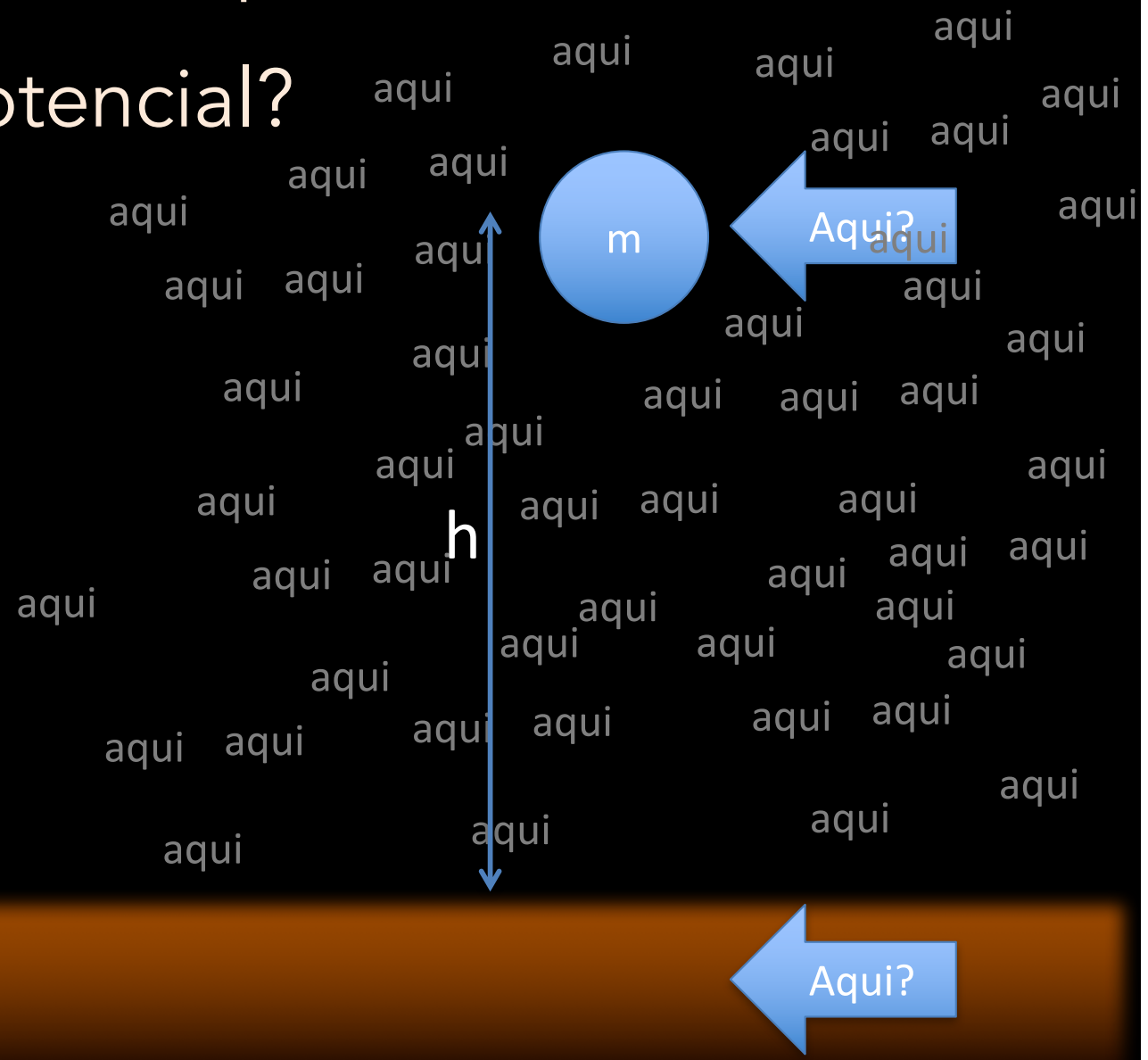
- Energia é substância?
  - Não é substância
- Cinética
- Potencial
- Calor
  - Energia cinética



Energia

uma grandeza que se conserva

- E a energia potencial?
  - E = mgh
- Onde está?



