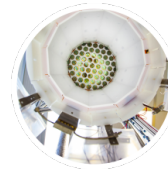


# Bem vindos (remotamente ...) ao LIP !



**Experimental particle and  
astroparticle physics**



**Development of new  
instruments and methods**



**Scientific computing**



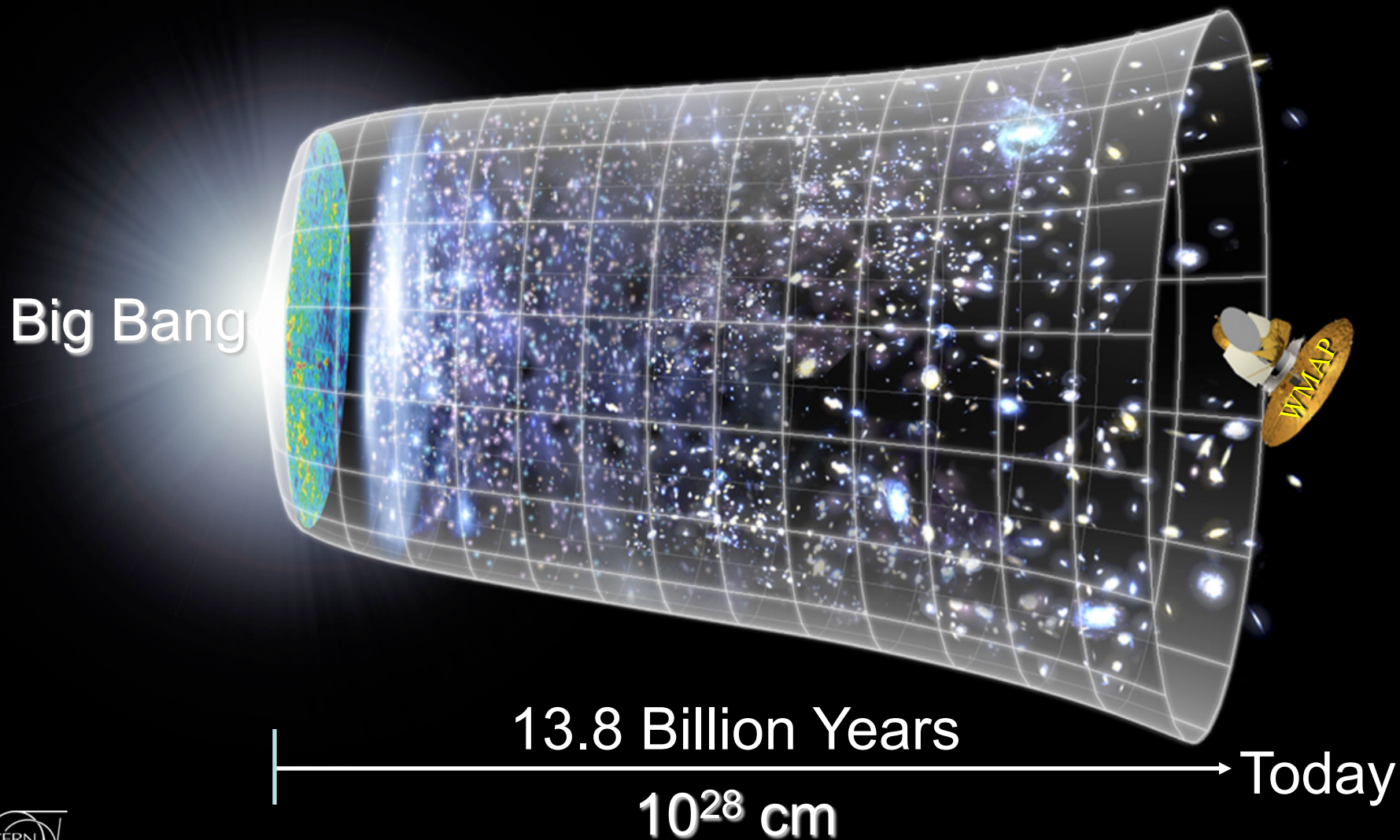
**Knowledge transfer,  
education and outreach**

# A aventura da Física de Partículas e Astropartículas

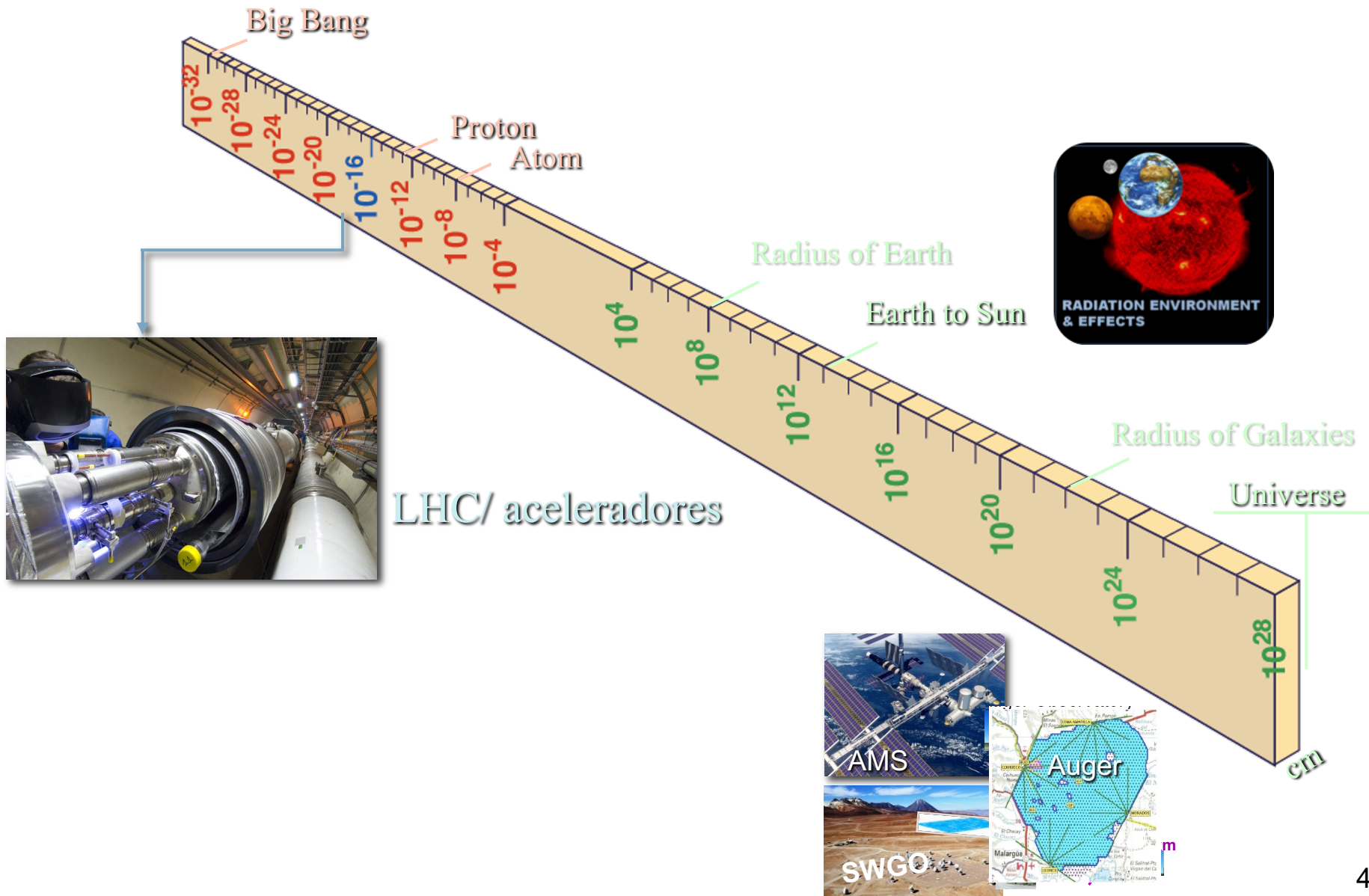


Mário Pimenta  
Lisboa, Julho 2022

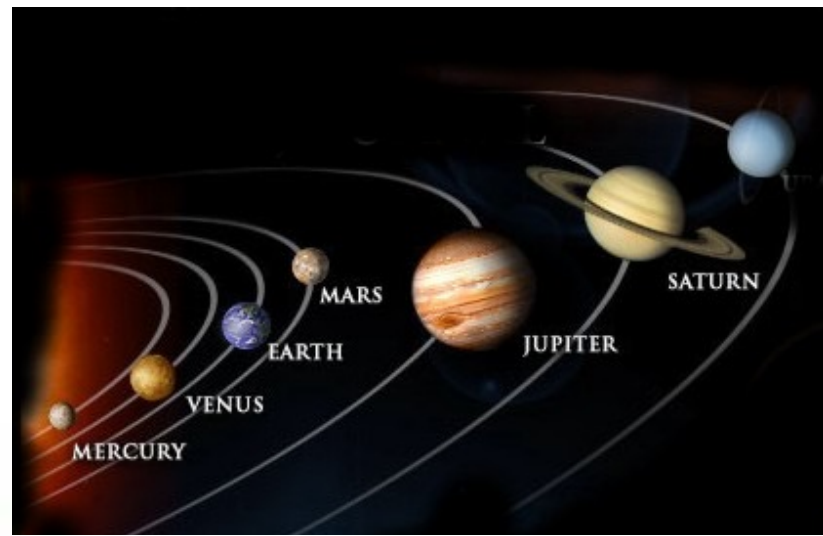
# O Universo para compreender, ...



# Escalas, ...



# Da maçã ao Universo



I. Newton

Lei da atracção  
Universal:

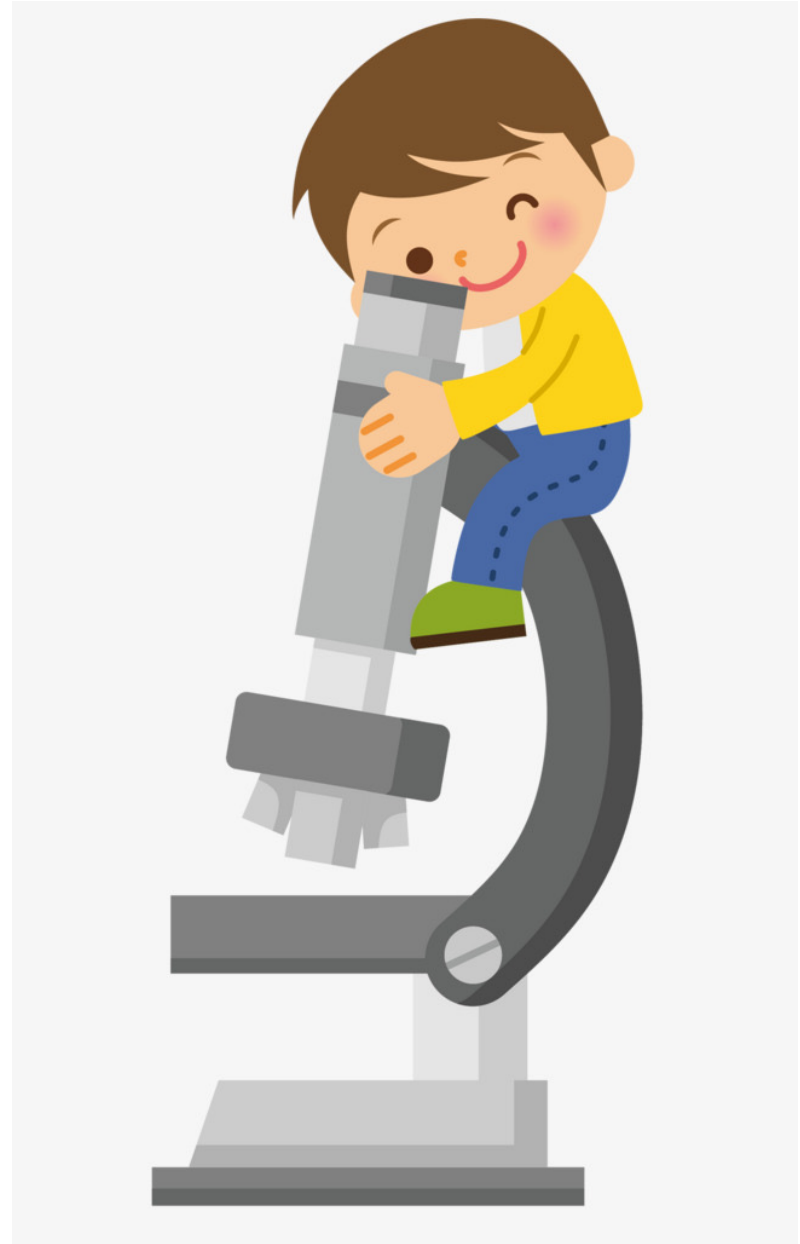
$$F = G \frac{m_{1g} m_{2g}}{r_{12}^2}$$

**A gravidade !**

Será que a maçã é  
elementar?

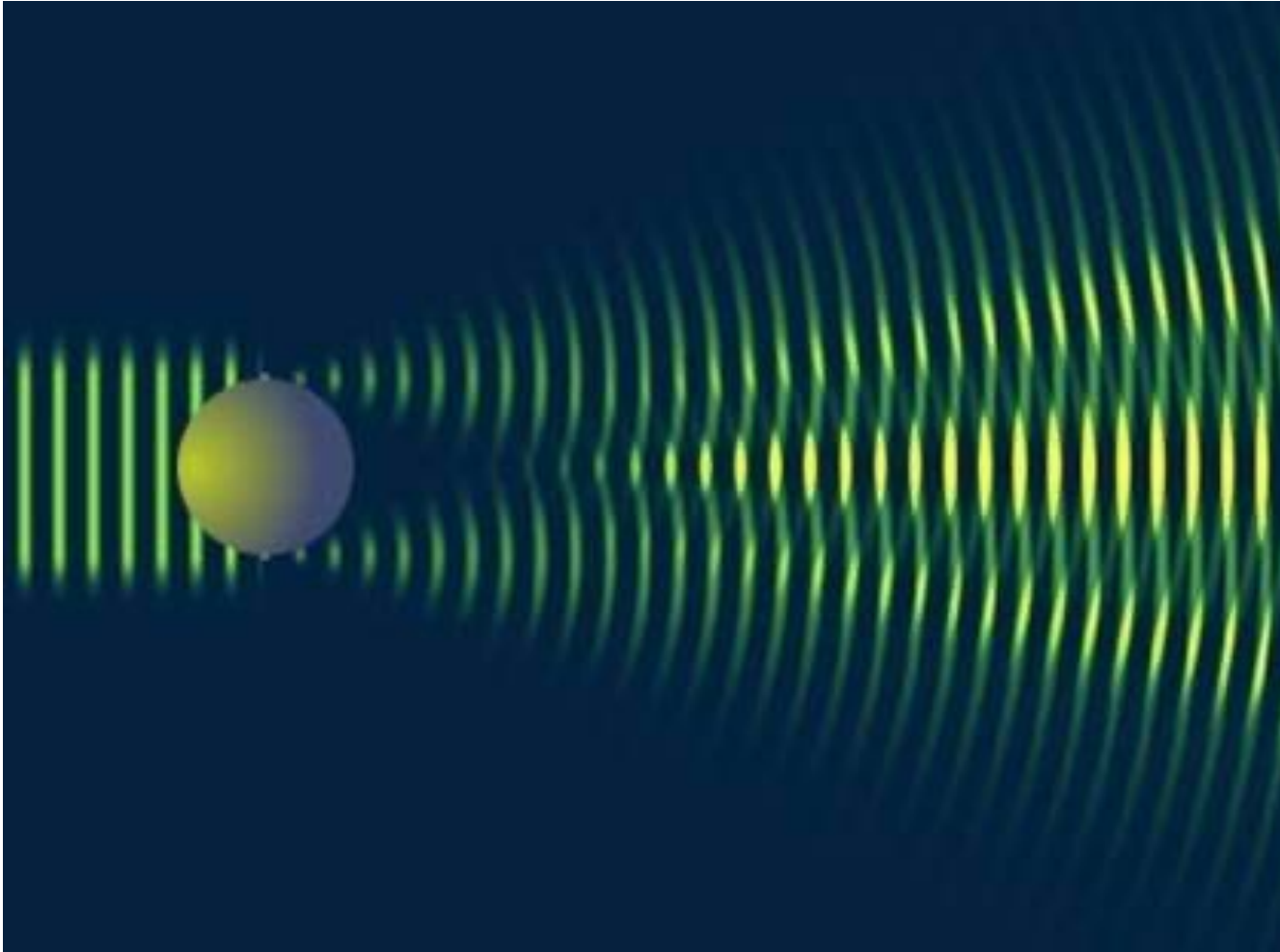


Ver o interior da  
maçã ???



# As ondas difractam-se ...

Se  $\lambda$  for da ordem do tamanho do objecto



Só se podem ver objectos com uma dimensão maior que  $\lambda$  !



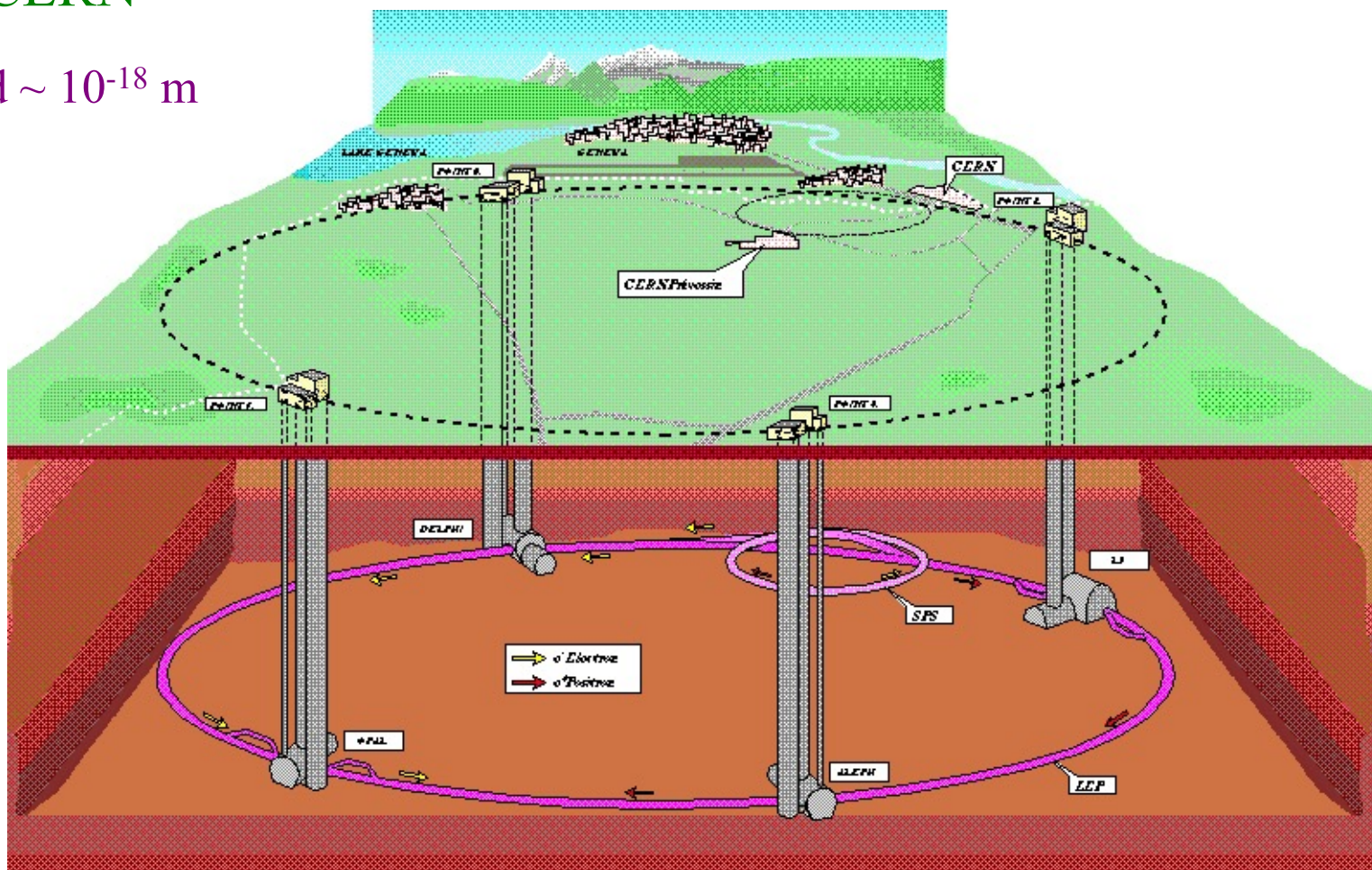
# Ver com partículas

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

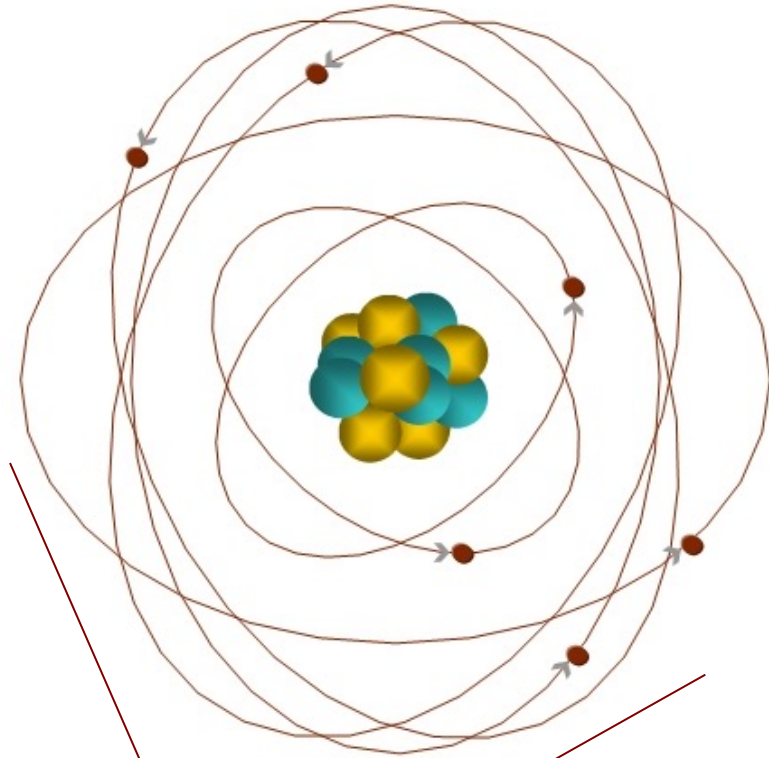


## CERN

$d \sim 10^{-18}$  m

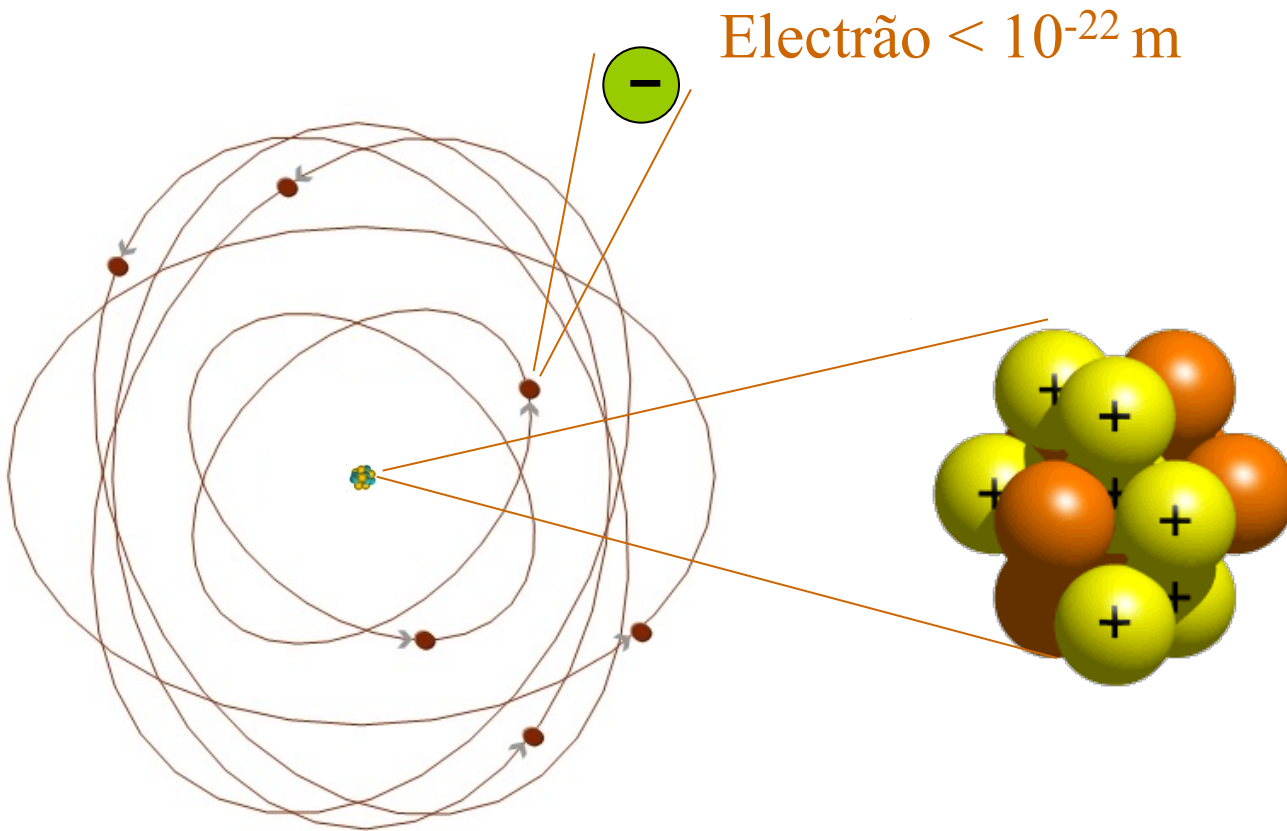


# Será que a maçã é elementar?



Átomo  $\sim 10^{-10}$  m

# No interior dos átomos

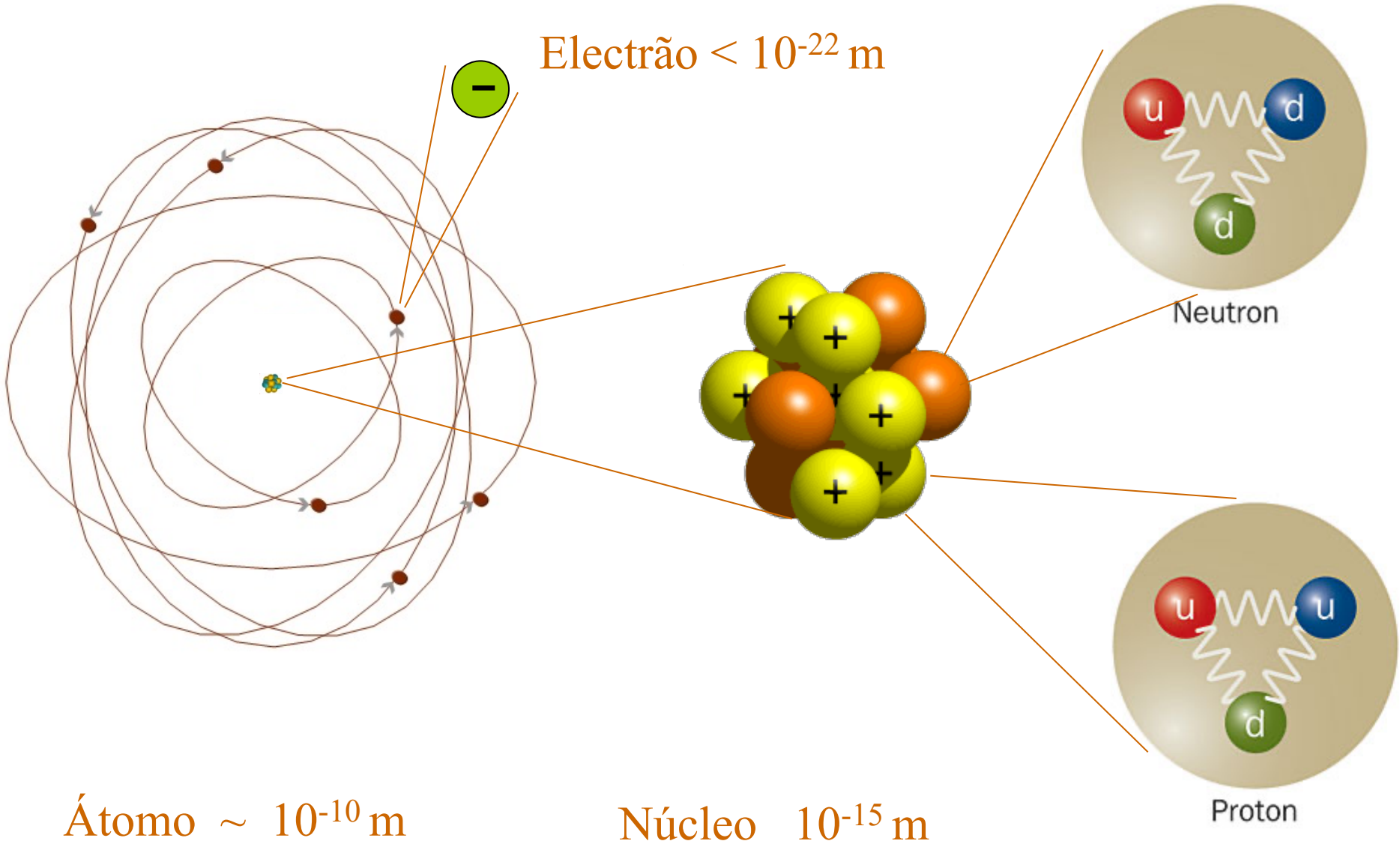


Electrão  $< 10^{-22}$  m

Átomo  $\sim 10^{-10}$  m

Núcleo  $10^{-15}$  m

# No interior dos átomos



# Vários quarks, muitas partículas !!!

Quarks:



$$\begin{pmatrix} u \\ d \end{pmatrix}$$

$$Q = + 2/3$$

$$Q = - 1/3$$

# Vários quarks, muitas partículas !!!

Quarks:

