¿ De qué está hecho el Universo ?

De las partículas elementales a las supercuerdas

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Univ. Murcia, 2 Noviembre 2009

RESUMEN

1. **Solo entenderemos la composición del Universo si conocemos las partículas elementales que lo constituyen y las fuerzas que se ejercen entre ellas**

- Describiremos todas las partículas y las interacciones conocidas

2. **Después especularemos**

- ¿Hacen falta más partículas en nuestra lista?

3. **Higgs, Supersimetría, Supercuerdas, ...**

- ¿De qué está hecha la materia oscura?

The mess at the beginning of the 20th century:
Heat, magnetism, electricity, light, X-rays, ultraviolet rays, …

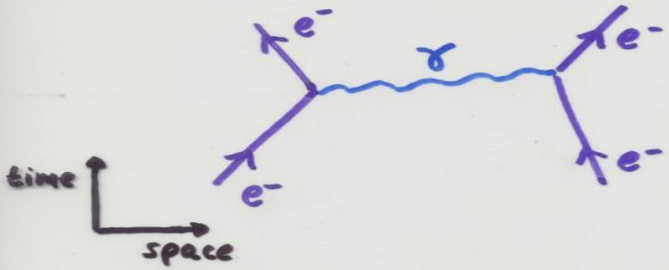
WAS SOLVED BY ONE THEORY, QUANTUM ELECTRODYNAMICS (1949)

QED

WITH THREE BASIC INGREDIENTS EXPLAINS THE INTERACTION OF LIGHT AND MATTER

QUANTUM MECHANICS
SPECIAL RELATIVITY
POINT-LIKE PARTICLES

Feynman, Schwinger, Tomonaga, Nobel Prize in 1965



e.g. THE FORCE OF REPULSION BETWEEN TWO ELECTRONS IS DUE TO THE TRANSFER OF PHOTONS BETWEEN THEM

SO-CALLED "SCATTERING PROCESS"

IN THIS WAY, CLASICAL ELECTROMAGNETISM (MAXWELL 1873) WAS "QUANTIZED"

ELECTROMAGNETIC FIELD ⟶ MESSENGER PARTICLE (PHOTON)

QED HAS BEEN THOROUGHLY TESTED AND

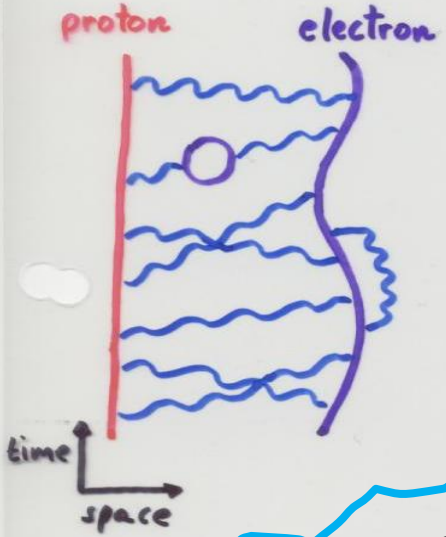
"AT THE PRESENT TIME I CAN PROUDLY SAY THAT THERE IS NO SIGNIFICANT DIFFERENCE BETWEEN EXPERIMENT AND THEORY"

FEYNMAN 1983

MOST OF THE PHENOMENA IN THE WORLD CAN BE EXPLAINED BY

QED

e.g. ALL THE ATOMS ARE MADE UP OF A CERTAIN NUMBER OF PROTONS EXCHANGING PHOTONS WITH ELECTRONS



HYDROGEN ATOM: AN ELECTRON IS KEPT WITHIN A CERTAIN RANGE OF DISTANCE TO THE PROTON BY PHOTON EXCHANGES

Sin la QED no existirían los átomos

GASES, METALS, INSULATORS, CRYSTALS, SOFT THINGS, HARD THINGS, COLORED THINGS, TRANSPARENT THINGS, ...

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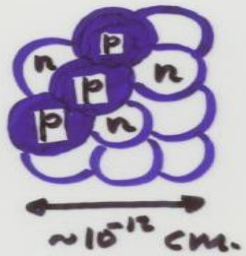
BUT NOT ALL OF THEM

WHY PROTONS ARE HELD TOGETHER IN THE NUCLEUS DESPITE ELECTROMAGNETIC REPULSIONS?



SOLVED BY ONE THEORY, QUANTUM CROMO DYNAMICS (1973)

QCD

A NEW TYPE OF FORCE HOLDS THEM :

STRONG NUCLEAR INTERACTION

$\alpha_s >> \alpha_{e.m.}$

Sin la QCD no existirían los núcleos átomicos

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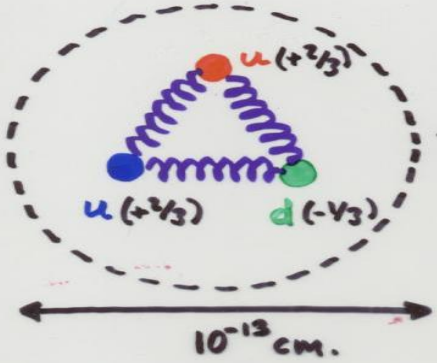
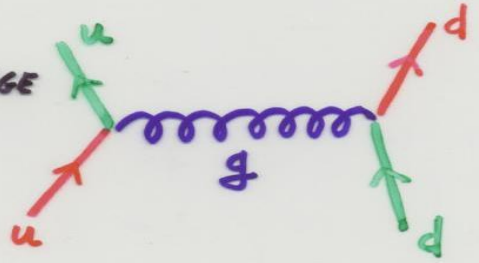
e.g. INSIDE THE PROTON

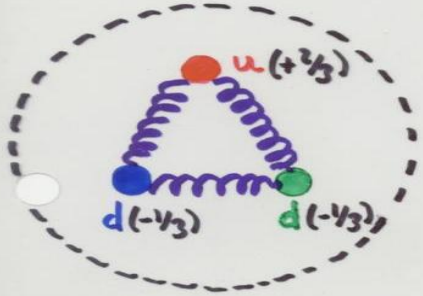


p^+ → IS NOT AN ELEMENTARY PARTICLE

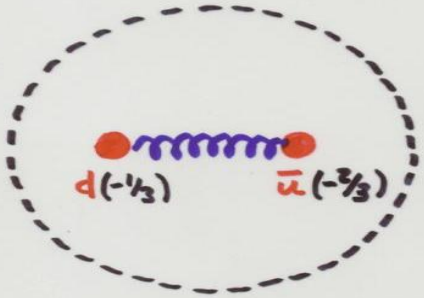
QUARKS ($s = 1/2$) CARRY **COLOR** CHARGE AND ARE HELD TOGETHER EXCHANGING GLUONS ($s = 1$)



ALL HADRONS (HUNDREDS!) CAN BE EXPLAINED IN THIS WAY



n^0 ,



π^- , KAON, LAMBDA, SIGMA, RHO, ...

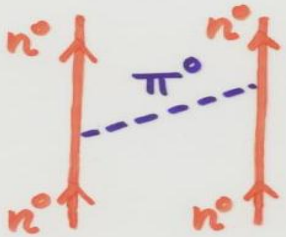
Gell-Mann,
Nobel Prize in 1969

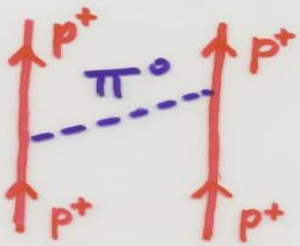
Zweig

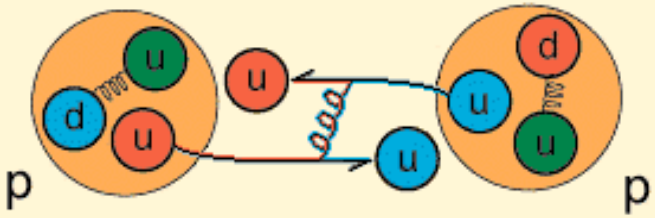
Friedman, Kendall, Taylor
Nobel Prize in 1990

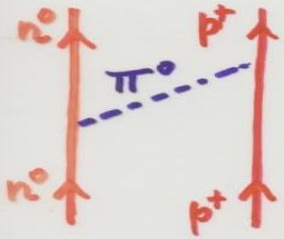
Gross, Wilczek, Politzer,
Nobel Prize in 2004

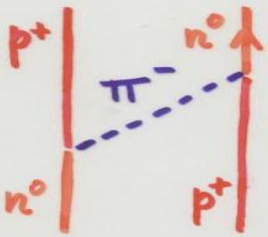
STRONG NUCLEAR INTERACTION BETWEEN NEUTRONS AND PROTONS IS A COMPLICATED MANIFESTATION OF THE MORE FUNDAMENTAL COLOUR FORCE ACTING BETWEEN THEIR CONSTITUENTS

