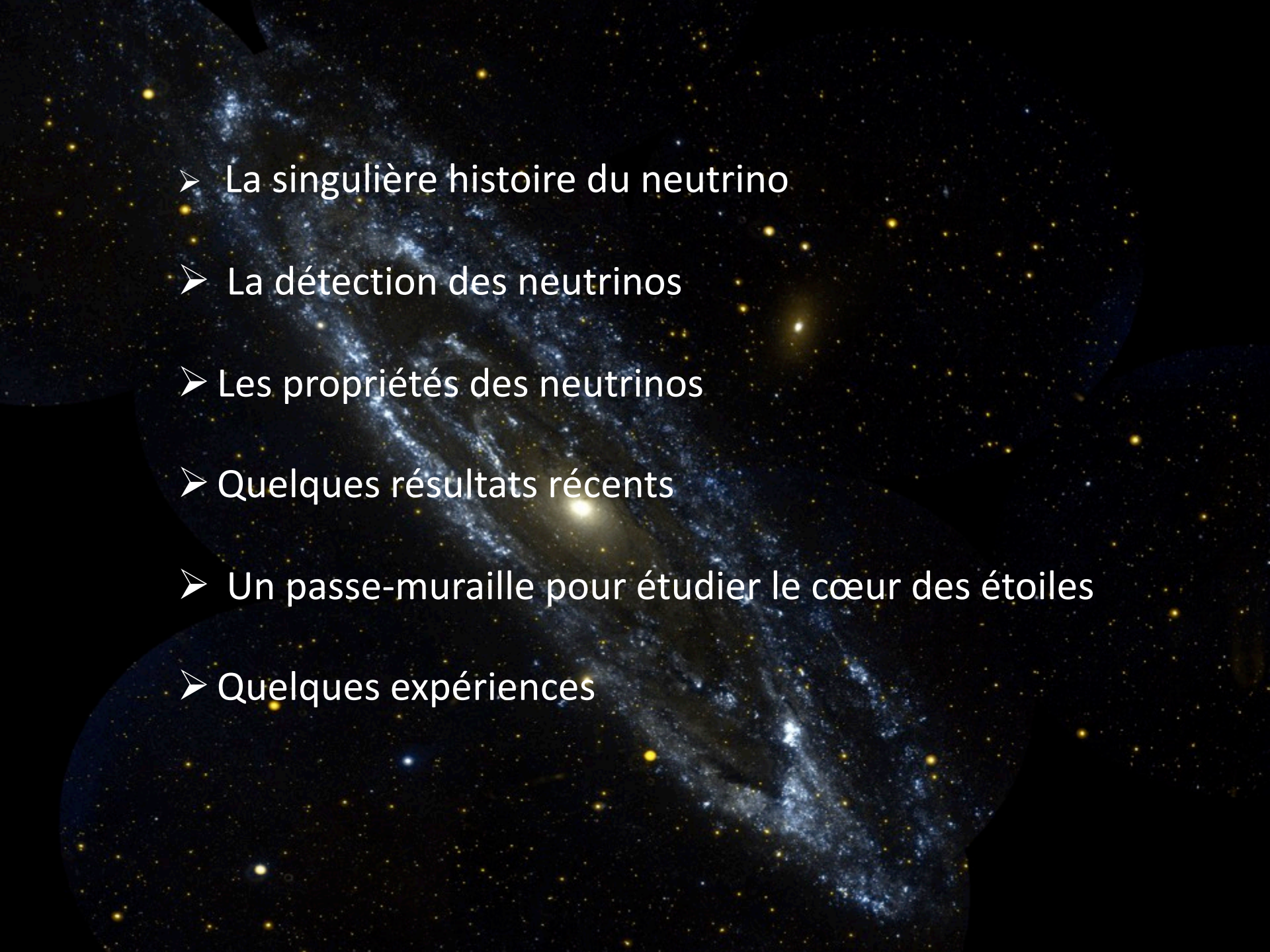


L'enigmatique neutrino

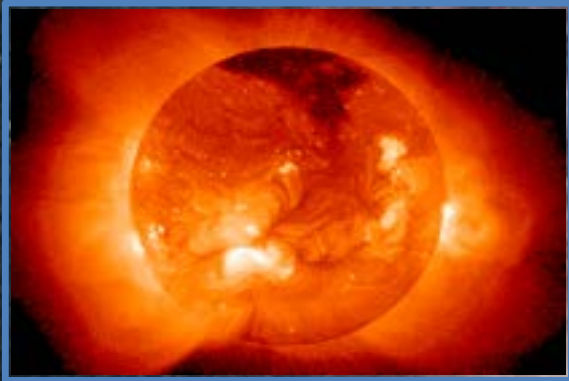
F. Piquemal (CNRS/IN2P3)

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

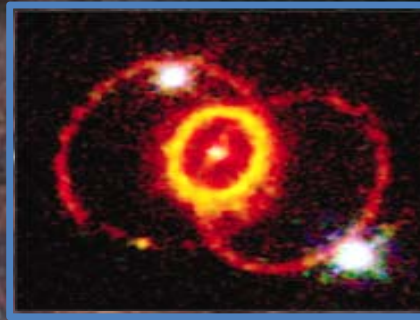
French Teacher Programme ,CERN, octobre. 2022

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

Il pleut des neutrinos de toute part...



Le soleil :
64 milliards par cm^2 par seconde



Une Super Nova de notre
Voie Lactée 5 milliards par cm^2
par seconde pendant 10 s



Le Big-Bang : chaque cm^3
d'espace est occupé par
300 neutrinos « reliques »



Les réacteurs nucléaires
(100 000 par cm^2 par
seconde à 200 km



Origine géophysique et
atmosphérique :
6 millions par cm^2 par seconde

Corps humain 8 000 par secondes !!

Quarks



Leptons

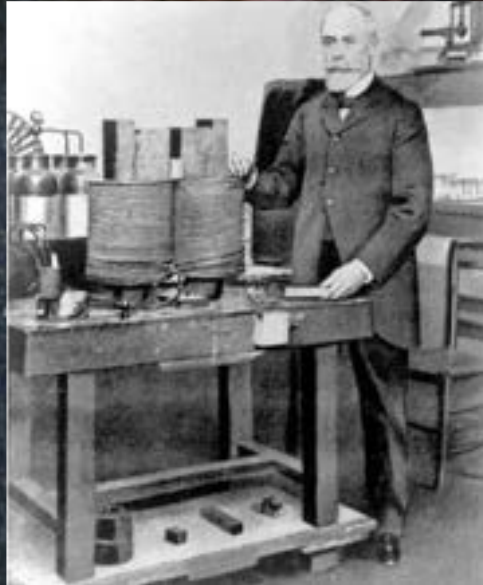


matière



anti-matière

La préhistoire du neutrino



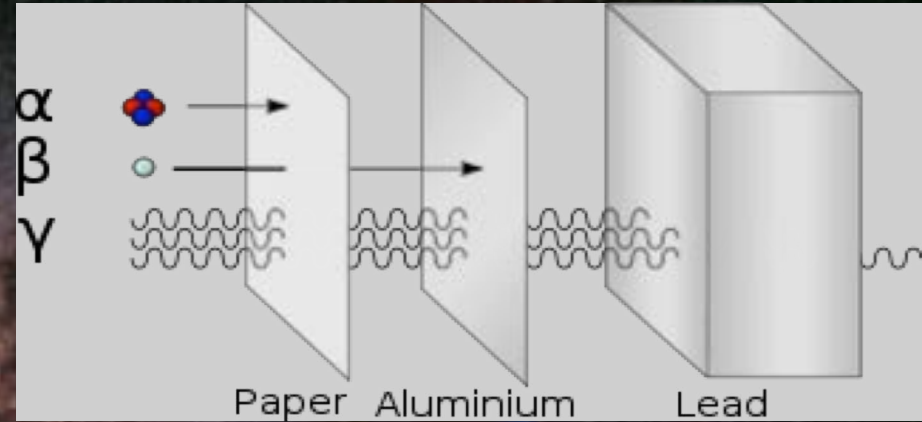
1896 - 1898:

Becquerel, Pierre et Marie Curie
découvrent la radioactivité

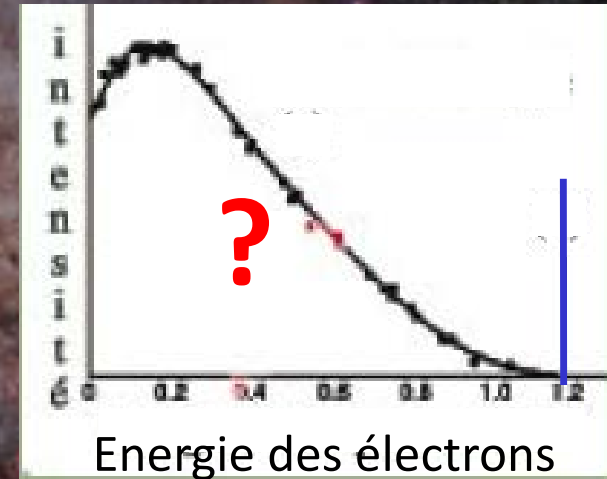


La préhistoire du neutrino

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



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 ?

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} 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.

1930 : Une lettre pour l'histoire de W.Pauli

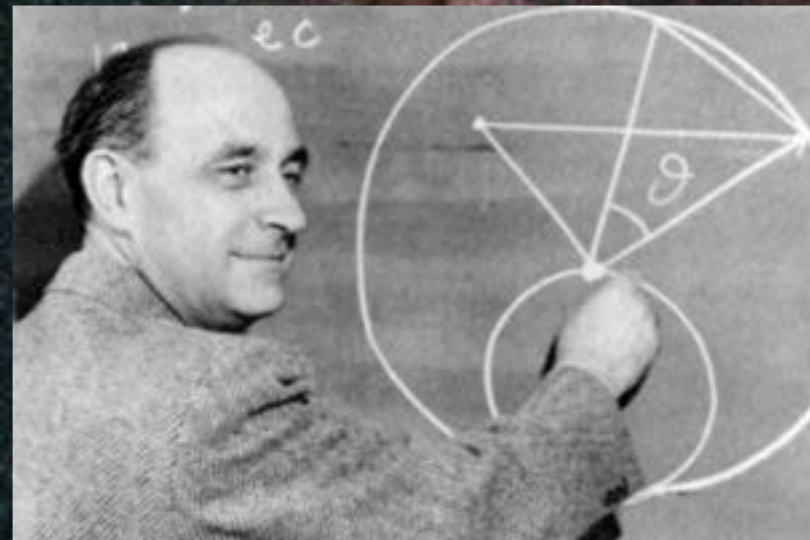
« un remède désespéré pour sauver la conservation de l'énergie »



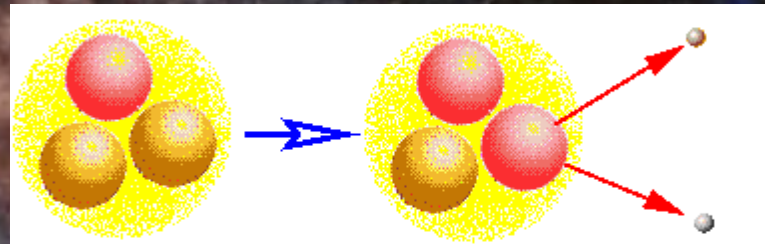
« Spin $\frac{1}{2}$ et ne voyage pas à la vitesse de la lumière »

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 le détecter



1933 : Fermi élabore la théorie de l'interaction faible

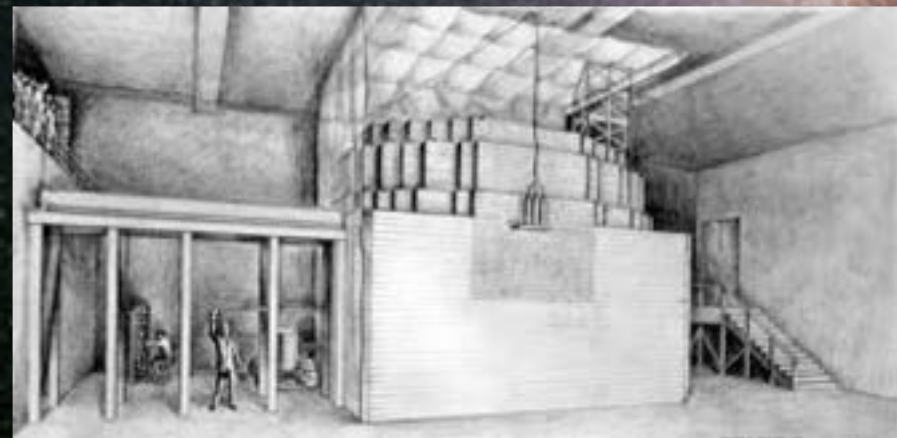


électron

neutron

proton

neutrino



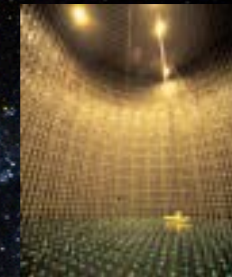
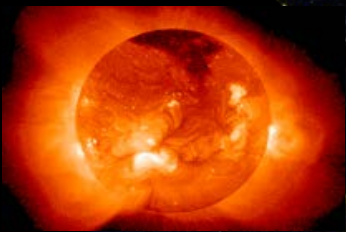
**1942 : Fermi met au point le premier réacteur nucléaire
Une source de neutrino !**

Piège à neutrino

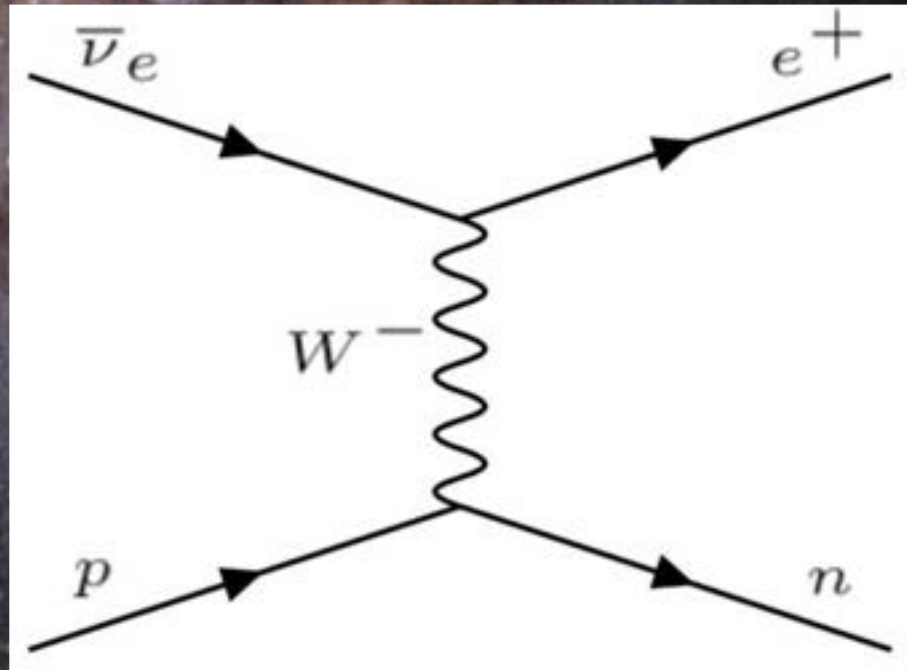
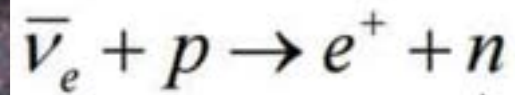
← 30 000 000 000 000 000 km de plomb →



Pour détecter des neutrinos:
beaucoup de neutrinos
et beaucoup de matière !

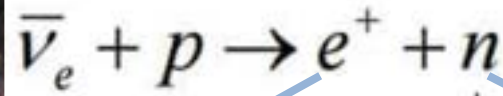


Comment détecter un neutrino ?



$$E_{\bar{\nu}} \cong E_{e^+} + \overset{10-40 \text{ keV}}{E_n} + \underbrace{(M_n - M_p)}_{1.8 \text{ MeV}} + m_{e^+}$$

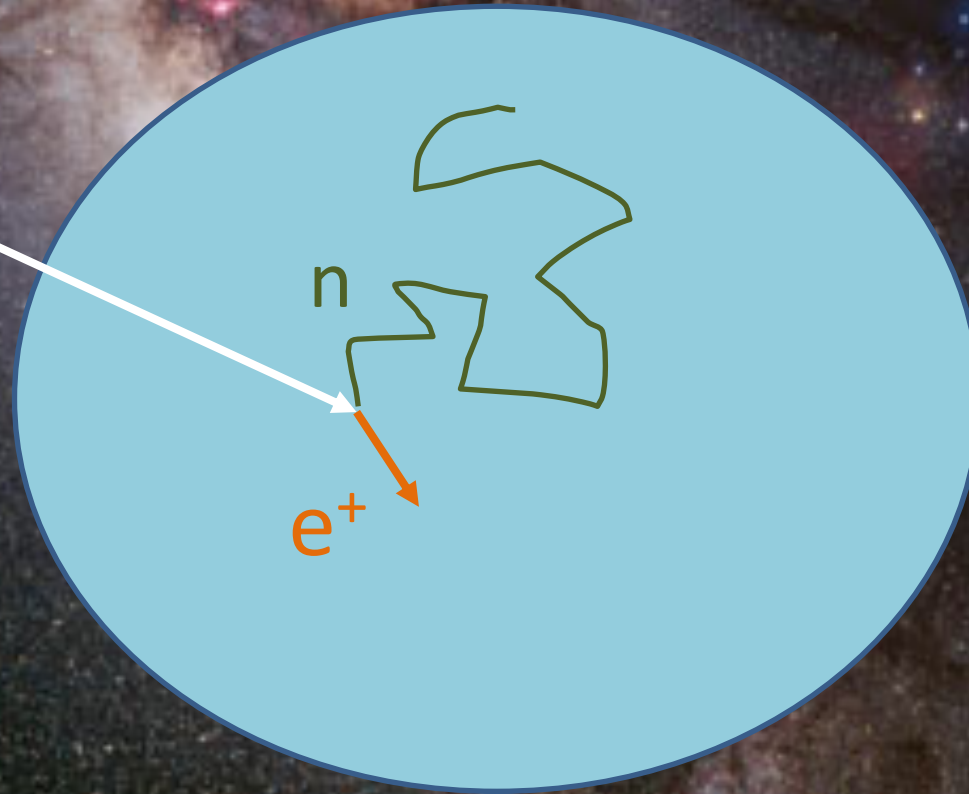
Comment détecter un neutrino ?



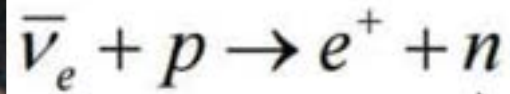
Energie prompte

Energie retardée

$\bar{\nu}_e$

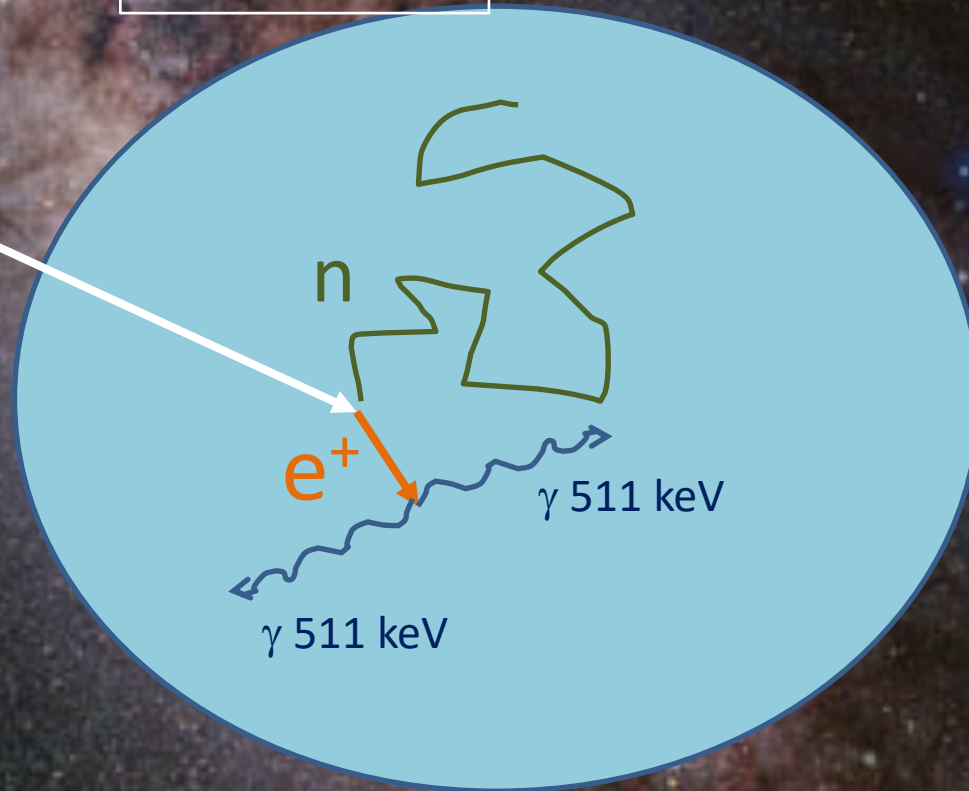


Comment détecter un neutrino ?



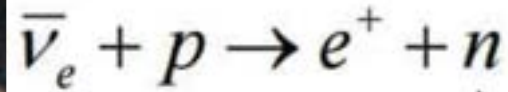
Energie prompte

$\bar{\nu}_e$



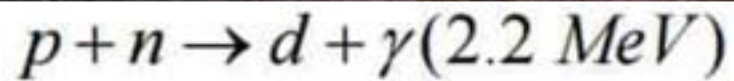
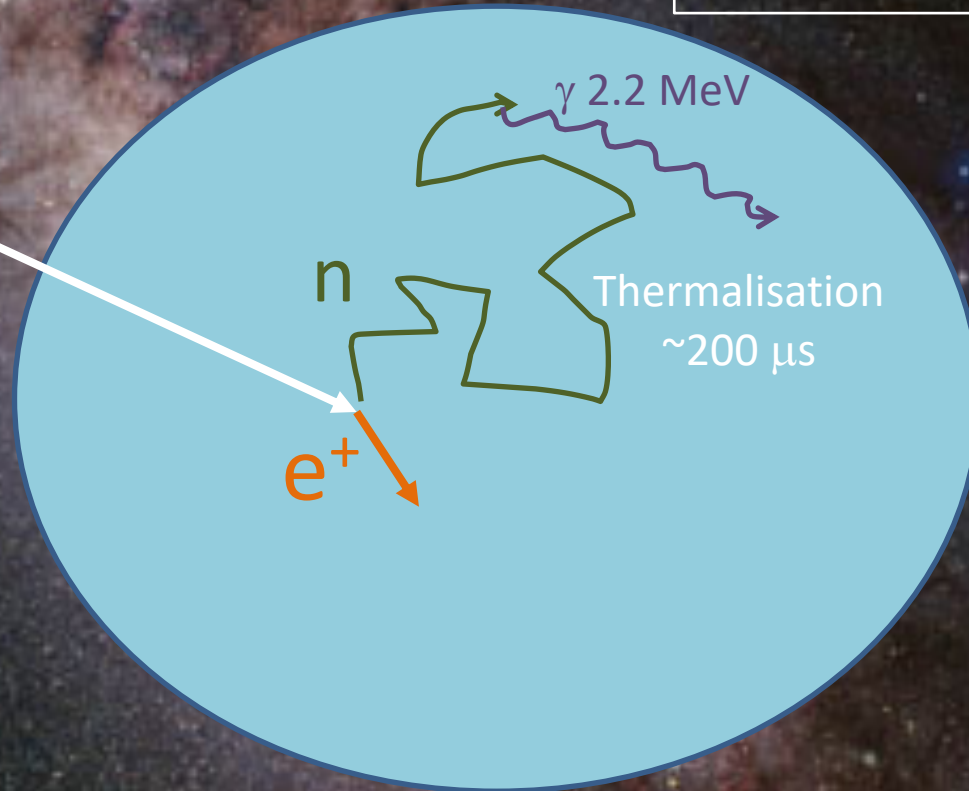
$$E_{\text{prompt}} = E_{\nu} - 0.8 \text{ MeV}$$

Comment détecter un neutrino ?

