

Física más allá del Modelo Estándar

Clara Murgui (UAB/IFAE/CERN)

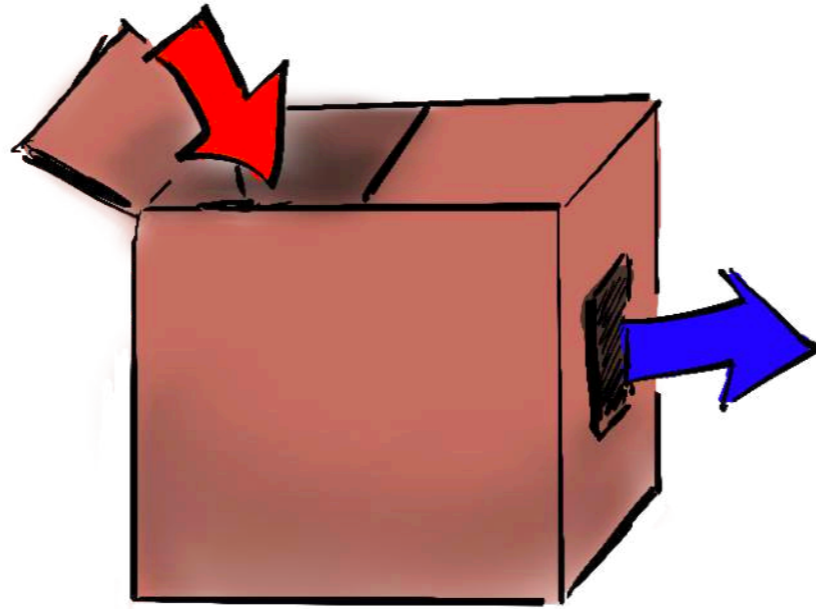
cmurgui@ifae.es

PROGRAMA ESPAÑOL PARA PROFESORES
CERN
24 Julio 2024



El Modelo Estándar (recap)

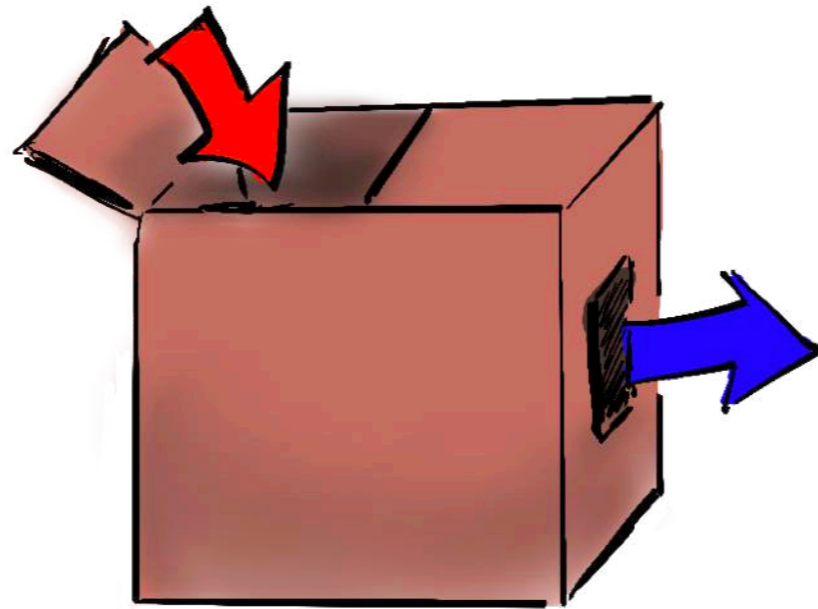
(experimento) INPUTS



OUTPUTS
(también experimento)

El Modelo Estándar (recap)

(experimento) INPUTS

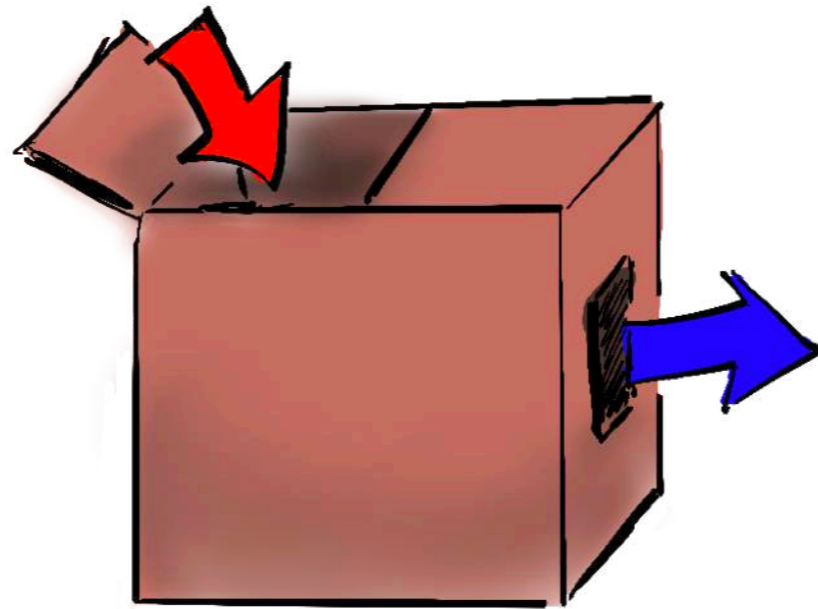


OUTPUTS
(también experimento)

(teóricos) “BONITA” , “SIMPLE”...

El Modelo Estándar (recap)

(experimento) INPUTS



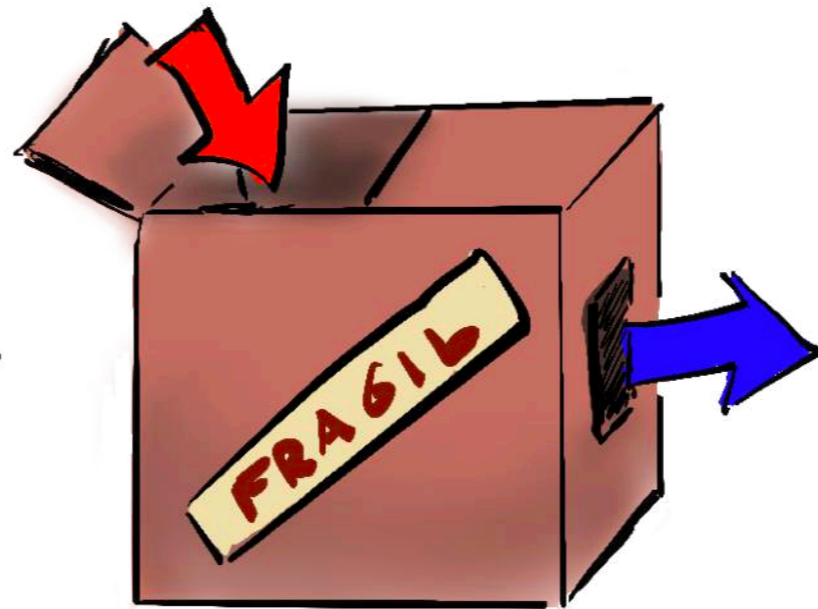
OUTPUTS
(también experimento)

(teóricos) “BONITA”, “SIMPLE”... \equiv POTENTE

$$\frac{\text{INPUTS}}{\text{OUTPUTS}} \ll 1$$

El Modelo Estándar (recap)

(experimento) INPUTS



OUTPUTS 
(también experimento)

(teóricos) “BONITA”, “SIMPLE”... \equiv POTENTE

$$\frac{\text{INPUTS}}{\text{OUTPUTS}} \ll 1$$

El Modelo Estándar (recap)

09:30

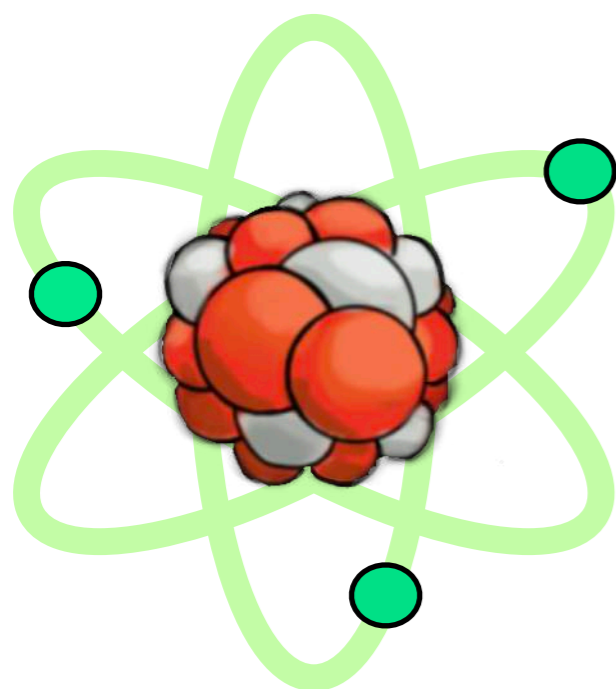
El Modelo estándar y la física fundamental (I)

Speaker: Miguel Escudero Abenza (CERN)


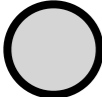

11:30

Física experimental de partículas

Speaker: Sergi Rodriguez (CERN)



10^{-15} m
 10^{-10} m

-  protones
-  neutrones
-  electrones



El Modelo Estándar (recap)

09:30

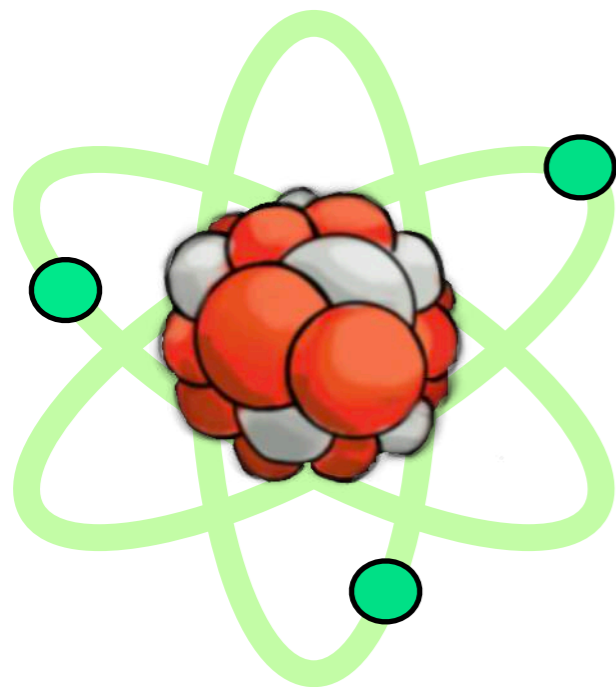
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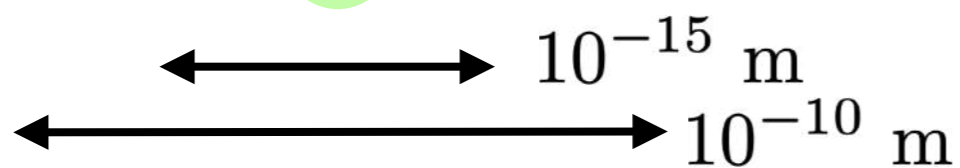
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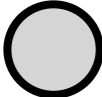

Física experimental de partículas

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Niels Bohr
1913



-  protones
-  neutrones
-  electrones

El Modelo Estándar (recap)

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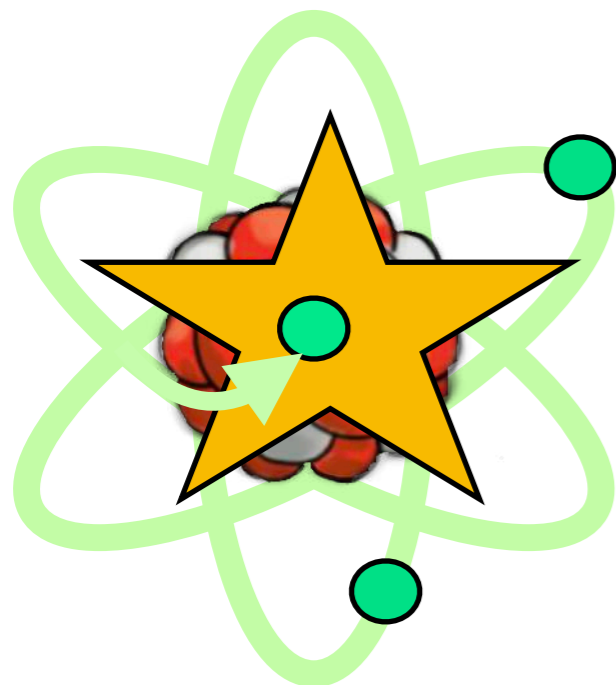
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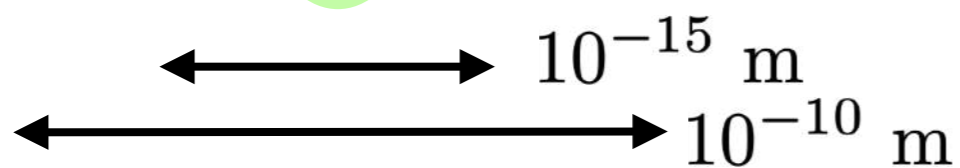
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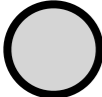

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Niels Bohr
1913



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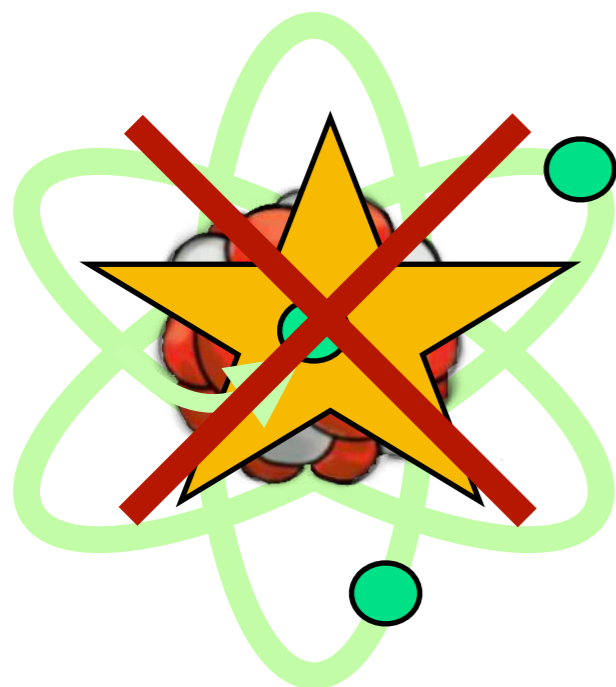
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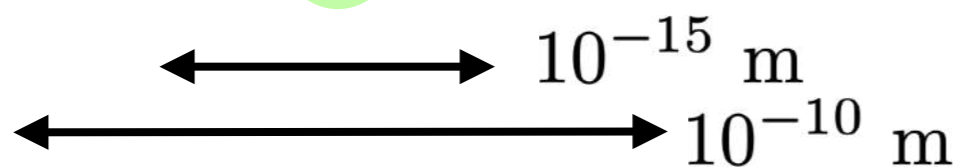
Niels Bohr
1913

$$\Delta x \Delta v \geq \frac{\hbar}{2m}$$



Werner Heisenberg
1927

0.511 MeV/c²
-1
1/2
e



- protones
- neutrones
- electrones

Planetary model	Quantum model
Niels Bohr	Erwin Schrödinger
1913	1926

[diapositiva de la charla de Sergi]

El Modelo Estándar (recap)

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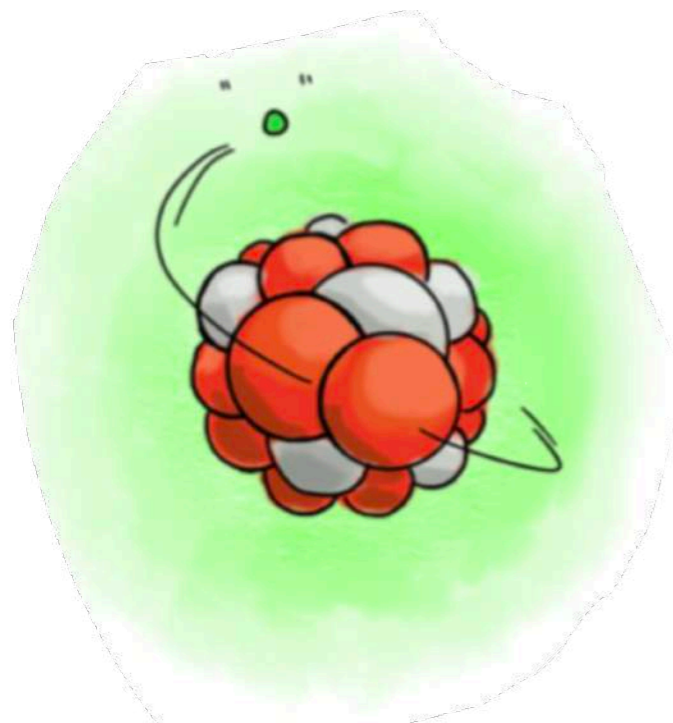
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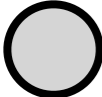

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Física experimental de partículas

Speaker: Sergi Rodriguez (CERN)



10^{-15} m
 10^{-10} m

-  protones
-  neutrones
-  electrones



El Modelo Estándar (recap)

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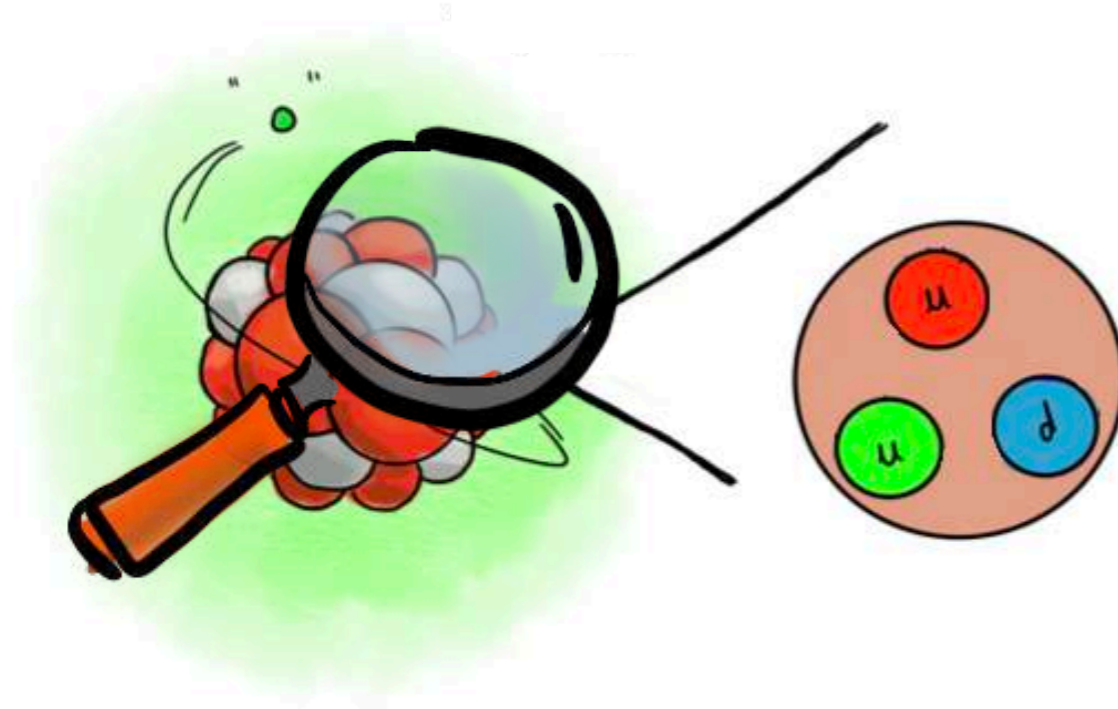
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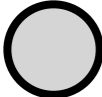

Física experimental de partículas

Speaker: Sergi Rodriguez (CERN)



$\approx 2.3 \text{ MeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	u	up
$\approx 4.8 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	d	down
$0.511 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	e	electron

10^{-15} m
 10^{-10} m

-  protones
-  neutrones
-  electrones

El Modelo Estándar (recap)

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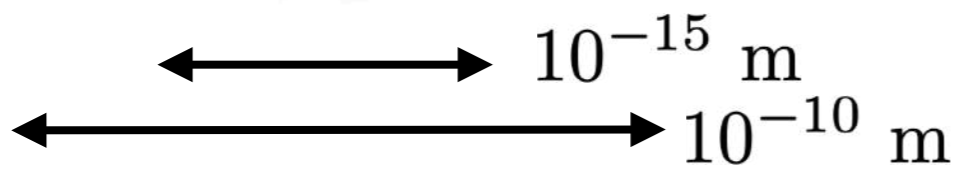
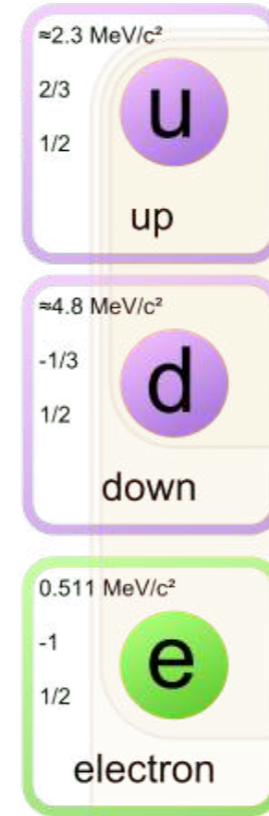
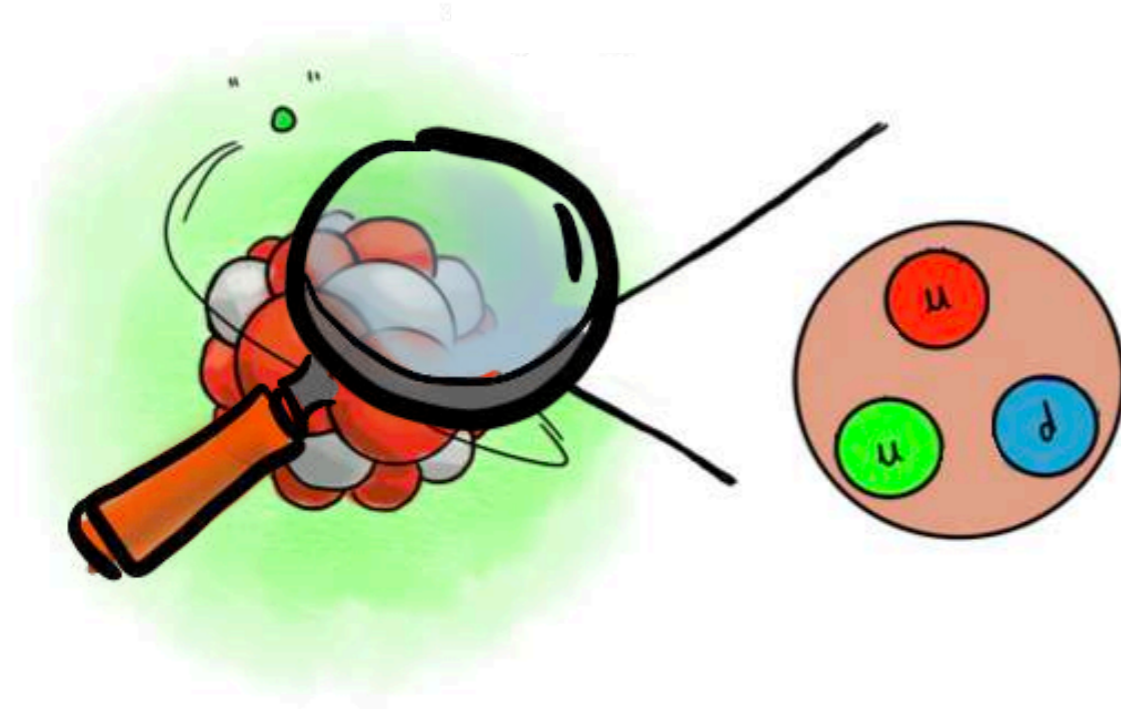
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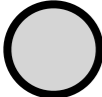

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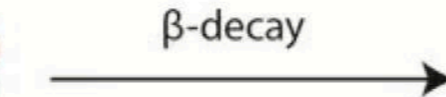
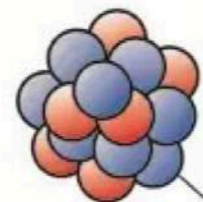
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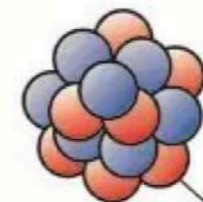


-  protones
-  neutrones
-  electrones

carbon-14
nucleus



nitrogen-14
nucleus



electron



proton

El Modelo Estándar (recap)

09:30

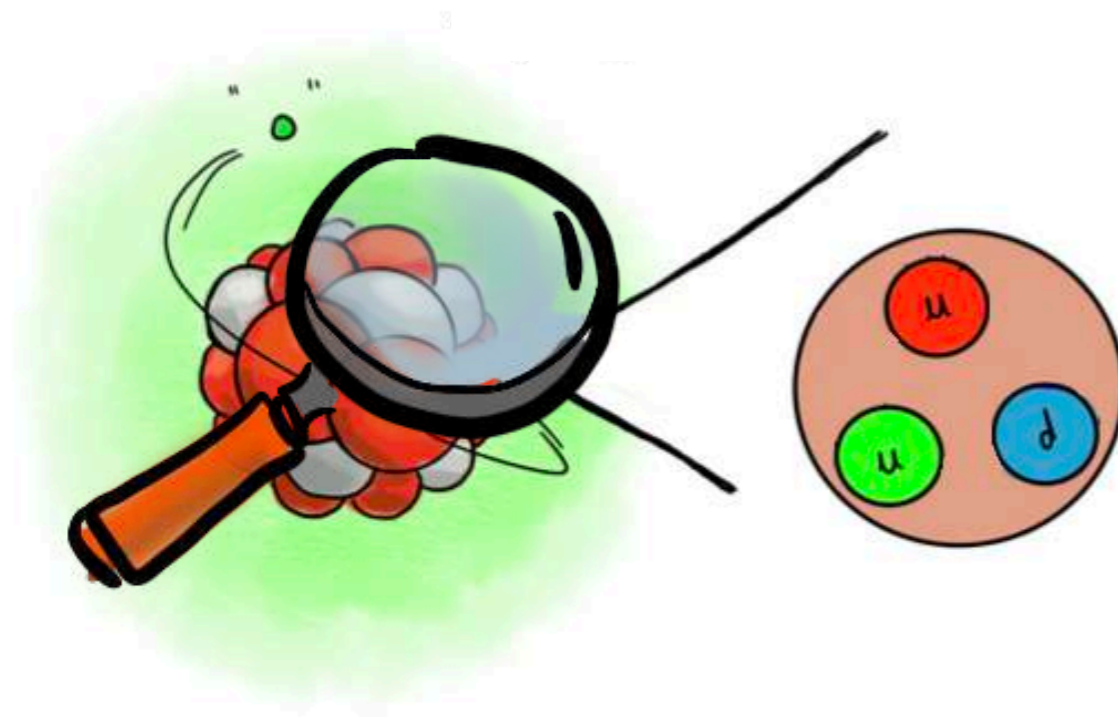
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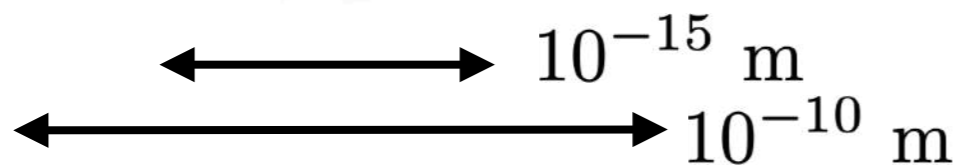
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Física experimental de partículas

Speaker: Sergi Rodriguez (CERN)

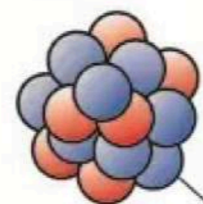


$\approx 2.3 \text{ MeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	u
			up
$\approx 4.8 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	d
			down
$0.511 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	e
			electron



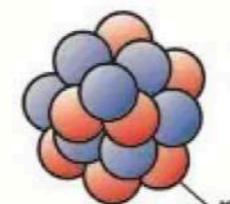
- protones
- neutrones
- electrones

carbon-14 nucleus



β -decay

nitrogen-14 nucleus



electron



proton

Esperado



El Modelo Estándar (recap)

09:30

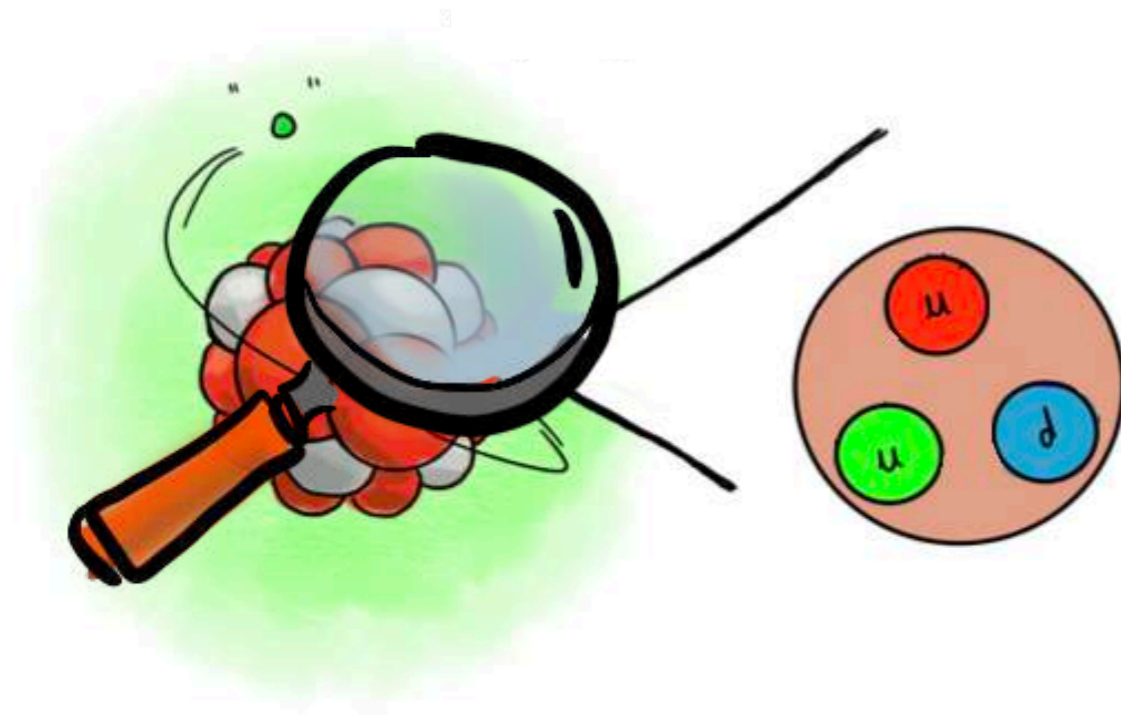
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

Física experimental de partículas

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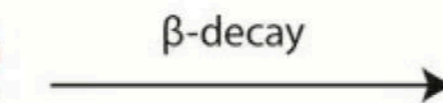
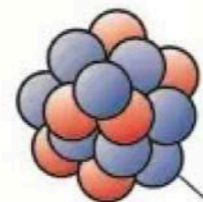


$\approx 2.3 \text{ MeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	u
			up
$\approx 4.8 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	d
			down
$0.511 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	e
			electron

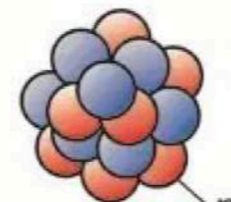
10^{-15} m
 10^{-10} m

-  protones
-  neutrones
-  electrones

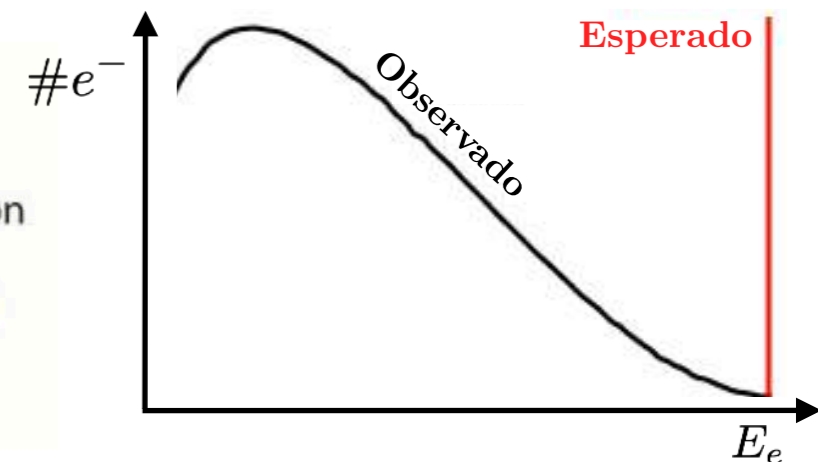
carbon-14 nucleus



nitrogen-14 nucleus



electron



El Modelo Estándar (recap)

09:30

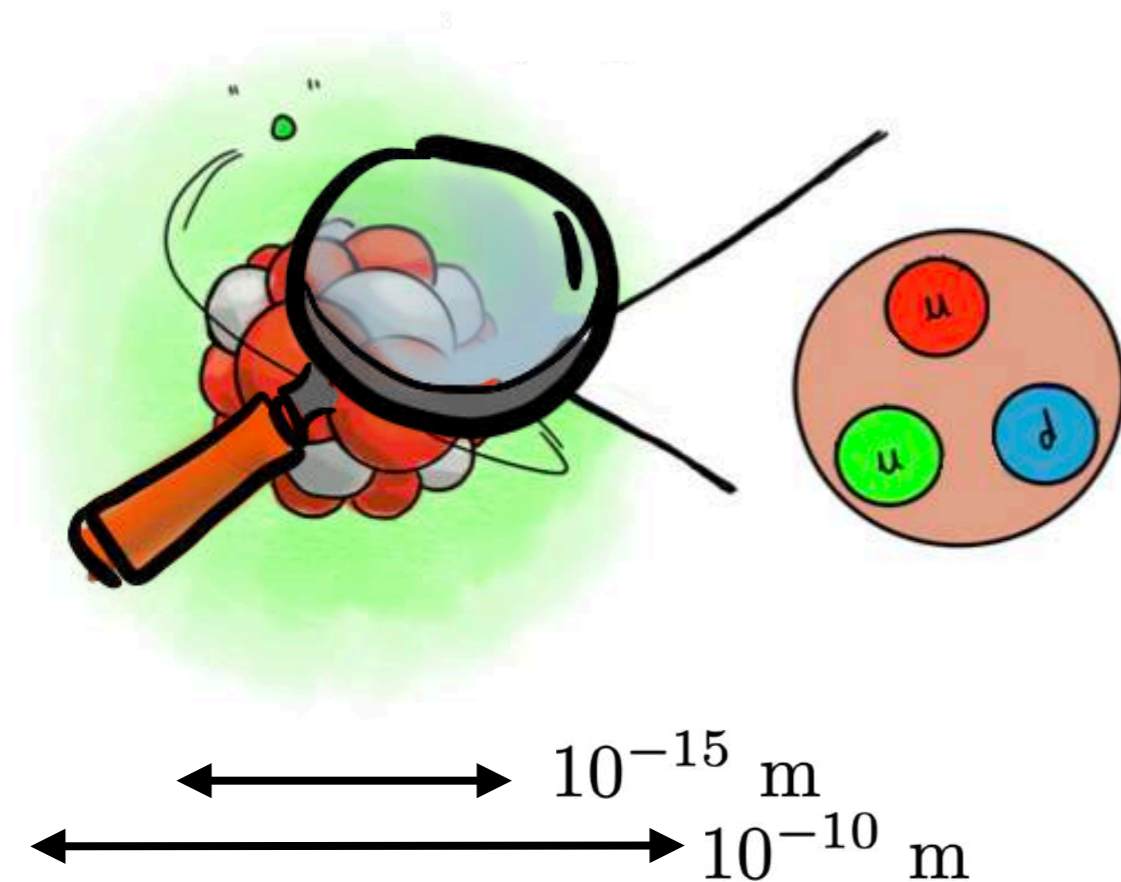
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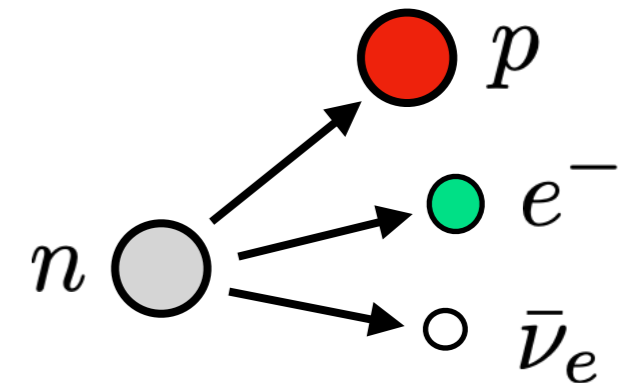
11:30

Física experimental de partículas

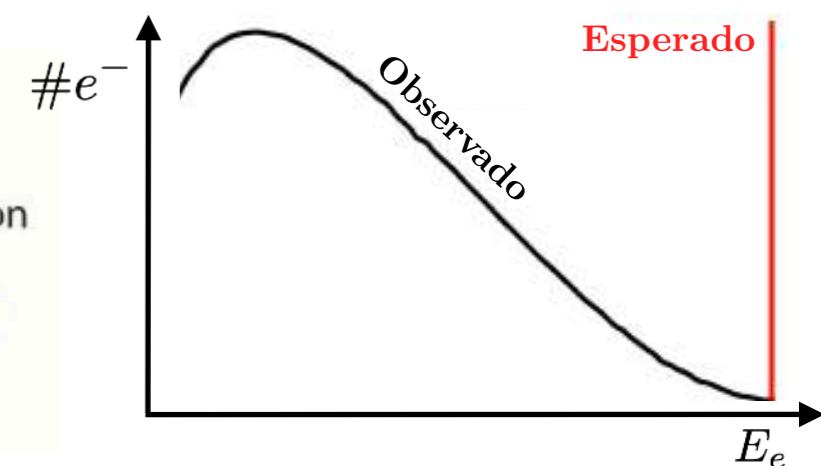
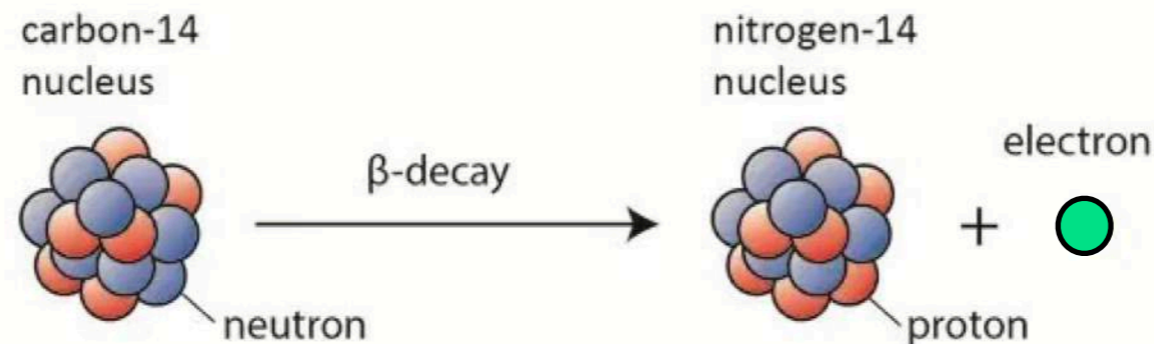
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$0.511 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	e	electron
$< 2.2 \text{ eV}/c^2$	0	$\frac{1}{2}$	ν_e	electron neutrino



- protones
- neutrones
- electrones



El Modelo Estándar (recap)