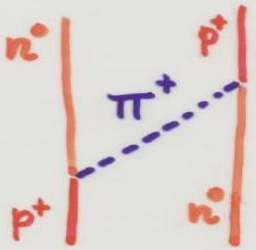












$m_\pi = 1/7\ m_p$ → SHORT RANGE FORCE

$\sim 10^{-12}$ cm

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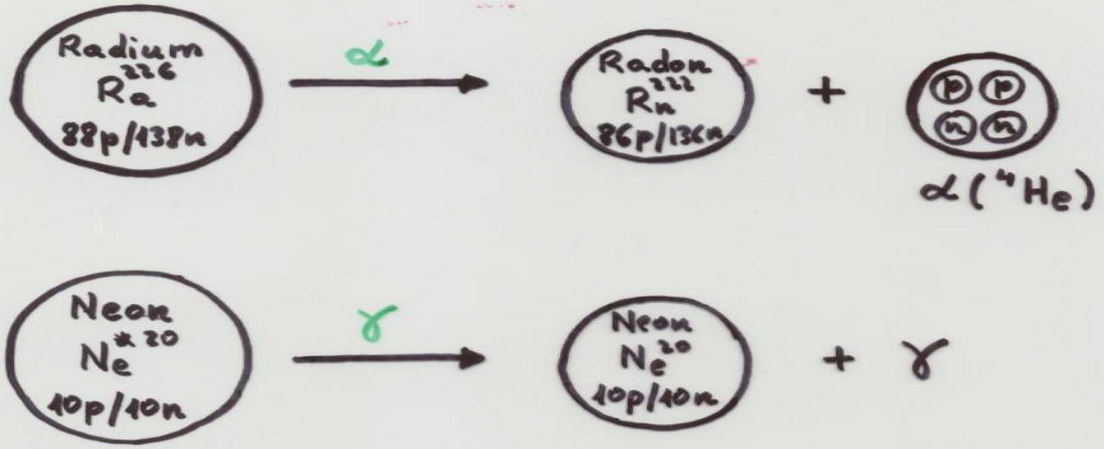
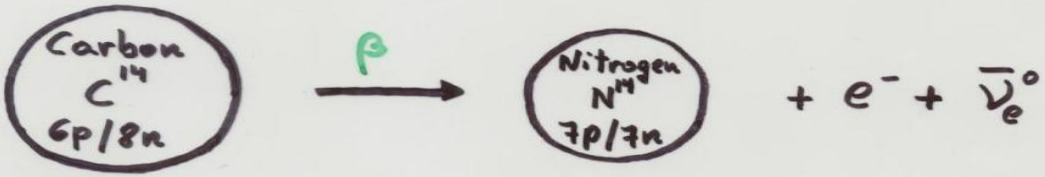
MOST OF THE NUCLEAR PHENOMENA CAN BE EXPLAINED BY QCD AND QED

e.g. α AND γ RADIOACTIVE DECAY



BUT NOT ALL OF THEM



WHY β DECAY PROCESS DOES NOT SEPARATELY CONSERVE THE NUMBER OF PROTONS AND NEUTRONS ?

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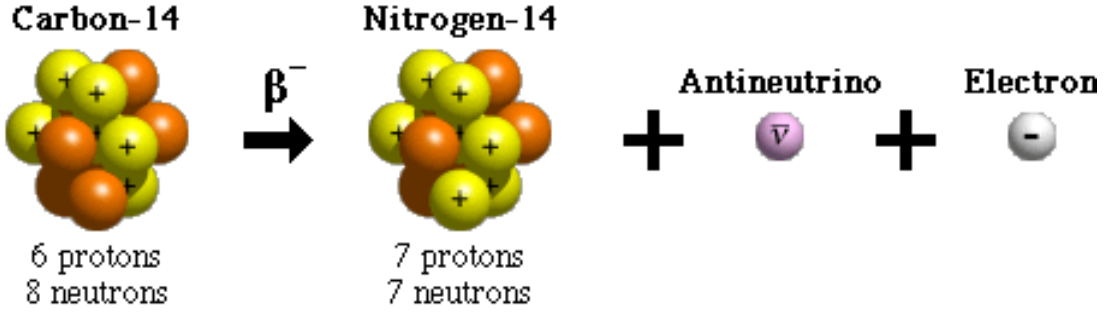
SOLVED BY ONE THEORY (~60's)

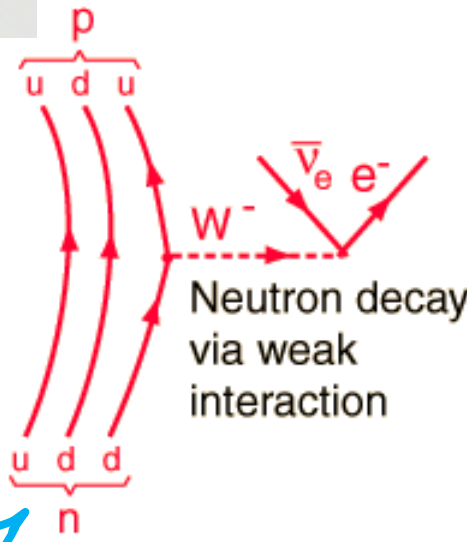
WEAK THEORY

A NEW TYPE OF FORCE IS RESPONSIBLE FOR THE DECAY:

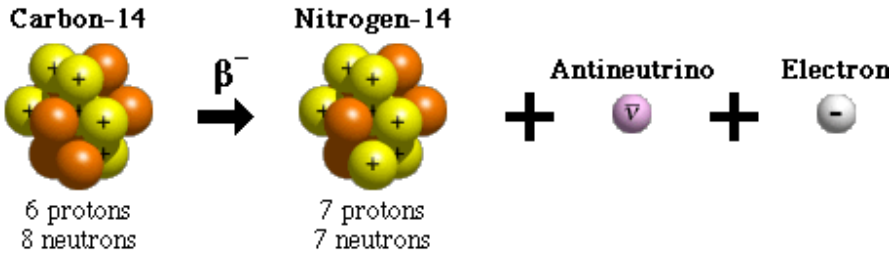
WEAK NUCLEAR INTERACTION

$\alpha_W << \alpha_{e.m.}$

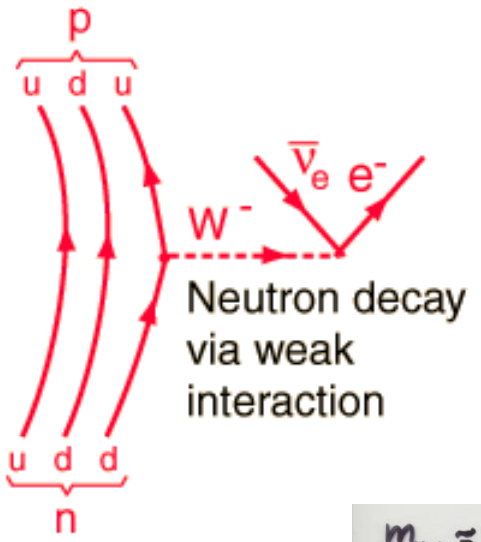




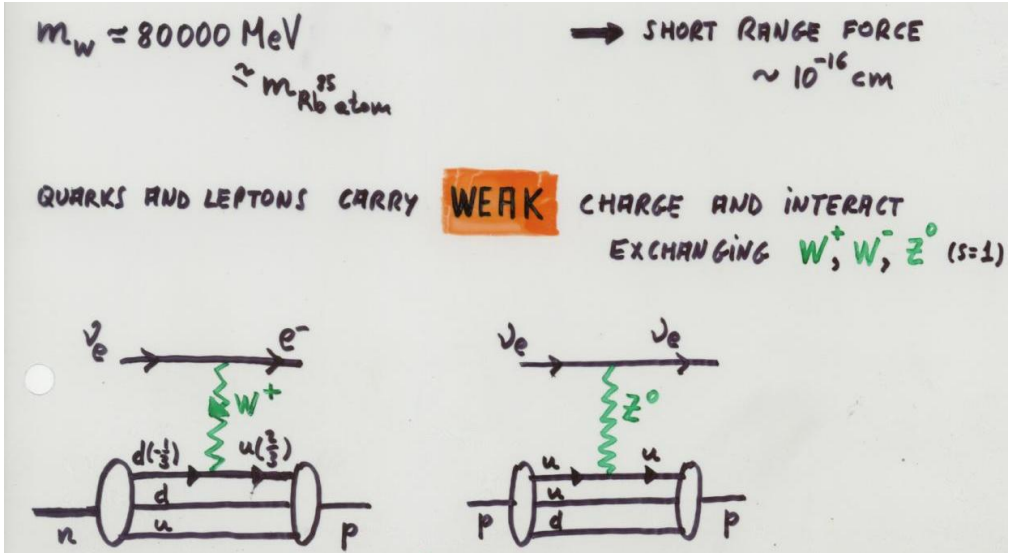
Sin la interacción débil no se producirían las reacciones de fusión nuclear en el Sol, sin las cuales no habría vida en la Tierra



La emisión de neutrinos está asociado a la desintegración beta.
Historicamente, parecía que este proceso no conservaba la energía y eso llevó a Pauli a postular en 1930 la existencia de una partícula nueva (el neutrino).
"Sólo" se tardó 25 años en descubrir el neutrino experimentalmente



la carga está relacionada con el estado de movimiento y no con el tipo de partícula (aquellas con espín antiparalelo a la dirección del movimiento poseen carga débil)