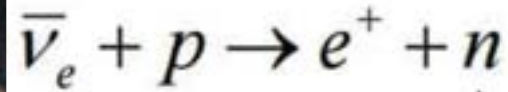


Energie retardée

$\bar{\nu}_e$



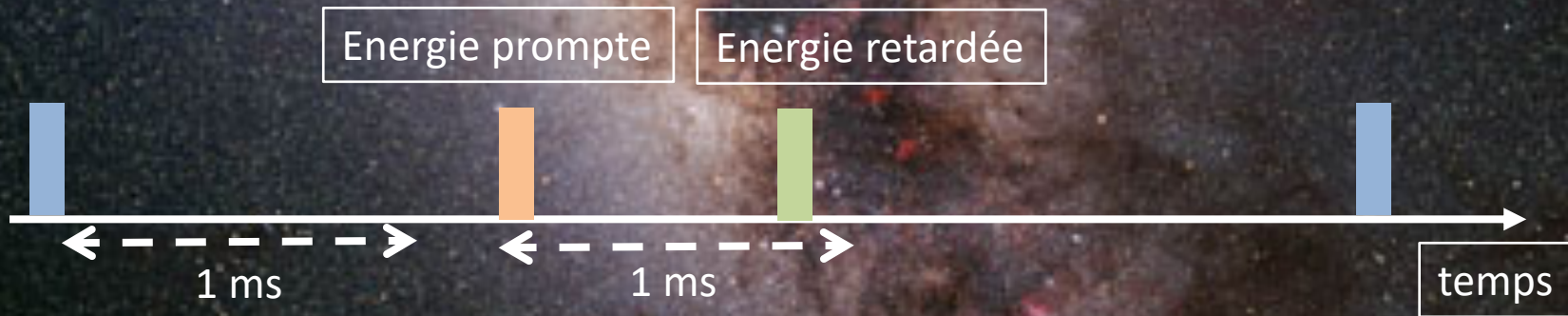
Comment détecter un neutrino ?



Energie prompte

Energie retardée

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

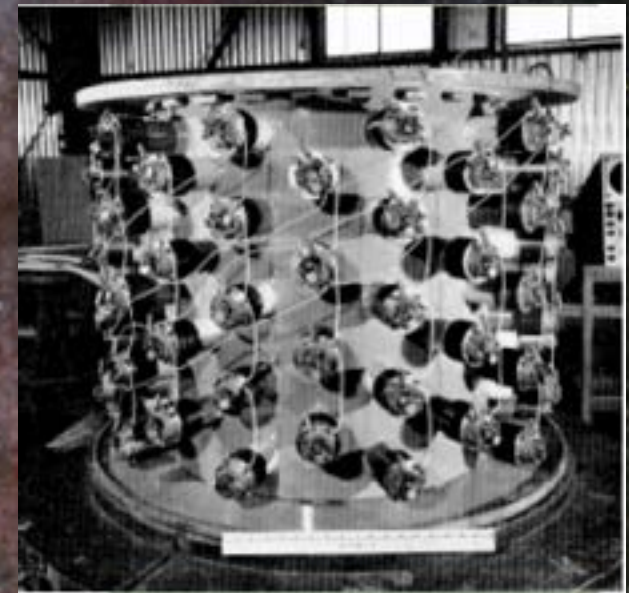
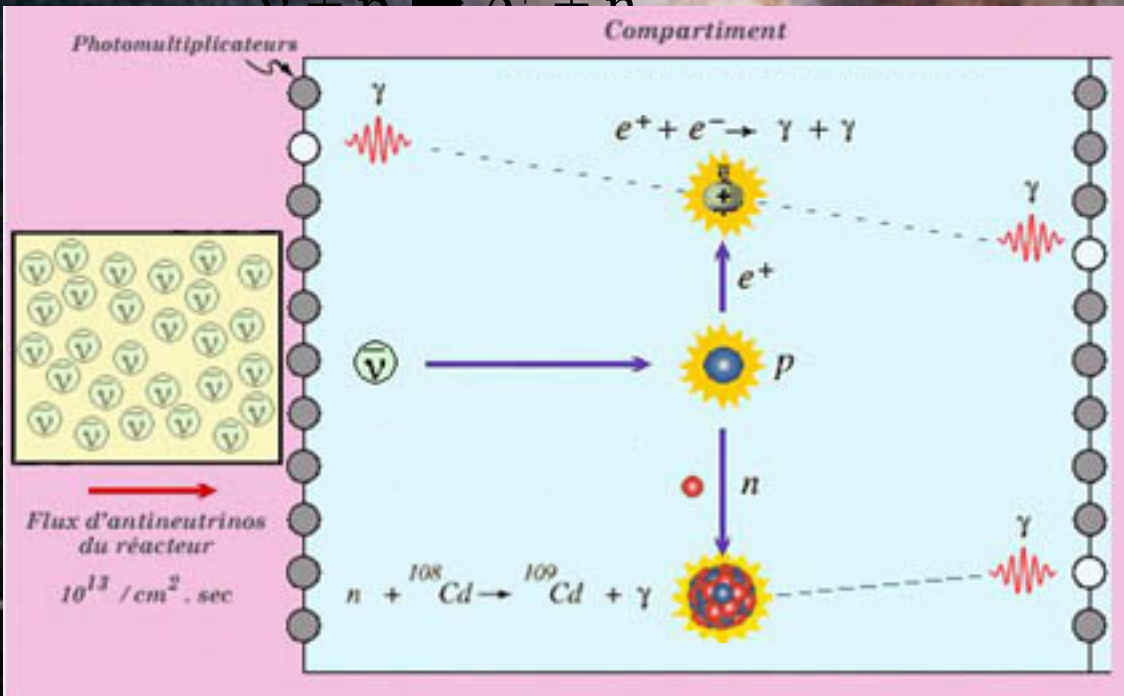


Une sélection supplémentaire : l'énergie retardée doit être de 2,2 MeV

1956: Découverte du neutrino par Reines et Cowan



Réacteur de Savannah River (USA)

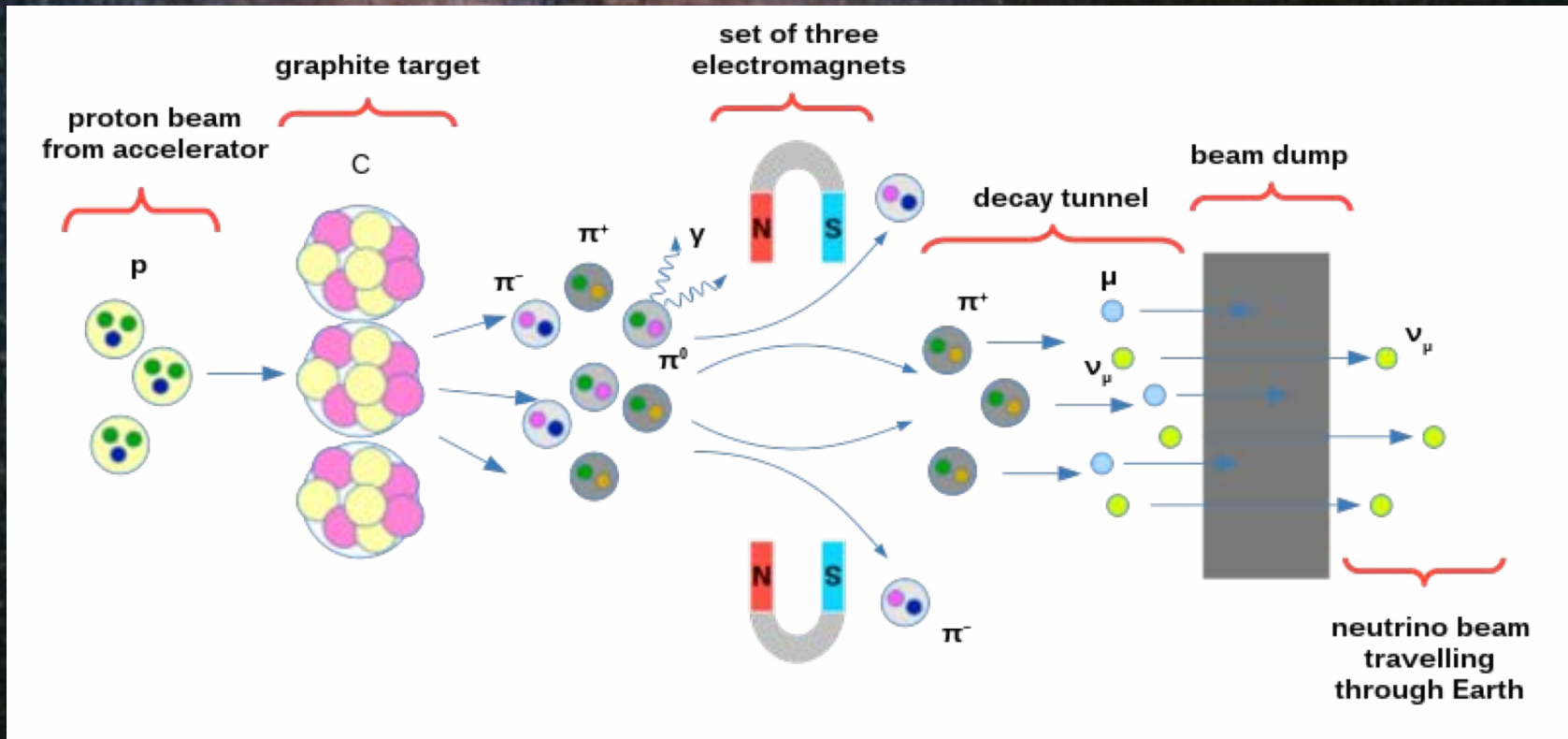


Détecteur Poltergeist

1956: Reines and Cowan envoient un télégramme à Pauli

RADIO-SCHWEIZ AG.		RADIOGRAMM - RADIOGRAMME		RADIO-SUISSE S. A.	
SBZ1311		ZHW UW1844 FM BZJ116 WH CHICAGOILL		56 14 1310	
				PLC 00253 ✓	
Erhalten - Reçu		„VIA RADIOSUISSE“		Befördert - Transmis	
von - de	Stunde - Heure	NAME - NOM	nach - A	Stunde - Heure	NAME - NOM
NEWYORK	15	100	Briefteleogramm	74 15	No. VI. 56 -1 10
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 <u>DEFINITELY DETECTED</u> <u>NEUTRINOS</u> 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 4500 X 100 3/54					

Comment créer un faisceau de neutrino ?



On a appris à fabriquer des
« faisceaux de neutrino »

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



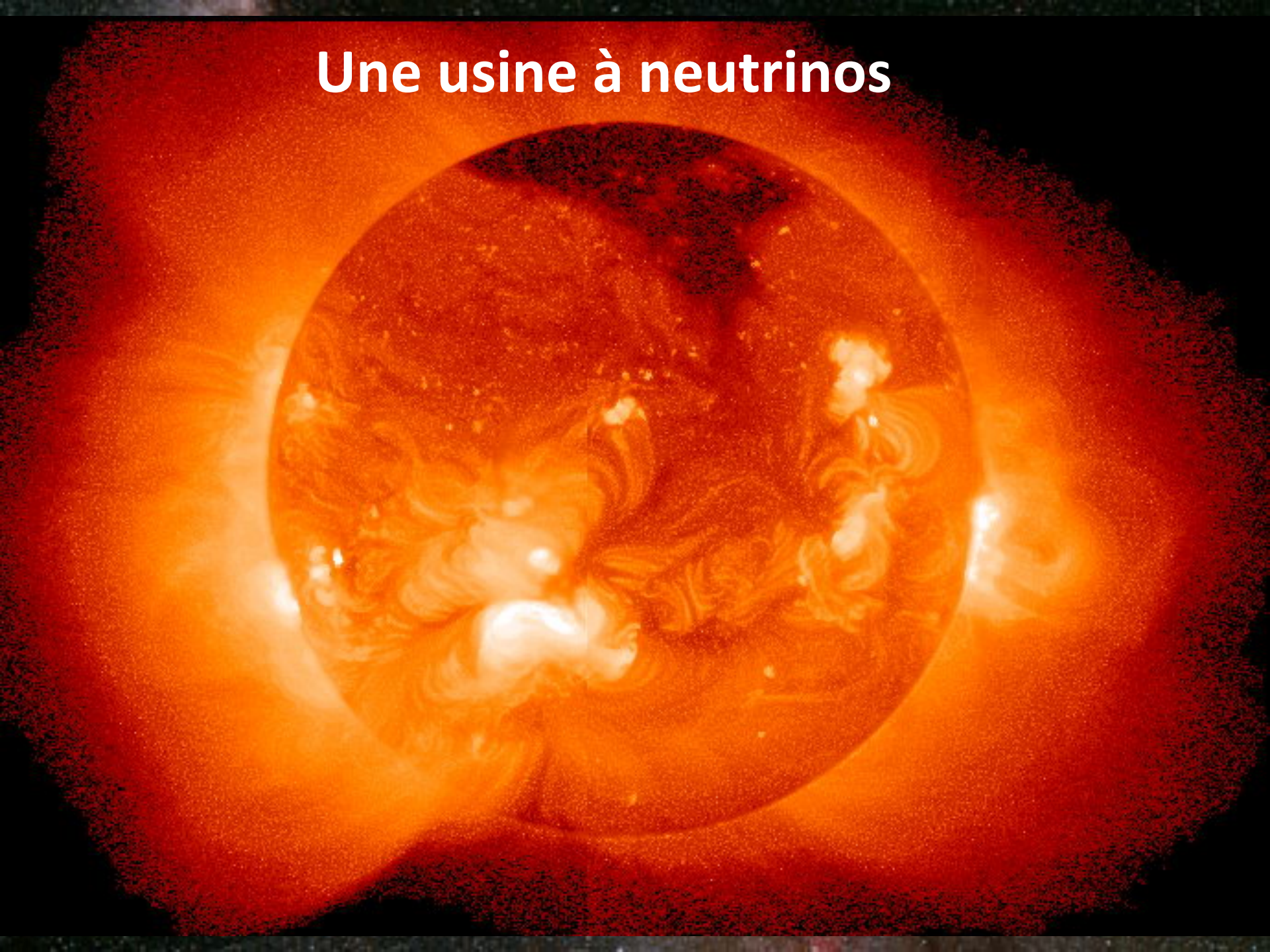
Il faut en produire des milliards
de milliards pour en voir 1 seul

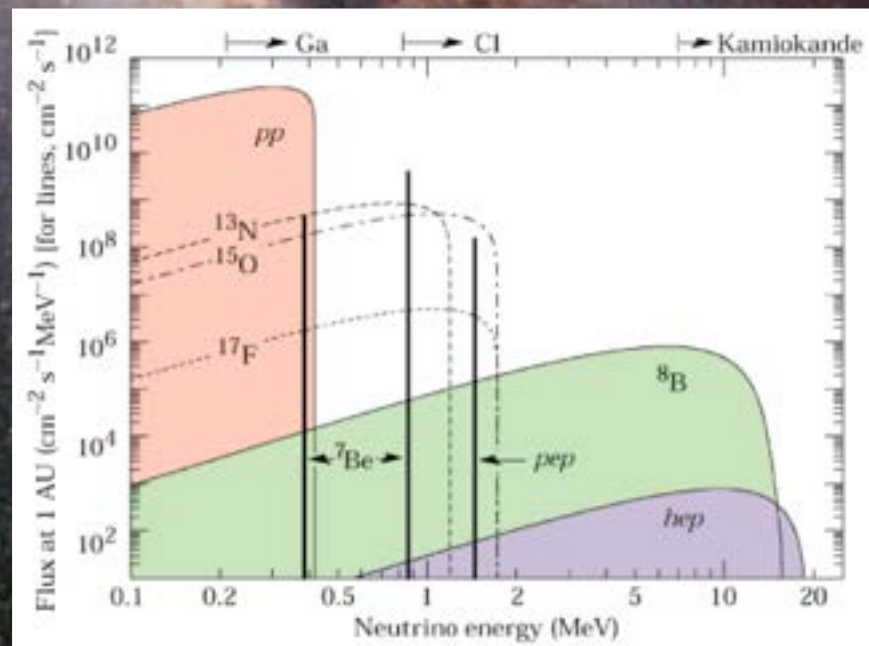
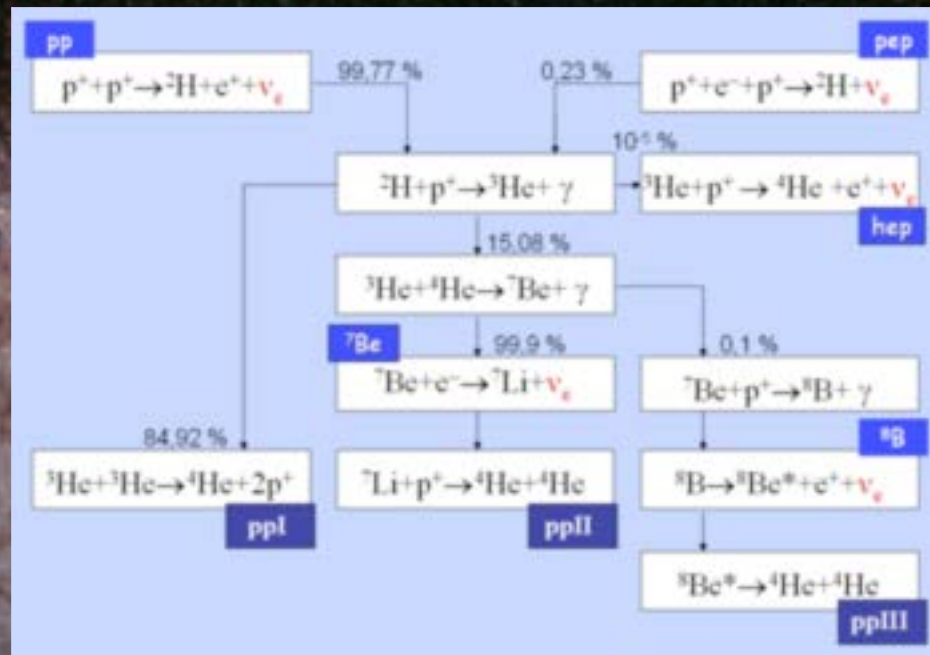
1962: découverte de ν_{μ}

2000: Découverte du ν_{τ}



Une usine à neutrinos



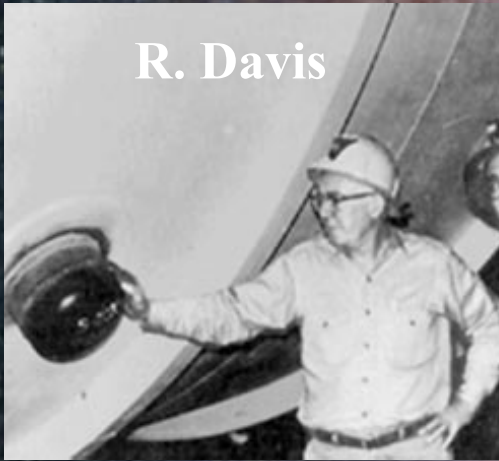


L'énigme des neutrinos solaires

1968: 1ère expérience radiochimique



R. Davis



600 tonnes de chlore



${}^{37}\text{Ar}$

Période de 35 j

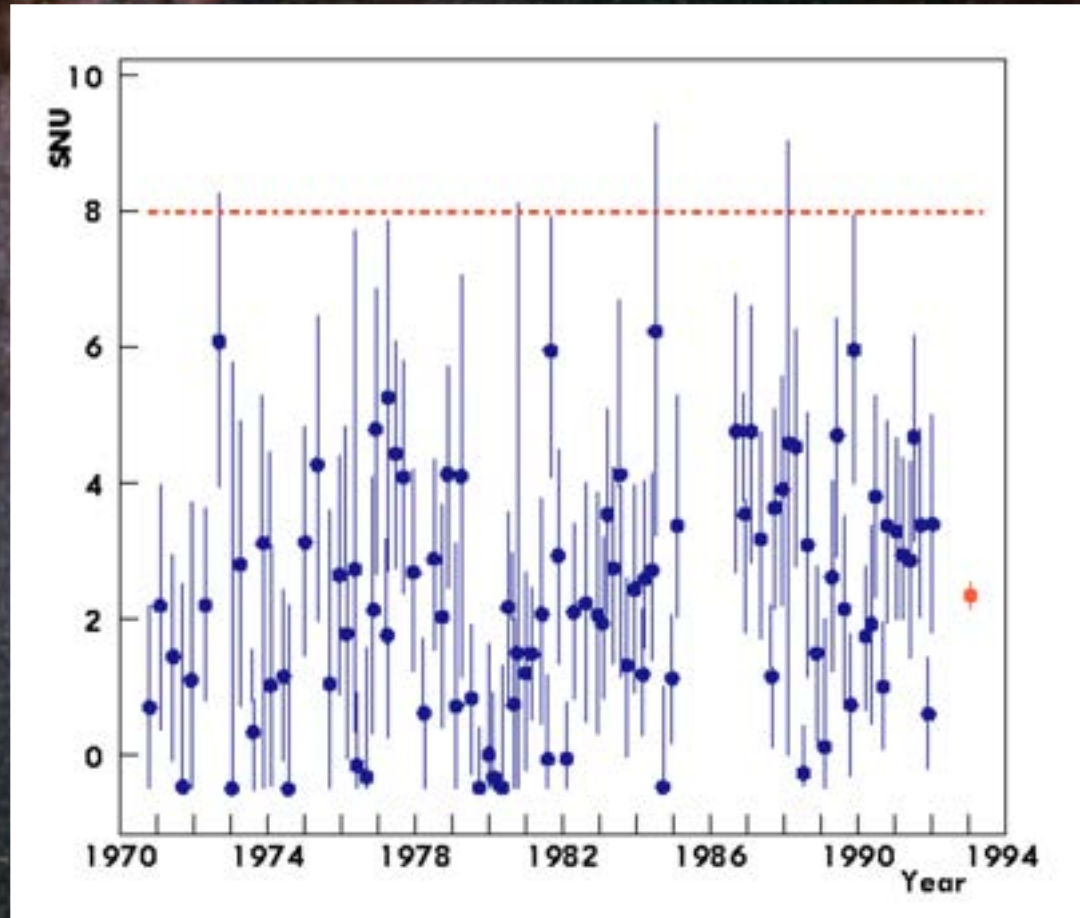
Capture électronique

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

Mine de
Homestake(USA)



L'énigme des neutrinos solaires

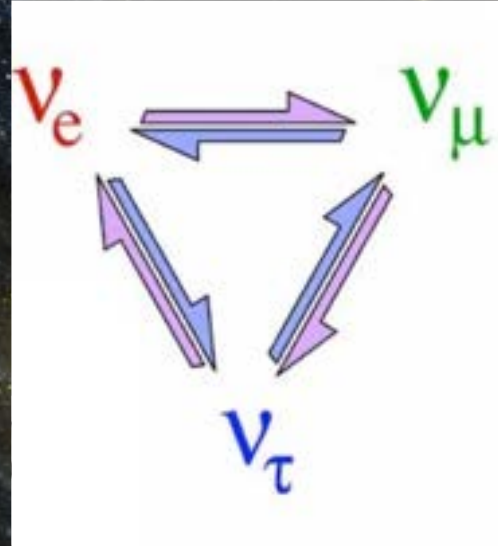


Il manque 75% des neutrinos !!!!

