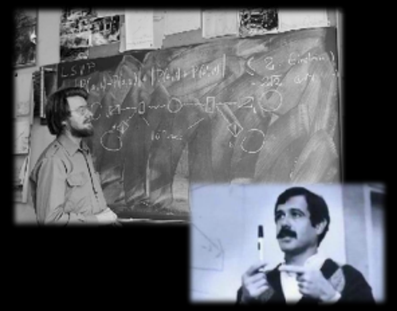
Le jeu de Bell

Alain Aspect, 1982



Ce qu'il fallait retenir

Ce qu'il fallait retenir

- Le formalisme quantique n'exprime aucune réalité
- La seule réalité est celle du monde classique qui inclut l'expérimentateur et ses instruments
- Le mystère de l'intrication : non localité et holisme quantiques
- La cohérence quantique est détruite dans les objets macroscopiques
- Applications concrètes

De l'atome antique à l'atome quantique

La nature insolite de l'univers quantique

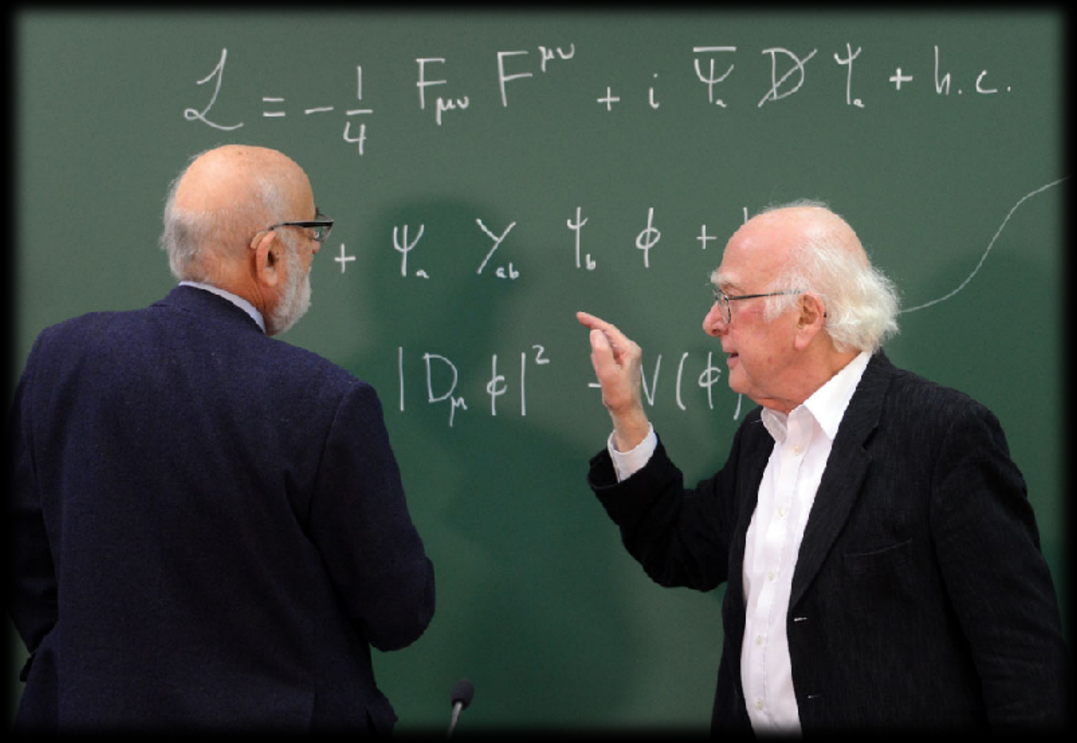
1. Il moto è come nullo, Galileo Galilei, 1610
2. Fiat quantum et photon fuit, Albert Einstein, 1905
3. Gott würfelt nicht, Albert Einstein vs Niels Bohr, 1927
4. Le jeu de Bell, Alain Aspect, 1982
5. La masse est dite ! CERN, 2012

De l'atome antique à l'atome quantique

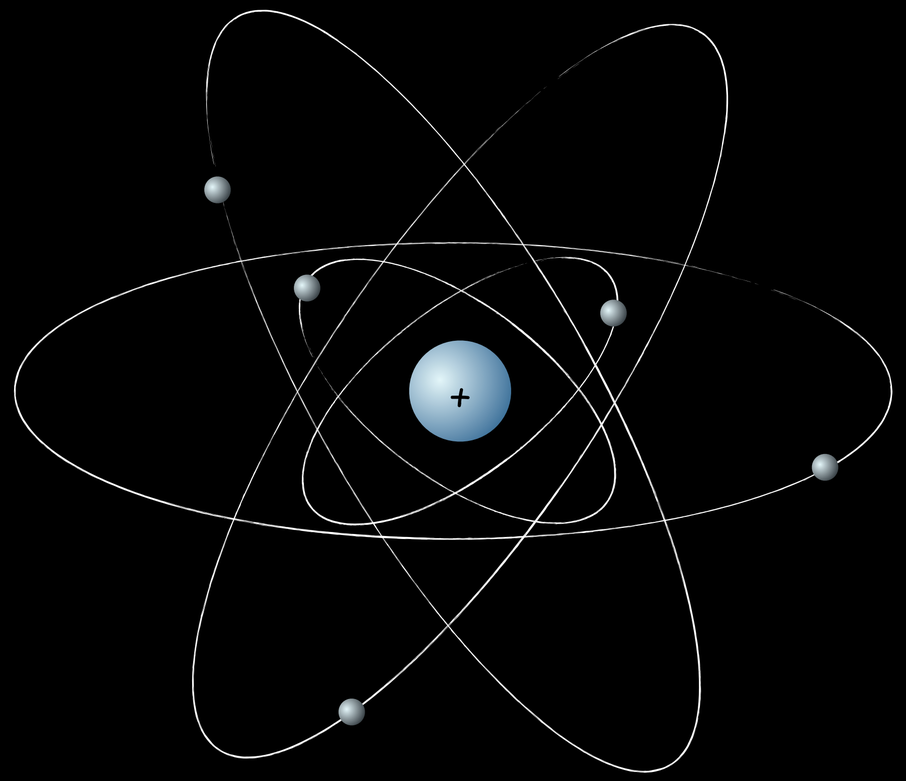
Epoque 5

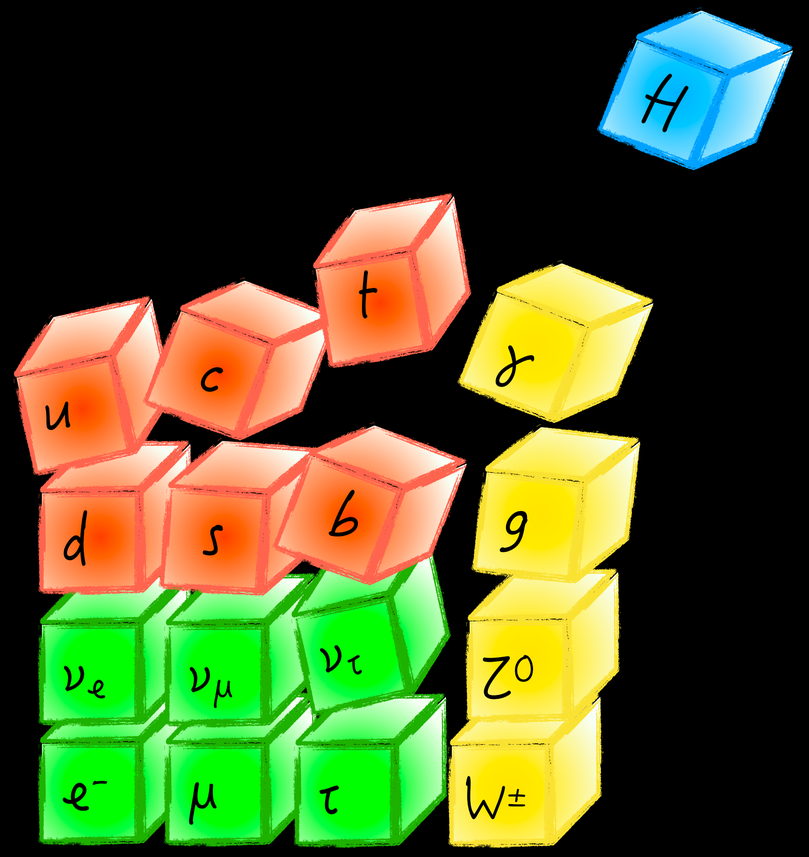
La masse est dite !

CERN, 2012

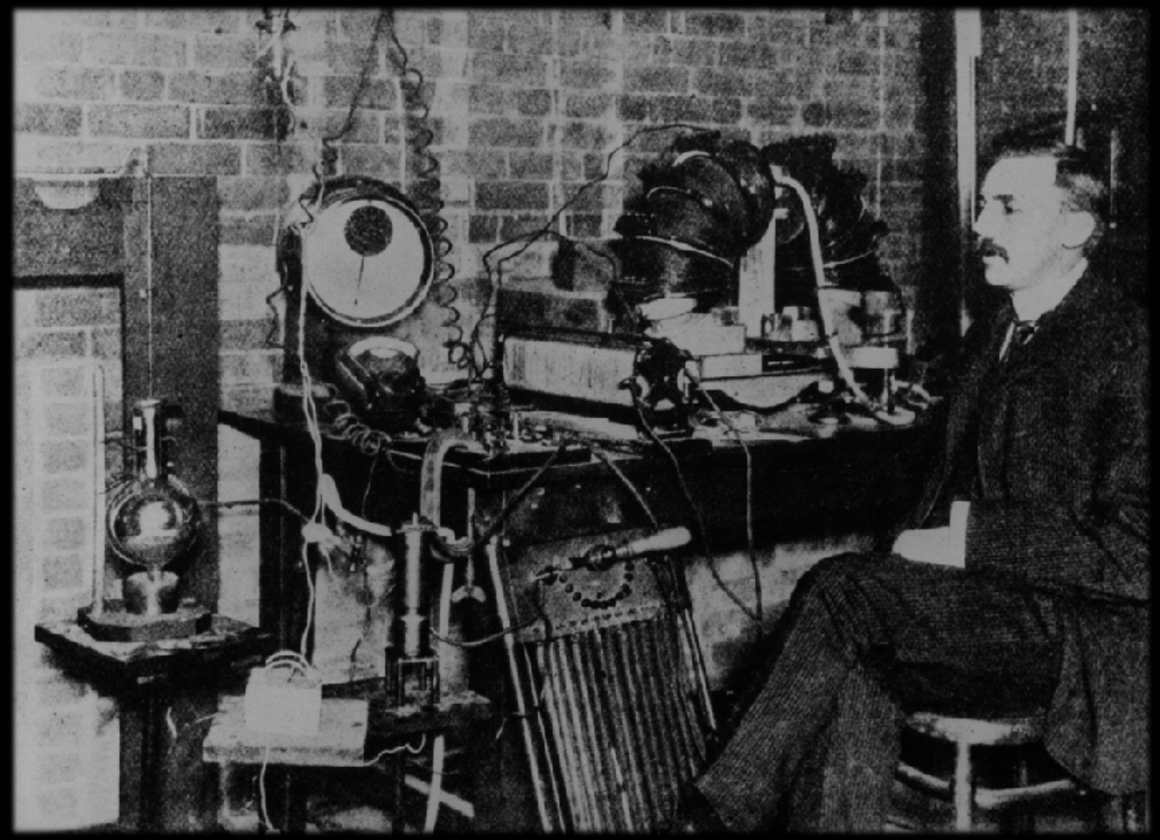


Fin d'une époque, début de la physique moderne





Fin d'une époque, début de la physique moderne



Actualités

1929

- Paul Adrien Maurice Dirac : 1933 - P
  - Equation d'onde relativiste

$$i\hbar\frac{\partial\psi}{\partial t}(\overrightarrow{x},t) = \left(mc^2\alpha_0 - i\hbar c\sum_{j=1}^{3}\alpha_j\frac{\partial}{\partial x_j}\right)\psi(\overrightarrow{x},t)$$

Actualités

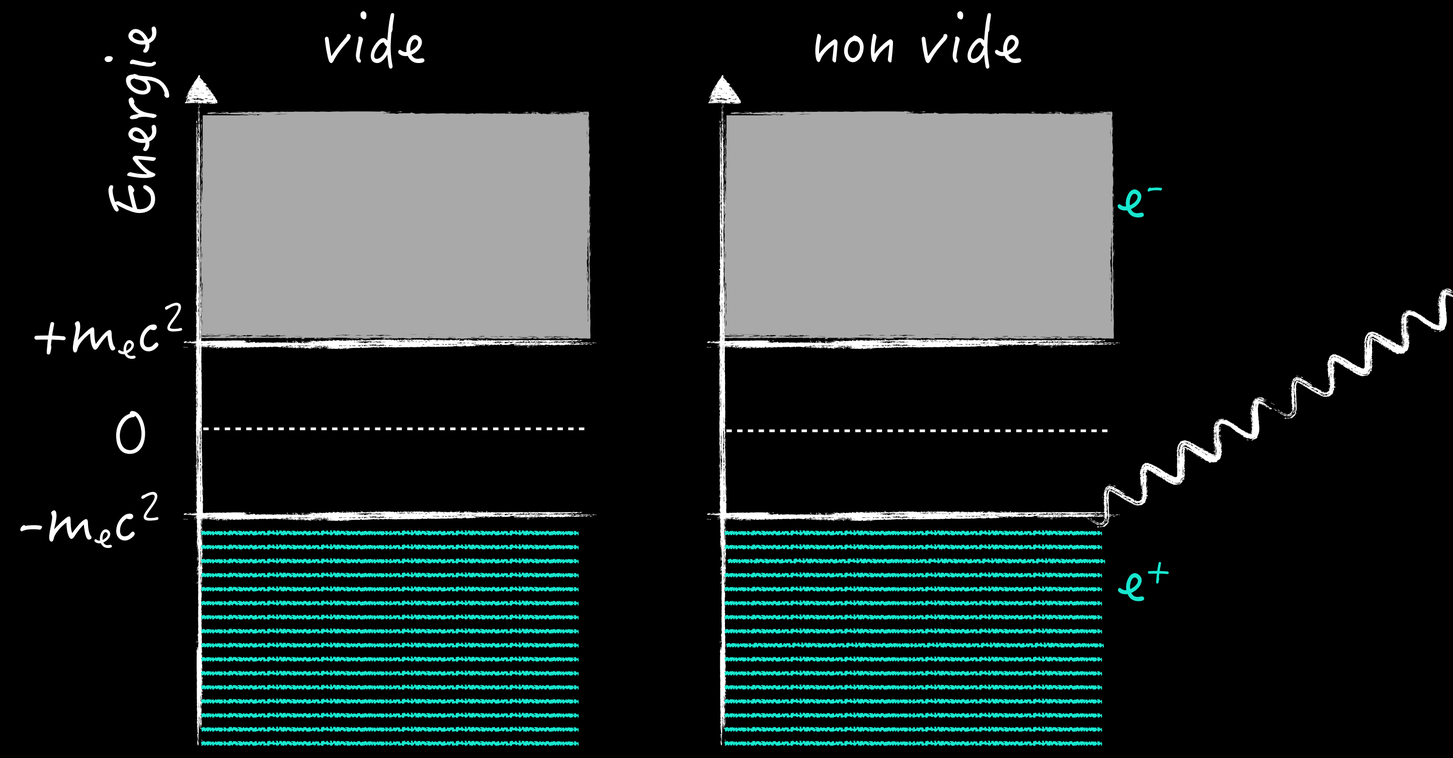
1929

- Paul Adrien Maurice Dirac :
  - Equation d'onde relativiste
  - Antimatière

$$E^2 = p^2c^2 + m_e^2c^4$$

Création

$$\gamma \rightarrow e^- + e^+$$



Actualités

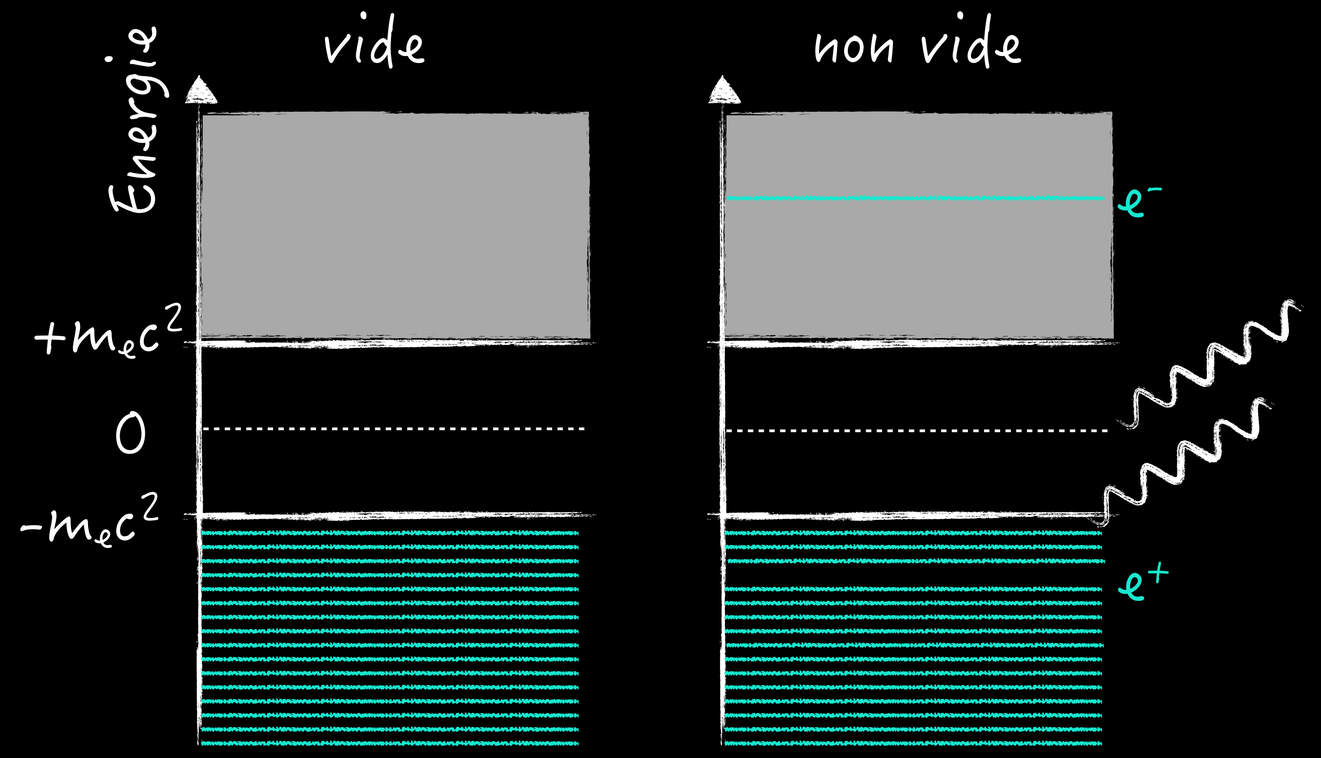
1929

- Paul Adrien Maurice Dirac :
  - Equation d'onde relativiste
  - Antimatière

$$E^2 = p^2c^2 + m_e^2c^4$$

annihilation

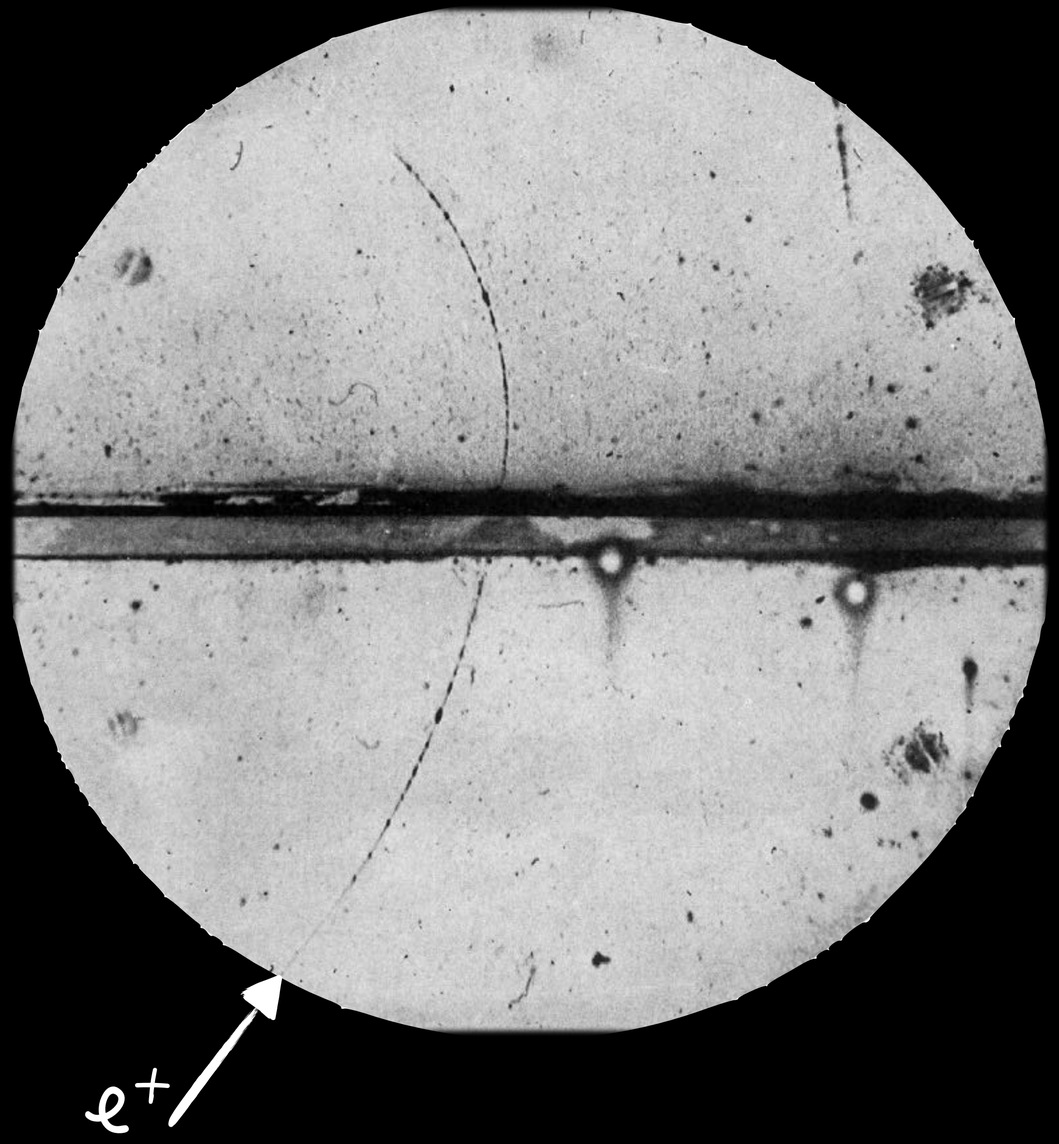
$$e^- + e^+ \rightarrow \gamma + \gamma$$



Actualités

1932, année prodigieuse : nouvelles particules

- Carl David Anderson : 1936 - P
  - découverte du positon



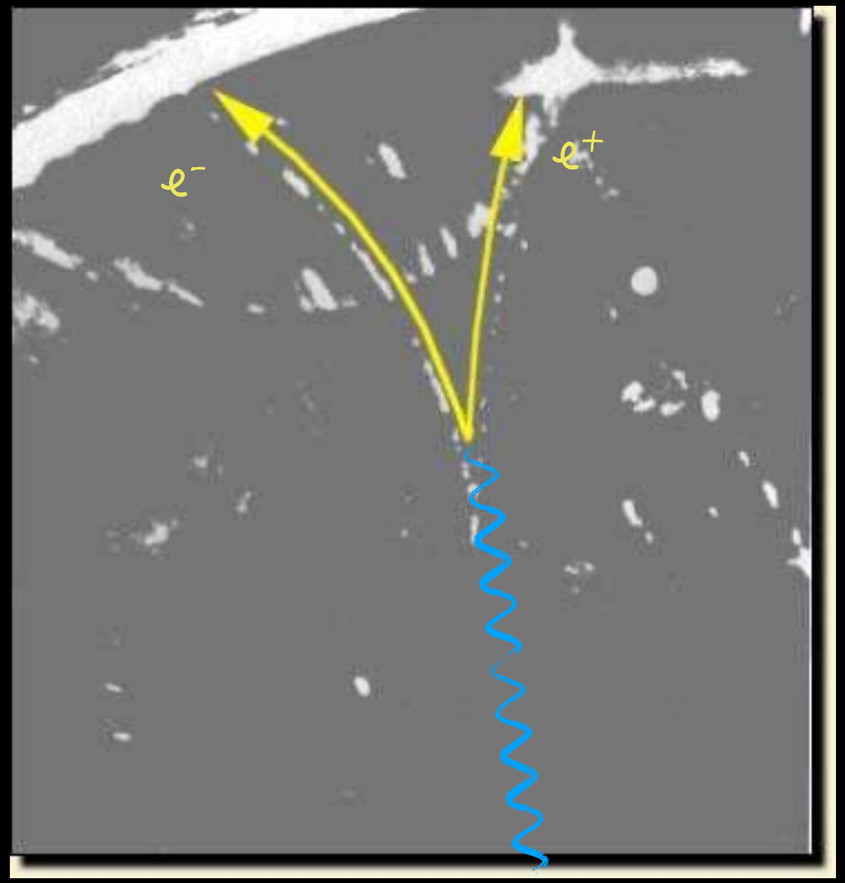
Actualités

1932, année prodigieuse : nouvelles particules

- Irène Curie & Frédéric Joliot

1935 - C

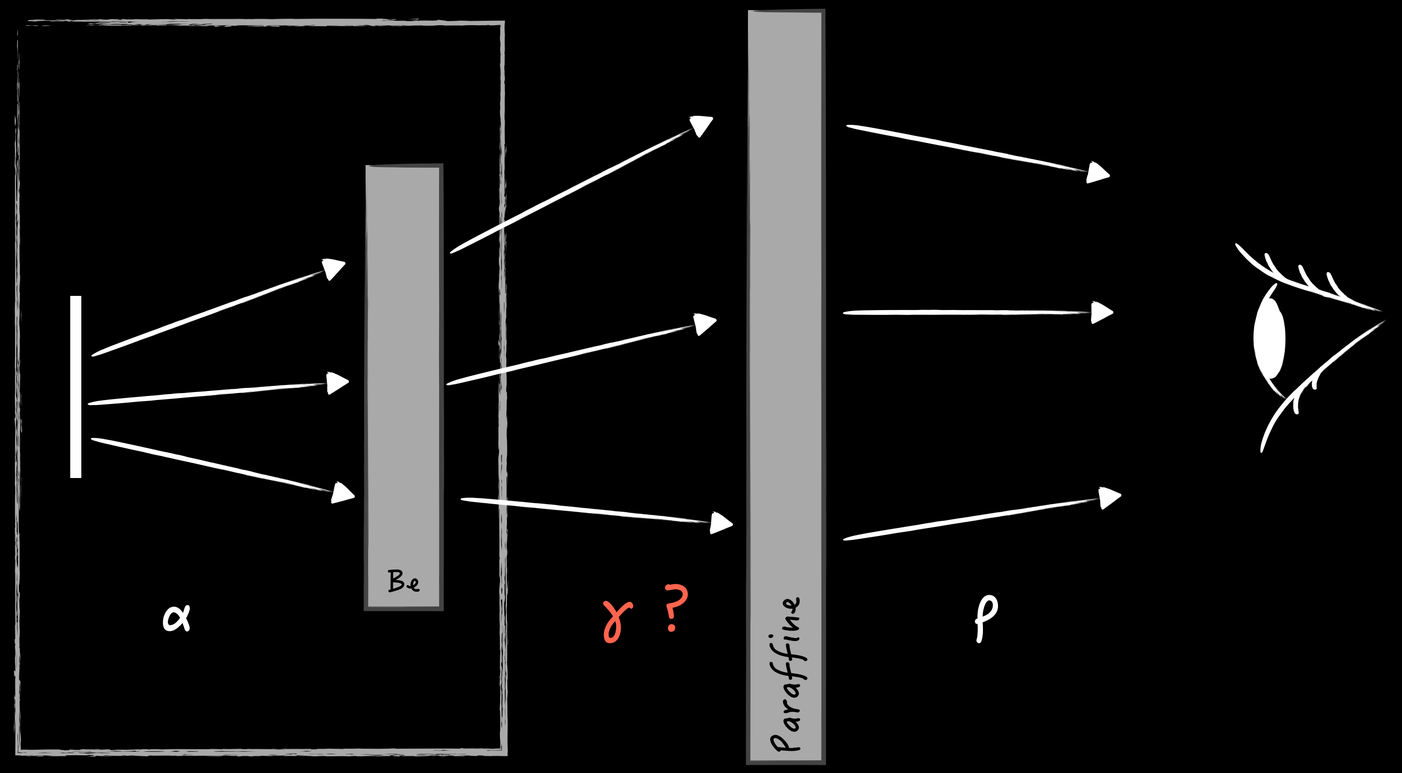
  - découverte conversion photon



Actualités

1932, année prodigieuse : nouvelles particules

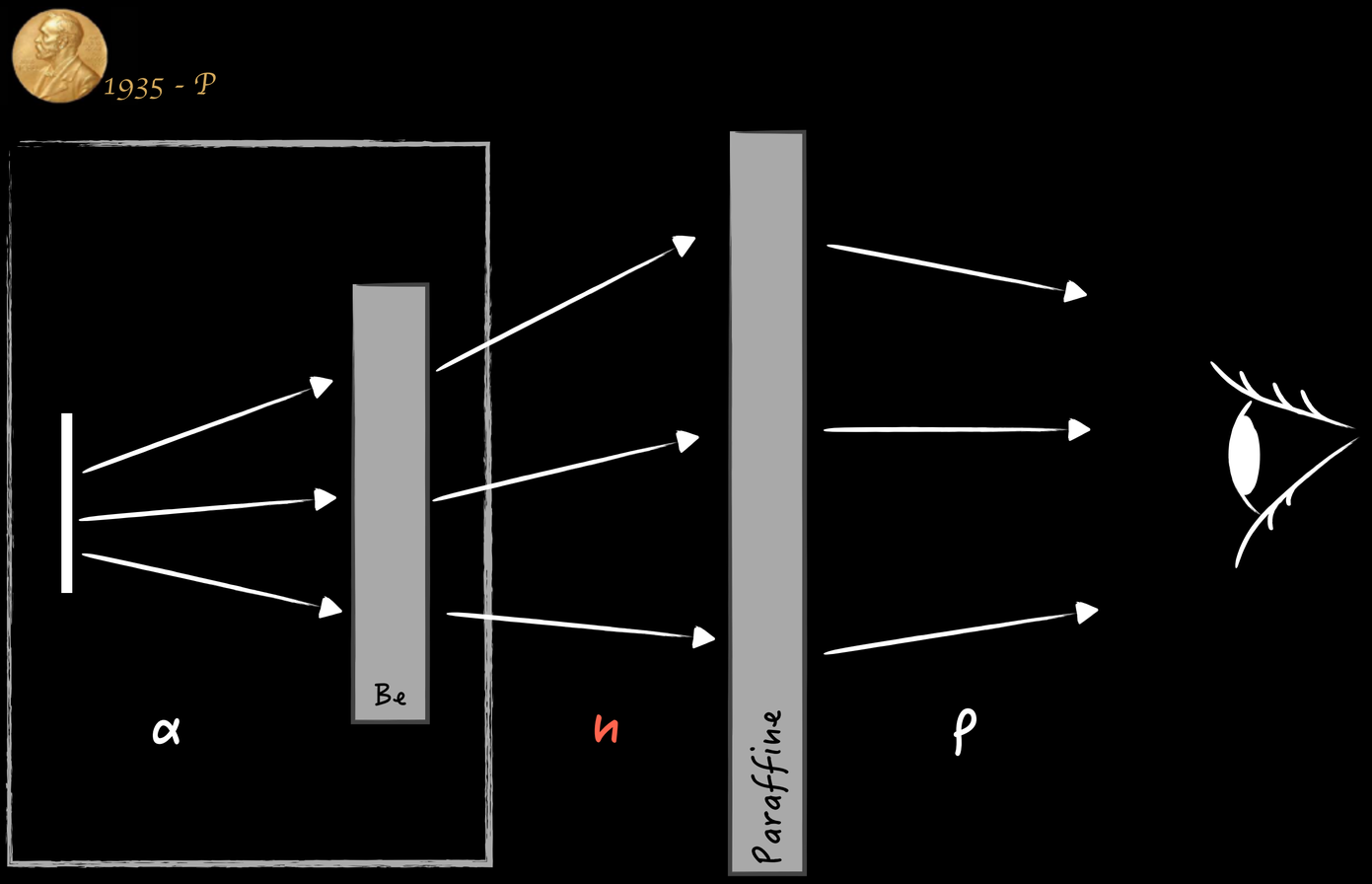
- Irène Curie & Frédéric Joliot :