Glashow, Weinberg, Salam, Nobel Prize in 1979

Rubia, Van der Meer, Nobel Prize in 1984

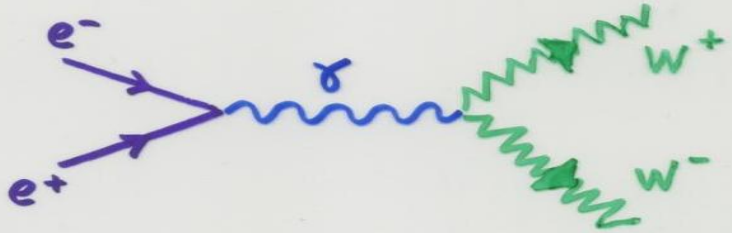
't Hooft, Veltman, Nobel Prize in 1999

CERN (GENEVE) HAS BUILT (1989) THE LARGEST PARTICLE ACCELERATOR IN THE WORLD (LEP) CIRCUNFERENCE 27 km

CAPABLE OF ACCELERATING e^- AND e^+ TO ENERGIES ~ 200000 MeV

W^+, W^-, Z^0 ARE CREATED

e.g.



$$E_e = \frac{m_e c^2}{\sqrt{1-\frac{v_e^2}{c^2}}} = \frac{0.5\ \text{MeV}}{\sqrt{1-\frac{v_e^2}{c^2}}} = 100000\ \text{MeV} \simeq m_W c^2 = 80000\ \text{MeV}$$

$v_e \simeq c$

THE PHYSICS THAT IS MET AT THESE (HIGH) ENERGIES IS THAT WHICH PREVAILED WHEN OUR EXPANDING UNIVERSE WAS 10^{-10} s. OLD

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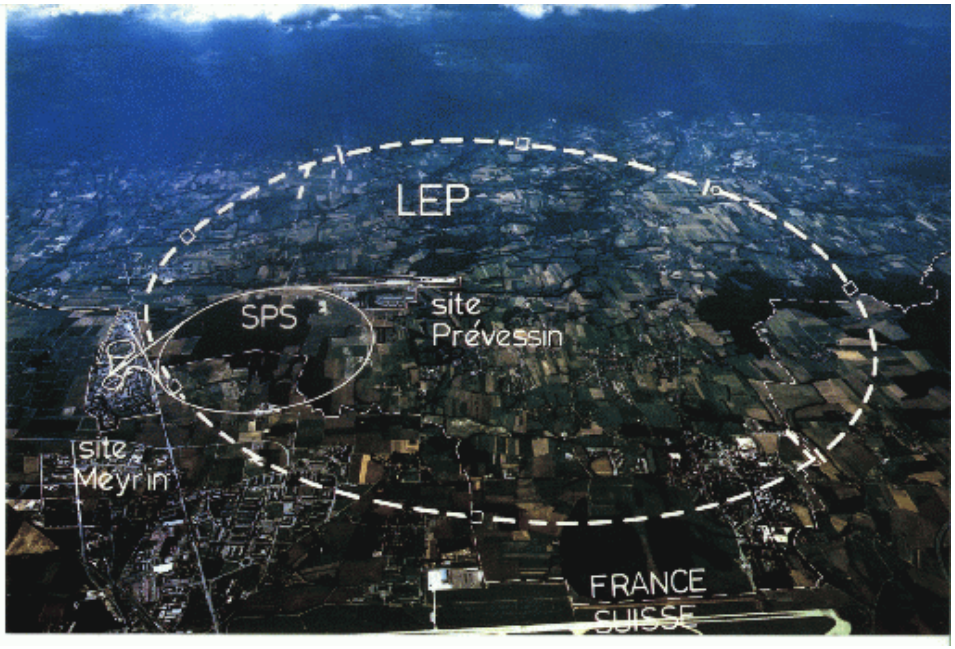
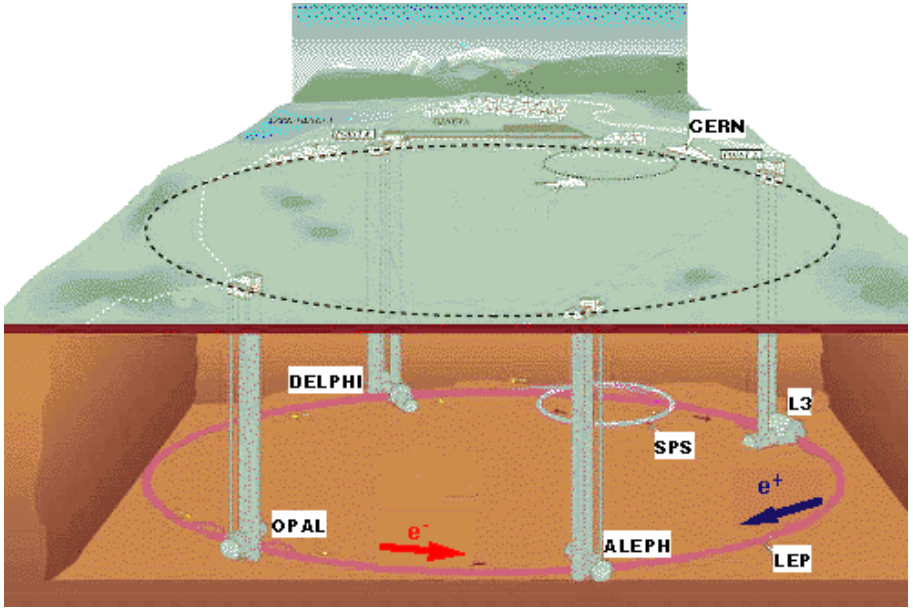
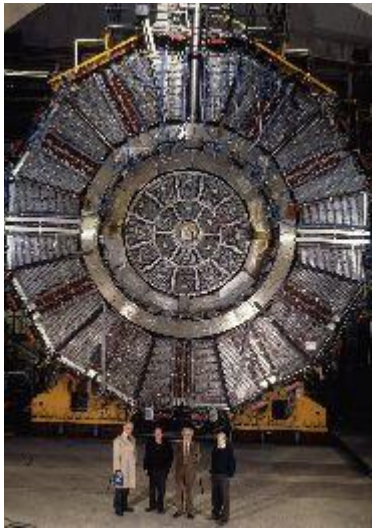
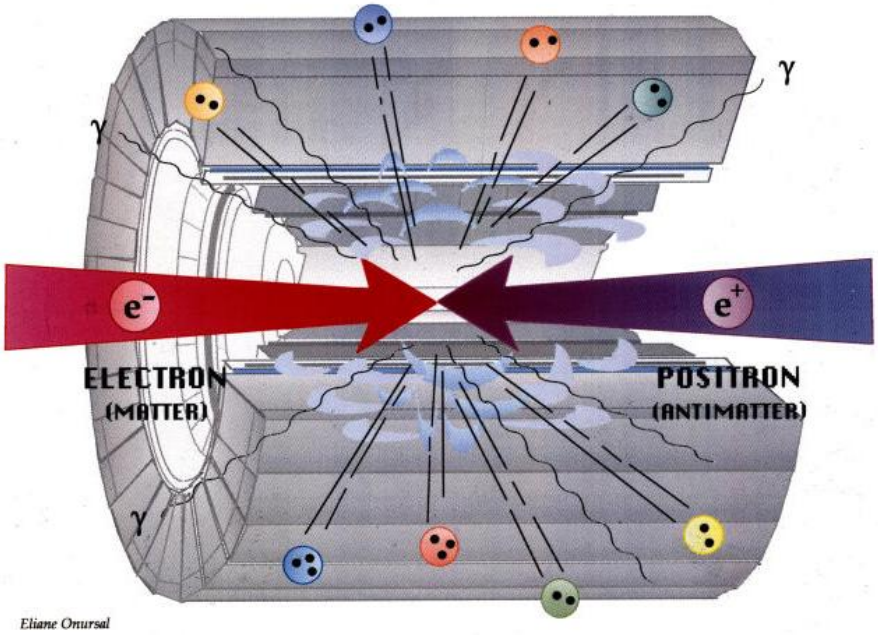