09:30

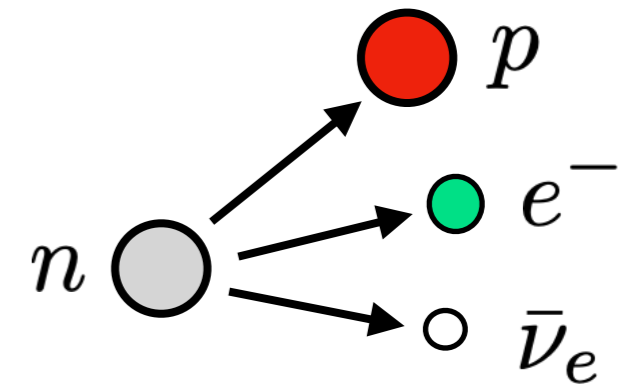
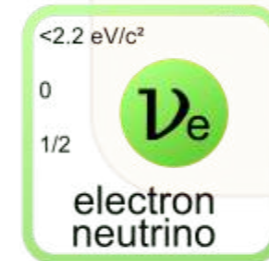
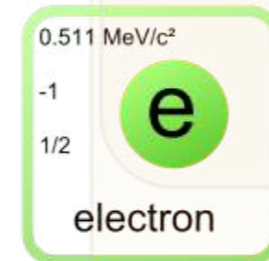
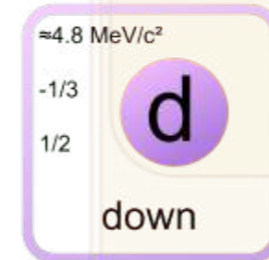
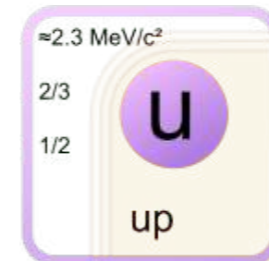
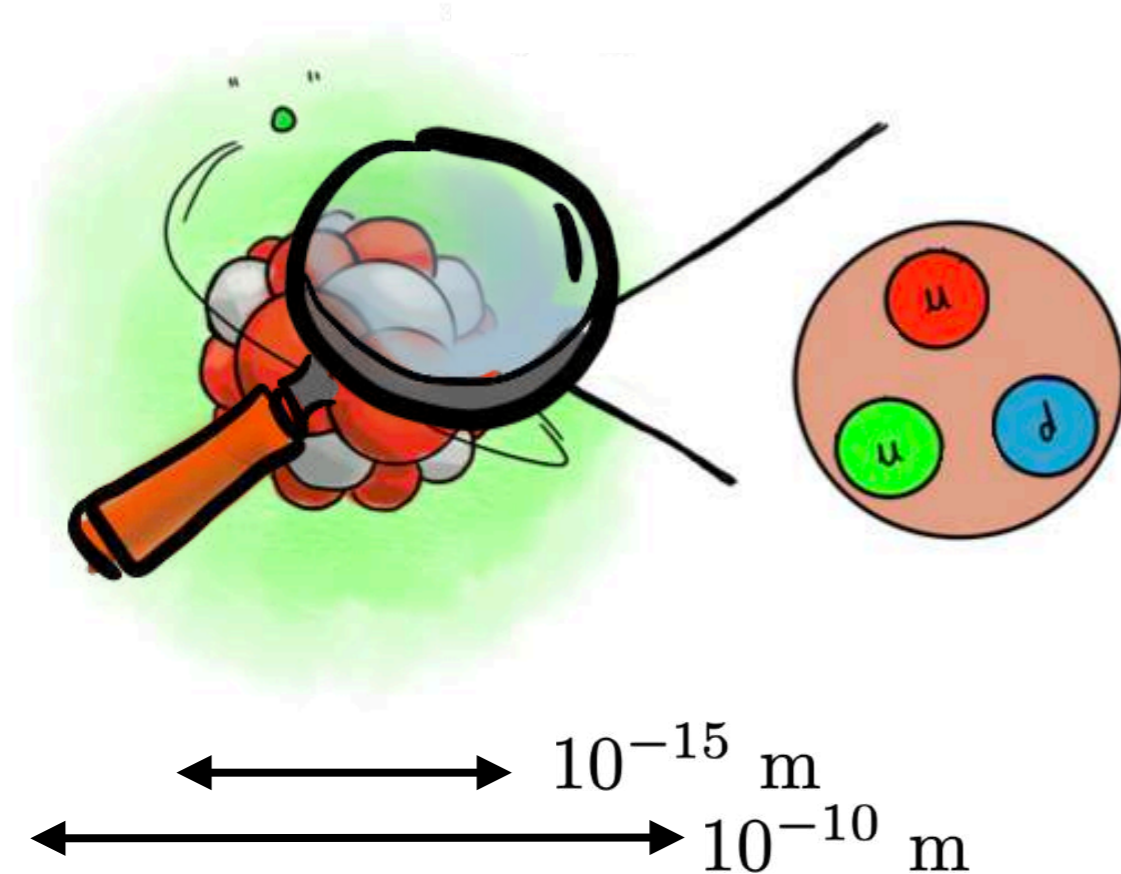
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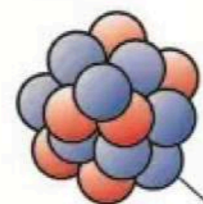
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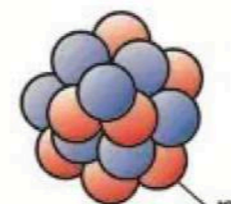
- protones
- neutrones
- electrones

carbon-14 nucleus

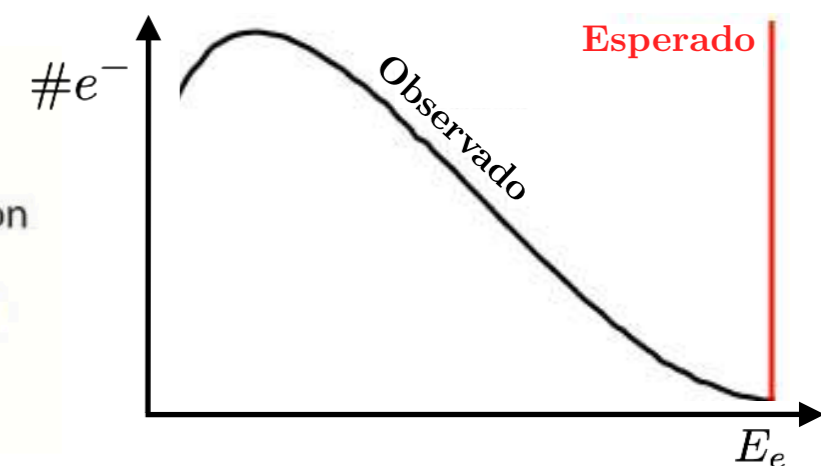


β -decay

nitrogen-14 nucleus



electron



El Modelo Estándar (recap)

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

09:30

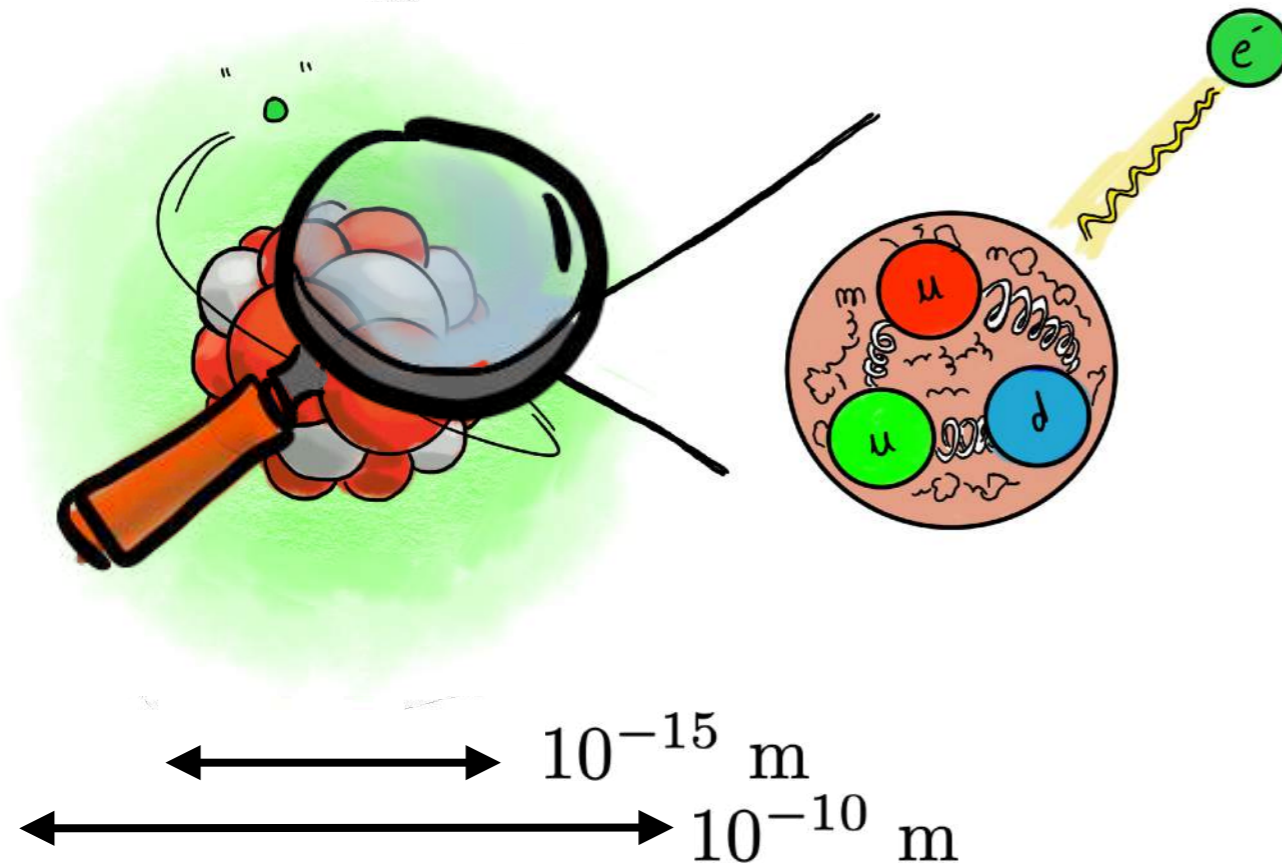
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Física experimental de partículas

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$\approx 2.3 \text{ MeV}/c^2$
 $2/3$
 $1/2$
u
 up

$\approx 4.8 \text{ MeV}/c^2$
 $-1/3$
 $1/2$
d
 down

$0.511 \text{ MeV}/c^2$
 -1
 $1/2$
e
 electron


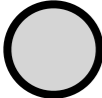

$< 2.2 \text{ eV}/c^2$
 0
 $1/2$
 ν_e
 electron neutrino

0
 0
 1
g
 gluon

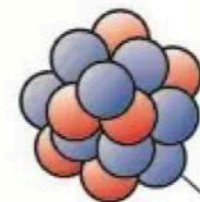
0
 0
 1
 γ
 photon

$91.2 \text{ GeV}/c^2$
 0
 1
Z
 Z boson

$80.4 \text{ GeV}/c^2$
 ± 1
 1
W
 W boson

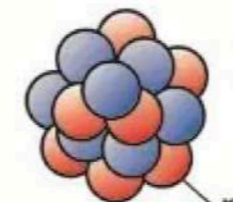
-  protones
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carbon-14 nucleus



β -decay

nitrogen-14 nucleus



electron



neutron

proton

El Modelo Estándar (recap)

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

09:30

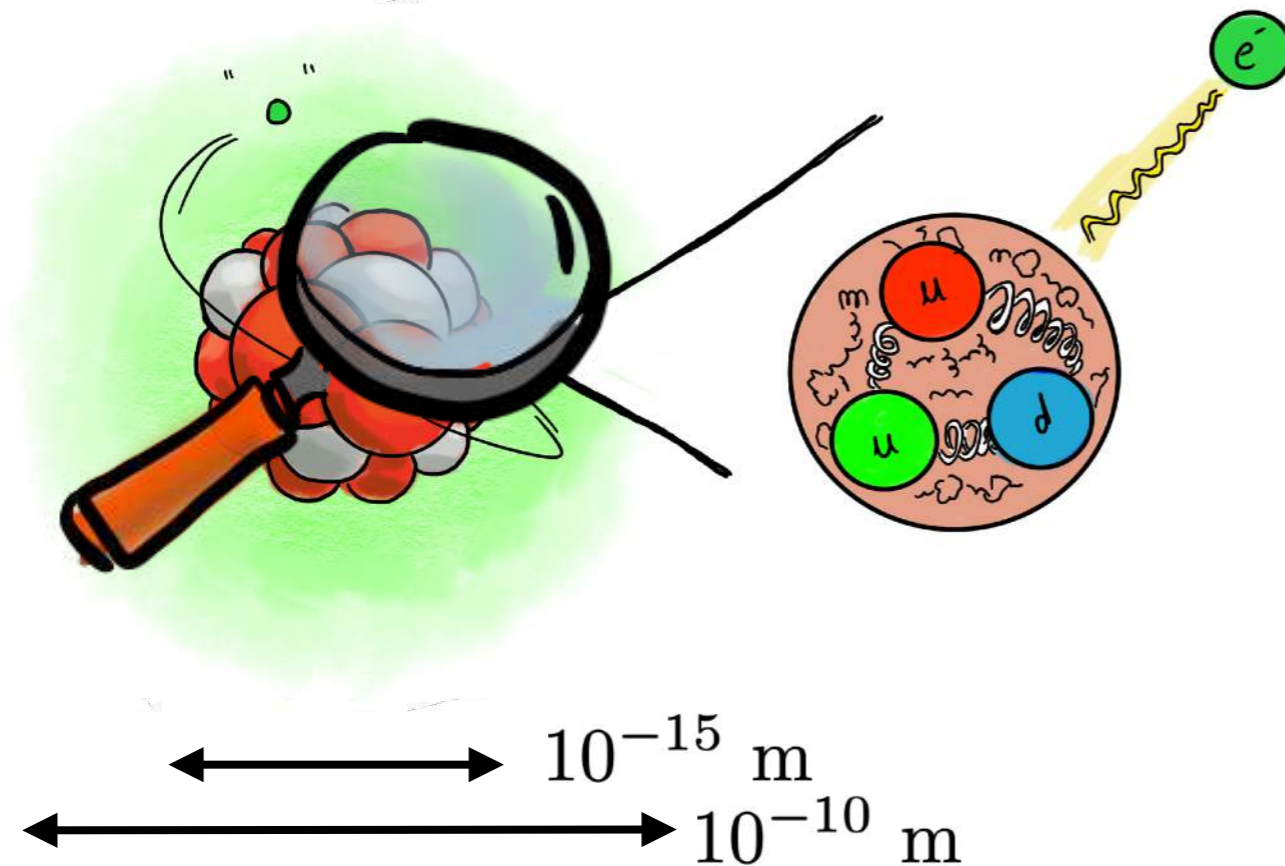
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$0.511 \text{ MeV}/c^2$
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$91.2 \text{ GeV}/c^2$
 0
 1
Z
 Z boson

$80.4 \text{ GeV}/c^2$
 ± 1
 1
W
 W boson

- protones
- neutrones
- electrones

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi$$

El Modelo Estándar (recap)

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

09:30

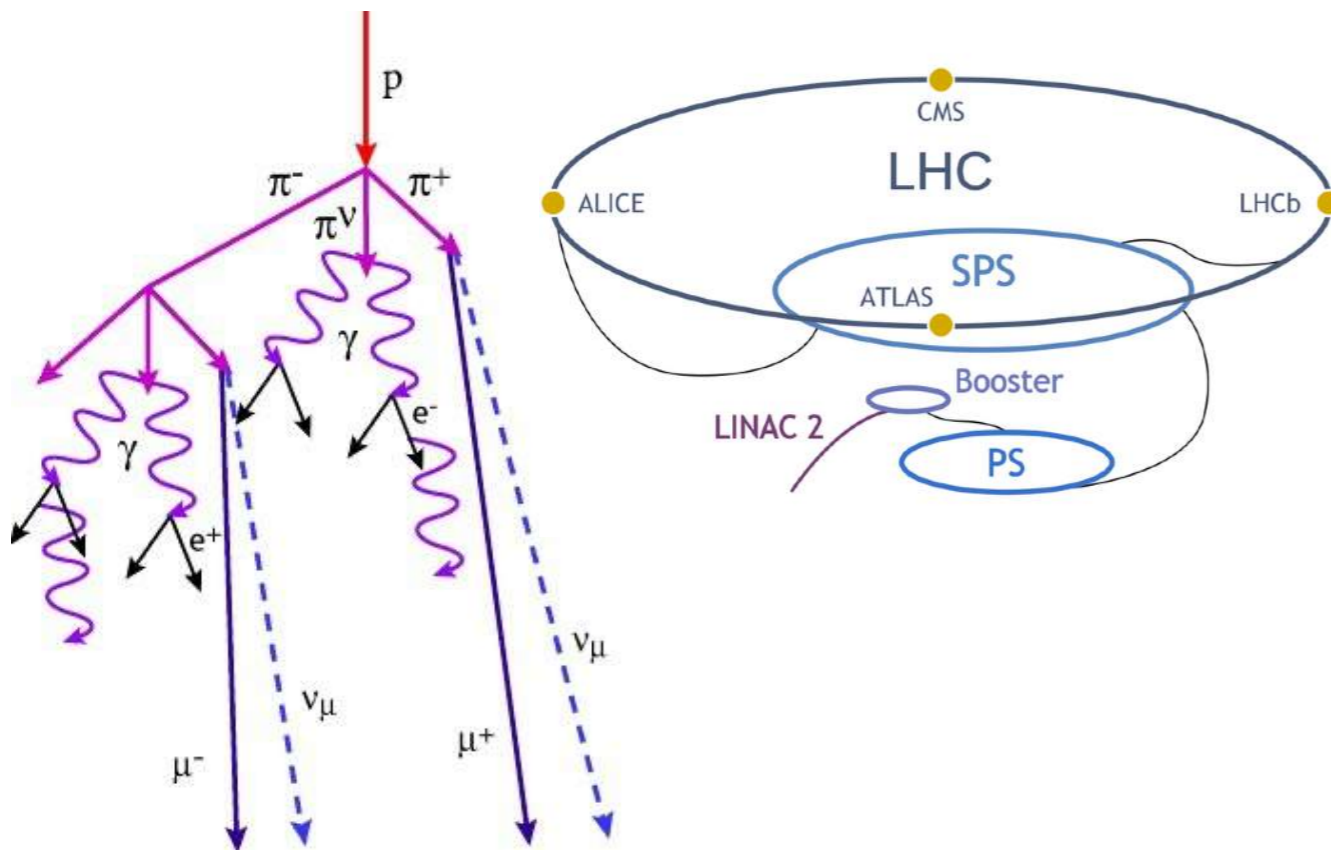
El Modelo estándar y la física fundame

Speaker: Miguel Escudero Abenza (CERN)

11:30

Física experimental de partículas

Speaker: Sergi Rodriguez (CERN)



$\approx 2.3 \text{ MeV}/c^2$ 2/3 1/2 u up	$\approx 1.275 \text{ GeV}/c^2$ 2/3 1/2 c charm	$\approx 173.07 \text{ GeV}/c^2$ 2/3 1/2 t top	0 0 1 g gluon
$\approx 4.8 \text{ MeV}/c^2$ -1/3 1/2 d down	$\approx 95 \text{ MeV}/c^2$ -1/3 1/2 s strange	$\approx 4.18 \text{ GeV}/c^2$ -1/3 1/2 b bottom	0 0 1 \gamma photon
$0.511 \text{ MeV}/c^2$ -1 1/2 e electron	$105.7 \text{ MeV}/c^2$ -1 1/2 \mu muon	$1.777 \text{ GeV}/c^2$ -1 1/2 \tau tau	$91.2 \text{ GeV}/c^2$ 0 1 Z Z boson
$< 2.2 \text{ eV}/c^2$ 0 1/2 \nu_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 1/2 \nu_\mu muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 1/2 \nu_\tau tau neutrino	$80.4 \text{ GeV}/c^2$ ± 1 1 W W boson

masa

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi$$

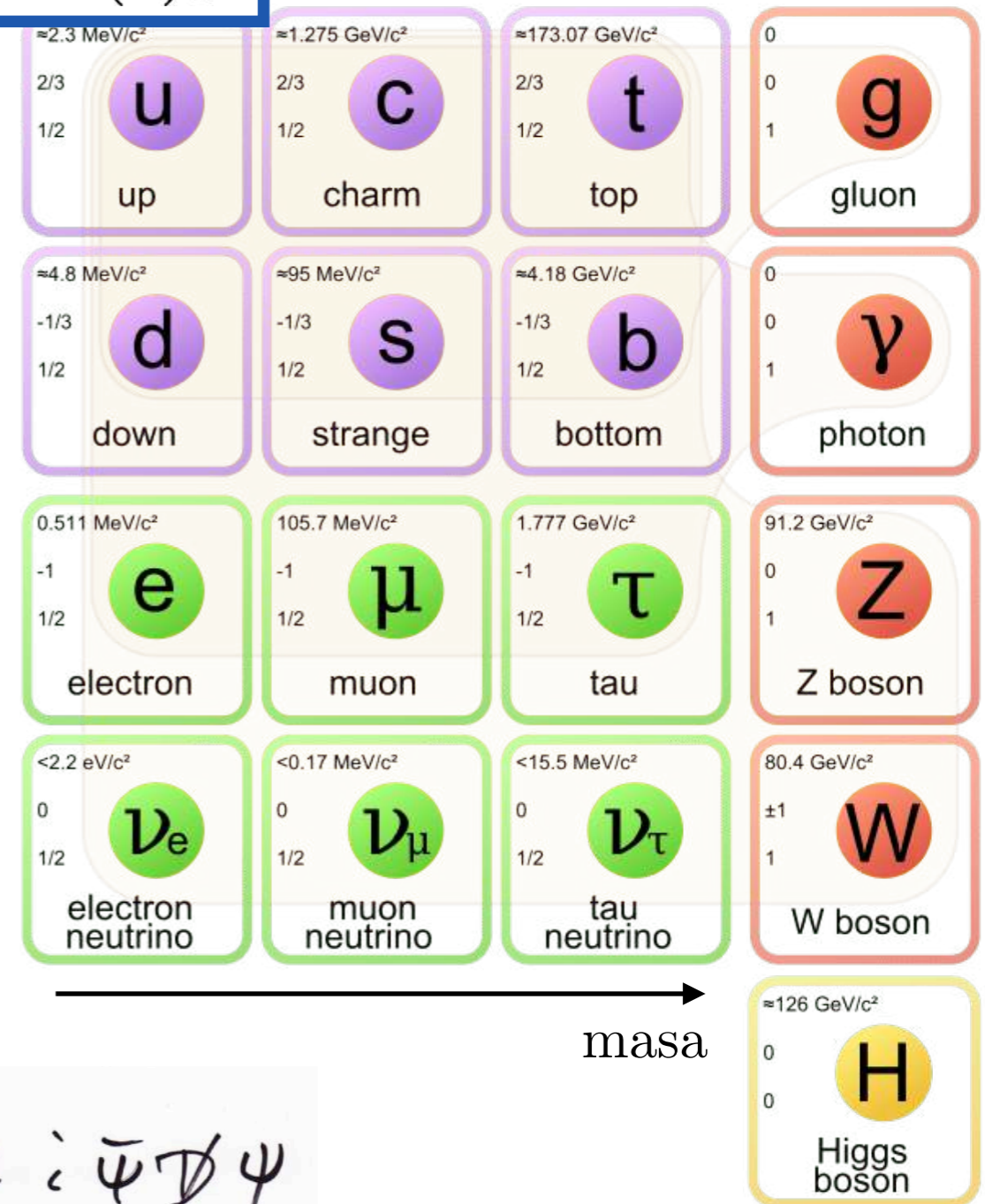
El Modelo Estándar (recap)

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

10:50

El descubrimiento del bosón de Higgs

Speaker: Luis Roberto Flores Castillo (The Chinese University of Hong Kong (HK))



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{\partial} \Psi$$

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

El Modelo Estándar (recap)

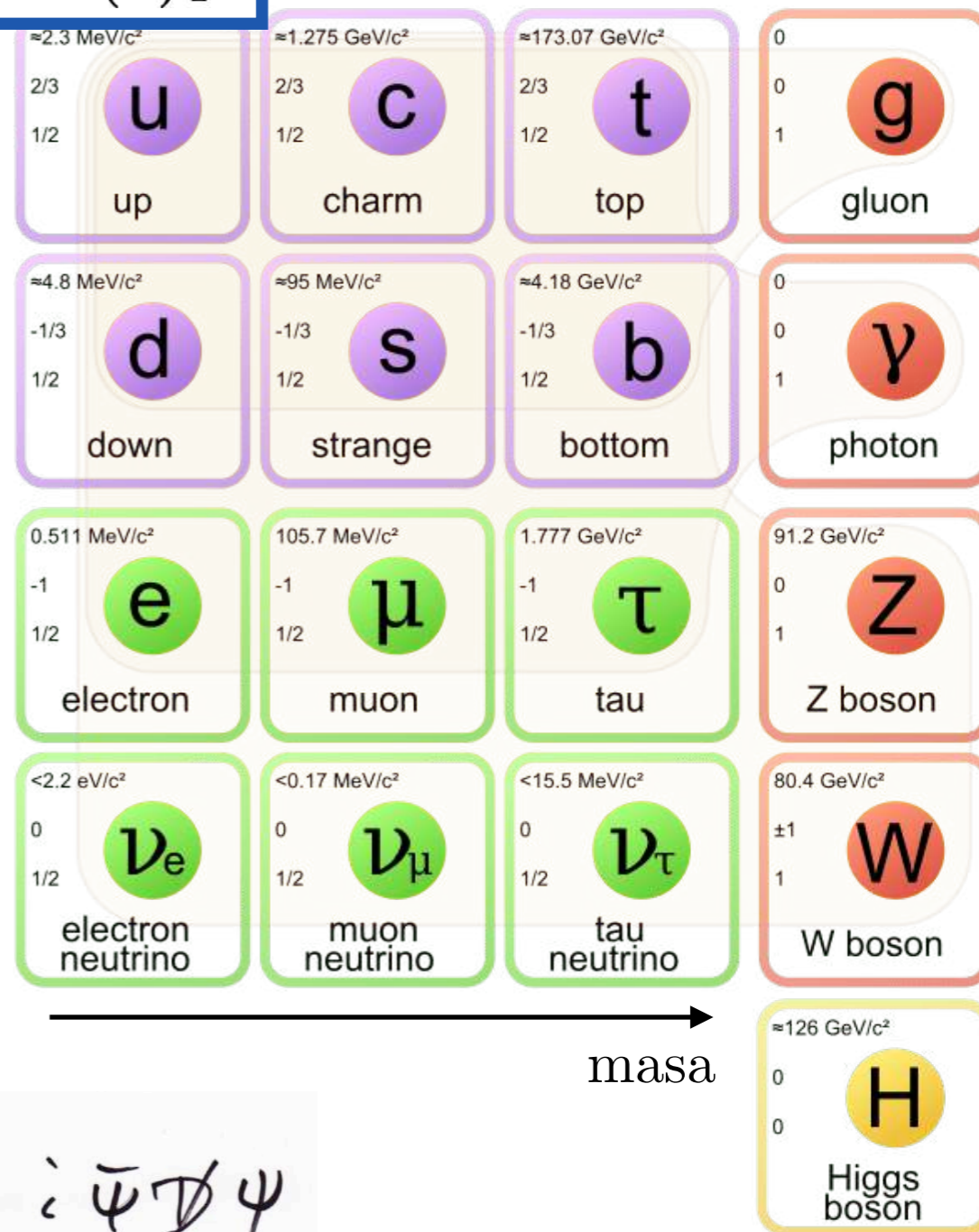
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

10:50

El descubrimiento del bosón de Higgs

Speaker: Luis Roberto Flores Castillo (The Chinese University of Hong Kong (HK))

e.g.
$$\underbrace{(\bar{\nu}_L^i \quad \bar{e}_L^i)}_{\bar{L}_L^i} y_{ij} \begin{pmatrix} 0 \\ H_0 \end{pmatrix} e_R^j + \text{h.c.}$$



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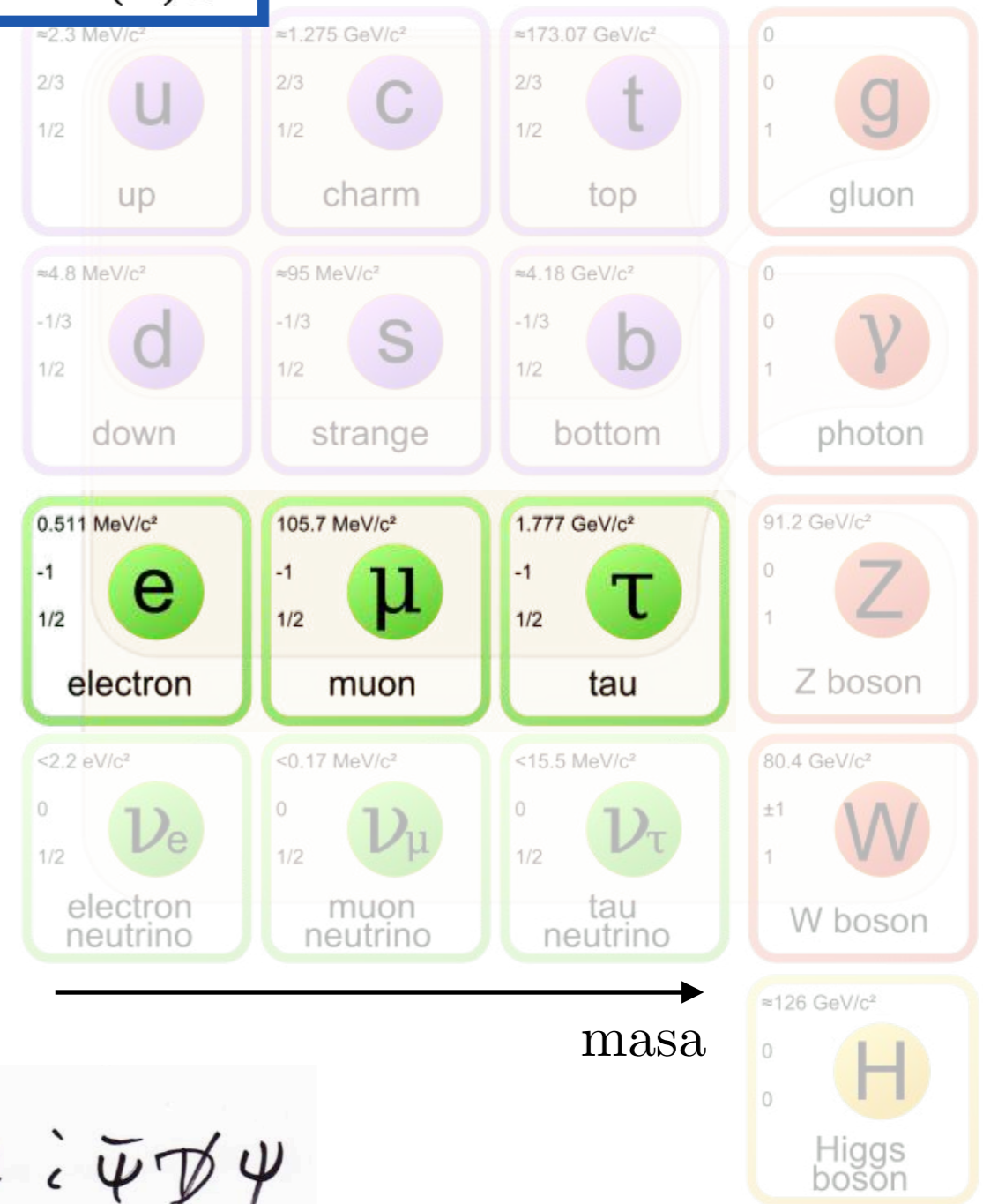
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10:50

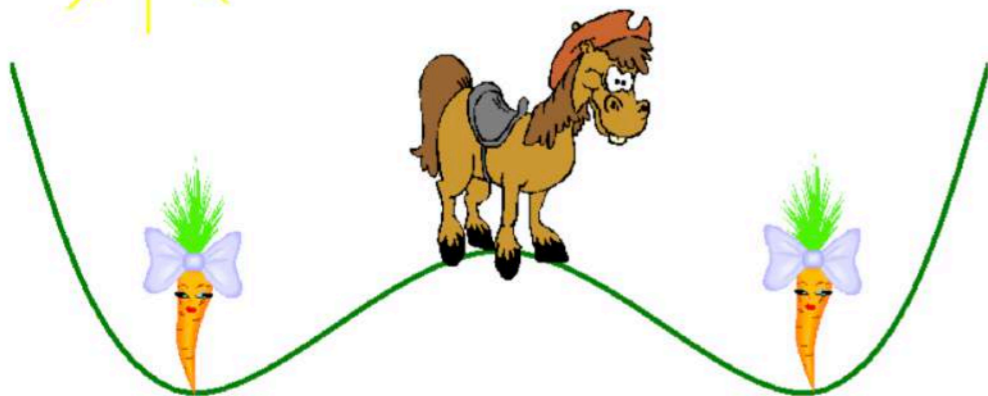
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$\approx 2.3 \text{ MeV}/c^2$ 2/3 1/2 u up	$\approx 1.275 \text{ GeV}/c^2$ 2/3 1/2 c charm	$\approx 173.07 \text{ GeV}/c^2$ 2/3 1/2 t top	0 0 1 g gluon
$\approx 4.8 \text{ MeV}/c^2$ -1/3 1/2 d down	$\approx 95 \text{ MeV}/c^2$ -1/3 1/2 s strange	$\approx 4.18 \text{ GeV}/c^2$ -1/3 1/2 b bottom	0 0 1 \gamma photon
$0.511 \text{ MeV}/c^2$ -1 1/2 e electron	$105.7 \text{ MeV}/c^2$ -1 1/2 \mu muon	$1.777 \text{ GeV}/c^2$ -1 1/2 \tau tau	$91.2 \text{ GeV}/c^2$ 0 1 Z Z boson
$< 2.2 \text{ eV}/c^2$ 0 1/2 \nu_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 1/2 \nu_\mu muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 1/2 \nu_\tau tau neutrino	$80.4 \text{ GeV}/c^2$ ± 1 1 W W boson
			$\approx 126 \text{ GeV}/c^2$ 0 0 H Higgs boson

masa

@Toni Pich
"Nicolás"

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi$$

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + \text{h.c.} + \frac{1}{2} D_\mu \phi |^2 - V(\phi)$$

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10:50

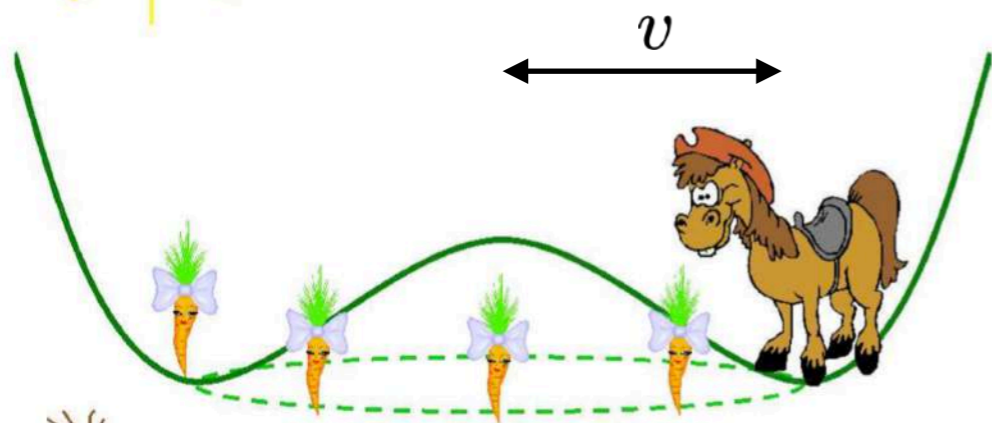
El descubrimiento del bosón de Higgs

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$\approx 2.3 \text{ MeV}/c^2$ $2/3$ $1/2$ up	$\approx 1.275 \text{ GeV}/c^2$ $2/3$ $1/2$ charm	$\approx 173.07 \text{ GeV}/c^2$ $2/3$ $1/2$ top	0 0 1 gluon
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masa

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$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

10:50

El descubrimiento del bosón de Higgs

Speaker: Luis Roberto Flores Castillo (The Chinese University of Hong Kong (HK))



Prof. David J. Miller



Prof. David J. Miller

[diapositiva de la charla de Luis Roberto]

El Modelo Estándar (recap)

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

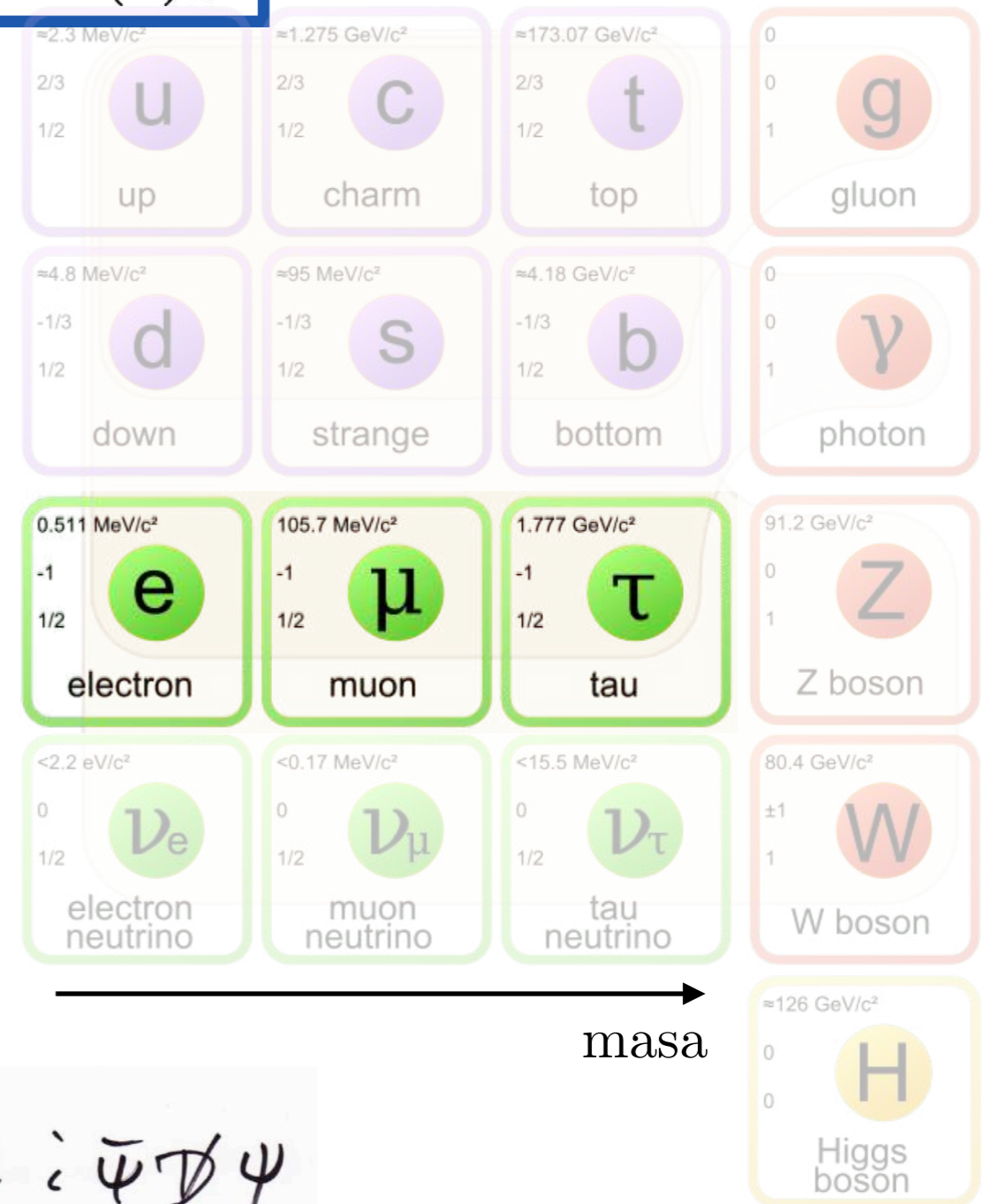
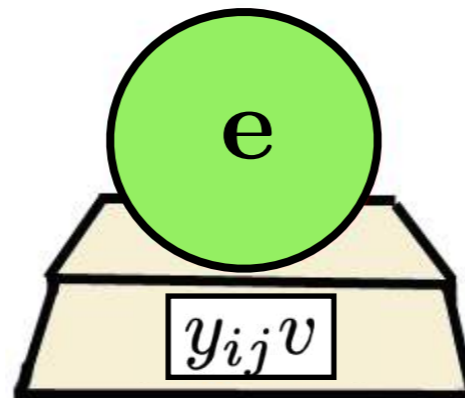
10:50

El descubrimiento del bosón de Higgs

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El Modelo Estándar (recap)

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

2013



Descubrimiento del bosón de Higgs - 4 Julio 2012

El Modelo Estándar (recap)

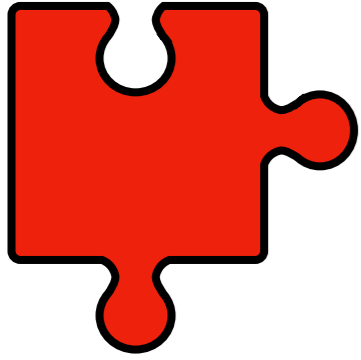
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

La última pieza del puzzle deja muchos otros puzzles por resolver...



