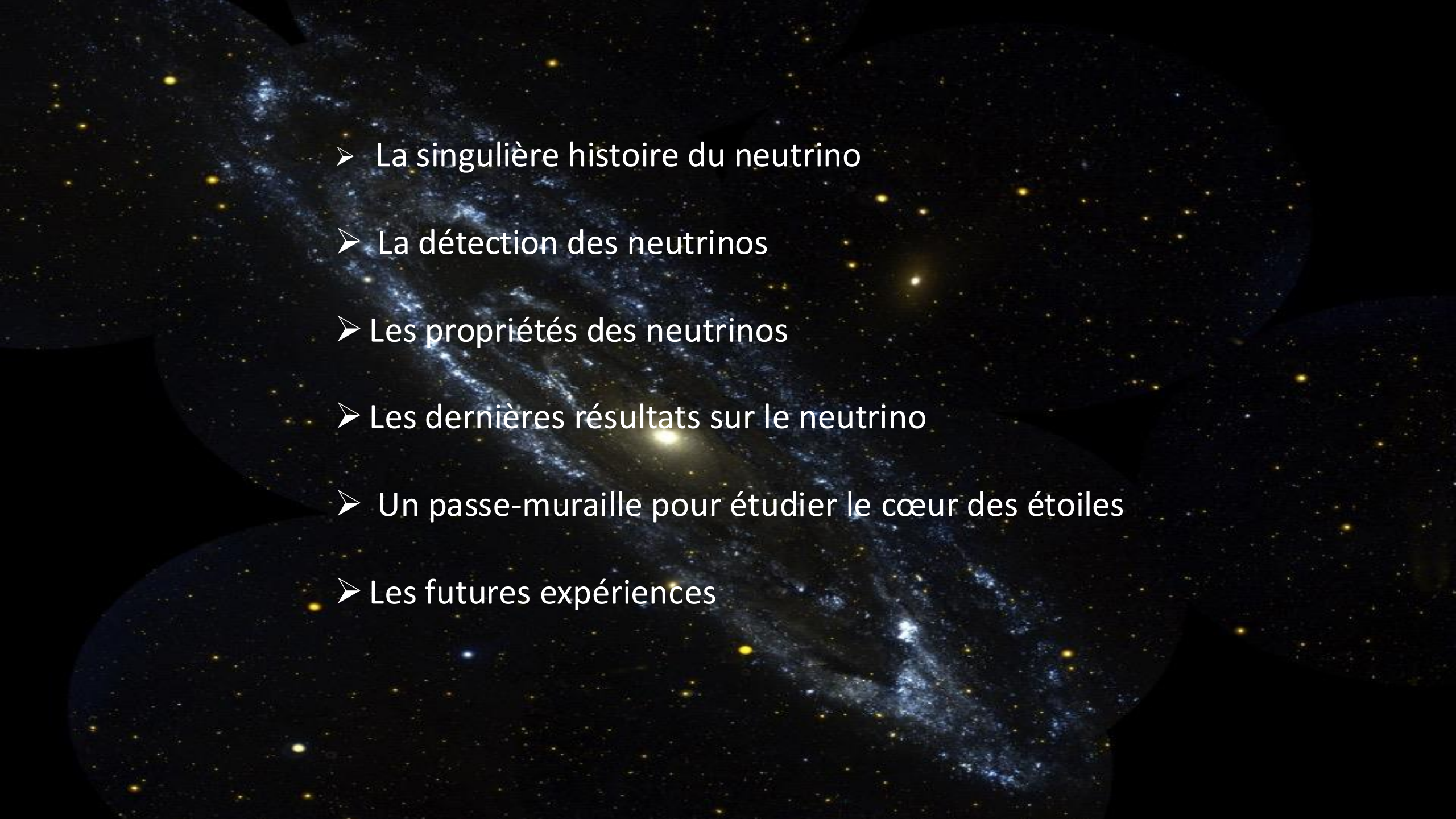


L'enigmatique neutrino

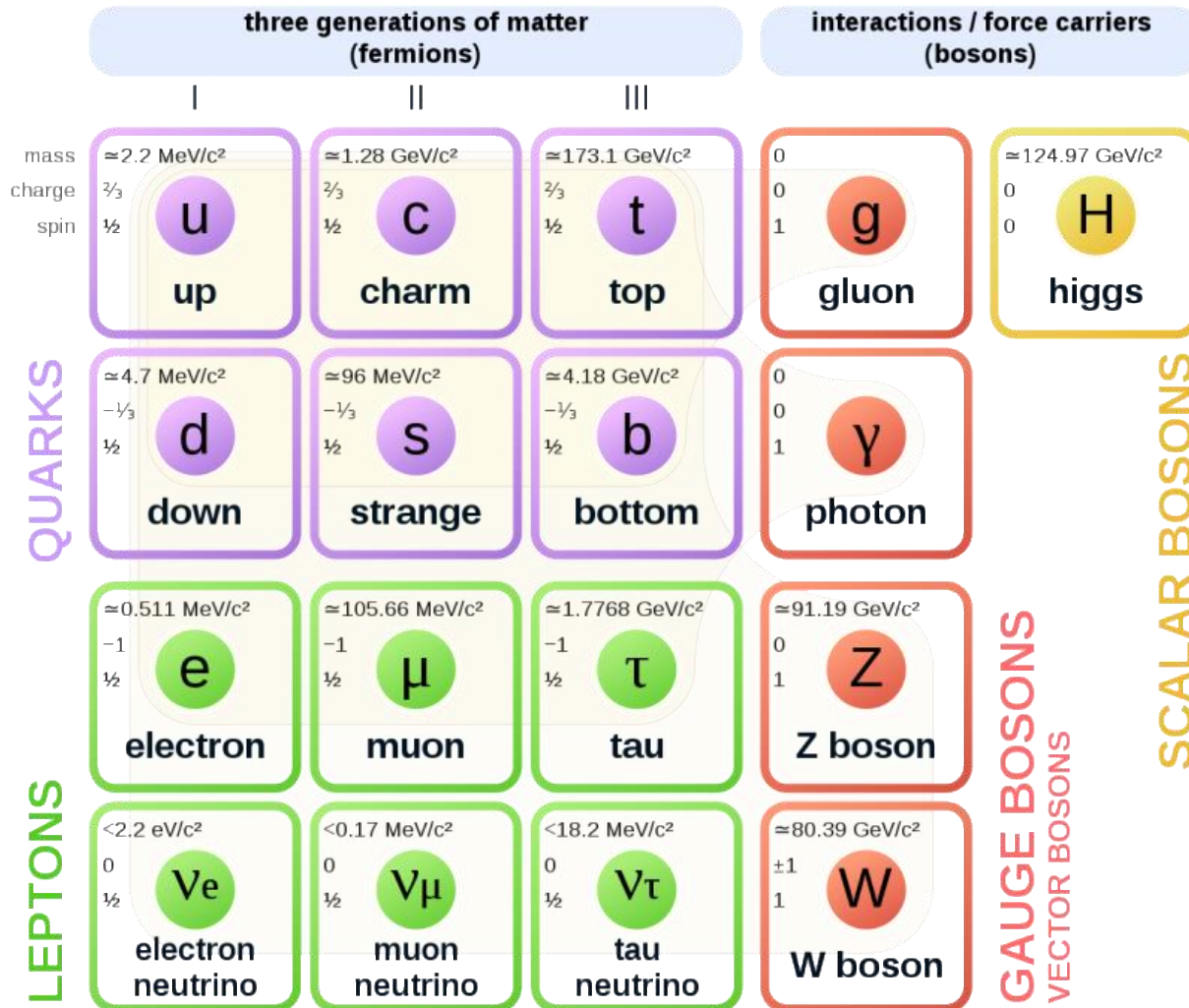
F. Piquemal (CNRS/IN2P3)

Laboratoire de Physique des 2 Infinis Bordeaux
(CNRS/IN2P3 et U. Bordeaux)

French Teacher Programme ,CERN, octobre 2024

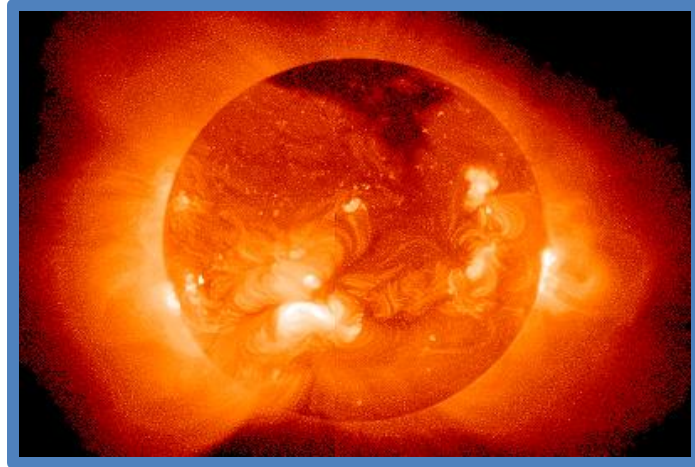
- 
- La singulière histoire du neutrino
 - La détection des neutrinos
 - Les propriétés des neutrinos
 - Les derniers résultats sur le neutrino
 - Un passe-muraille pour étudier le cœur des étoiles
 - Les futures expériences

Standard Model of Elementary Particles

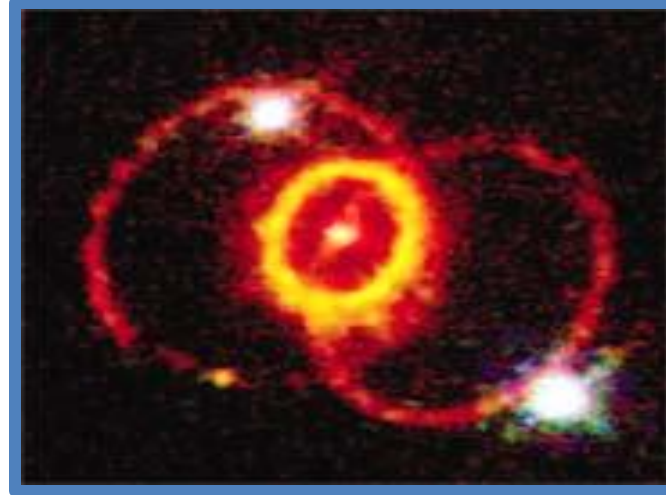


Dans le Modèle Standard de base le neutrino n'a pas de masse

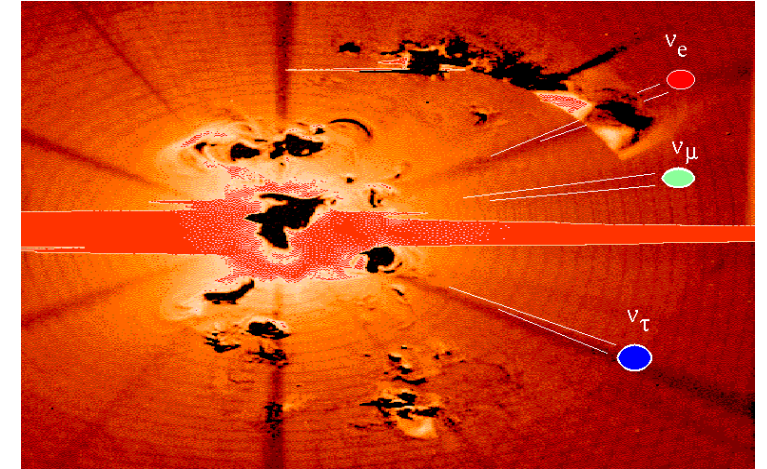
Il pleut des neutrinos de toute part...



64 milliards par cm^2 / s



5 milliards par cm^2 / s pendant 10 s



300 neutrinos « reliques » / cm^3



100 000 par cm^2 / s à 200 km

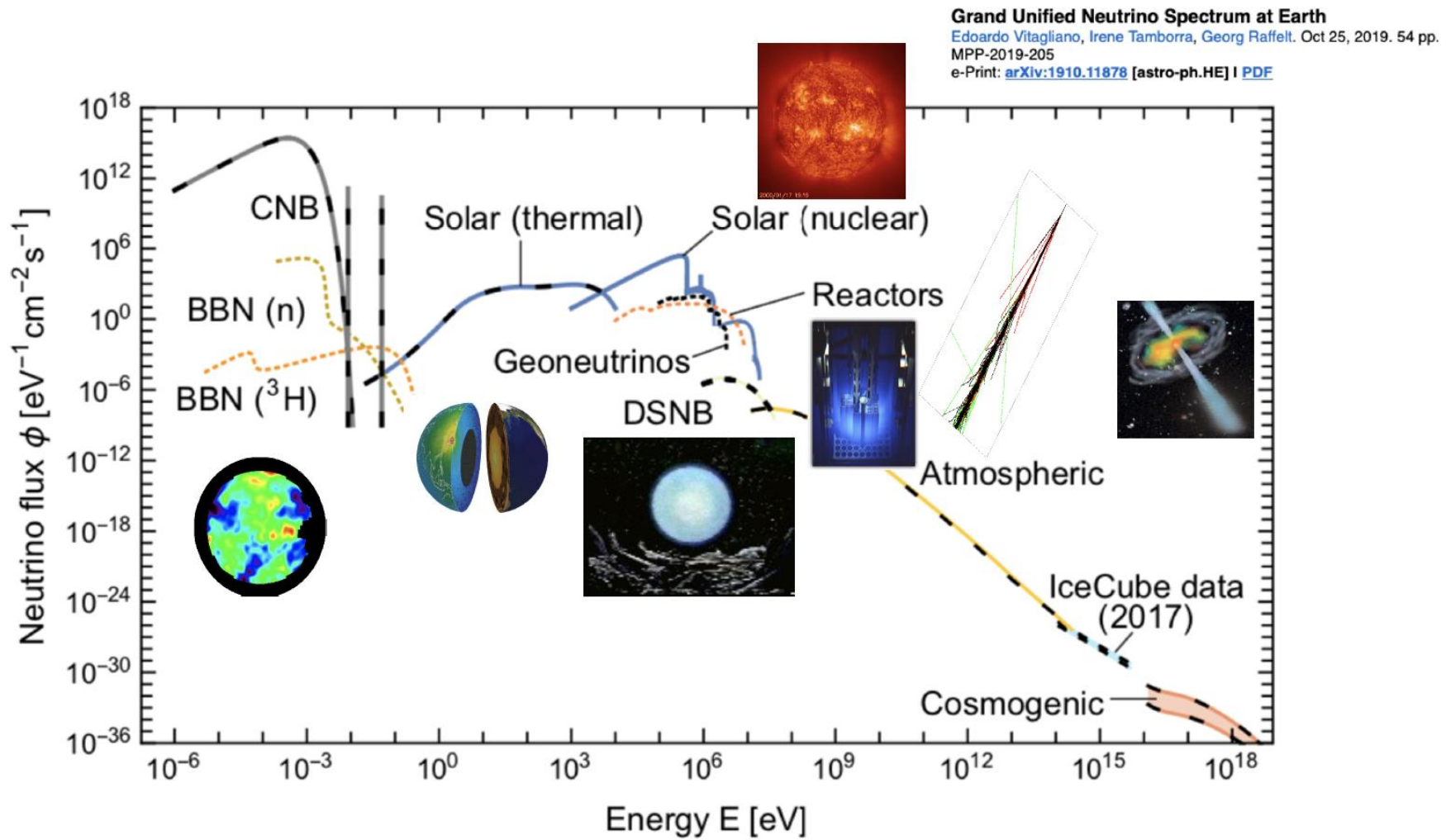


Corps humain 8 000 par secondes !!

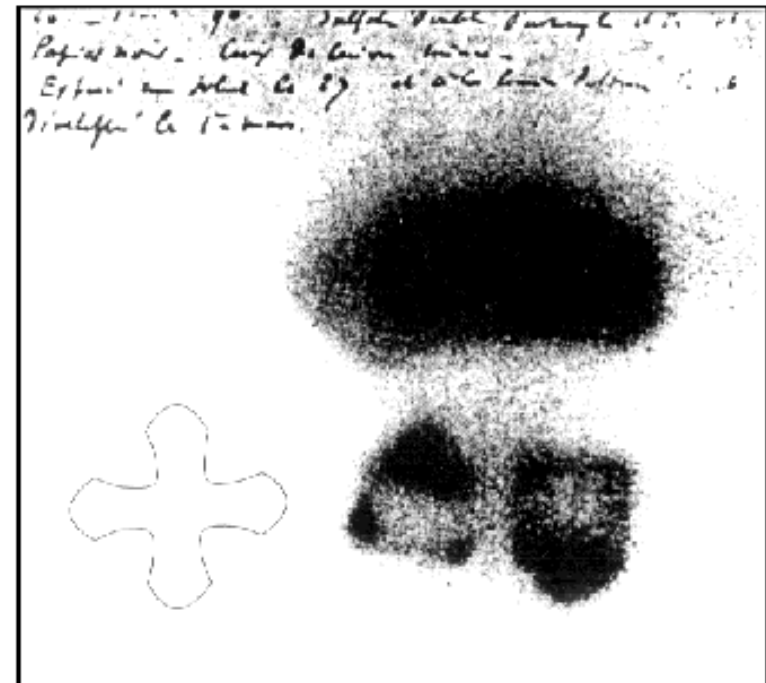
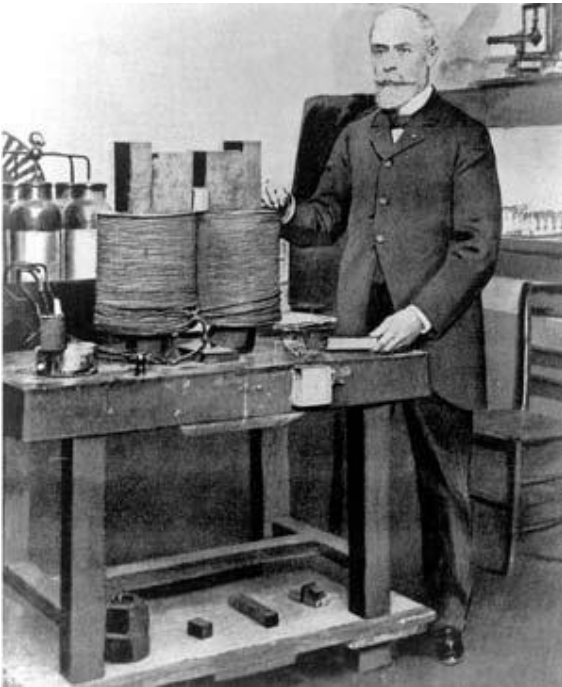


Terre: 6 millions par cm^2 / s

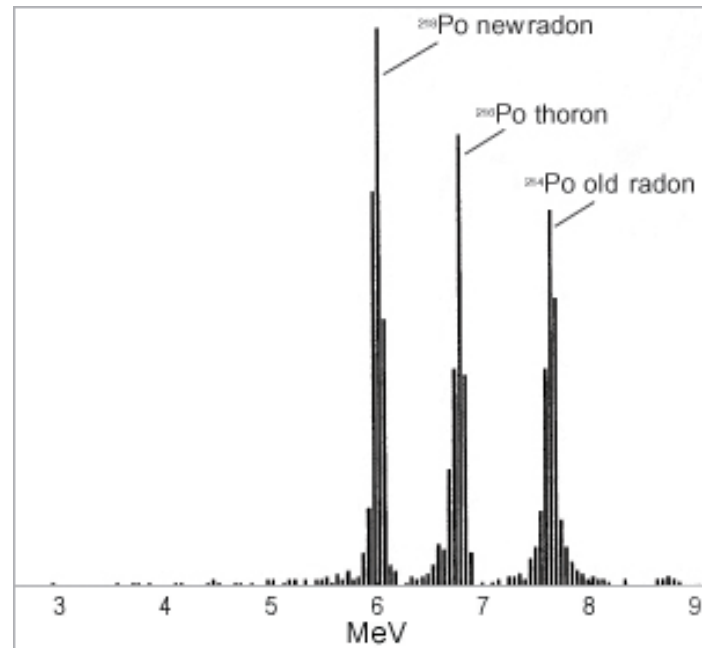
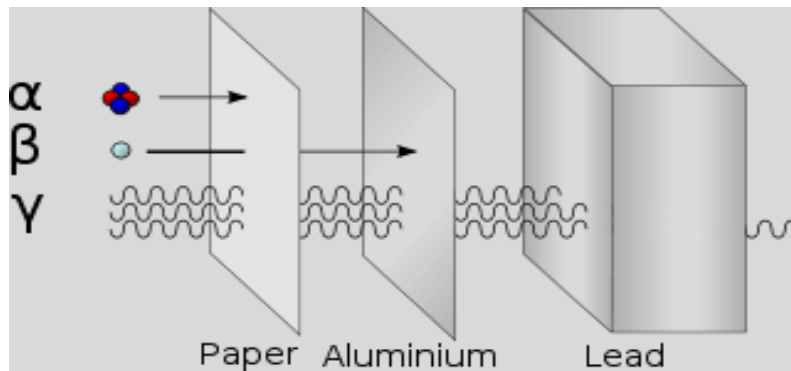
Il pleut des neutrinos de toute part...



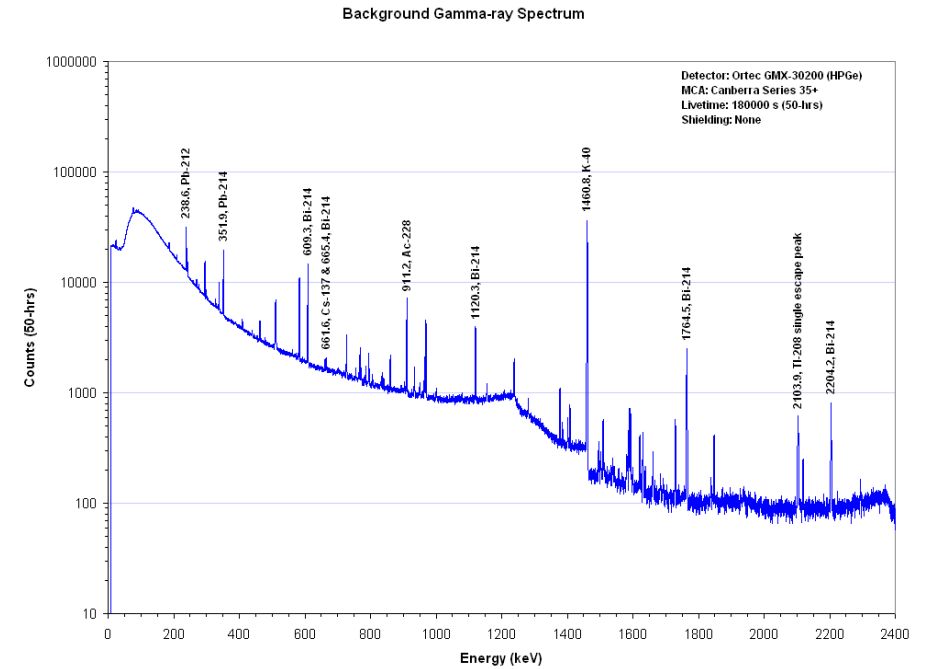
1896 - 1898: Becquerel, Pierre et Marie Curie découvrent la radioactivité



Rutherford, Chadwick, P. et M. Curie et Villard identifient 3 types de rayonnements

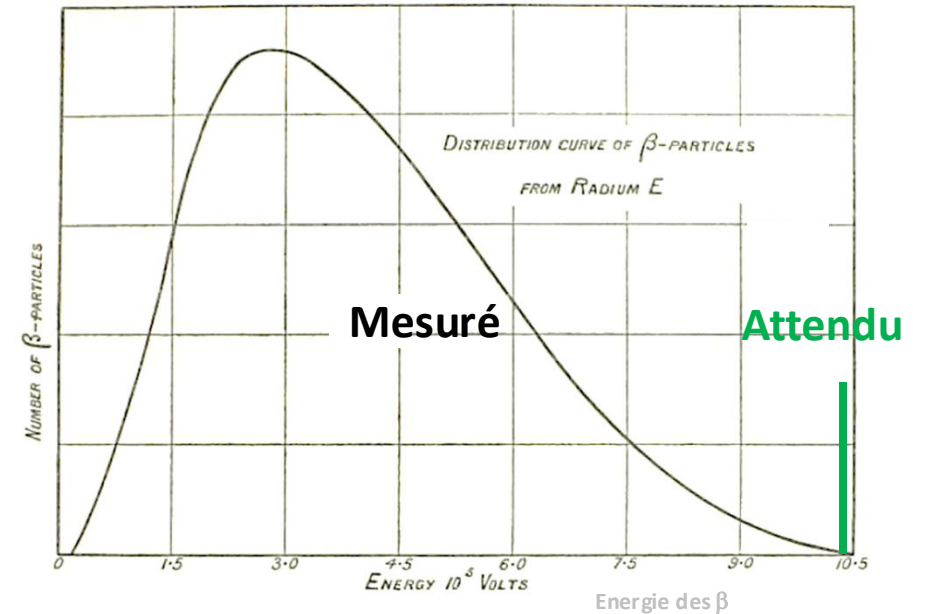


Energie des α



Energie des γ

1914 : Chadwick, Hahn et Meitner mesure le spectre en énergie des rayonnements bêta



1914 – 1930 : crise de l'énergie dans le monde subatomique

Et si l'énergie n'était pas conservée ?

1930 : Wolfgang Pauli



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen.

As the bearer of these lines, to whom I ask you to lend most graciously your ears, will explain in greater detail, I have hit, in view of the "false" statistics of the N and Li-6 nuclei and of the continuous β -spectrum, upon a desperate expedient for saving the "Wechselsatz"[†] of statistics and energy conservation. This is the possibility that electrically neutral particles, which I shall call neutrons, might exist in the nucleus, having spin 1/2 and obeying the exclusion principle. In addition they differ from light quanta in that they do not travel at the speed of light. The mass of the neutron should be of the same order of magnitude as that of the electron and in any event **no greater than 0.01 of the proton mass.** The continuous β -spectrum would then be comprehensible on the assumption that on β -decay a neutron is emitted with the electron in such a way that the sum of the neutron and the electron energy is constant.

Furthermore the question arises which forces act on the neutron. For reasons of wave mechanics (the bearer of these lines knows more about this) the likeliest model for the neutron seems to me to be, that the neutron at rest is a magnetic dipole with a certain moment μ . Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a γ -ray, in which case **μ should be no greater than $e(10^{-13} \text{ cm})$.**

For the moment I would not venture to publish anything on this notion and should like first of all to turn trustingly to you, dear Radioactives, with the question concerning the **prospects for experimental verification of the existence of such a neutron if it were to have the same or perhaps a 10 times greater penetrating power as a γ -ray.**

I admit that my expedient may seem rather improbable from the first, because if neutrons existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained, and the seriousness of the situation with the continuous β -spectrum is illustrated by a statement by my esteemed predecessor in office, Mr. Debye, who recently told me in Brussels: "Oh, it's better to ignore that completely, just like the new taxes". We should therefore be seriously discussing every path to salvation. So, dear Radioactives, consider and judge. Unfortunately I cannot come to Tübingen in person since my presence here is essential as a result of a ball held on the night of 6th to 7th December in Zürich.

With kind regards to all of you and Mr. Back, I remain,
your humble servant,

(signed) W. Pauli

[†] This states: Fermi statistics and half-numbered spin for nuclei with an odd total number of particles; Bose statistics and integer spin for nuclei with an even total number of particles.

