

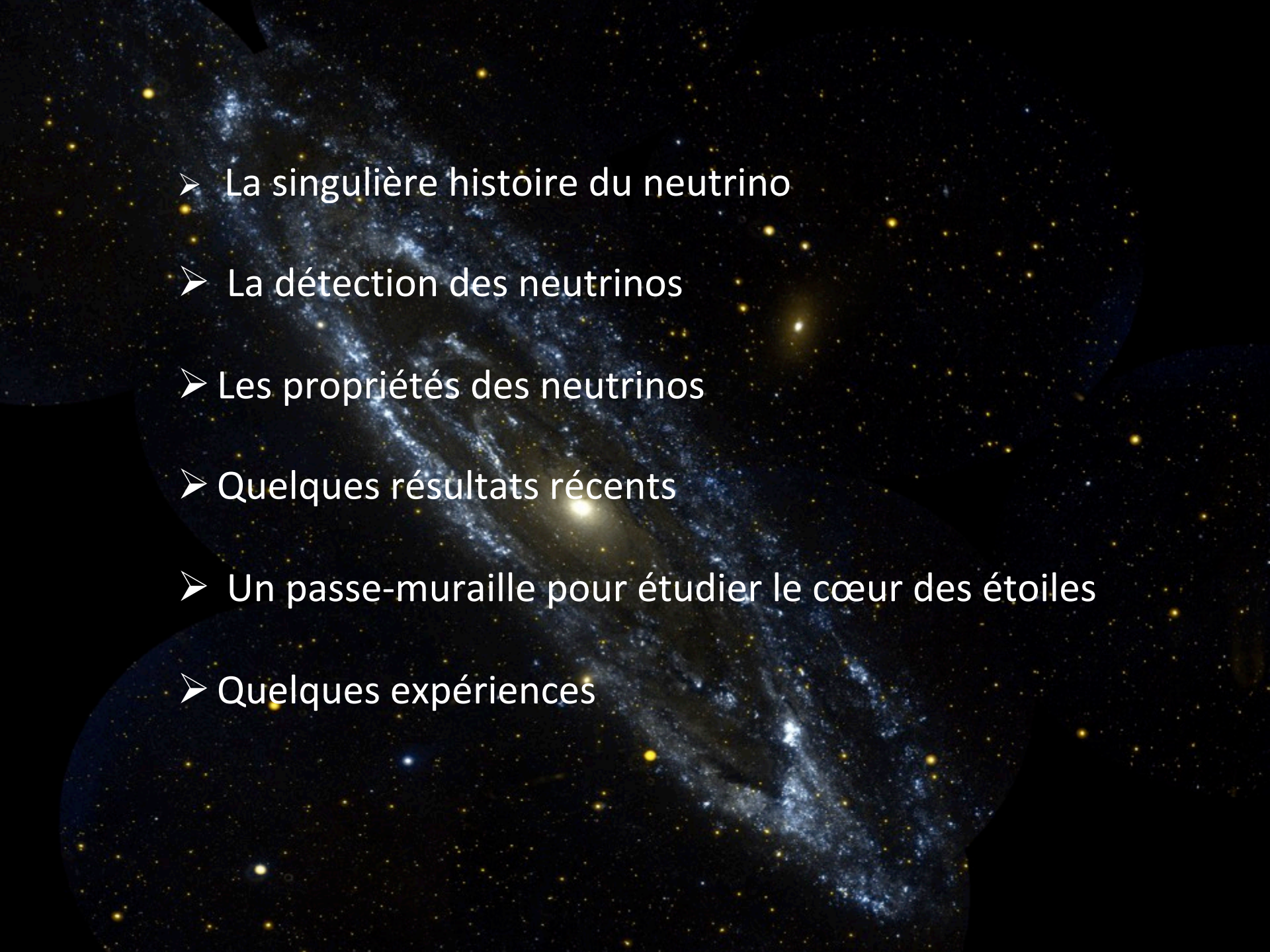
# L'enigmatique neutrino

**F. Piquemal (CNRS/IN2P3)**

**Laboratoire Souterrain de Modane  
(CNRS/IN2P3 et U. Grenoble-Alpes)**

**et**

**Centre d'Etudes Nucléaires de Bordeaux-Gradignan  
(CNRS/IN2P3 et U. Bordeaux)**

- 
- 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

## Quarks



up



down



charm



strange



top



bottom

## Leptons



e - neutrino  
1956



electron



μ - neutrino  
1963



muon



τ - neutrino  
2000



tau

matière



$\bar{u}$



$\bar{d}$



$\bar{c}$



$\bar{s}$



$\bar{t}$



$\bar{b}$



$\bar{\nu}_e$

e - neutrino



$\bar{e}$

electron



$\bar{\nu}_\mu$

μ - neutrino



$\bar{\mu}$

muon



$\bar{\nu}_\tau$

τ - neutrino

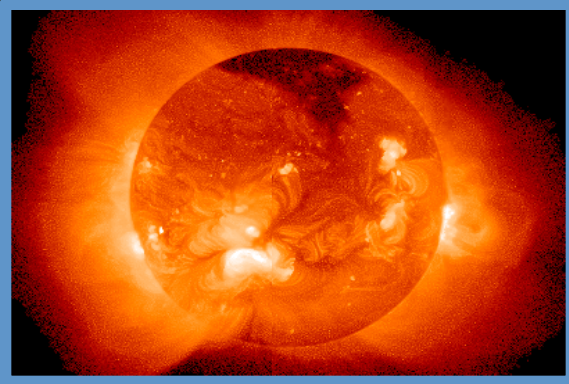


$\bar{\tau}$

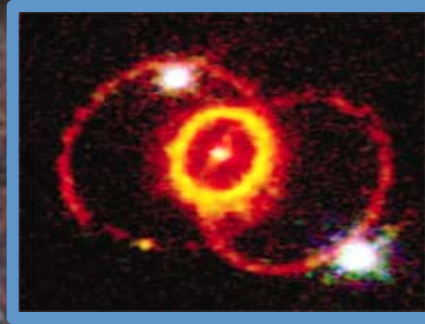
tau

anti-matière

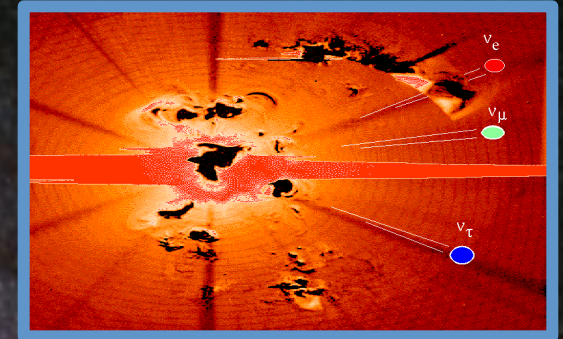
# Il pleut des neutrinos de toute part...



Le soleil :  
64 milliards par  $\text{cm}^2$  par seconde



Une Super Nova de notre  
Voie Lactée 5 milliards par  $\text{cm}^2$   
par seconde pendant 10 s



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



Les réacteurs nucléaires  
(100 000 par  $\text{cm}^2$  par  
seconde à 200 km

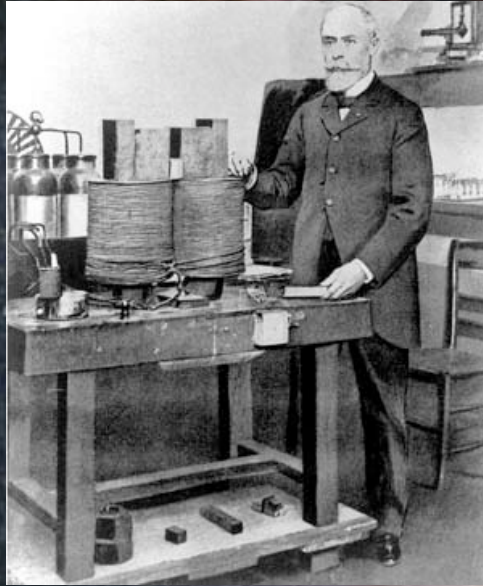


Corps humain 8 000 par secondes !!



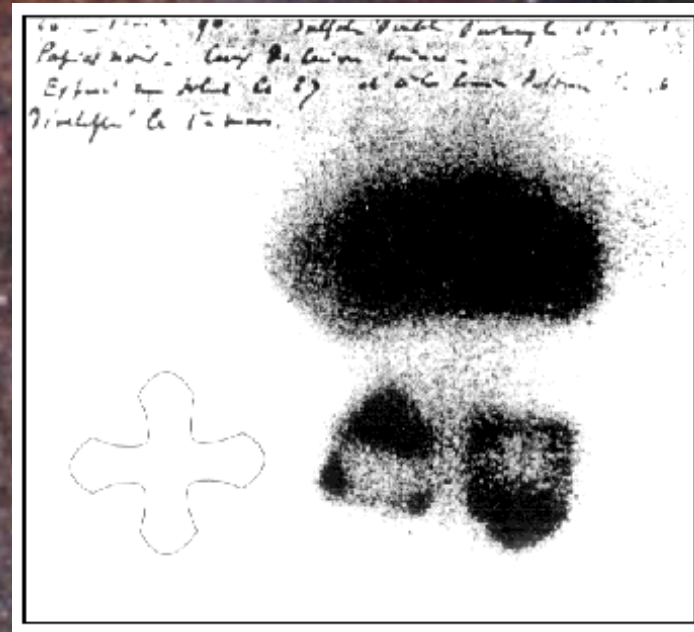
Origine géophysique et  
atmosphérique :  
6 millions par  $\text{cm}^2$  par seconde

# La préhistoire du neutrino



1896 - 1898:

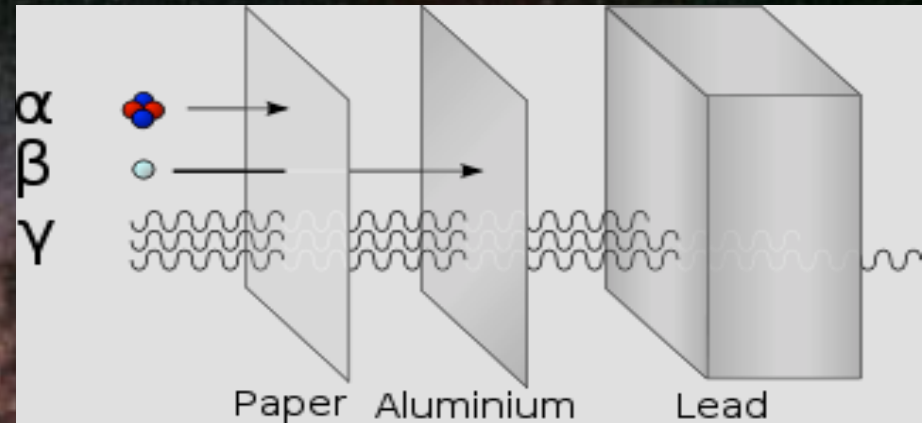
Becquerel, Pierre et Marie Curie  
découvrent la radioactivité



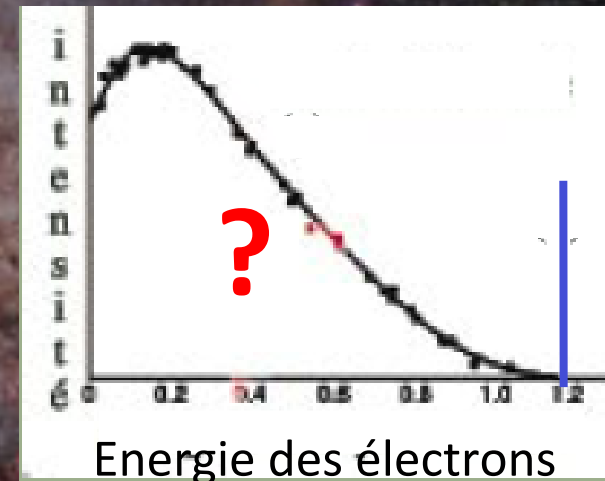


# La préhistoire du neutrino

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  $\beta$ -spectrum, upon a desperate expedient for saving the "Wechselsatz"<sup>†</sup> of statistics and energy conversation. 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  $\beta$ -spectrum would then be comprehensible on the assumption that on  $\beta$ -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  $\mu$ . Experiments apparently demand that the ionising effect of such a neutron is no greater than that of a  $\gamma$ -ray, in which case  $\mu$  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  $\gamma$ -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  $\beta$ -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

<sup>†</sup> 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 »

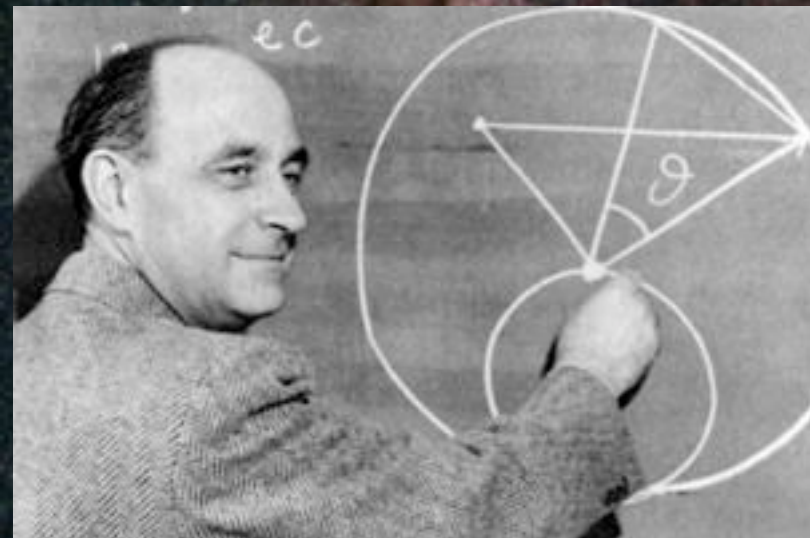


« Spin  $\frac{1}{2}$  et ne voyage pas à la vitesse de la lumière »

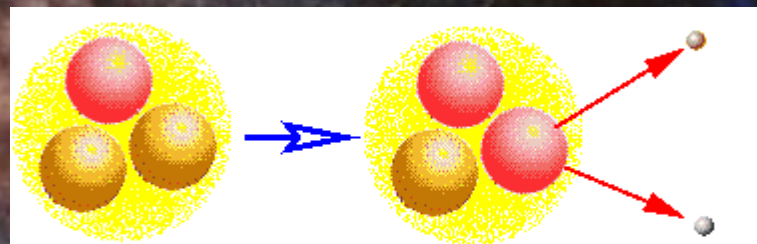
**Pauli : « J'ai fait une chose terrible, j'ai inventé une particule que l'on ne pourra jamais détecter »**

**Pauli met au défi les expérimentateurs de le détecter**





**1933 : Fermi élabore la théorie de l'interaction faible**

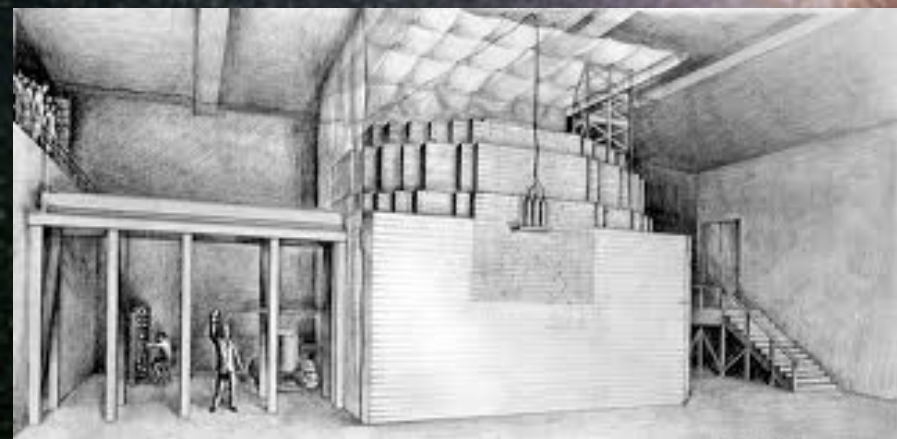


**électron**

**neutron**

**proton**

**neutrino**



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

# Piège à neutrino

← 30 000 000 000 000 000 000 km de plomb →

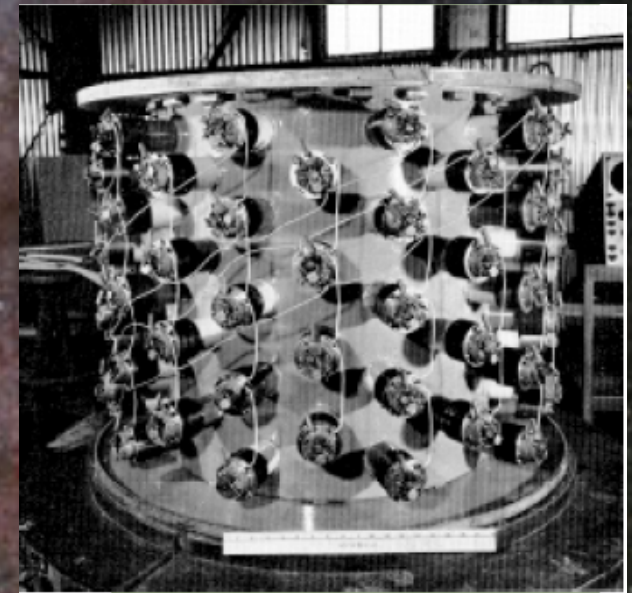
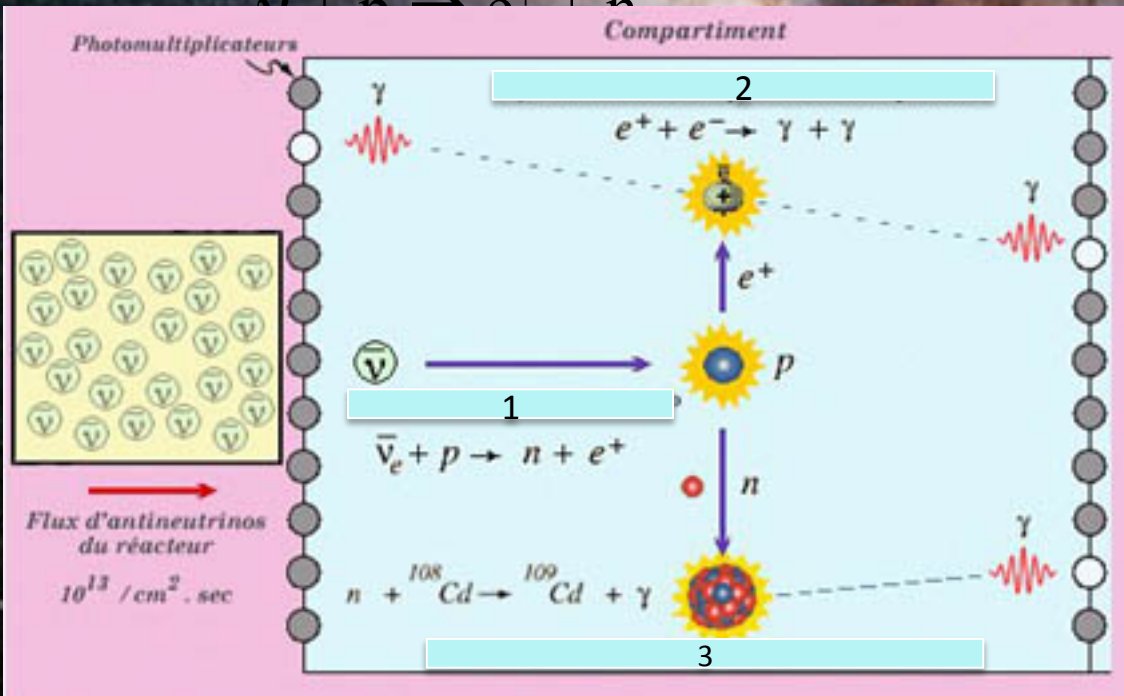
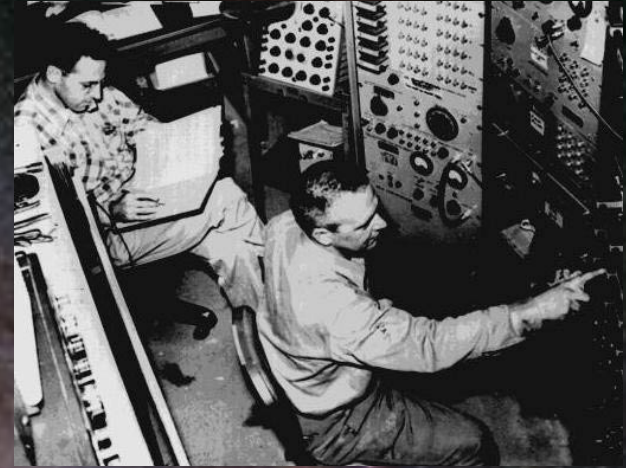
Vol en avion de 40 millions d'années



# 1956: Découverte du neutrino par Reines et Cowan



Réacteur de Savannah River (USA)



Détecteur Poltergeist

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).



