

# *Les Particules Élémentaires*

*... de A comme Atome ...*

*à*

*Z comme  $Z^0$*

# la Physique des Particules

- Quels sont les constituants élémentaires de la matière ? **Matière**
- Quelles sont les forces fondamentales qui contrôlent le comportement de ces constituants ? **Force**

# Histoire en 4 chapitres

- les Grecs

*Démocrite*

- des Grecs à 1900

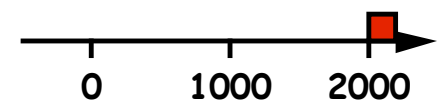
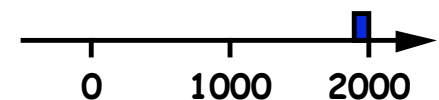
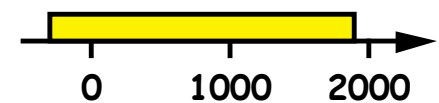
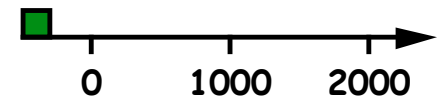
*Newton Maxwell*

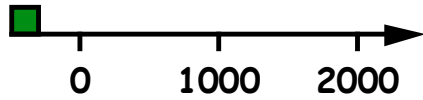
- le XX<sup>ième</sup> siècle

*Rutherford Einstein Heisenberg*

- le Modèle Standard

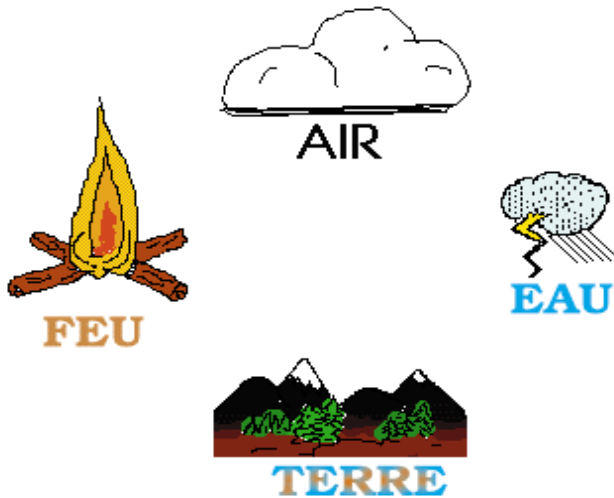
*Glashow t'Hooft Salam Weinberg*





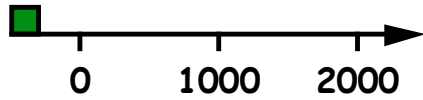
# des idées

- La matière, c'est:



- La force, c'est:

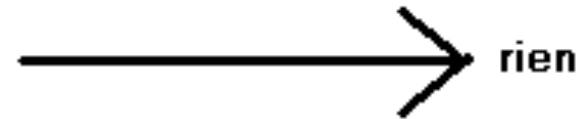
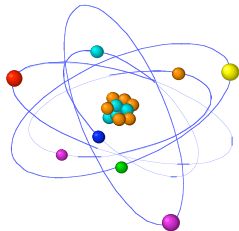




# des bonnes idées

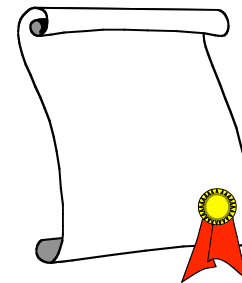
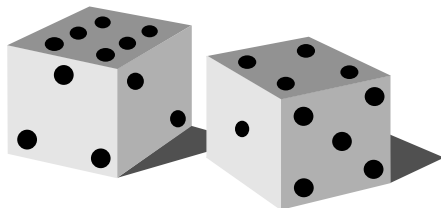
Démocrite et al. - 440

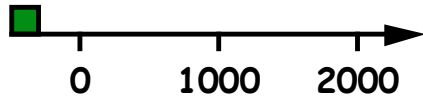
- Matière élémentaire et « indivisible »
- Le vide



- Comportement au hasard

- Lois pour expliquer les observations





# des mots

Μηχανη *mecane* machine

Les lois du mouvement s'appellent: la MECANIQUE

Μαγνης *magnes* aimant

Les lois des aimants s'appellent: le MAGNETISME

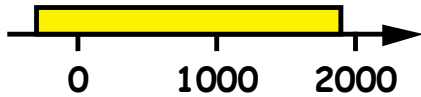
Οπτομαι *optomai* je vois

Les lois de la lumière s'appellent: l'OPTIQUE

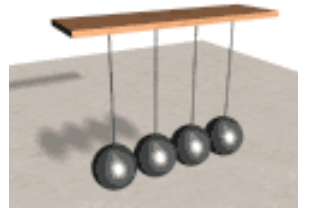
Ηλεκτρον *electron* ambre jaune

Les lois de l'ambre s'appellent: l'ELECTRICITE

... et bien d'autres ...

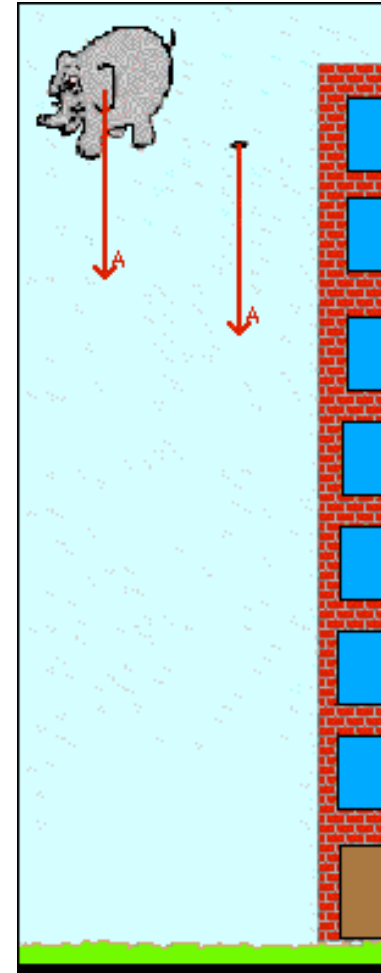


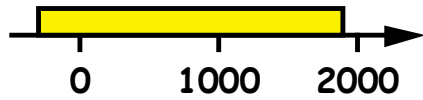
# Galilée



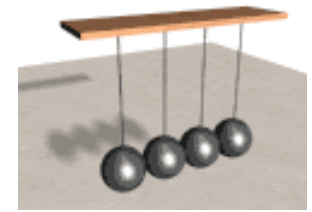
1564 - 1642

- Il lâche  
du bois,  
du plomb,  
du papier,  
etc...  
du sommet  
de la tour  
de Pise →



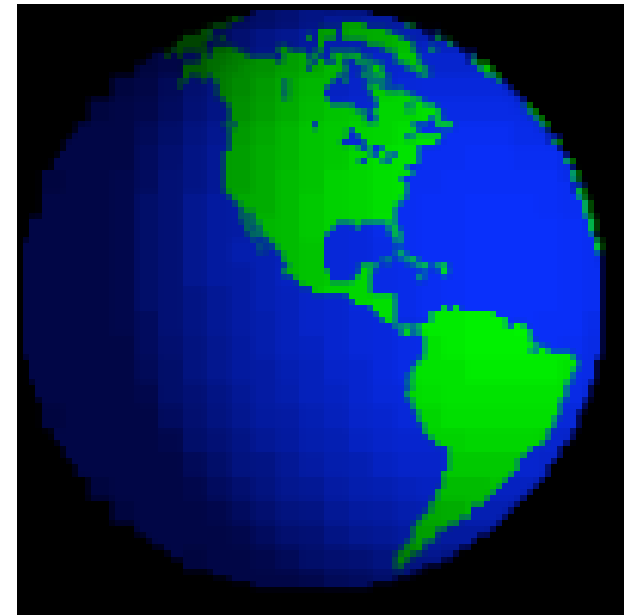
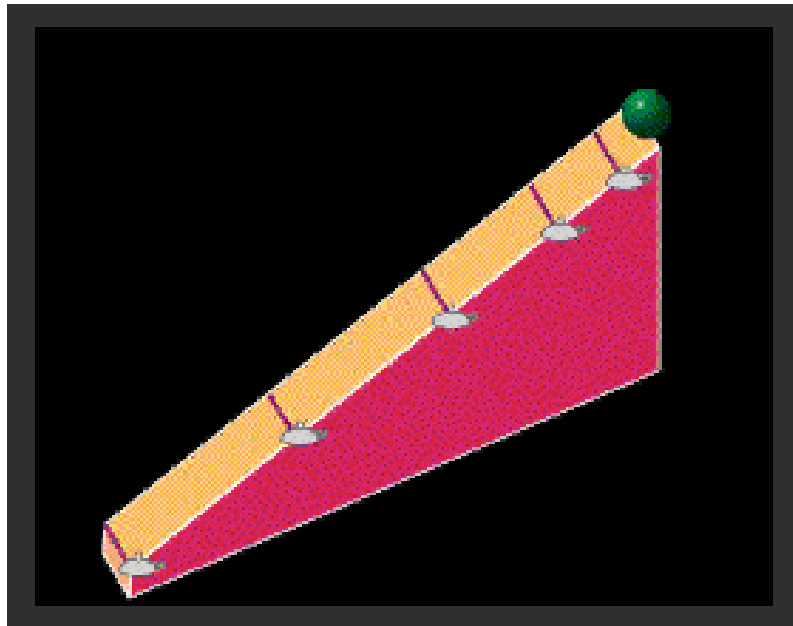