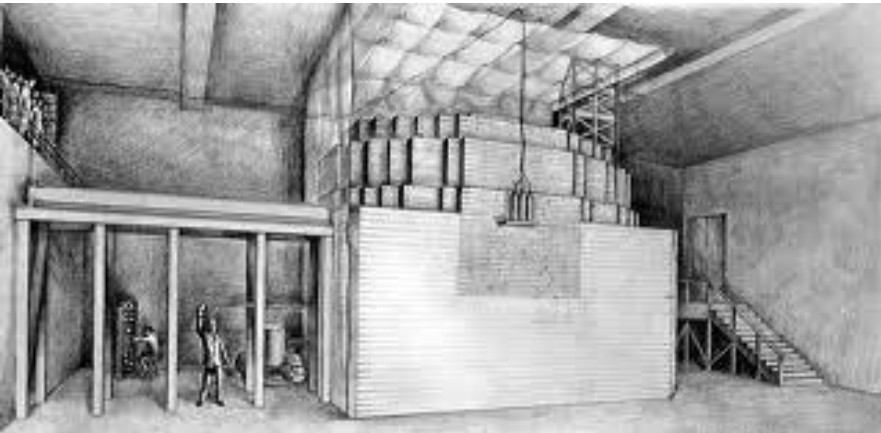
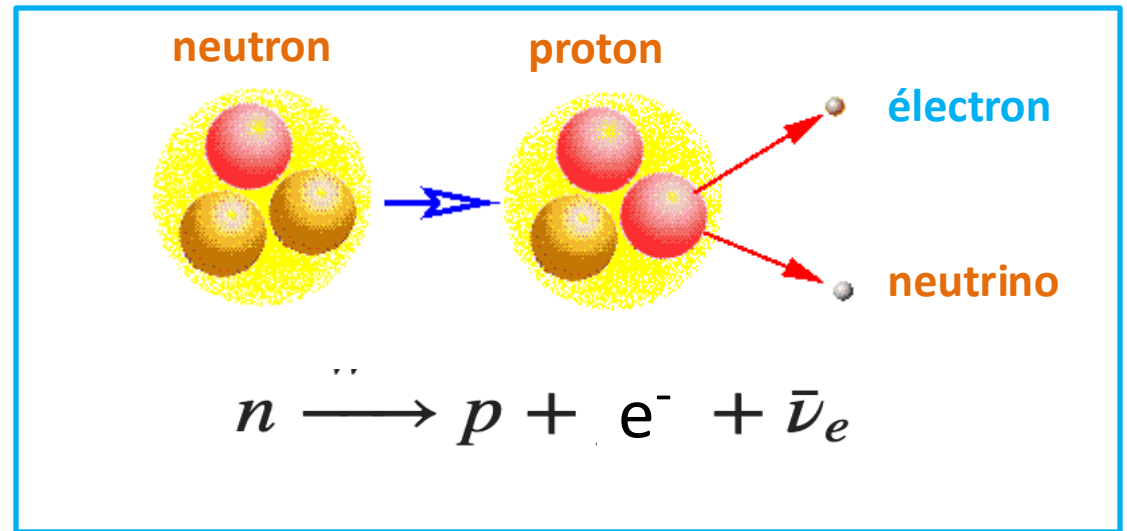
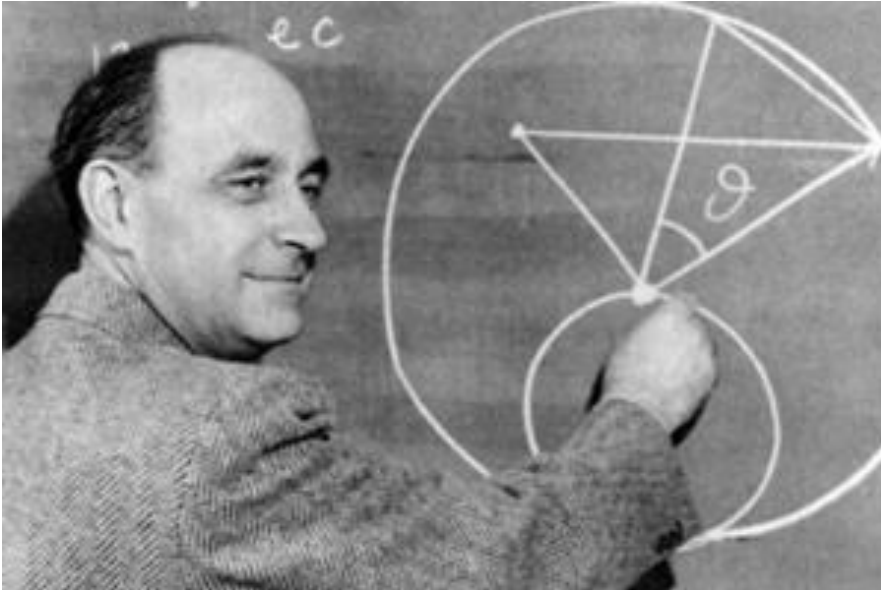
« un remède désespéré pour sauver la conservation de l'énergie »

« Spin $\frac{1}{2}$ et ne voyage pas à la vitesse de la lumière »

Pauli : « J'ai fait une chose terrible, j'ai inventé une particule que l'on ne pourra jamais détecter »

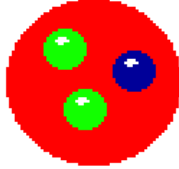
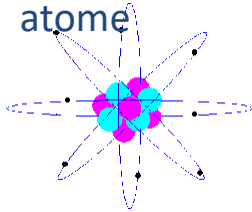
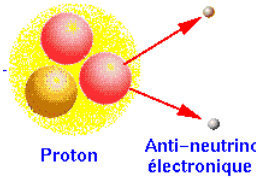

Pauli met au défi les expérimentateurs de détecter les neutrinos

1933 : Fermi élabore la théorie de l'interaction faible

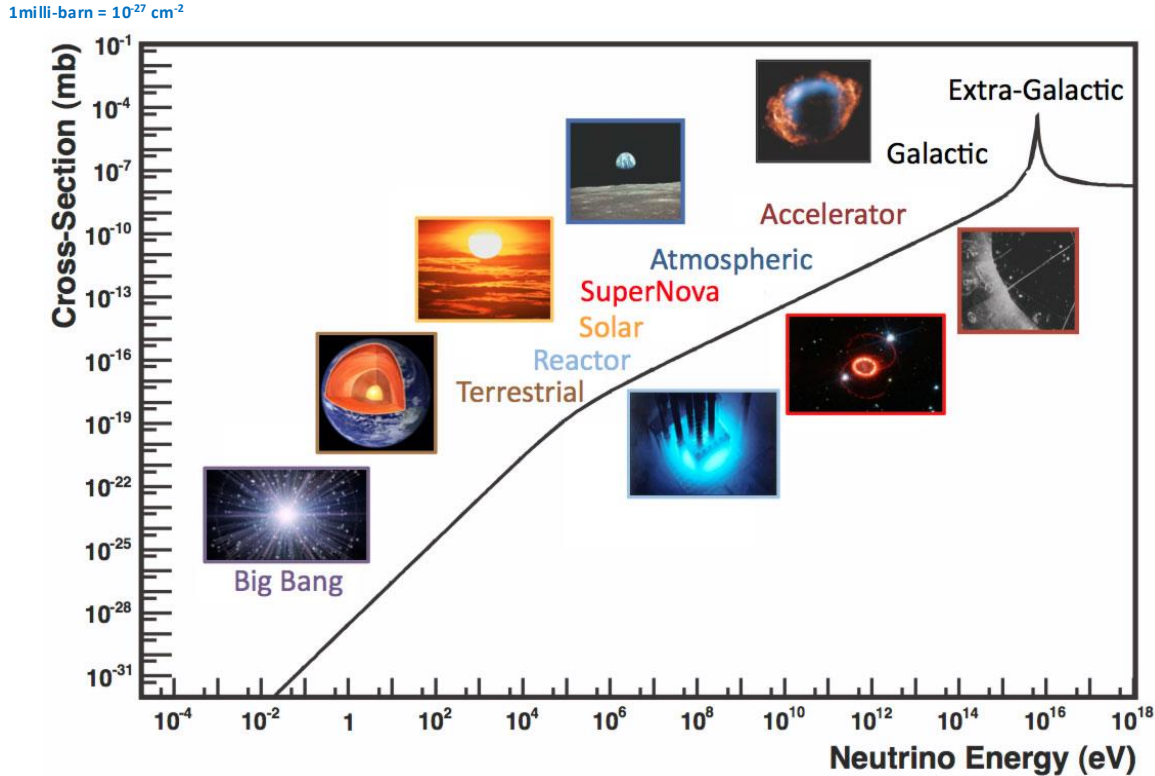


1942 : Fermi met au point le premier réacteur nucléaire
Une source de neutrino !

L'interaction des neutrinos

Force	MEDIATEUR	FORCE RELATIVE	PORTEE (m)	
FORTE	GLUONS	~ 1	$\sim 10^{-15}$	 quarks
ELECTRO-MAGNETIQUE	PHOTON	$\sim 10^{-2}$	infinie	 atome
FAIBLE	W^+, W^-, Z^0	$\sim 10^{-8}$	$\sim 10^{-18}$	 Radioactivité électron Proton Anti-neutrino électronique
GRAVITATION	GRAVITON ?	$\sim 10^{-38}$	infinie	

Section efficace d'interaction des neutrinos



Neutrino 1 MeV : $\sigma \sim 10^{-20}$ barn

Photon 1 MeV : $\sigma \sim 10$ barn

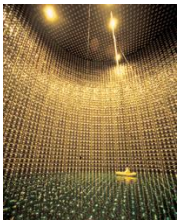
Piège à neutrino

← 30 10^{15} km de plomb →



Pour détecter des neutrinos:

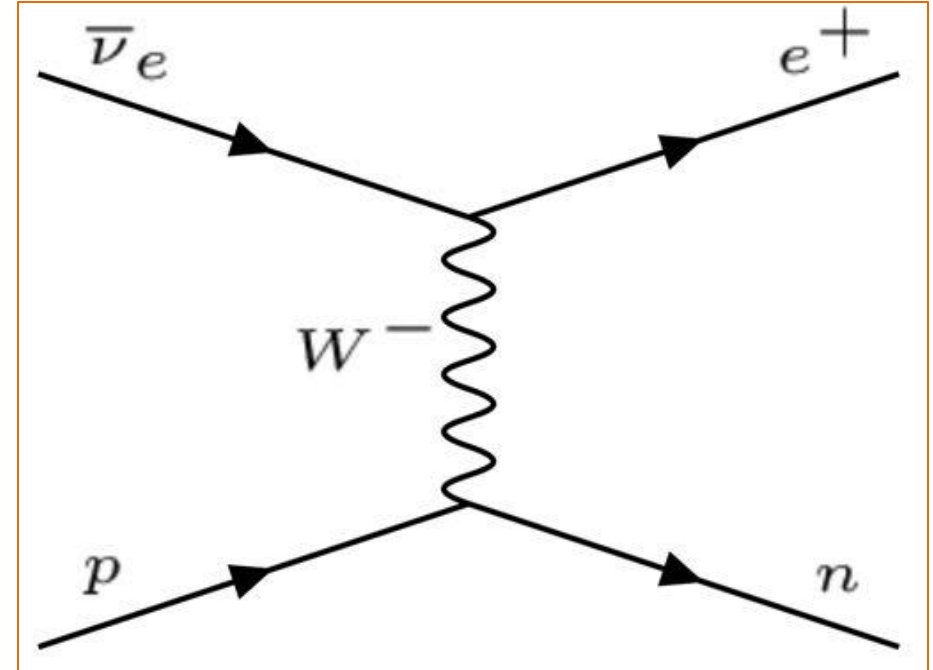
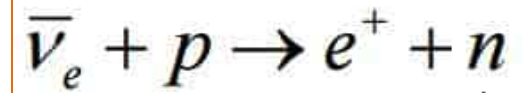
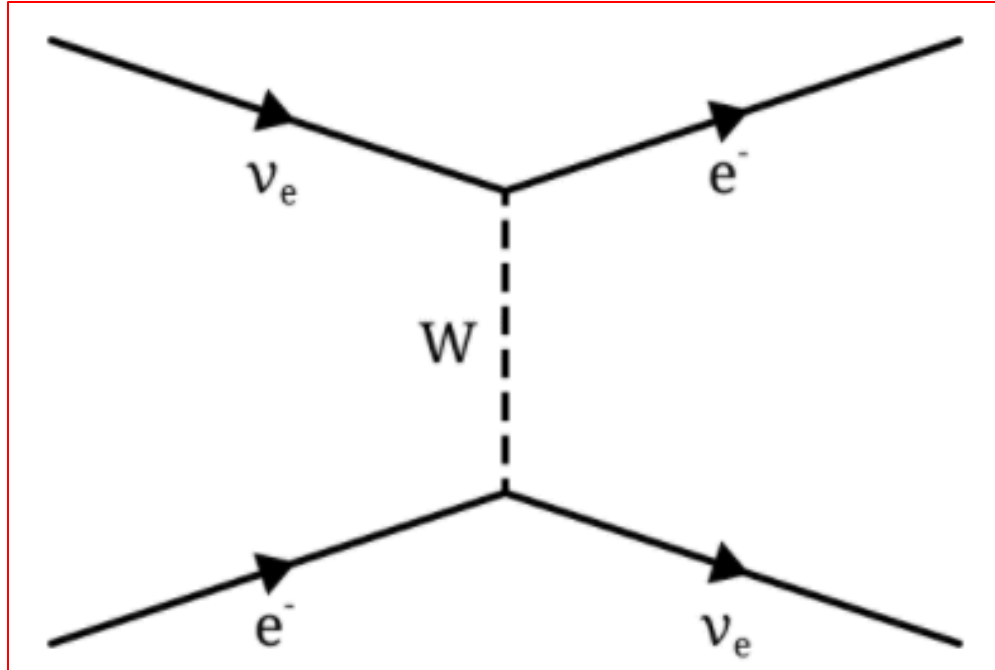
Source intense de neutrinos



..... beaucoup de matière !



L'interaction des neutrinos



$$E_{\bar{\nu}} \cong E_{e^+} + E_n + \underbrace{(M_n - M_p)}_{1.8 \text{ MeV}} + m_{e^+}$$

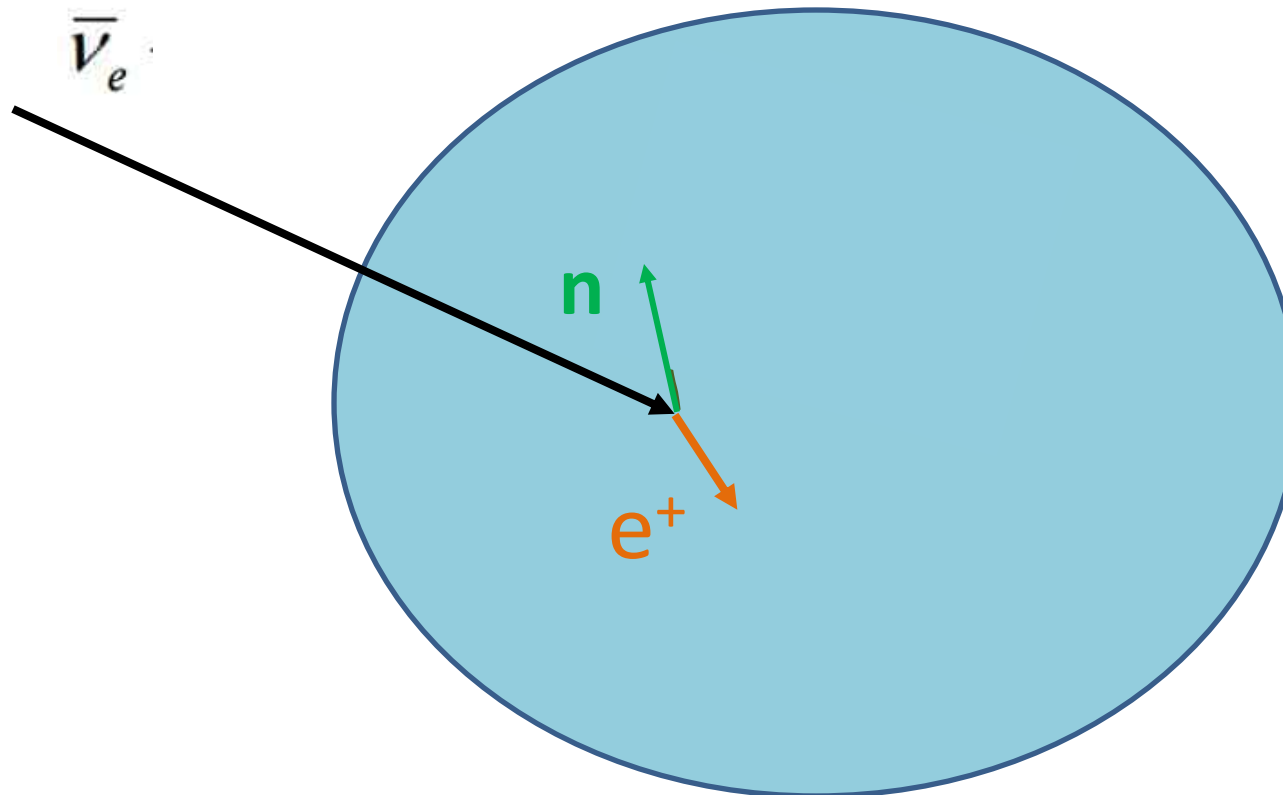
10-40 keV

L'interaction des neutrinos



Energie prompte

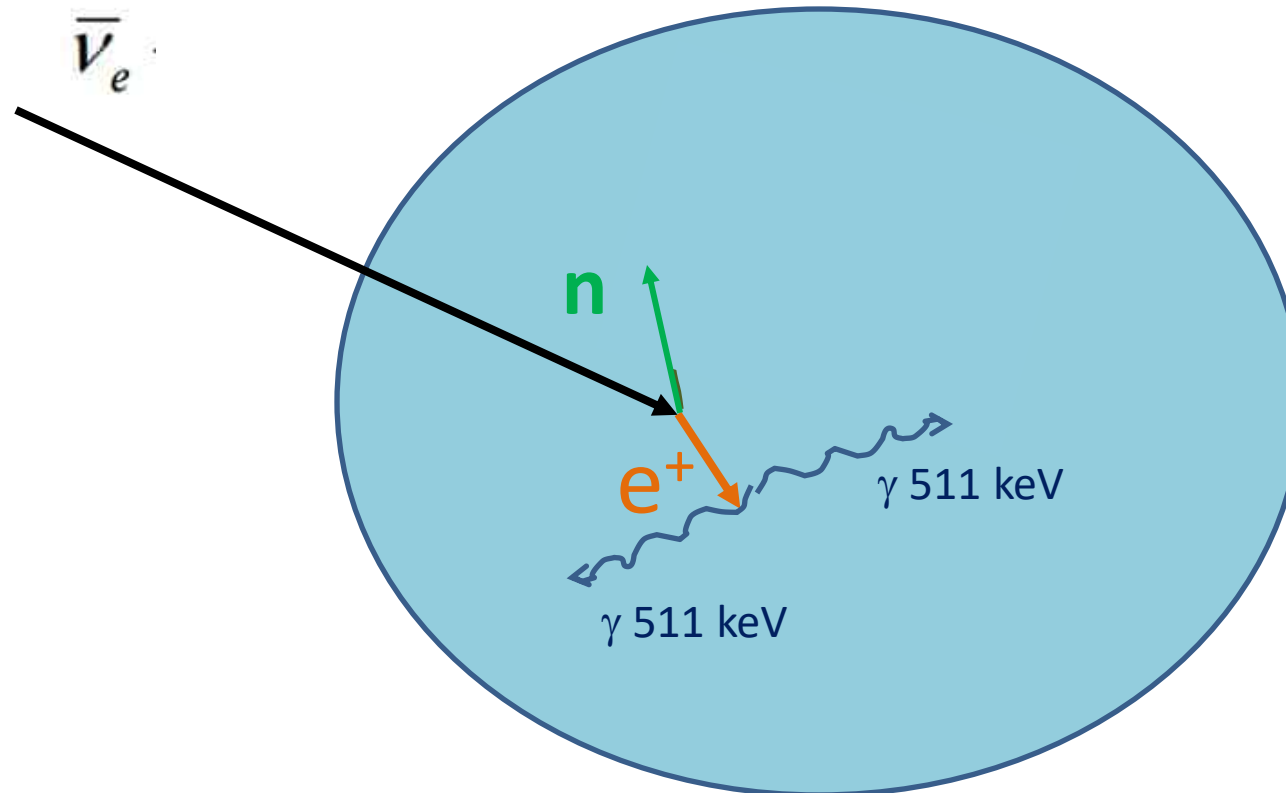
Energie retardée



L'interaction des neutrinos



Energie prompte



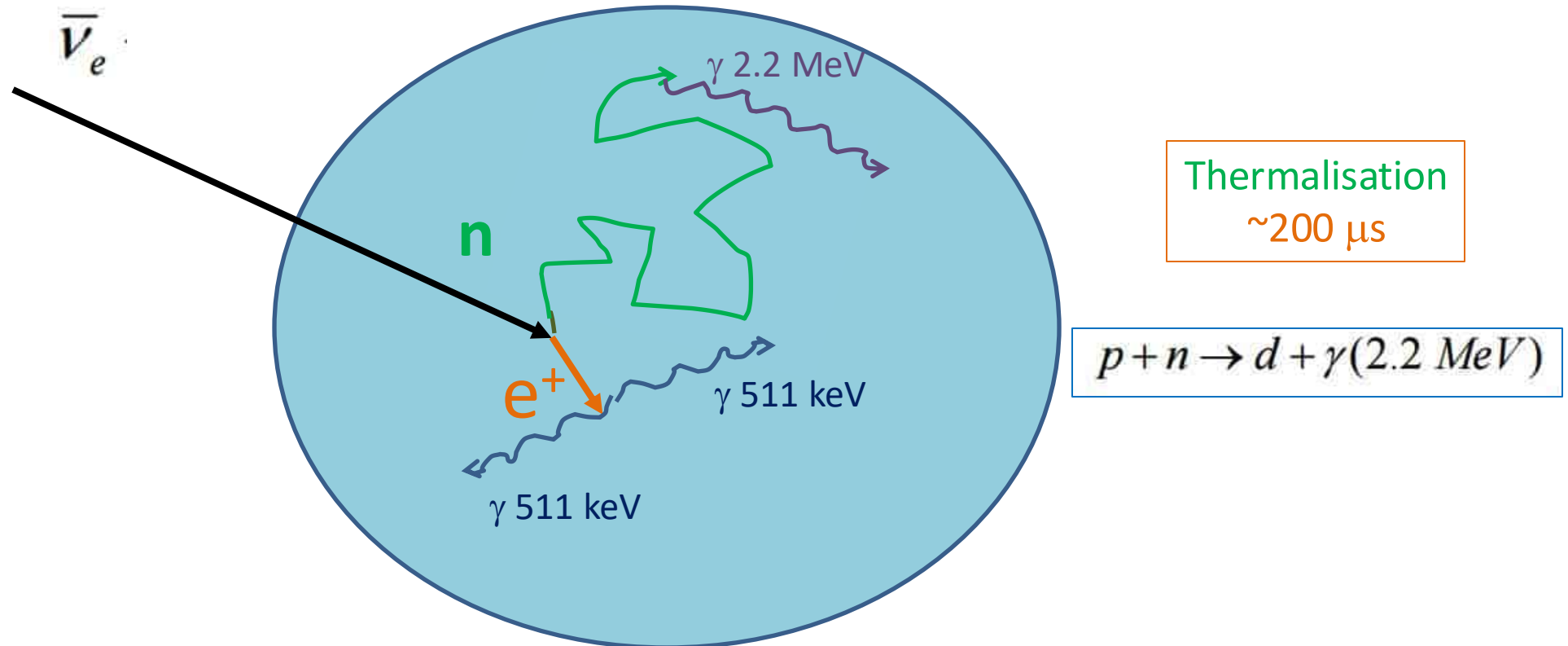
$$E_{\text{prompt}} = E_{\nu} - 0.8 \text{ MeV}$$

L'interaction des neutrinos

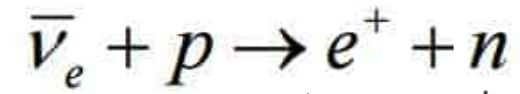


Energie prompte

Energie retardée



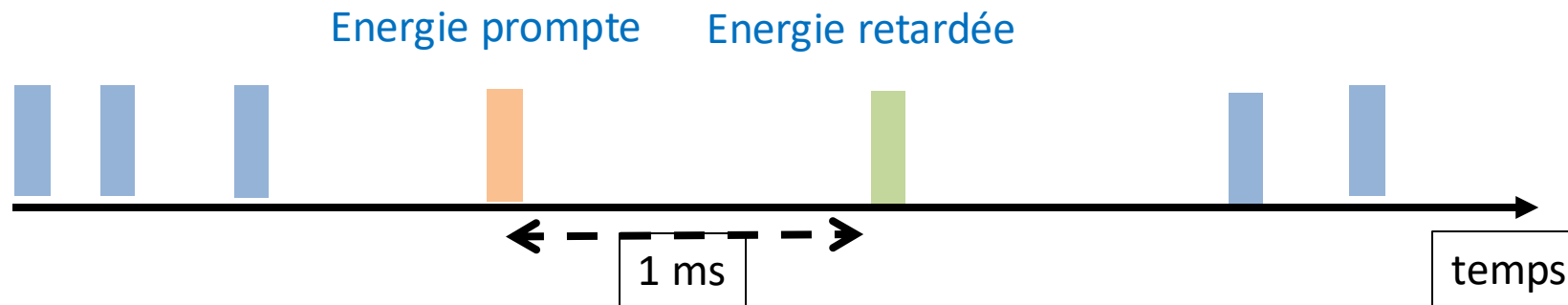
L'interaction des neutrinos



Energie prompte

Energie retardée

Mesure dans le temps des dépôts d'énergie dans le détecteur



Une sélection supplémentaire : l'énergie retardée doit être de **2,2 MeV**

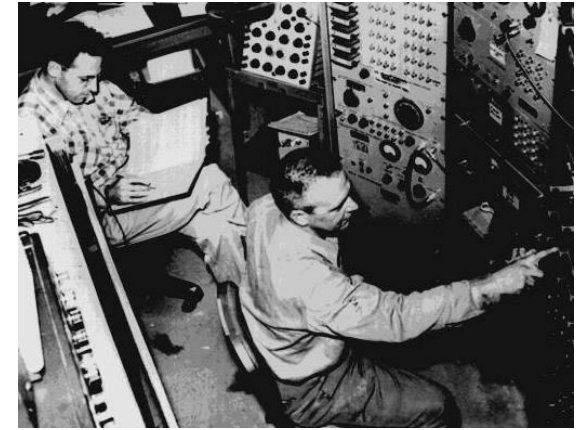
La découverte des neutrinos



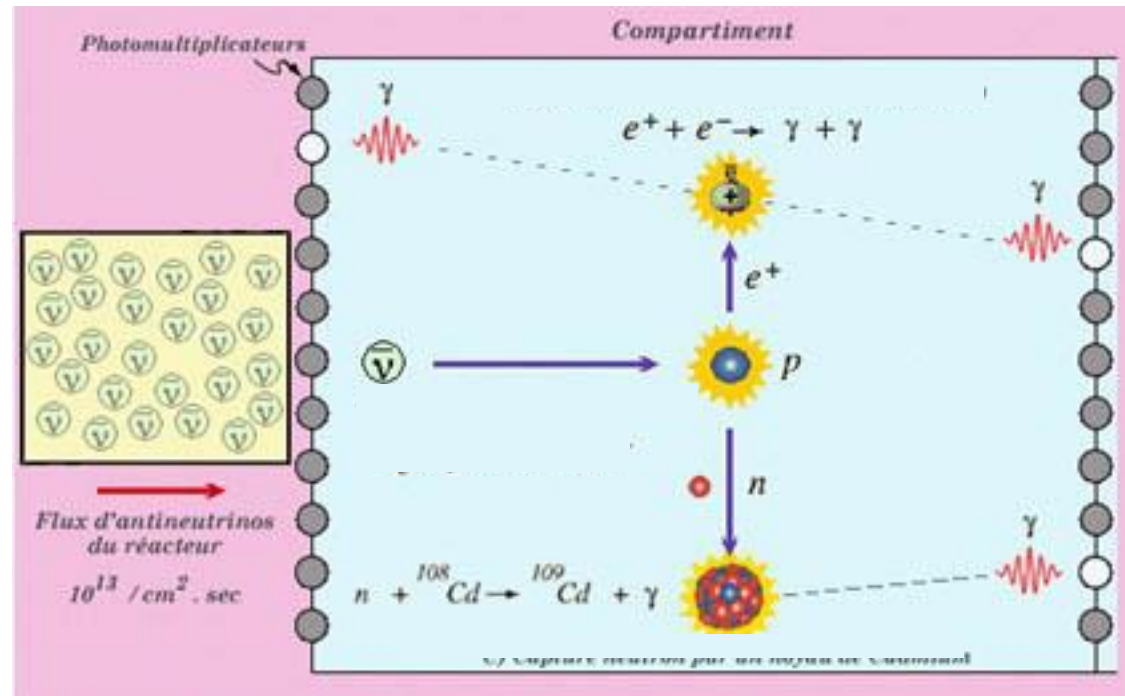
Réacteur de Savannah River (USA)