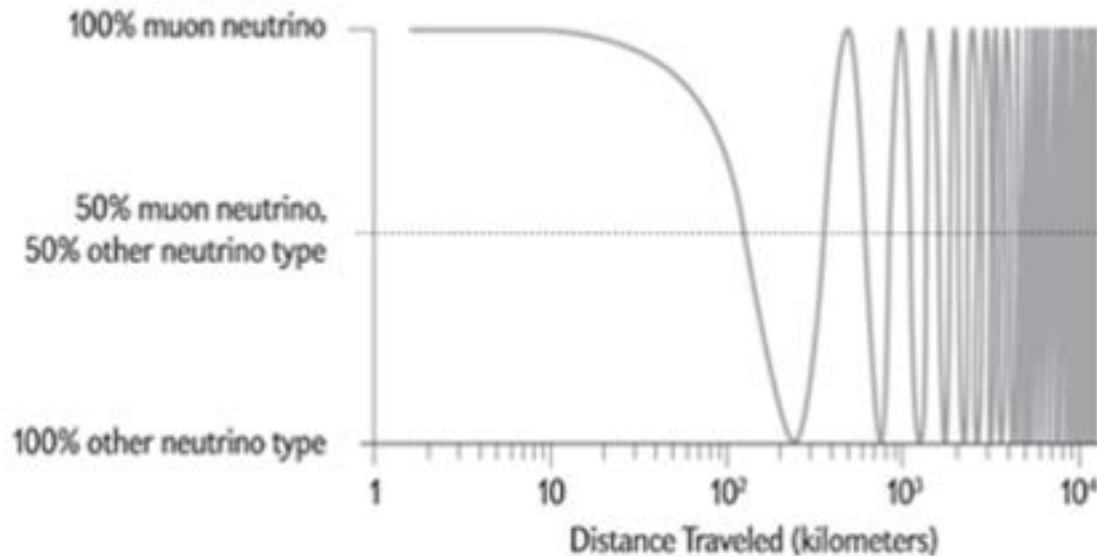
Confirmé par d'autres expériences radiochimiques dans les années 90



1957: Bruno Pontecorvo prédit l'oscillation des neutrinos



Neutrino Oscillations



Neutrinos de « base »: ν_1 ν_2 ν_3

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

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

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

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

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

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

Neutrinos
Atmosphériques
Accélérateurs

Neutrinos
Réacteurs
Accélérateurs

Neutrinos
Solaires
Réacteurs

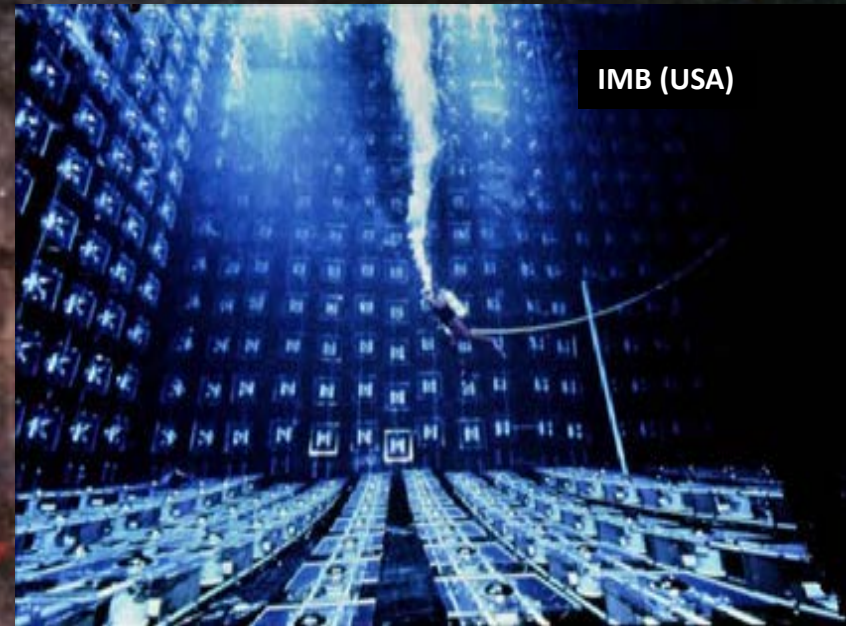
$$C_{ij} = \cos\theta_{ij}$$

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

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



Kamiokande (Japon)

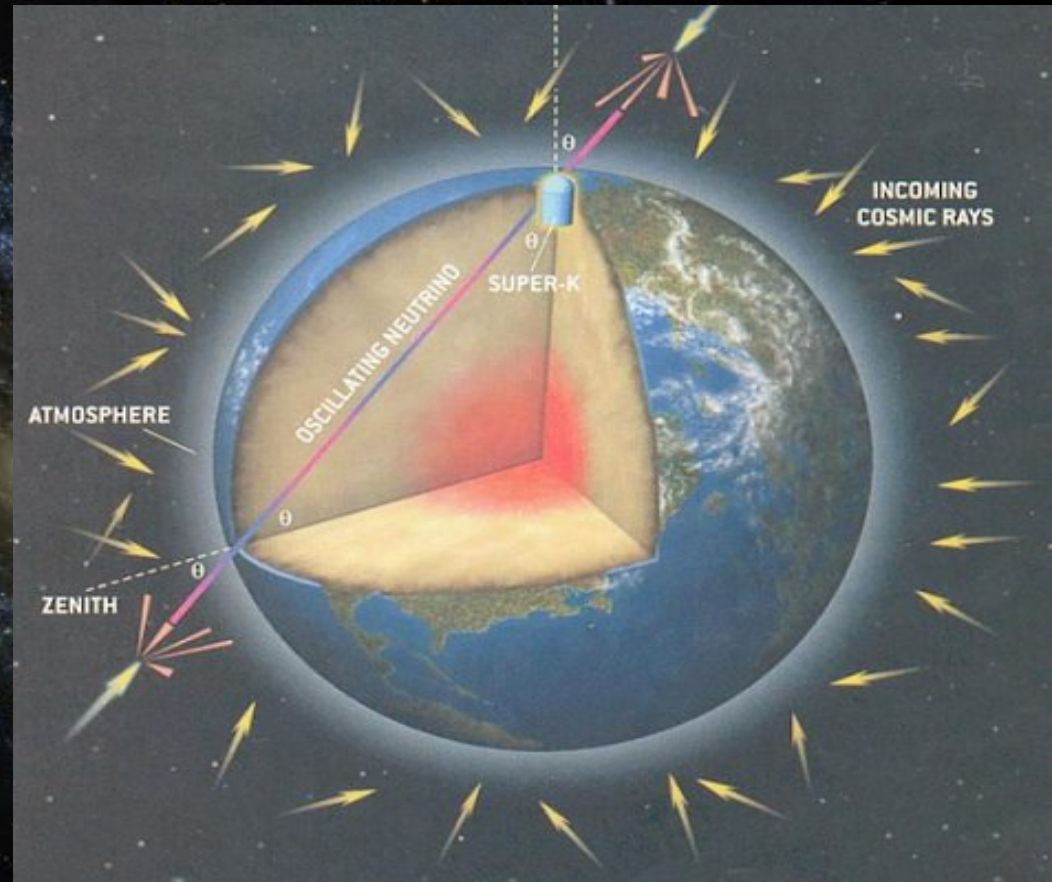
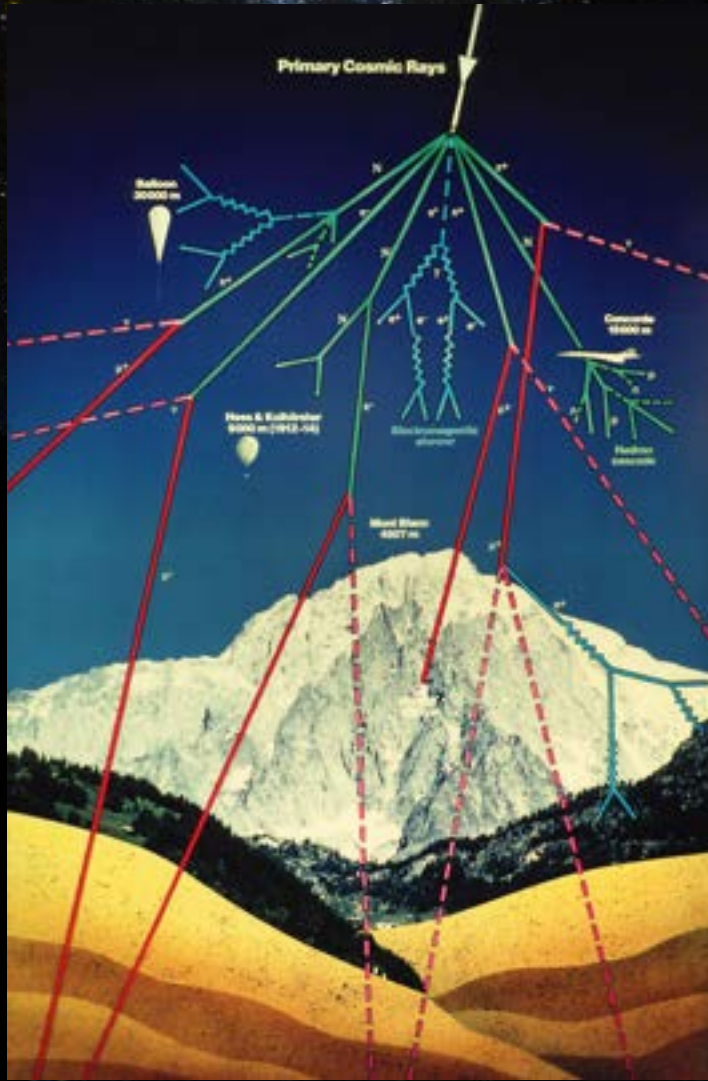


IMB (USA)



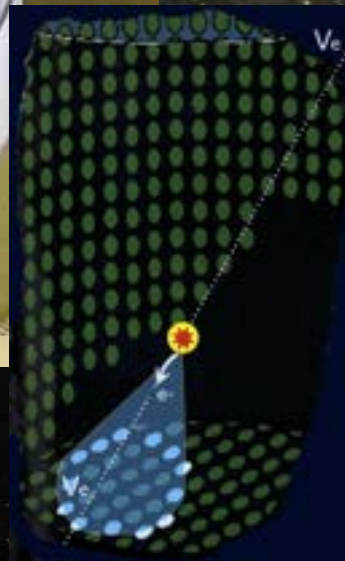
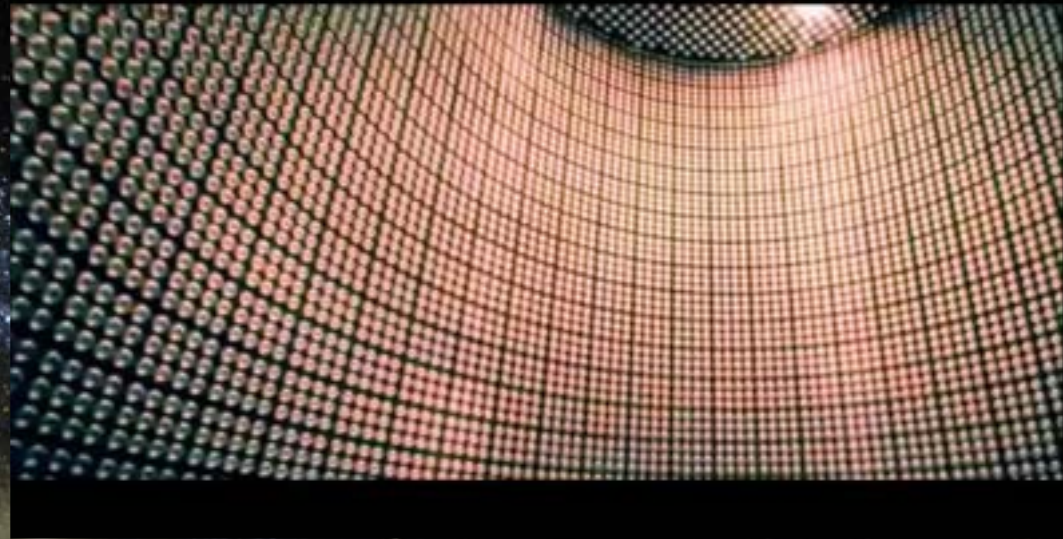
Taup (France)

Les neutrinos produits dans l'atmosphère



Il manque 40 % de neutrinos par rapport aux prédictions

SuperKamiokande (Japon)



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

Muons

$\nu_\mu \rightarrow \mu$

Electron

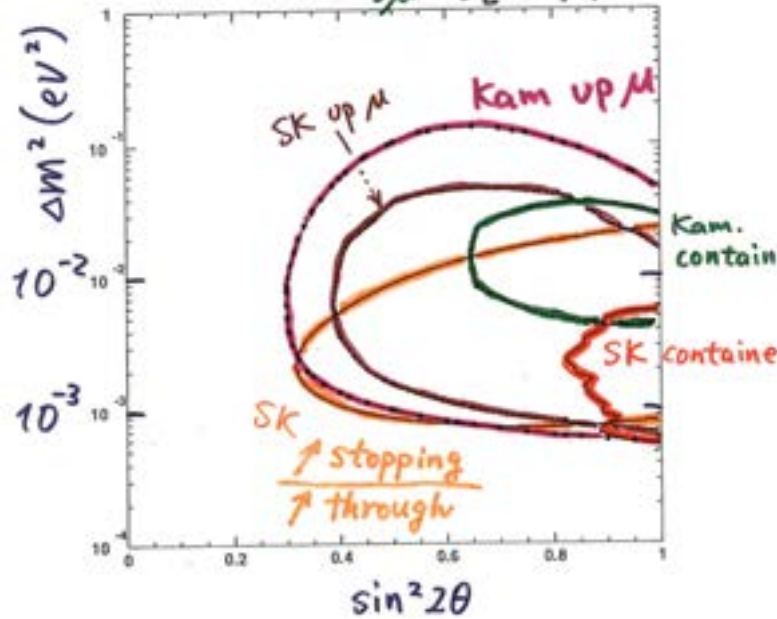
$\nu_e \rightarrow e^-$

Summary

1998

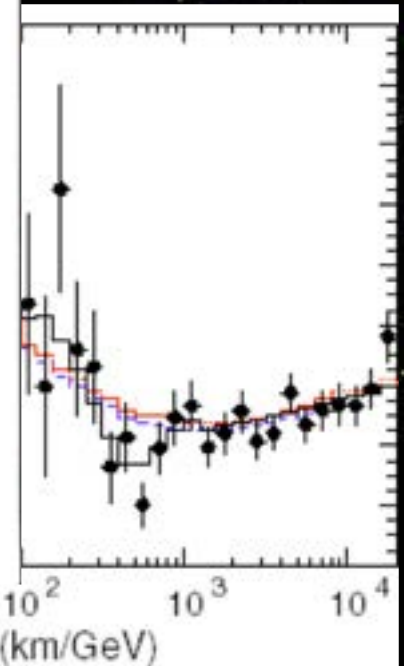
Evidence for ν_μ oscillations

$\nu_\mu \rightarrow \nu_e$ 90% C.L.

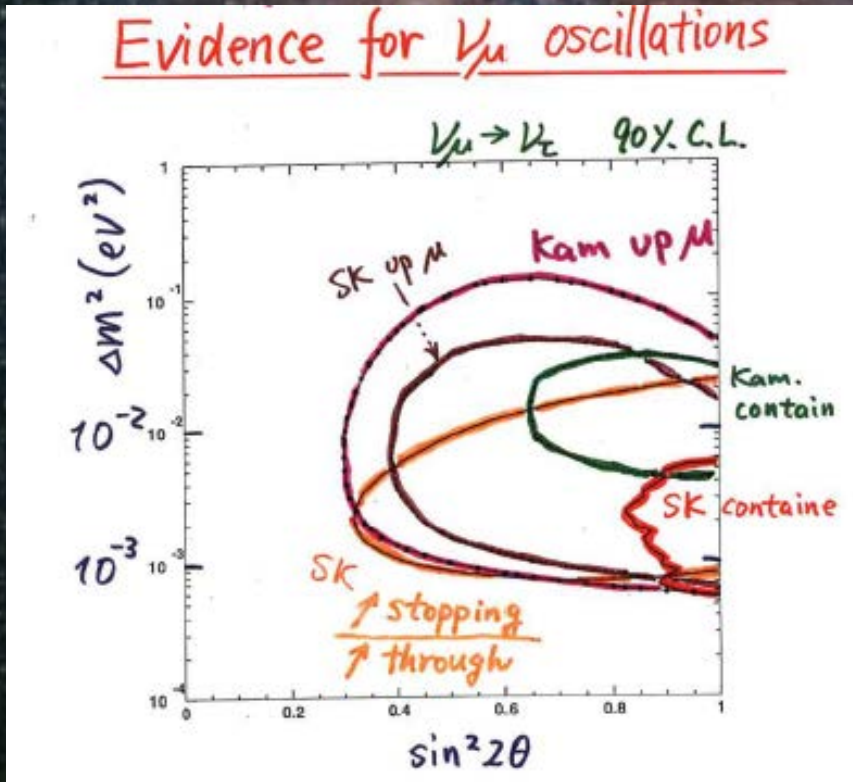


- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

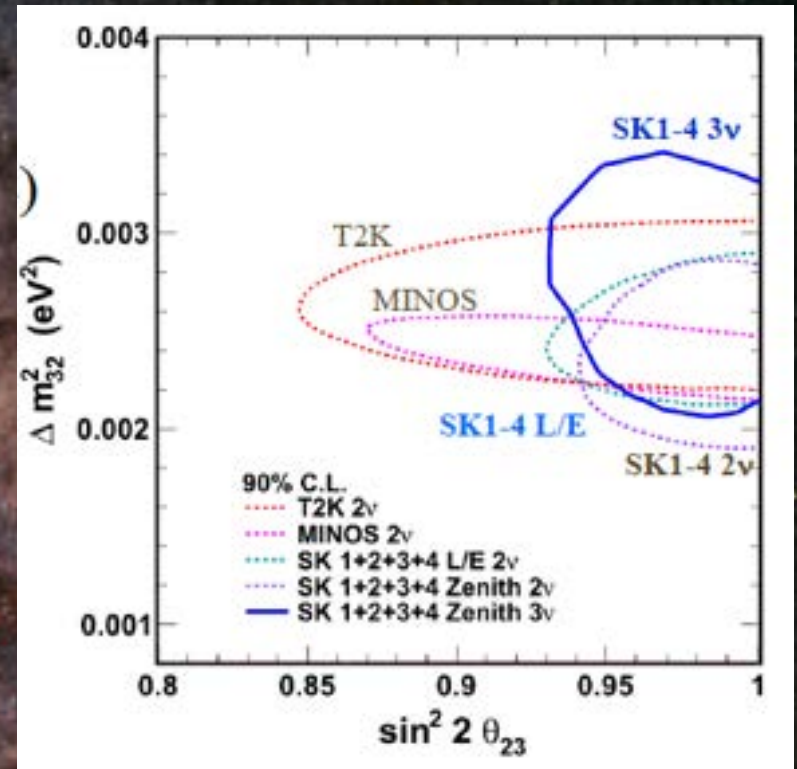
(• $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_s$?)