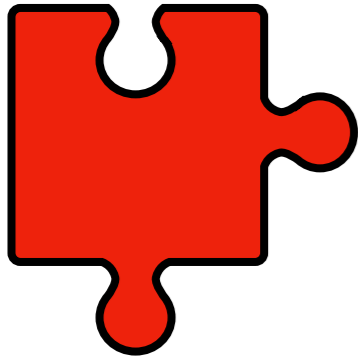
Descubrimiento del bosón de Higgs - 4 Julio 2012

El puzzle de los neutrinos solares



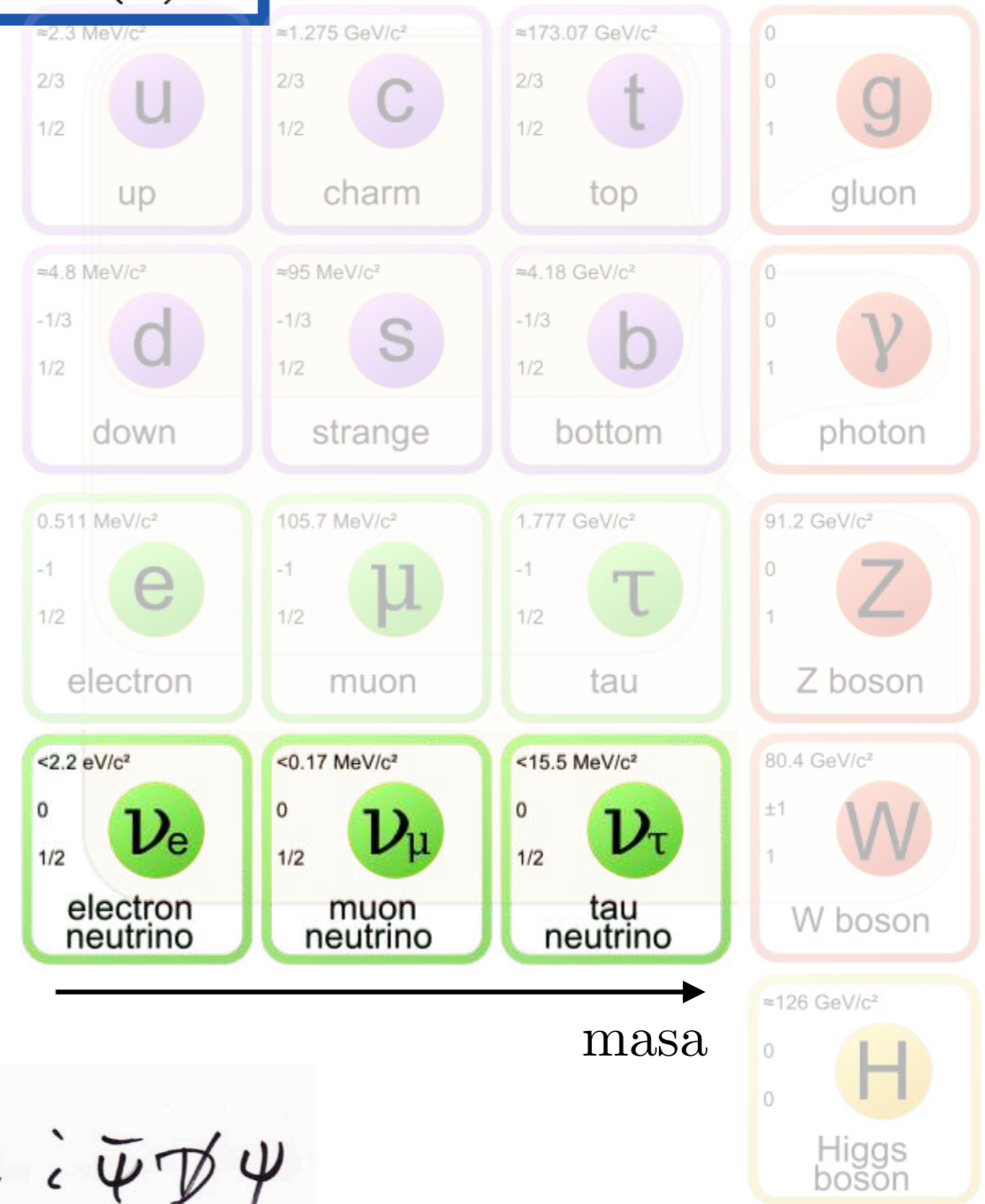
El puzzle de los neutrinos solares

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



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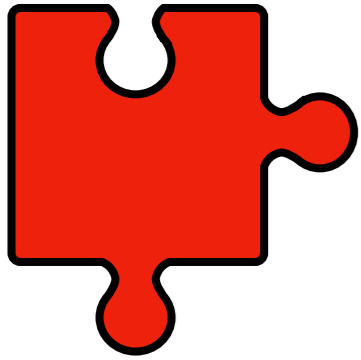


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi$$

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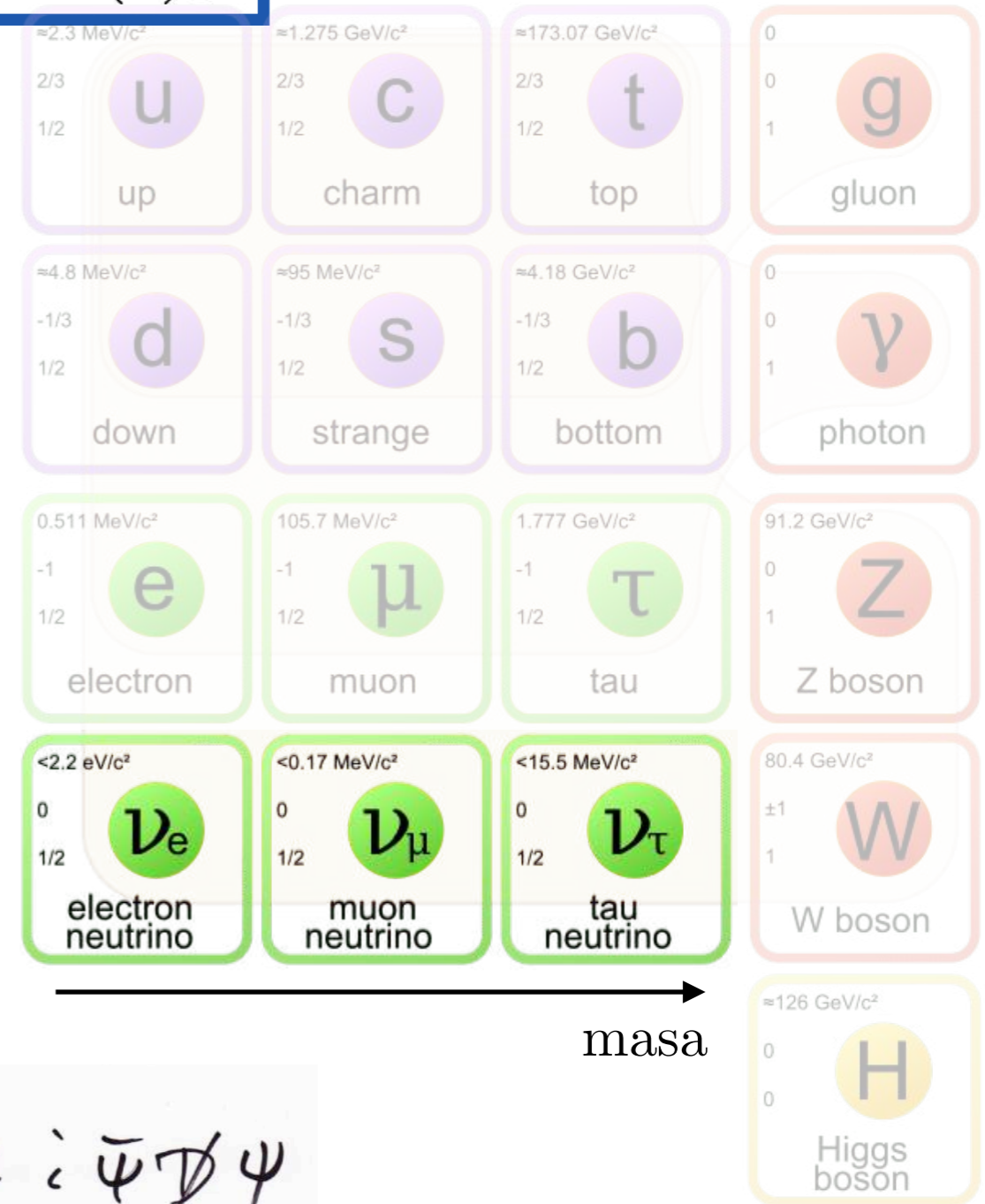
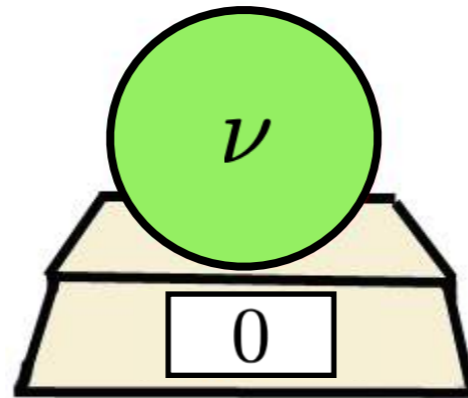
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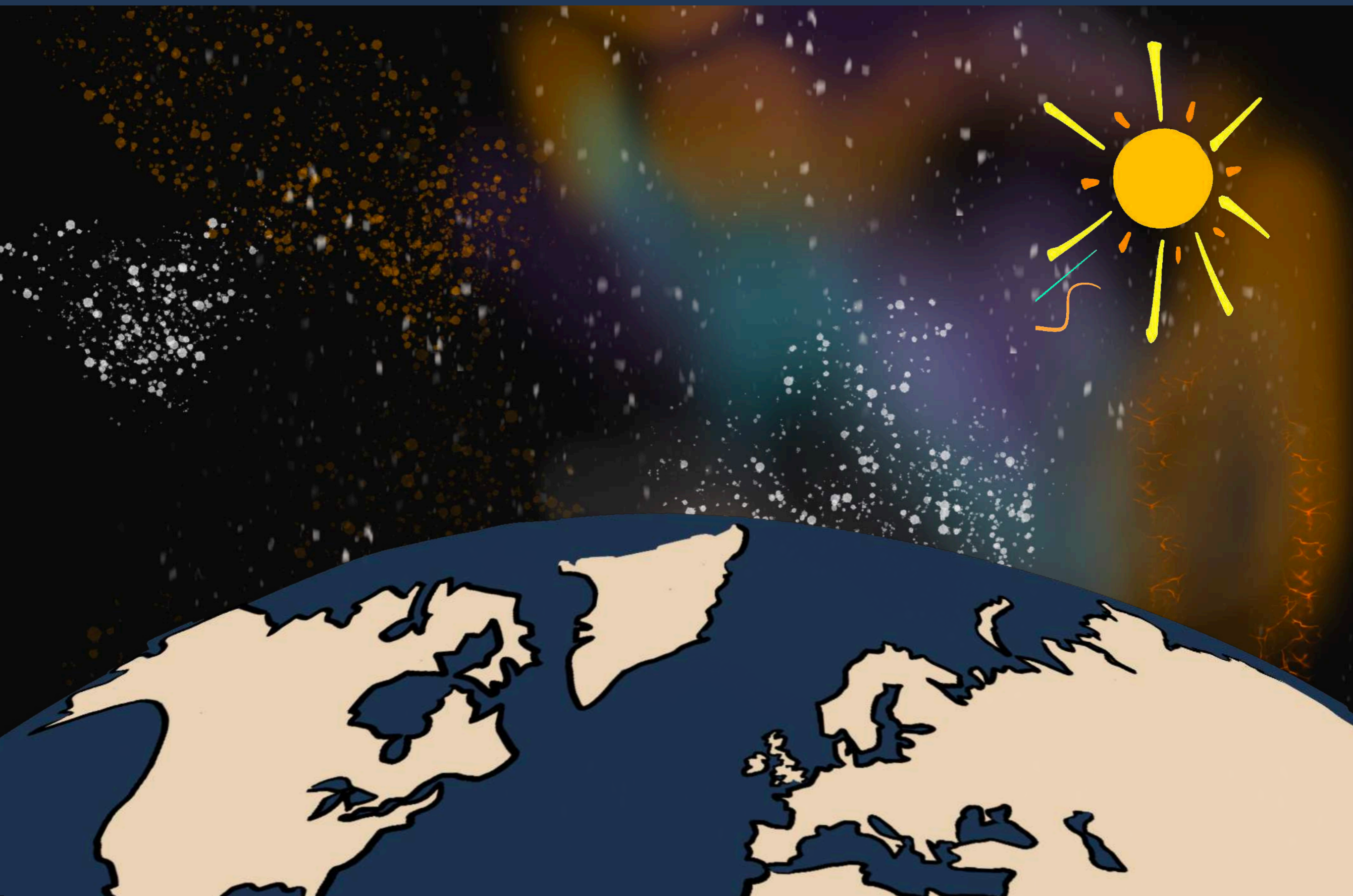
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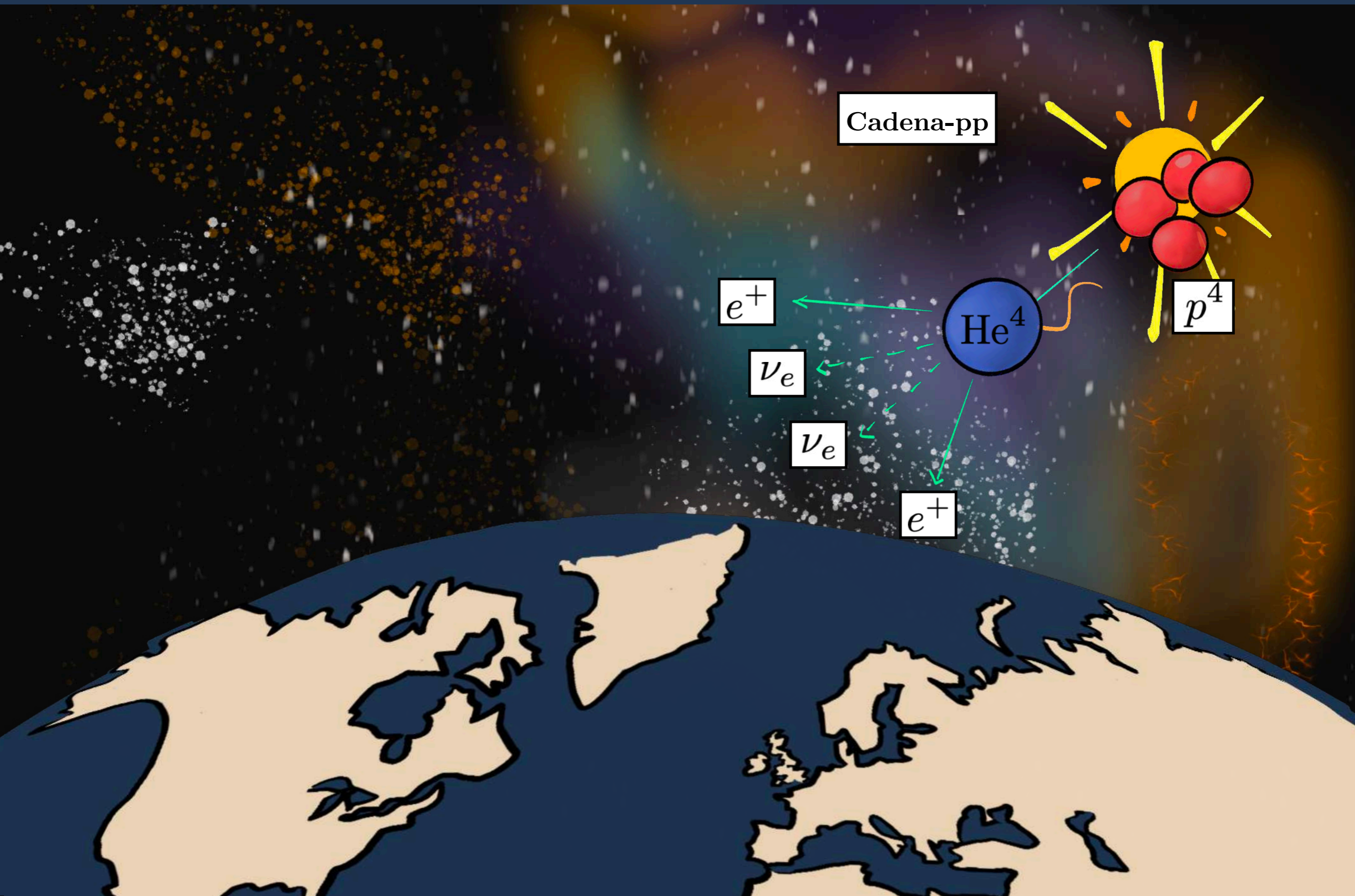
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El puzzle de los neutrinos solares

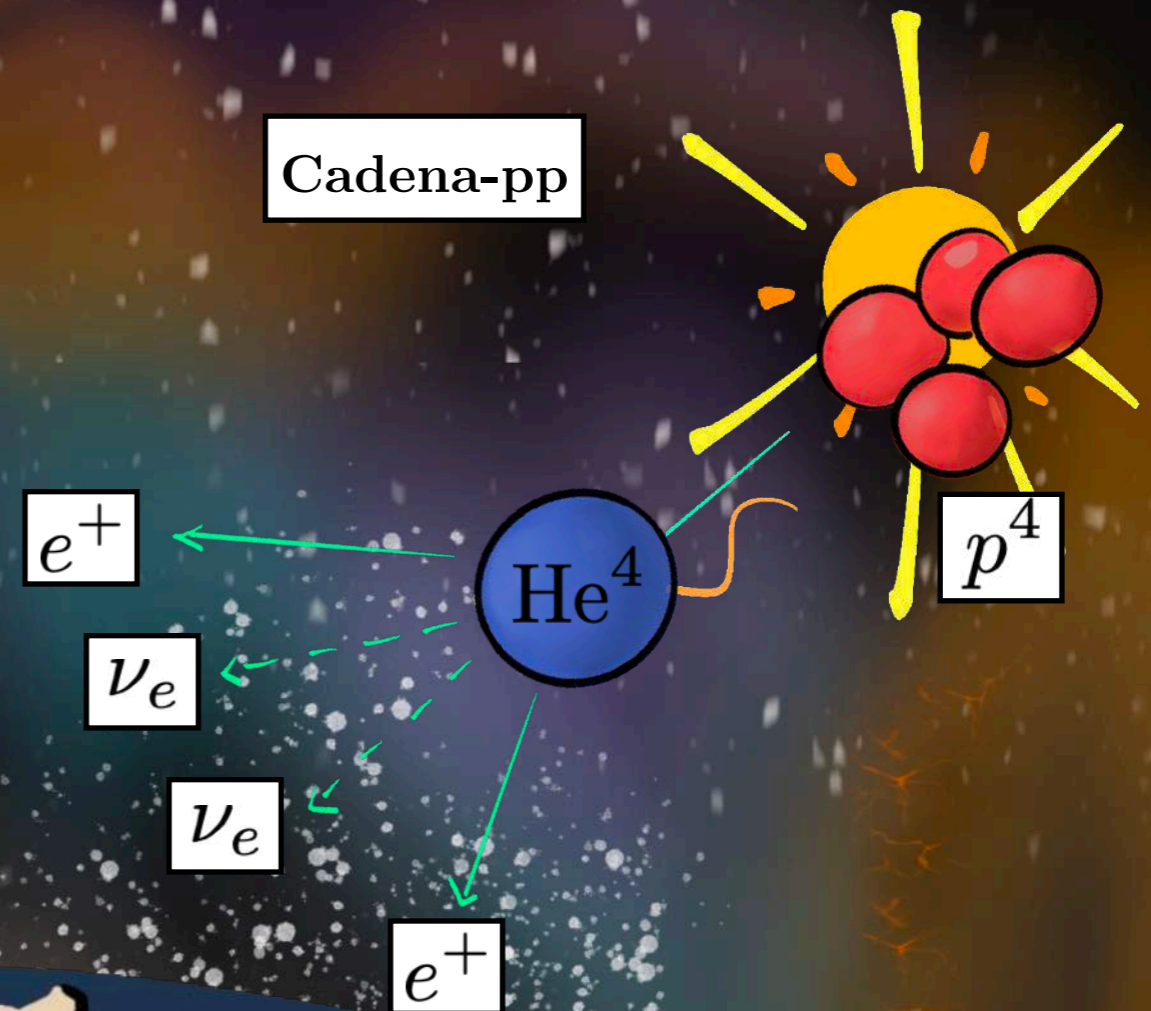


El puzzle de los neutrinos solares

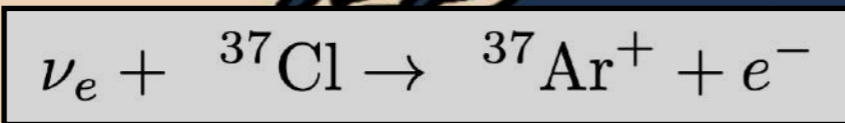


El puzzle de los neutrinos solares

Cadena-pp



Davis & Bahcall
[Homestake, 1960]



El puzzle de los neutrinos solares

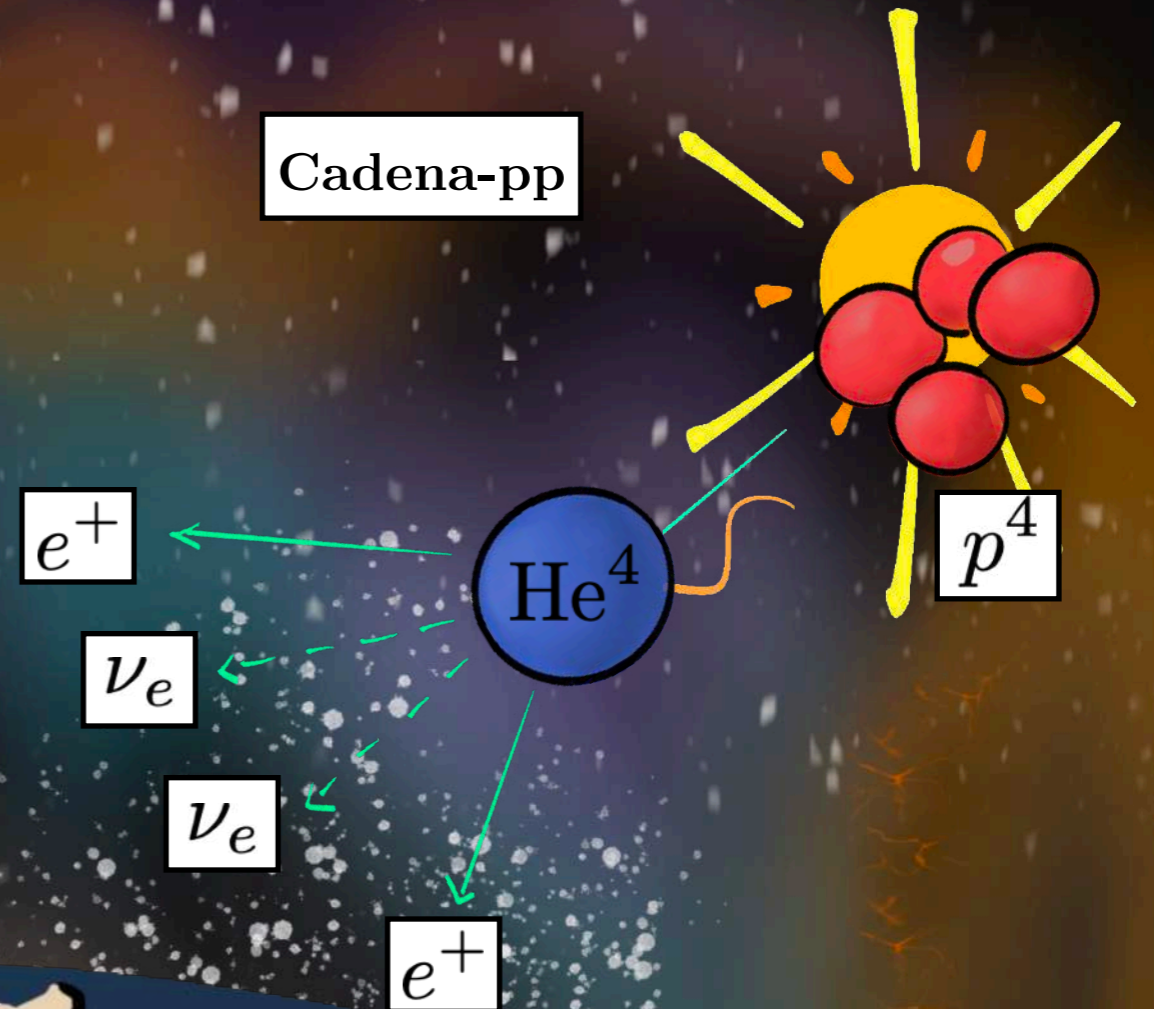


2002 - Davis & Koshiba



1/3

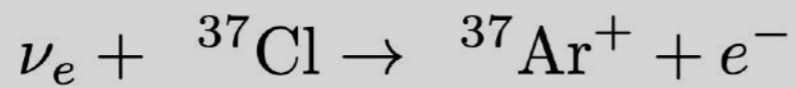
Cadena-pp



Davis & Bahcall
[Homestake, 1960]



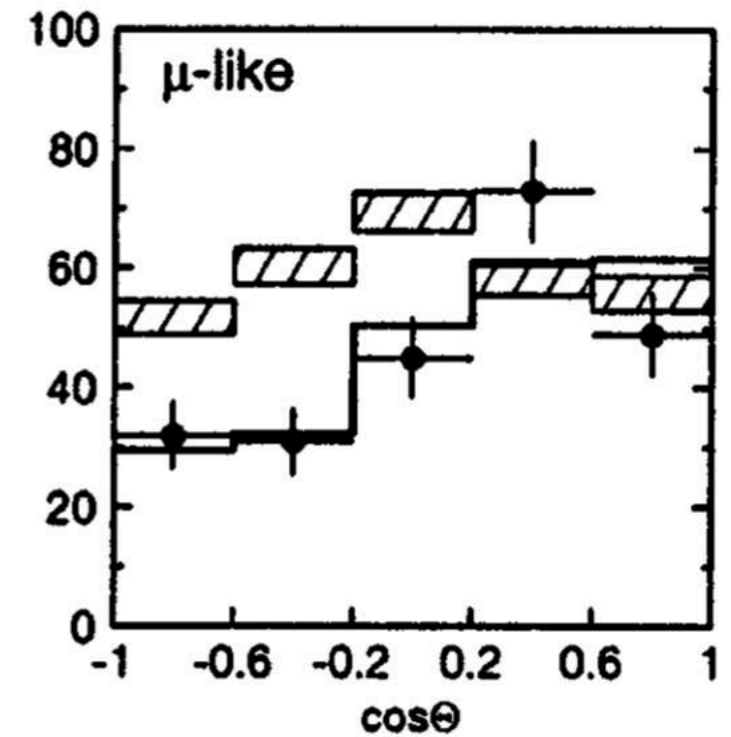
^{35}Cl



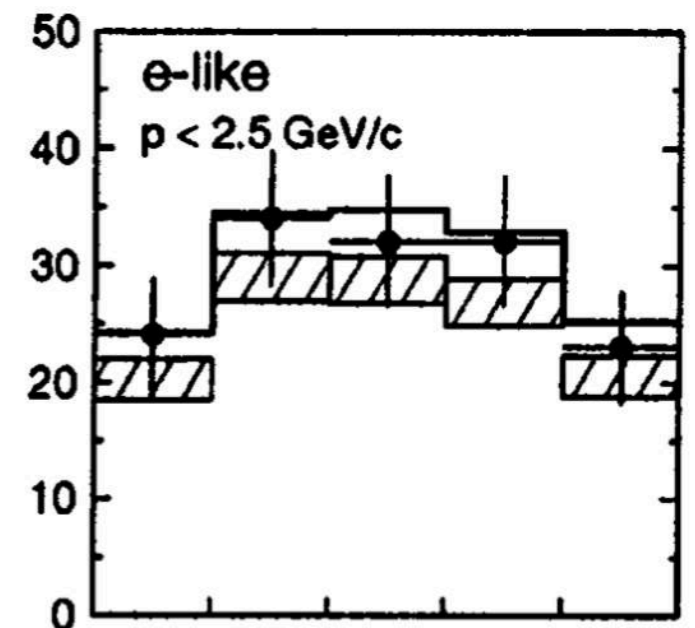
La masa de los neutrinos



2002 - Davis & Koshiba



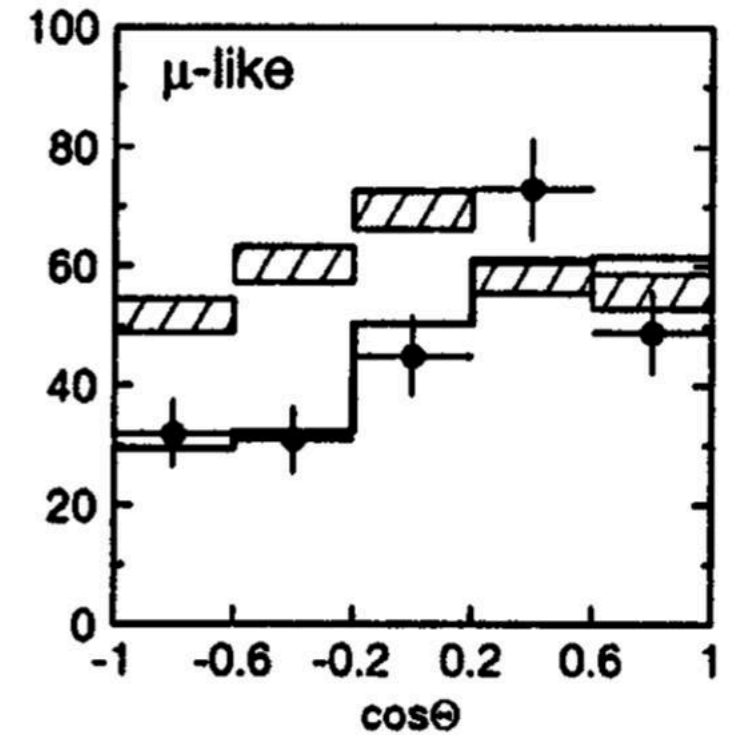
2015 - Kajita & McDonald



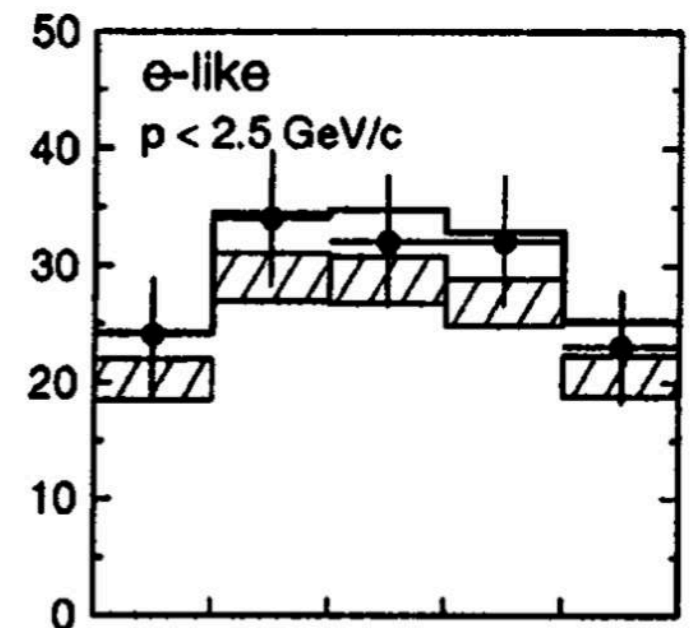
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2002 - Davis & Koshiba



2015 - Kajita & McDonald

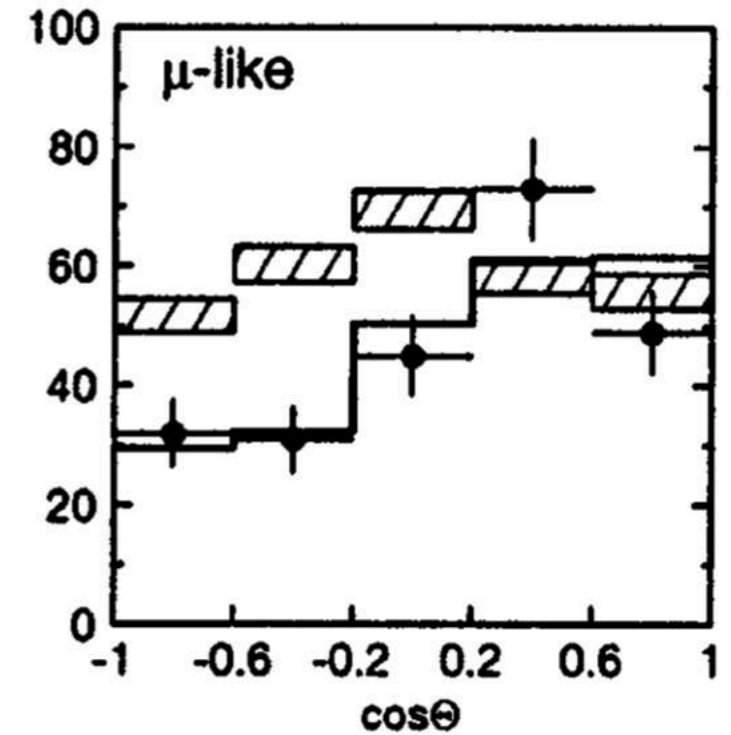


La masa de los neutrinos

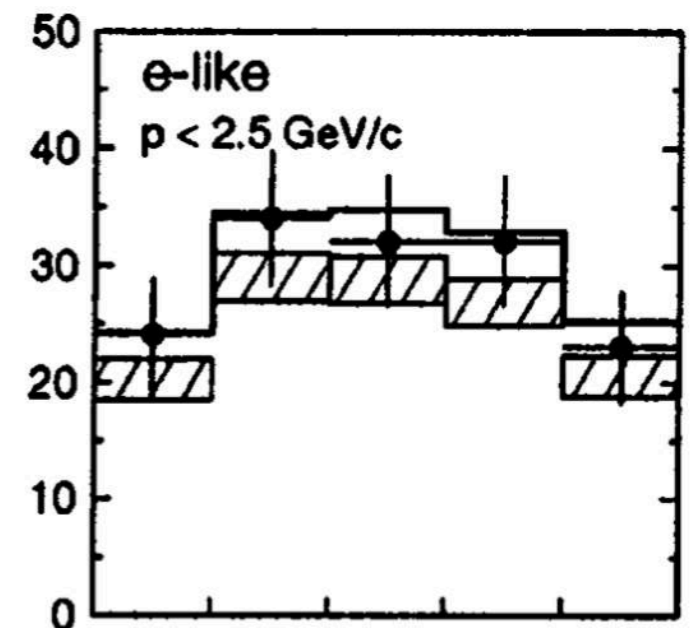


2002 - Davis & Koshiba

$$P_{\alpha \rightarrow \beta} = |\langle \nu_{\beta} | \nu_{\alpha}(L) \rangle|^2 = \left| \sum_j U_{\alpha j}^* U_{\beta j} \right|_{\text{ME}}^2 = \delta_{\alpha\beta}$$



2015 - Kajita & McDonald

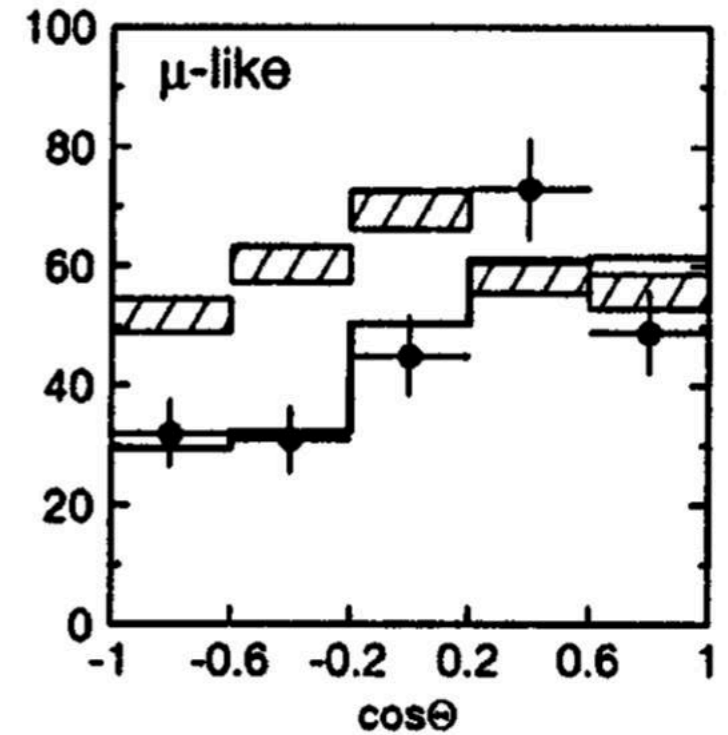


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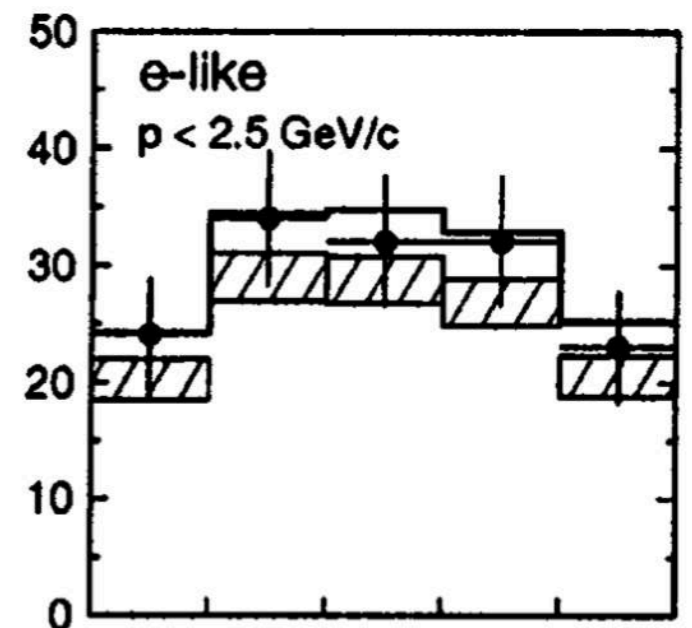


2002 - Davis & Koshiba

$$P_{\alpha \rightarrow \beta} = |\langle \nu_{\beta} | \nu_{\alpha}(L) \rangle|^2 = \left| \sum_j U_{\alpha j}^* U_{\beta j} e^{-im_j^2 L / (2E)} \right|^2$$



2015 - Kajita & McDonald

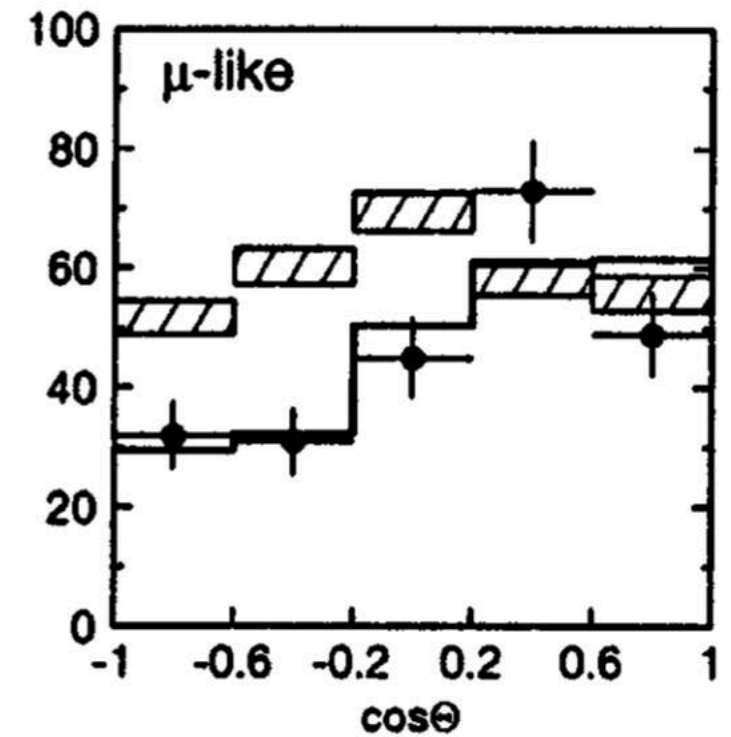
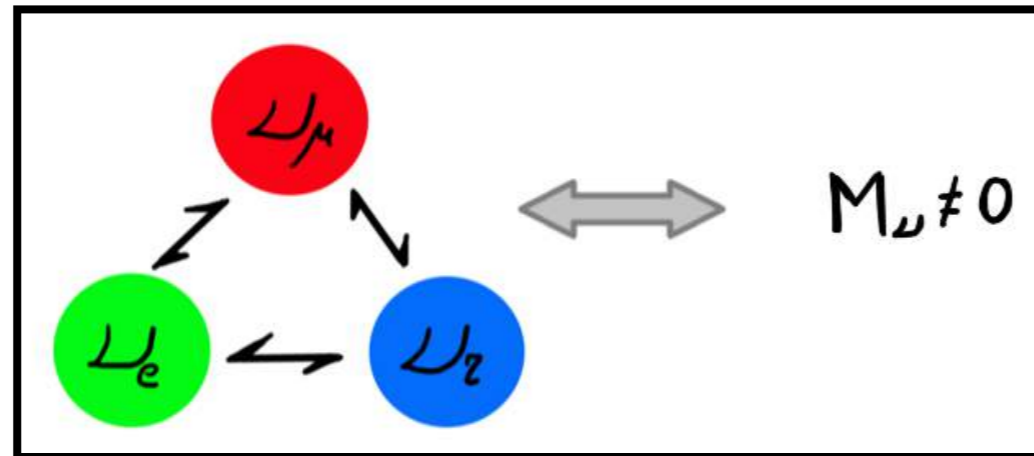


La masa de los neutrinos

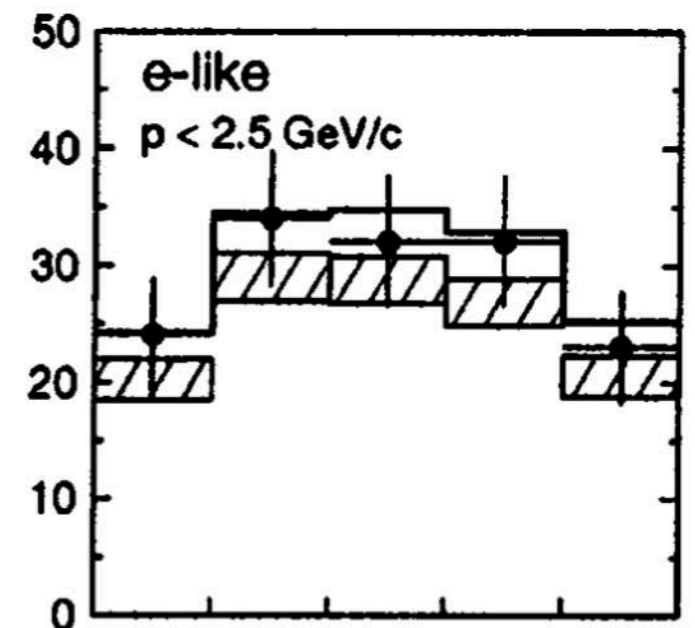


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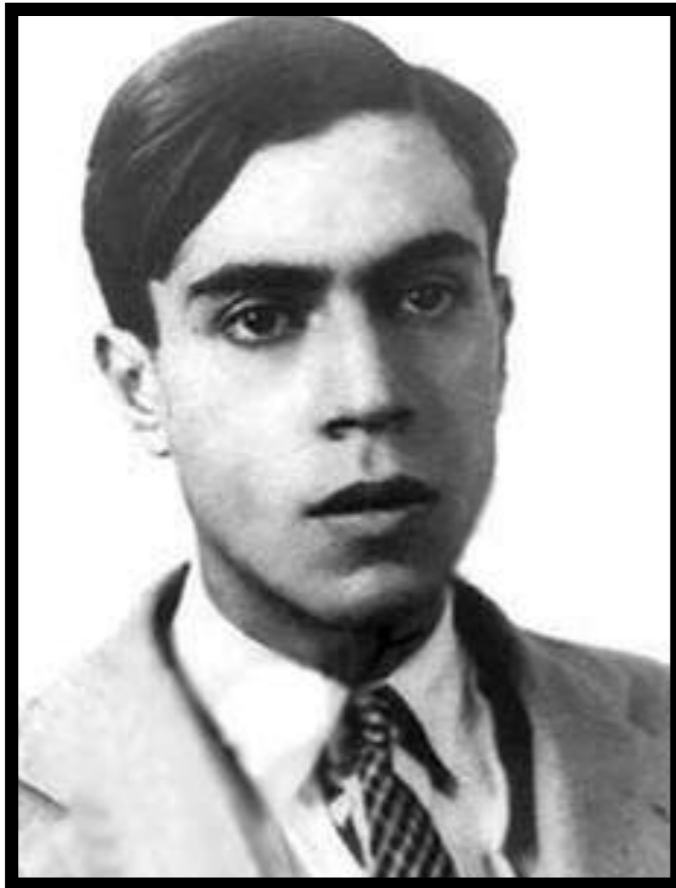


2015 - Kajita & McDonald

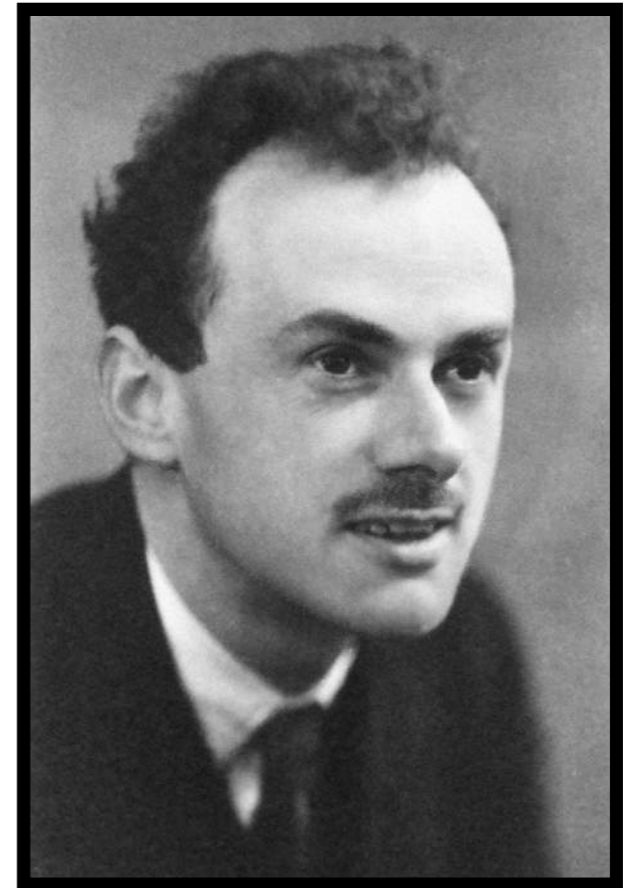


Majorana o Dirac?

