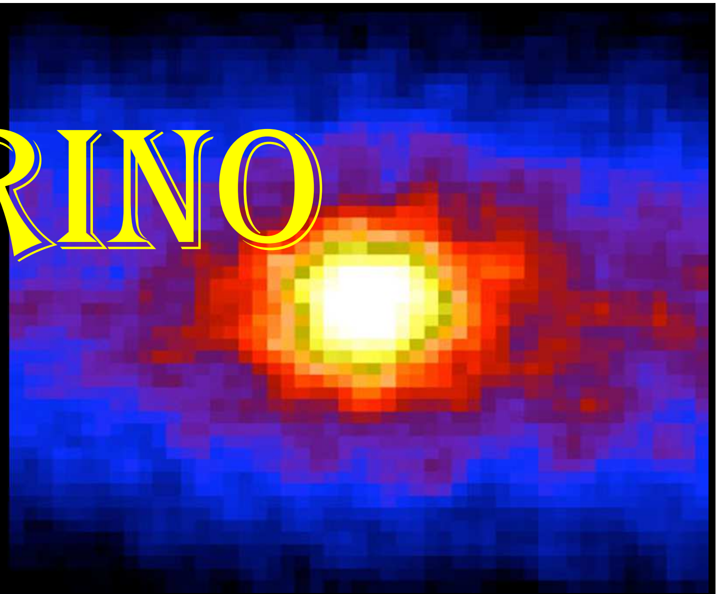
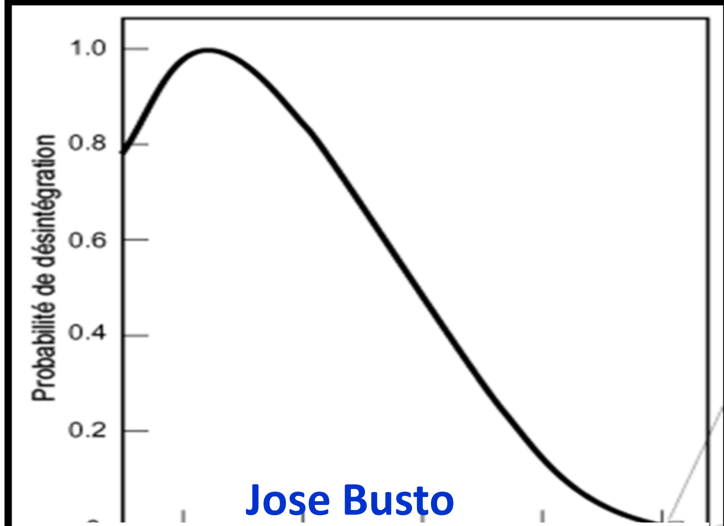
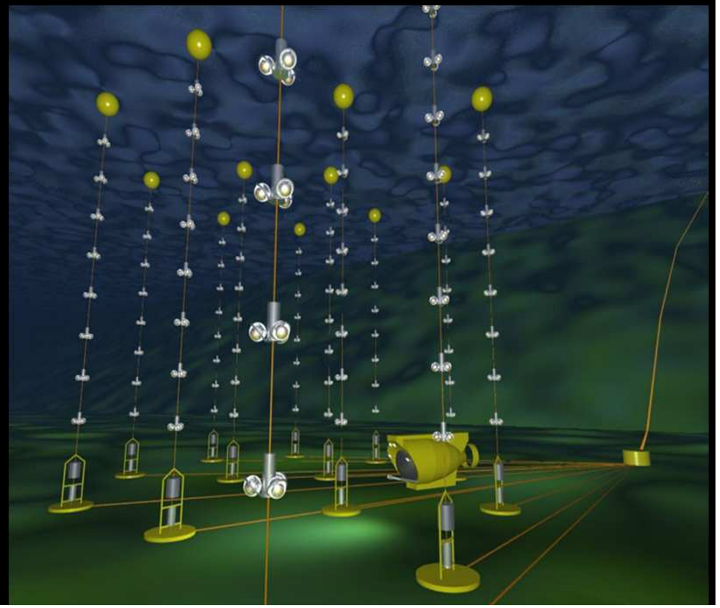


LE NEUTRINO

Histoire et Physique d'un invraisemblable Remède



Jose Busto
(CPPM / Univ. Aix – Marseille)



Préhistoire

du neutrino

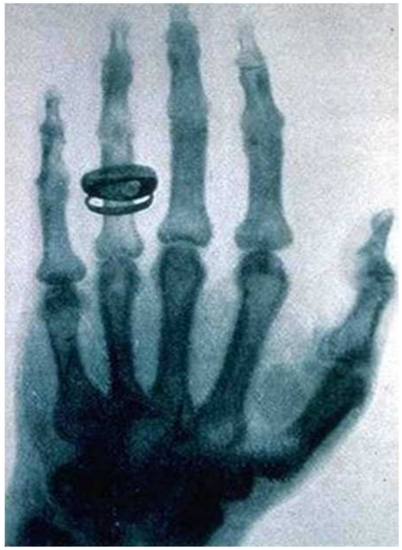
Naissance de la radioactivité

DÉCOUVERTE DES RAYONS X

1895

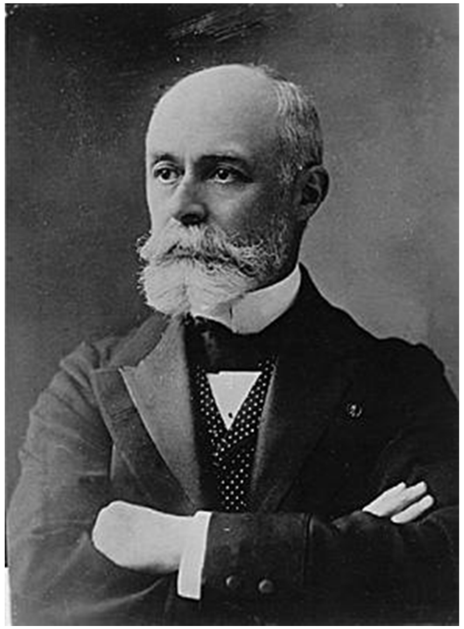
Wilhelm Conrad Röntgen

Tube de Crookes



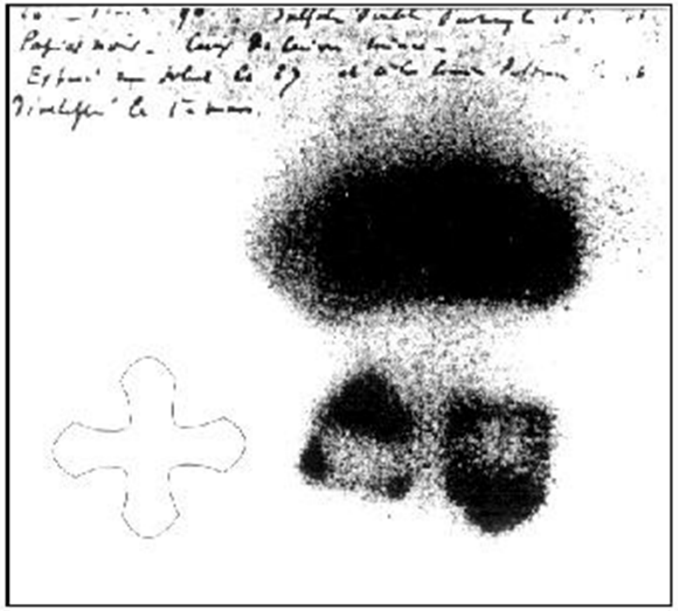
Radiographie aux rayons X

DÉCOUVERTE DE LA RADIOACTIVITÉ



Henri Becquerel

Janvier 1896

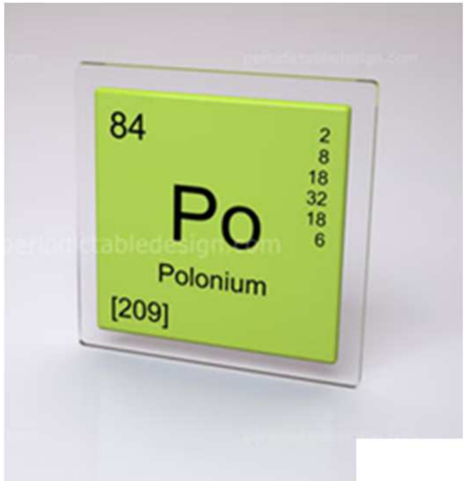


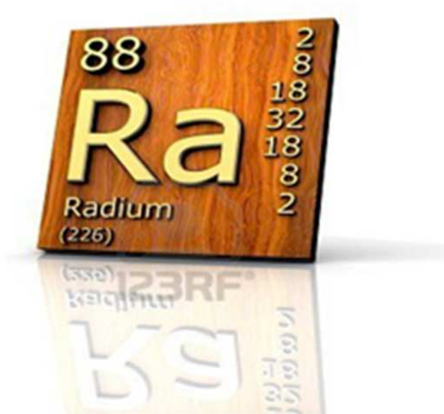
Plaque photographique impressionnée par la radioactive

DÉCOUVERTE DES PREMIERS RADIOÉLÉMENTS

1898

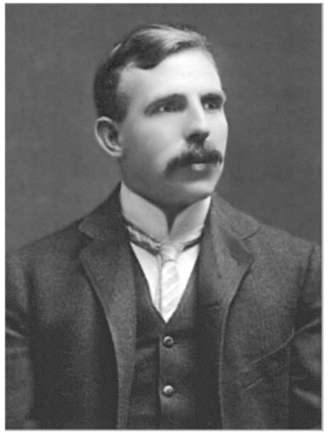
Pierre et Marie Curie





PROPRIÉTÉS DES RAYONNEMENTS

1900 . . .



Rutherford

Curie

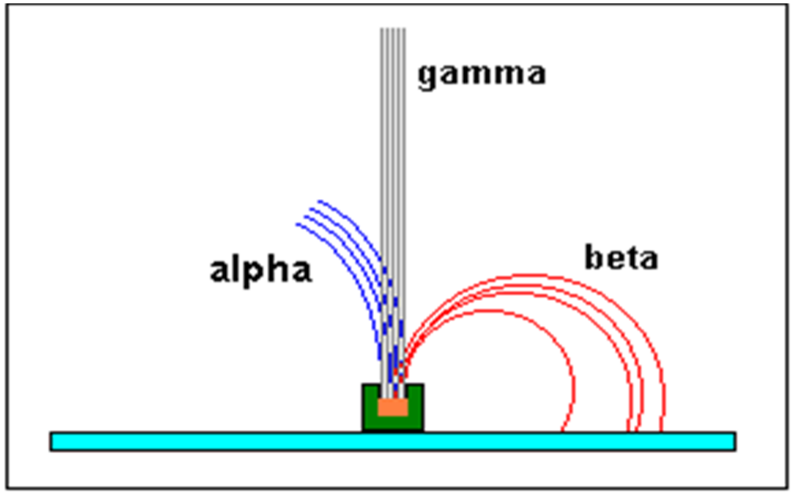
Soddy

Geiger

Villard

et bien d'autres

PROPRIÉTÉS DES RAYONNEMENTS



- Radioactivité alpha : charge positive => noyau d'He
- Radioactivité beta : charge négative => électrons
- Radioactivité gamma : photons de haute énergie

$$\text{Noyau\_A} \rightarrow \text{Noyau\_B} + \left\{\begin{array}{l}\alpha\\ \beta\\ \gamma\end{array}\right.$$

PROPRIÉTÉS DES RAYONNEMENTS

En général :

Noyau_A → Noyau_B + Particule

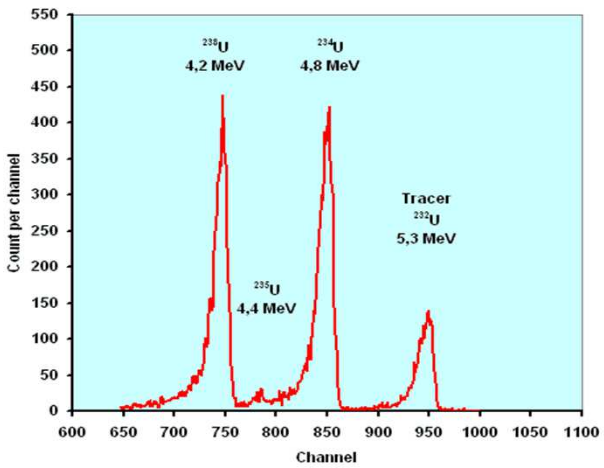
Avec Masse (Noyau) >> Masse (Particule)

Conservation de :

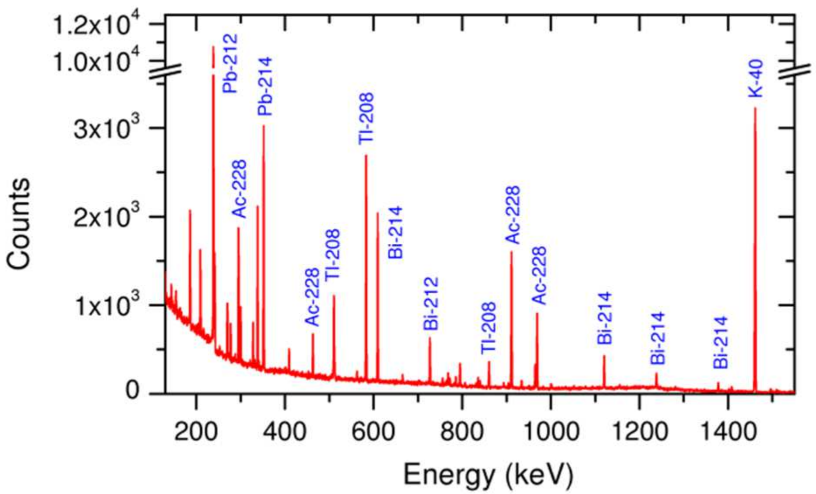
- **Energie** $E_A = E_B + E_P$
- **Impulsion** $\vec{P}_A = \vec{P}_B + \vec{P}_p$

$$\Rightarrow \quad E_p = (M_A - M_B - M_p) \times \frac{M_B}{M_B + M_p} = C^{te}$$

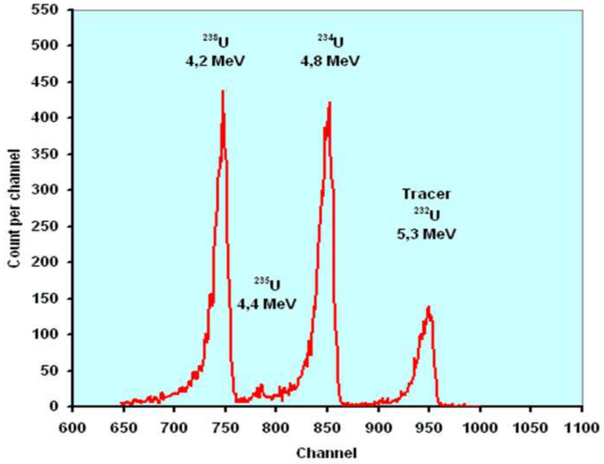
=> l' énergie de la particule est « discrète »



Spectre alpha => OK

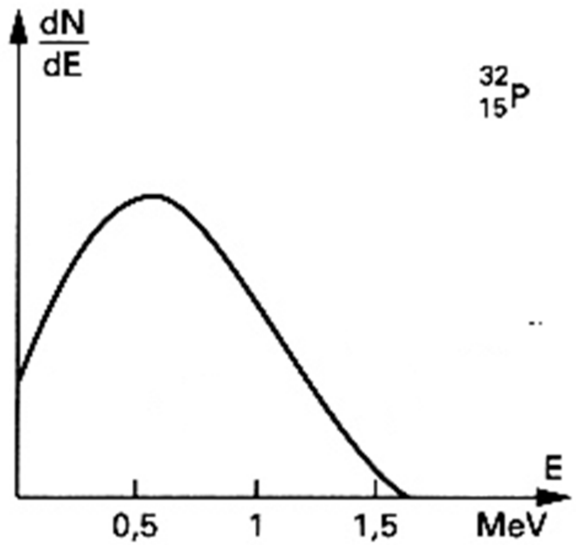


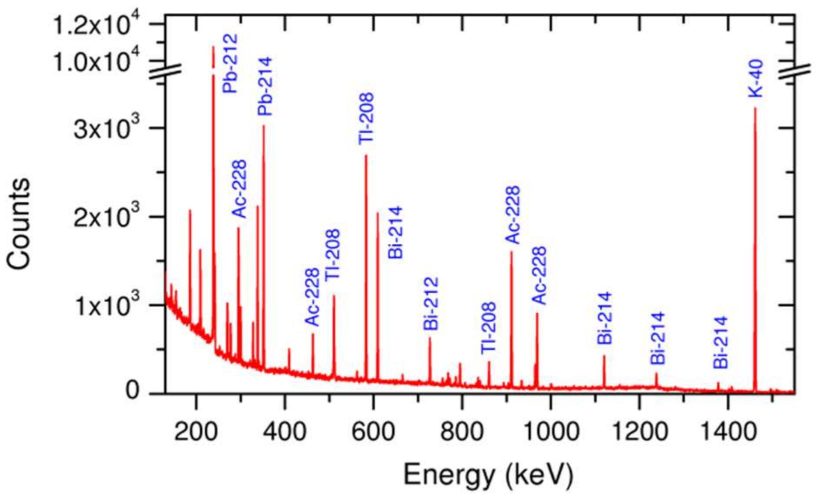
Spectre gamma => OK



Spectre alpha => OK

Spectre beta => !!!!???





Spectre gamma => OK

L’énergie n’est elle pas conservée ?!


Histoire
du neutrino

NAISSANCE D'UNE IDÉE

December 4, 1930

Dear radioactive ladies and gentlemen,

...I have hit upon a 'desperate remedy' to save...the law of conservation of energy. Namely the possibility that there exists in the nuclei electrically neutral particles, that I call neutrons...I agree that my remedy could seem incredible...but only the one who dare can win...

Unfortunately I cannot appear in person, since I am indispensable at a ball here in Zurich.

Your humble servant
W. Pauli

Original-Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

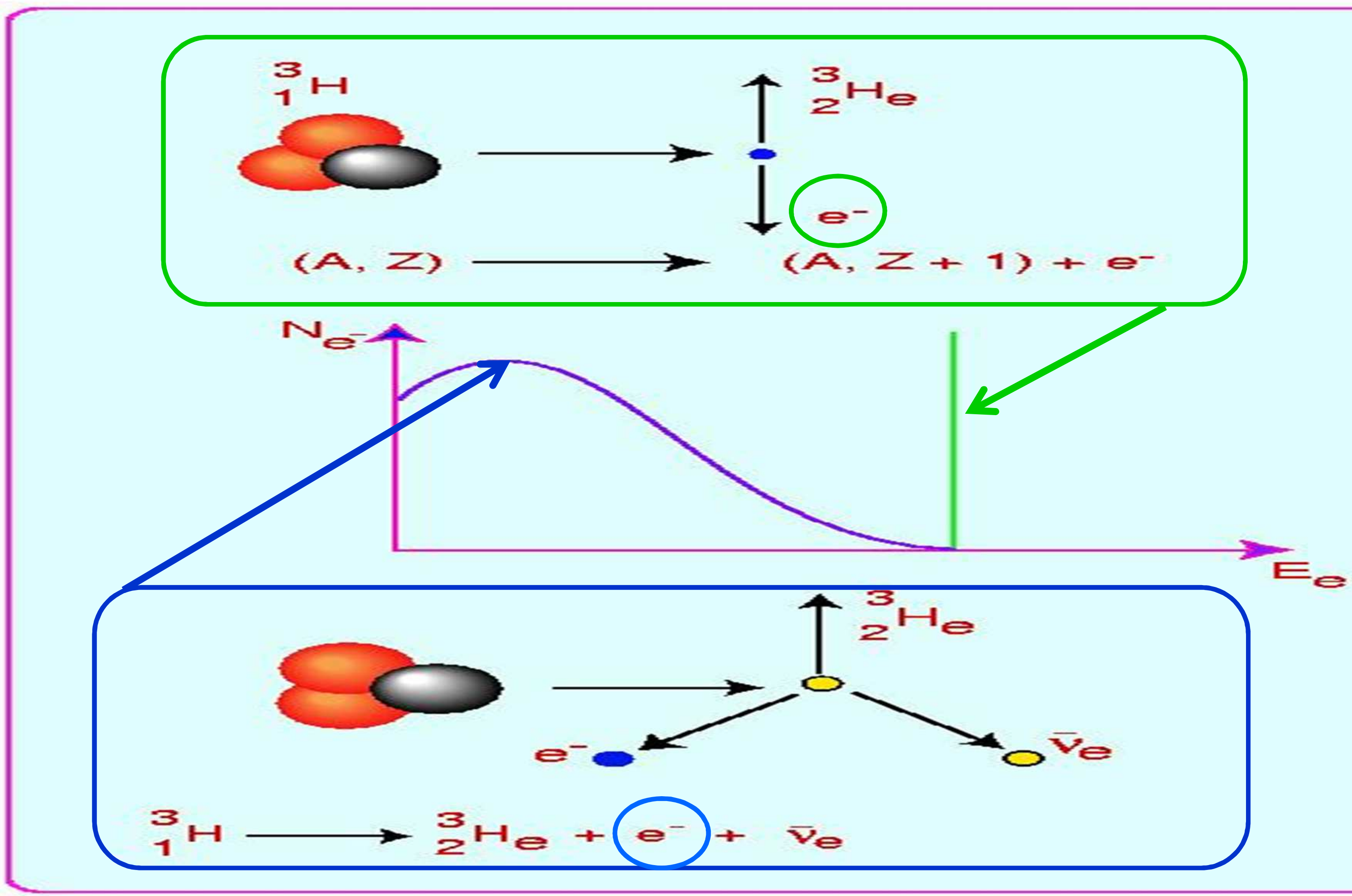
UNE IDÉE INVÉRIFIABLE ?