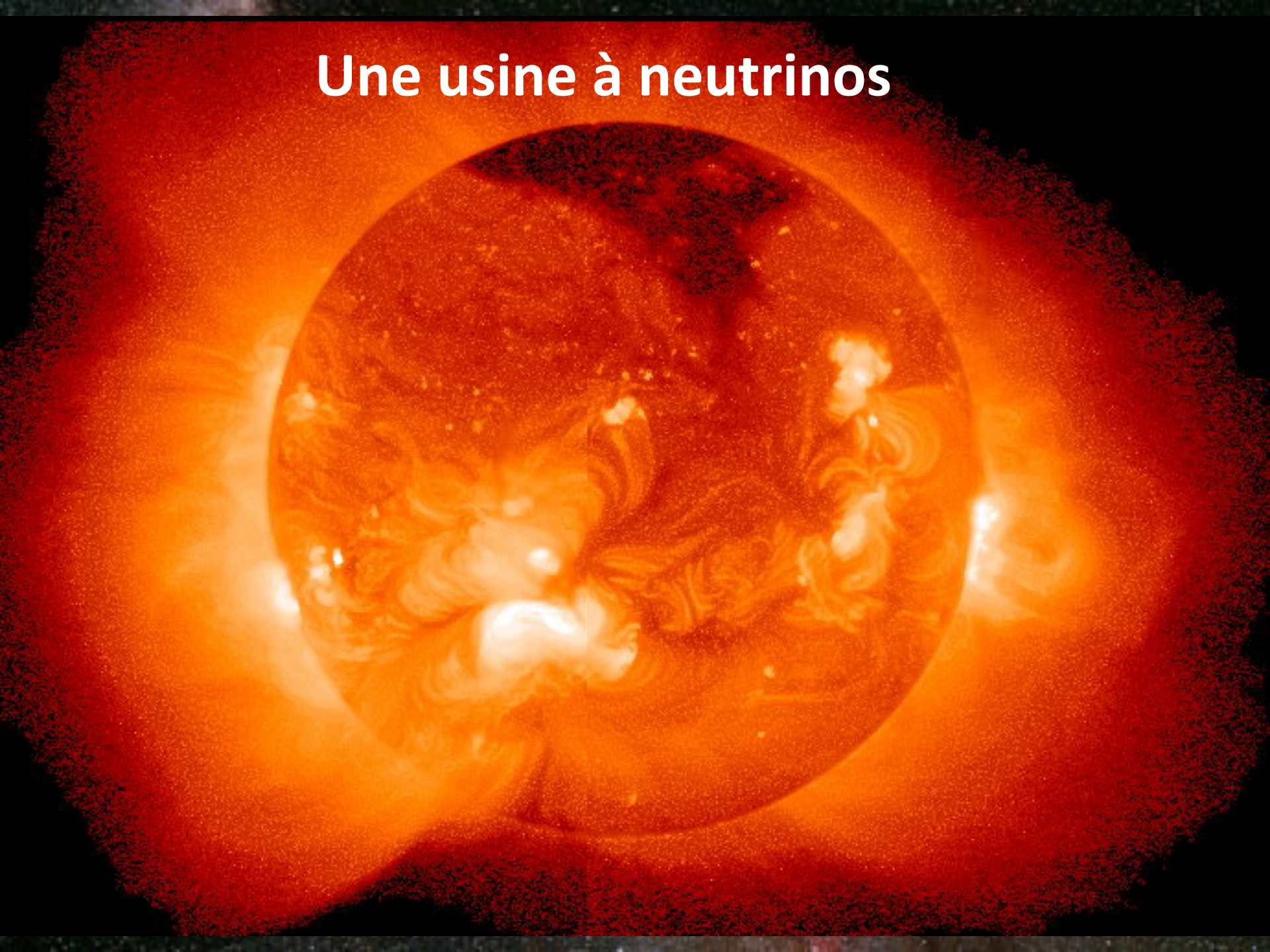
Il faut en produire des milliards  
de milliards pour en voir 1 seul

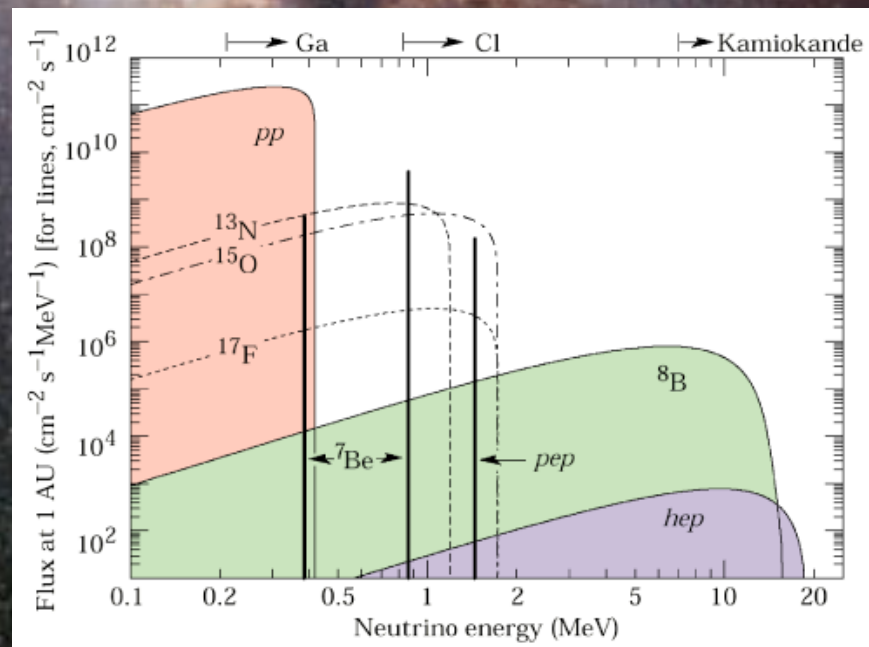
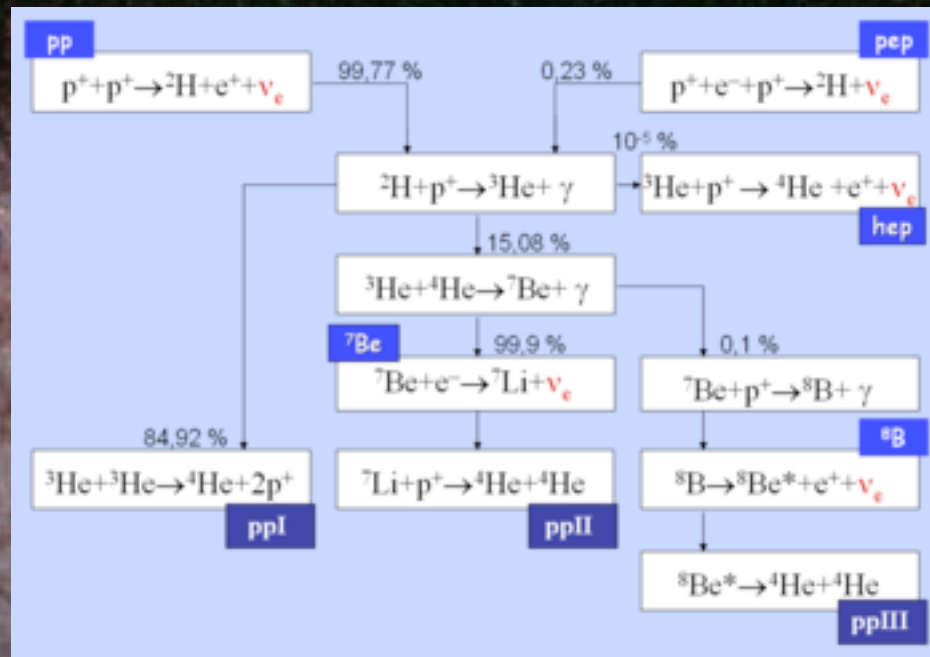
1962: découverte de  $\nu_{\mu}$

2000: Découverte du  $\nu_{\tau}$



# Une usine à neutrinos

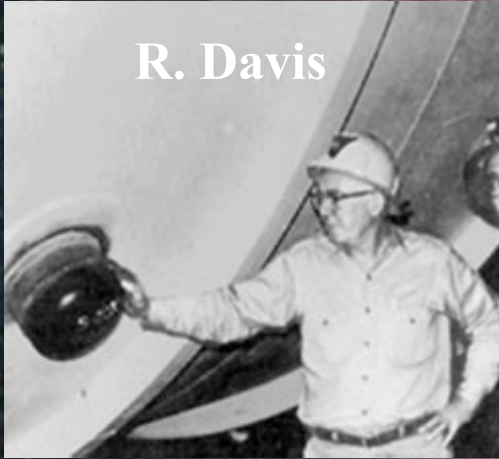




# L'énigme des neutrinos solaires

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

R. Davis



600 tonnes de chlore



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

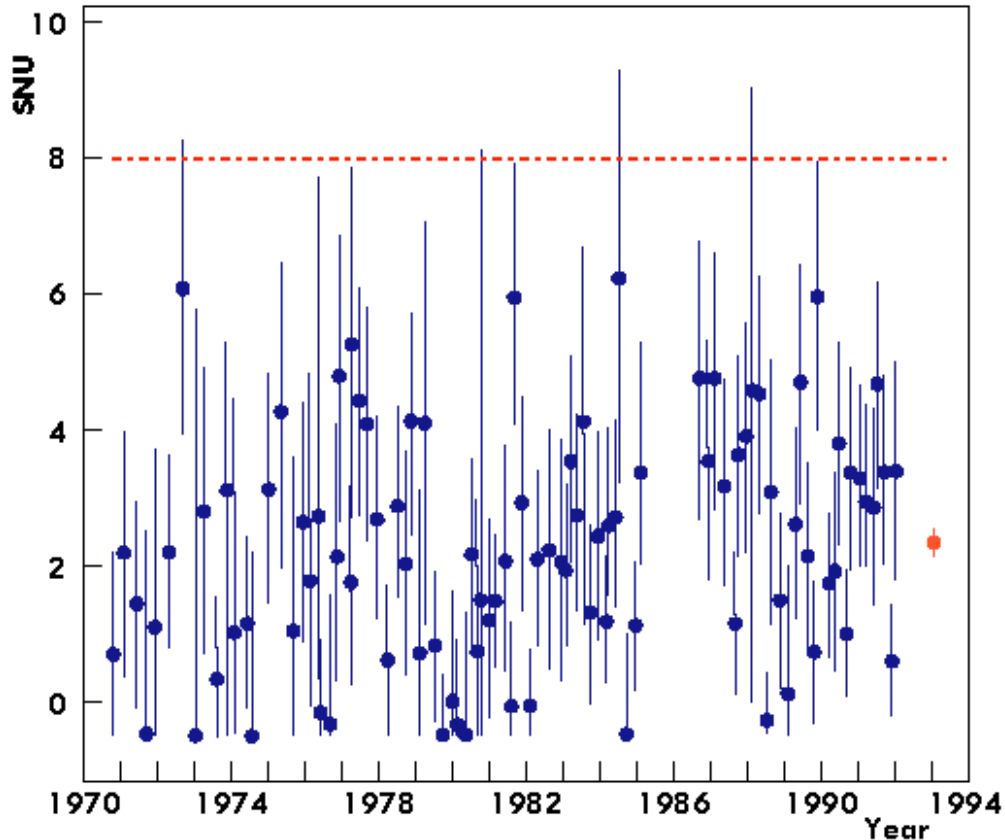
Période de 35 j

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



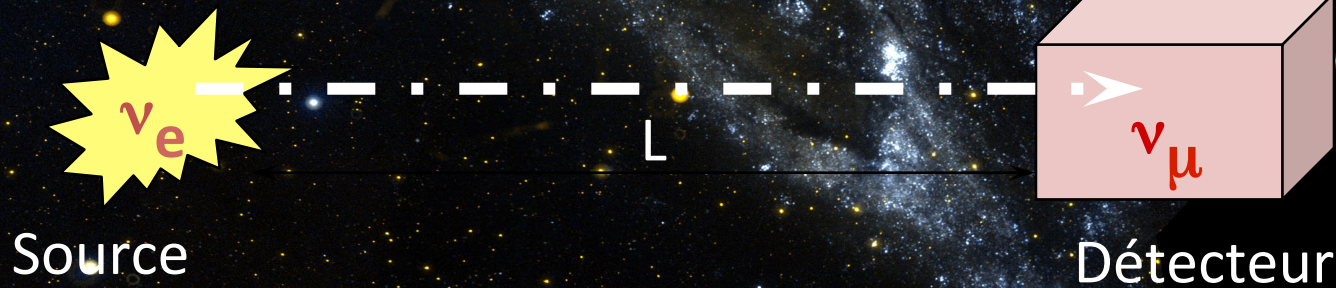
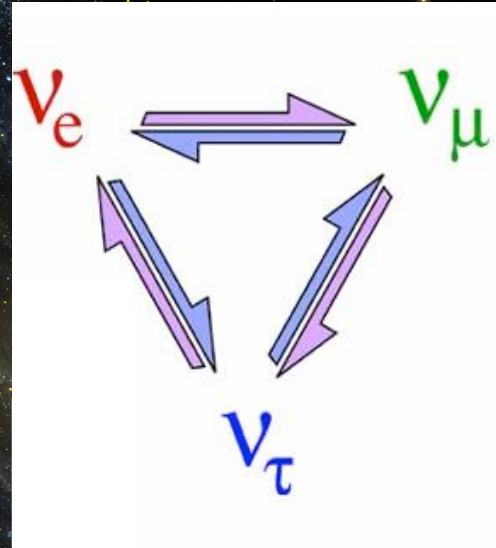
**Il manque 75% des neutrinos !!!!**

Confirmé par d'autres expériences radiochimiques dans les années 90

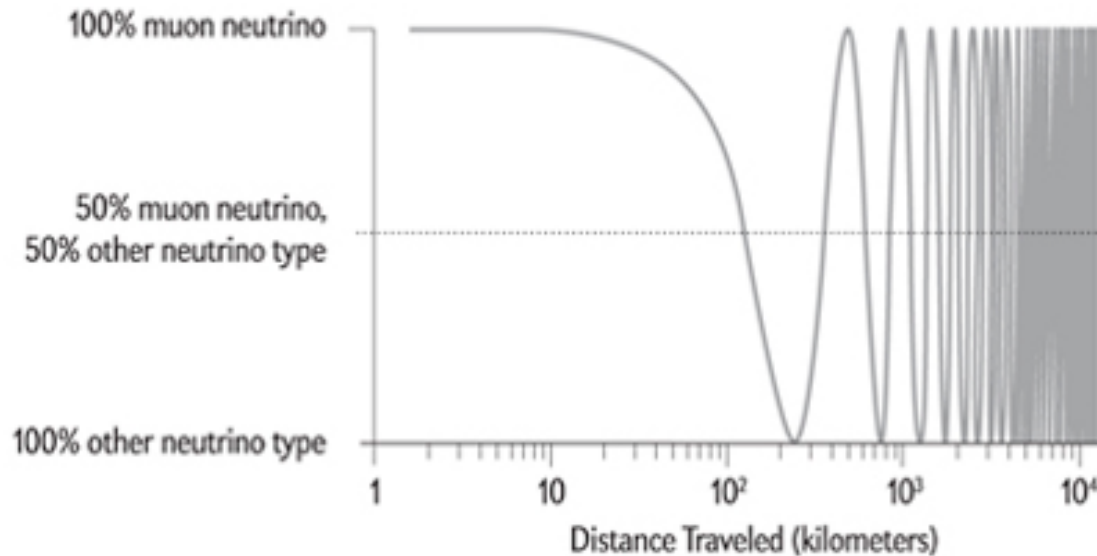




1957: Bruno Pontecorvo prédit l'oscillation des neutrinos



## Neutrino Oscillations



Neutrinos de « base »:  $\nu_1$   $\nu_2$   $\nu_3$

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

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

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

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

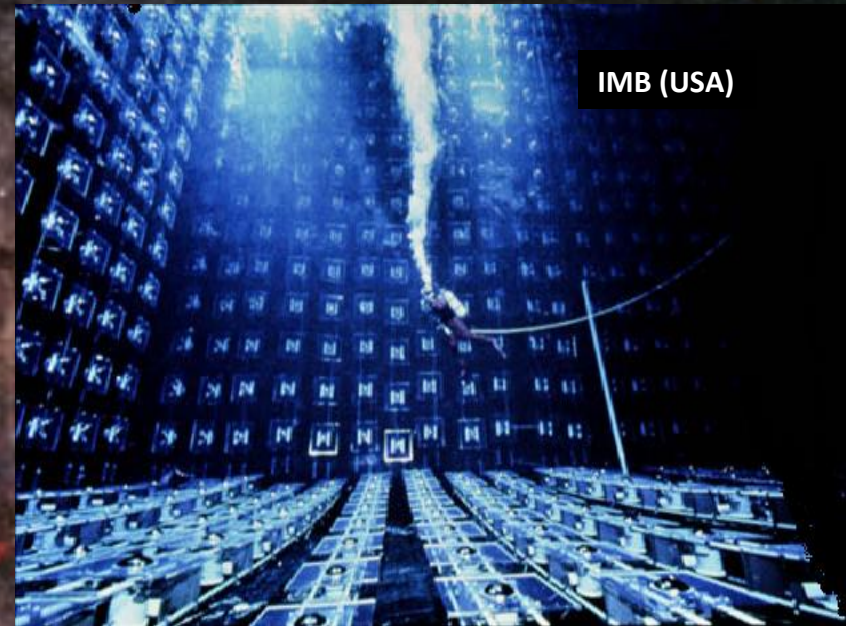
$$C_{ij} = \cos\theta_{ij}$$

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

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



Kamiokande (Japan)