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



V/S

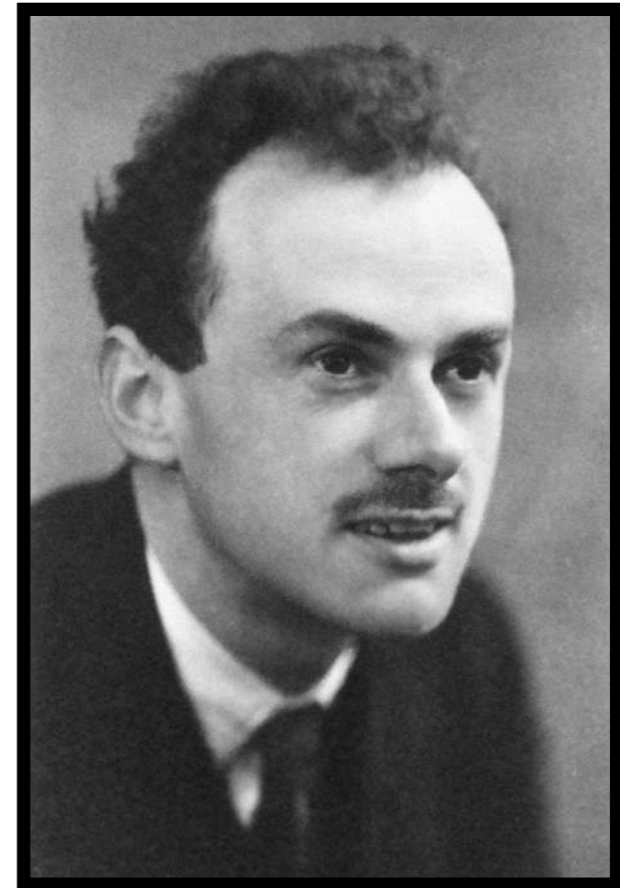


$$\nu = \bar{\nu}$$
$$M_M \nu^T C \nu$$

$$\nu \neq \bar{\nu}$$
$$m_D \bar{\nu} \nu$$

Majorana o Dirac?

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



$$\nu = \bar{\nu}$$

$$M_M \nu^T C \nu$$

$$\Delta L = 2$$

$$\nu \rightarrow e^{i\theta} \nu$$

$$\nu \neq \bar{\nu}$$

$$m_D \bar{\nu} \nu$$

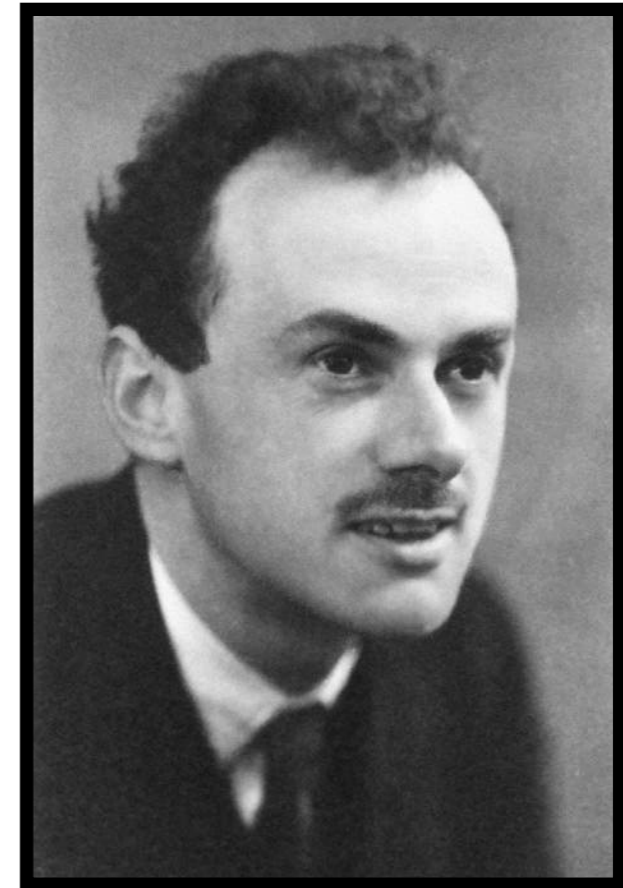
$$\Delta L = 0$$

Majorana o Dirac?

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



V/S

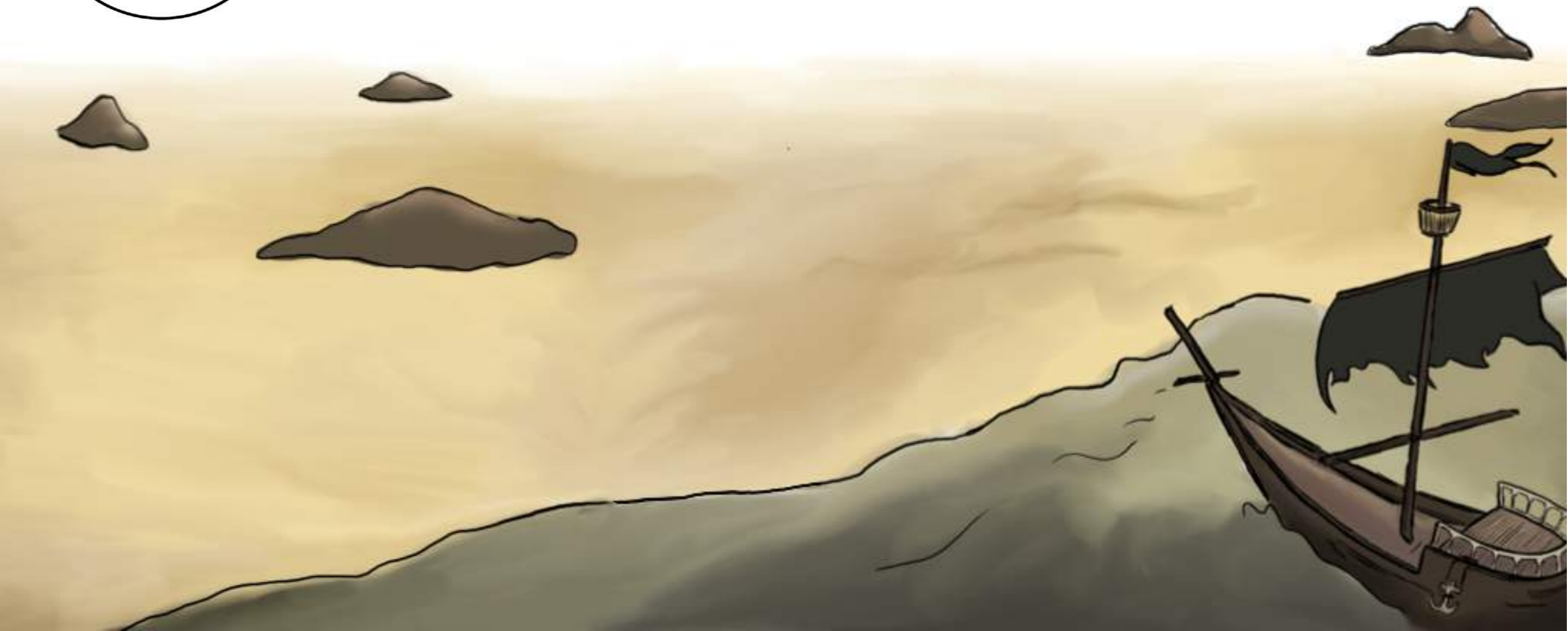
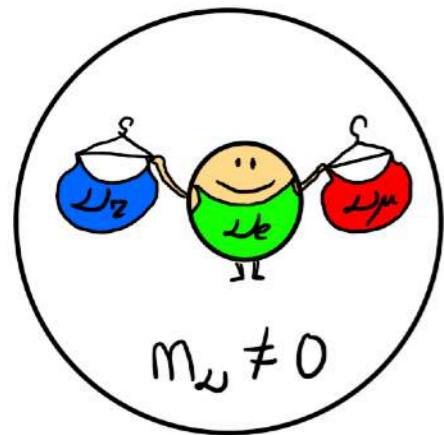


$$\begin{aligned} \nu &= \bar{\nu} \\ M_M \nu^T C \nu \\ \Delta L &= 2 \end{aligned}$$

Se necesita contenido extra!

$$\begin{aligned} \nu &\neq \bar{\nu} \\ m_D \bar{\nu} \nu \\ \Delta L &= 0 \end{aligned}$$

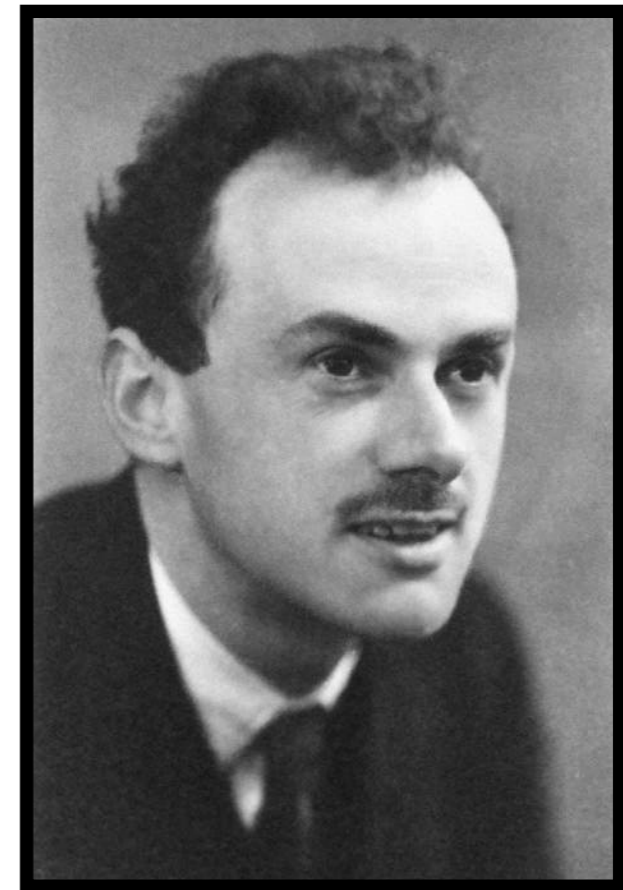
Más allá del modelo estandar



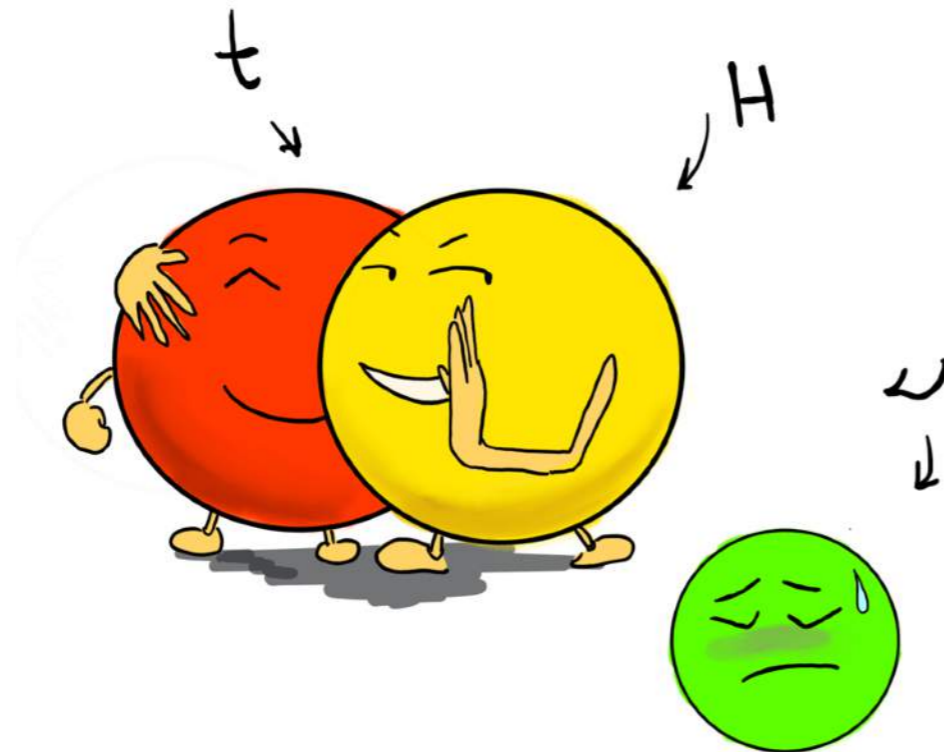
Mecanismos para generar la masa

Añadimos un singlete ν_R

Si son Dirac...



$$m_\nu < 10^{-10} \text{ GeV} \Rightarrow Y_\nu \sim 10^{-12}$$



$$\nu \neq \bar{\nu}$$

$$\mathcal{L} \supset Y_\nu \bar{L}_L (i\sigma_2) H^* \nu_R$$

Mecanismos para generar la masa

Añadimos un singlete ν_R



Si en vez son Majorana...

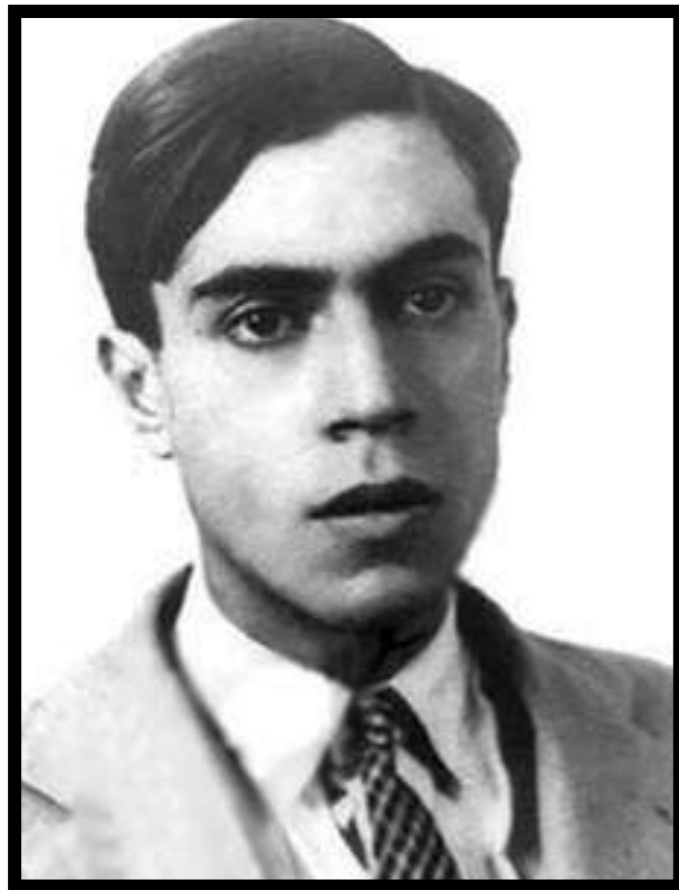
$$M_\nu = \begin{pmatrix} 0 & y_\nu v \\ y_\nu v & M_R \end{pmatrix}$$

$$\nu = \bar{\nu}$$

$$M_R \nu_R^T C \nu_R$$

Mecanismos para generar la masa

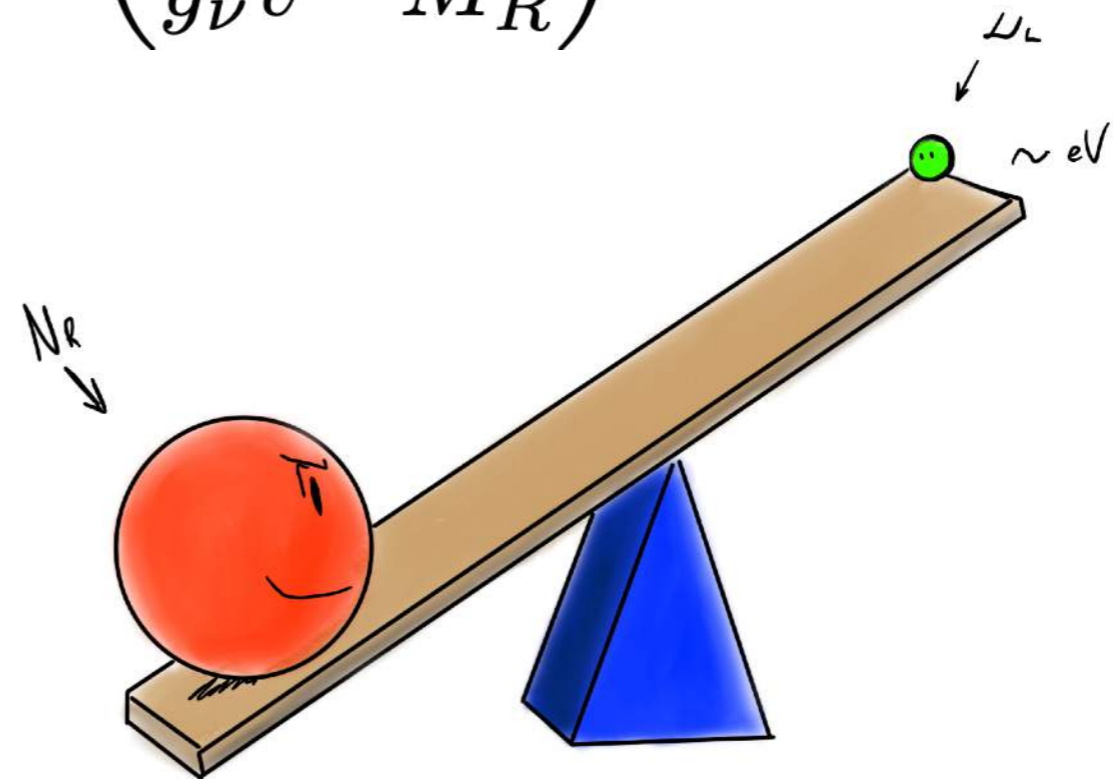
Añadimos un singlete ν_R



Si en vez son Majorana...

El mecanismo del “balancín”

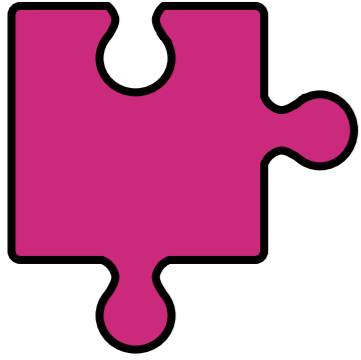
$$M_\nu = \begin{pmatrix} 0 & y_\nu v \\ y_\nu v & M_R \end{pmatrix} \quad m_\nu \sim \frac{(y_\nu v)^2}{M_R}$$



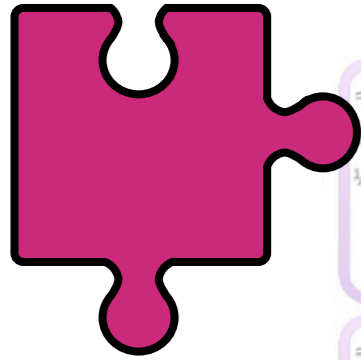
$$\nu = \bar{\nu}$$

$$M_R \nu_R^T C \nu_R$$

Y la antimateria?

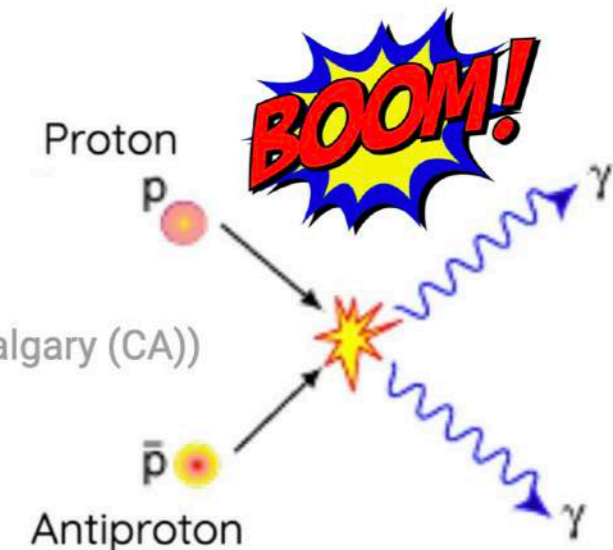


Y la antimateria?



$\approx 2.2 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top	$\approx 2.2 \text{ MeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ \bar{u} antiup	$\approx 1.28 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ \bar{c} anticharm	$\approx 173.1 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ \bar{t} antitop	0 0 1 g gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	$\approx 4.7 \text{ MeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ \bar{d} antidown	$\approx 96 \text{ MeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ \bar{s} antistrange	$\approx 4.18 \text{ GeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ \bar{b} antibottom	0 0 1 γ photon	
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ τ tau	$\approx 0.511 \text{ MeV}/c^2$ 1 $\frac{1}{2}$ e^+ positron	$\approx 105.66 \text{ MeV}/c^2$ 1 $\frac{1}{2}$ $\bar{\mu}$ antimuon	$\approx 1.7768 \text{ GeV}/c^2$ 1 $\frac{1}{2}$ $\bar{\tau}$ antitau	$\approx 91.19 \text{ GeV}/c^2$ 0 1 Z Z ⁰ boson	
$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ ν_τ tau neutrino	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_e$ electron antineutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_\mu$ muon antineutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ $\bar{\nu}_\tau$ tau antineutrino	$\approx 80.360 \text{ GeV}/c^2$ 1 1 W^+ W ⁺ boson	$\approx 80.360 \text{ GeV}/c^2$ -1 1 W^- W ⁻ boson

[diapositiva de la charla de Alberto Jesús]

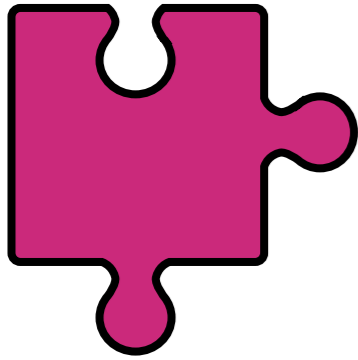


08:30

Physics Snacks: Antimateria en el CERN

Speaker: Alberto Jesus Uribe Jimenez (Dep. of Phys. and Astronomy University of Calgary (CA))

Y la antimateria?



10:50

El Modelo estándar y la física fundamental (II)

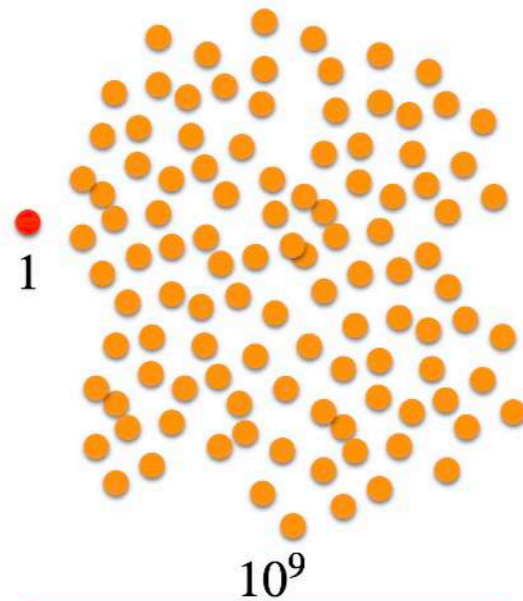
Speaker: Miguel Escudero Abenza (CERN)

[diapositiva de la charla de Miguel]

El problema

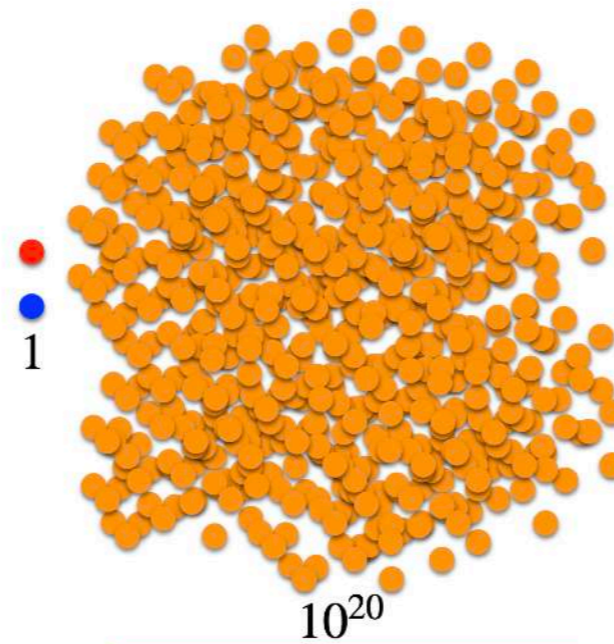
Universo observado

● foton ● proton ● antiproton

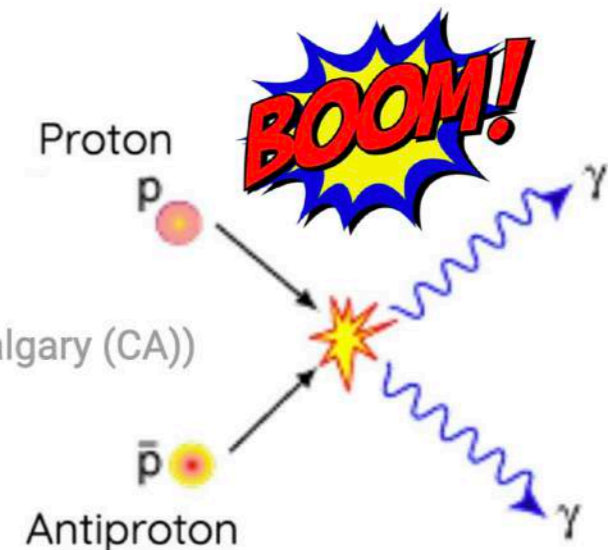


Hay 10^9 fotones por cada núcleo atómico!

Universo esperado según el modelo estándar



Misma cantidad de materia y antimateria 😞



08:30

Physics Snacks: Antimateria en el CERN

Speaker: Alberto Jesus Uribe Jimenez (Dep. of Phys. and Astronomy University of Calgary (CA))

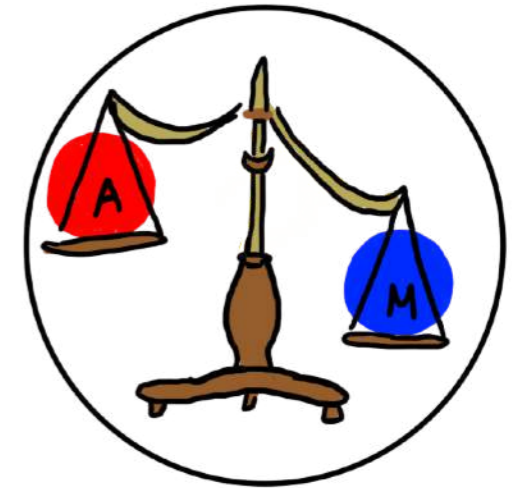
Y la antimateria?

Condiciones de Sakharov

Uno: Violación de Carga conjugada - Paridad (CP)

Dos: Violación del número bariónico

Tres: Salida del equilibrio térmico



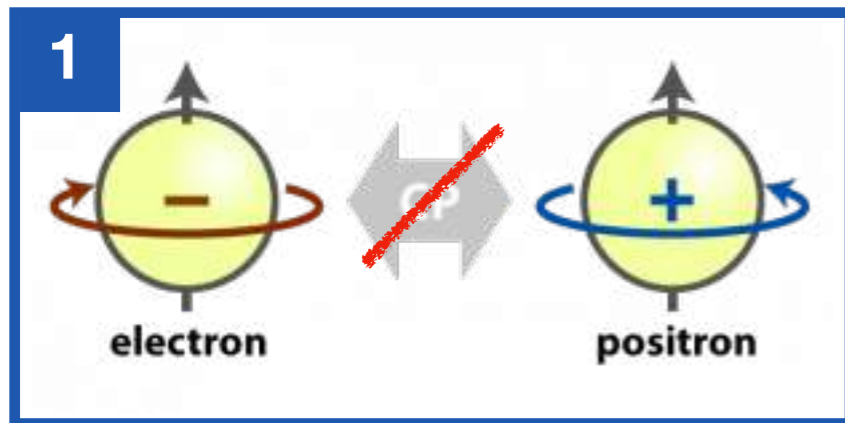
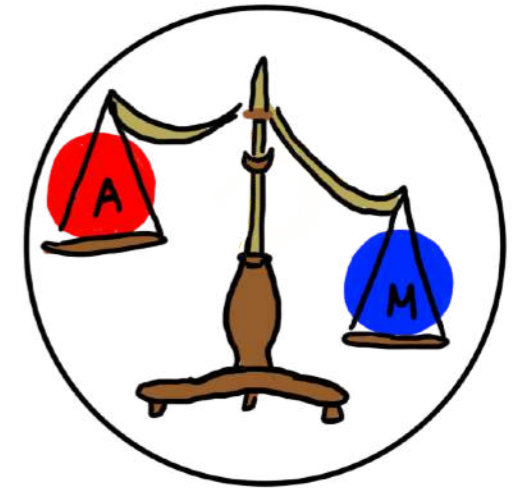
Y la antimateria?

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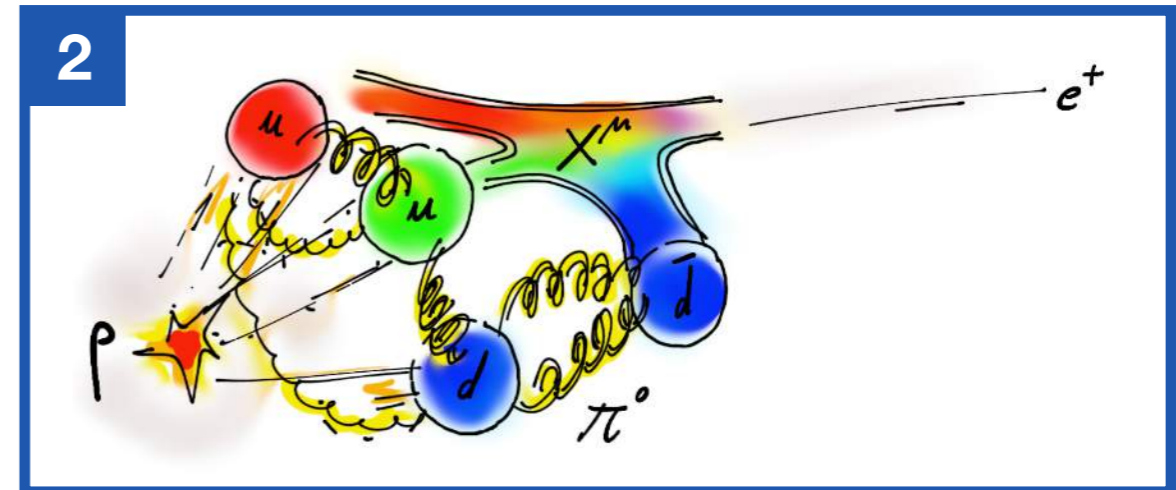
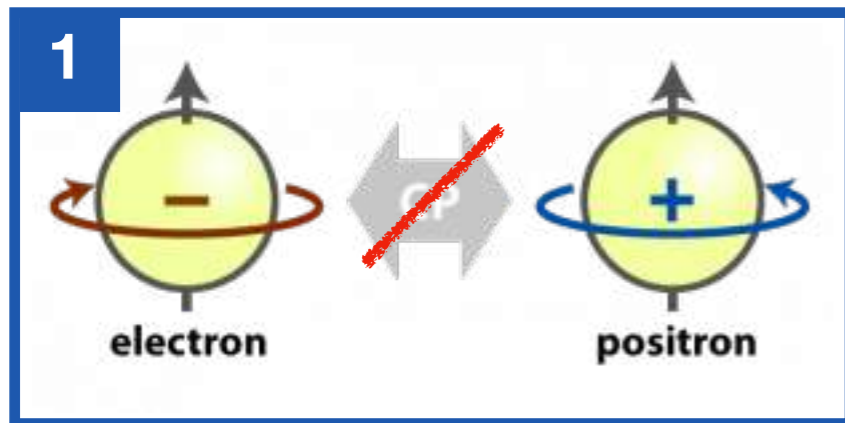
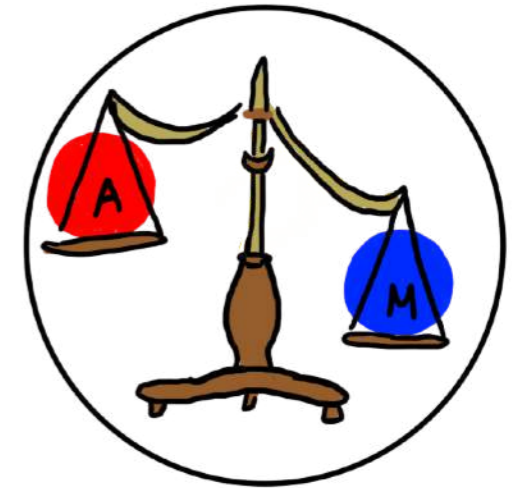
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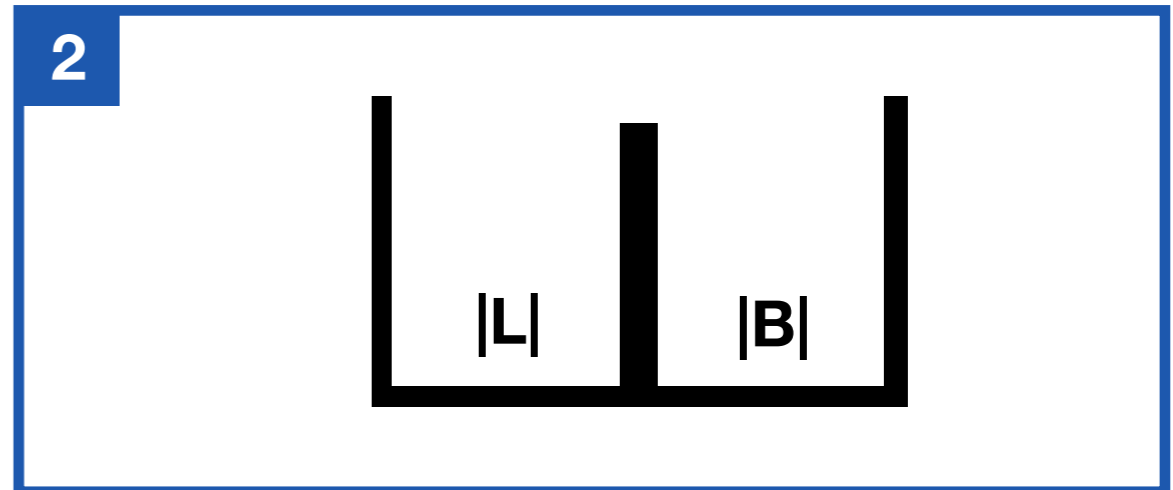
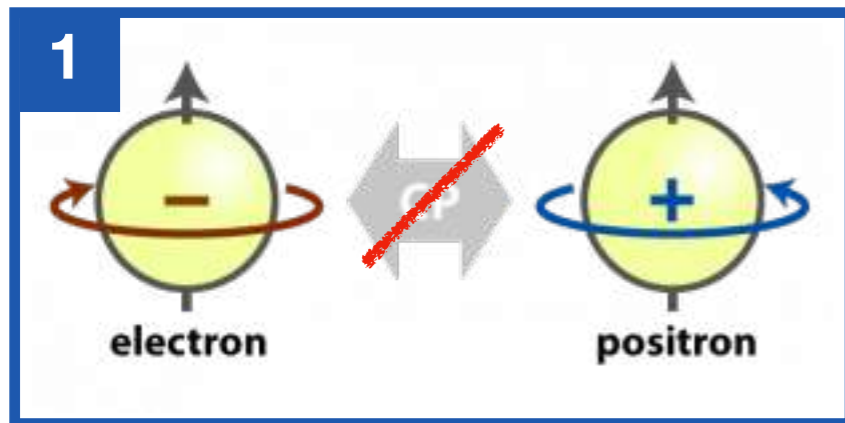
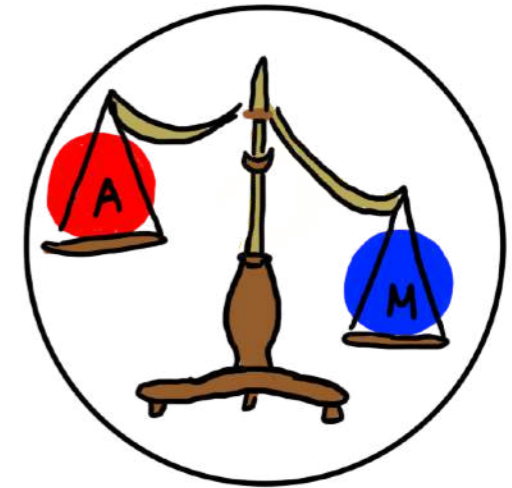
Y la antimateria?

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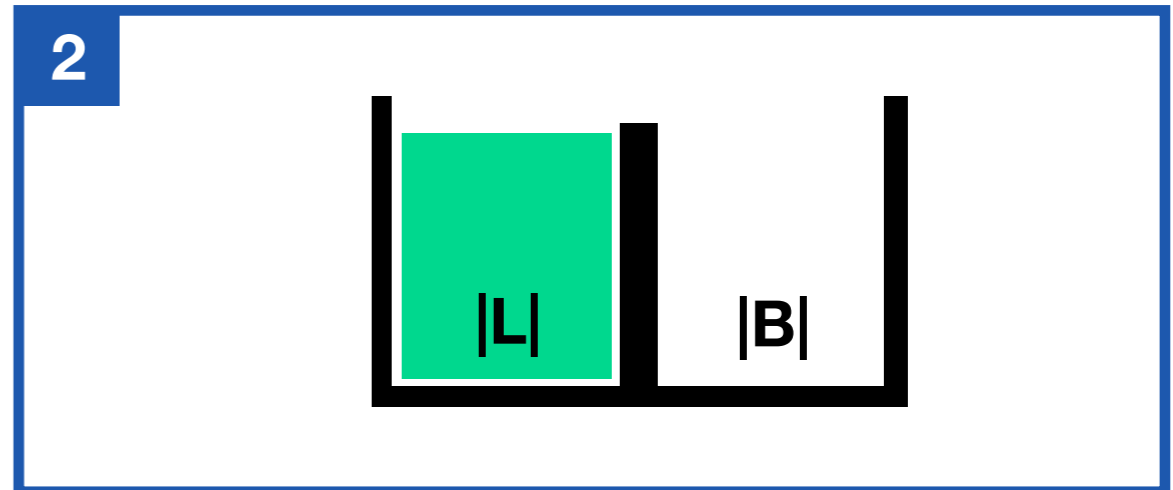
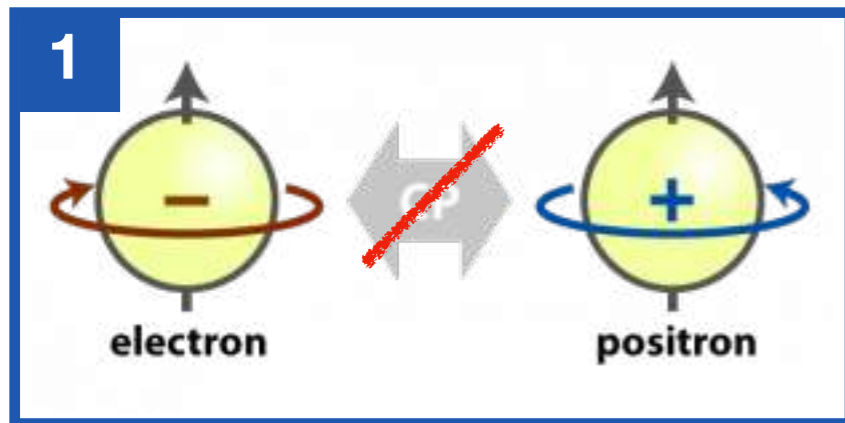
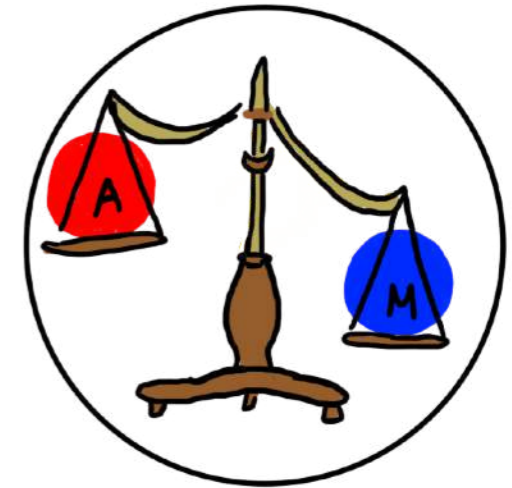
Y la antimateria?

Condiciones de Sakharov

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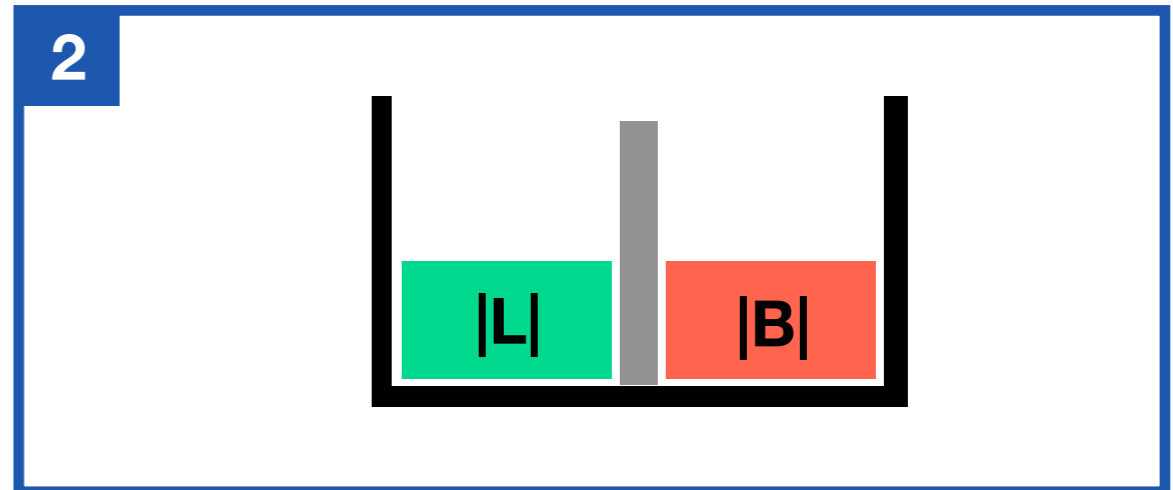
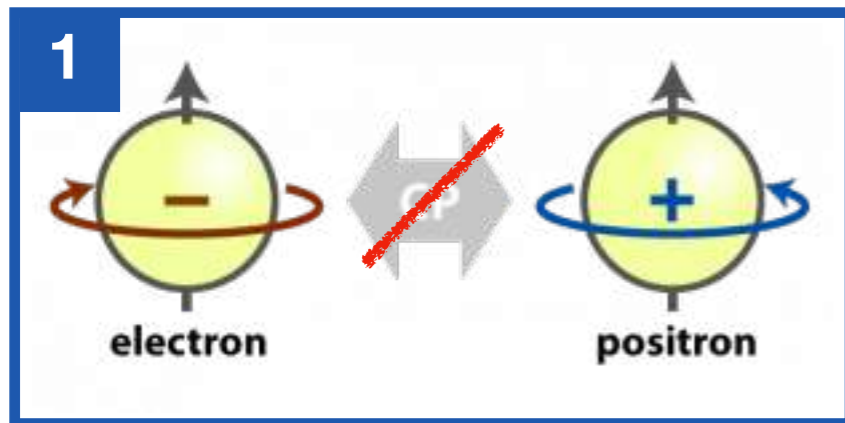
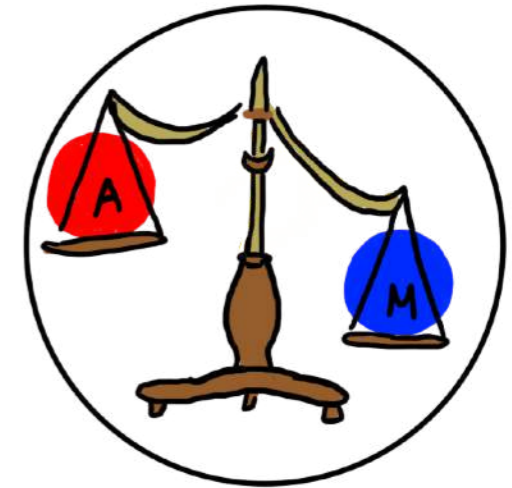
Y la antimateria?