- Masse très faible ou nulle
- Charge nulle
- Interaction tres difficile

« Je viens de faire quelque chose d'horrible.
J'ai invente une particule indétectable »


« Sur les 10000 milliards de neutrinos qui venant du
Soleil traversent chaque seconde notre corps,
seulement un, en moyenne,
interagira avec lui au cours de notre vie! »

L'idée de Pauli

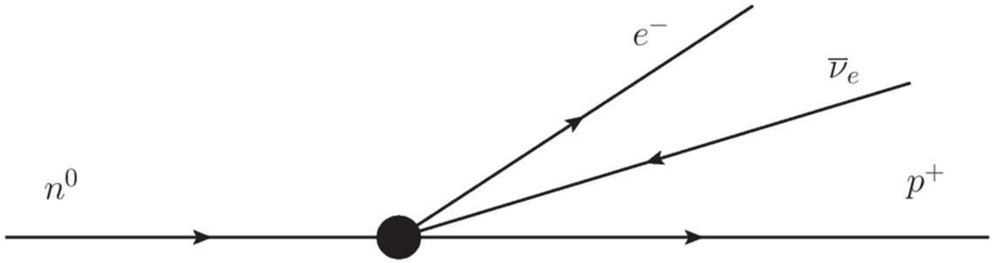


ADOPTION DU NEUTRINO

Fermi 1933

Théorie de la décroissance beta

$$ {}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu} $$



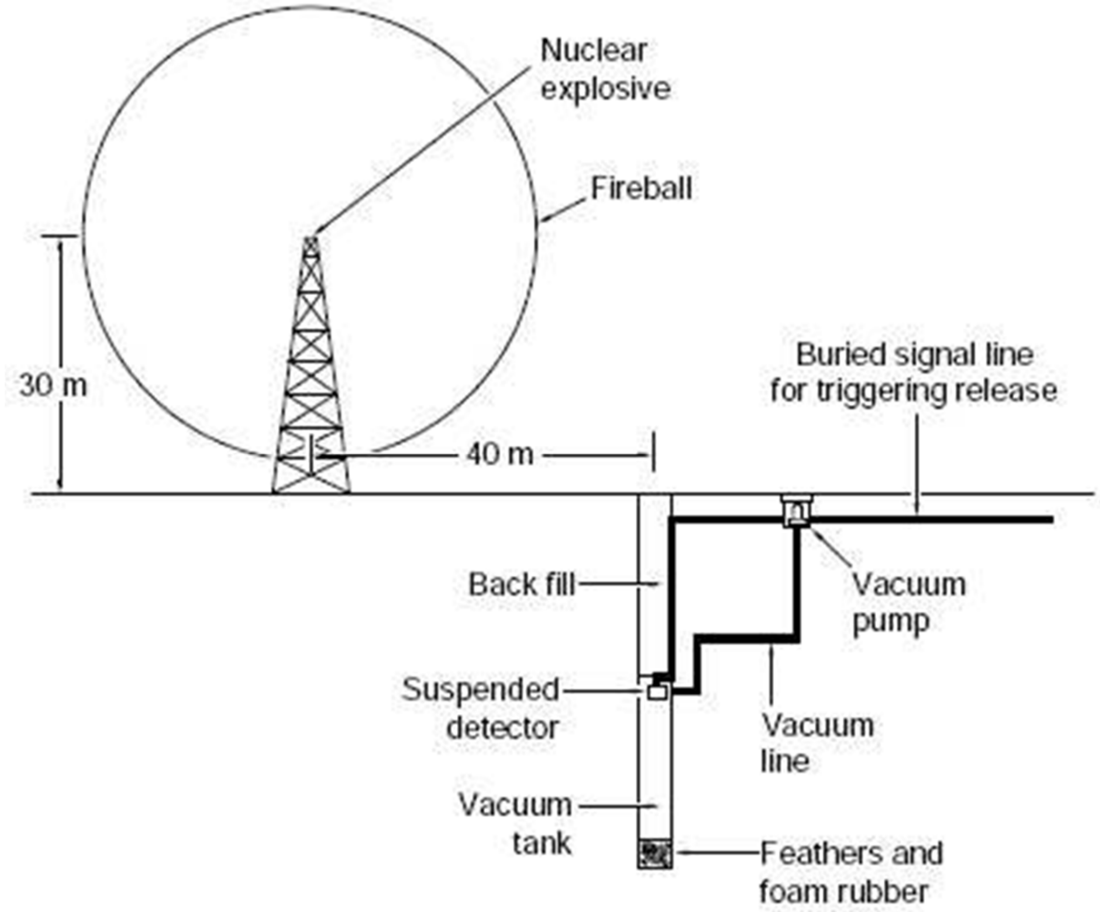
$$ (n \longrightarrow p + e^- + \overline{\nu}) $$

Le « neutron » de Pauli devient le neutrino de Fermi

Où peut-on trouver des neutrinos en grande quantité ?

Les produit de fission sont des émetteurs beta => neutrinos

Premières idées



Mieux dans une centrale nucléaire

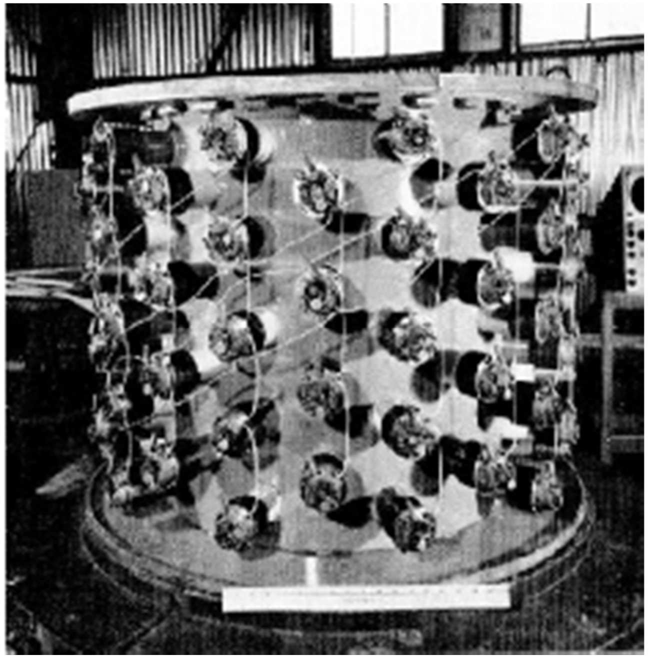
Expérience plotergeist

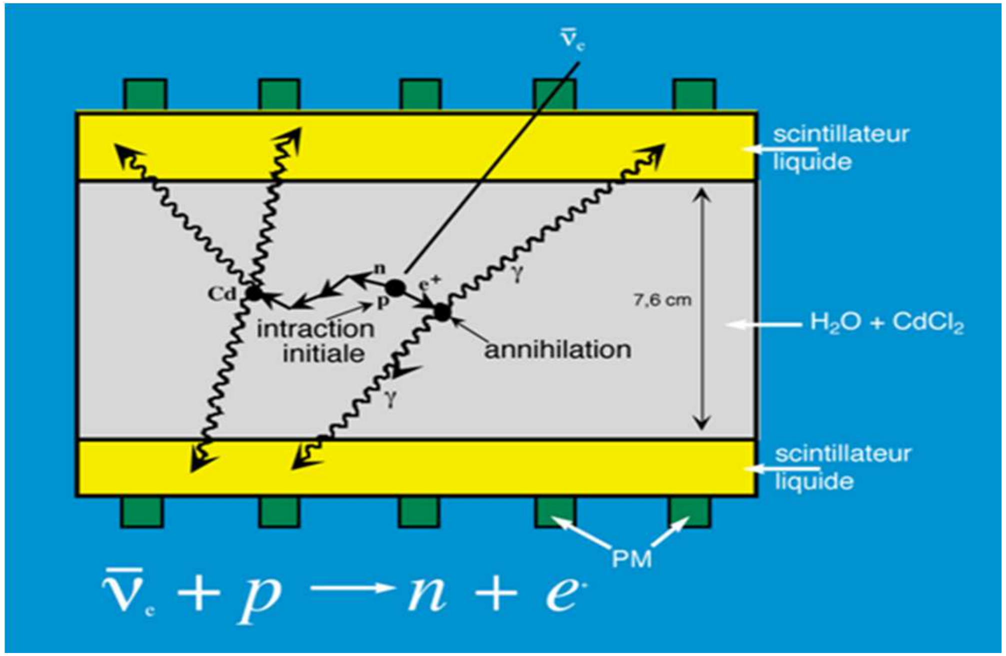
Réacteur nucléaire de Handford

Réacteur nucléaire de Savannah River

C. Cowan F. Reines

1953 a 1956





$\bar{\nu}_e$
scintillateur
liquide
n
e+
p
Cd
γ
7,6 cm
$H_2O + CdCl_2$
intraction
initiale
annihilation
γ
scintillateur
liquide
PM
$\bar{\nu}_e + p \longrightarrow n + e^{+}$

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

74 15.VI.56

LT

PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS
PROF. W. PAULI

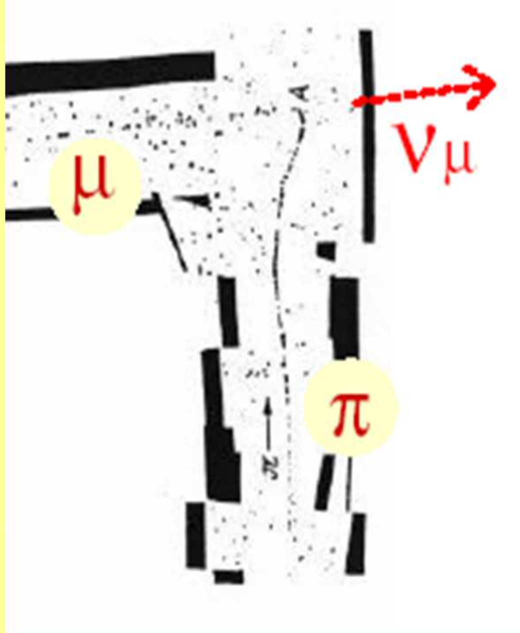
NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED
NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECA
OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX
TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

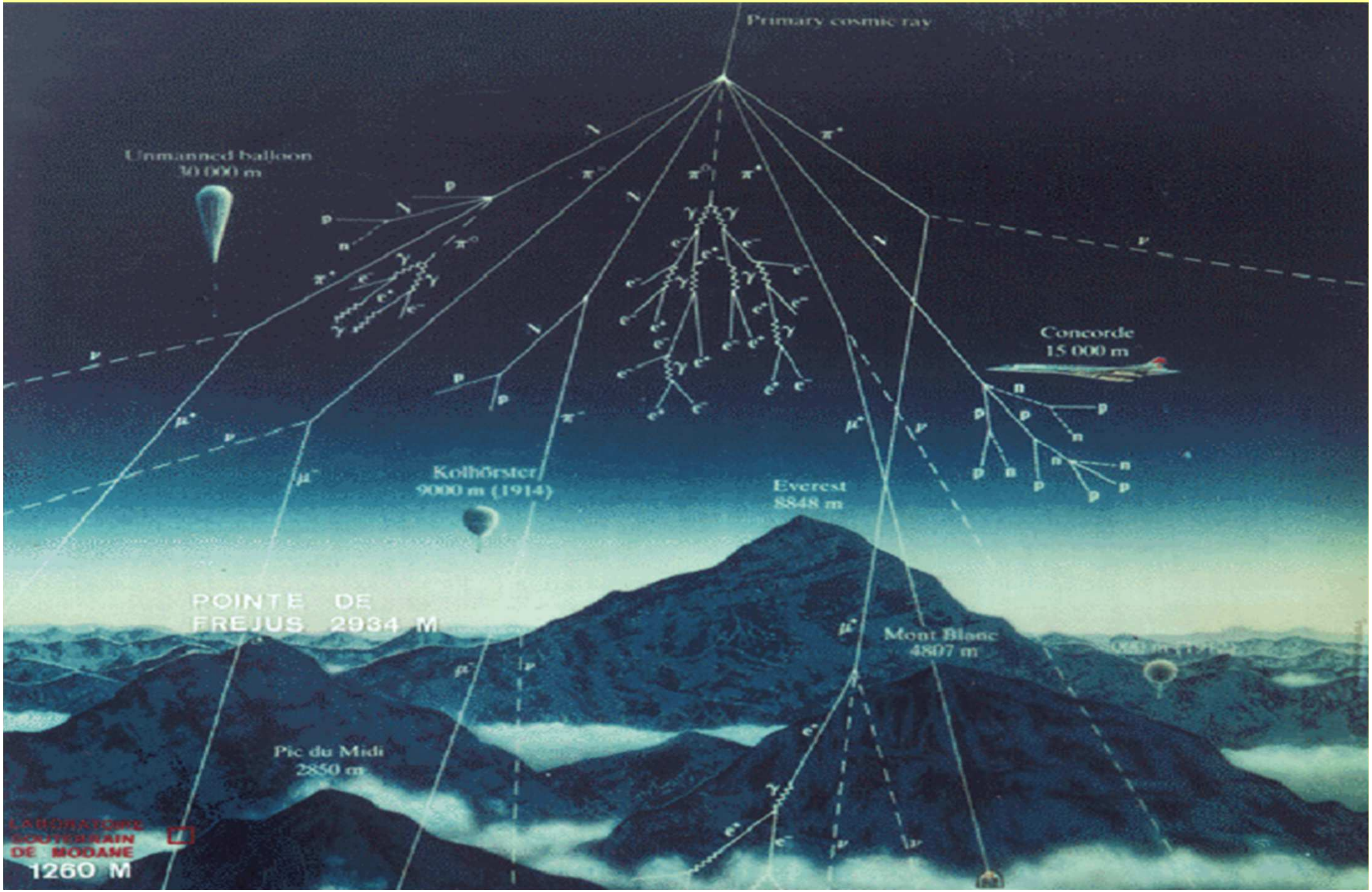
UNE BALADE EN MONTAGNE

1st Observed $\pi \to \mu\nu$ decay



Découverte du muon (électron lourd) dans les rayons cosmiques en 1937 : Anderson et Neddermeyer

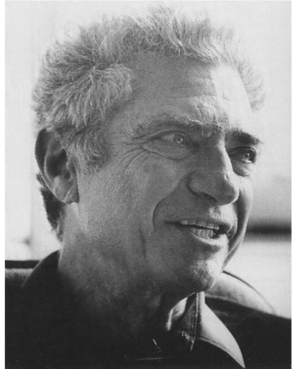
Les Rayons Cosmiques avec l'atmosphère comme cible



Deux Neutrinos

1962

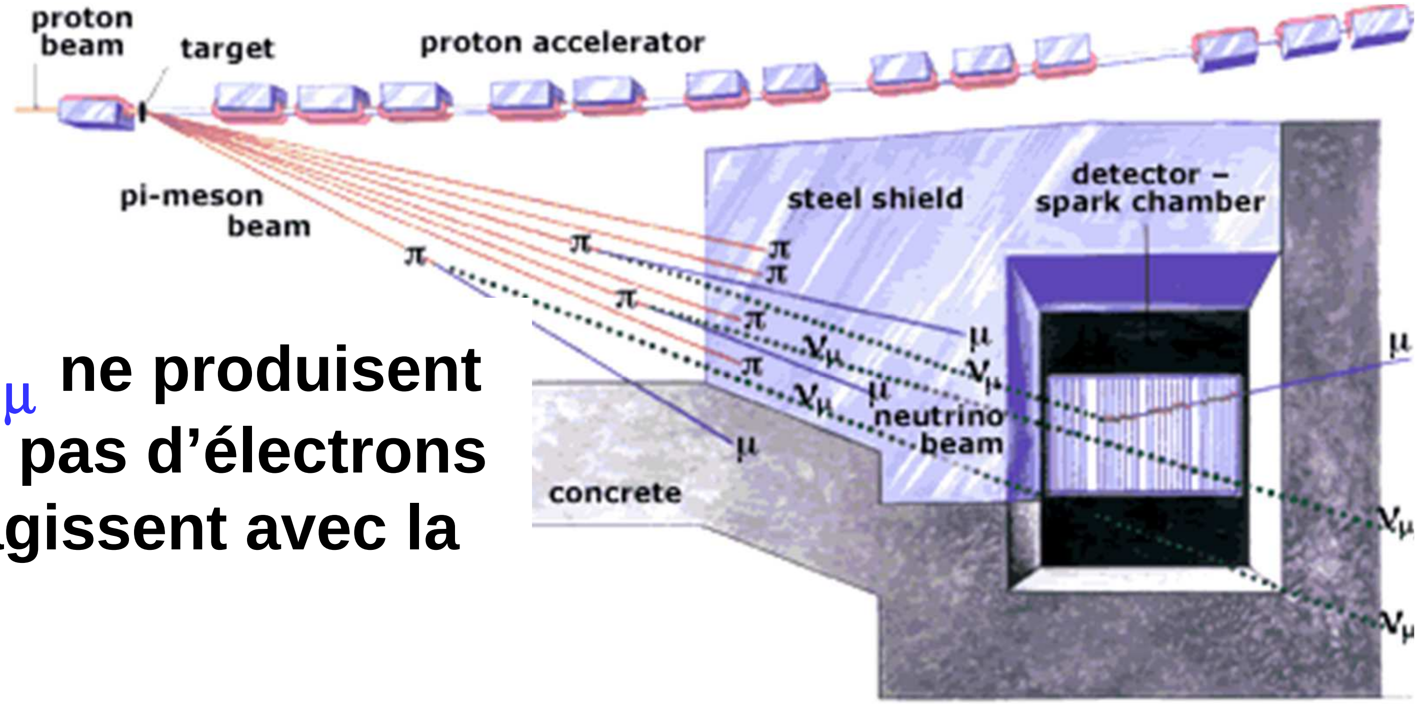




Schwartz Lederman Steinberger

Premier faisceau de neutrinos artificiels

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$



Ces neutrinos ν_μ ne produisent que des muons, pas d'électrons quand ils intéragissent avec la matière