Campo

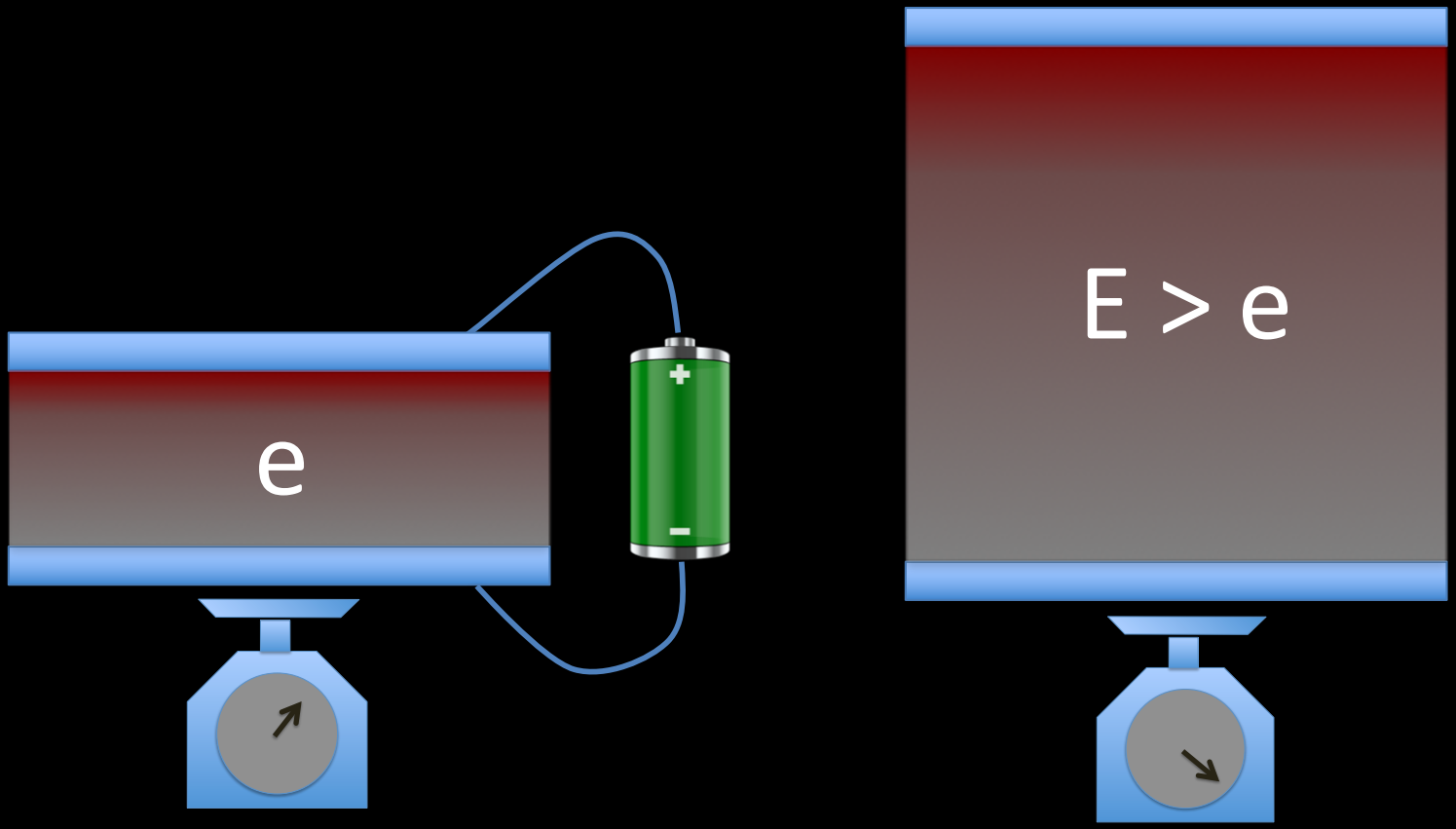
Campo

- Energia contida no campo
  - Densidade de energia
- Soma em todo universo = mgh

Campo, energia e massa

Energia PESA!!!!

Energia tem massa!!!!