LEP
SPS
site
Prévessin
site
Meyrin
FRANCE
SUISSE


CERN
DELPHI
L3
SPS
e+
OPAL
e-
ALEPH
LEP




γ
γ
γ
e⁻
e⁺
ELECTRON
(MATTER)
POSITRON
(ANTIMATTER)
Eliane Onursal

PARTICLE ZOO

e — simbol
0.51 — mass (MeV)

spin $\frac{1}{2}$ particles

$u_{1,2,3}$
~5

$d_{1,2,3}$
~10

e
~0.51

ν_e
~0.00000001

spin 1 particles

γ
0

$g_{1...8}$
0

$W^{\pm}, Z^0$
~80000

PARTICLE ZOO

e — simbol
0.51 — mass (MeV)

spin ½ particles

$u_{1,2,3}$
~5

$d_{1,2,3}$
~10

e
~0.51

ν_e
~0.00000001

spin 1 particles

γ
0

$g_{1,\dots,8}$
0

$W^{\pm}, Z^{0}$
~80000

~1970's

THE ONLY ELEMENTARY PARTICLES IN THE WORLD ARE
- QUARKS
- ELECTRONS
- NEUTRINOS
- GLUONS
- FOTONS
- $W^{\pm}, Z^{0}$

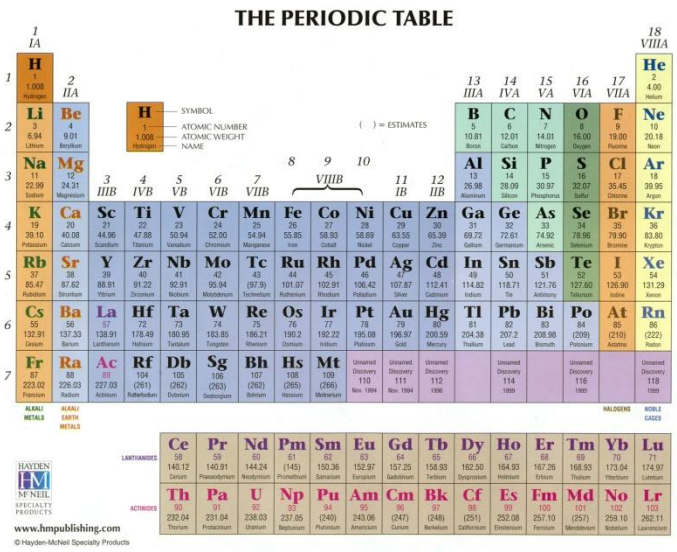
DEMOCRITUS (440 B.C.) WAS RIGHT!

THE MATTER IS MADE FROM ATOMS BUT

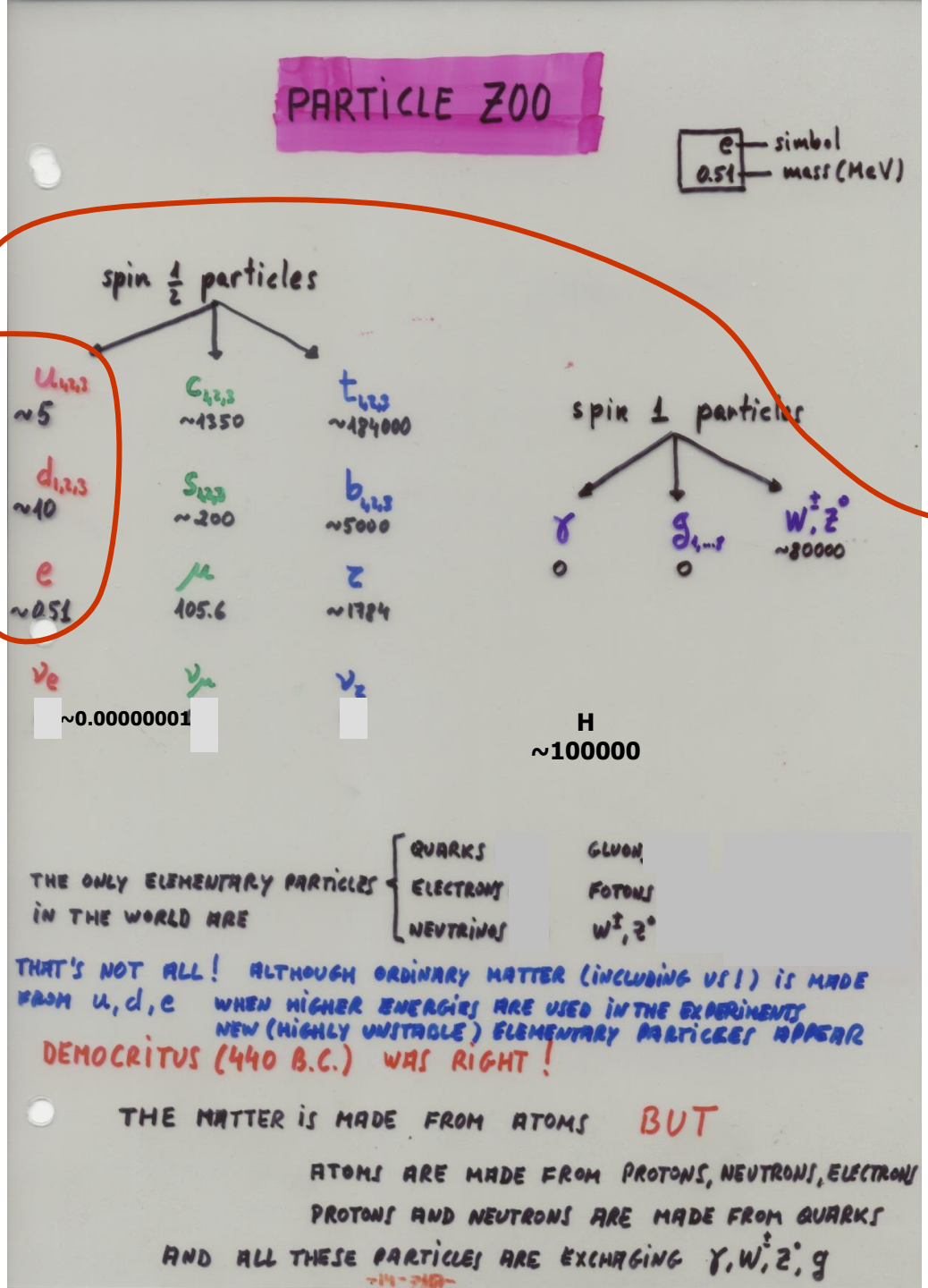
ATOMS ARE MADE FROM PROTONS, NEUTRONS, ELECTRONS

PROTONS AND NEUTRONS ARE MADE FROM QUARKS

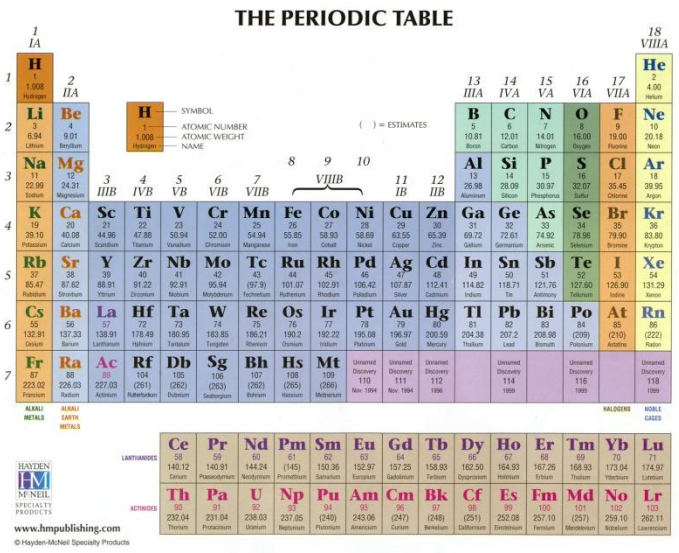
AND ALL THESE PARTICLES ARE EXCHANGING $\gamma, W^{\pm}, Z^{0}, g$



Mendeleiev, 1869



~1970's



Mendeleiev, 1869

And, in addition there should exist the so-called Higgs boson

Kobayashi, Maskawa,

predicted in 1972 the existence of 3 families

Nobel Prize in 2008

PRESENT

THE SO-CALLED **STANDARD MODEL** OF ELEMENTARY PARTICLES

$$\text{QCD} + \text{WEAK THEORY} + \text{QED}$$

NOTICE THAT THEY ARE VERY SIMILAR TO QED

$e^- \longleftrightarrow q$

$\gamma \longleftrightarrow g, W^{\pm}, Z^0$

WRITTEN IN A MORE ELEGANT WAY

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

$$\begin{pmatrix} u_R \\ u_G \\ u_B \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}$$

SAYS THAT THE STANDARD MODEL IS GAUGE INVARIANT (INTERNAL SYMMETRY)

e.g. U(1) INVARIANCE $\rightarrow \mathcal{L}_{QED}$ MUST BE INVARIANT UNDER

$$\begin{cases} \psi_e(x) \rightarrow e^{-ie f(x)} \psi_e(x) \\ A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu f(x) \end{cases}$$