# Galilée

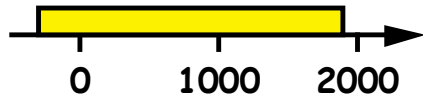


- Étudie le mouvement des corps:

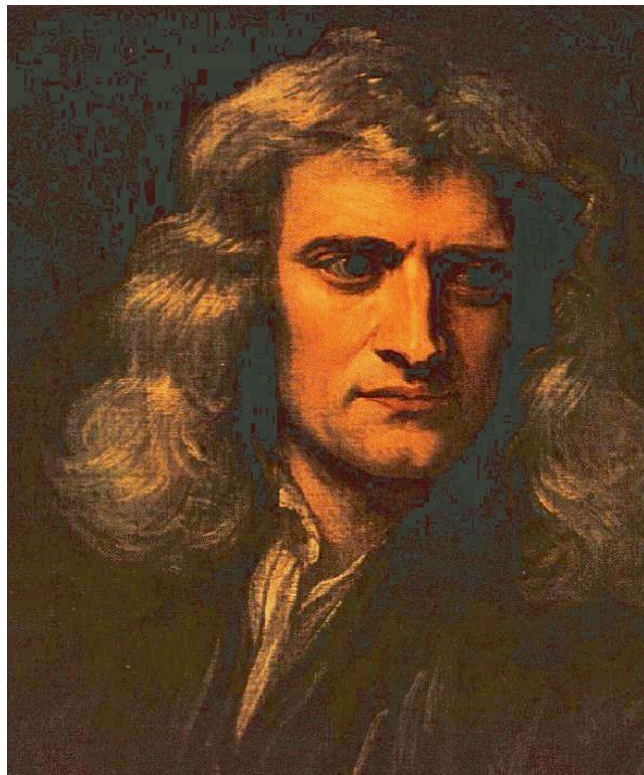
Et des planètes:







# Newton



1642 - 1727

- Les Maths:
  - analyse (les fonctions)

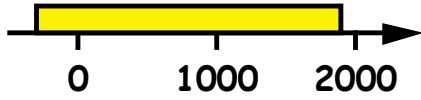
- l'Optique:
  - améliore le télescope
  - décompose la



- l'Astronomie:



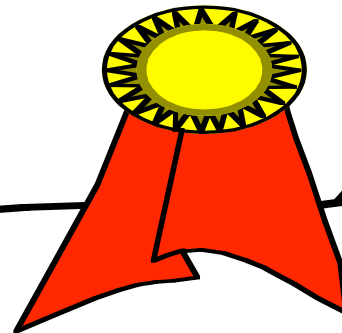
- avec son pote Halley
- mouvement des planètes (merci Kepler)

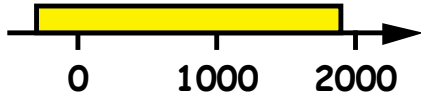


# Newton



$$F = G \frac{mM}{r^2}$$





# Newton

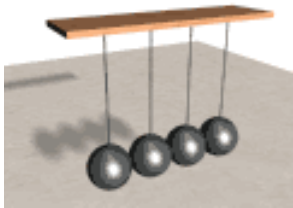


Et alors ?

- Newton vient d'inventer la

## Gravitation universelle

- Explique tous les mouvements (ou presque)



+

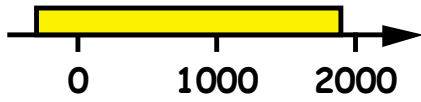


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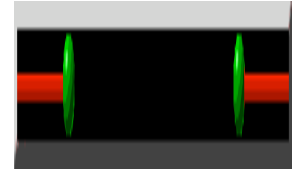


- Important:

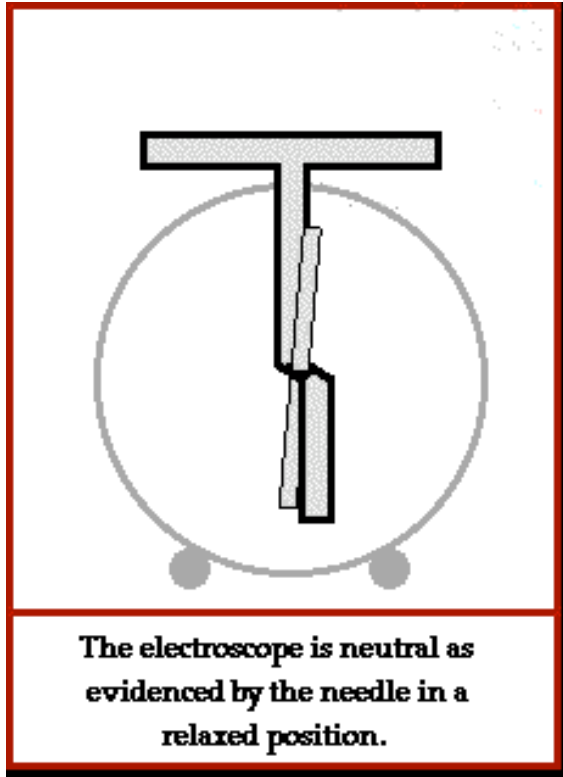
- La source de la force, c'est la masse
- La portée de la force est (ici) infinie



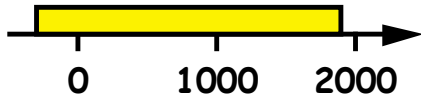
# Électricité



Coulomb 1736 - 1806



$$F = C \frac{qQ}{r^2}$$

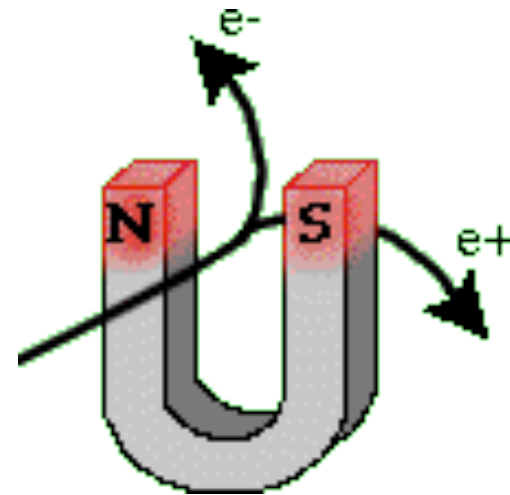
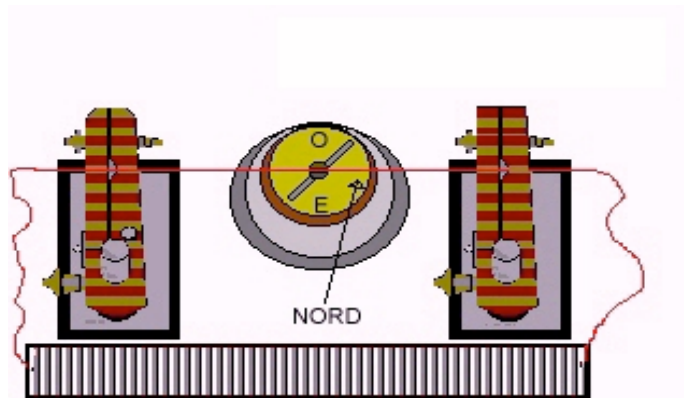