Relação entre massa e energia

$$E = mc^2 \rightarrow \sqrt{m_0^2 c^4 + p^2 c^2}$$

C + O → CO + energia

p + n → d + energia

d + energia → p + n

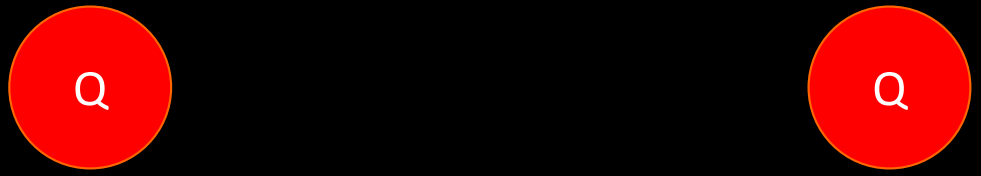
$e^+ + e^-$ → energia

energia → $e^+ + e^-$

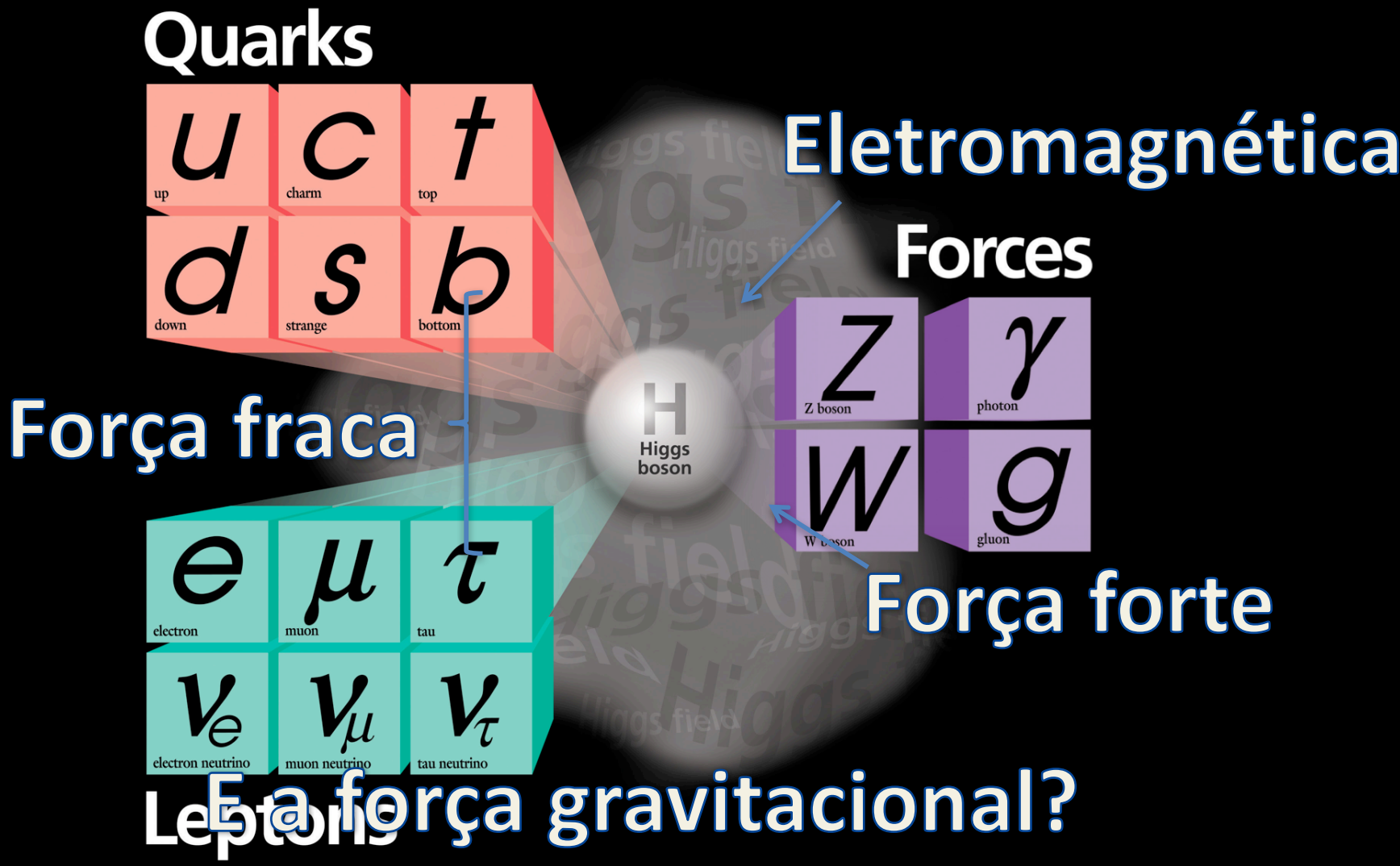
energia → matéria + antimatéria

E o campo? Do que é feito?

A força entre duas partículas



As forças fundamentais



E o próton?

- 3 quarks (uud) unidos pela força forte
- Massa do próton
  - ~938 MeV/c^2
    - ~ 1.6 x 10^{-27} kg
- Massa dos quarks no próton
  - ~ 10-20 MeV/c^2
  - ~ 1-2% do total da massa!
- E o resto da massa?
  - Essencialmente no campo da força forte

E o bóson de Higgs?

- Ouvi dizer que o bóson de Higgs é o responsável por gerar a massa das coisas.
- Isto não está em contradição com tudo que foi dito até agora?
  - SIM e NÃO !
- A pergunta certa é "de onde vem as massas das partículas elementares?"