"GAUGE SYMMETRY DICTATES THE FORM OF THE INTERACTION" YANG

WORKS **OUTSTANDINGLY WELL** IN PRACTICE

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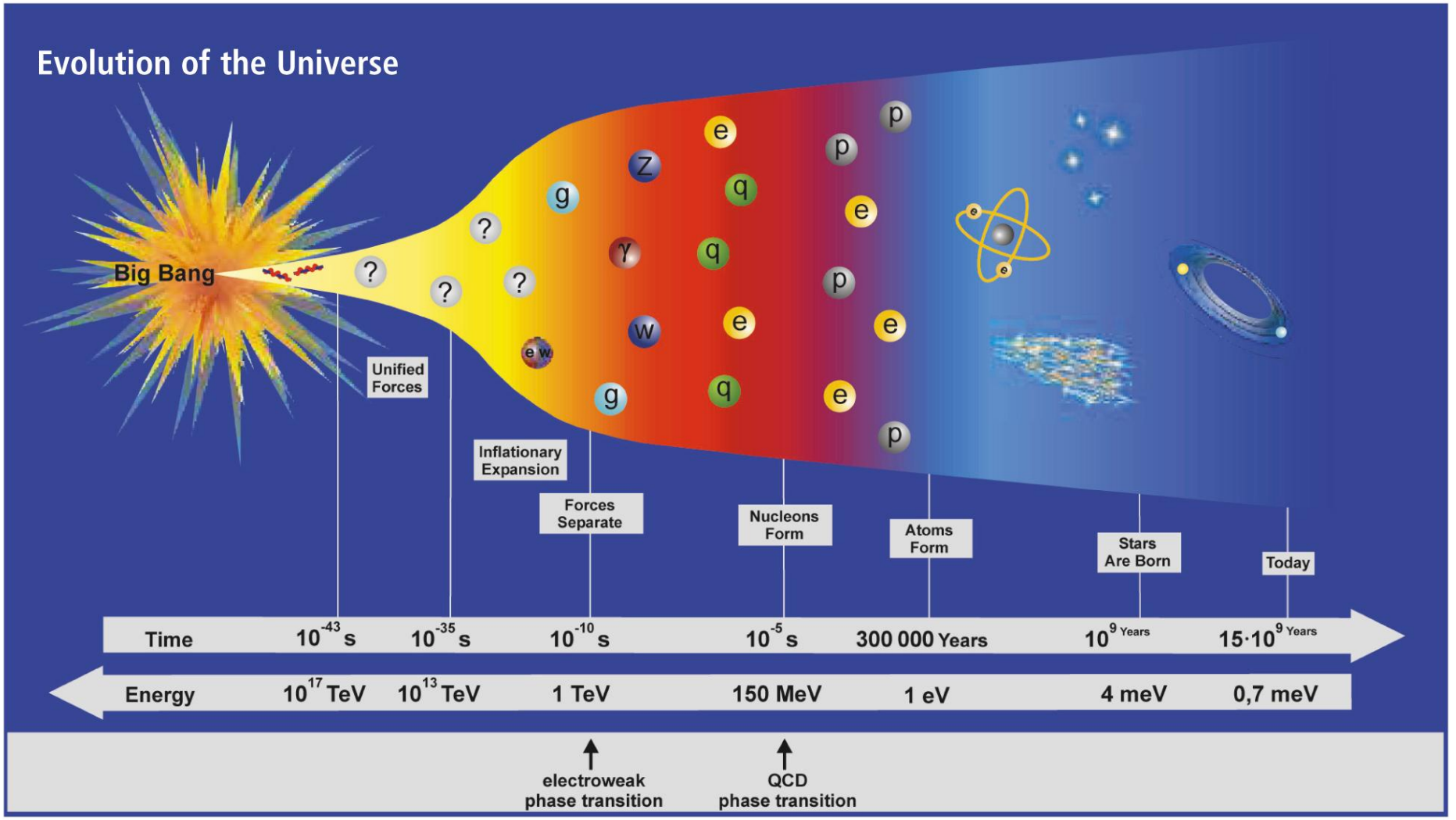


Besides, the standard model provides
the fundaments of the early Universe cosmology

SPECULATION: Do other particles exist still undetected ?

History

Symmetries are crucial in physics

The laws of modern physics are invariant under certain symmetries:

- Lorentz transformations [special relativity]
- Local gauge transformations $[SU(3)_C x SU(2)_L x U(1)_Y]$

Supersymmetry (SUSY) was proposed in the early 1970's:

Golfand, Likhtman, 1971
Volkov, Akulov, 1972
Wess, Zumino, 1974

❖ An invariance of the theory under interchange of fermions and bosons

Boson → Fermion

Fermion → Boson

$\mathcal{L}$ (bosons, fermions) → L (fermions, bosons) = $\mathcal{L}$ (bosons, fermions)

But known bosons and fermions are not married up in this fashion

Quarks (u,d)
Electron
Neutrino

Gluons
W, Z
Photon

Instead, every known particle should have a (super) partner Fayet, 1976

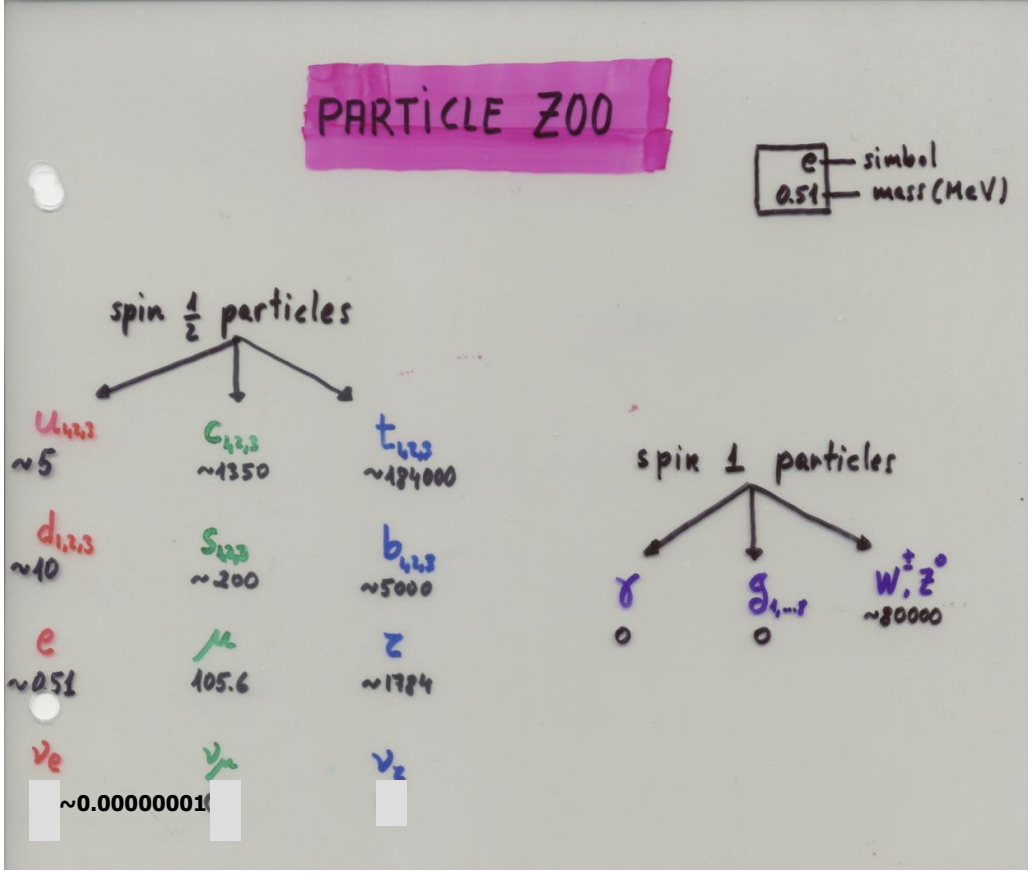
The spectrum of elementary particles is doubled ! With masses ≈ 1000 m_p