Condiciones de Sakharov

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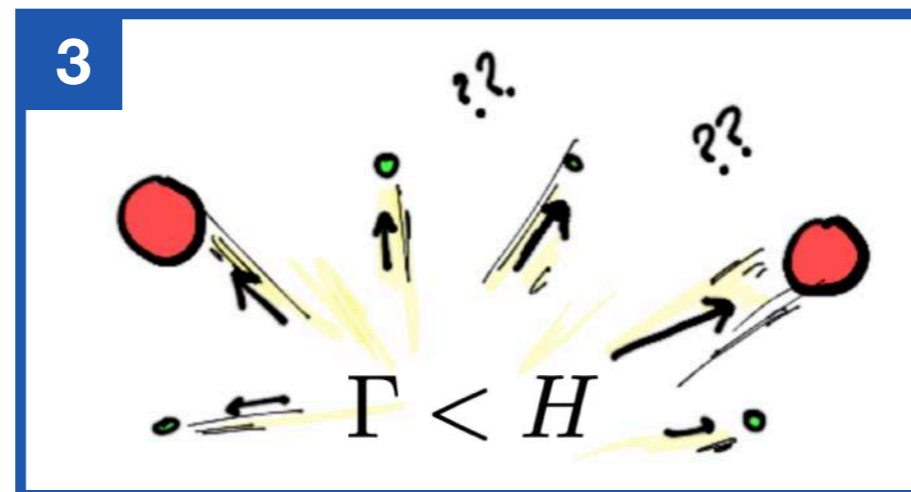
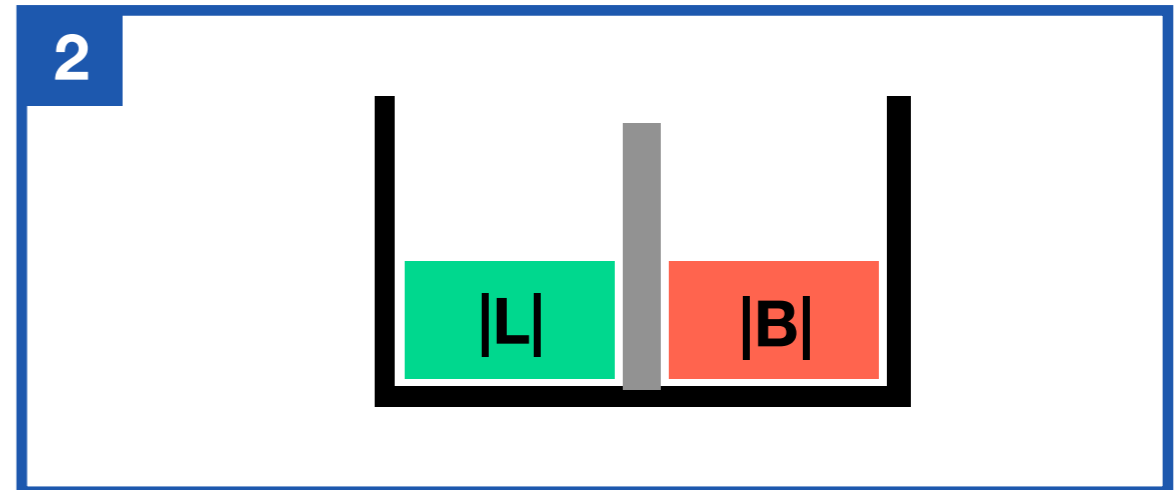
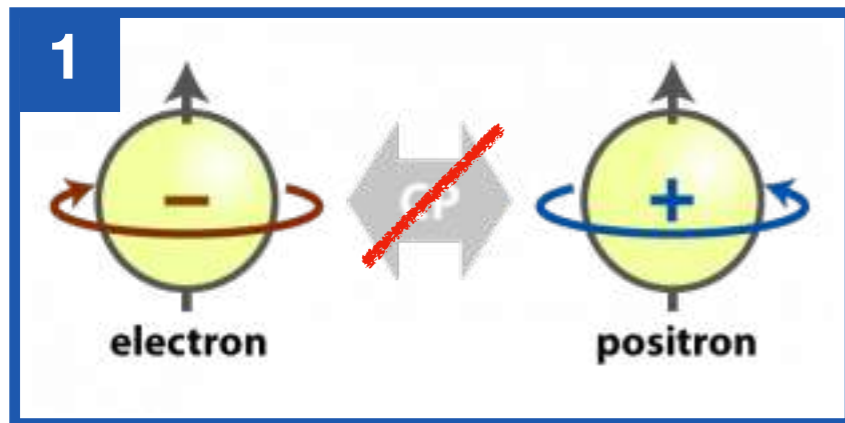
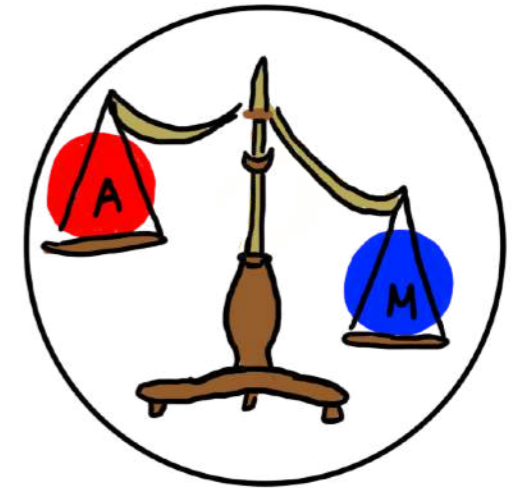
Y la antimateria?

Condiciones de Sakharov

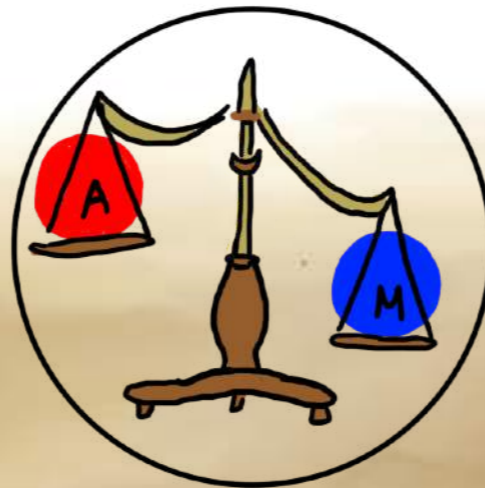
Uno: Violación de Carga conjugada - Paridad (CP)

Dos: Violación del número bariónico

Tres: Salida del equilibrio térmico



Bariogénesis



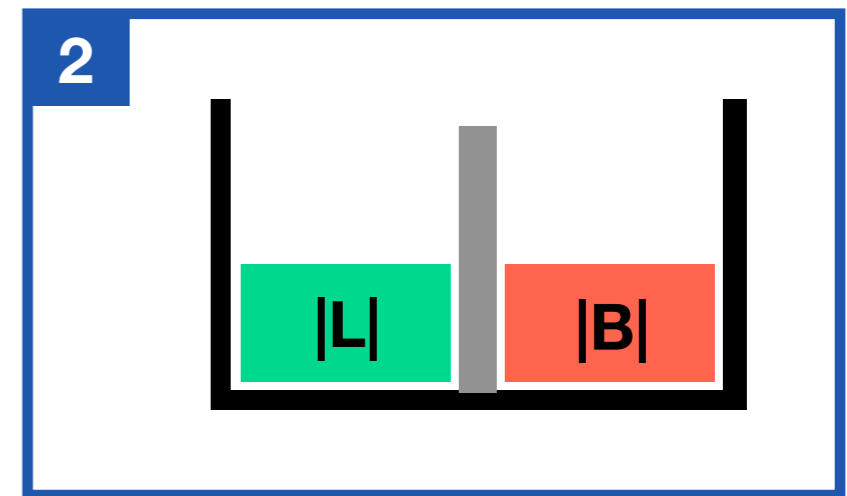
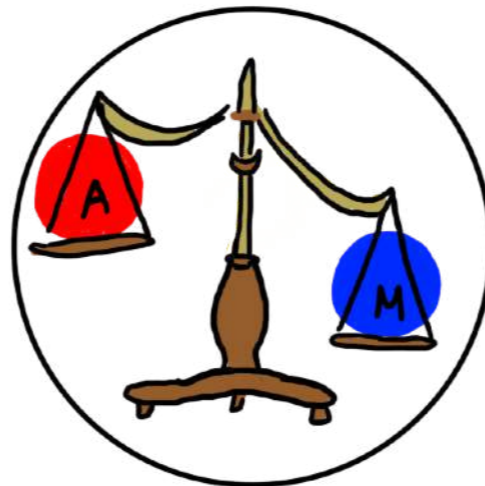
Bariogénesis via Leptogenesis

Condiciones de Sakharov

Uno: Violación de Carga conjugada - Paridad (CP)

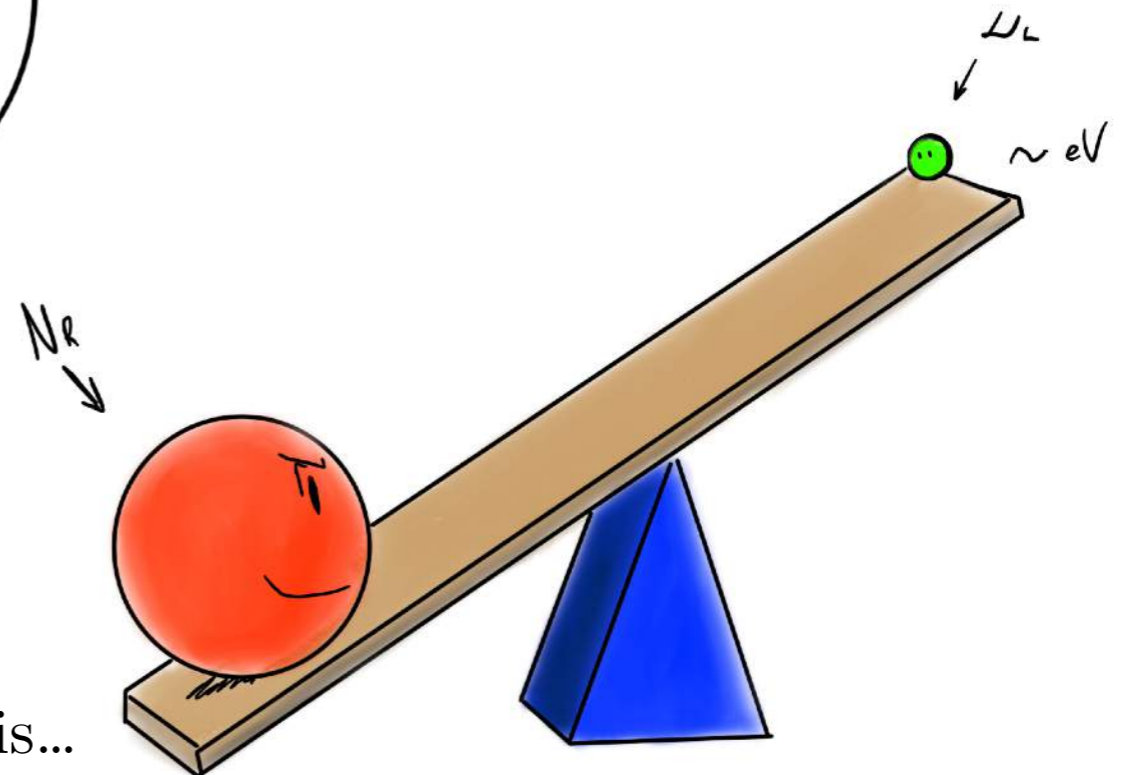
Dos: Violación del número bariónico

Tres: Salida del equilibrio

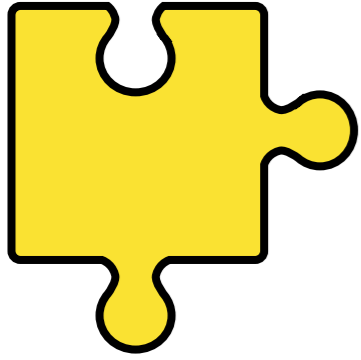


$$\nu = \bar{\nu} \quad \Delta L = 2$$

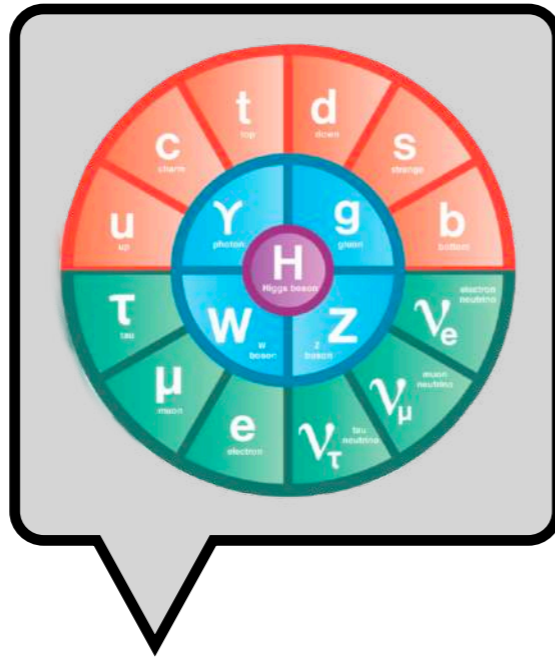
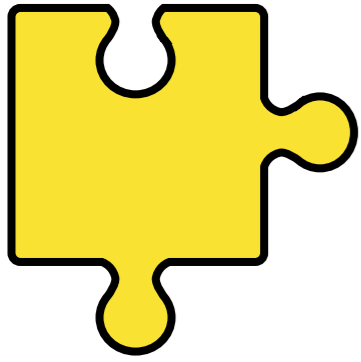
e.g. EW baryogenesis, Affleck-Dine, B-mesogenesis...



Más “materia” de la que vemos!



Más “materia” de la que vemos!



09:30

El Modelo estándar y la física fundamental (I)

Speaker: Miguel Escudero Abenza (CERN)

11:30

Física experimental de partículas

Speaker: Sergi Rodriguez (CERN)

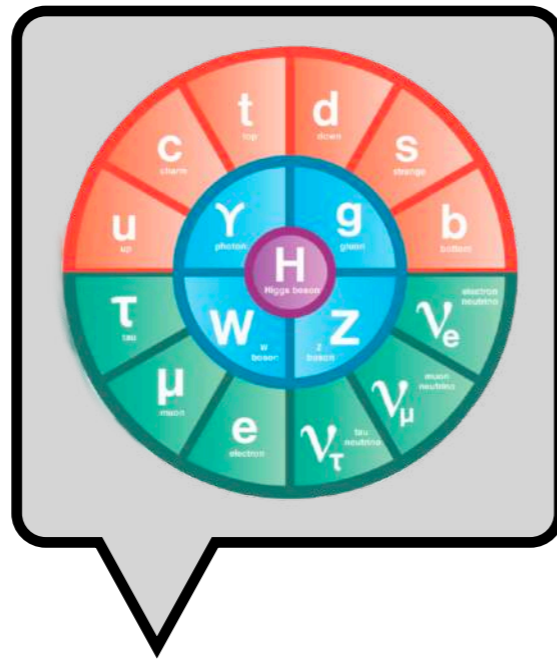
10:50

El descubrimiento del bosón de Higgs

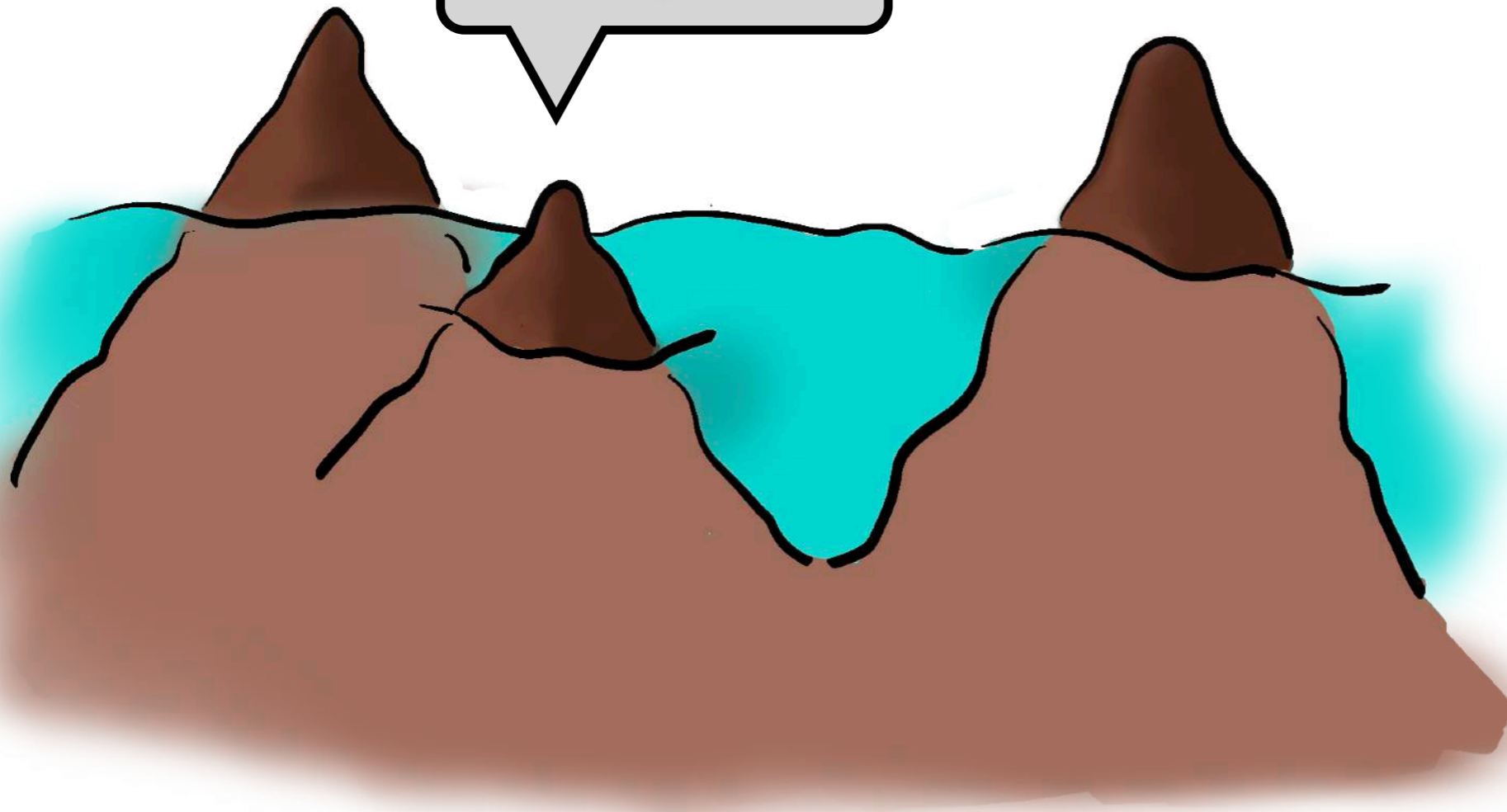
Speaker: Luis Roberto Flores Castillo (The Chinese University of Hong Kong (HK))



Más “materia” de la que vemos!

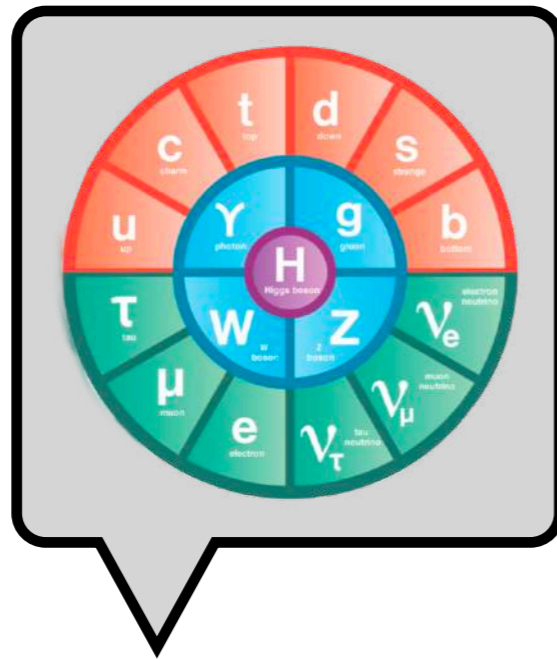


$\sim 5\%$

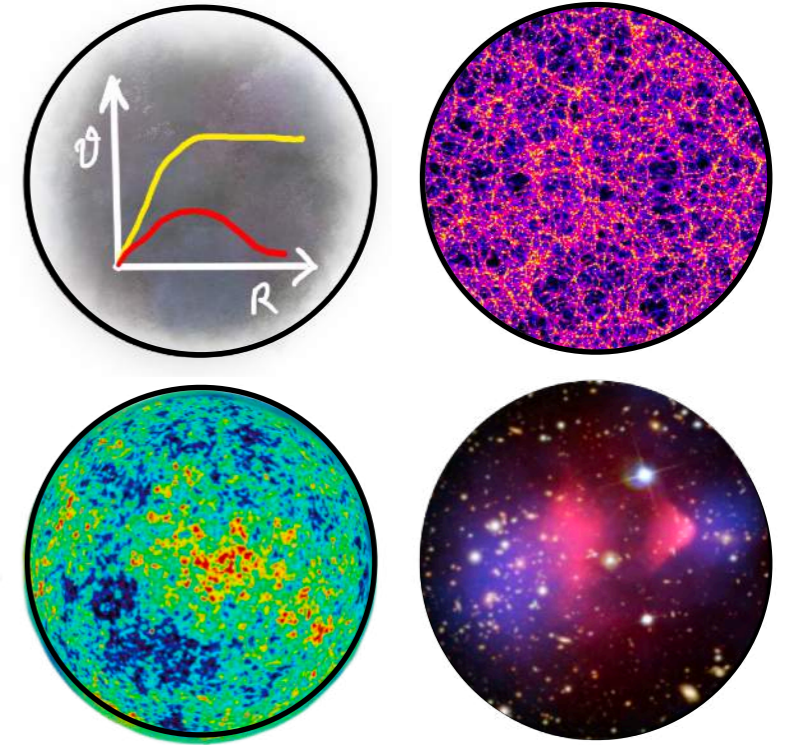


$\sim 25\%$

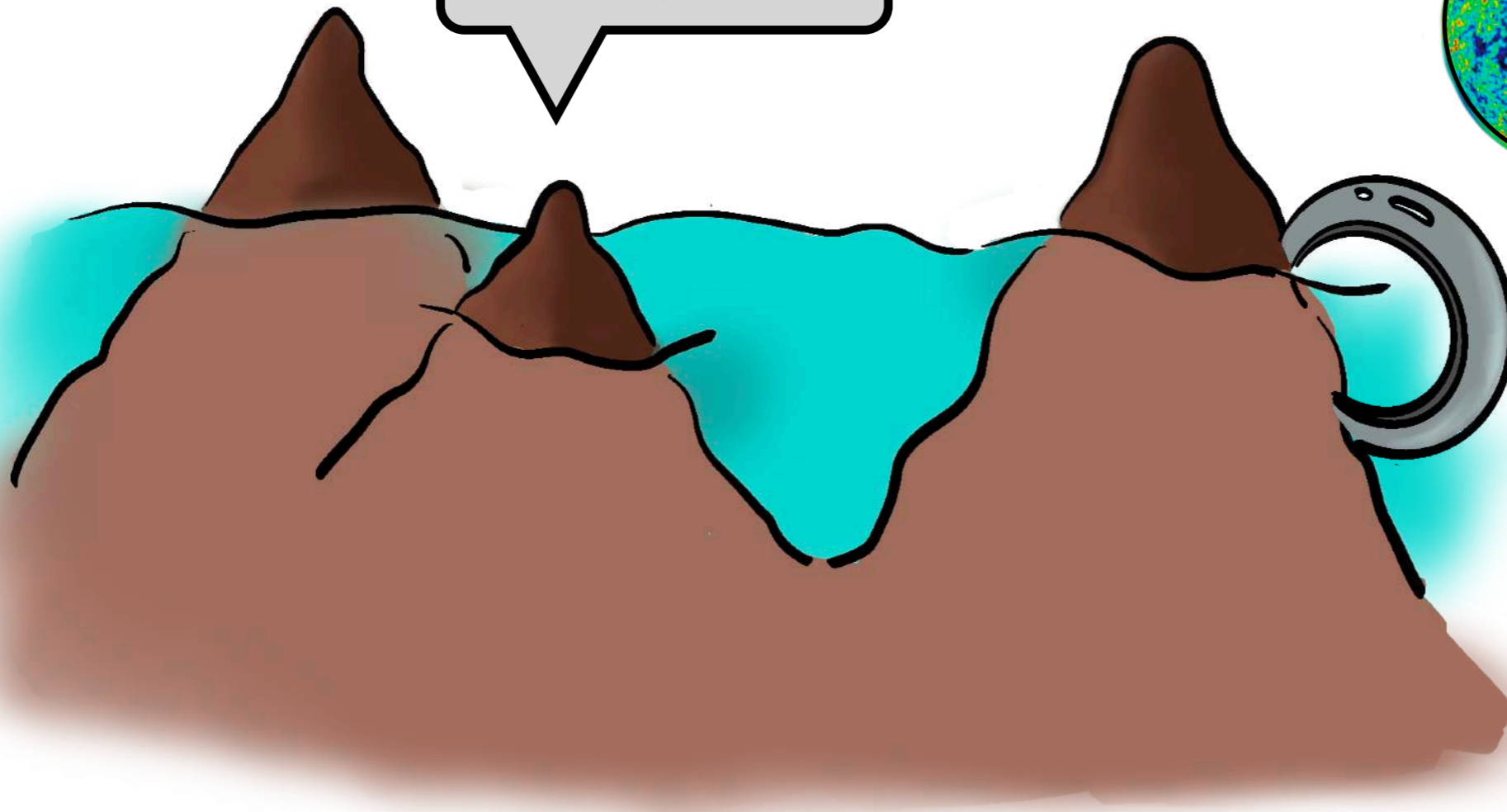
Más “materia” de la que vemos!



~ 5%

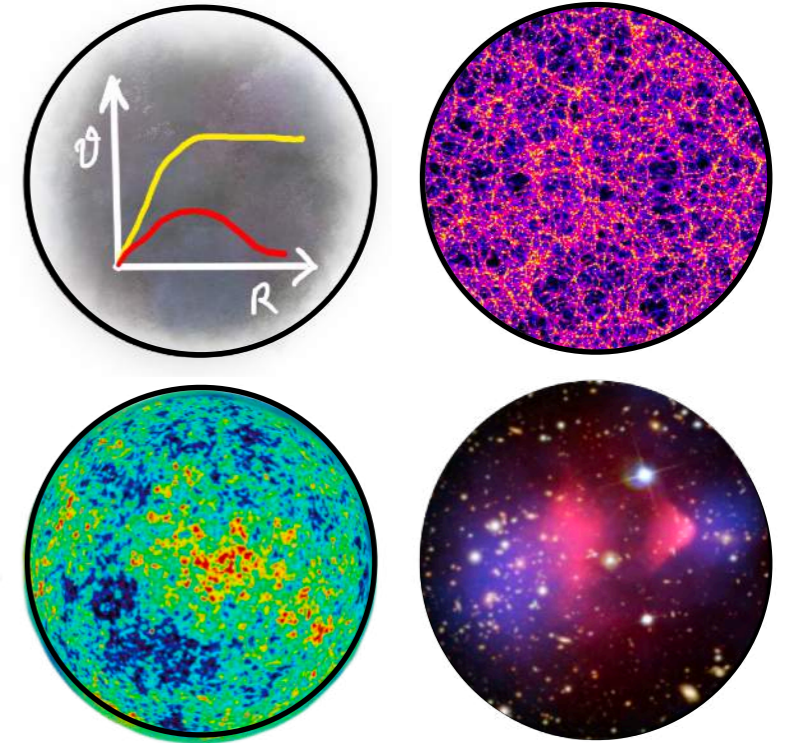


Evidencia gravitatoria



~ 25%

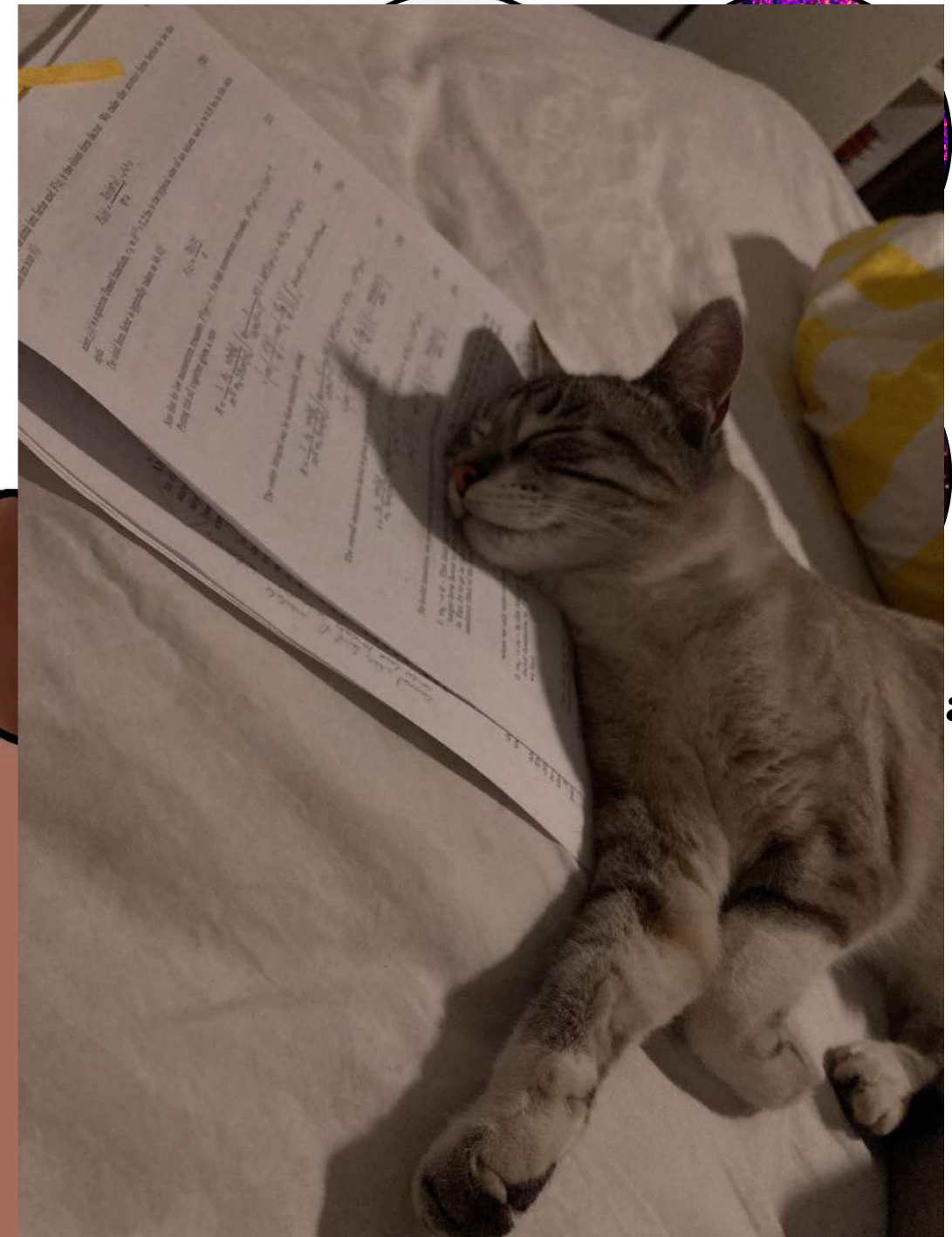
Más “materia” de la que vemos!



Evidencia gravitatoria

~ 25%

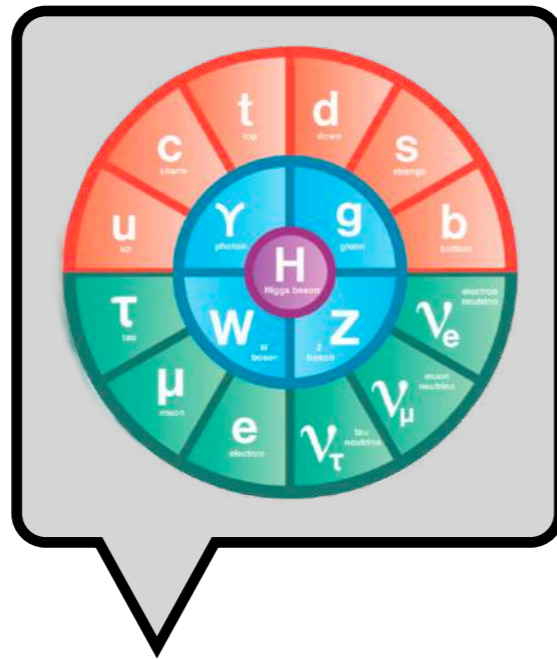
Más “materia” de la que vemos!



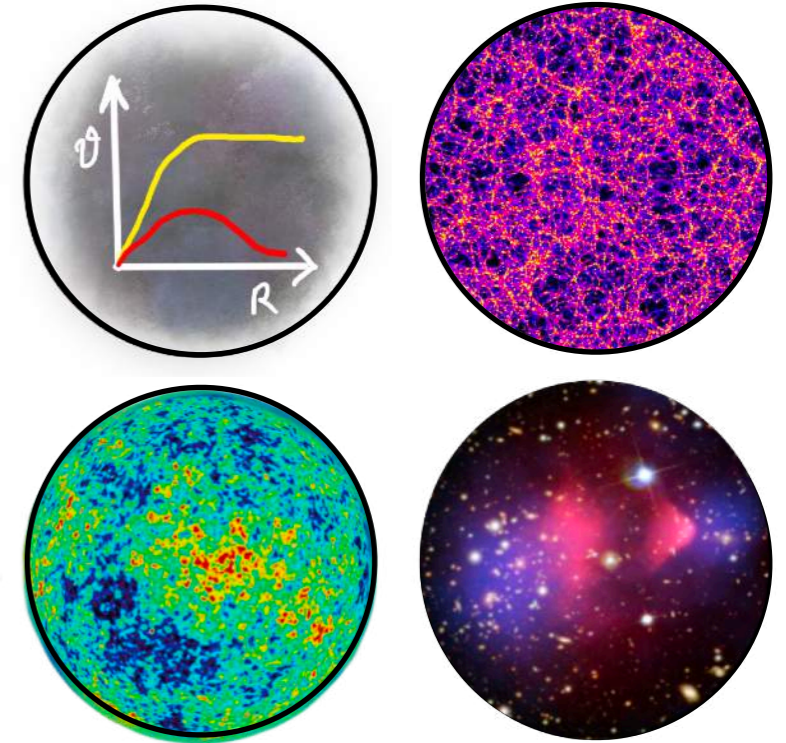
~ 25%

a

Más “materia” de la que vemos!

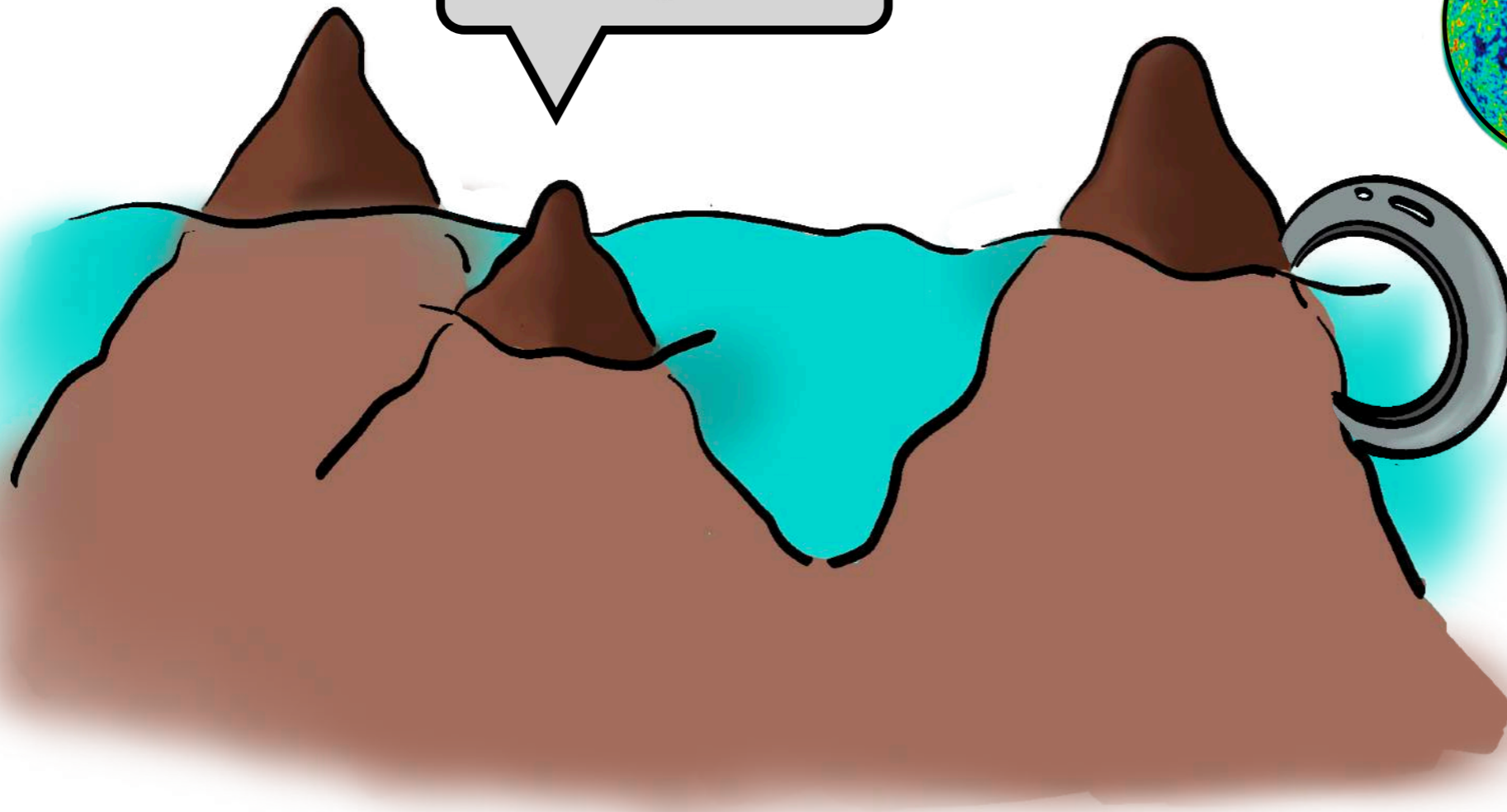


$\sim 5\%$

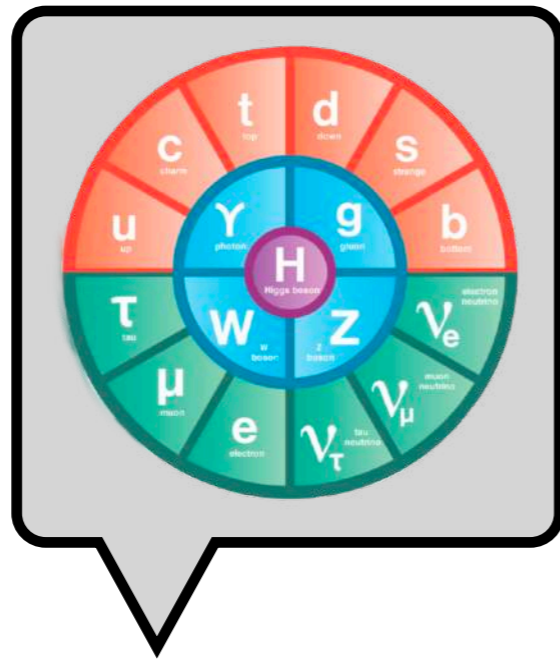


Evidencia gravitatoria

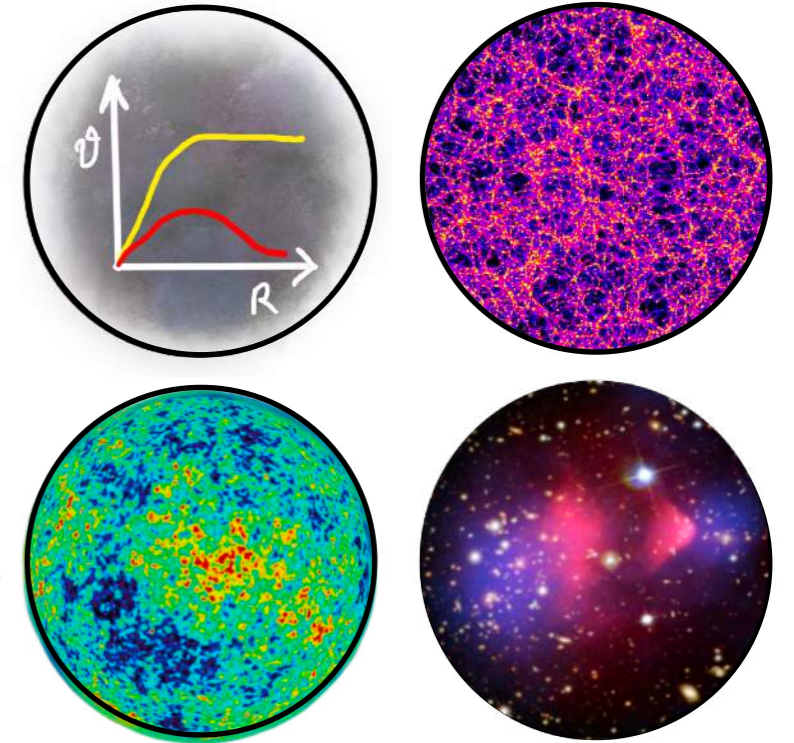
$\sim 25\%$



Más “materia” de la que vemos!