Actualités

1932, année prodigieuse : nouvelles particules

- James Chadwick :
  - découverte du neutron



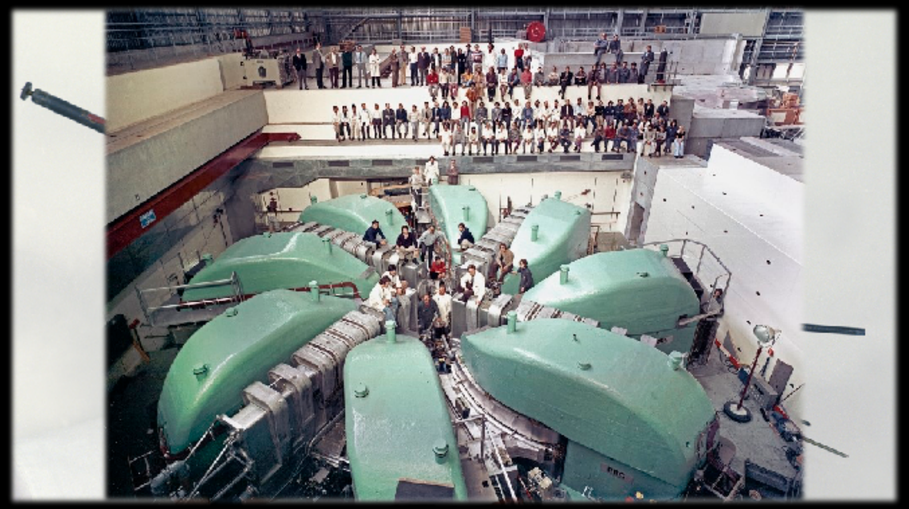
Actualités

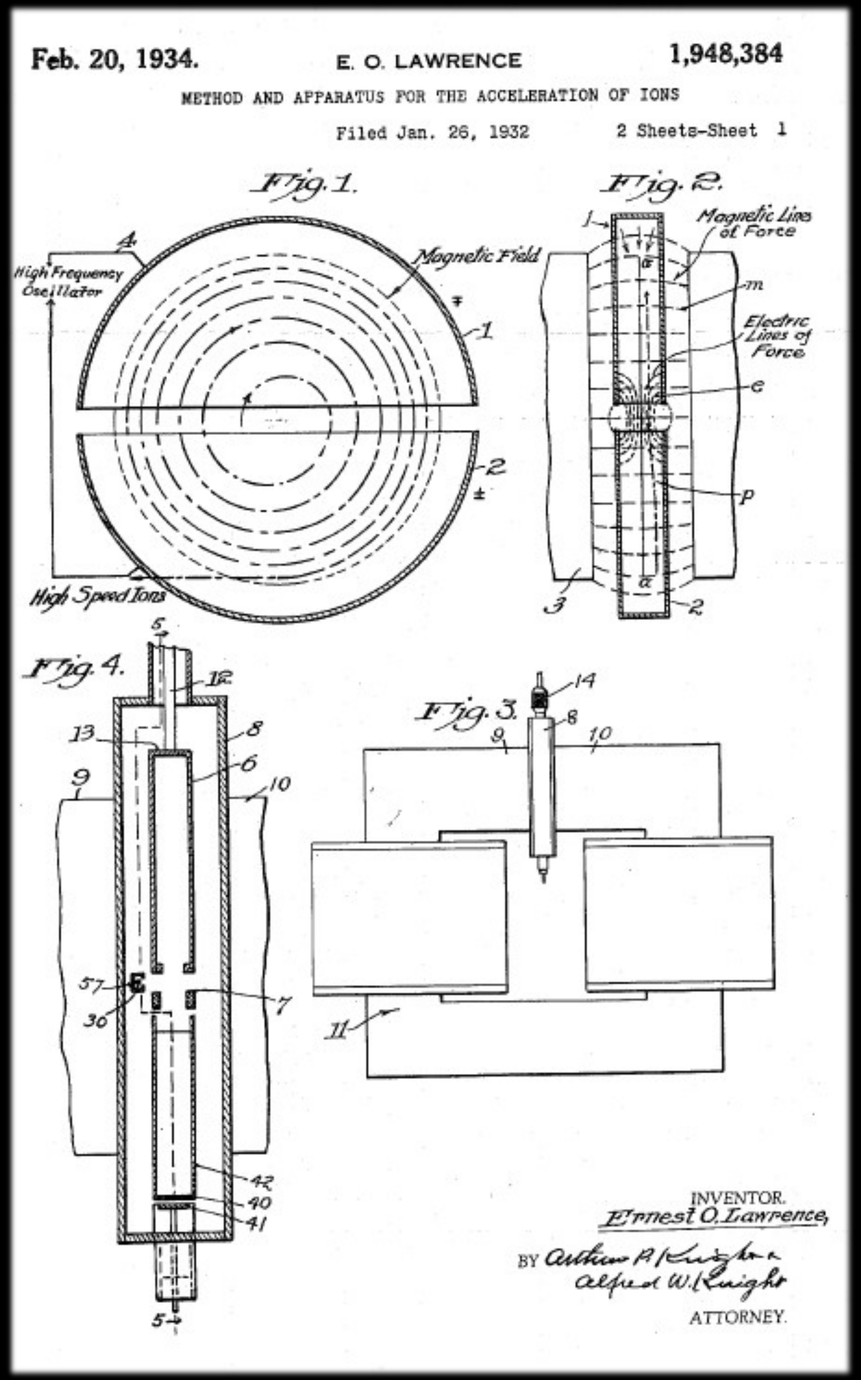
1932, année prodigieuse : accélérateurs

- Ernest Orlando Lawrence

1939 - P

  - Cyclotron





Feb. 20, 1934. E. O. LAWRENCE 1,948,384

METHOD AND APPARATUS FOR THE ACCELERATION OF IONS

Filed Jan. 26, 1932 2 Sheets-Sheet 1

Fig. 1.

Fig. 2.

Fig. 4.

Fig. 3.

INVENTOR.
Ernest O. Lawrence,
BY Arthur P. Knight
Alfred W. Knight
ATTORNEY.

$$E_c = m_0 c^2 (\gamma - 1)$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}}$$

$$\beta = \sqrt{1 - \left(\frac{m_0 c^2}{E_c + m_0 c^2} \right)}$$

Actualités

1932, année prodigieuse : accélérateurs

- John Cockcroft & Ernest Walton

1951 - P

  - Accélérateur électrostatique
  - Transmutation nucléaire :

$$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$$

Actualités

1932, année prodigieuse : accélérateurs

- John Cockcroft & Ernest Walton

1951 - P

  - Accélérateur électrostatique
  - Transmutation nucléaire :

$$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$$

- Robert Van de Graaf

Aujourd'hui

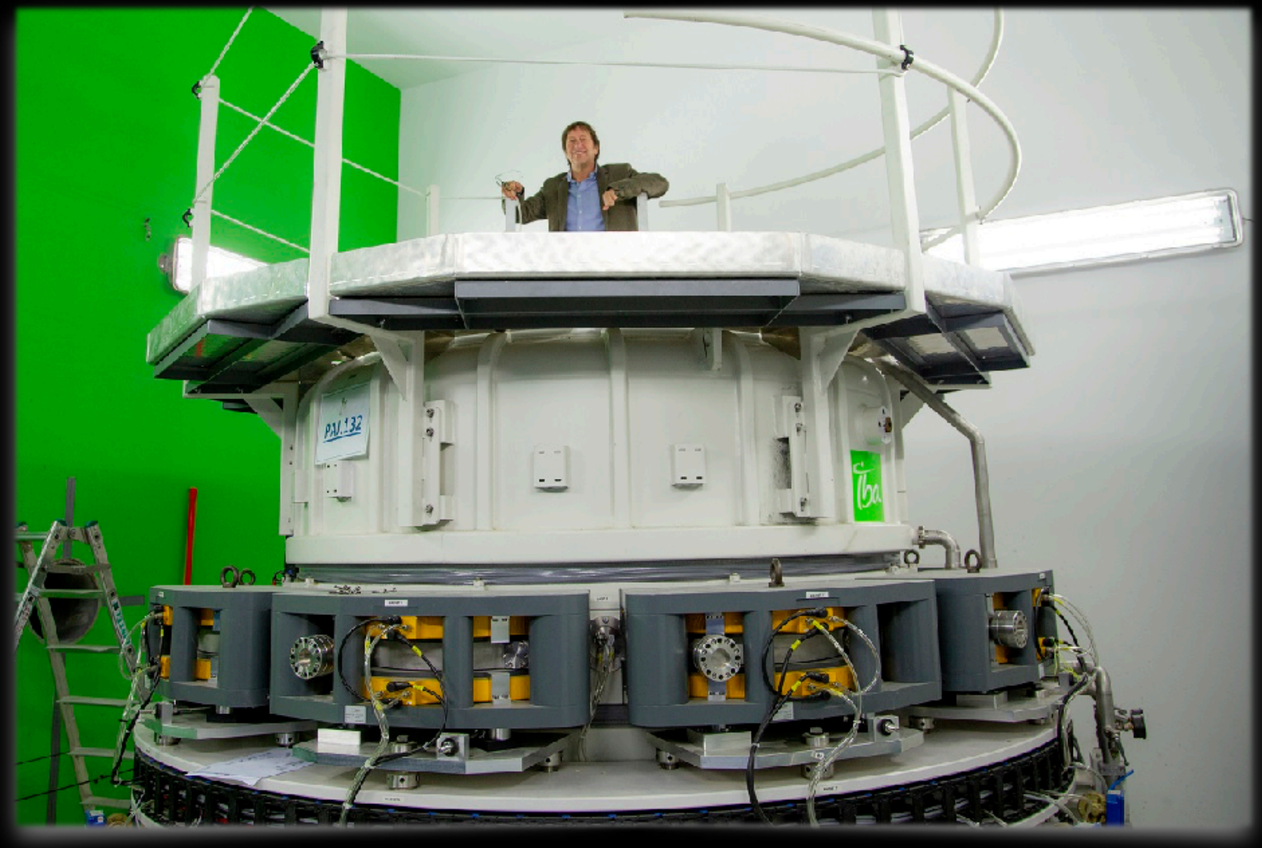
2013 : cyclotron alsacien Cyrcé

Cronenbourg

Aujourd'hui

2018 : rhodotron alsacien

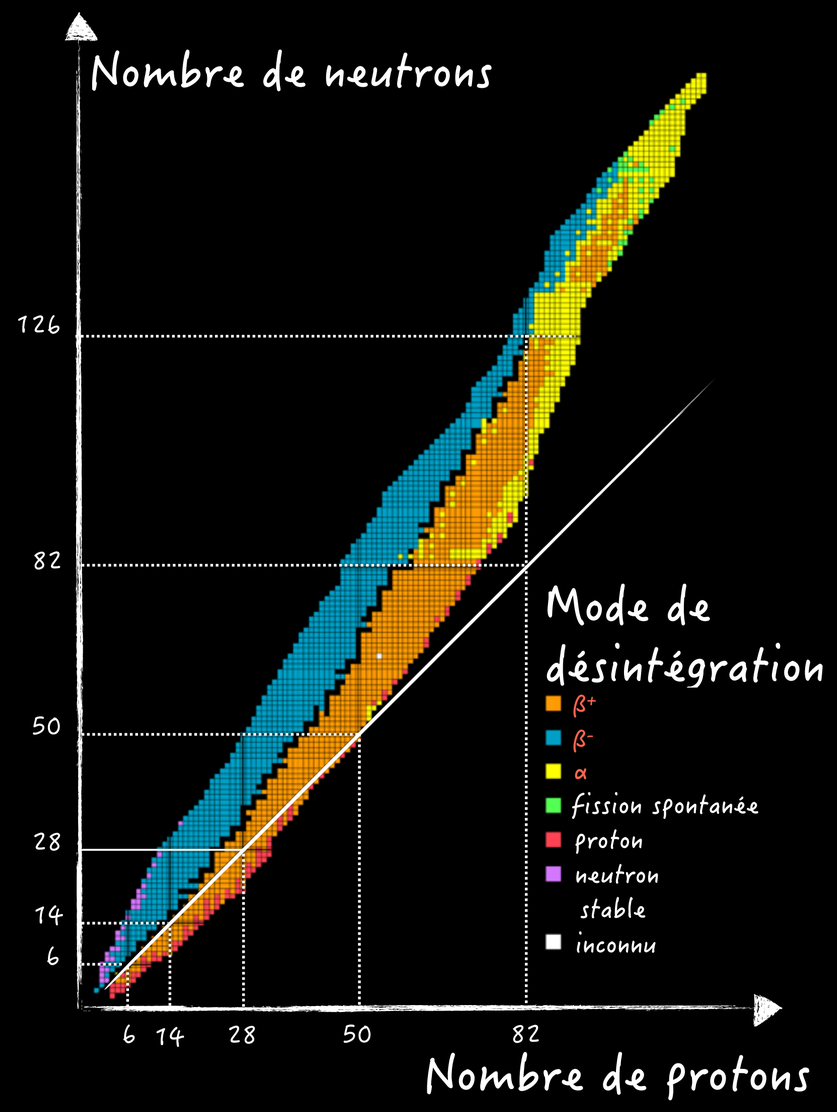
Aerial Illkirch



Physique nucléaire

1933 ...

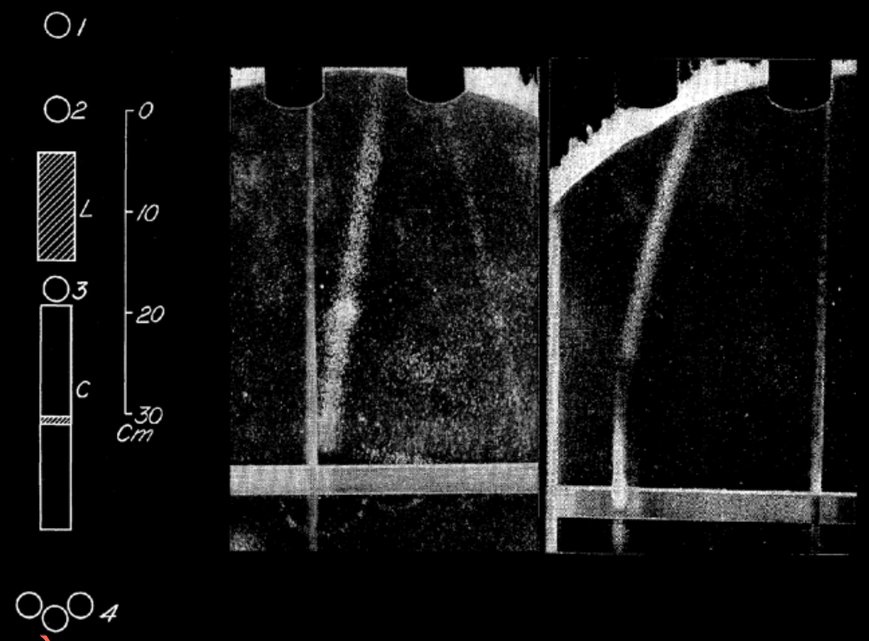
- Noyau = protons + neutrons → nucléon
- Cohésion du noyau et force nucléaire
- $n \rightarrow p + e^- + \bar{\nu}_e$
- La théorie des quanta de Bohr s'étend à l'étude des noyaux
- Fission des noyaux d'uranium



Physique des particules

1933 ...

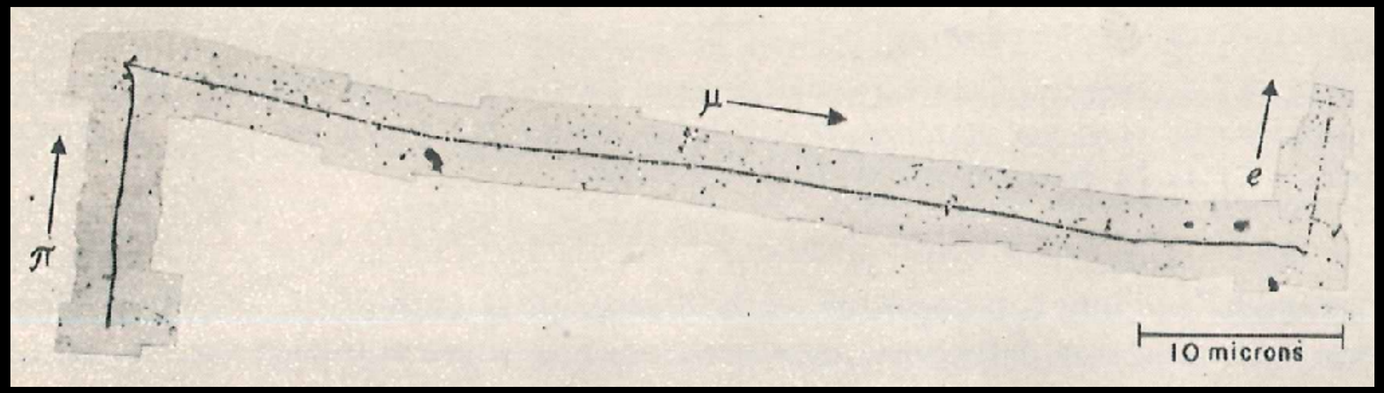
- Particules connues : e^+, e^-, p, n, γ
- Nouvelles particules :
  - 1936, Carl David Anderson :



μ (muon)

Physique des particules

1933 ...



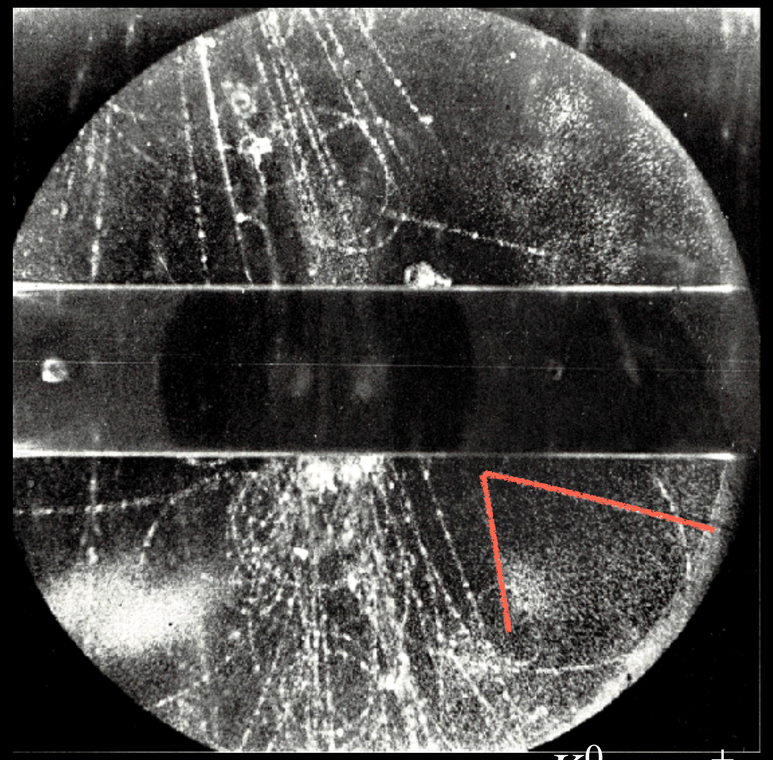
- Particules connues : e^+, e^-, p, n, γ
- Nouvelles particules :
  - 1936, Carl David Anderson : μ (muon)
  - 1947, Cecil Frank Powell : π (pion)

1950 - P

Physique des particules

1933 ...

- Particules connues : e^+, e^-, p, n, γ
- Nouvelles particules :
  - 1936, Carl David Anderson : μ (muon)
  - 1947, Cecil Frank Powell : π (pion)
  - 1947, Clifford Butler & George Rochester : k (kaon)



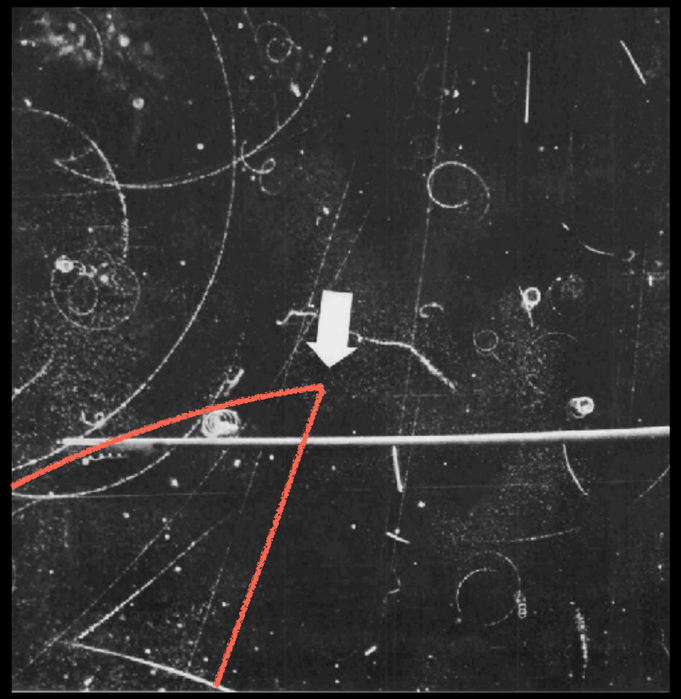
$K^0 \rightarrow \pi^+ + \pi^-$

1950 - P

Physique des particules

1933 ...

- Particules connues : e^+, e^-, p, n, γ
- Nouvelles particules :
  - 1936, Carl David Anderson : μ (muon)
  - 1947, Cecil Frank Powell : π (pion)
  - 1947, Clifford Butler & George Rochester : k (kaon)
  - 1950, Victor Hopper & S. Biswas : Λ (lambda)



$$\Lambda^0 \rightarrow p + \pi^-$$

1950 - P

Physique des particules

1933 ...

- Particules connues : e^+, e^-, p, n, γ
- Nouvelles particules :
  - 1936, Carl David Anderson : μ (muon)
  - 1947, Cecil Frank Powell : π (pion)

1950 - P

  - 1947, Clifford Butler & George Rochester : k (kaon)
  - 1950, Victor Hopper & S. Biswas : Λ (lambda)

Ξ, Σ, $\bar{p}$, $\bar{n}$, ... des centaines de nouvelles particules

PDG Live — particle data group

Send Feedback

Home | pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

2020 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Gauge & Higgs Bosons reviews
- γ
- gluon
- graviton
- W
- Z
- H^0
- Neutral Higgs Bosons, Searches for
- Charged Higgs Bosons ($H^\pm$, $H^{\pm\pm}$)
- Heavy Bosons
- Axions

Leptons reviews
- e
- μ
- τ
- Heavy Charged Lepton
- Neutrino Properties
- Number of Neutrino Types
- Double β-Decay
- Neutrino Mixing
- Heavy Neutral Leptons

Quarks
- Light quarks (u, d, s
- c
- b
- t
- b'
- t'
- Free quark

Mesons reviews
- Light Unflavored
  - Further States
- Strange
- Charmed
- Charmed, Strange
- Bottom
- Bottom, Strange
- Bottom, Charmed
- $c\bar{c}$ (including possibly non-$q\bar{q}$ states)
- $b\bar{b}$ (including possibly non-$q\bar{q}$ states)
- Non $q\bar{q}$ Candidates

Baryons reviews
- N Baryons
- Δ Baryons
- Λ Baryons
- Σ Baryons
- Ξ Baryons
- Ω Baryons
- Charmed Baryons
- Doubly-Charmed
- Bottom Baryons
- Exotic Baryons

Other Searches
- Magnetic Monopole
- Supersymmetric Pa
- Technicolor
- Quark and Lepton C
- Extra Dimensions
- WIMPs
- Other Particle Sear

Conservation Laws reviews
- Discrete Space-Time Symm.
- Number Conservation Laws

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

See related reviews:
- Form Factors for Radiative Pion and Kaon Decays
- Scalar Mesons below 2 GeV
- $\rho(770)$
- Pseudoscalar and Pseudovector Mesons in the 1400 MeV Region
- $\rho(1450)$ and $\rho(1700)$

• $\pi^\pm$	$1^-(0^-)$	$f_1(1510)$	$0^+(1^{++})$	$\pi_2(2005)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $f'(1525)$	$0^+(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• η	$0^+(0^{-+})$				
• $f_0(500)$ aka σ; was $f_0(600)$	$0^+(0^{++})$				
• $\rho(770)$	$1^+(1^{--})$				
• $\omega(782)$	$0^-(1^{--})$				
• $\eta'(958)$	$0^+(0^{-+})$				
• $f_0(980)$	$0^+(0^{++})$				
• $a_0(980)$	$1^-(0^{++})$				
• $\phi(1020)$	$0^-(1^{--})$				
• $h_1(1170)$	$0^-(1^{+-})$				

$\pi^\pm$ $I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters B204 1 (1988).

See related review:
- Form Factors for Radiative Pion and Kaon Decays

$\pi^\pm$ MASS	139.57039 ± 0.00018 MeV (S = 1.8)
$m_{\pi^+} - m_{\mu^+}$	
$(m_{\pi^+} - m_{\pi^-})/m_{\text{average}}$	$(2 \pm 5) \times 10^{-4}$
$\pi^\pm$ MEAN LIFE	$(2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$(\tau_{\pi^+} - \tau_{\pi^-})/\tau_{\text{average}}$	$(6 \pm 7) \times 10^{-4}$
π ELECTRIC POLARIZABILITY α_π	$(2.0 \pm 0.9) \times 10^{-4}$ fm^3
π^+ – POLARIZATION OF EMITTED μ^+	
$\pi^+ \to \mu^+\nu$	
$\pi^\pm$ FORM FACTORS	
F_V, VECTOR FORM FACTOR	0.0254 ± 0.0017
F_A, AXIAL-VECTOR FORM FACTOR	0.0119 ± 0.0001
VECTOR FORM FACTOR SLOPE PARAMETER a	0.10 ± 0.06
R, SECOND AXIAL-VECTOR FORM FACTOR	$0.059^{+0.009}_{-0.008}$
$\pi^\pm$ CHARGE RADIUS	0.659 ± 0.004 fm

Decay Modes

Expand all decays

π^- modes are charge conjugates of the modes below.
For decay limits to particles which are not established, see the section on Searches for Axions and Other Very Light Bosons.

Mode			*Fraction* (Γ_i/Γ)	*Scale Factor/ Conf. Level*	*P (MeV/c)*
Γ_1	$\mu^+\nu_\mu$	[1]	$(99.98770 \pm 0.00004)\%$		30
Γ_2	$\mu^+\nu_\mu\gamma$	[2]	$(2.00 \pm 0.25) \times 10^{-4}$		30