1998

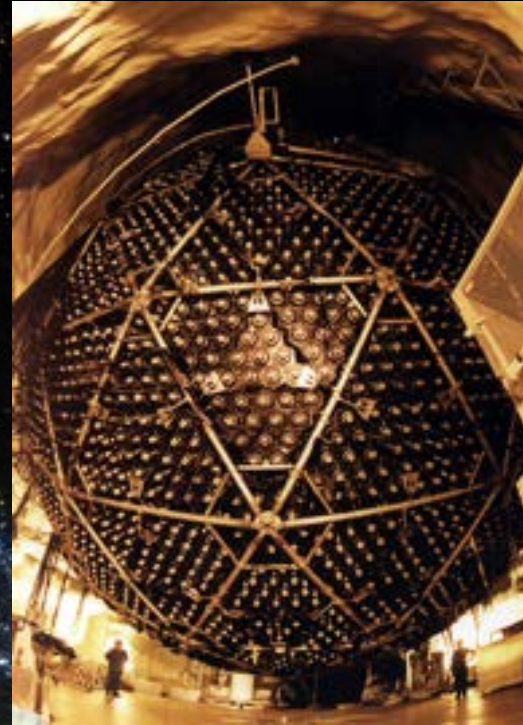
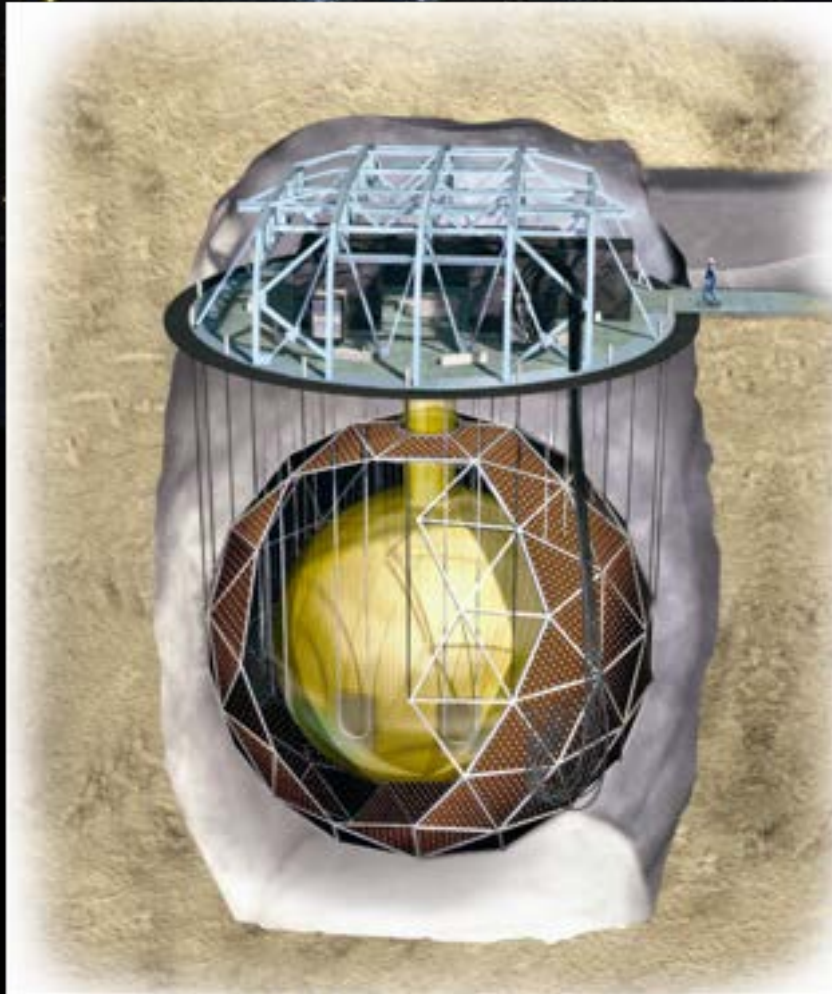


2012



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

Détecteur SNO

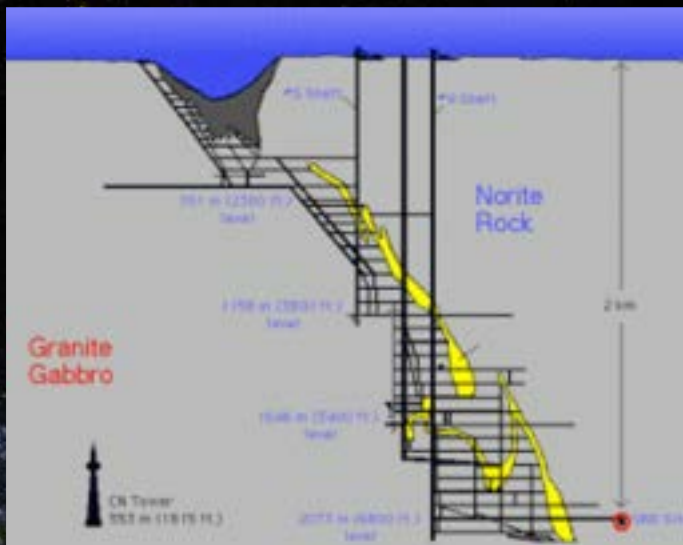
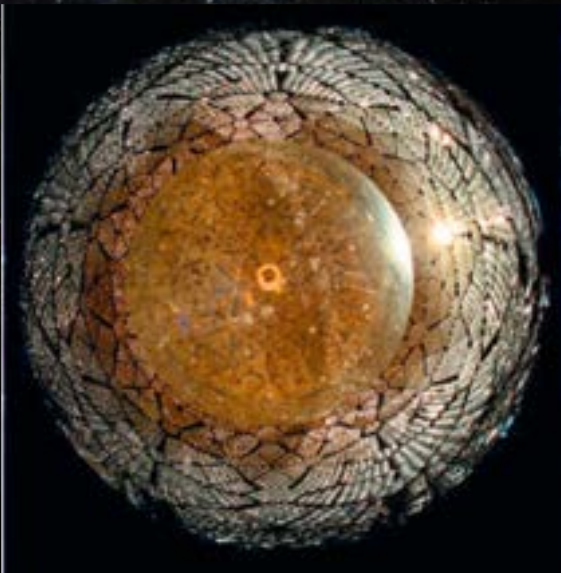


12 m de diamètre

1000 tonnes d'eau lourde (D_2O)

10 000 Photomultiplicateurs

Mesure des neutrinos solaires: flux de ν_e et flux total



$$\nu_x + e^- \rightarrow e^- + \nu_x$$

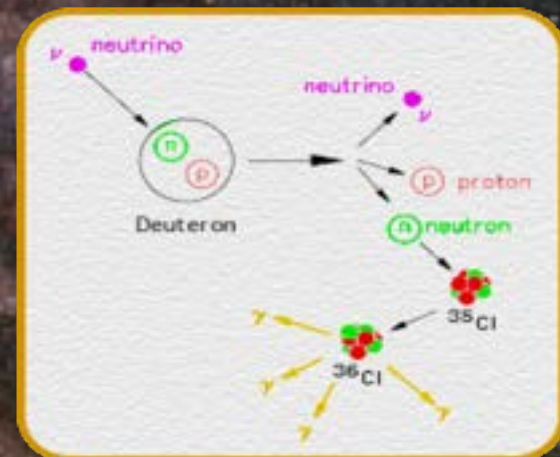
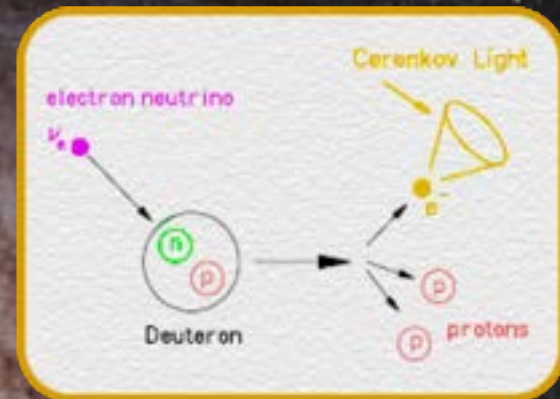
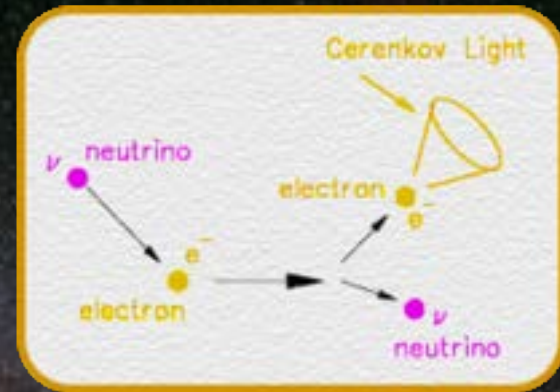
Sensible à tous les types de neutrinos mais
6 fois plus sensible pour les ν_e

$$\nu_e + d \rightarrow p + p + e^-$$

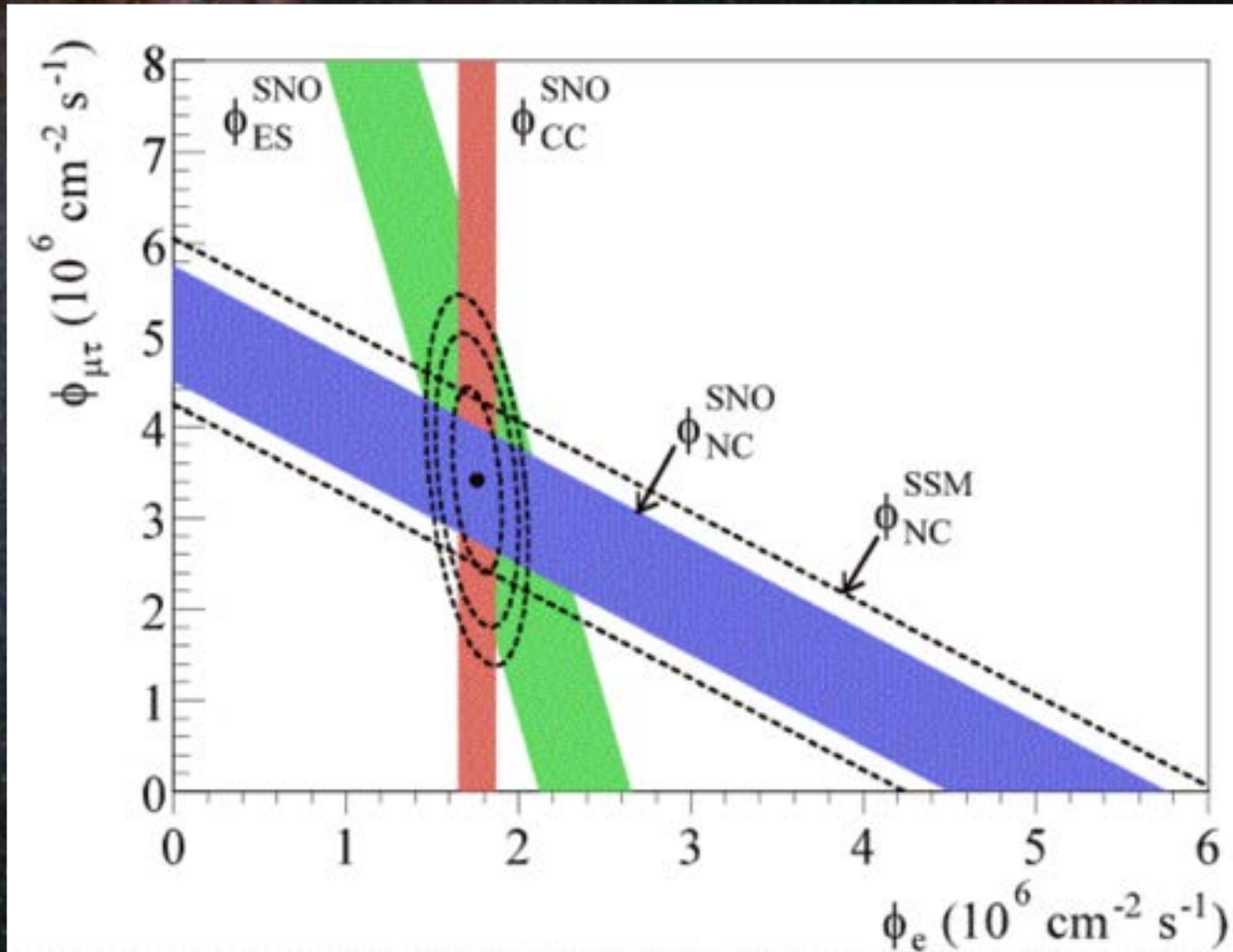
Sensible uniquement aux ν_e

$$\nu_x + d \rightarrow p + n + \nu_x^-$$

Sensible aux 3 saveurs



Résultats de SNO



Le flux total mesuré est bien le flux total prédit et il manque des neutrinos ν_e

The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



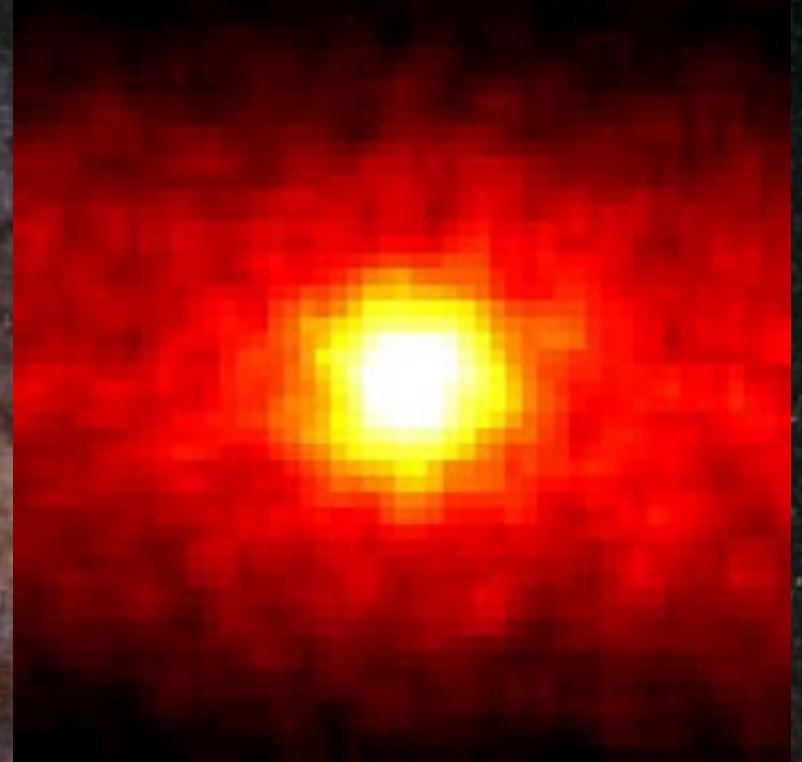
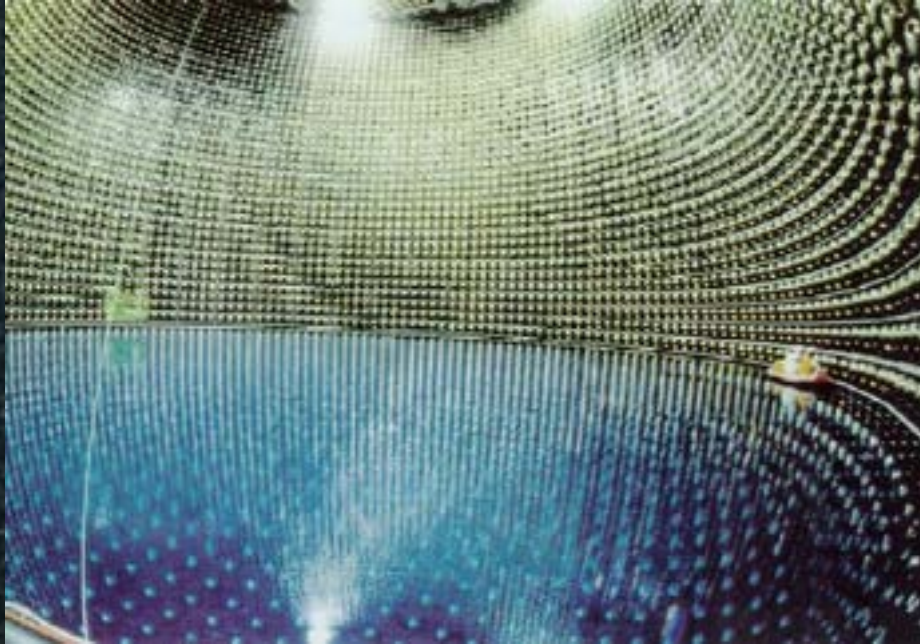
Photo: K. MacFarlane,
Queen's University
/SNOLAB

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'astronomie neutrino



Temps de pose : 365 jours

1000 m sous terre

Poids de l'appareil: 50 000 tonne d'eau

10 000 pixels

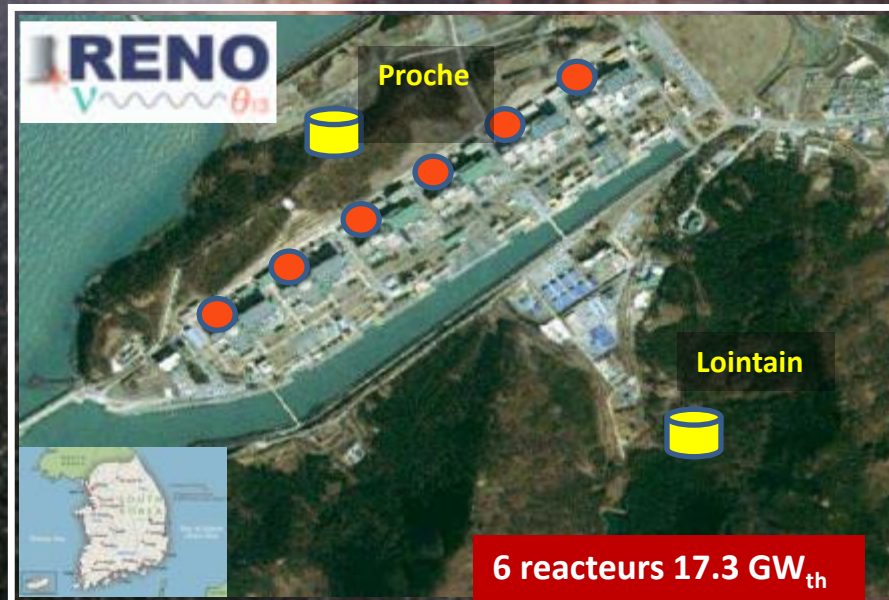
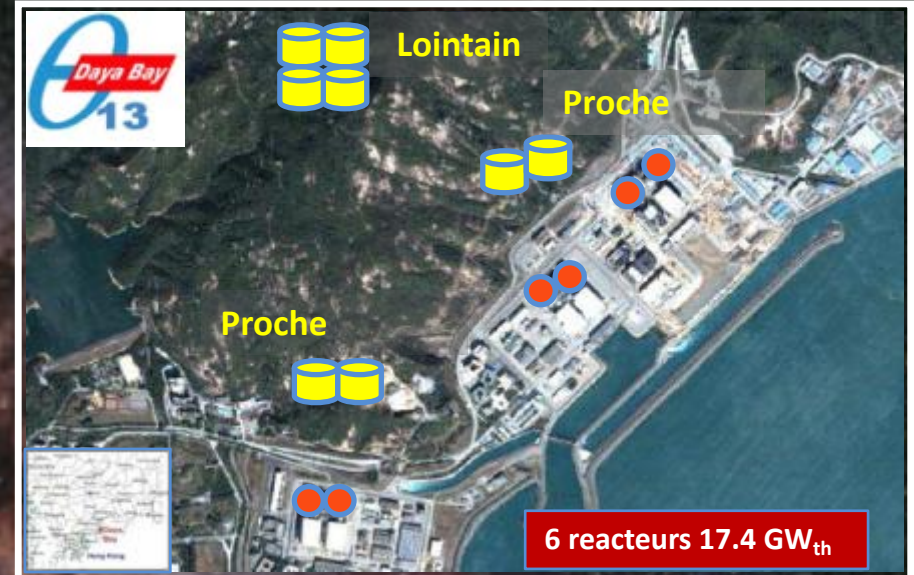
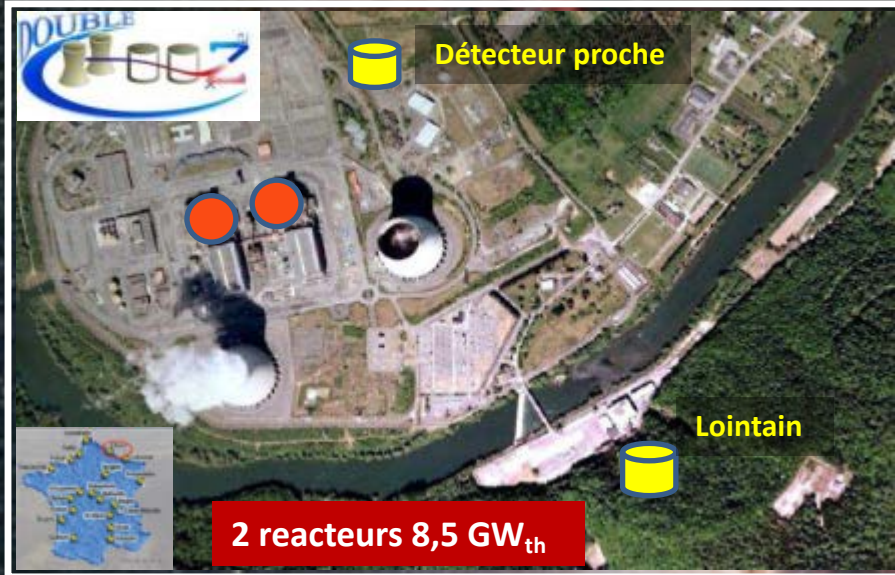
1987: détection des neutrinos venant de SN1987 A

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

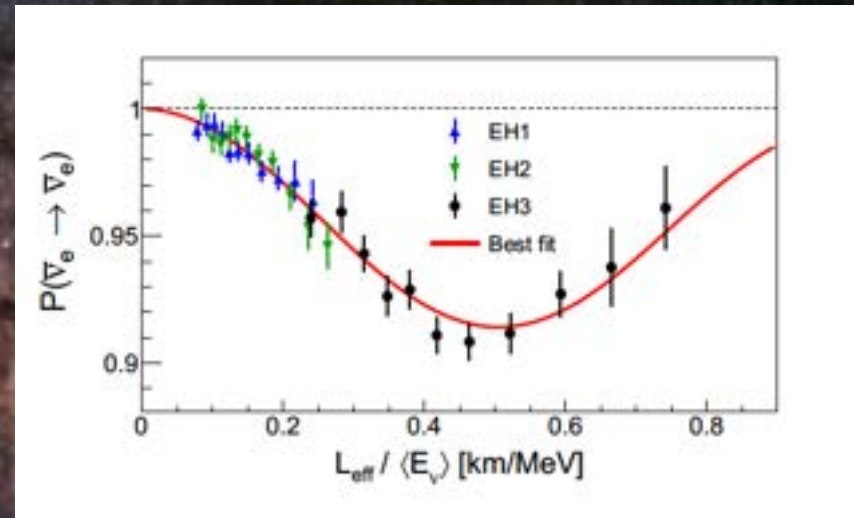
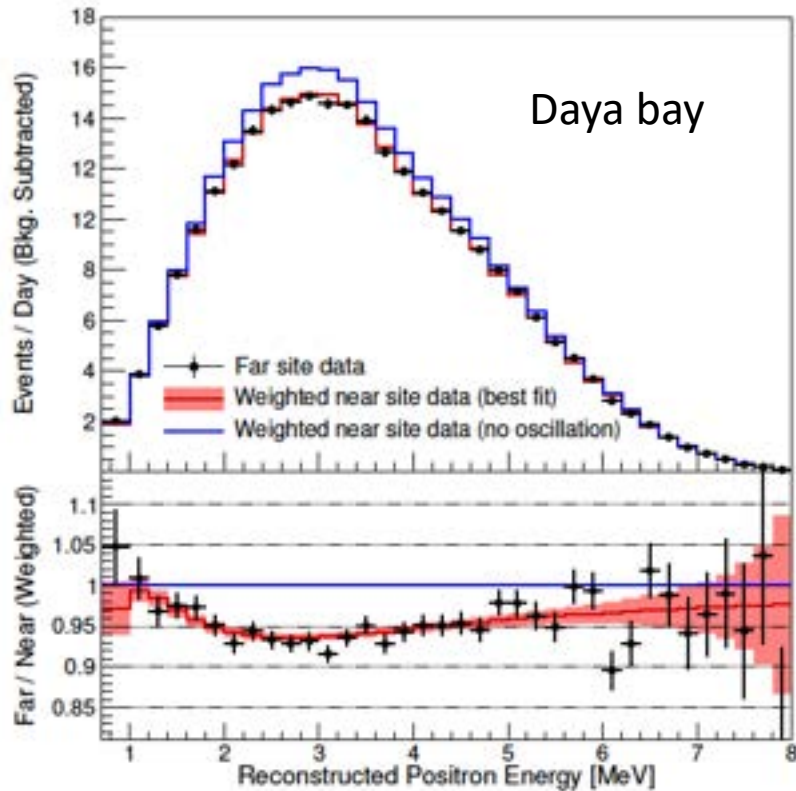