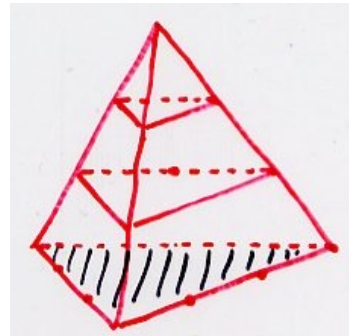


$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{pmatrix} ? \\ ? \end{pmatrix} \quad \begin{matrix} Q = + 2/3 \\ Q = - 1/3 \end{matrix}$$

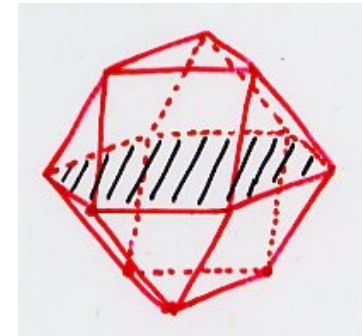
Combinar



$$q_i q_j q_k$$



$$q_i \bar{q}_i$$

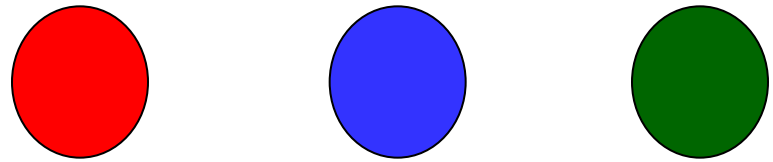


$$p, n, \Sigma, \lambda, \Xi, \Delta, \dots$$

$$\pi, k, \eta, \rho, \psi, \dots$$

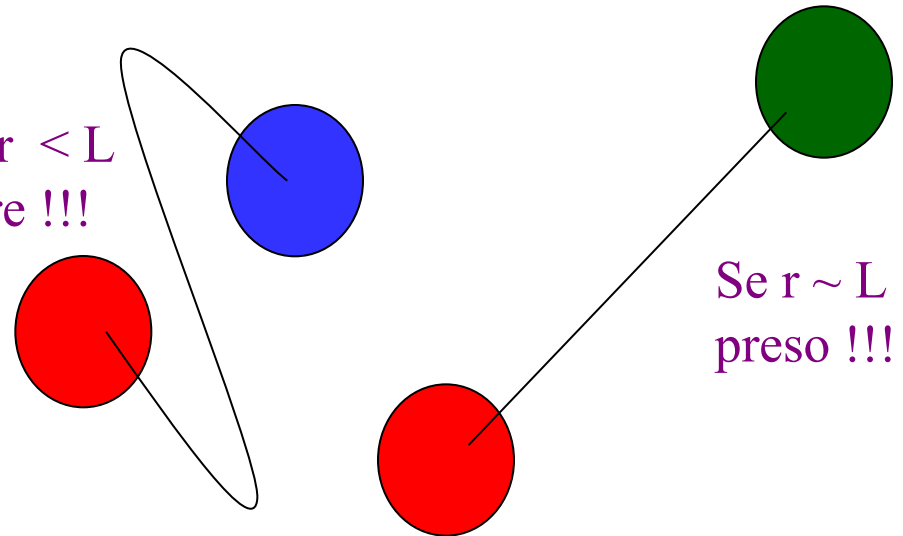
# A força forte

Quarks de três cores:



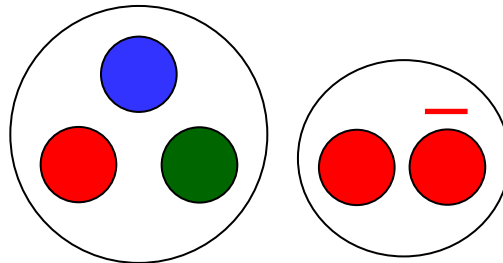
Ligados por “cordas”

Se  $r < L$   
livre !!!



Se  $r \sim L$   
preso !!!

Partículas “sem cor”

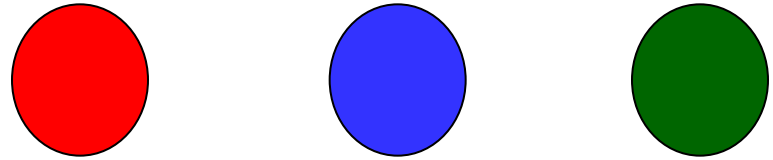


Bariões

Mesões

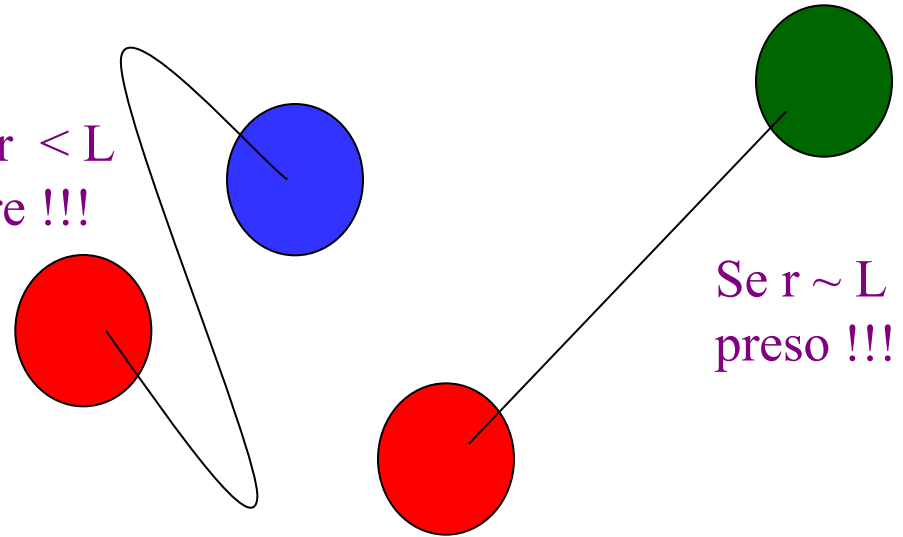
# A força forte

Quarks de três cores:



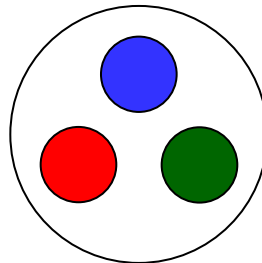
Ligados por “cordas”

Se  $r < L$   
livre !!!

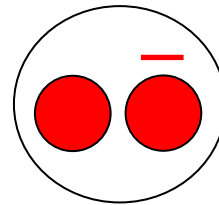


Se  $r \sim L$   
preso !!!

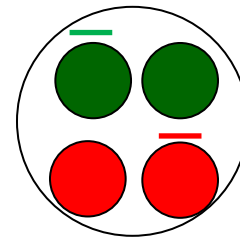
Partículas “sem cor”



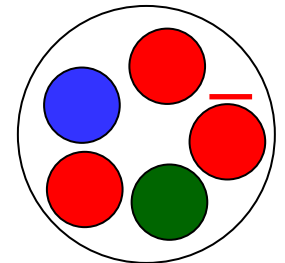
Bariões



Mesões



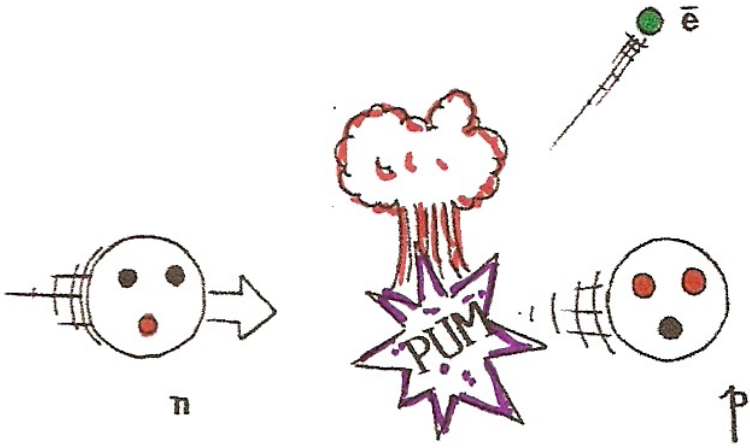
Tetraquarks



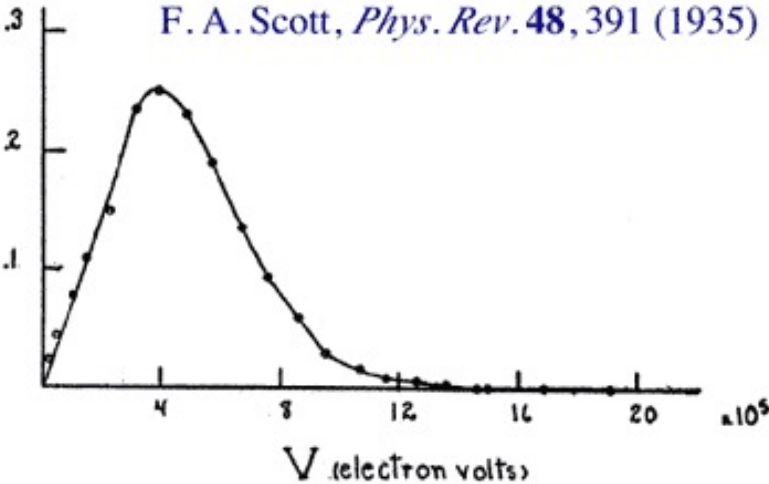
Pentaquarks



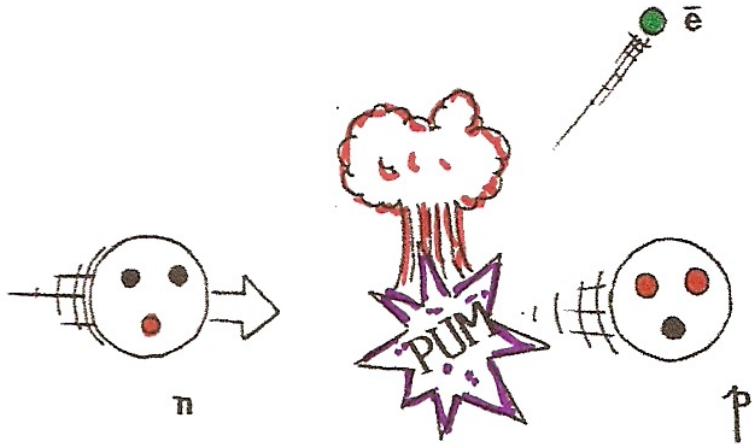
# O neutrão decai...



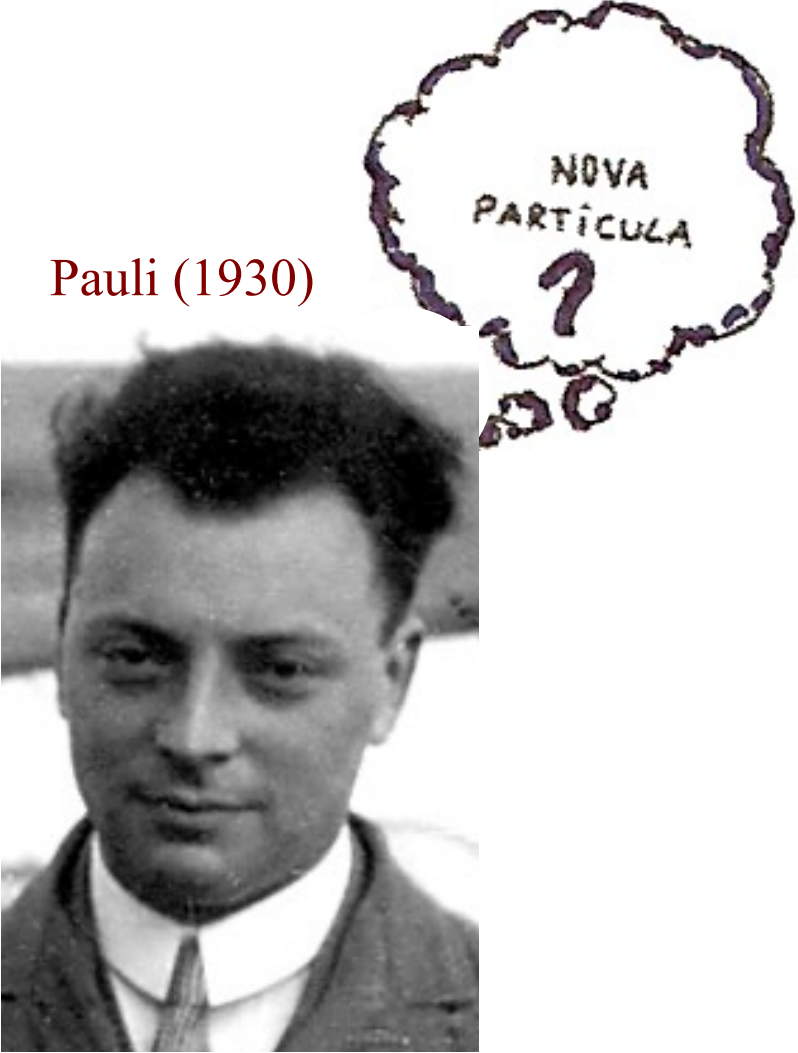
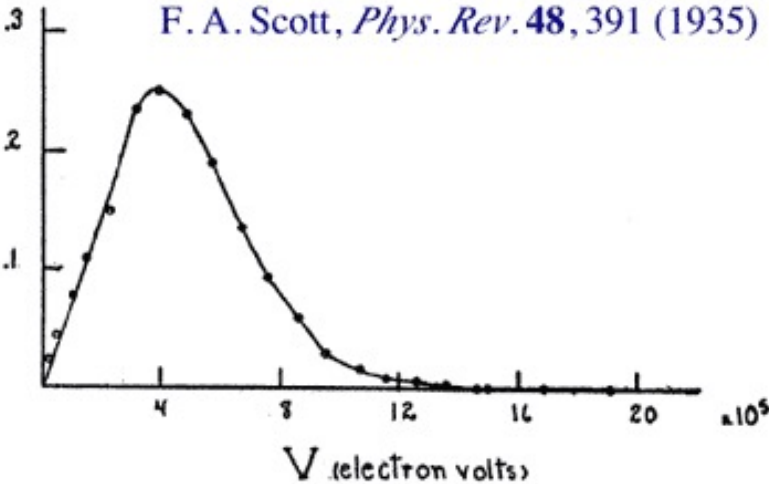
conservação  $E$  e  $\vec{P}$  ???



# O neutrão decai...



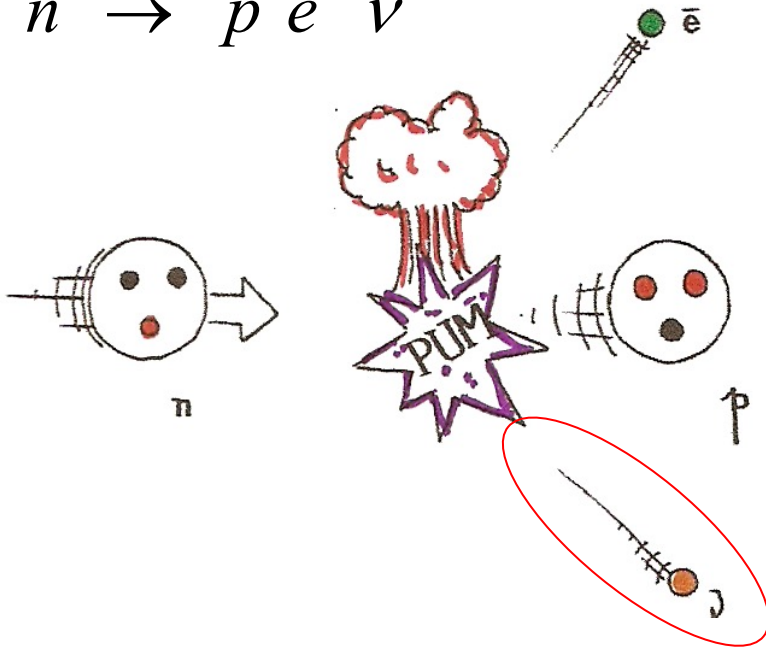
conservação  $E$  e  $\vec{P}$  ???



O neutrino !!!

# A força fraca

$$n \rightarrow p e^- \bar{\nu}$$



ANNO IV - VOL. II - N. 12      QUINDICINALE      31 DICEMBRE

## LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

### Tentativo di una teoria dell'emissione dei raggi "beta"

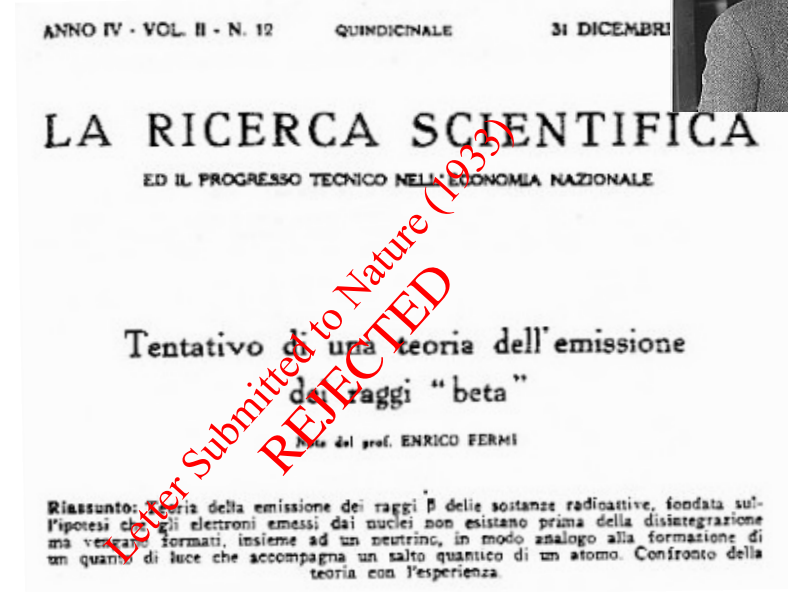
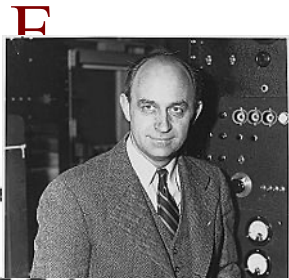
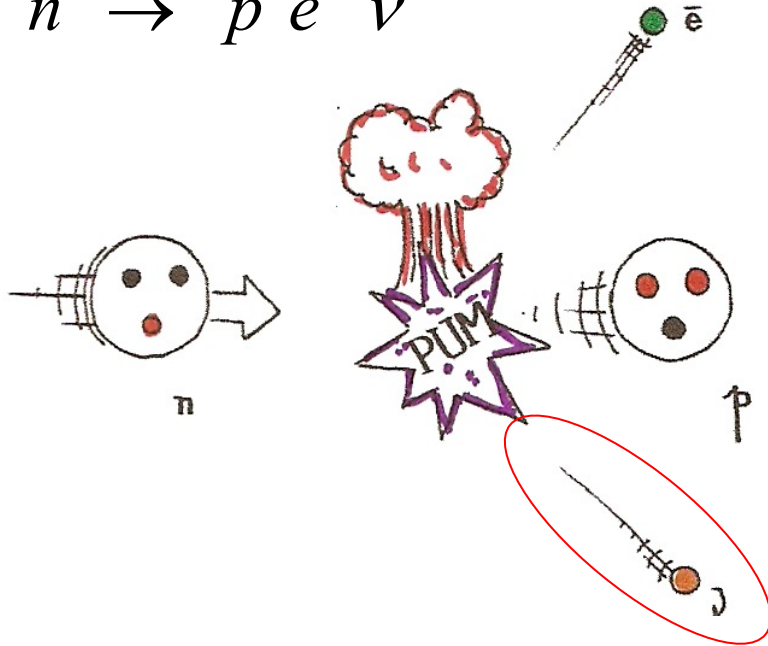
Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi  $\beta$  delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Nuovo Cimento and Zeitschrift fur Physik

# A força fraca

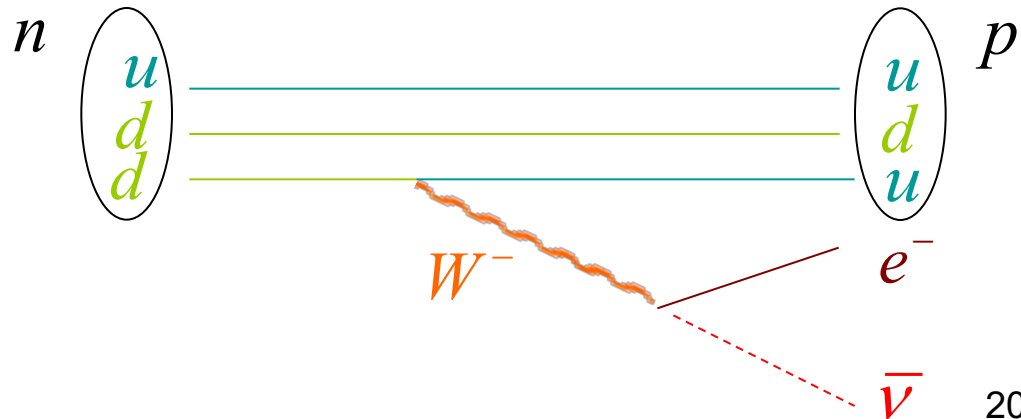
$$n \rightarrow p e^- \bar{\nu}$$



Nuovo Cimento and Zeitschrift fur Physik

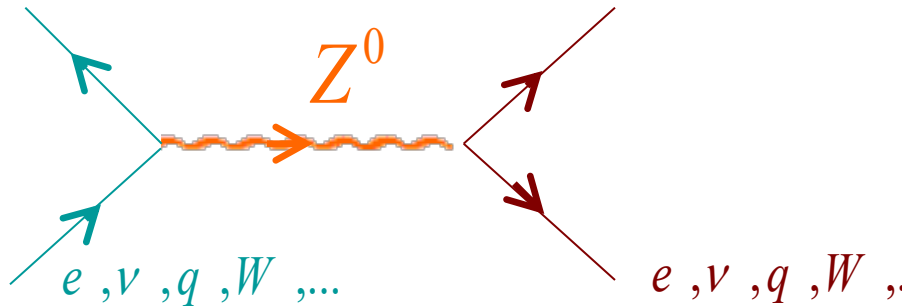
## A visão moderna !