https://pdglive.lbl.gov/Viewer.action

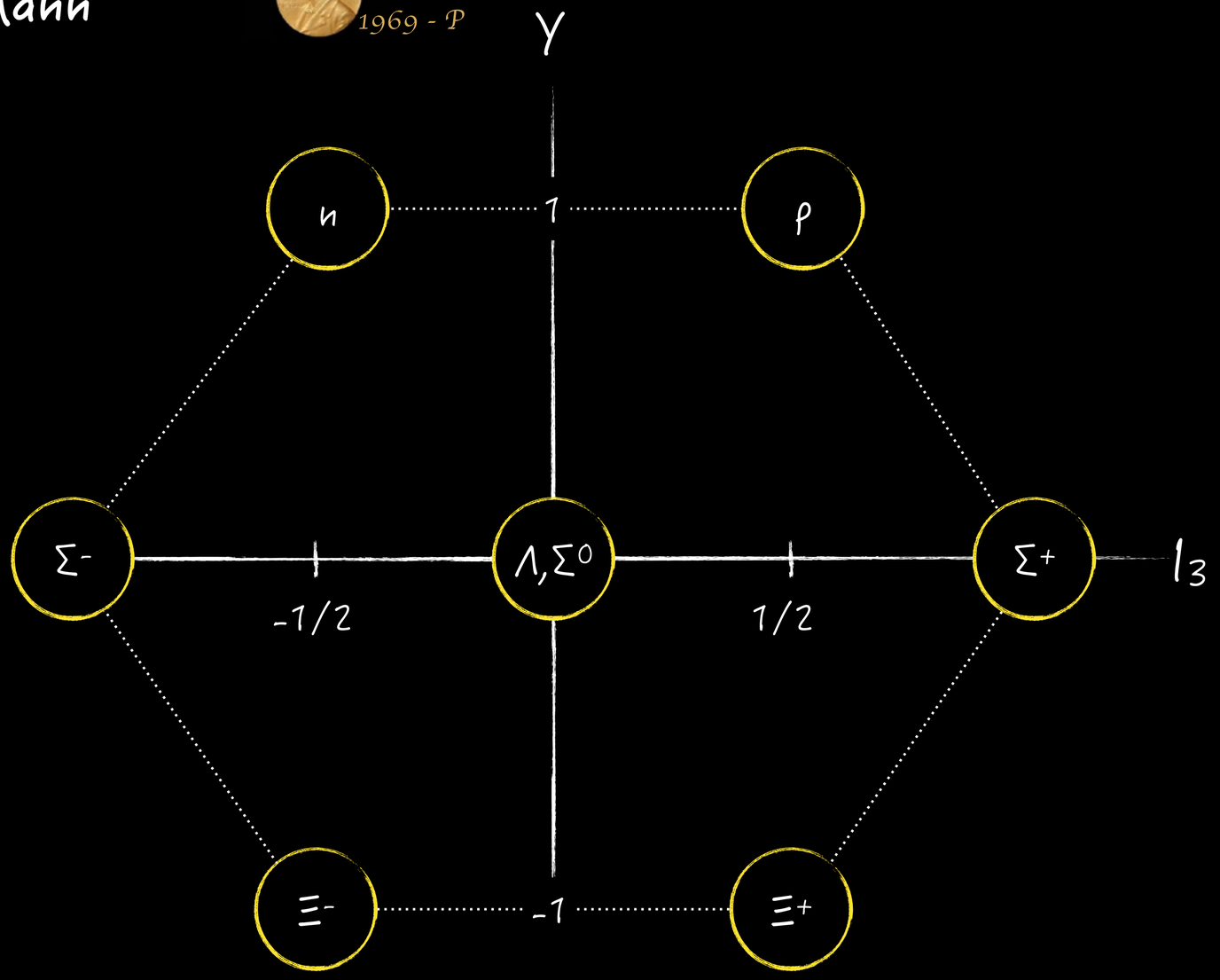
De l'ordre dans le zoo des particules

1961 Murray Gell-Mann

1969 - P

Hadrons

Baryons



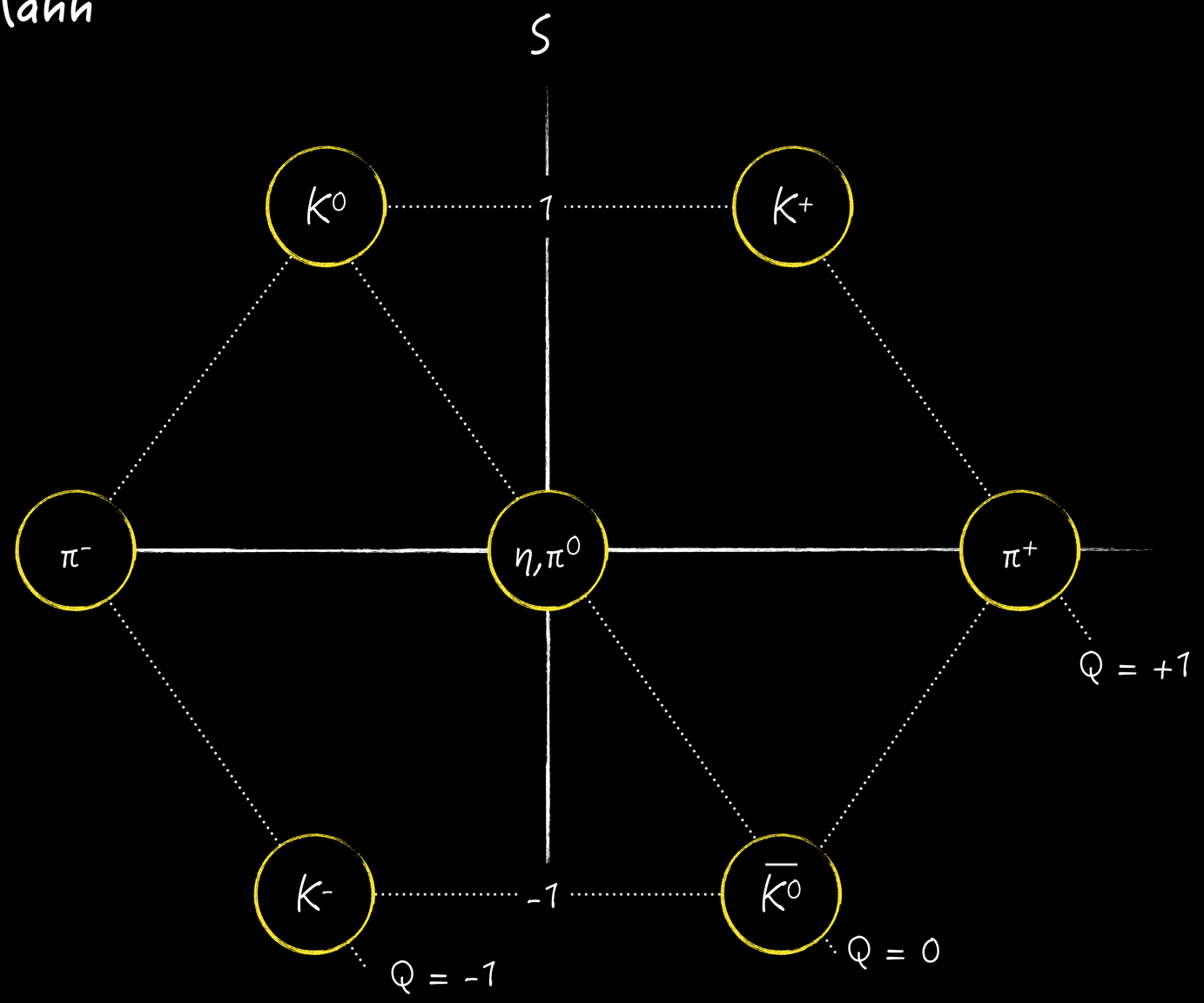
De l'ordre dans le zoo des particules

1961 Murray Gell-Mann

Hadrons

Baryons

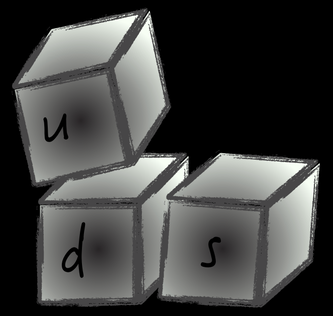
Mésons



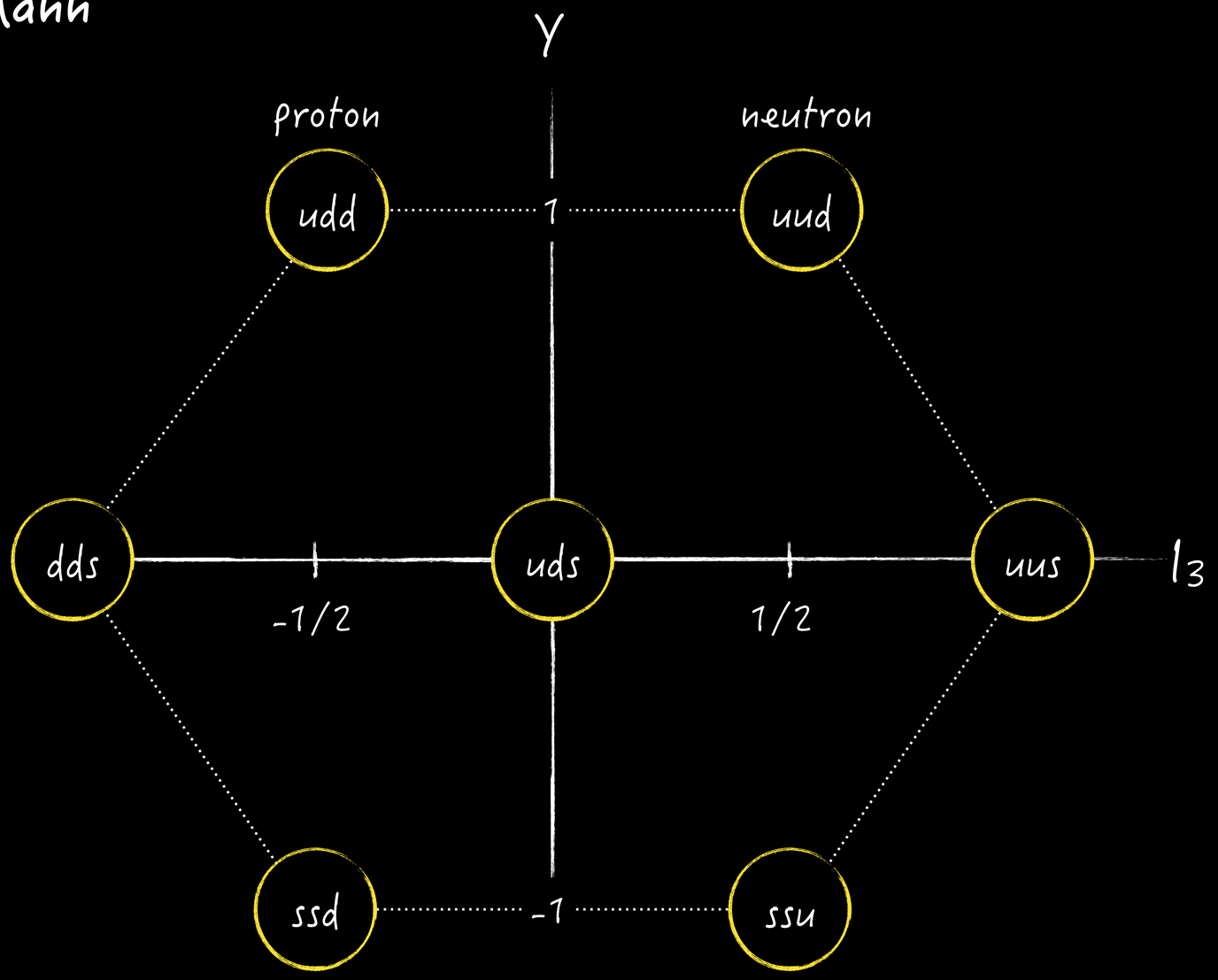
Classification des particules

1963 Murray Gell-Mann

Baryons: 999



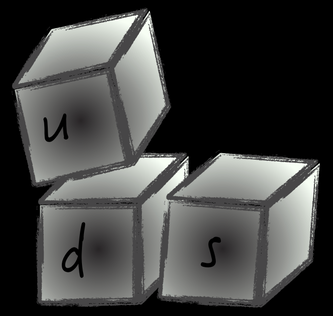
quarks



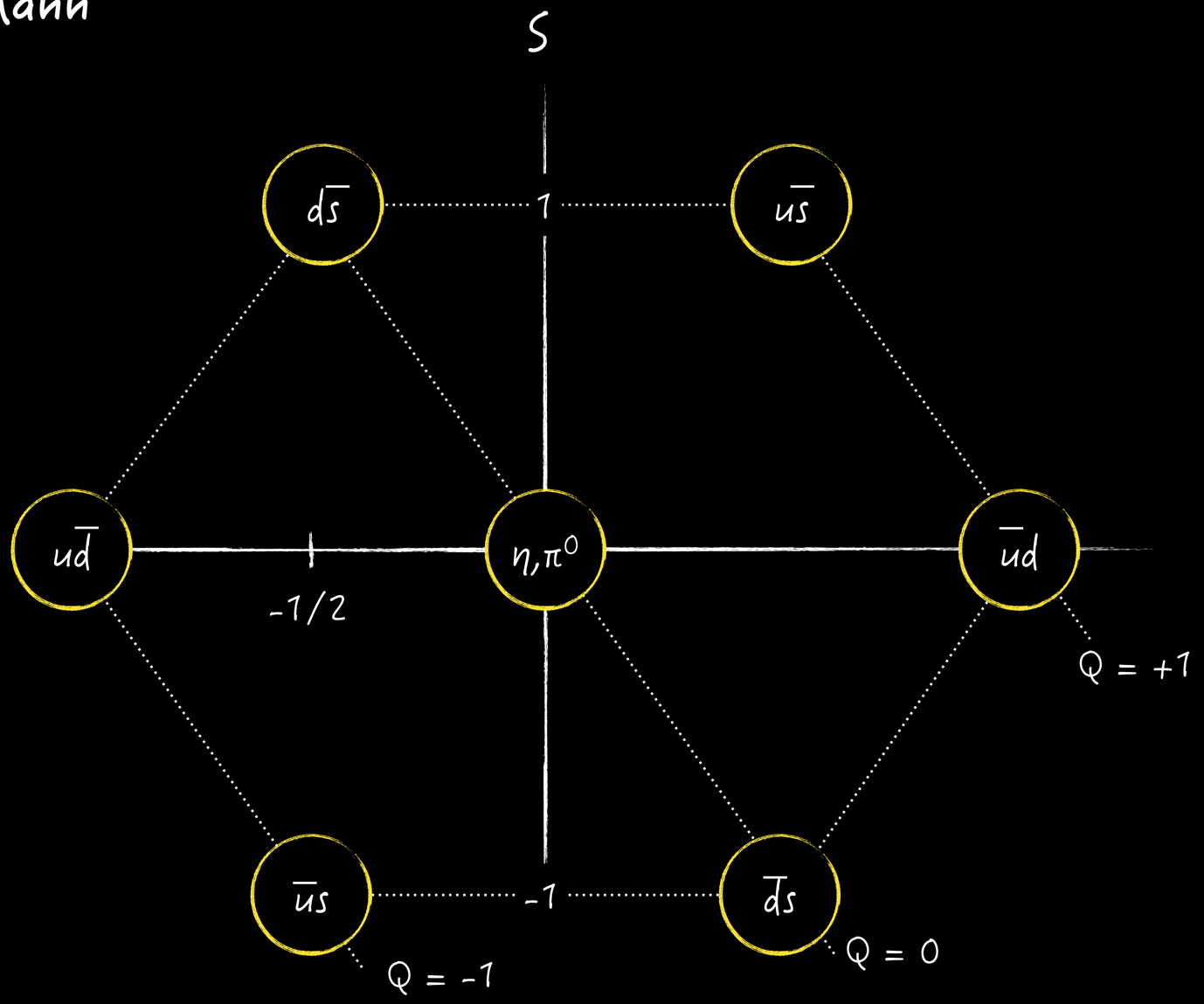
Classification des particules

1963 Murray Gell-Mann

Mésons : $q\bar{q}$

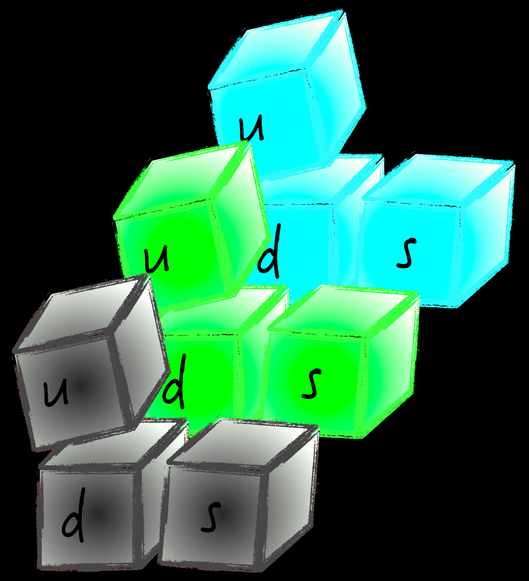


quarks

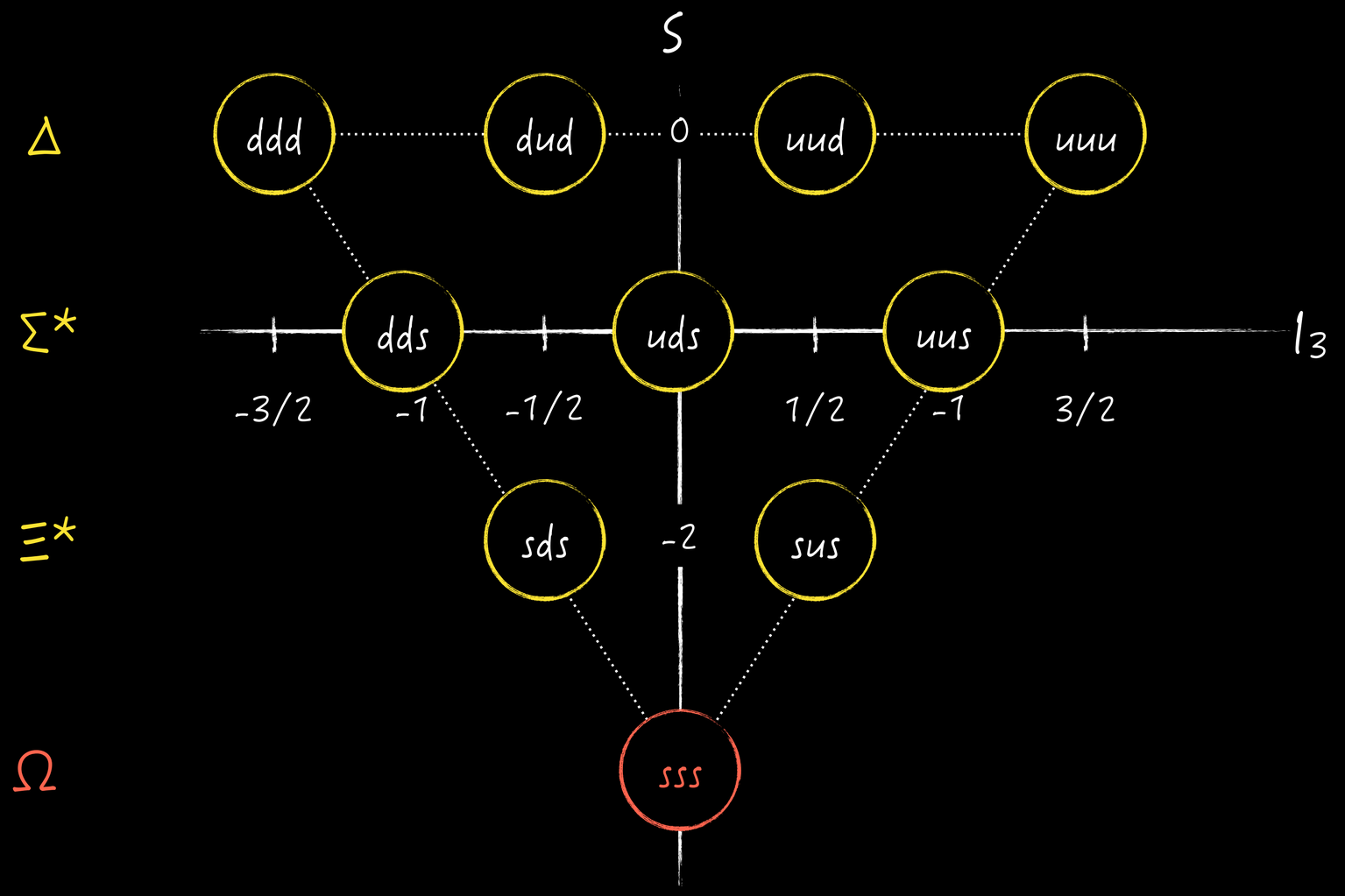


Classification des particules

1963 Murray Gell-Mann



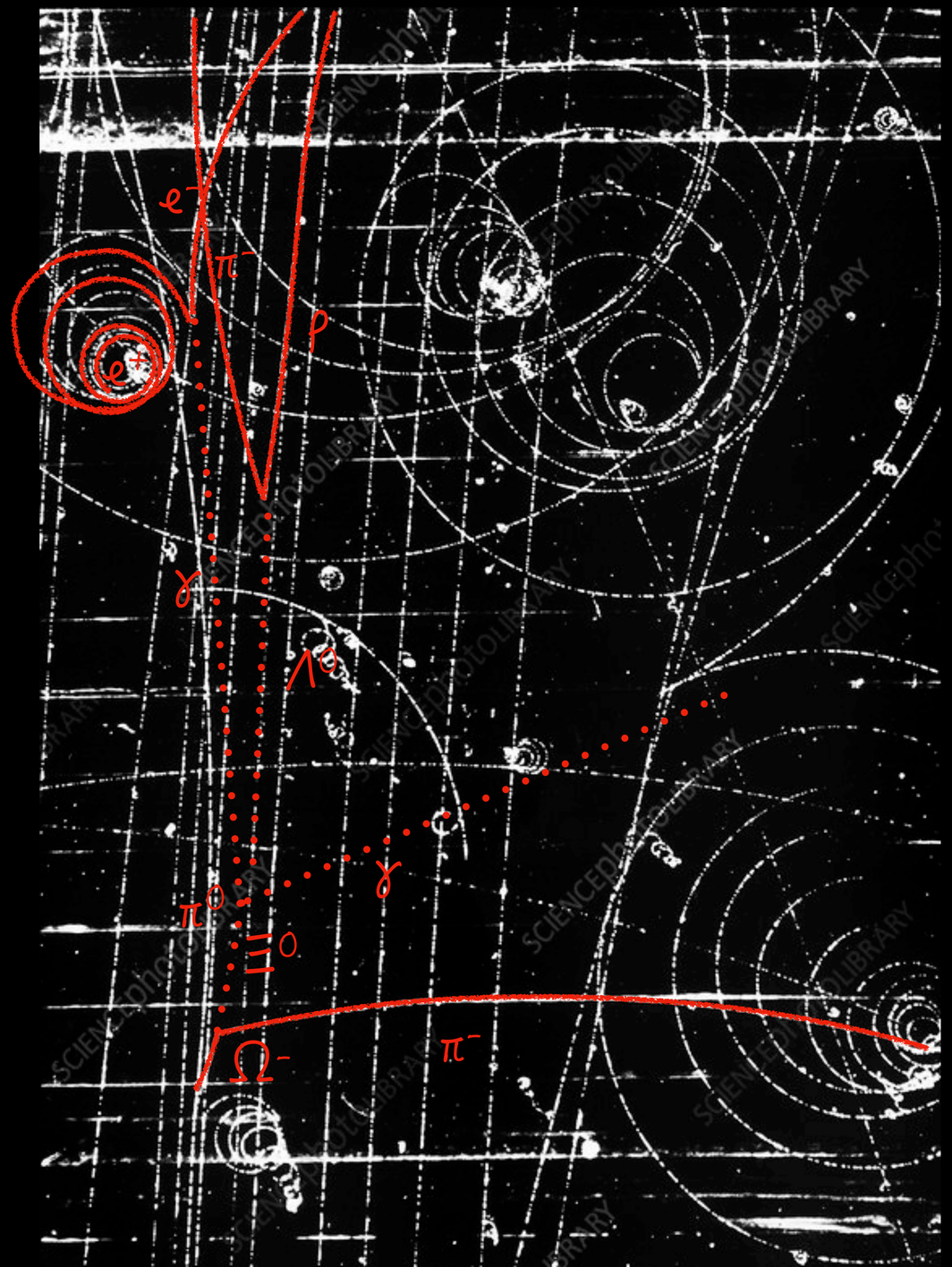
quarks



Classification des particules

1964 Découverte du hadron Ω^-

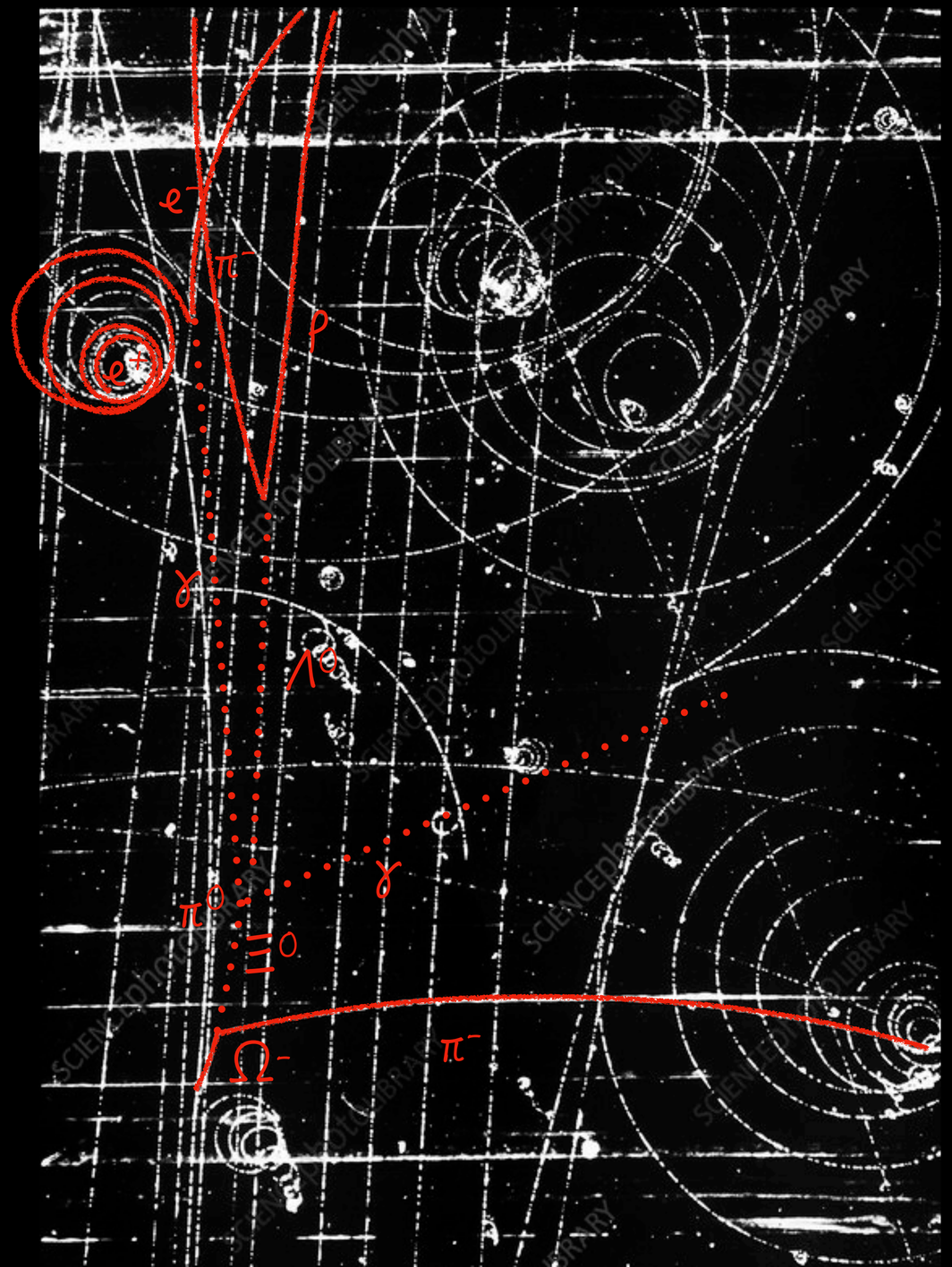
Bien vu, Pr Gell-Man !



Classification des particules

1964 Découverte du hadron Ω^-

Bien vu, Pr Gell-Man !



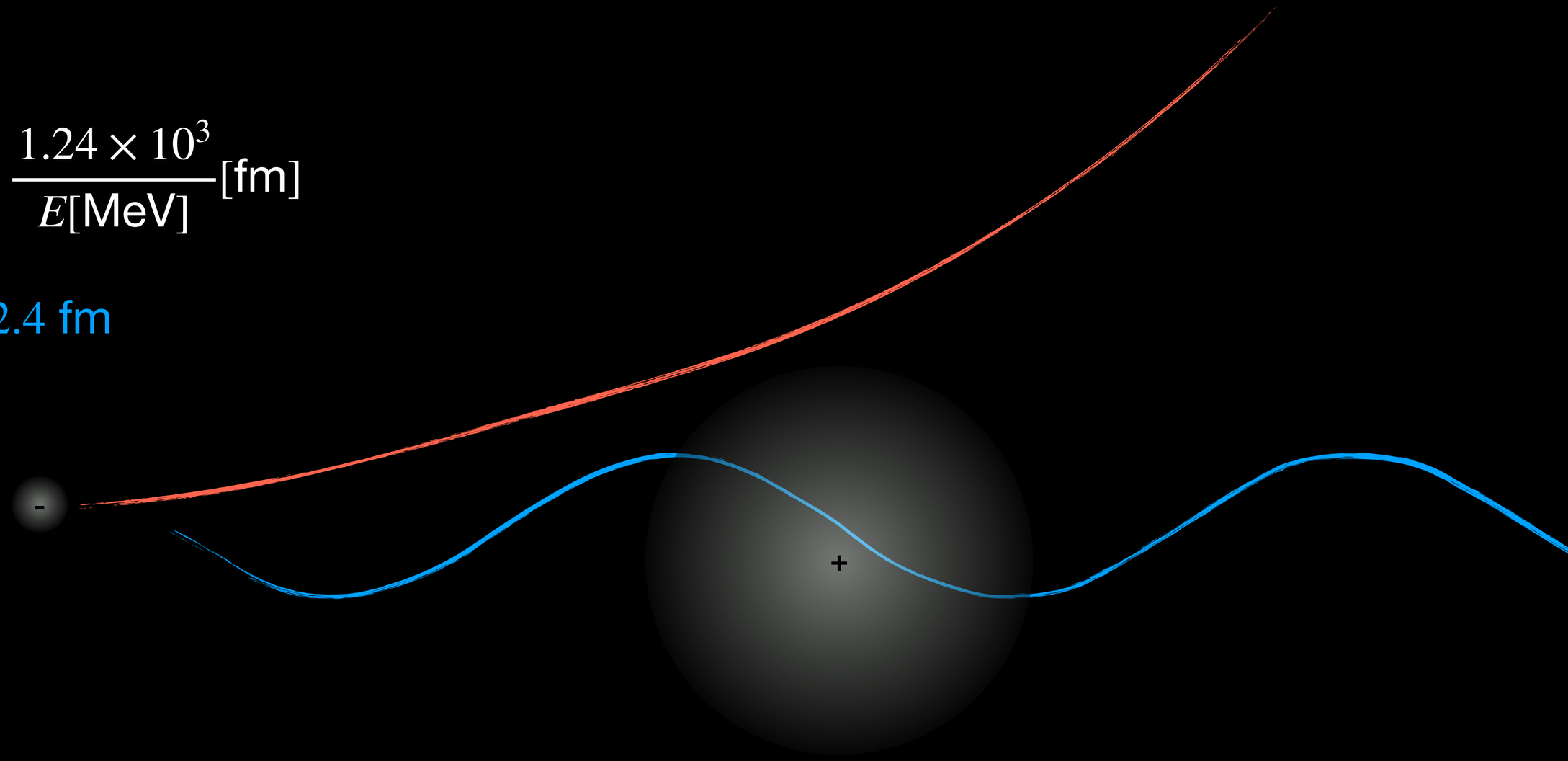
Structure composite du proton

Robert Hofstadter

1961 - P

$$\lambda = \frac{h}{p} = \frac{1.24 \times 10^3}{E[\text{MeV}]}[\text{fm}]$$

$\lambda_{100} = 12.4$ fm



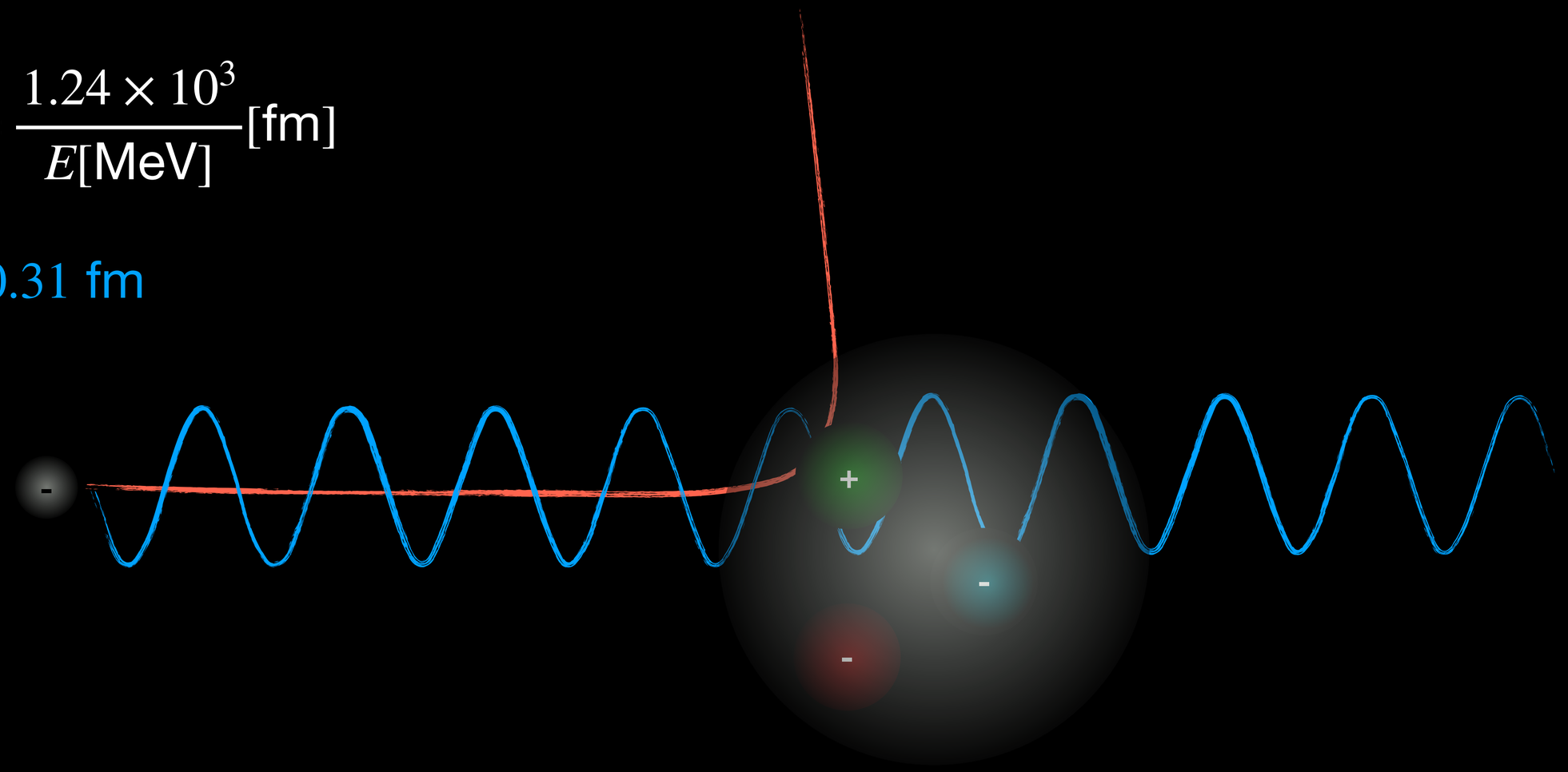
Structure composite du proton

Jérome Friedman, Henry Kendall & Richard Taylor

1990 - P

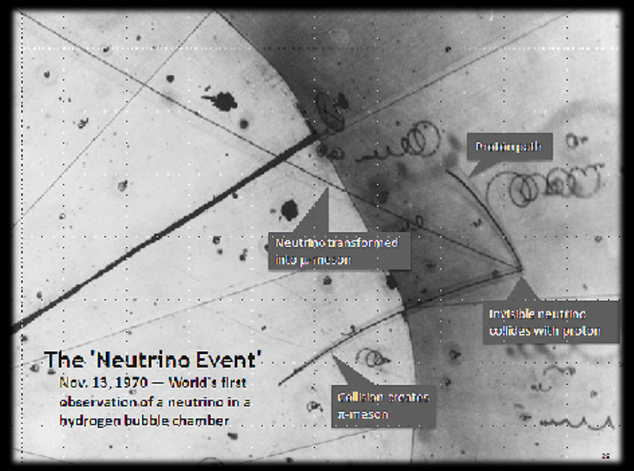
$$\lambda = \frac{h}{p} = \frac{1.24 \times 10^3}{E[\text{MeV}]}[\text{fm}]$$