Vues par 3 détecteurs dans le monde, Quelques événements en 10 s

Mesure de l'angle Theta13



Mesure de l'angle Theta13



$$\theta_{13} \sim 8.8^\circ$$

Des mesures de précision

Neutrinos solaires et réacteurs

parameter	best fit $\pm 1\sigma$
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	$7.60^{+0.19}_{-0.18}$

Neutrinos atmosphériques et accélérateurs

$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$	$2.48^{+0.05}_{-0.07}$
---	------------------------

Neutrinos solaires et réacteurs

$\theta_{12}/^\circ$	34.6 ± 1.0
----------------------	----------------

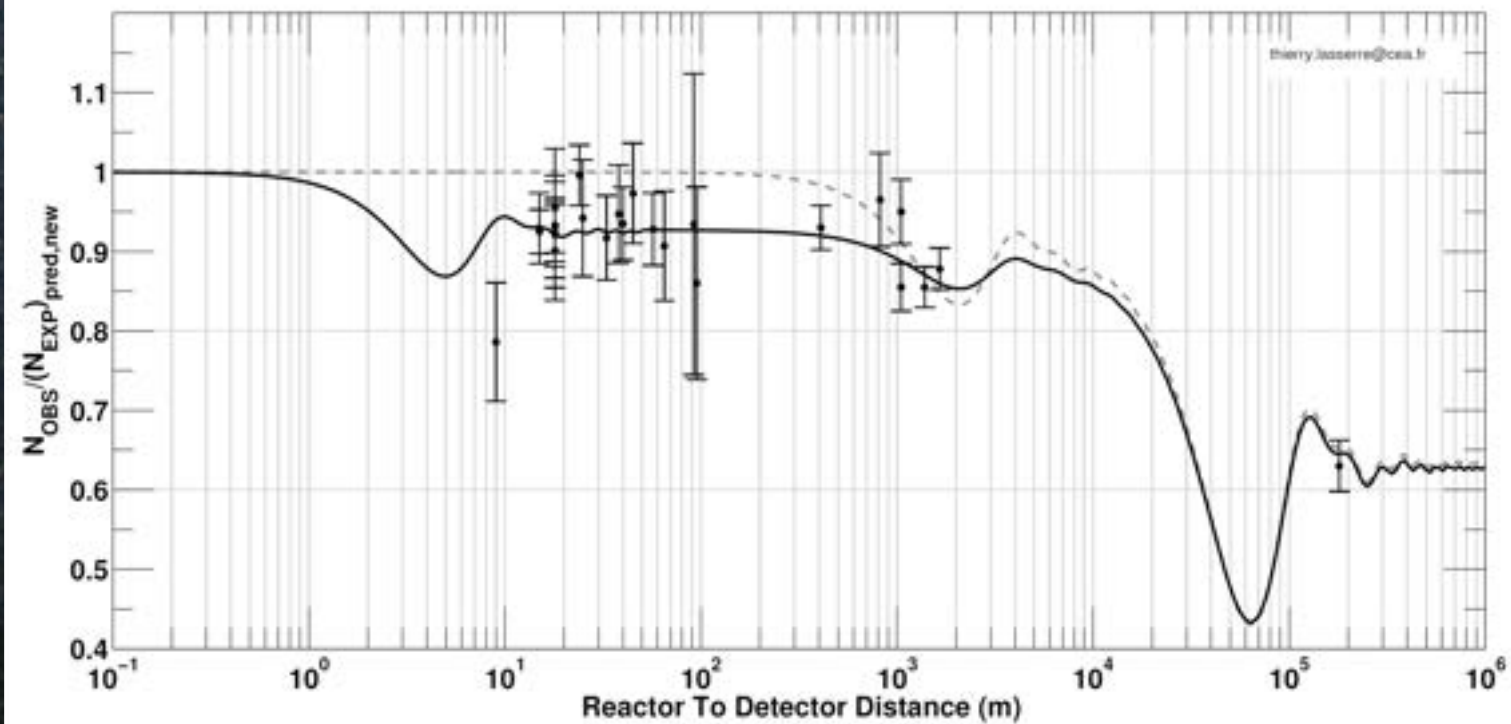
Neutrinos atmosphériques et accélérateurs

$\theta_{23}/^\circ$	$48.9^{+1.9}_{-7.4}$
----------------------	----------------------

Neutrinos réacteurs

$\theta_{13}/^\circ$	8.8 ± 0.4
----------------------	---------------

Une anomalie ?



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

Nature ?

Masse absolue ?

Hiérarchie de masse ?

Violation de CP ?

Comment il acquière sa masse ?

Est-il composite ?

Moment magnétique ?

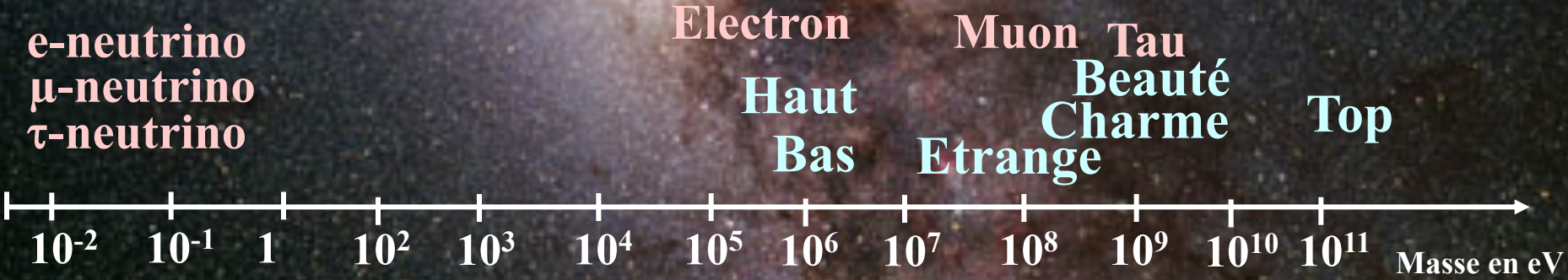
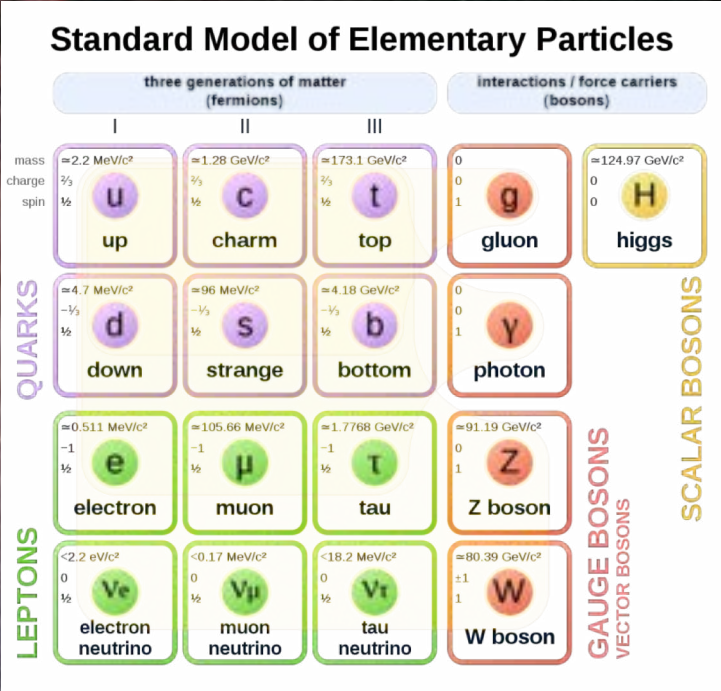
Moment électrique ?

Courant droit de l'interaction faible ?

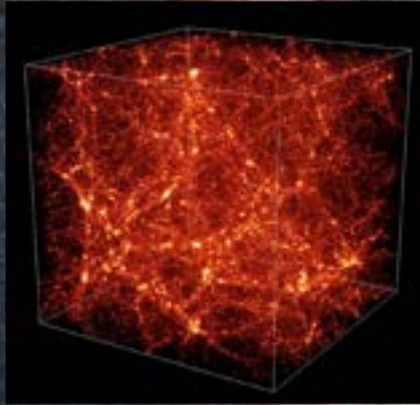
Neutrinos stériles ?

.....

Une énigme: la masse du neutrino



Une masse mais laquelle ?

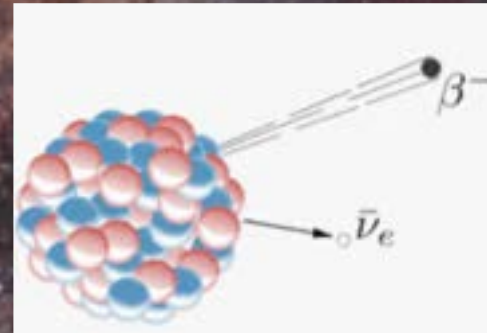


Etudes des structures à grande échelle

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

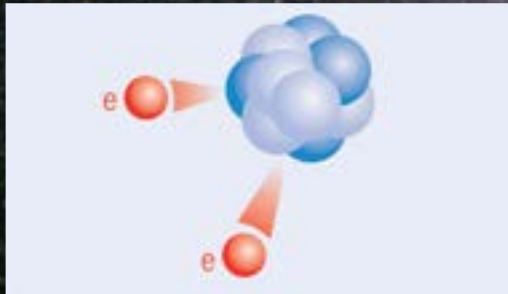
Désintégration bêta

$$m(\nu_e) < 0,8 \text{ eV}$$

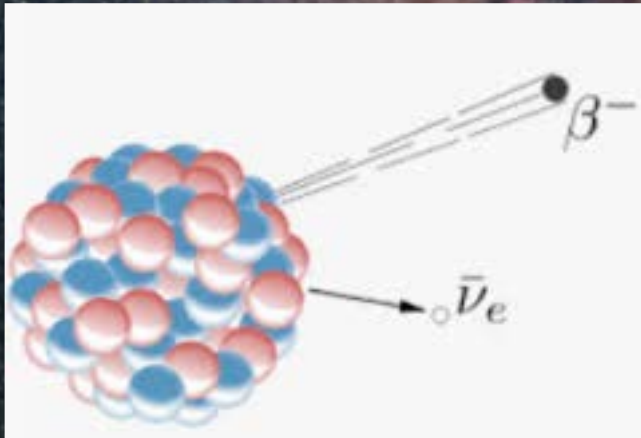


Double Désintégration bêta

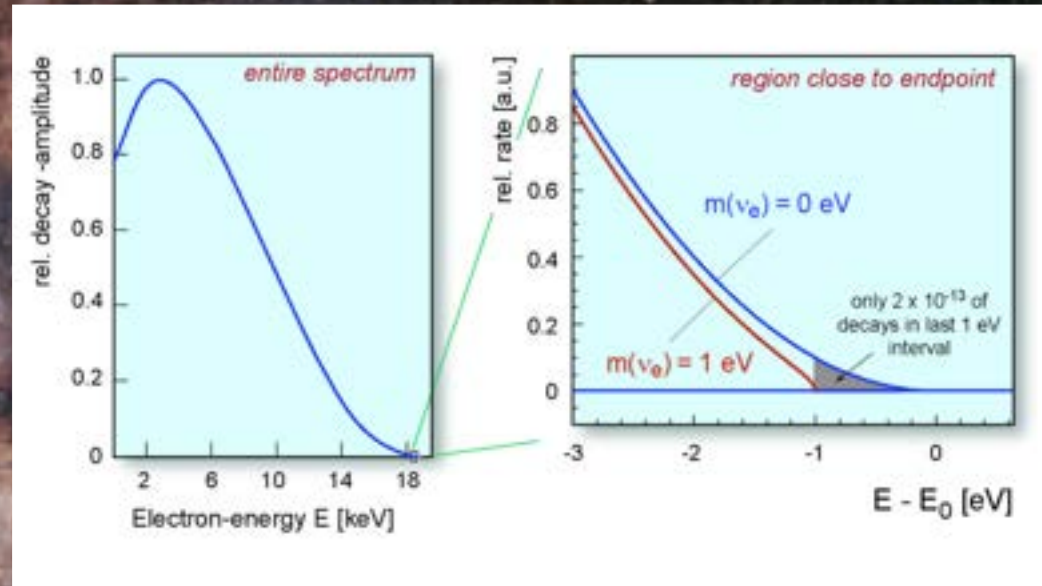
$$\langle m \rangle < 0,08 - 0,2 \text{ eV}$$



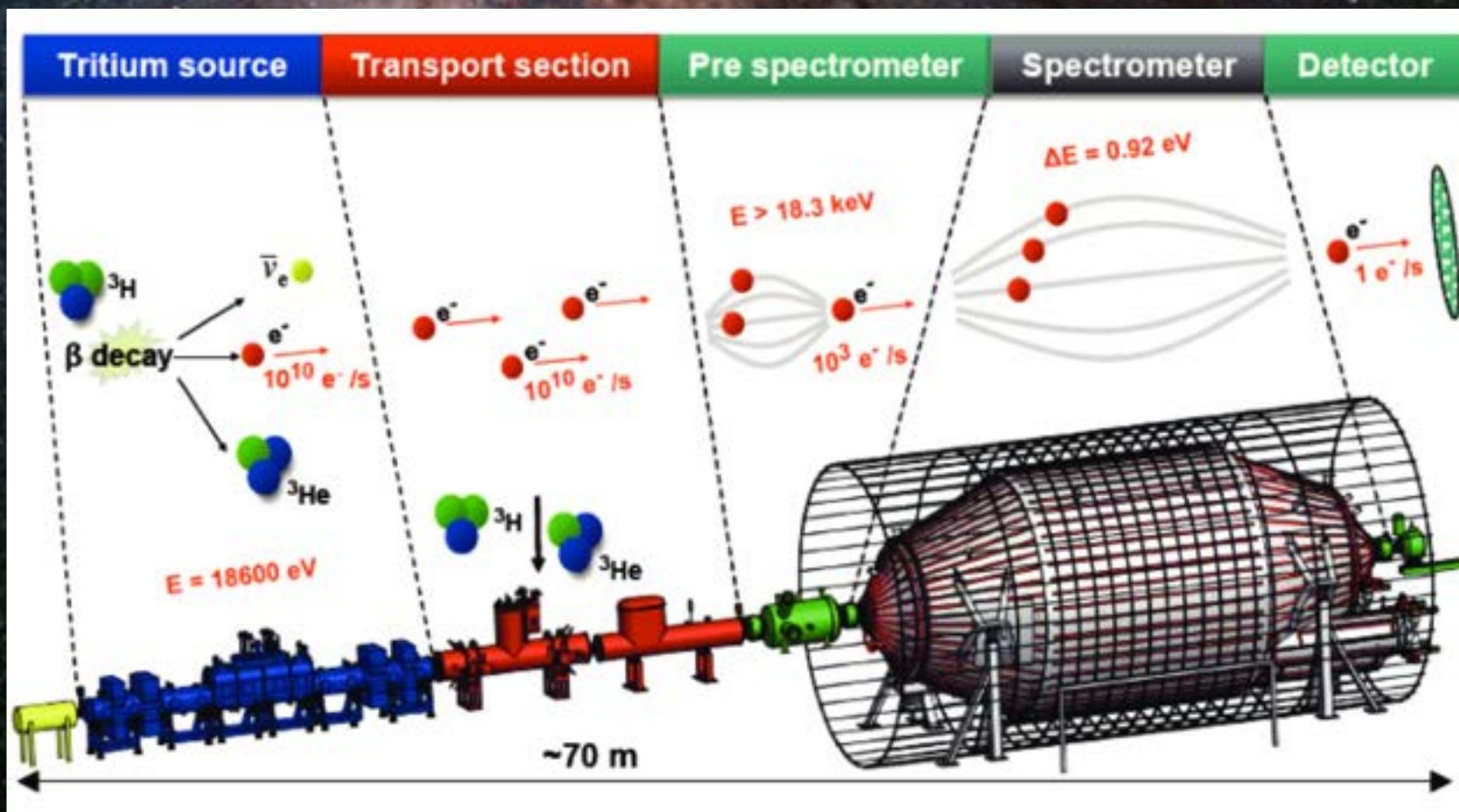
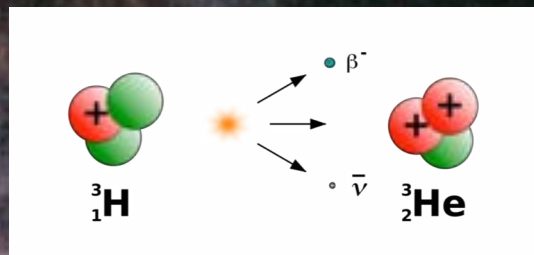
La balance radioactive