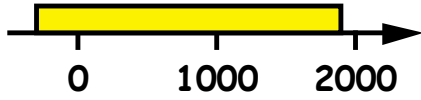
# Magnétisme



Ørsted 1736 - 1806

Faraday 1736 - 1806





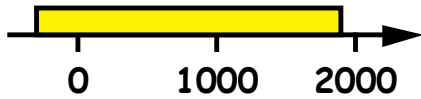
# Maxwell



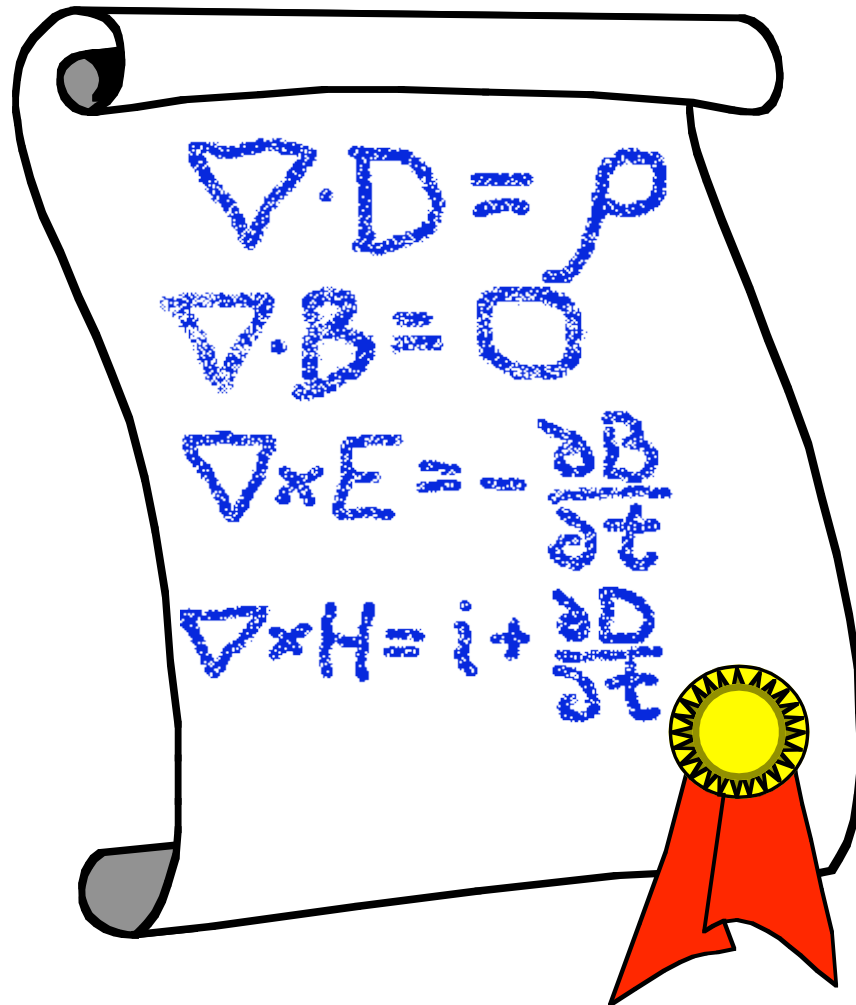
1831 - 1879

- Comme Newton, c'est un matheux !
- Étudie aussi les gaz, l'astronomie
- Mais surtout:

## les Équations

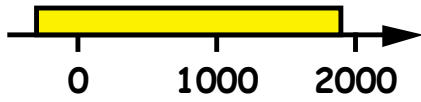


# Maxwell



- $Q_e \Rightarrow$  champ E
- $Q_m$  non !
- Conducteur dans champ M  $\Rightarrow$  Volts
- Courant  $\Rightarrow$  champ M

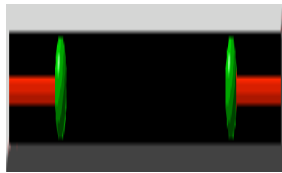
les ONDES E.M.



# Maxwell



## Unification



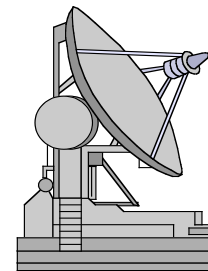
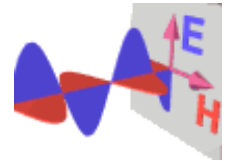
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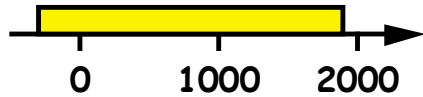
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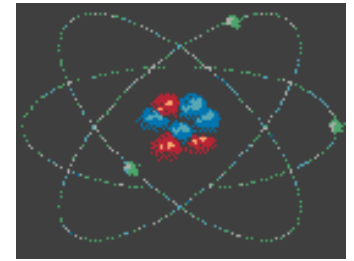
## les Ondes Électromagnétiques







# Atomes

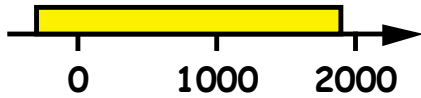


## Avogadro 1776 - 1856

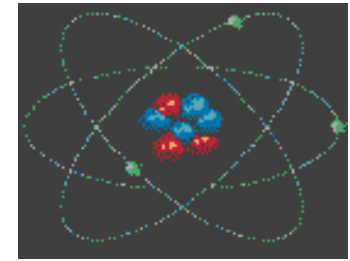
- Il existe de grands espaces entre les molécules d'un gaz
- Les gaz ont les mêmes lois de compressibilité et de dilatation ...doivent avoir le même nombre de "vides »

"Des volumes égaux de gaz différents, aux mêmes conditions de température et de pression, contiennent le même nombre de molécules"

$$N = 6,02 \times 10^{23}$$



# Atomes



## Mendeleïev 1834 - 1907

*Опубликовано в журнале "Современник",  
 1869 г. № 1. Автор: Д. Менделѣев.  
 I = 50    Z = 90    ? = 130*

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra		104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110	111	112						
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

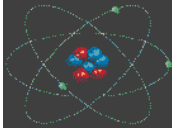
# État des lieux en ~ 1900

- Les forces:

- la gravitation  (Newton)

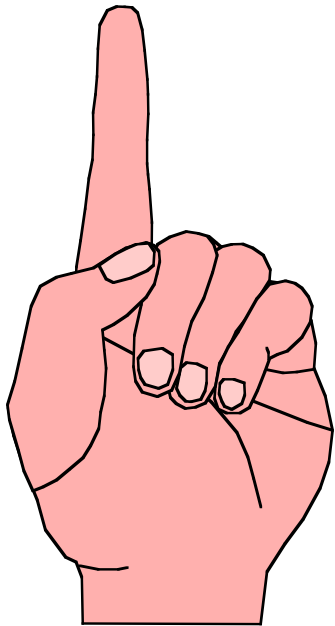
- l'électromagnétisme  (Maxwell)

- La matière:

- les atomes  (Avogadro)

- ... et la lumière?  (Maxwell/Newton)

# le XX<sup>ième</sup> siècle va commencer

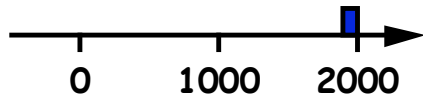


Tout ce qui a été dit jusqu'à  
maintenant est toujours vrai  
(macroscopique)

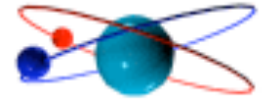
MAIS MAINTENANT

+ petit

+ vite



# la Révolution Expérimentale

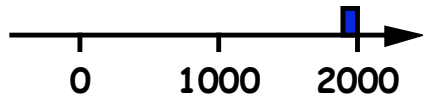


## • W. Röntgen: les rayons X 1895

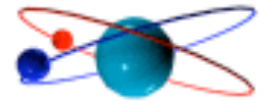
- décharges tube à vide (Crookes)
  - « rayons cathodiques »
  - ... dûs à charges  $< 0$   
(voir suivante)
- ? traversent le carton (Röntgen)

rayons X →

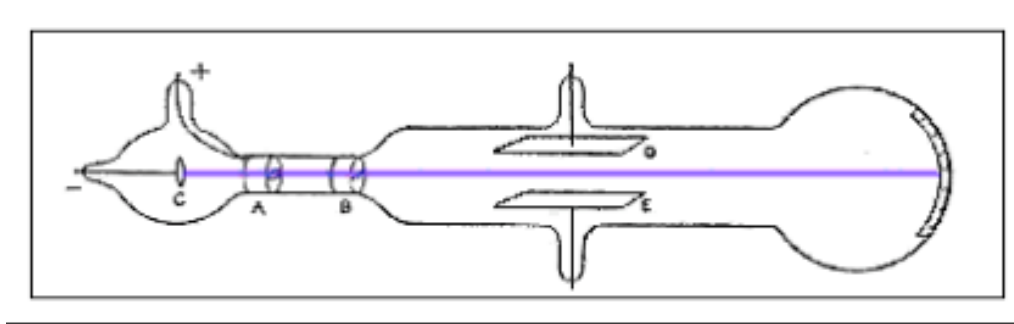




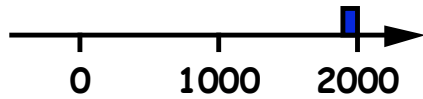
# la Révolution Expérimentale



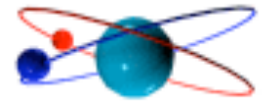
- **J.J. Thomson**  : l'électron **1897**



« Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen? which itself is so small that a crowd of these atoms equal in number to the population of the whole world would be too small to have been detected by any means then known to science. »