- 1973 Découverte d'un nouveau « électron » super lourd : le tau

SPEAR @ SLAC

Trois Neutrinos

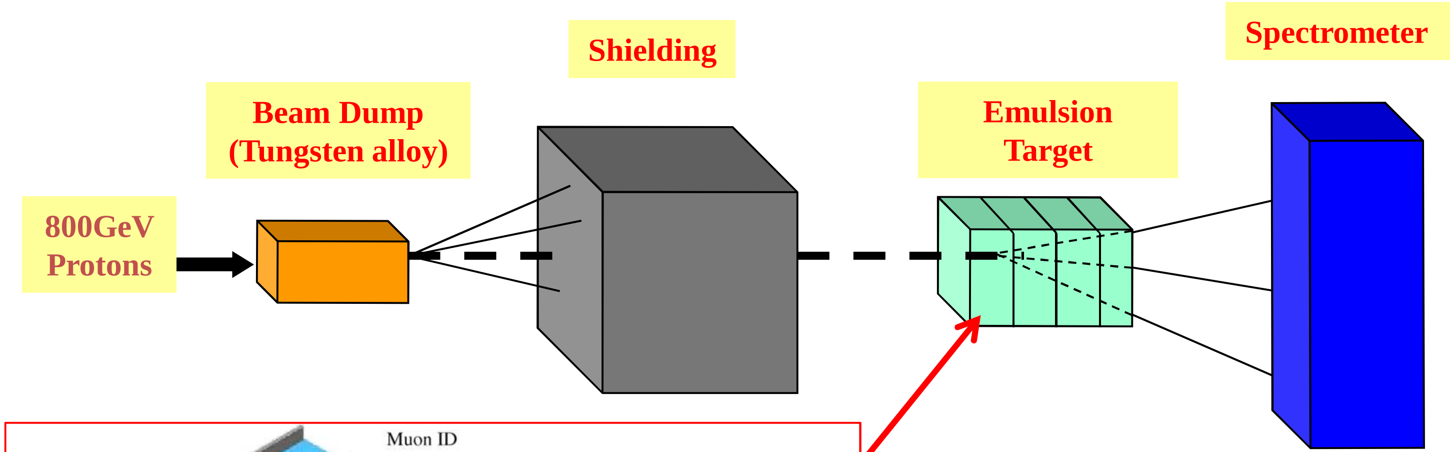
DONUT @ FERMILAB

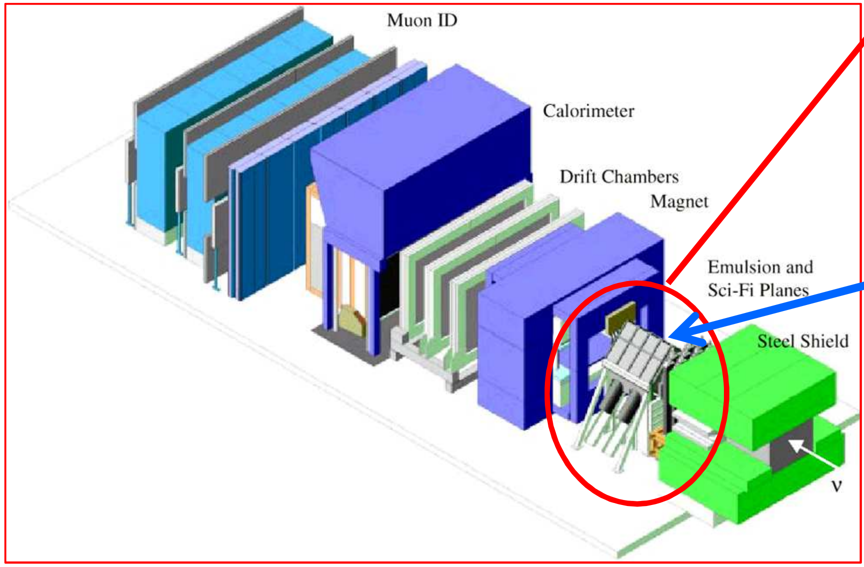
- **2001 découverte du neutrino de tau**

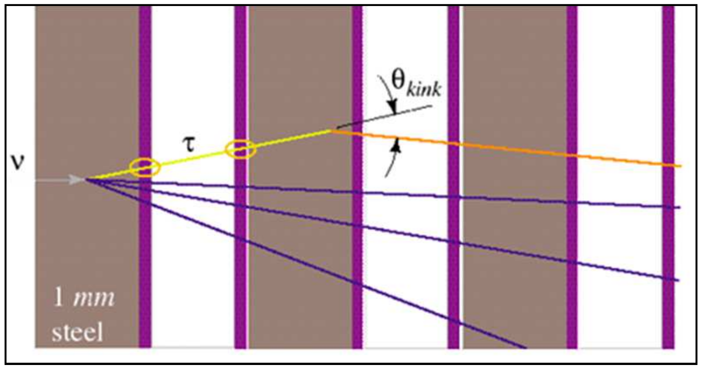
$p + N \rightarrow X + \tau$

$\tau \rightarrow \nu_\tau + X$

$\nu_\tau \rightarrow \tau + X$







Emulsion photo

Le neutrino

Aujourd'hui en France

et ailleurs

En 1932, 5 particules (dont une hypothétique le ν)

e^-	p	n	γ	ν

En 2000, ~ 200 particules

e^-	p	n	γ	ν
π^-	π^+	π^o	μ	τ
Δ^o	Δ^-	Ω^-	Λ^+	Σ^0
K^+	K^0	……		

Tout cela ne peut pas être « élémentaire » !

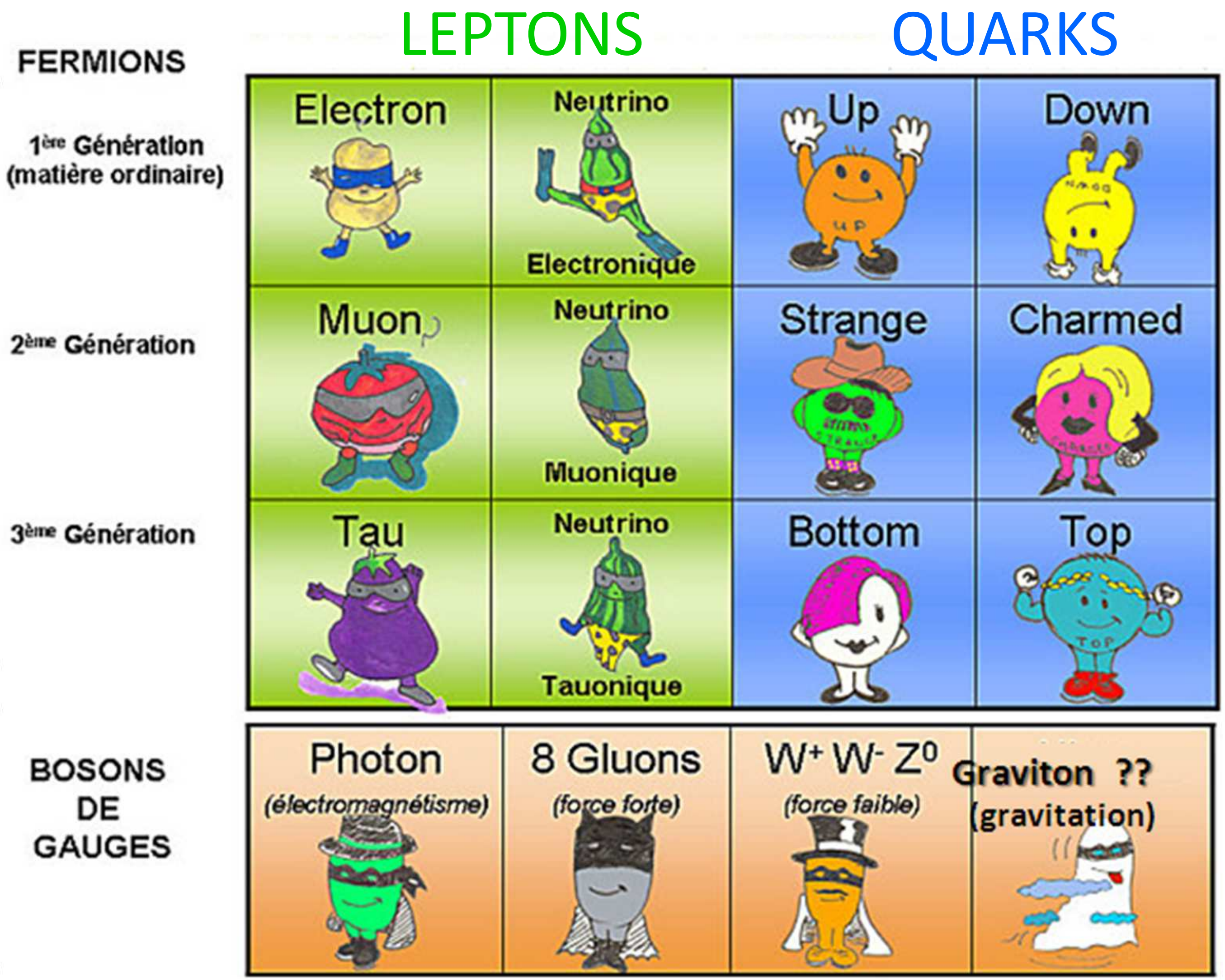
Modelé Standard

12 particules élémentaires

4 forces fondamentales

Particules de Matière

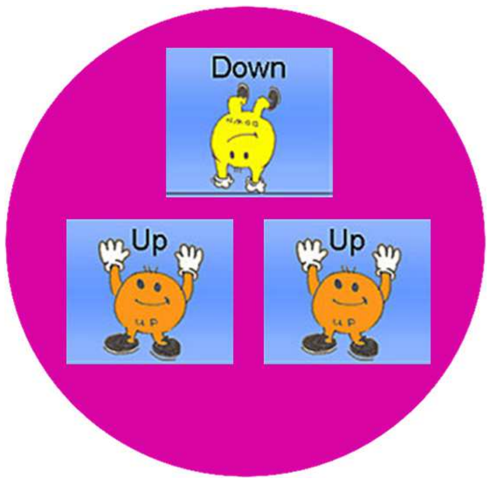
Particules de Interaction



Modelé Standard

12 particules élémentaires

Agrégats

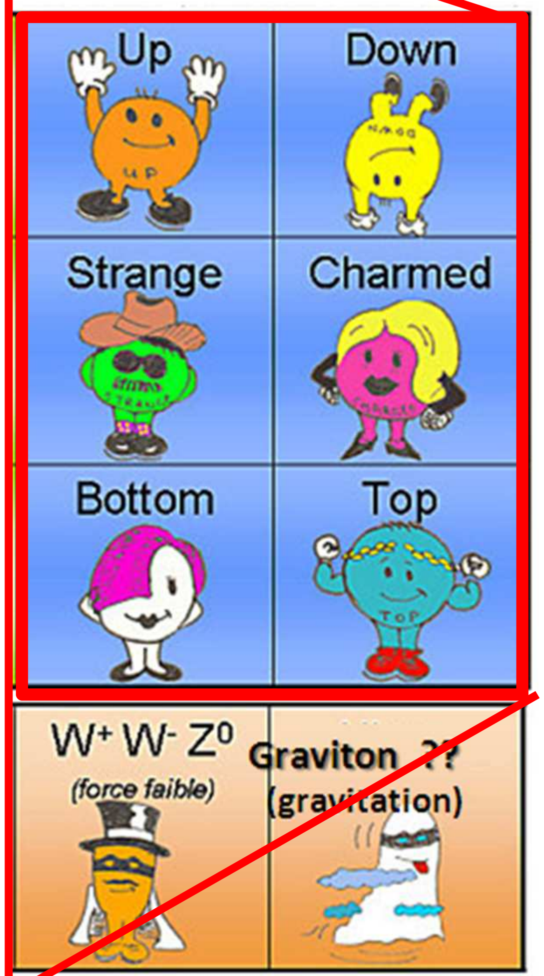


proton

Mais aussi :

n, π, Κ, Δ, Λ, Σ, Ξ, Ω ...

QUARKS



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

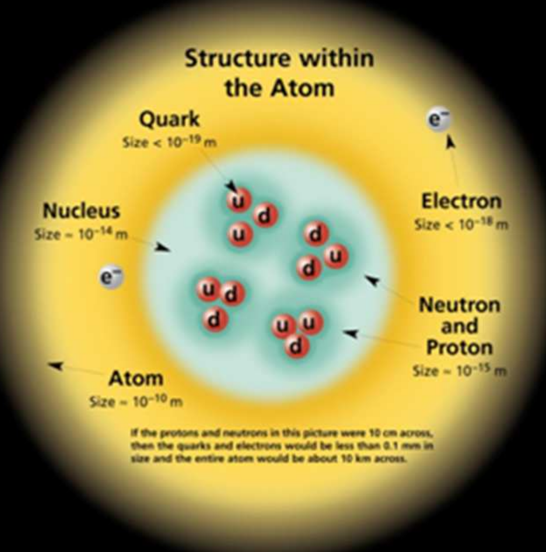
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

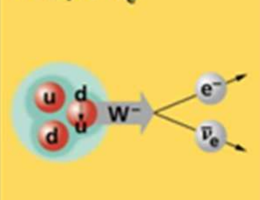
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

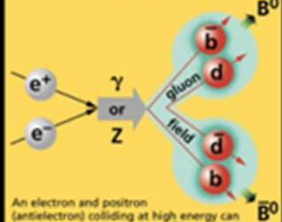
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

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



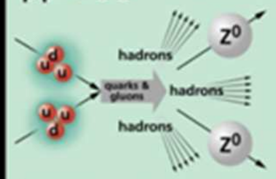
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
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U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
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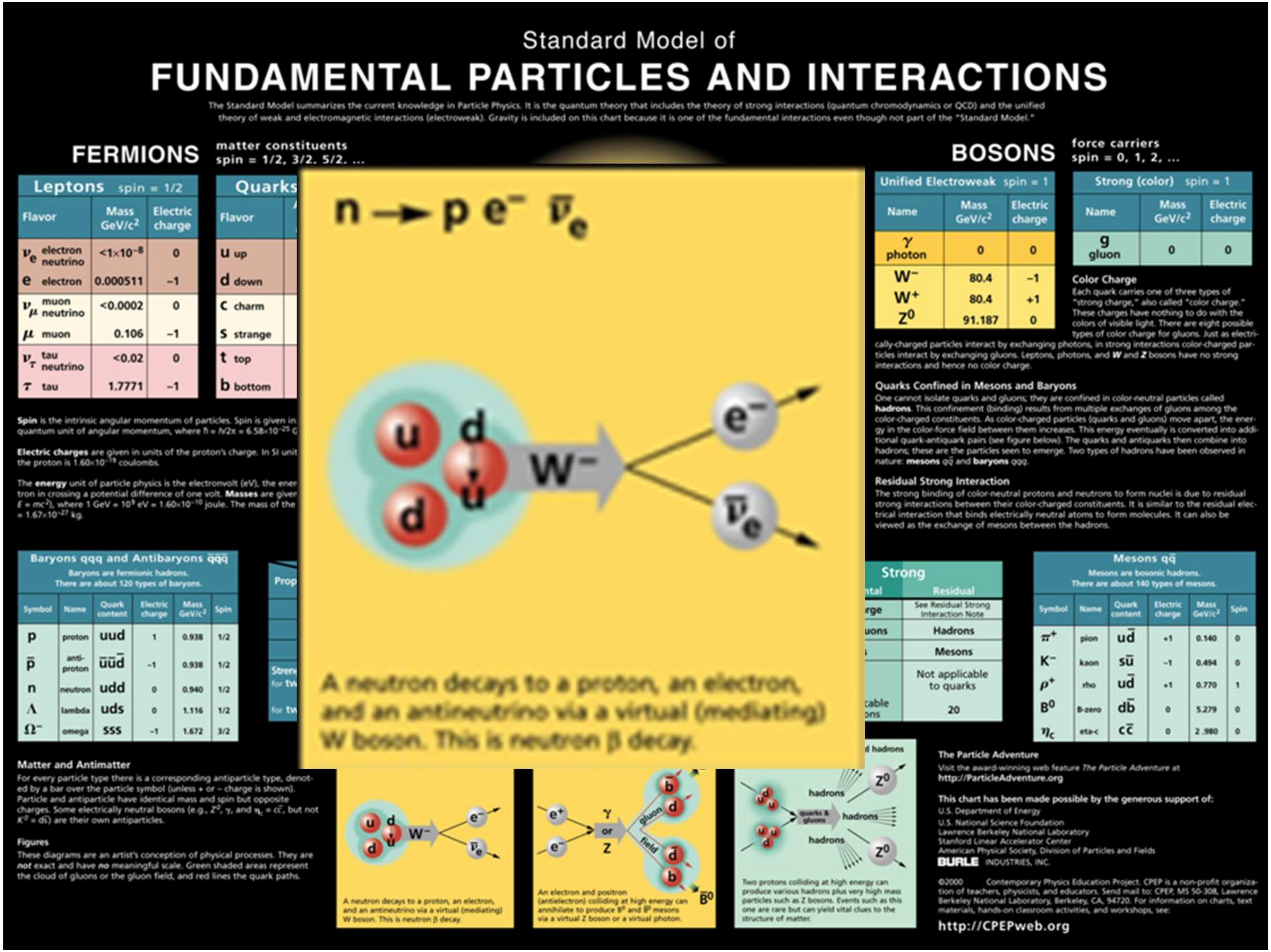
http://CPEPweb.org



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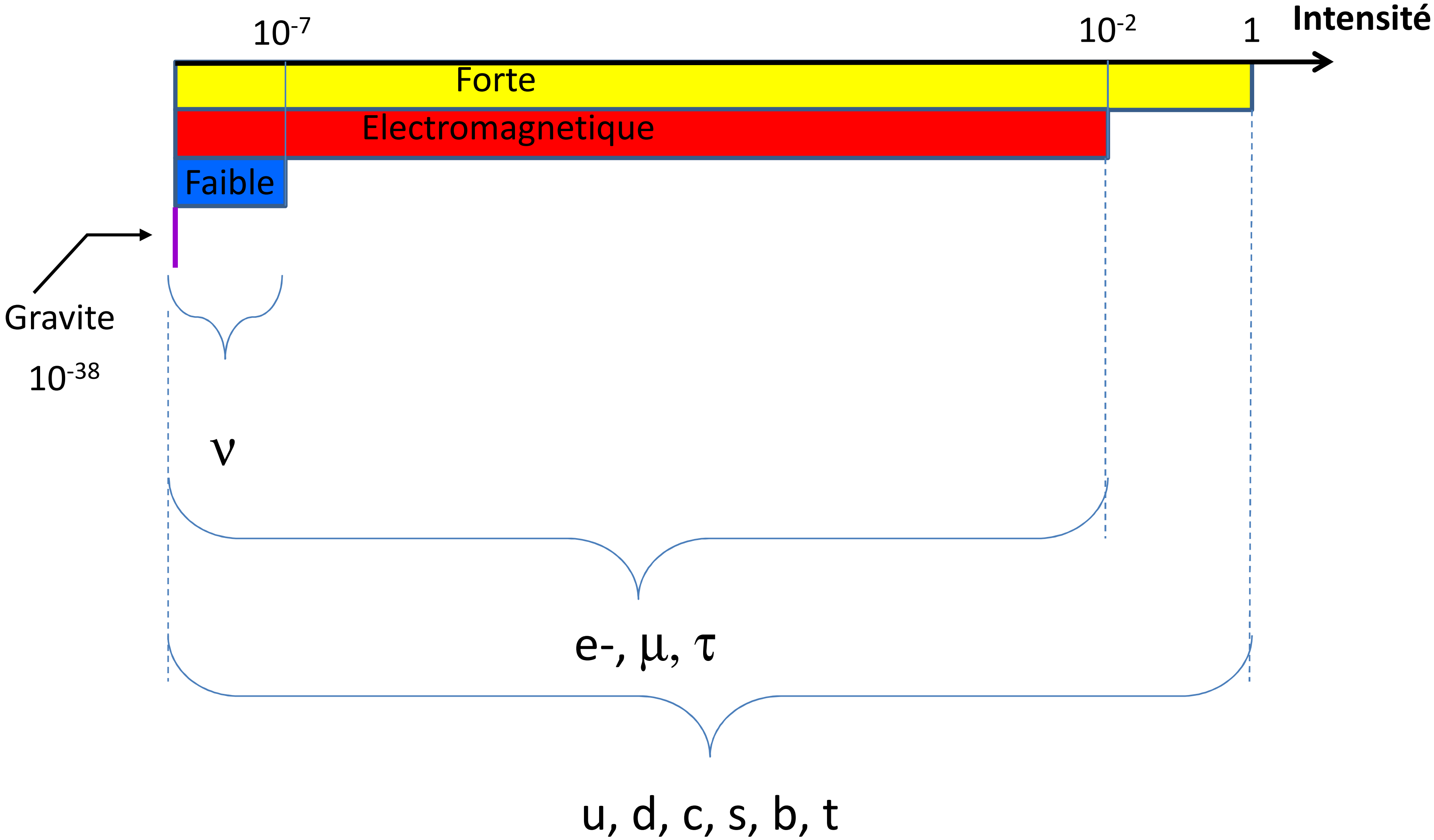
FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...
BOSONS
force carriers
spin = 0, 1, 2, ...
Leptons spin = 1/2
Flavor
Mass GeV/c²
Electric charge
electron neutrino
<1×10⁻⁸
0
electron
0.000511
−1
muon neutrino
<0.0002
0
muon
0.106
−1
tau neutrino
<0.02
0
tau
1.7771
−1
Quarks
u up
d down
c charm
s strange
t top
b bottom
Unified Electroweak spin = 1
Name
photon
0
0
W⁻
80.4
−1
W⁺
80.4
+1
Z⁰
91.187
0
Strong (color) spin = 1
g gluon
0
0
Color Charge
Quarks Confined in Mesons and Baryons
Residual Strong Interaction
n → p e⁻ ν̄e
W⁻
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.
Baryons qqq and Antibaryons q̄q̄q̄
Baryons are fermionic hadrons.
There are about 120 types of baryons.
Mesons qq̄
Mesons are bosonic hadrons.
There are about 140 types of mesons.
Matter and Antimatter
Figures
The Particle Adventure
http://ParticleAdventure.org
http://CPEPweb.org