1956: Découverte du neutrino par Reines et Cowan



Détecteur Poltergeist



La découverte des neutrinos

RADIO-SCHWEIZ AG. **RADIOGRAMM - RADIOGRAMME** RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGO ILL 56 14 1310
PLC 00253

Erhalten - Reçu **„VIA RADIOSUISSE“** Befördert - Transmis

von - de	Stunde - Heure	NAME - NOM	nach - à	Stunde - Heure	NAME - NOM
NEWYORK	15:36	100		7 4	No. VI. 56 --1 10

Brieftelegramm

NACHLASS
PROF. W. PAULI

LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

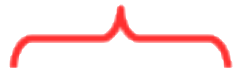
Per Post ①

NACHLASS
PROF. W. PAULI

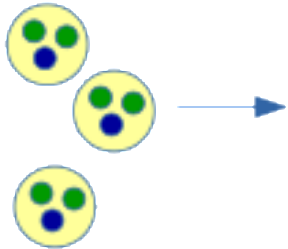
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED
NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY
OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX
TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 X 100 3/54

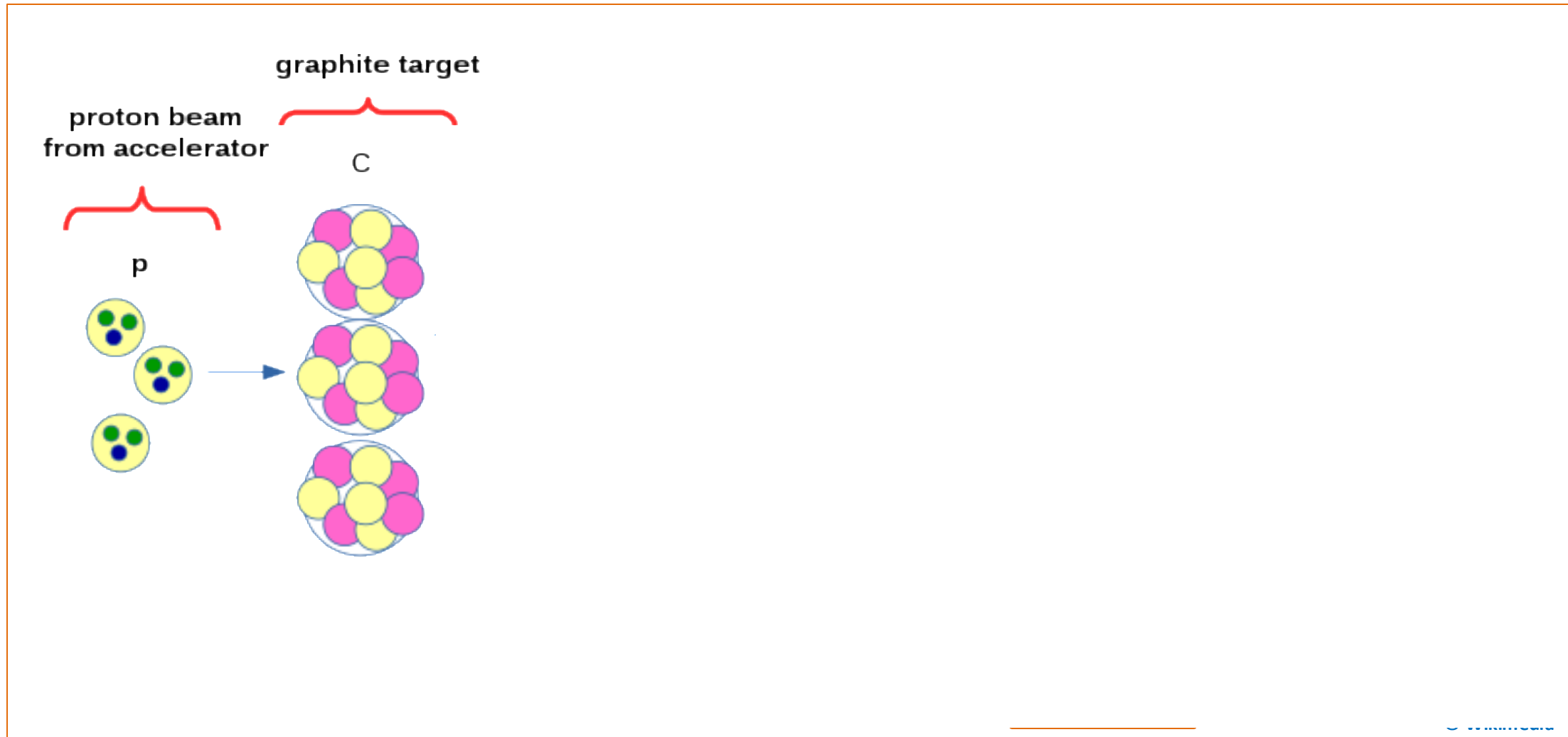
proton beam
from accelerator

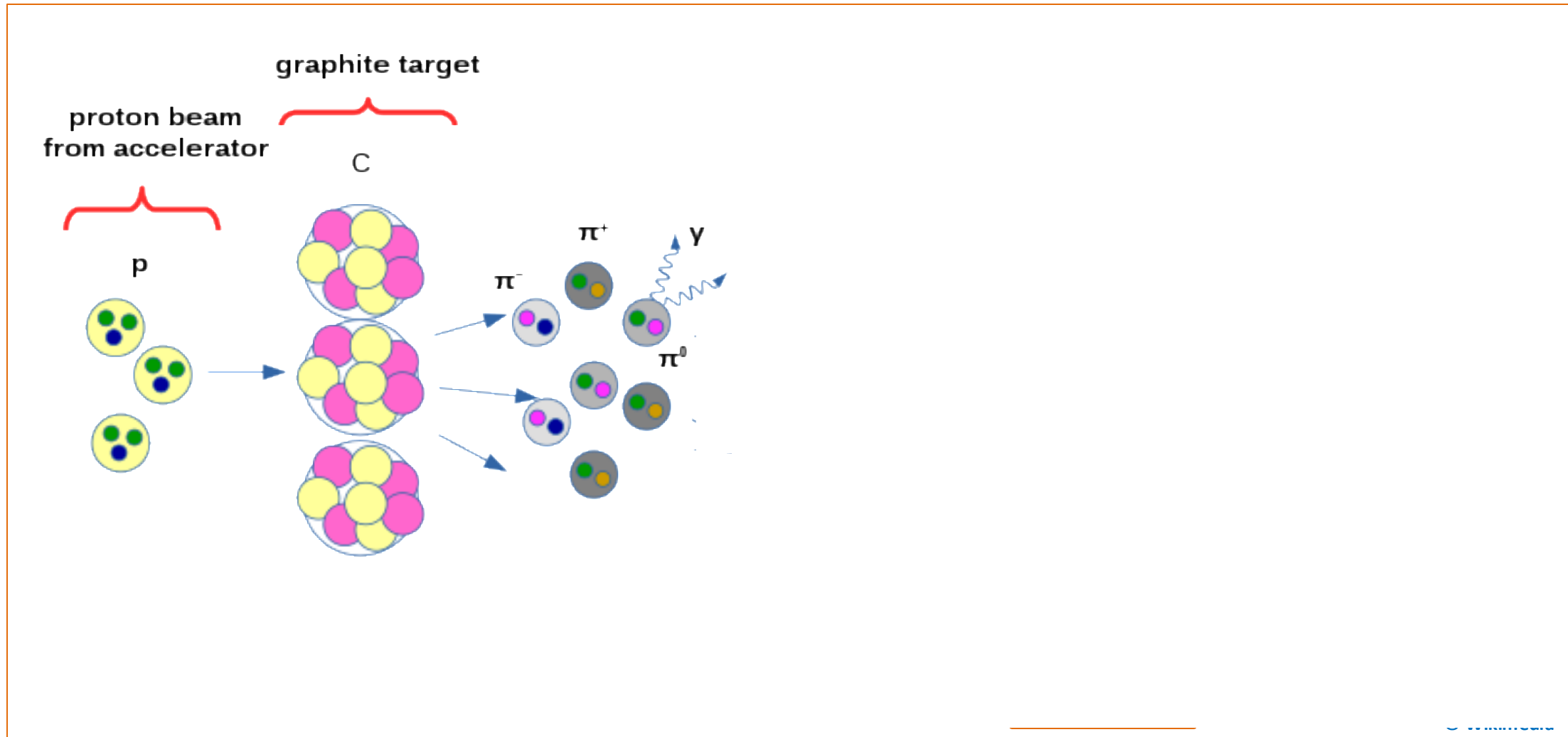


p

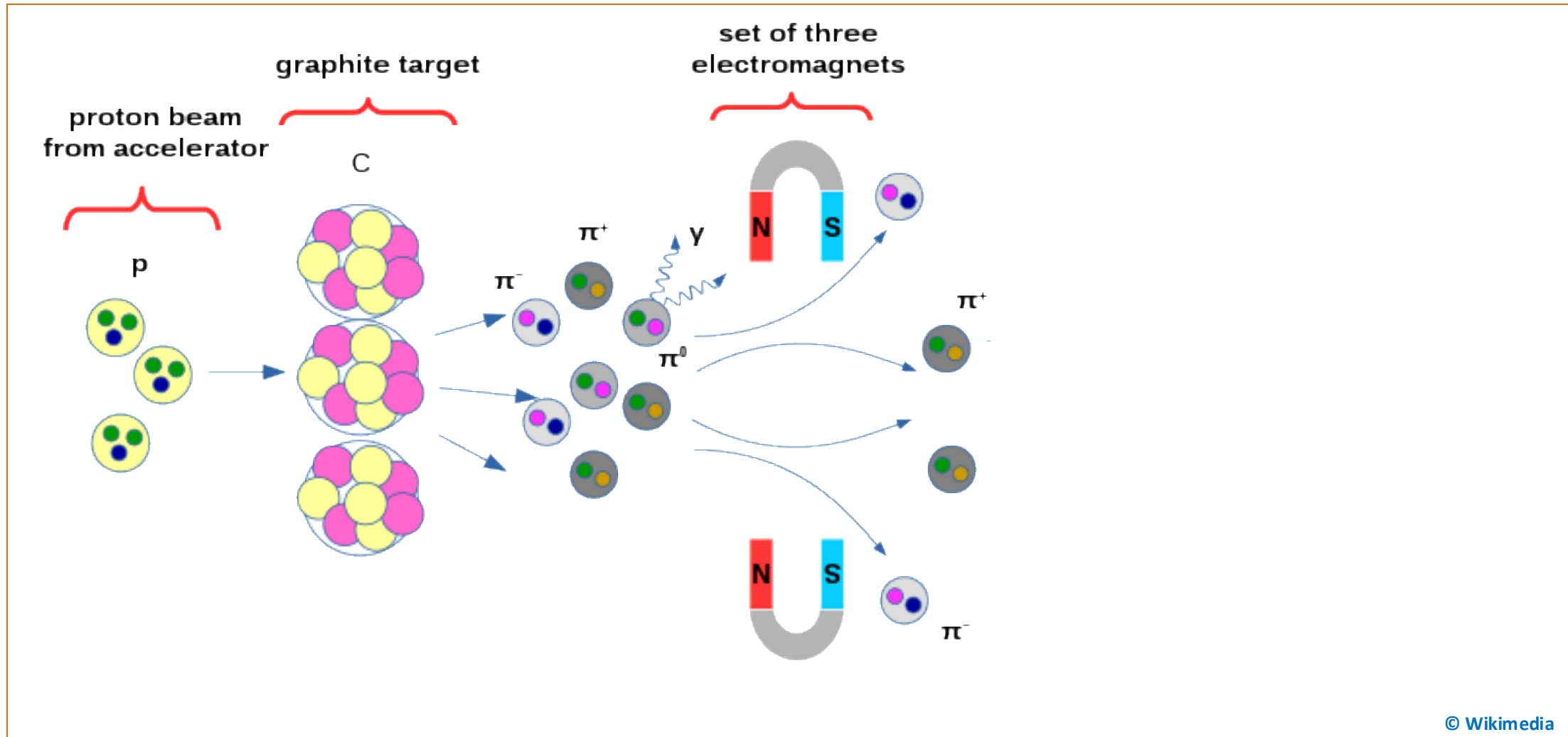


© 2011-2012





Créer des neutrinos avec un accélérateur



Créer des neutrinos avec un accélérateur

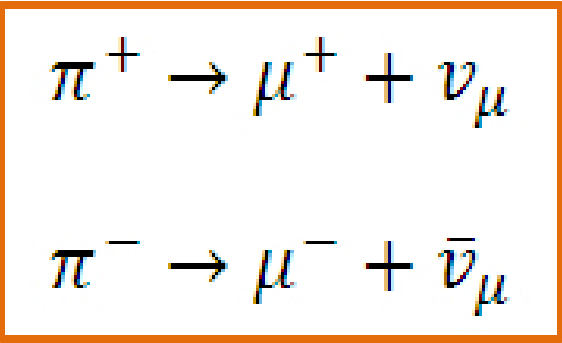
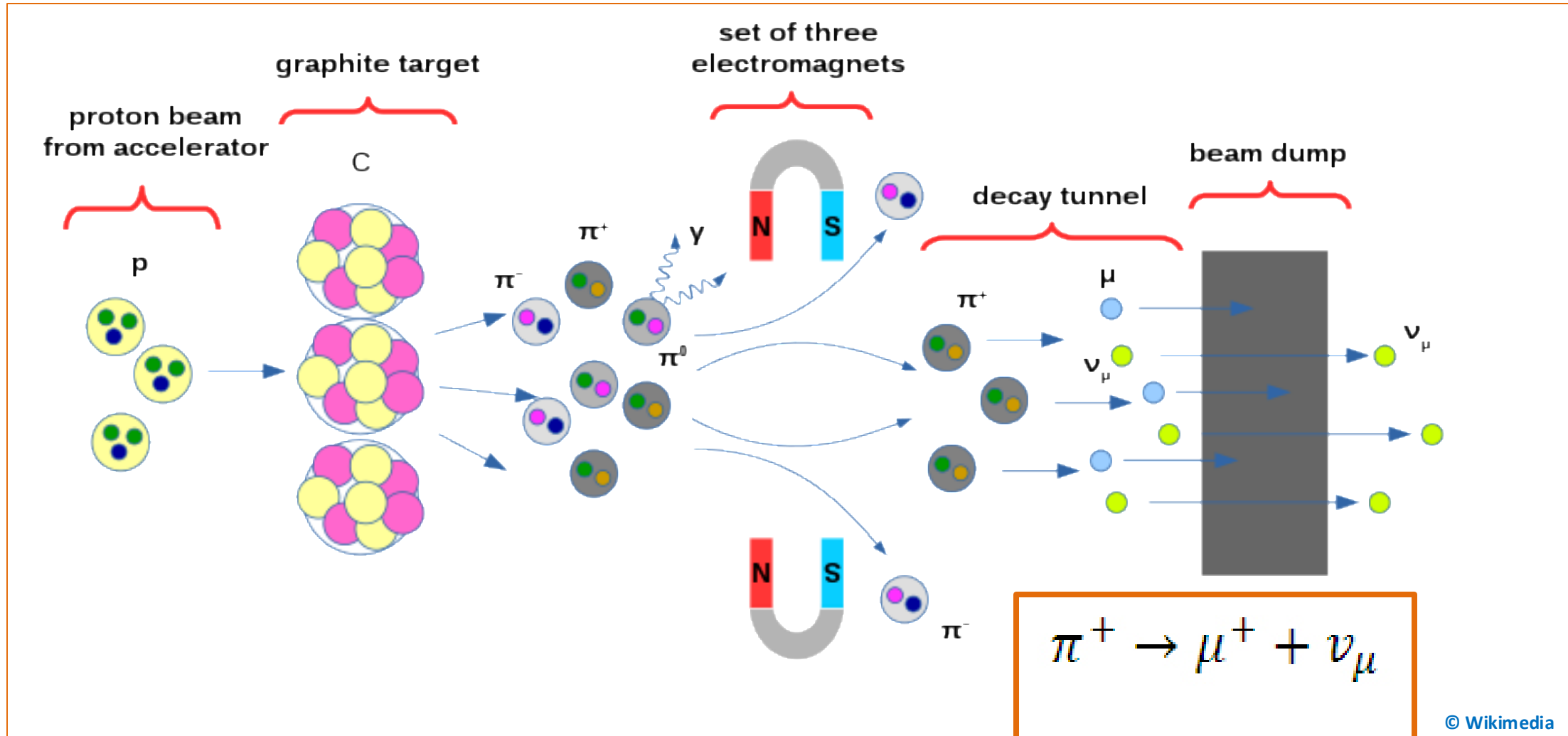
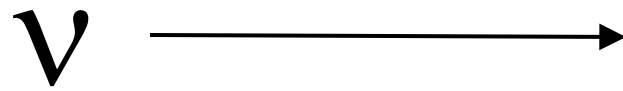


Photo d'une interaction de neutrino d'un faisceau produit au CERN prise dans la chambre à bulle BEBC (1978).

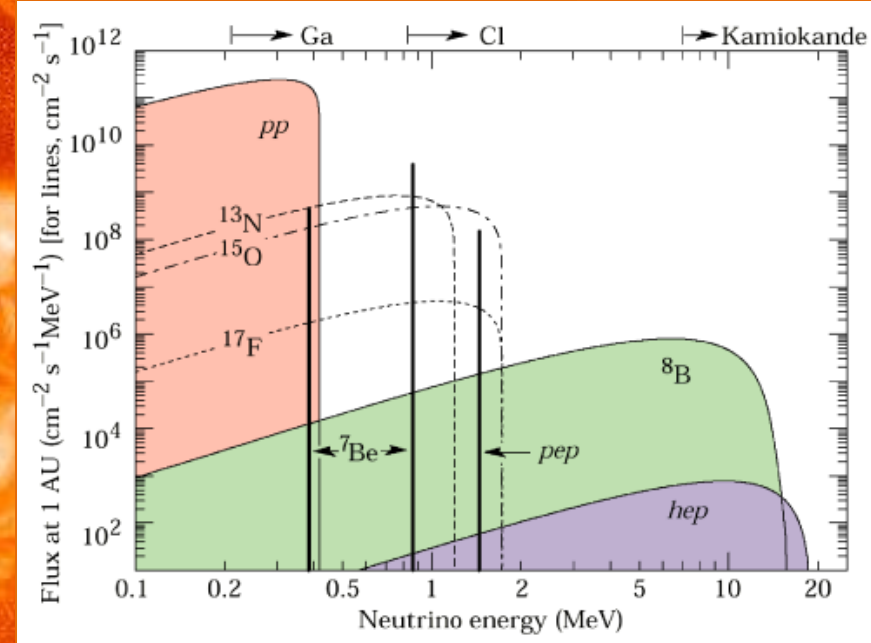
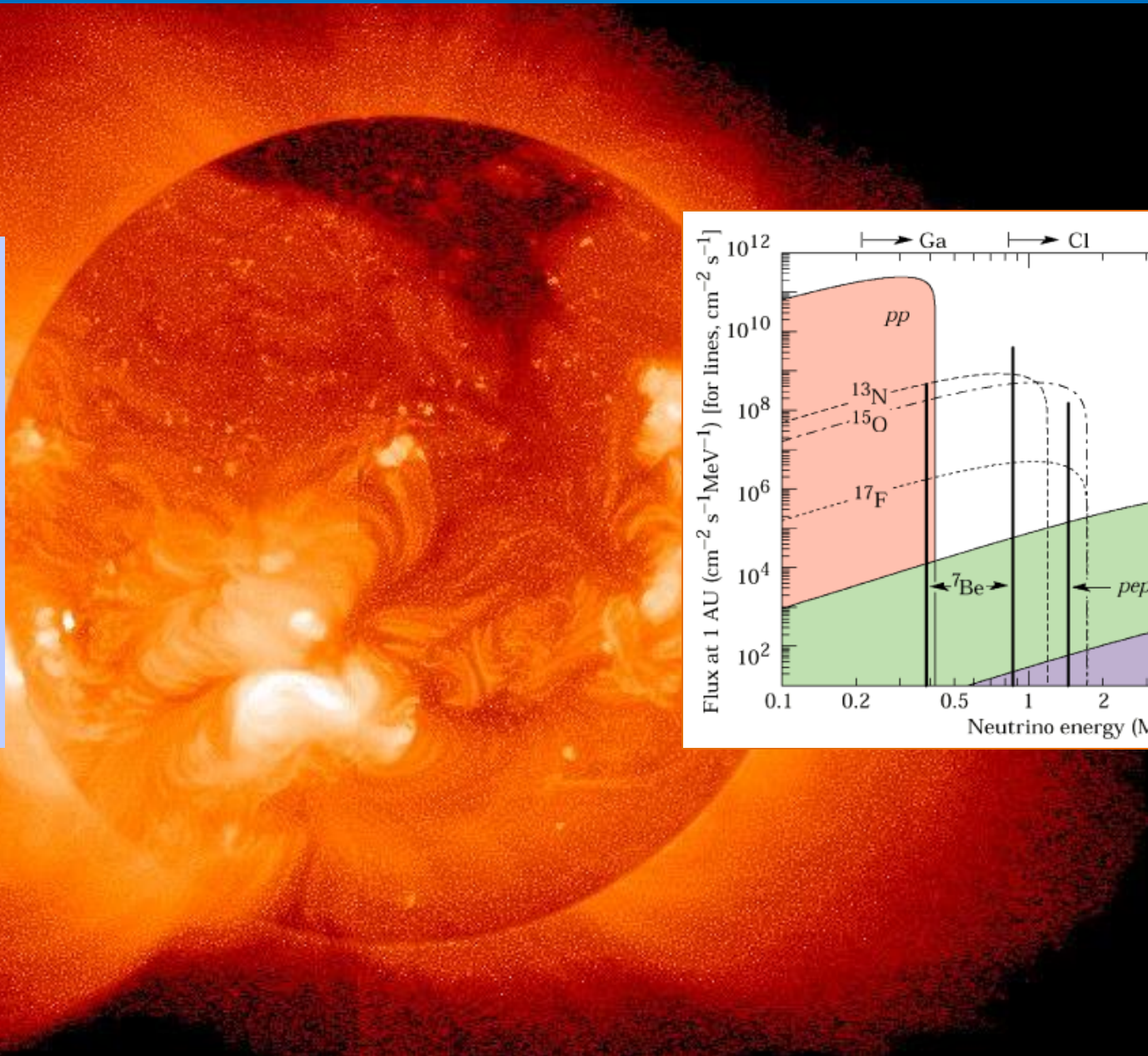
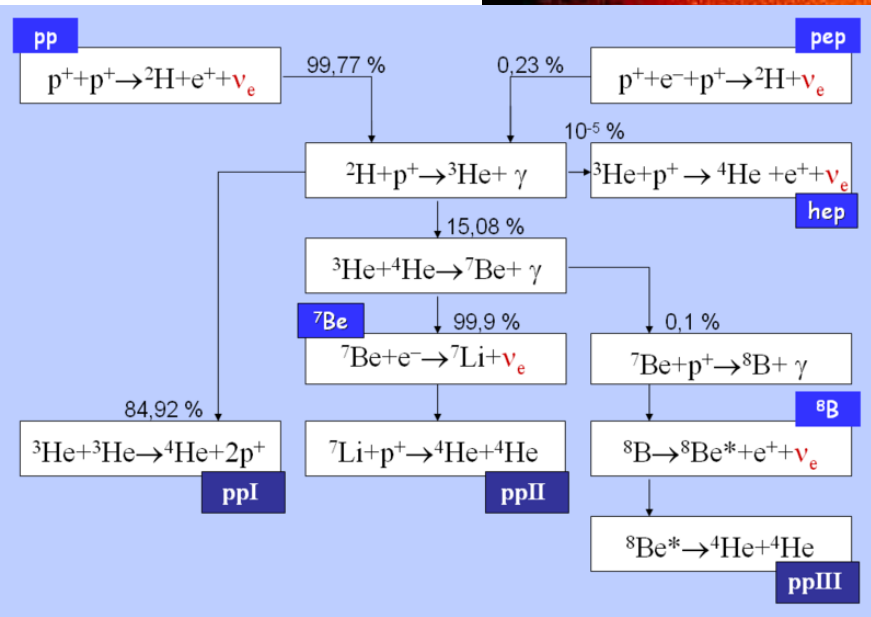