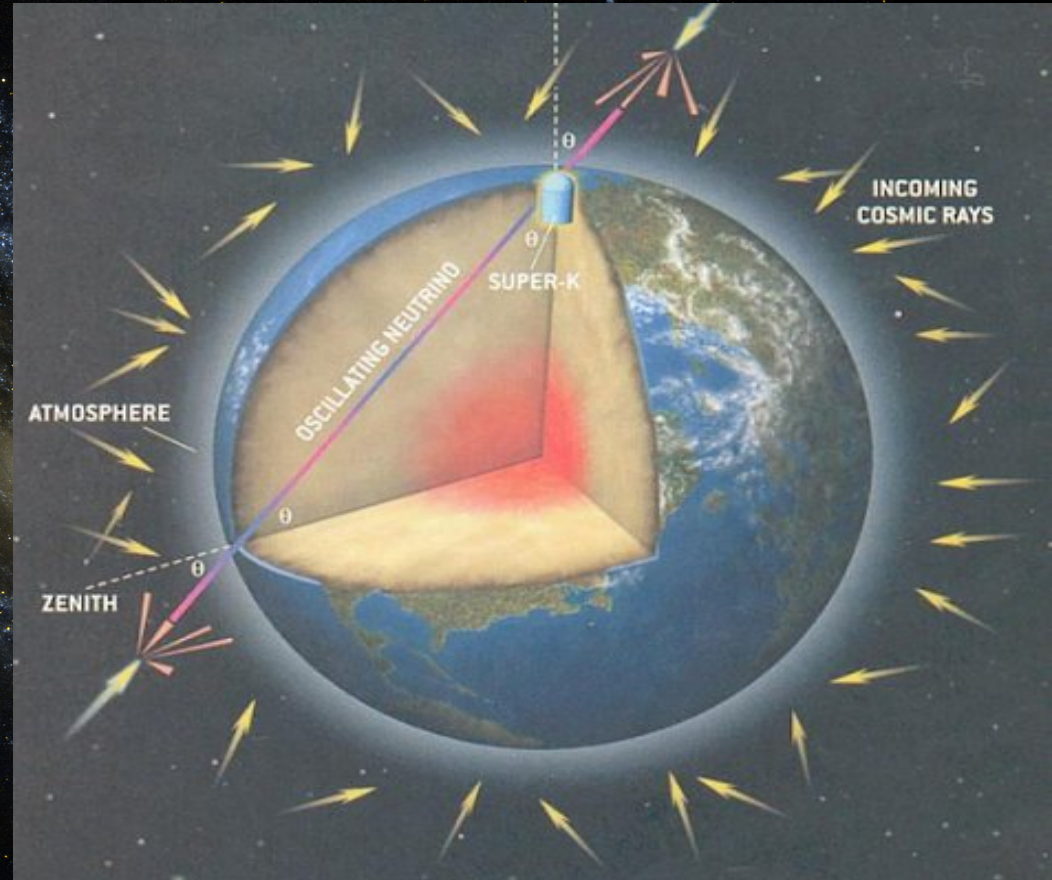
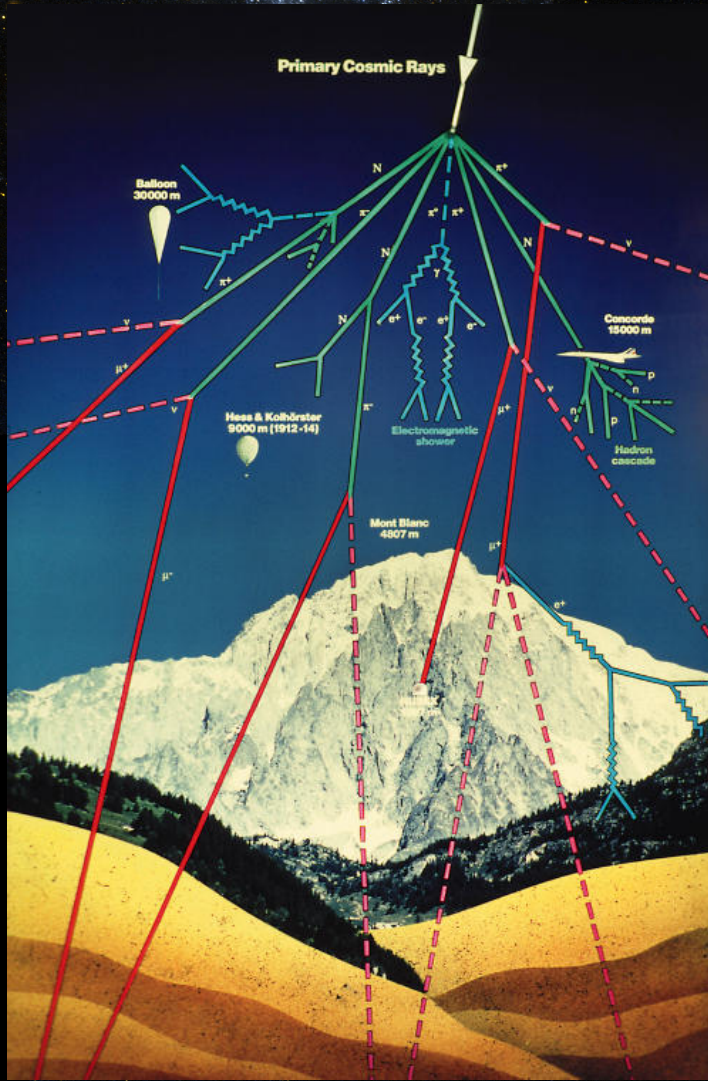
IMB (USA)



Taup (France)

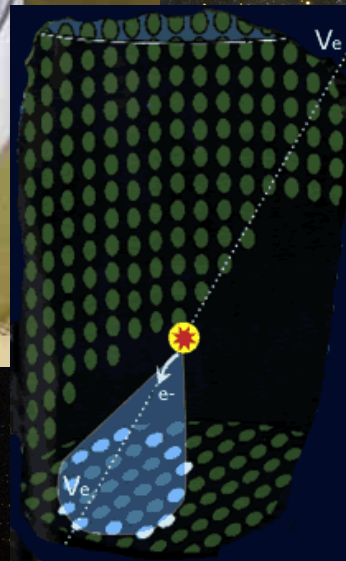
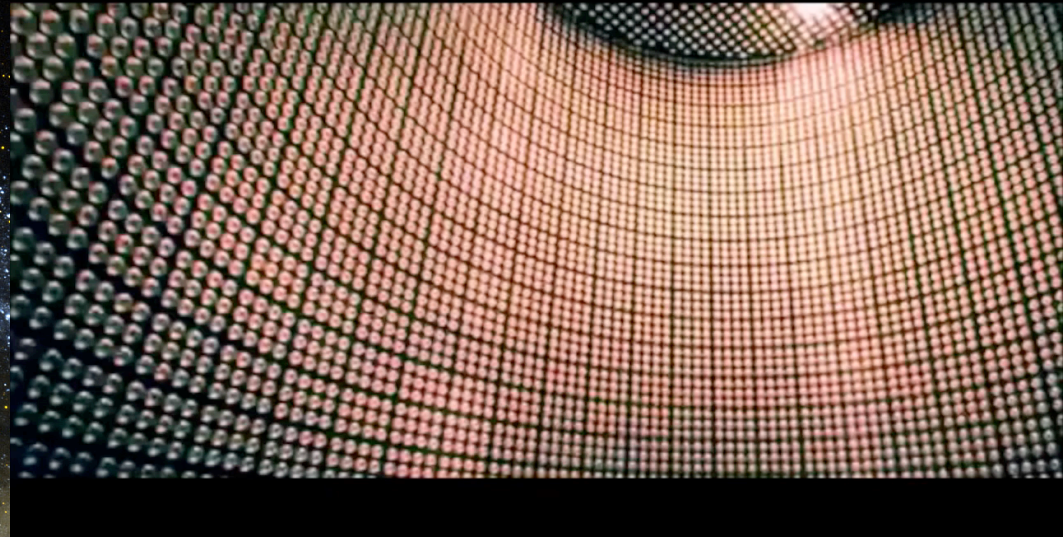


# Les neutrinos produits dans l'atmosphère



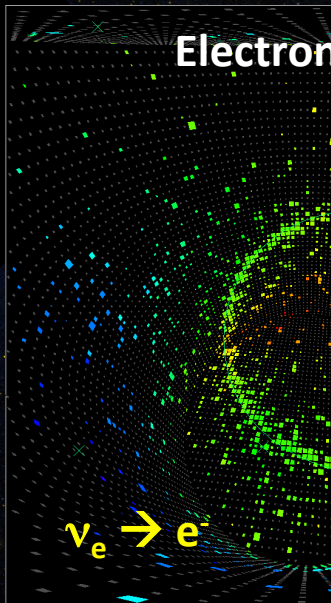
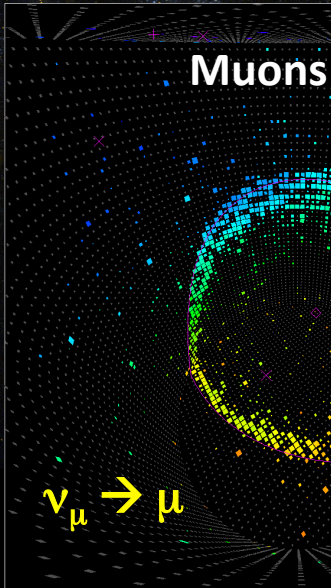
Il manque 40 % de neutrinos par rapport aux prédictions

# SuperKamiokande (Japon)



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

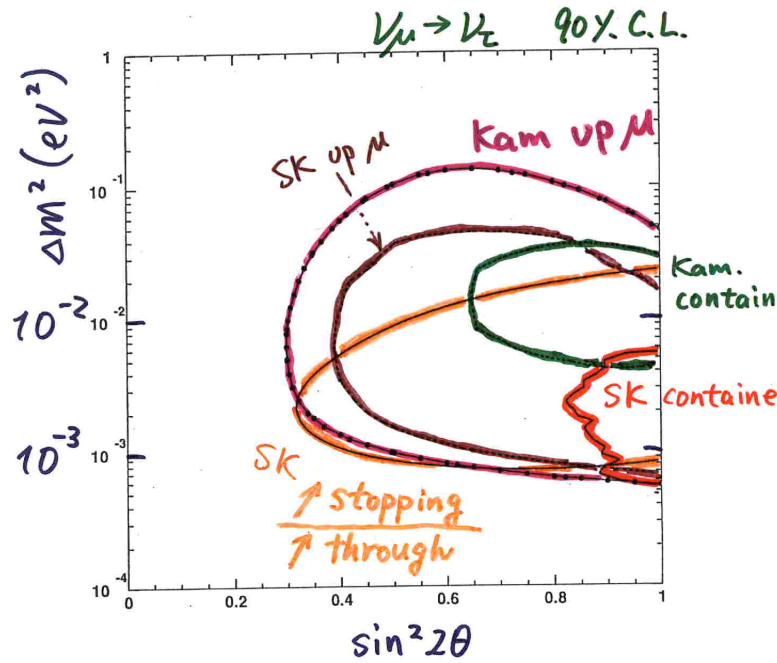
Neutrino atmosphériques  
Neutrinos solaires  
Neutrinos de Supernovae  
Durée de vie du proton



# Summary

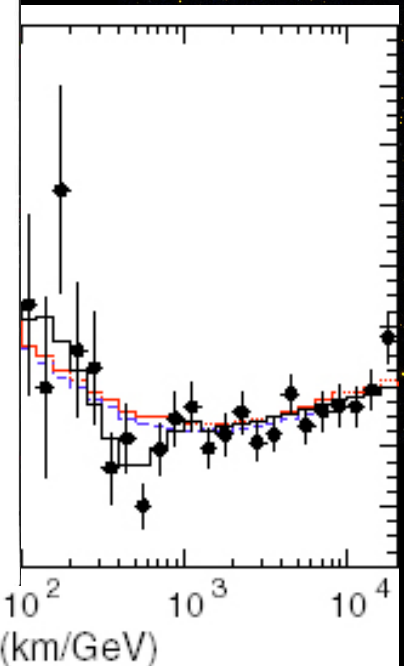
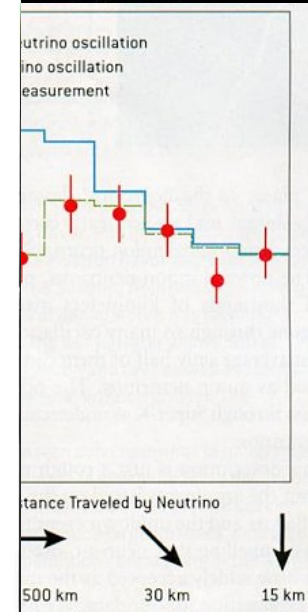
1998

## Evidence for $\nu_\mu$ oscillations



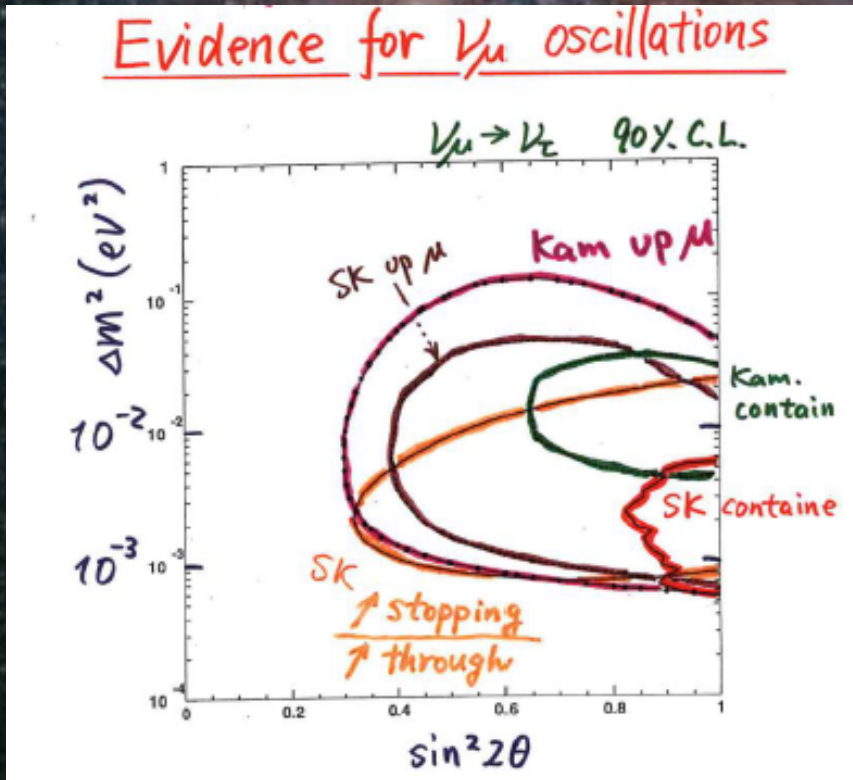
- $$\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$$

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

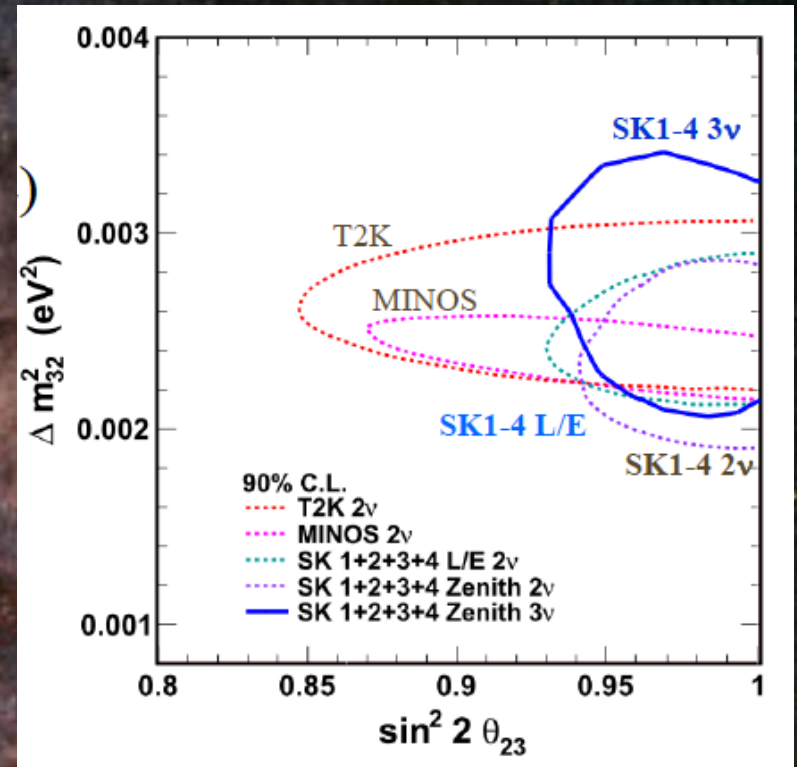




1998

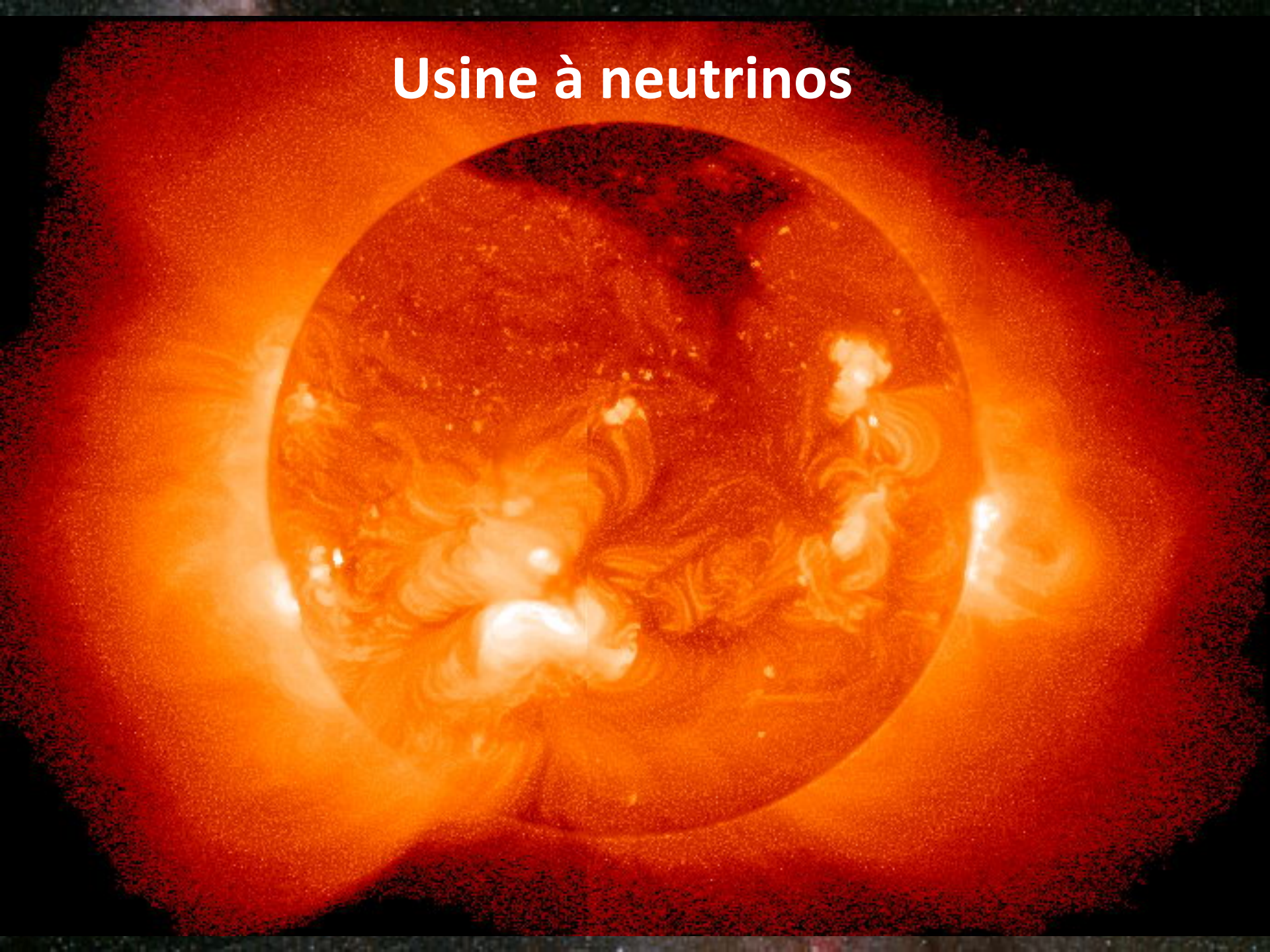


2012

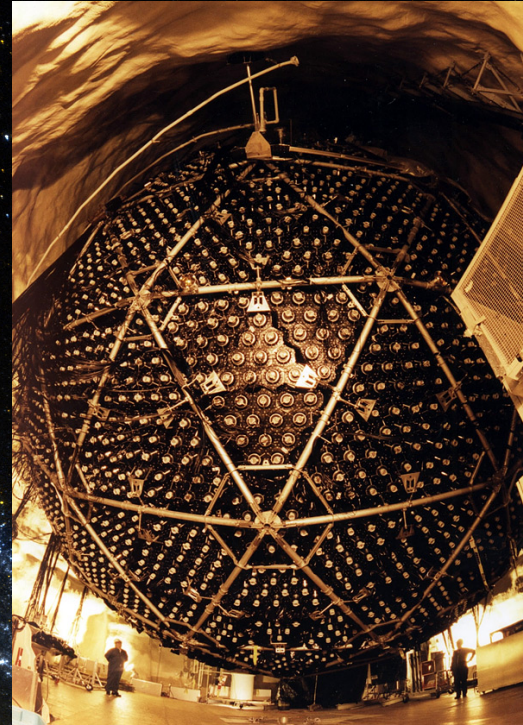
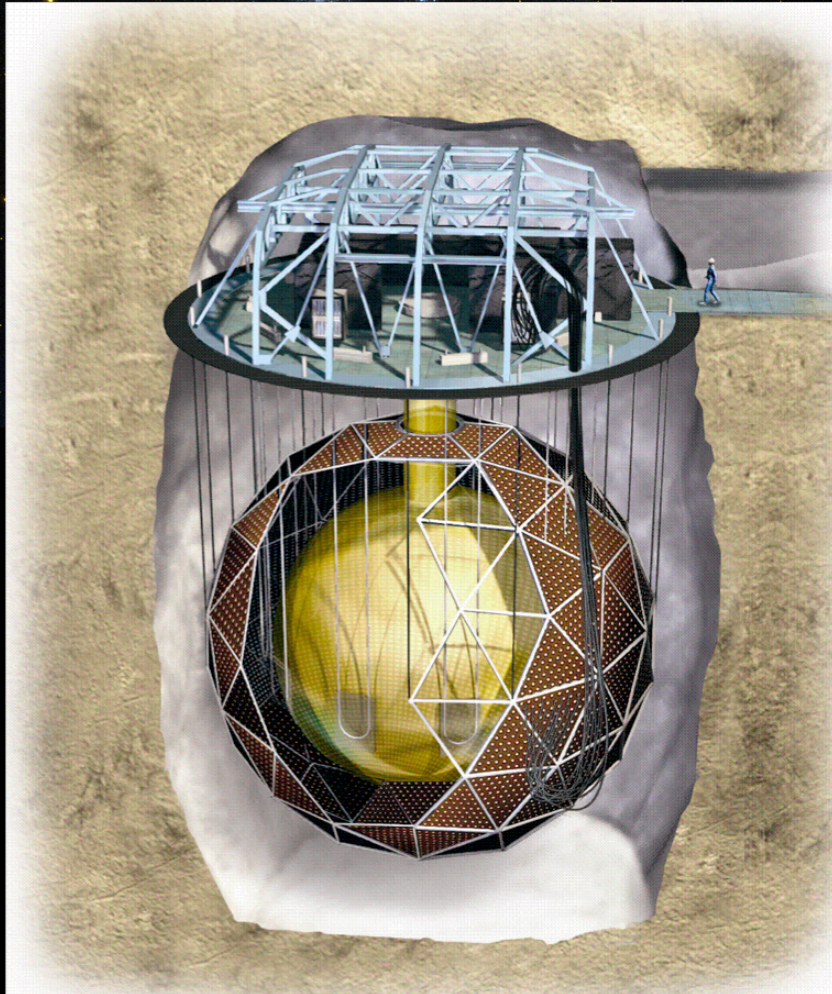