Un mot sur l'interaction entre particules



Le neutrino : petit par la taille mais grand par le nombre

$\sim 1000\ \gamma\ /\ cm^3$

$\sim 330\ \nu\ /\ cm^3$

$\sim 10^{-7} p\ /\ cm^3$

Physique imprécise

- **Masse** $\begin{cases} \nu_e & < 2 \text{ eV} \\ \nu_\mu & < 190 \text{ keV} \\ \nu_\tau & < 18.2 \text{ MeV} \end{cases}$ $\longrightarrow$ $\boxed{\neq 0}$

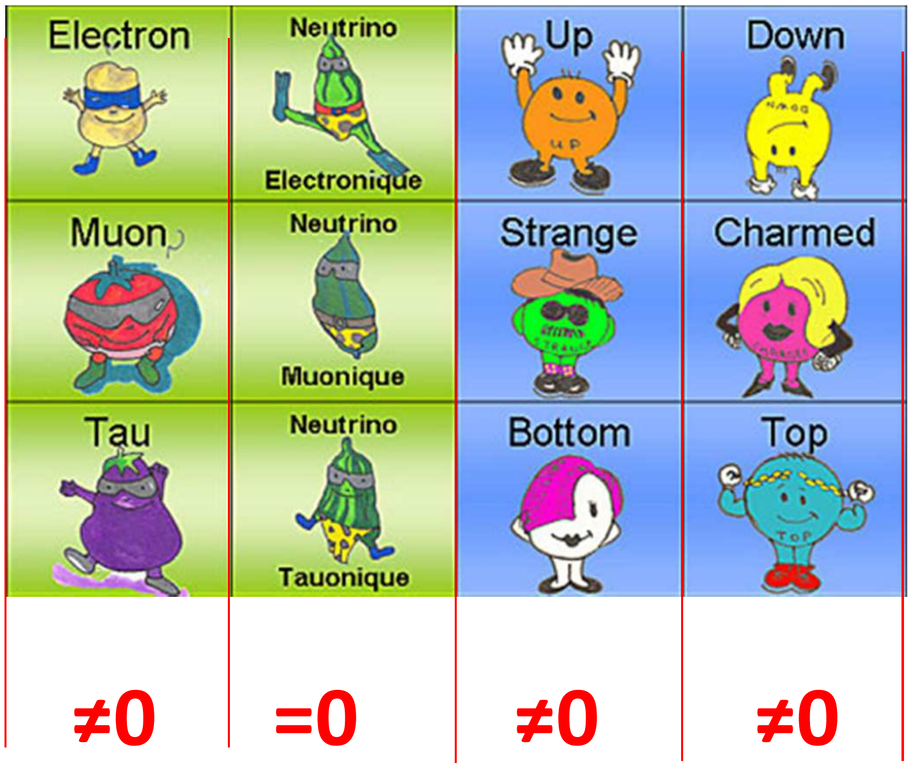
- **Charge** $< 3.7 \cdot 10^{-12}\ Q_e$

- **Vie moyenne** $> 7 \cdot 10^{9}$ s /eV

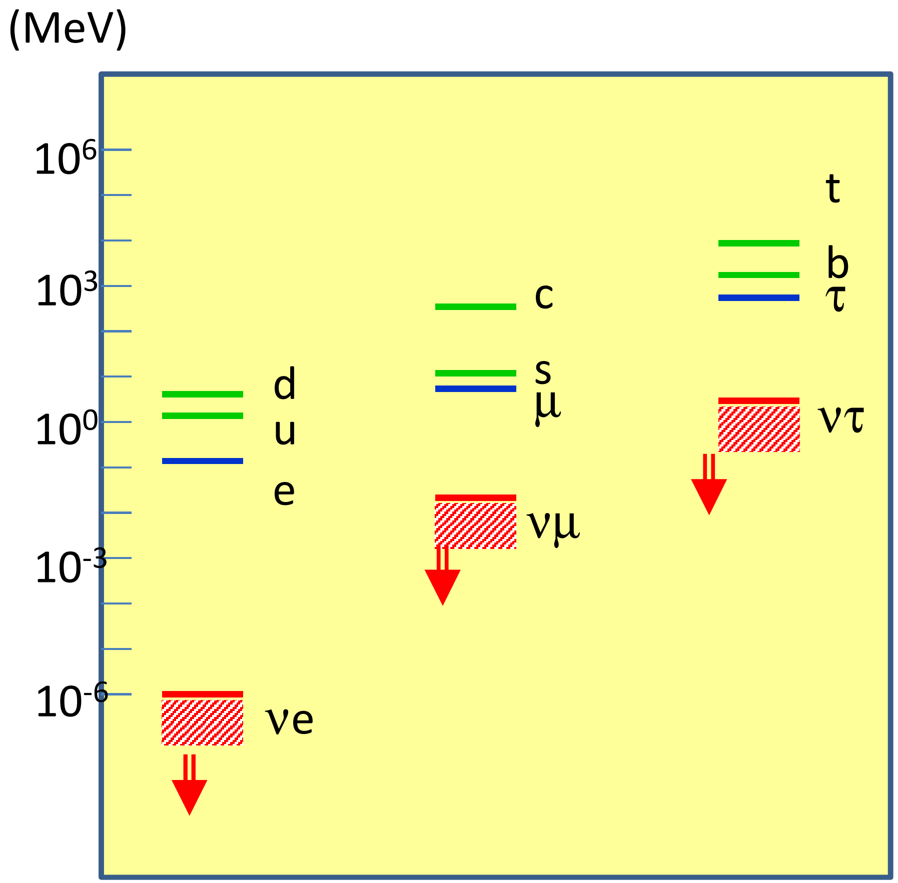
- **Moment magnétique** $< 9 \cdot 10^{-11}\ \mu_B$ $\longrightarrow$ $\boxed{\neq 0}$

Particule particulière

Charge électrique

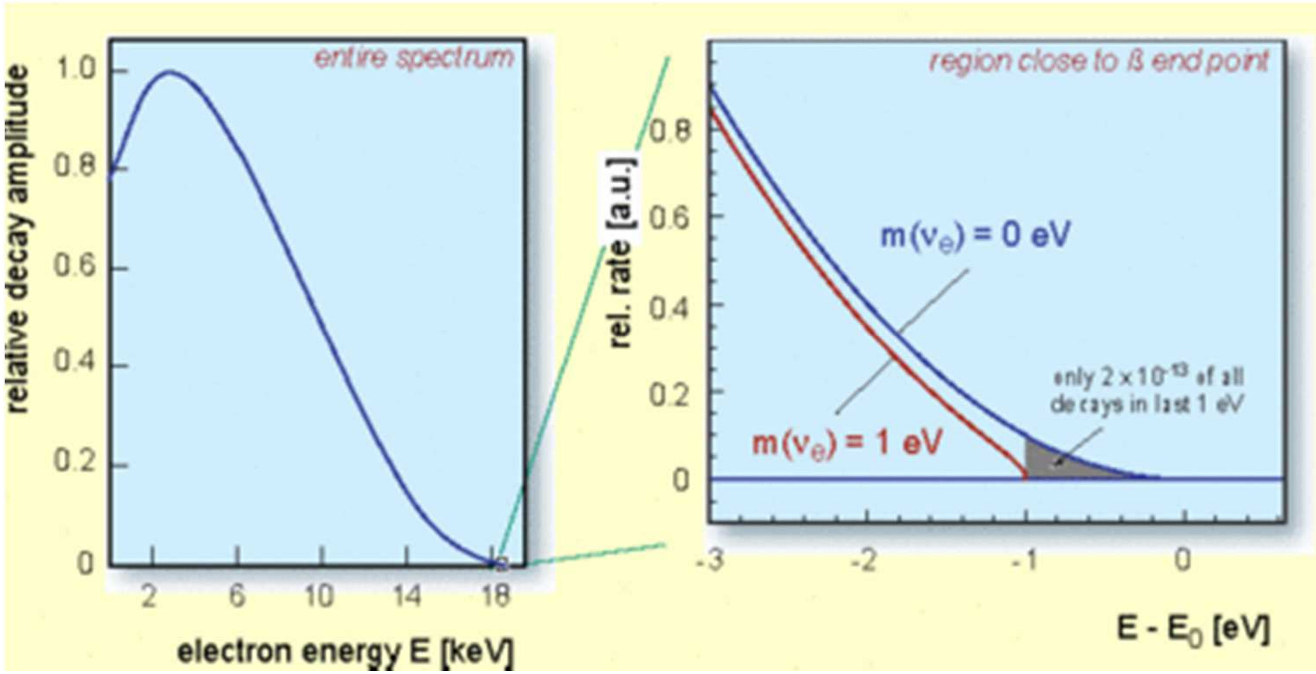


Masse



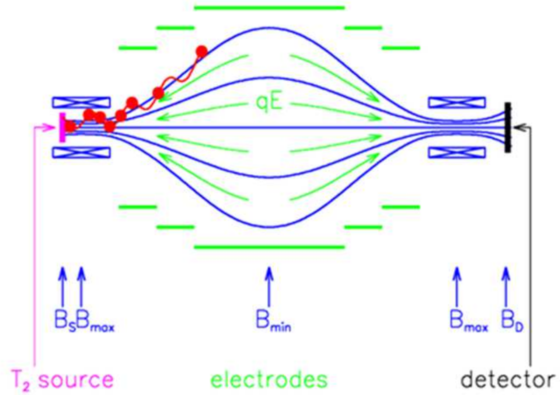
Comment peser les neutrinos ?

E. Fermi

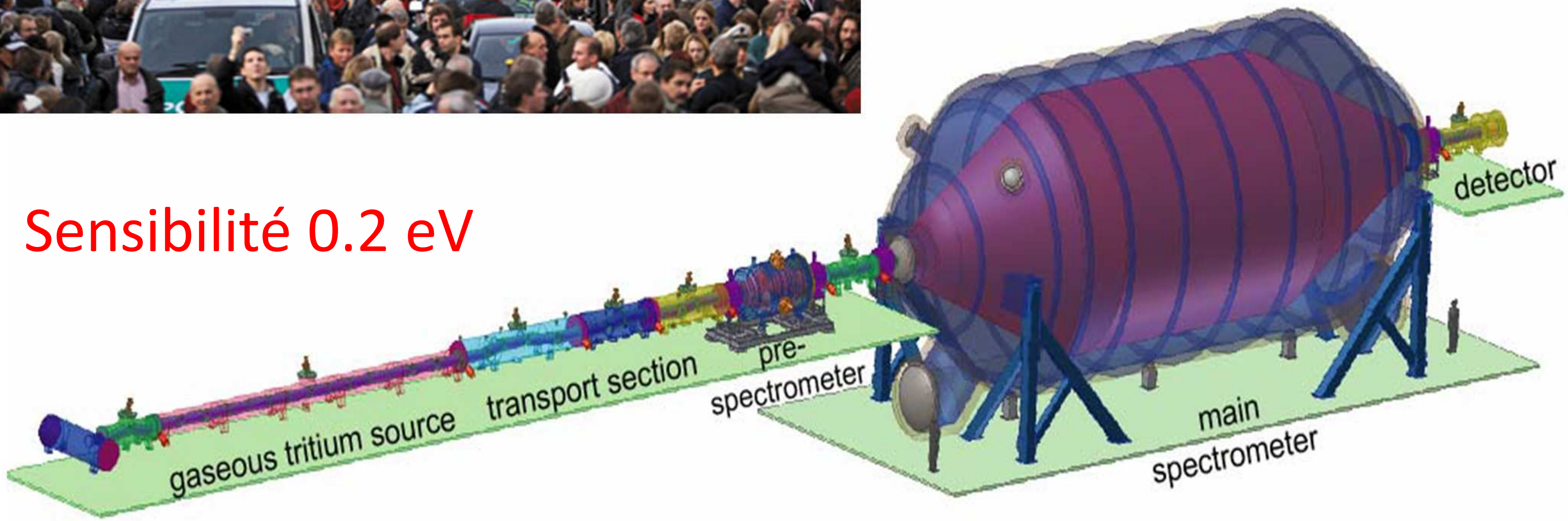


Mesure de la fin du spectre beta

Expérience KATRIN



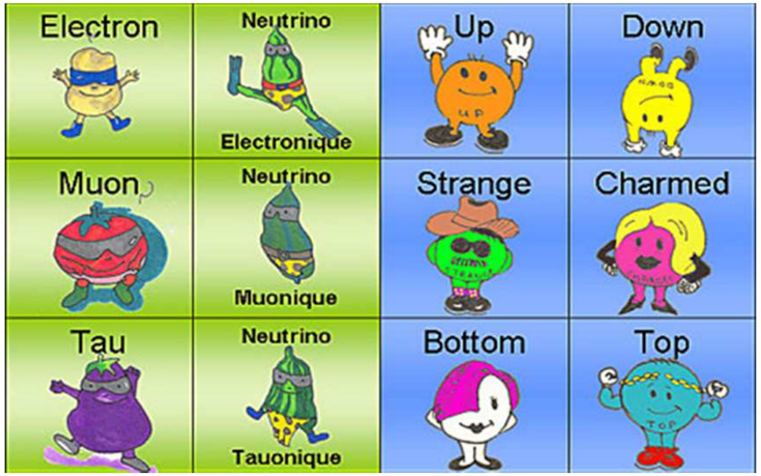
Sensibilité 0.2 eV



Une physique laborieuse !

Particule ou AntiParticule ?

Particules



Anti-Particules

Q < 0

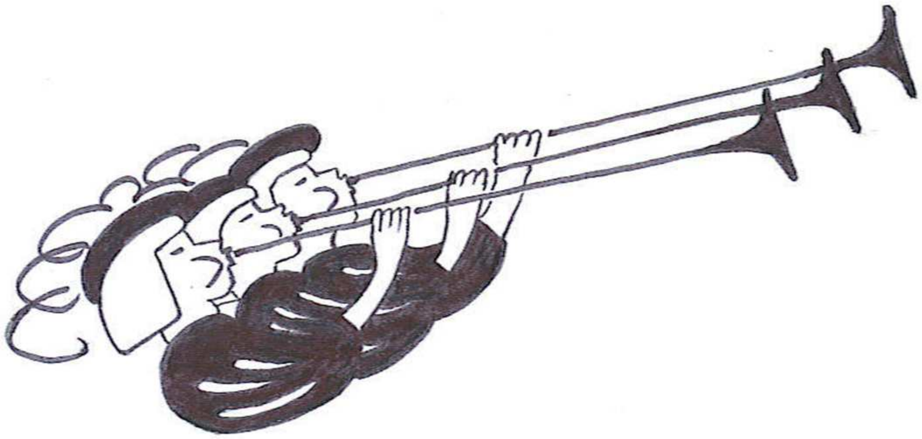
Q > 0

Q < 0

Q > 0

Facile pour les particules chargées

Pour le neutrino ? Hmmmm . . . .



Décret

Oyez, oyez

Les leptons ont un nombre « Leptonique » = +1
Les antilepton ont un nombre « Leptonique » = -1
Les autres ont un nombre « Leptonique » = 0

Les barions (3 quarks) ont un nombre « Barionique » = +1
Les antibarions ont un nombre « Barionique » = -1
Les autres ont un nombre « Barionique » = 0

Le nombre Leptonique et le Nombre Barionique se conservent.

Exemple

	n	$\longrightarrow$	p	$+$	e^-	$+$	ν
Nombre Lepton. :	0		0		1		-1
Nombre Barion. :	1		1		0		0
Charge :	0		+1		-1		0

C'est donc un antineutrino

$$\boxed{n \longrightarrow p + e^- + \bar{\nu}}$$

et ca marche toujours (jusqu'à présent)

MAIS PAS DE SYMETRIE PROFONDE ASSOCIEE

Hmmm…

Peut être que ca ne marche pas ?

Ettore Majorana

$\Rightarrow$ Neutrino = Anti-Neutrino

=> Neutrino Majorana

Seulement possible pour le neutrino

(fermion élémentaire)

=> Nature du neutrino (Dirac / Majorana) non connue !

Comment savoir si $\nu = \bar{\nu}$

$$n \longrightarrow p + e^{-} + \bar{\nu} \quad : \beta-$$

$$\nu + n \longrightarrow p + e^{-} \quad : \text{capture } \nu$$

$$n \longrightarrow \left\{ \begin{array}{l} e \\ p \\ \bar{\nu} \end{array} \right. \qquad \beta \text{ simple}$$

$$n \longrightarrow \left\{ \begin{array}{l} e \\ p \\ \bar{\nu} \end{array} \right.$$

$$n \longrightarrow \left\{ \begin{array}{l} e \\ p \\ \bar{\nu} \end{array} \right.$$

β double avec neutrino

Comment savoir si $\nu = \bar{\nu}$

$$n \longrightarrow p + e^{-} + \bar{\nu} \quad : \beta-$$

$$\nu + n \longrightarrow p + e^{-} \quad : \text{capture } \nu$$

Processus radioactif le plus rare jamais observe

$T_{1/2}$ ~ 10^{24} années

Un million de milliards plus long que l'âge de l'Univers

$$n \longrightarrow \left\{ \begin{array}{l} e \\ p \\ \bar{\nu} \end{array} \right.$$

$$n \longrightarrow \left\{ \begin{array}{l} e \\ p \\ \bar{\nu} \end{array} \right.$$

β double avec neutrino

$$n \longrightarrow \begin{cases} e \\ p \\ \boxed{\bar{\nu} \;+ n} \end{cases} \longrightarrow \begin{cases} e \\ p \end{cases}$$

β double sans neutrino

OK si $\nu = \bar{\nu} = \nu_{\text{Majorana}}$

$$n \longrightarrow \begin{cases} e \\ p \\ \boxed{\bar{\nu} + n} \longrightarrow \begin{cases} e \\ p \end{cases} \end{cases}$$

β double sans neutrino

OK si $\nu = \bar{\nu} = \nu_{Majorana}$

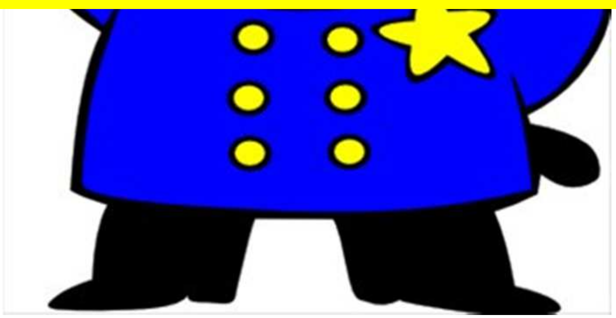
Impossible dans le Modelé Standard car le nombre leptonioque n'est pas conserve

$$n \longrightarrow \left\{ \begin{array}{l} e \\ p \\ \boxed{\bar{\nu} + n} \longrightarrow \left\{ \begin{array}{l} e \\ p \end{array} \right. \end{array} \right.$$

β double sans neutrino

$$\text{OK si } \nu = \bar{\nu} = \nu_{\text{Majorana}}$$

Impossible dans le
Modelé Standard
car le
lepto
pas c



Tant mieux !