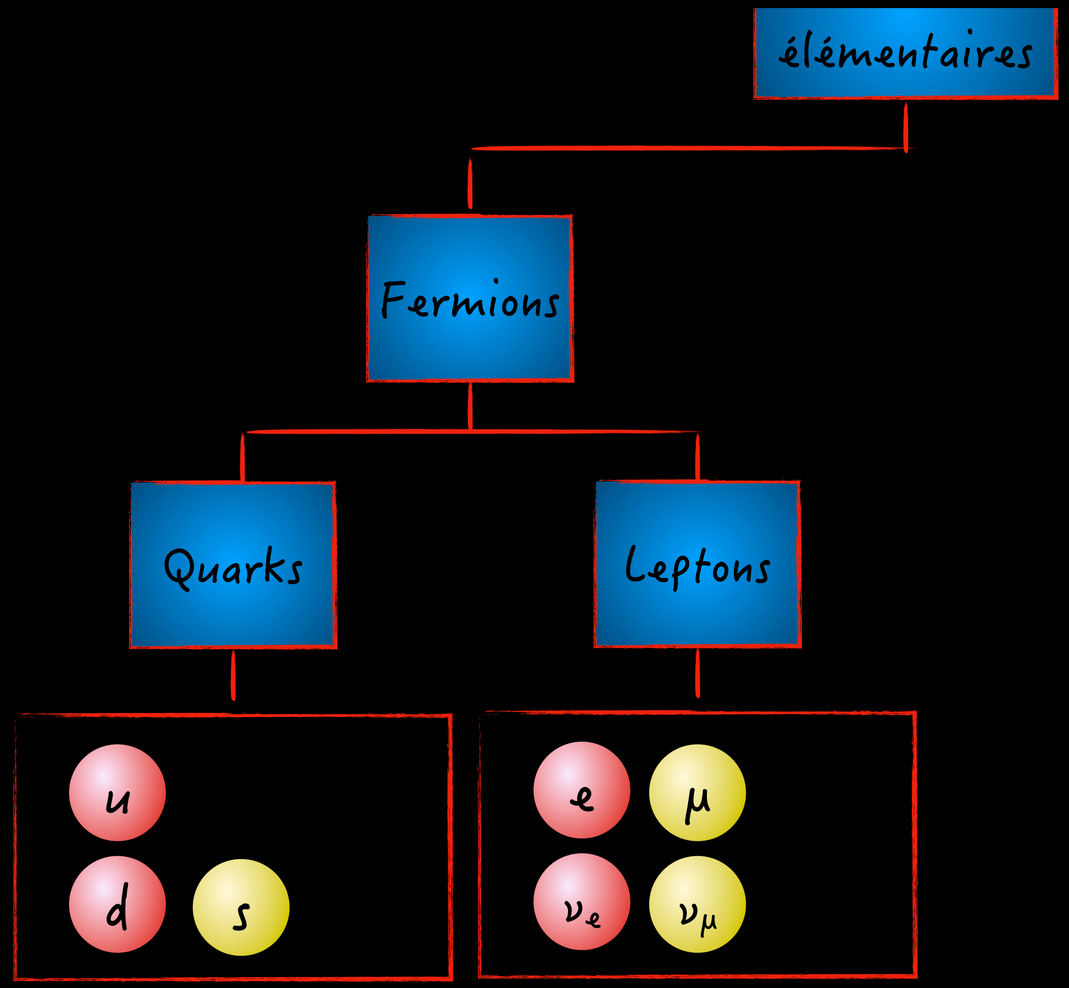
$$\lambda_{4000} = 0.31 \text{ fm}$$



Les particules élémentaires

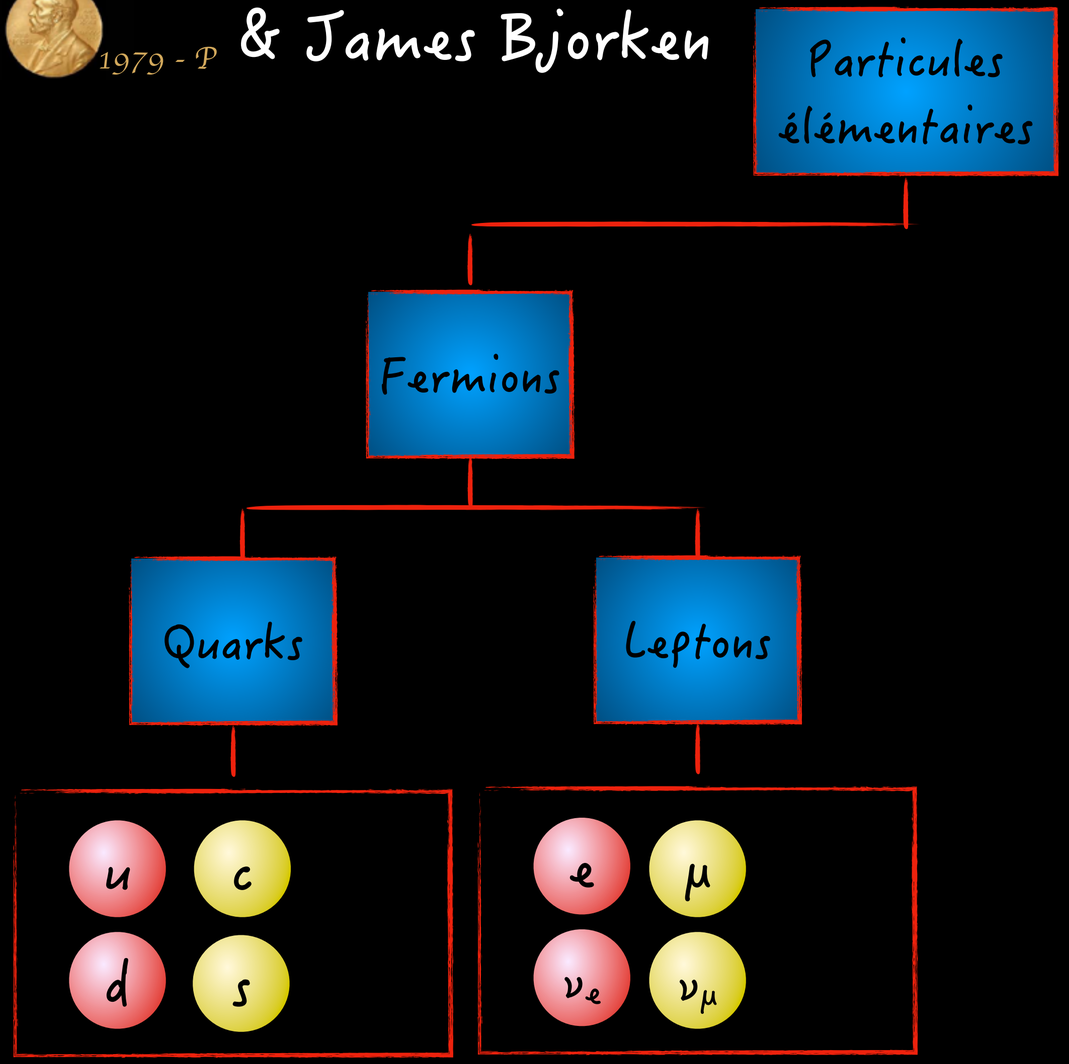
1962 Leon Lederman, Melvin Schwartz & Jack Steinberger





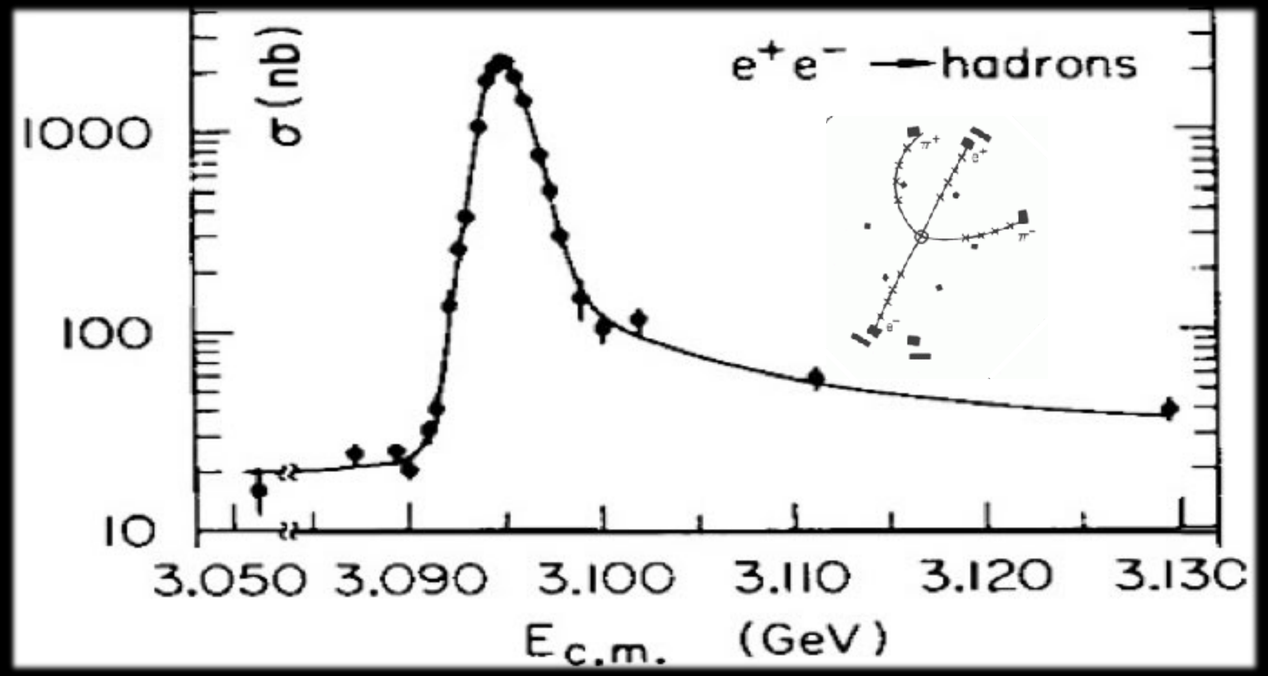
Les particules élémentaires

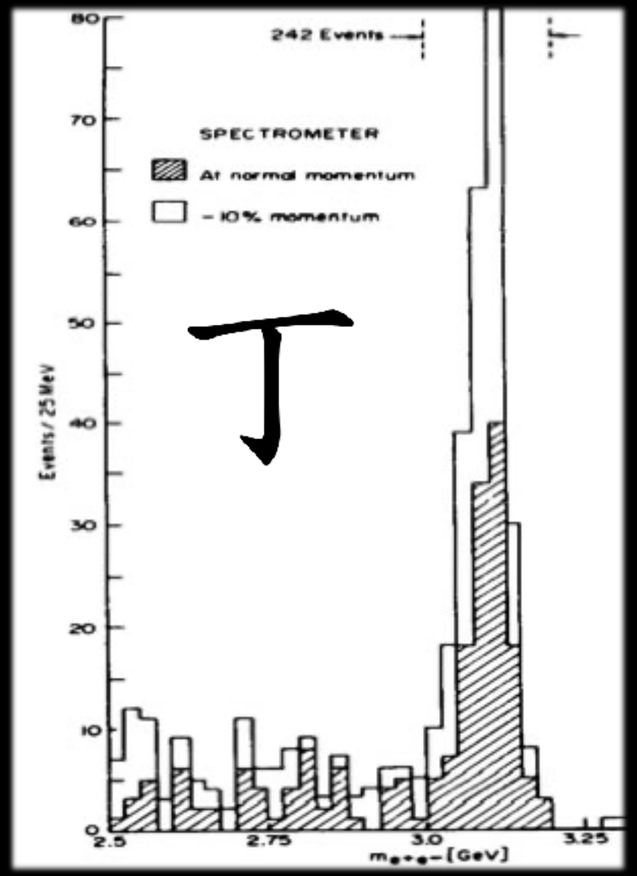
1964 Sheldon Glashow 1979 - P & James Bjorken



La révolution de novembre : découverte du charme

1974 Stanford & Brookhaven
1976 - P

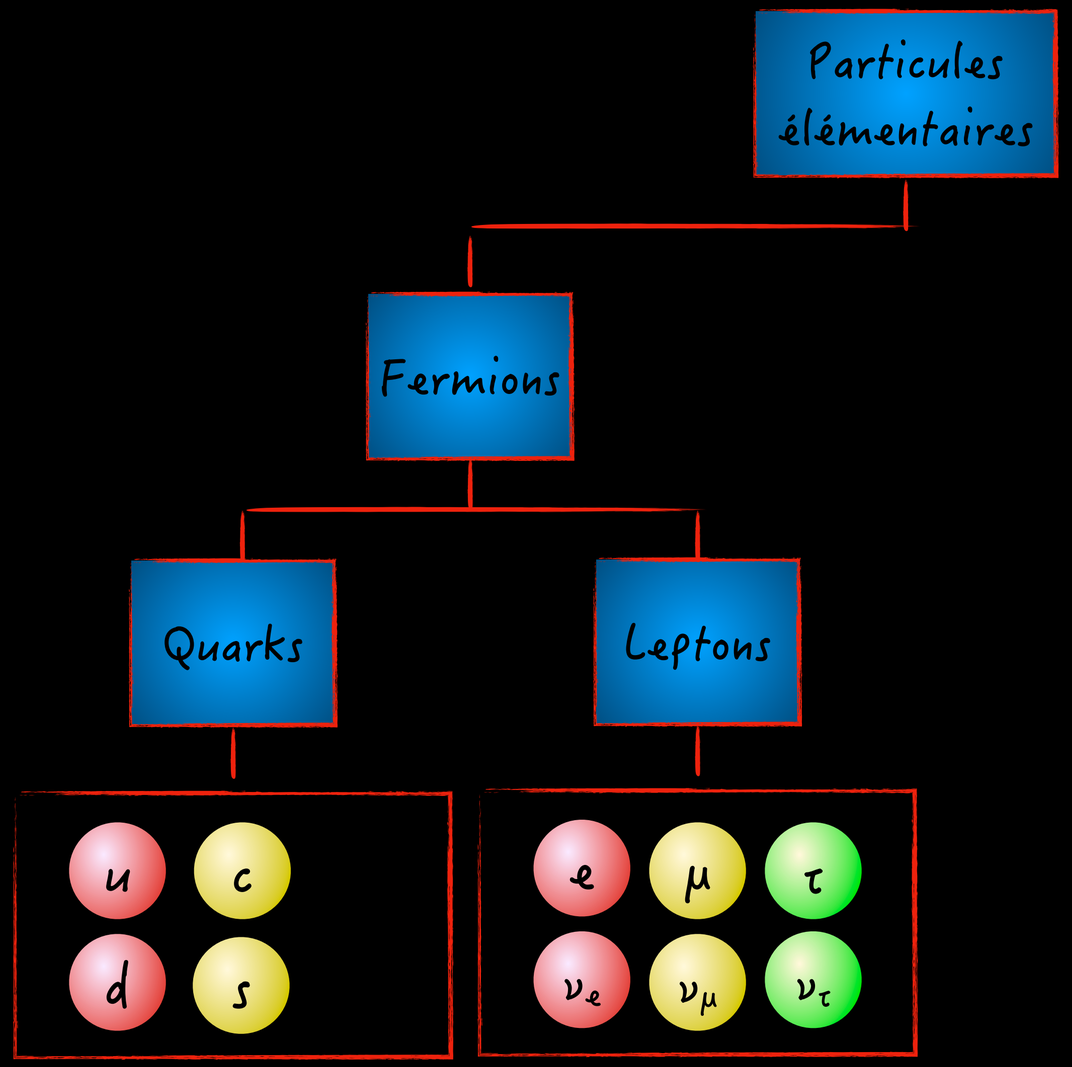




pBe @ 7 TeV

Les particules élémentaires

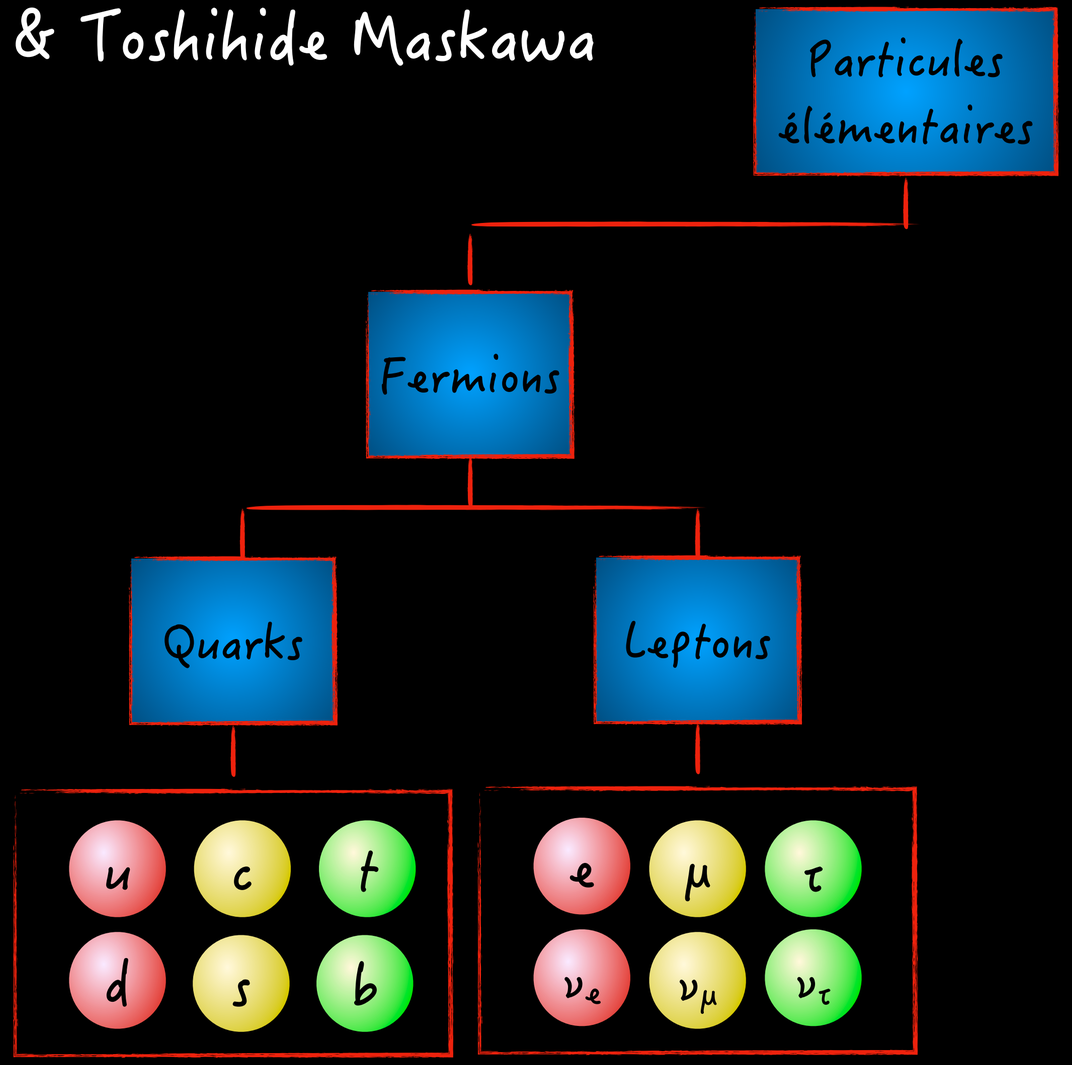
1971 Yung-Su Tsai



Les particules élémentaires

1973 Makoto Kobayashi & Toshihide Maskawa

2008 - P

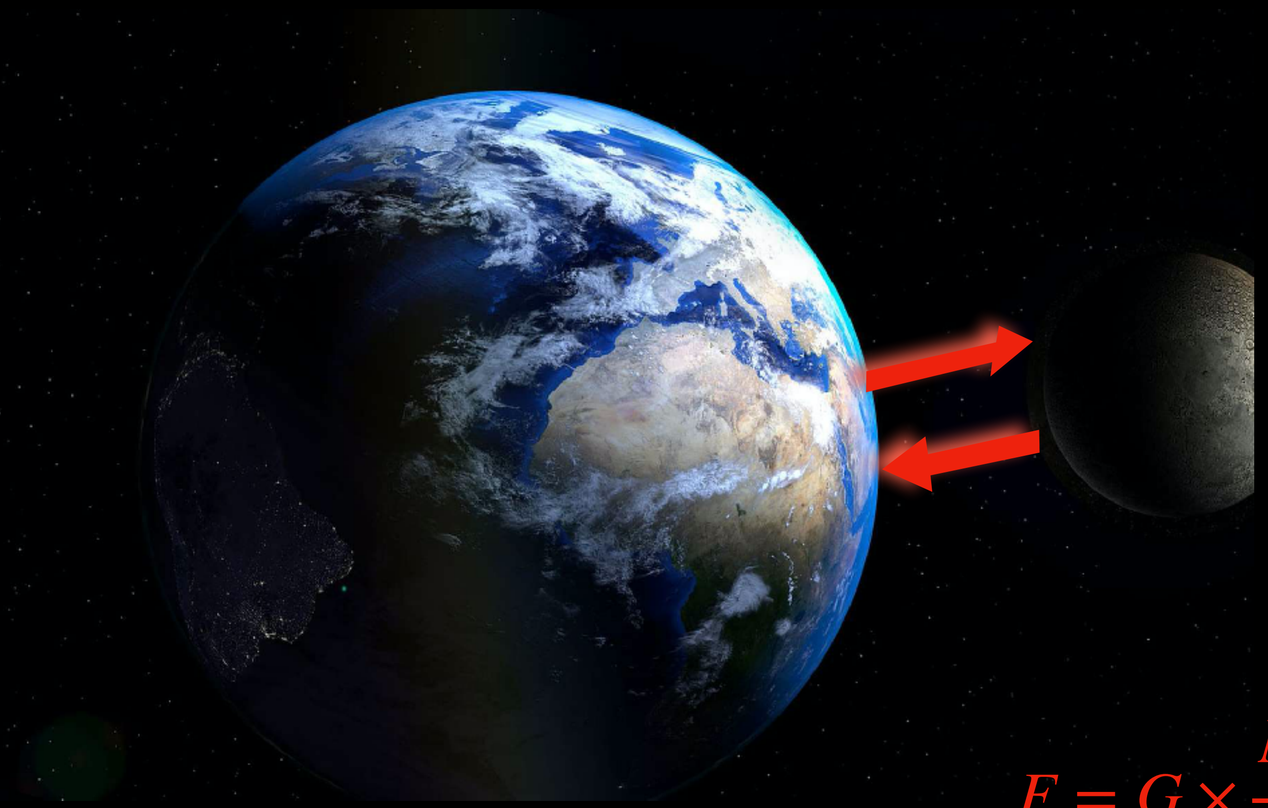


Les forces

Classique … à distance !

Hypotheses non fingo

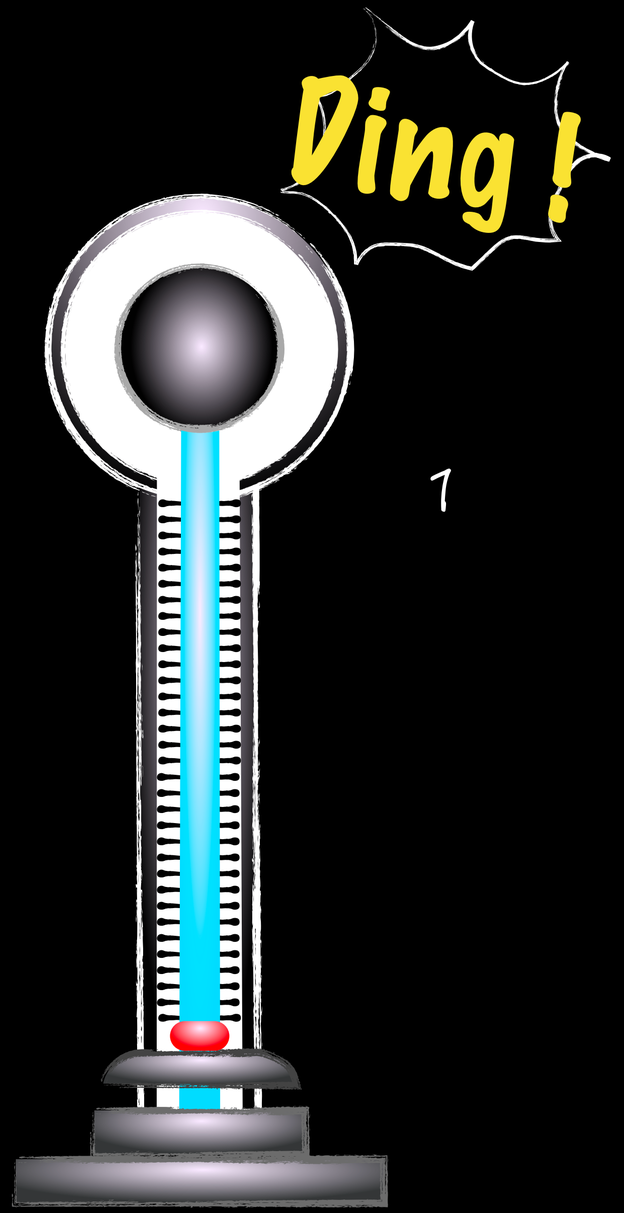
I. Newton



$$F = G \times \frac{M_{\text{Terre}} \times M_{\text{Lune}}}{d_{\text{Terre-Lune}}}$$

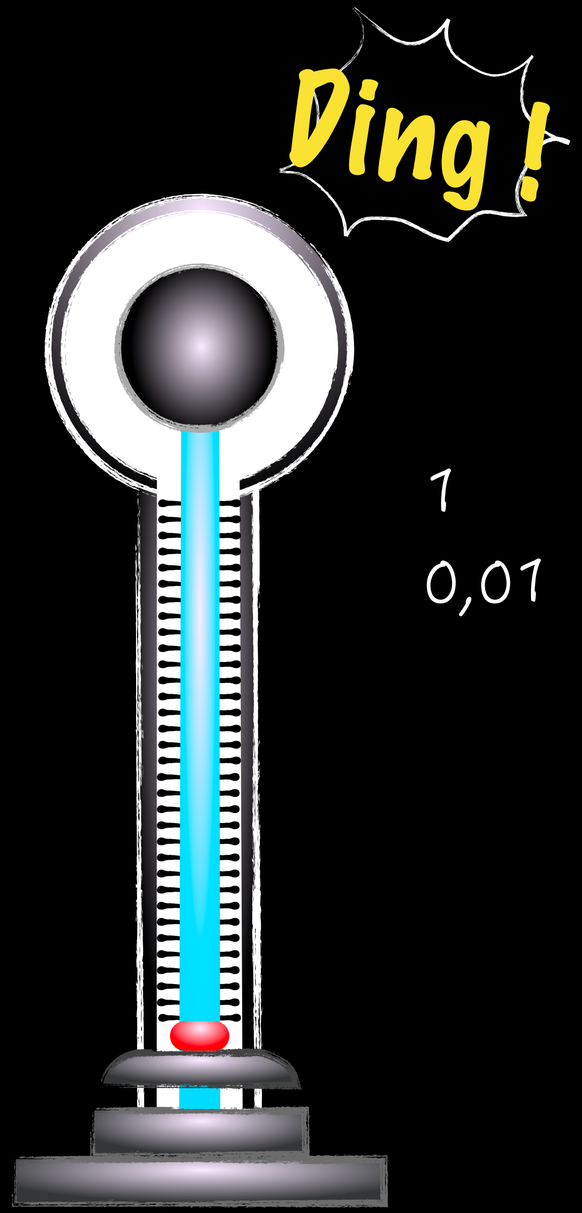
L'intensité des forces

Interaction forte



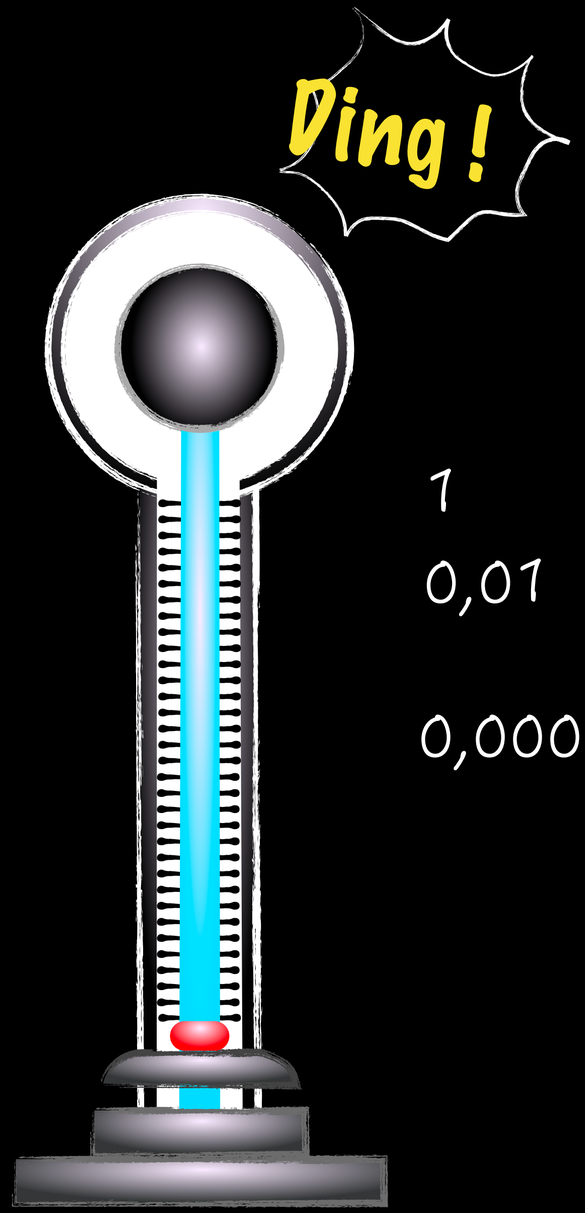
1

L'intensité des forces



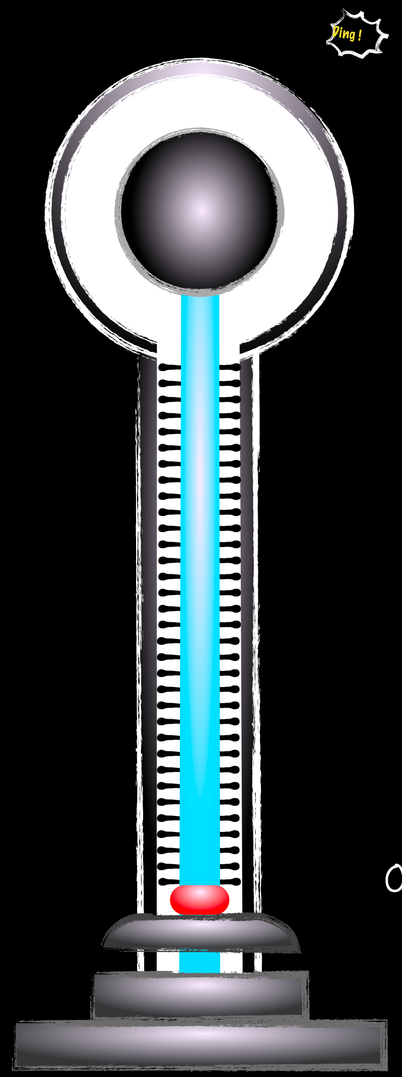
Interaction forte	1
Interaction EM	0,01

L'intensité des forces



Interaction forte	1
Interaction EM	0,01
Interaction faible	0,00001

L'intensité des forces



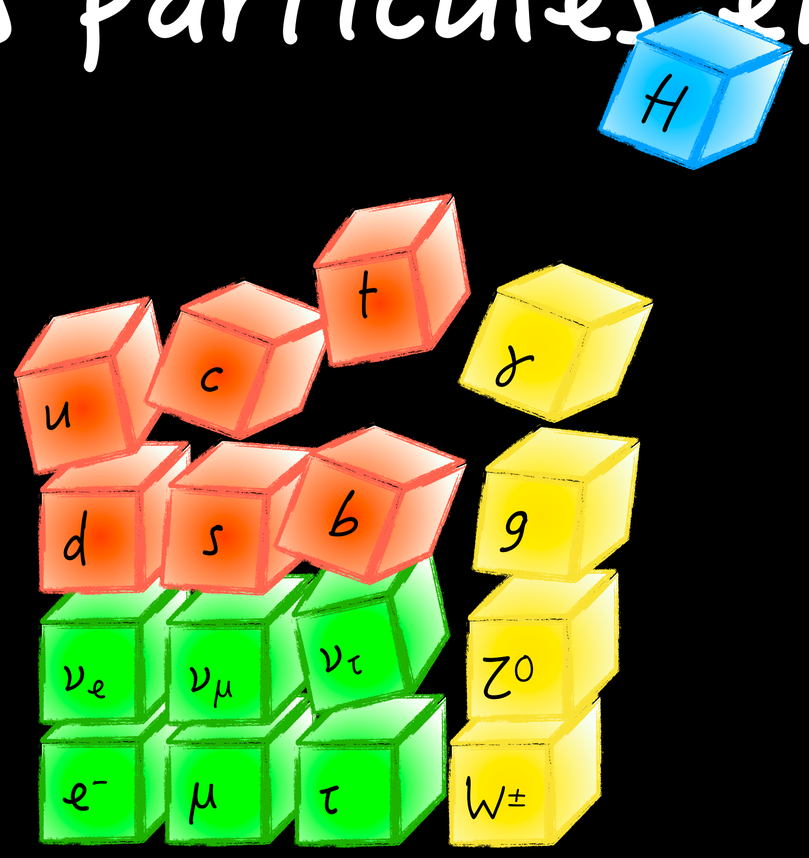
Interaction forte	1
Interaction EM	0,01
Interaction faible	0,00001
Interaction Gravitationnelle	0,00000000000000000000000000000000000001