1962: découverte du ν_{μ}

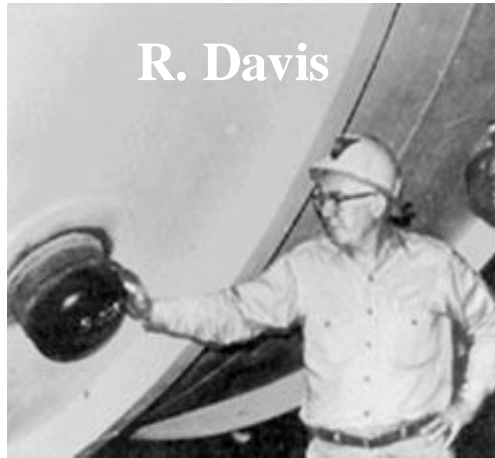
2000: Découverte du ν_{τ}



Expériences avec les neutrinos solaires



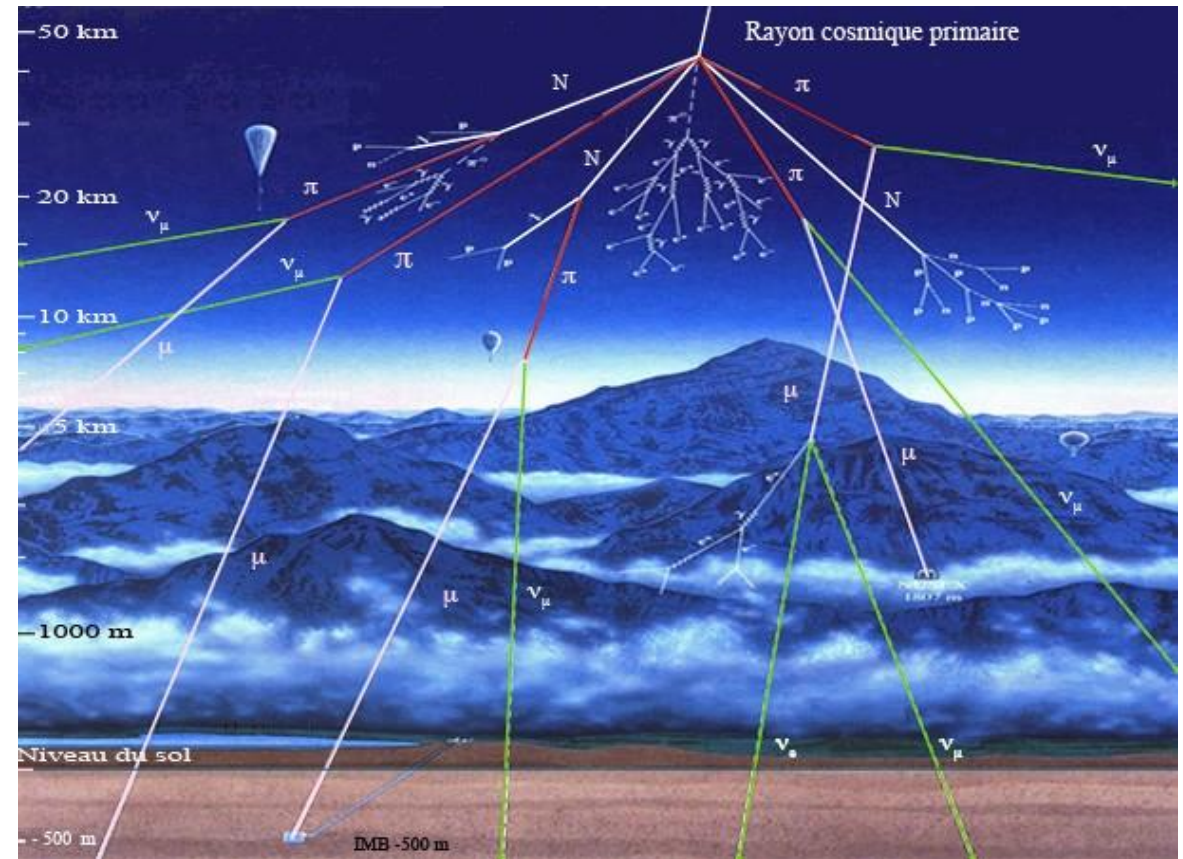
1968: 1ère expérience radiochimique $\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$

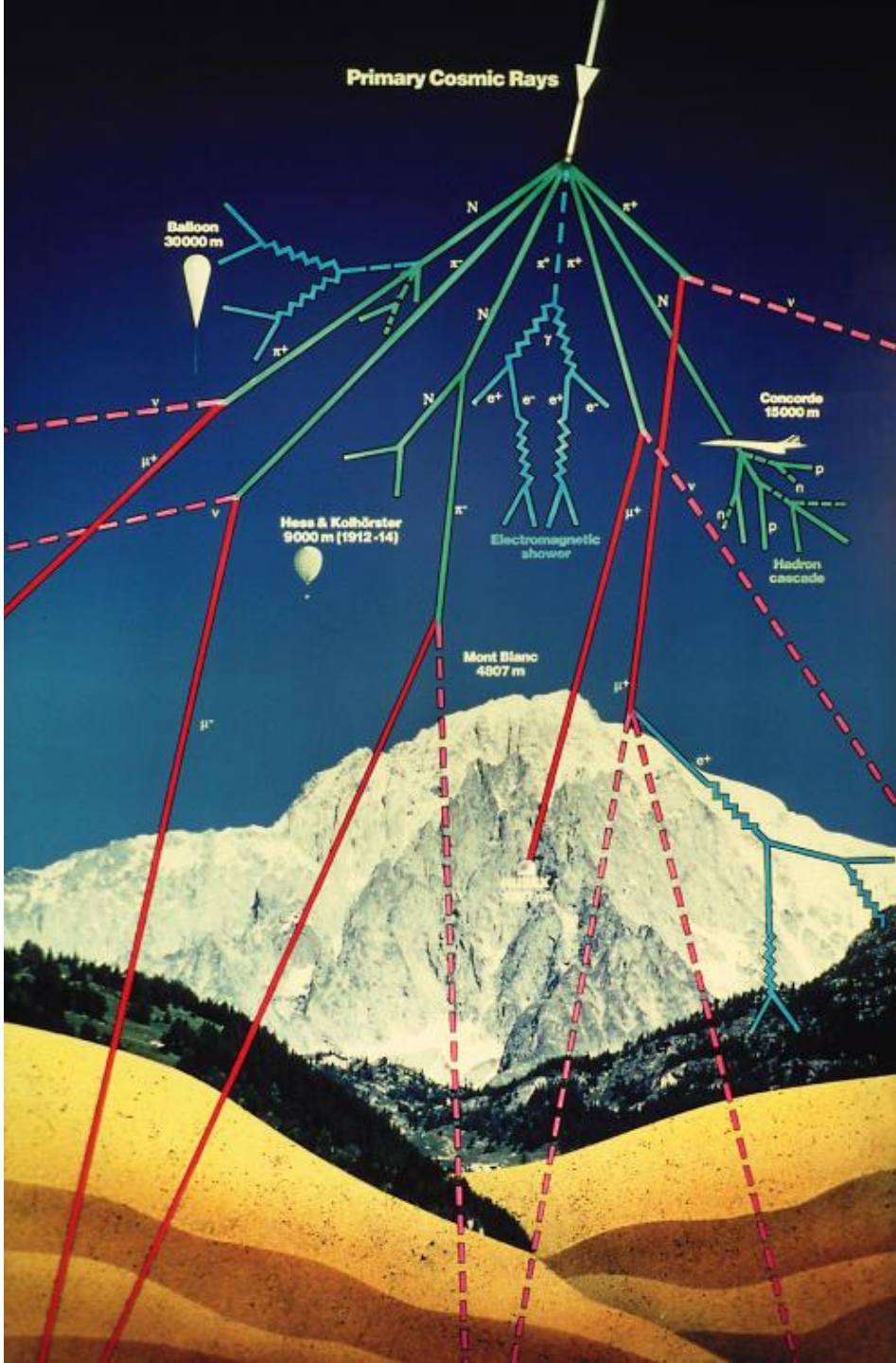


${}^{37}\text{Ar}$
Période de 35 j
Capture électronique

Quelques atomes de ${}^{37}\text{Ar}$
produits/mois pour
 $2 \cdot 10^{29}$ atomes de ${}^{37}\text{Cl}$

Les neutrinos solaires





En surface:
10 000 000 de rayonnements cosmiques
 par m² et par jour

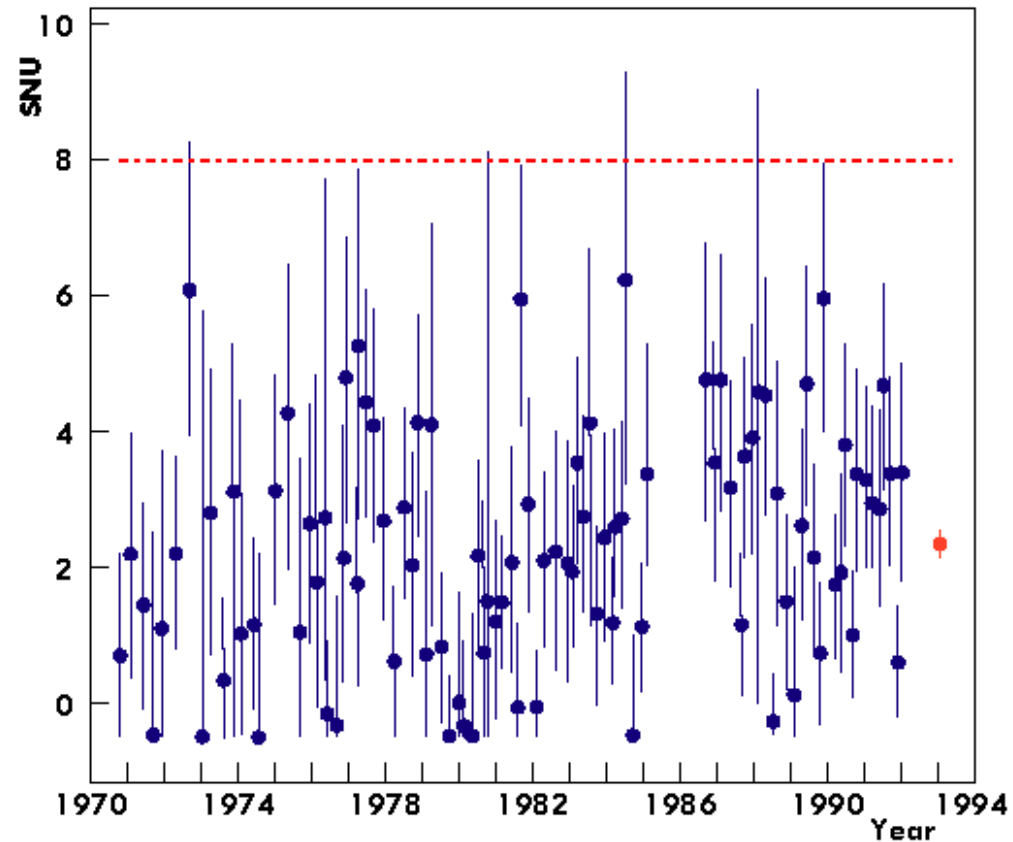


© terra-canada.com



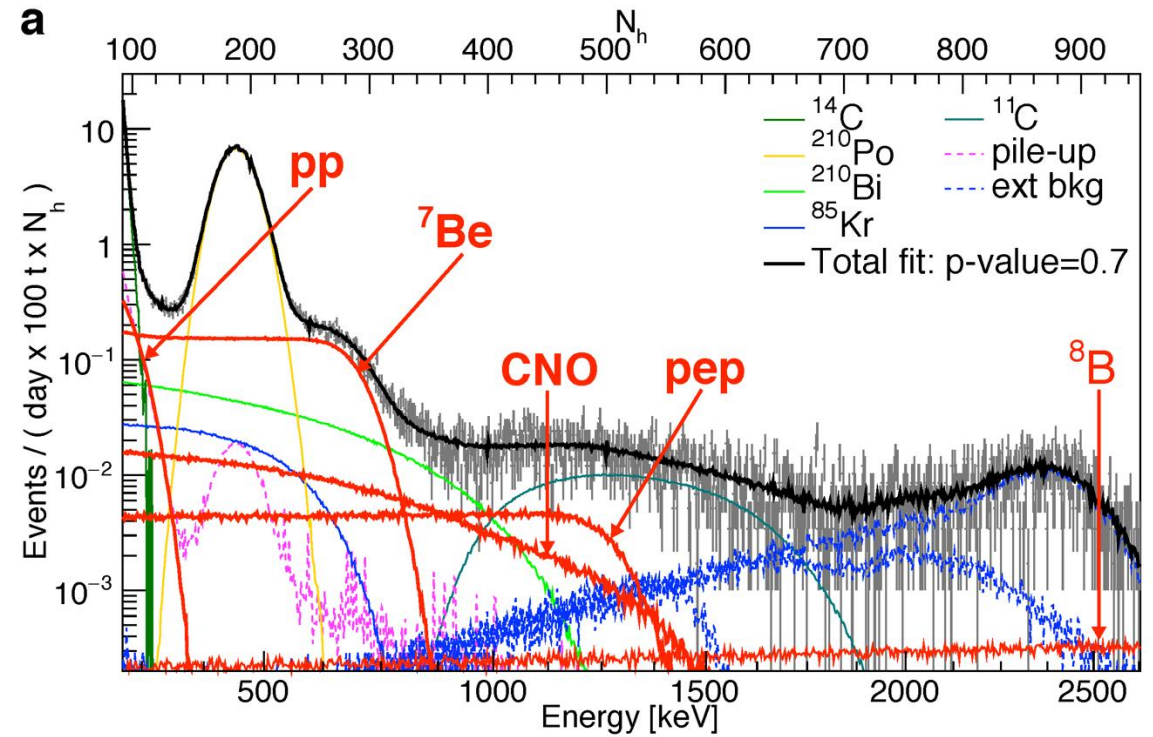
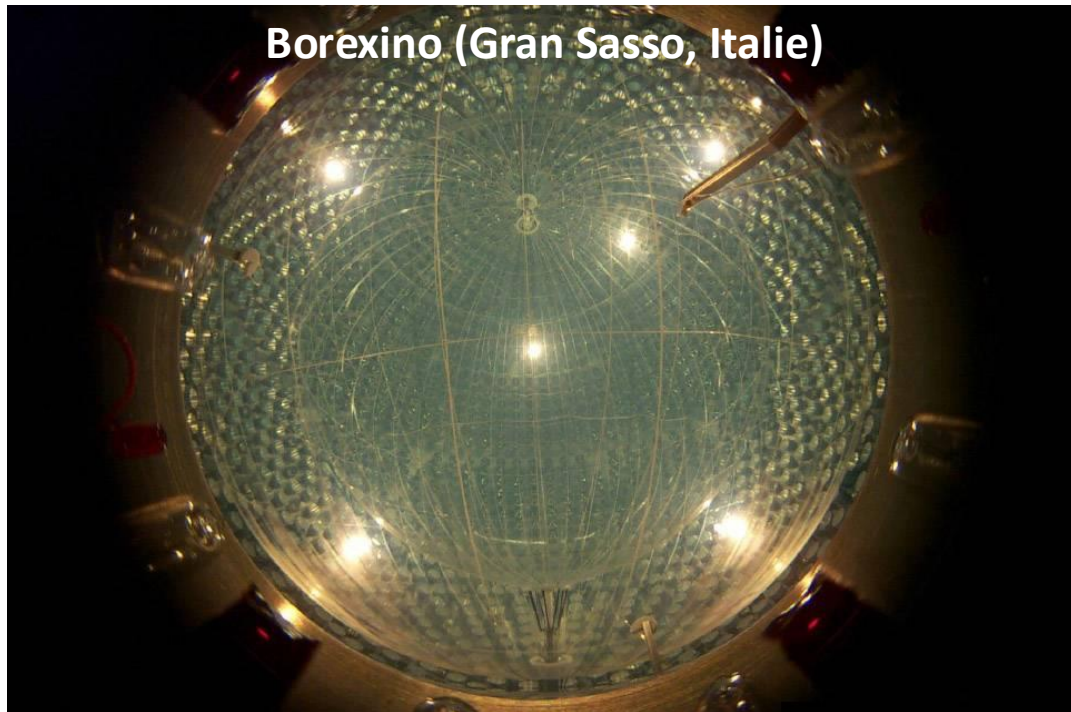
Sous la montagne au LSM (- 1800 m):
4 rayonnements cosmiques par m² et par jour

Les neutrinos solaires



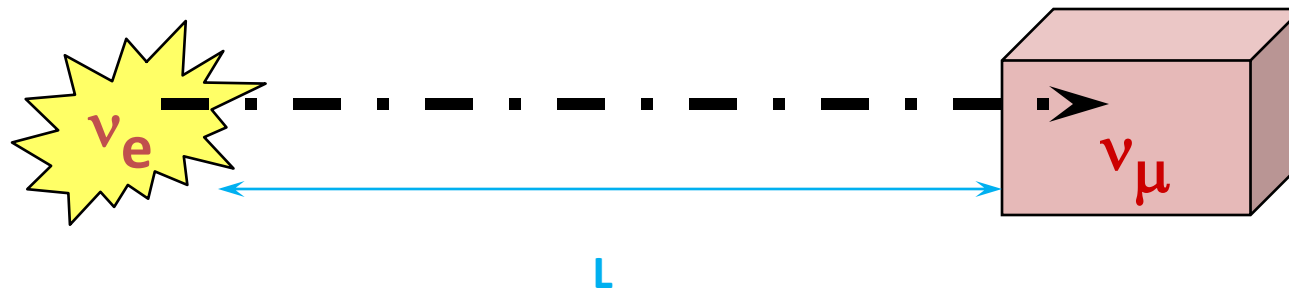
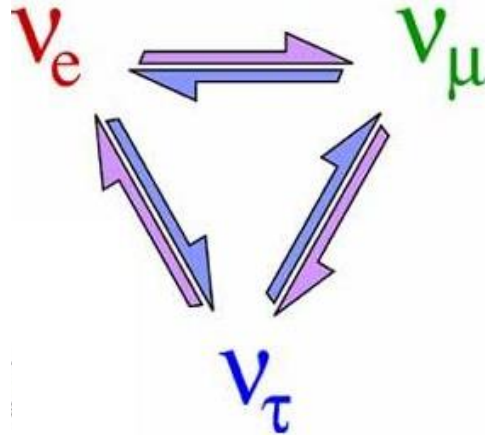
Il manque 75% des neutrinos !!!!

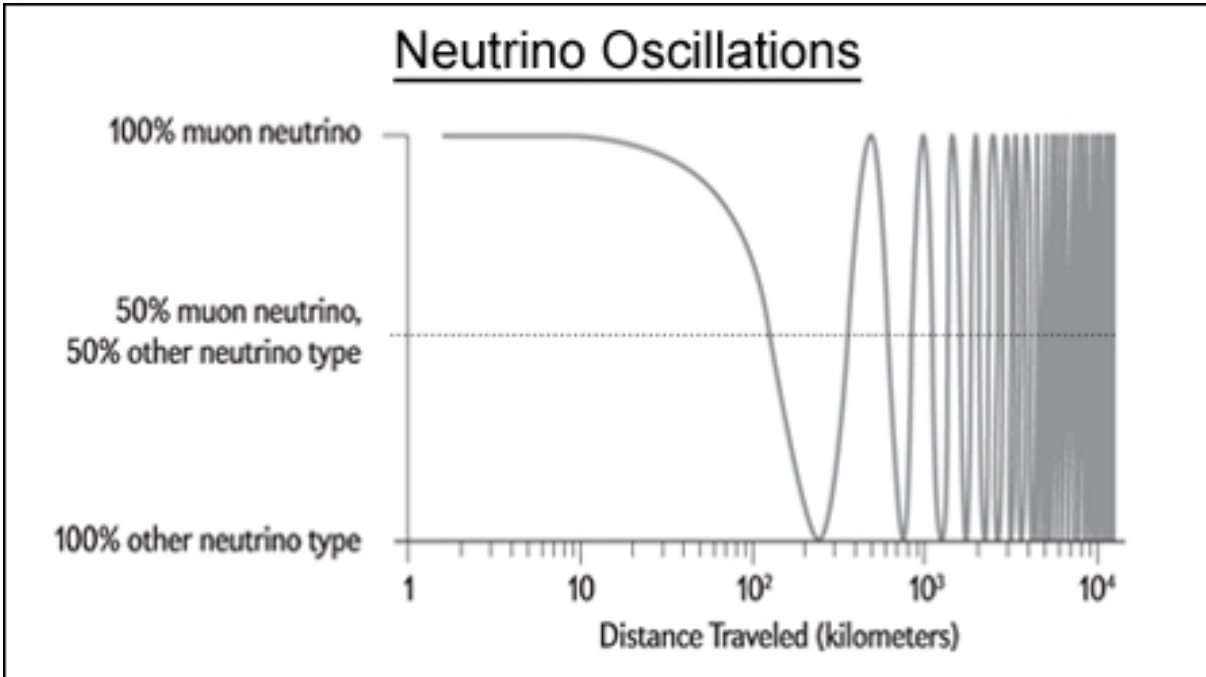
Confirmé par d'autres expériences radiochimiques dans les années 90





1957: Bruno Pontecorvo prédit l'oscillation des neutrinos





Neutrinos de « base »: ν_1 ν_2 ν_3

$$\nu_e = \cos\theta\nu_1 + \sin\theta\nu_2$$

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

$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \left[\frac{1,27 \cdot (m^2_1 - m^2_2) \cdot L}{E_\nu} \right]$$

Les oscillations n'existent que si le neutrino à une masse !

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$C_{ij} = \cos\theta_{ij}$$

$$S_{ij} = \sin\theta_{ij}$$

Neutrinos

Atmosphériques

Accélérateurs

Neutrinos

Réacteurs

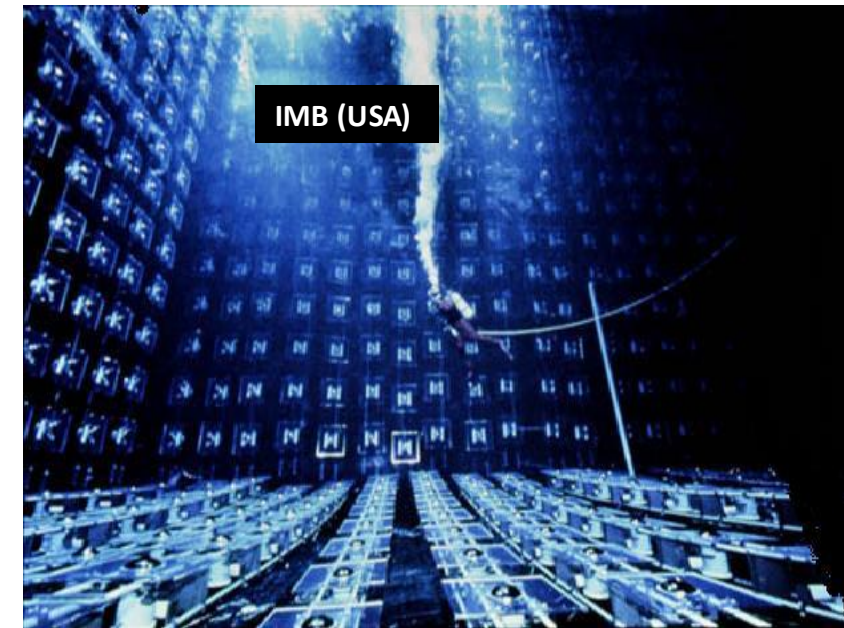
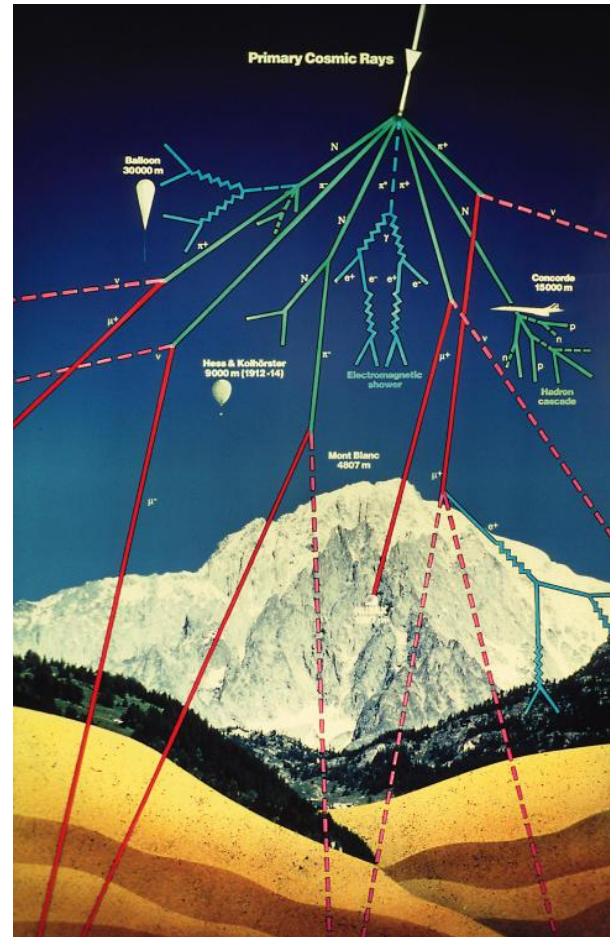
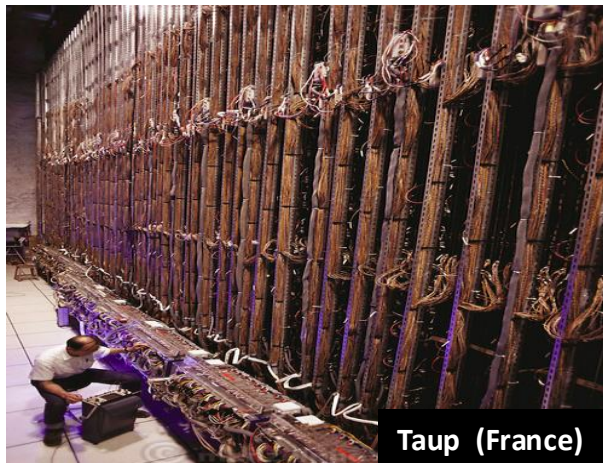
Accélérateurs

Neutrinos

Solaires

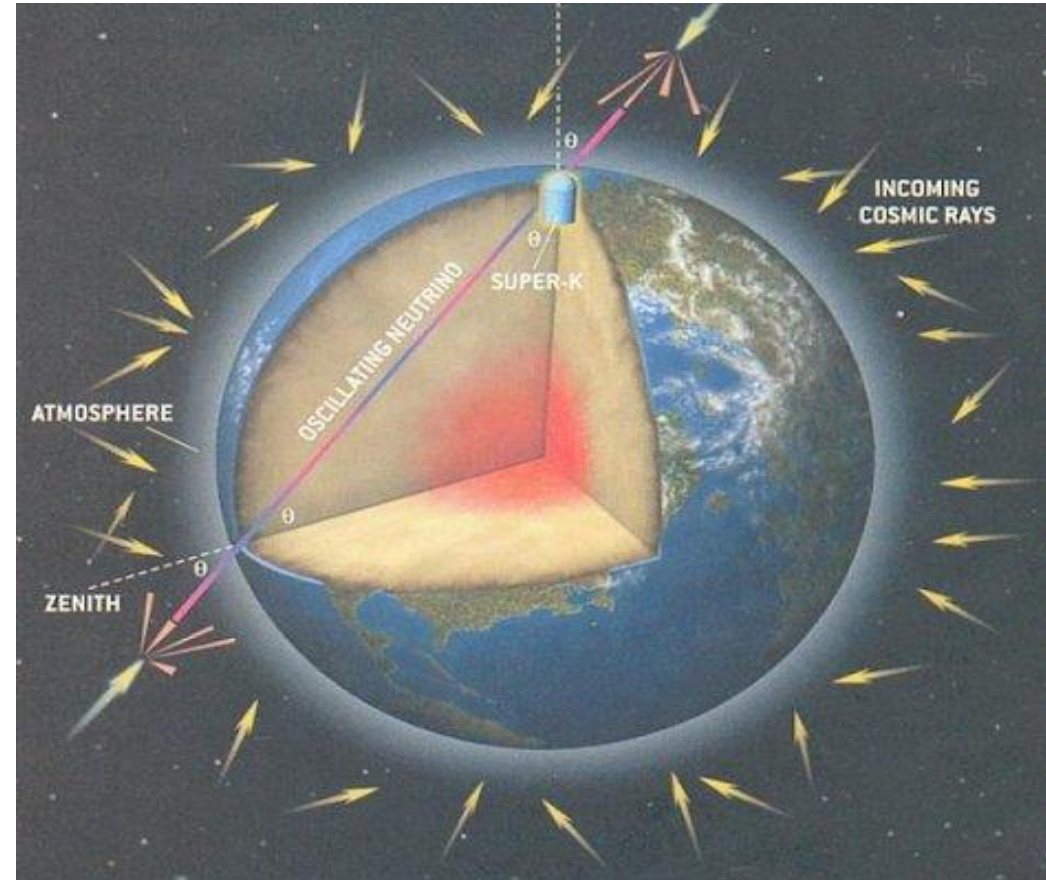
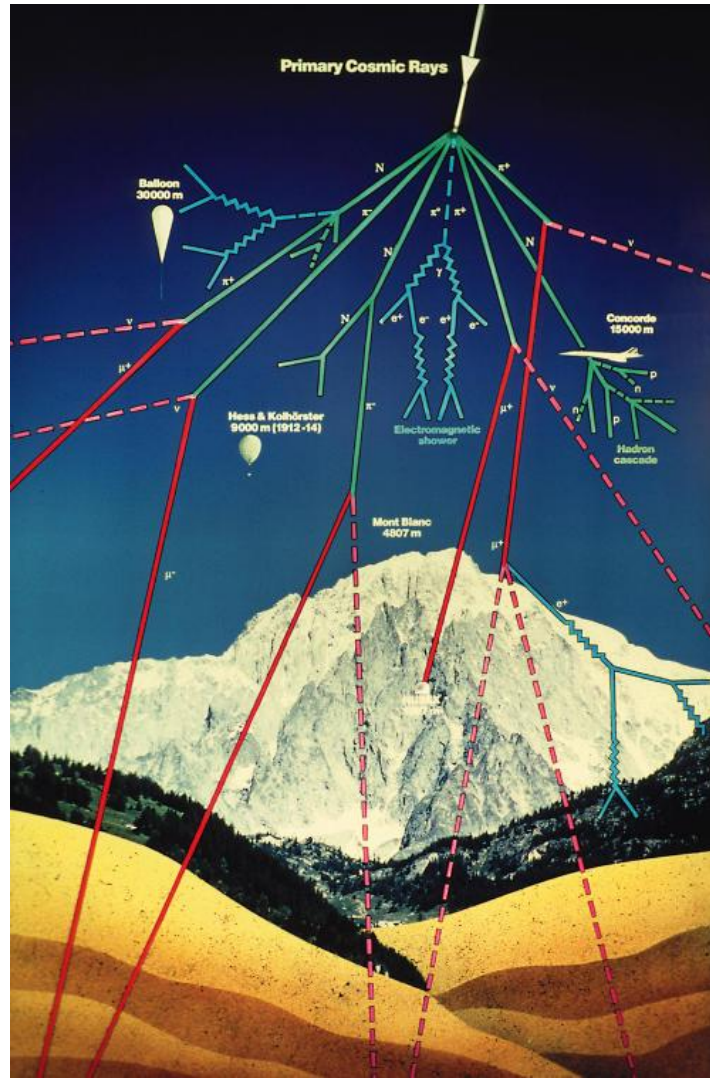
Réacteurs

Recherche de la décroissance du proton (1980-....)