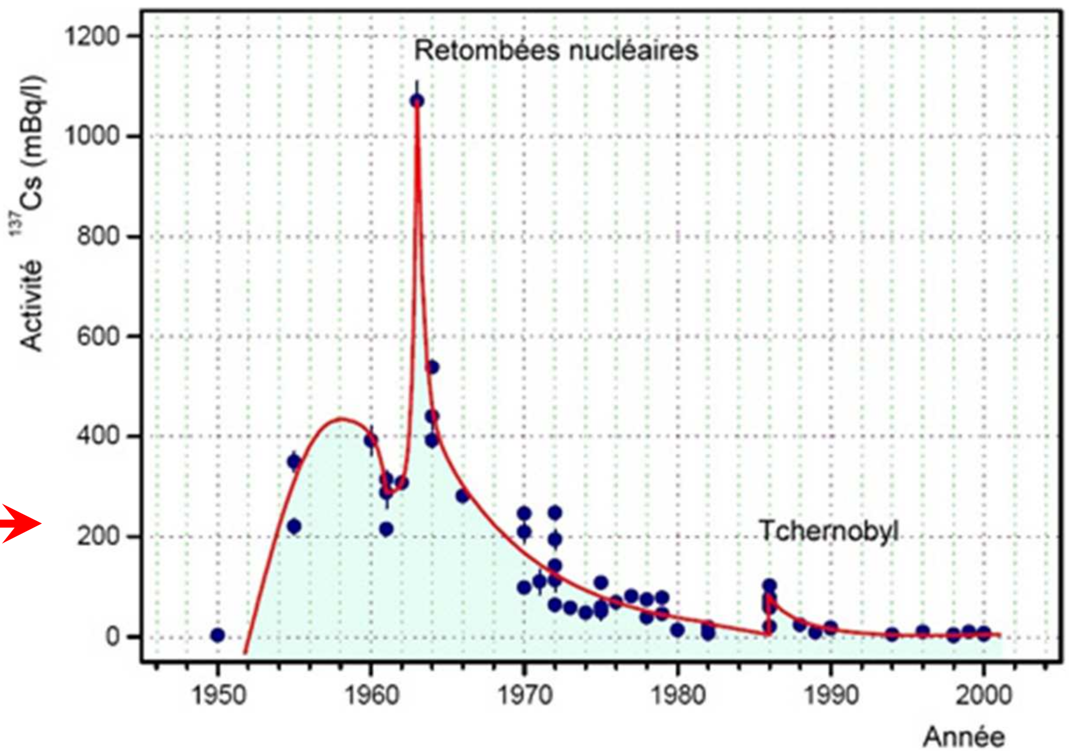
=> recherche de nouvelle physique

Physique d'extrême propreté

1 noyau d'uranium sur 10^{13} de cuivre
1 noyau de radon sur 10^{21} de gaz

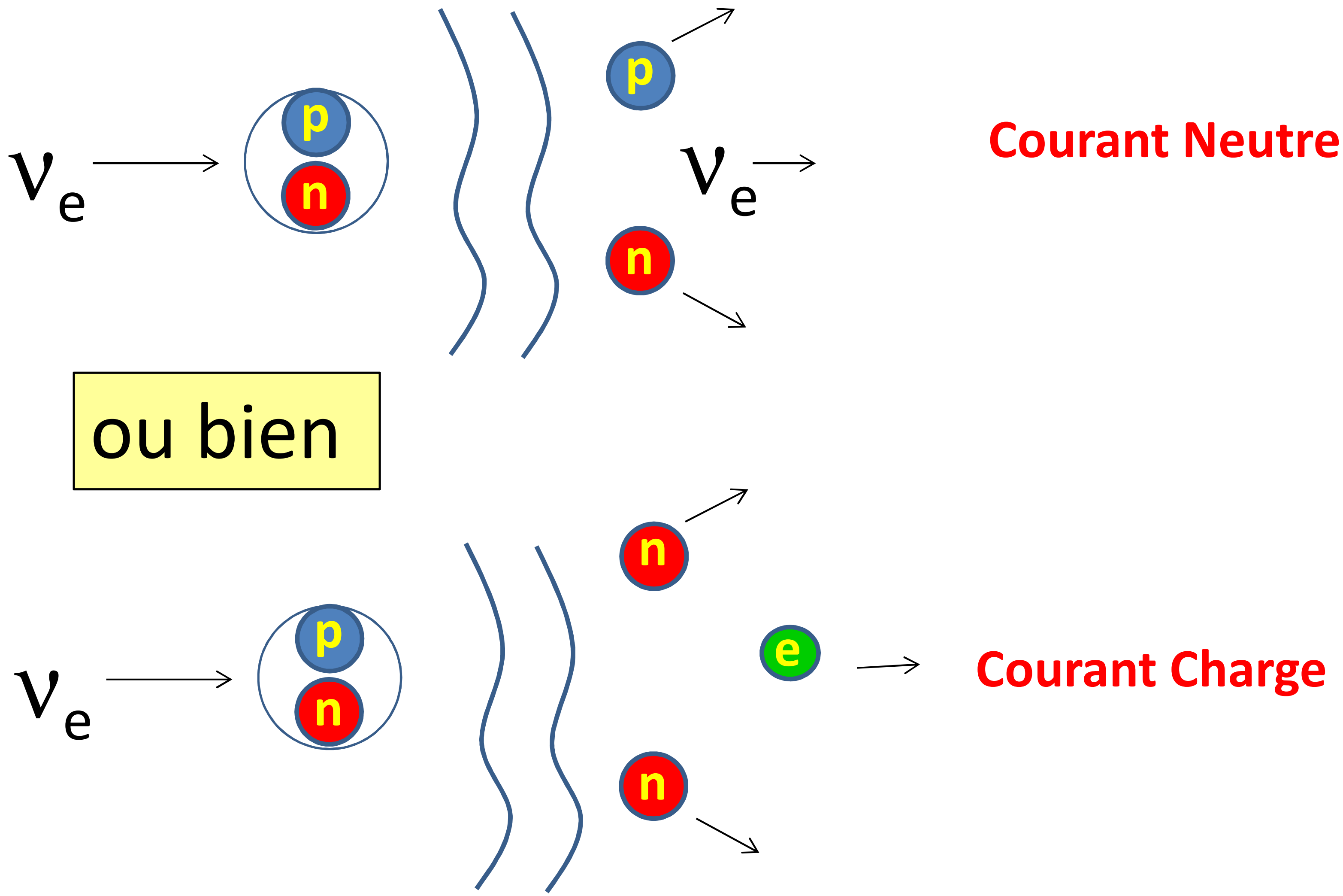
Retombées inattendues

Détecteurs ultra base activité issus de la recherche de la nature du neutrino



Radioactivité du vin
(Lutte contre la contrefaçon)

Un mot sur l’interaction des neutrinos



Une particule vraiment insaisissable

- Lorsqu'un neutrino interagit il le fait suivant une saveur

  électronique, muonique, tauique

$\nu_e + N \text{--->} e^- + \ldots.$
$\nu_\mu + N \text{--->} \mu^- + \ldots.$
$\nu_\tau + N \text{--->} \tau^- + \ldots.$

e ---> ν_e
μ ---> ν_μ
τ ---> ν_τ

« Etats propres de saveur »

- Lorsqu'un neutrino se déplace il le fait avec une masse définie

$$|\nu(t)\rangle = e^{-Et}|\nu\rangle$$

$$E = \sqrt{P^2c^2 + m^2c^4}$$

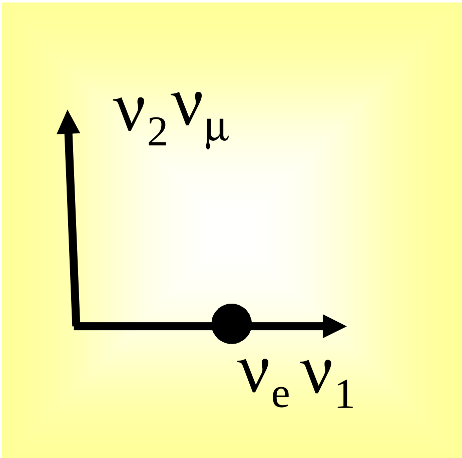
m_1 ---> ν_1
m_2 ---> ν_2
m_3 ---> ν_3

« Etats propres de masse »

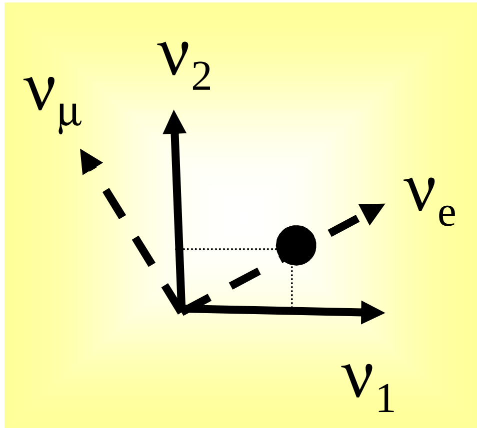
Mélange de saveurs (2 neutrinos)

Pontecorvo
1957

Etats propres de saveur et masse ne sont pas confondus



Etats propres de masse
et saveur confondus



Etats propres de masse
et saveur NON confondus

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

$$\Rightarrow \begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{bmatrix}$$

Matrice de mélange

Apres quelques approximations, un peu d'algèbre simple et des bases en Mécanique Quantique on obtient :

Probabilité pour qu'un neutrino d'énergie E au départ électronique devienne à la distance L muonique

$$P(\nu_e \rightarrow \nu_\mu) \cong \sin^2(2\theta)\sin^2[\frac{\Delta m^2}{4}\frac{L}{E}]$$

avec $\Delta m^2 = m_2{}^2 - m_1{}^2$

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avec $\Delta m^2 = m_2^2 - m_1^2$

Impossible dans le Modelé Standard car le neutrino est SANS masse

Apres quelques approximations, un peu d'algèbre simple et des bases en Mécanique Quantique on obtient :

Probabilité pour qu'un neutrino d'énergie E au départ électronique devienne à la distance L muonique

$$P(\nu_e \rightarrow \nu_\mu) \cong \sin^2(2\theta)\sin^2\left[\frac{\Delta m^2}{4}\frac{L}{E}\right]$$

avec $\Delta m^2 = m_2^2 - m_1^2$

Impossi
Modelé
car le ne
SANS m

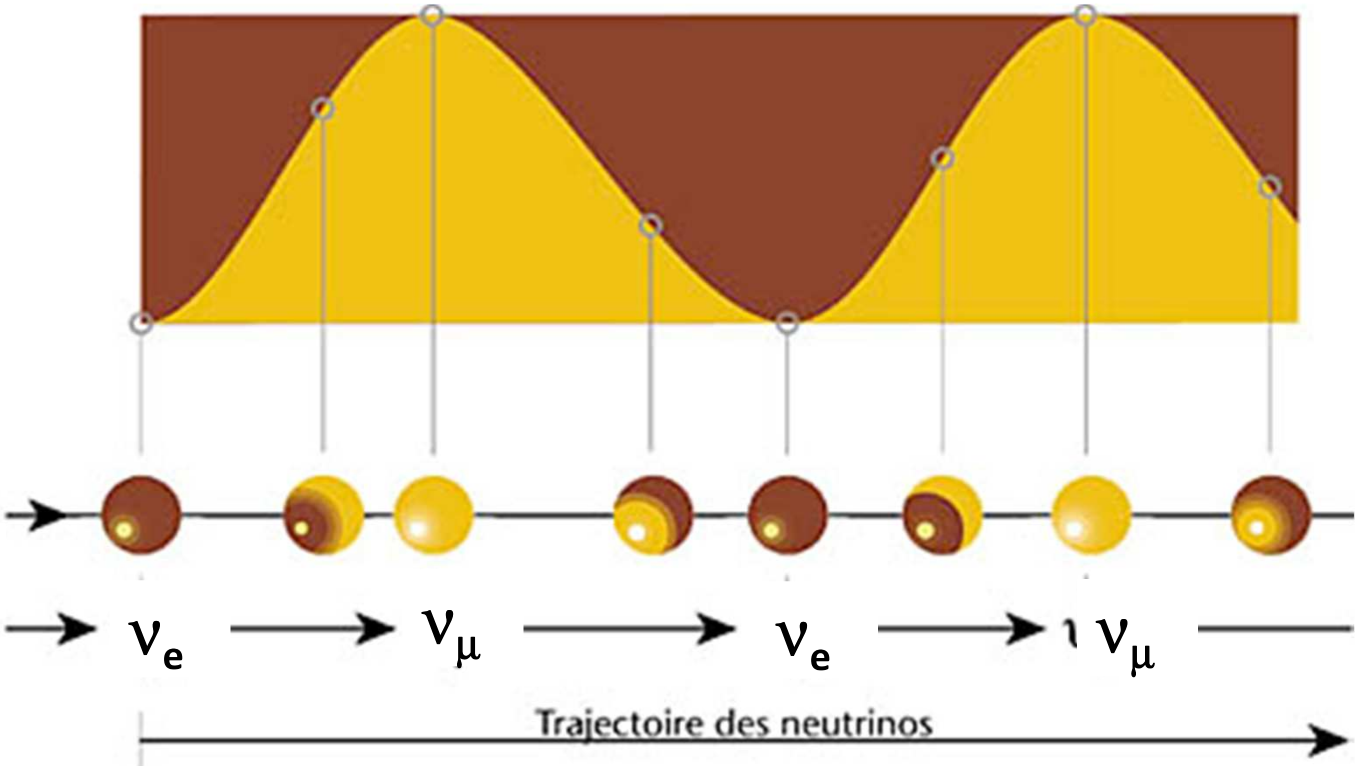
Tant mieux !

=> Physique au-delà du SM

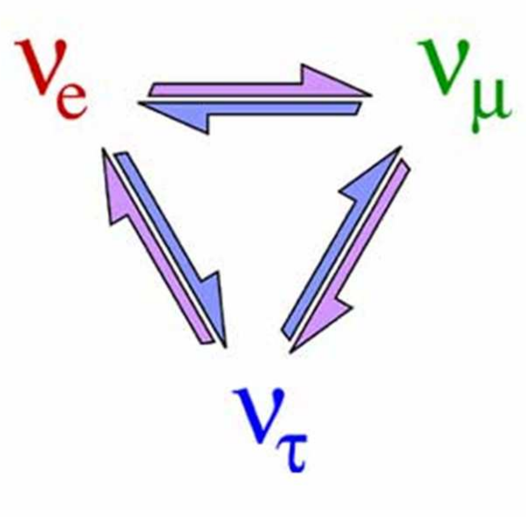
Oscillations de neutrinos

$$P(\nu_e \rightarrow \nu_\mu) \cong \boxed{\sin^2(2\theta)}\ \boxed{\sin^2[\frac{\Delta m^2}{4}\frac{L}{E}]}$$

Amplitude Oscillation



Oscillations à trois neutrinos

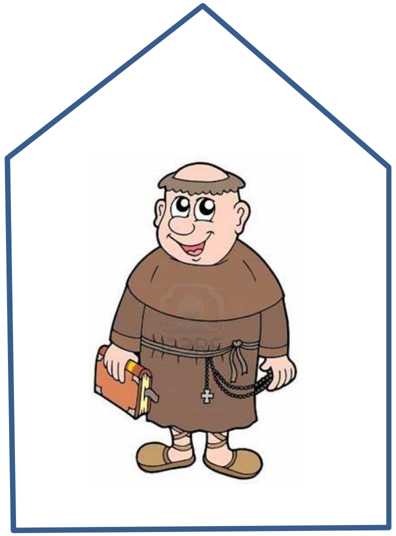


Ca se complique un peu !

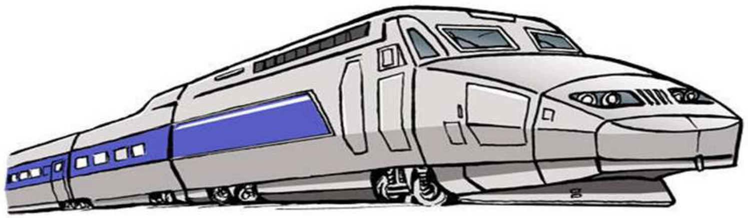
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Matrice de mélange Pontecorvo - Maki - Makagawa - Sakata

« Neutrino oscillations for pedestrians »



Paris Gare de Lyon



Marseille Gare St Charles

Transformation en solitaire

(Oscillations dans le vide)

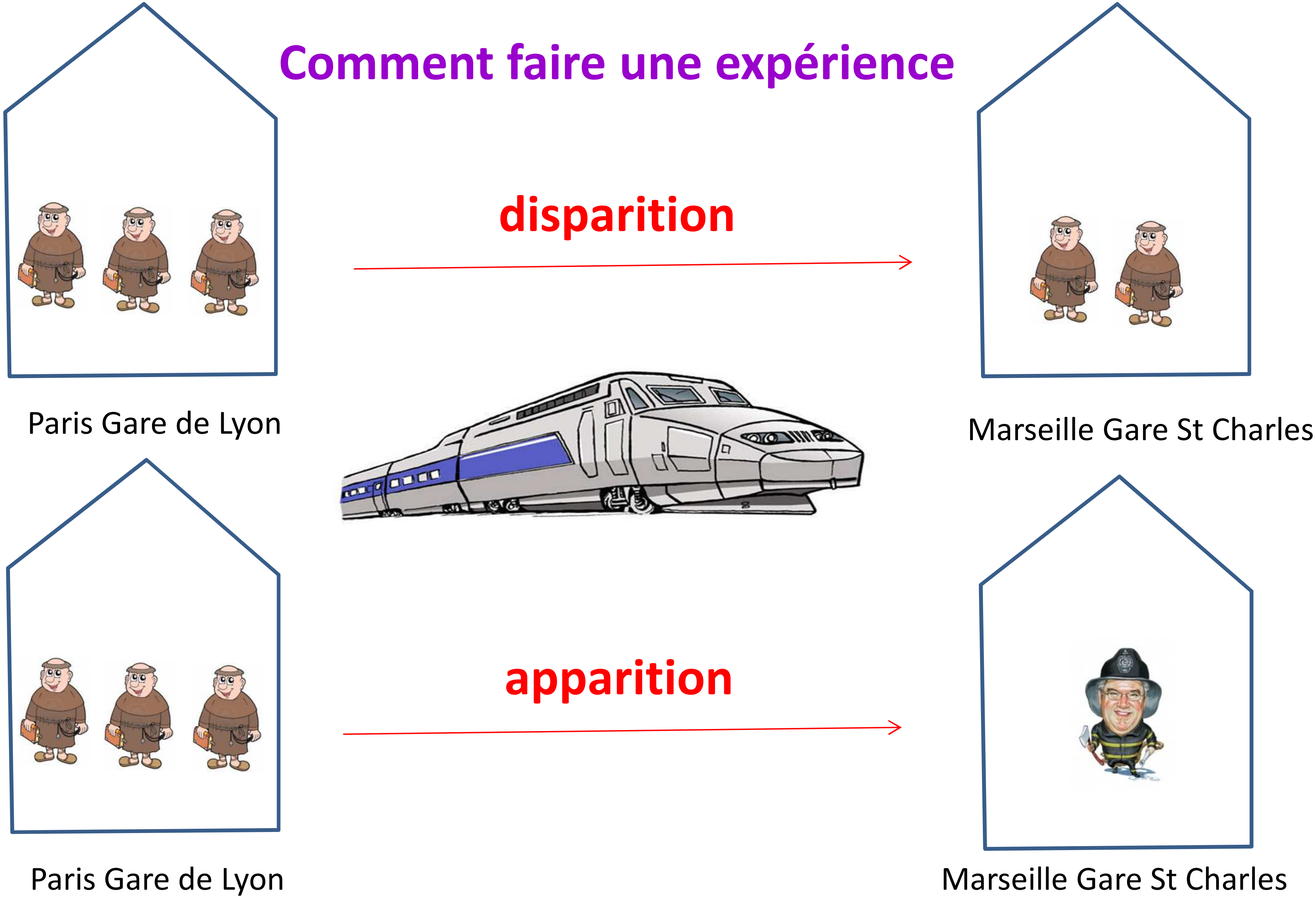
ou

Transformation par influence du milieu

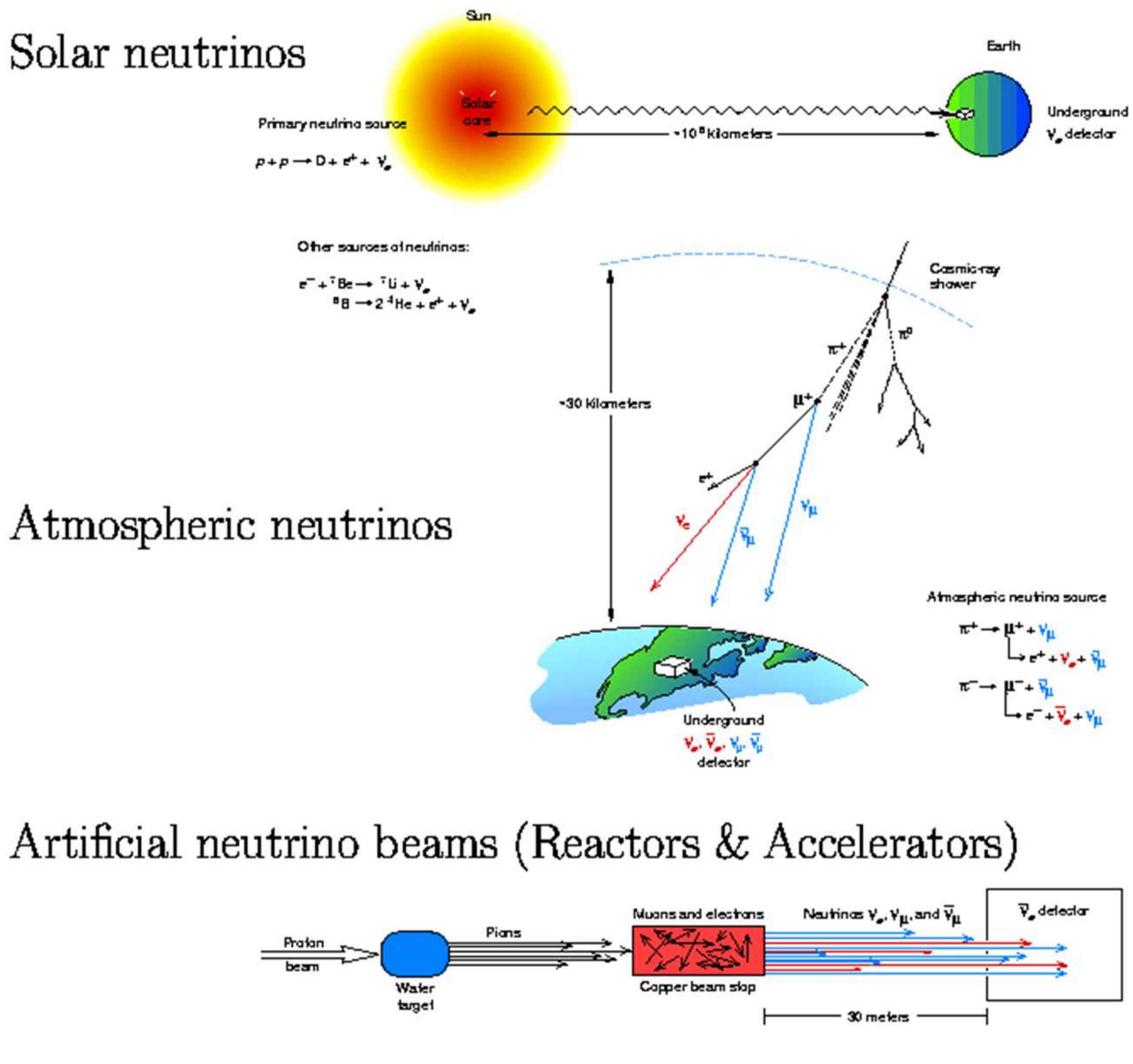
(Oscillations dans la matière : MSW)