Le Modèle Standard des particules et des forces

Une théorie cantique des chants

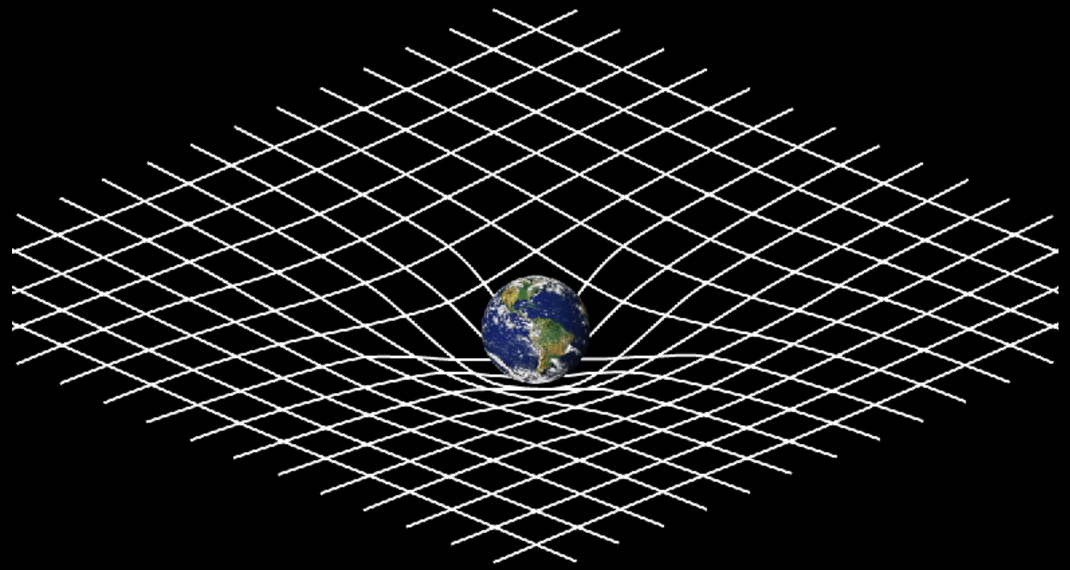
Le Modèle Standard des particules et des forces

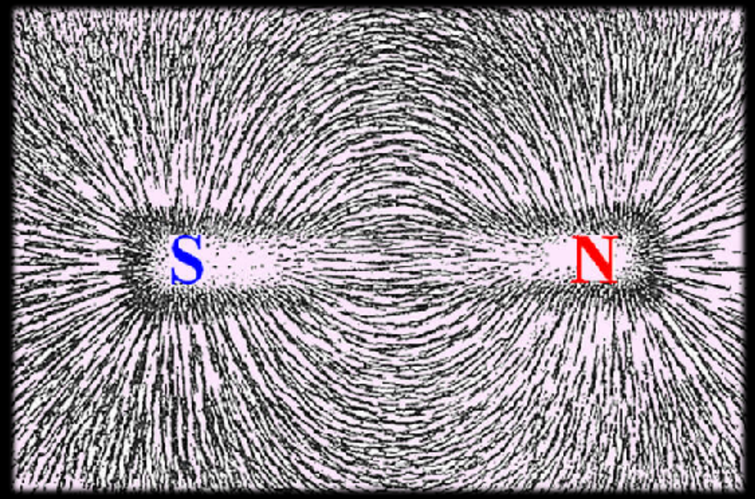
Une théorie quantique des champs

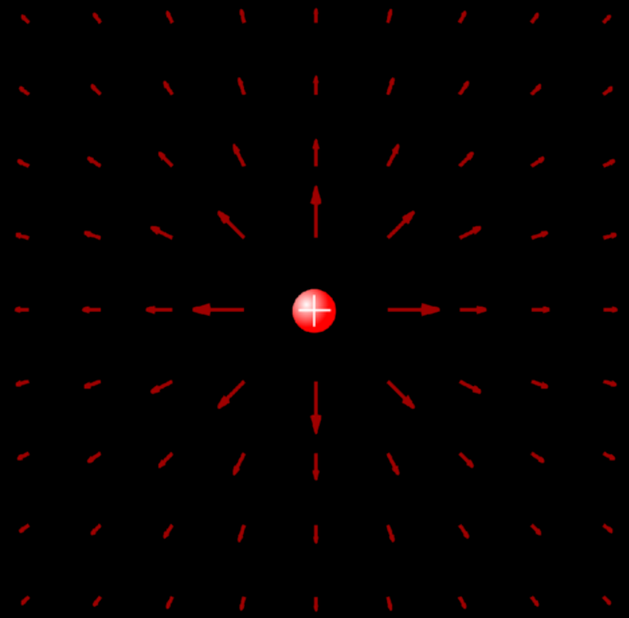


Les forces et les champs

Gravitation, électrique et magnétique … locale

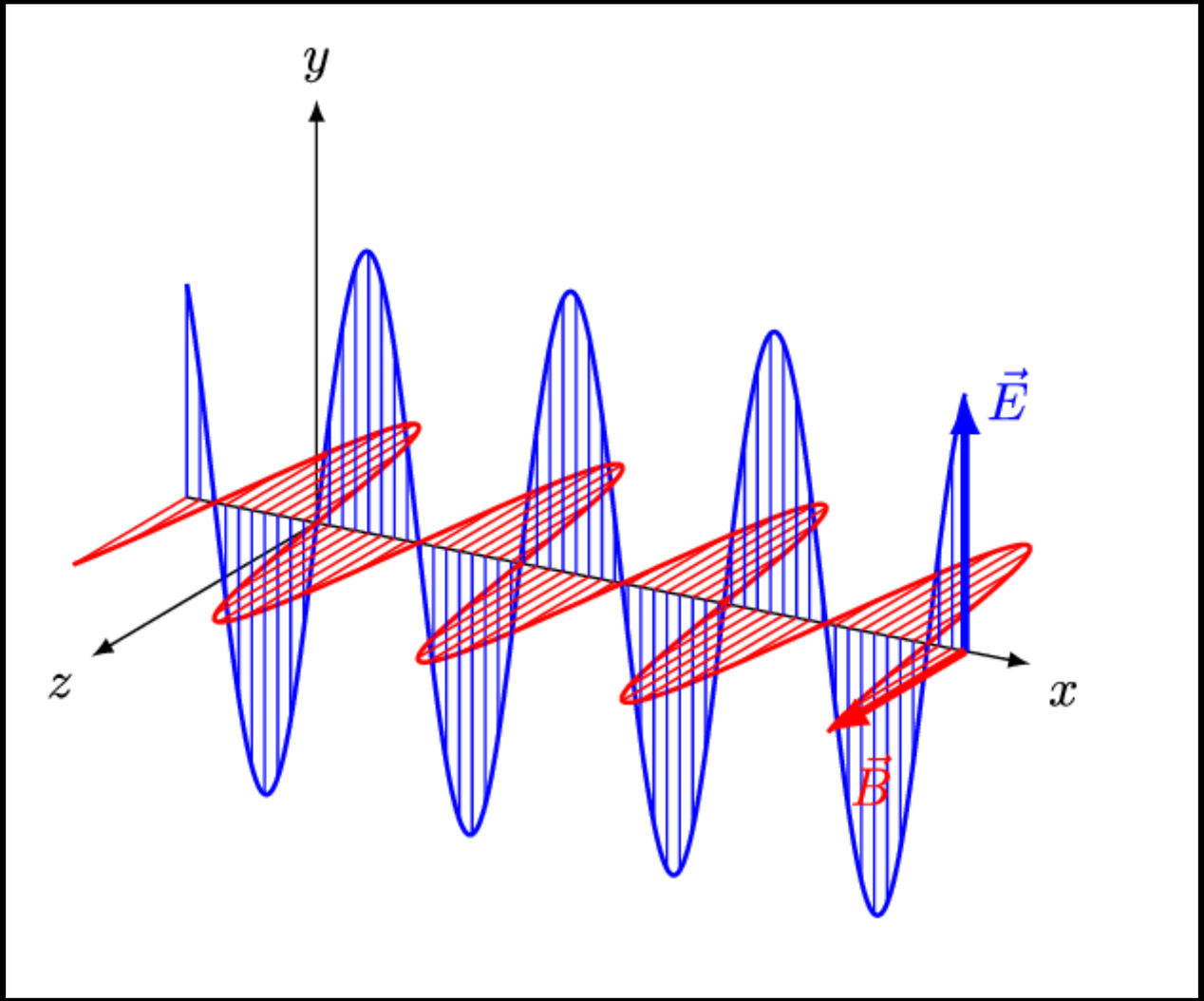




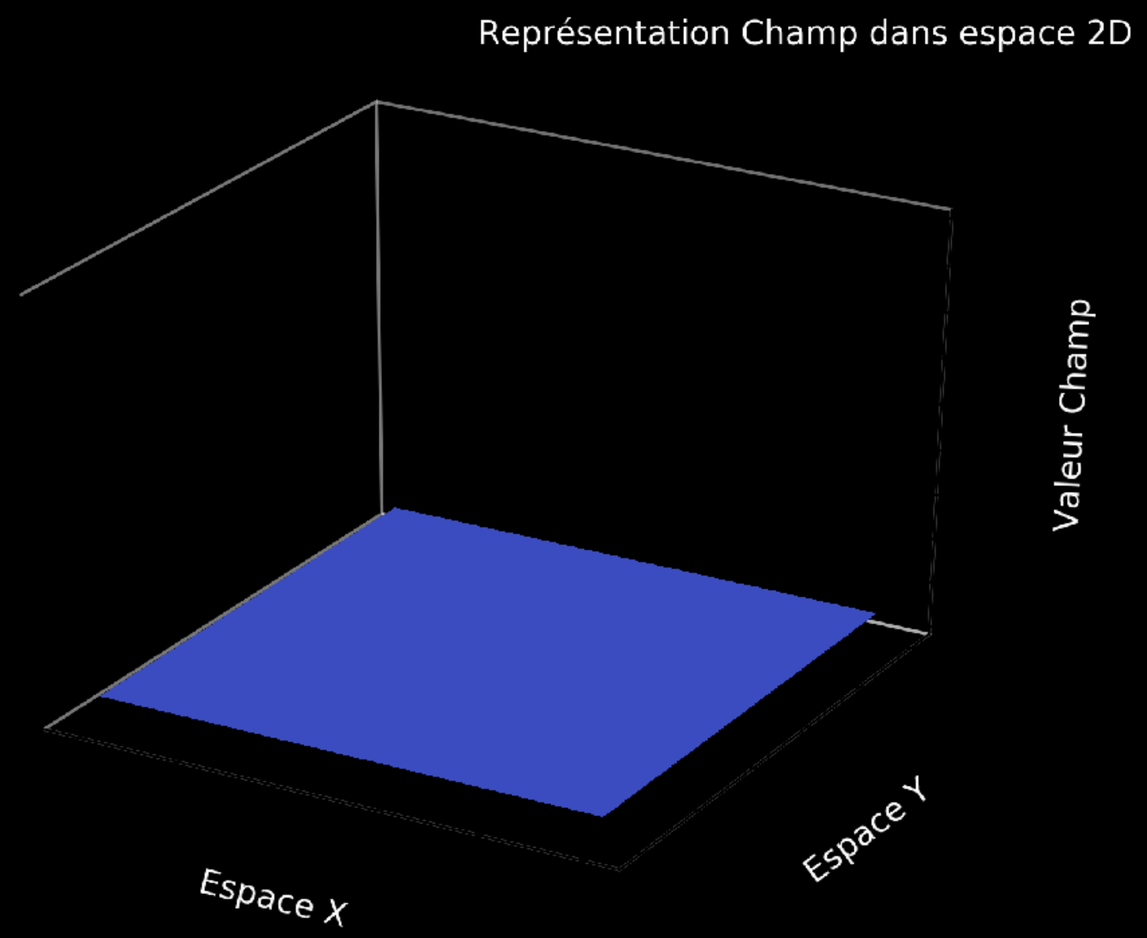


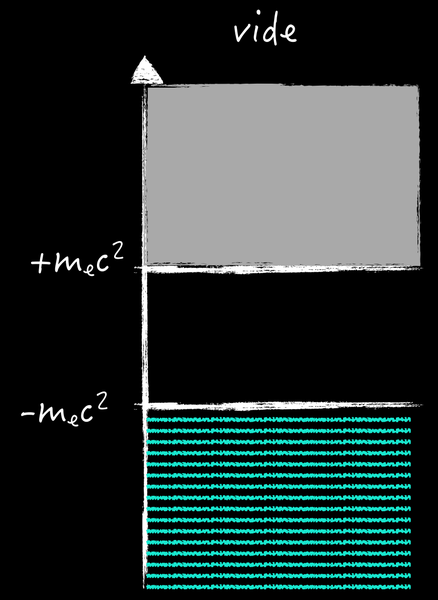
Les forces et les champs

Onde électromagnétique



Les champs quantiques

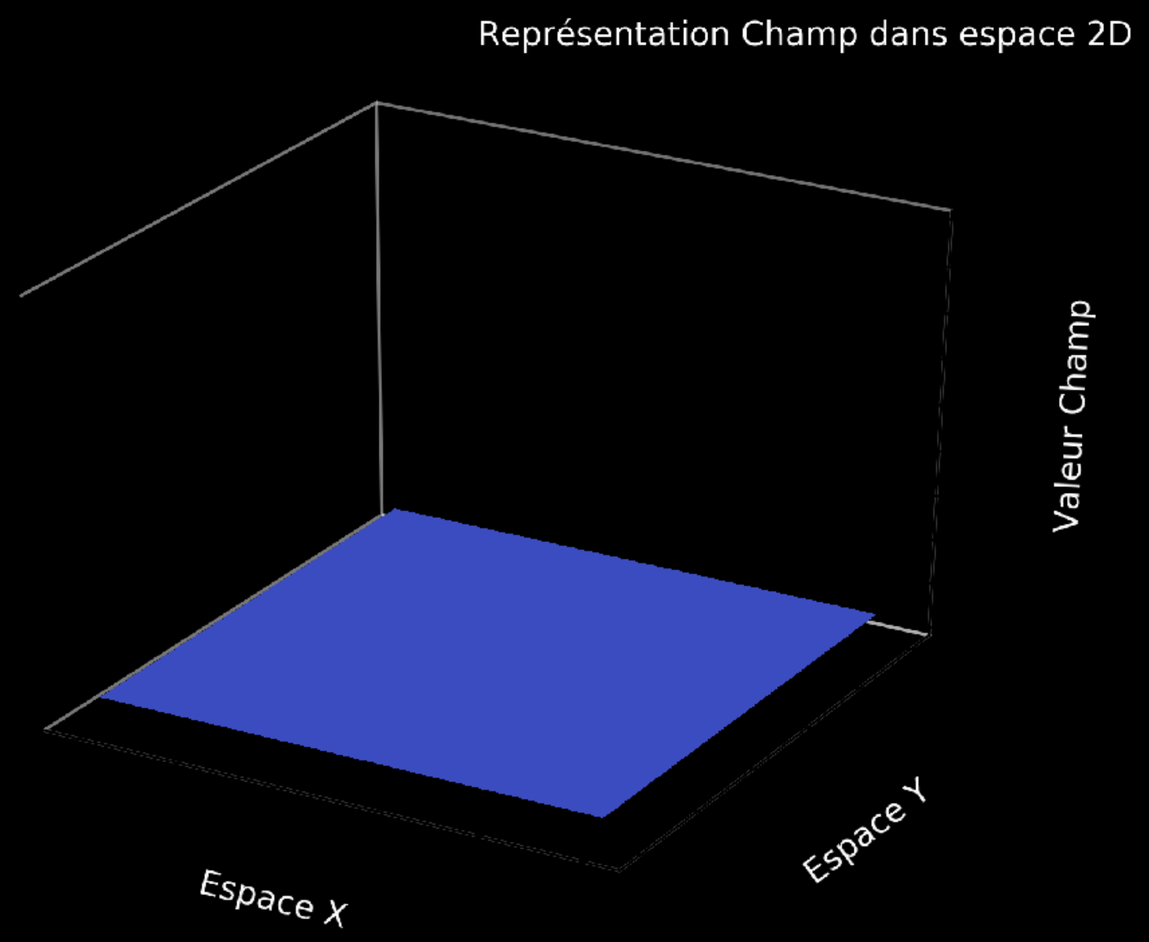




1. Mer de Dirac

Les champs quantiques

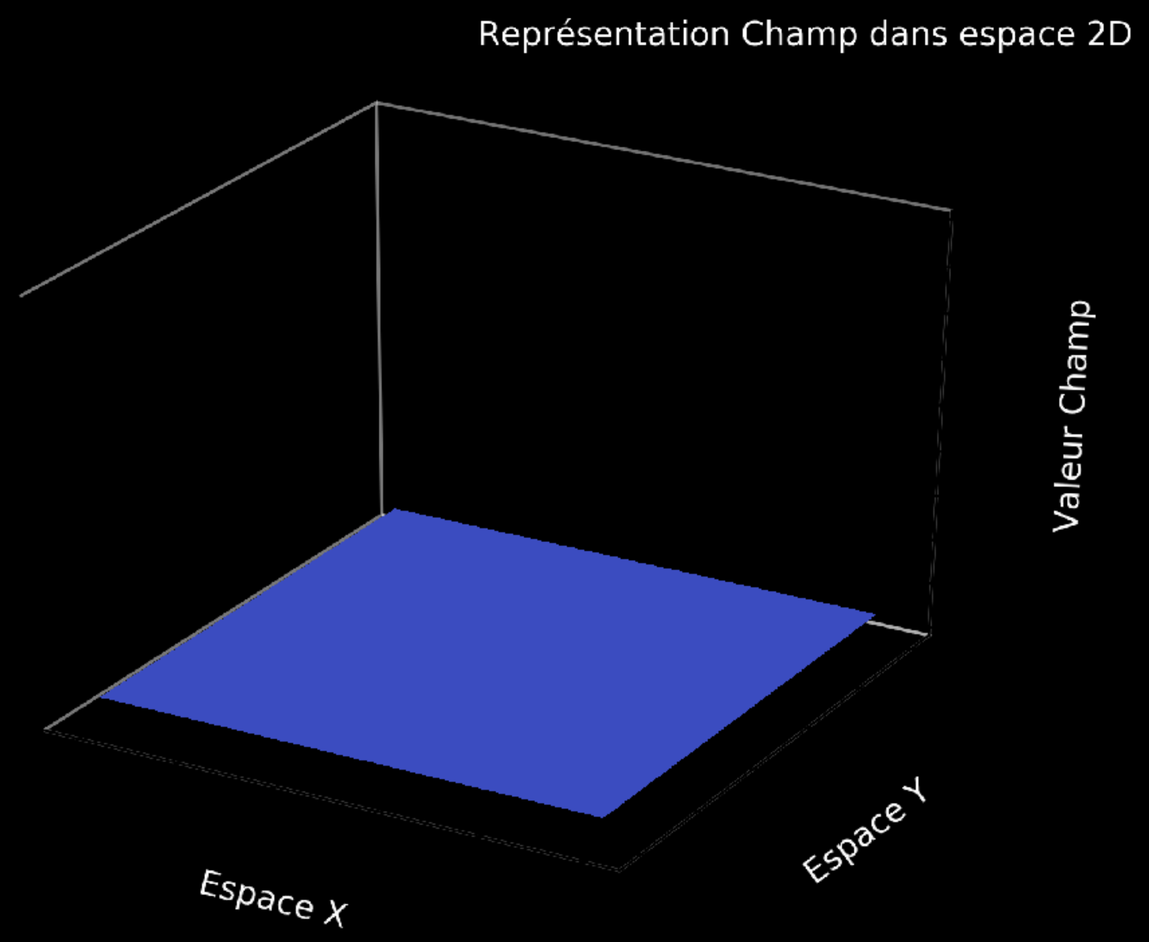
$$\Delta E \times \Delta t \geq \hbar/2$$