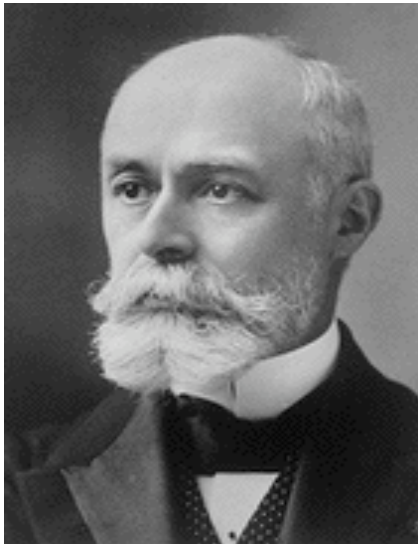
# la Révolution Expérimentale

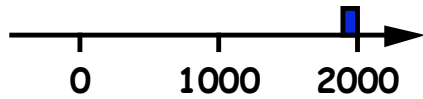


• **Becquerel, Pierre et Marie Curie:**

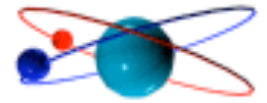


la radioactivité **1896-1898**

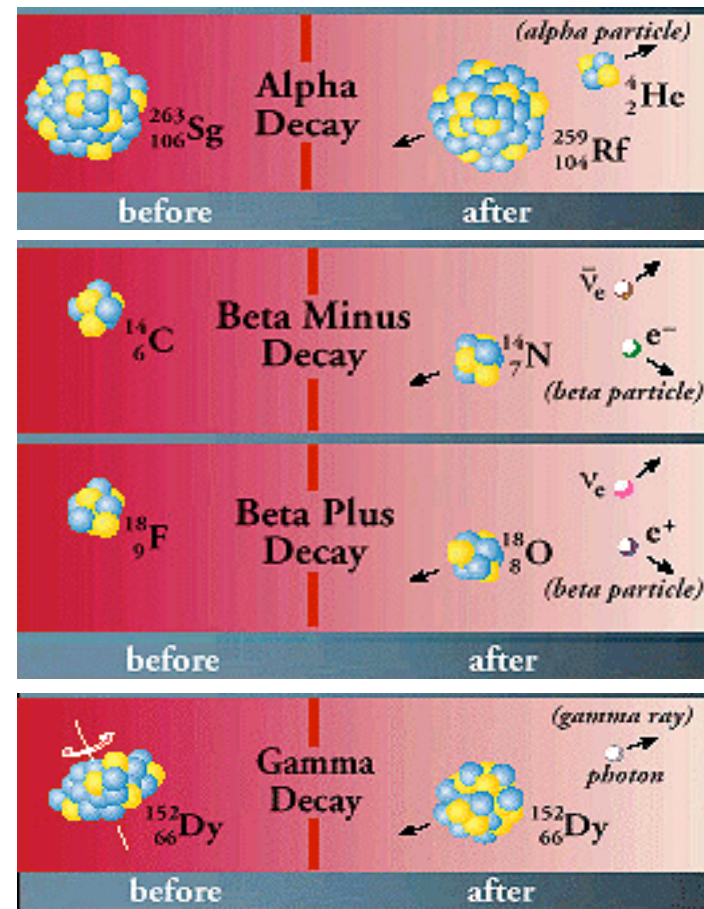
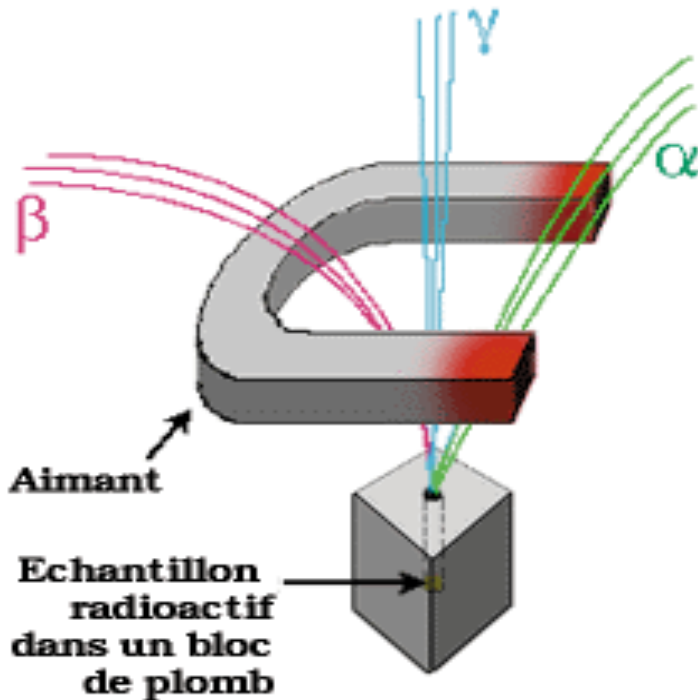




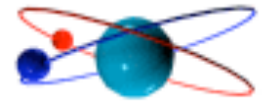
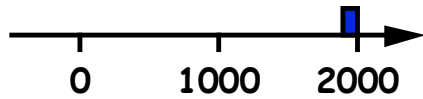
# la Révolution Expérimentale



## la radioactivité (suite)



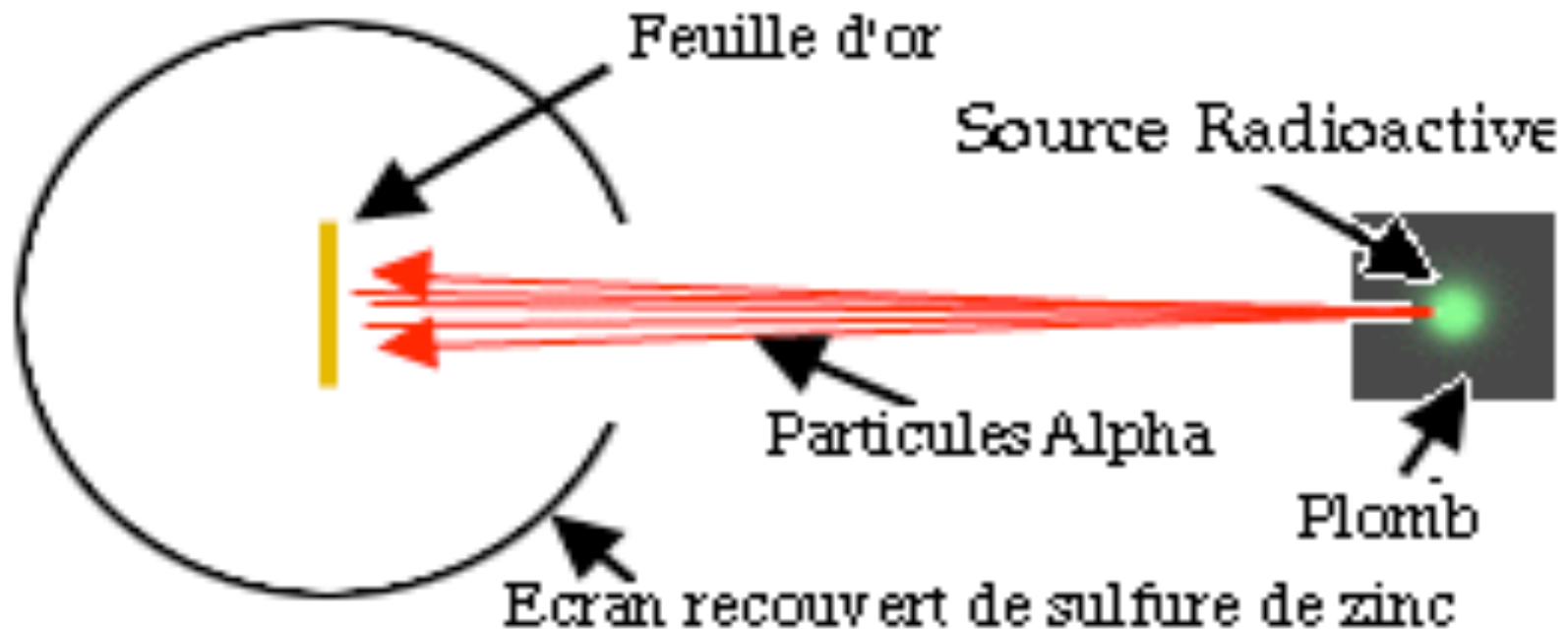


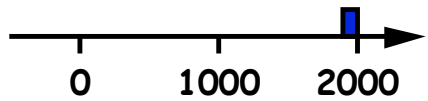


# la Révolution Expérimentale

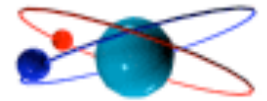
• E. Rutherford: le noyau 1899-1911

L'expérience:

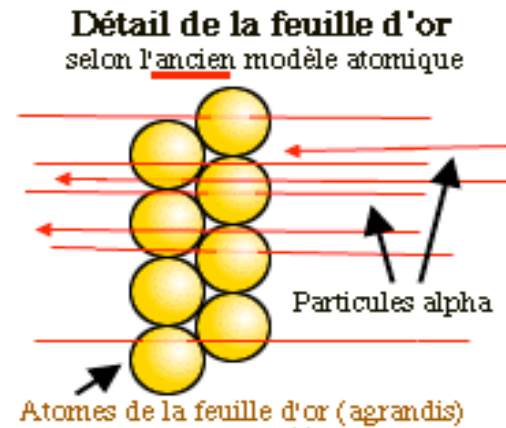
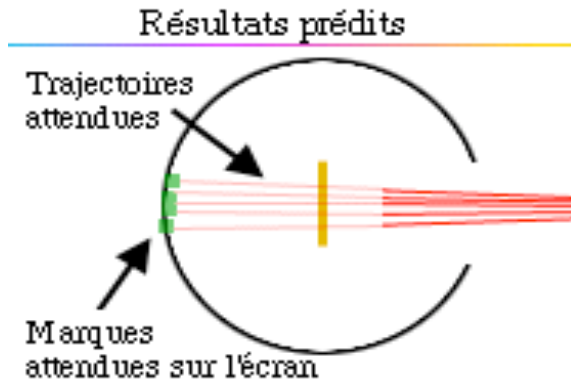