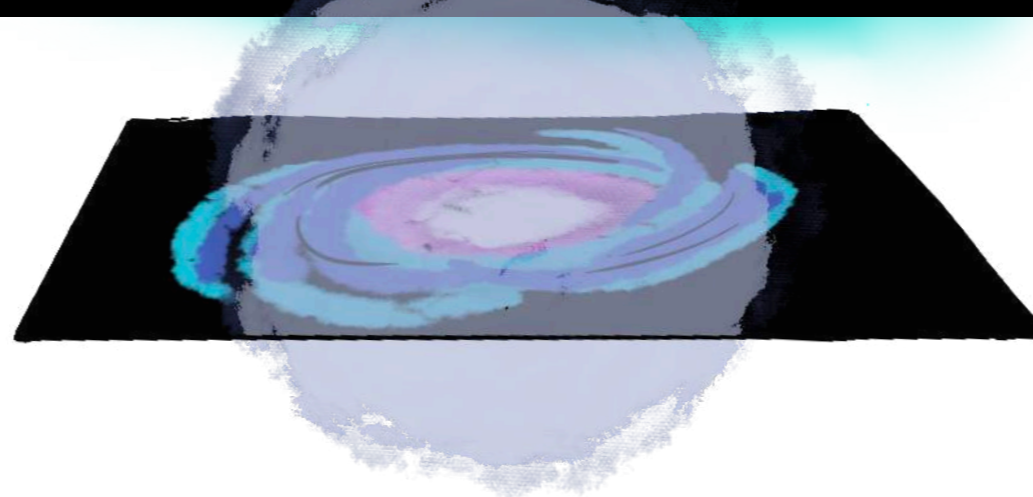


$\sim 5\%$



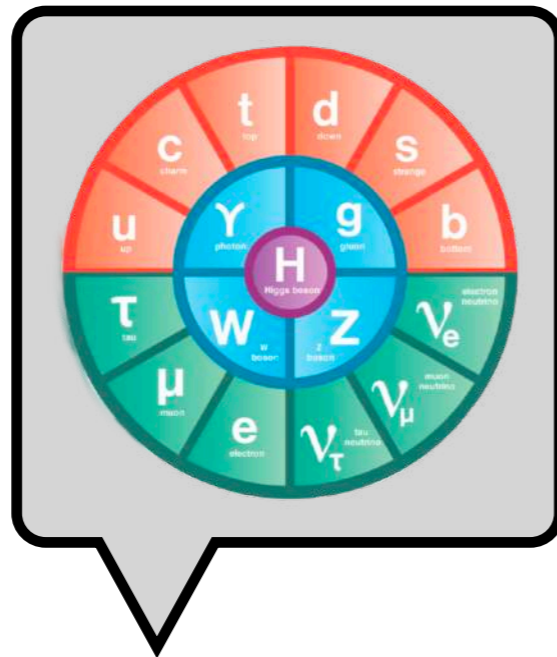
Evidencia gravitatoria

Sabemos muy poco... pero para lo poco sabemos, sabemos bastante

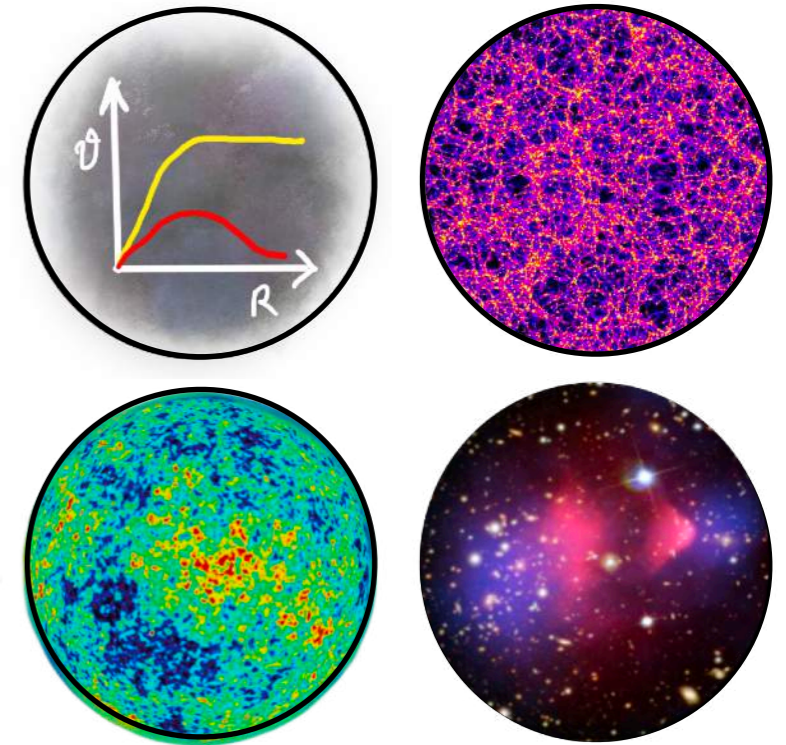


$$\Omega_{\text{DM}} h^2 = 0.12$$

Más “materia” de la que vemos!



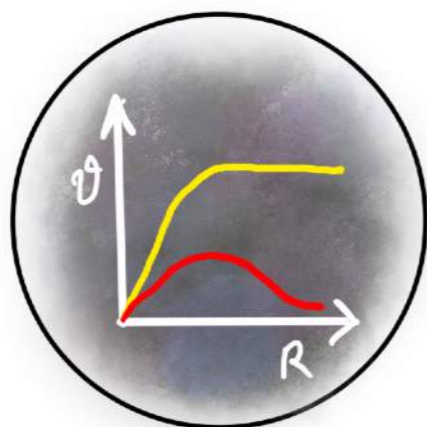
~ 5%



Pero de la masa ni idea

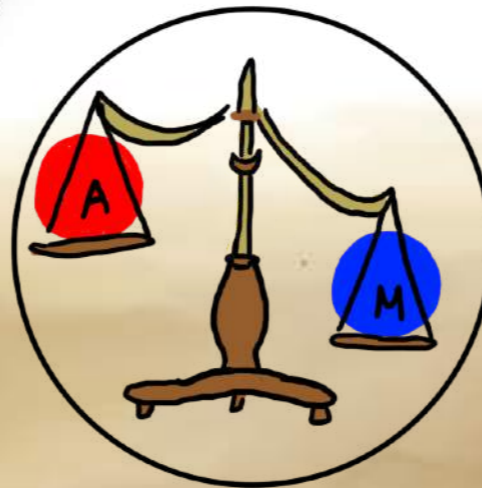
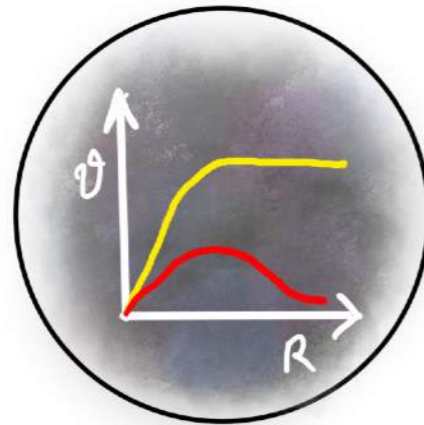
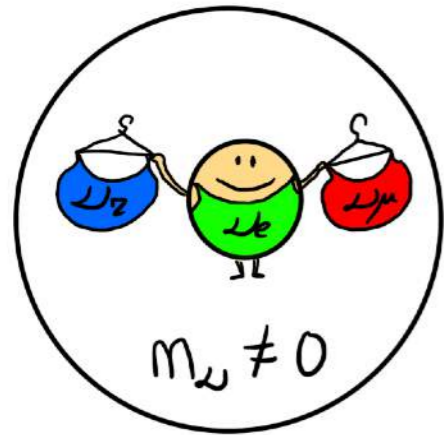


La materia oscura



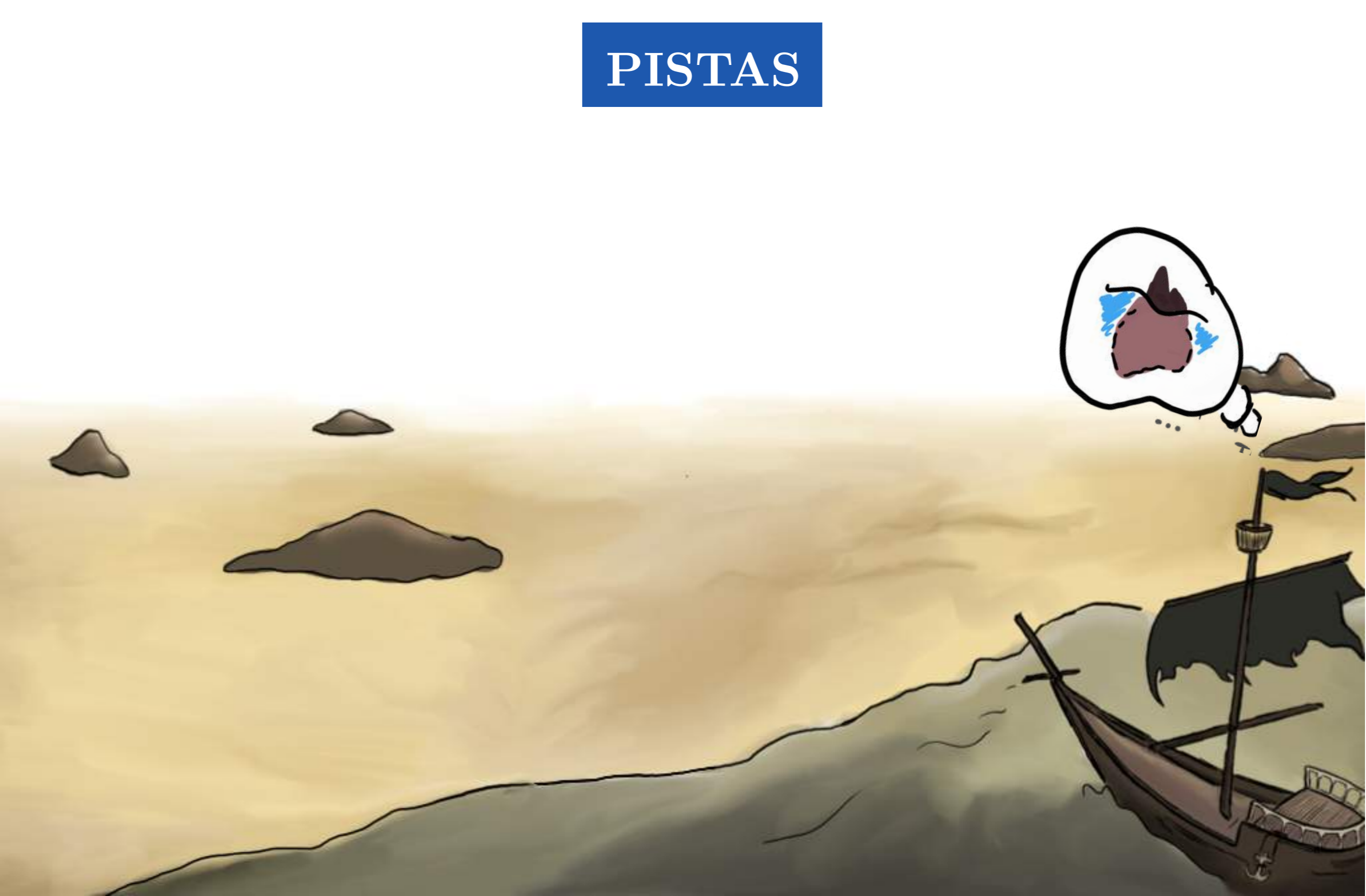
Más allá del modelo estandar

EVIDENCIAS



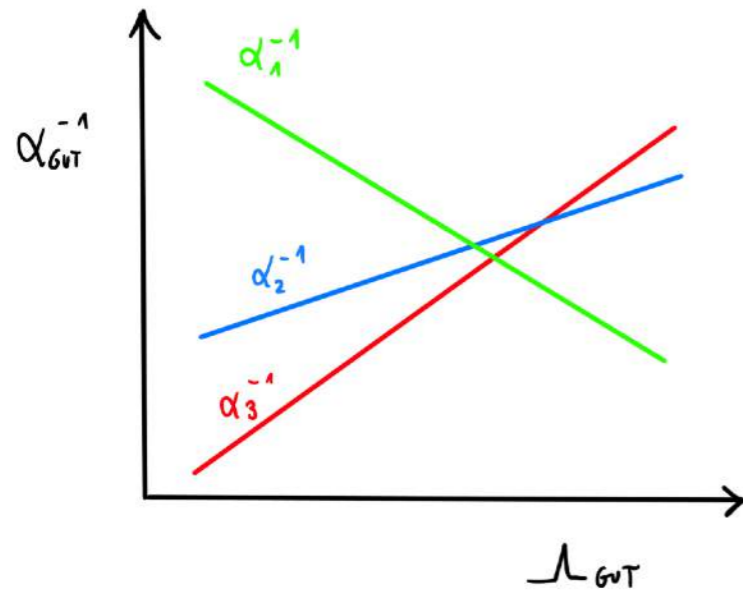
Más allá del modelo estandar

PISTAS



Gran Unificación (GUT)

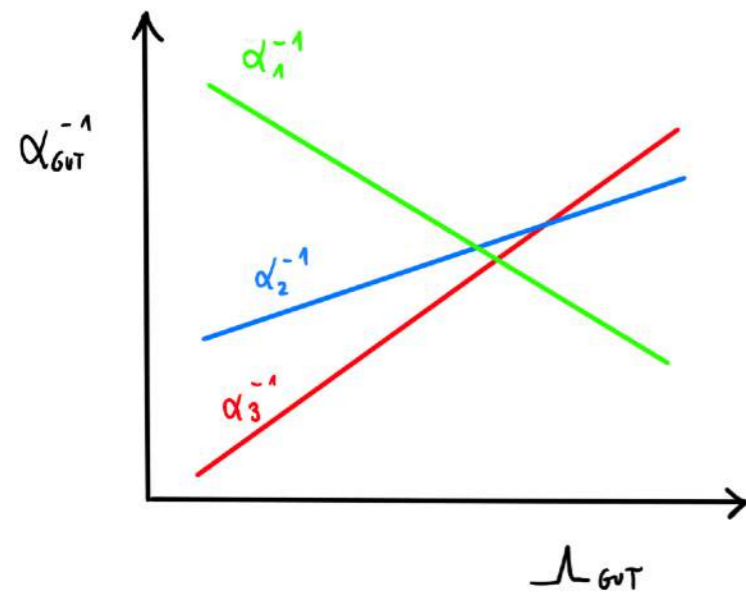
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



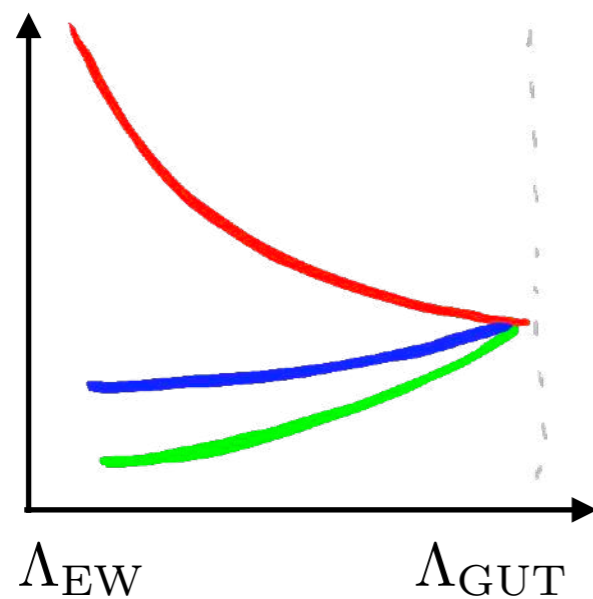
Gran Unificación (GUT)

$$\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)_Y$$

$$\text{SU}(5)$$



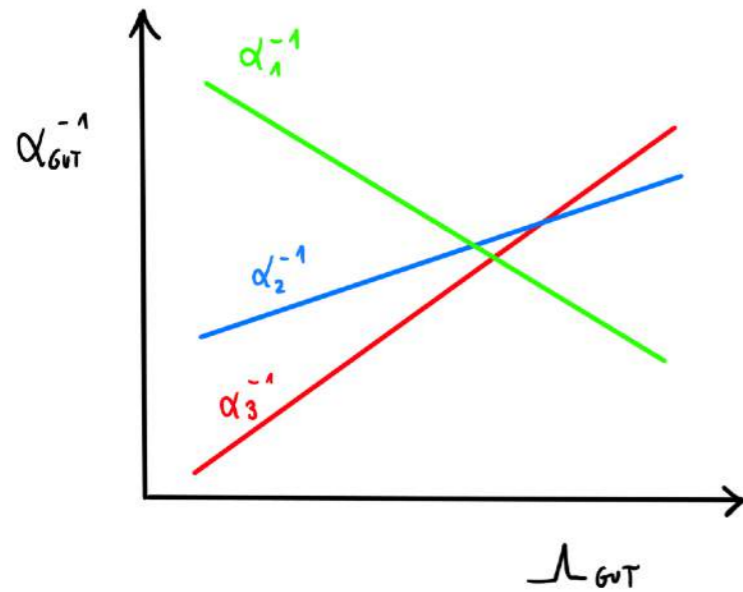
SU(5)



Gran Unificación (GUT)

$$\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)_Y$$

$$\text{SU}(5)$$

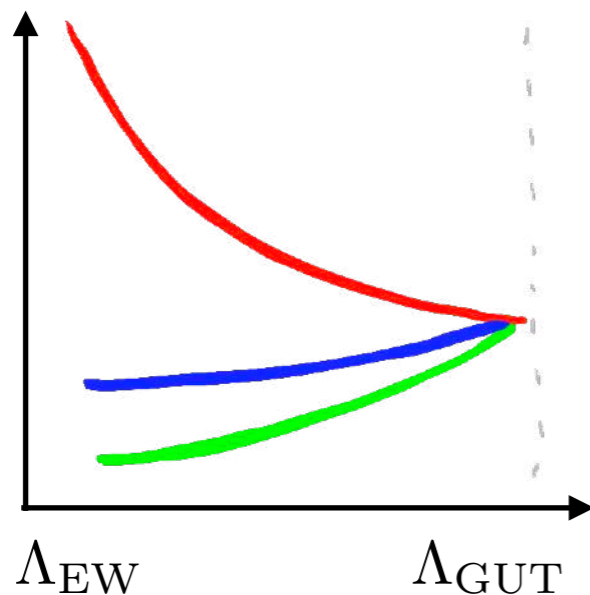


$$\bar{5} = \begin{pmatrix} (d_R)^c \\ L_L \end{pmatrix},$$

$$10 = \begin{pmatrix} (u_R)^c & Q_L \\ -Q_L^T & (e_R)^c \end{pmatrix}$$



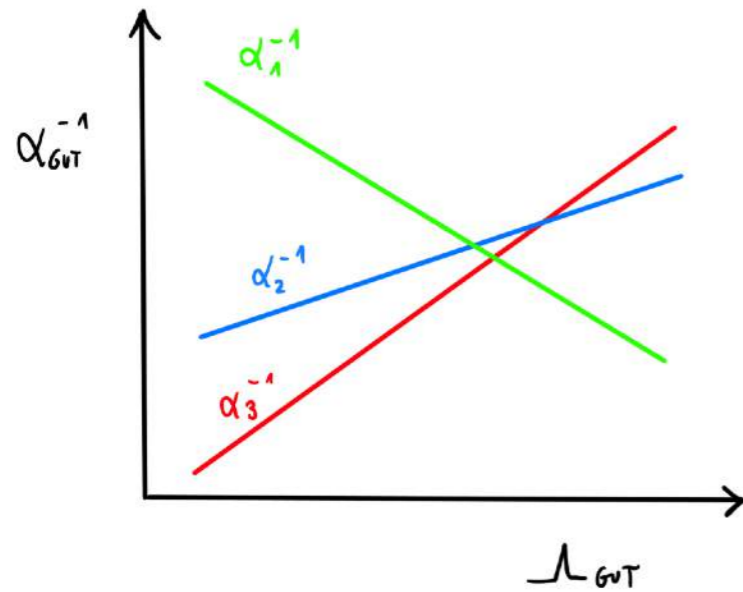
SU(5)



Gran Unificación (GUT)

$$\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)_Y$$

$$\text{SU}(5)$$

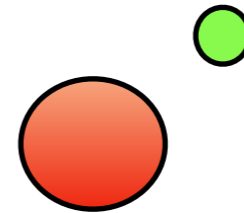
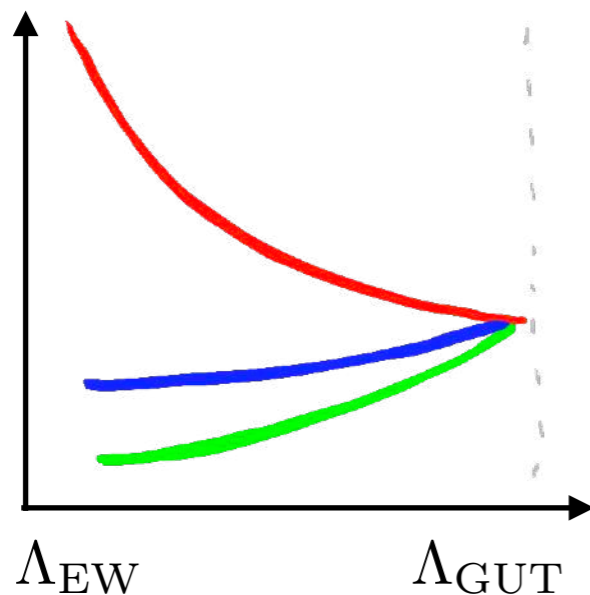


$$\bar{5} = \begin{pmatrix} (d_R)^c \\ L_L \end{pmatrix},$$

$$10 = \begin{pmatrix} (u_R)^c & Q_L \\ -Q_L^T & (e_R)^c \end{pmatrix}$$



SU(5)

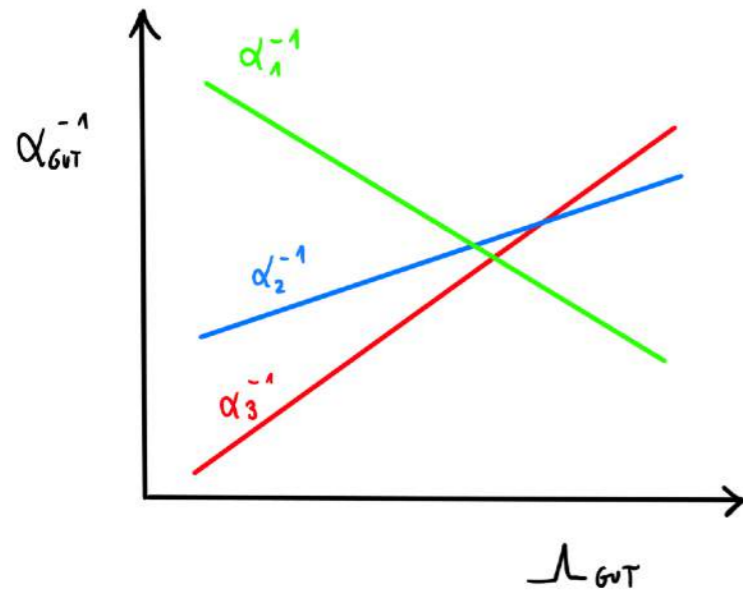


$$Q(p) + Q(e) = 0$$

Gran Unificación (GUT)

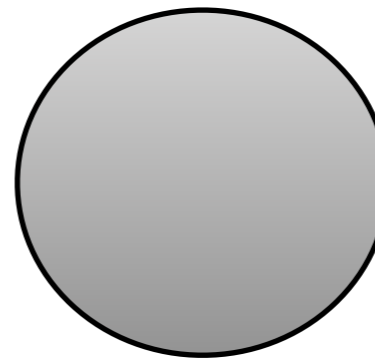
$$\text{SU}(3) \otimes \text{SU}(2) \otimes \text{U}(1)_Y$$

$$\text{SU}(5)$$

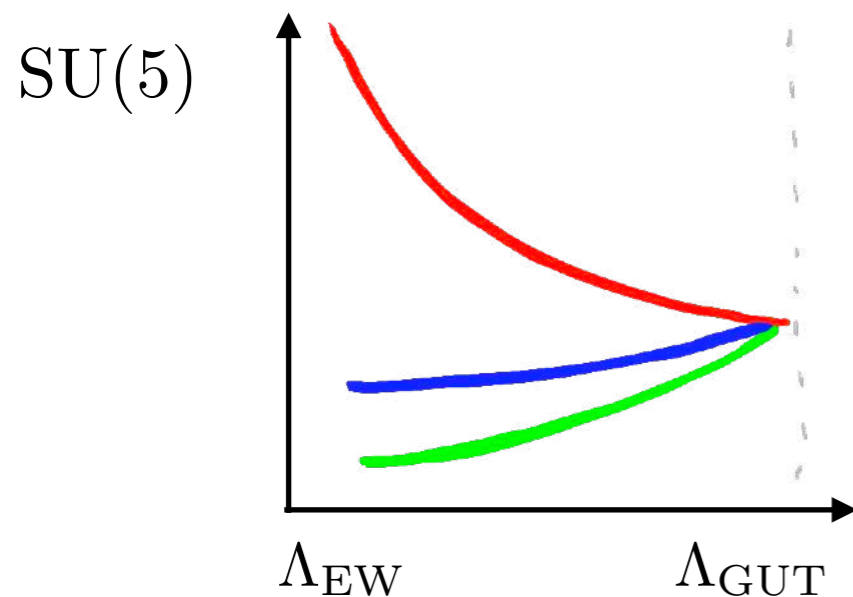


$$\bar{5} = \begin{pmatrix} (d_R)^c \\ L_L \end{pmatrix}, \quad 10 = \begin{pmatrix} (u_R)^c & Q_L \\ -Q_L^T & (e_R)^c \end{pmatrix}$$

El átomo de hidrogen es neutro!



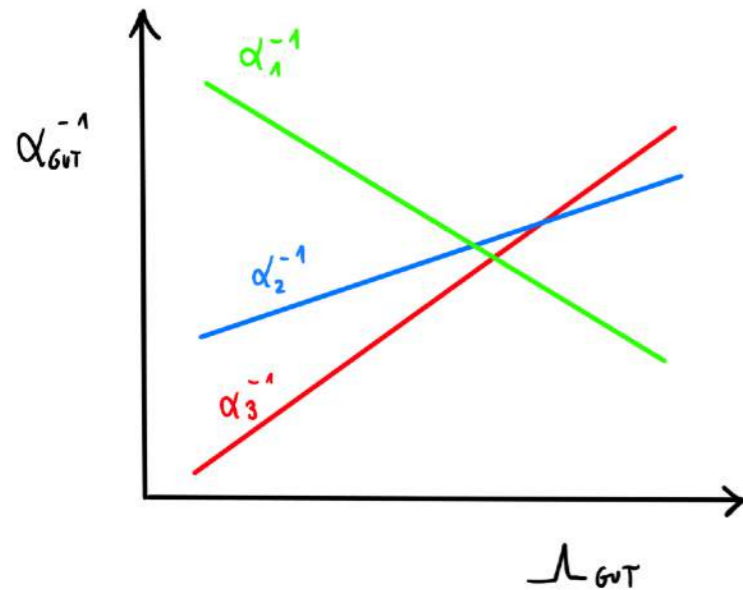
$$Q(p) + Q(e) = 0$$



Gran Unificación (GUT)

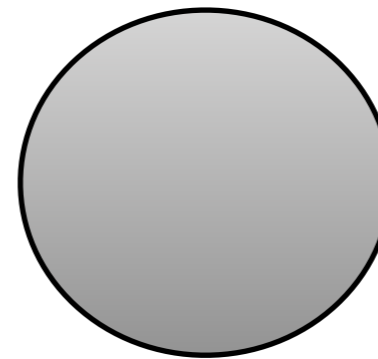
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

$$SU(5)$$



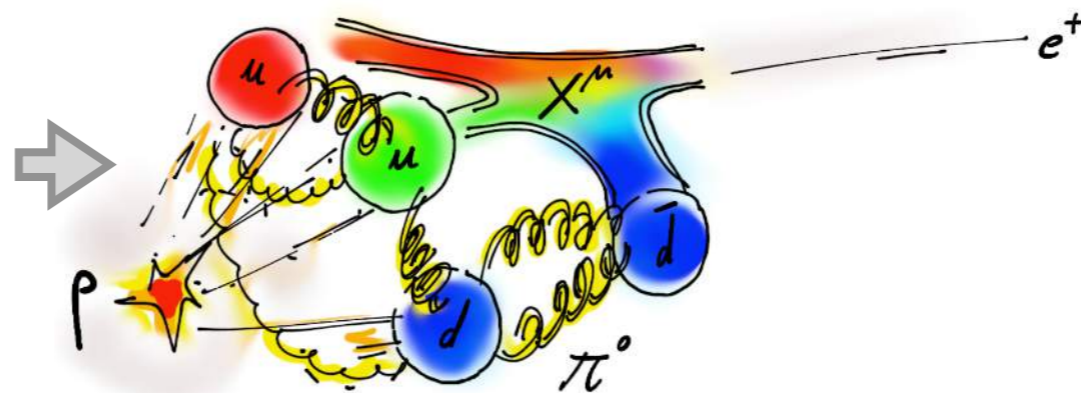
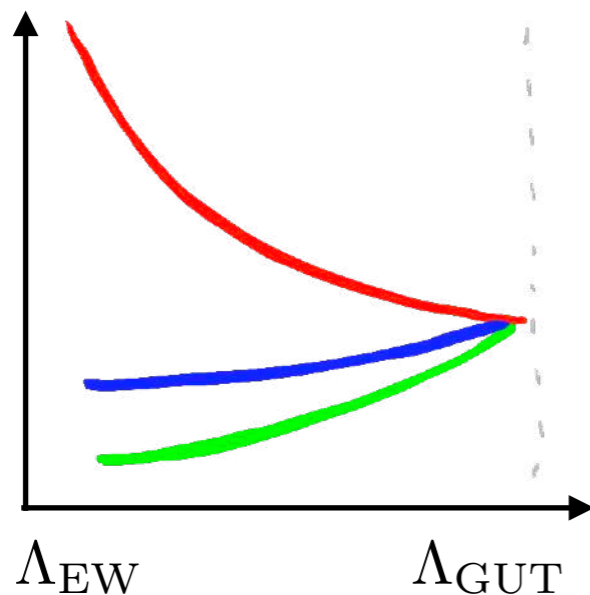
$$\bar{5} = \begin{pmatrix} (d_R)^c \\ L_L \end{pmatrix}, \quad 10 = \begin{pmatrix} (u_R)^c & Q_L \\ -Q_L^T & (e_R)^c \end{pmatrix}$$

El átomo de hidrogen es neutro!



$$Q(p) + Q(e) = 0$$

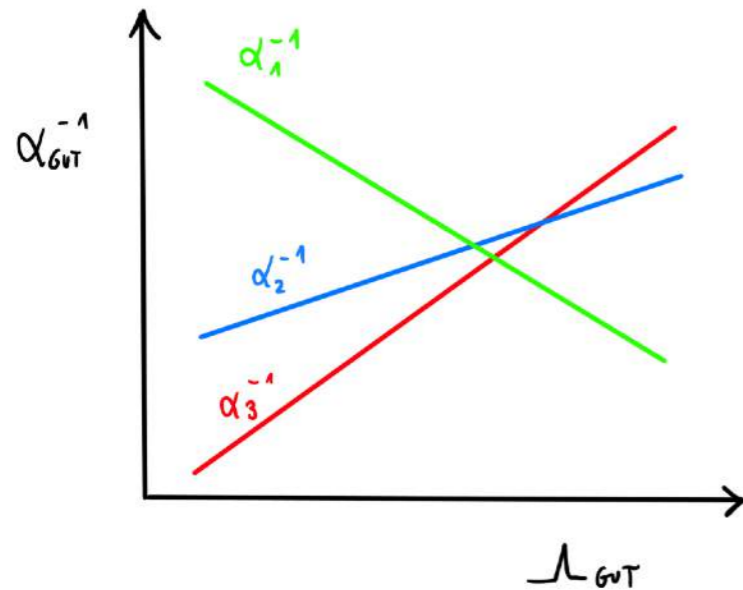
SU(5)



Gran Unificación (GUT)

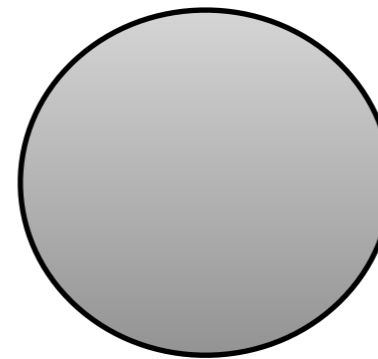
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

$$SU(5)$$



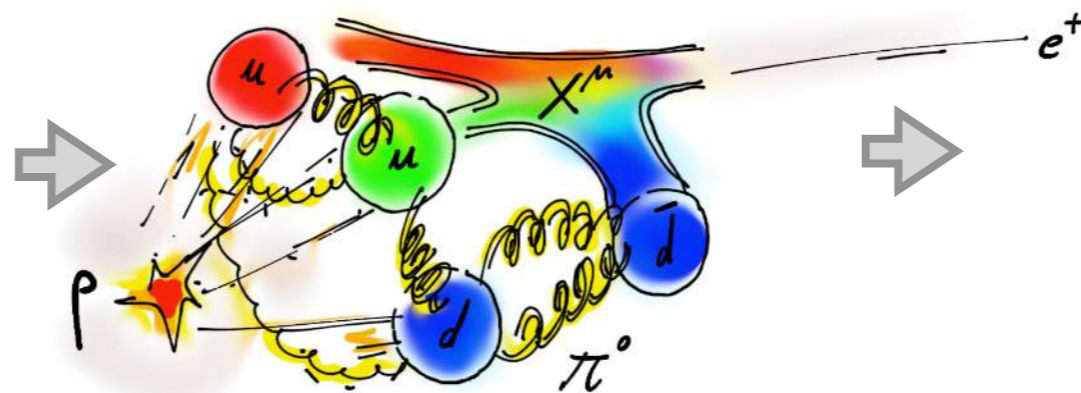
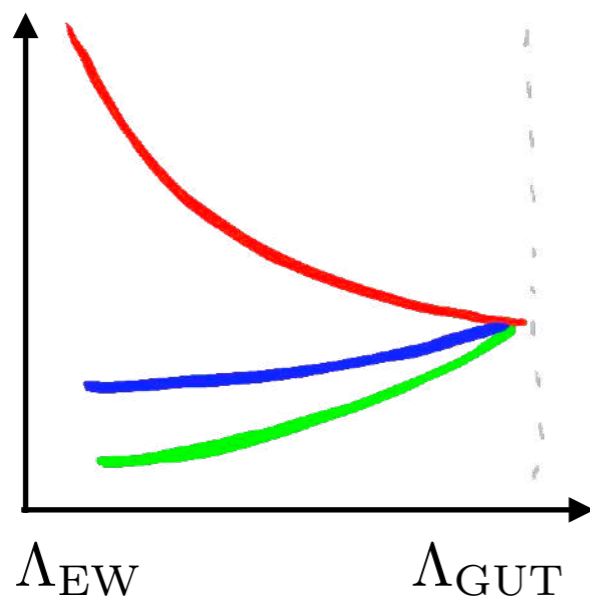
$$\bar{5} = \begin{pmatrix} (d_R)^c \\ L_L \end{pmatrix}, \quad 10 = \begin{pmatrix} (u_R)^c & Q_L \\ -Q_L^T & (e_R)^c \end{pmatrix}$$

El átomo de hidrogen es neutro!



$$Q(p) + Q(e) = 0$$

SU(5)



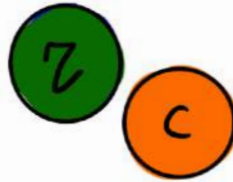
$$\tau_p > 10^{34} \text{ años!!}$$

$$\Lambda_{GUT} \gtrsim 10^{15} \text{ GeV}$$



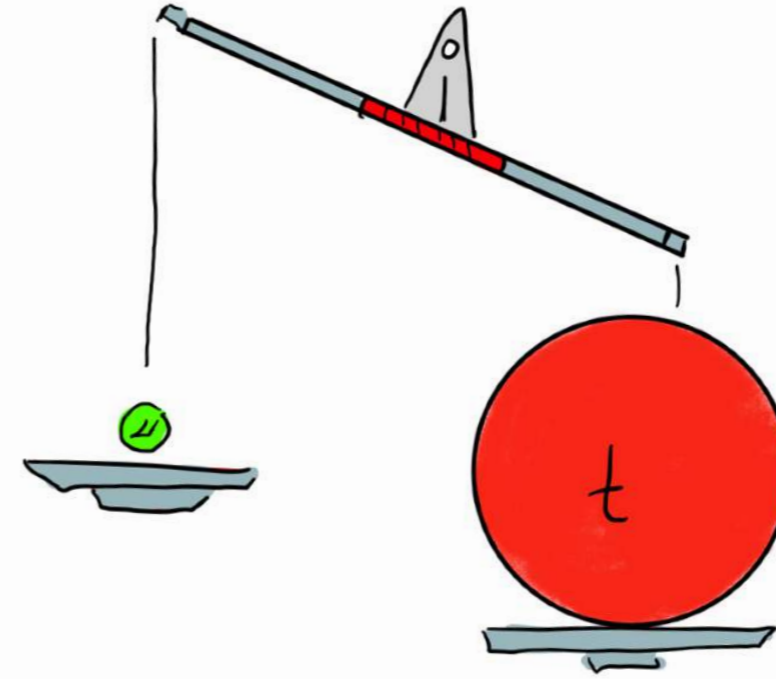
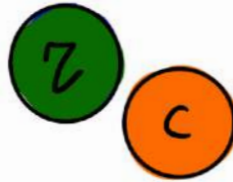
Herarquías

contacte
amb
el Higgs



Herarquías

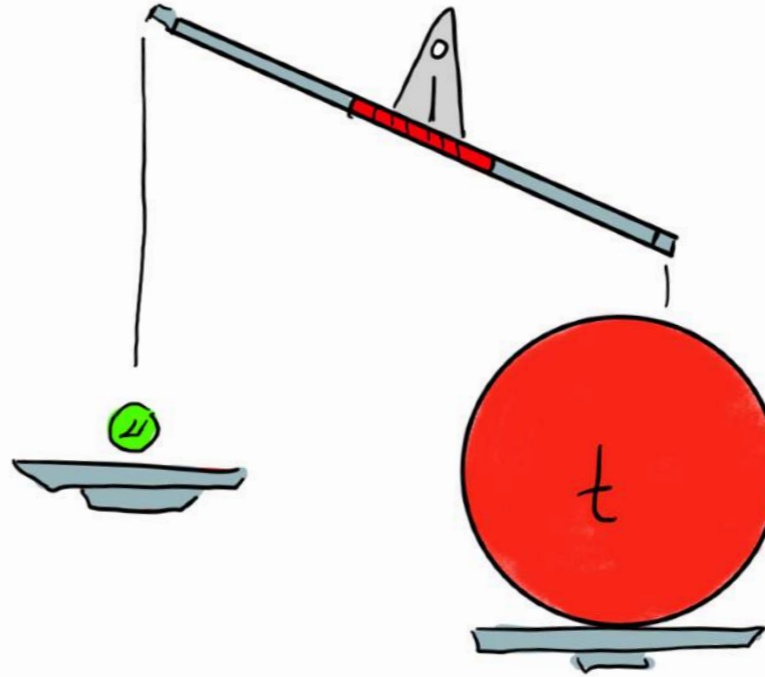
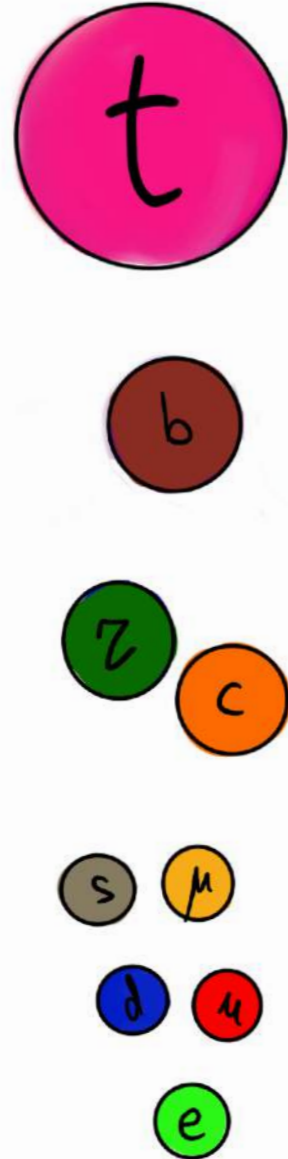
contacte
amb
el Higgs



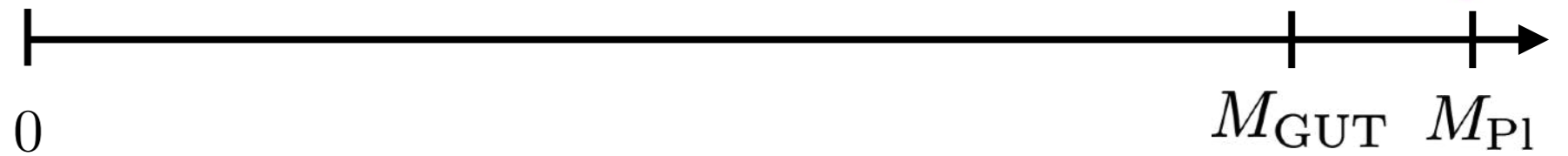
$$m_t \sim 1000000000000 m_\mu$$

Herarquías

contacte
amb
el Higgs

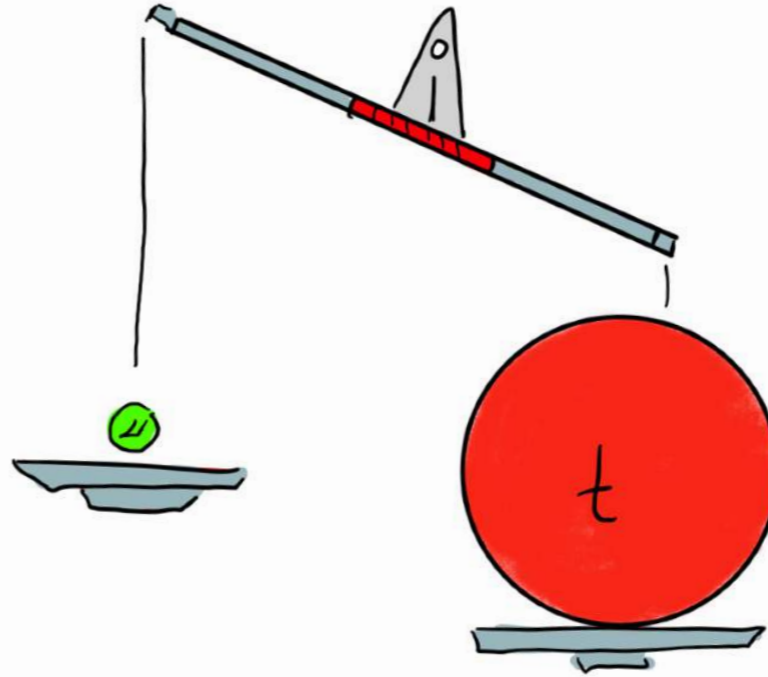
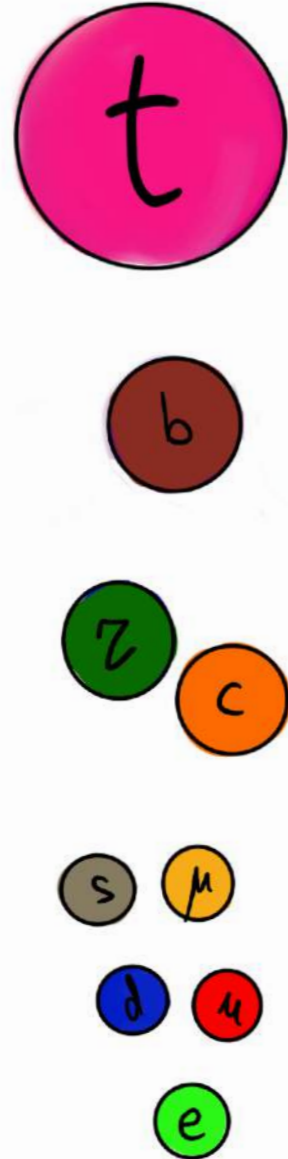


$$m_t \sim 1000000000000 m_\mu$$

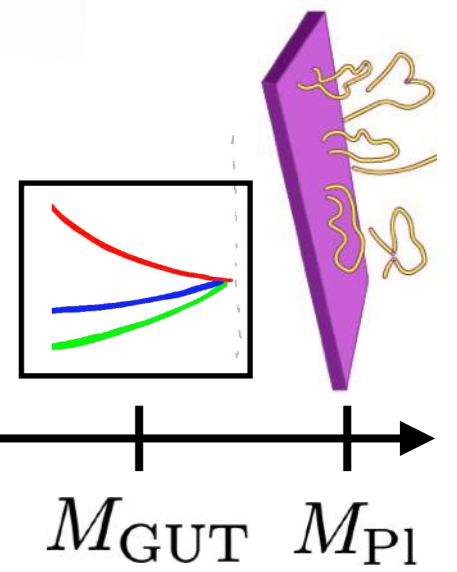
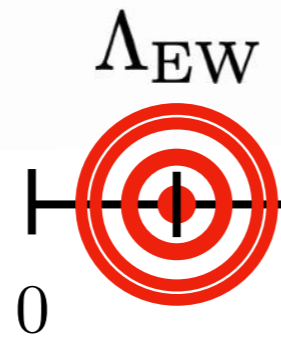


Herarquías

contacte
amb
el Higgs

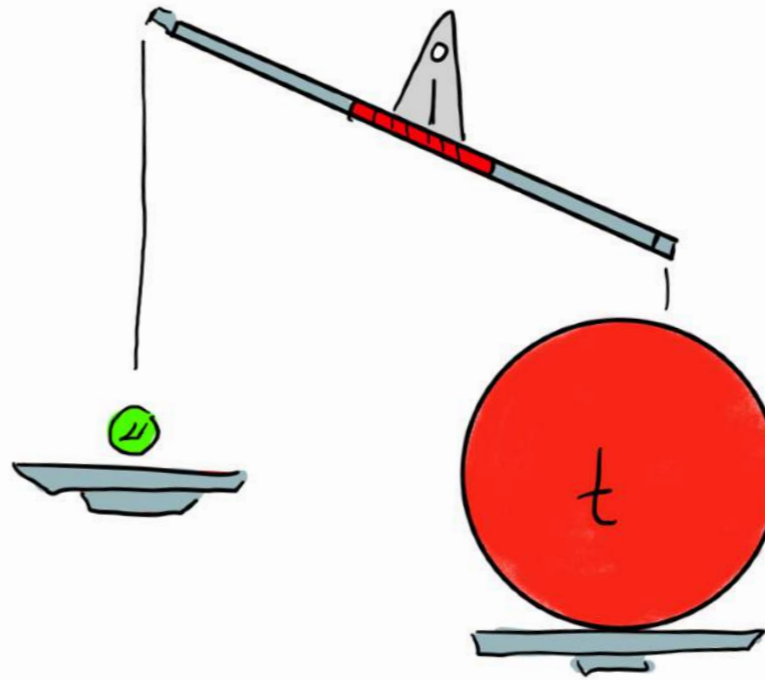
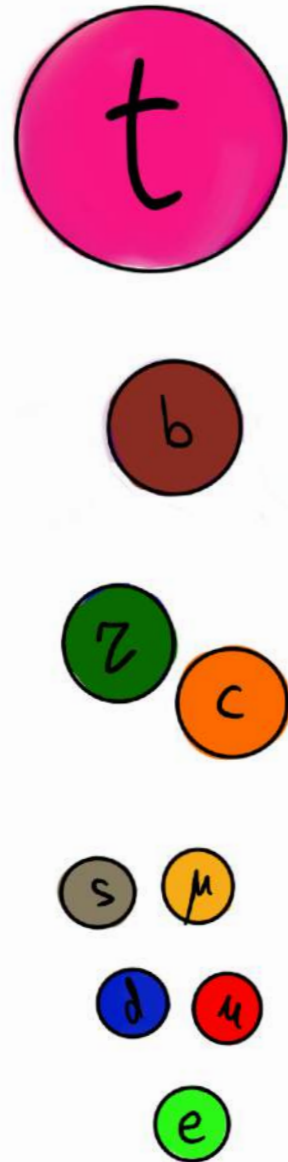


$$m_t \sim 1000000000000 m_\mu$$



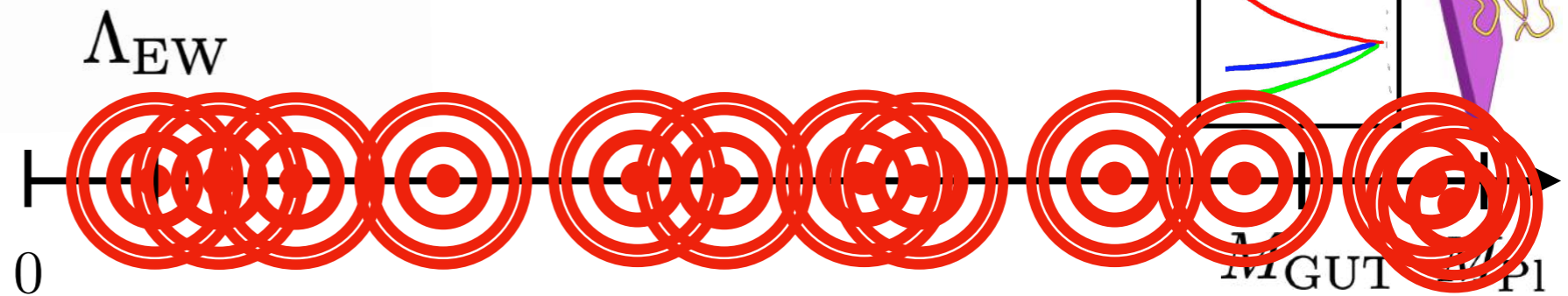
Herarquías

contacte
amb
el Higgs



$$m_t \sim 1000000000000 m_u$$

[Multi-universo]



El puzzle de sabor

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

u	d	e	\mathcal{L}_e
-----	-----	-----	-----------------

c	s	μ	\mathcal{L}_μ
-----	-----	-------	-------------------

t	b	τ	\mathcal{L}_τ
-----	-----	--------	--------------------

Por qué 3? Y no 5? O sólo 1? O 40000?