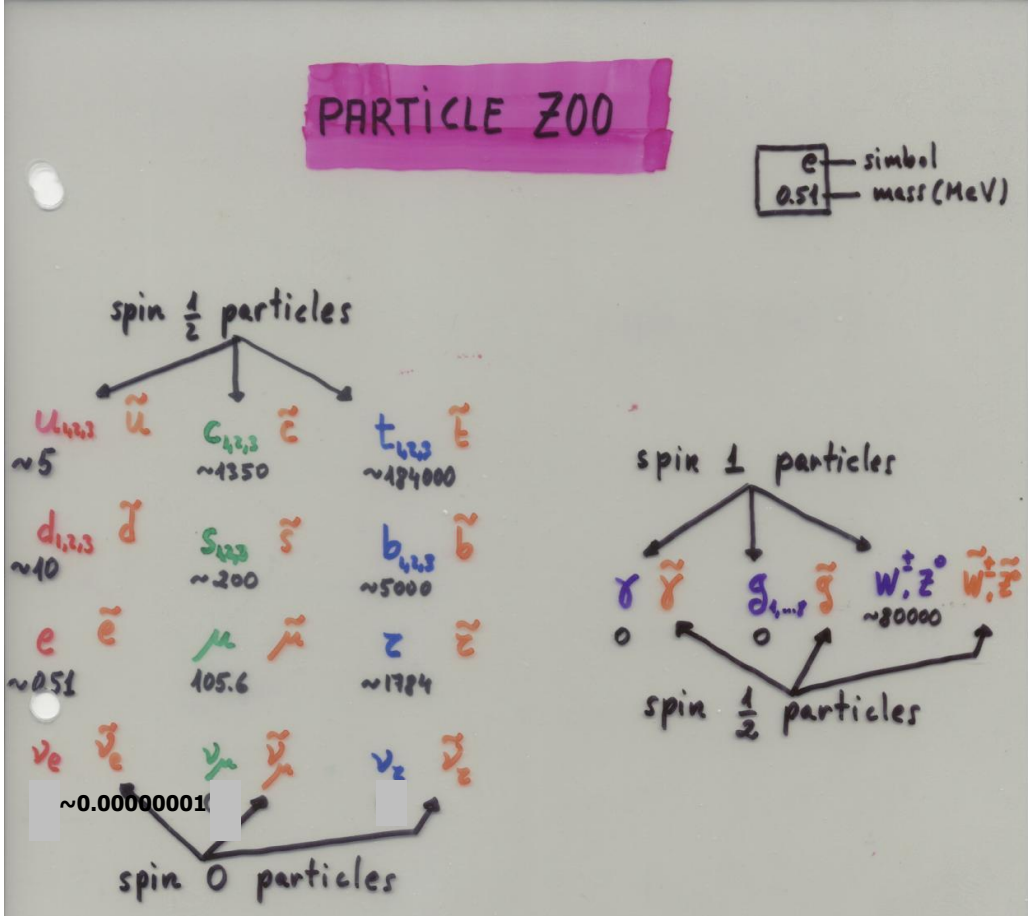
Quarks
Electron
Neutrino

Squarks
Selectron
Sneutrino

Gluons
Photon
W, Z

Gluino
Photino
Wino, Zino


PARTICLE ZOO
e
0.51
simbol
mass (MeV)
spin 1/2 particles
~5
~1350
~184000
~10
~200
~5000
e
~0.51
105.6
~1784
~0.00000001
spin 1 particles
0
0
~80000


PARTICLE ZOO
e
0.51
simbol
mass (MeV)
spin 1/2 particles
~5
~1350
~184000
~10
~200
~5000
~0.51
105.6
~1784
~0.00000001
spin 0 particles
spin 1 particles
0
0
~80000
spin 1/2 particles

CAN THESE SPECULATIONS BE TESTED

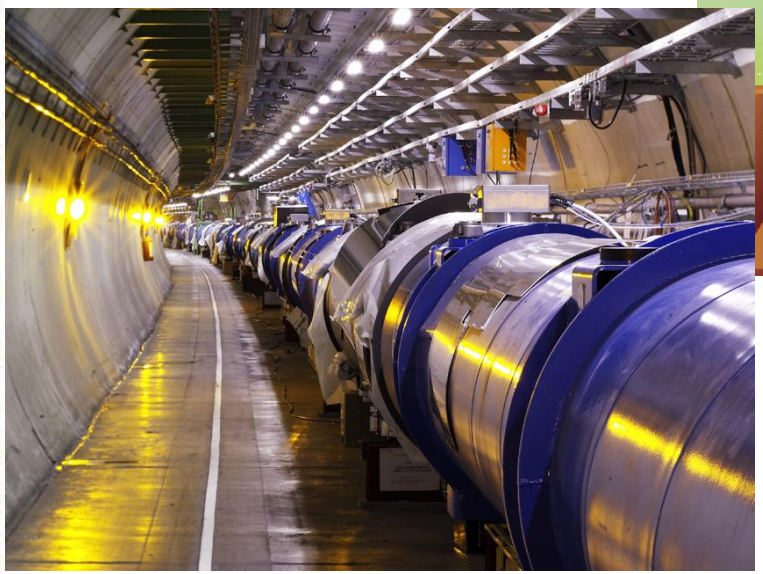
HIGGSES, SUSY PARTICLES, ...

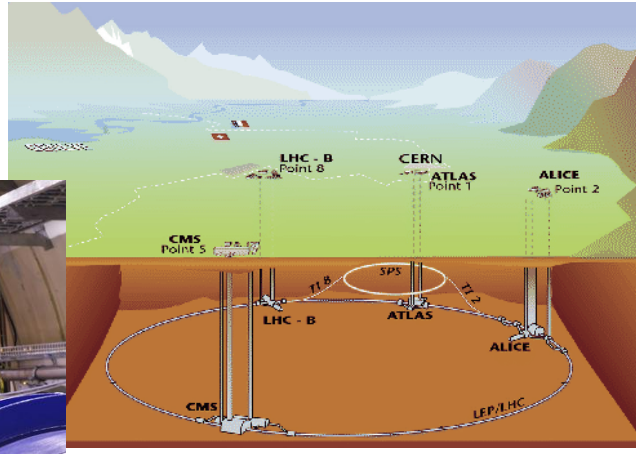
ONLY WITH MORE ENERGY SINCE $m_{susy} \sim 1000\ m_p$

LEP (~ 100 m_p) $e^- e^+$ —CERN→ LHC (~ 1000 m_p) $p^+ p^+$

LEP

LHC

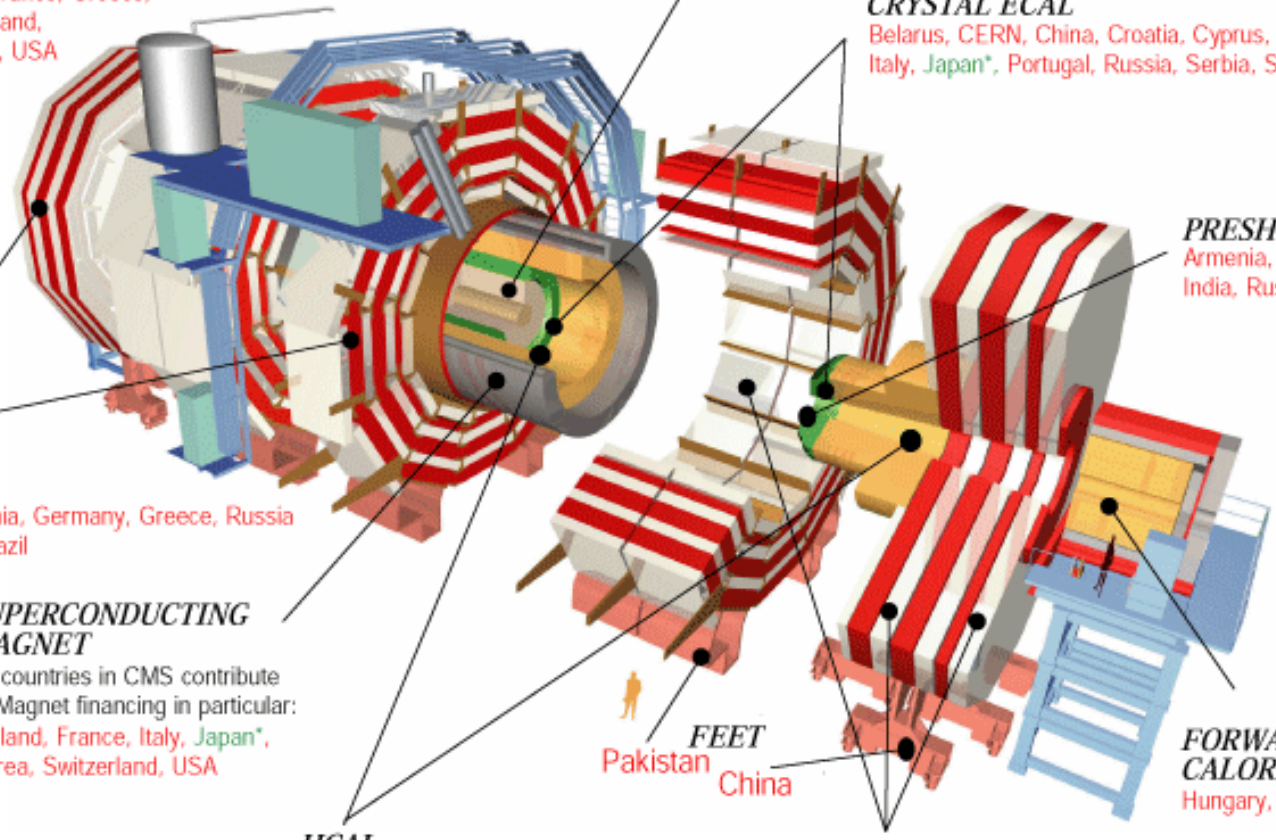




Cost of the LHC:
4.000 million euros

CMS Collaboration

36 Nations, 160 Institutions, 2008 Scientists and Engineers (November 2003)



TRIGGER & DATA ACQUISITION
Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, CERN, Finland, France, New Zealand Germany, Italy, Japan*, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, CERN, China, Croatia, Cyprus, France, Ireland Italy, Japan*, Portugal, Russia, Serbia, Switzerland, UK, USA

PRESHOWER
Armenia, Belarus, CERN, Greece, India, Russia, Taipei, Uzbekistan

RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA, Brazil

SUPERCONDUCTING MAGNET
All countries in CMS contribute to Magnet financing in particular:
Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET
Pakistan
China