O campo de Higgs

- Campo que permeia todo o Universo
- A partícula de Deus?
  - "The God Particle"- Leon Lederman

Criando e observado o bóson de Higgs

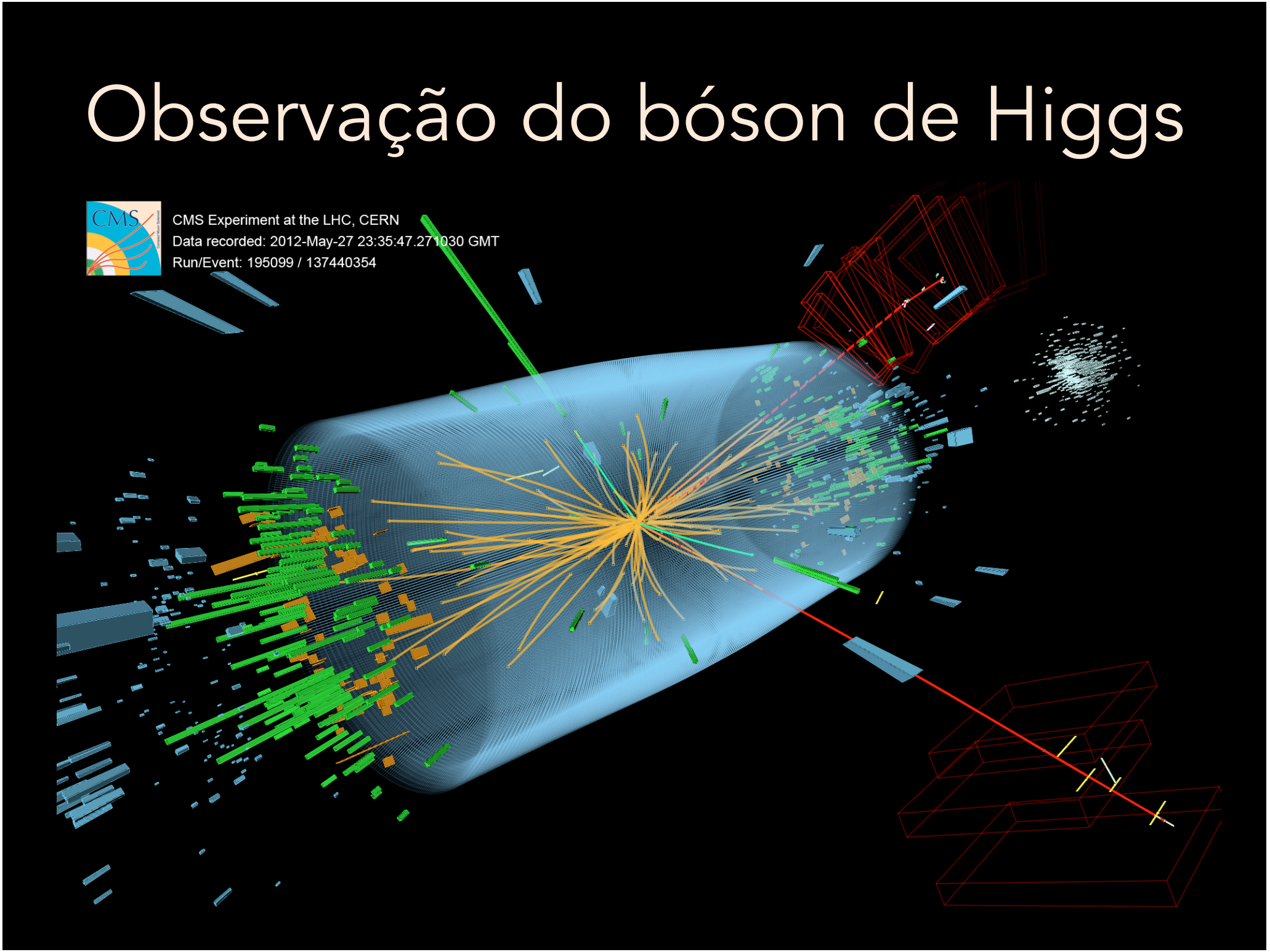
- Fornecer energia para excitar o campo e tirar uma partícula deste campo