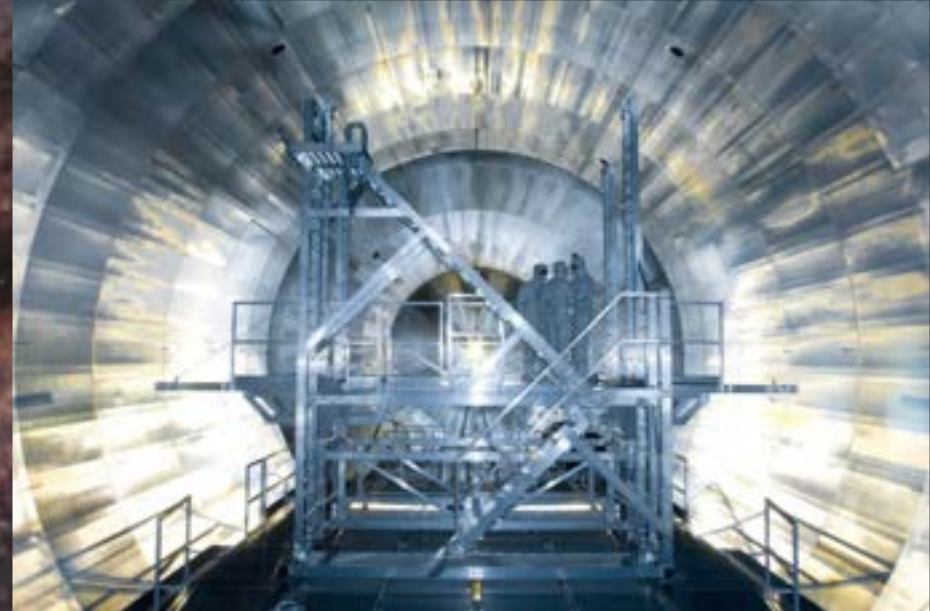
Désintégration bêta



L'expérience KATRIN

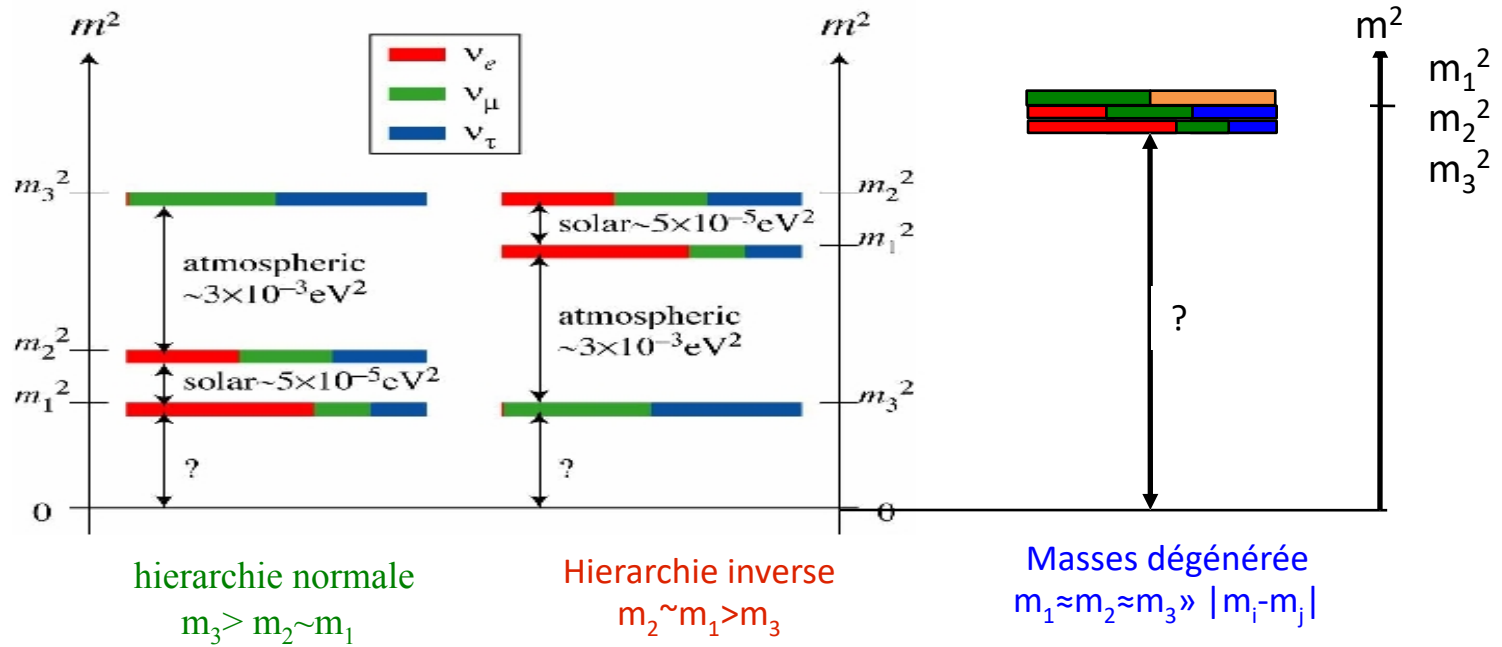


L'expérience KATRIN

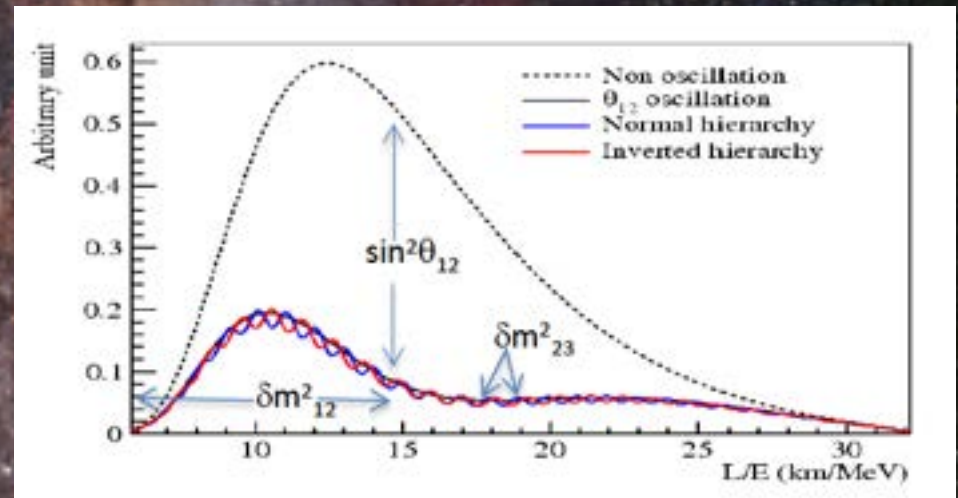
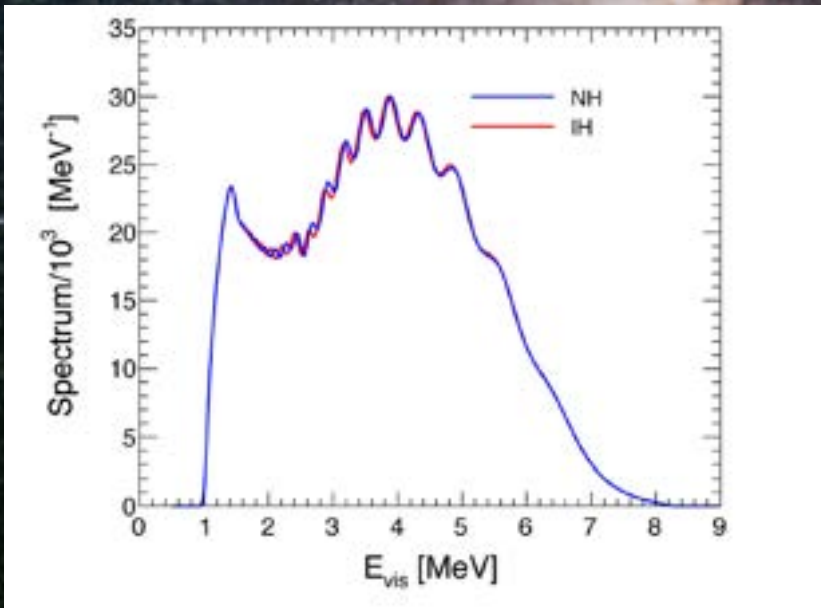
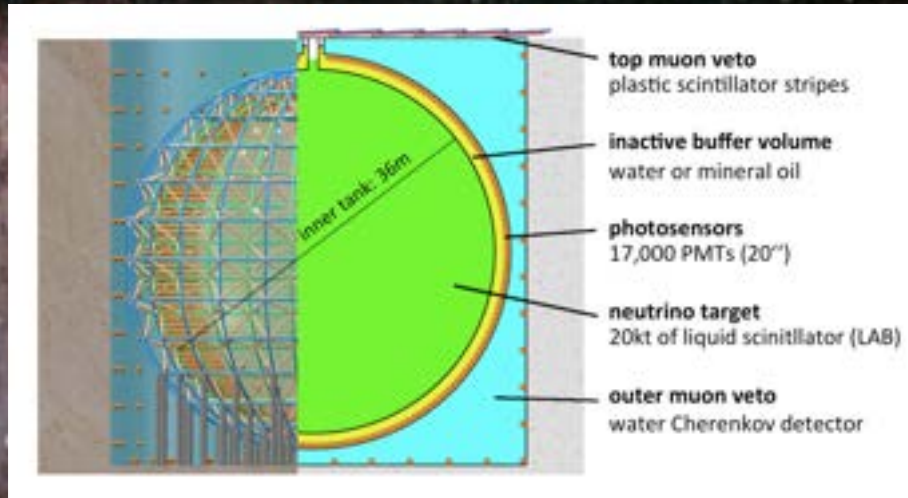


$$m(\nu_e) < 0,8 \text{ eV}$$

Hiérarchie de masse ?



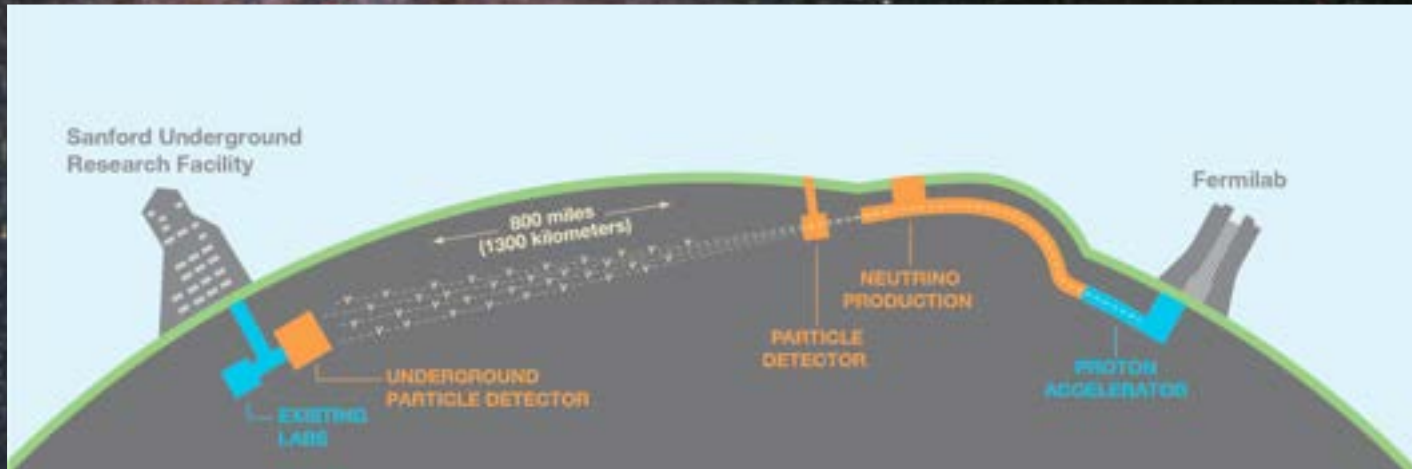
JUNO (Chine): Hiérarchie de masse



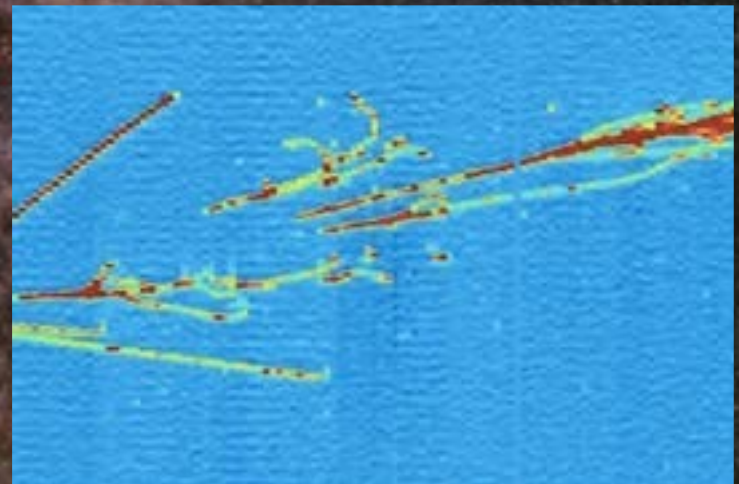
Peut aussi être mesuré avec neutrinos accélérateurs ou neutrinos cosmiques

DUNE : Violation de CP

Probabilité d'oscillation différentes pour neutrino et anti-neutrino



Détecteur argon liquide





La nature du neutrino ?

Mesurer la masse du neutrino sans neutrino

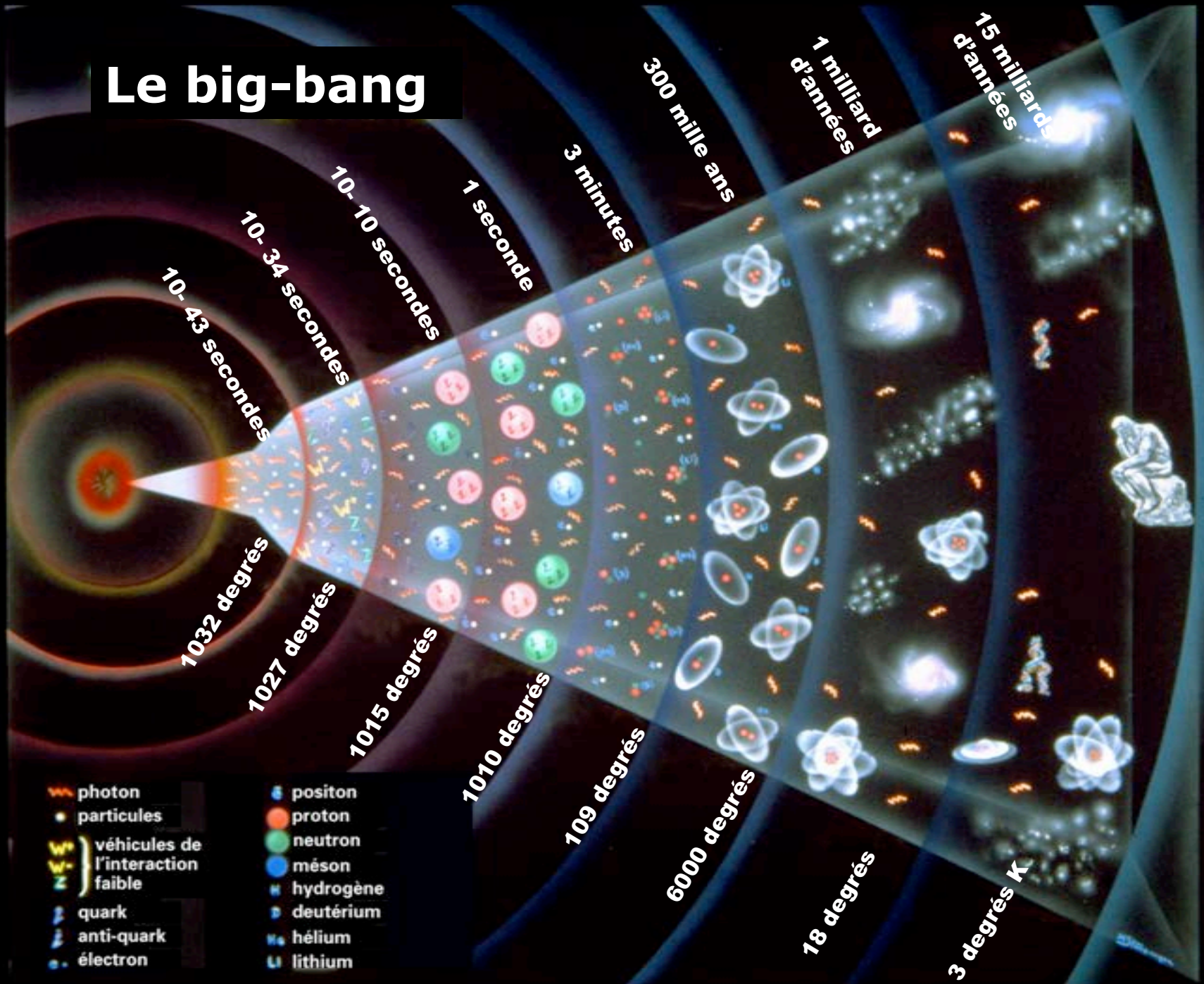


1937: Ettore Majorana

Neutrino = anti-neutrino ?

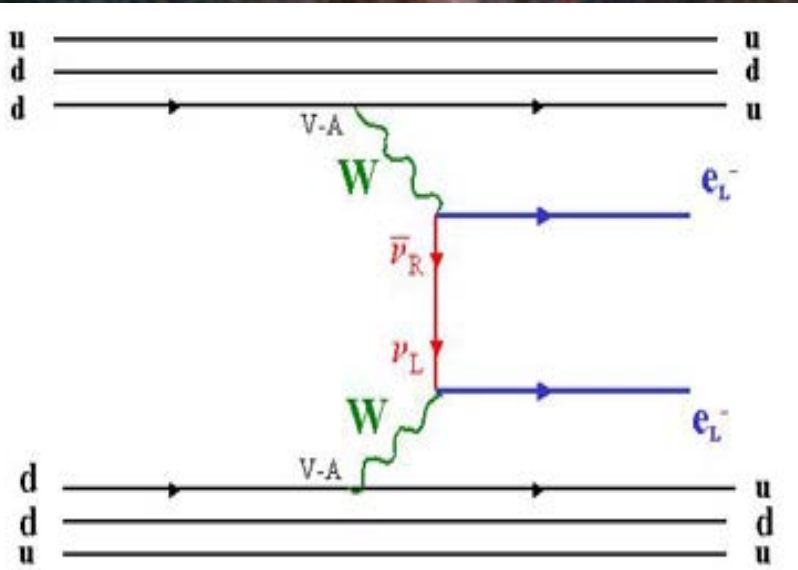
Le neutrino est-il à l'origine de la matière ?

Le big-bang



- ☞ photon
- particules
- W⁺ } véhicules de l'interaction faible
- W⁻ }
- Z
- ☞ quark
- ☞ anti-quark
- électron
- positon
- proton
- neutron
- méson
- hydrogène
- deutérium
- hélium
- lithium

Double désintégration bêta



Phase space factor

Nuclear matrix element

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

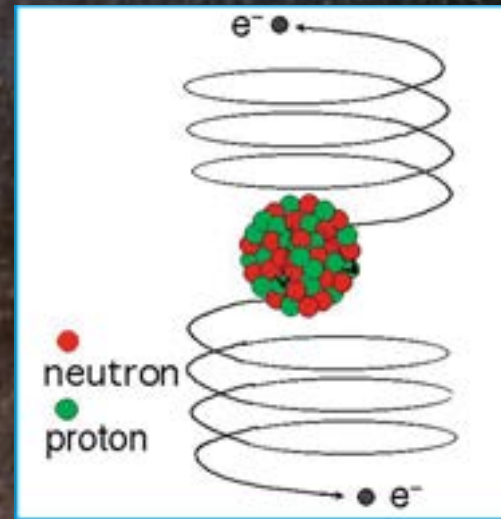
Effective mass:

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

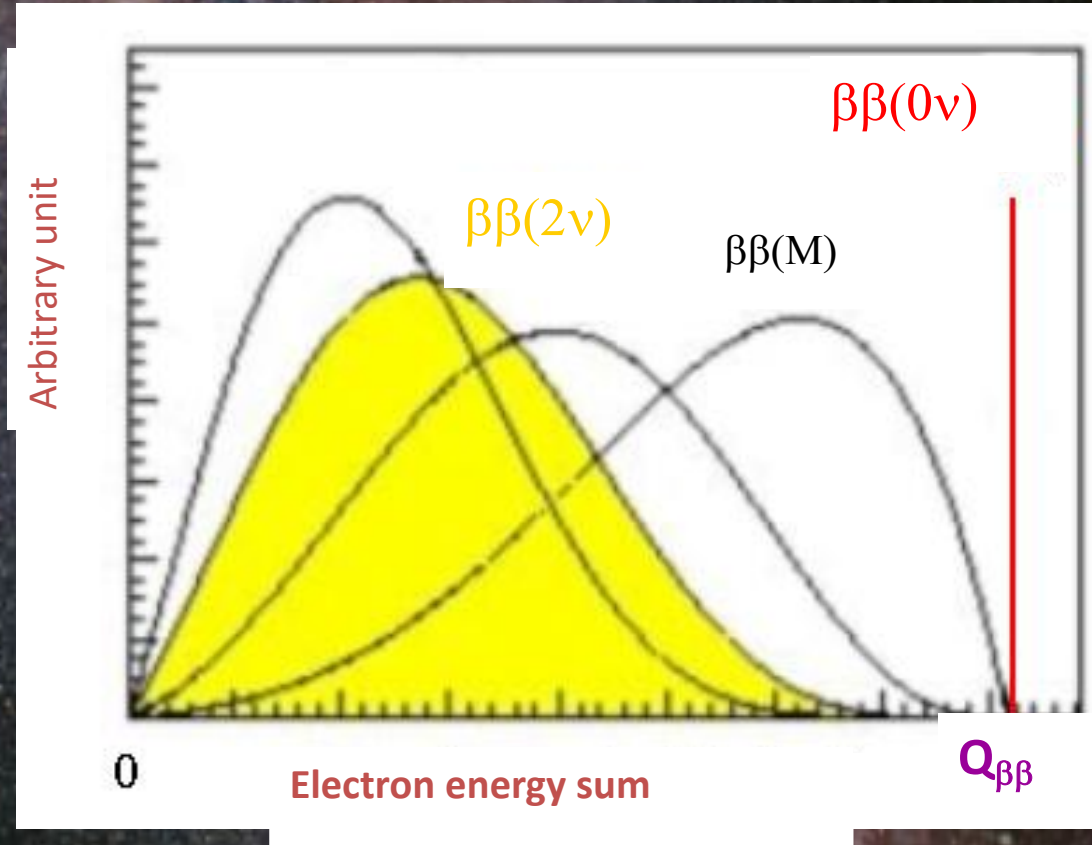
$|U_{ei}|$: mixing matrix element
 α_1 et α_2 : Majorana phase

Neutrino = anti-neutrino
 Neutrino massif

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

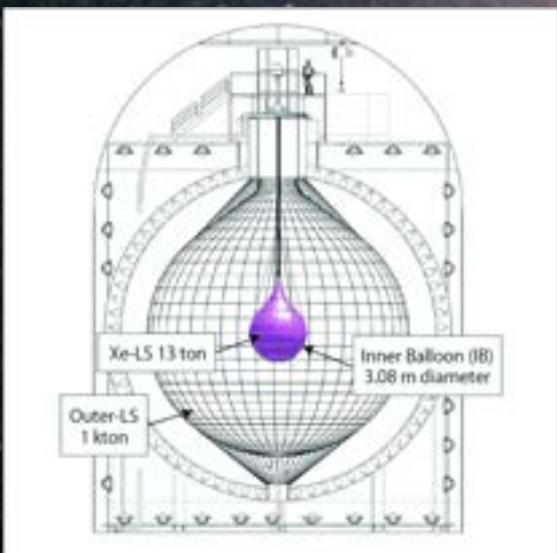
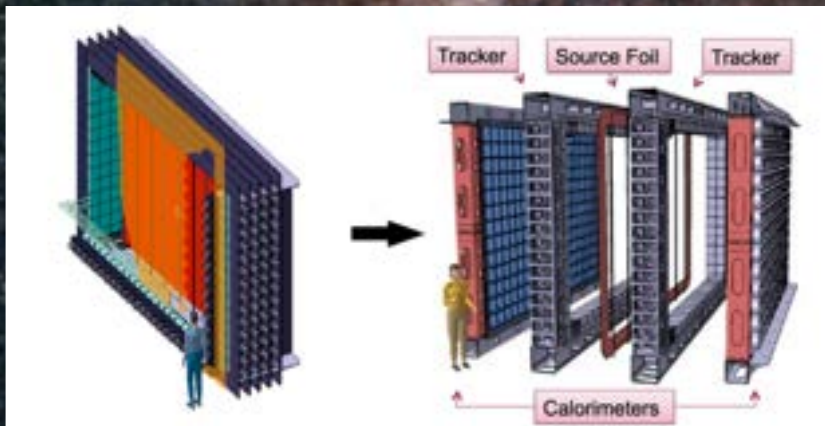


Double désintégration bêta

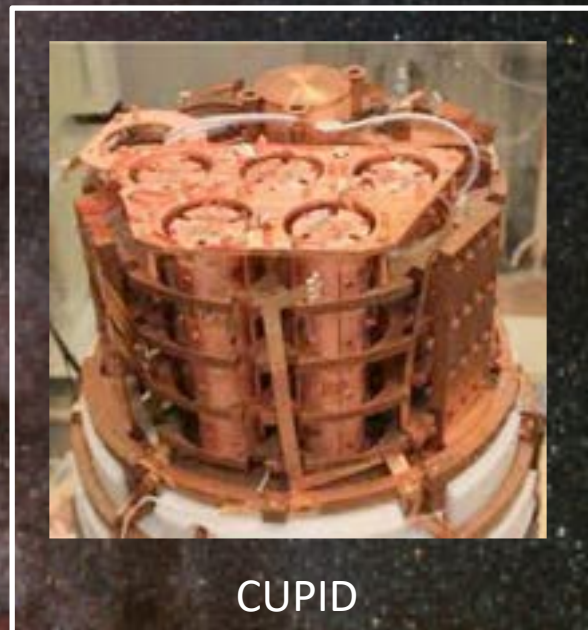


Détecteurs pour la recherche de la Double désintégration bêta

SuperNEMO



KamLAND-Zen

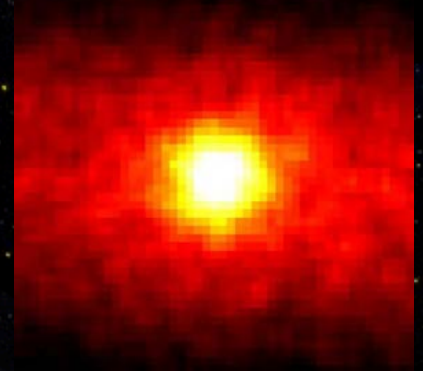


CUPID

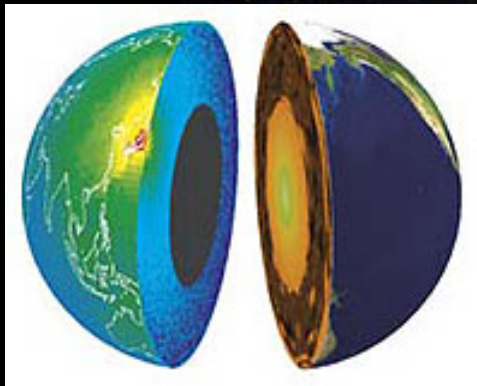
Masse, nature, oscillation,
violation CP, neutrino stérile,...