Um quark **d** transforma-se num quark **u** emitindo um bosão **W** que “decai” num par electrão, anti-neutrino

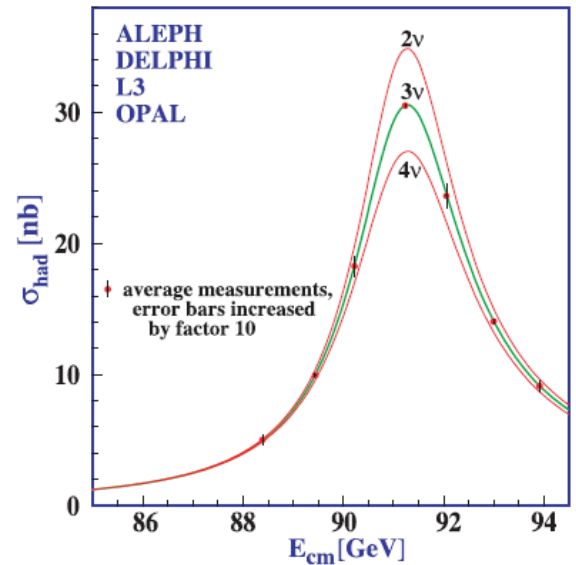
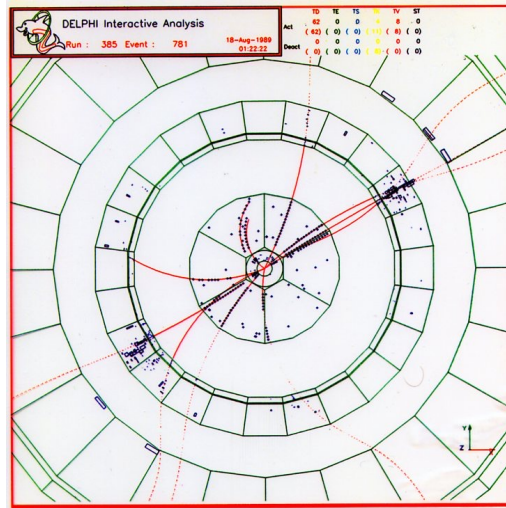
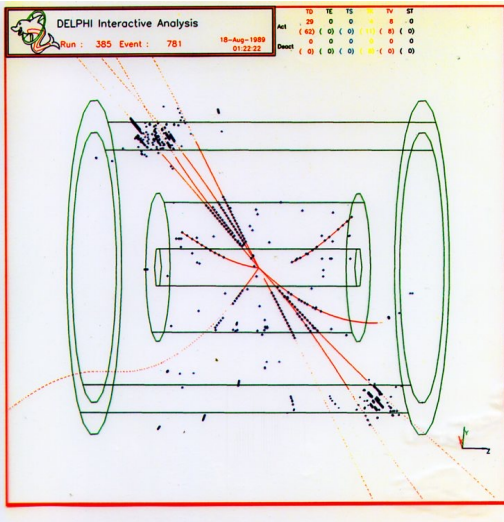
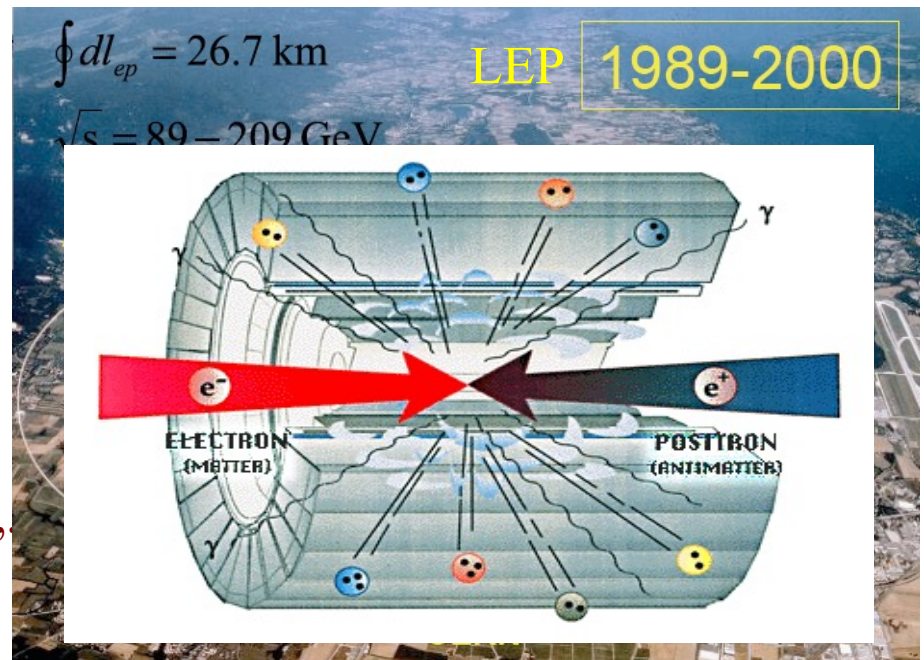


$Z^0$

Parceiro neutro dos  $W$ 's



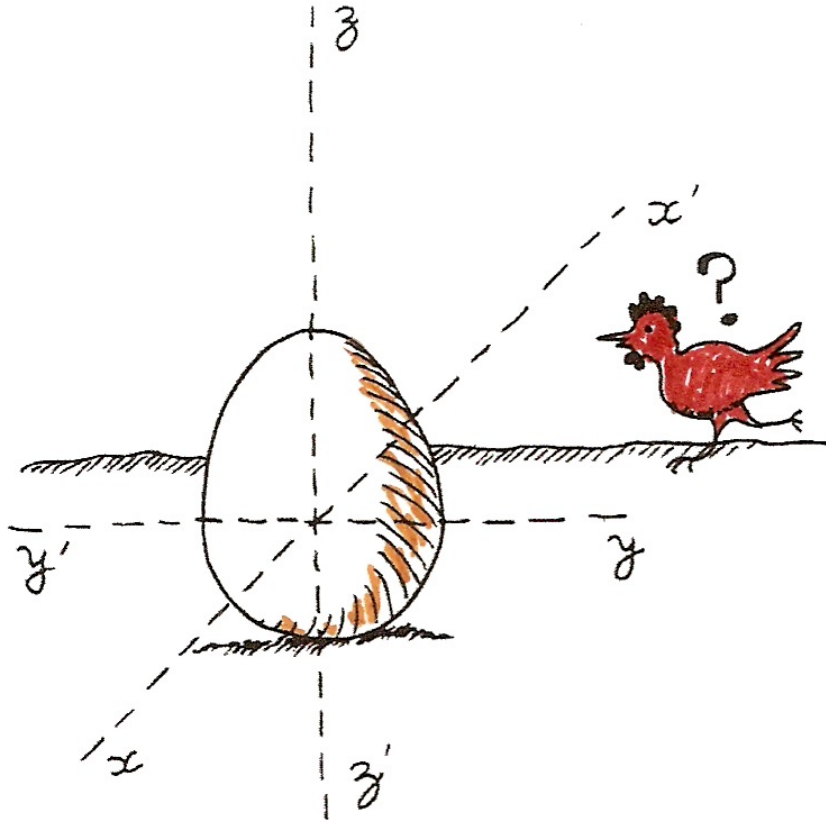
$e^+e^- \rightarrow q\bar{q}$



$M_Z = 91.1875 \pm 0.0021 \text{ GeV}/c^2$

# Simetrias !!!

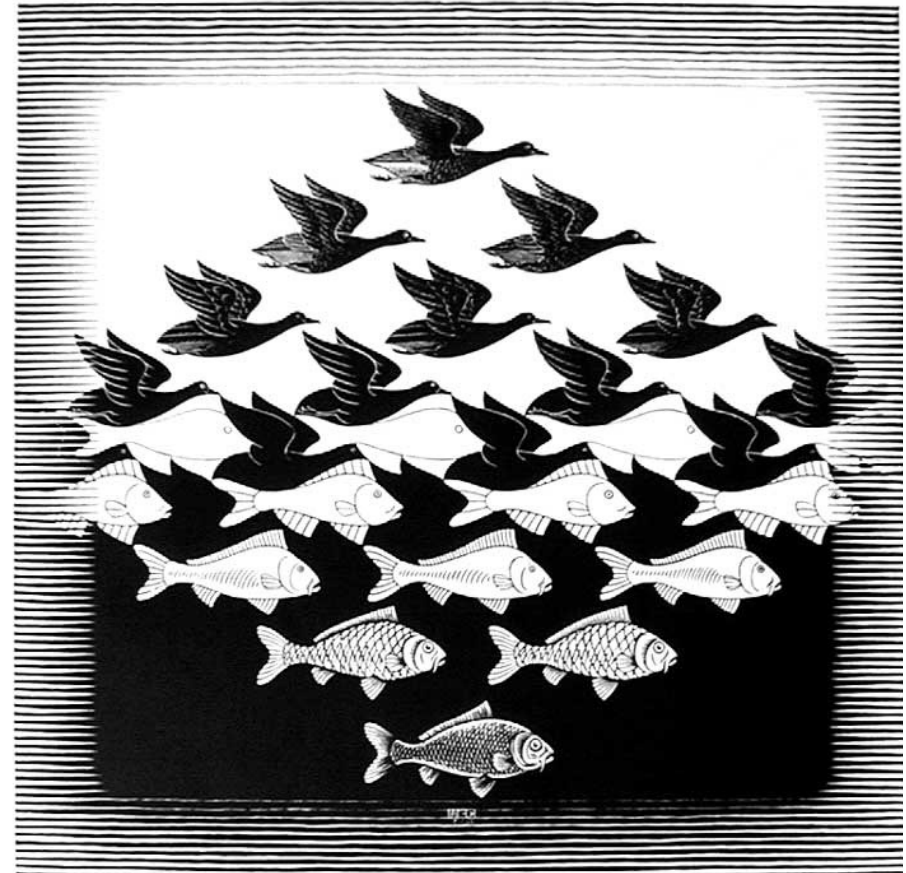
## Globais



Leis de conservação:  
Energia, Momento linear,  
Momento Angular

## Locais

M.C.Escher

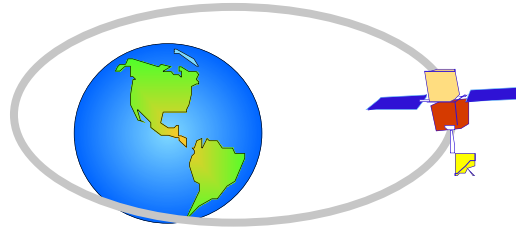


Campos de interacção:  
Electromagnético, fraco, forte,  
gravítico???,

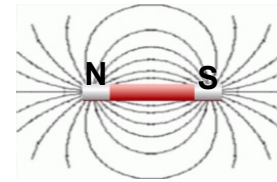
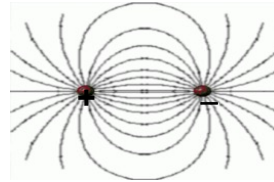
# As interações

## Unificação e Simetrias (locais)

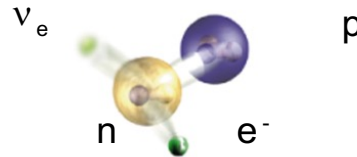
gravíticas



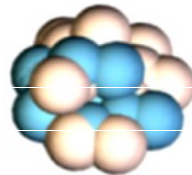
electromagneticas



fracas



fortes



# Mas as Partículas têm massa

em  $eV/c^2$

$$m_\nu \sim 10^{-1}$$

$$m_\gamma = 0$$

$$m_e \sim 500 \cdot 10^3$$

$$m_W \sim 80 \cdot 10^9$$

$$m_u \sim 5 \cdot 10^6$$

$$m_Z \sim 91 \cdot 10^9$$

$$m_t \sim 174 \cdot 10^9$$

$$m_H \sim 125 \cdot 10^9$$

...

Como é que as massas são geradas ???

Por é que são tão diferentes ???

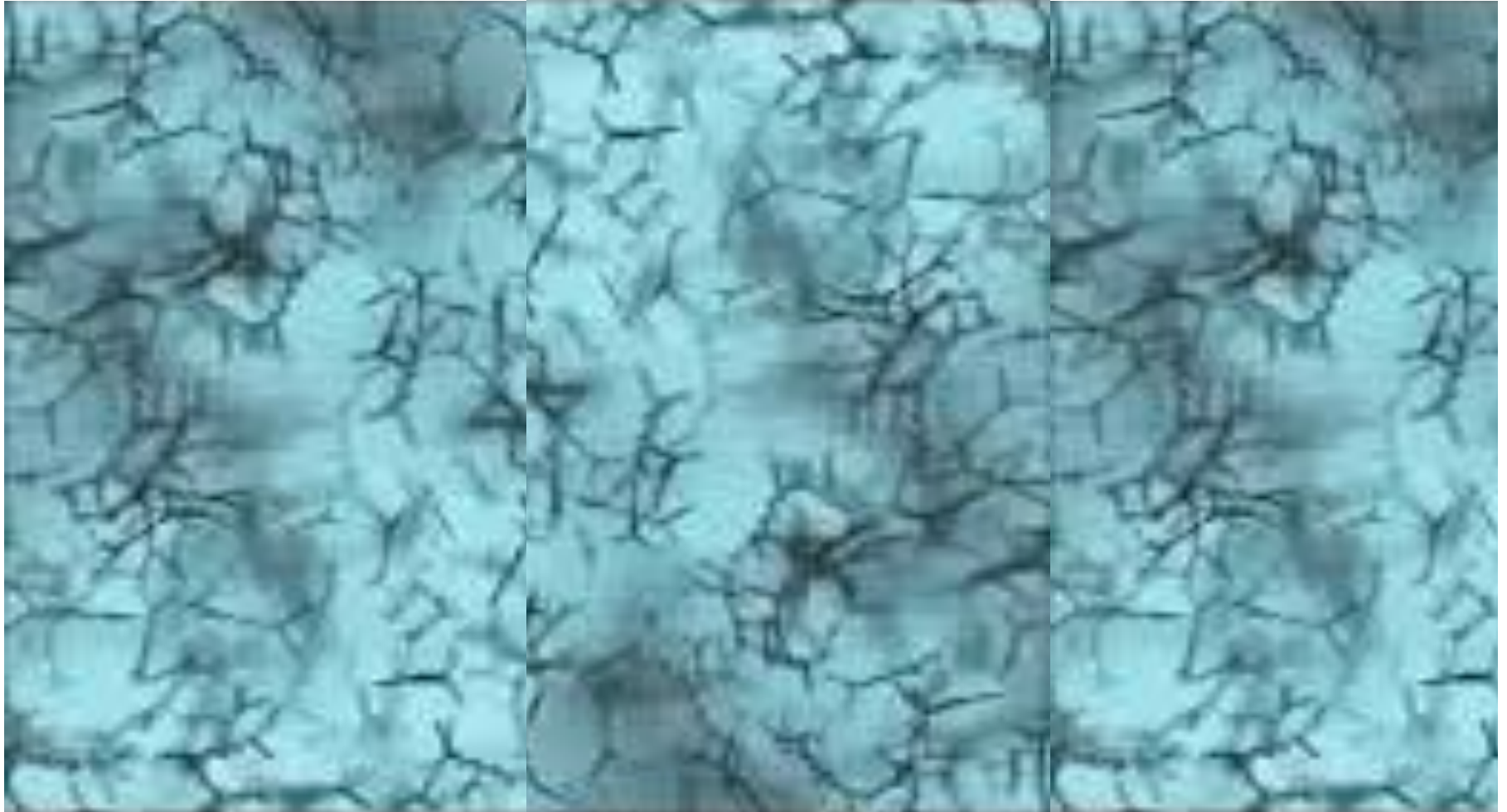
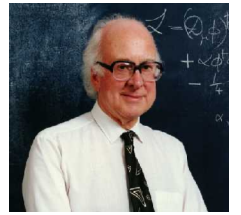
$$1 eV \sim 1.8 \cdot 10^{-36} Kg$$



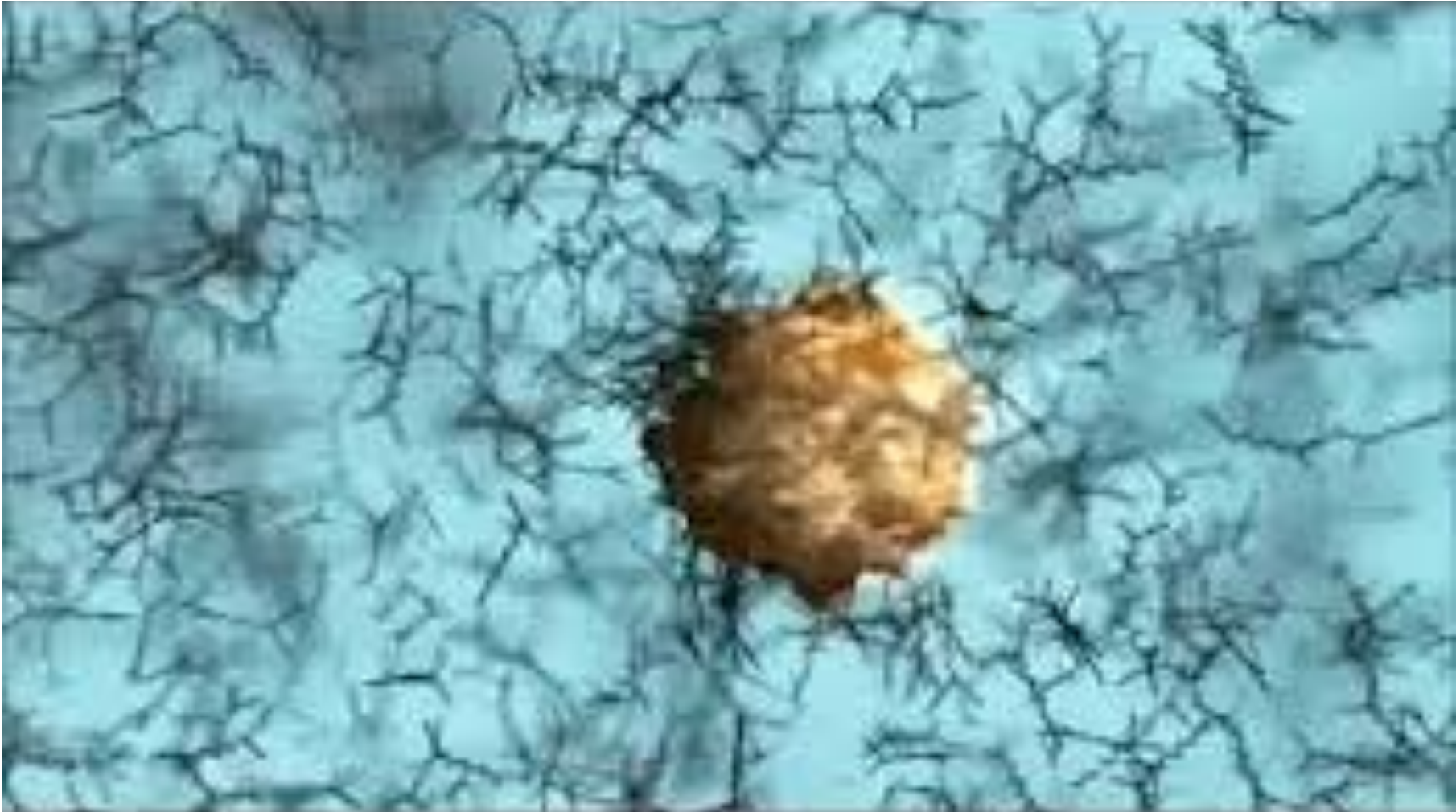
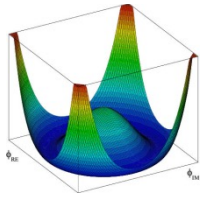
# O campo de Higgs

Higgs, Englert, Brout - 1964

Peter Higgs

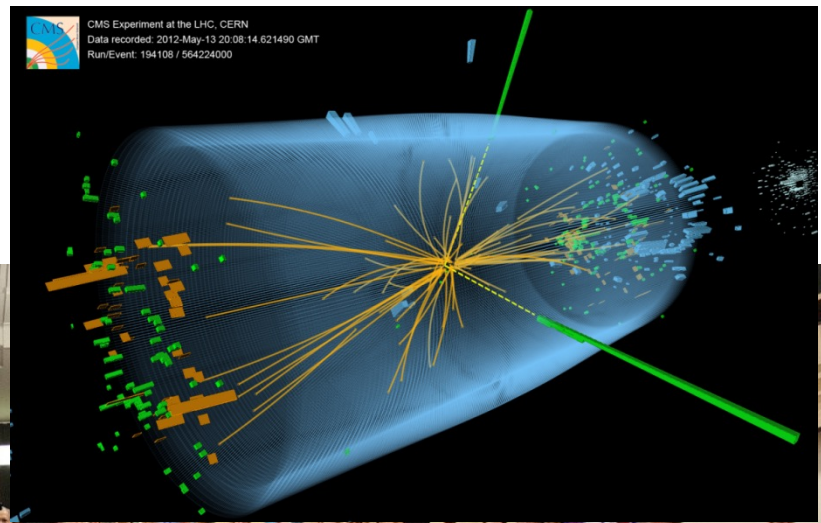


# O mecanismo de Higgs



A massa é gerada na interacção com o campo

# O bóson de Higgs



4 Julho 2012: CERN

# As partículas elementares hoje!

Three Generations  
of Matter (Fermions) spin  $\frac{1}{2}$

	I	II	III
mass →	2.4 MeV	1.27 GeV	173.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top
	Left Right	Left Right	Left Right
Quarks	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom
	Left Right	Left Right	Left Right
Leptons	$0$	$0$	$0$
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino
	Left Right	Left Right	Left Right
	0.511 MeV	105.7 MeV	1.777 GeV
	$-1$	$-1$	$-1$
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau
	Left Right	Left Right	Left Right

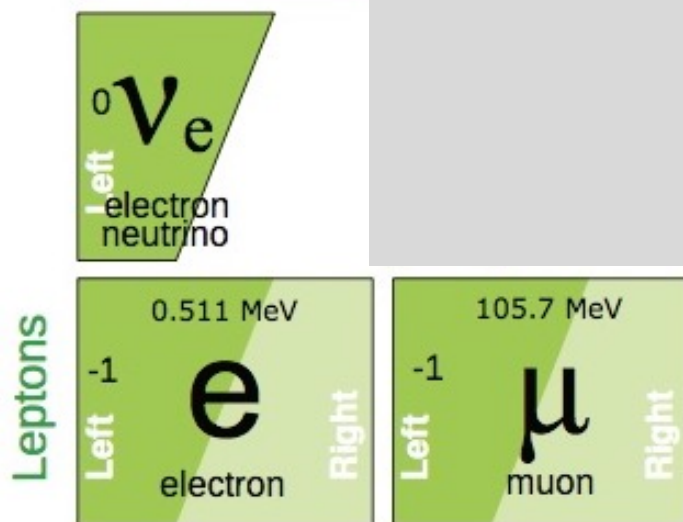
Bosons (Forces) spin 1

0	<b>g</b> gluon
0	<b><math>\gamma</math></b> photon
91.2 GeV	$0$ <b>Z</b> weak force
80.4 GeV	$\pm 1$ <b>W<sup>±</sup></b> weak force

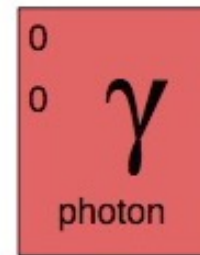
126 GeV	<b>H</b> Higgs boson
0	spin 0

# As partículas elementares em 1957

Three Generations  
of Matter (Fermions) spin  $\frac{1}{2}$

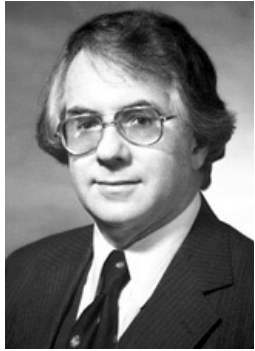


Bosons (Forces) spin 1



# O Modelo Padrão: $SU(2)_L \otimes U_1$

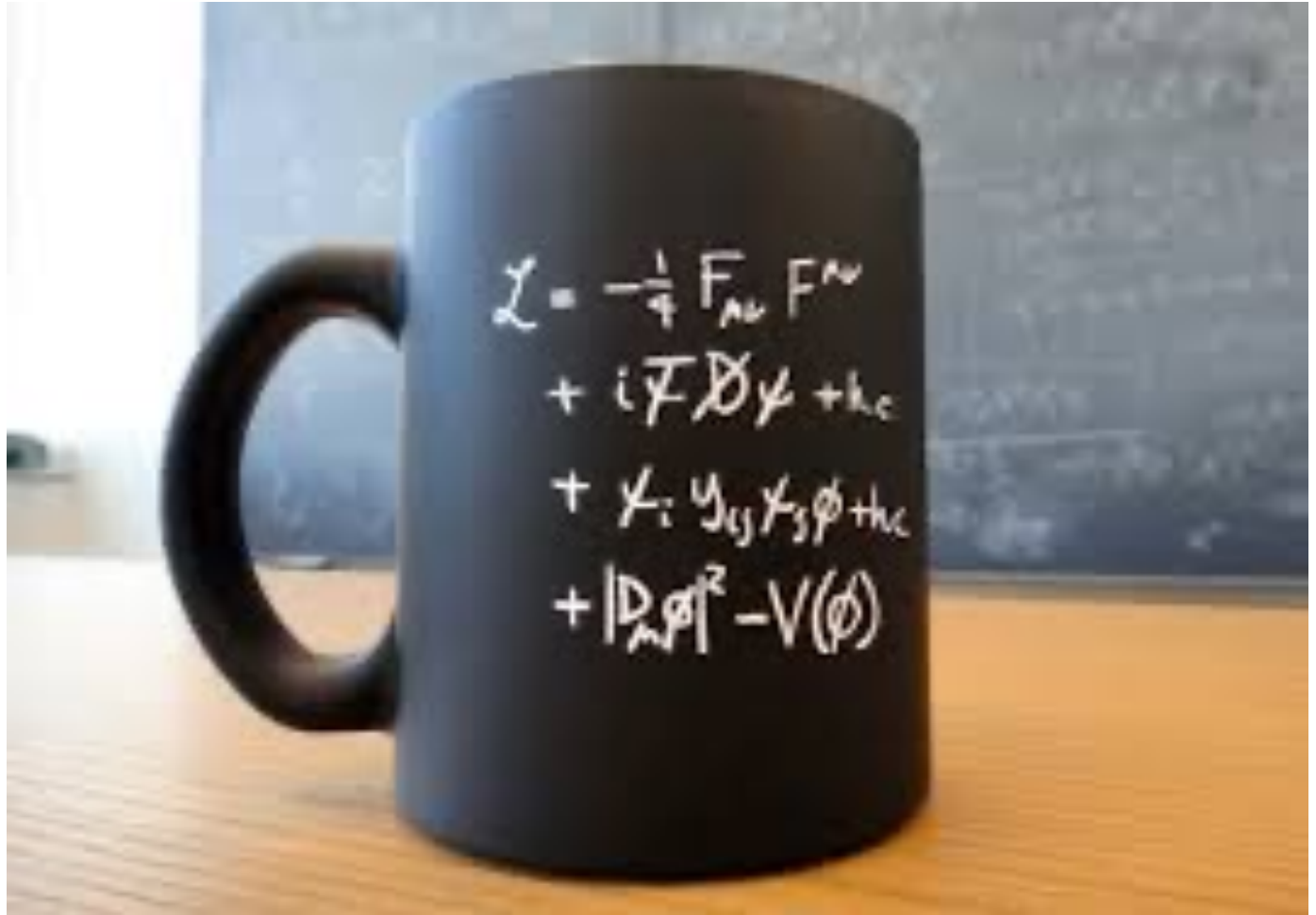
Glashow



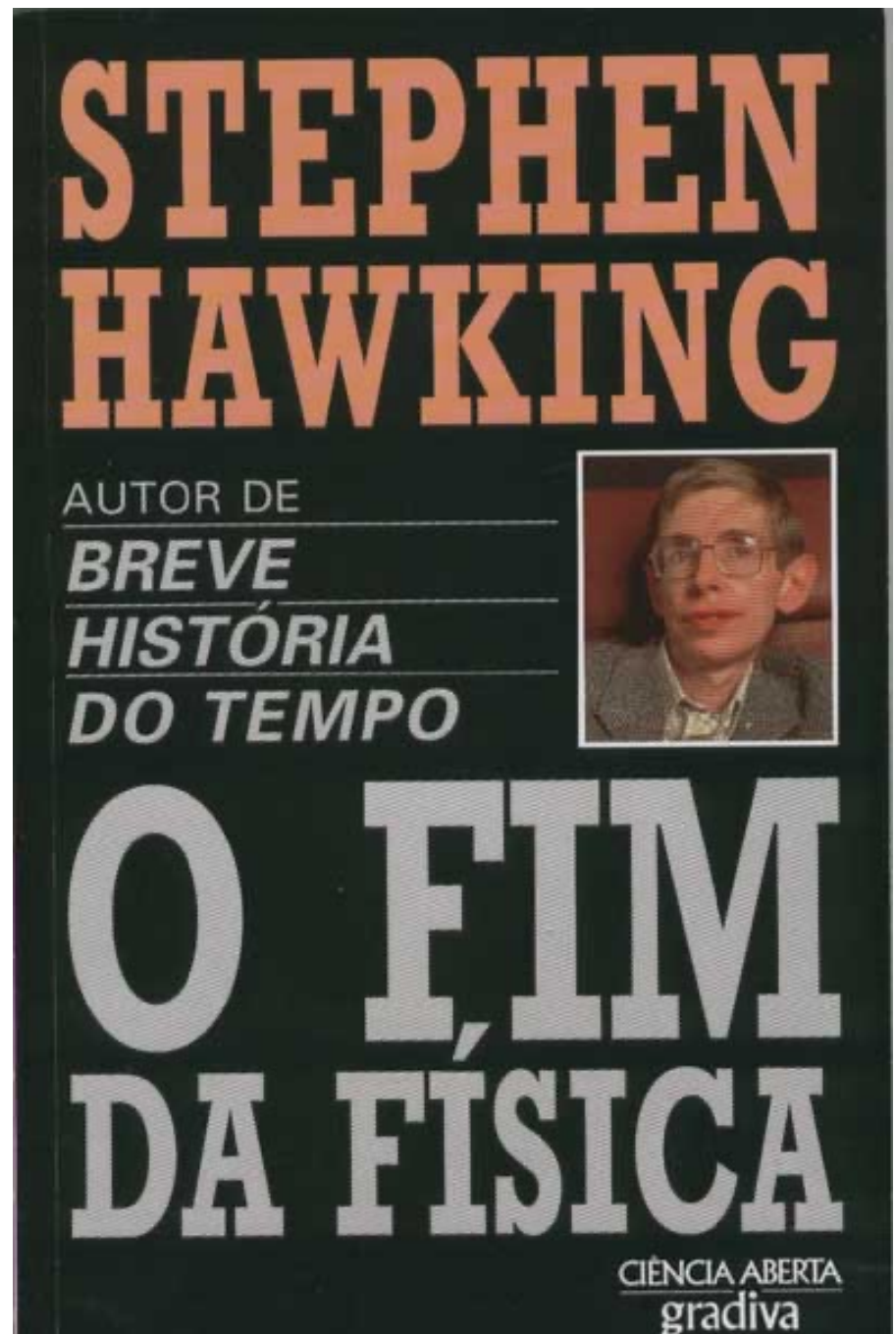
Salam



Weinberg



O fim da Física ?