$$P_{\text{oscillation}} \sim \sin^2 2\theta \sin^2(\Delta m_{12} x L/E)$$

# Usine à neutrinos



# Détecteur SNO

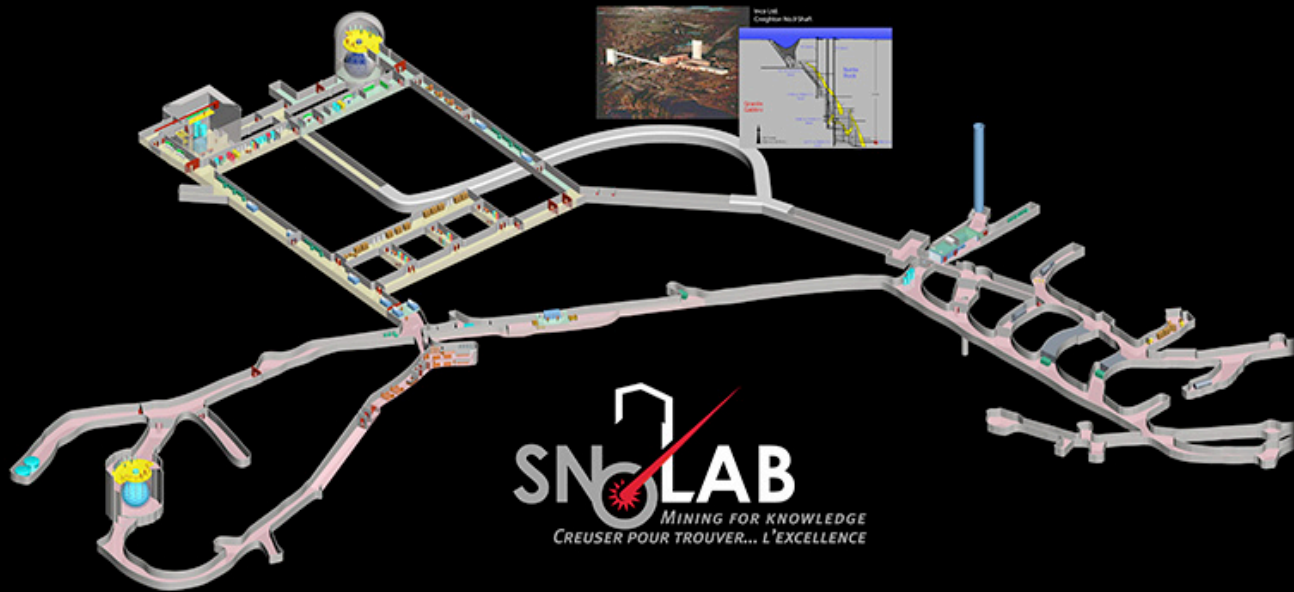
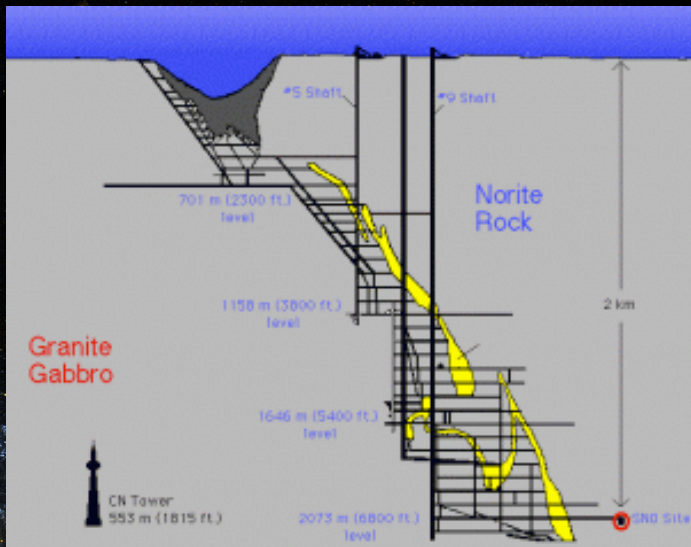


12 m de diamètre

1000 tonnes d'eau lourde ( $D_2O$ )

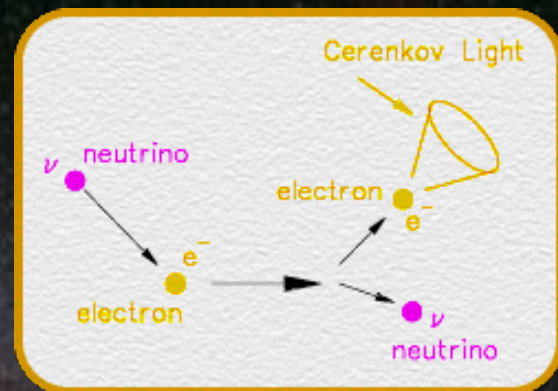
10 000 Photomultiplicateurs

Mesure des neutrinos solaires: flux de  $\nu_e$  et flux total



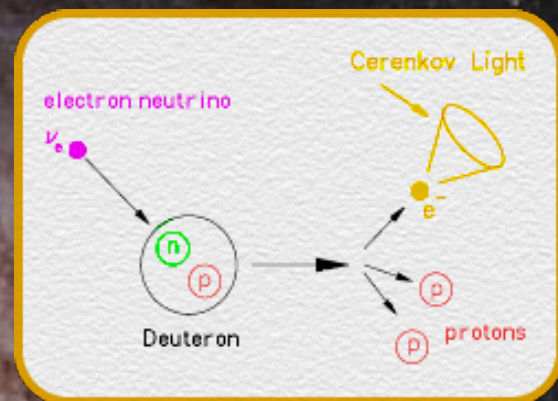
$$\nu_x + e^- \rightarrow e^- + \nu_x$$

Sensible à tous les types de neutrinos mais  
6 fois plus sensible pour les  $\nu_e$



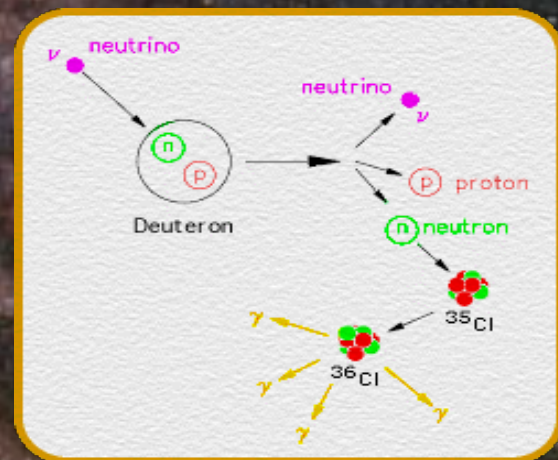
$$\nu_e + d \rightarrow p + p + e^-$$

Sensible uniquement aux  $\nu_e$

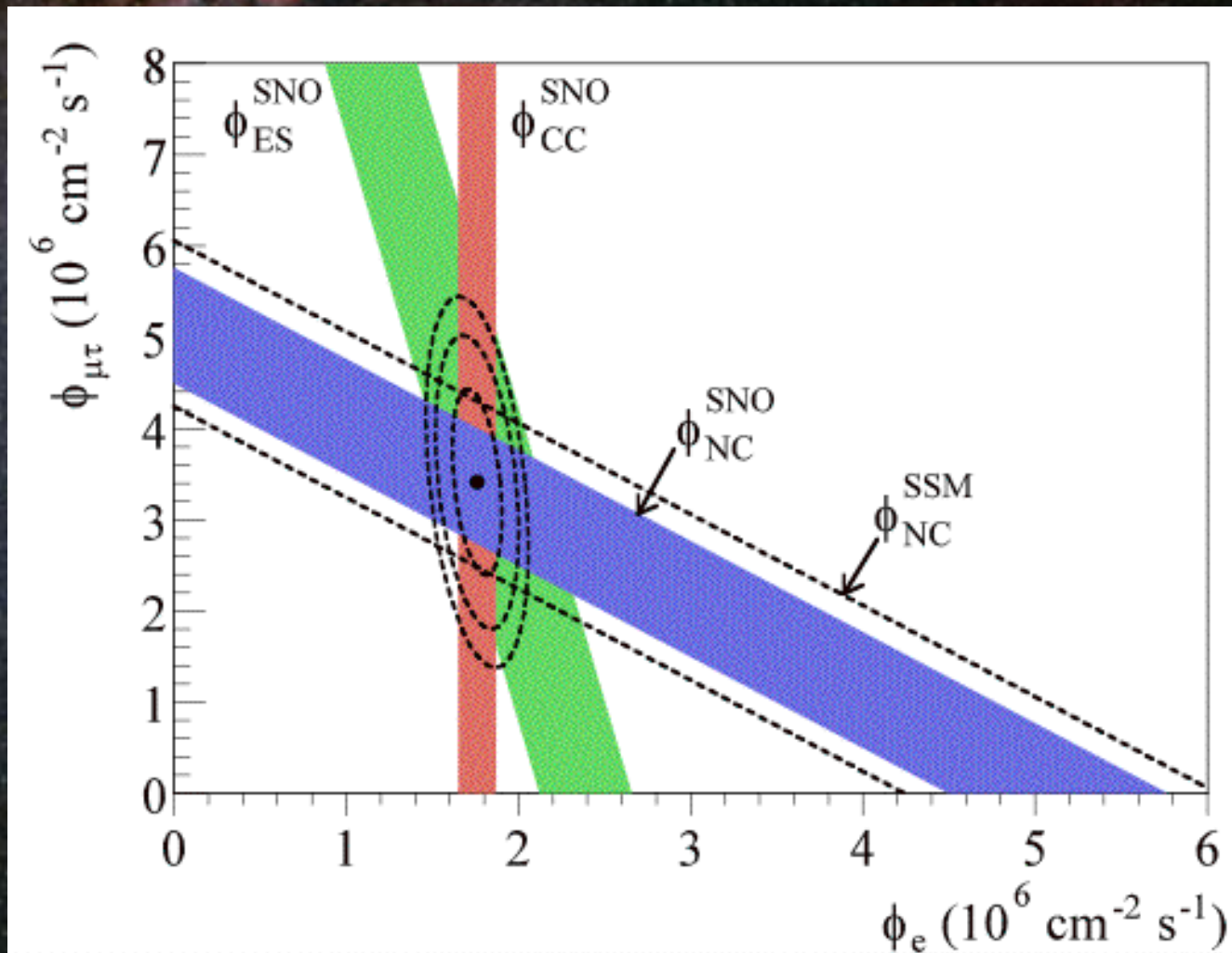


$$\nu_x + d \rightarrow p + n + \nu_x$$

Sensible aux 3 saveurs



## Résultats de SNO



Le flux total mesuré est bien le flux total prédit et il manque des neutrinos  $\nu_e$

# The Nobel Prize in Physics 2015



Photo © Takaaki Kajita

**Takaaki Kajita**

Prize share: 1/2

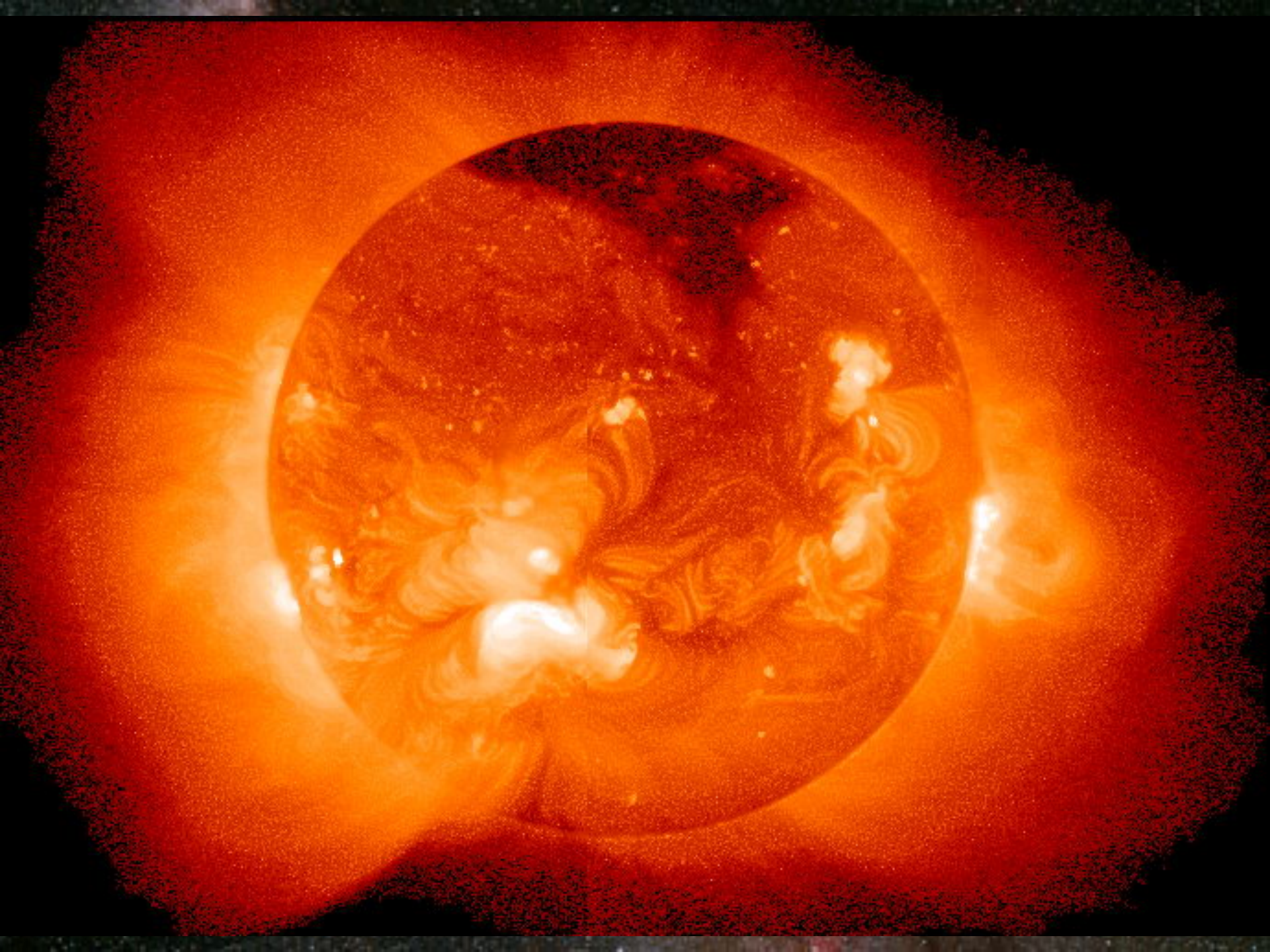


Photo: K. MacFarlane.  
Queen's University  
/SNOLAB

**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"*





# Les différentes lumières du soleil

Rayons gamma

Rayons X

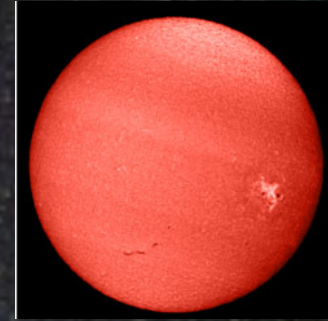
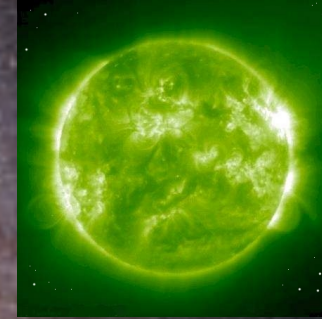
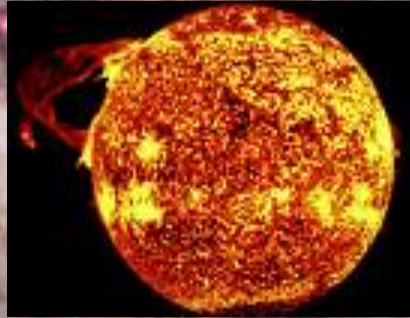
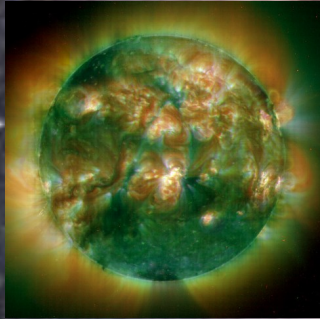
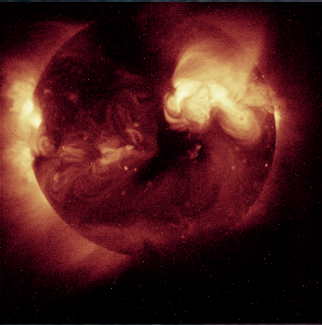
UV