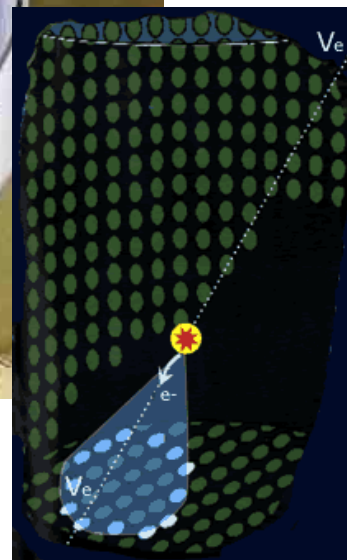
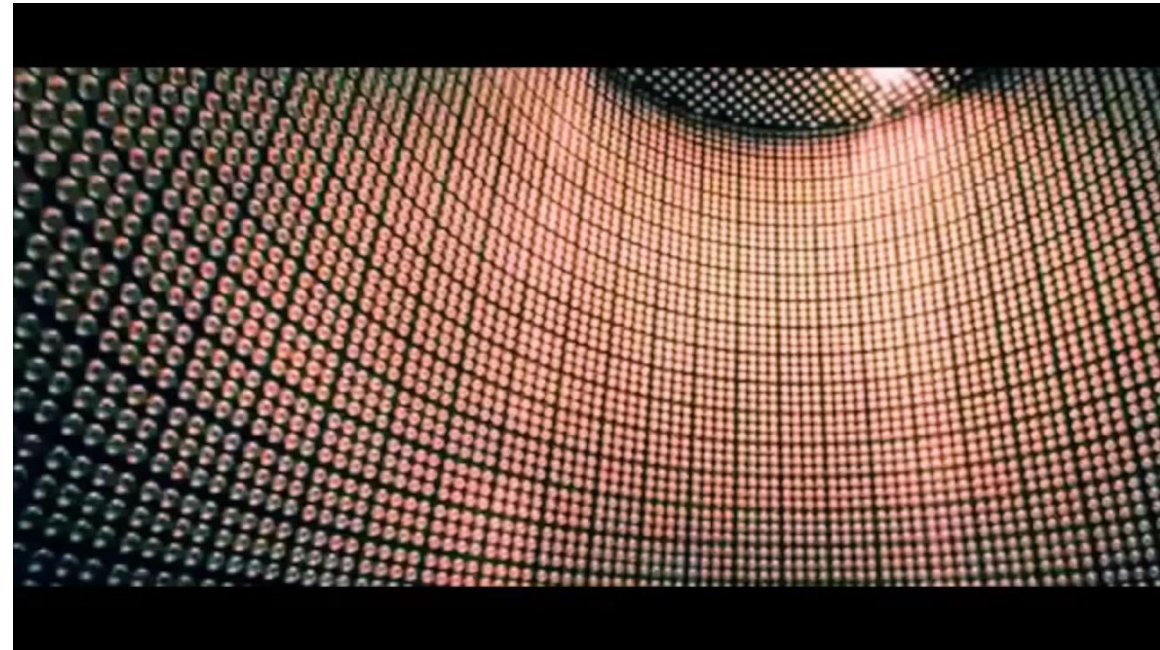
Les neutrinos atmosphériques sont une source de bruit de fond

L'oscillation des neutrinos



Il manque 40 % de neutrinos par rapport aux prédictions

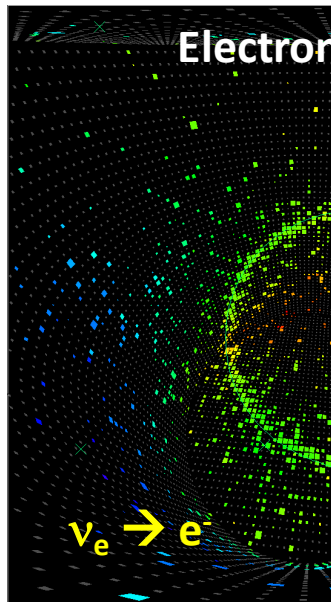
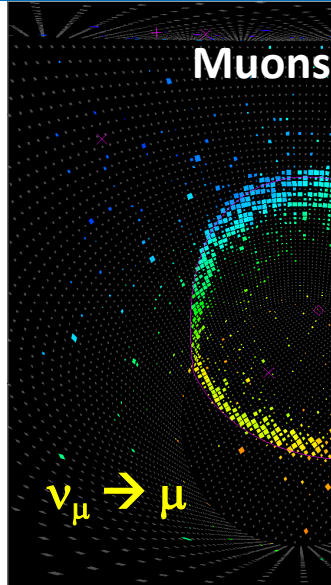
L'oscillation des neutrinos



50 000 tonnes d'eau
39 m de diamètre
52 m de haut
12 000 photomultiplicateurs

Neutrino atmosphériques
Neutrinos solaires
Neutrinos de Supernovae
Durée de vie du proton

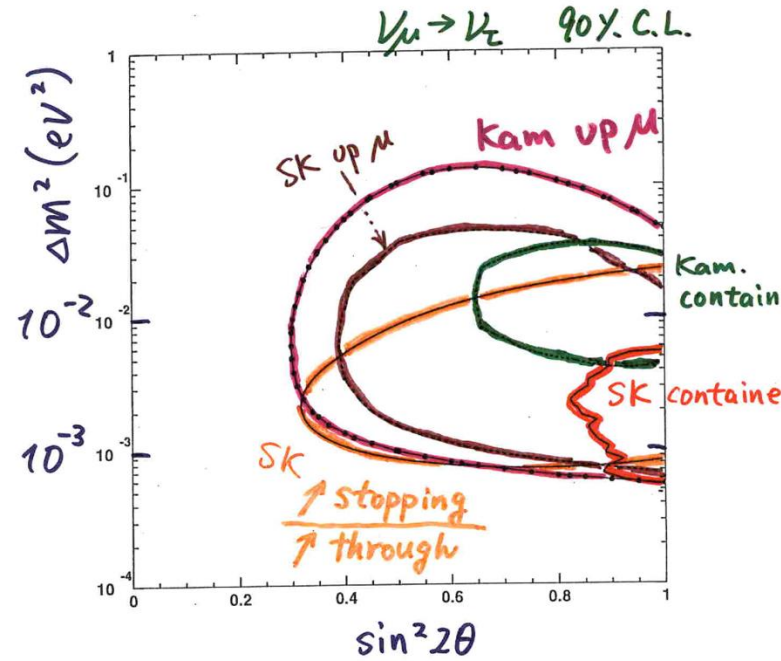
L'oscillation des neutrinos



Summary

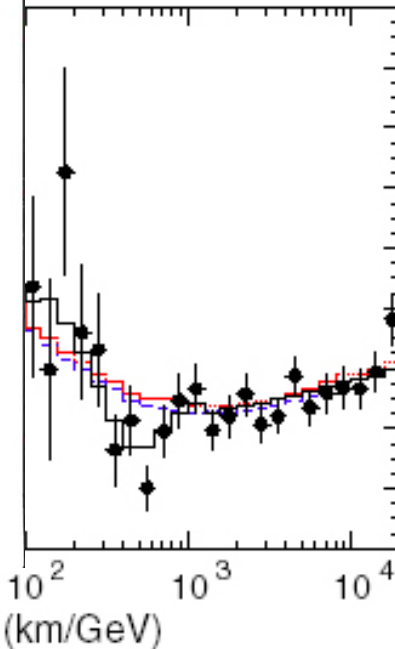
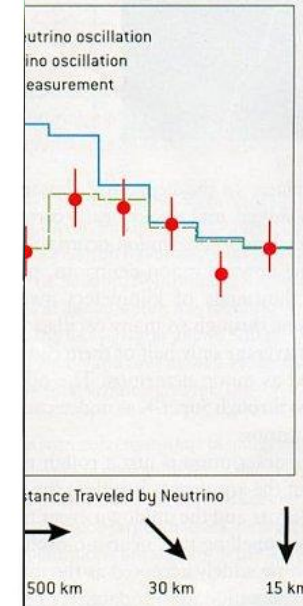
1998

Evidence for ν_μ oscillations

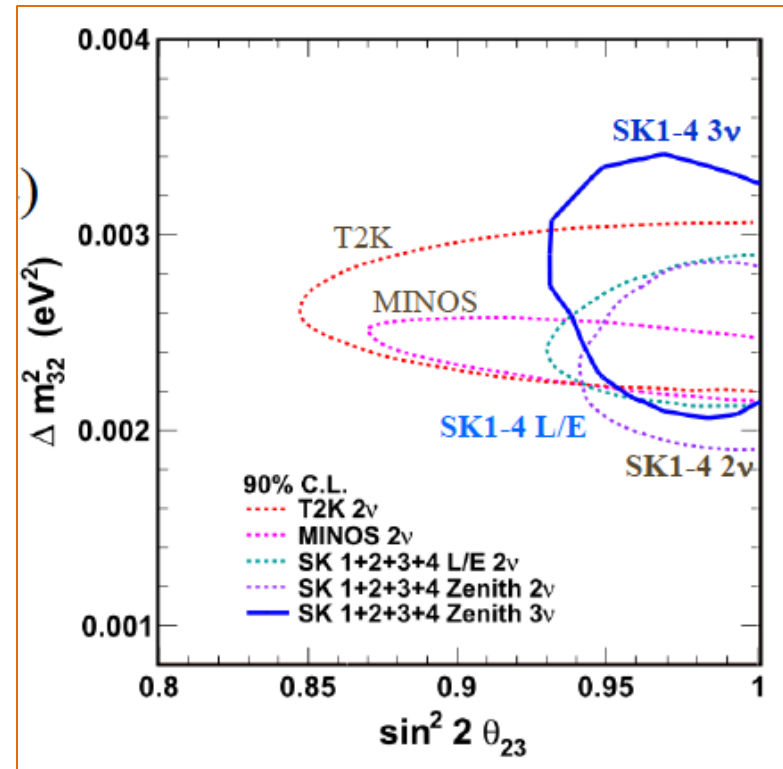
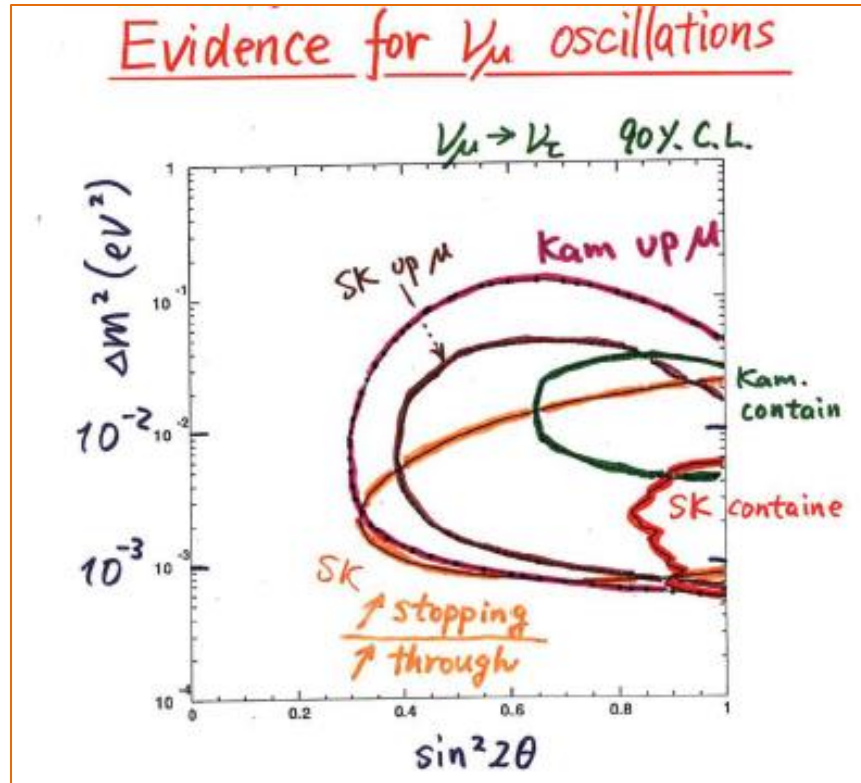


- $$\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$$

(• $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_s$?)

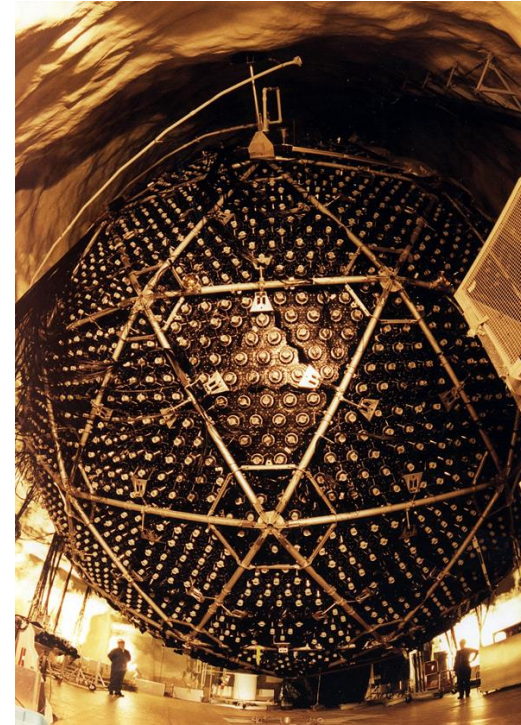
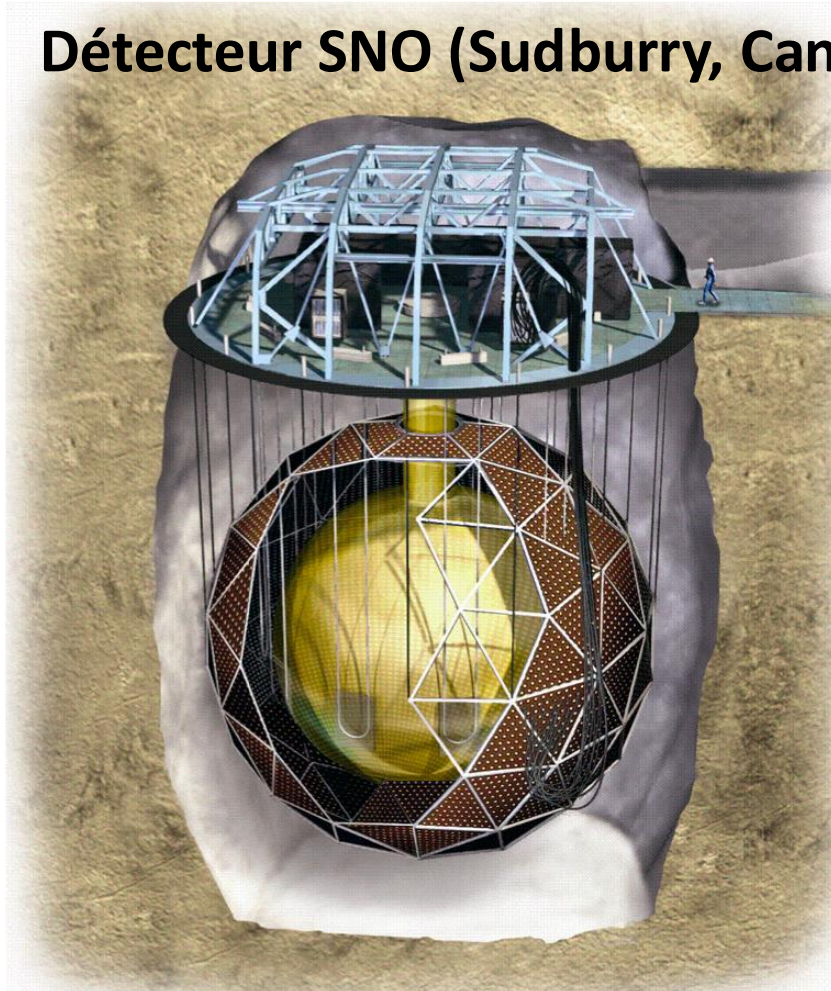


L'oscillation des neutrinos



$$P_{\text{oscillation}} \sim \sin^2 2\theta \sin^2(\Delta m_{12} L/E)$$

Détecteur SNO (Sudbury, Canada)



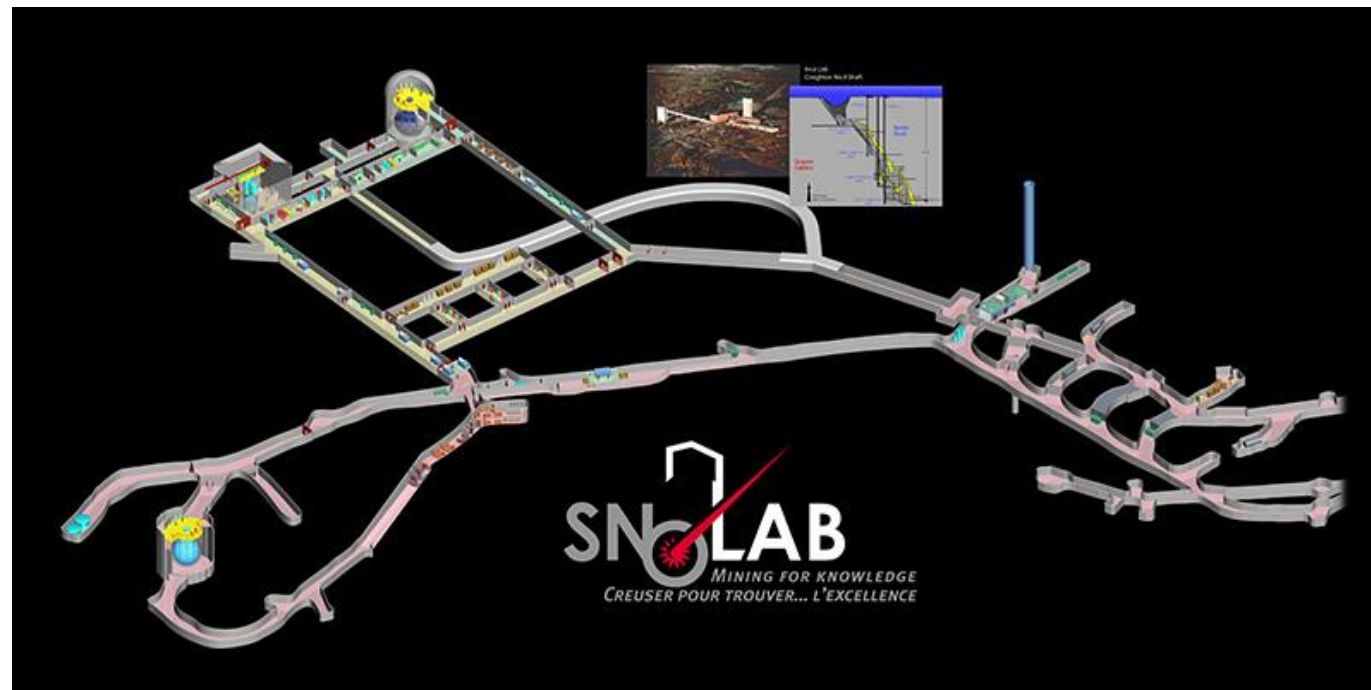
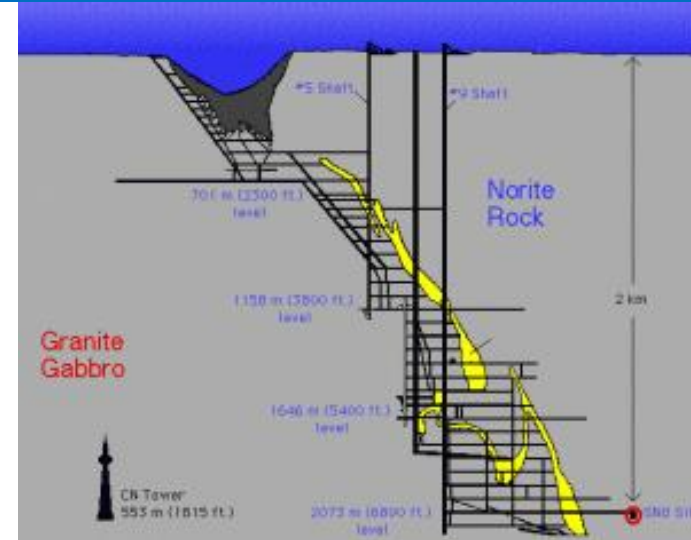
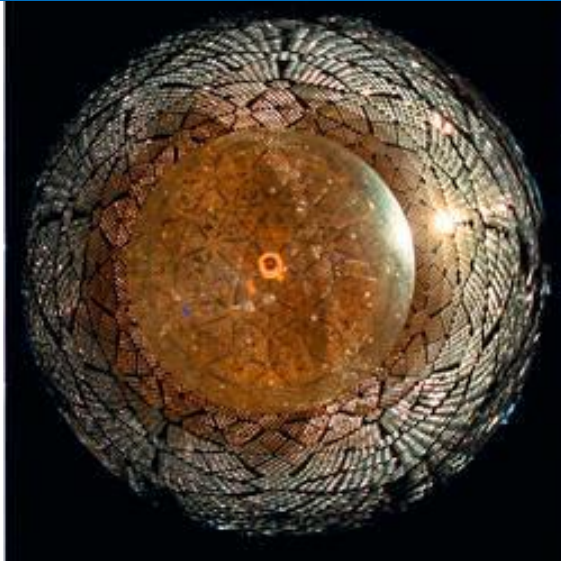
12 m de diamètre

1000 tonnes d'eau lourde (D_2O)

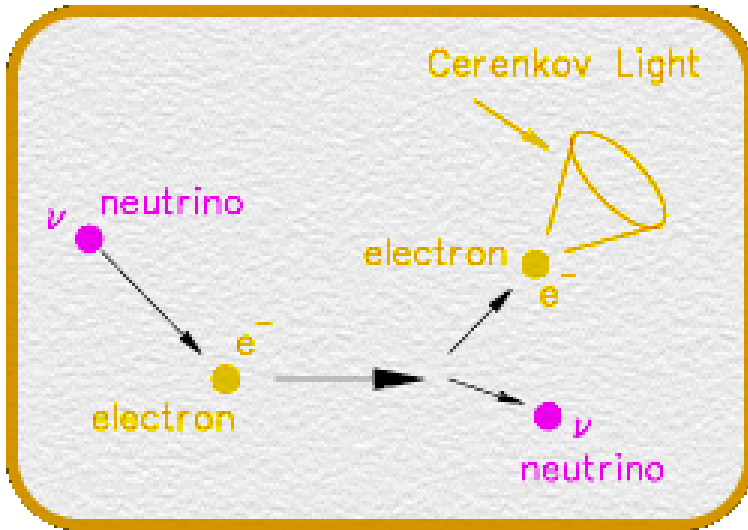
10 000 Photomultiplicateurs

Mesure des neutrinos solaires: flux de ν_e et flux total

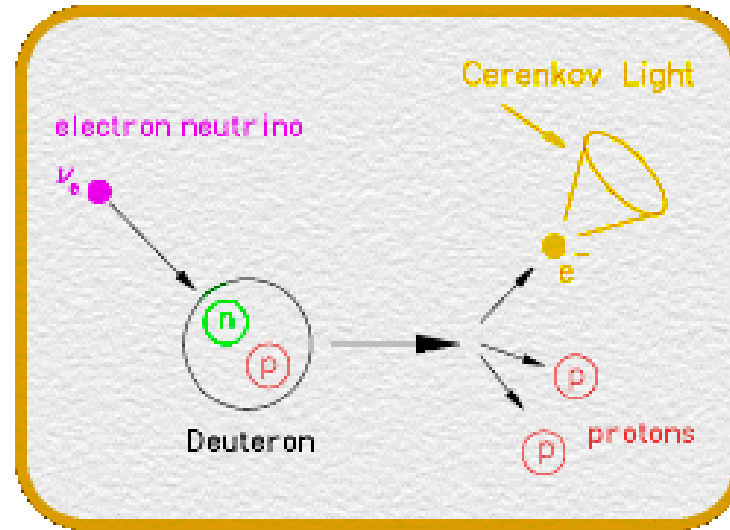
L'oscillation des neutrinos



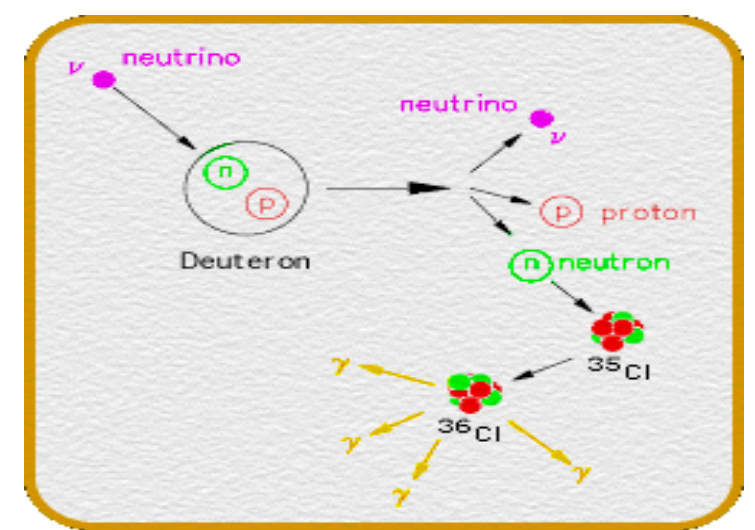
L'oscillation des neutrinos



Sensible à tous les types de neutrinos mais 6 fois plus sensible pour les ν_e

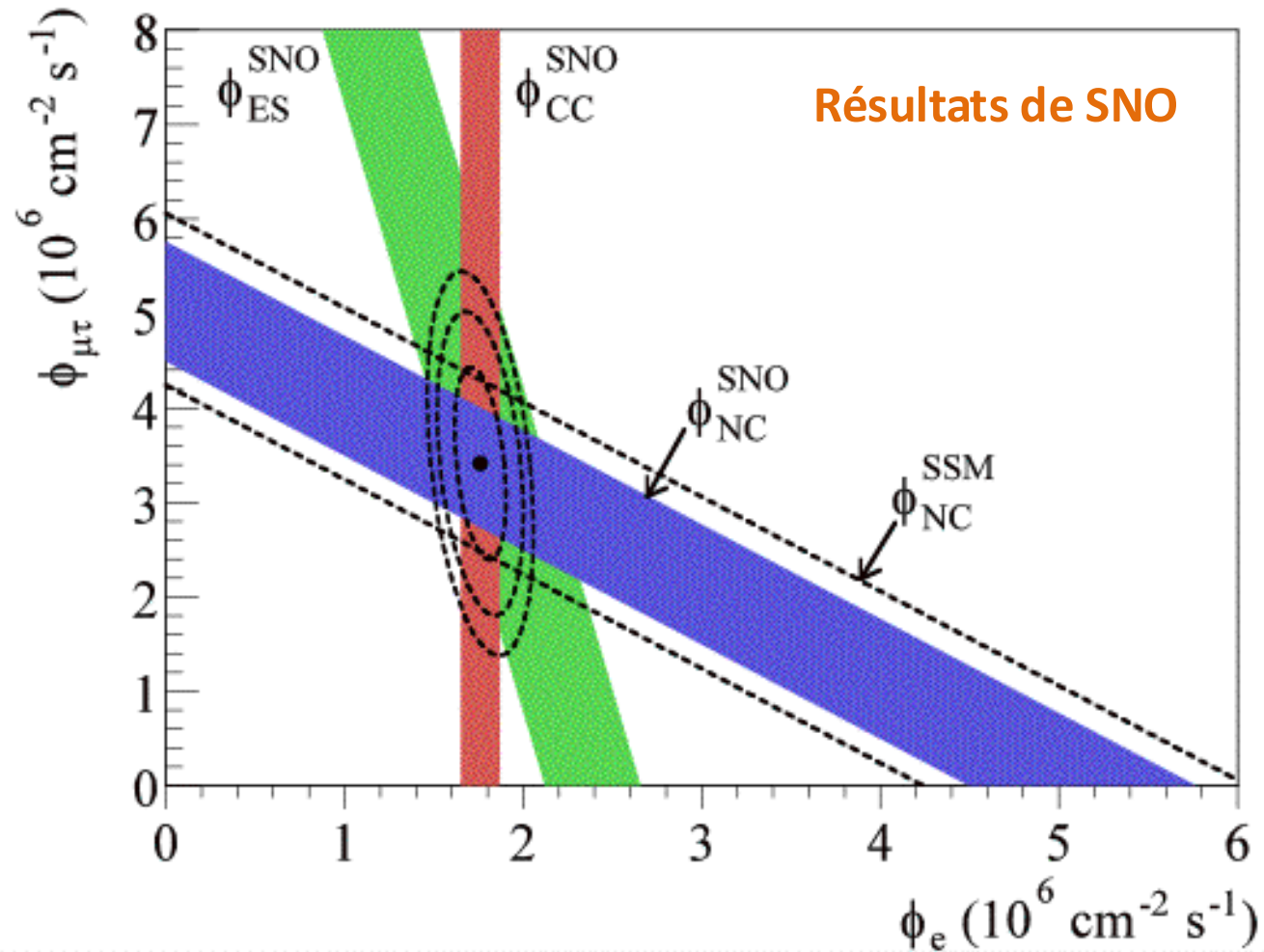


Sensible **uniquement** aux ν_e



Sensible aux ν_e , ν_μ , et ν_τ

L'oscillation des neutrinos



Le flux total mesuré est bien le flux total prédit et il apparait des neutrinos ν_μ et ν_τ