# A matéria luminosa

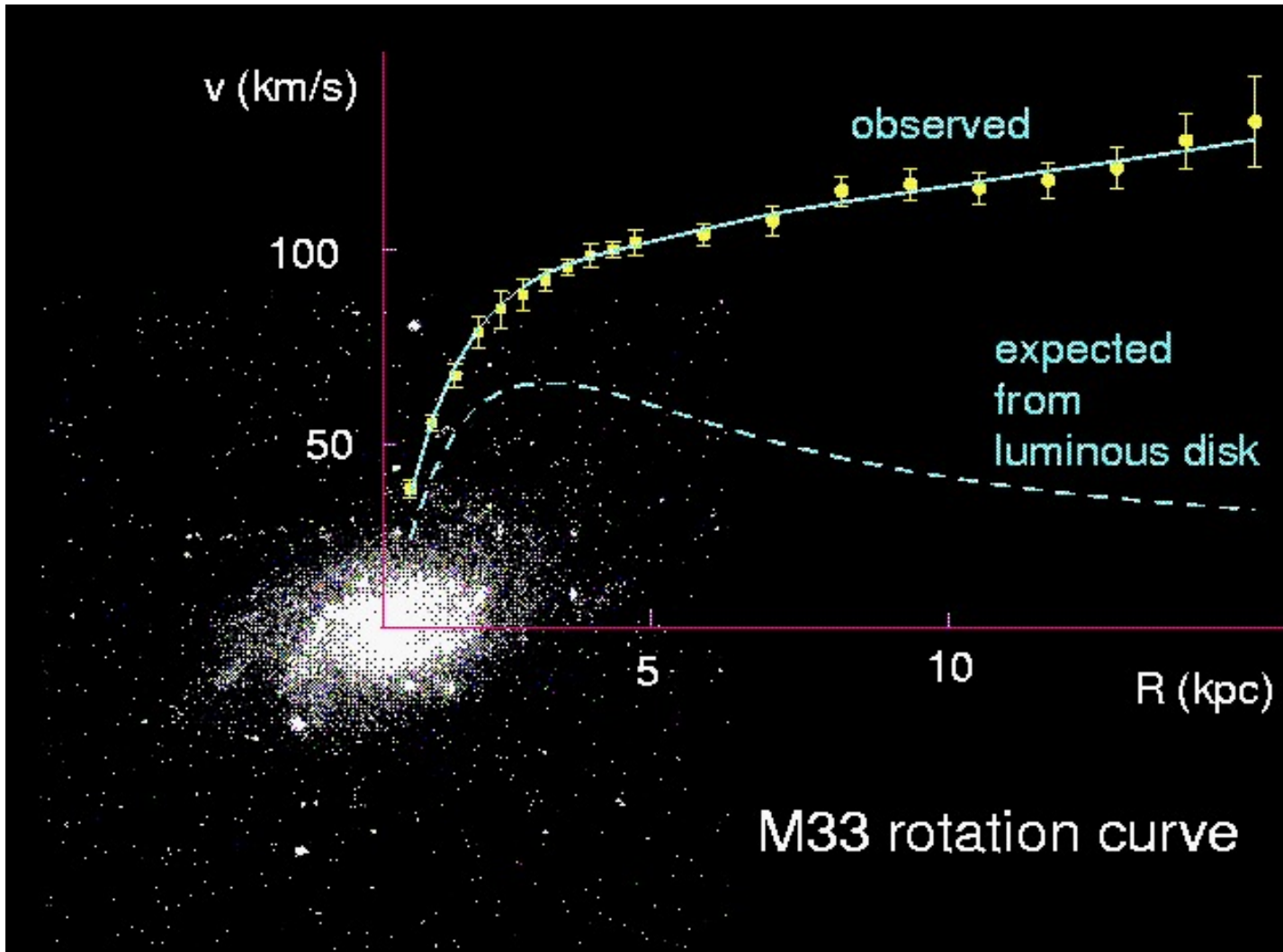




# A velocidade de rotação das estrelas periféricas

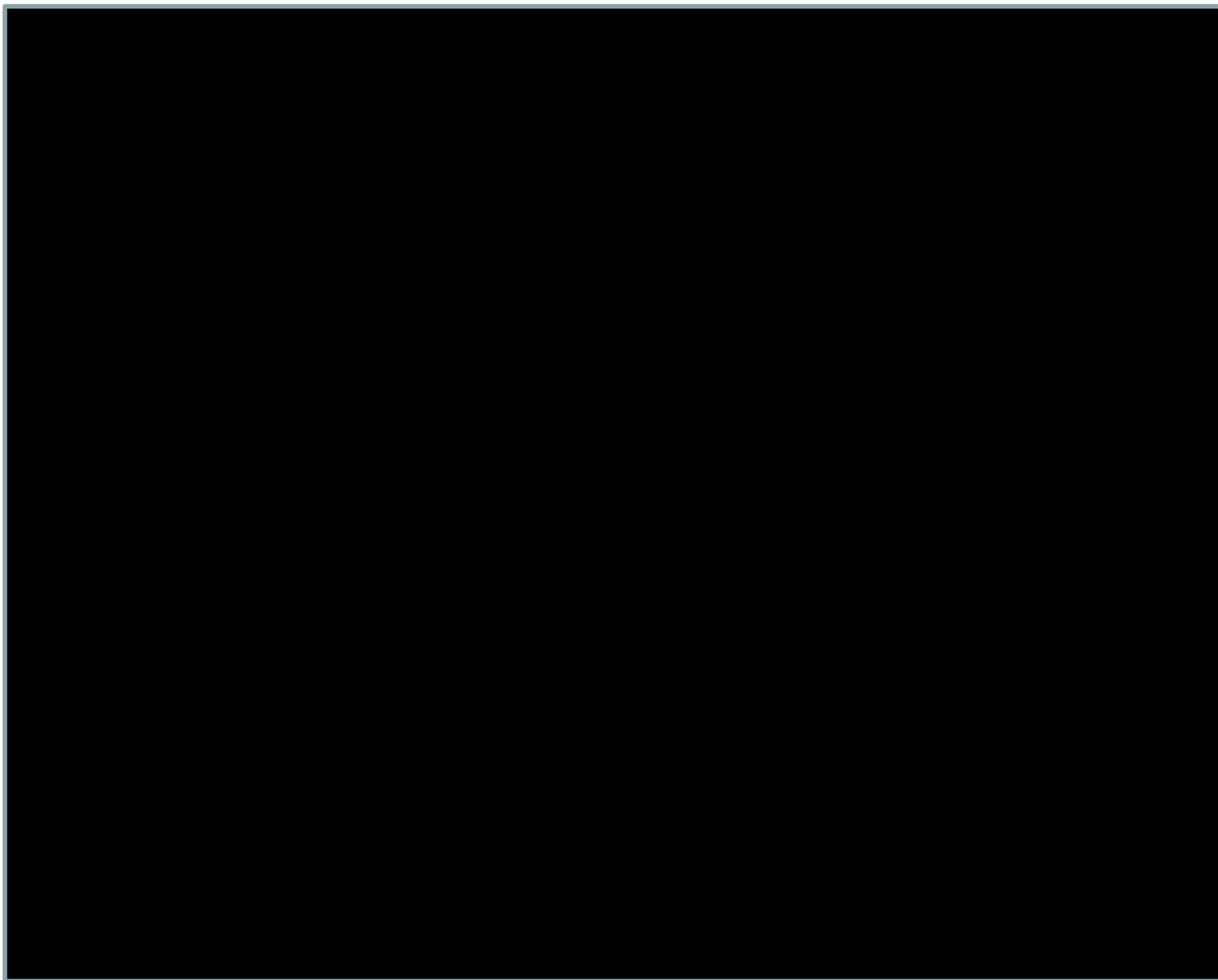


# Rodar em torno do centro da galáxia

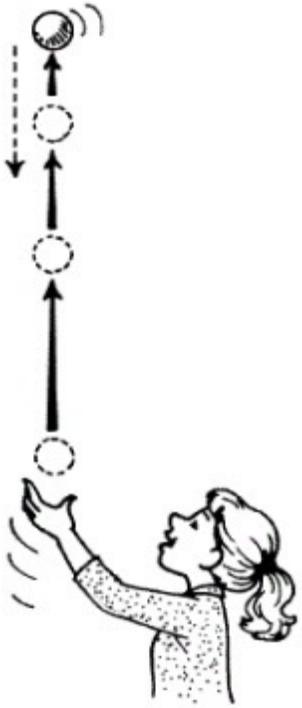


Um halo de matéria escura!

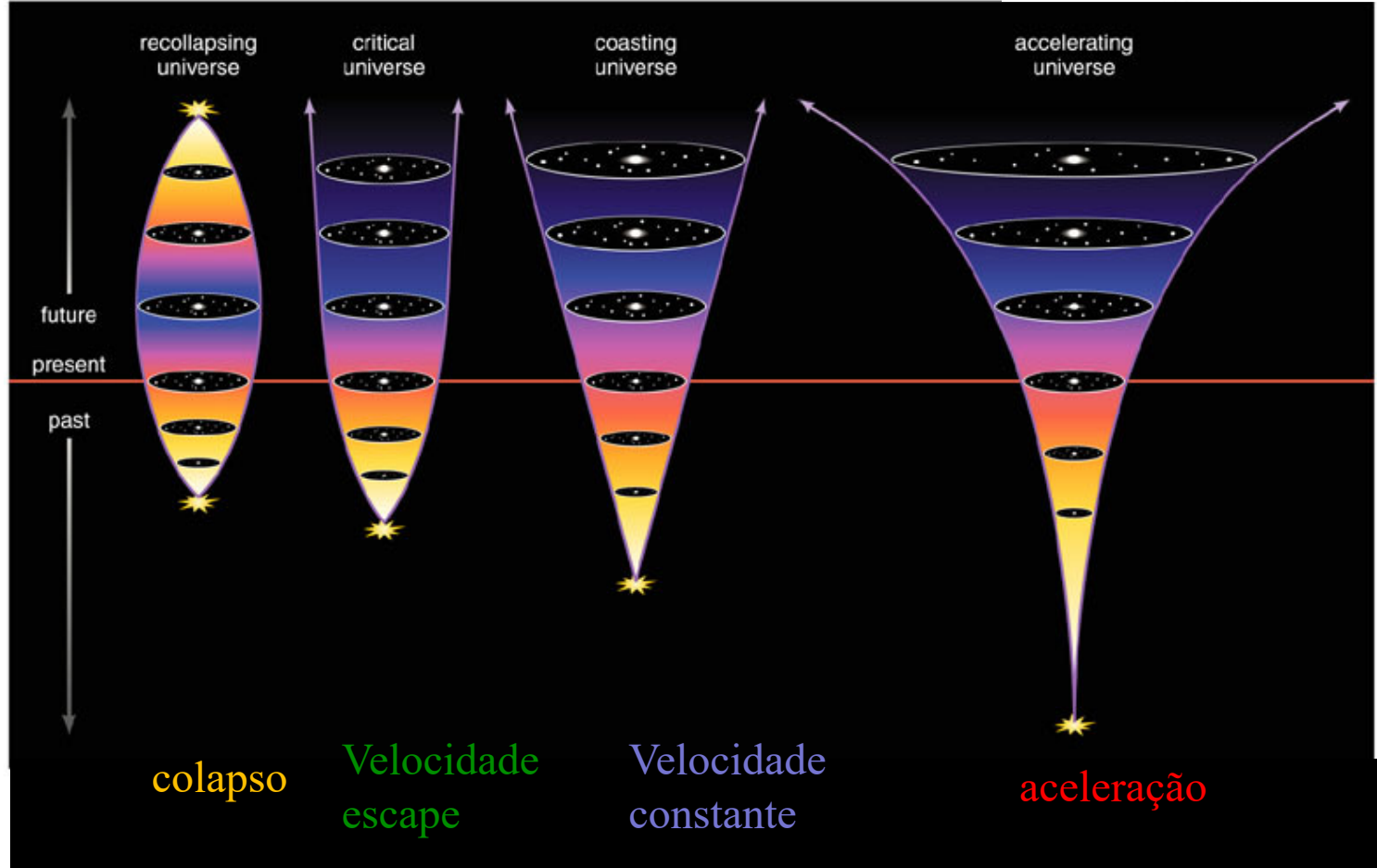
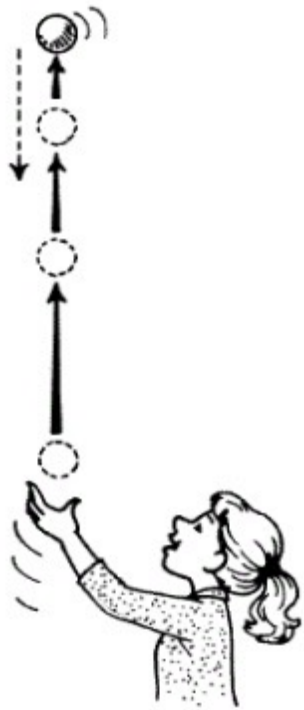
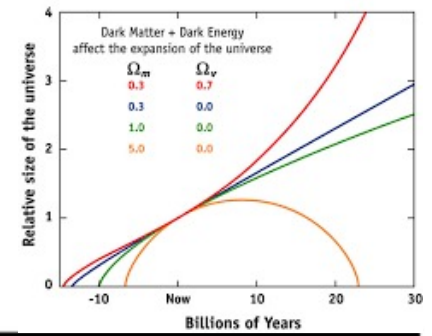
# A matéria escura



# A expansão do Universo

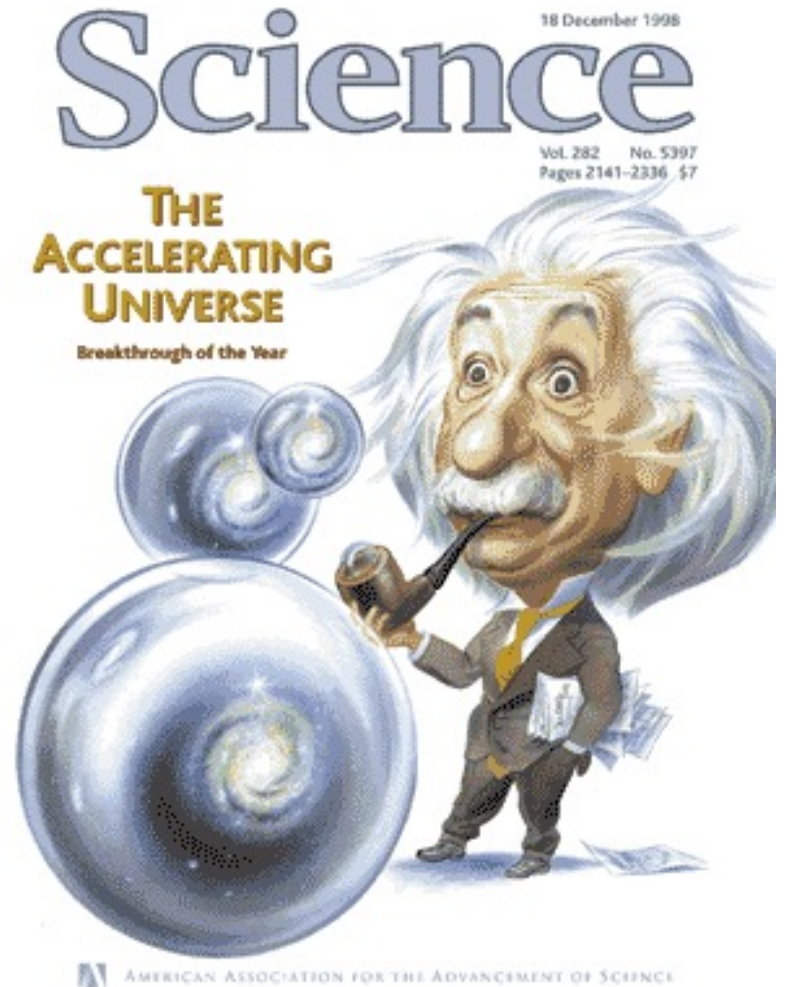
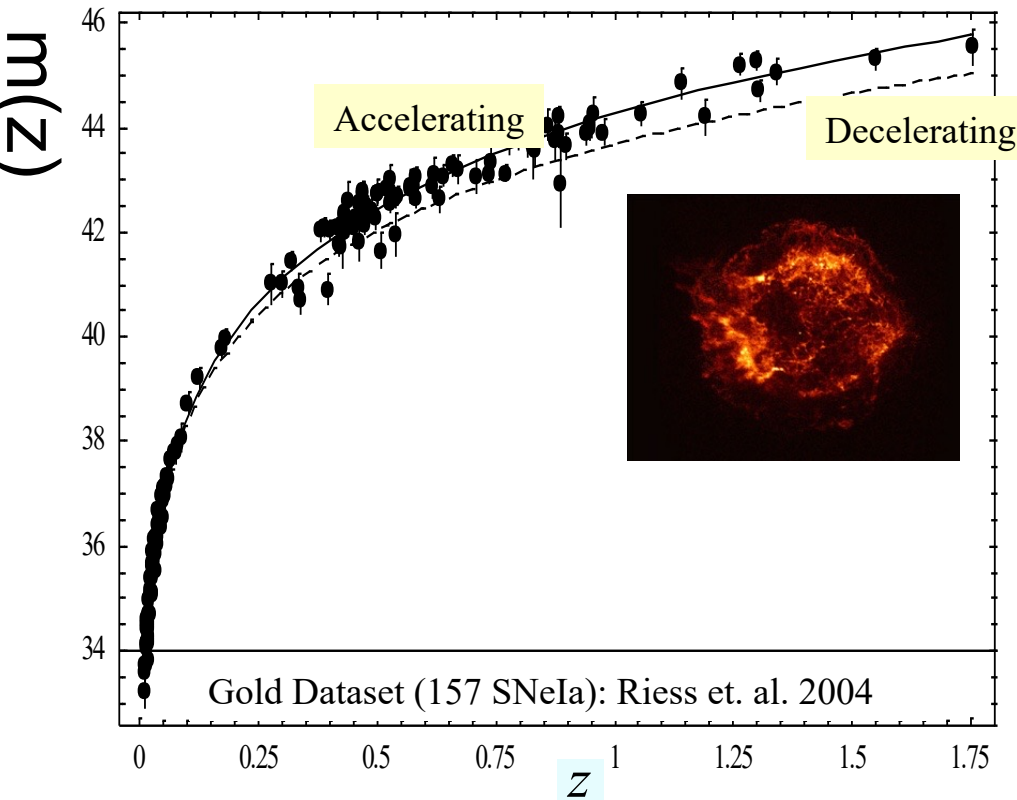


# A expansão do Universo



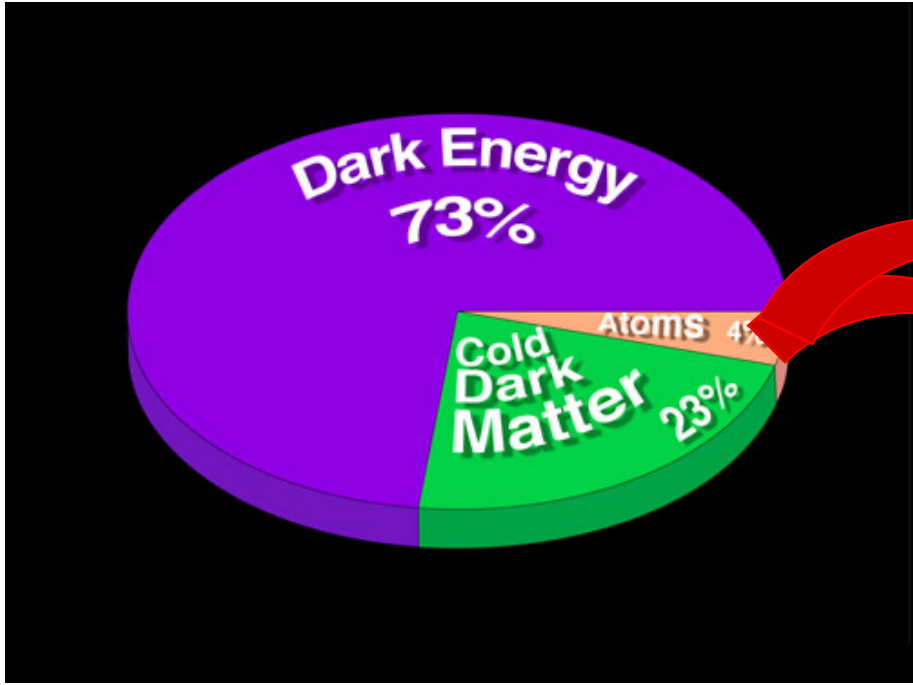
# A energia escura !

## Diagrama de Hubble



O Universo encontra-se numa expansão acelerada !!!  
Energia escura – anti-gravítica

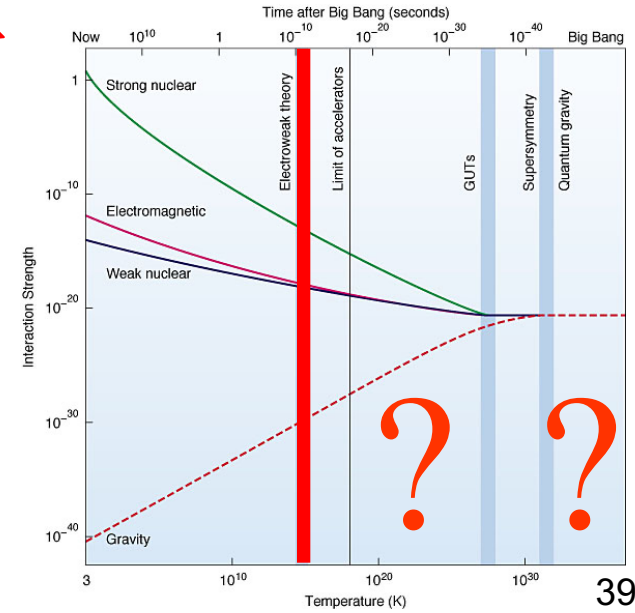
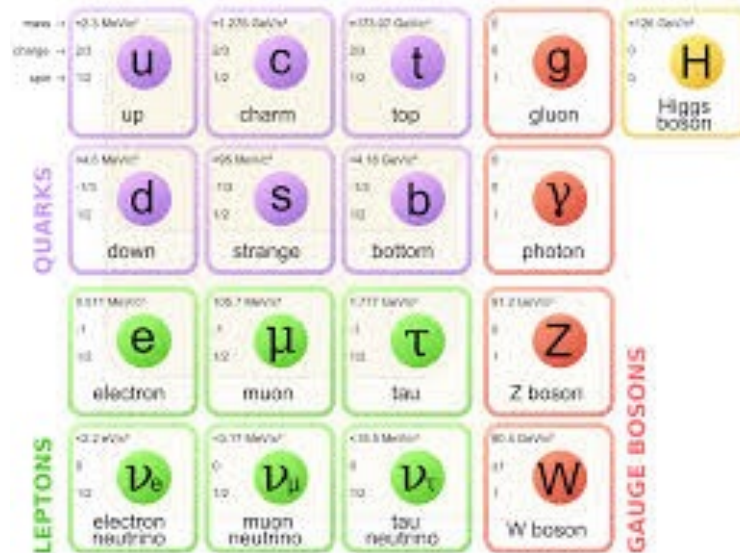
# Fronteiras do nosso (des)conhecimento



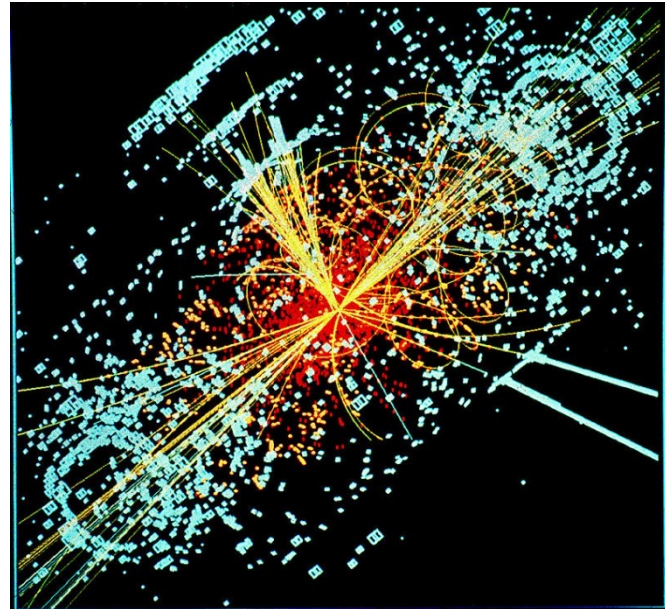
O modelo padrão

$E_{CM} \sim 1 \text{ TeV}$

$R \sim 10^{-18} \text{ m}$



# Olhar o Universo no sec. XXI

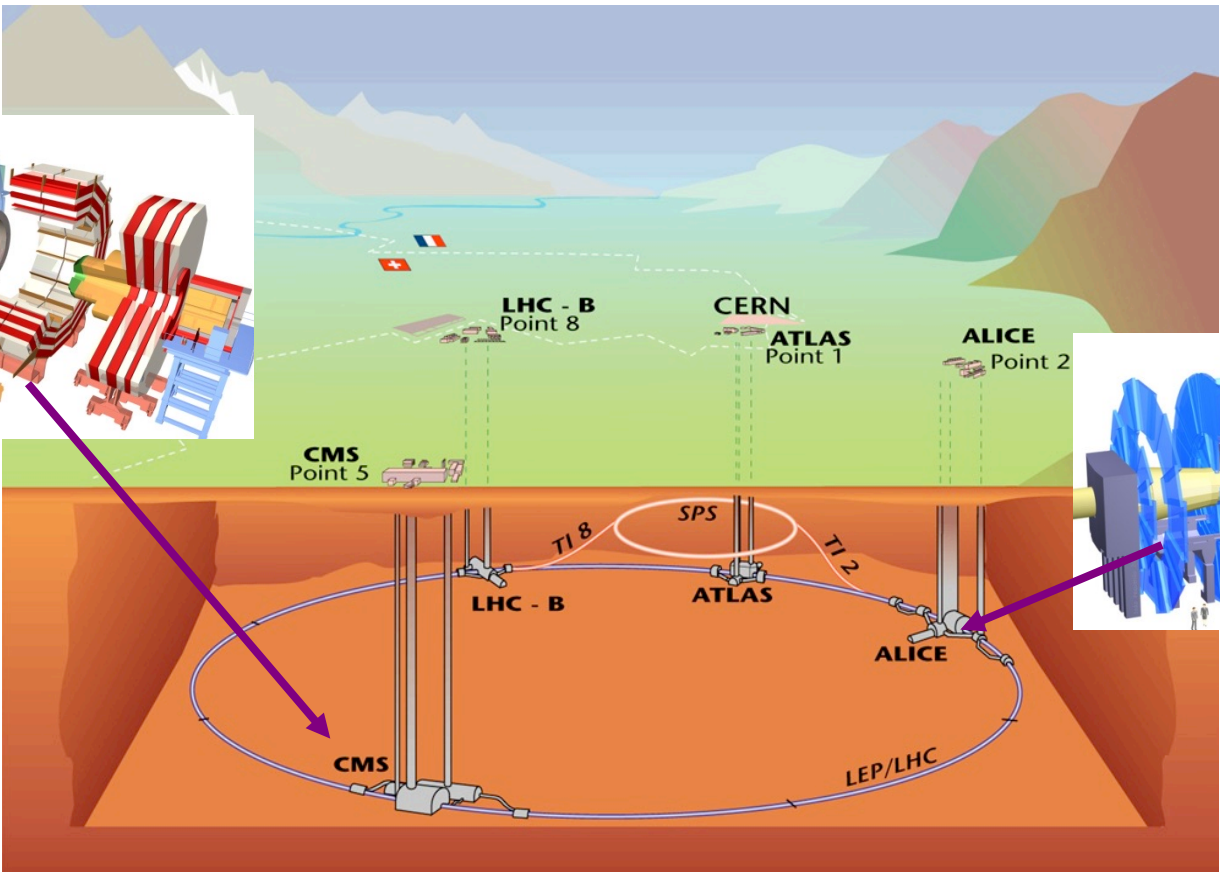
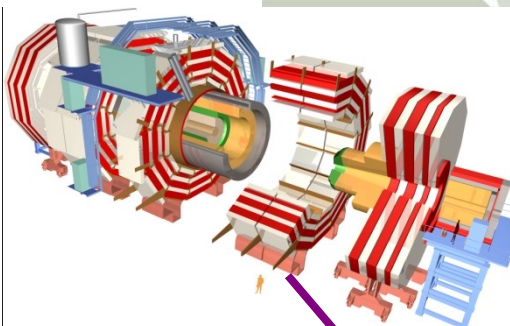