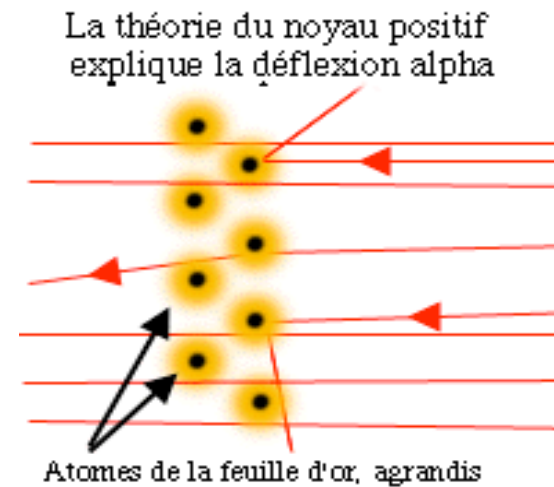
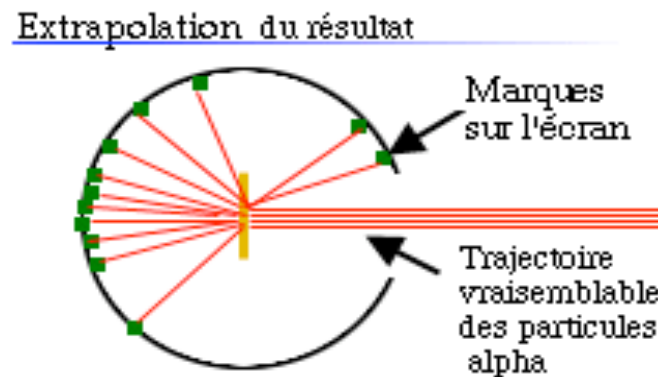
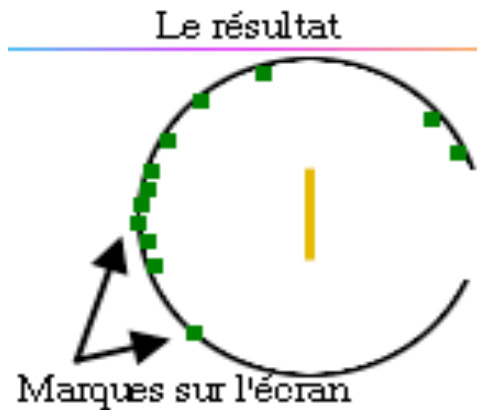
# la Révolution Expérimentale

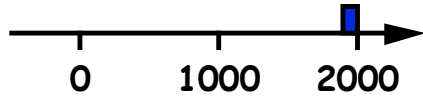


## Le résultat attendu et son explication:

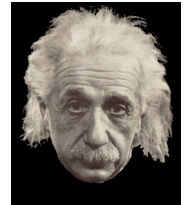


## Le résultat observé et la découverte:





# la Révolution Théorique



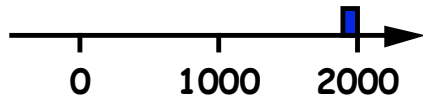
Il va falloir expliquer tout ça ...

+ Vite

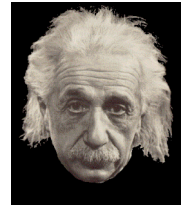
La **Relativité** (Einstein)

+ Petit

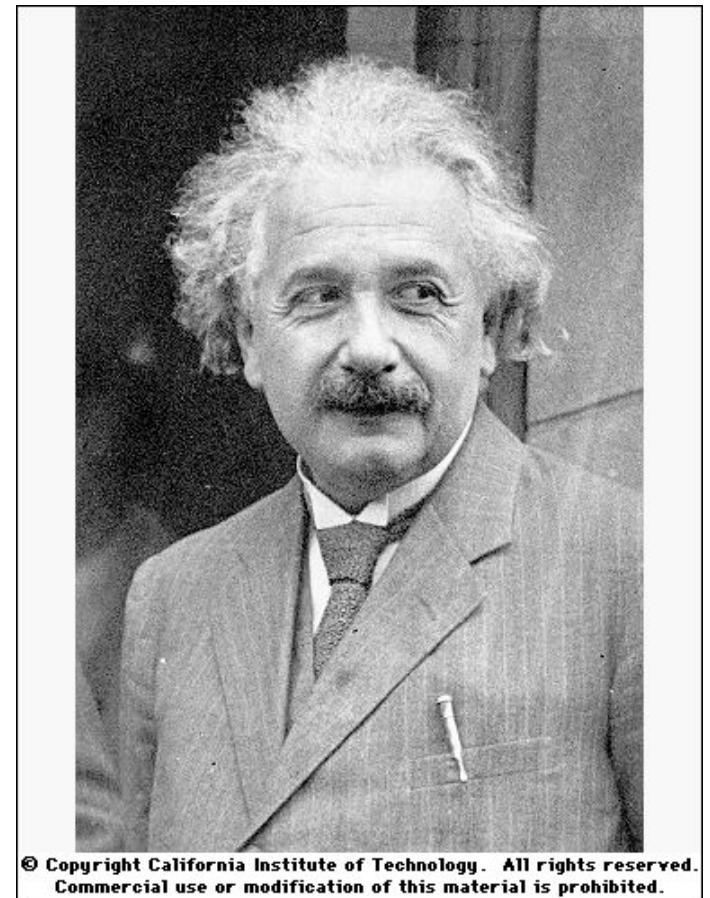
La **Mécanique Quantique** (Heisenberg et al.)



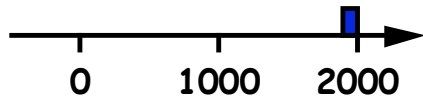
# Einstein



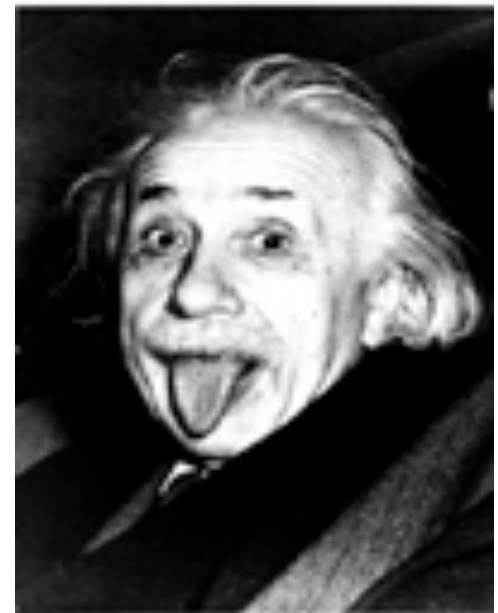
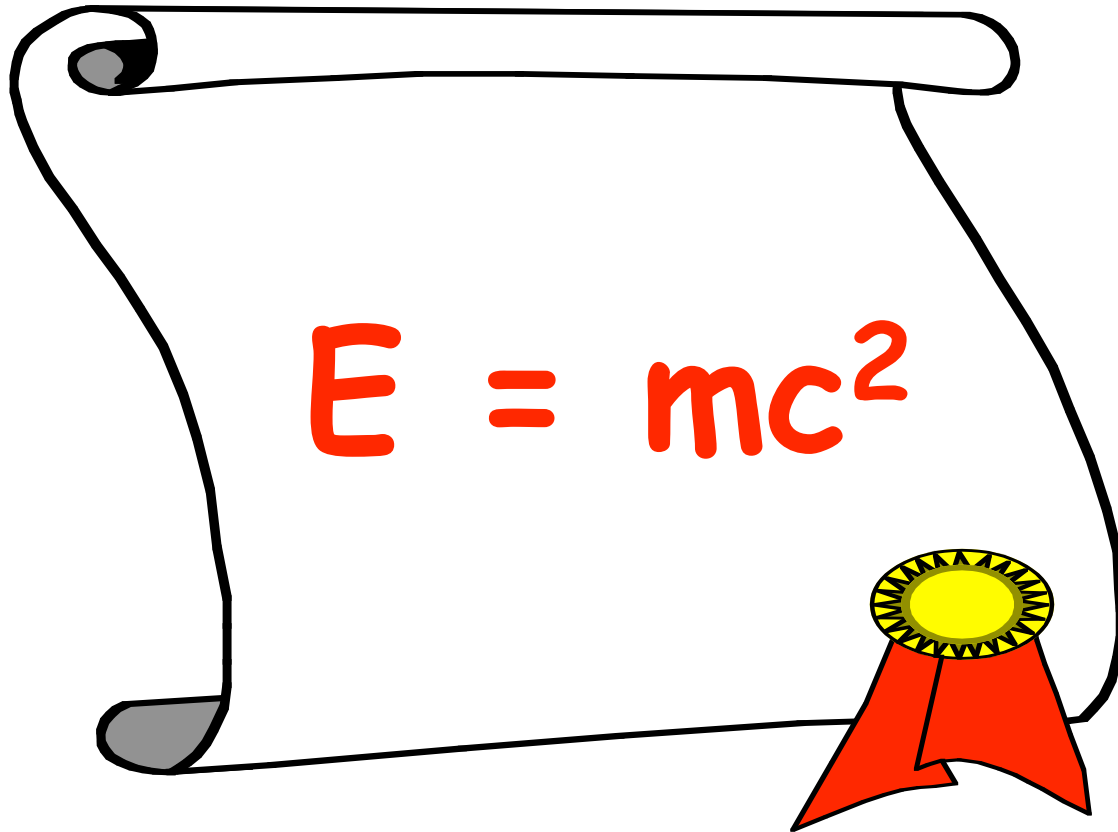
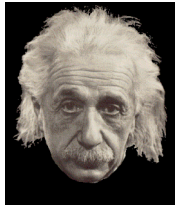
- Avant Albert:
  - Effet photo-électrique?
  - Où est l'éther?
  - et la lumière: onde ou particule?
- Albert en 1905:
  - « Rien ne va plus vite que ... la lumière »