energia → Higgs

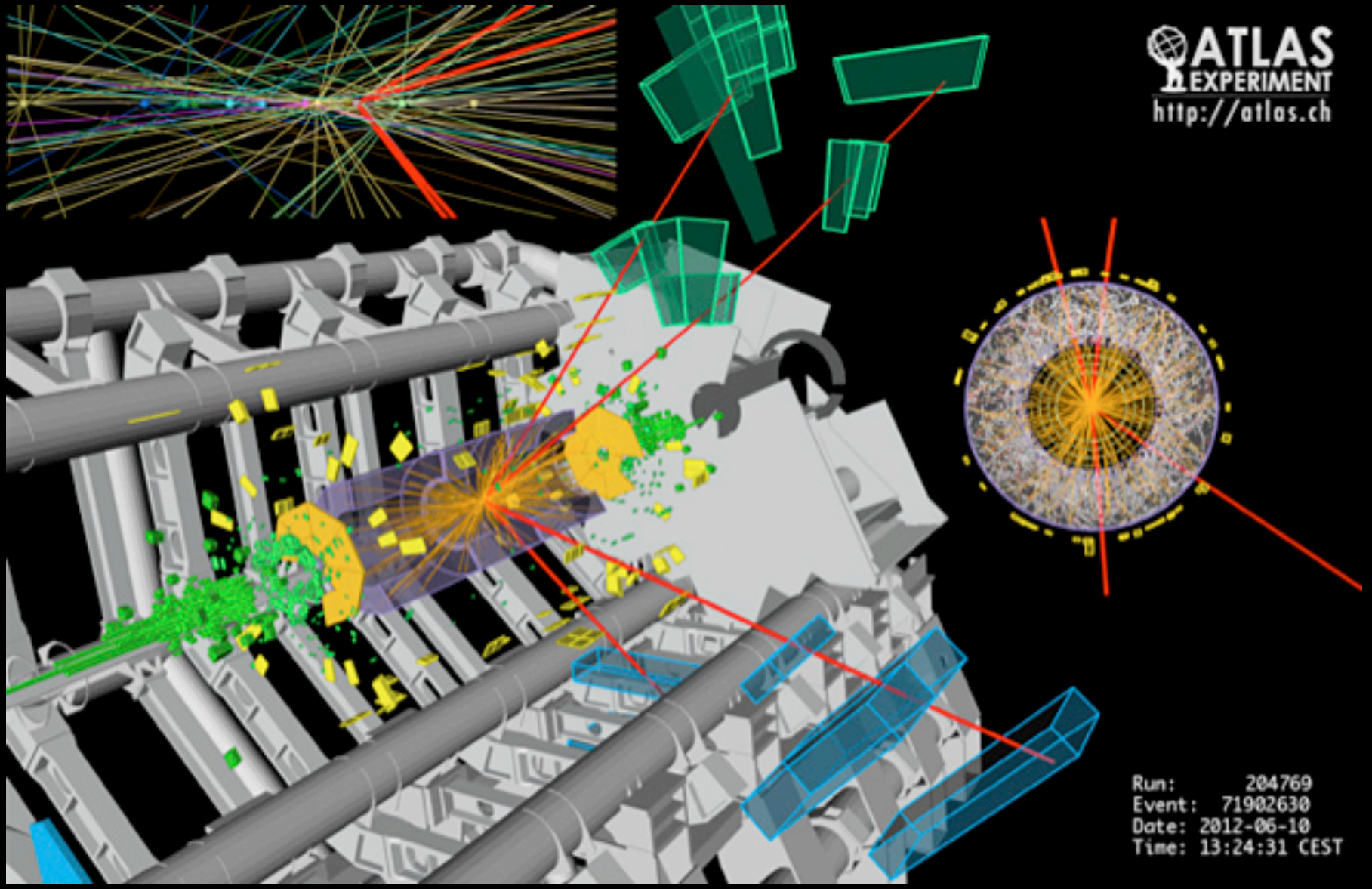
- Muito raro
  - 1 bóson de Higgs a cada 1 trilhão de colisões

- Vive pouco tempo
  - Cerca de 10^{-22} s

Observação do bóson de Higgs



Observação do bóson de Higgs



Só 3% da massa do próton?

- Por que é tão importante saber isso?
  - A massa das ***partículas elementares*** vêm do campo de Higgs
    - Quarks, elétrons, múons, etc.
- O Universo existiria como ele é hoje sem o campo de Higgs?
- Como as massas das partículas elementares afetam o nosso dia a dia?

Um exemplo: o átomo de hidrogênio

- Raio de Bohr do átomo de hidrogênio é inversamente proporcional à massa do elétron

$$a = \frac{\hbar}{m_e c \alpha}$$

- E se a massa do elétron fosse menor? E se ele não tivesse massa?

Algumas perguntas da *física*

- Como o Universo surgiu? Como ele vai evoluir?
- Por que há muito mais matéria do que antimatéria no Universo?
- Porque temos massa?
- Existem mais de três dimensões espaciais?
- Quais são os elementos básicos que formam a matéria?