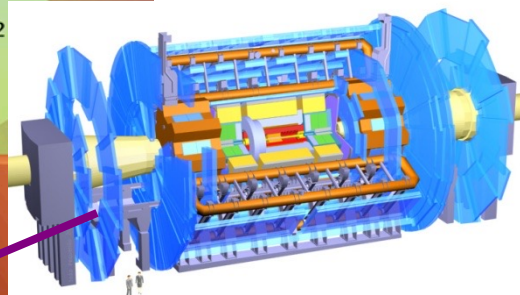
# O LHC no CERN



CMS

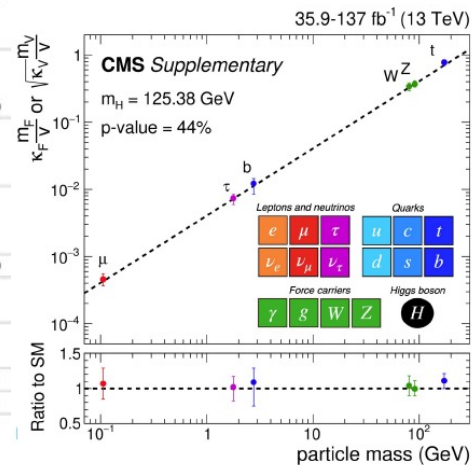
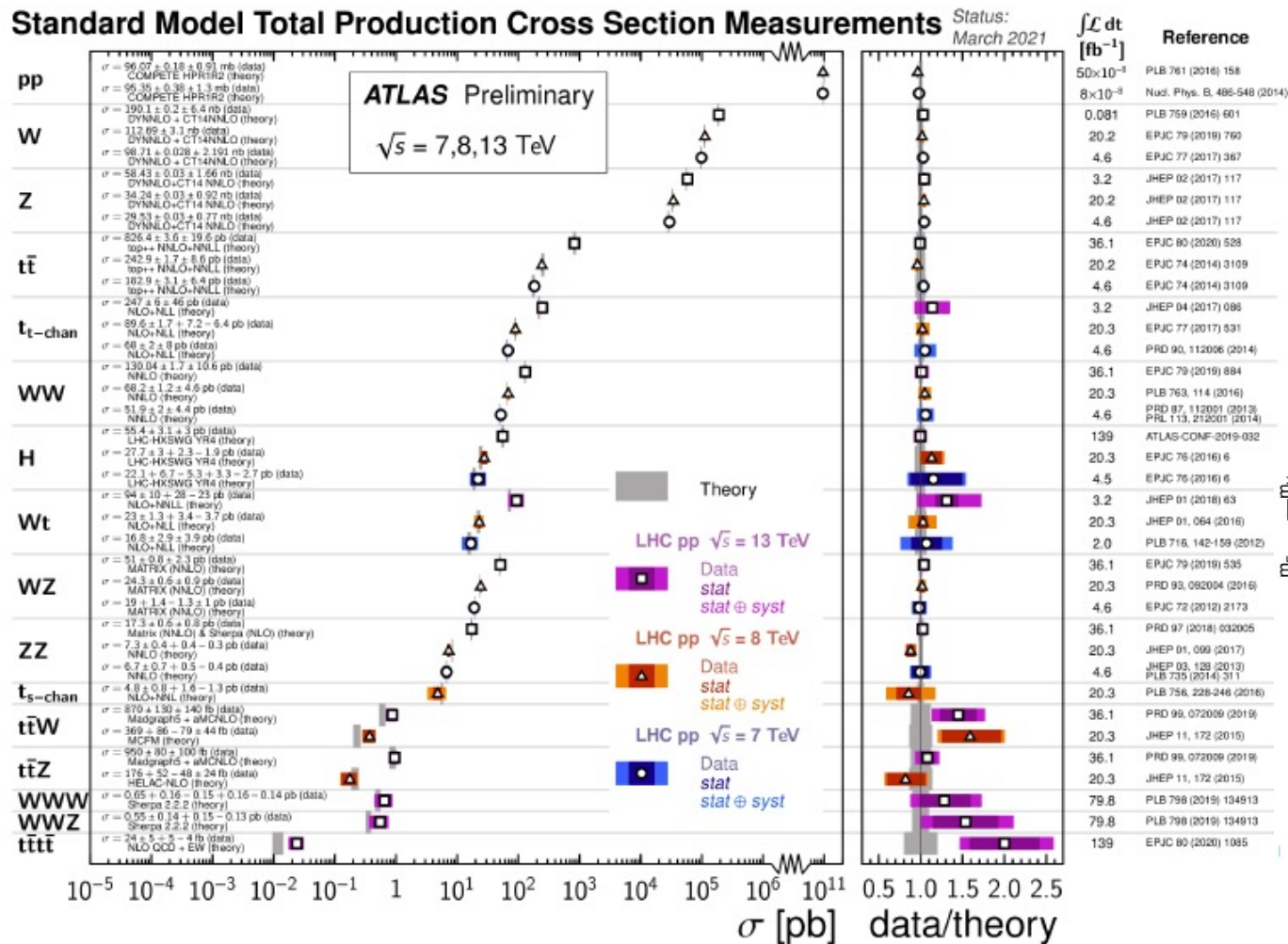


ATLAS



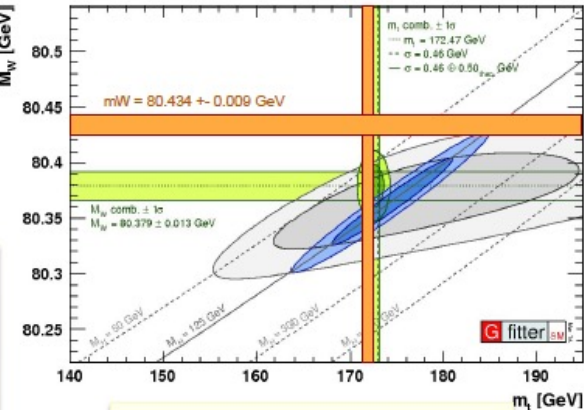
# SM (Particle Physics) extensively tested

## 10 years of LHC

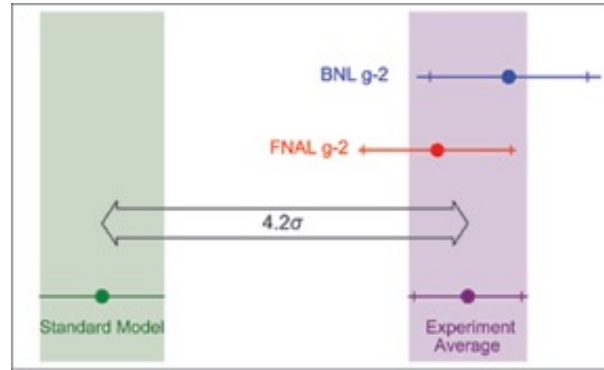


# But some “Tensions” and Discoveries

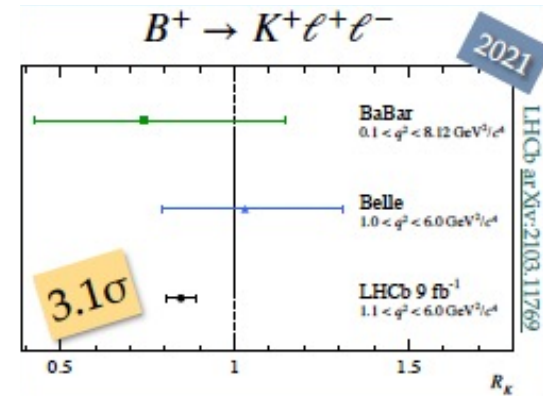
$M_W \sim 7\sigma$



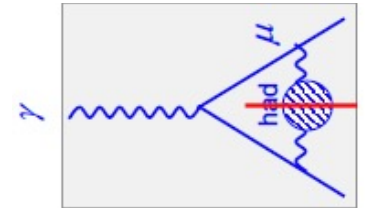
$g-2 \sim 4\sigma$



Heavy decays  $\sim 3\sigma$



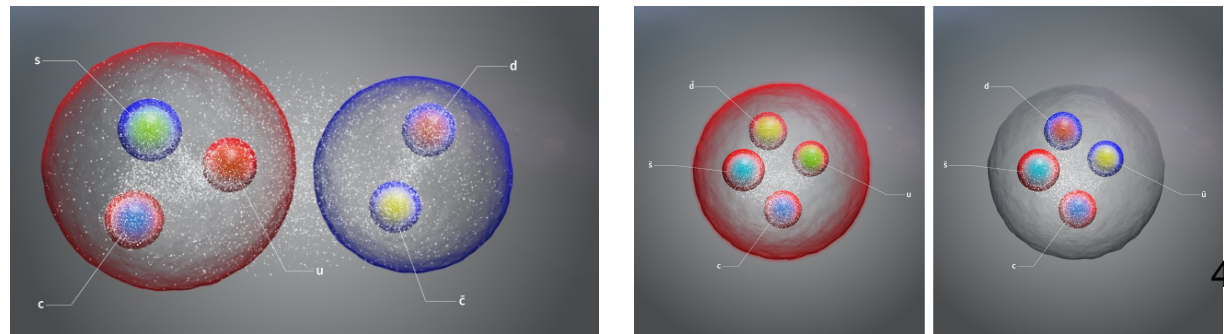
But be aware of the experimental and theoretical systematics, namely of the Hadronic Vacuum Polarization:



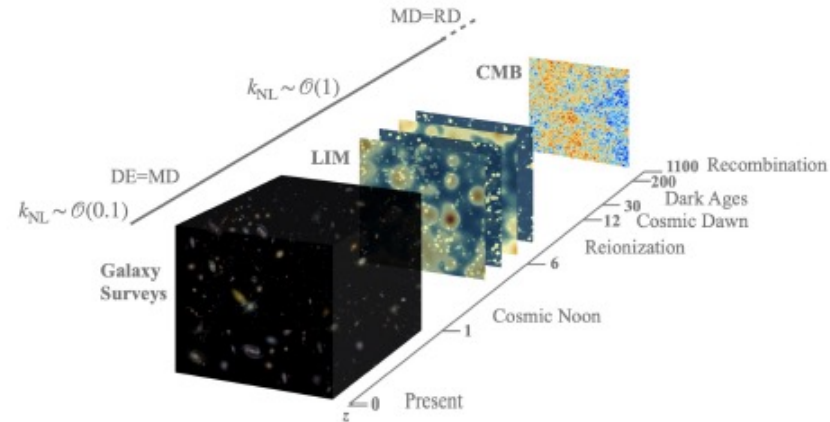
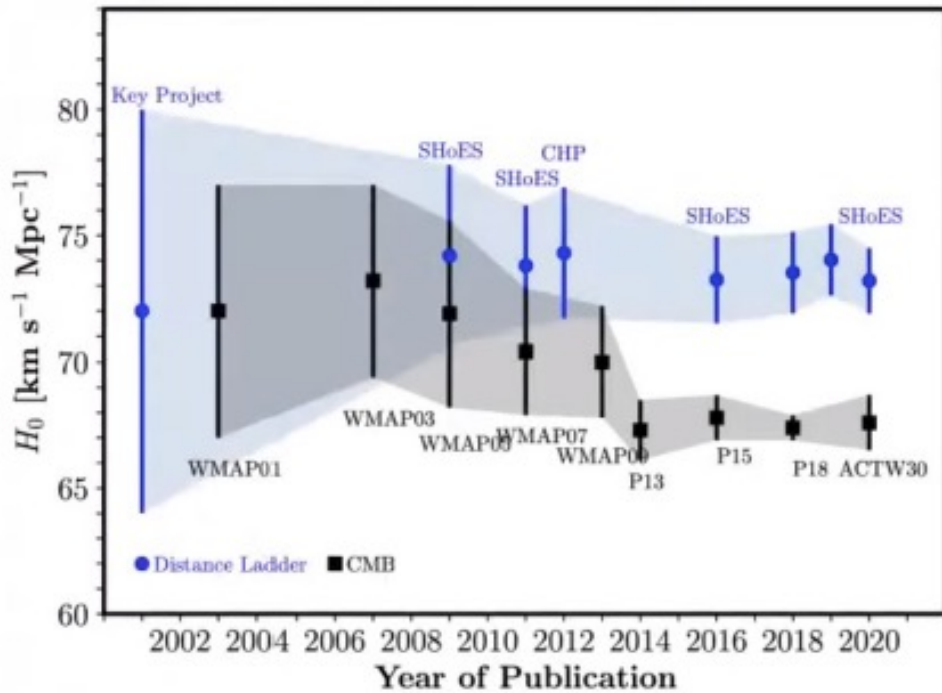
## Tetra and Penta quarks

e.g. LHCb - this week announcement ...

A zoo of Exotic hadrons



# “Tensions” also in the Skies ...



Euclid mission (ESA)  
launch planned for 2023.

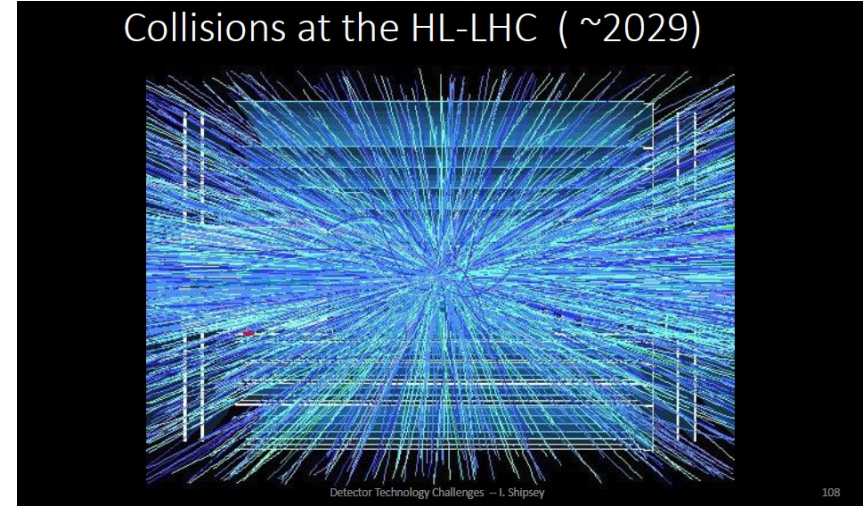
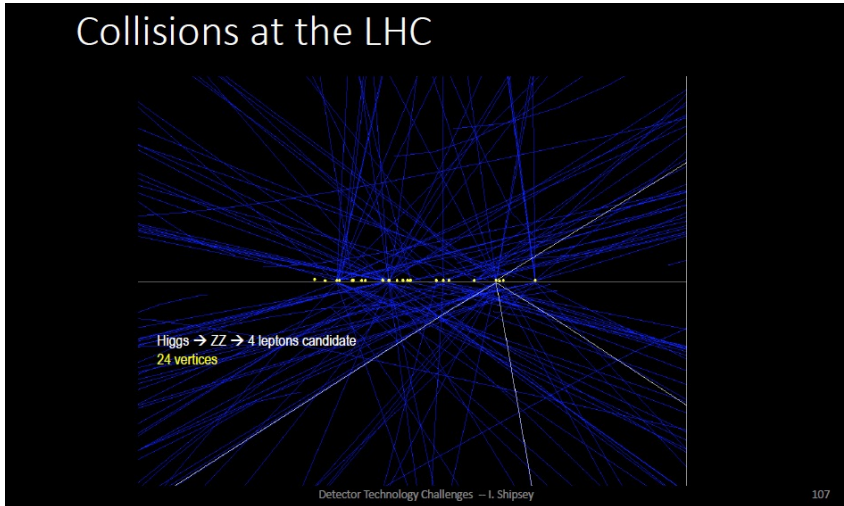
The crisis of the Hubble constant: CMB  
vs Expansion rate measurements.

Problems with the measurements or New  
Physics?

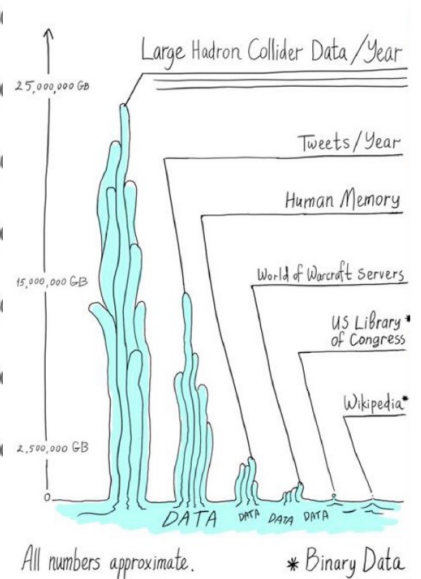
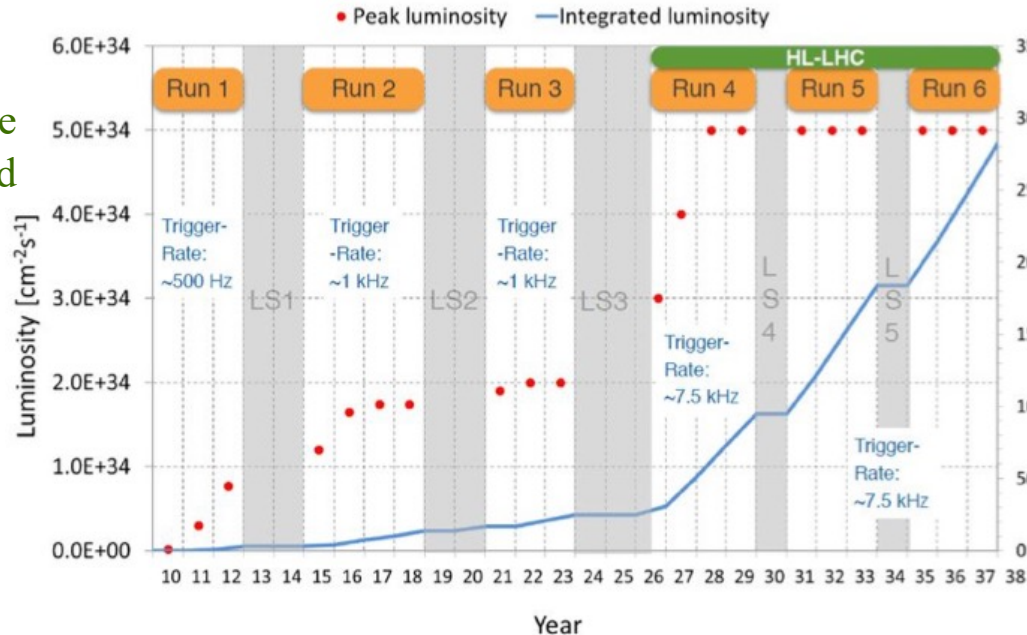


# LHC/ HL-LHC

## An enormous challenge

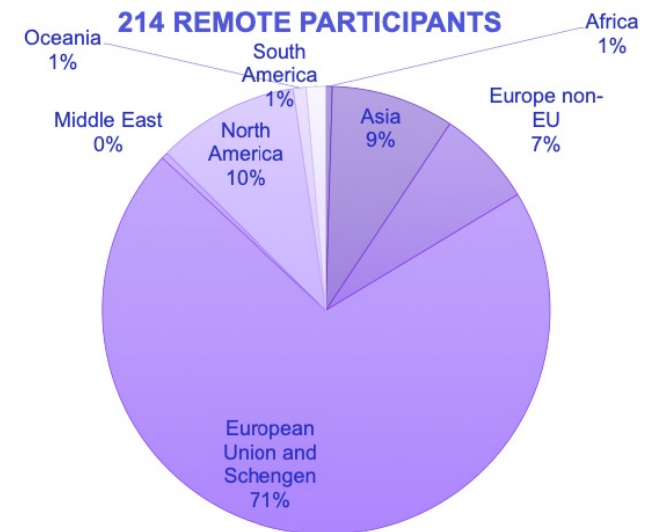
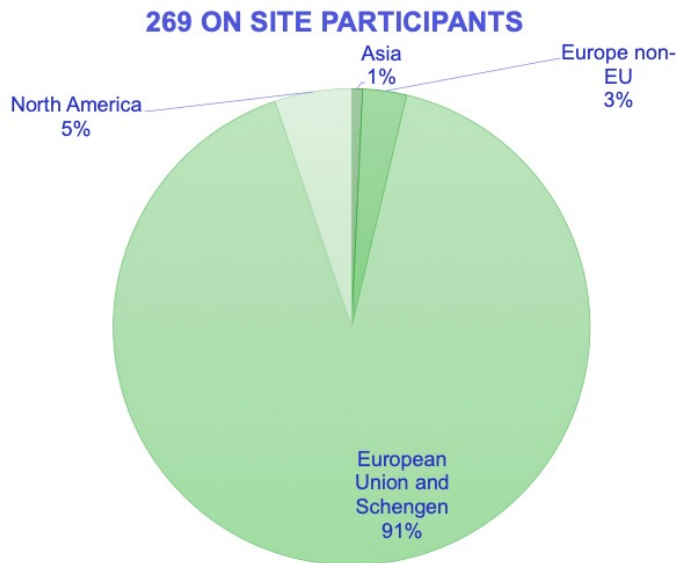
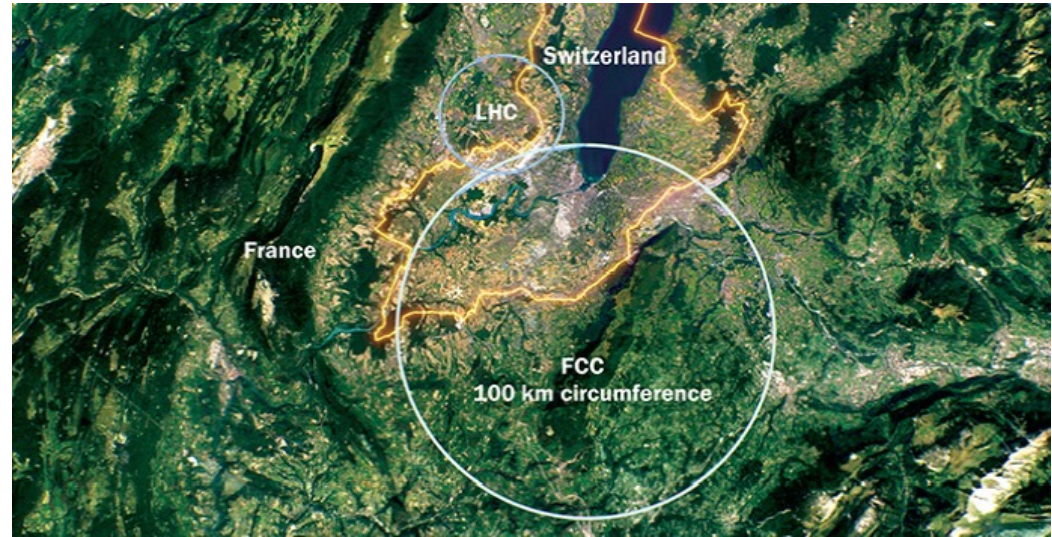


Multiply by ~20 the present integrated luminosity



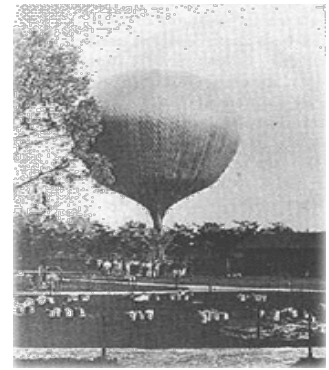
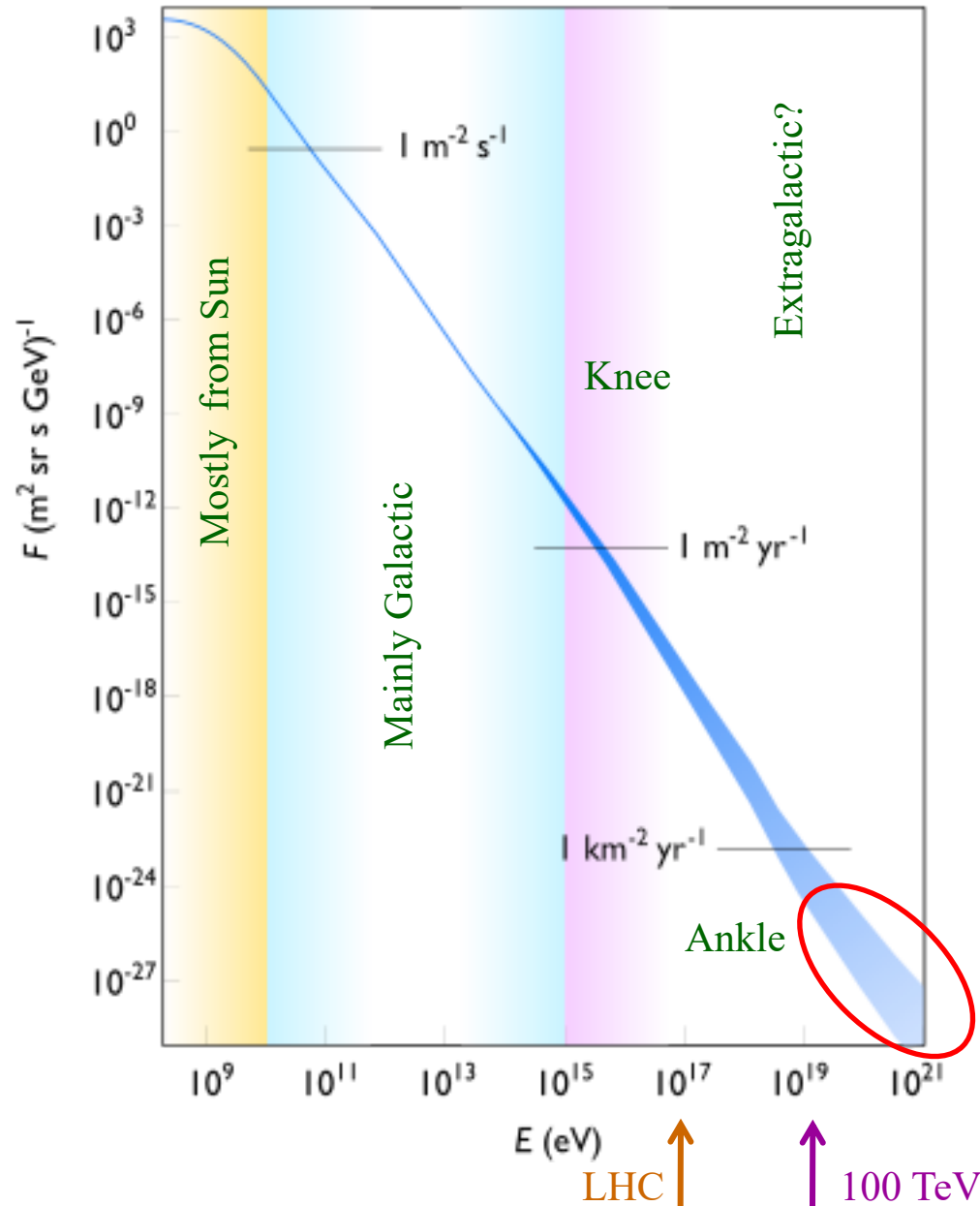
# FCC – ee , hh, ...