Optique

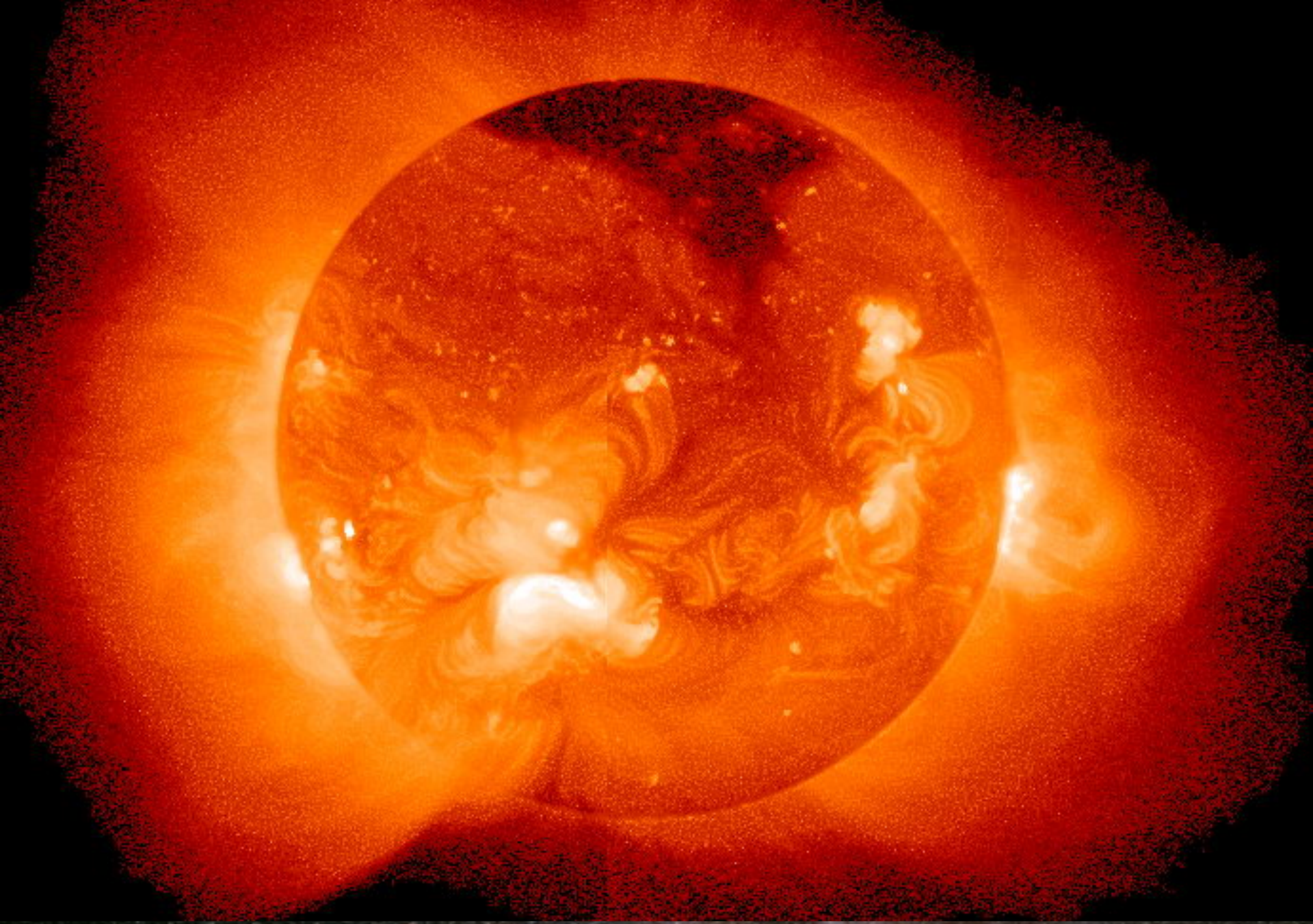
Infrarouge

Micro-onde

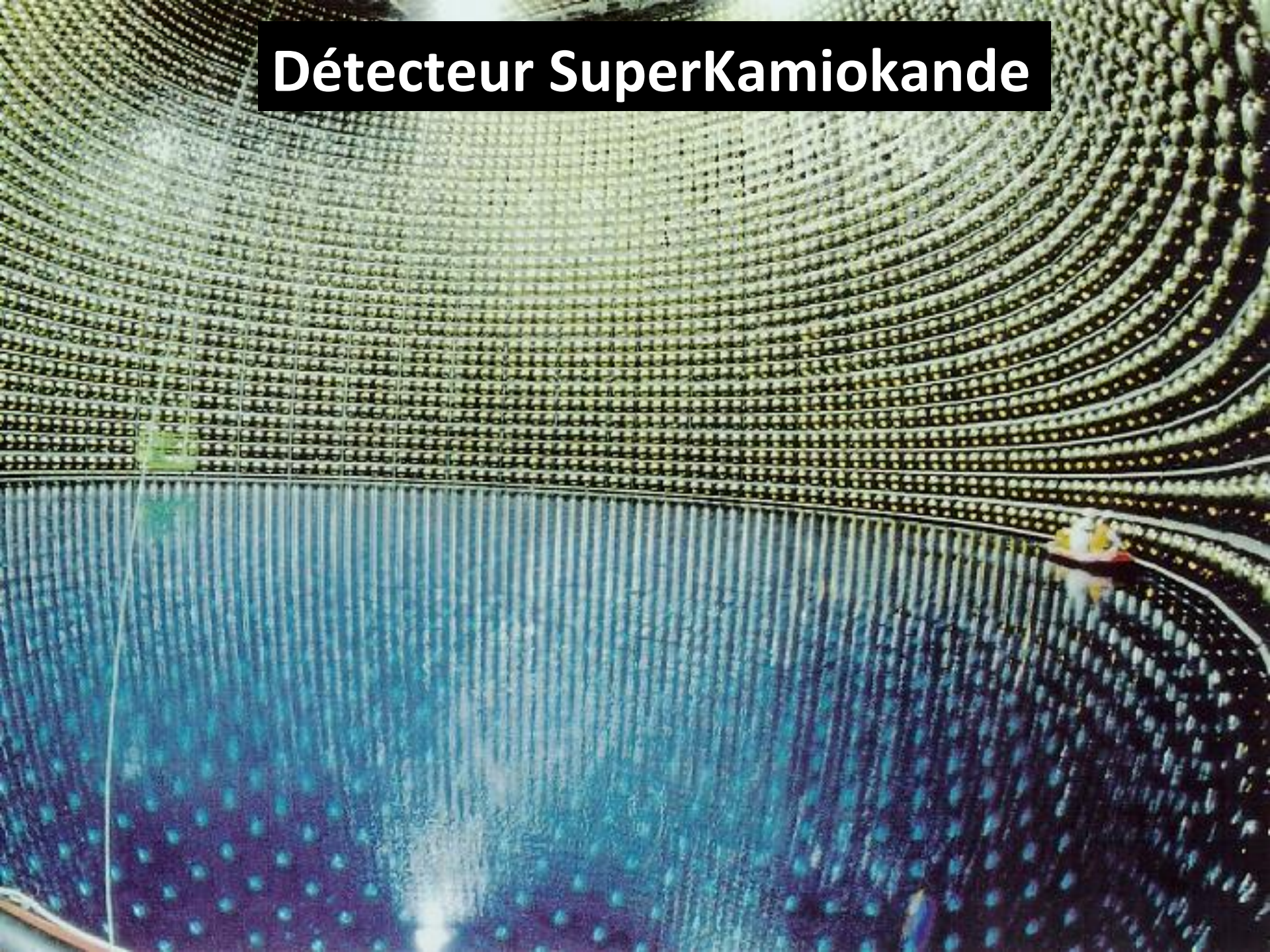
Radio



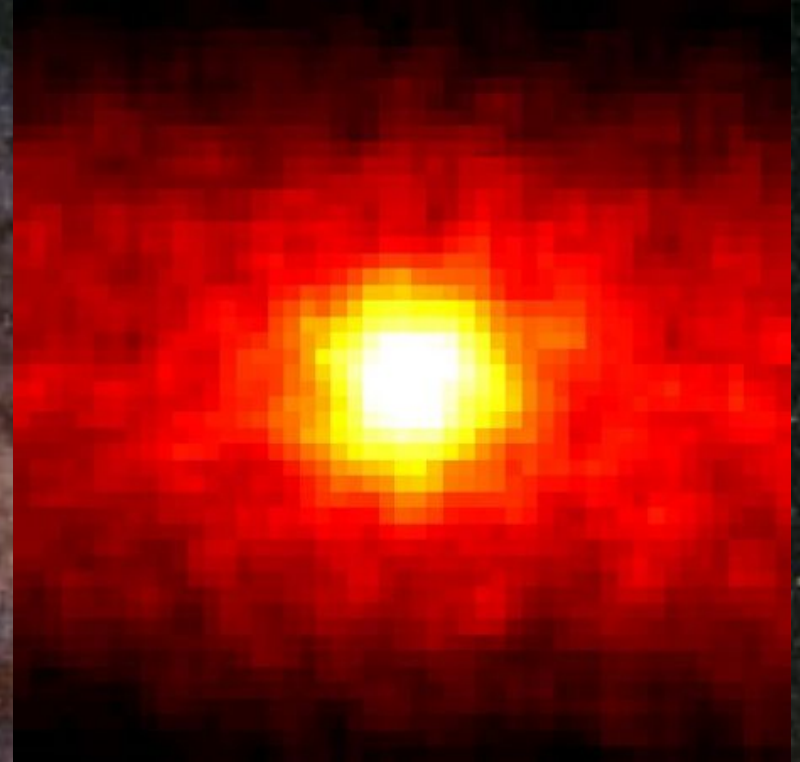
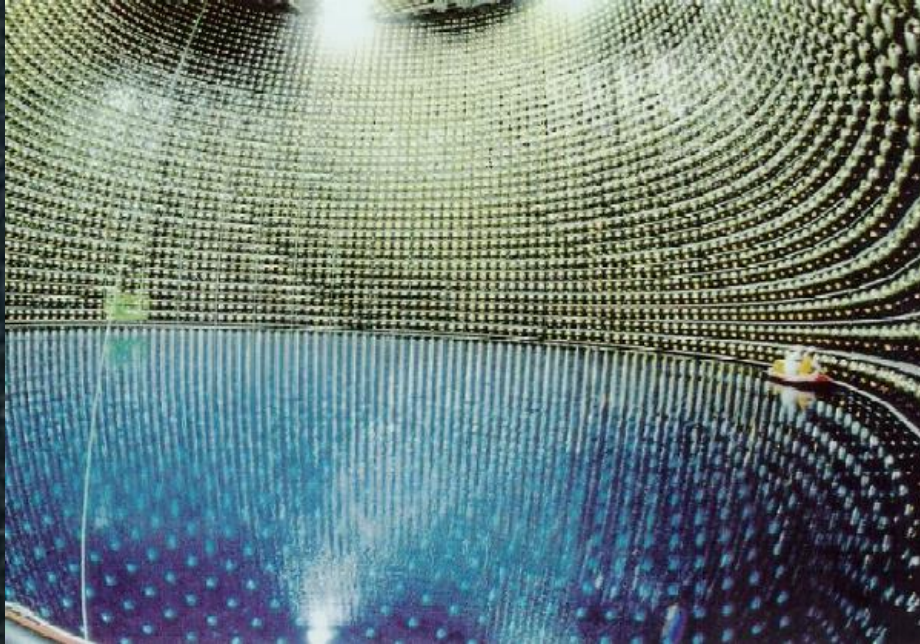
L'œil ne voit que  
la surface des  
choses



# Détecteur SuperKamiokande



# L'astronomie neutrino



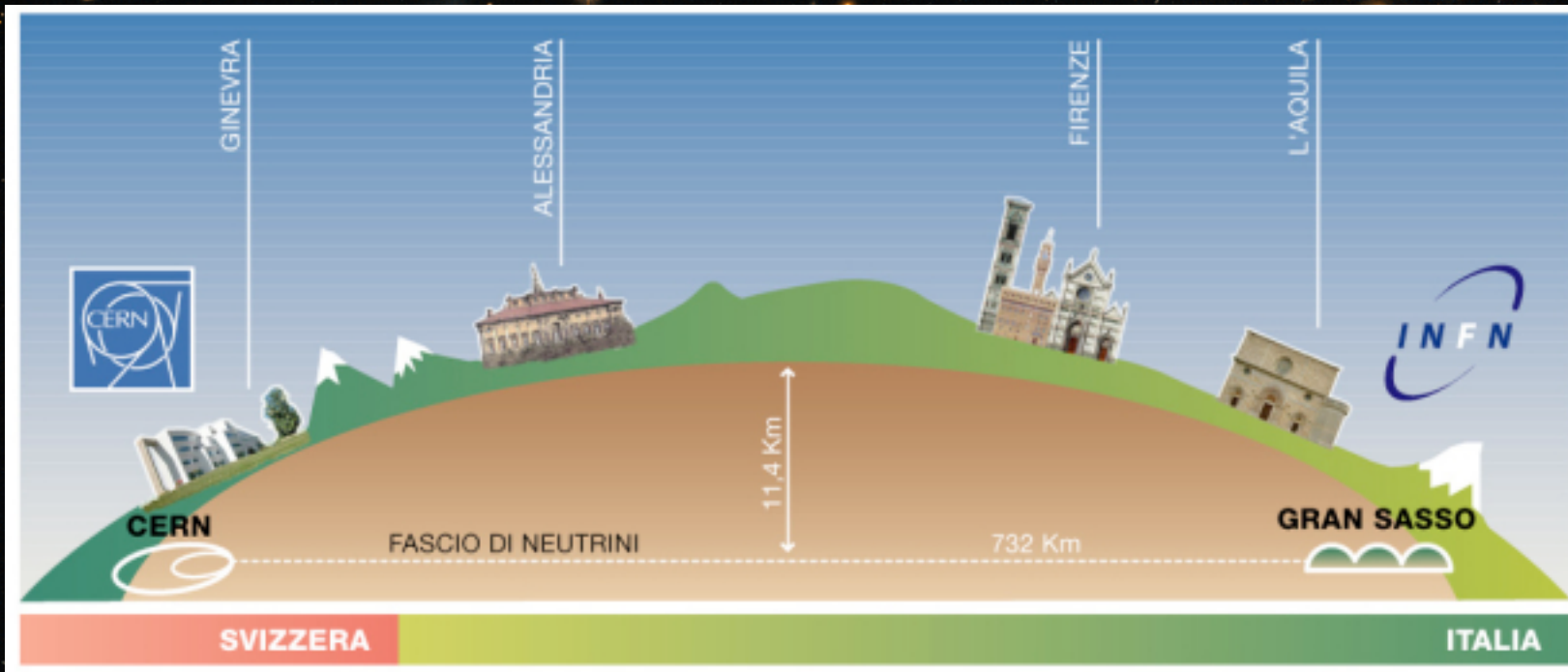
Temps de pose : 365 jours  
1000 m sous terre  
Poids de l'appareil: 50 000 tonne d'eau  
10 000 pixels

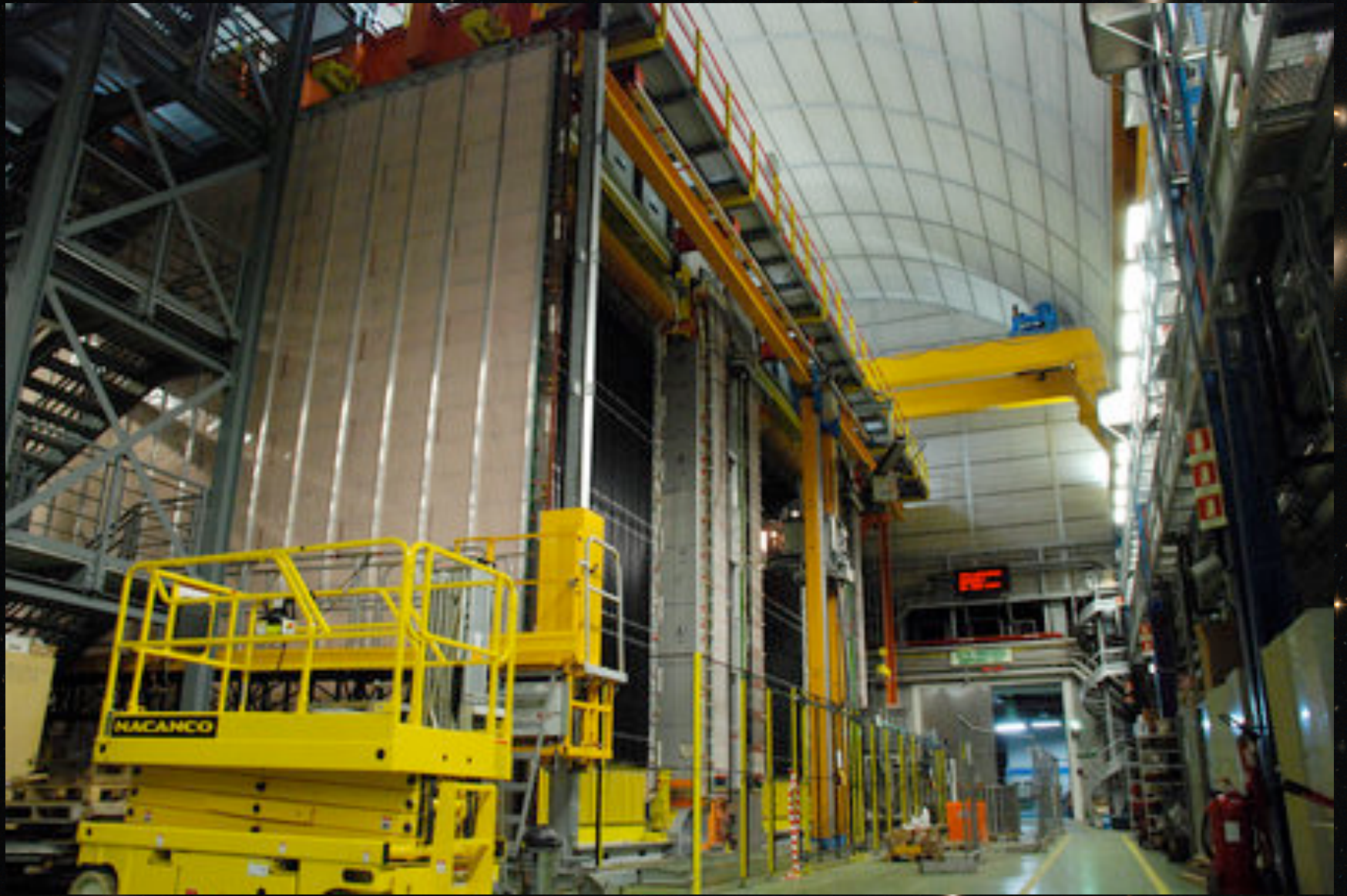
**1987: détection des neutrinos venant de SN1987 A**

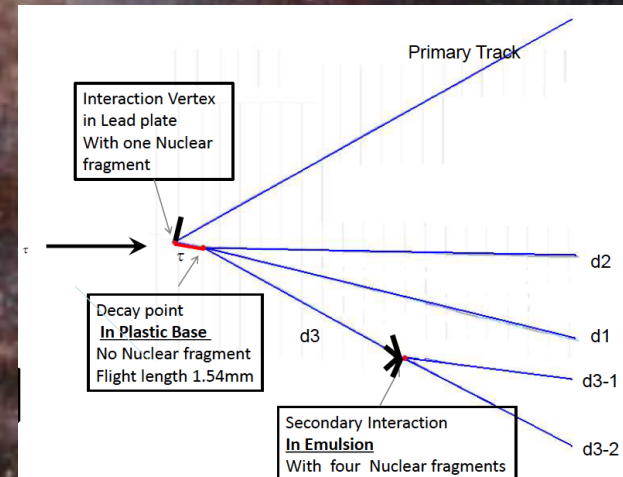
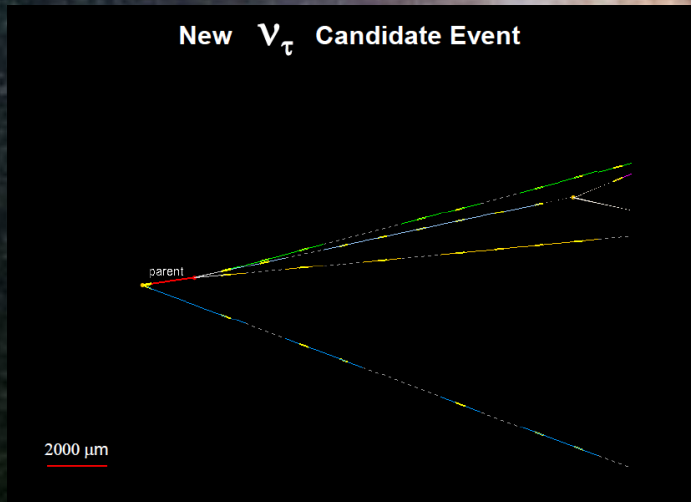
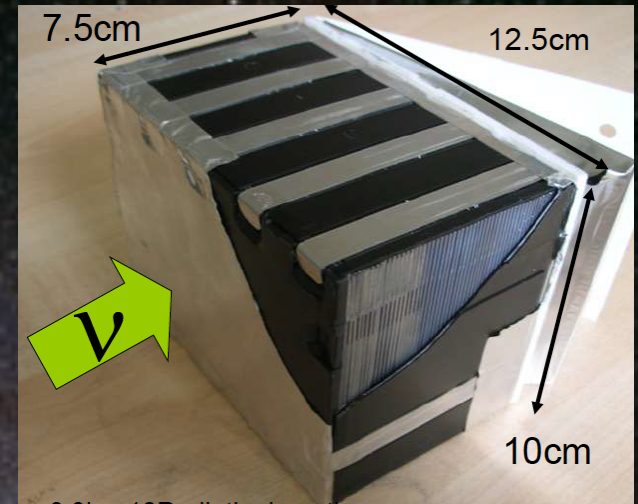
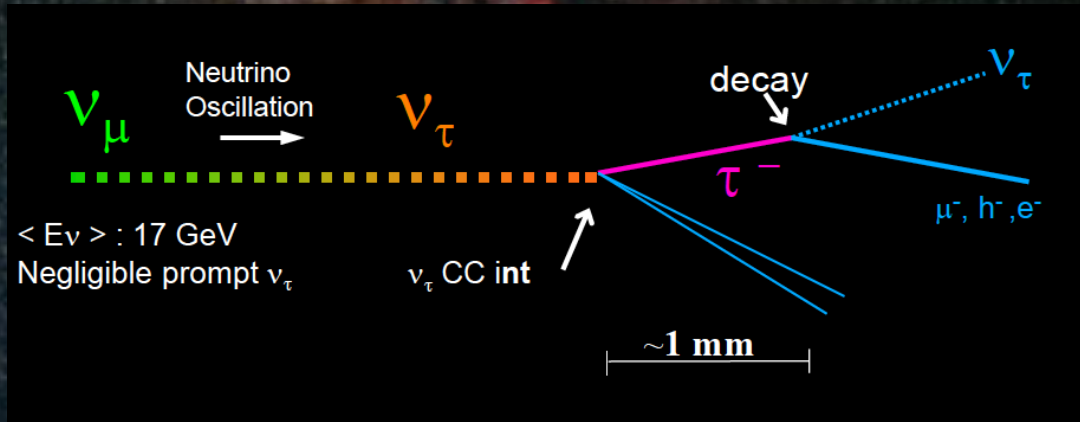
99 % de l' énergie d' une supernovae emportée par les neutrinos