« Neutrino oscillations for pedestrians »

Comment faire une expérience



Diverses sources pour étudier les oscillations



Paramètres d'oscillation

$$\sin^2[\frac{\Delta m^2}{4}\frac{L}{E}]$$

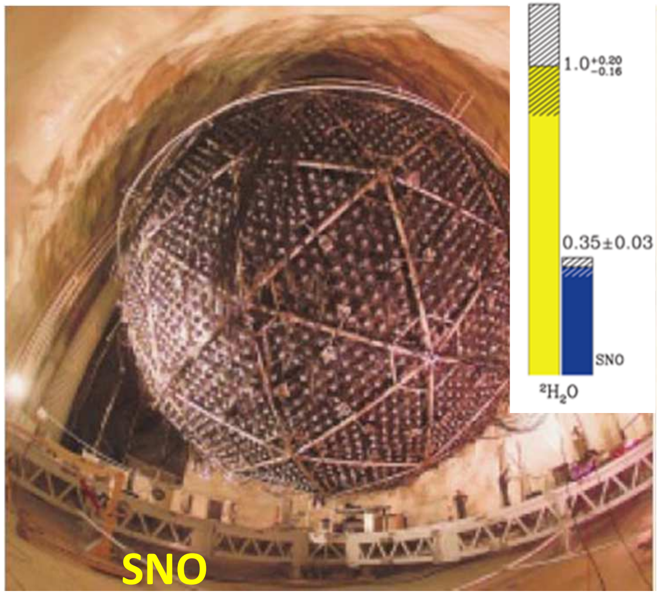
Distance : L

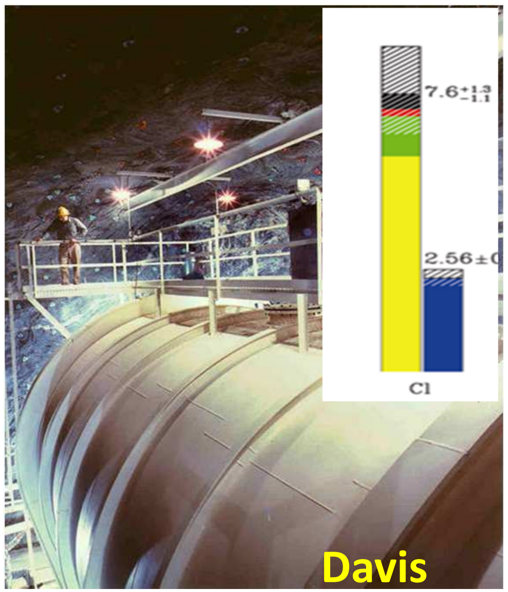
Energie : E

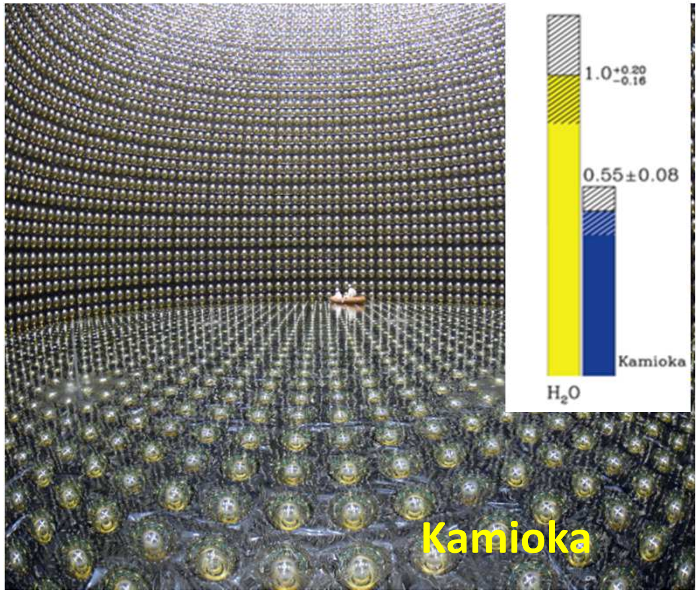
Neutrinos du soleil

Déficit de neutrinos

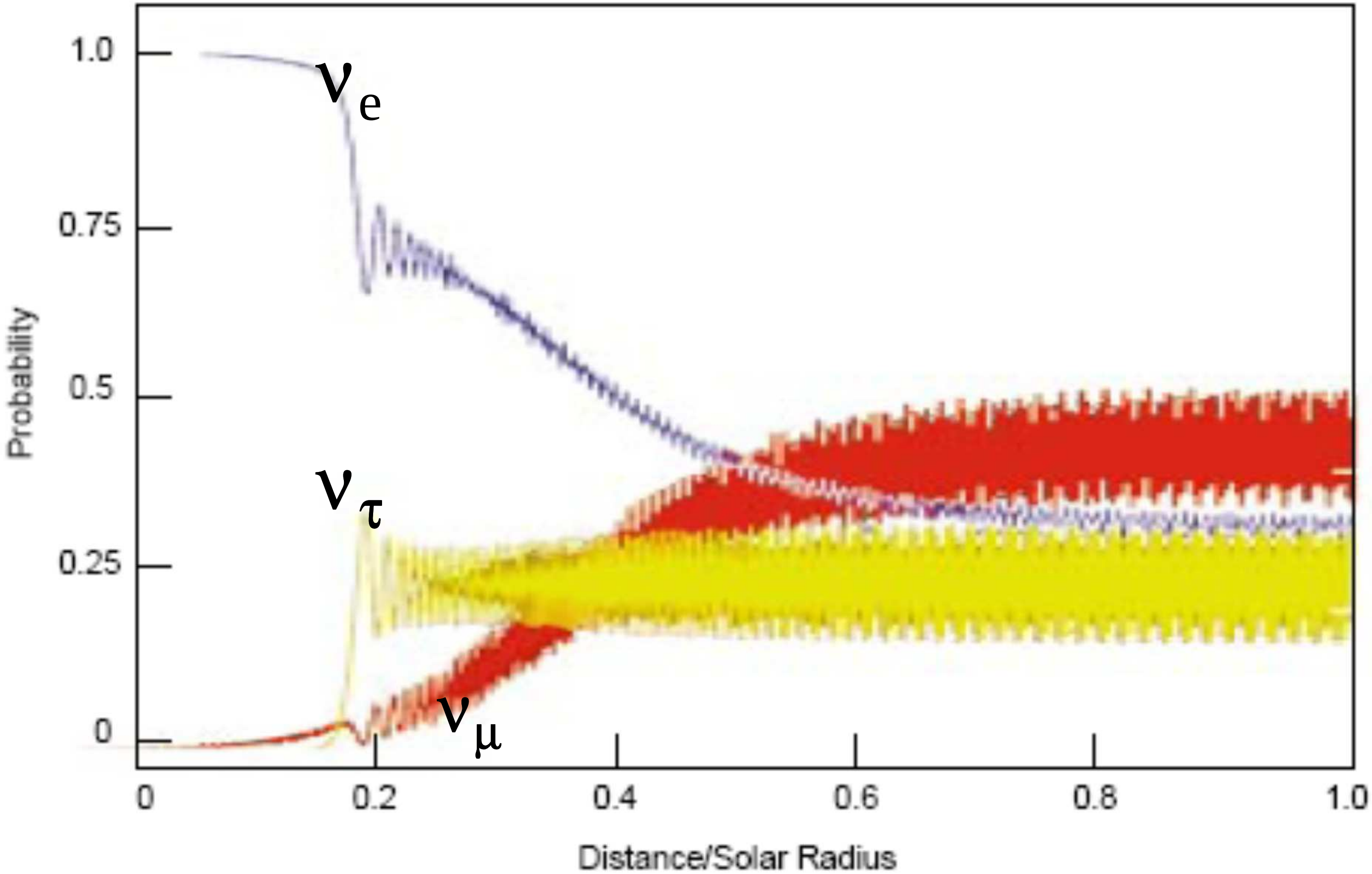
=> ν_e ---> ν_μ



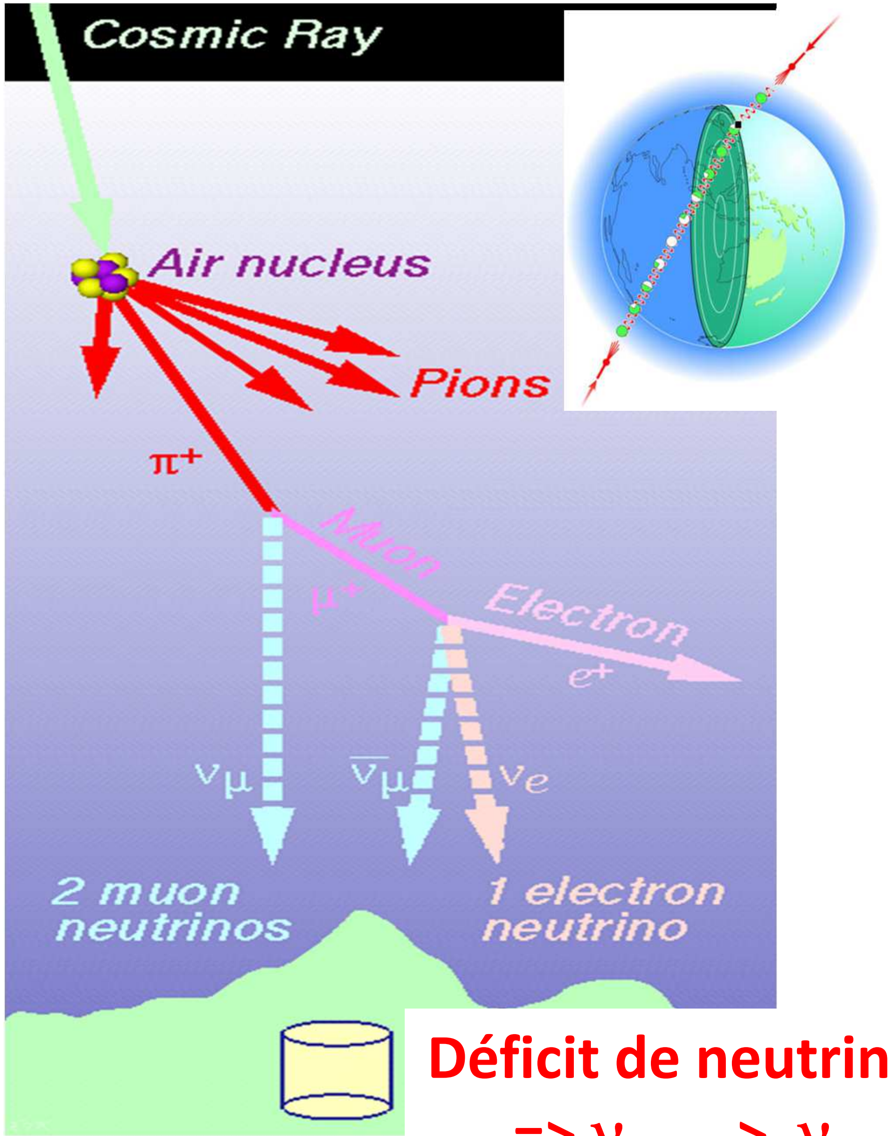


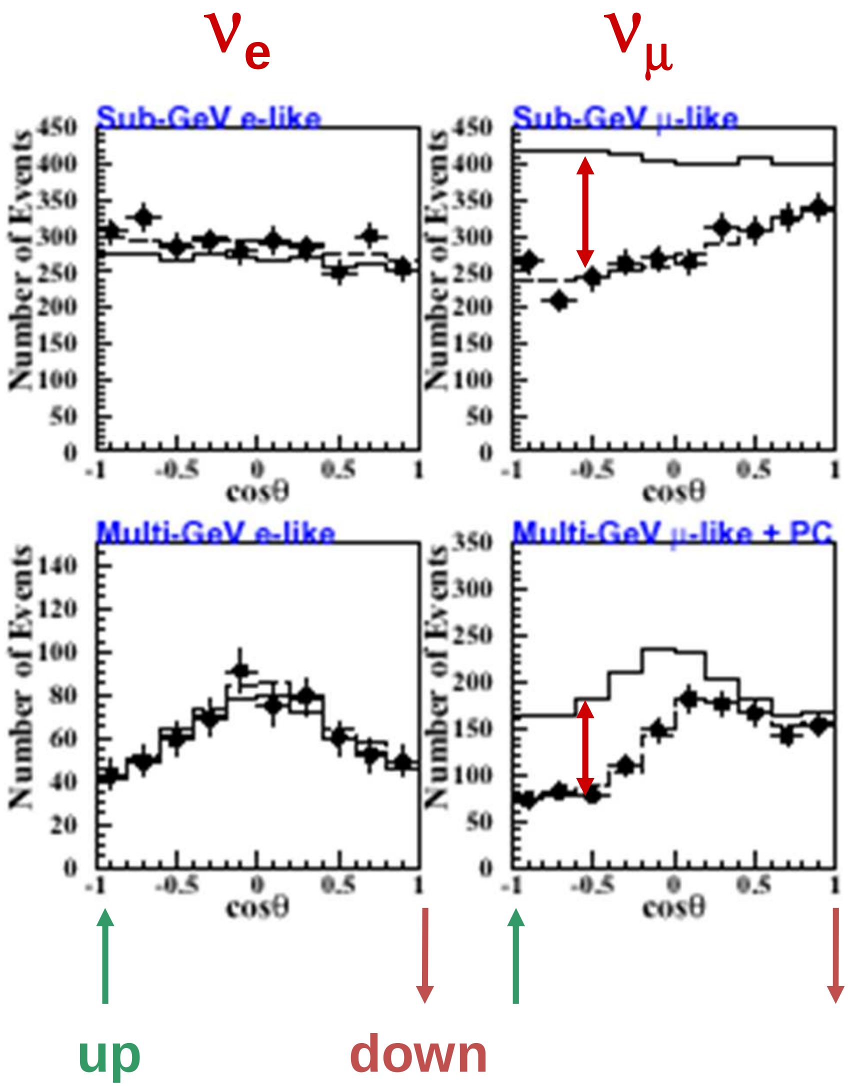


Oscillations dans la matière solaire



Neutrinos atmosphériques

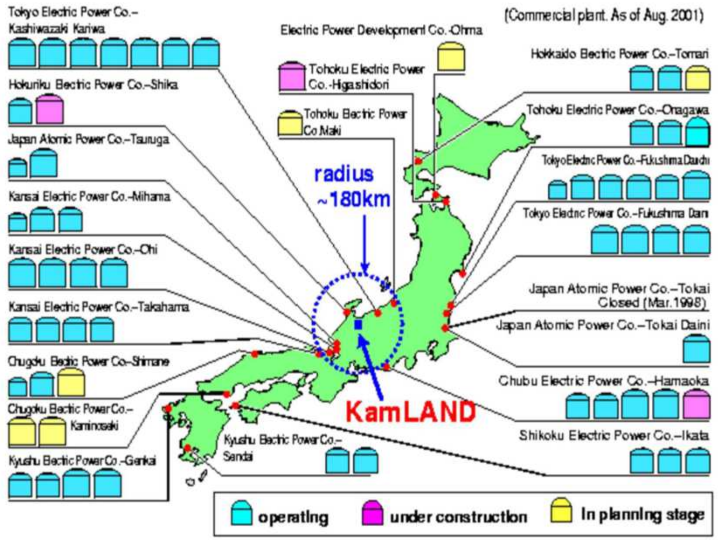


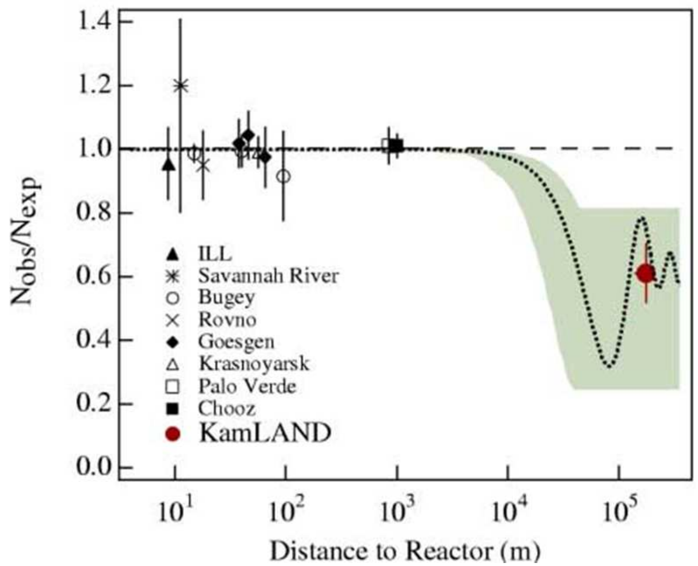


Déficit de neutrinos

=> ν_μ ---> ν_τ

Neutrinos « nucléaires »