1. Mer de Dirac
2. Principe d'indétermination

Les champs quantiques

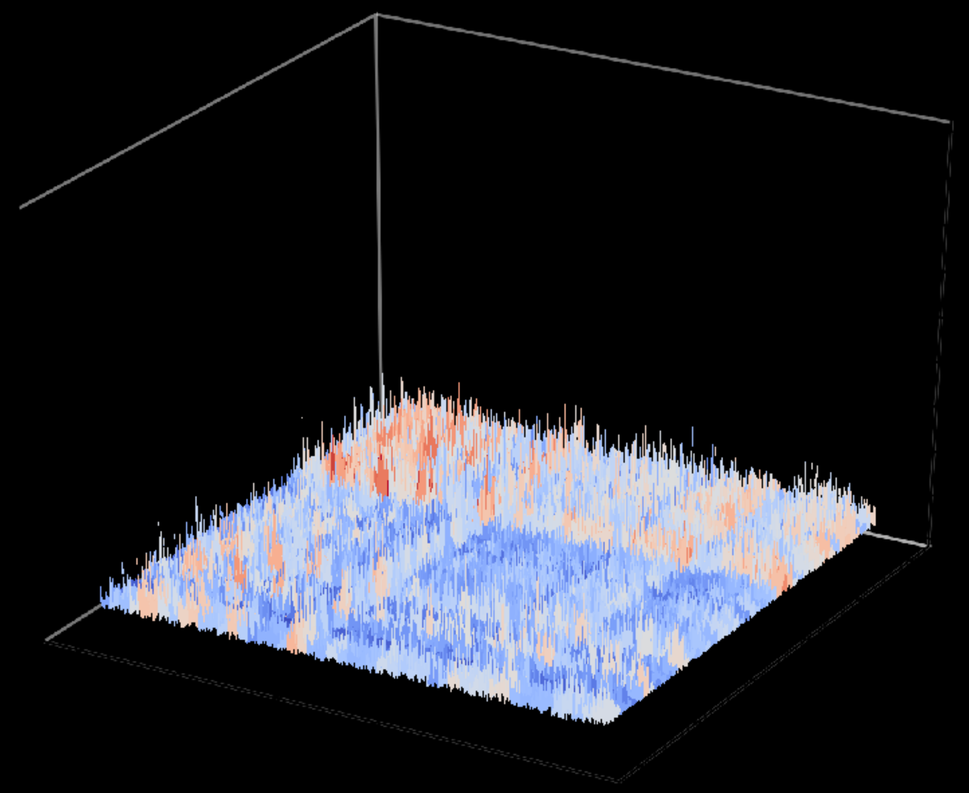
$E = mc^2$



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

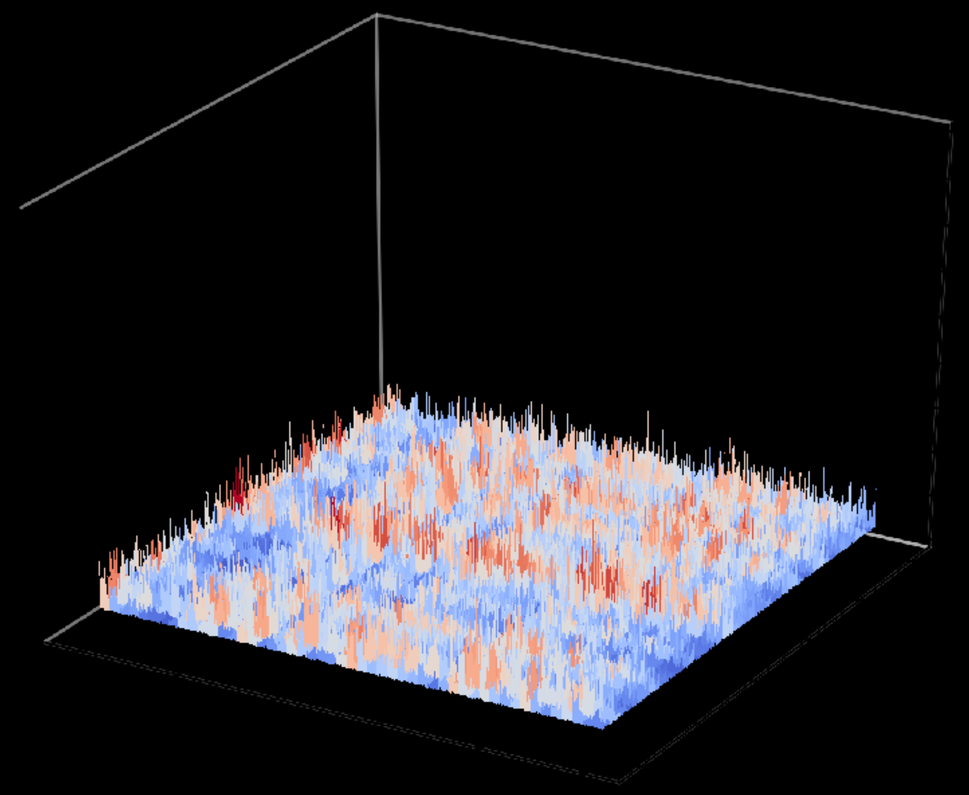
$E \rightarrow e^+ e^-$



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

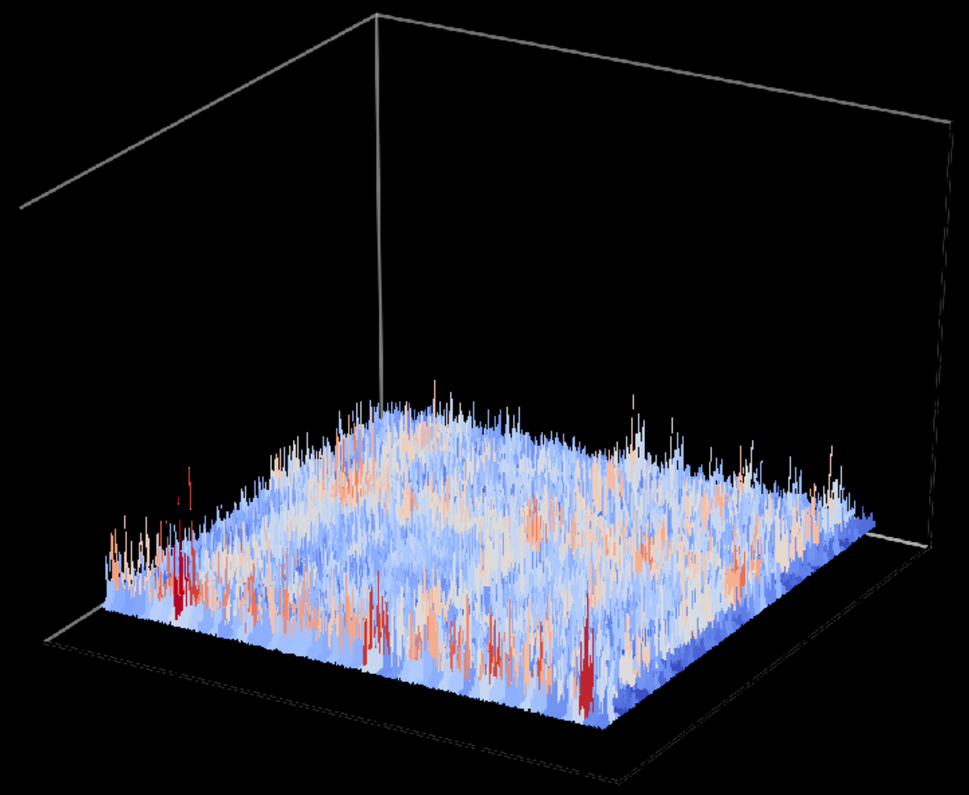
$E \rightarrow e^+ e^-$



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

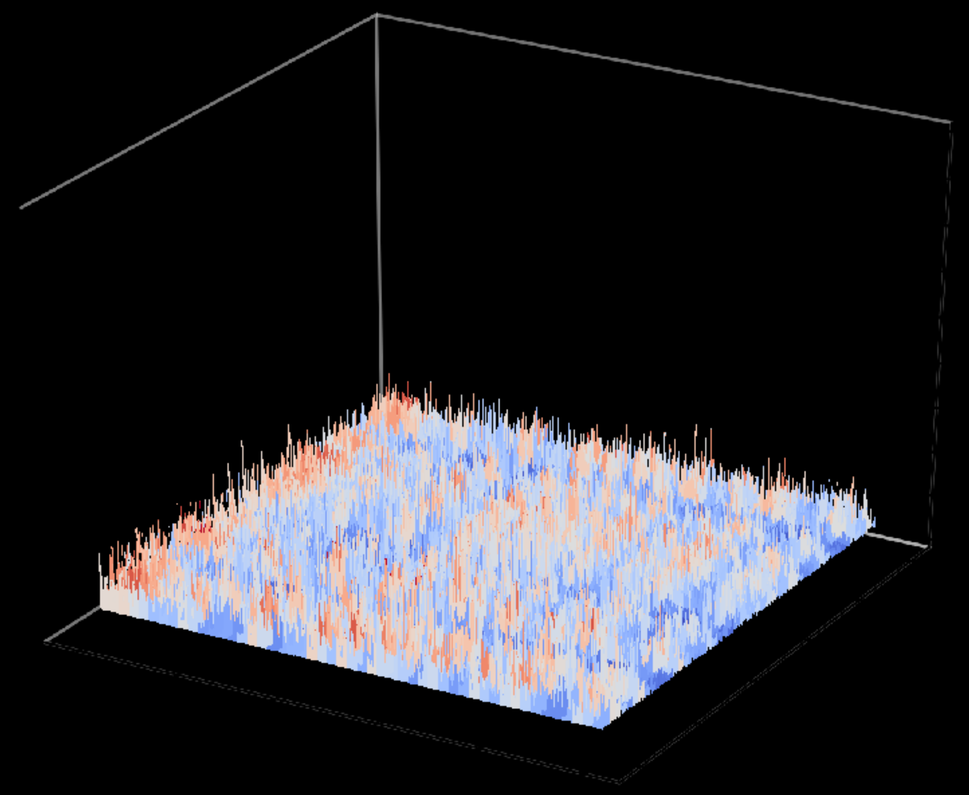
$E \rightarrow e^+ e^-$



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

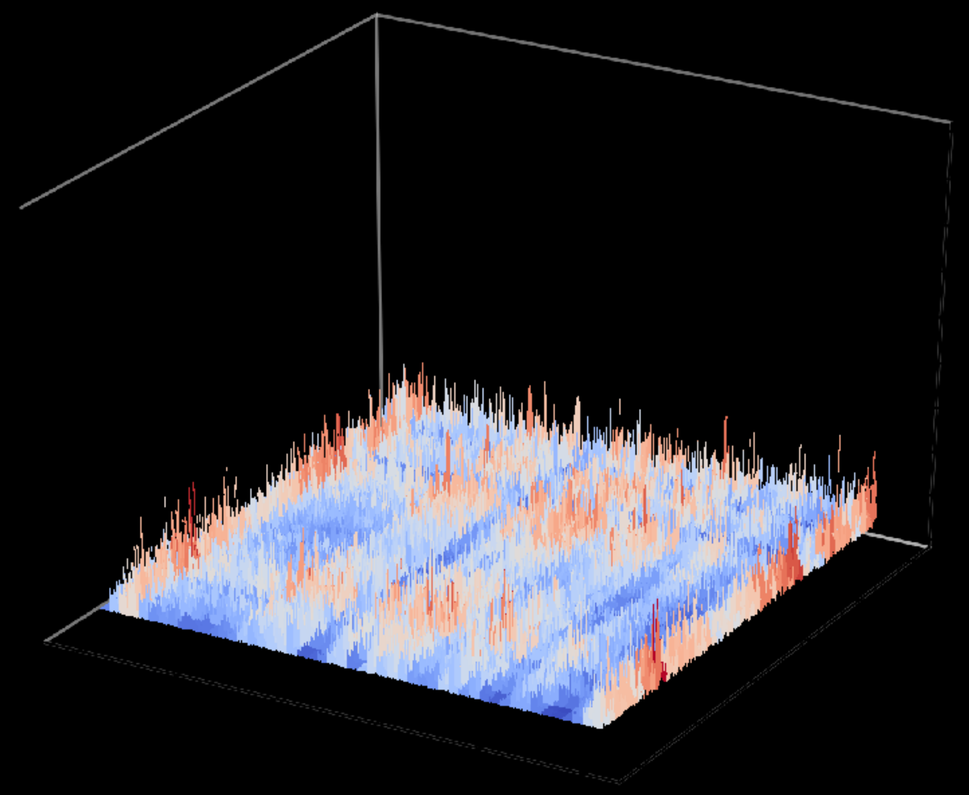
$E \rightarrow e^+ e^-$



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

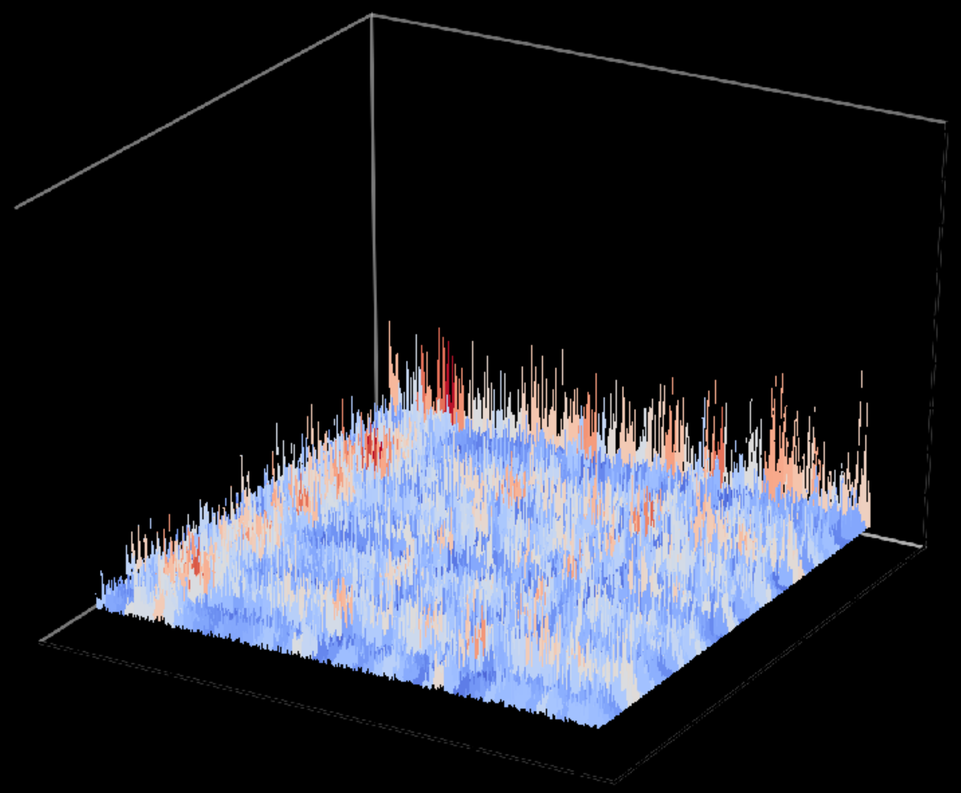
$E \rightarrow e^+ e^-$



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

$E \rightarrow e^+ e^-$

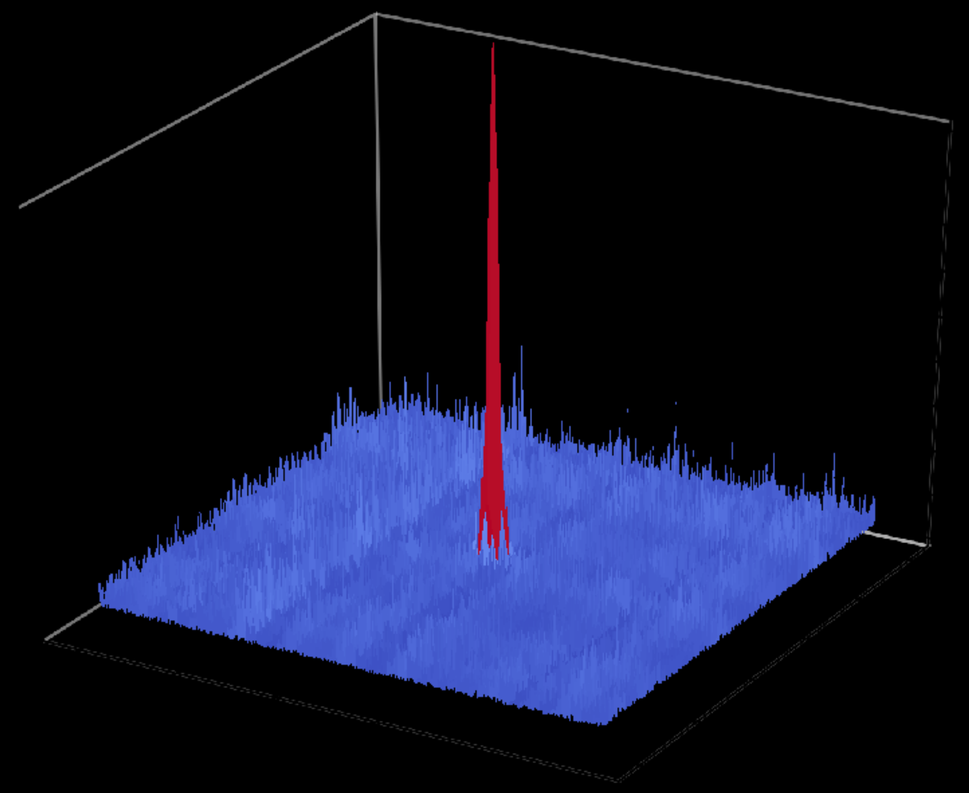


1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

Champ de matière

Électron dans vide quantique



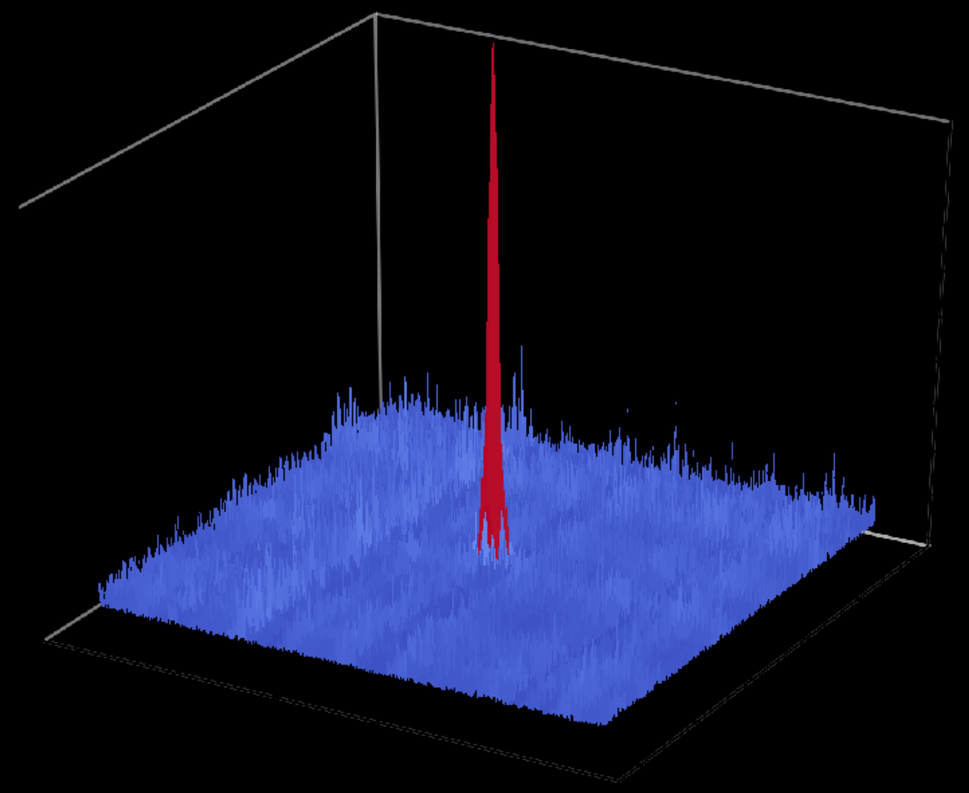
1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie

Les champs quantiques

Champ de matière

$$|\psi\rangle = \sum_n a_n |n\rangle, \; P_n = a_n^2$$

Électron dans vide quantique



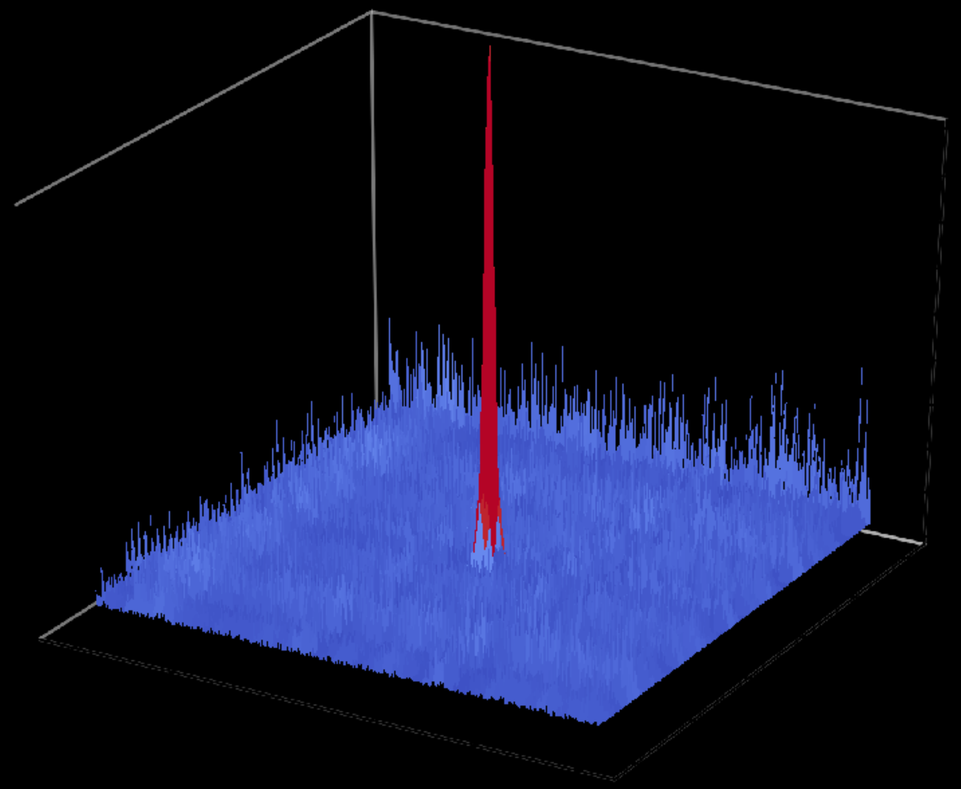
1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie
4. Principe de superposition

Les champs quantiques

Champ de matière

$$|\psi\rangle = \sum_n a_n |n\rangle, \; P_n = a_n^2$$

Électron dans vide quantique



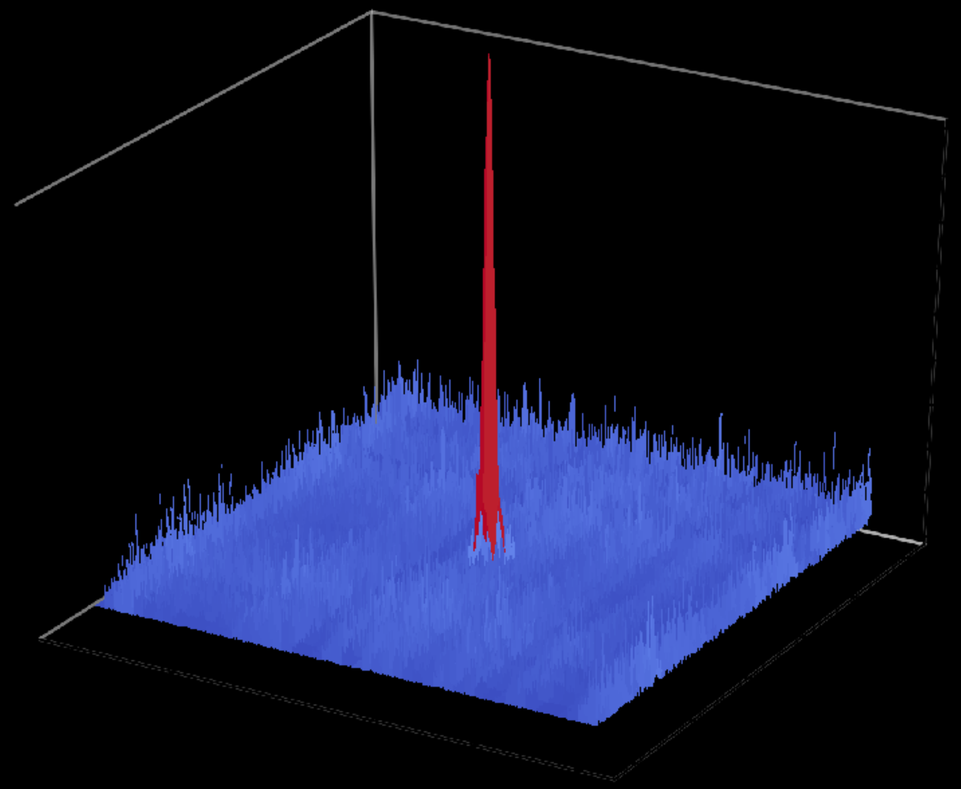
1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie
4. Principe de superposition

Les champs quantiques

Champ de matière

$$|\psi\rangle = \sum_n a_n |n\rangle, \; P_n = a_n^2$$

Électron dans vide quantique



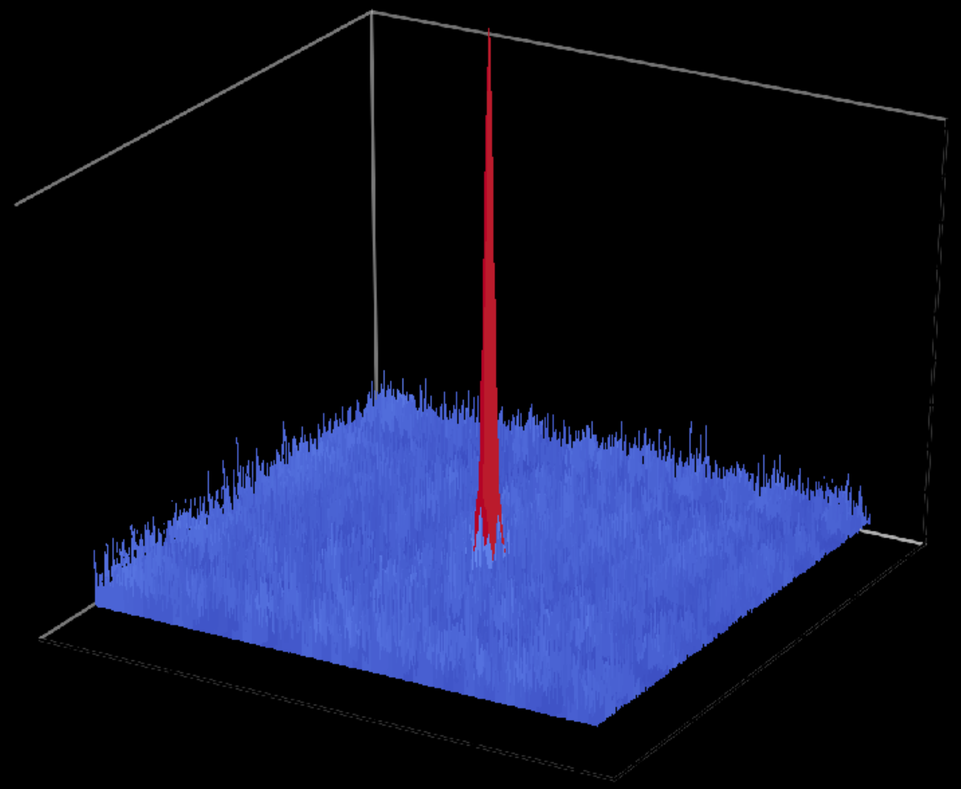
1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie
4. Principe de superposition

Les champs quantiques

Champ de matière

$$|\psi\rangle = \sum_n a_n |n\rangle, \; P_n = a_n^2$$

Électron dans vide quantique



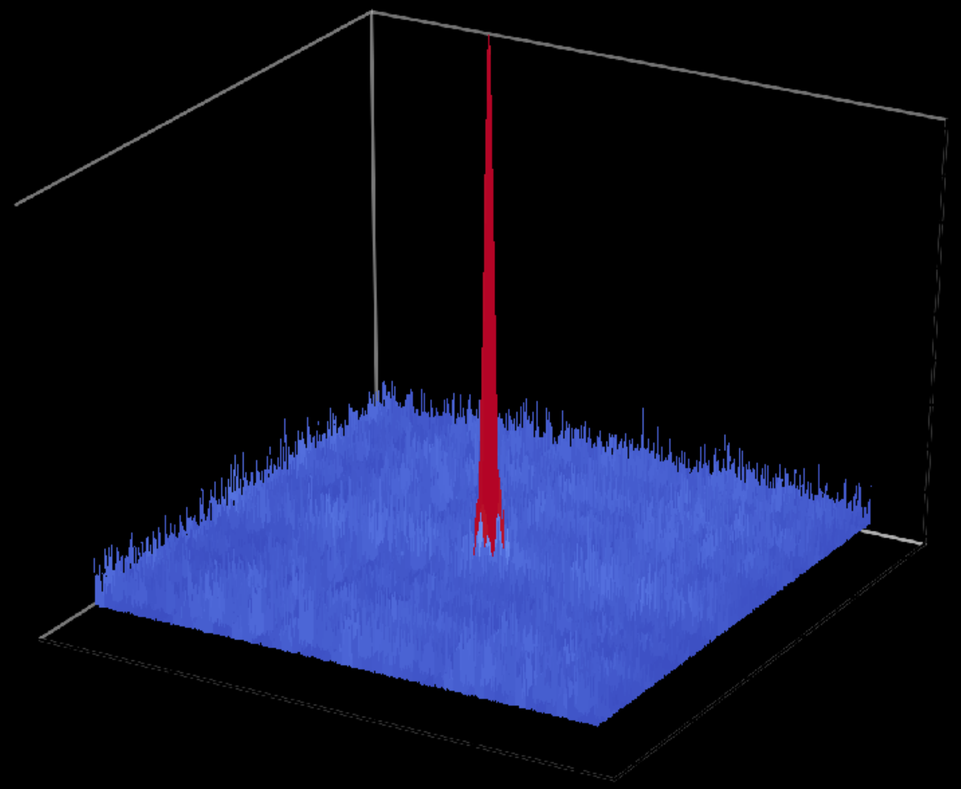
1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie
4. Principe de superposition

Les champs quantiques

Champ de matière

$$|\psi\rangle = \sum_n a_n |n\rangle, \; P_n = a_n^2$$

Électron dans vide quantique



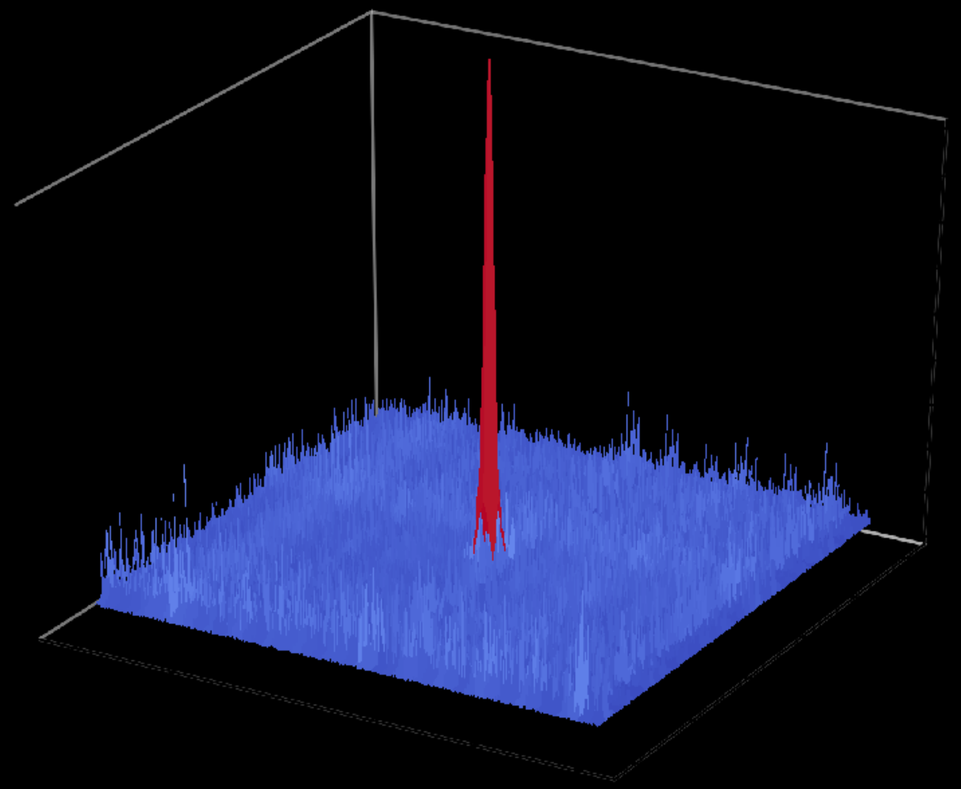
1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie
4. Principe de superposition

Les champs quantiques

Champ de matière

$$|\psi\rangle = \sum_n a_n |n\rangle, \; P_n = a_n^2$$

Électron dans vide quantique



1. Mer de Dirac
2. Principe d'indétermination
3. Equivalence masse/énergie
4. Principe de superposition

Les forces

Champ de force

Décrire l'interaction entre deux charges électriques

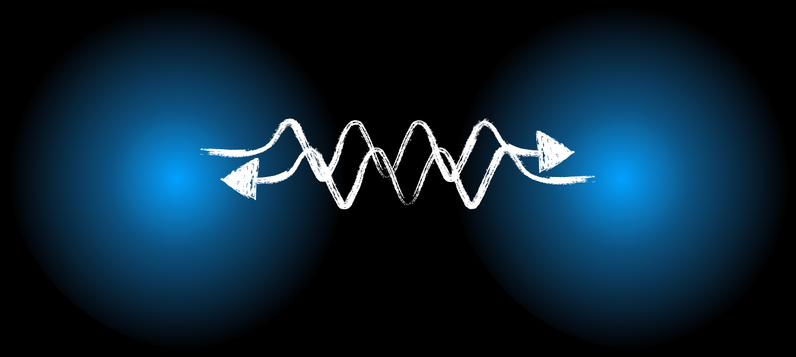
- Formuler un Lagrangien
  - Principe de moindre action
  - Localité
  - Invariance de Lorentz
  - Invariance de jauge

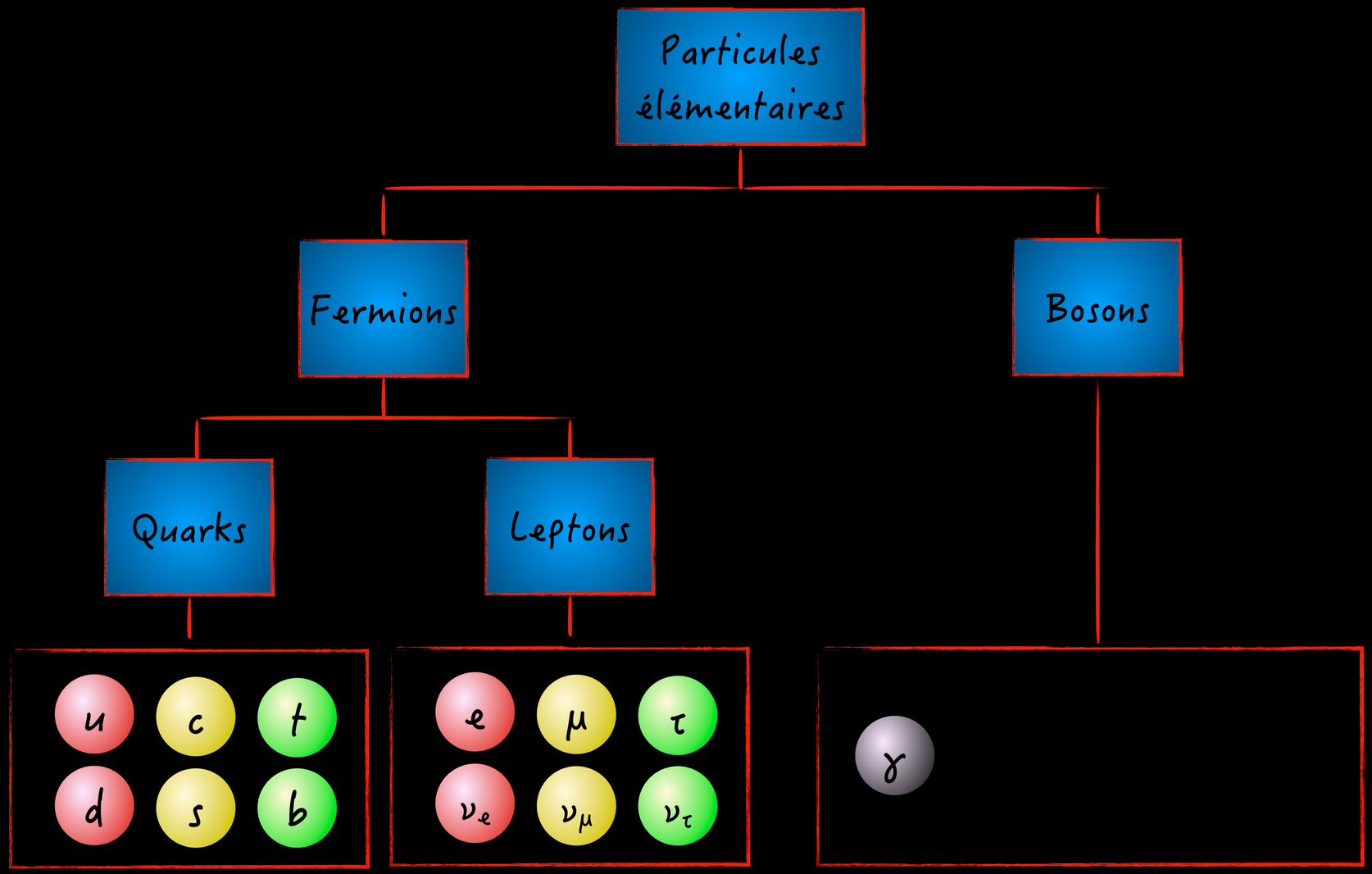
La force électromagnétique

Champ de force : Électrodynamique quantique

- Dirac, Pauli, Wigner, Jordan, Heisenberg
- Sin-ItiroTomonaga, Julian Schwinger, Richard Feynman

1965 - P




Particules élémentaires
Fermions
Bosons
Quarks
Leptons
u
c
t
d
s
b
e
μ
τ
ν_e
ν_μ
ν_τ
γ

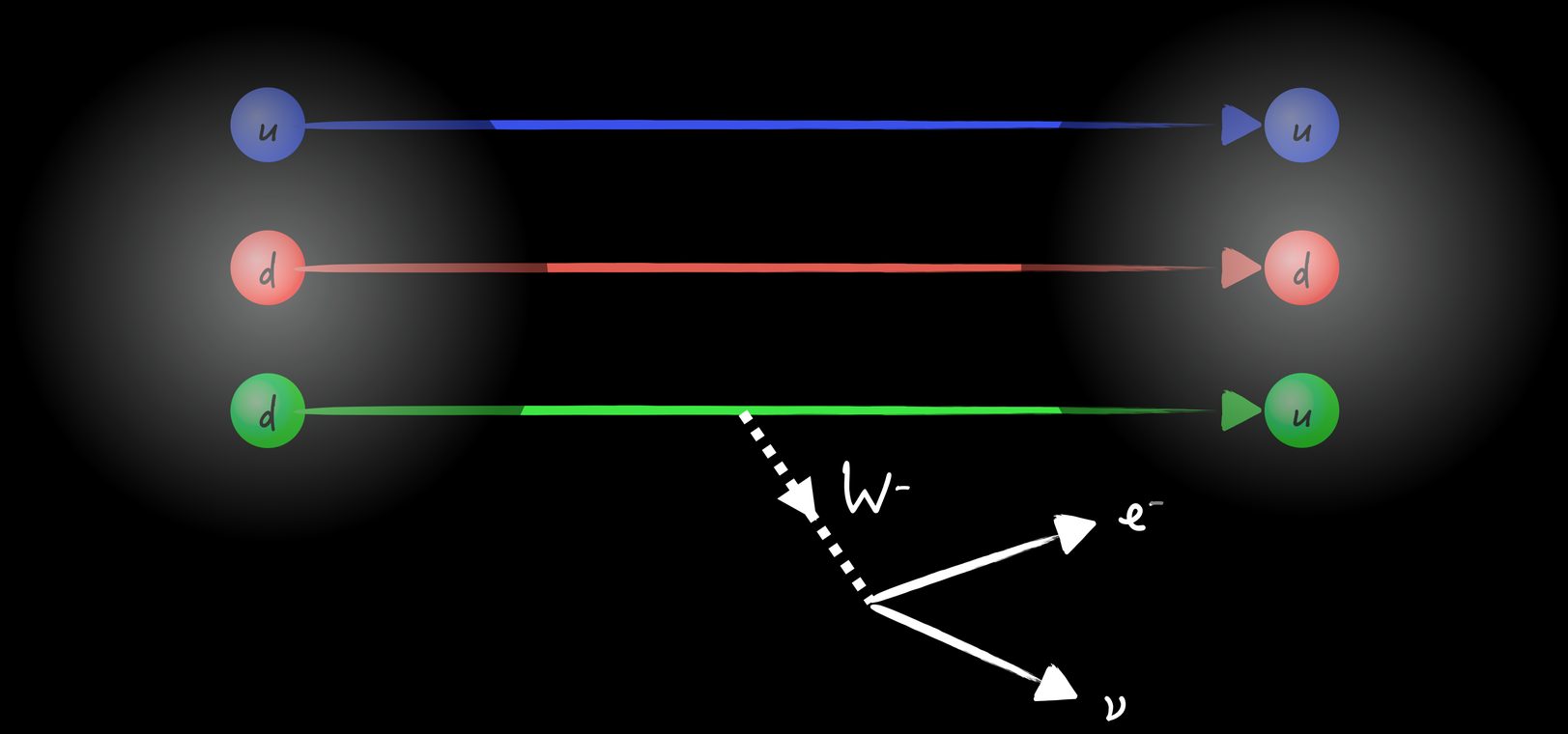
La force faible

- Années 1930 : Pauli, Fermi, Feynman, Gell-Mann, ⋯

Radioactivité β, neutrino : $n \to p + e^- + \bar{\nu}_e$

La force faible

- Années 1930 : Pauli, Fermi, Feynman, Gell-Mann, ...