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







4 événements détectés

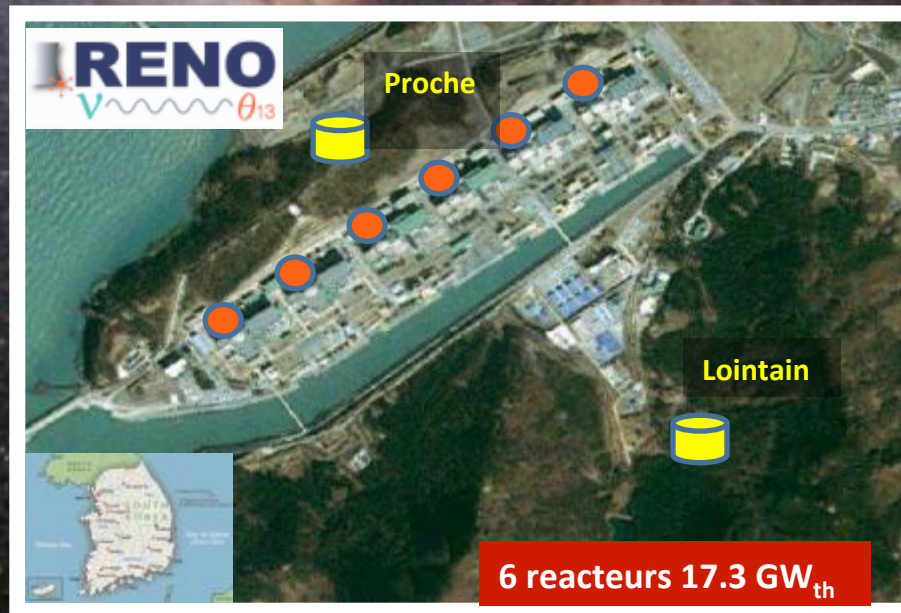
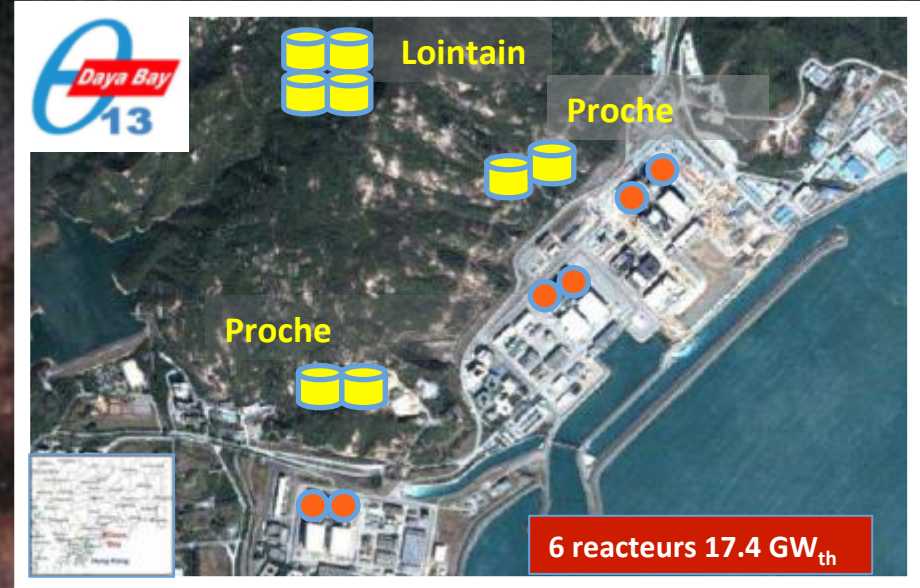
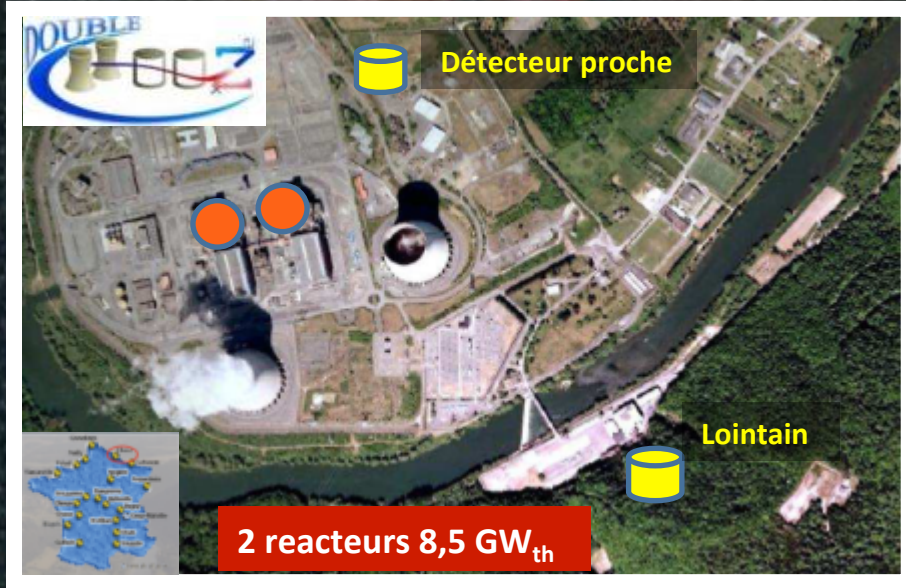


# Mesure de l'angle Theta13

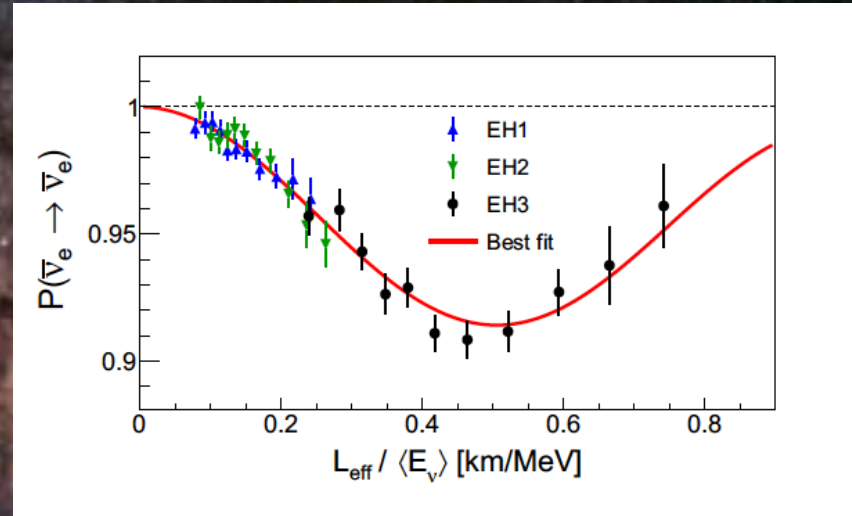
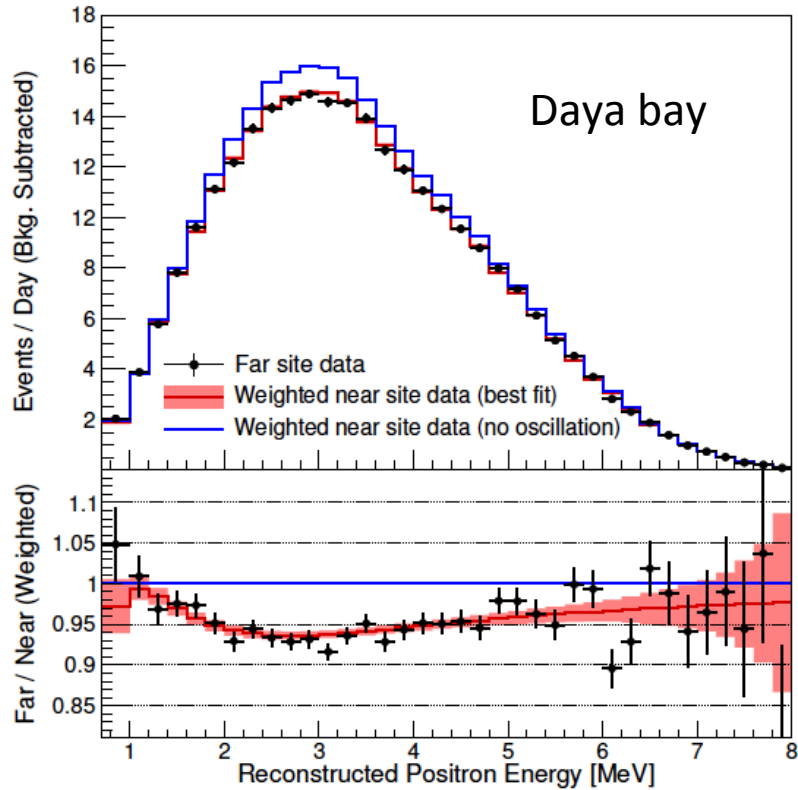
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\delta$  : violation de CP pour les neutrinos

# Mesure de l'angle Theta13

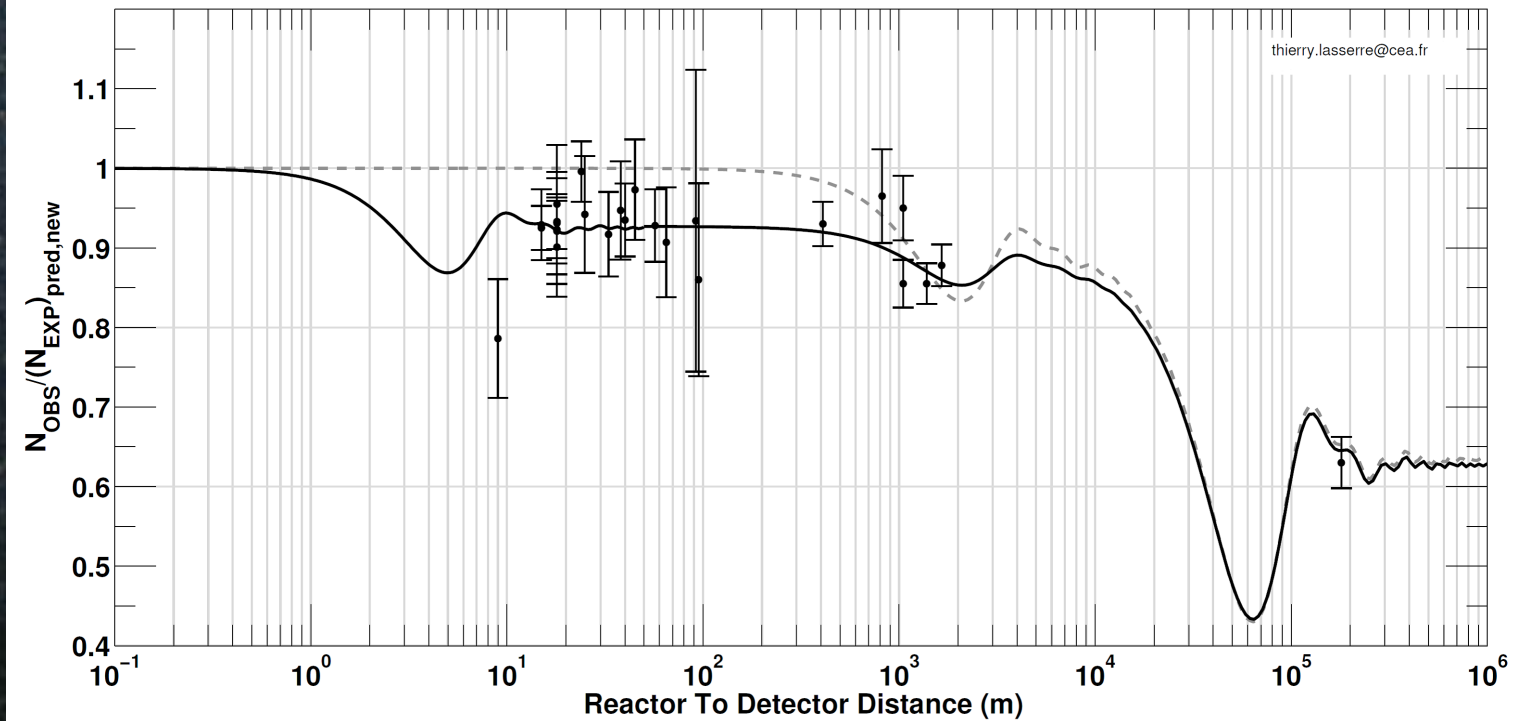


# Mesure de l'angle Theta13

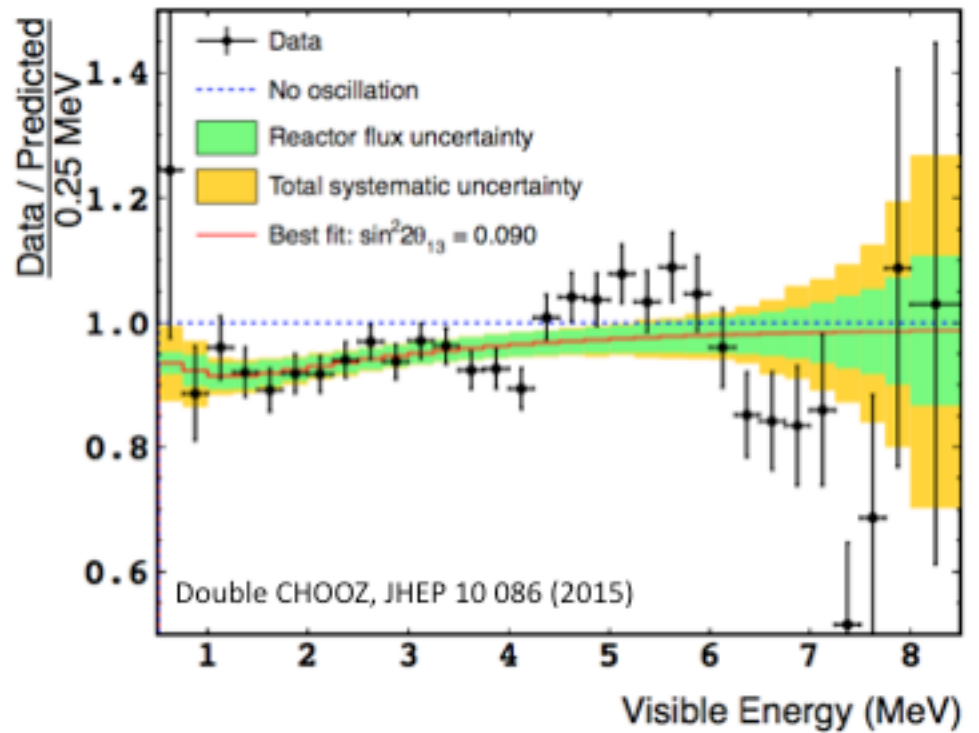
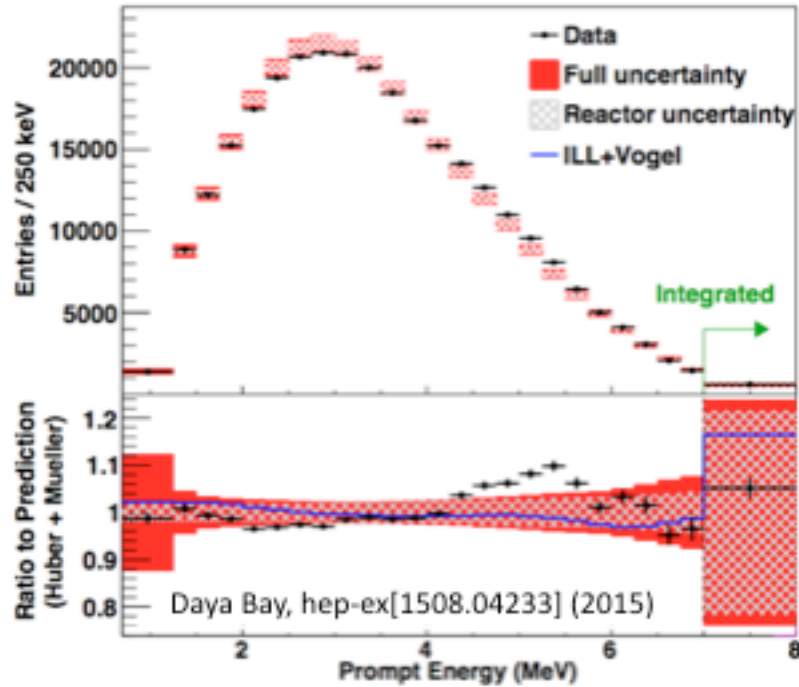


$$\theta_{13} \sim 8.8^\circ$$

# Une anomalie ? .....



# Ou 2 anomalies ? .....

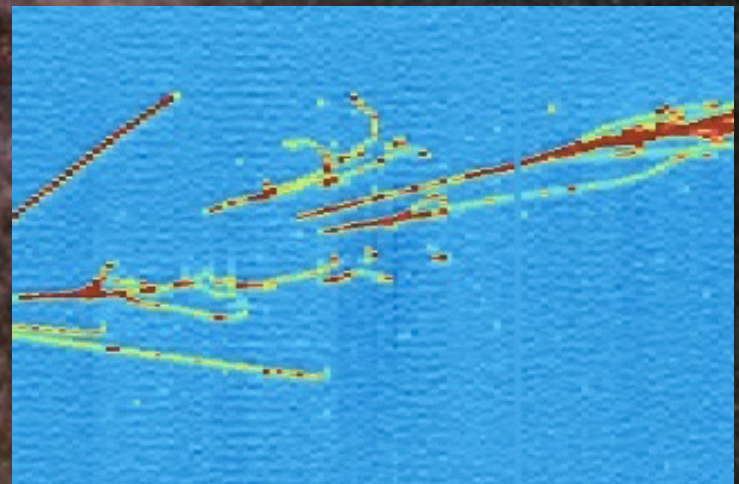
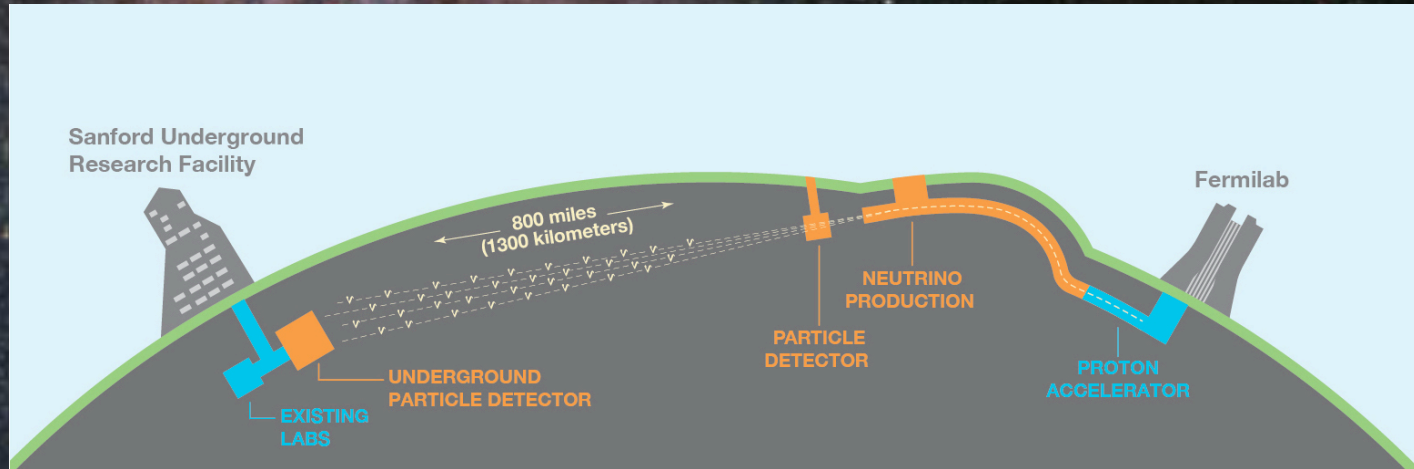