FORWARD CALORIMETER
Hungary, Iran, Russia,Turkey, USA

HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

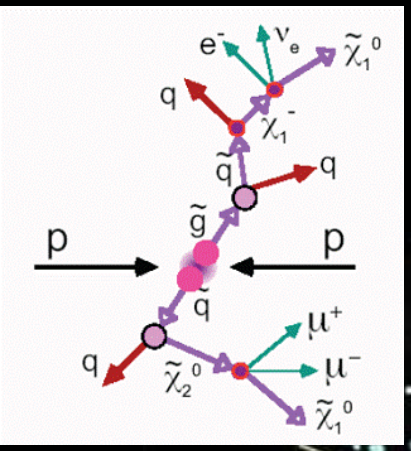
MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

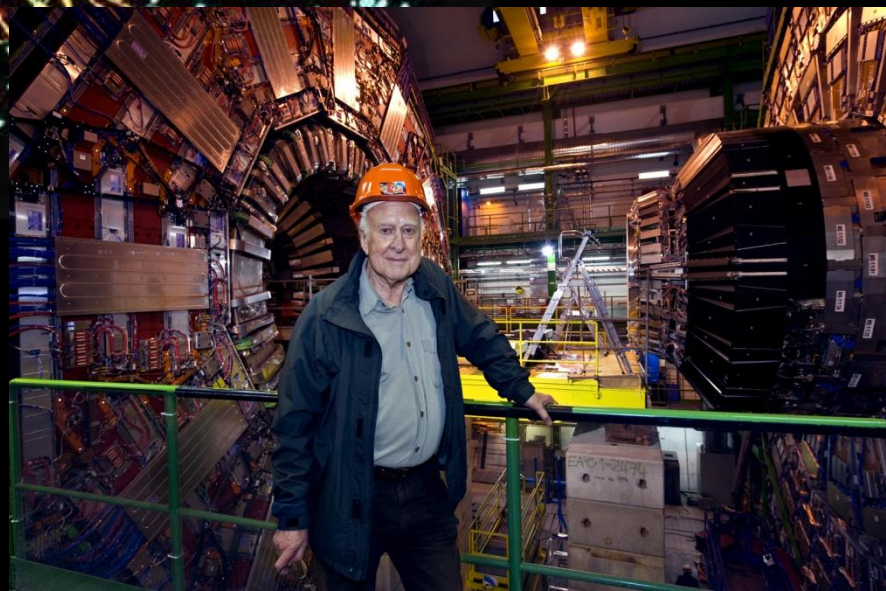
* Only through industrial contracts

Total weight	**:**	**12500 T**
Overall diameter	**:**	**15.0 m**
Overall length	**:**	**21.5 m**
Magnetic field	**:**	**4 Tesla**

Aunque cada haz tiene 300 billones de protones, solo se producen 60.000 colisiones

Pero como los protones dan 10.000 vueltas alrededor del LHC cada segundo, se producirán en total 600 millones de colisiones por segundo.
¡Y eso hay que analizarlo!





One of the great enigmas still unsolved is the existence of dark matter

- Por ejemplo, usando simples argumentos gravitacionales , uno puede calcular la velocidad de rotación de estrellas aisladas o nubes de Hidrógeno en las partes externas de Galaxias

- Esa velocidad calculada usando la ley de Newton

$$\frac{v_{\text{rot}}^2}{r} = \frac{G\ M(r)}{r^2}$$

no coincide con la que miden los astrónomos.

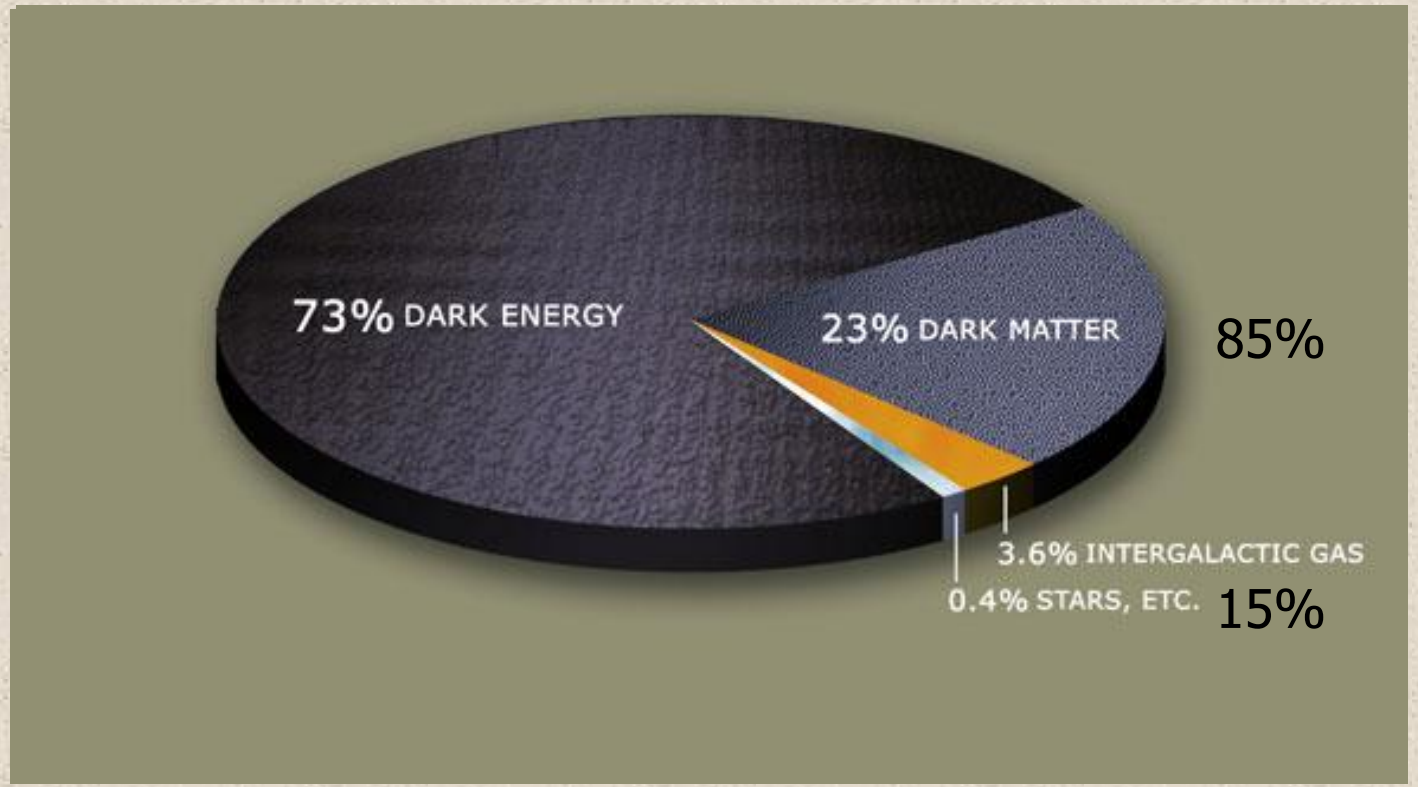
Salvo que asumamos que existe más materia que la luminosa.

Zwicky, 1933

Dark Matter

This hypothesis is not so odd if we remember that the existence of Neptune was suggested on the basis of the irregular motion of Uranus

- Actually, about 85% of the matter in the Universe is dark



We are not made of what most of the Universe is made of !

¿De qué está hecha la materia oscura?

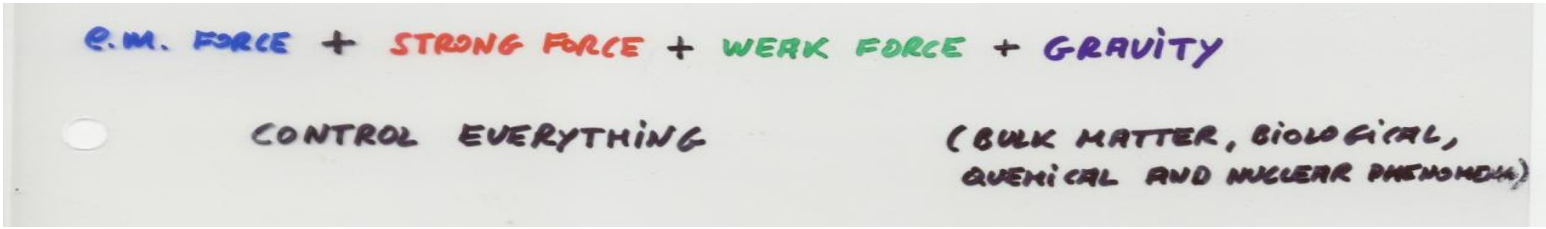
Ninguna de las partículas del modelo estándar tiene las propiedades adecuadas para constituir la materia oscura;
Ni los quarks, ni los electrones, ni los neutrinos, …