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

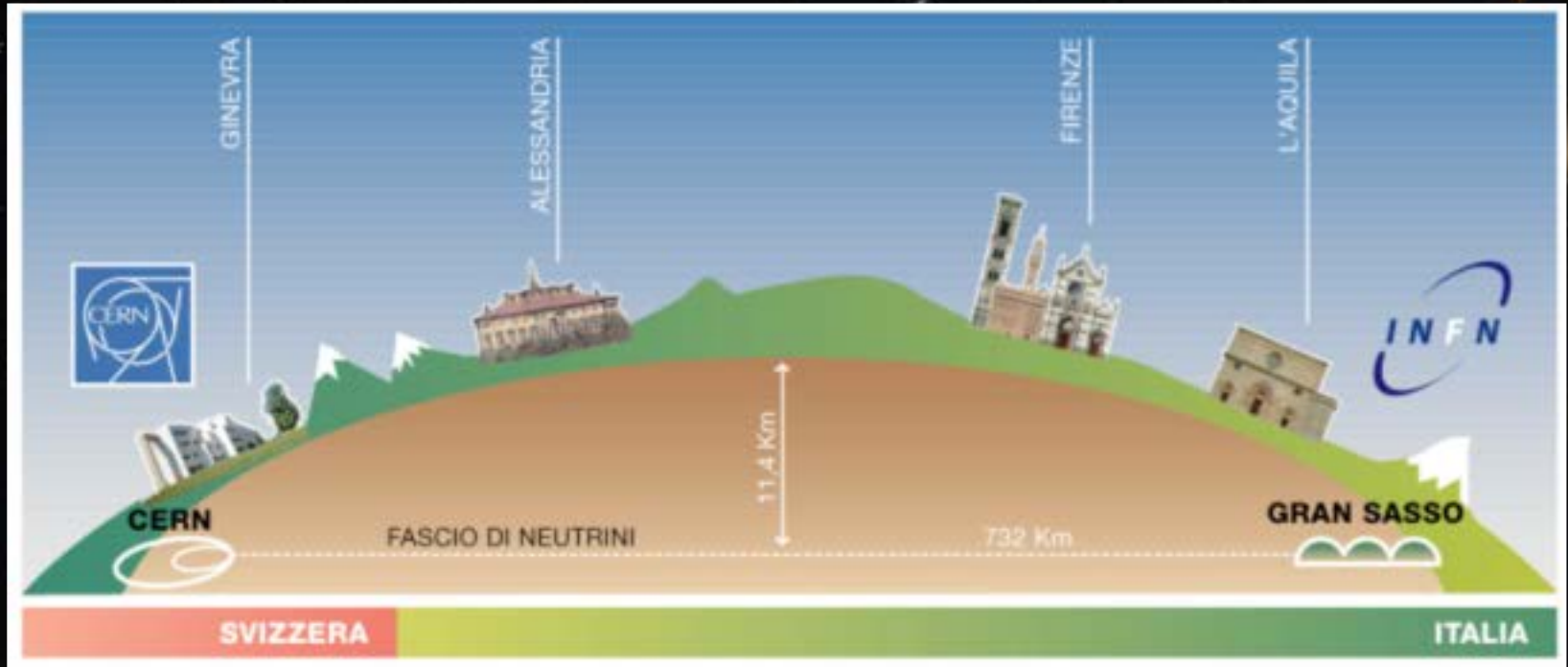


A vibrant nebula in space, featuring a large, glowing cloud of gas and dust. The nebula is primarily yellow and orange, with a bright blue and cyan glow at its top. The background is a dark, deep blue space filled with numerous small, bright stars. Two prominent stars with purple and pink flares are visible in the upper left and lower right corners. A large, white, sans-serif number is overlaid in the center of the image.

270 000 000 000 000 000

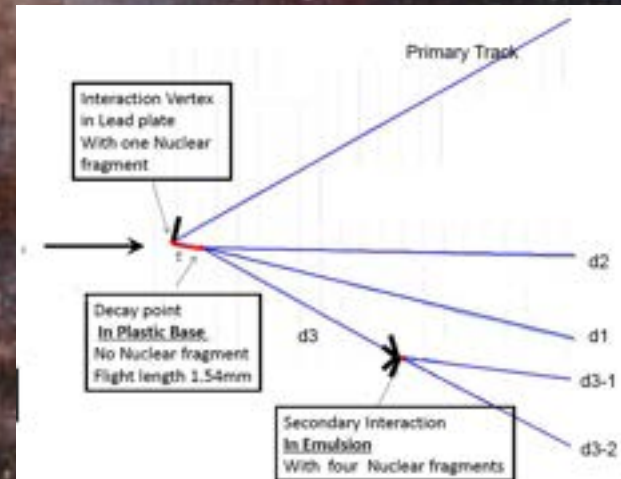
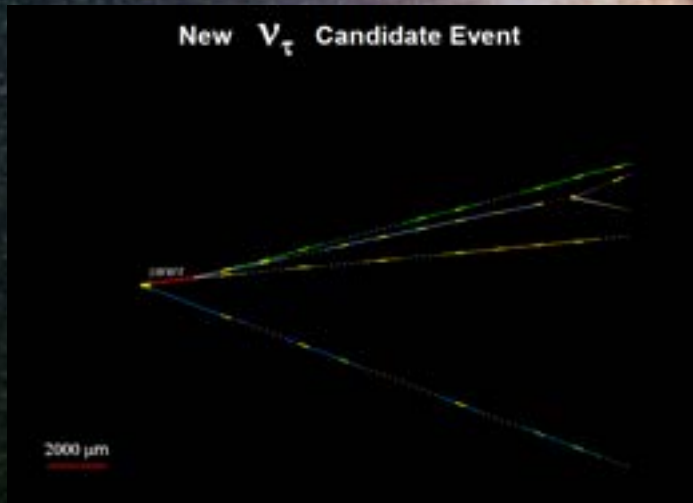
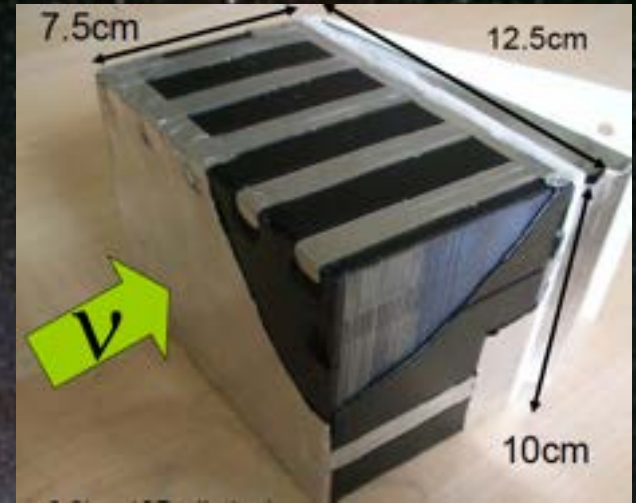
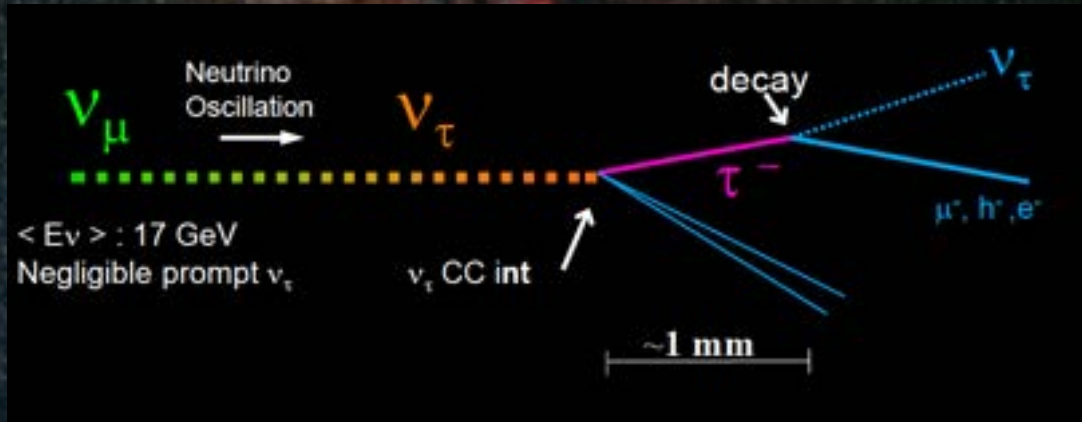


L'expérience OPERA

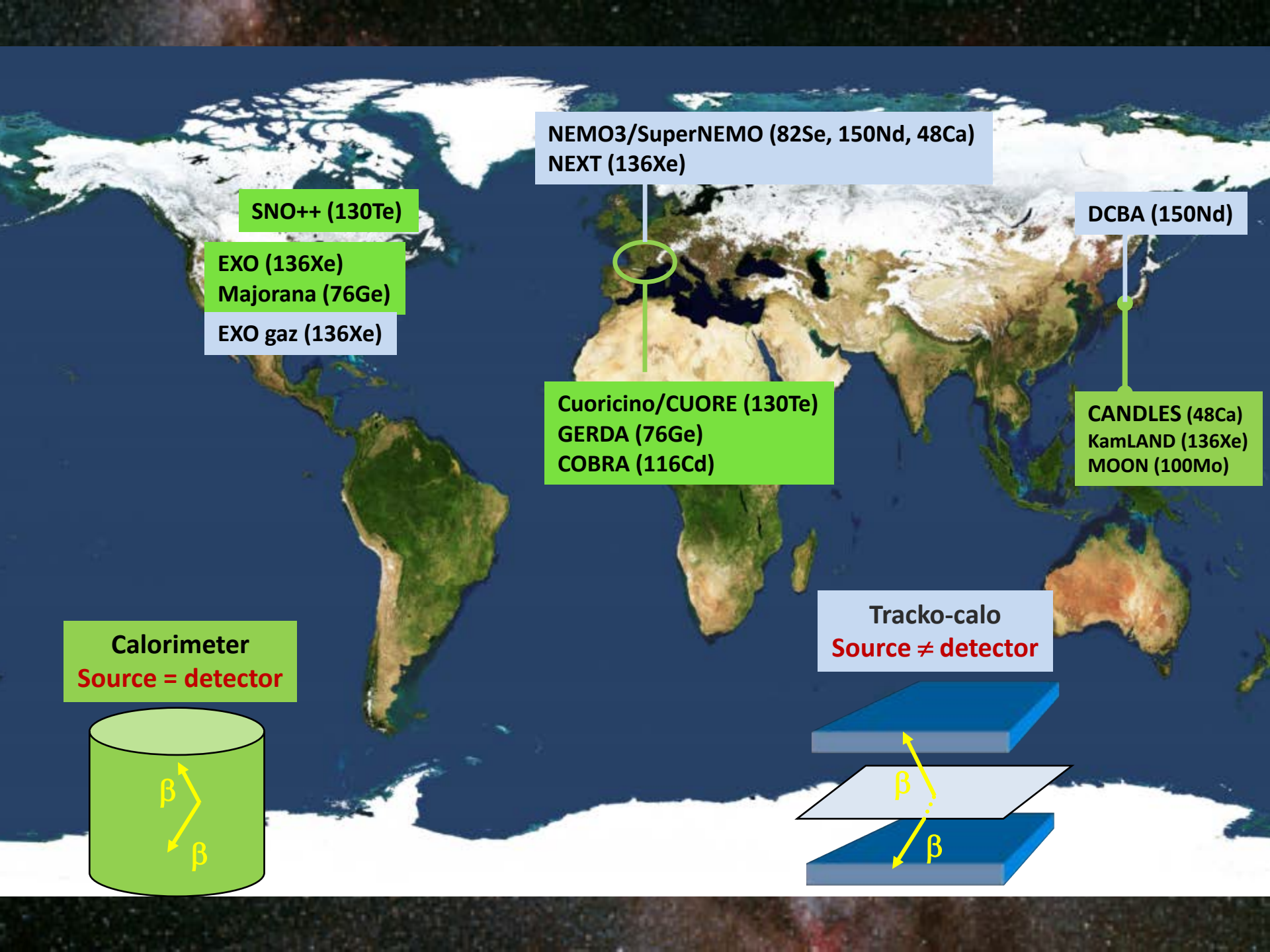


Apparition du neutrino tau dans un faisceau de neutrino mu





10 événements détectés



NEMO3/SuperNEMO (82Se, 150Nd, 48Ca)
NEXT (136Xe)

SNO++ (130Te)

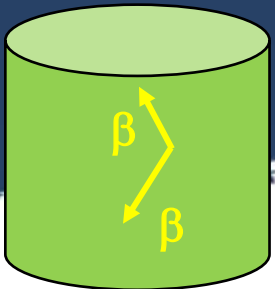
EXO (136Xe)
Majorana (76Ge)
EXO gaz (136Xe)

DCBA (150Nd)

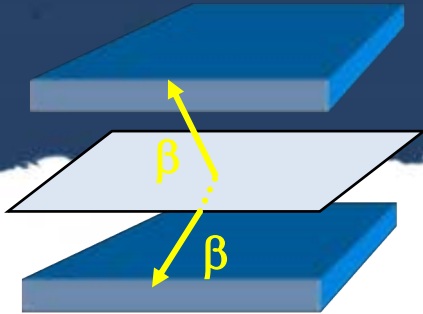
Cuoricino/CUORE (130Te)
GERDA (76Ge)
COBRA (116Cd)

CANDLES (48Ca)
KamLAND (136Xe)
MOON (100Mo)

Calorimeter
Source = detector



Tracko-calo
Source ≠ detector





Laboratoire Souterrain de Modane



Image © 2010 DigitalGlobe

WWW.LSM.FR

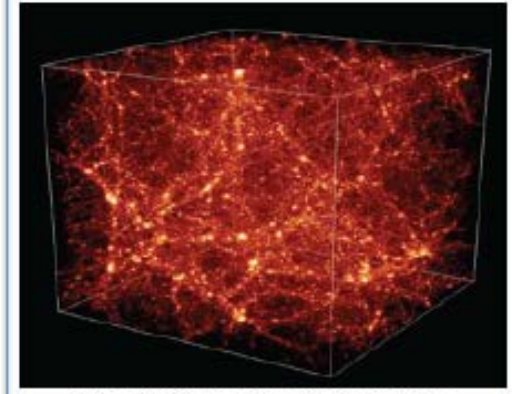
Les activités scientifiques au LSM



Création de la matière



Recherche de la matière noire



Evolution de l'univers



Environnement



Nano-électronique



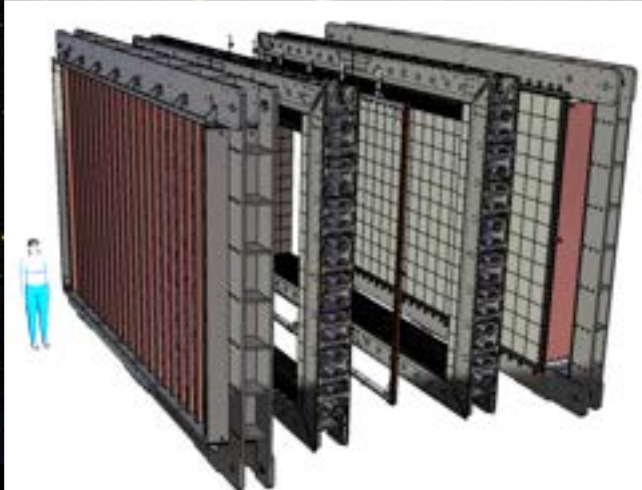
Biologie



Datation vin Bordeaux

Et aussi : climatologie, océanographie, effets de l'homme sur l'environnement, glaciologie, archéologie,....