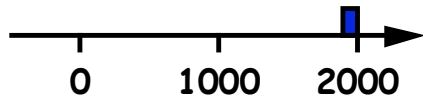
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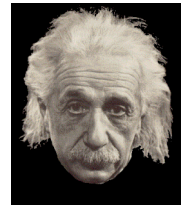
# Einstein



Naissance de la relativité



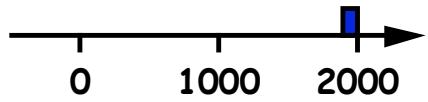
# Einstein



$$E = mc^2 \text{ et alors ?}$$

- Après Albert:
  - le temps est une notion ... *relative*
  - tout s'explique
  - les photons (« quanta »)
- unités:  $1 \text{ eV}/c^2 = E \text{ d'1 } e^- \text{ dans ddp 1 Volt}$
- unités:  $1 \text{ GeV}/c^2 \sim 1.6 \times 10^{-27} \text{ kg} \sim m_H$



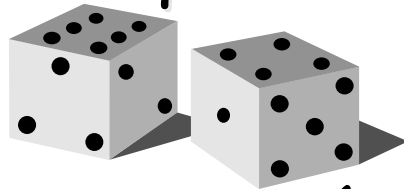


# Heisenberg et al.

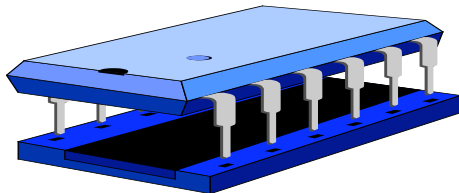


- Une nouvelle mécanique pour les objets petits

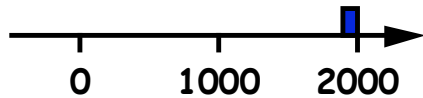
- Une conséquence:



- Une autre conséquence:



1901-1976



# La Méca Q.



« Vous avez dit ~~antique~~ quantique »

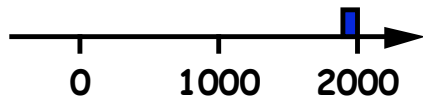
- Planck: corps noir (juste une hypothèse) 1900
- Bohr: ~~passage~~ atome à niveaux 1913
- De Broglie:  $\lambda = h/p$  onde-particule 1924
- Heisenberg: le principe d'incertitude 1927



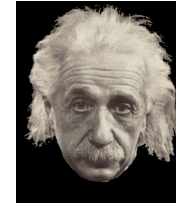
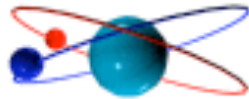
La mécanique quantique est née  $\Delta x \Delta p > h$

Note : (Longueur) d'Onde  $\sim$  (Energie) de particule





# En vrac



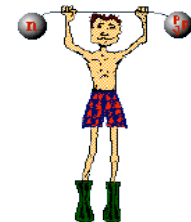
## Expérimental

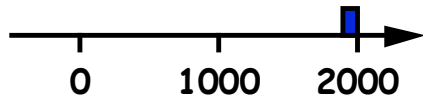
- Neutron 1932
- Positron 1932
- Radioactivité artificielle 1934
- Réaction en chaîne 1934
- Fission 1939

## Théorique

(Méca Q et Relativité)

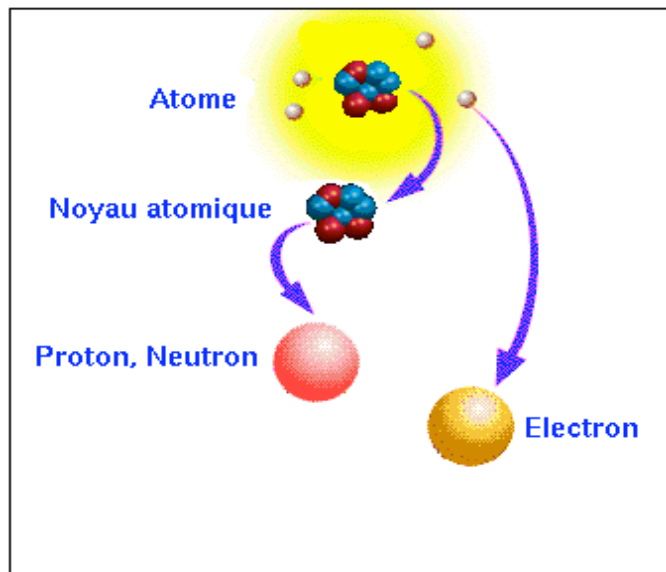
- Dirac et son équation
  - anti-particules
- Hypothèse du  $\nu$  (Pauli)
- Fermi: nouvelle force:
  - ... faible
  - ... le  $\nu$





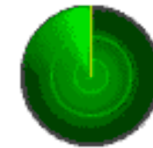
# État des lieux avant WW2

## Particules



+  $\nu$  + antiparticules

## Forces



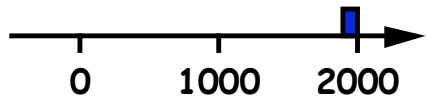
## Lois

Newton:  $G = gmM/r^2$

Maxwell:  $\nabla D = \rho \dots$

Einstein:  $E = mc^2$

Heisenberg et al.:  $\Delta x \Delta p > h$



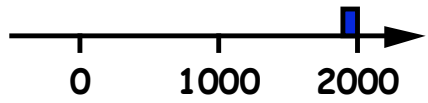
# WW2 et les 40 's

Le pire



Le « meilleur »



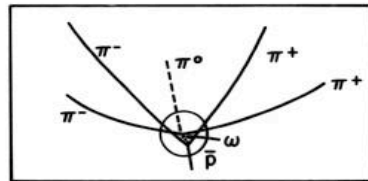
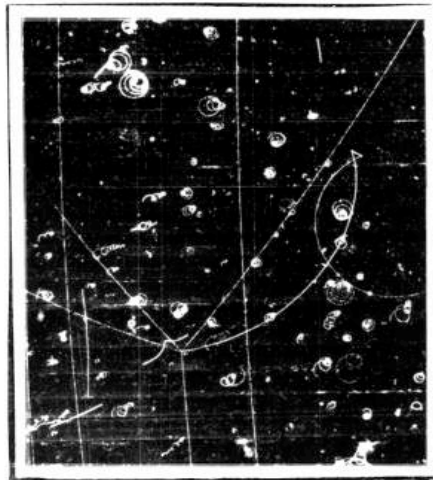


# les années 50-60

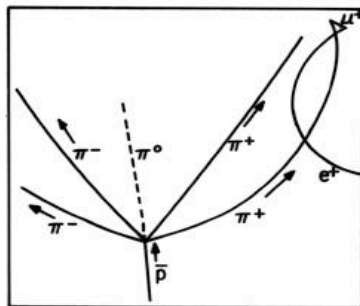
## Particules

## Forces

... des tas ...