Esta es una indicación contundente de que necesitamos ir

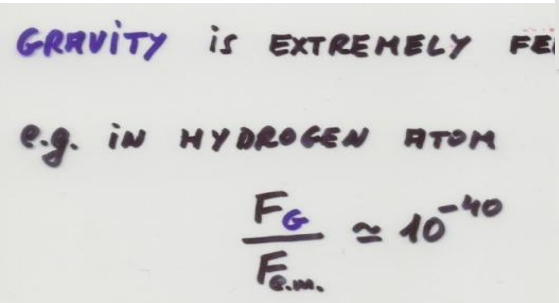
Más allá del modelo estándar de la física de partículas

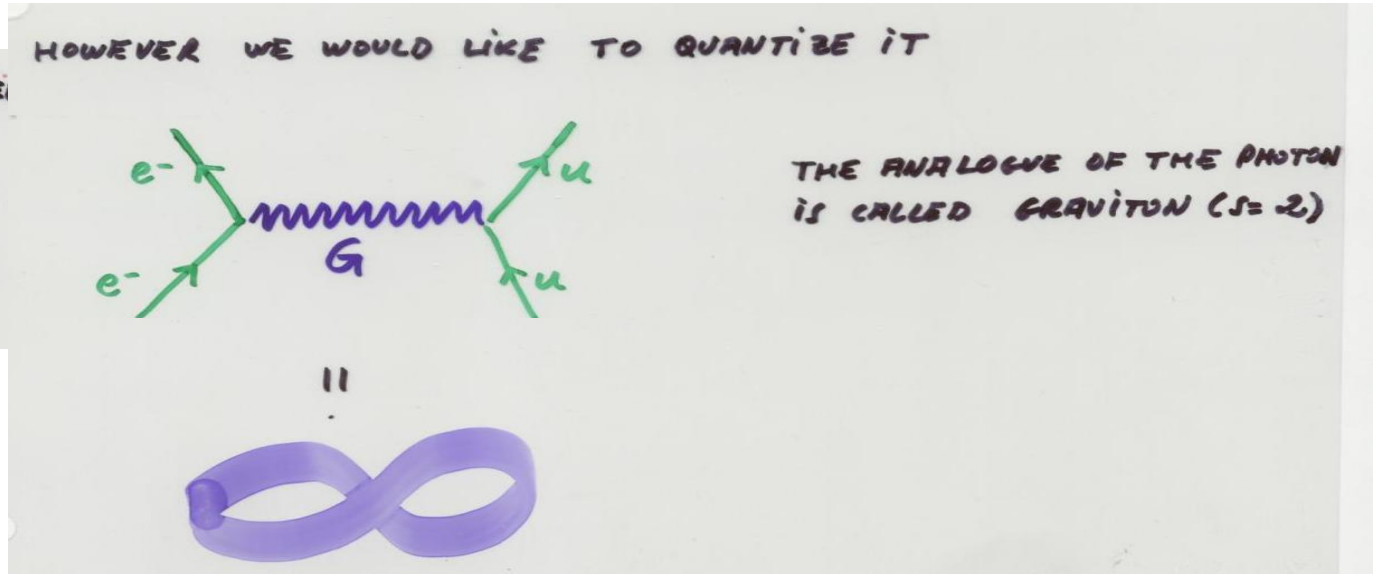
Y precisamente, algunas de las **partículas supersimétricas** tienen las propiedades adecuadas para constituir la materia oscura

Sin embargo, si queremos
unificar la gravedad con las demás interacciones,
tenemos que ir incluso **más allá de la supersimetría**



Sin la gravedad los seres humanos no se mantendrían sobre la Tierra, los planetas no girarían alrededor del Sol, las estrellas no formarían galaxias, las galaxias no formarian cumulos de galaxias y, …, el Universo no sería como lo conocemos.





FUTURE?

STRING THEORY

"POINT-LIKE" PARTICLE • ⟶ STRING

$L_p \sim 10^{-33}$ cm

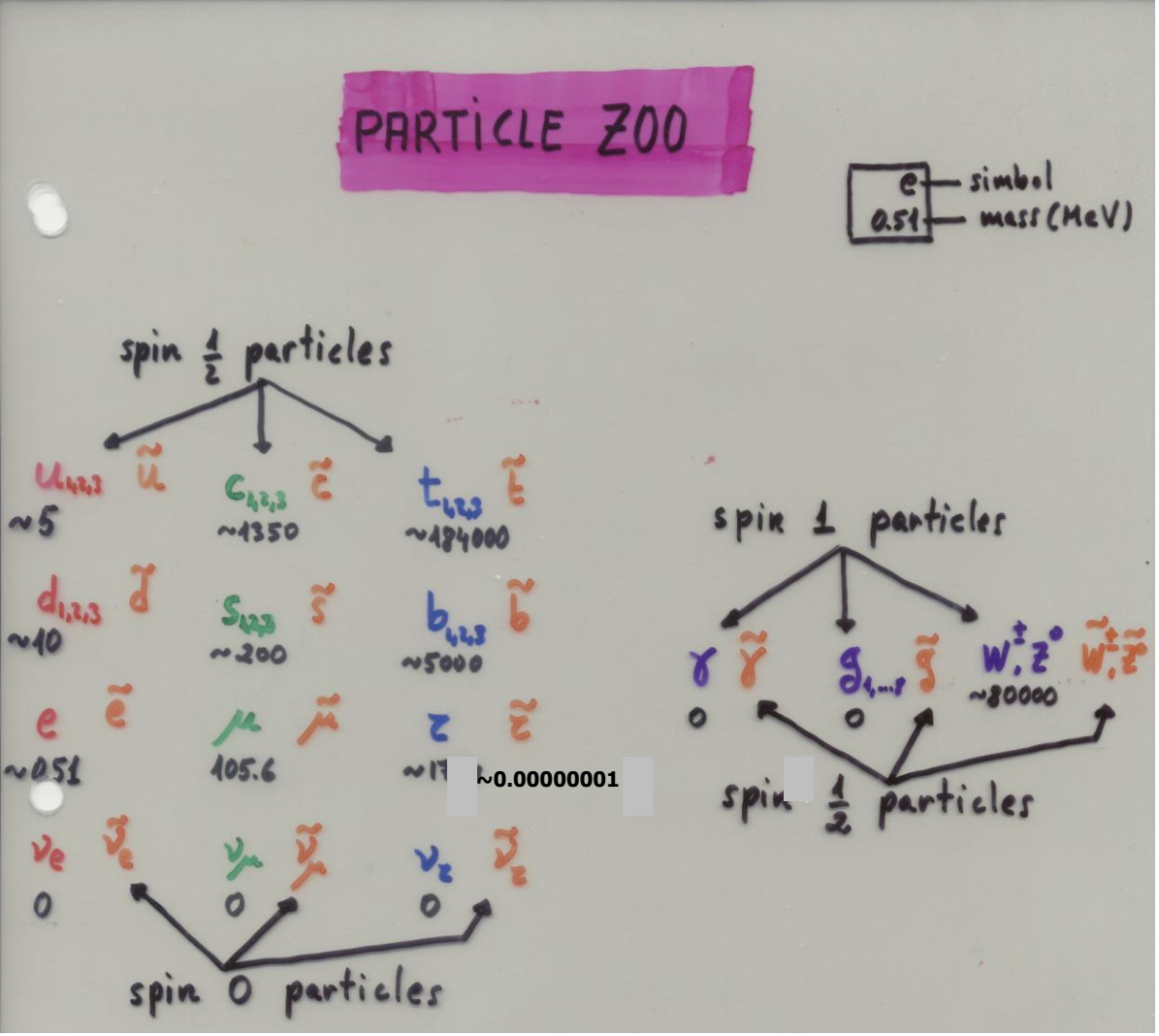
* THE PARTICLES CORRESPOND TO THE DIFFERENT MODES OF VIBRATION OF THE STRING

PRESENT ACCELERATORS CANNOT RESOLVE $L < 10^{-16}$ cm
THAT'S WHY THE POINT PARTICLE APPROXIMATION IS SO SUCCESFUL

* THE GRAVITON APPEARS IN THE SPECTRUM

UNIFIED THEORY OF GRAVITY AND STANDARD MODEL

* IS FINITE



Todo este zoo se unifica en un único objeto fundamental

STRING THEORY

IS THE ONLY CANDIDATE TO BE

THE THEORY OF EVERYTHING

ANSWERING, WHY DOES THE UNIVERSE BEHAVE THE WAY IT DOES?

IS ONLY CONSISTENT IN $D=10$ $(9+1)$

→ 6 DIMENSIONS MUST BE COMPACTIFIED IN A VERY SMALL SPACE

$L_c \sim 10^{-33}$ cm

e.g. 

-32-

CONCLUSIONS

The standard model of particle physics "almost" answers the question: What is the Universe made of?

- However, one of the great enigmas still unsolved is the existence of dark matter

- Within the standard model there are no possible candidates, thus we need to assume the existence of new particles

- Supersymmetry, that predicts that every known particle should have a partner, has candidates for dark matter, which could be tested in the LHC

- Supersimetría no es suficiente para unificar la gravedad con las demás interacciones de la Naturaleza, pero quizá la teoría de Supercuerdas nos permita conseguir este objetivo

THE END