Feasibility study 2021-2025  
(technical and financial)



# Raios cósmicos carregados

Viktor Hess, 1912



$$\frac{dN}{dE} \propto E^{-\alpha}$$

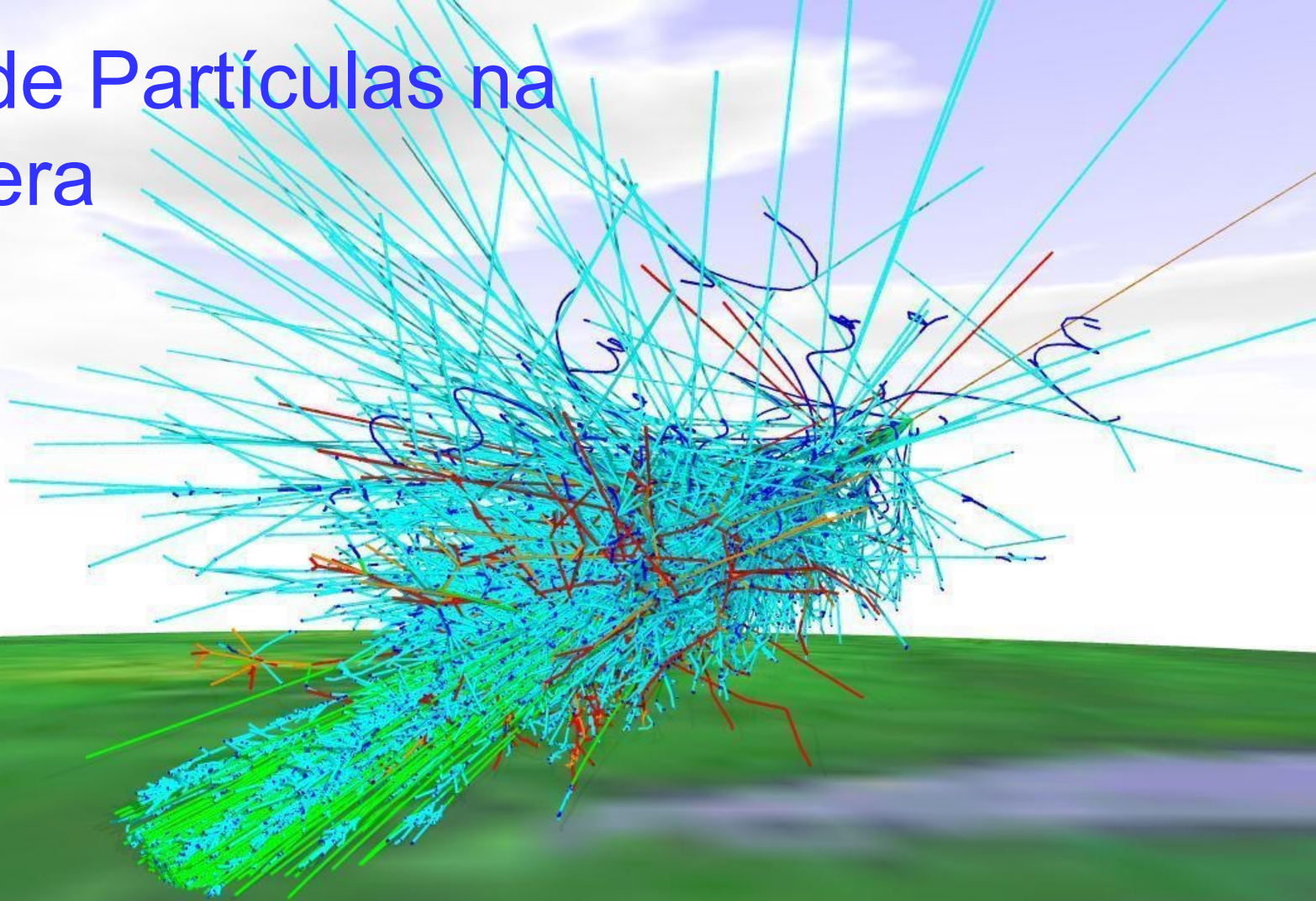
$$\alpha = \begin{cases} 2.7 & E < 10^{16} \\ 3.0 & 10^{16} < E < 10^{18} \\ 2.7? & E > 10^{18} \end{cases}$$

# Um LHC do tamanho da órbita de Mercúrio !!!

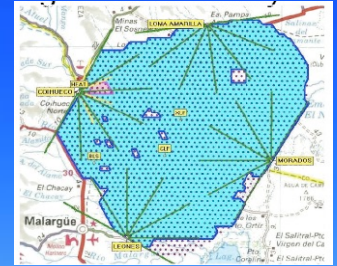




# Física de Partículas na atmosfera



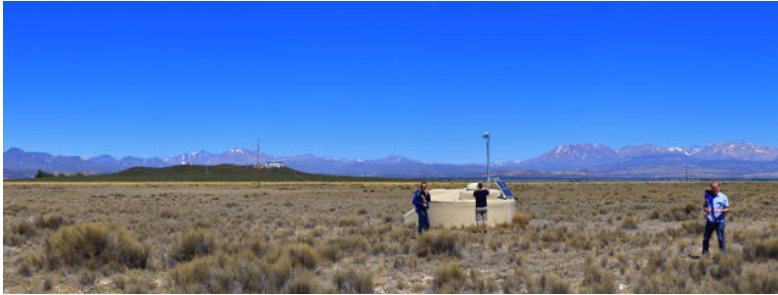
# Na pampa argentina



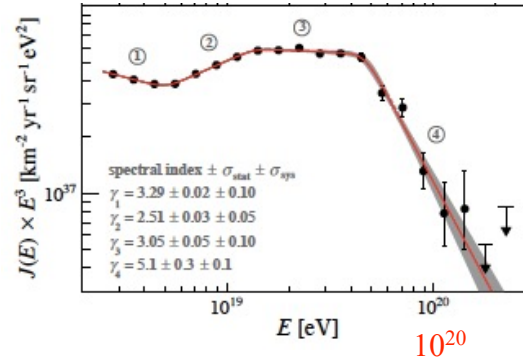
# Ultra High Energy Cosmic Rays (UHECR)

Present

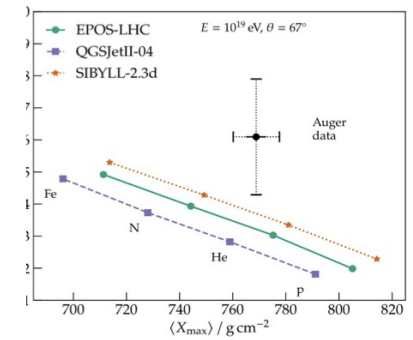
## Pierre Auger Observatory



## Energy spectrum

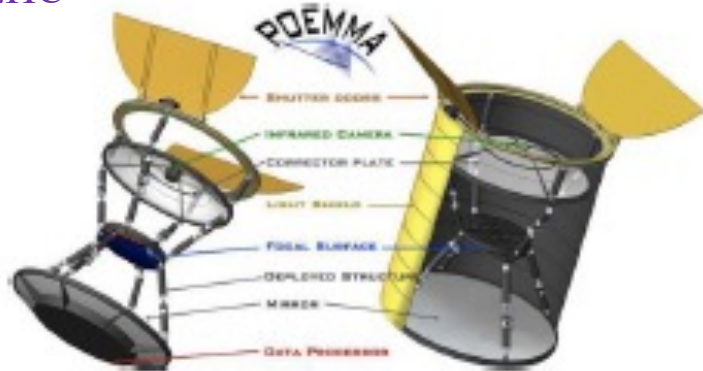


## Muons ...

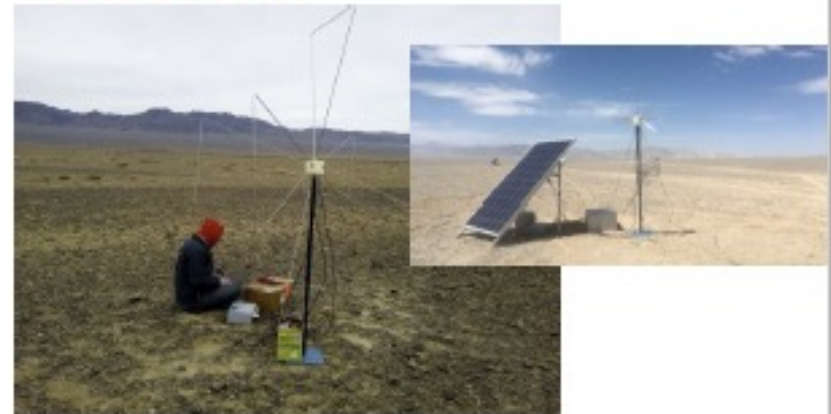


Future

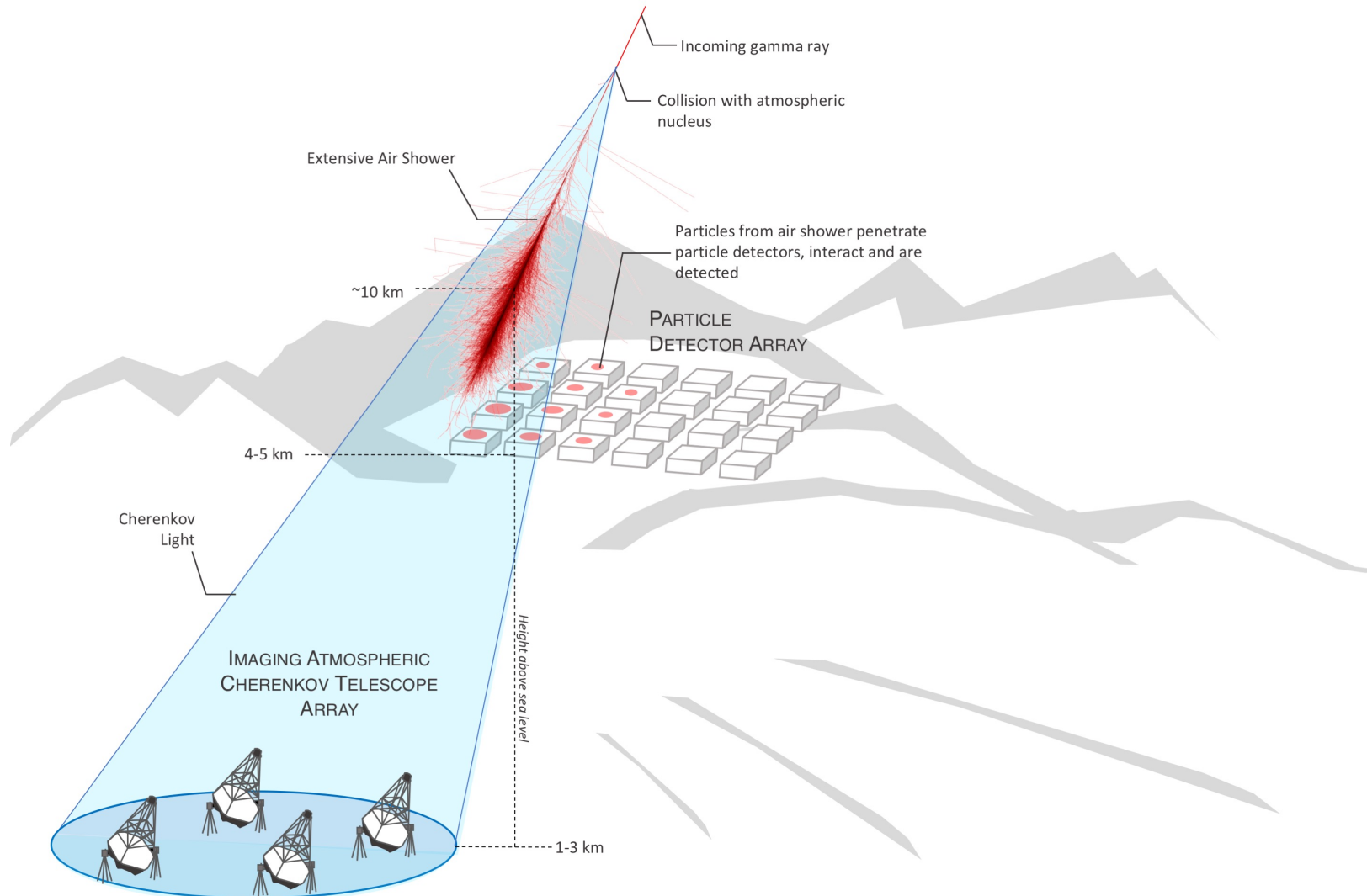
HL-LHC



## GRAND



# Detector fotões no alto das montanhas ..

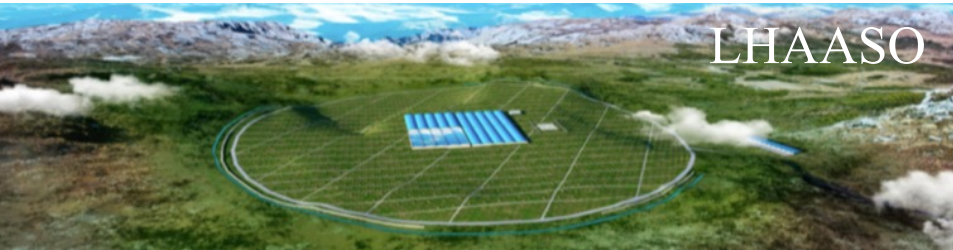
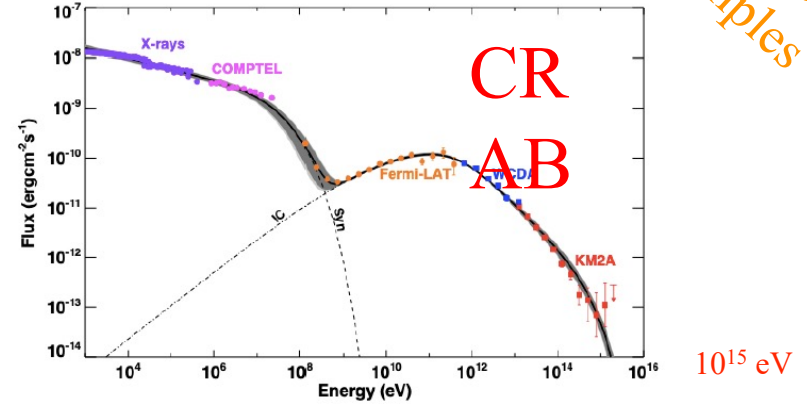


*Not to scale*

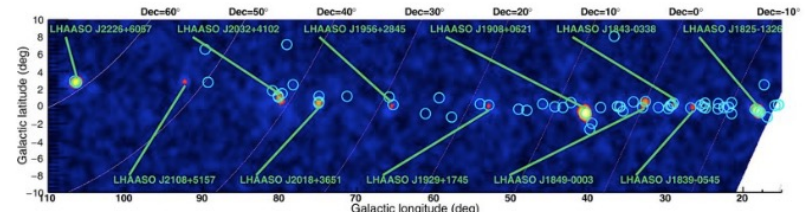
# High Energy Gamma Rays

Just a few examples

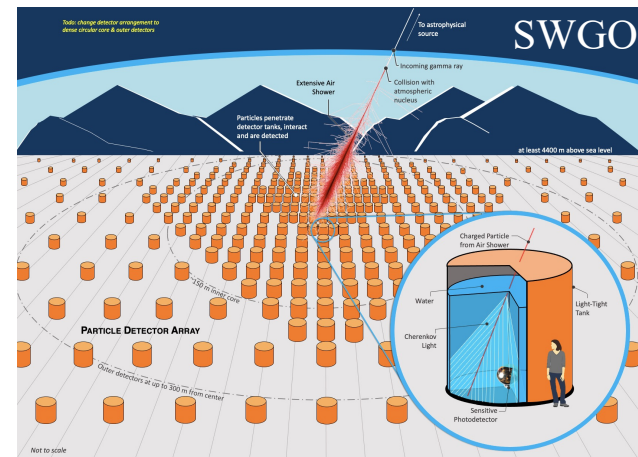
## Present



## 12 Pevatron sources

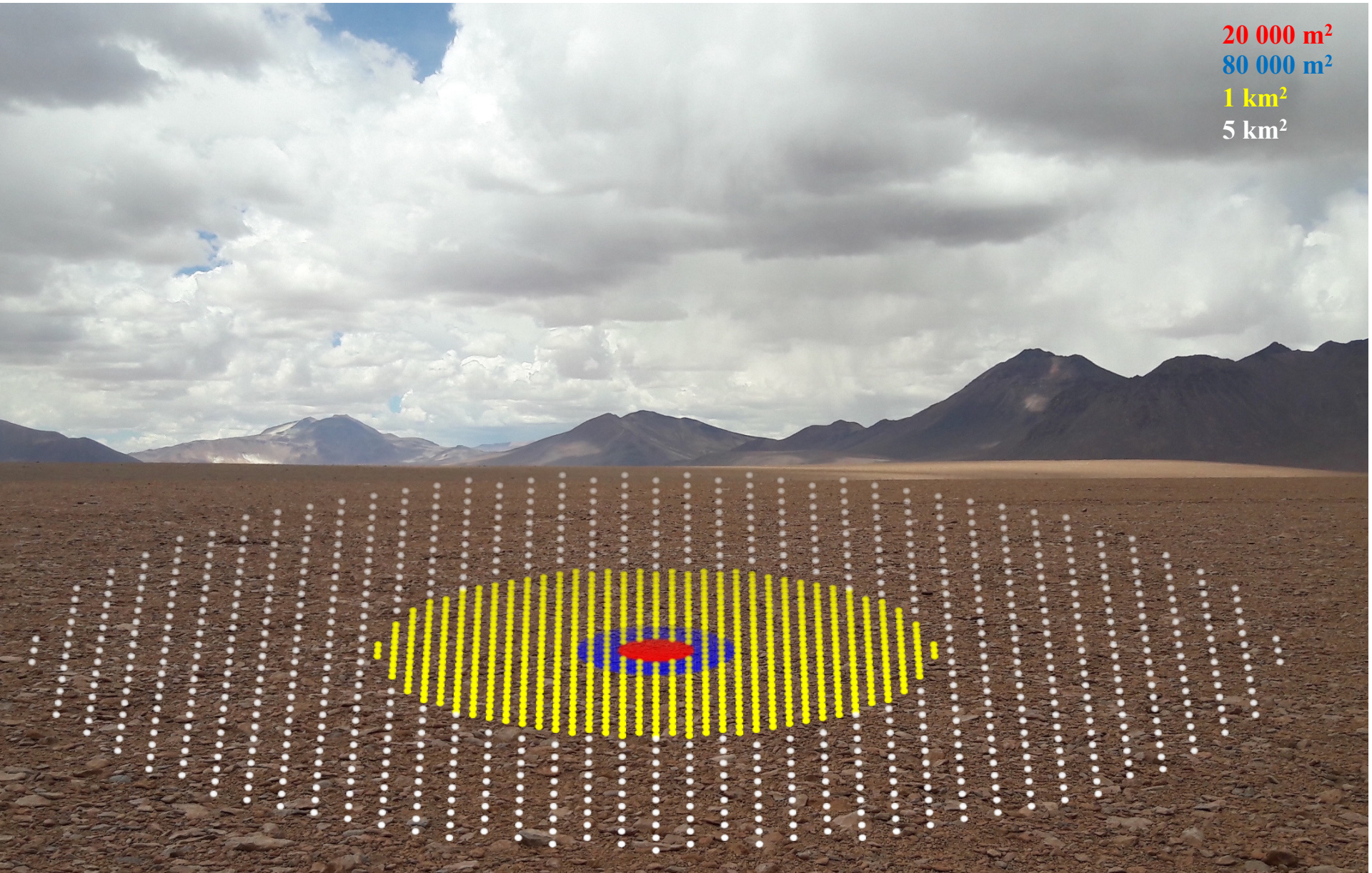


## Future

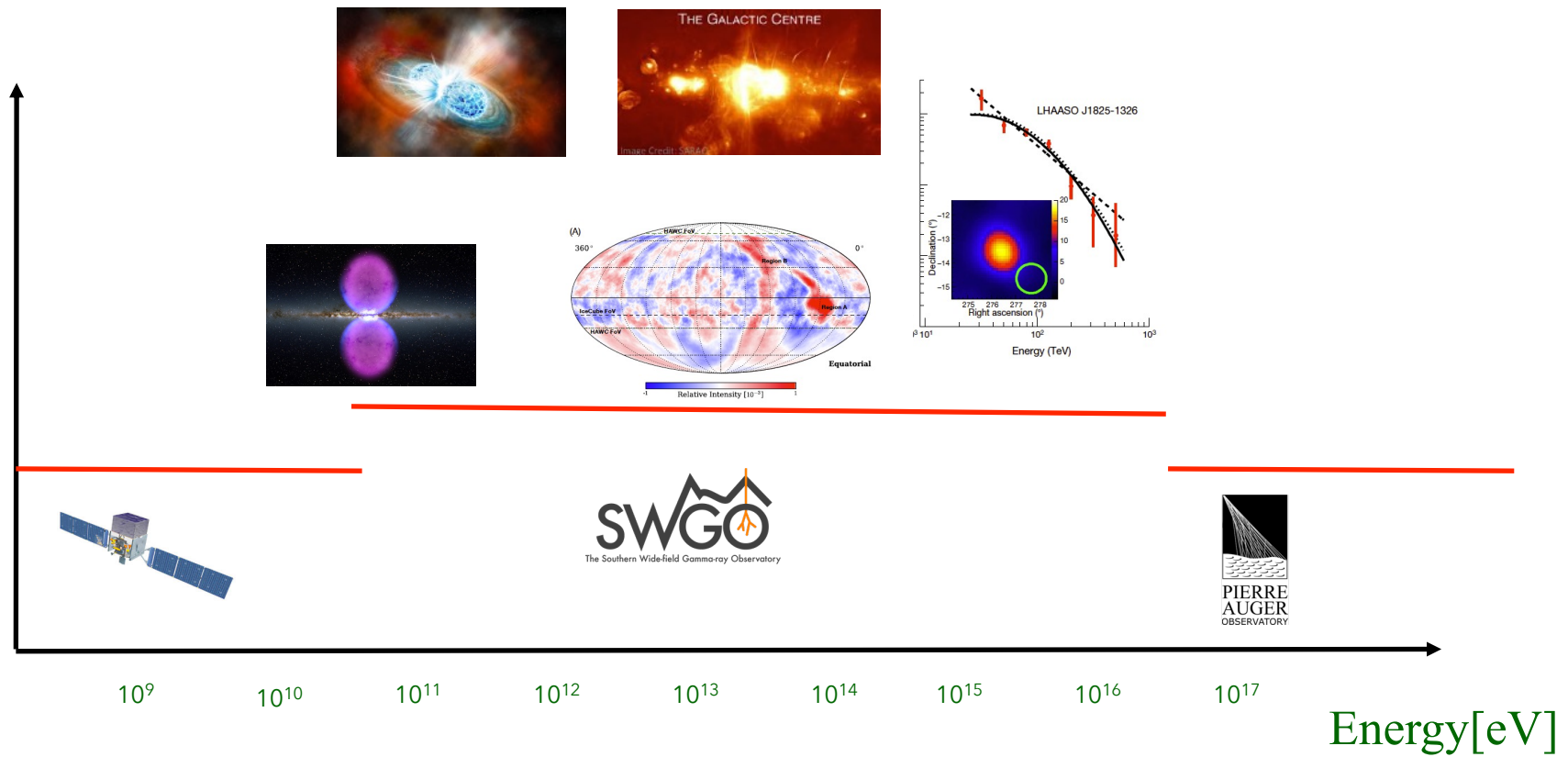


Olhar para o centro da galáxia e para o Universo a 4500-5000 m de altitude na América do Sul com um detector de fótons energéticos

20 000 m<sup>2</sup>  
80 000 m<sup>2</sup>  
1 km<sup>2</sup>  
5 km<sup>2</sup>

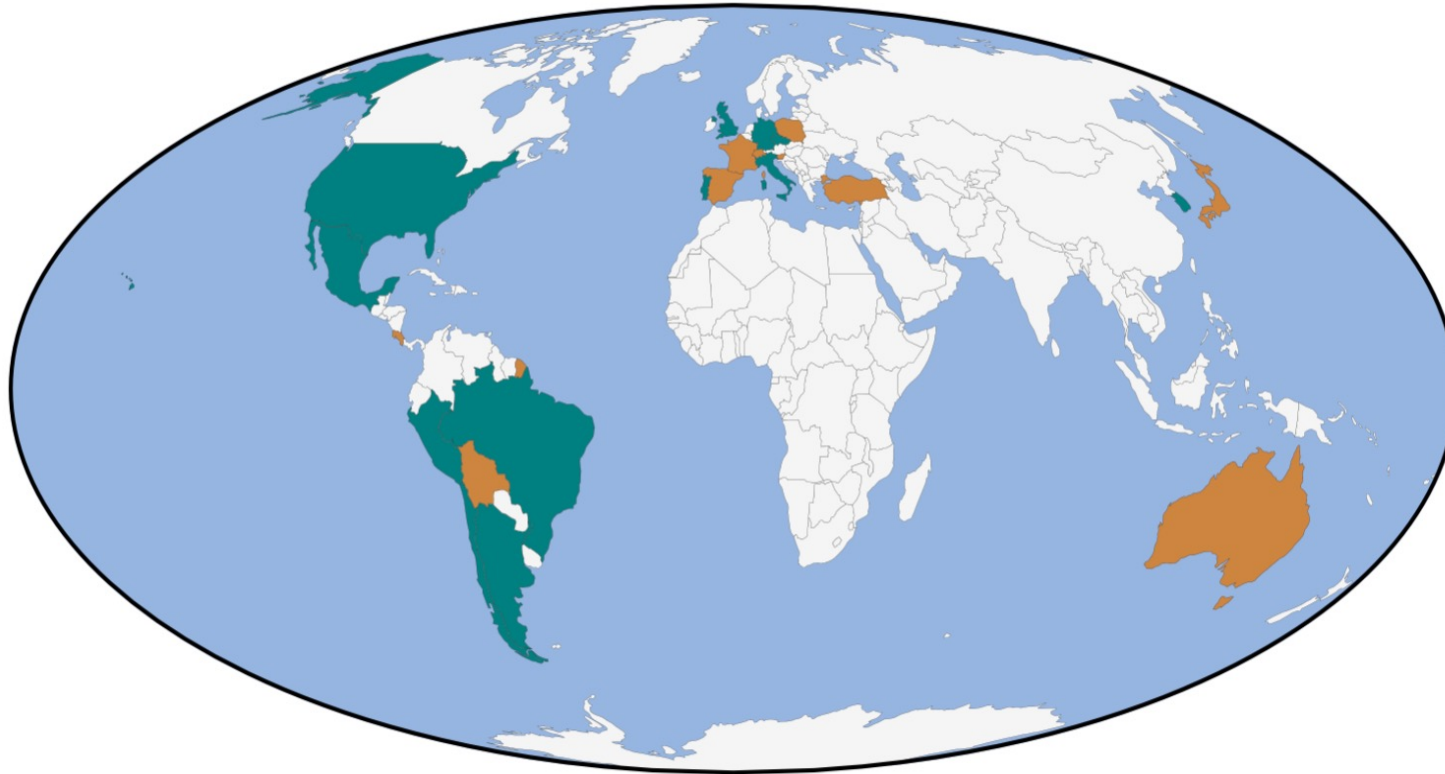


# Das dezenas de GeV às dezenas de TeV



# SWGGO

## Southern Wide-field Gamma-ray Observatory



### Countries in SWGGO

#### Institutes

Argentina\*, Brazil, Chile, Czech Republic, Germany\*, Italy, Mexico, Peru, Portugal, South Korea, United Kingdom, United States\*