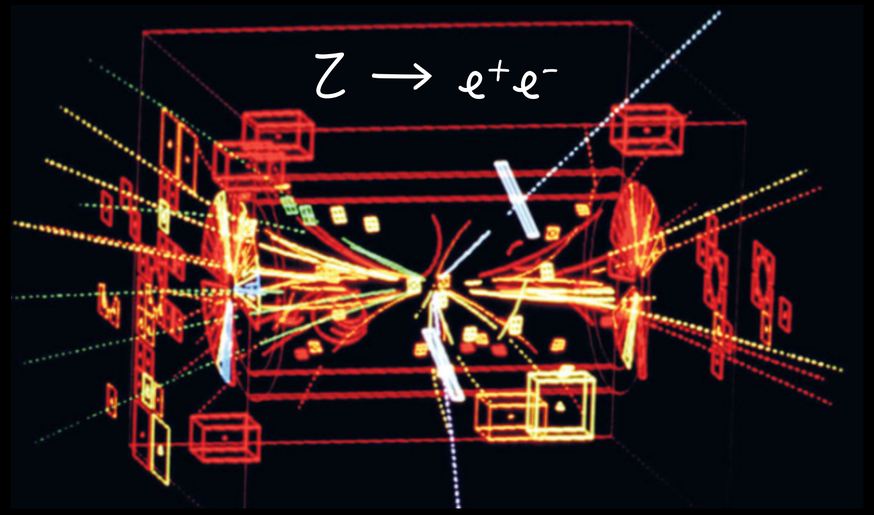
La force faible ··· électrofaible

- Années 1930 : Pauli, Fermi, Feynman, Gell-Mann, ···
- 1968 : Abdus Salam, Sheldon Glashow, Steven Weinberg

1979 - P

Unification des interactions électromagnétique et faible

La force faible ··· électrofaible



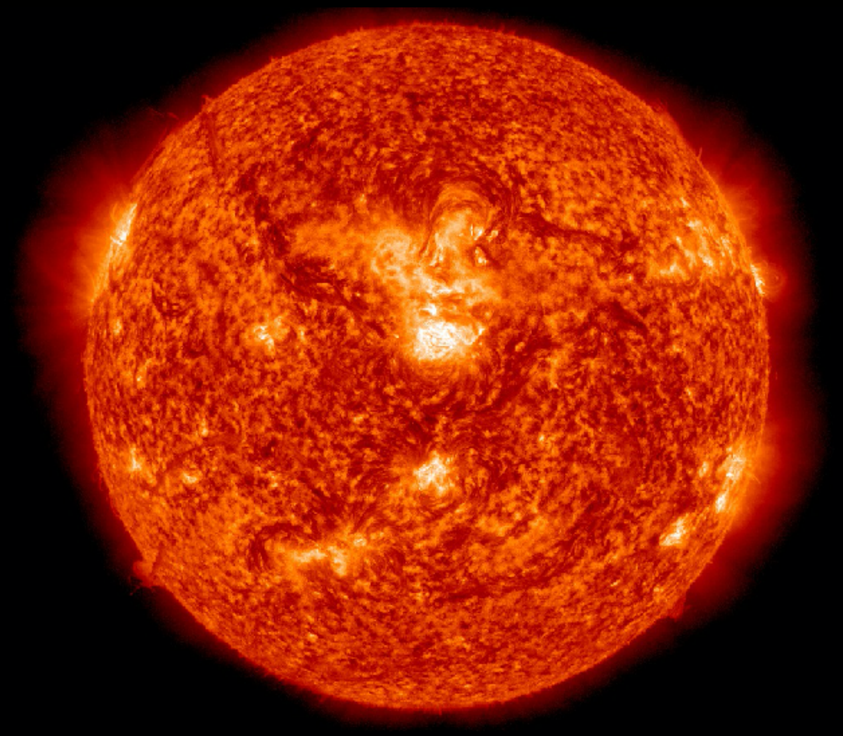
- Années 1930 : Pauli, Fermi, Feynman, Gell-Mann, ···
- 1968 : Abdus Salam, Sheldon Glashow, Steven Weinberg
- 1983 : Carlo Rubbia, Simon van der Meer

1979 - P

1984 - P

Découverte des médiateurs Z^0, $W^\pm$

La force faible … électrofaible

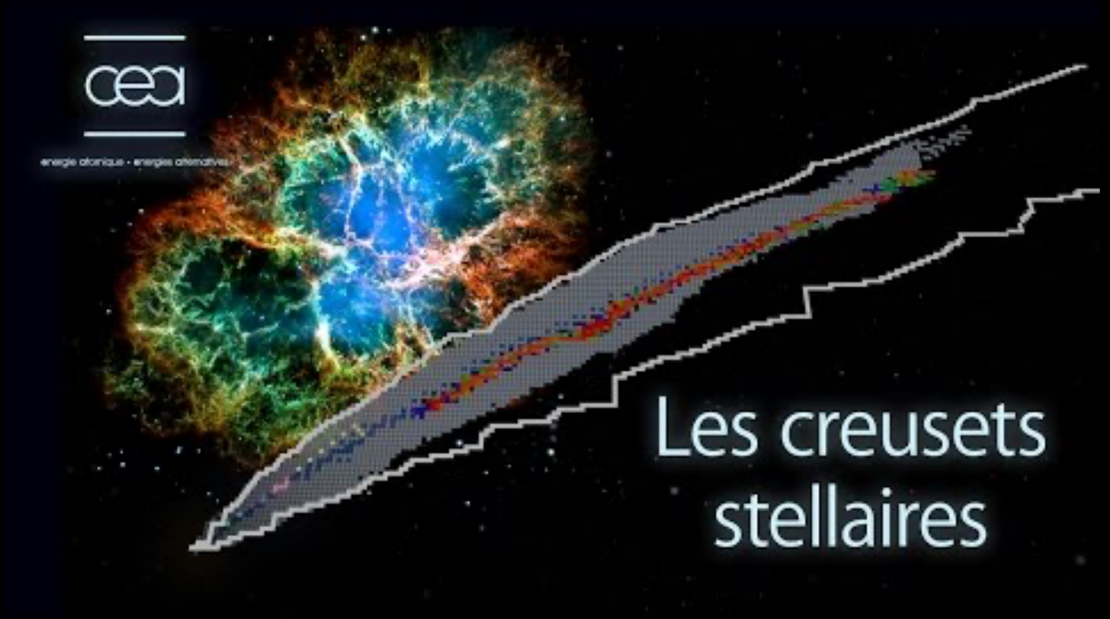


- Années 1930 : Pauli, Fermi, Feynman, Gell-Mann, …
- 1968 : Abdus Salam, Sheldon Glashow, Steven Weinberg
- 1983 : Carlo Rubbia, Simon van der Meer

Fusion de l'hydrogène → fait briller le soleil

La force faible … électrofaible

- Années 1930 : Fermi, Feynman, Gell-Mann, …
- 1968 : Abdus Salam, Sheldon Glashow, Steven Weinberg
- 1983 : Carlo Rubbia, Simon van der Meer

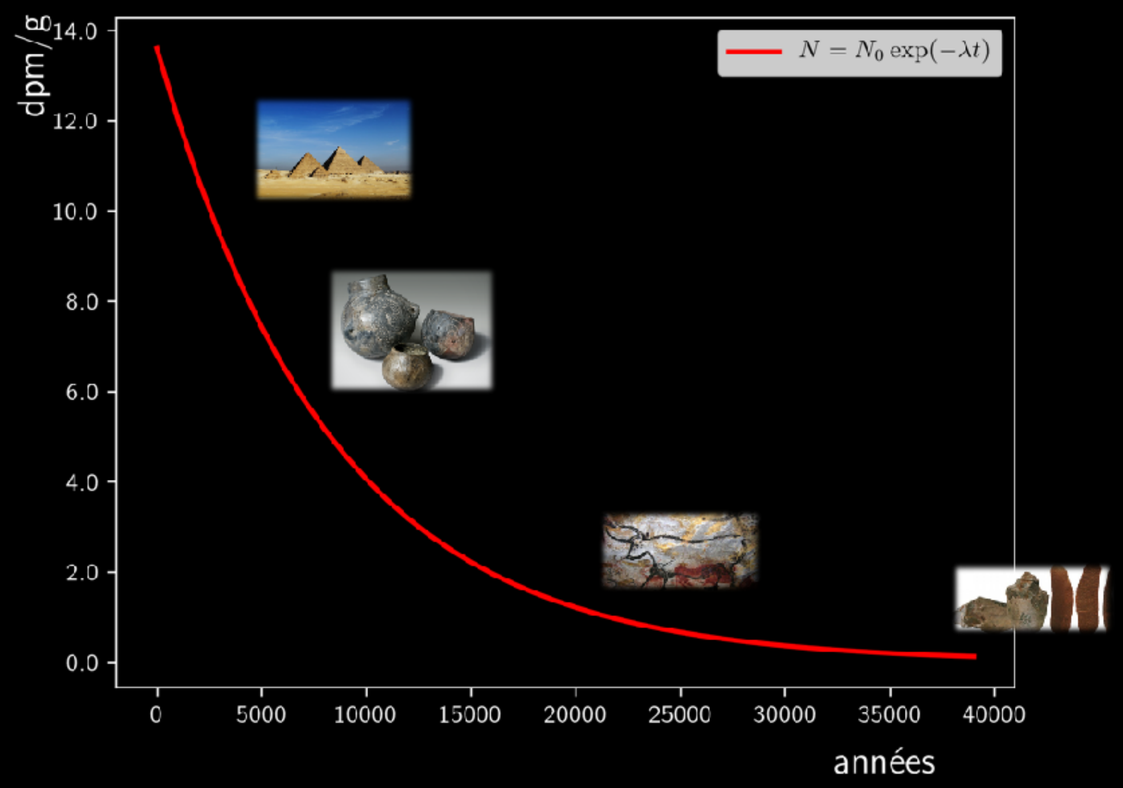


Fusion de l'hydrogène → fait briller le soleil

Radioactivité β → nucléosynthèse dans les étoiles

La force faible ··· électrofaible

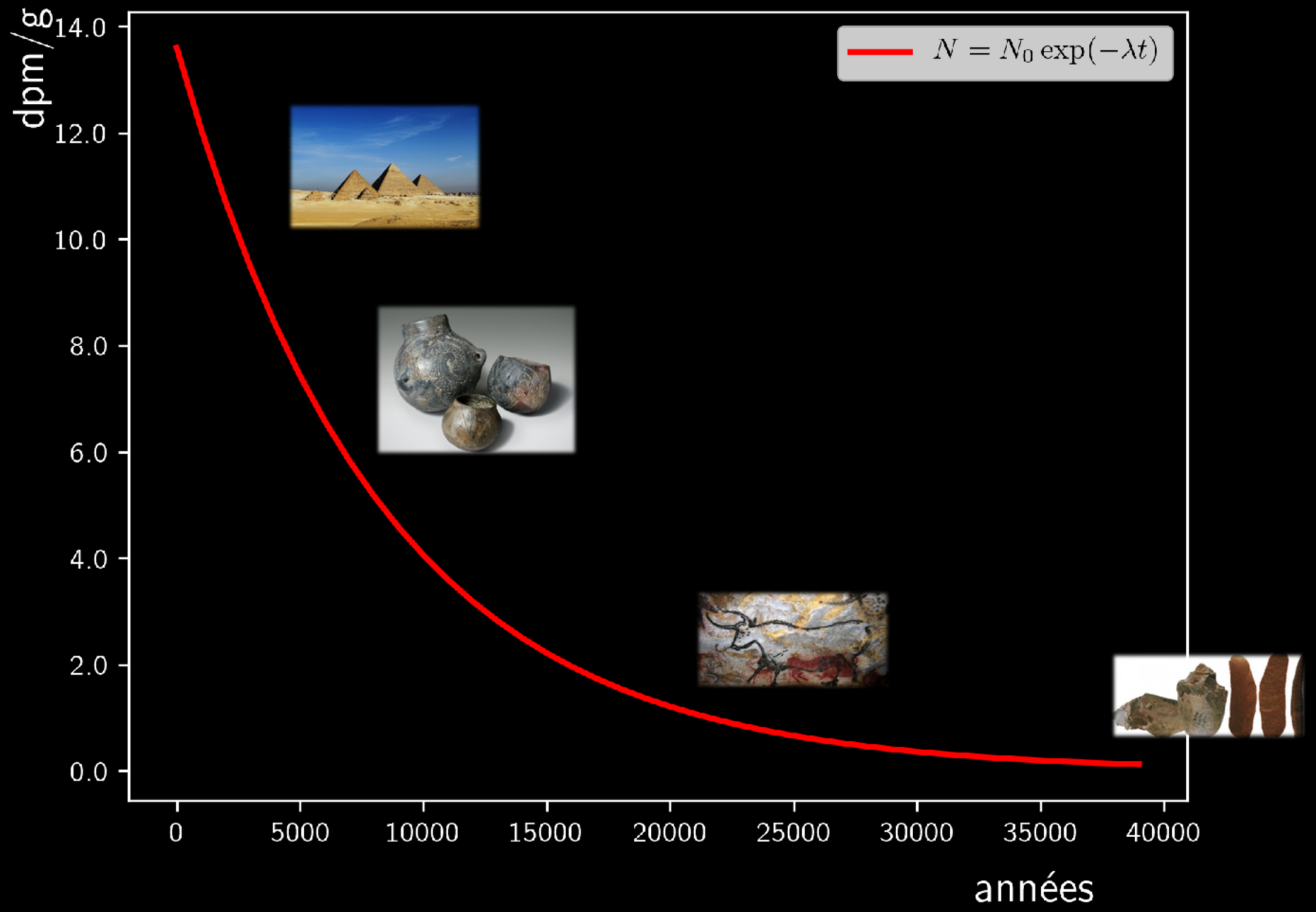
- Années 1930 : Fermi, Feynman, Gell-Mann, ···
- 1968 : Abdus Salam, Sheldon Glashow, Steven Weinberg
- 1983 : Carlo Rubbia, Simon van der Meer

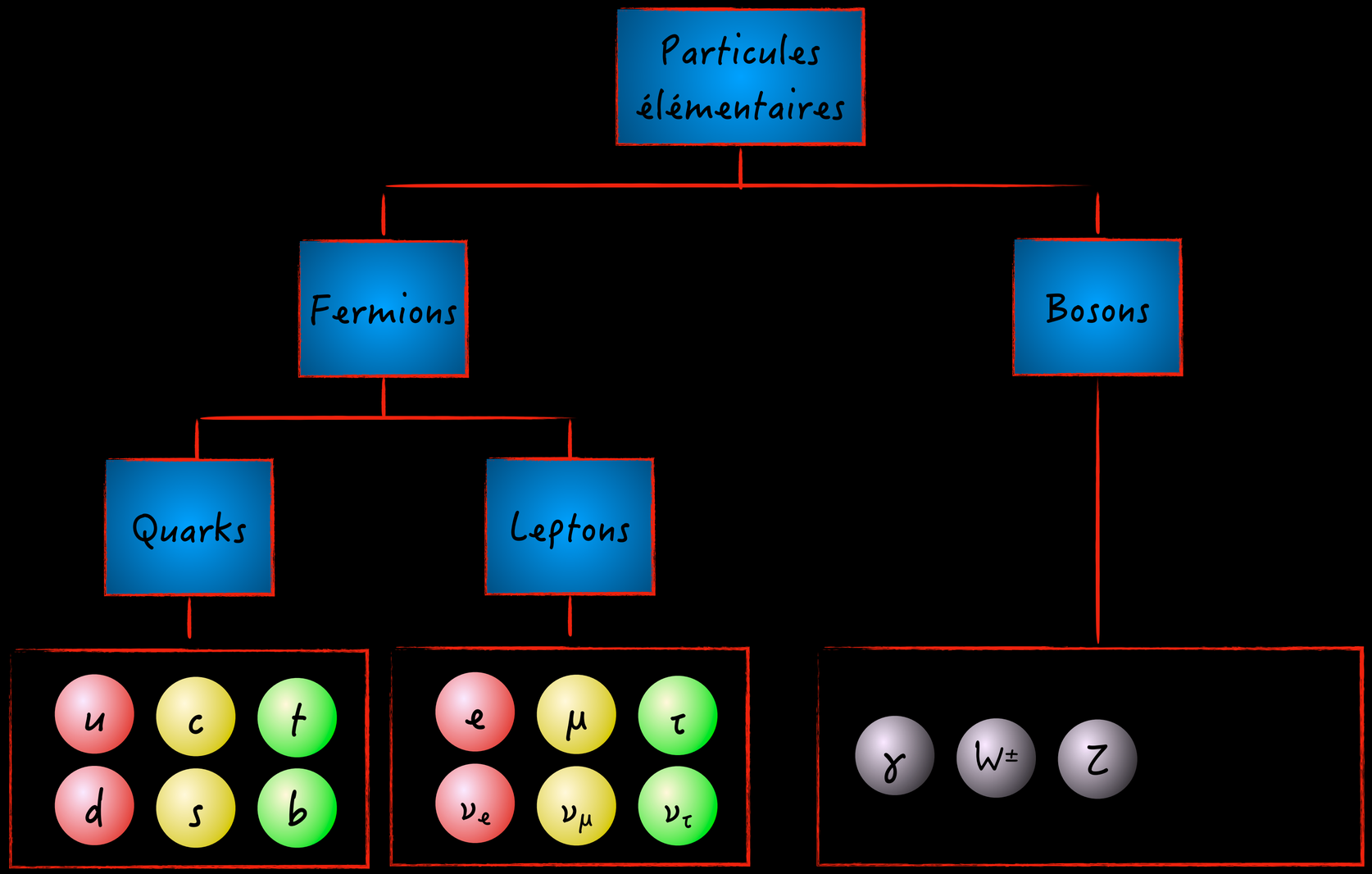


Fusion de l'hydrogène → fait briller le soleil

Radioactivité β → nucléosynthèse dans les étoiles

$^{14}C \rightarrow {}^{14}N$ → datation

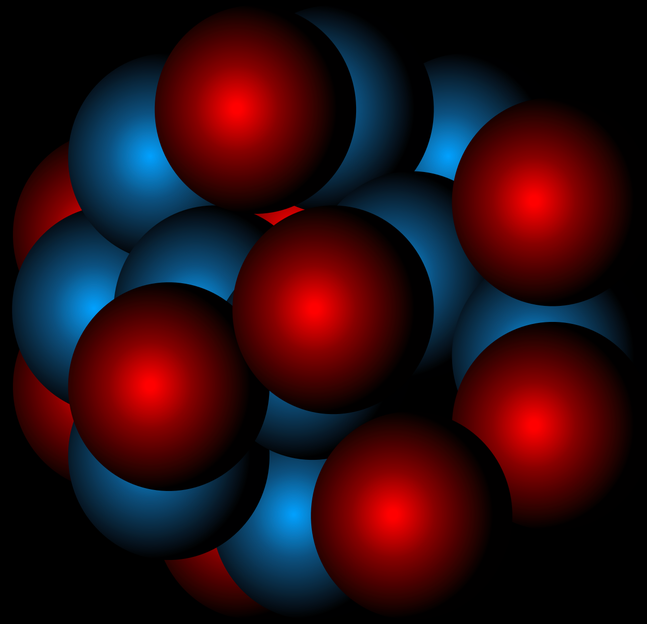

dpm/g
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
35000
40000
années
$N = N_0 \exp(-\lambda t)$


Particules élémentaires
Fermions
Bosons
Quarks
Leptons
u
c
t
d
s
b
e
μ
τ
ν_e
ν_μ
ν_τ
γ
$W^\pm$
Z

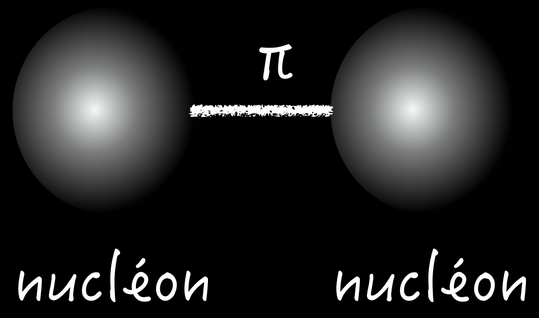
La force forte

Force nucléaire

- 1935 : Hideki Yukawa, cohésion du noyau → interaction forte 1949 - P



Noyau = neutron + proton

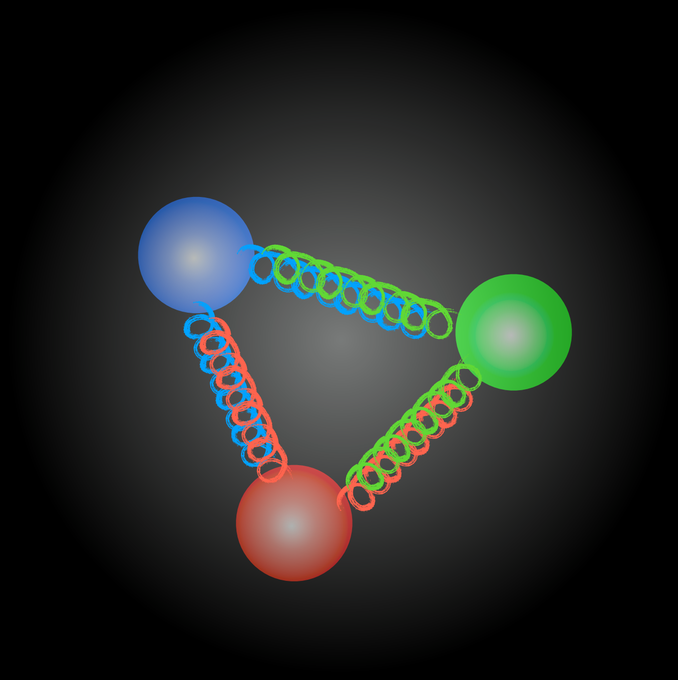


La force forte

Chromodynamique quantique

- 1973 : H. David Politzer, Frank Wilczek, David Gross

2004 - P

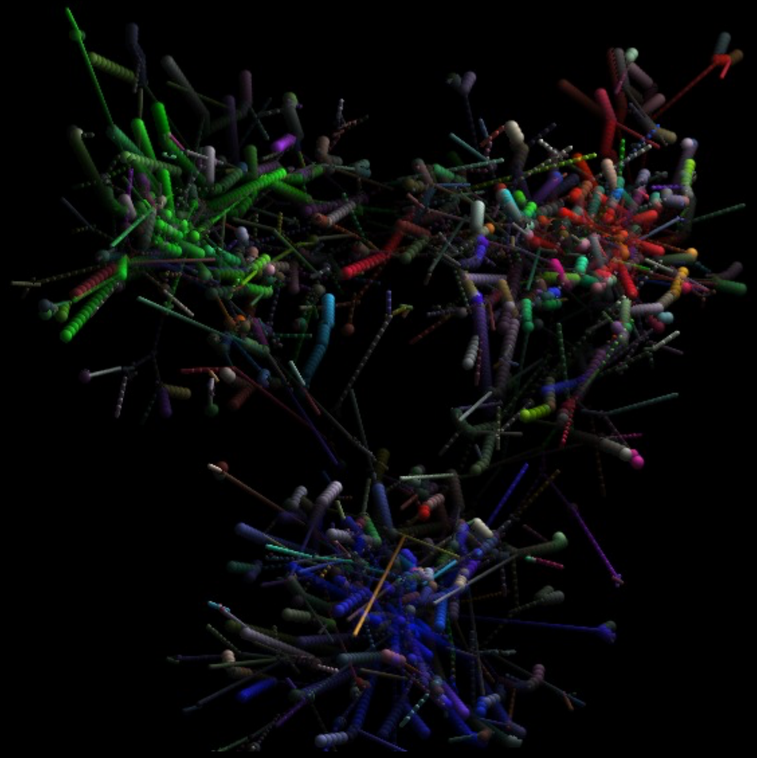


La force forte

Chromodynamique quantique

- 1973 : H. David Politzer, Frank Wilczek, David Gross

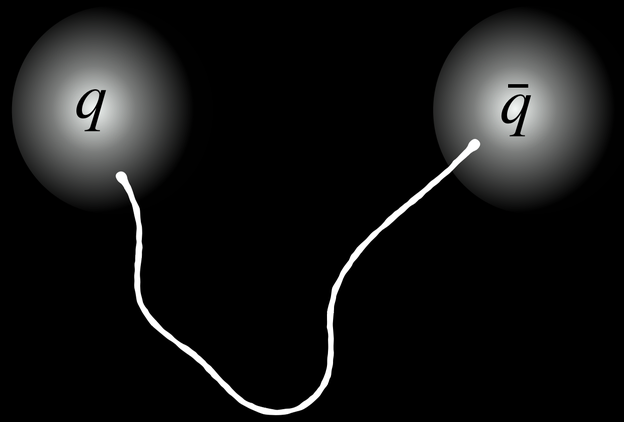
2004 - P



La force forte

Chromodynamique quantique

- 1973 : H. David Politzer, Frank Wilczel, David Gross

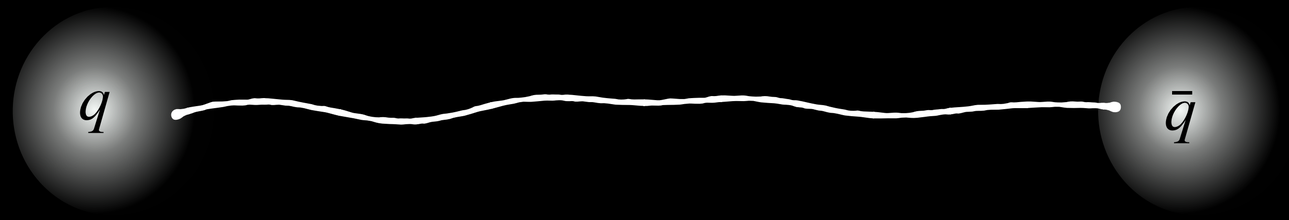


La force forte

Chromodynamique quantique

- 1973 : H. David Politzer, Frank Wilczel, David Gross

2004 - P

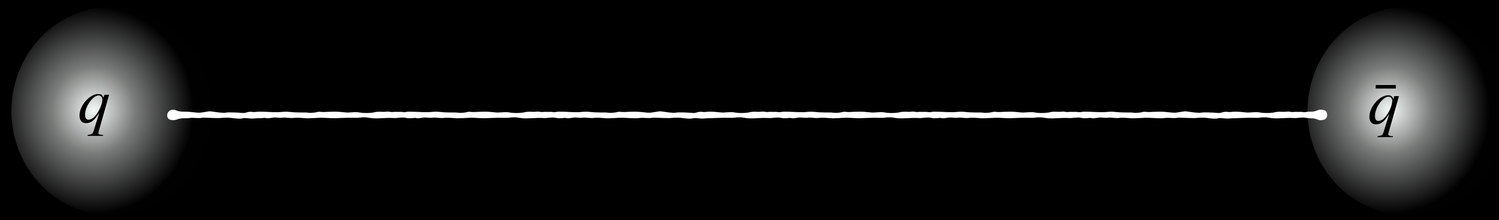


La force forte

Chromodynamique quantique

- 1973 : H. David Politzer, Frank Wilczel, David Gross

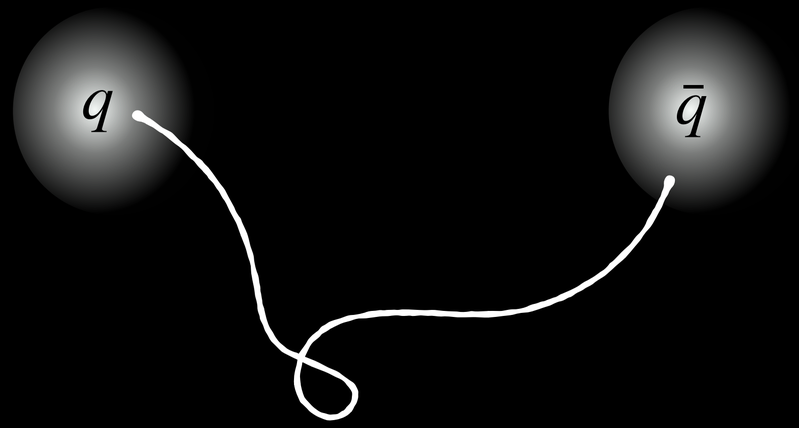
2004 - P

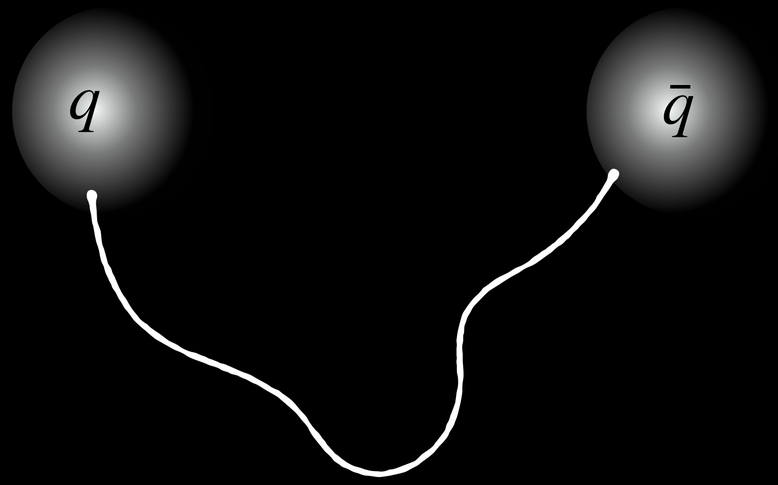


La force forte

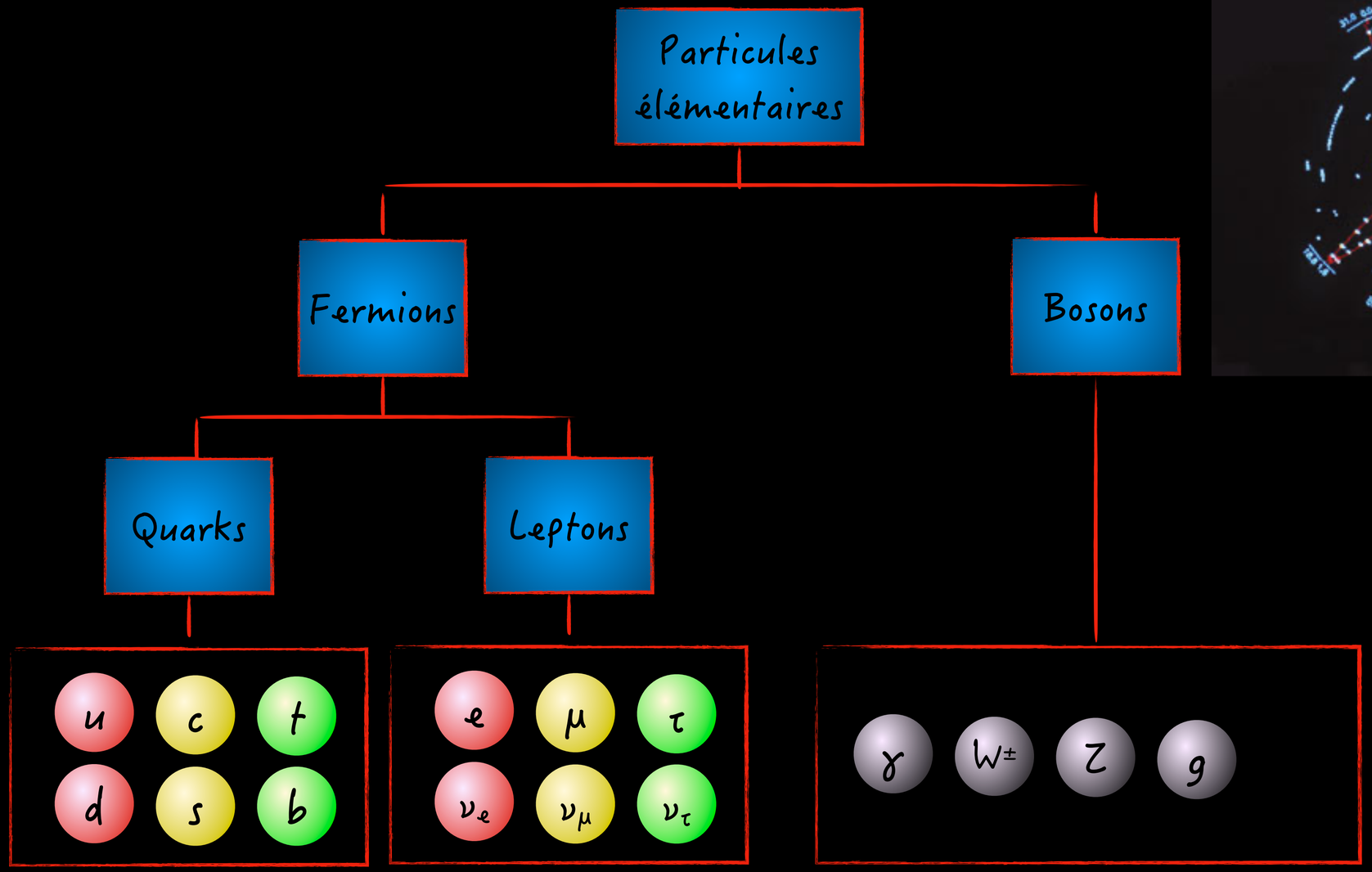
Chromodynamique quantique

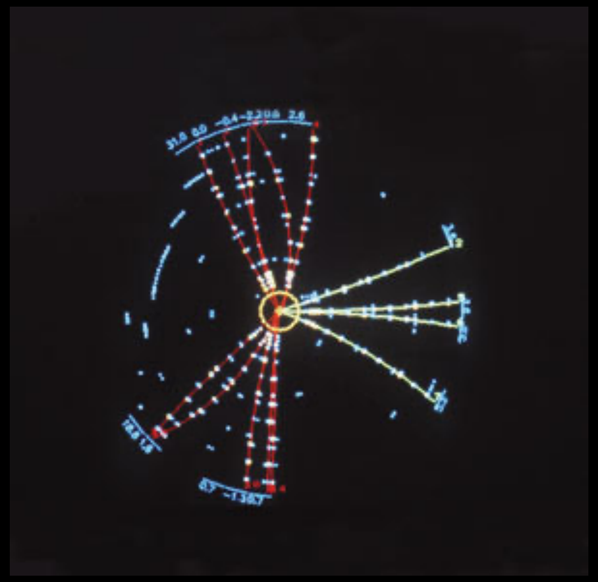
- 1973 : H. David Politzer, Frank Wilczel, David Gross