El puzzle de sabor

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



Por qué 3? Y no 5? O sólo 1? O 40000?



1st GEN



2nd GEN



3rd GEN



El puzzle de sabor

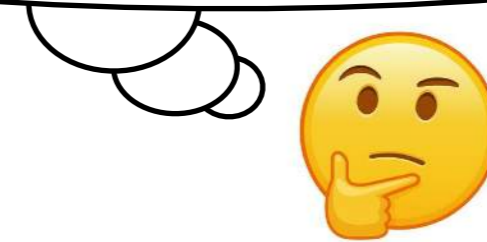
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

u	d	e	\mathcal{L}_e
-----	-----	-----	-----------------

c	s	μ	\mathcal{L}_μ
-----	-----	-------	-------------------

t	b	τ	\mathcal{L}_τ
-----	-----	--------	--------------------

Por qué 3? Y no 5? O sólo 1? O 40000?



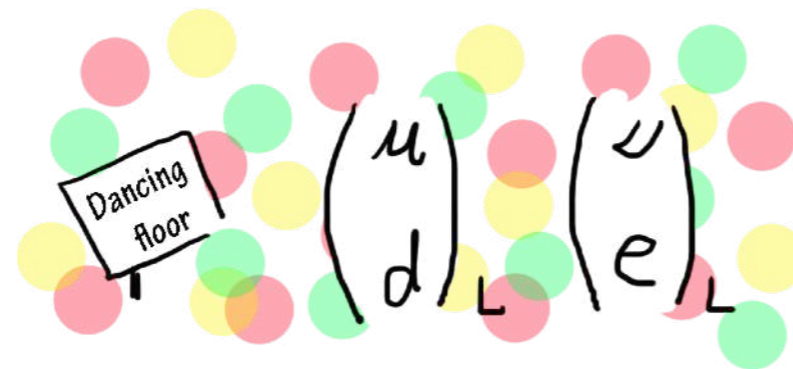
1st GEN



2nd GEN

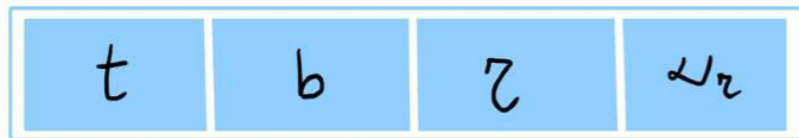
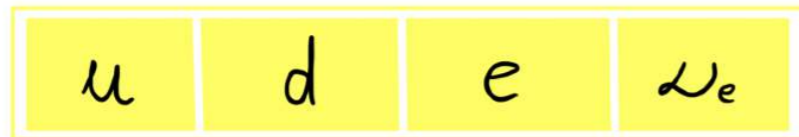


3rd GEN



El puzzle de sabor

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



e.g. $SO(18)$

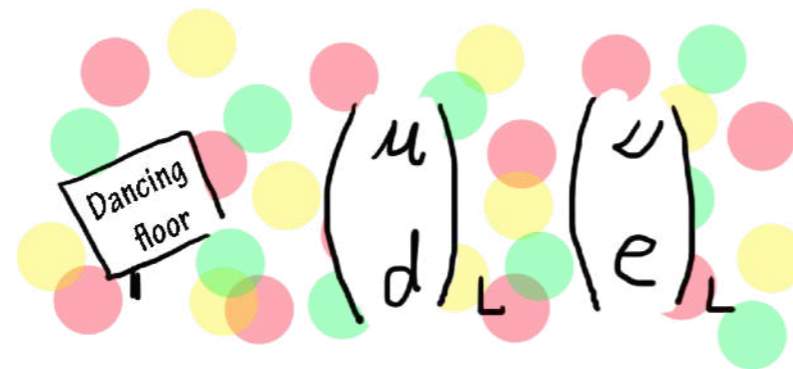
1st GEN



2nd GEN



3rd GEN



El puzzle de sabor

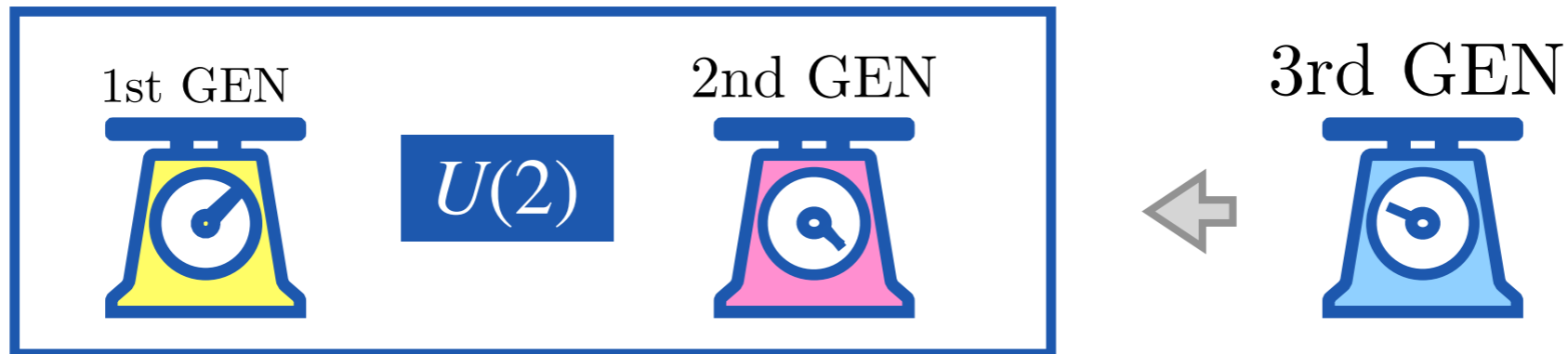
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

u	d	e	\mathcal{L}_e
-----	-----	-----	-----------------

c	s	μ	\mathcal{L}_μ
-----	-----	-------	-------------------

t	b	τ	\mathcal{L}_τ
-----	-----	--------	--------------------

e.g. $SO(18)$



Dancing floor $\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$

Unfair... We do also want a partner!
 $e_R \nu_R d_R$

El puzzle de sabor

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

u	d	e	\mathcal{L}_e
---	---	---	-----------------

c	s	μ	\mathcal{L}_μ
---	---	-------	-------------------

t	b	τ	\mathcal{L}_τ
---	---	--------	--------------------

e.g. $SO(18)$

dimensiones extra

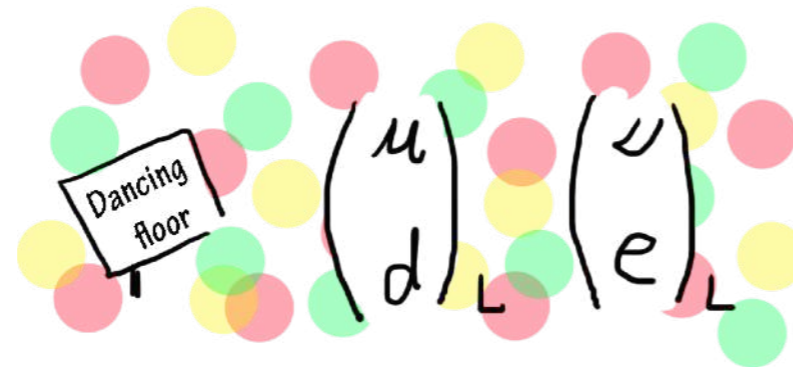
1st GEN



2nd GEN



3rd GEN



El puzzle de sabor

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

u	d	e	\mathcal{L}_e
c	s	μ	\mathcal{L}_μ
t	b	τ	\mathcal{L}_τ

$$\overline{\mathbb{1}}_L = \begin{bmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_L \\ \begin{pmatrix} \nu \\ e \end{pmatrix}_L \end{bmatrix} \quad \overline{\mathbb{1}}_R = \begin{bmatrix} \begin{pmatrix} u \\ d \end{pmatrix}_R \\ \begin{pmatrix} \nu \\ e \end{pmatrix}_R \end{bmatrix}$$

Unificación de quarks y leptones

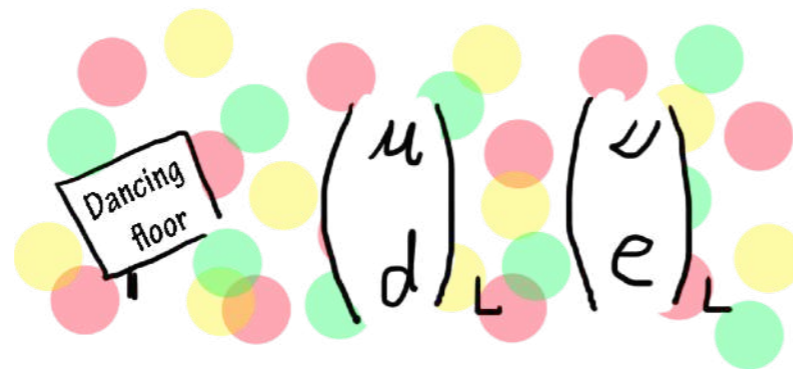
1st GEN



2nd GEN

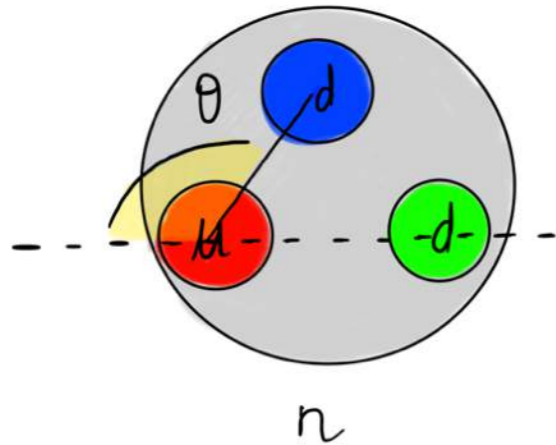


3rd GEN



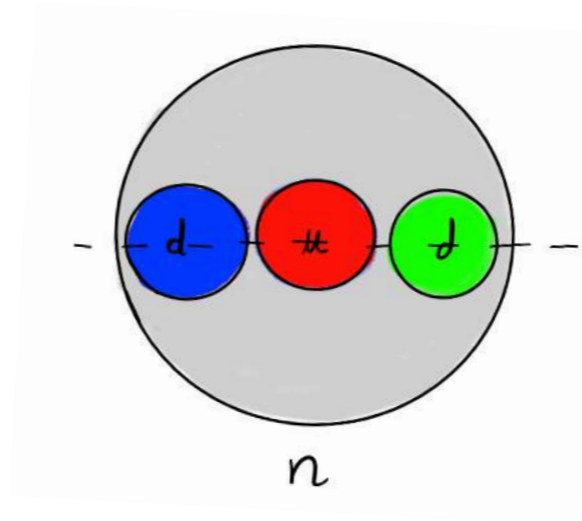
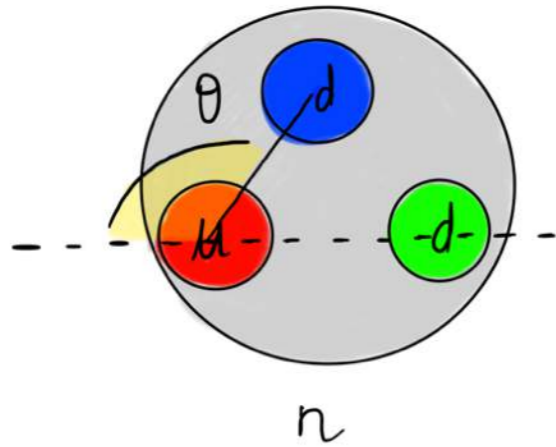
El problema fuerte de CP

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



El problema fuerte de CP

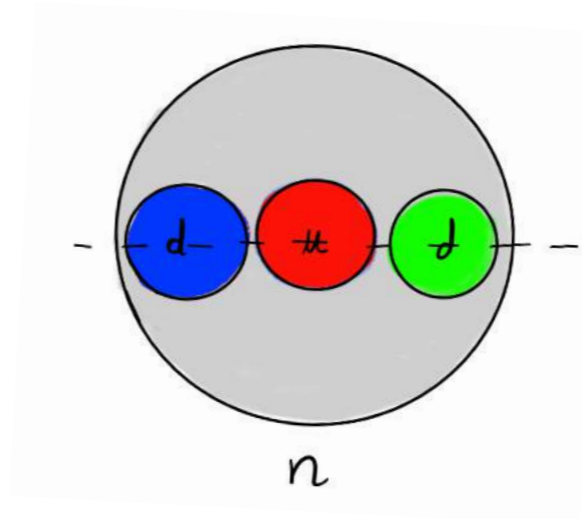
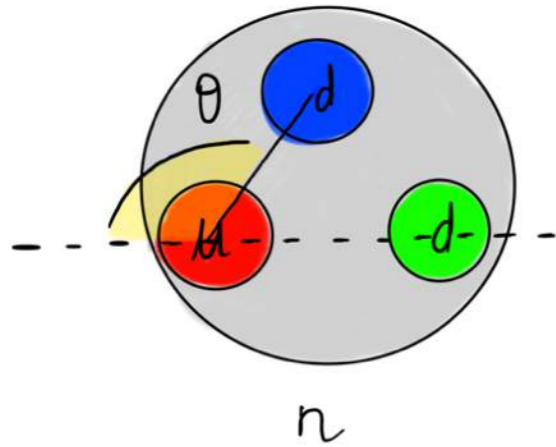
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



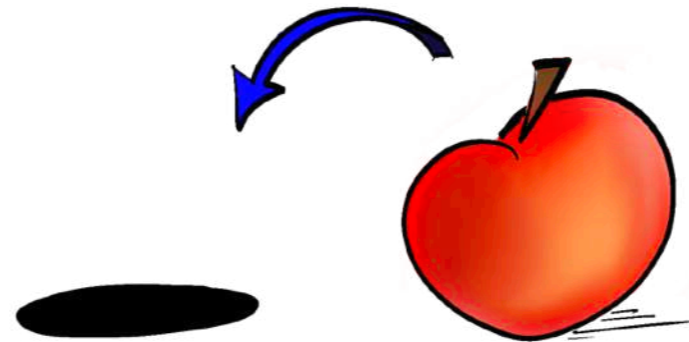
$$\theta_{\text{QCD}} < 10^{-10}$$

El problema fuerte de CP

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

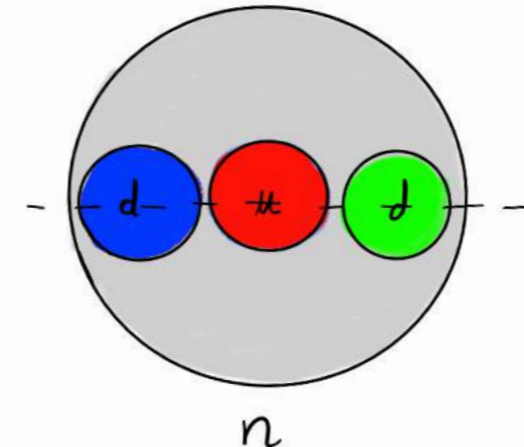
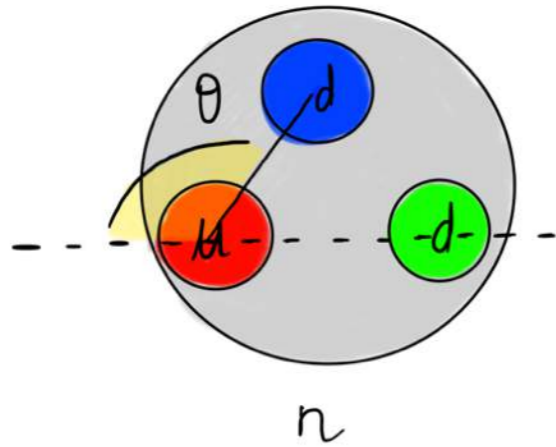


$$\theta_{\text{QCD}} < 10^{-10}$$

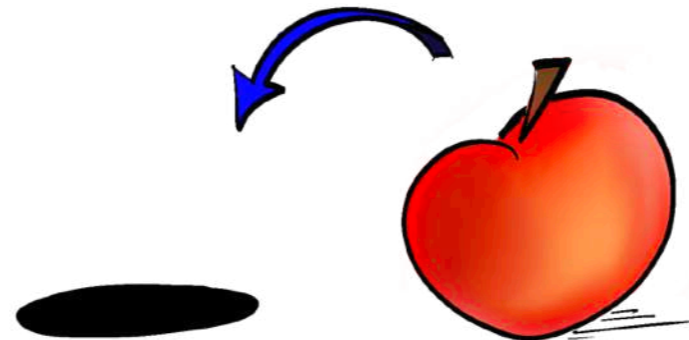


El problema fuerte de CP

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

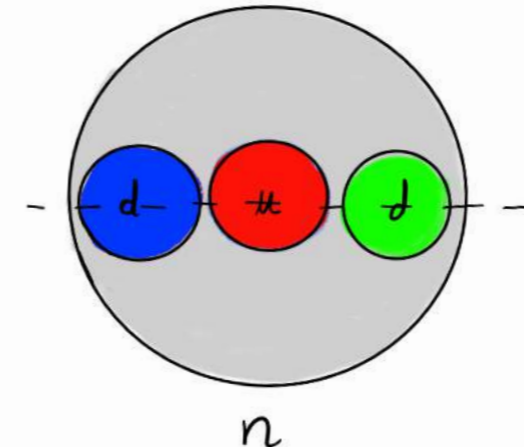
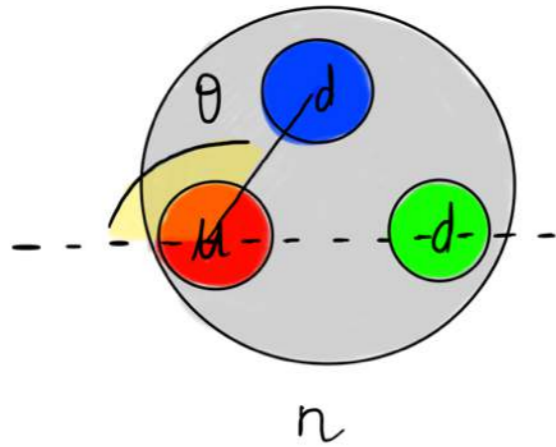


$$\theta_{\text{QCD}} < 10^{-10}$$

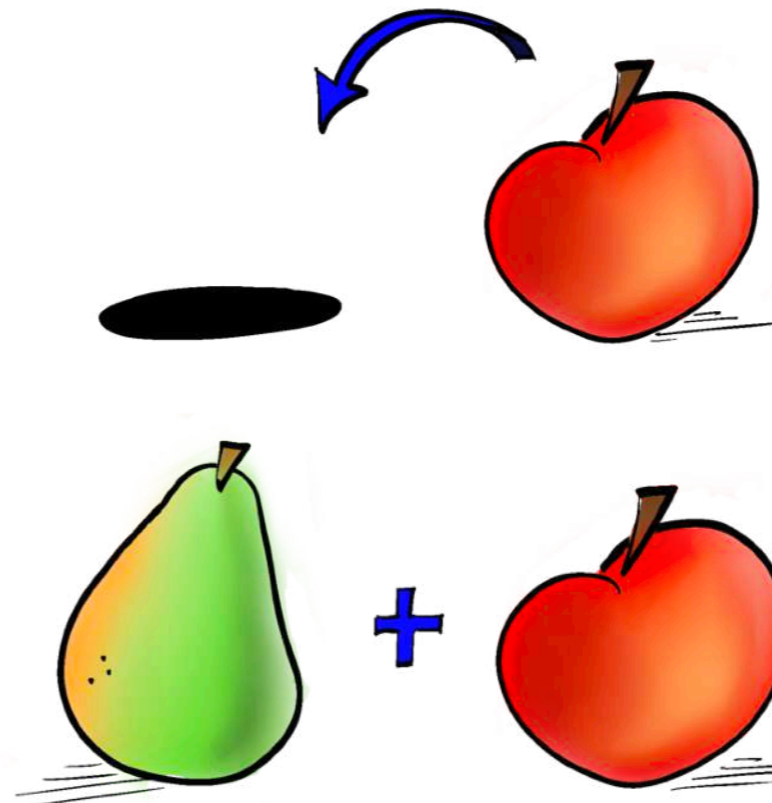


El problema fuerte de CP

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

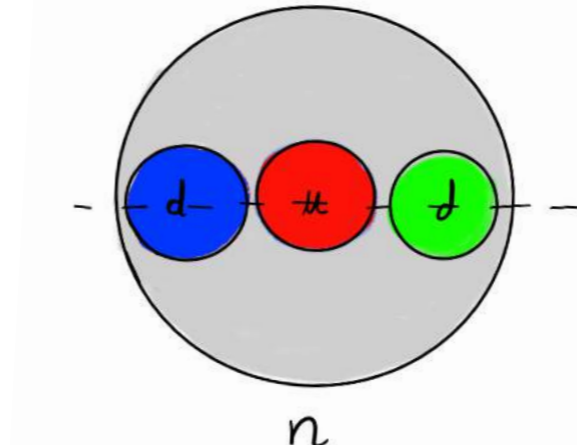
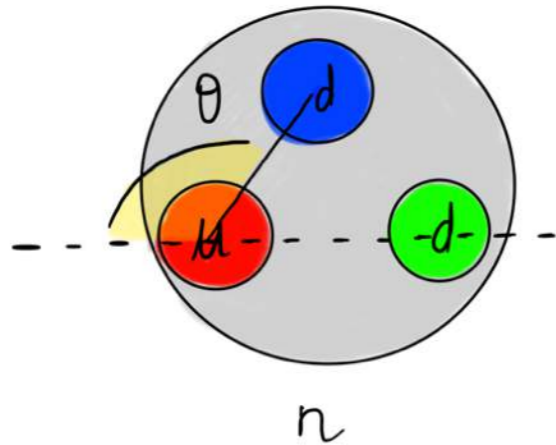


$$\theta_{\text{QCD}} < 10^{-10}$$

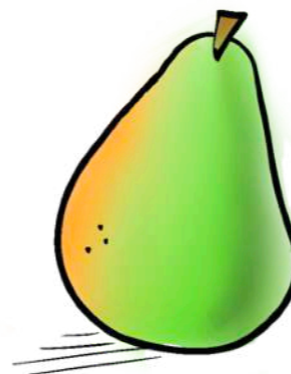
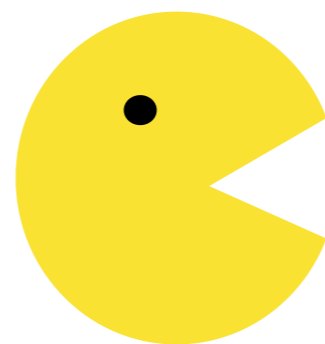


El problema fuerte de CP

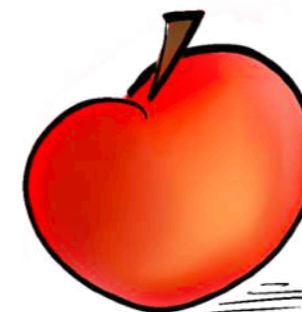
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



$$\theta_{\text{QCD}} < 10^{-10}$$



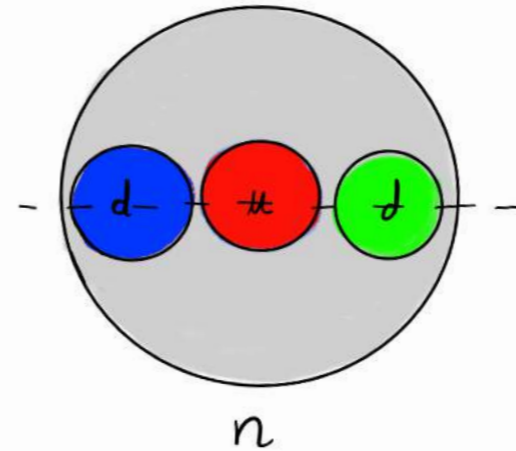
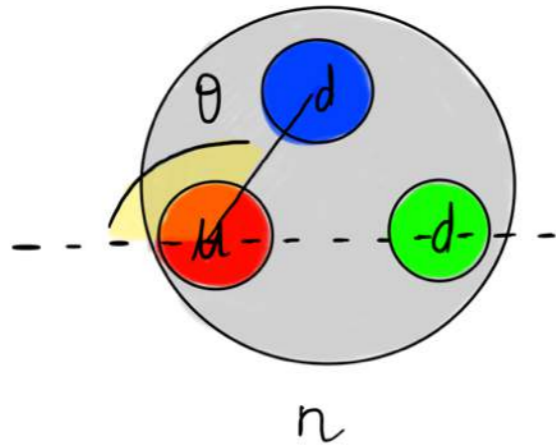
+



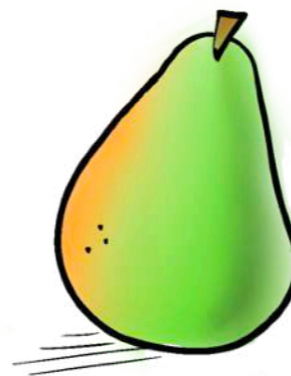
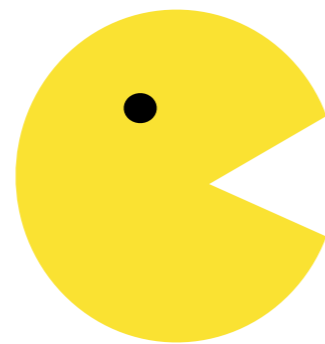
$$< 10^{-10}$$

El problema fuerte de CP

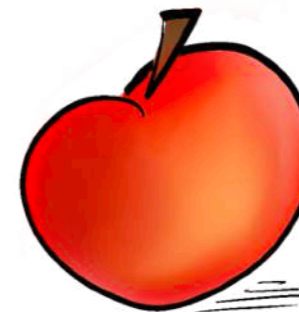
$$SU(3) \otimes SU(2) \otimes U(1)_Y$$



$$\theta_{\text{QCD}} < 10^{-10}$$



+

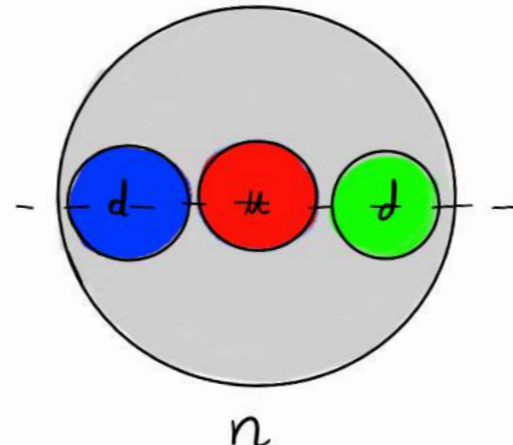
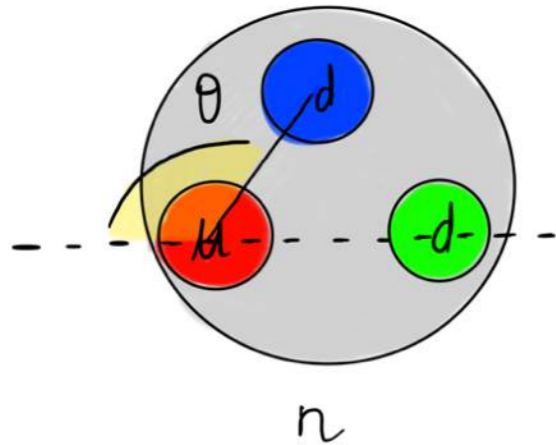


$$< 10^{-10}$$

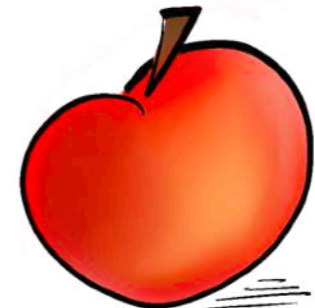
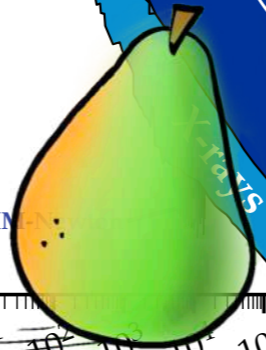
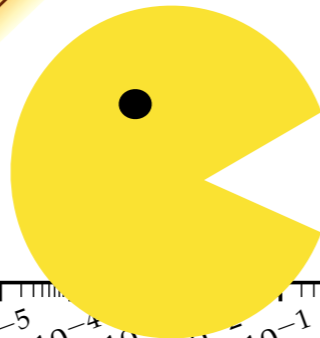
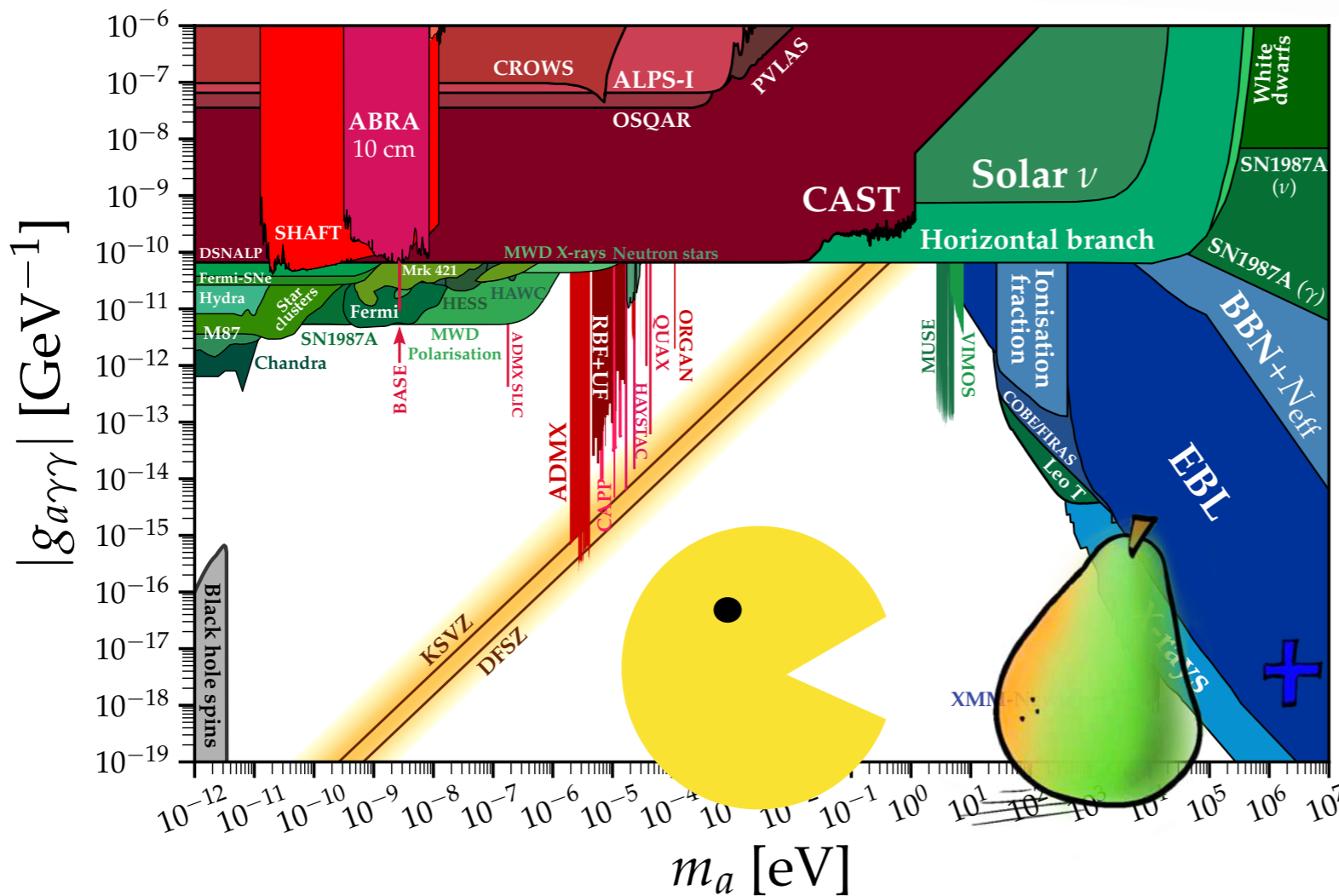


El problema fuerte de CP

$$SU(3) \otimes SU(2) \otimes U(1)_Y$$

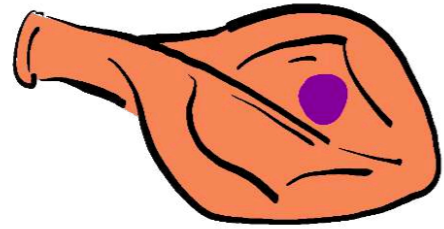


$$\theta_{\text{QCD}} < 10^{-10}$$

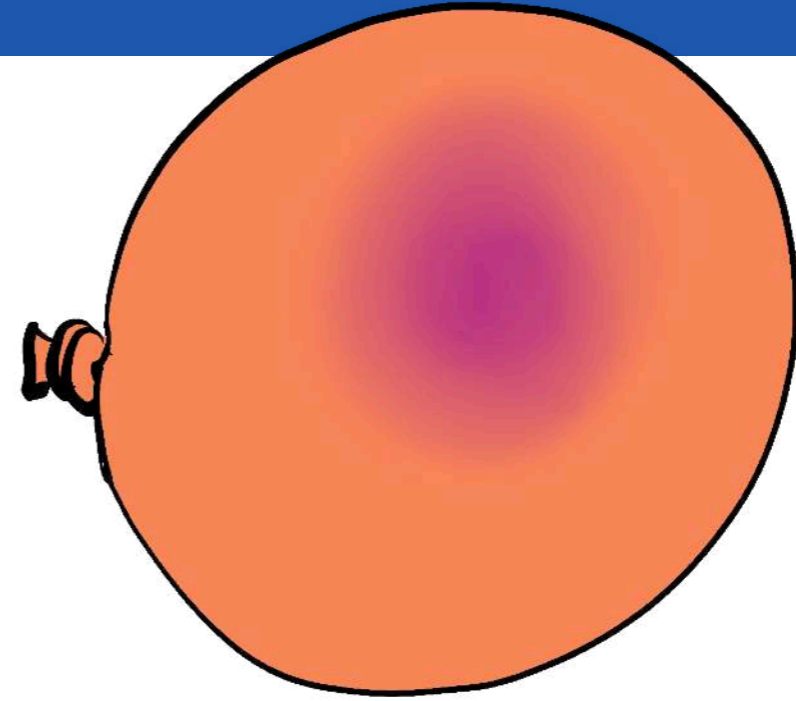


$$< 10^{-10}$$

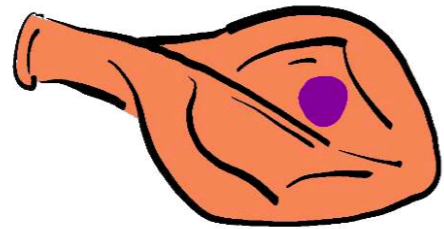
Parámetros del universo



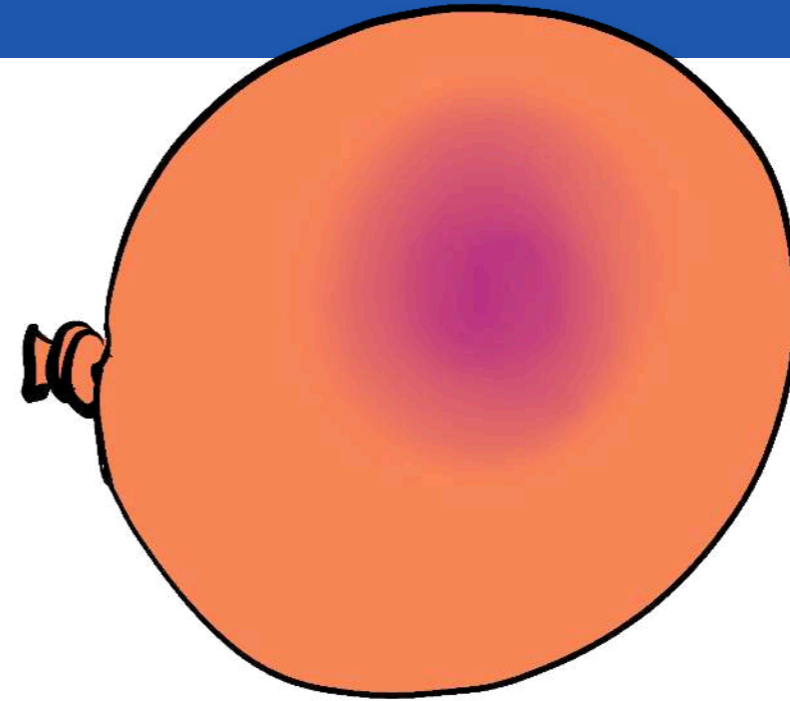
Inflación?