#### Supporting scientists

Australia, Bolivia, Costa Rica, France, Japan, Poland, Slovenia, Spain, Switzerland, Turkey

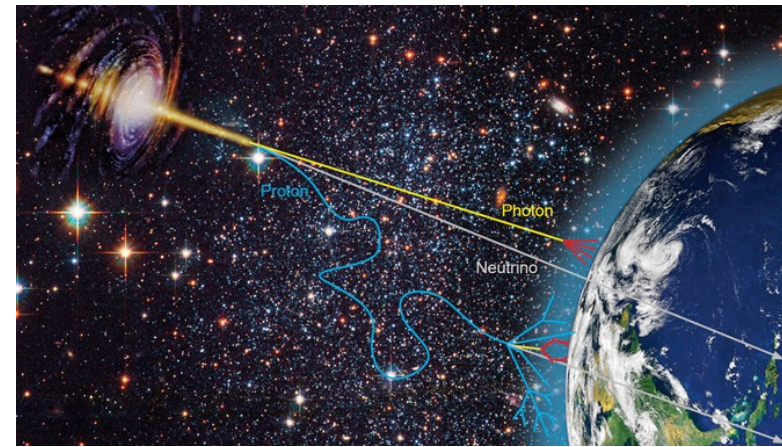
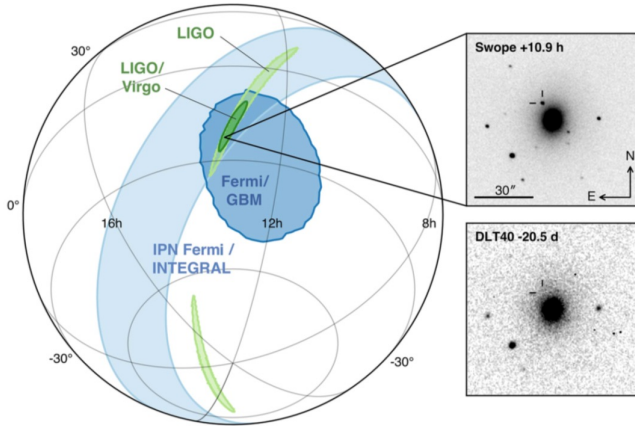
*\*also supporting scientists*

100 + 32 cientistas, 53 institutos, 13 países



# The Multi-messenger Era

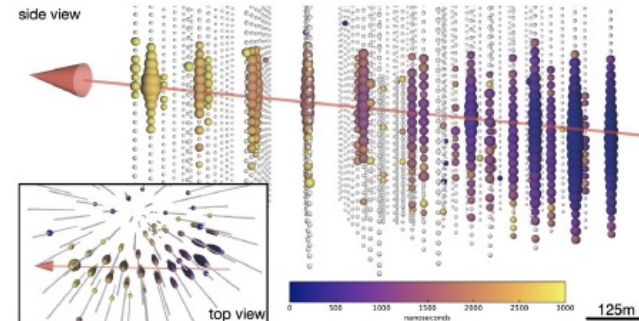
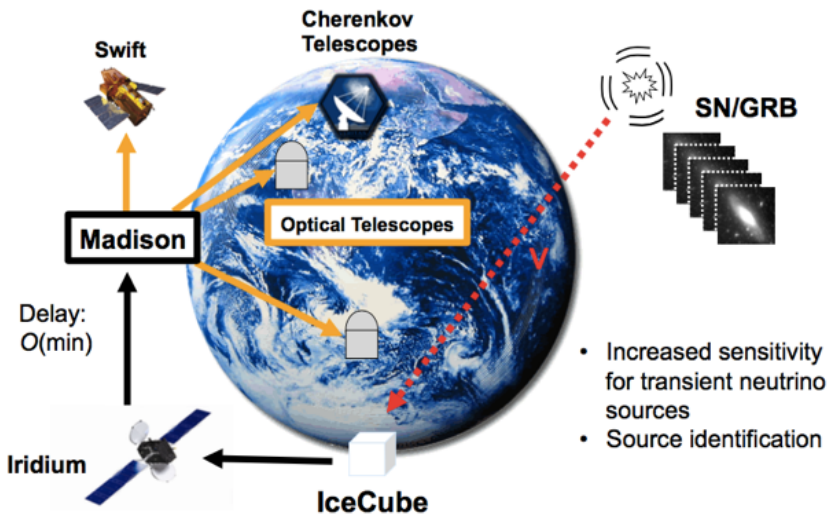
GW170817



First multi-messenger discovery of a binary neutron star merger

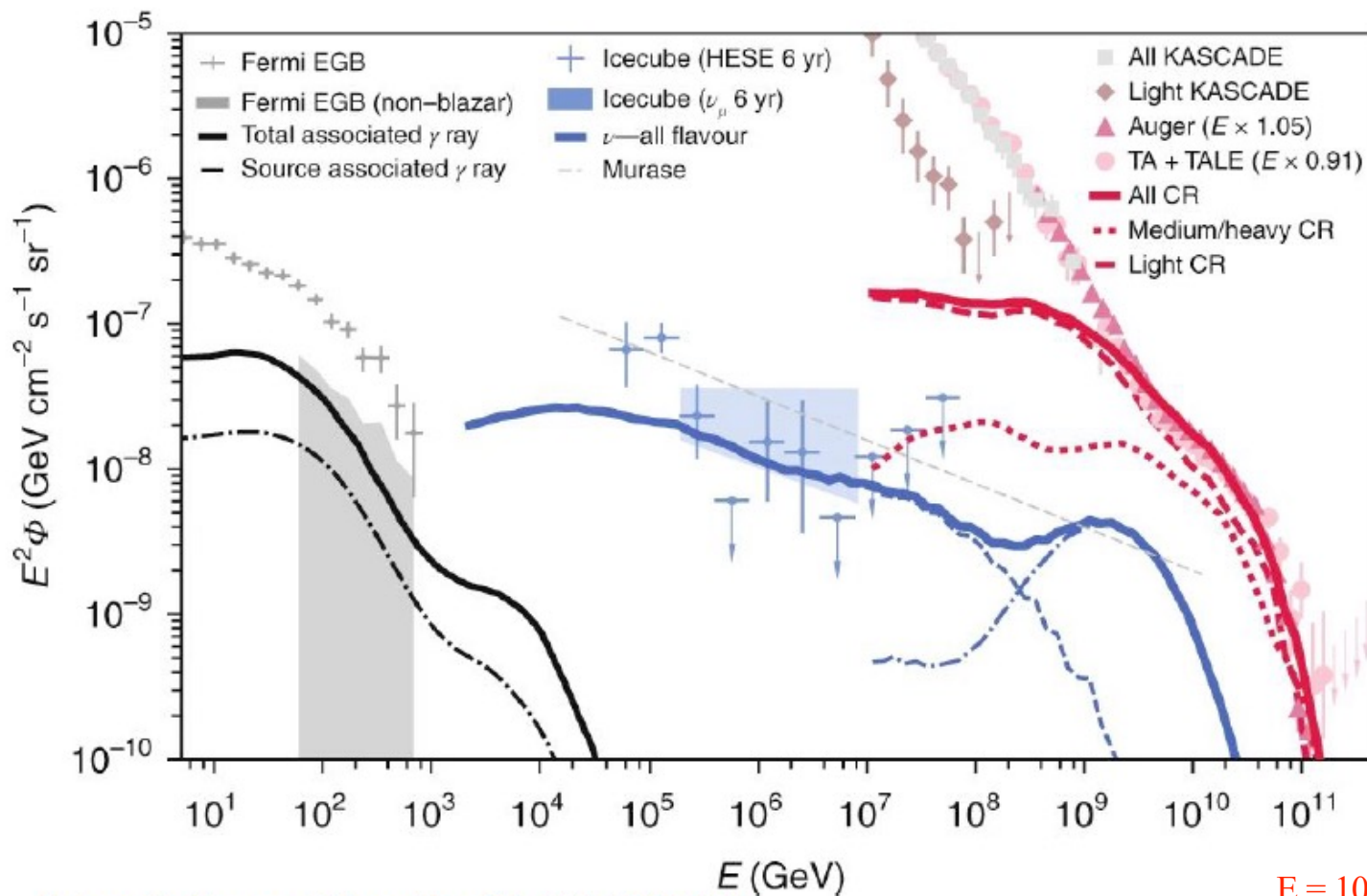
First simultaneous observation of very high energy neutrino and of electromagnetic waves

$\gamma$ -ray blazar TXS 0506+056



ICE Cube muon

# The Universe at the highest energies



K. Fang, K. Murase, Nature Phys 14, 396–398 (2018).

The energy density per decade is similar in all the three messenger particles

$$E^2 \frac{dN}{dE} = E \frac{dN}{d \ln E}$$

$$\rho_{\text{decade}} = \int_{\text{decade}} E \frac{dN}{d \ln E} d \ln E$$

# Neutrino sector



The Nobel Prize in Physics 2002: Raymond Davis Jr.,

*The detection of cosmic neutrinos*

The Nobel Prize in Physics 2015: Takaaki Kajita, Arthur

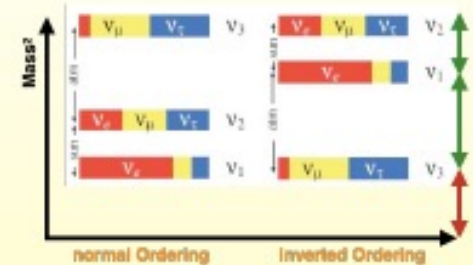
Present state of neutrino physics: PMNS; 3x3 or 4x4? nature (Majorana or Dirac); mass ordering

$$U_{3 \times 3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times (U_{\text{Maj}})$$

atmospheric +  
accelerator disapp

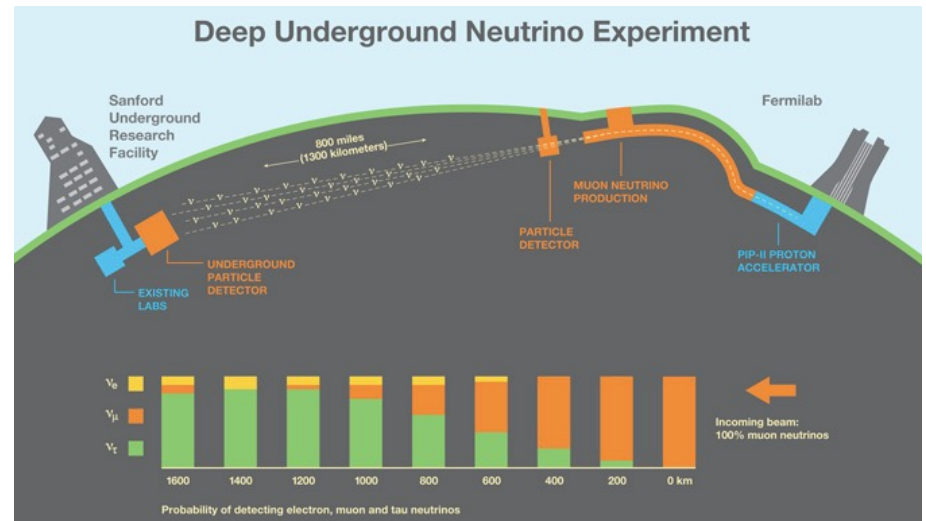
SBL reactor +  
accelerator app

solar +  
KamLAND

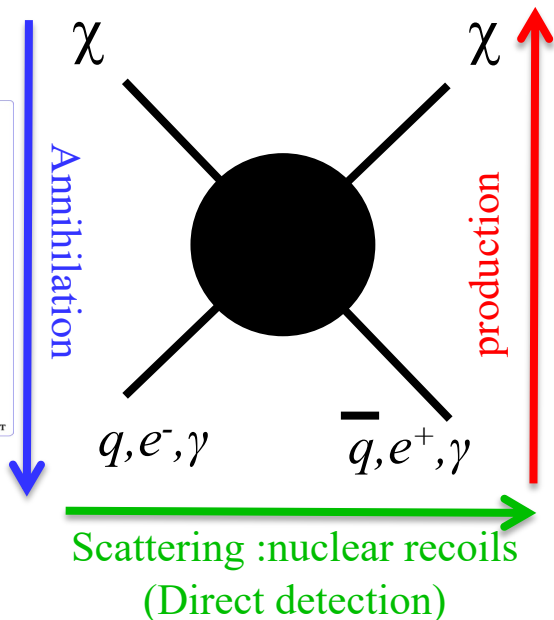
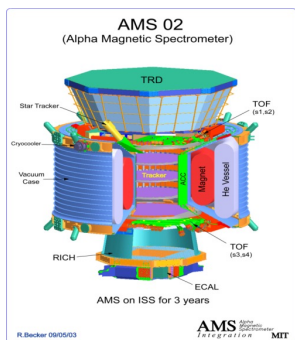
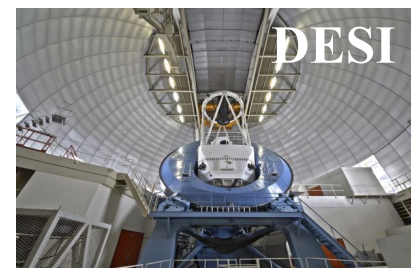
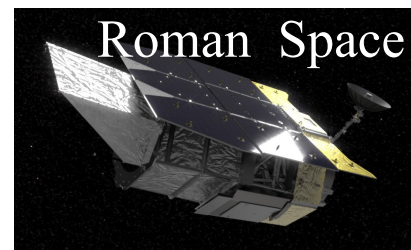
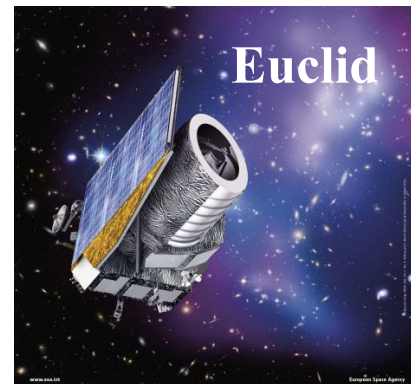
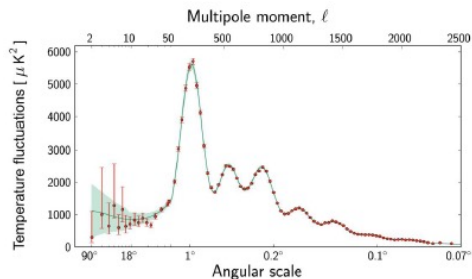
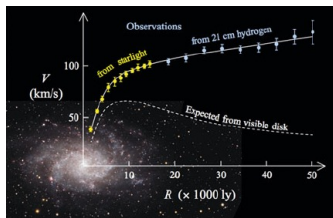
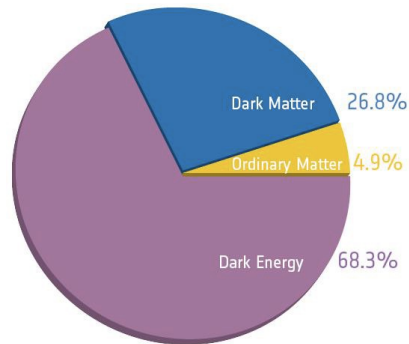


A rich experimental program in the next 10/20 years:

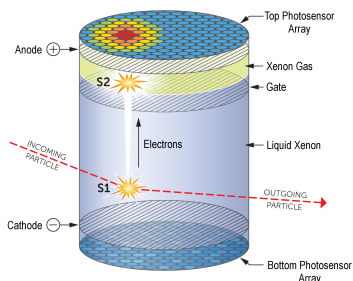
- Accelerator-based long-baseline;

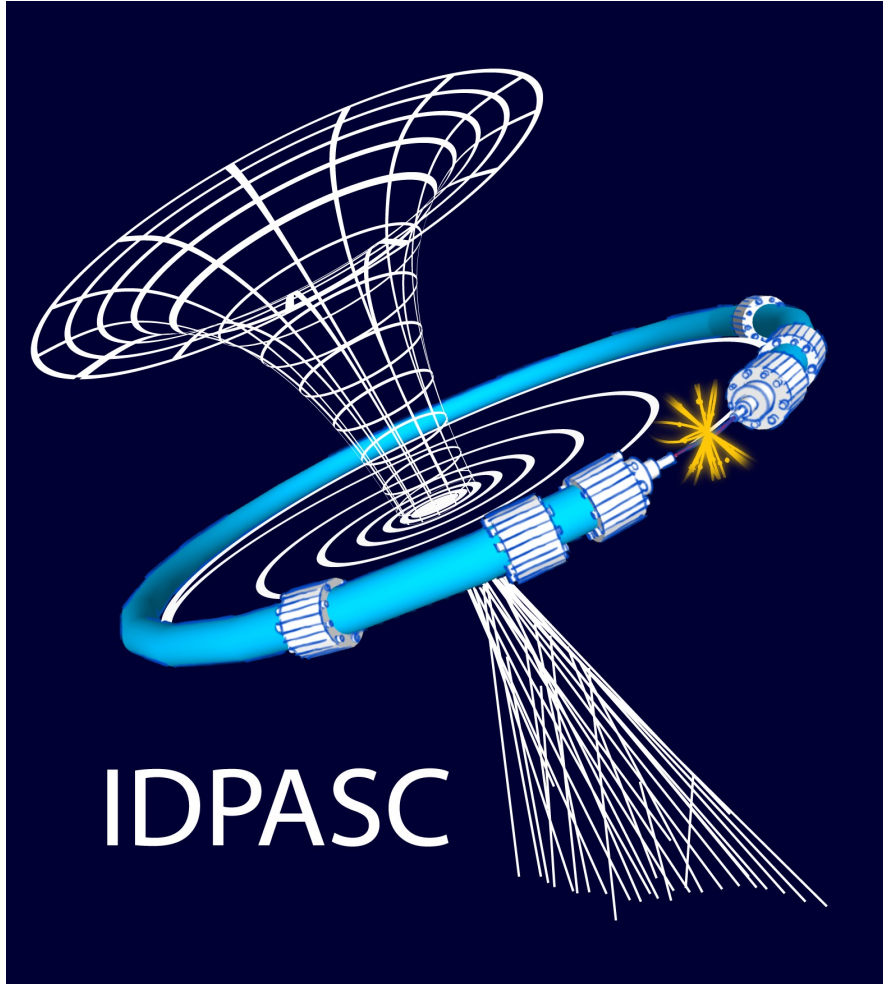


# Dark Matter/Dark Energy



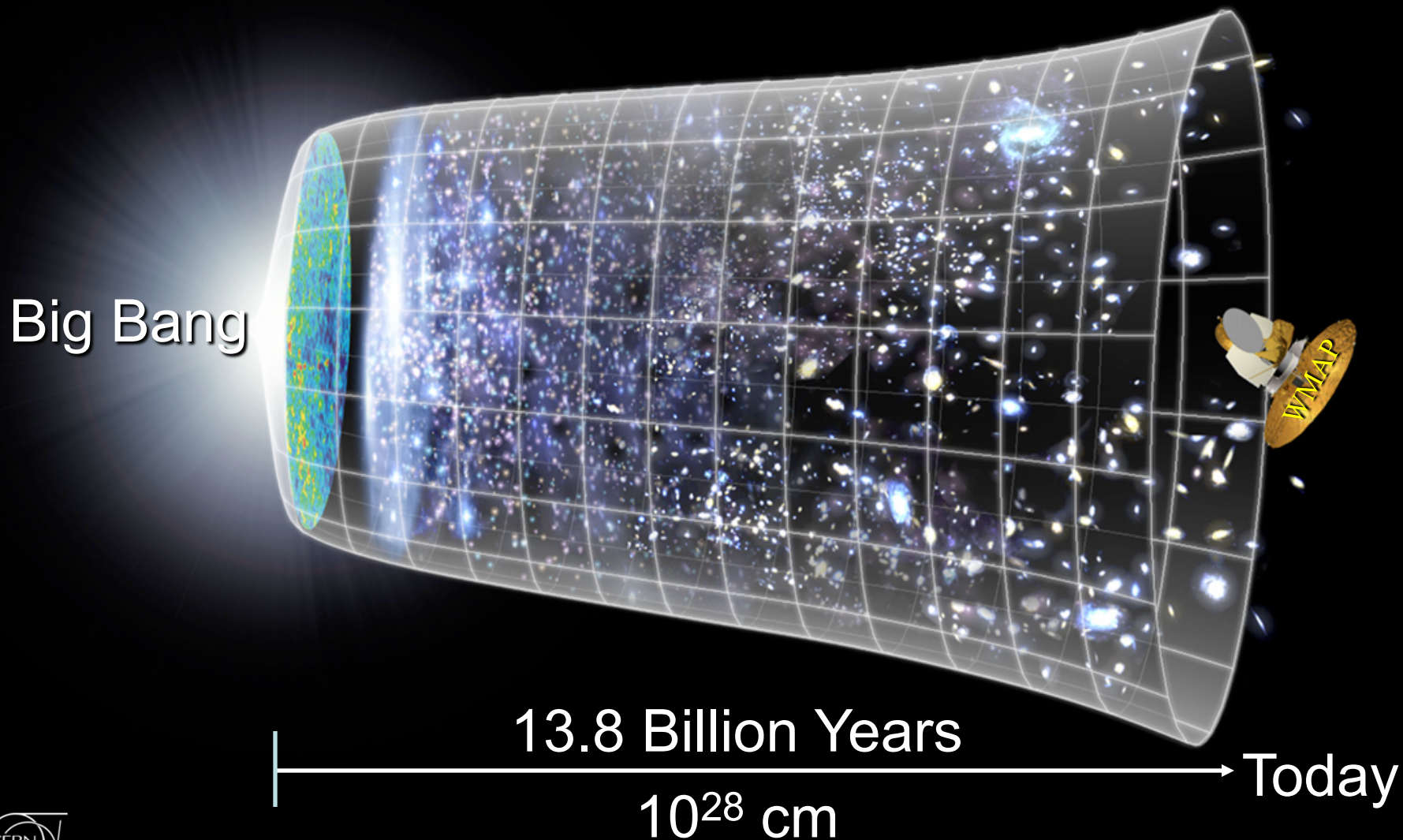
XLZD.  
Next DM  
experiment





# International Doctorate Network in Particle Physics, Astrophysics and Cosmology

# O Universo para compreender, ...

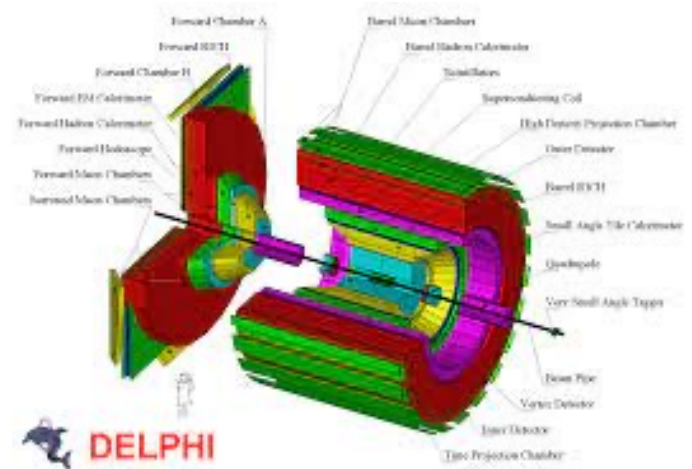
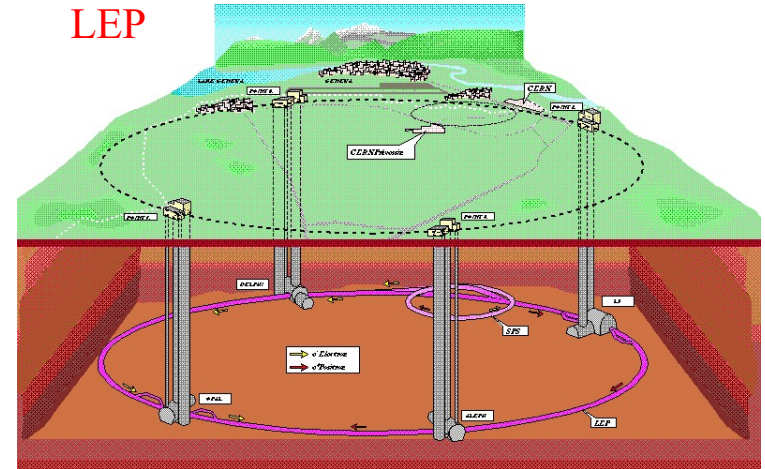
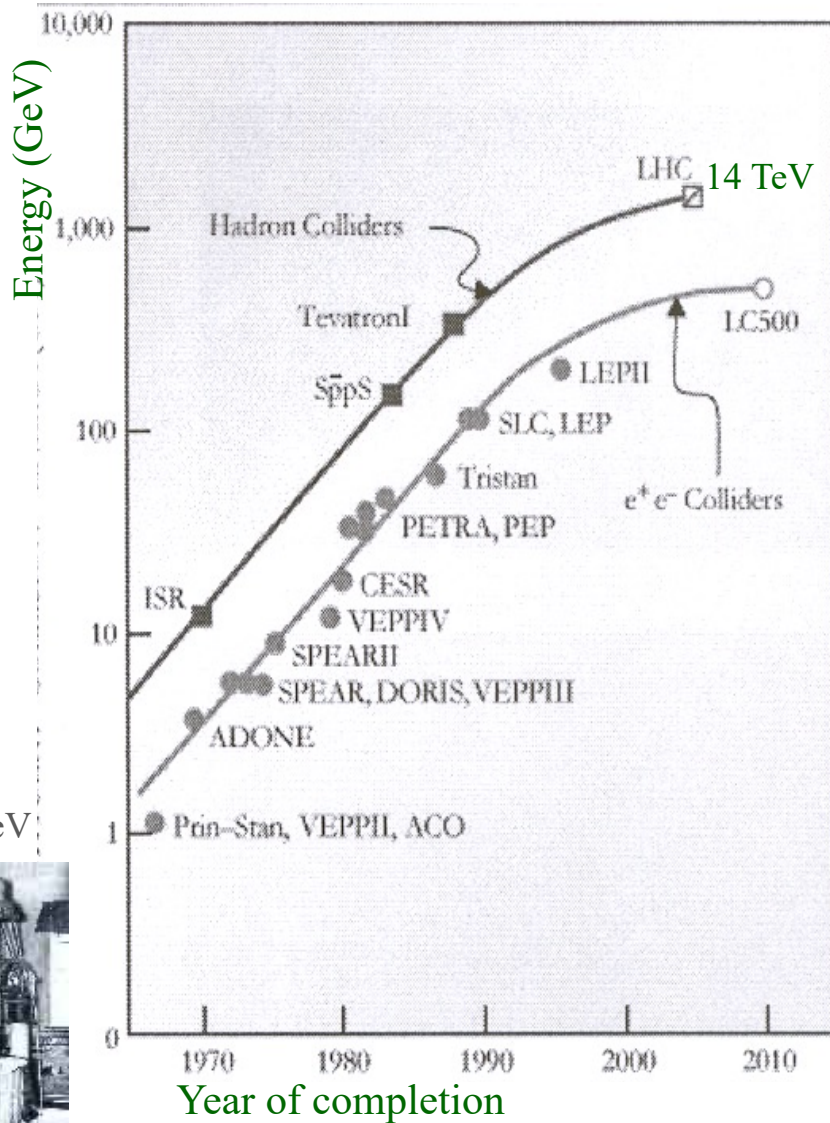