The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



Photo: K. MacFarlane,
Queen's University
/SNOLAB

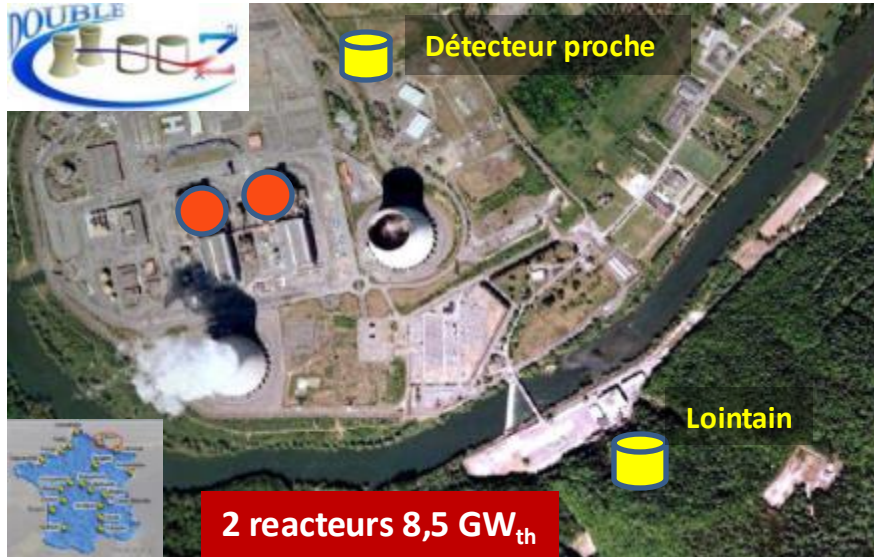
Arthur B. McDonald

Prize share: 1/2

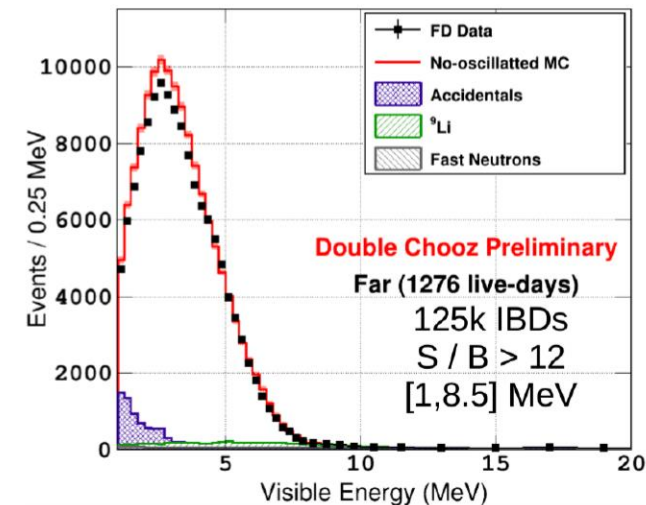
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

L'oscillation des neutrinos

Expérience Double Chooz (France): mesure de l'angle Θ_{13}

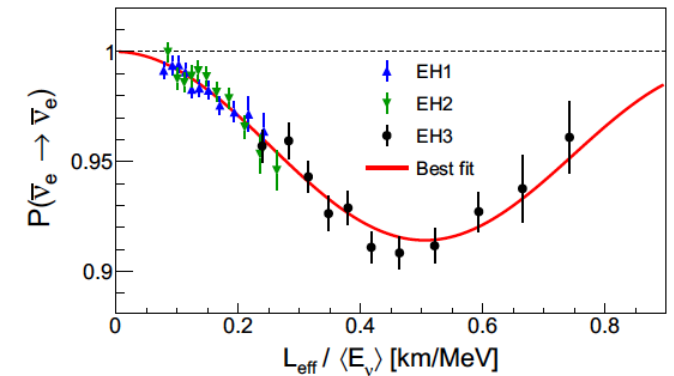
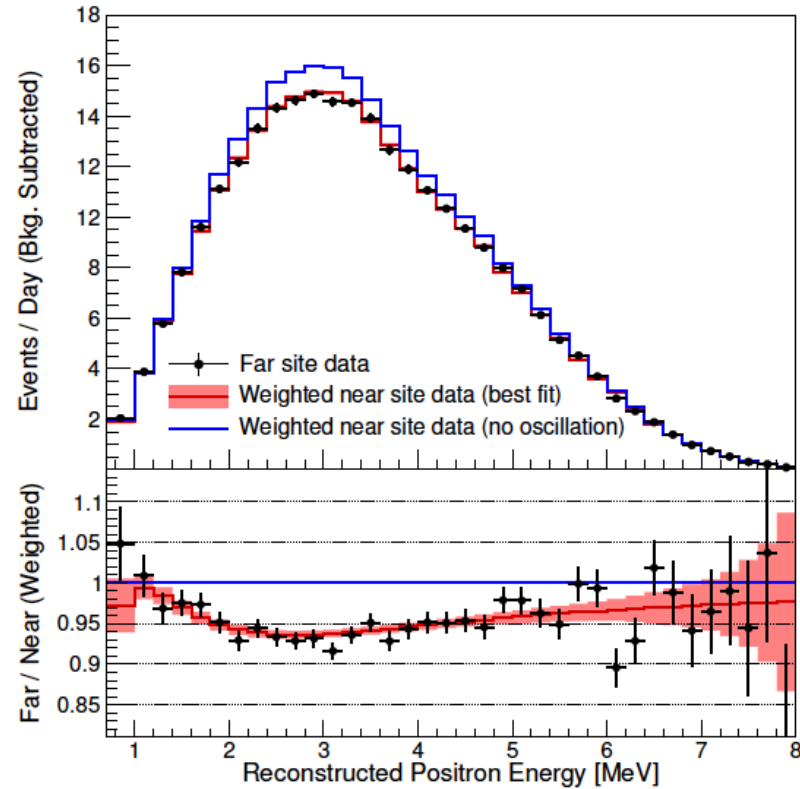
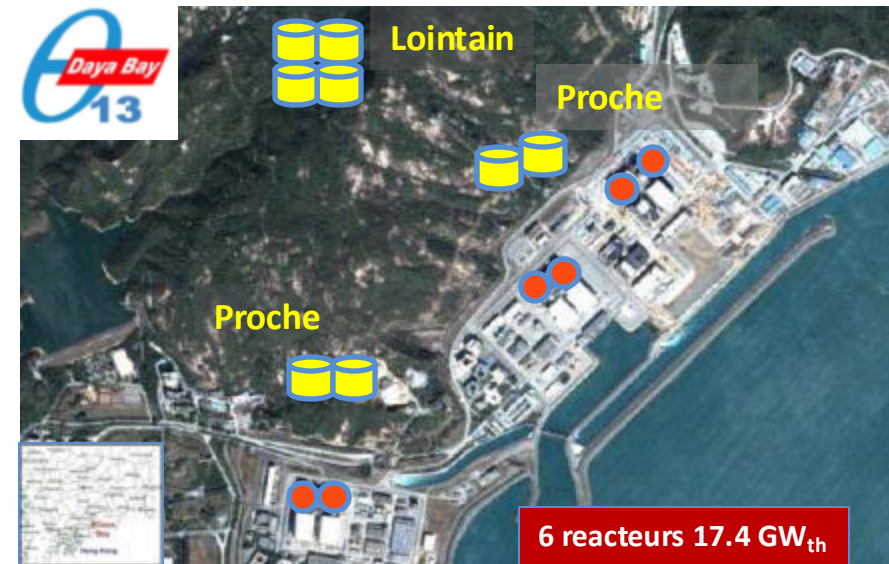


parameter	relative error (%)		
reaction cross section	1.9%	→	~0.1%
number of protons	0.8%	→	<0.5%
detection efficiency	1.5%	→	<0.5%
reactor power	0.7%	→	~0.1%
energy released per fission	0.6%	→	~0.0%
combined	2.7%		



L'oscillation des neutrinos

Expérience Daya Bay (Chine) : mesure de l'angle θ_{13}



$$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$$

Des mesures de précision

Neutrinos solaires et réacteurs

Neutrinos atmosphériques et accélérateurs

Neutrinos réacteurs

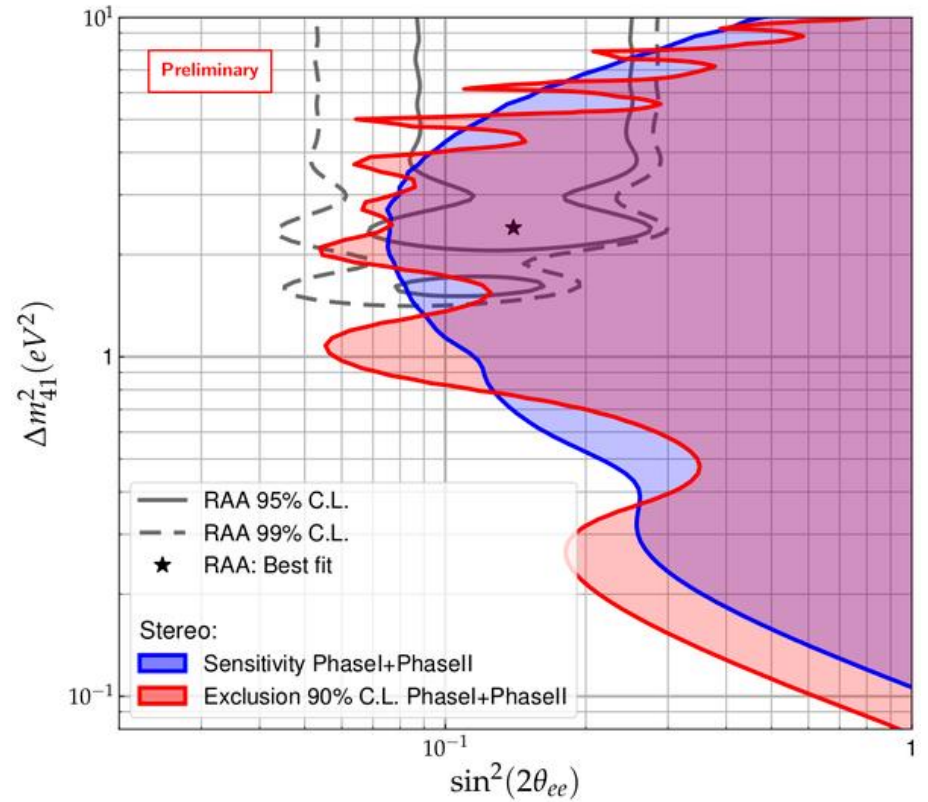
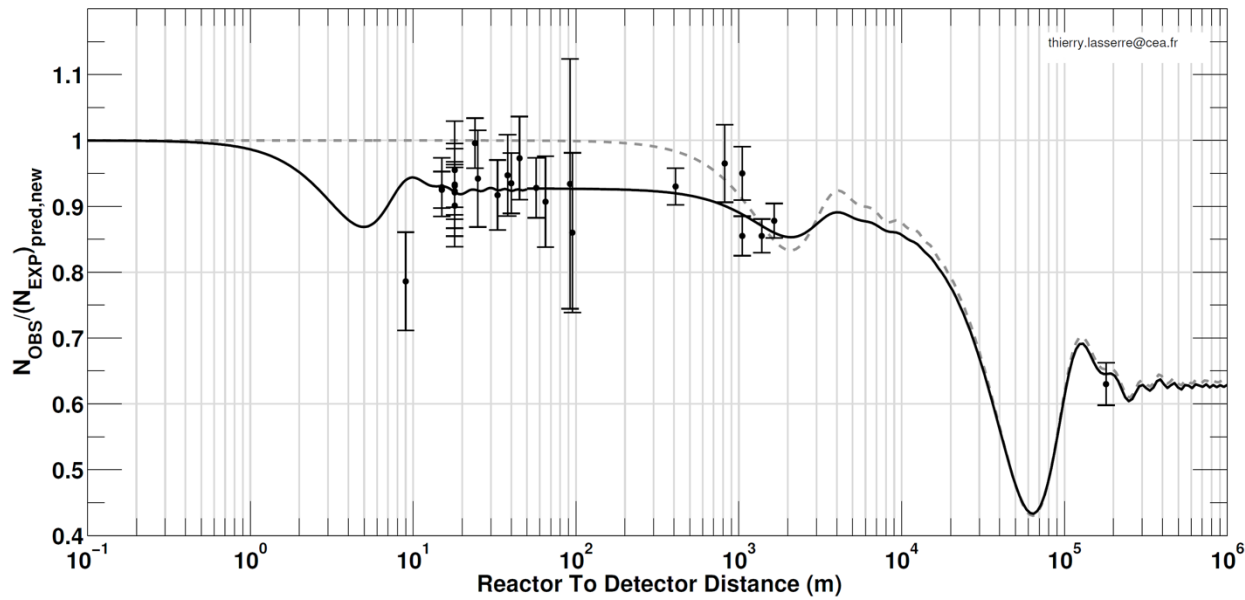
Neutrinos solaires et réacteurs

Neutrinos atmosphériques et accélérateurs

	Ref. [188] w/o SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2 \theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	2.75 \rightarrow 3.50
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	31.61 \rightarrow 36.27
$\frac{\sin^2 \theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	4.27 \rightarrow 6.09
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	40.8 \rightarrow 51.3
$\frac{\sin^2 \theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	2.046 \rightarrow 2.440
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	8.22 \rightarrow 8.99
$\delta_{CP}/^\circ$	222^{+38}_{-28}	141 \rightarrow 370
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.39^{+0.21}_{-0.20}$	6.79 \rightarrow 8.01
$\frac{\Delta m_{32}^2}{10^{-3} \text{ eV}^2}$	$2.449^{+0.032}_{-0.030}$	2.358 \rightarrow 2.544

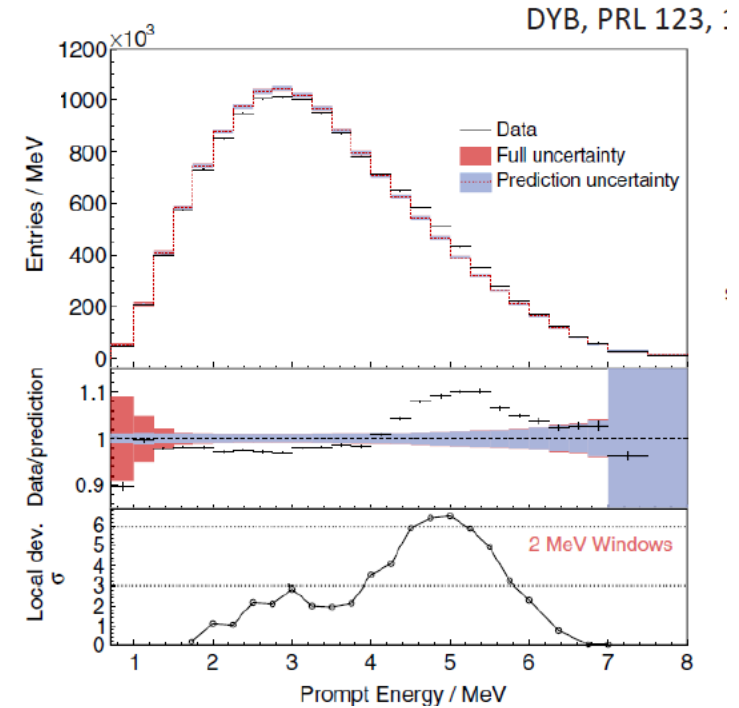
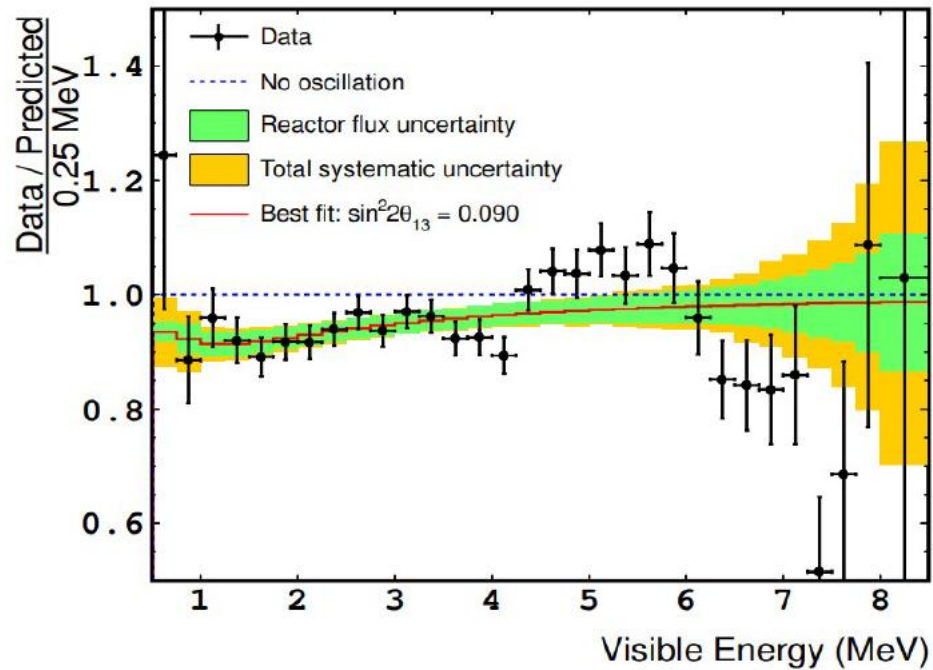
©Particle data group

Une anomalie ? Existence d'un 4eme neutrino stérile ?



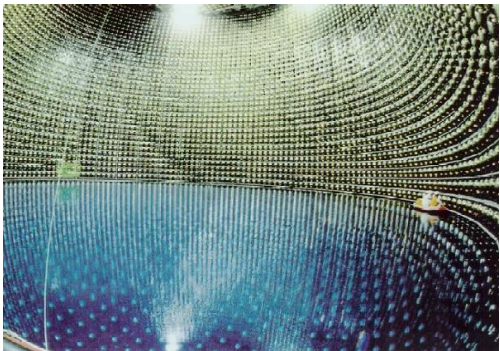
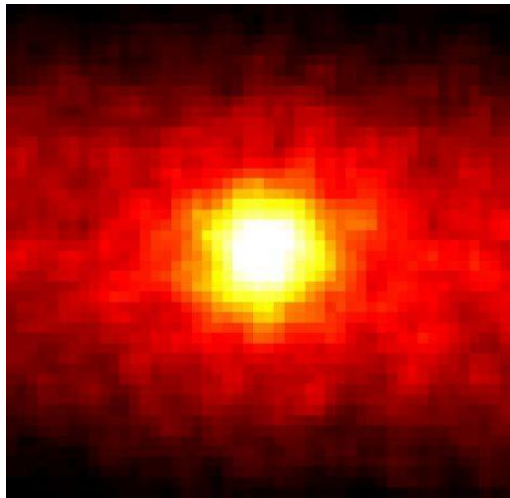
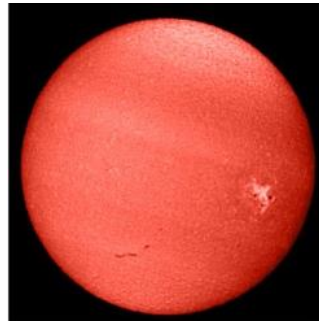
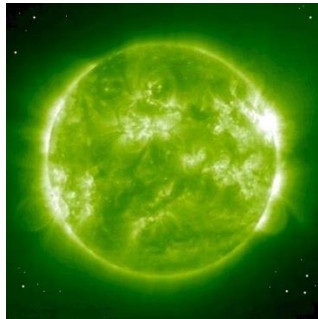
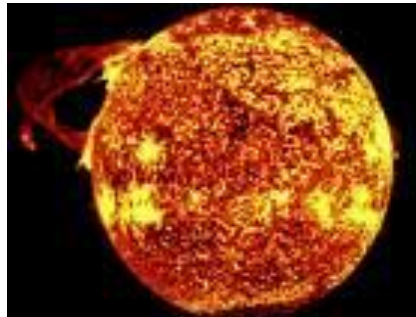
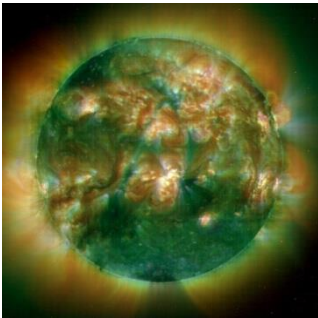
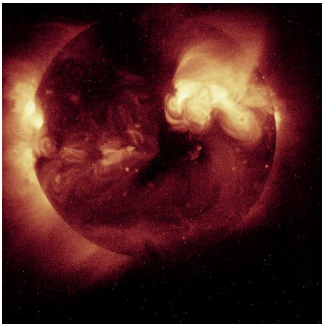
Résultats rejettent l'hypothèse d'un neutrino stérile

Distorsion du spectre des neutrino ? Nouvelle physique ?



Semble lié à la composition du combustible du réacteur
Des données nucléaires sont manquantes

Astronomie neutrinos



Temps de pose : **365 jours**
1000 m sous terre
Poids de l'appareil: 50 000 tonne d'eau
10 000 pixels

1987: détection des neutrinos venant de SN1987 A

99 % de l'énergie d'une supernovae emportée par les neutrinos

Vues par 3 détecteurs dans le monde, Quelques événements en 10 s

Que reste-il à mesurer ou découvrir sur le neutrino ?

Nature ?

Masse absolue ?

Hiérarchie de masse ?

Violation de CP ?

Comment il acquière sa masse ?

Est-il composite ?

Moment magnétique ?

Moment électrique ?