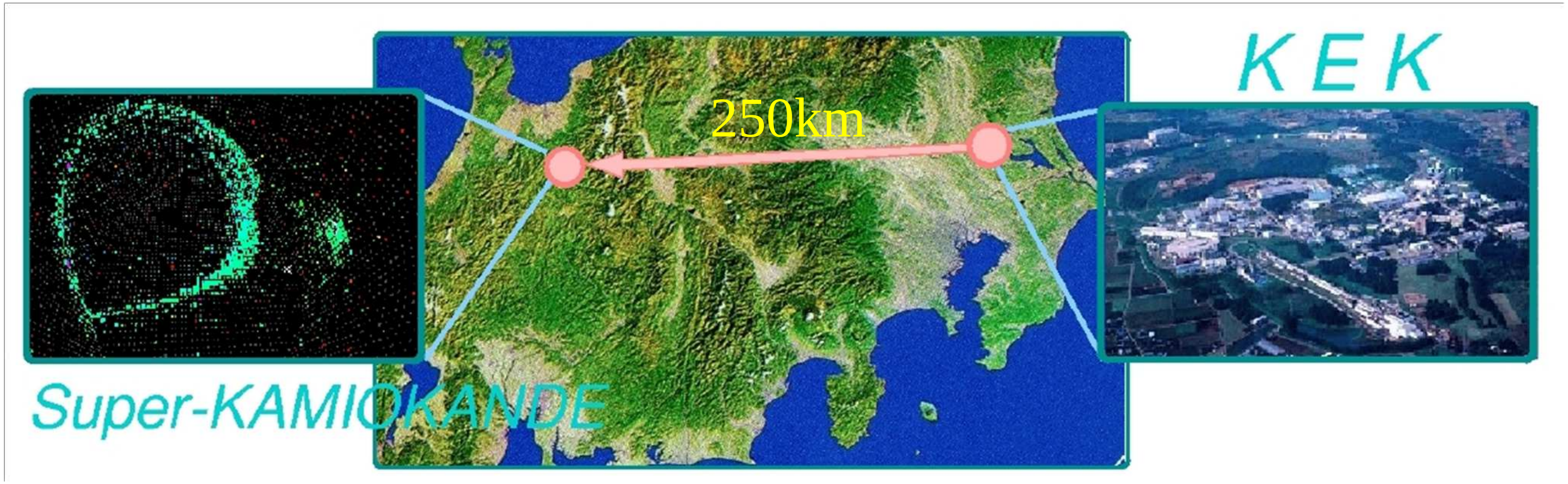




Déficit de neutrinos **(en fin)**

=> ν_e ---> ν_μ

Neutrinos des accélérateurs



ν_e <--- ν_μ

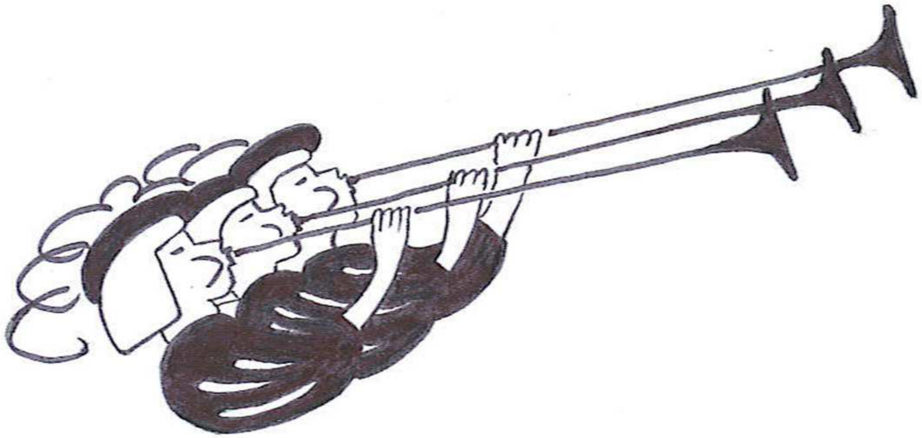
81 évènements ν_μ si pas d'oscillation

56 évènements ν_μ observes

Deficit de neutrinos

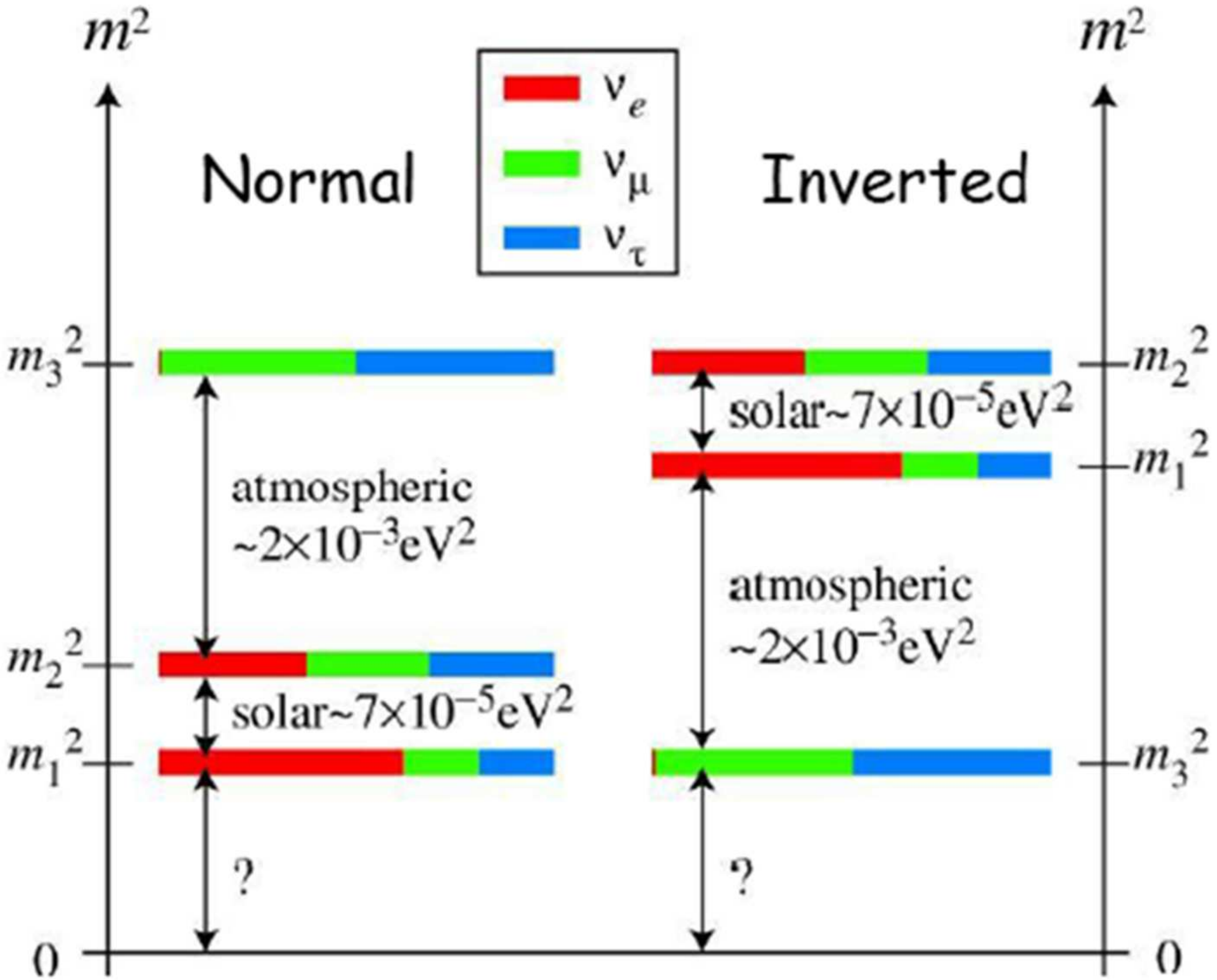
Les neutrinos oscillent !

$$\Delta m^2 = m_2^2 - m_1^2$$



Le Modèle Standard est « Faux »

Massifs et mélangés



Hiérarchie ???

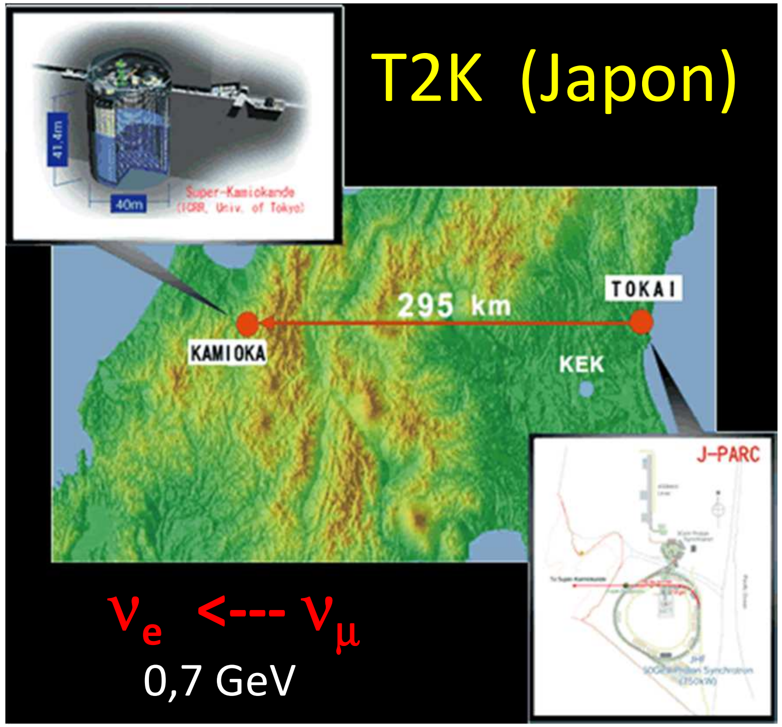
A la recherche d’une apparition

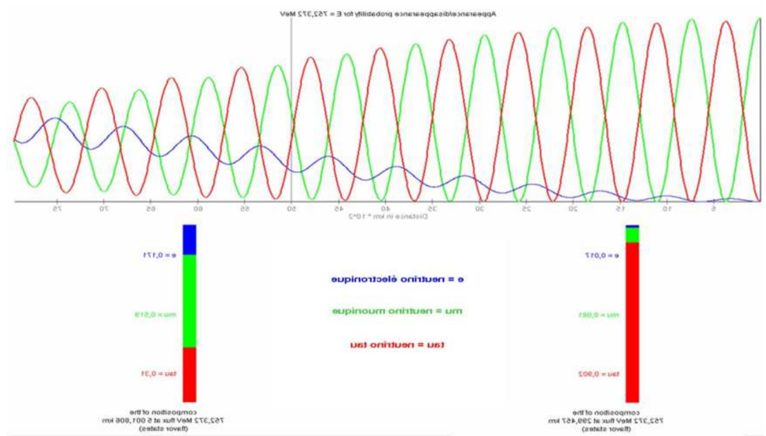
MINOS (USA)

ν_e <--- ν_μ

2 – 6 GeV

735 km

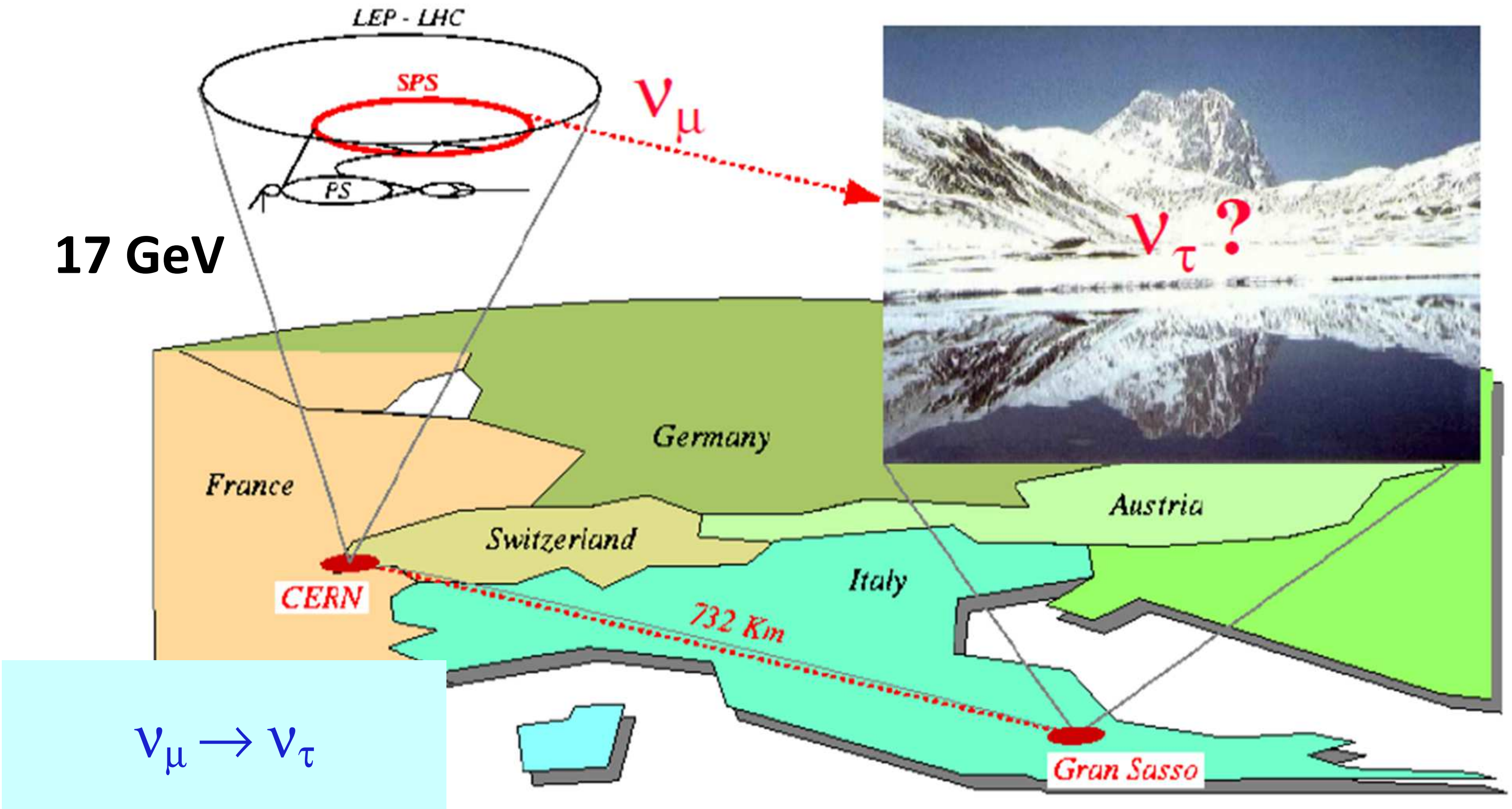




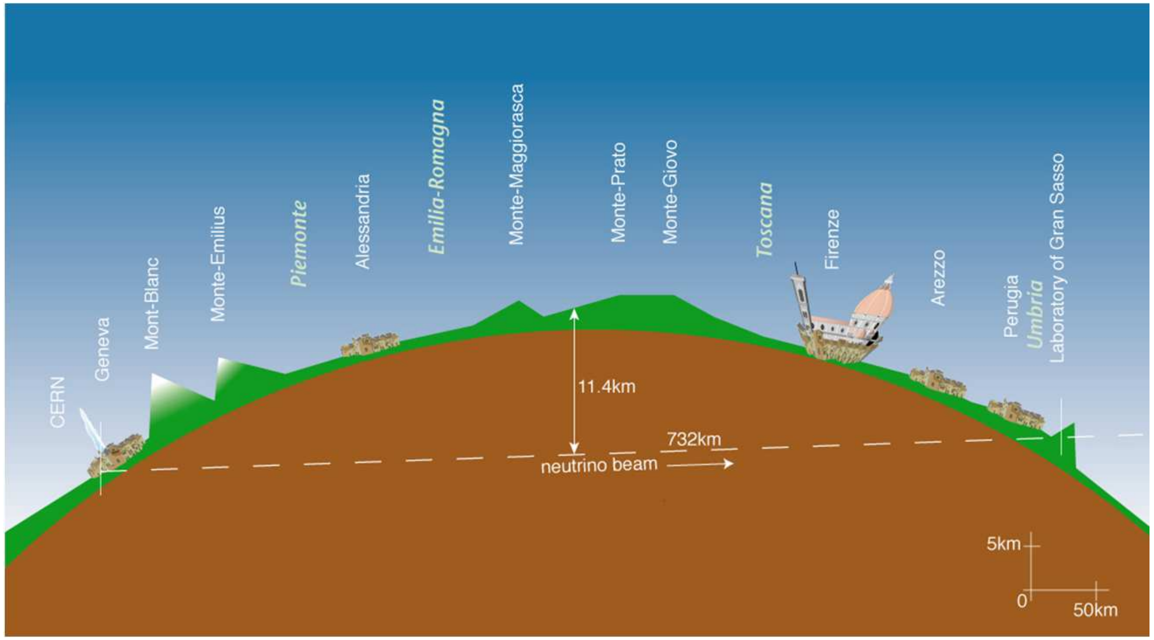
A la recherche d'une apparition

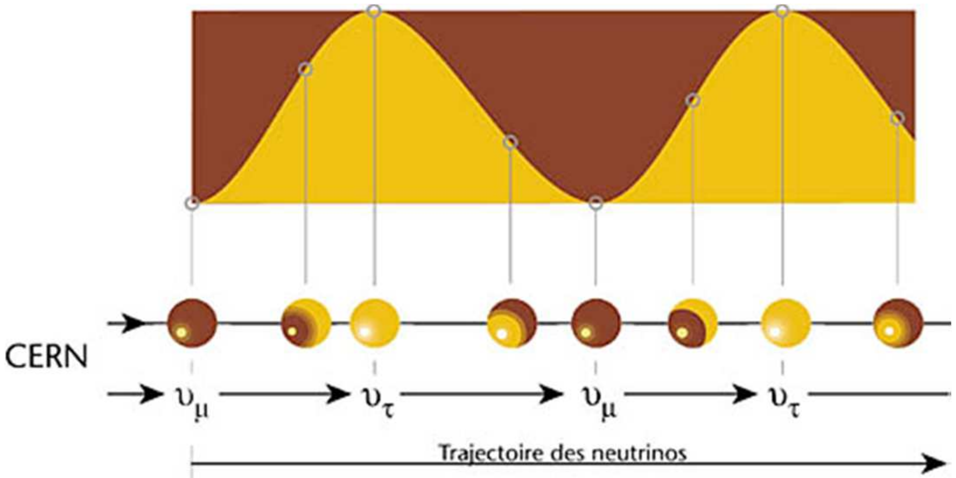
OPERA :