Vertex magnified about  $10^{12}$  times

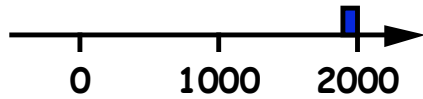


A  $\bar{p}$  annihilation with four charged pions and neutral pion consistent with the production of an omega meson

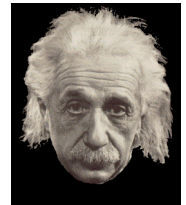


## Lois

# QED

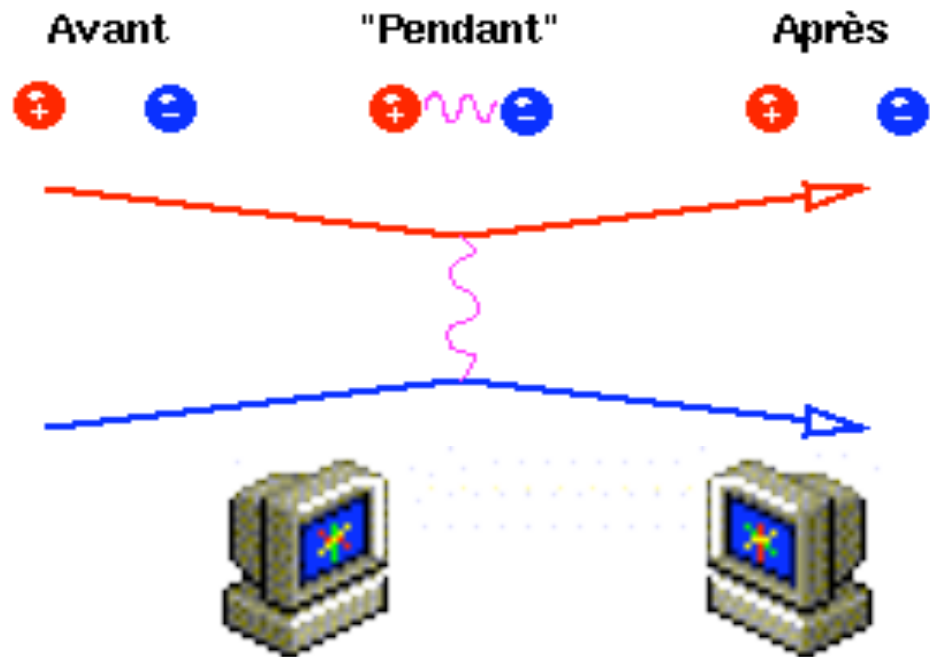


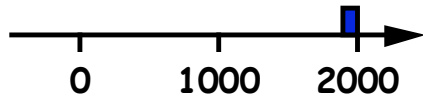
# QED



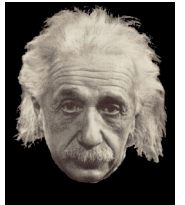
« Théorie de  
l'électromagnétisme  
quantique relativiste »

Force  
=  
Interaction  
=  
Échange





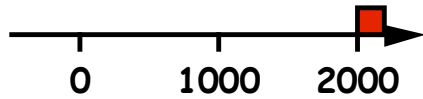
# QED encore !



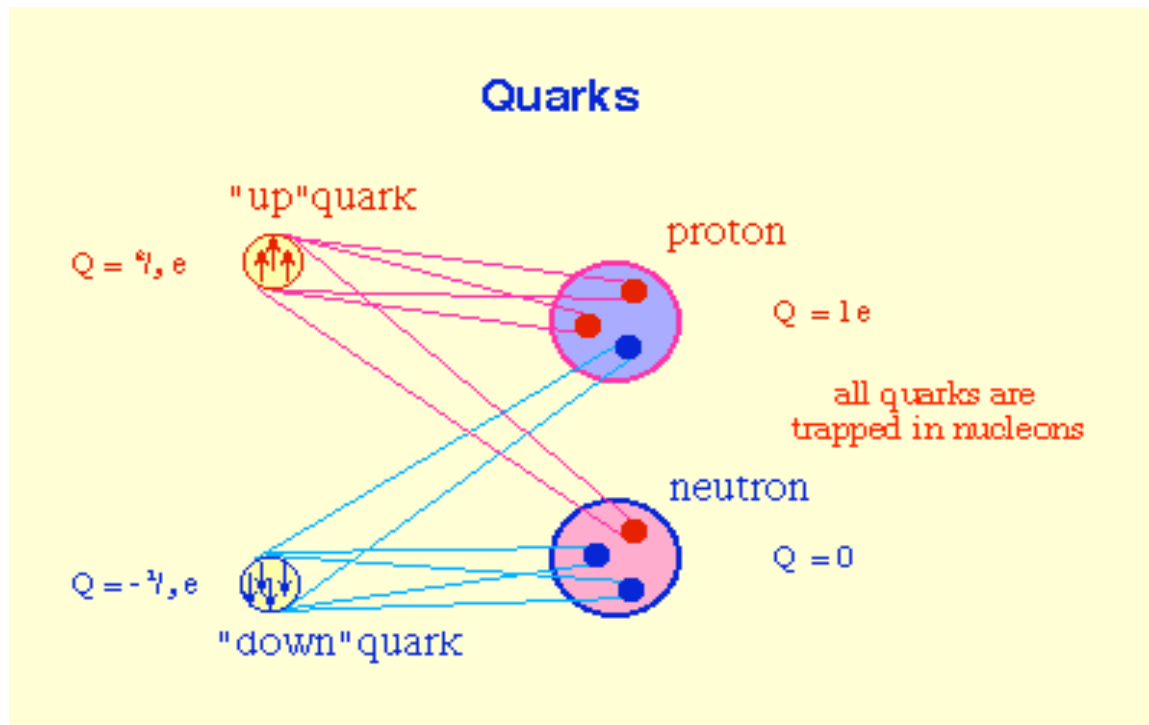
- Force et Matière → Particules
- pour QED:
  - Force = photon
  - (propriété de la) Matière = charge
- pour Gravitation
  - Force = graviton
  - (propriété de la) Matière = masse

« Théorie la + précise de TOUTES ! »





# le Modèle Standard en ... Quarks



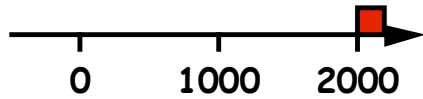
Baryons



Mésons



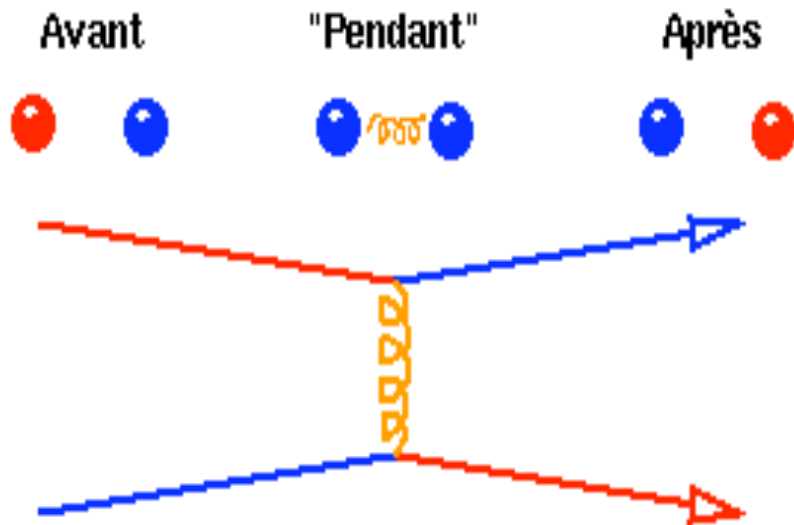




# le Modèle Standard



avec de la ... COULEUR



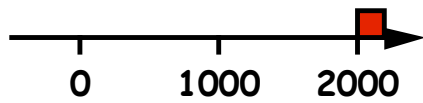
Les Quarks portent une couleur



Les Anti Quarks portent une anti couleur



Les Gluons portent une couleur et une anti couleur



# le Modèle Standard



Tous Les Quarks:

u



d



s



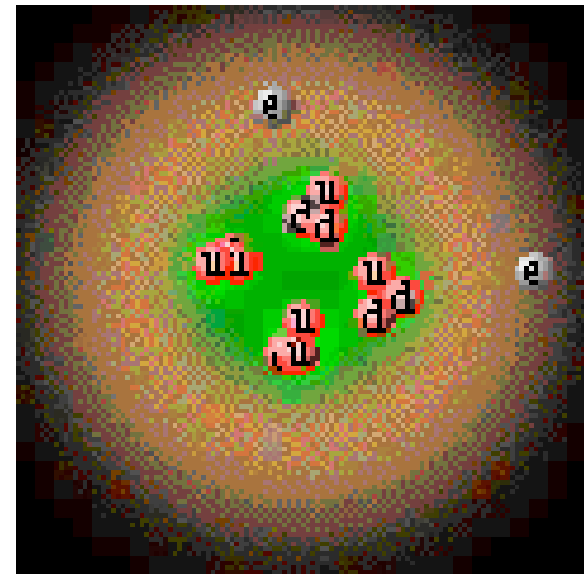
c



b

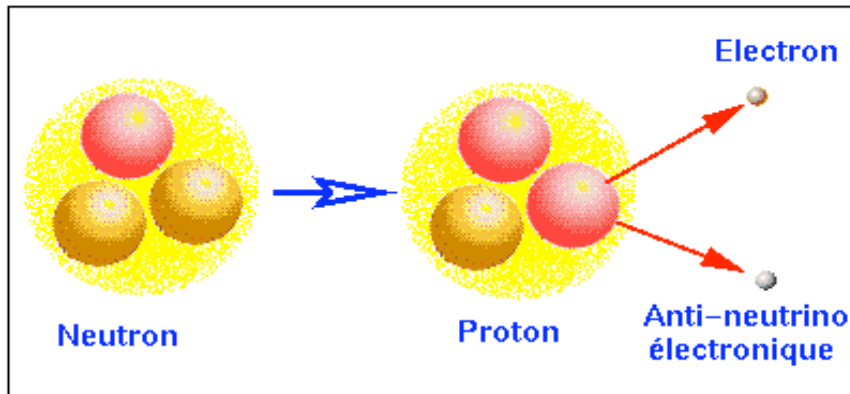
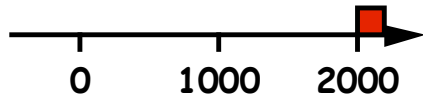