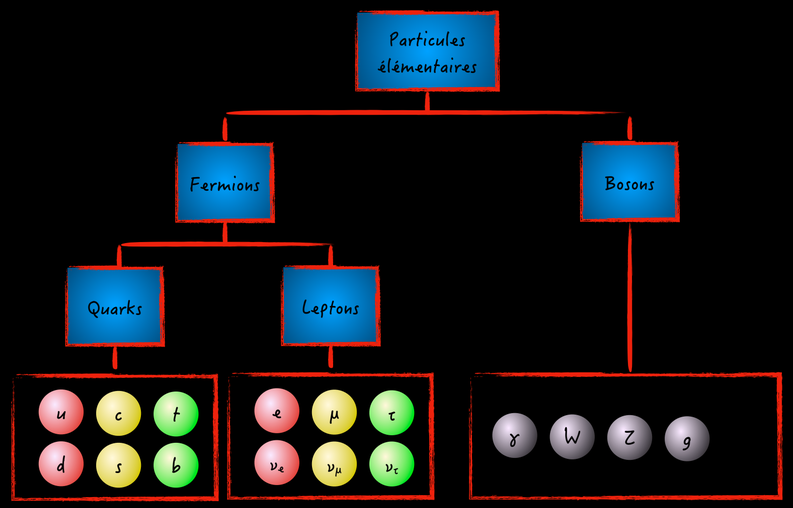


Liberté asymptotique


Particules élémentaires
Fermions
Bosons
Quarks
Leptons
u c t
d s b
e μ τ
ν_e ν_μ ν_τ
γ $W^\pm$ Z g

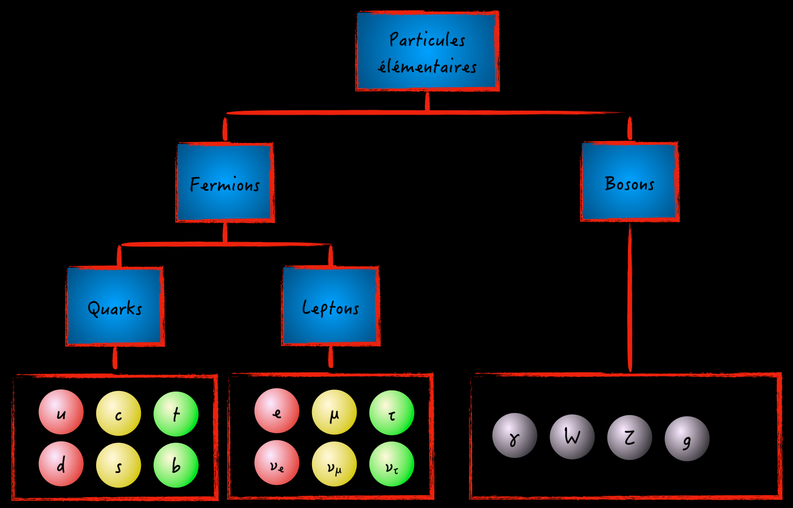


Le Modèle Standard



$$M_{\gamma WZ} = 0 \; !$$

Le Modèle Standard



$$M_{\gamma WZ g q l} = 0 \ !$$

Le Modèle Standard

Champ de Higgs

- 1964 : Robert Brout, François Englert, Peter Higgs

1. Les particules élémentaires sont sans masse
2. Un champ quantique imprègne le vide
3. La masse résulte de l'interaction de 1) avec 2)

Le Modèle Standard

Champ de Higgs

- 1964 : Robert Brout, François Englert, Peter Higgs

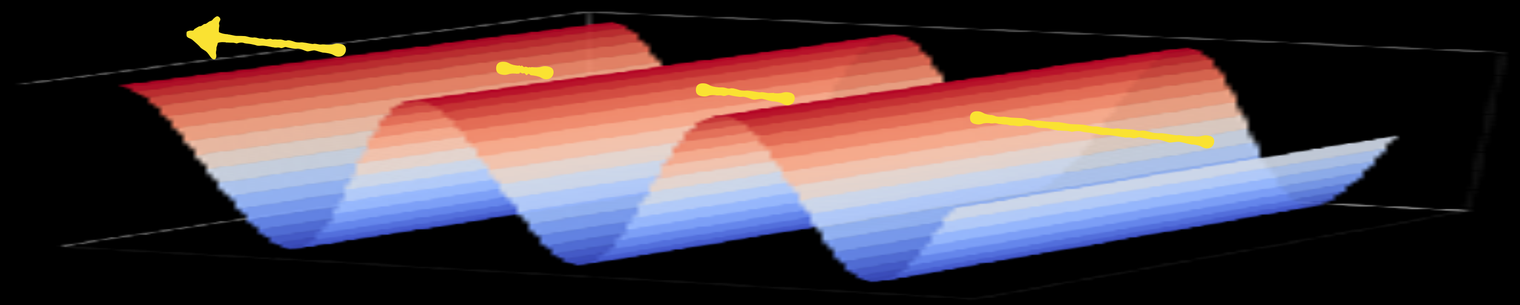
1. Les particules élémentaires sont sans masse

2. Un champ quantique imprègne le vide

3. La masse résulte de l'interaction de 1) avec 2)

$m_{W,Z} > 0$

$v_{W,Z} < c$



Le Modèle Standard

Champ de Higgs

- 1964 : Robert Brout, François Englert, Peter Higgs

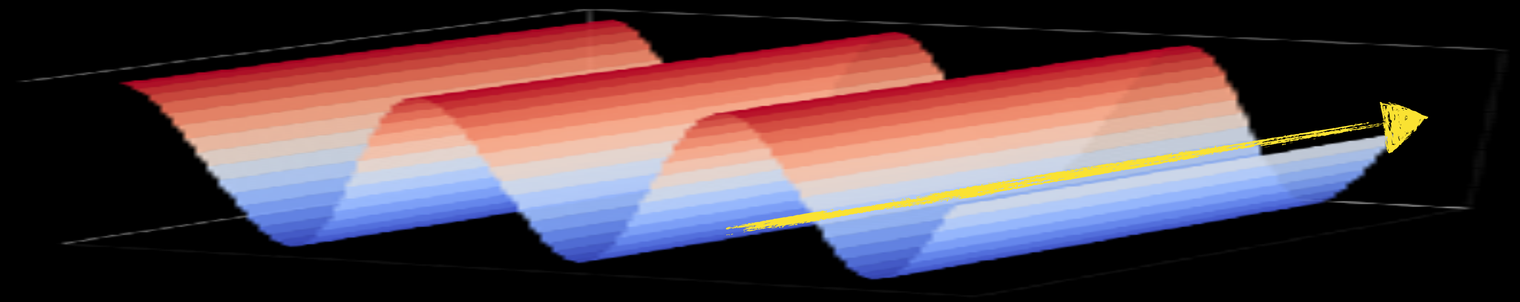
1. Les particules élémentaires sont sans masse

2. Un champ quantique imprègne le vide

3. La masse résulte de l'interaction de 1) avec 2)

$$m_\gamma = 0$$

$$v_\gamma = c$$



Le Modèle Standard

Champ de Higgs

- 1964 : Robert Brout, François Englert, Peter Higgs

2013 - P

1. Les particules élémentaires sont sans masse
2. Un champ quantique imprègne le vide
3. La masse résulte de l'interaction de 1) avec 2)
4. Le boson de Higgs est le quantum

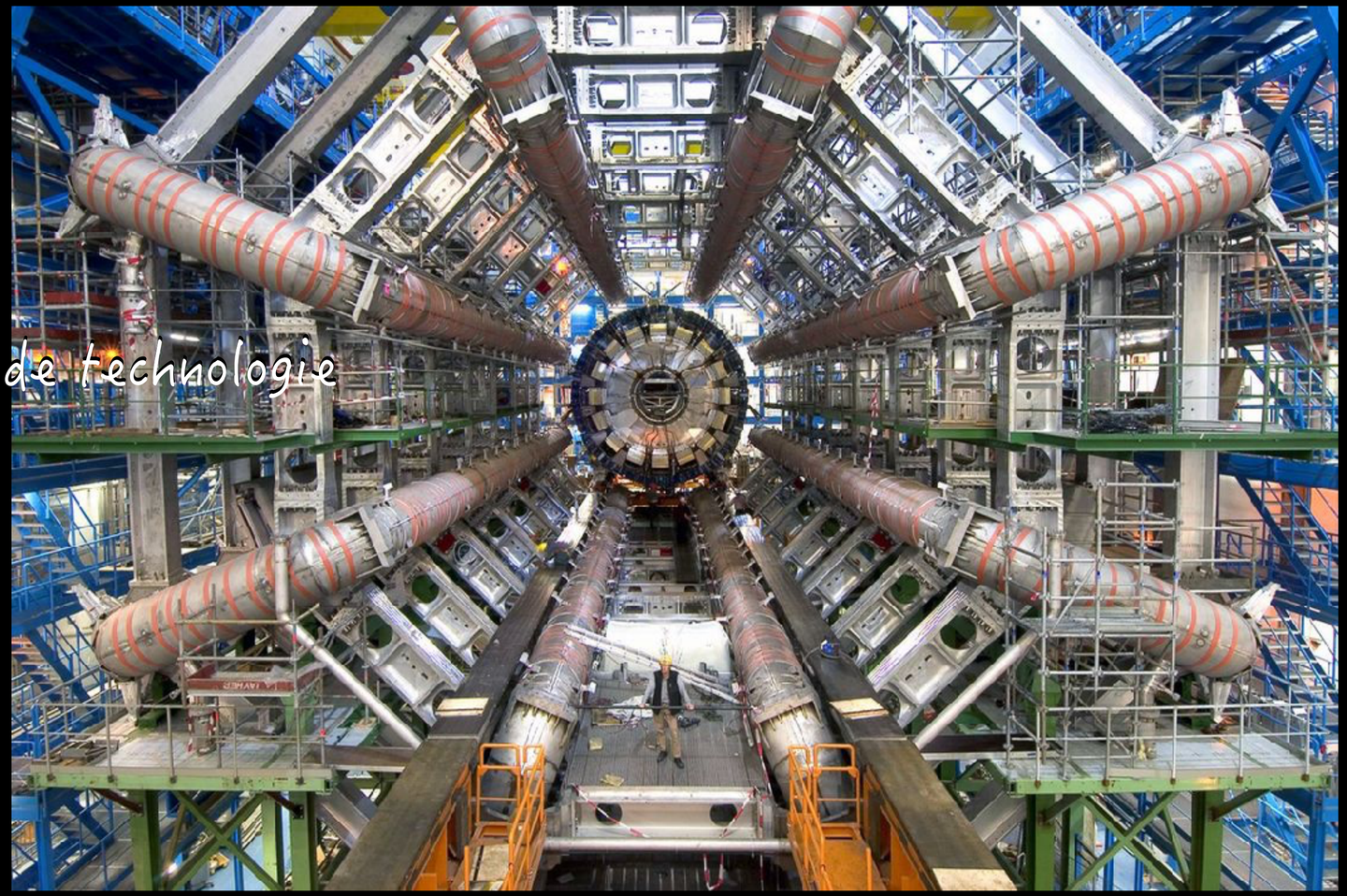
Boson de Higgs

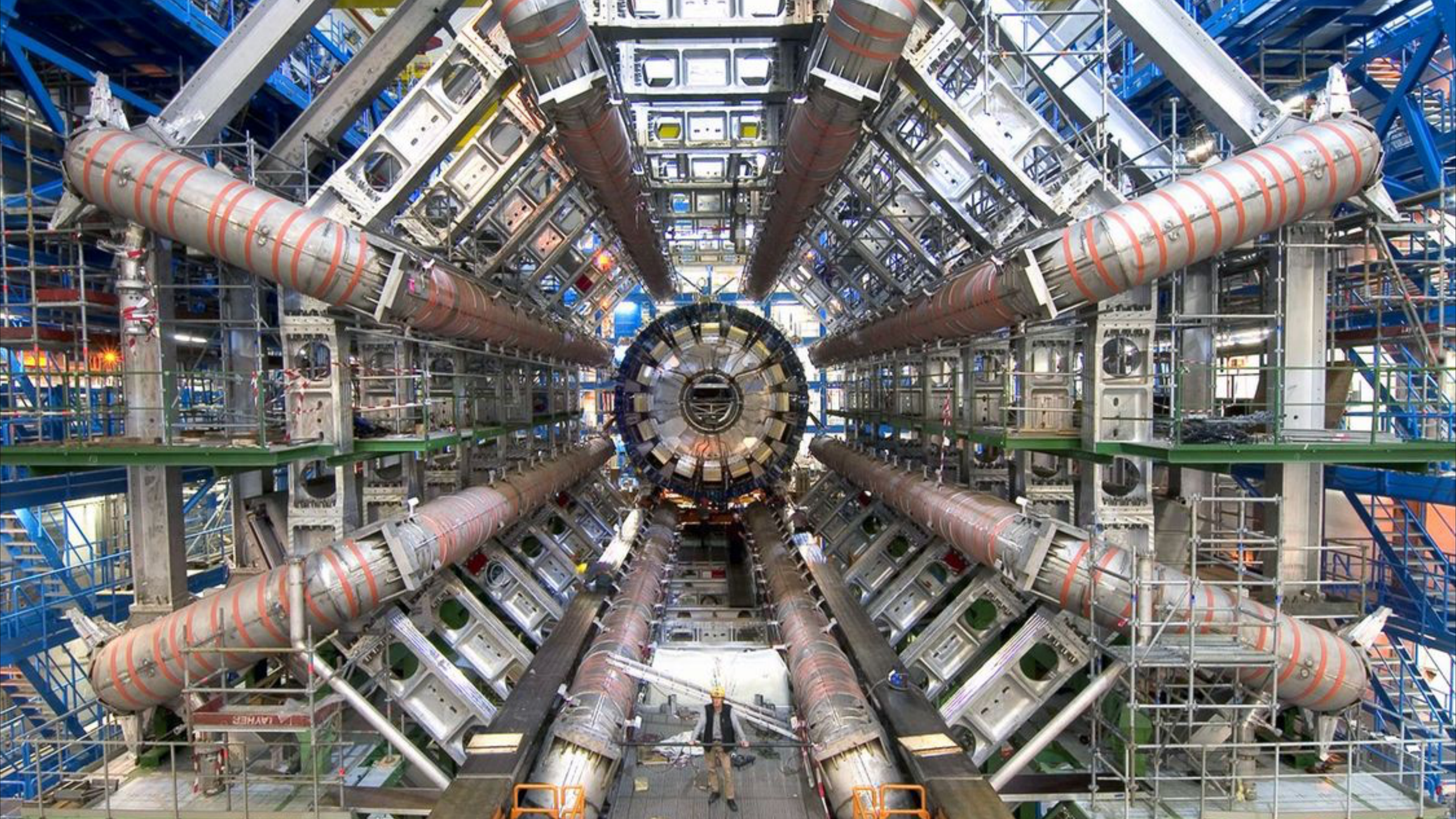
- 4 juillet 2012 au CERN :
  - LHC, le seigneur des anneaux

$\frac{v_p}{c} = 0.999999973957773$

Boson de Higgs

- 4 juillet 2012 au CERN :
  - LHC, le seigneur des anneaux
  - ATLAS & CMS, des cathédrales de technologie



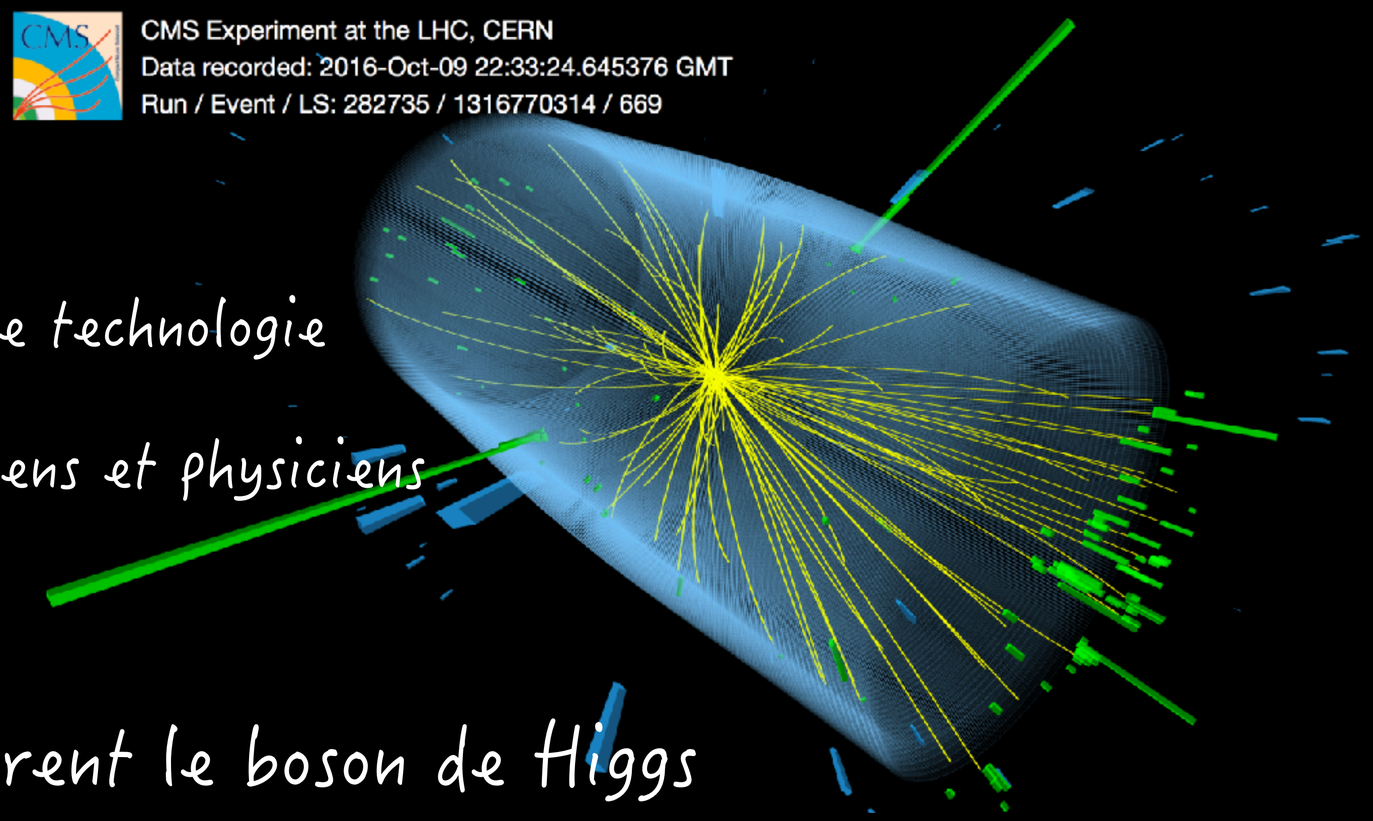


Boson de Higgs

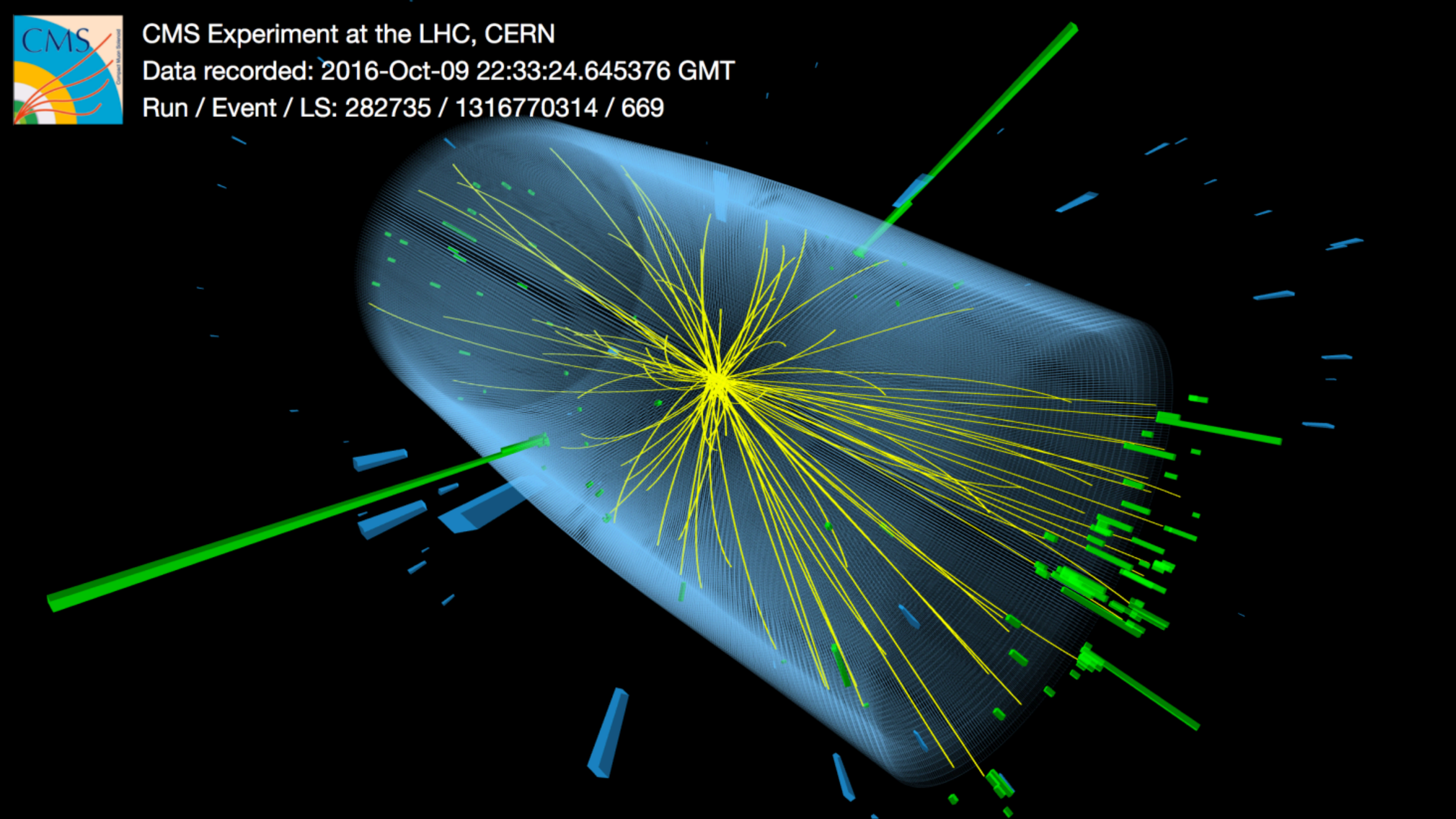
- 4 juillet 2012 au CERN :
  - LHC, le seigneur des anneaux
  - ATLAS & CMS, des cathédrales de technologie
  - Des milliers d'ingénieurs, techniciens et physiciens

Boson de Higgs

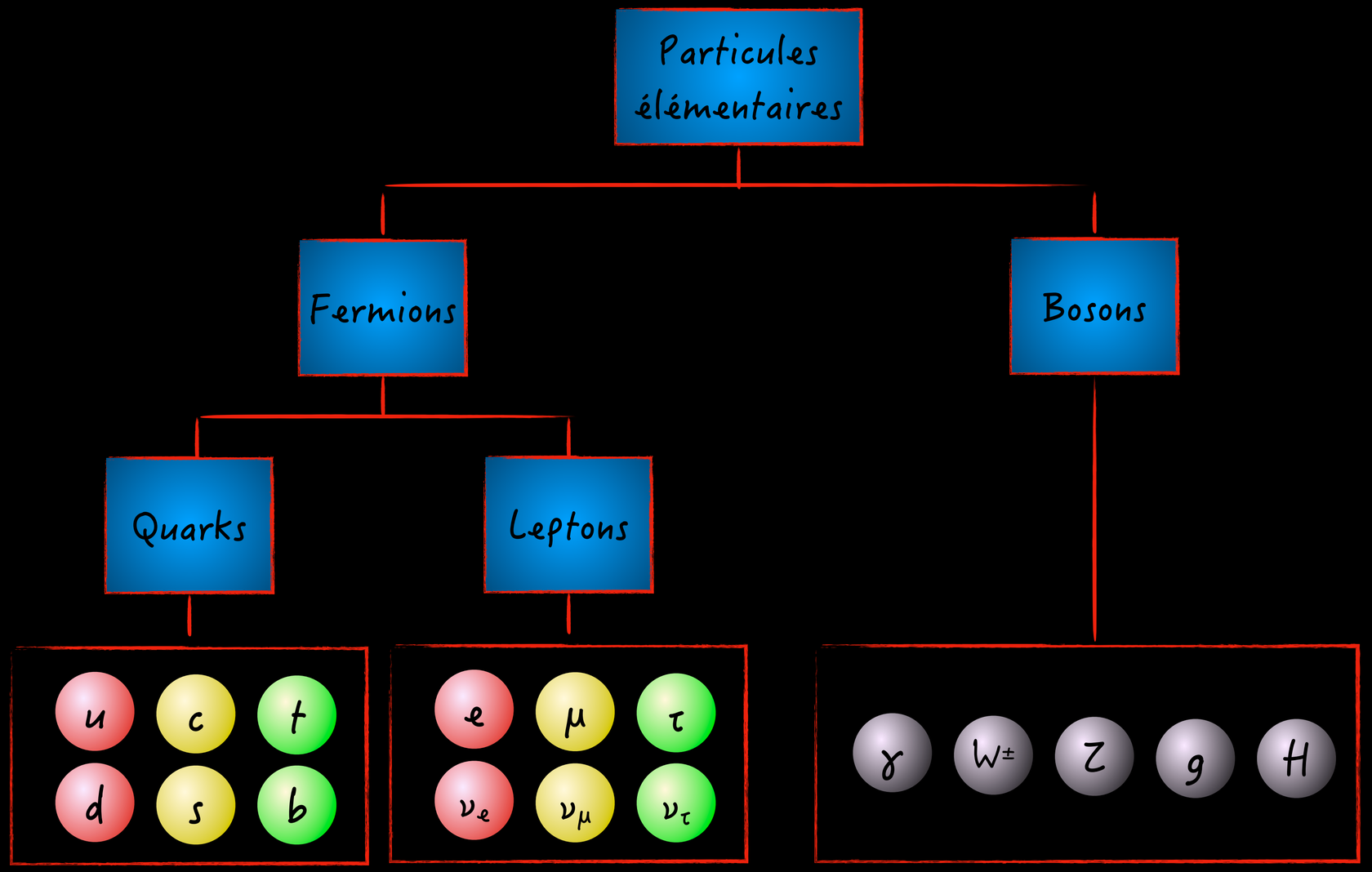
- 4 juillet 2012 au CERN :
  - LHC, le seigneur des anneaux
  - ATLAS & CMS, des cathédrales de technologie
  - Des milliers d'ingénieurs, techniciens et physiciens



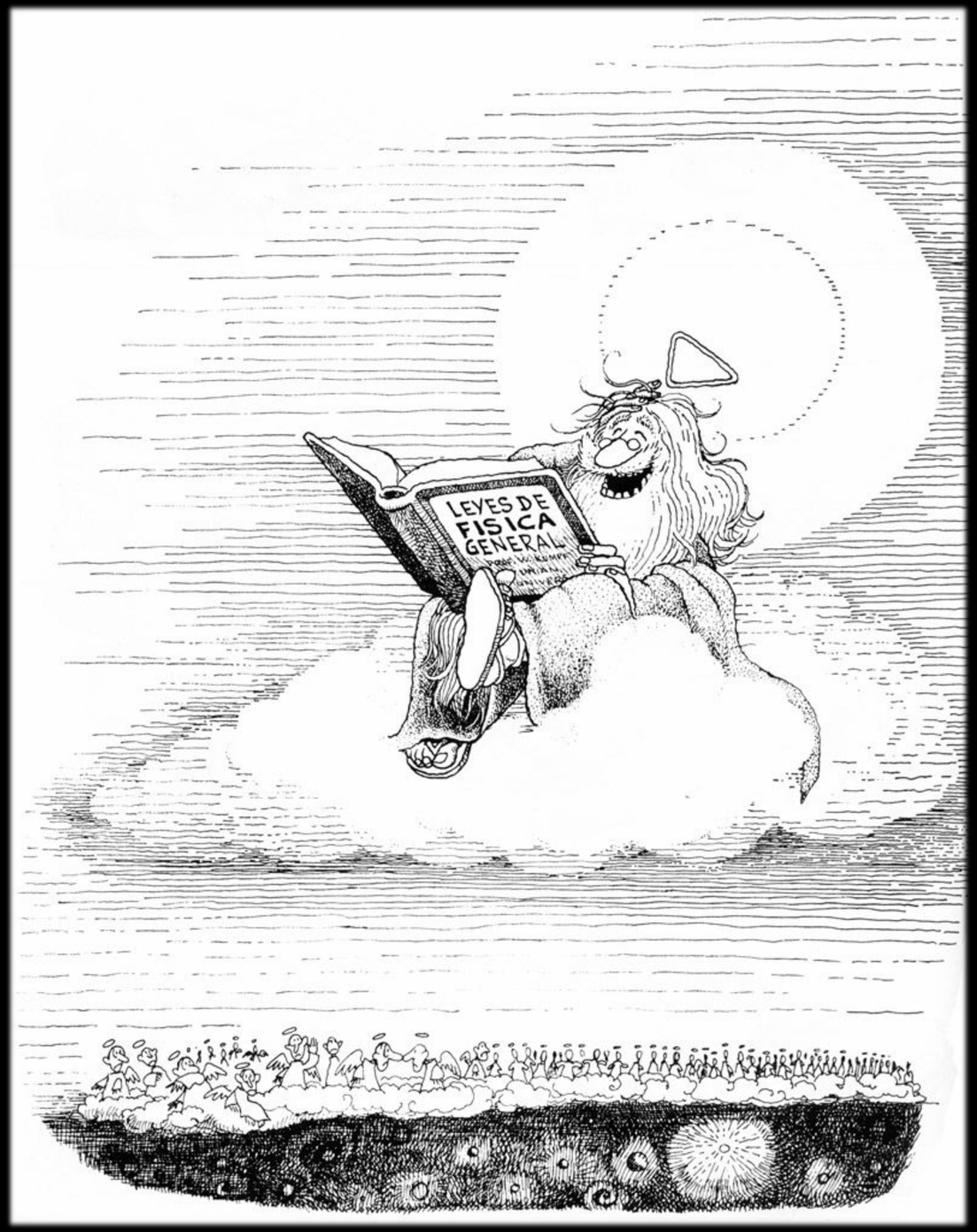
Découvrent le boson de Higgs


CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-09 22:33:24.645376 GMT
Run / Event / LS: 282735 / 1316770314 / 669

Le Modèle Standard



La fin de l'histoire ?


LEYES DE
FISICA
GENERAL