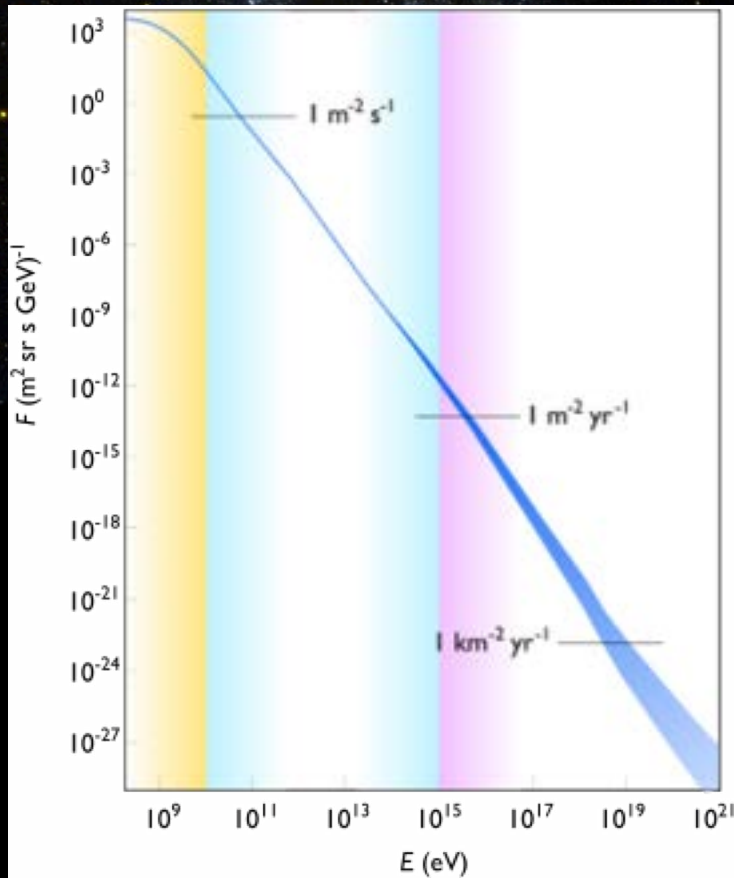
SuperNEMO



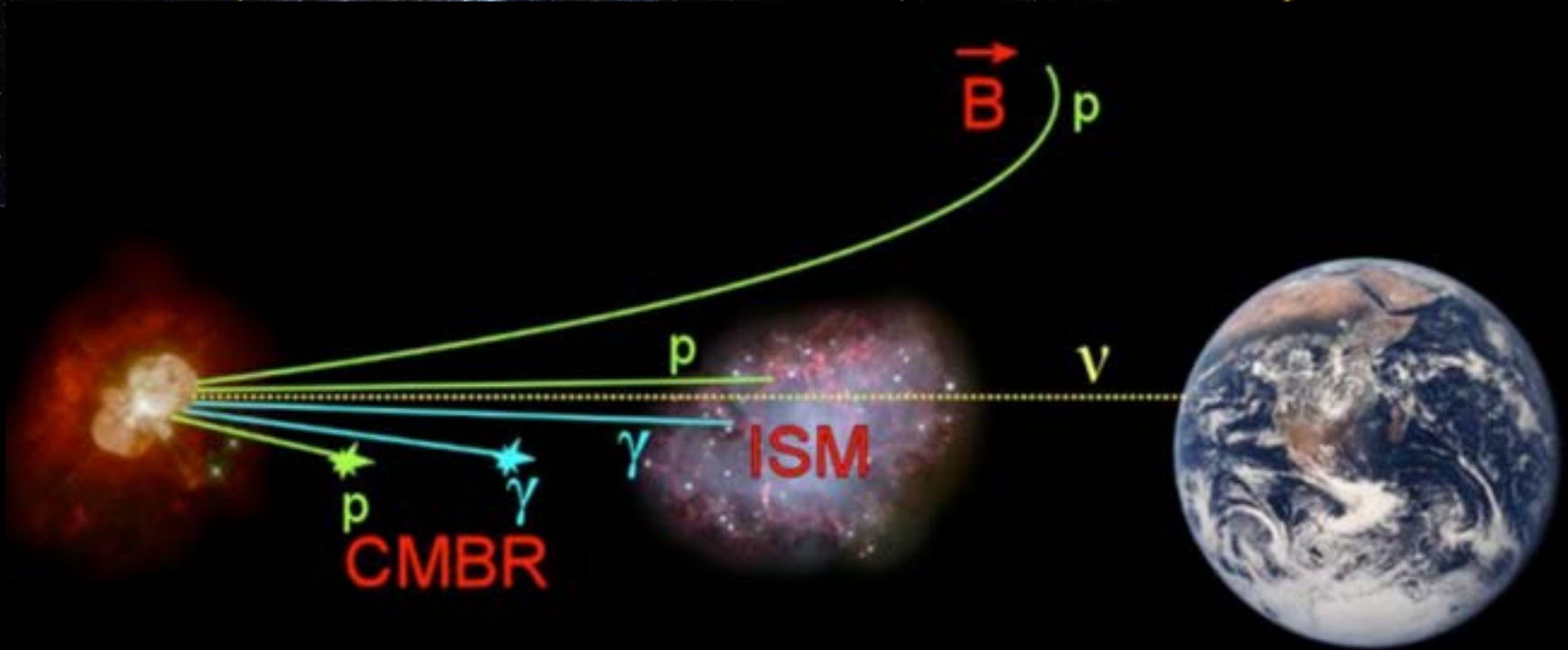
5 kg d'isotopes double bêta * 20



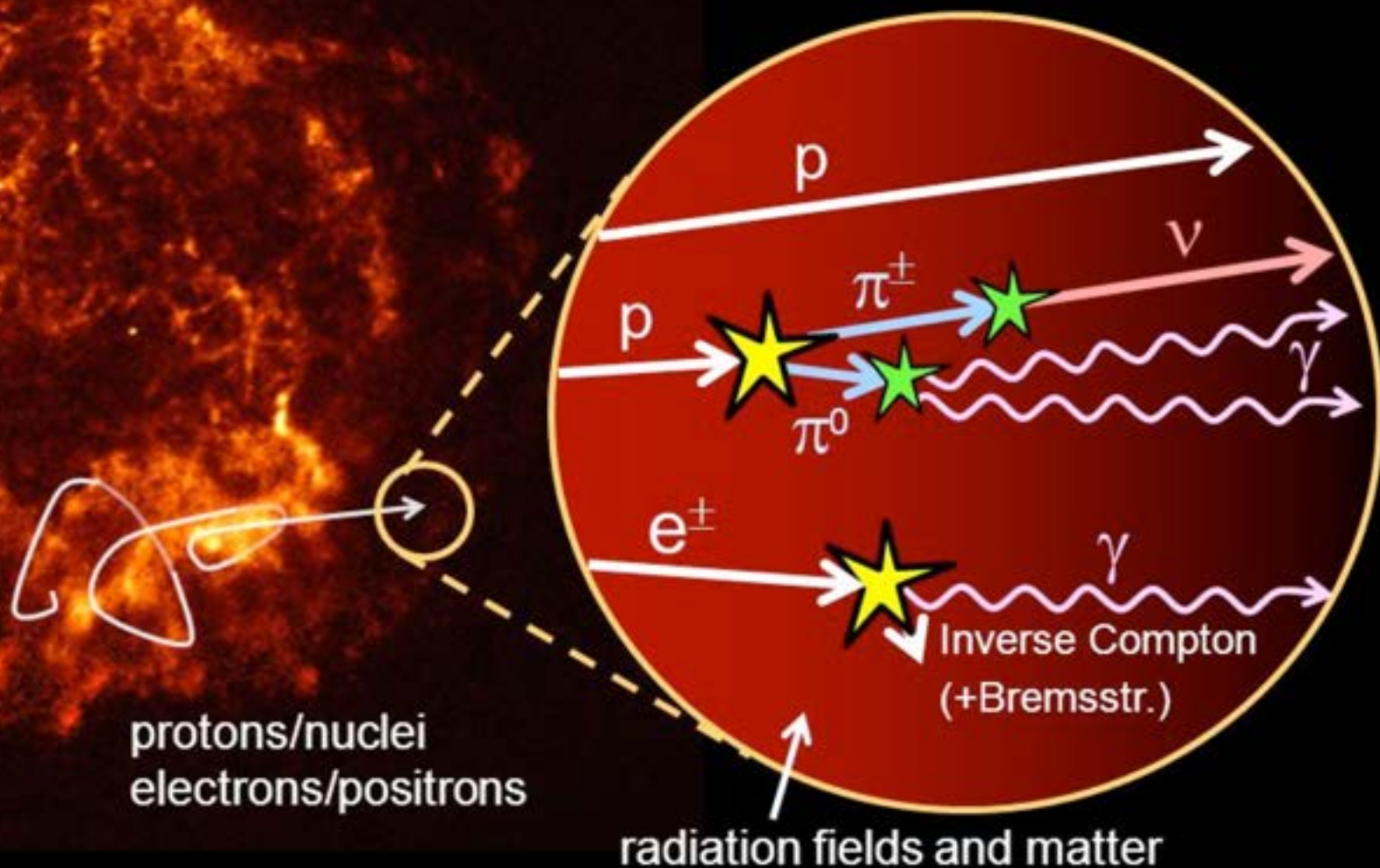
Rayonnement cosmique

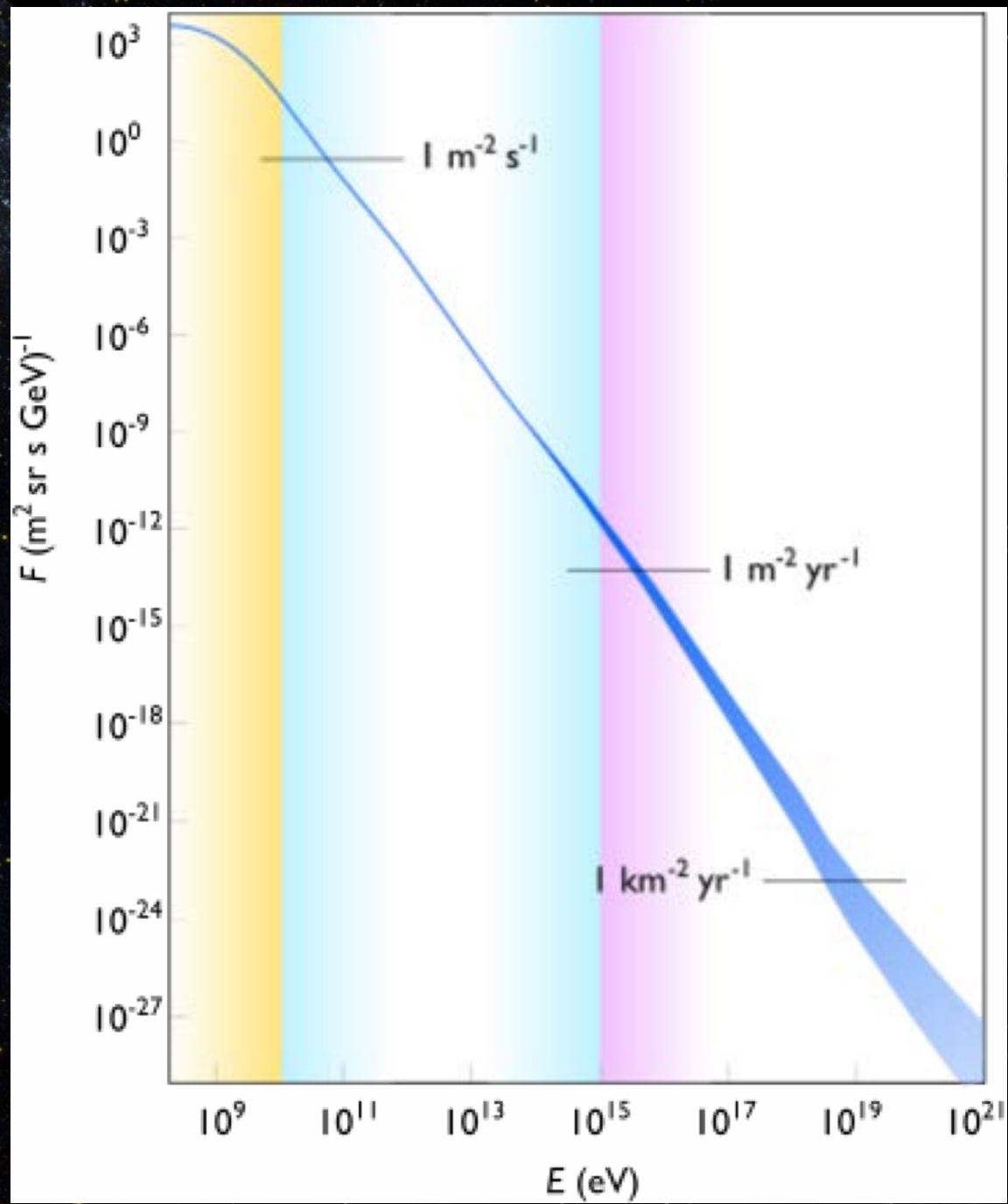


Le neutrino un messenger cosmique ?

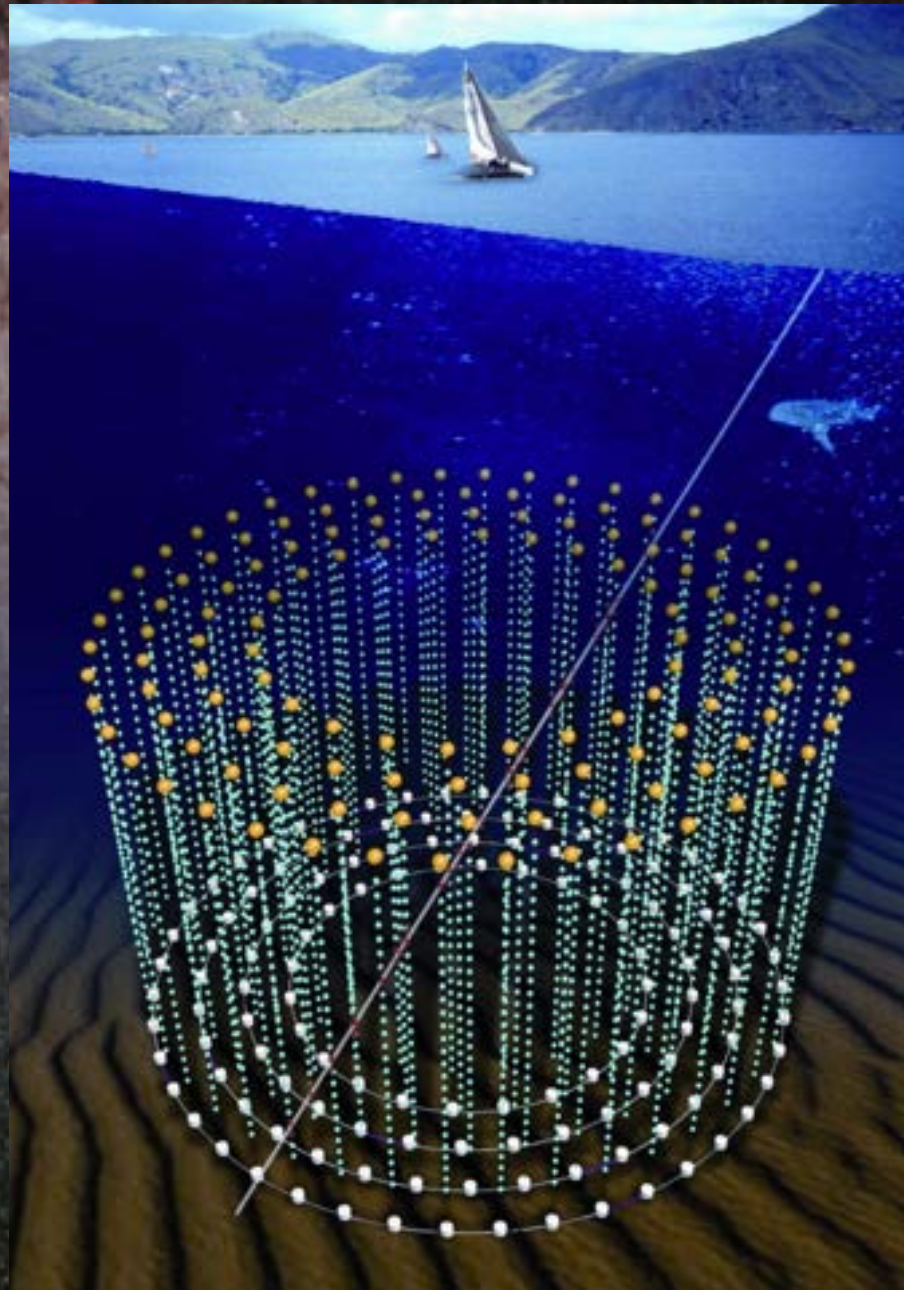


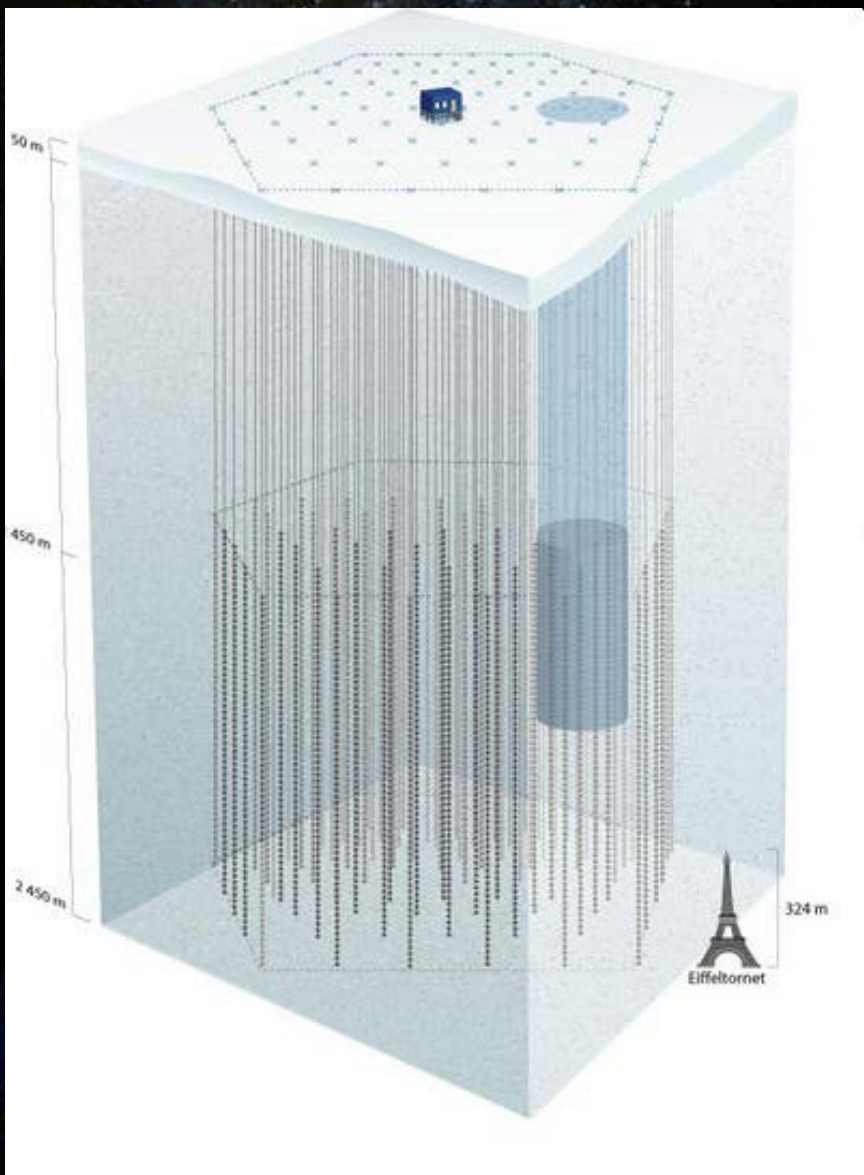
Production in Cosmic Accelerators

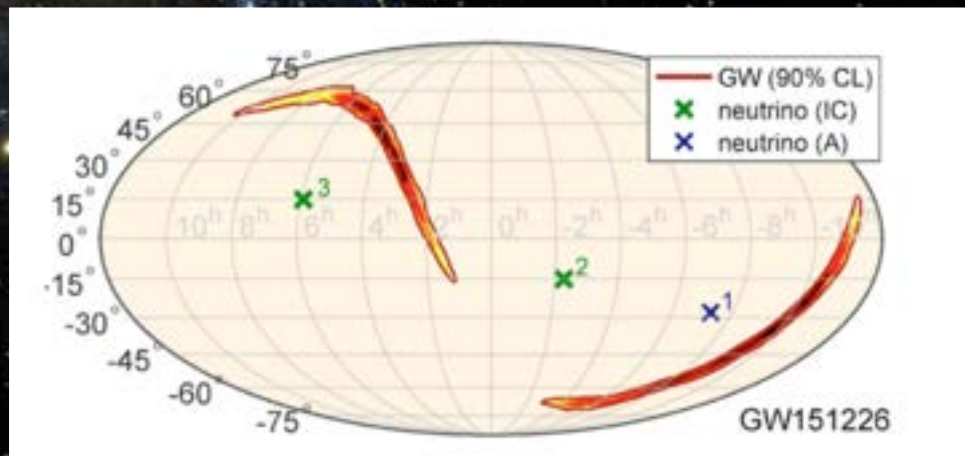
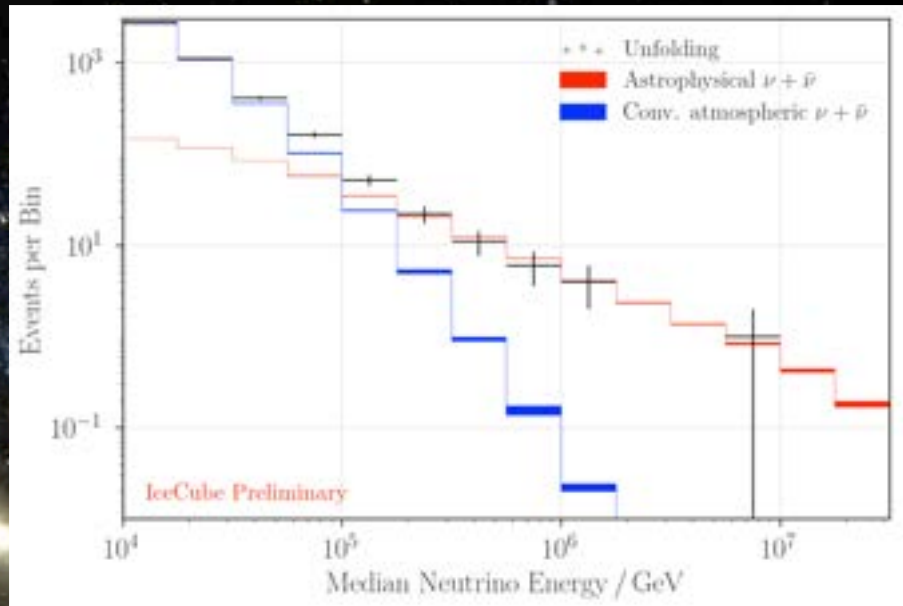
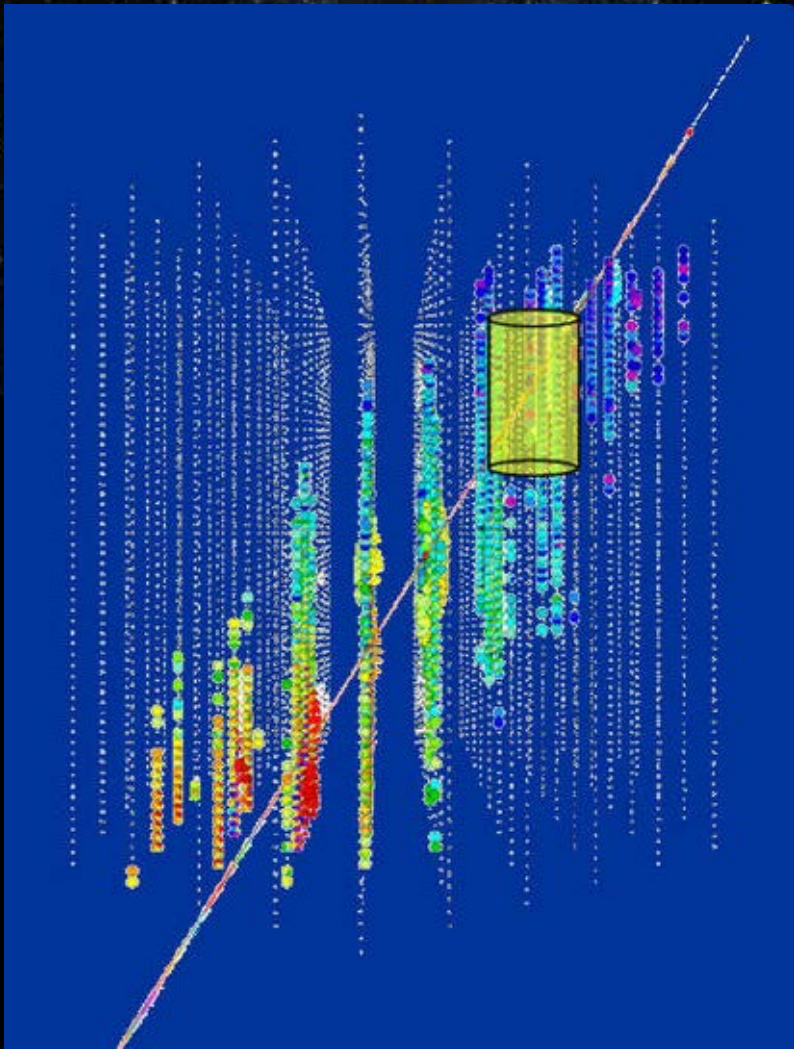




ANTARES et KM3Net







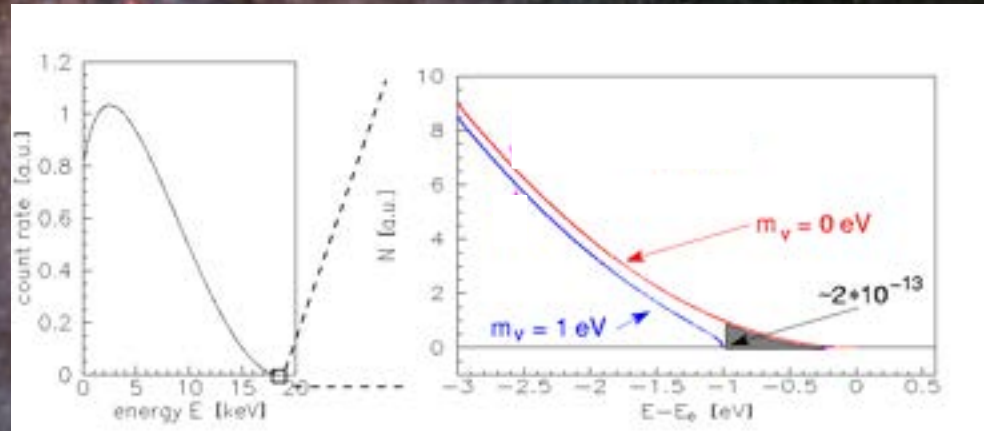




En 2000 apparition sur le marché de bouteilles de Château Margaux de 1900

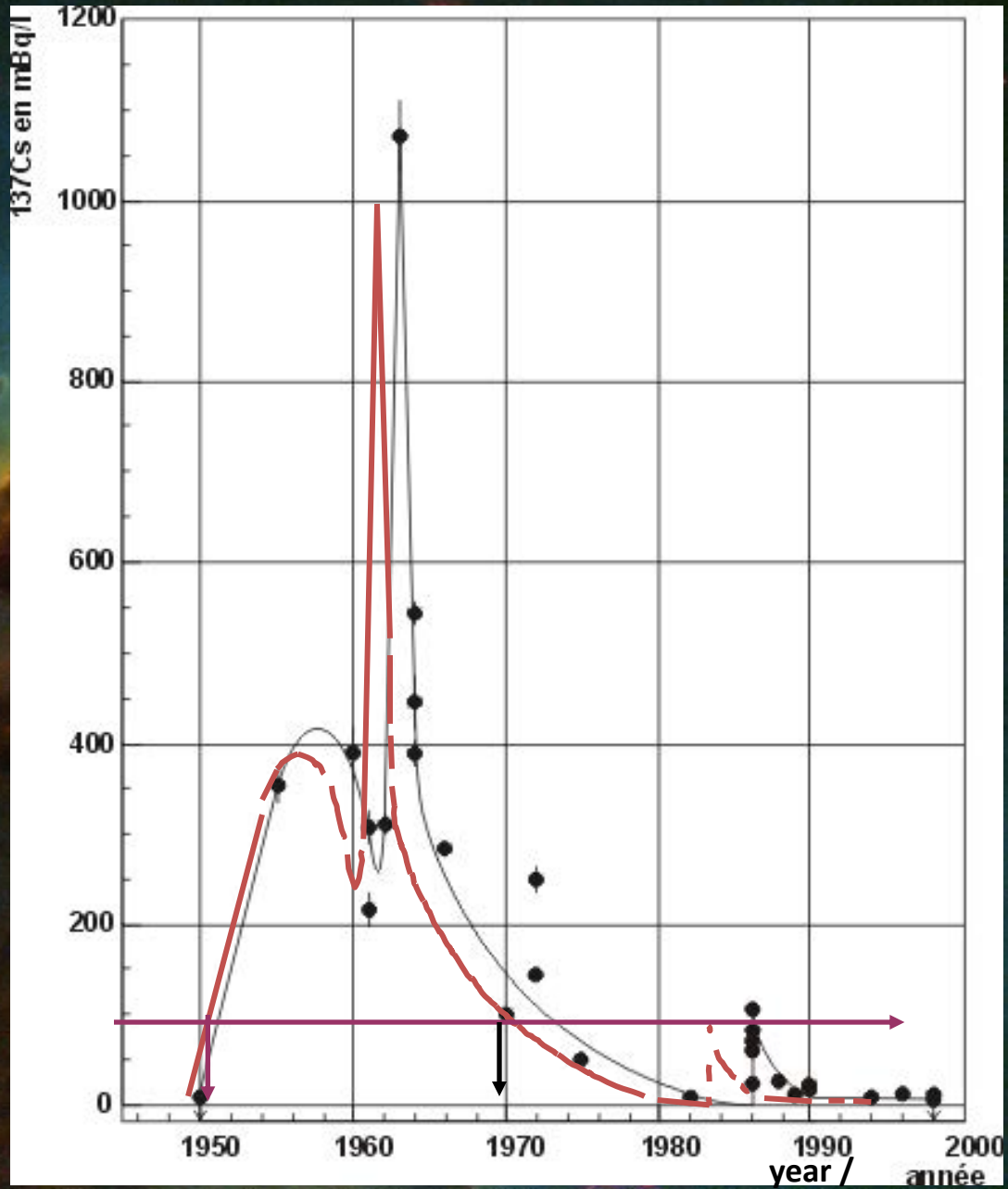
Question de la repression des fraudes: comment expertiser ces bouteilles ?

$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$



$m_\nu < 0,8 \text{ eV}$ (95% C.L.)

Mesure du ^{137}Cs en fonction de temps





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