t



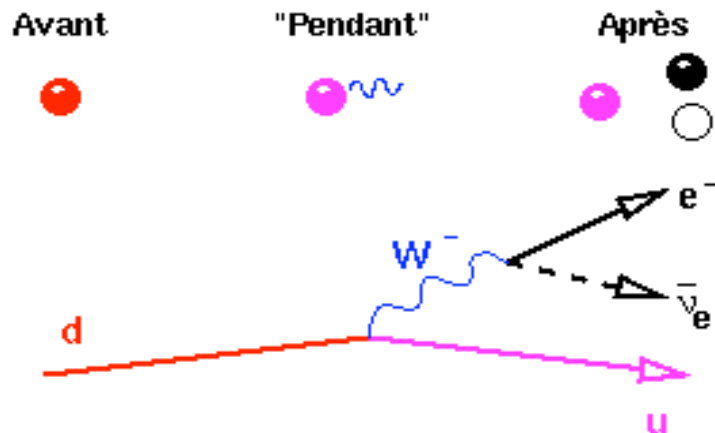
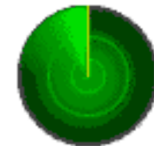
Un atome d'He

# le Modèle Standard

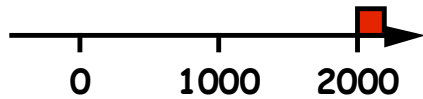


- Agit sur:
  - électron
  - neutrino
  - quark

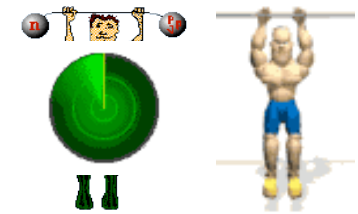
• « analogue » à:



- courte portée
- La force « faible » est portée par  $W^\pm$  et  $Z^0$



# le Modèle Standard



Si vous n'y croyez pas:

1964: idée des quarks (Gell-Mann, Zweig)

1967: idée d'unifier e.m. et faible (Weinberg)

1969: idée d'un 4ième quark, le charme (G. I. M.)

1970: idée du Modèle Standard -électrofaible- (G. S. W.)

1973: idée du Modèle Standard - fort- (G. P. W.)

1973: découverte des courants neutres

1974: découverte du quark charmé

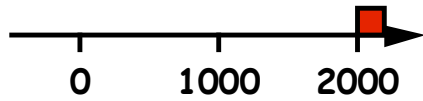
1975: découverte de l'existence des quarks

1977: découverte du quark beau

1979: découverte (indirecte) du gluon

1983: découverte du W et du Z (à la masse prévue)

1995: découverte du quark top (à la masse prévue)



# le Modèle Standard

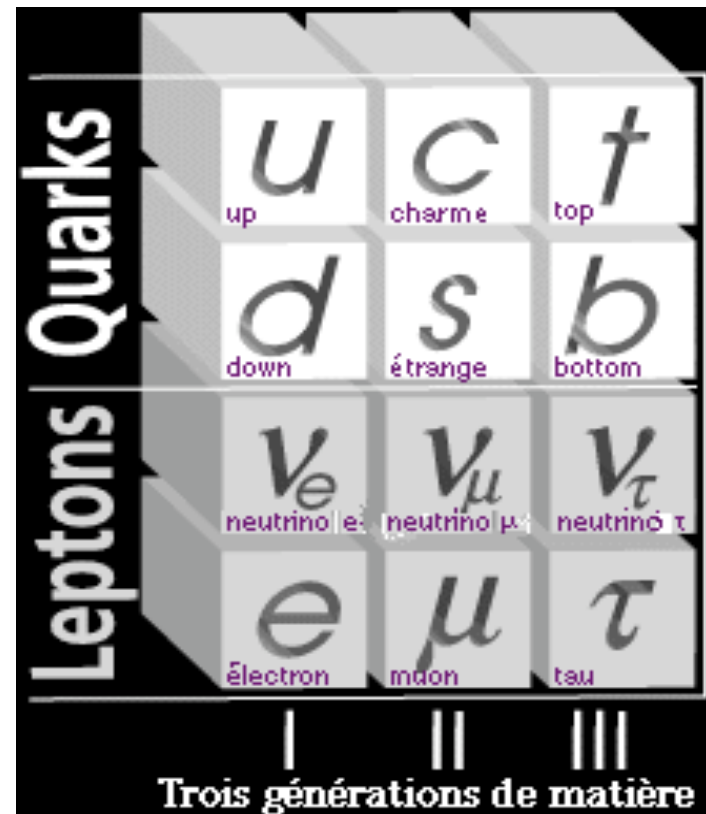
## La Matière

La famille des Quarks:

**u d s c b t**

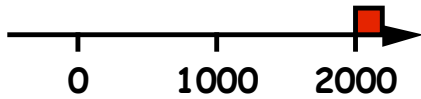
La famille des Leptons:

**e μ τ ν<sub>e</sub> ν<sub>μ</sub> ν<sub>τ</sub>**



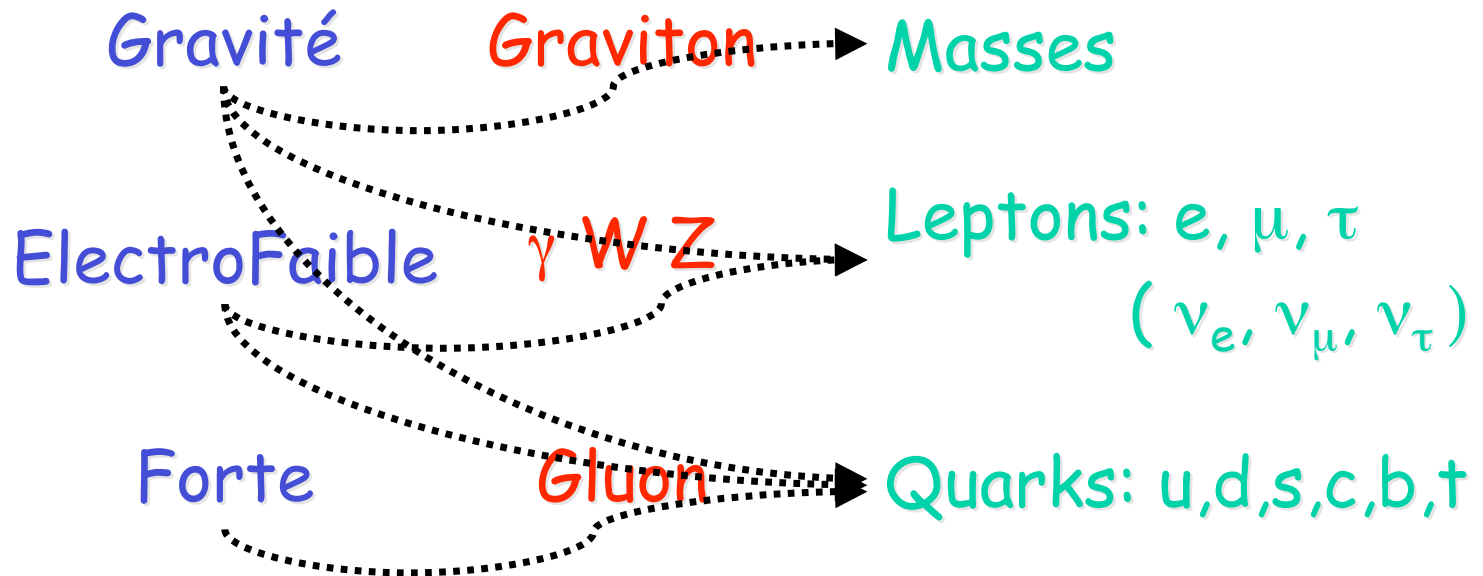
# le Modèle Standard

## Les Forces



Force Messenger Action sur les

---



# le Modèle Standard

Les  
Lois