# Accelerators



high Luminosity, sophisticated detectors

# As partículas elementares em 1980

Three Generations  
of Matter (Fermions) spin  $\frac{1}{2}$

	I	II	III
mass →	2.4 MeV	1.27 GeV	
charge →	$\frac{2}{3}$	$\frac{2}{3}$	
name →	<b>u</b> up	<b>c</b> charm	
Quarks	Left Right	Left Right	
	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom
	Left Right	Left Right	Left Right
	$0$ <b><math>\nu_e</math></b> electron neutrino	$0$ <b><math>\nu_\mu</math></b> muon neutrino	
	Left Right	Left Right	
Leptons	0.511 MeV	105.7 MeV	1.777 GeV
	-1	-1	-1
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau
	Left Right	Left Right	Left Right

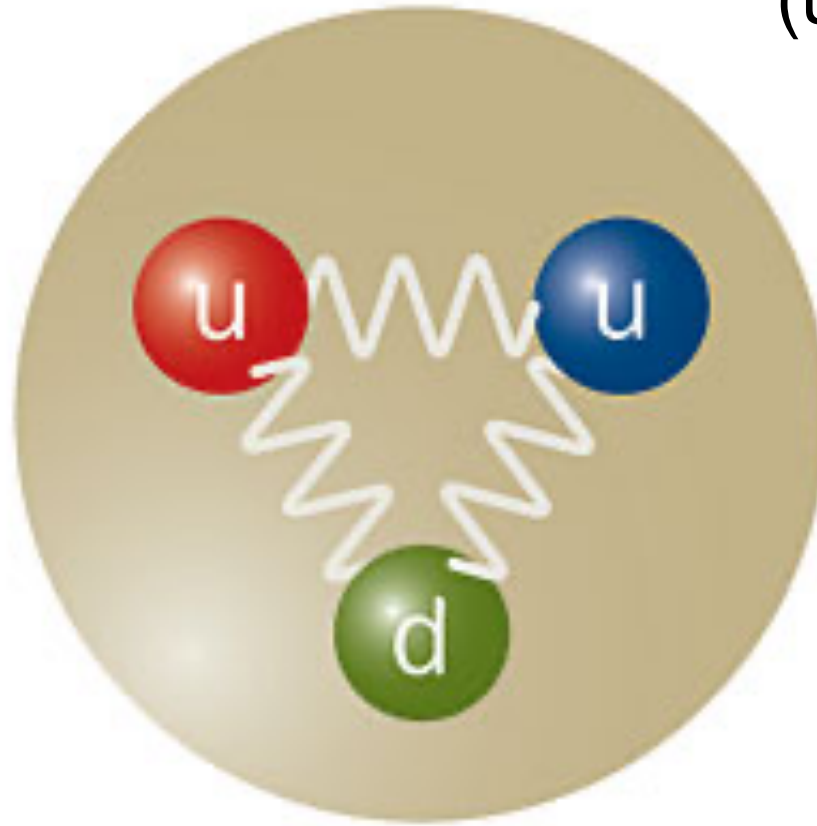
0  
0  
**g**  
gluon

0  
0  
 **$\gamma$**   
photon

Bosons (Forces) spin 1

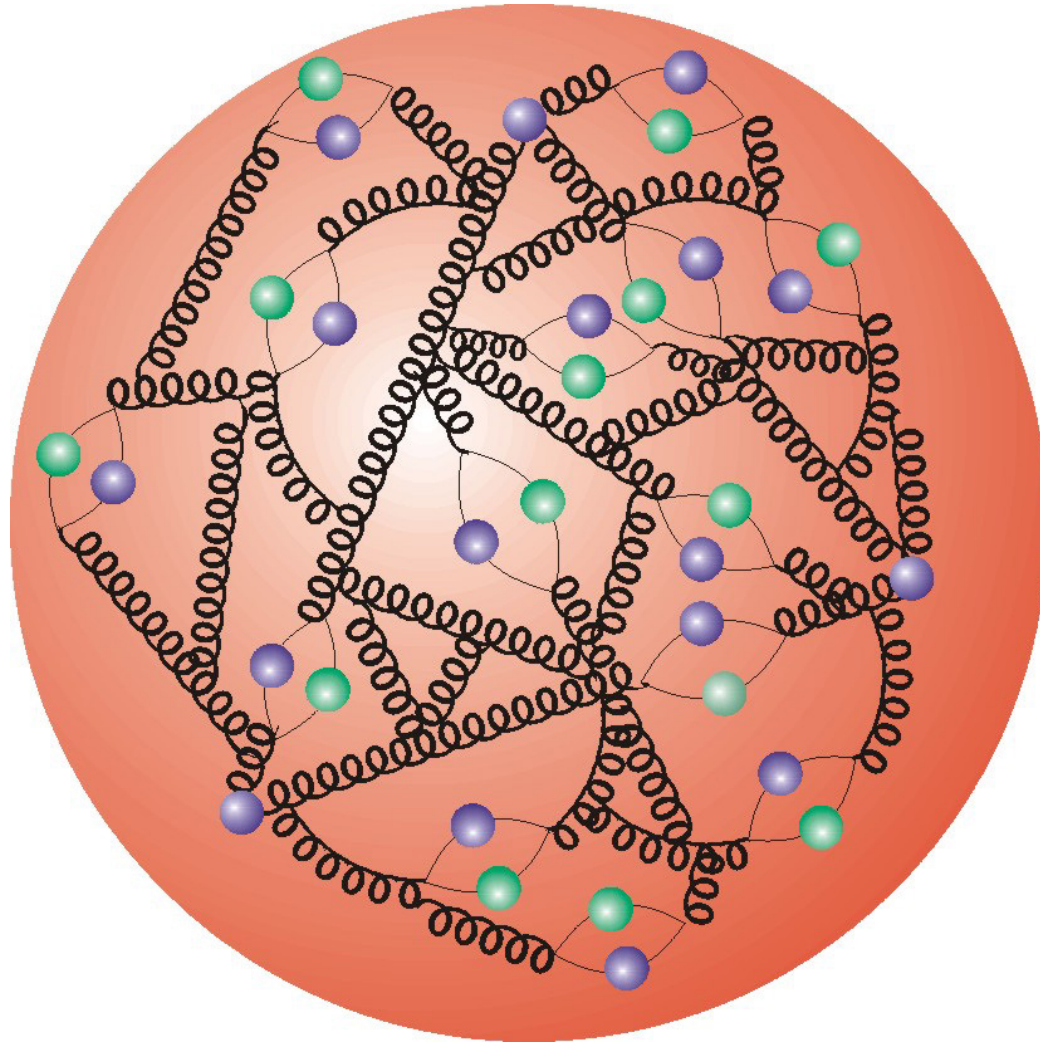
# O Protão

(uud)



$10^{-14}$  m

# O Protão



# A massa do Protão



$$M = \sum m_{\text{quarks}} + E_{\text{campo}}/c^2$$



# A massa do Protão

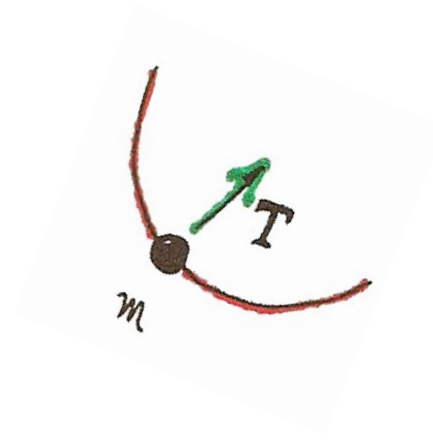
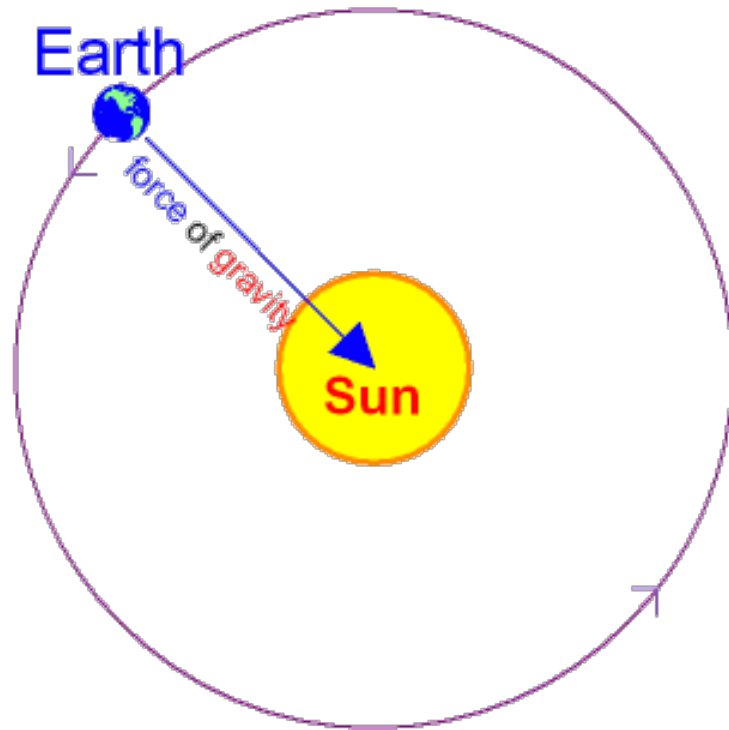


$$M = \sum m_{\text{quarks}} + E_{\text{campo}}/c^2$$

$$938 \sim ( 15 + 925) \text{ MeV}/c^2$$

$$1 \text{ MeV}/c^2 \sim 1.8 \cdot 10^{-30} \text{ Kg}$$

# A massa do Sol

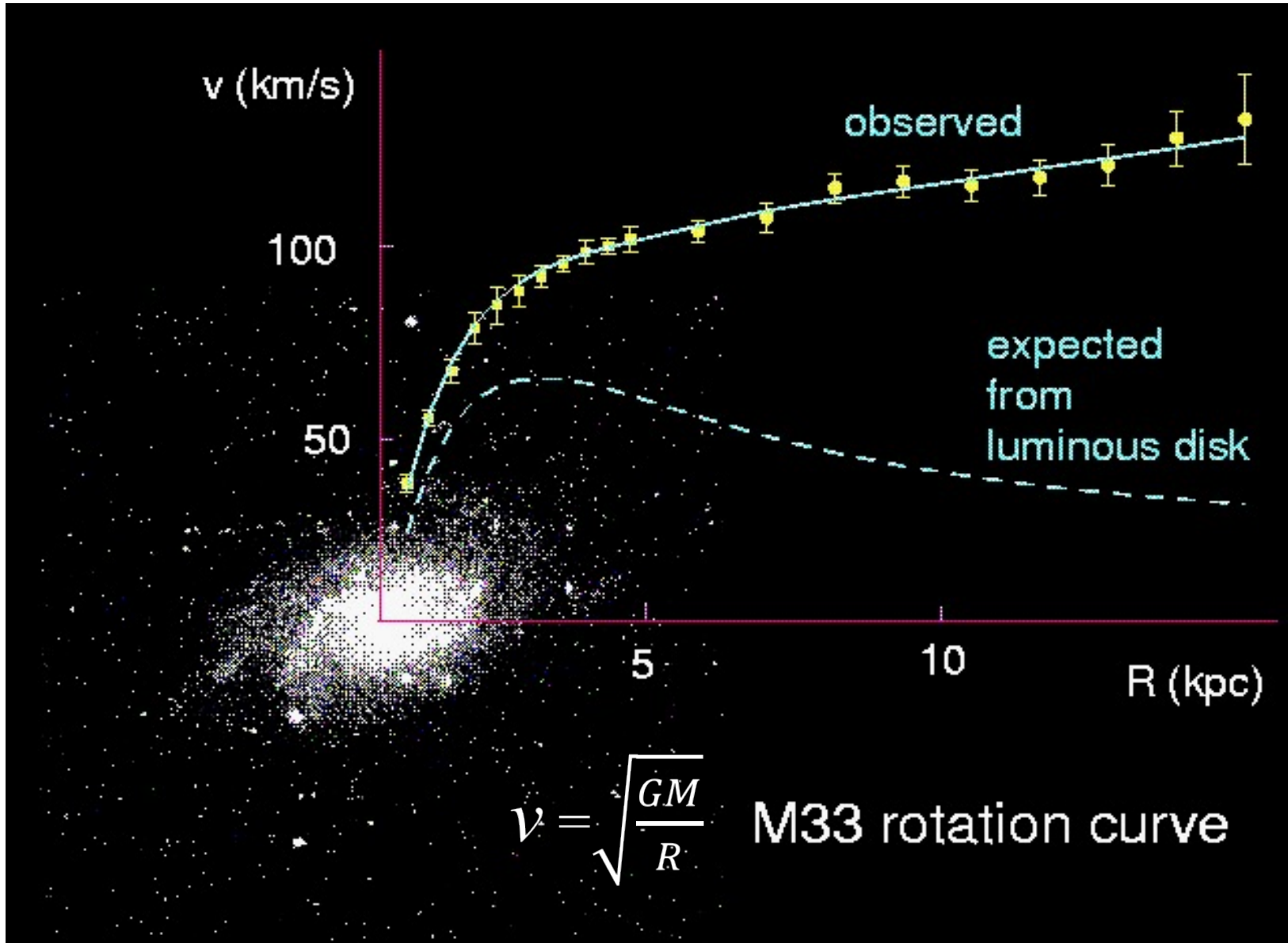


$$F_c = \frac{m v^2}{r}$$

$$\frac{m_T v^2}{R} \approx G \frac{m_T M_S}{R^2}$$

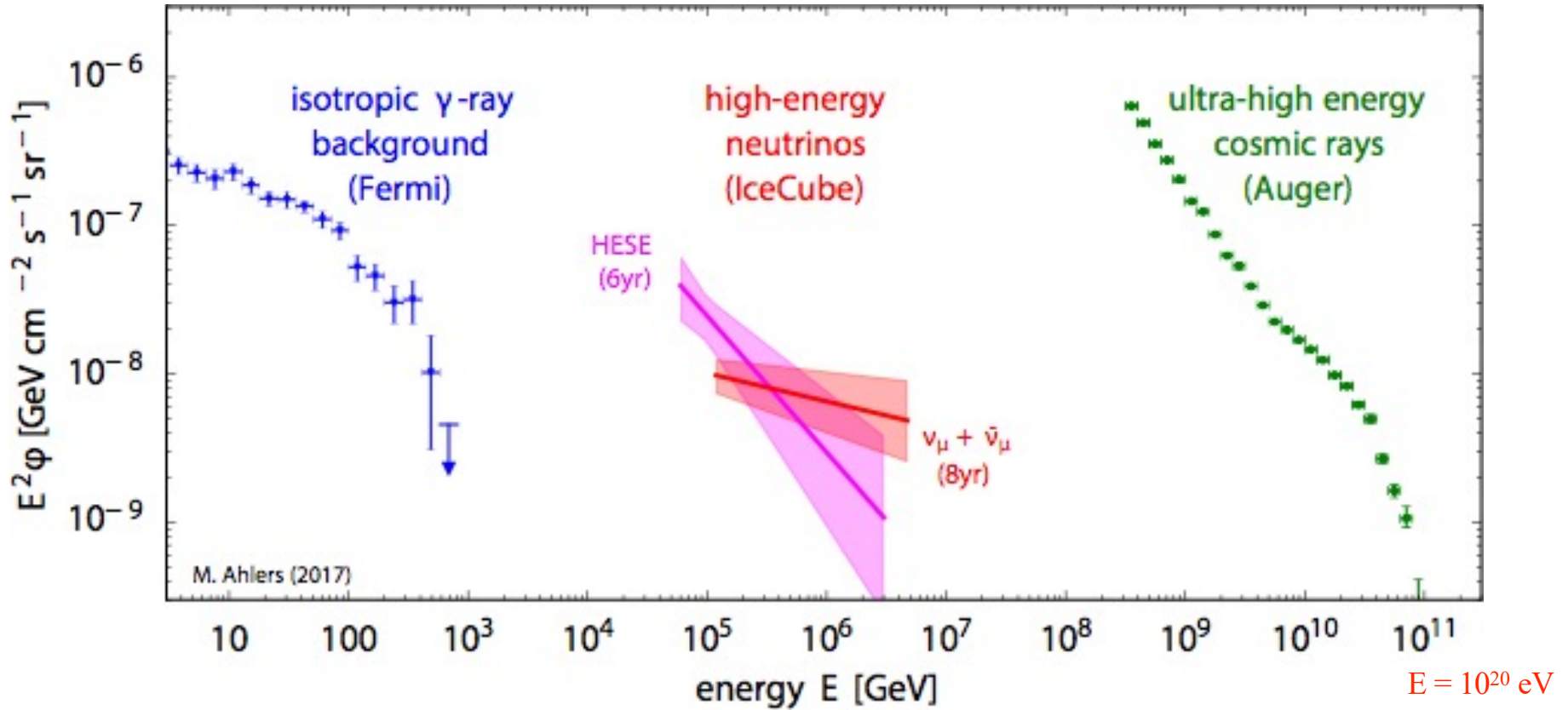
$$M_S \sim 1.98 \cdot 10^{30} \text{ kg}$$

# A velocidade de rotação das estrelas periféricas



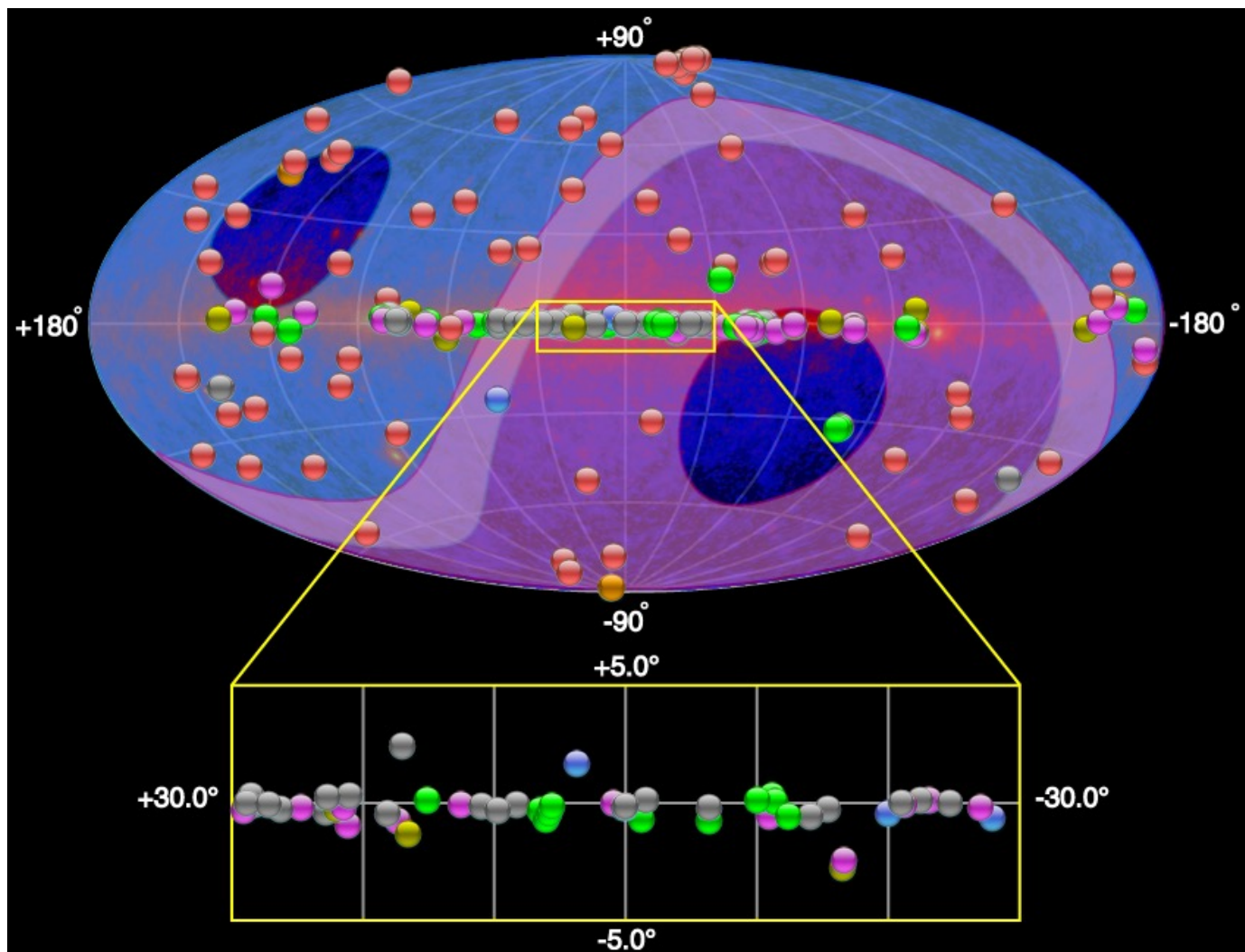


# The Universe at the highest energies !



Energy density per decade similar in all three messenger particles

# Fontes raios gamma de alta energia (TeV)

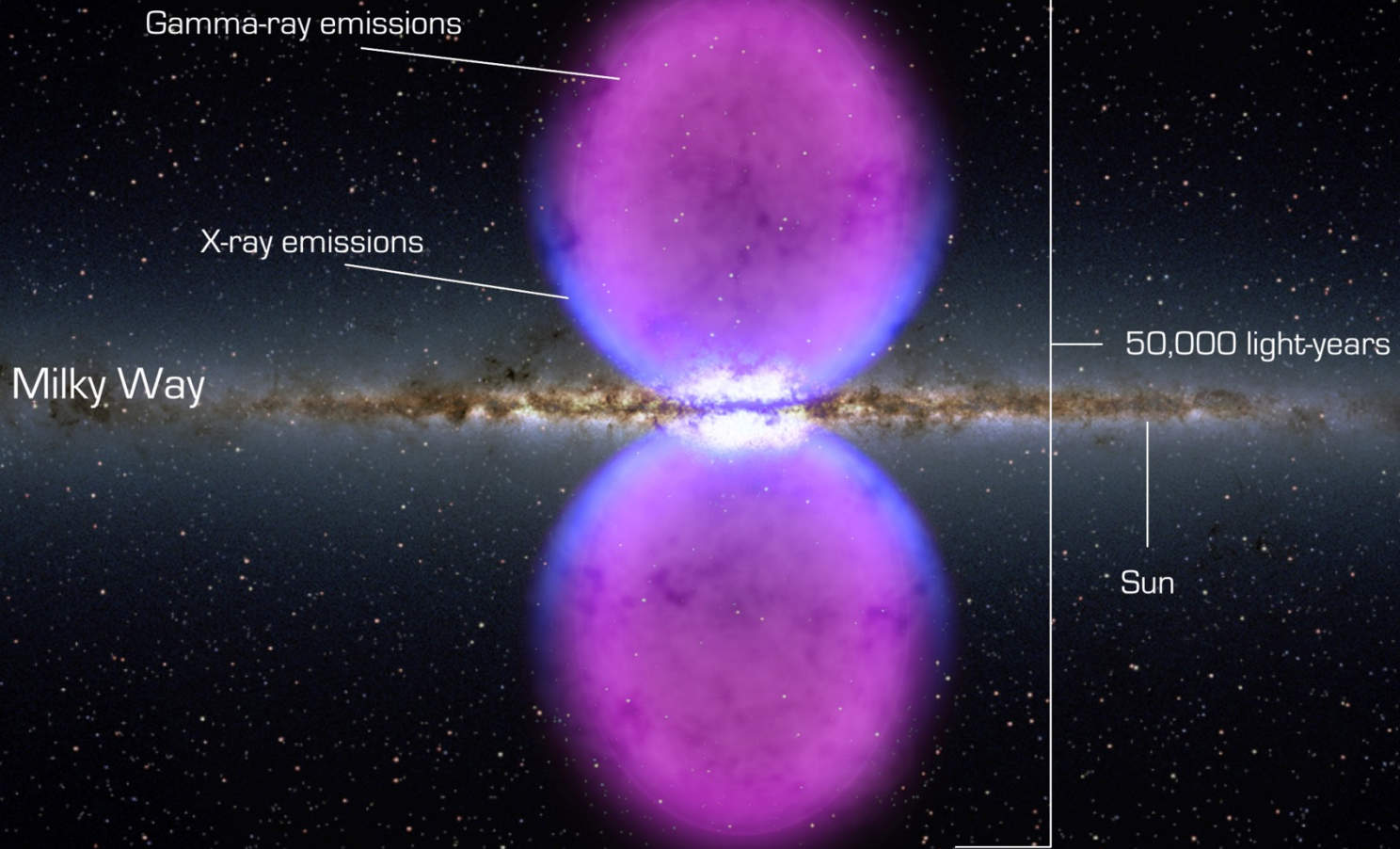


## Source Types

- PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

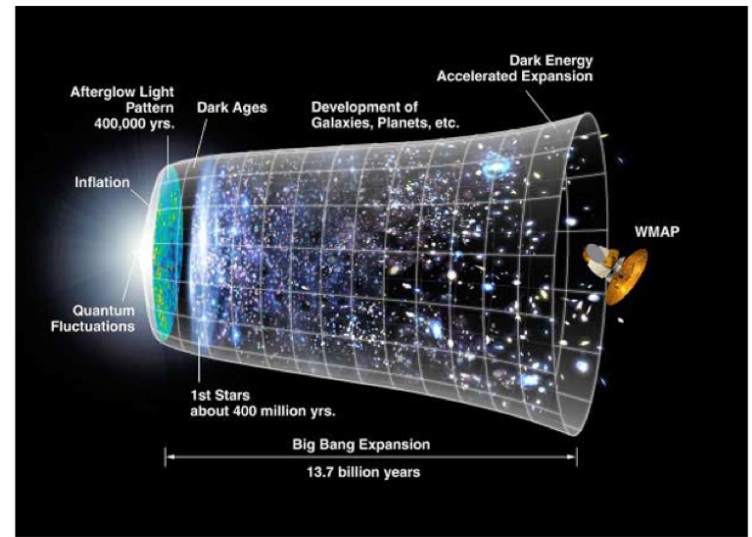
( $>200$ )

# As bolhas de Fermi



# The Big Bang

## Expansion and cooling



Big Bang Expansion

Source - WMAP