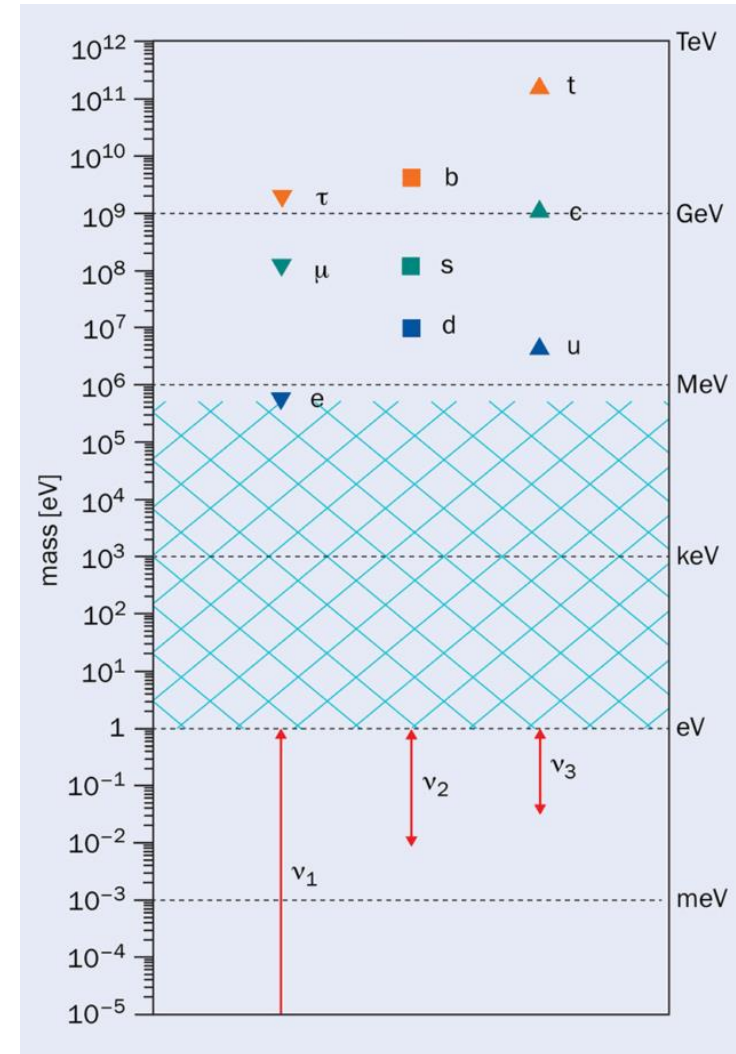
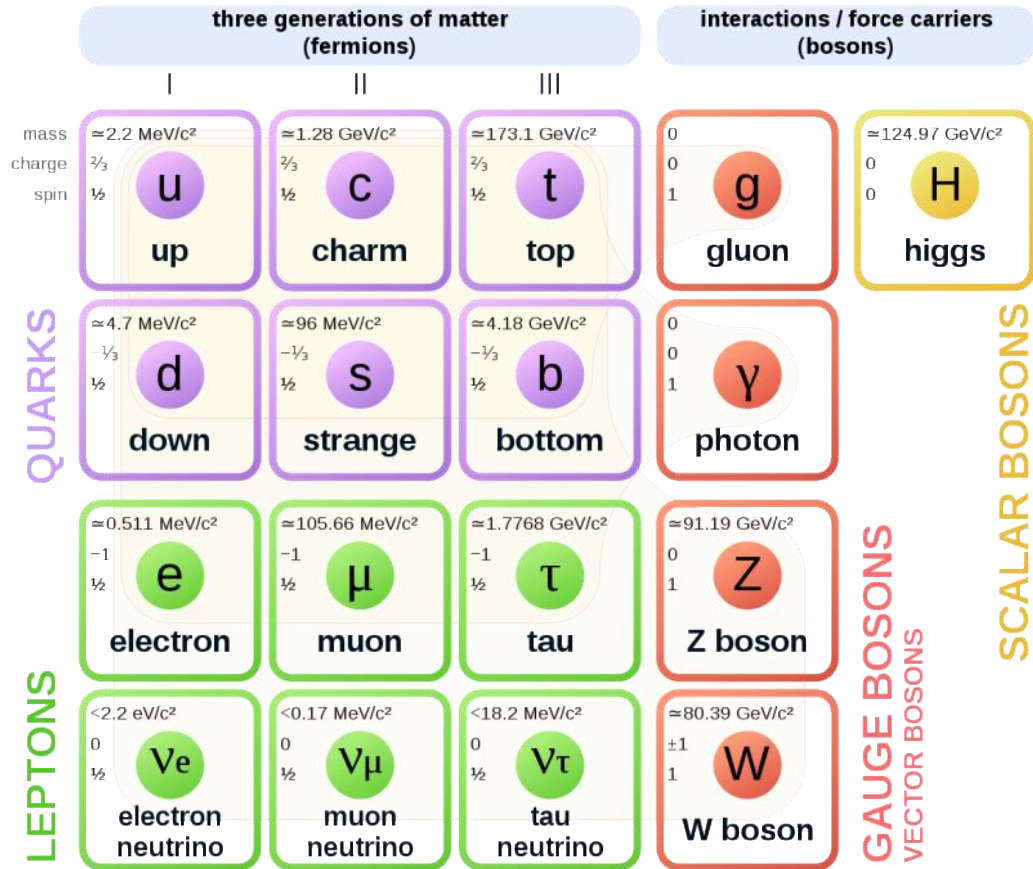
Courant droit de l'interaction faible ?

Neutrinos stériles ?

.....

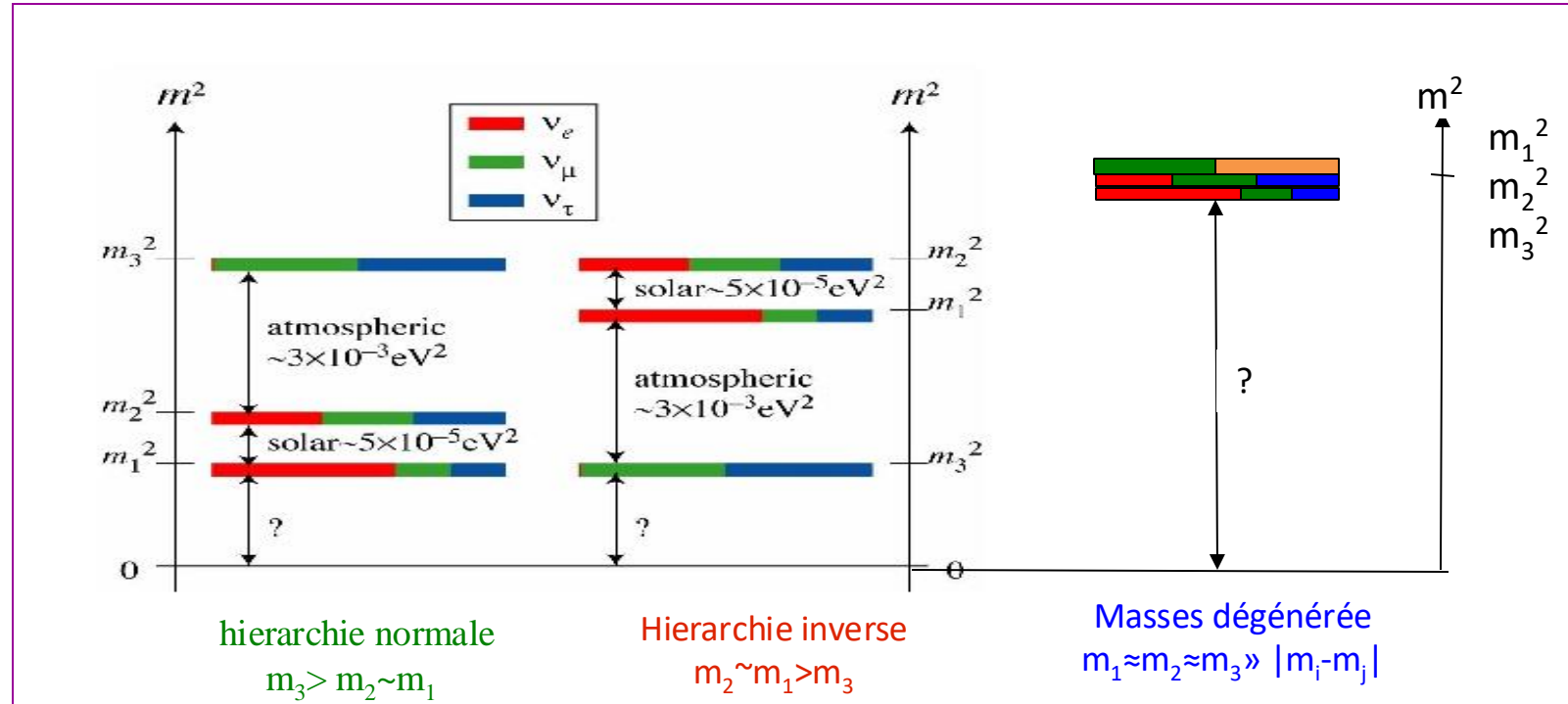
Masse des neutrinos : seule preuve aujourd'hui de physique au delà du Modèle Standard !!!!

Standard Model of Elementary Particles

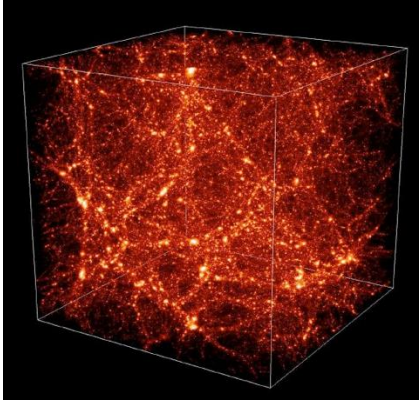


Crédit : A. de Gouvêa

Hiérarchie de masse ?



$$P_{\nu_e \rightarrow \nu_\mu} = \sin^2 2\theta \sin^2 \left[\frac{1,27 \cdot (m_1^2 - m_2^2) \cdot L}{E_\nu} \right]$$

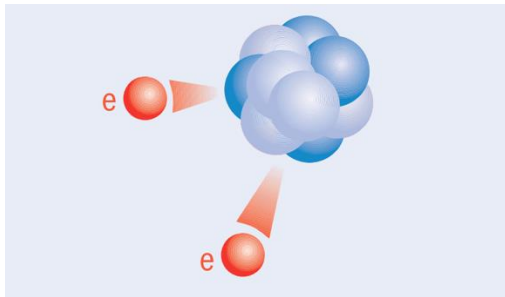
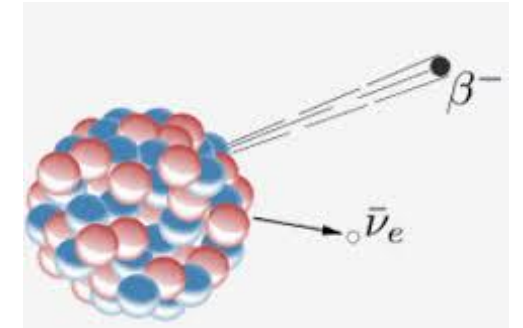


Etudes des structures à grande échelle

$$\Sigma m(\nu) < 0,09 \text{ eV}$$

Désintégration bêta

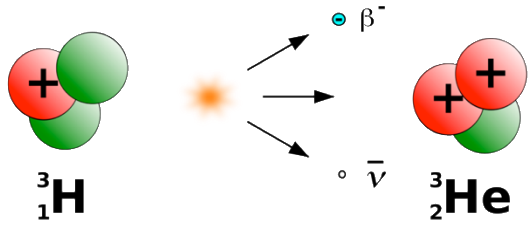
$$m(\nu_e) < 0,4 \text{ eV}$$



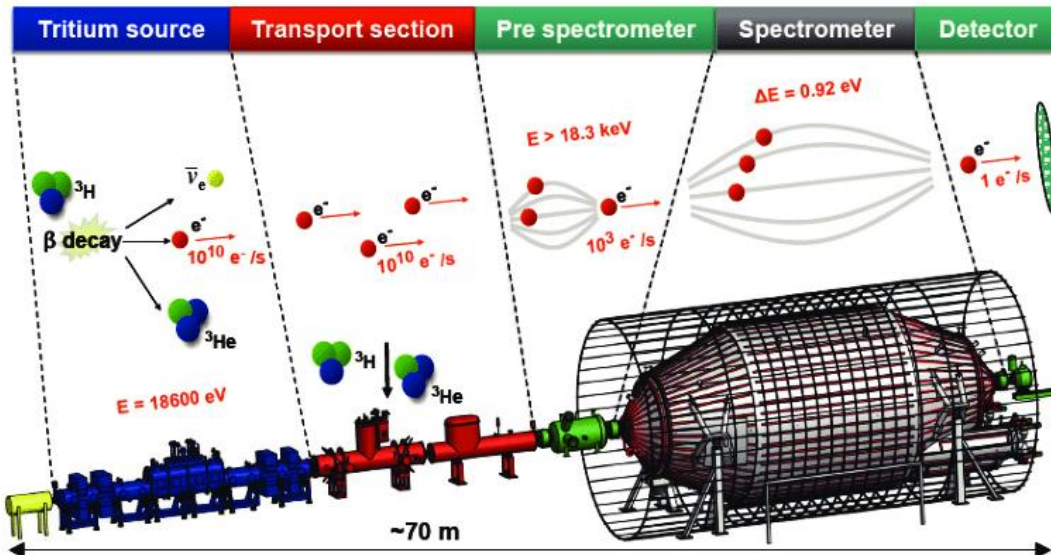
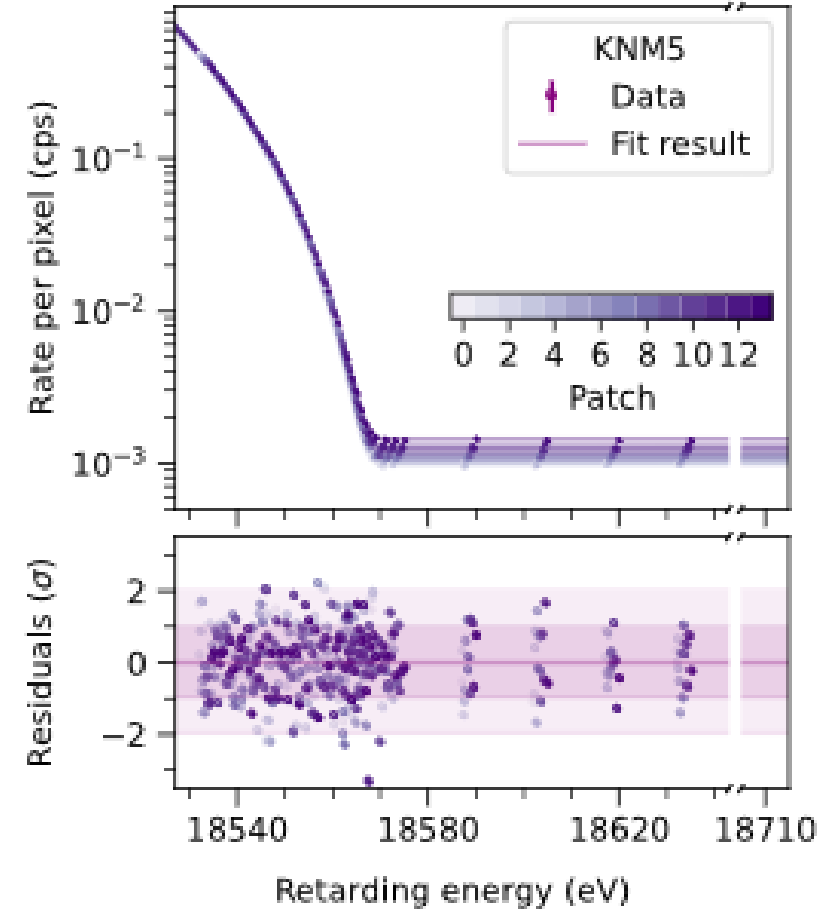
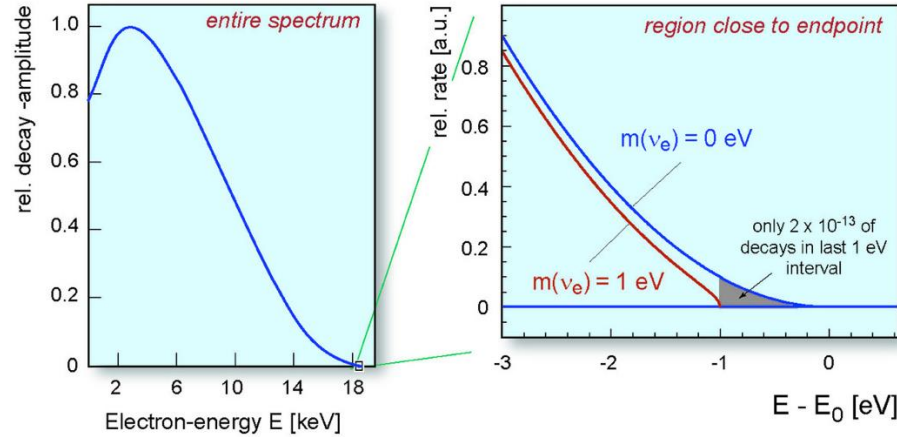
Double Désintégration bêta

$$\langle m \rangle < 0,02 - 0,2 \text{ eV}$$

Désintégration beta



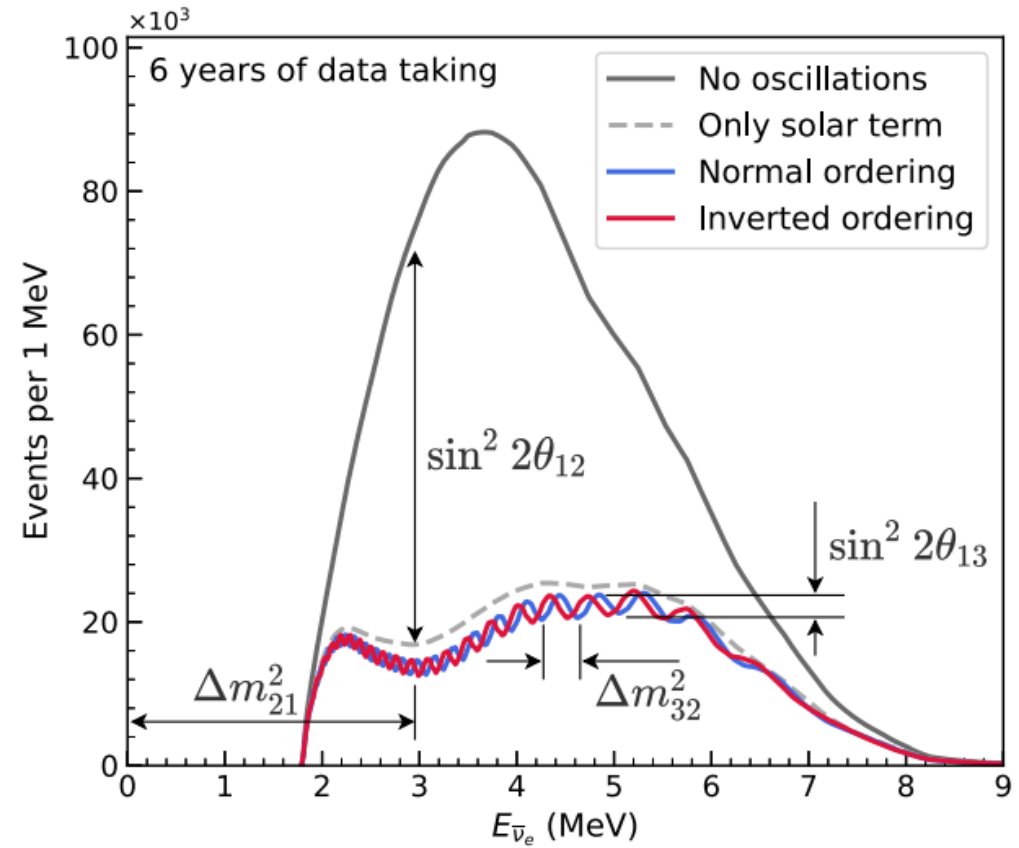
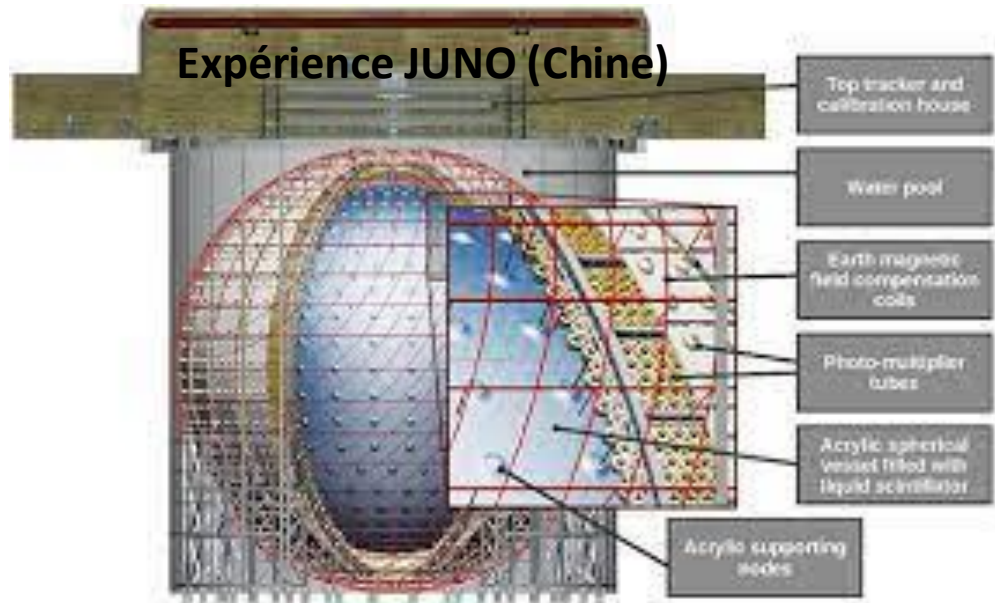
Expérience KATRIN (Karlsruhe, Allemagne)



$m_\nu < 0.45 \text{ eV}$ at 90 % CL

La masse des neutrinos

Expérience JUNO (Chine)



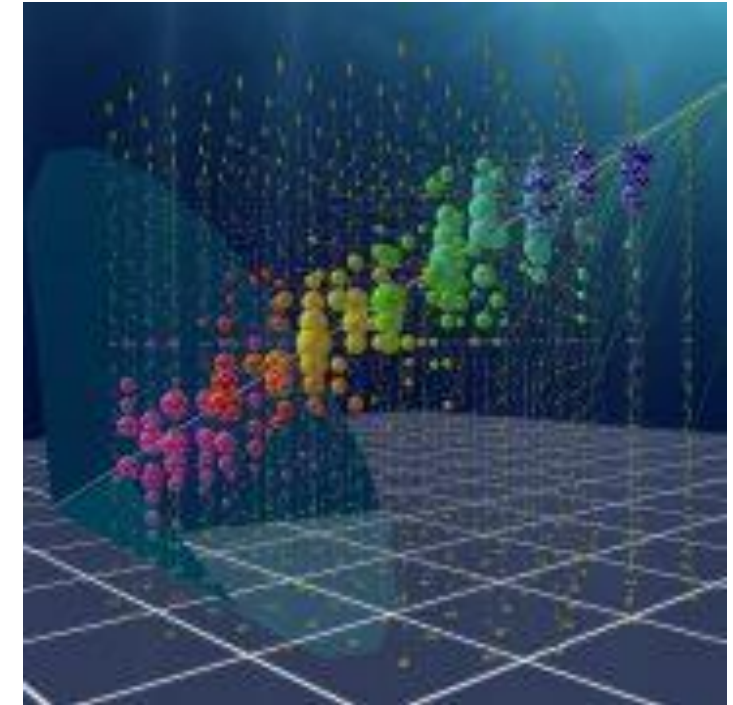
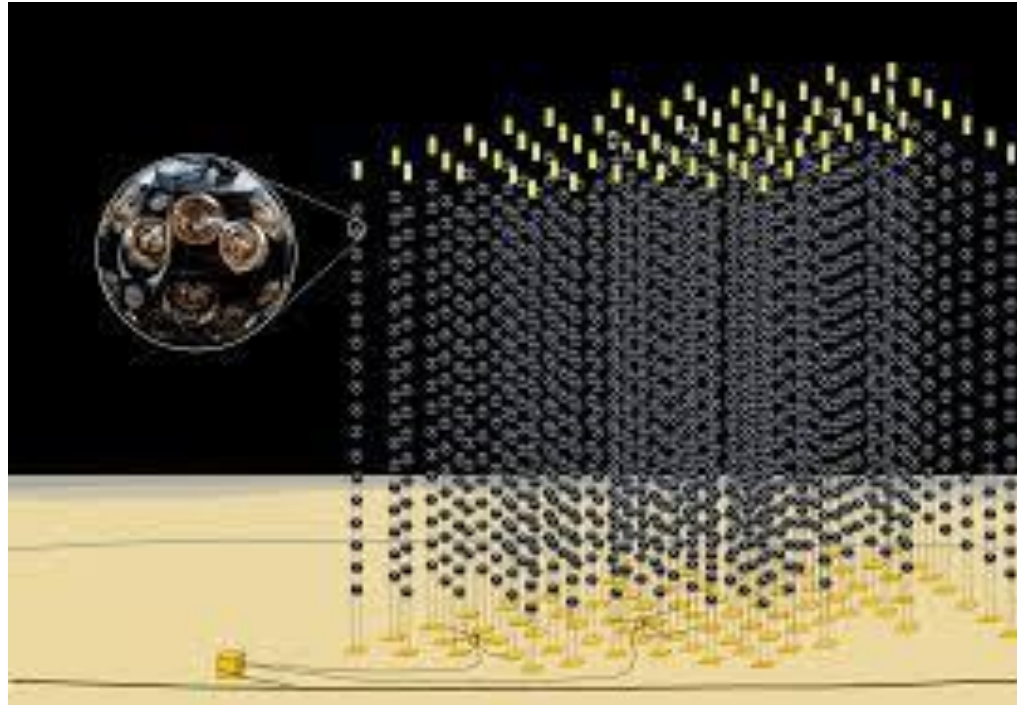
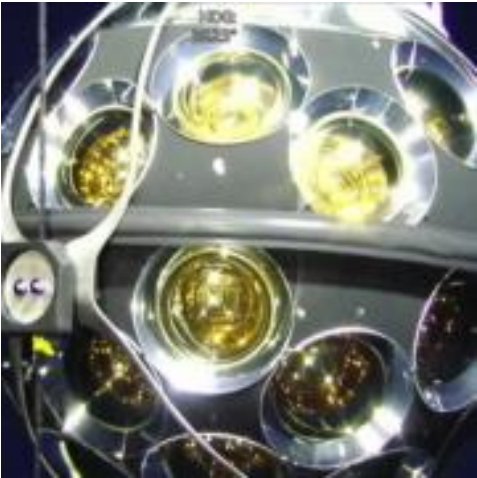
$$\theta_{12}, \Delta m_{21}^2, \Delta m_{32}^2$$

Mesure de la hiérarchie de masse

Peut aussi être mesuré avec neutrinos accélérateurs ou neutrinos atmosphériques

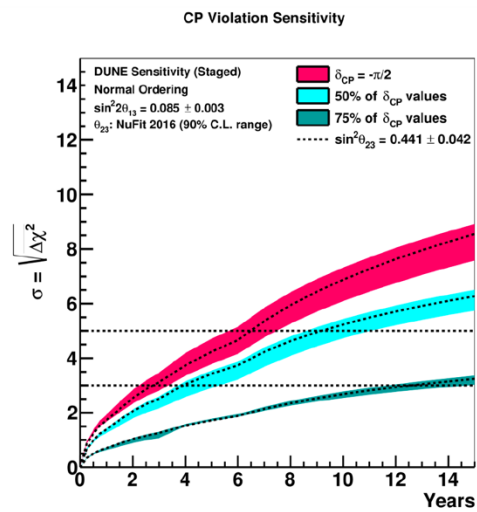
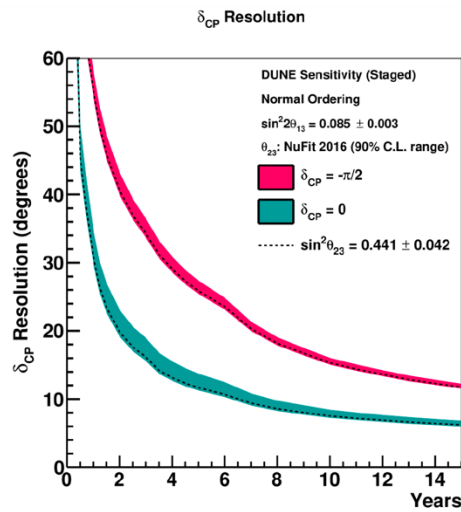
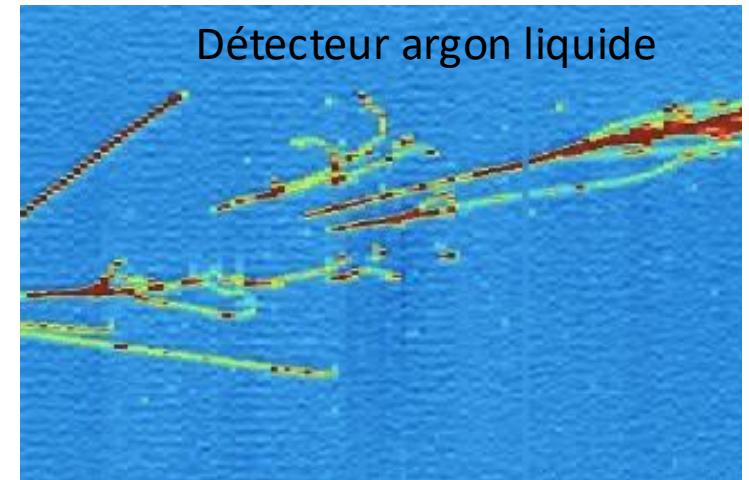
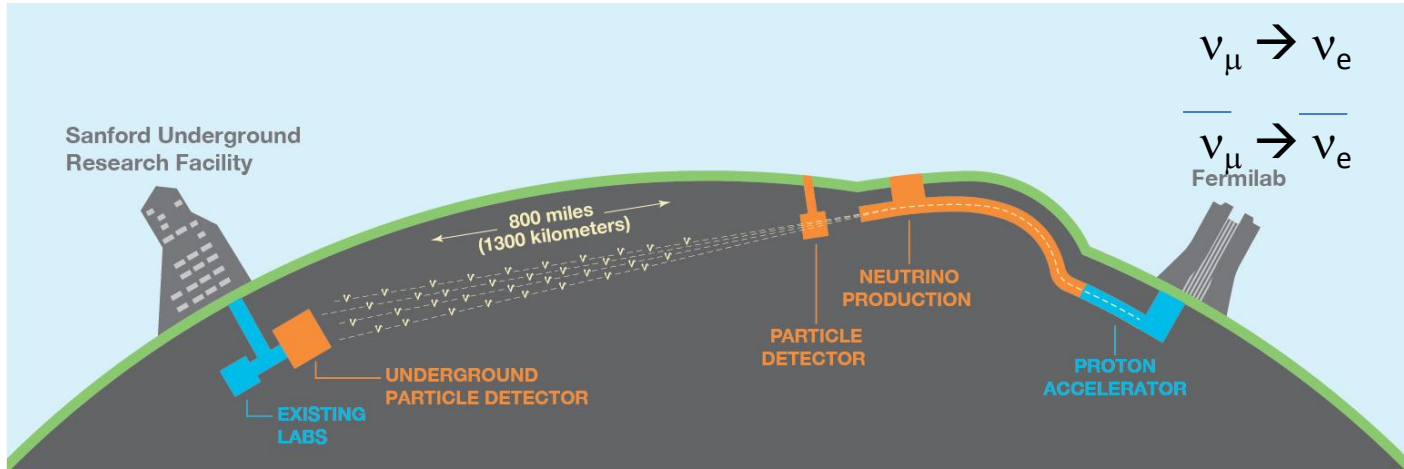
La masse des neutrinos