recherche de l'oscillation des neutrinos entre le CERN et le Gran Sasso

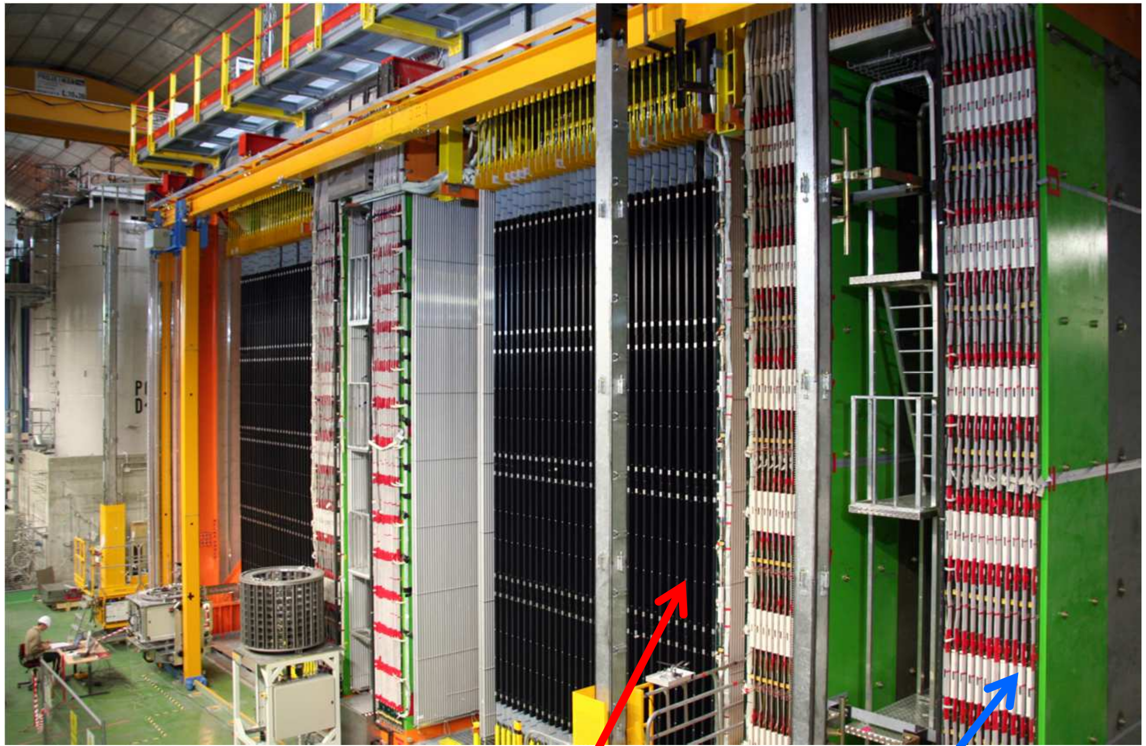


Expérience OPERA



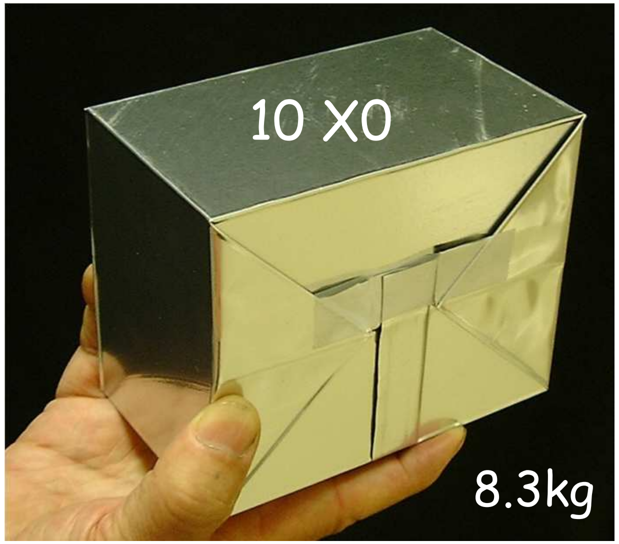


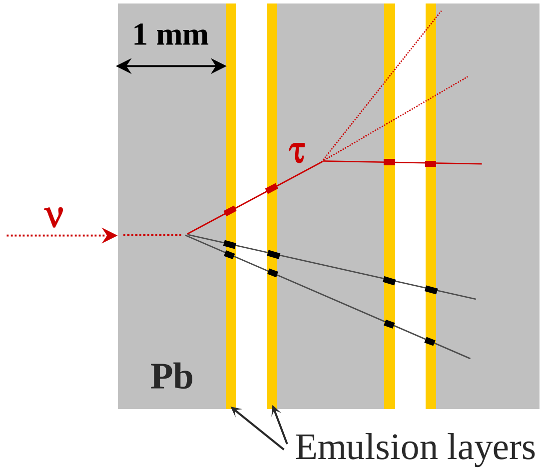
Détecteur OPERA



Plaques photo

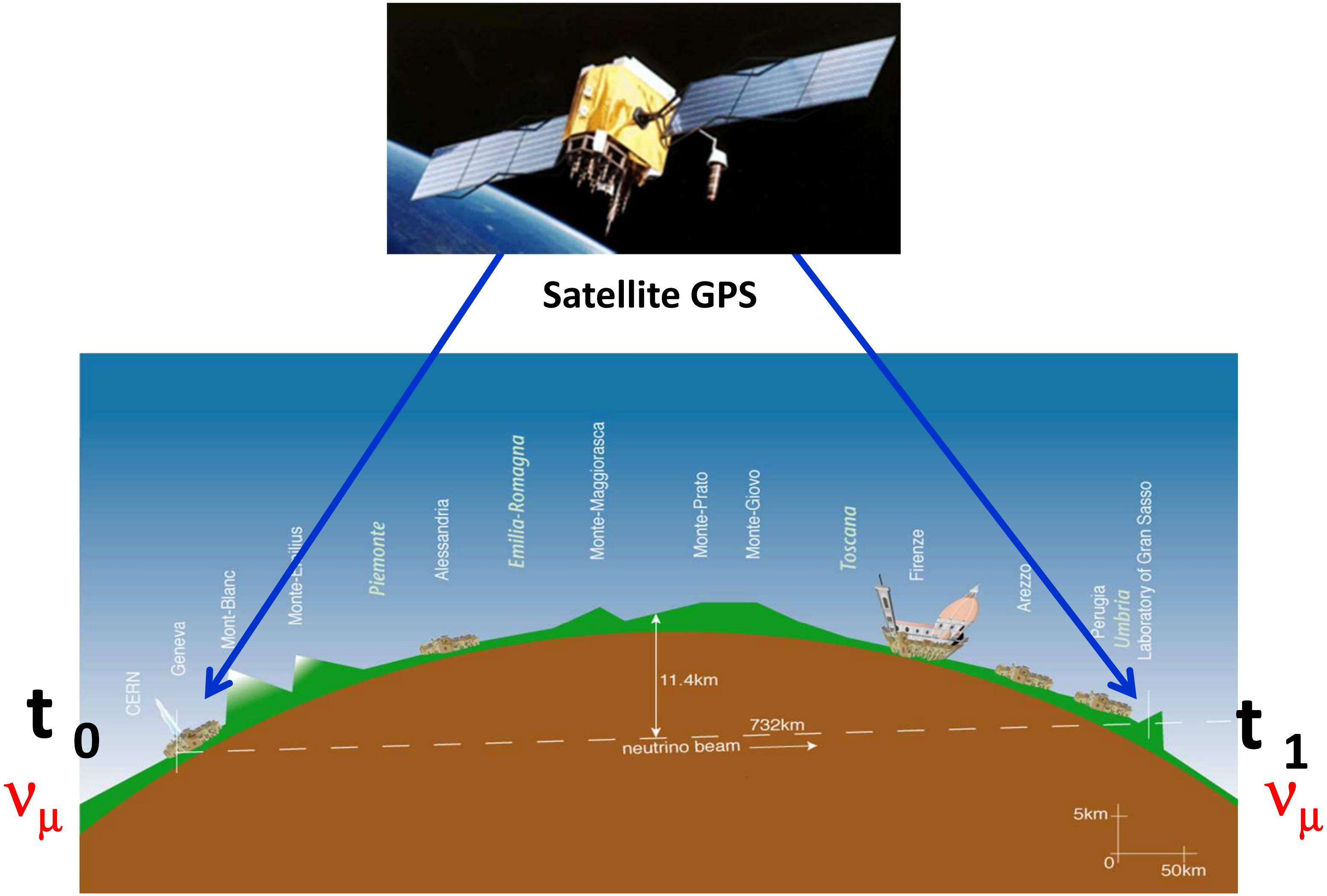
target Tracker





Oscillation $\nu_\mu \rightarrow \nu_\tau$ déjà observée

Comment savoir si le neutrino est plus rapide que la lumière ?



Connaissant Δt et la distance => vitesse

± 20 cm !!

$$\frac{v-c}{c} = (2,48 \pm (0,28)_{stat} \pm (0,30)_{syst}) \times 10^{-5}$$

v : vitesse du neutrino

c : vitesse de la lumière dans le vide

=> v > c !!!

$\Rightarrow$ **7 Km/s de plus que la vitesse de la lumière**

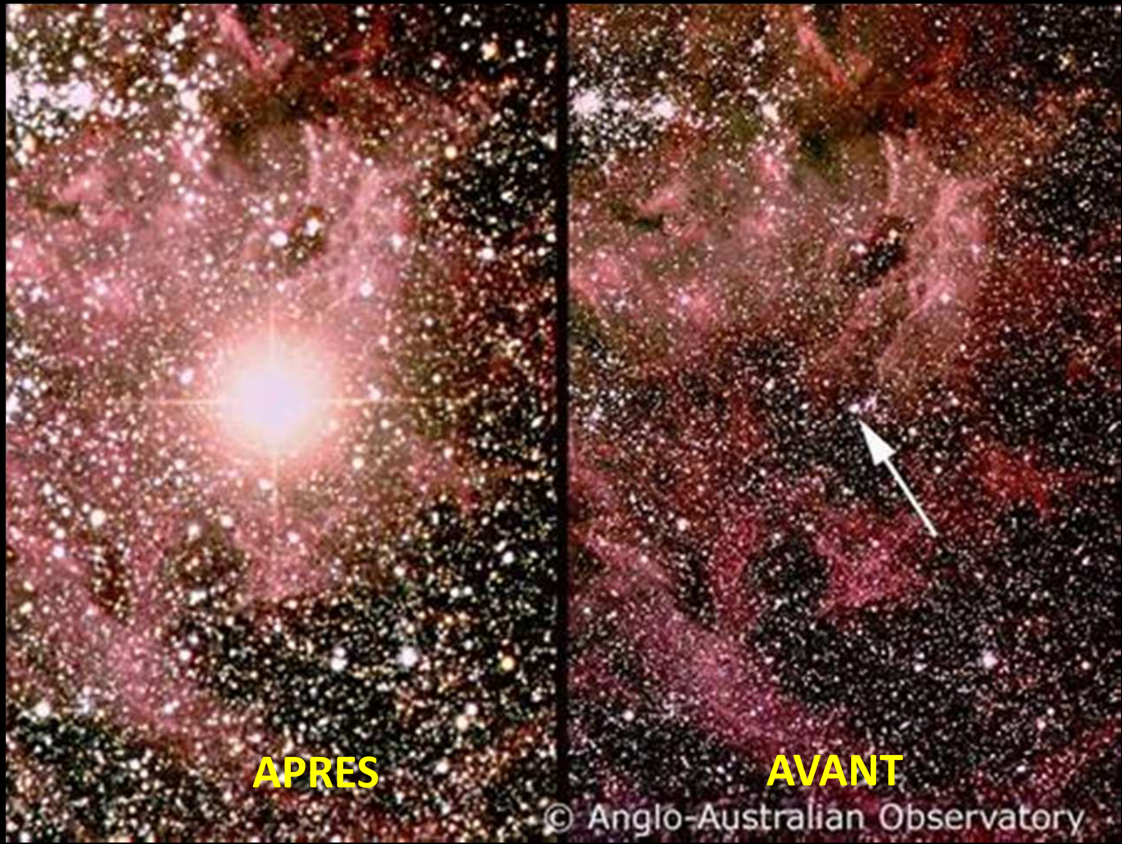
$\Rightarrow$ **60 ns avant la lumière**

En relativité c est la vitesse d'information la plus grande possible

!?!?!?!?

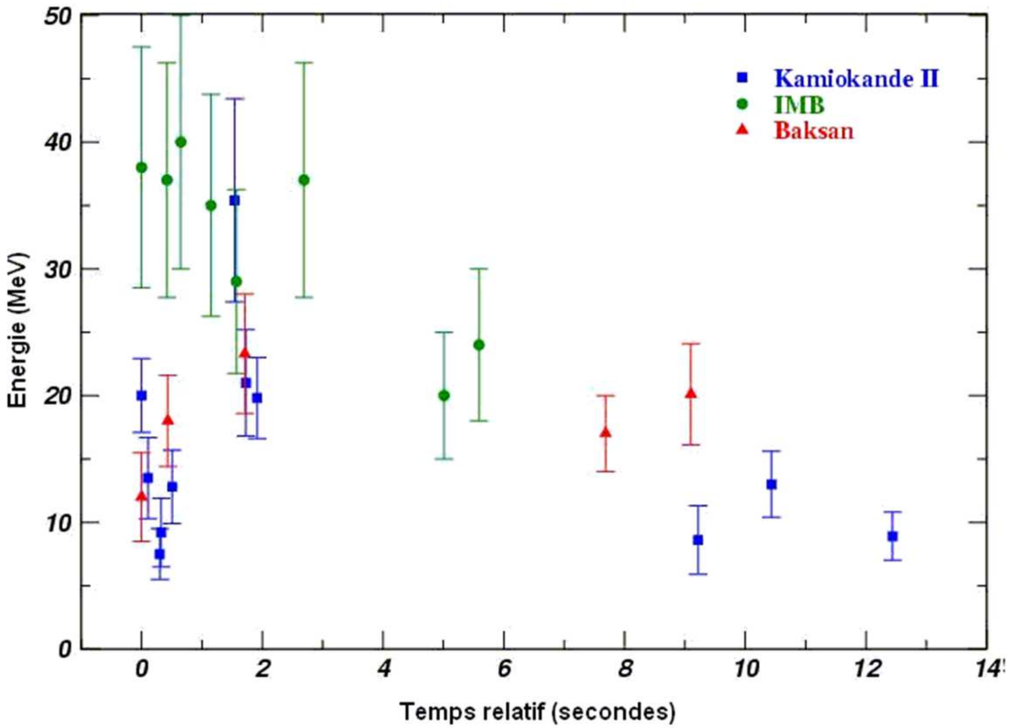
SN1987A

SN 1987 A Grand Nuage de Magellan
~ 179 000 a.l.



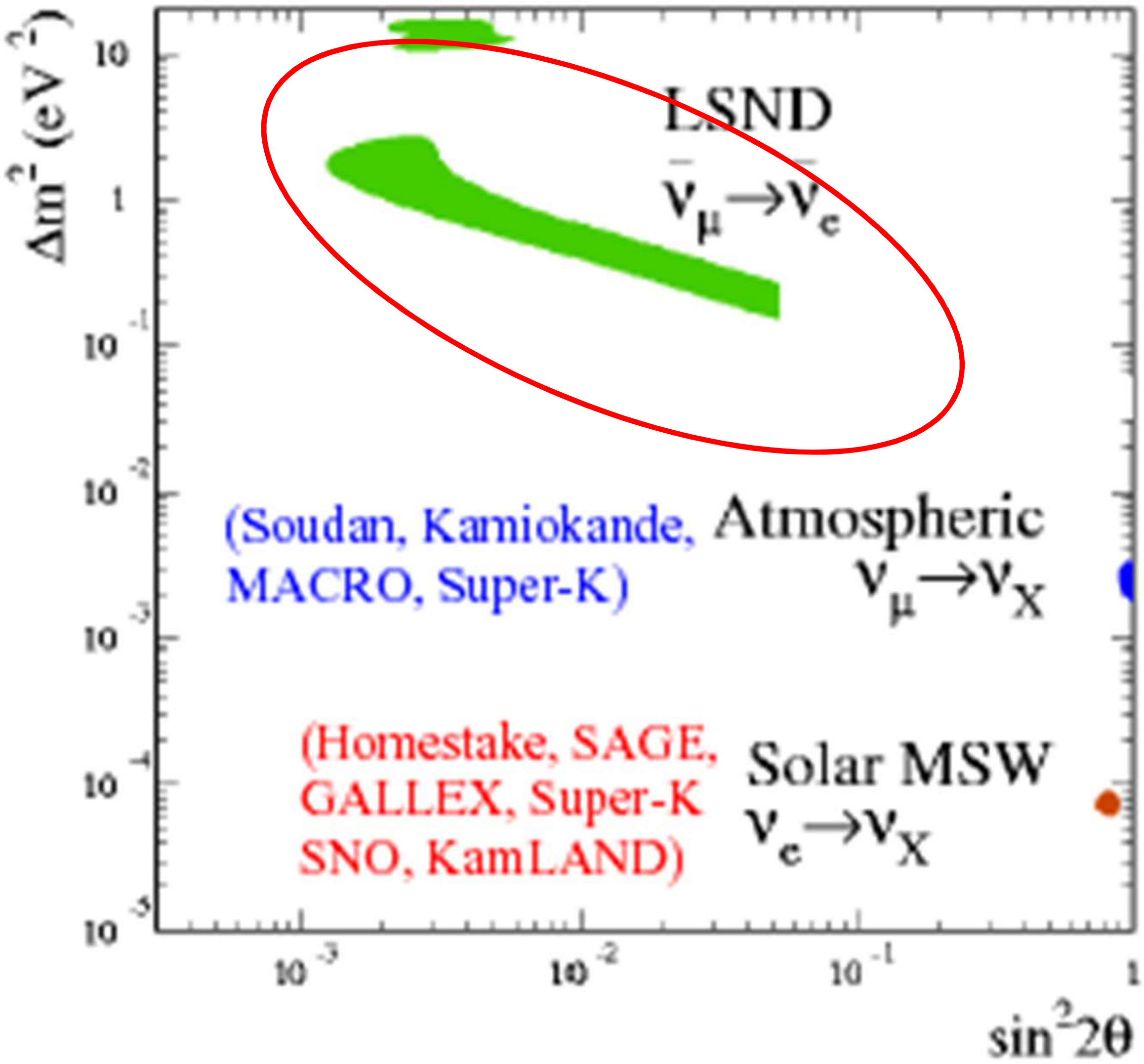
On a vu les neutrinos de SN1987A

~ 4 avant la lumière



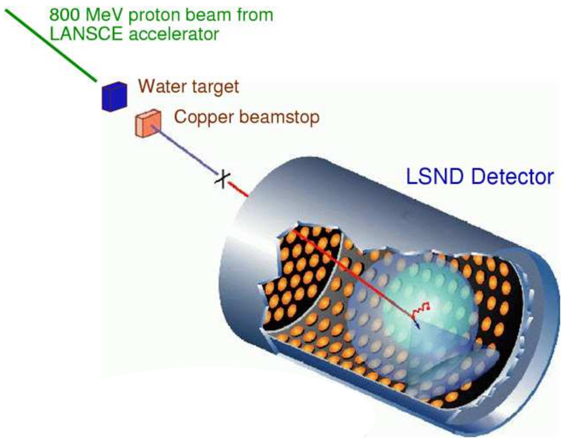
OPERA => les neutrinos doivent arriver ~ 4 ans avant la lumière !!???

REVENONS AUX OSCILLATIONS



Effets oscillations positifs

LSND $\overline{\nu}_{\mu} \rightarrow \overline{\nu}_{e}$



Apparition de ν_e (~2000)

Incompatible avec neutrinos solaires, atmosphériques et réacteur.

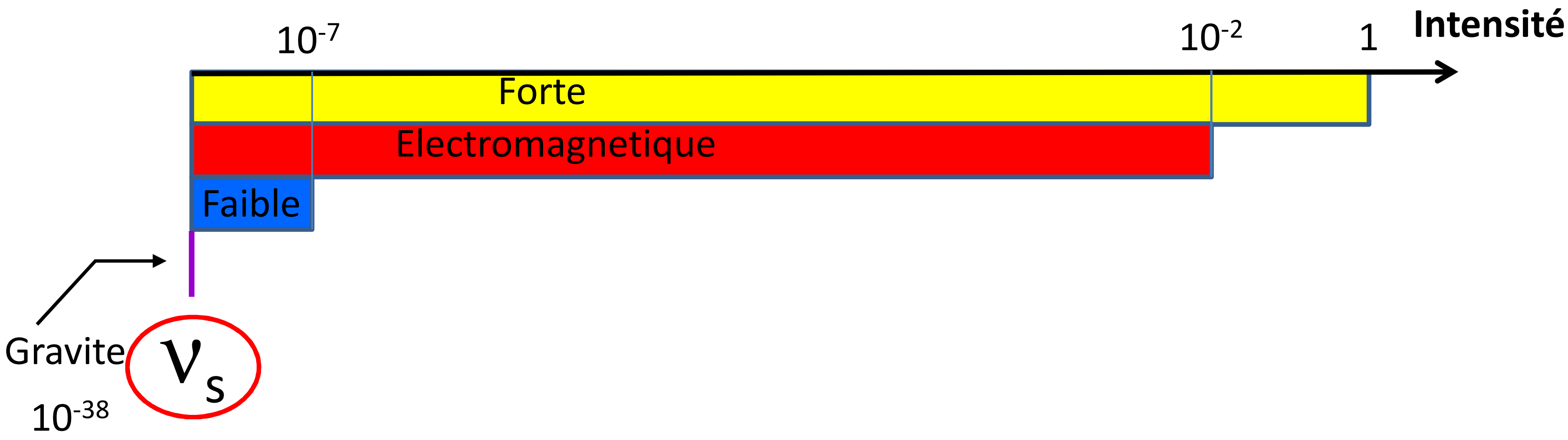
Neutrino stérile !!

MiniBooNE

Confirmation de LSND !!

(2011)

Neutrino stérile



Il ne sent que la gravite (??!!)

Intéressant en cosmologie
Désespèrent pour la détection

Neutrinos et comologie

ρ_ν ~ 330 /cm^3 (from Big Bang)
<E> ~ 0.0004 eV (from Big Bang)

$R_{universe}$ ~ 10^{10} lightyears
$V_{universe}$ ~ 4×10^{84} cm^3

N_ν ~ 10^{87}

E_ν(total) ~ 4×10^{83} eV

M_ν(equivalent) ~ 7×10^{47} kg

$M_{universe}$(visible) ~ 4×10^{52} kg

Are Neutrinos Massless?


Le neutrino est la particule
la plus fantastique connue.