## Des mesures de précision

	parameter	best fit $\pm 1\sigma$
Neutrinos solaires et réacteurs	$\Delta m_{21}^2$ [ $10^{-5} \text{eV}^2$ ]	$7.60^{+0.19}_{-0.18}$
Neutrinos atmosphériques et accélérateurs	$ \Delta m_{31}^2 $ [ $10^{-3} \text{eV}^2$ ]	$2.48^{+0.05}_{-0.07}$
Neutrinos solaires et réacteurs	$\theta_{12}/^\circ$	$34.6 \pm 1.0$
Neutrinos atmosphériques et accélérateurs	$\theta_{23}/^\circ$	$48.9^{+1.9}_{-7.4}$
Neutrinos réacteurs	$\theta_{13}/^\circ$	$8.8 \pm 0.4$

# DUNE : Violation de CP

Probabilité d'oscillation différentes pour neutrino et anti-neutrino





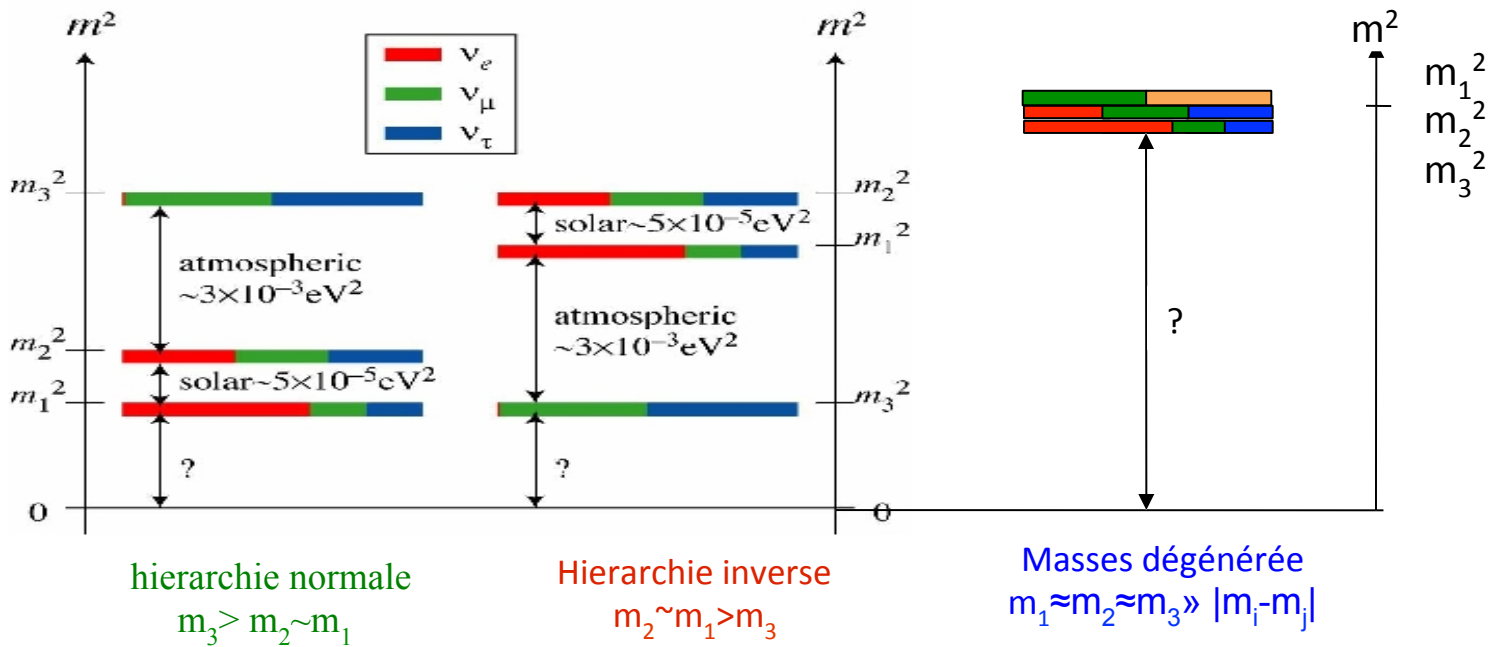


$$\nu_{\mu} \longrightarrow \nu_{\tau}$$

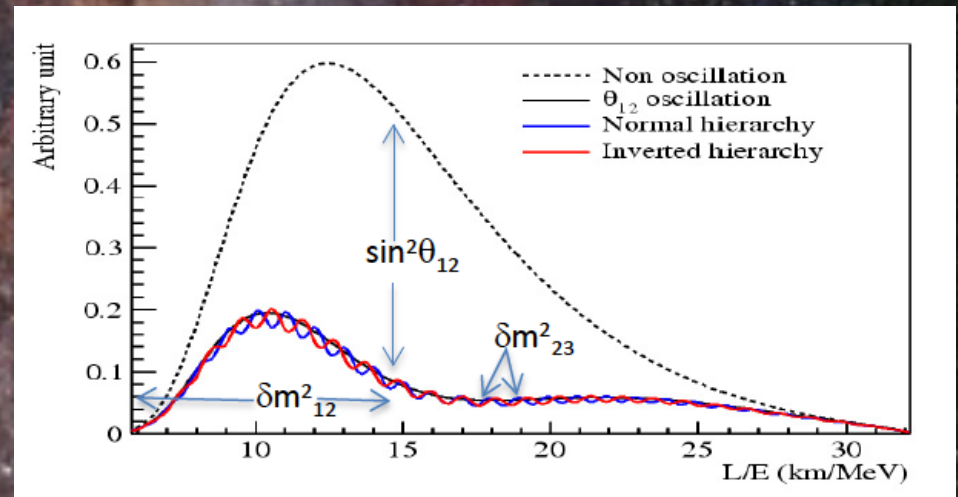
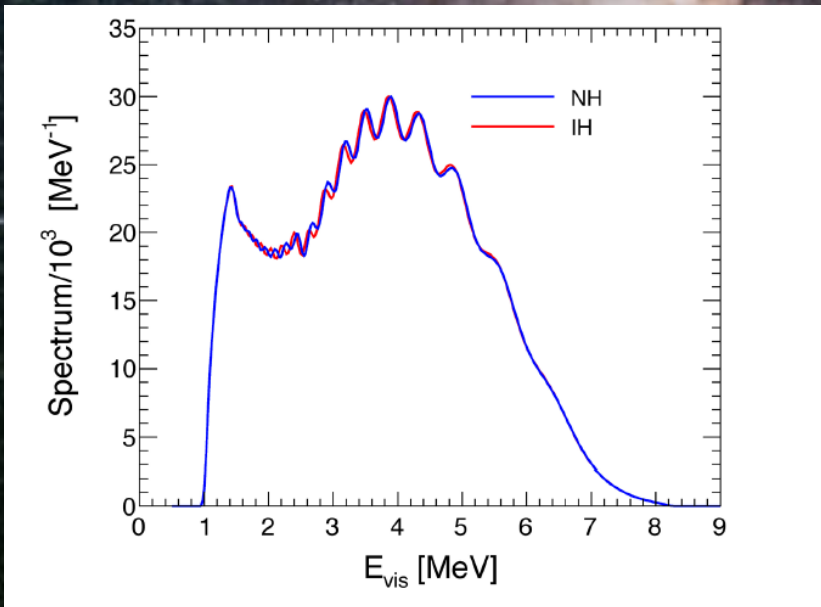
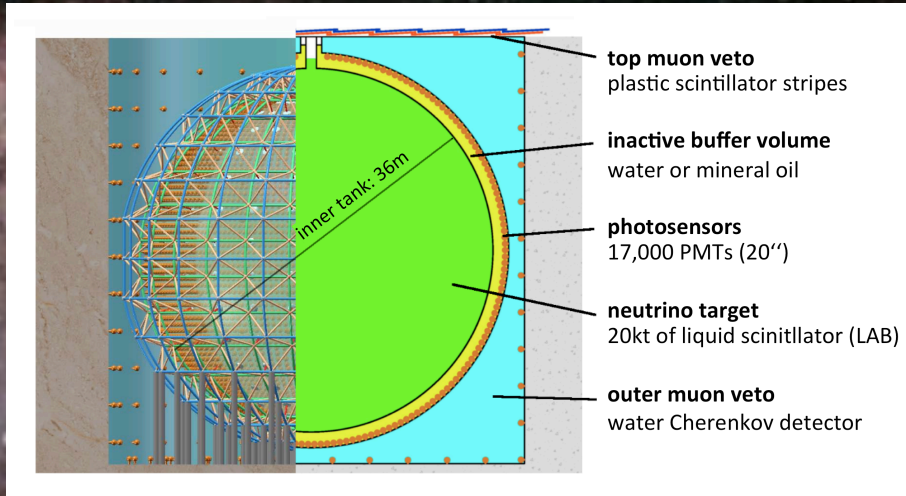
$$\Delta m_{23}^2 \sim 2 \cdot 10^{-3} \text{ eV}^2$$

$$\nu_e \longrightarrow \nu_{\mu}$$

$$\Delta m_{12}^2 \sim 5 \cdot 10^{-5} \text{ eV}^2$$

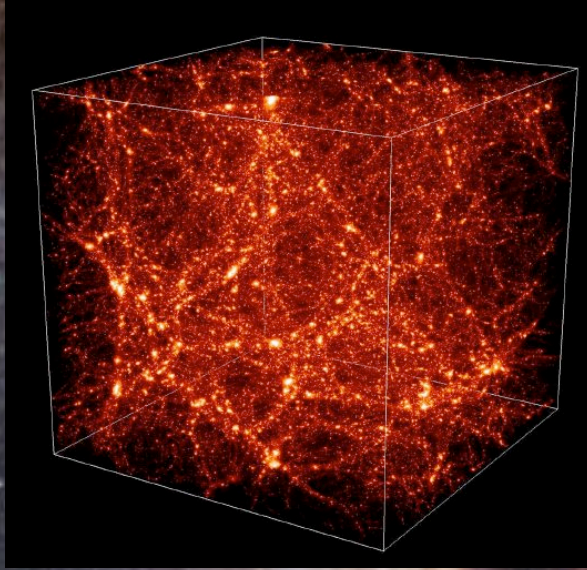


# JUNO (Chine): Hiérarchie de masse



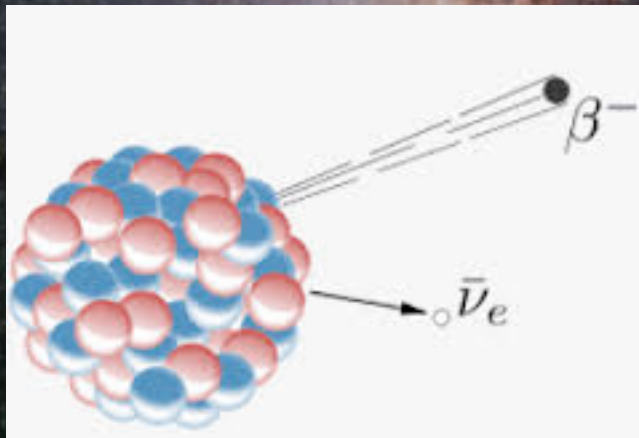
Peut aussi être mesuré avec neutrinos accélérateurs ou neutrino cosmiques

# Une masse mais laquelle ?



Etudes des structure à grande échelle

$$\Sigma m(\nu) < 0,23 \text{ eV}$$



$$m(\nu_e) < 2,3 \text{ eV}$$

Désintégration bêta<sup>M</sup>

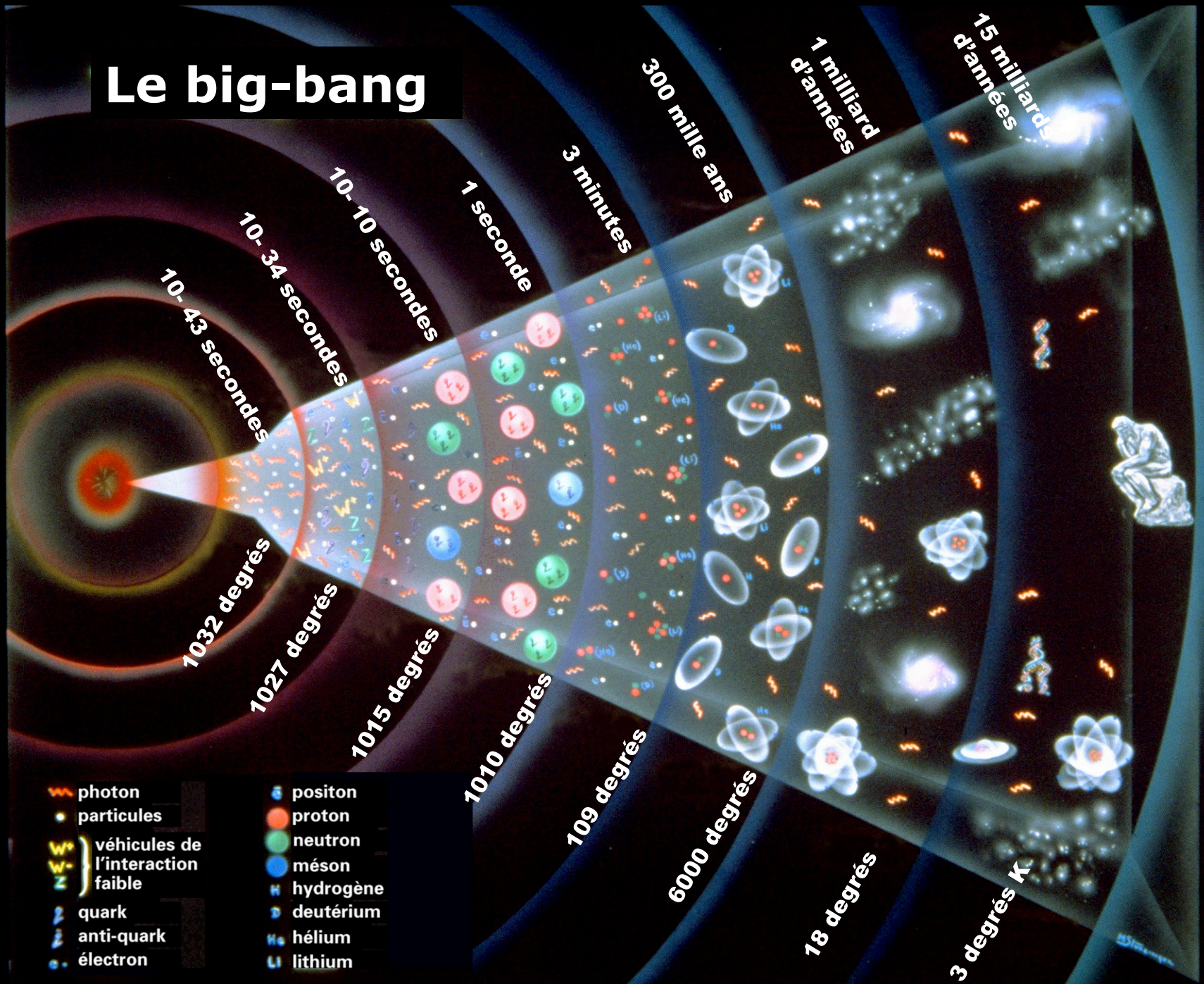


**1937: Ettore Majorana**

**Neutrino = anti-neutrino ?**

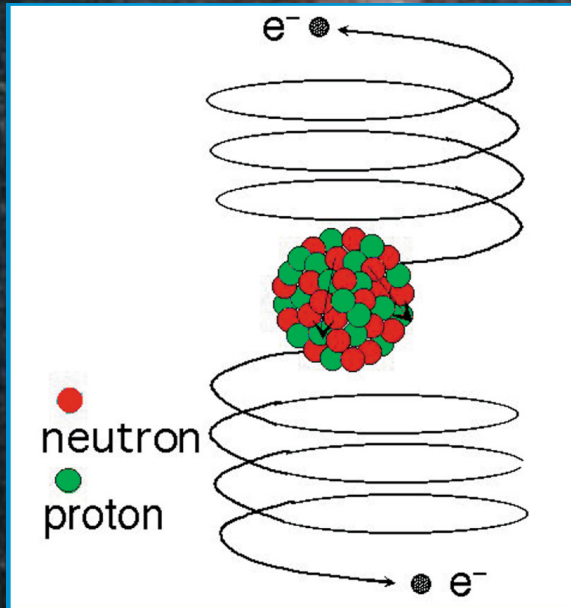
**Le neutrino est-il à l'origine de la matière ?**

# Le big-bang



- photon
- particules
- véhicules de l'interaction faible
- quark
- anti-quark
- électron
- positon
- proton
- neutron
- méson
- hydrogène
- deutérium
- hélium
- lithium