Expérience KM3NET (La Seyne sur Mer, France)



Lignes de 700 m de haut amarrées à 3 000 m de profondeur
4 000 unités de détection

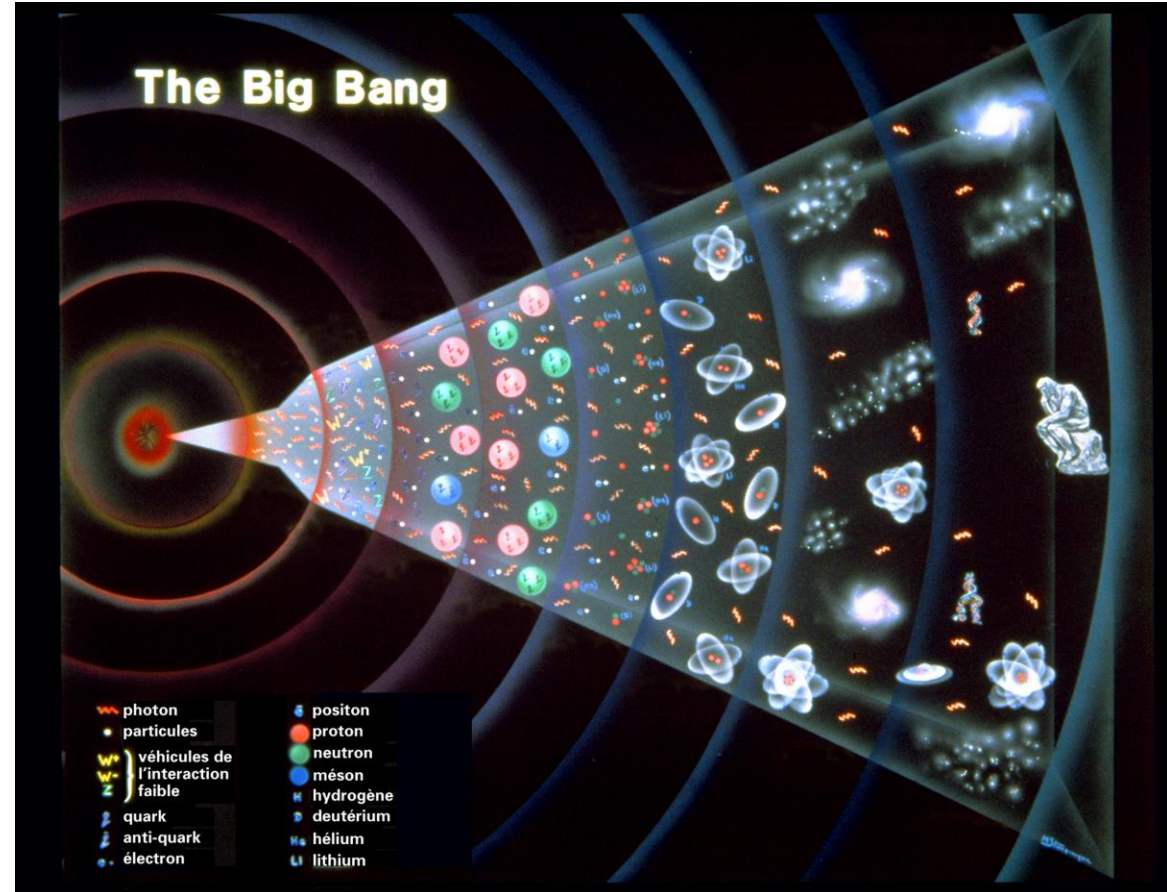
Probabilité d'oscillation différentes pour neutrino et anti-neutrino



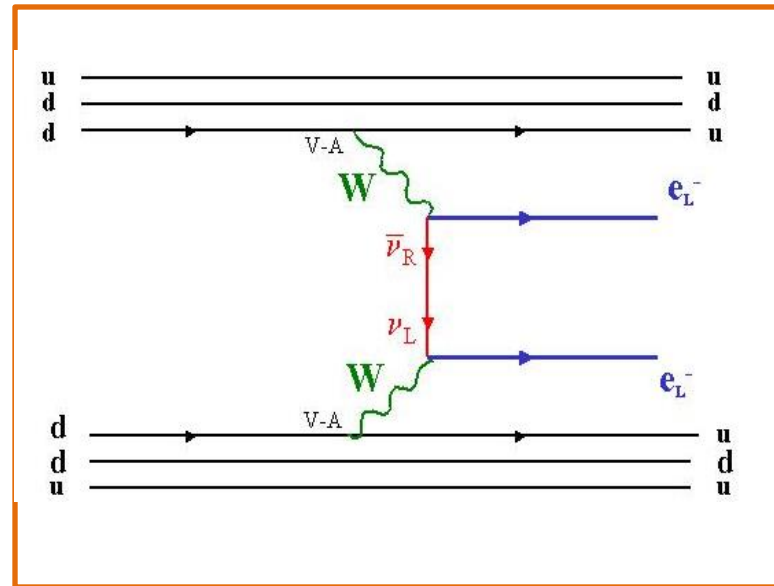
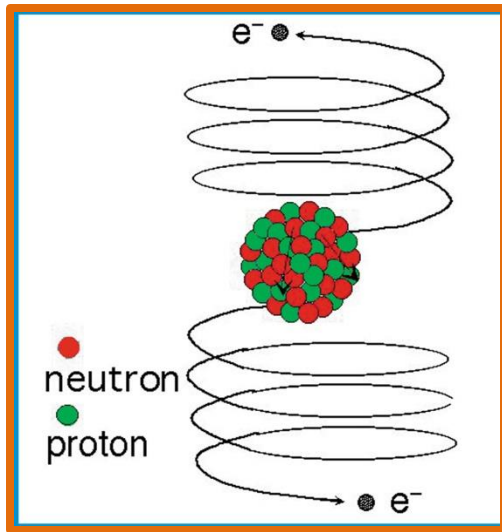


1937: Ettore Majorana

Neutrino = anti-neutrino ?



Le neutrino est-il à l'origine de la matière ?



Phase space factor Nuclear matrix element

$$T_{1/2}^{-1} = F(Q_{\beta\beta}^5, Z) |M|^2 \langle m_\nu \rangle^2$$

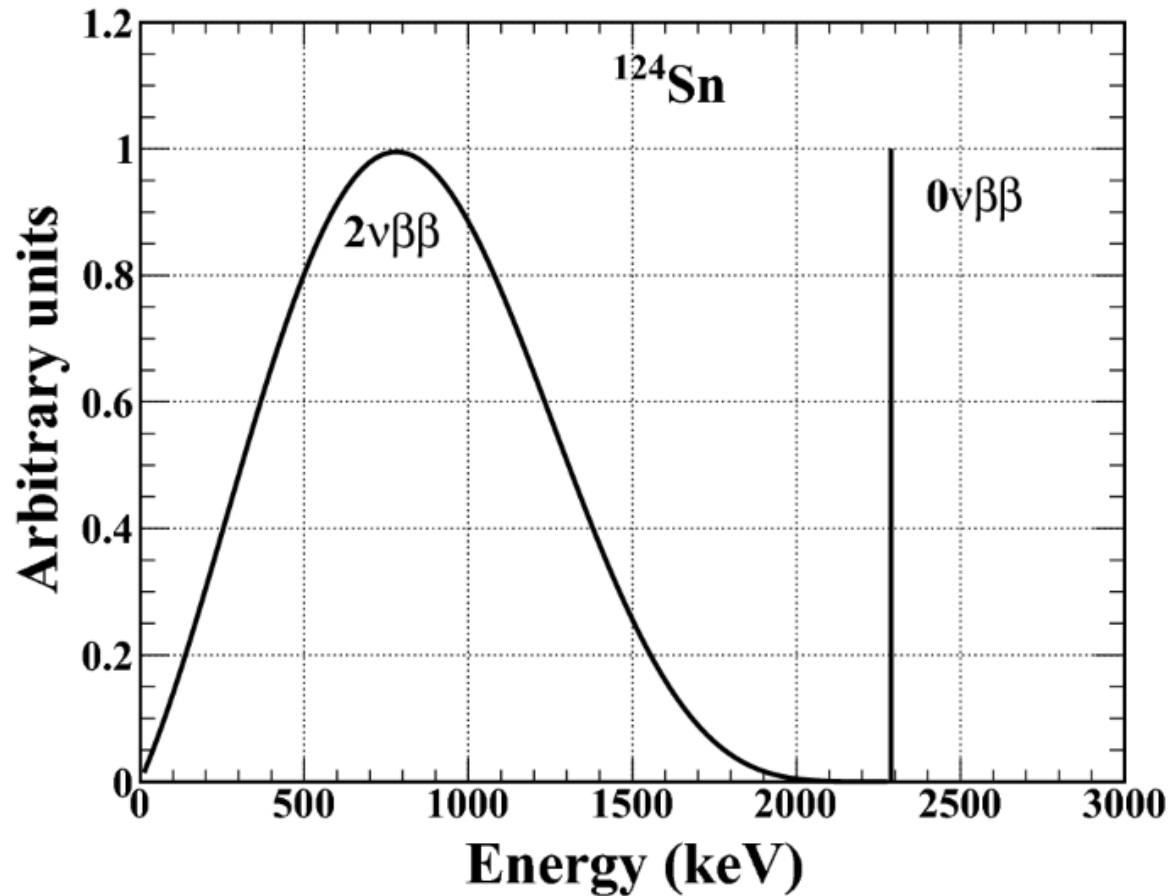
Effective mass:

$$\langle m_\nu \rangle = m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \cdot e^{i\alpha_1} + m_3 |U_{e3}|^2 \cdot e^{i\alpha_2}$$

$|U_{ei}|$: mixing matrix element
 α_1 et α_2 : Majorana phase

Neutrino = anti-neutrino
Neutrino massif

Période attendue $> 10^{25}$ ans
(âge de l'univers $15 \cdot 10^9$ ans)



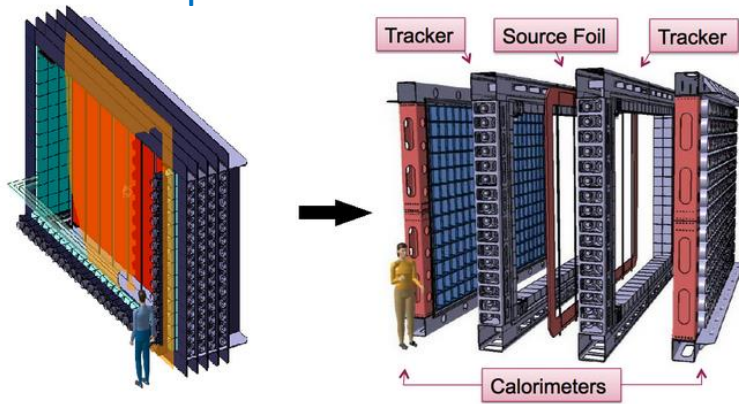
Energie de transition : 2 – 3 MeV

Domaine d'énergie de la radioactivité naturelle

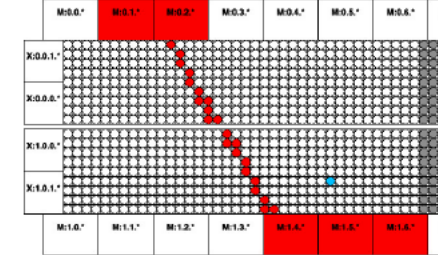
Sélection des matériaux

La nature du neutrino

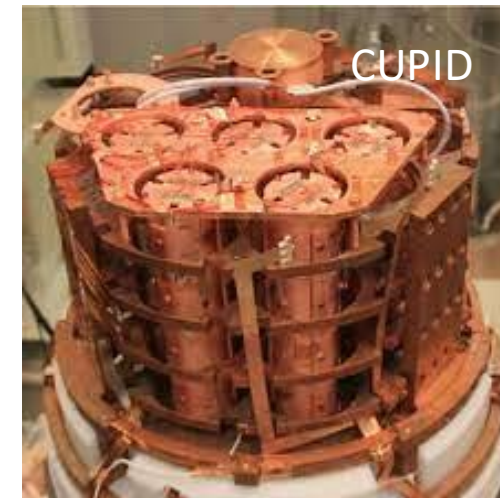
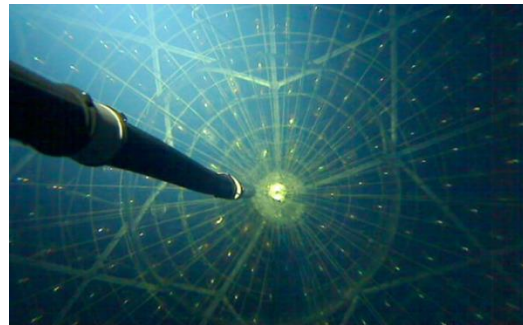
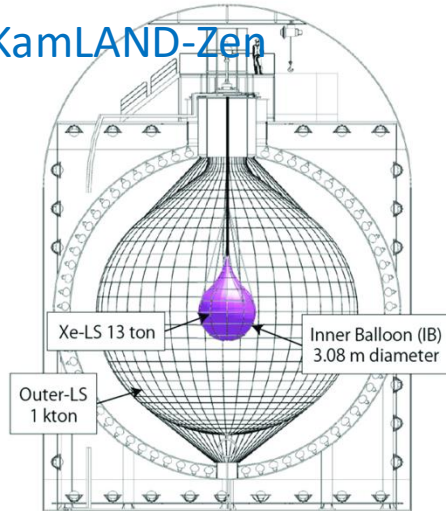
SuperNEMO



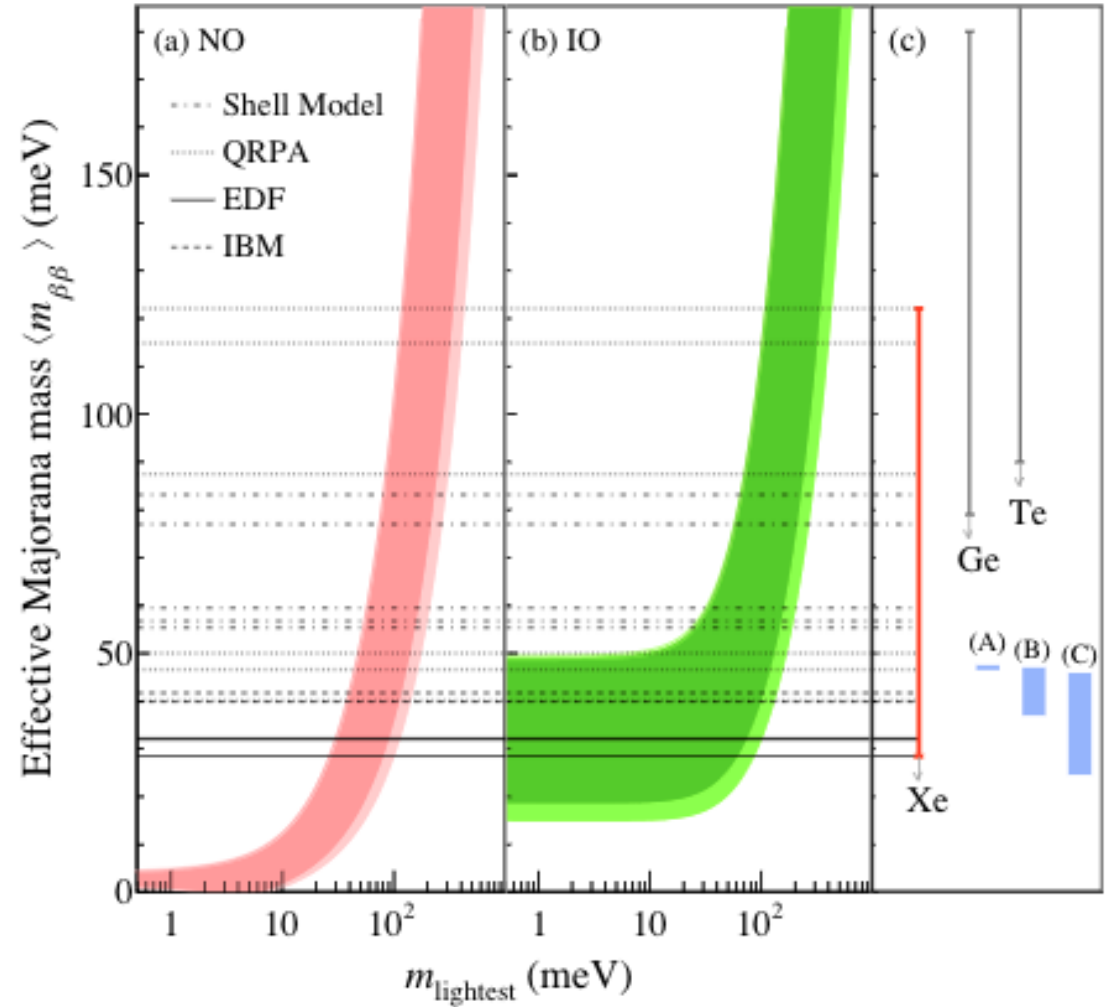
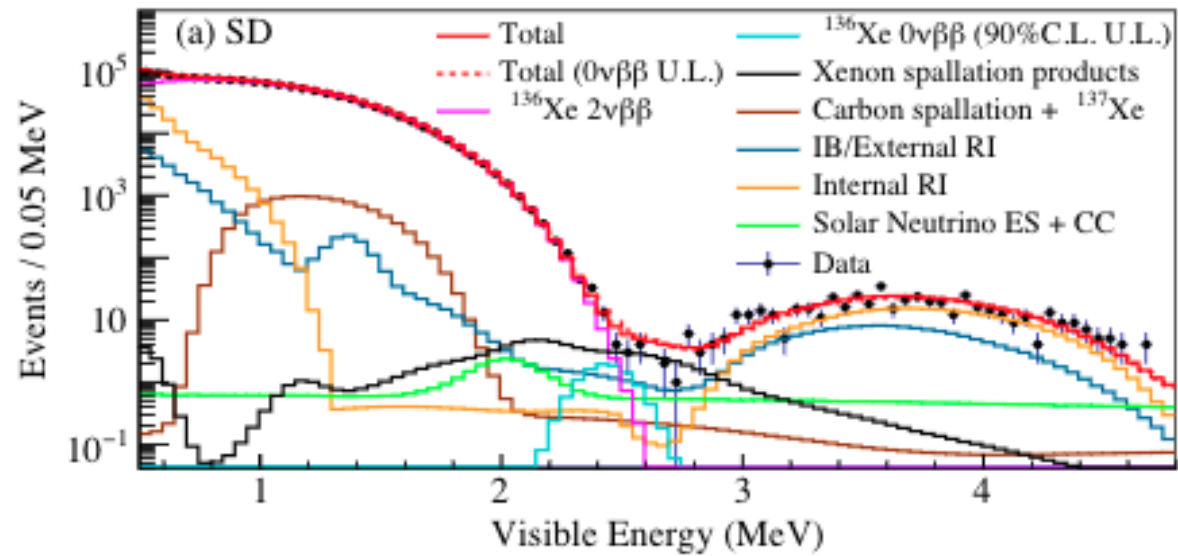
RUN 709 // TRIGGER 95736



KamLAND-Zen



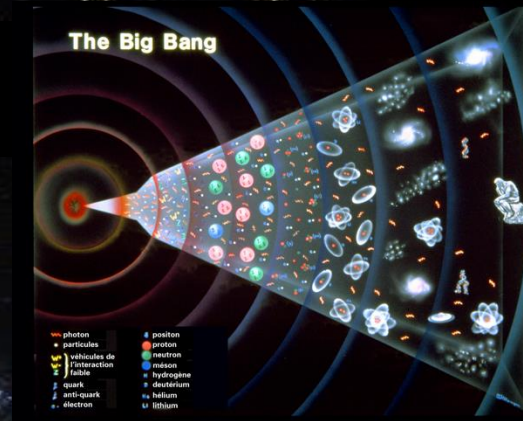
La nature du neutrino



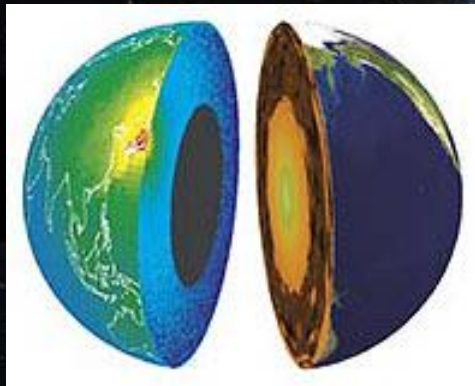
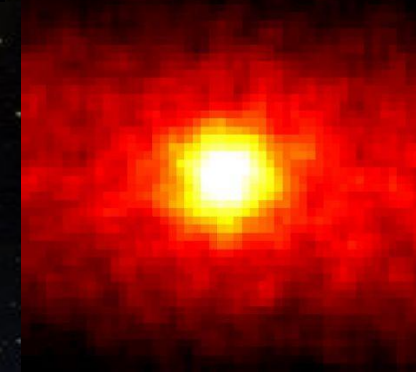
Masse, nature, oscillation,
violation CP, neutrino stérile,...

Rôle en cosmologie ?

Preuve de physique au-delà du
Modèle standard



Astronomie neutrino
Etoile, Supernovea,...



Sonder la terre

De la recherche des neutrinos
à la vérification des millésimes de vin



A vibrant nebula in space, featuring a large, glowing cloud of gas and dust. The nebula is illuminated with bright yellow and orange light, transitioning to blue and purple at the edges. The background is a dark, starry sky with several bright stars, some of which have prominent diffraction spikes. The overall scene is a stunning display of cosmic beauty.

270 000 000 000 000 000 000



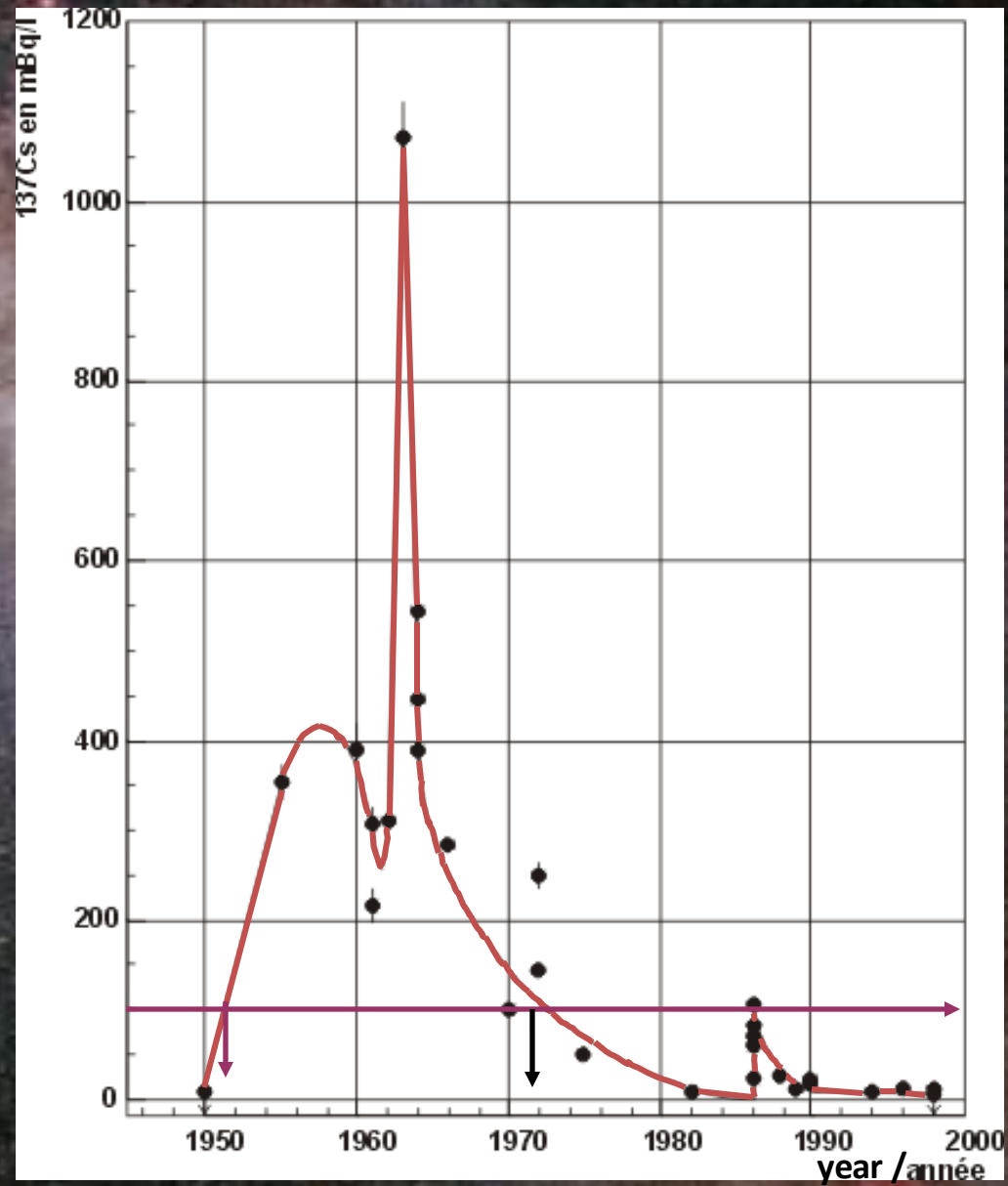


En 2000 apparition sur le marché de bouteilles de Château Margaux de 1900

Question de la repression des fraudes: comment expertiser ces bouteilles ?



Mesure du ^{137}Cs en fonction de temps



Méthode non destructive





Photography of the expected Thomas Jefferson bottles of wine from 1784 and 1787. Two bottles are from Chateau Lafite, the two other are from Branne Mouton, which nowadays is called Mouton Rothschild

The 5