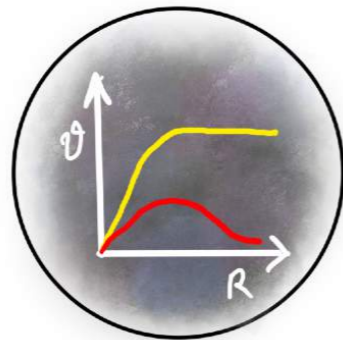
Parámetros del universo



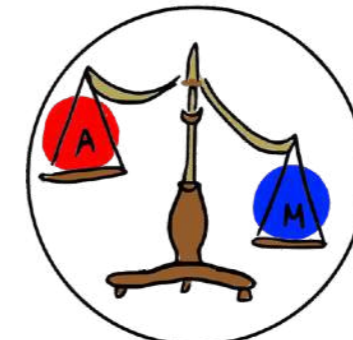
Inflación?



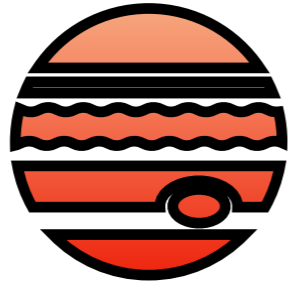
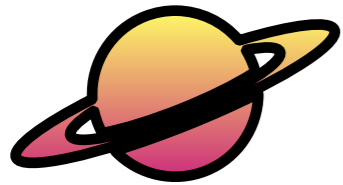
Mecanismo



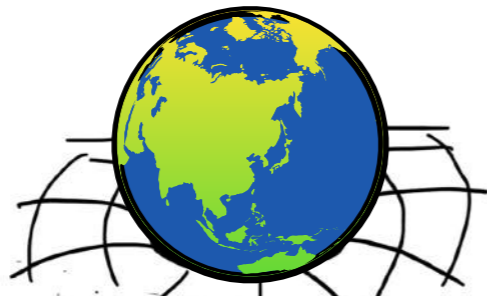
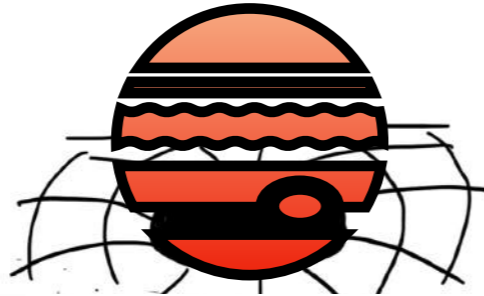
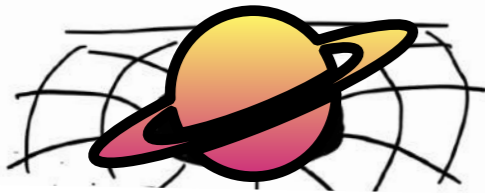
$$\Lambda_{DM} \sim 5\Lambda_B$$



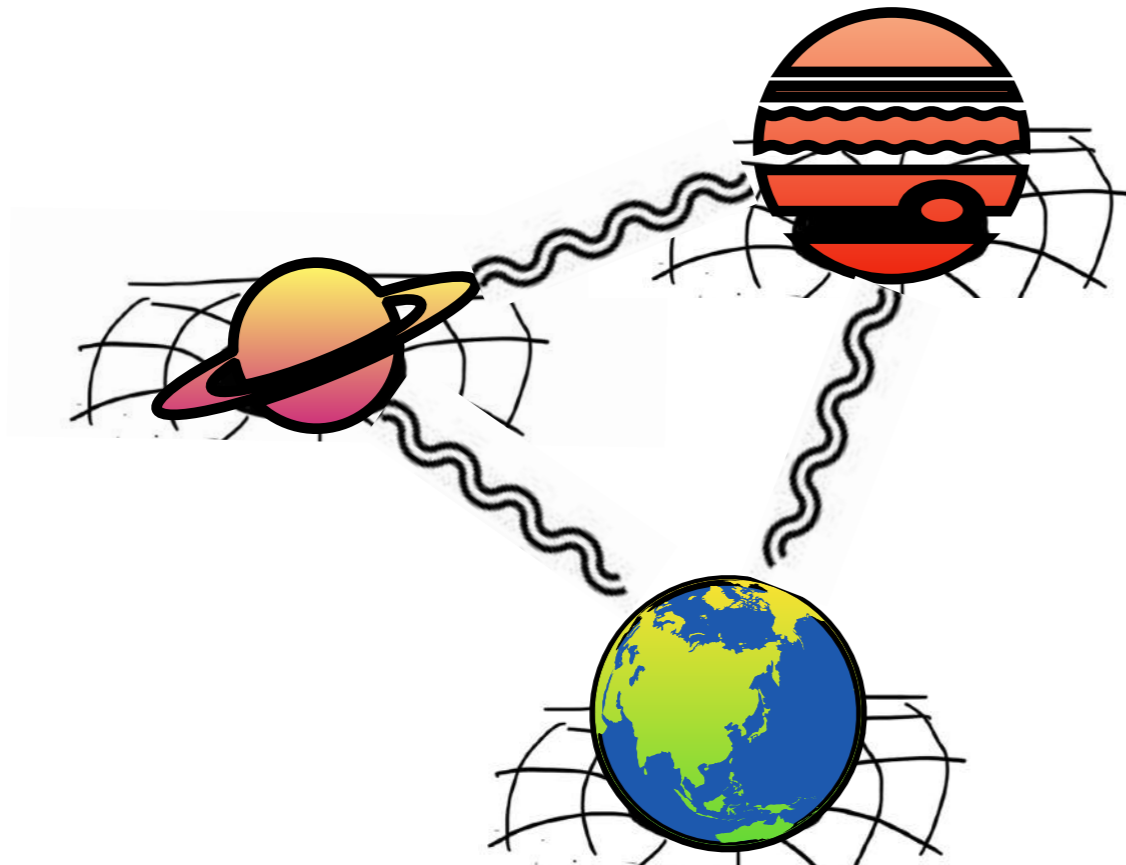
Y la gravedad?



Y la gravedad?

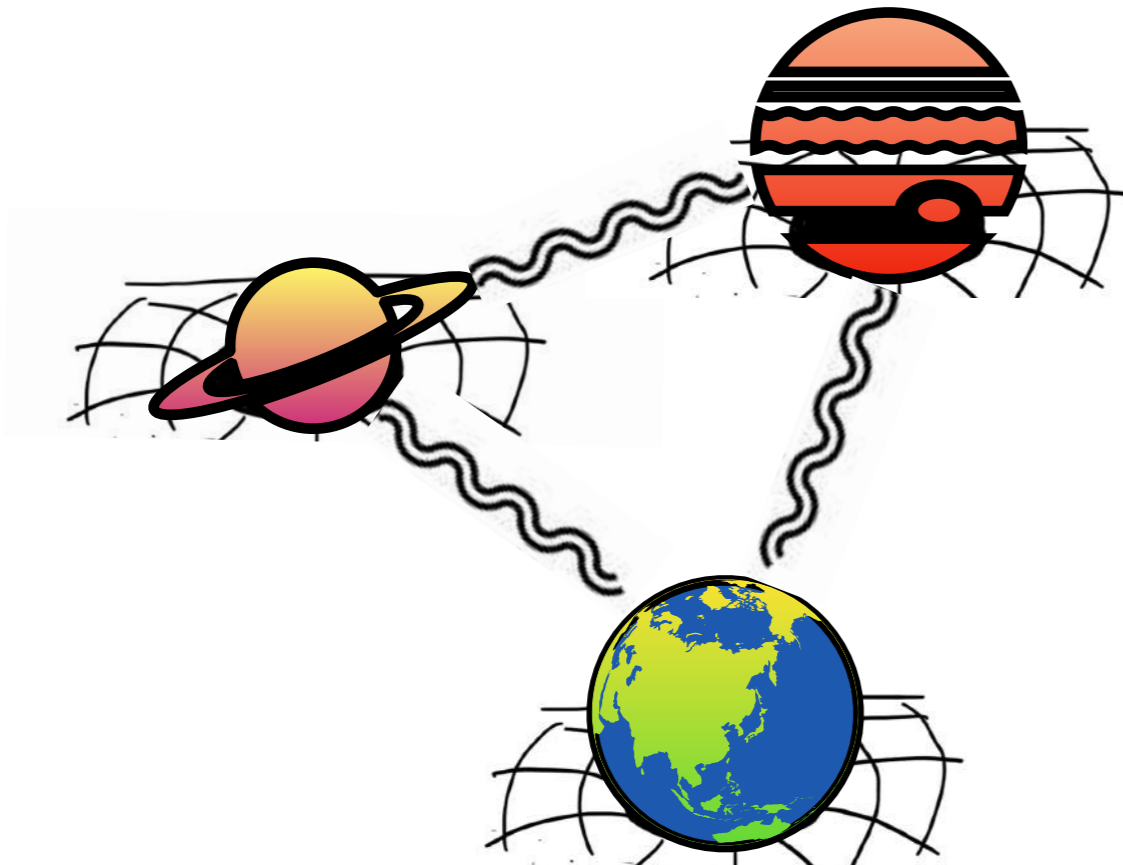


Y la gravedad?



Interacciones	Intensidad	Mediador	Alcance
F. Fuerte	1000	Gluones	Largo (M=0)
Electromagnetismo	1	Fotones	Largo (M=0)
F. Débil	100	W, Z	M
Gravedad		¿¿Gravitón??	Largo (M=0)

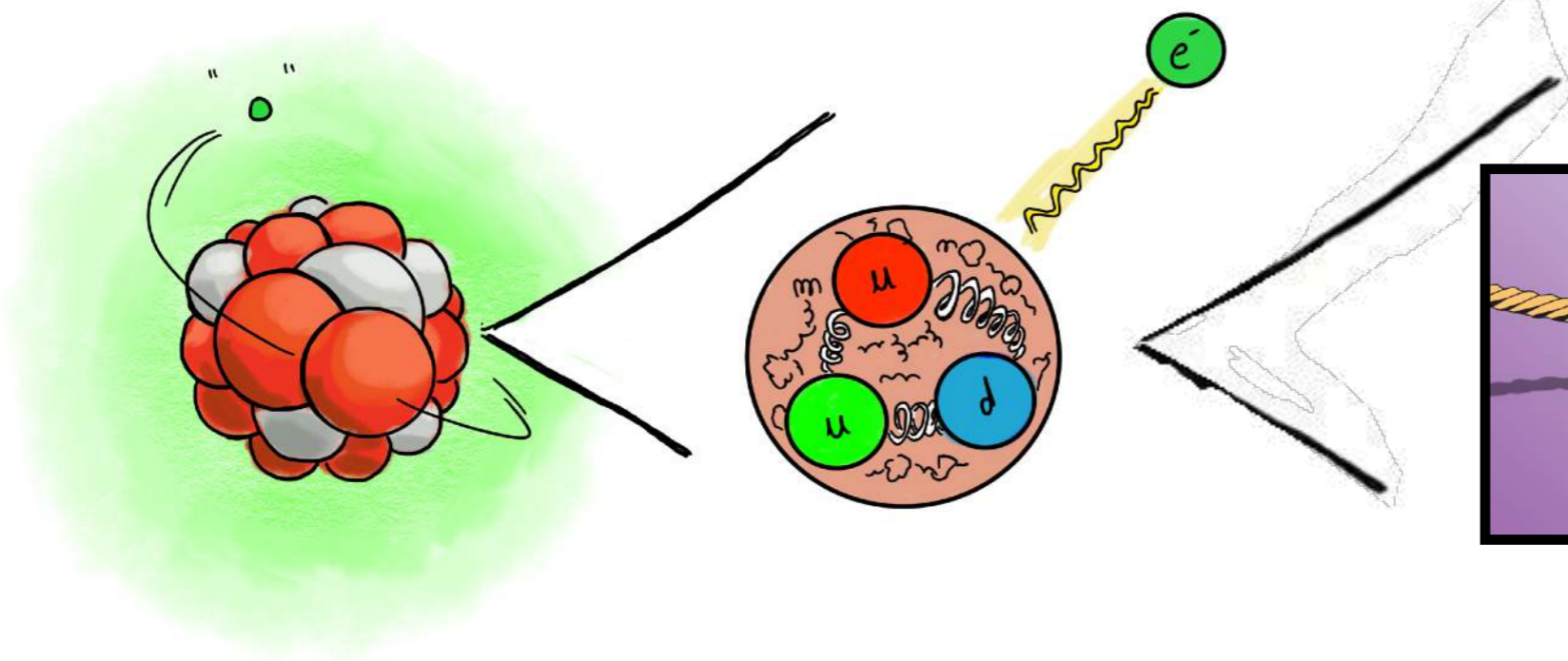
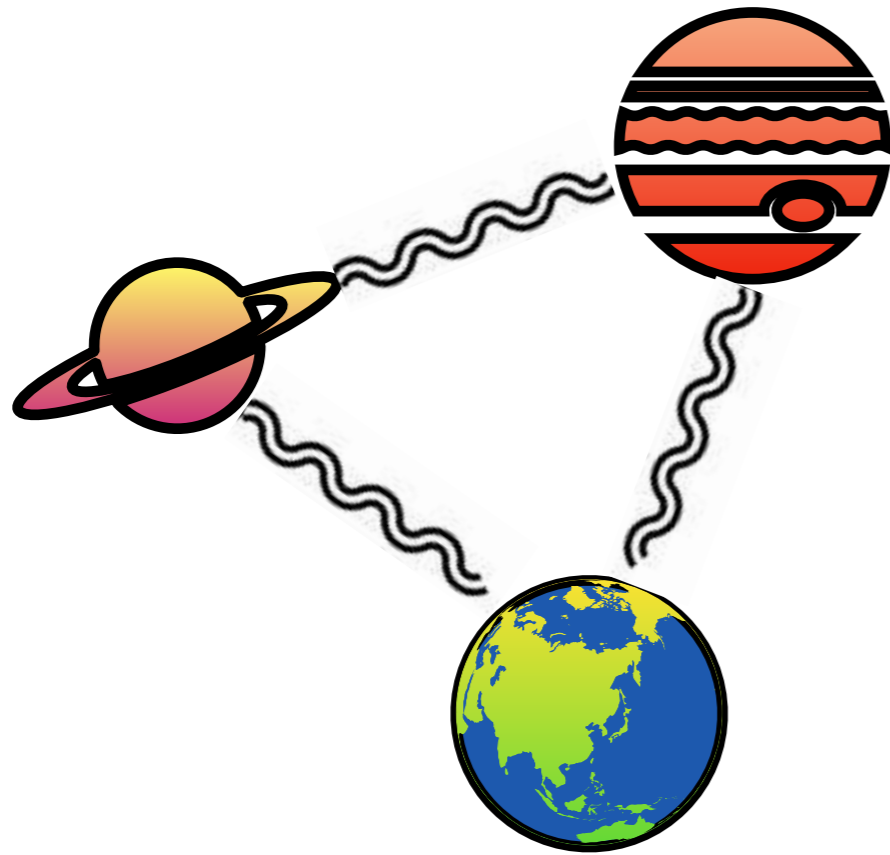
Y la gravedad?



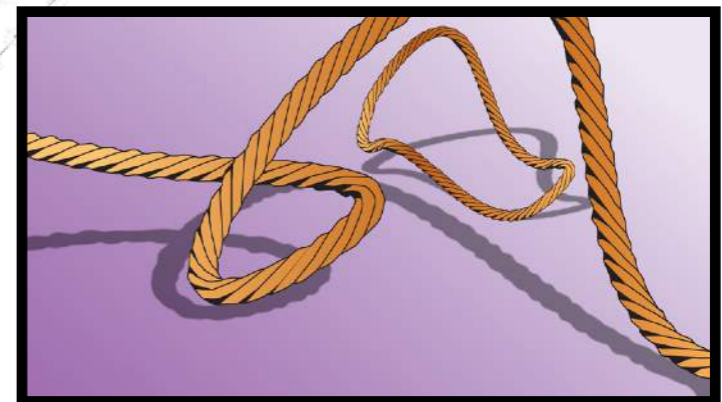
Dimensiones extra?

Interacciones	Intensidad	Mediador	Alcance
F. Fuerte	1000	Gluones	Largo (M=0)
Electromagnetismo	1	Fotones	Largo (M=0)
F. Débil	100	W, Z	M
Gravedad	10^{-33}	¿¿Gravitón??	Largo (M=0)

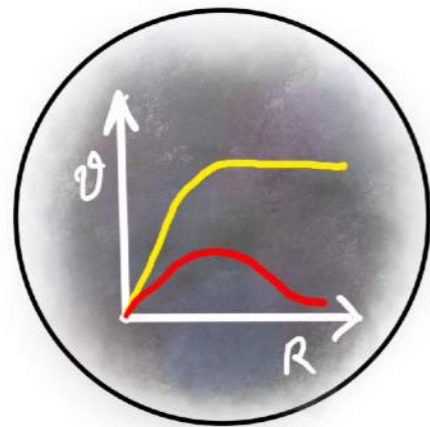
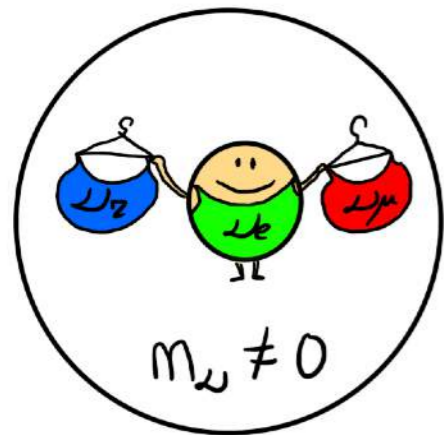
Y la gravedad?



Teoría de cuerdas



En búsqueda de la nueva física





Teorías efectivas

Parametrizando la nueva física

e.g. serie de Taylor

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} + \dots = \sum_{k=0}^{\infty} \frac{x^{2k+1}}{(2k+1)!} (-1)^k$$



Teorías efectivas

Parametrizando la nueva física

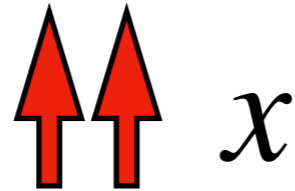
e.g. serie de Taylor

$$?? = x$$



Teorías efectivas

Parametrizando la nueva física



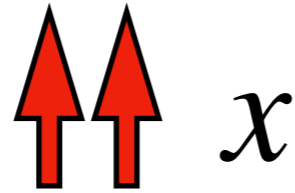
e.g. serie de Taylor

$$\sin(x) = x - \boxed{\frac{x^3}{3!} + \frac{x^5}{5!} + \dots} = \sum_{k=0}^{\infty} \frac{x^{2k+1}}{(2k+1)!} (-1)^k$$



Teorías efectivas

Parametrizando la nueva física



x



e.g. serie de Taylor

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} + \dots = \sum_{k=0}^{\infty} \frac{x^{2k+1}}{(2k+1)!} (-1)^k$$

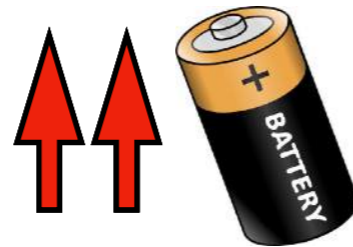
$$x = \frac{E}{M_{??}}$$



Teorías efectivas

Parametrizando la nueva física

Construcción de
super-colisionadores



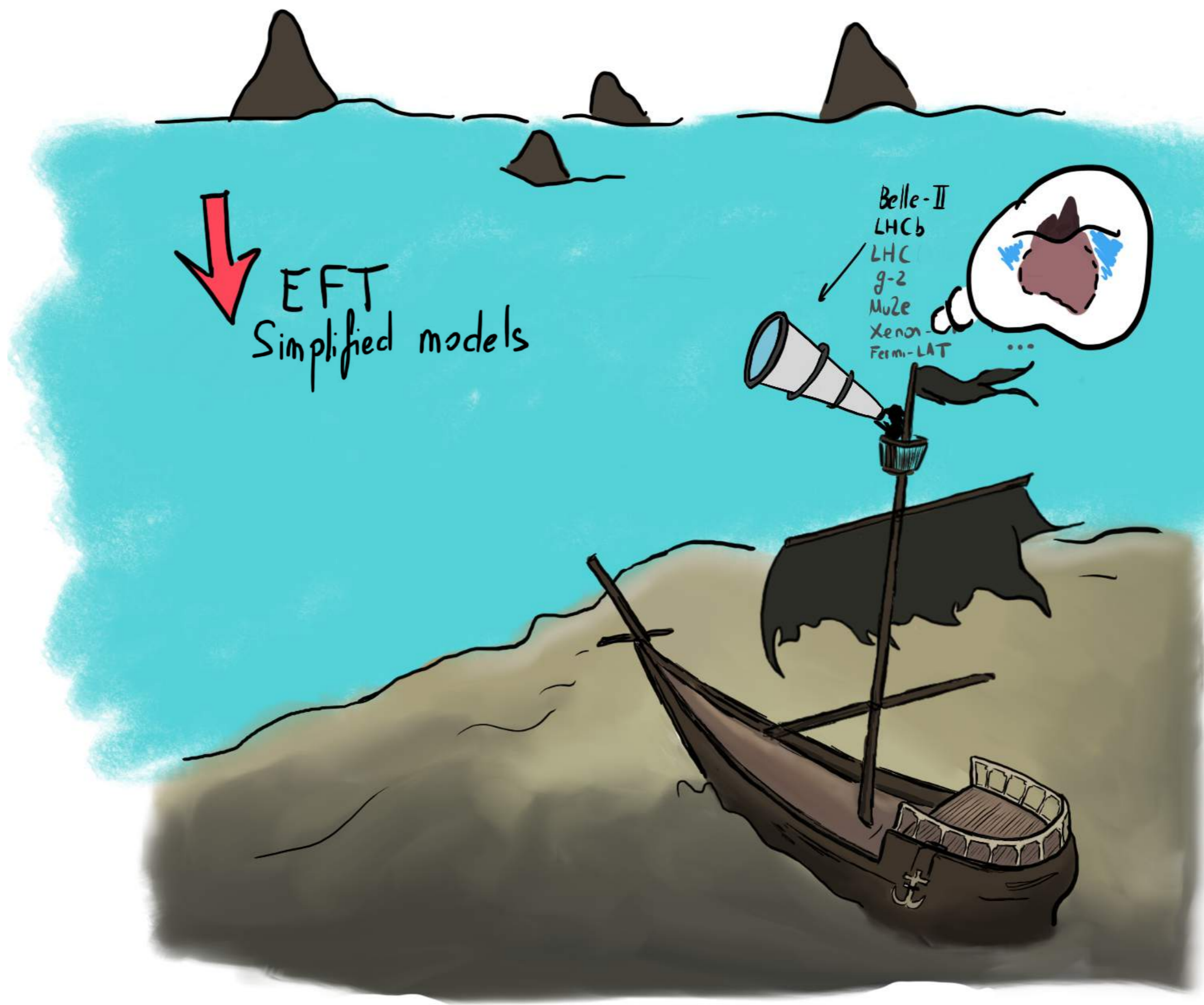
Física de
Precisión



e.g. serie de Taylor

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} + \dots = \sum_{k=0}^{\infty} \frac{x^{2k+1}}{(2k+1)!} (-1)^k$$

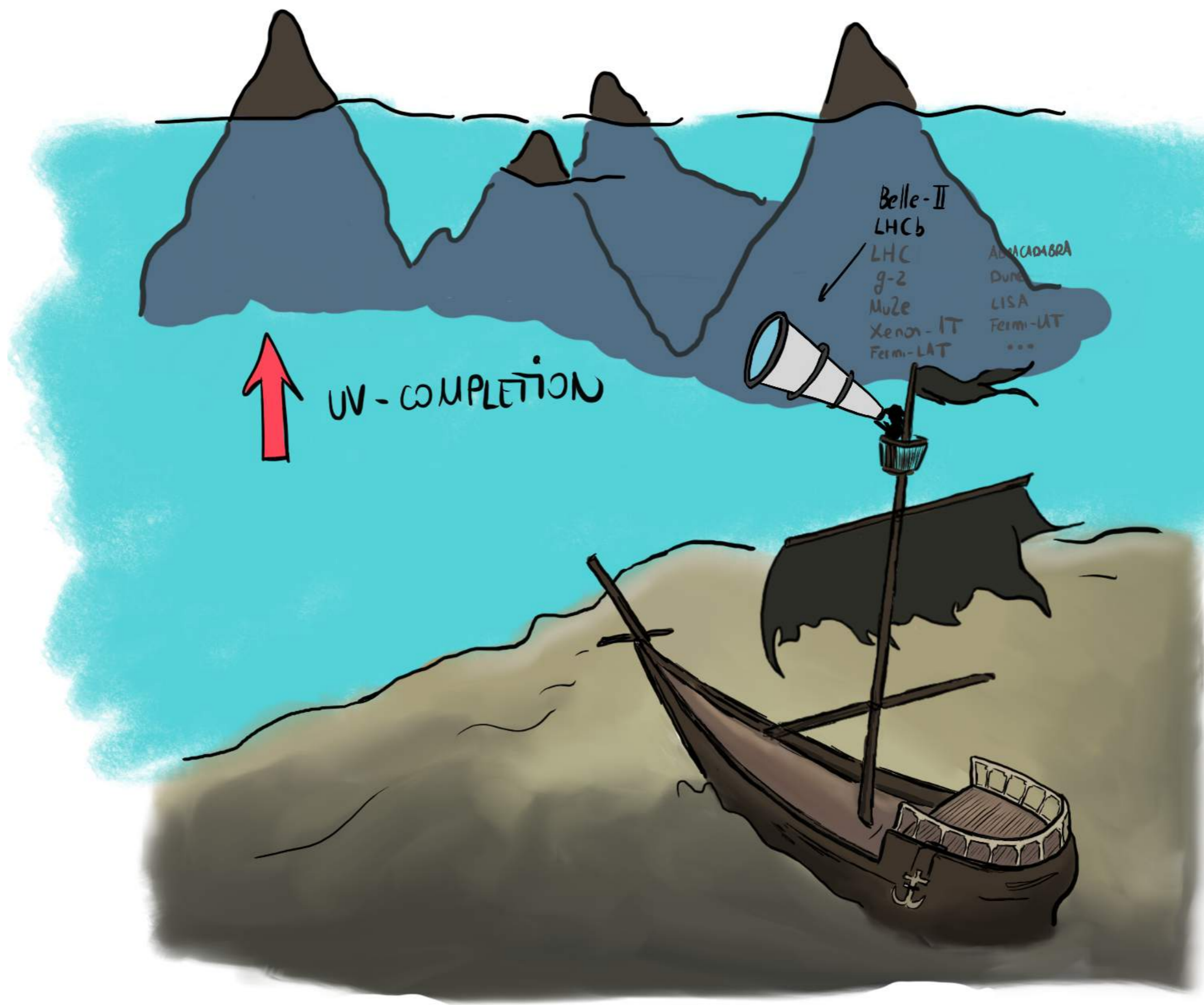
$$x = \frac{E}{M_{??}}$$



EFT
Simplified models

- Belle-II
- LHCb
- LHC
- g-2
- Mu2e
- Xenon
- Fermi-LAT
- ...

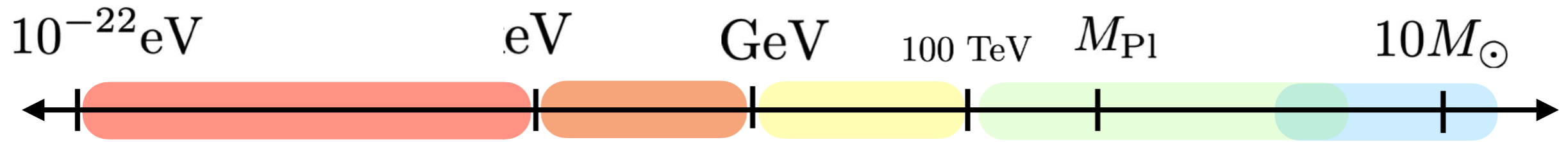




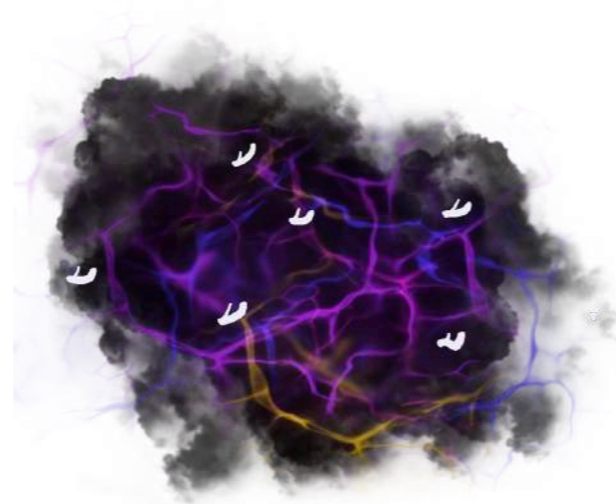
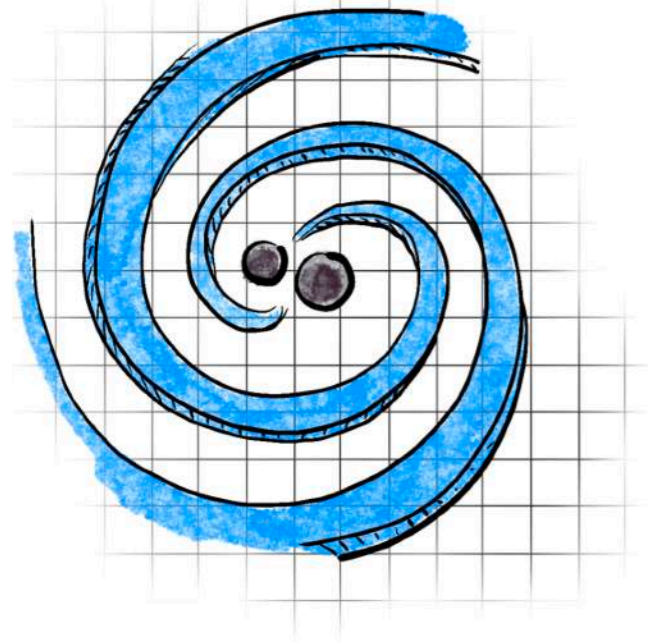
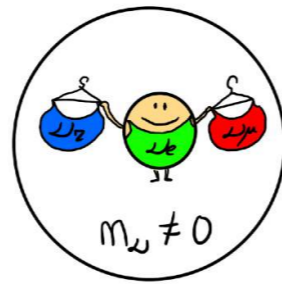
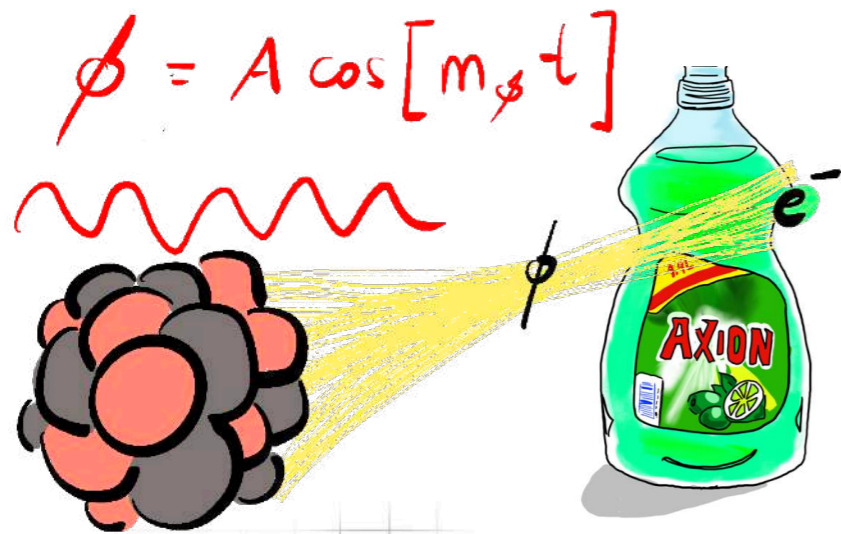
UV-COMPLETION

Belle-II
LHCb
LHC
g-2
Mu2e
Xenon-1T
Fermi-LAT
ADMETA
DUNE
LISA
Fermi-LAT
...

En búsqueda de “nueva” física (elusiva)



Colisionadores
Experimentos de sabor

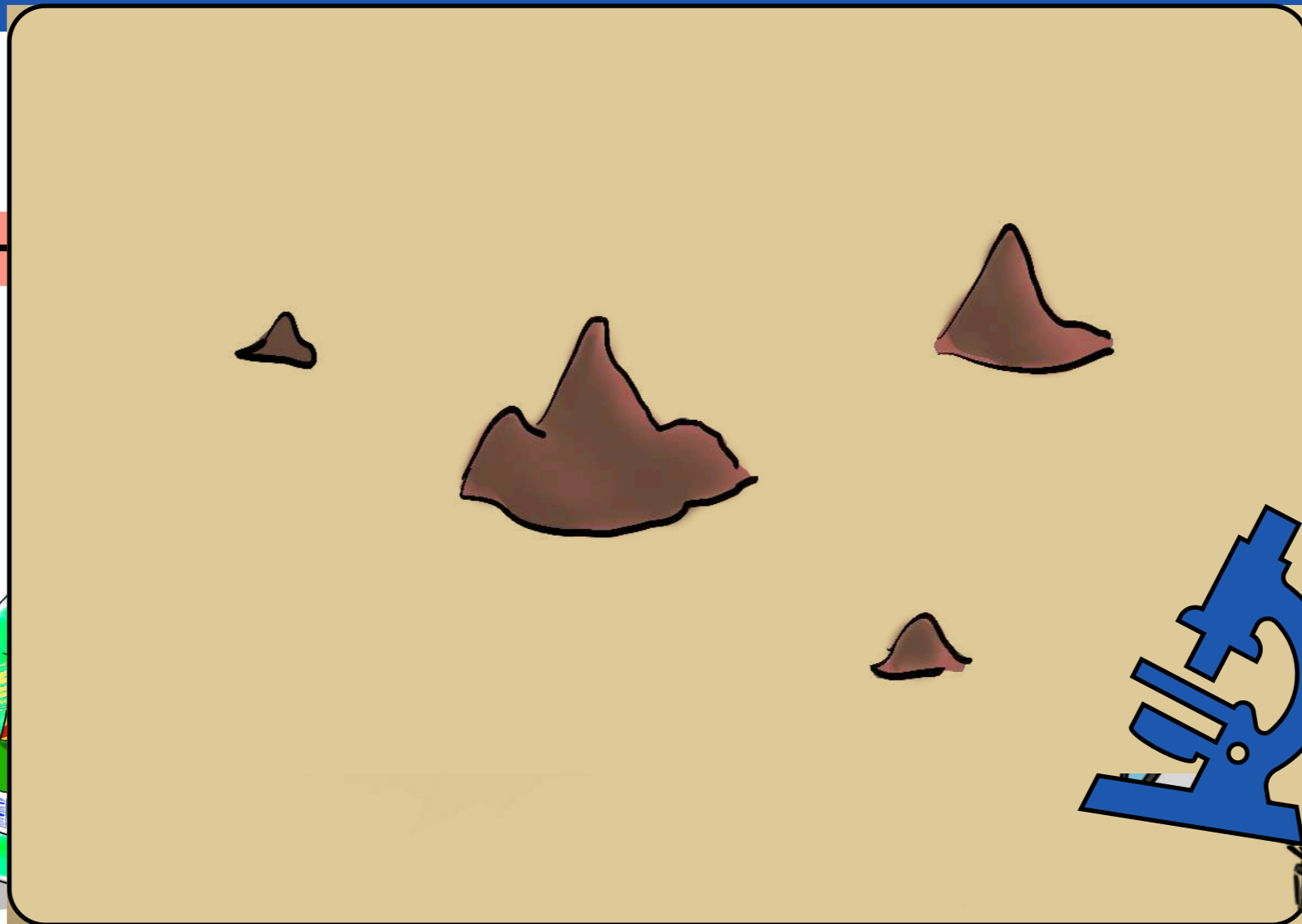
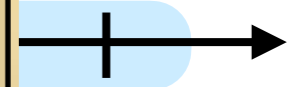


En búsqueda de “nueva” física (elusiva)

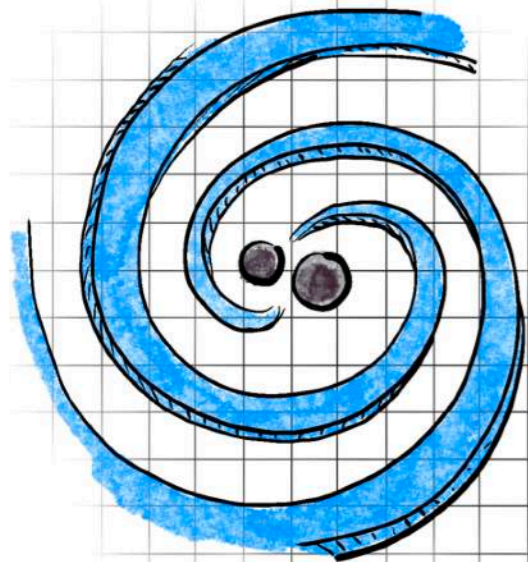
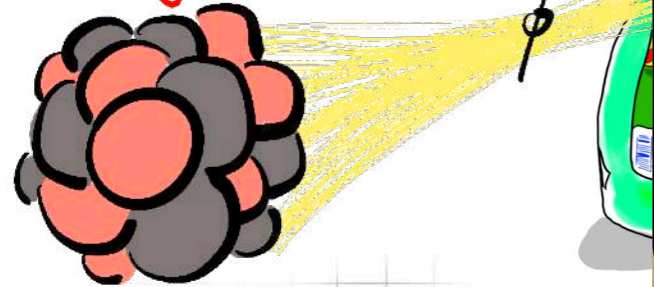
10^{-22}eV

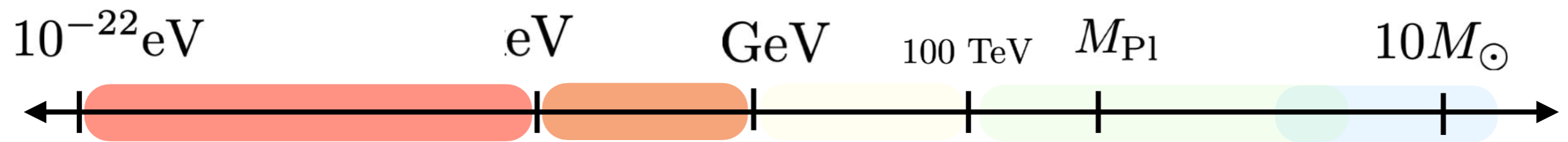


$10M_{\odot}$

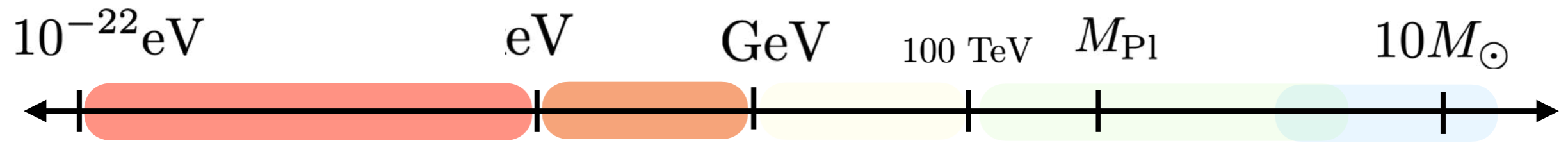


$$\phi = A \cos[m_{\phi} t]$$



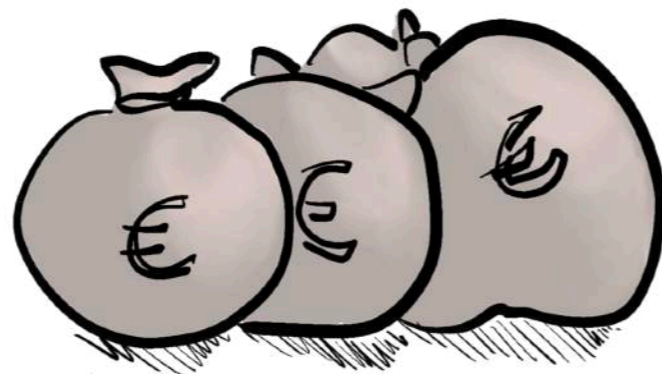


¡Hazte con todos!

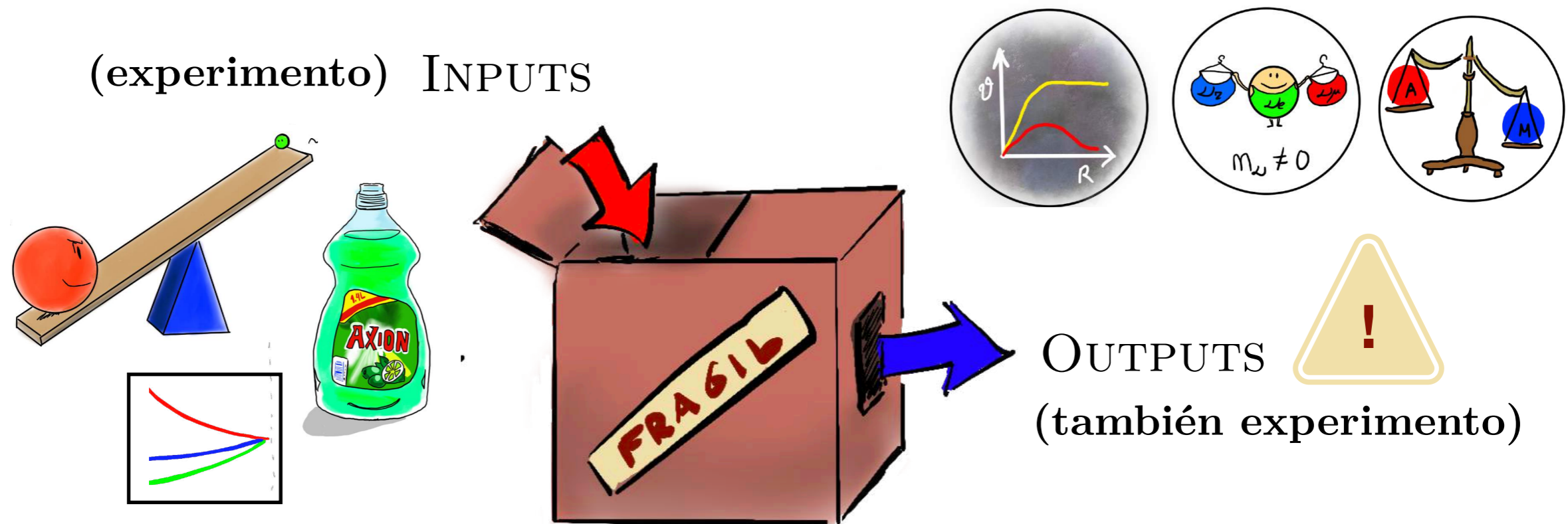


¡Hazte con todos!

(los que buenamente puedas)



El Modelo Estándar (recap)



(teóricos) “BONITA”, “SIMPLE”... \equiv POTENTE

$$\frac{\text{INPUTS}}{\text{OUTPUTS}} \ll 1$$

THE NEW WORLD

Beyond the Standard Model



Flavour
Anomalies

Neutrino
Masses

Matter
- Antimatter
asymmetry

CP
violation

The Standard Model
of particle physics

Dark Matter