# Double désintégration bêta

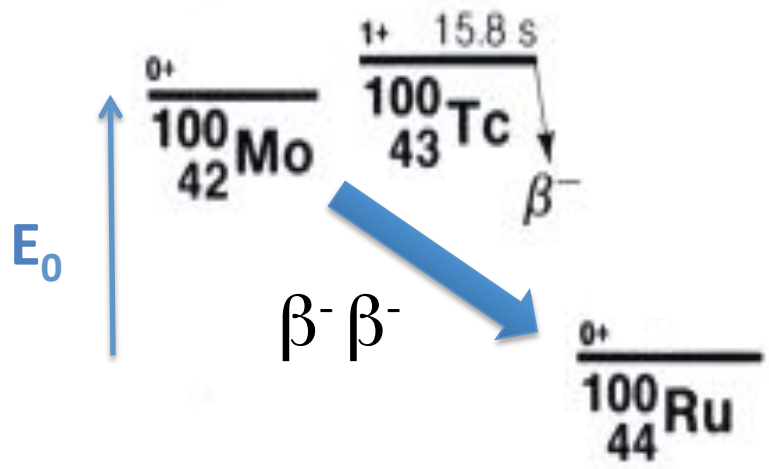


Neutrino = anti-neutrino  
Neutrino massif

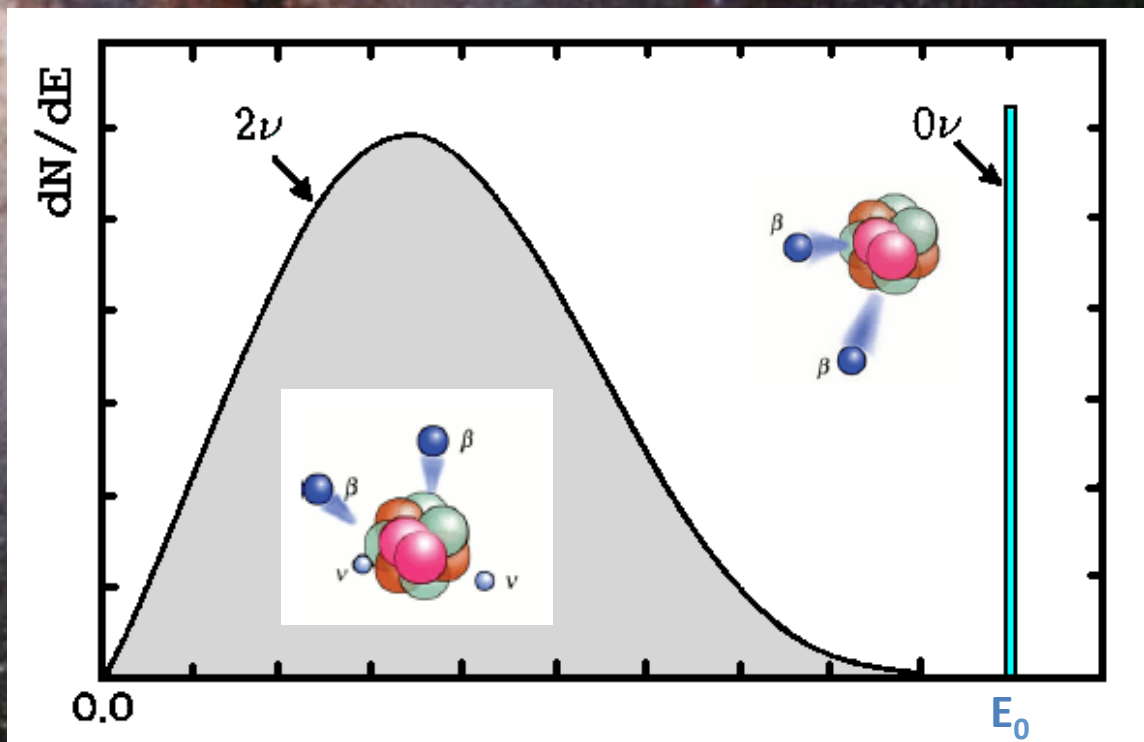


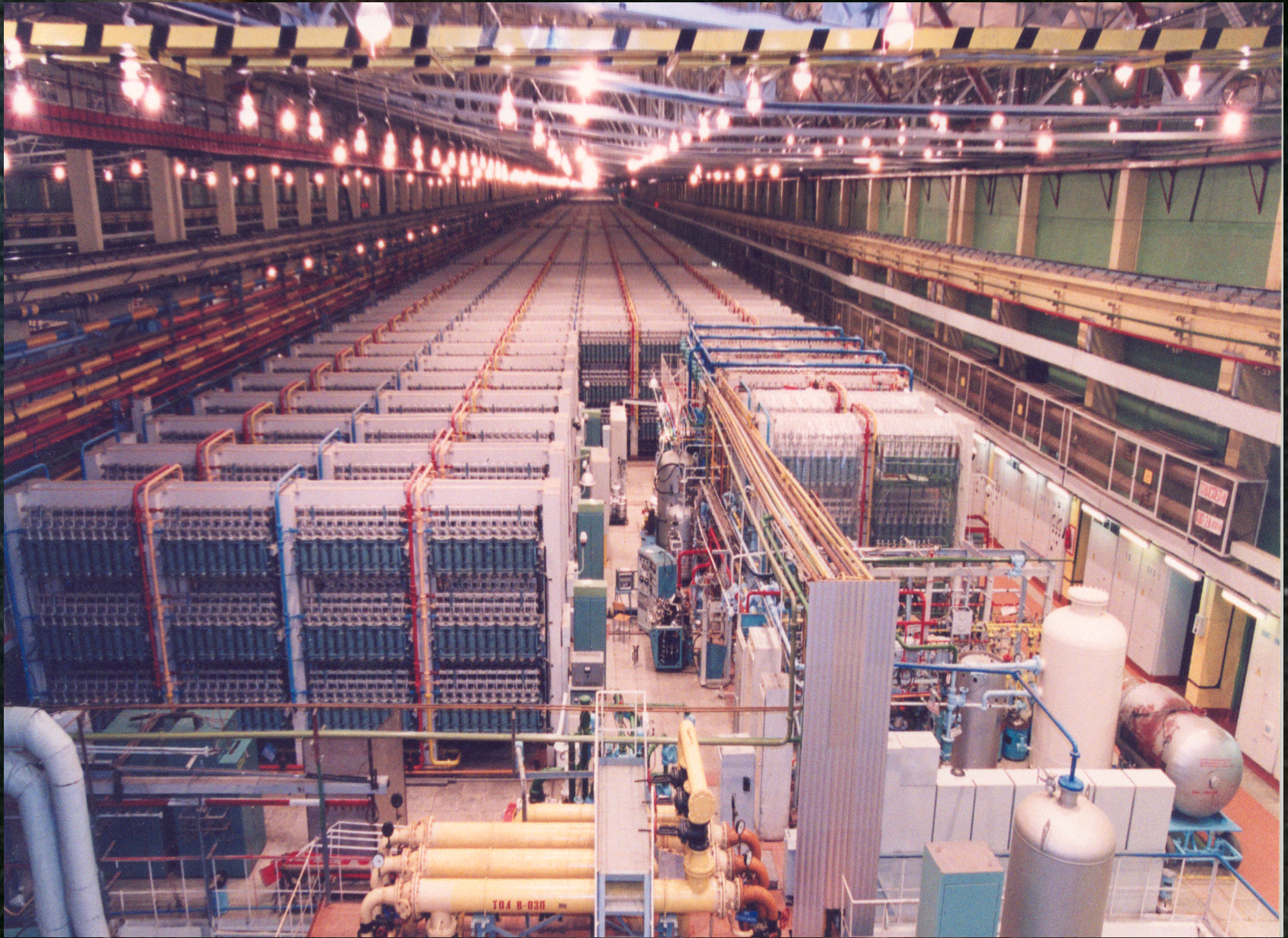
Période attendue  $> 10^{25}$  ans  
(âge de l'univers  $15 \cdot 10^9$  ans)

Période



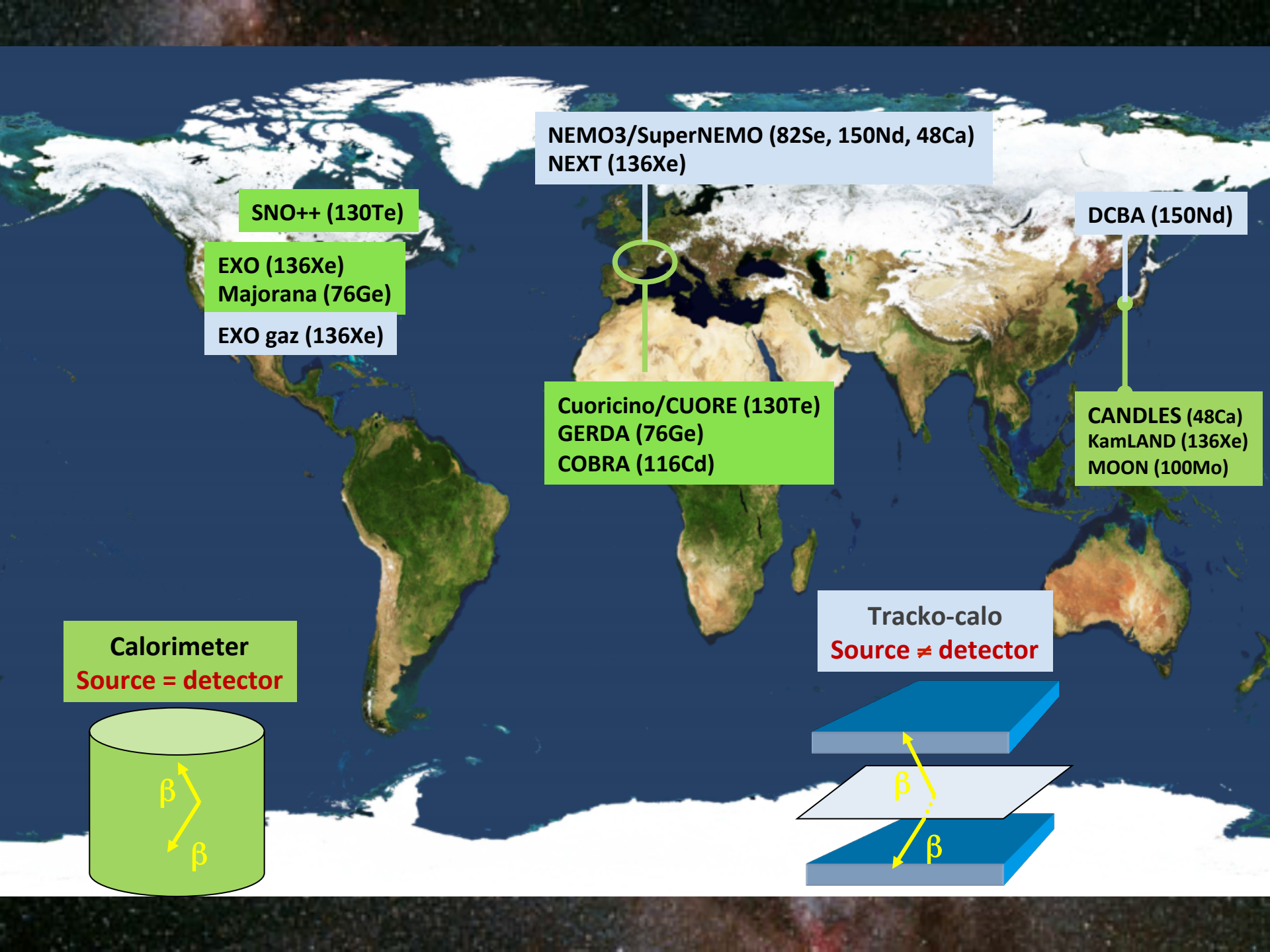
$$T_{1/2} \propto 1/\langle m_\nu \rangle^2$$





Enrichissement  $^{100}\text{Mo}$  10%  $\rightarrow$  95%





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

SNO++ (130Te)

DCBA (150Nd)

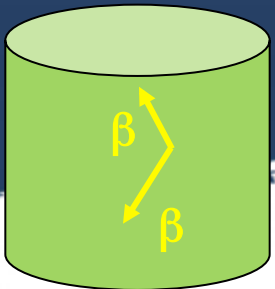
EXO (136Xe)  
Majorana (76Ge)

EXO gaz (136Xe)

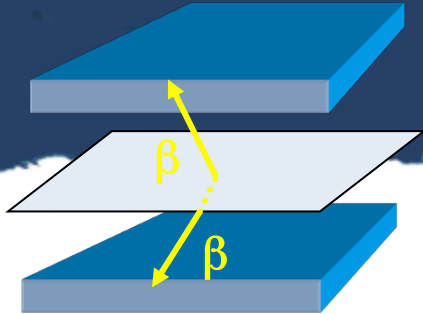
Cuoricino/CUORE (130Te)  
GERDA (76Ge)  
COBRA (116Cd)

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

Calorimeter  
Source = detector



Tracko-calorimeter  
Source ≠ detector





# Laboratoire Souterrain de Modane



Image © 2010 DigitalGlobe

[WWW.LSM.FR](http://WWW.LSM.FR)

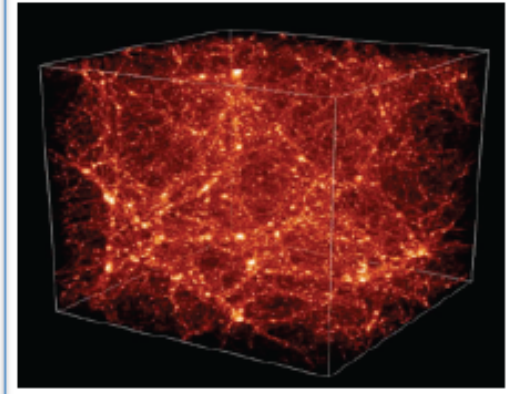
# Les activités scientifiques au LSM



Création de la matière



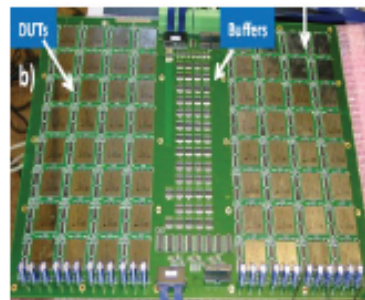
Recherche de la matière noire



Evolution de l'univers



Environnement



Nano-électronique

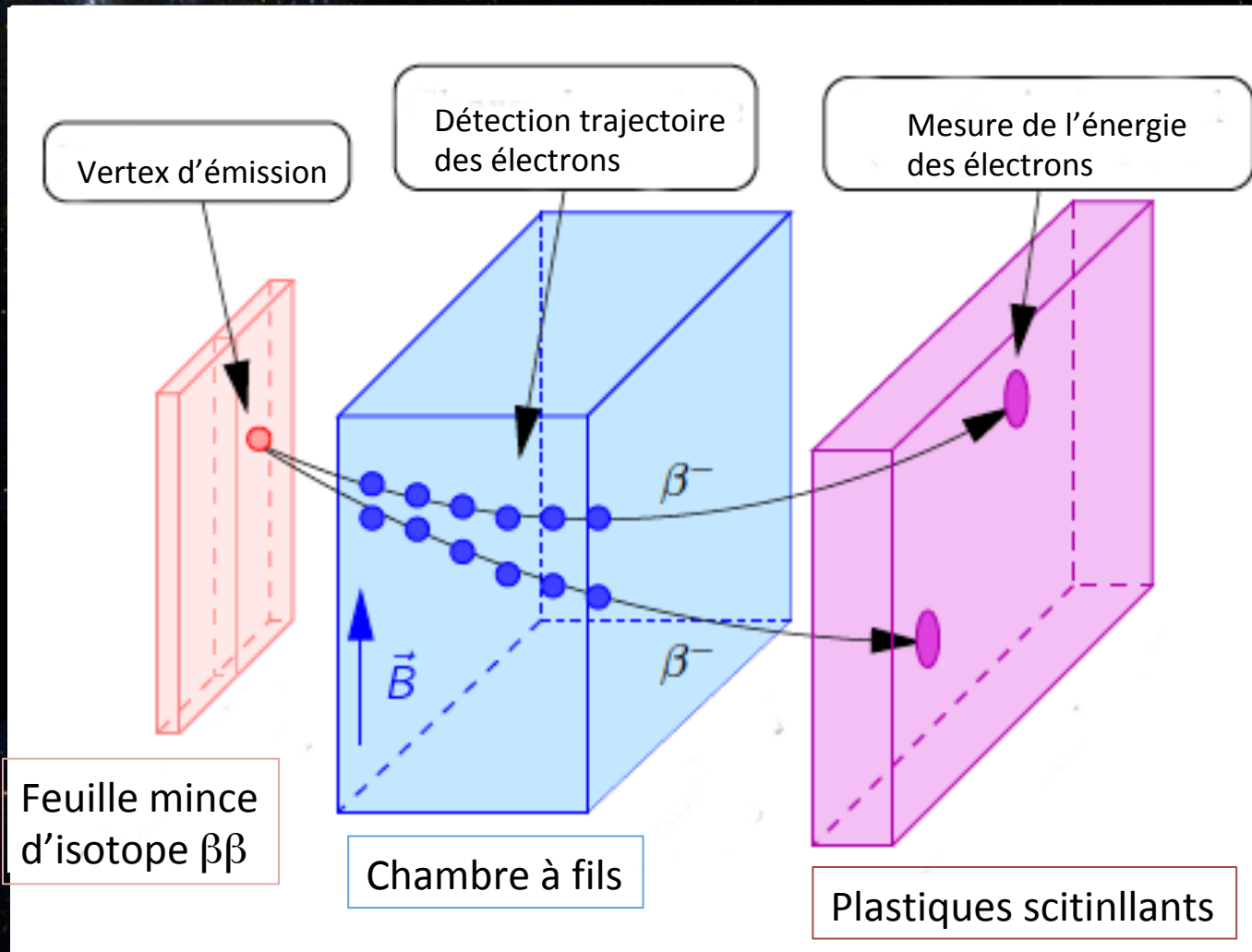


Biologie

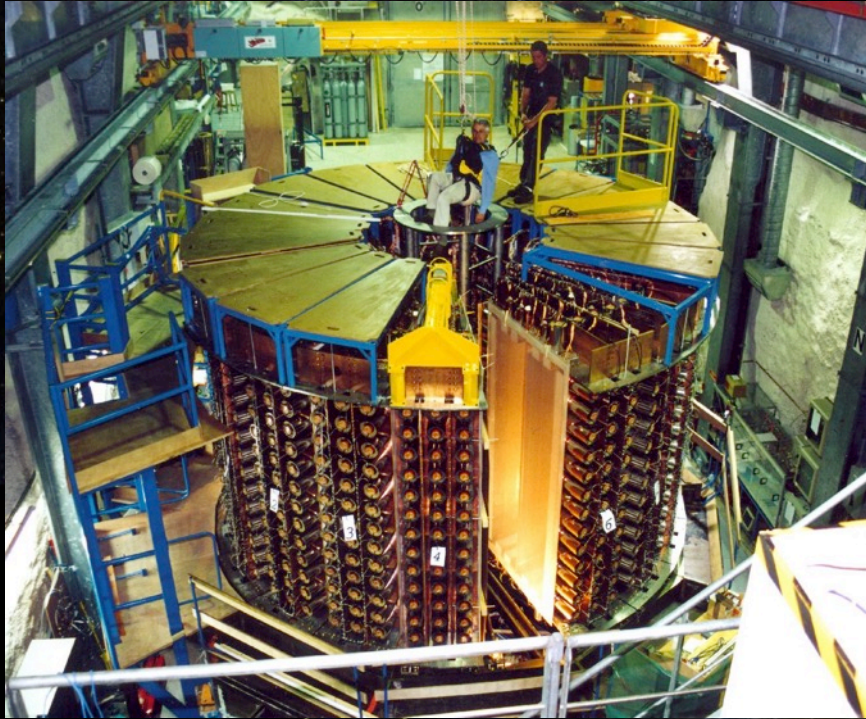


Datation vin Bordeaux

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



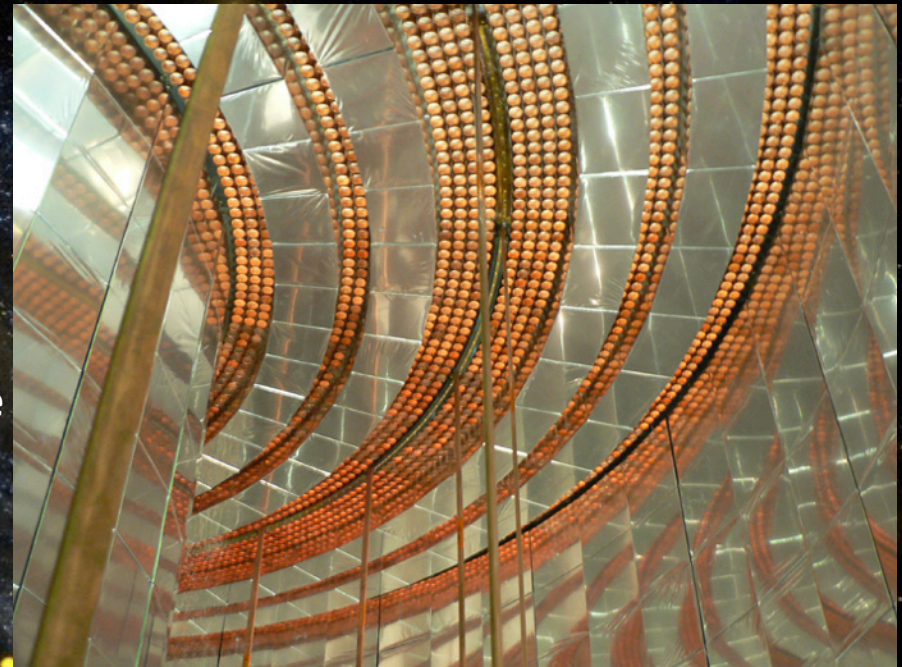
# EXPERIENCE NEMO3 (2003 – 2015)



Installée au laboratoire souterrain de Modane

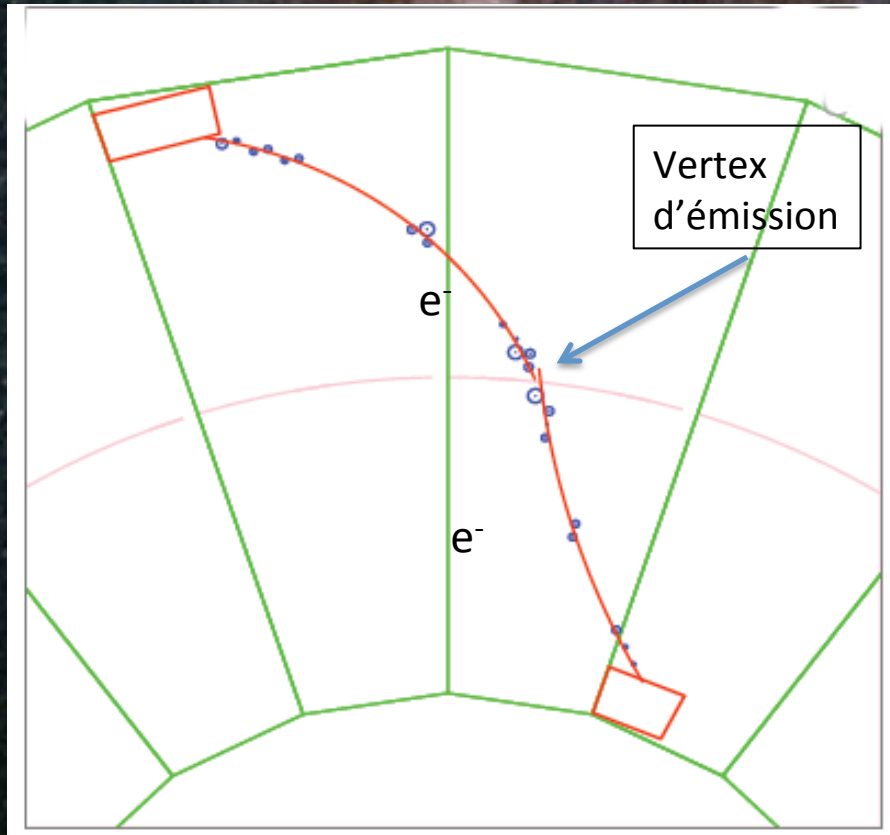
Participation du CENBG

10 kg d'isotopes double bêta

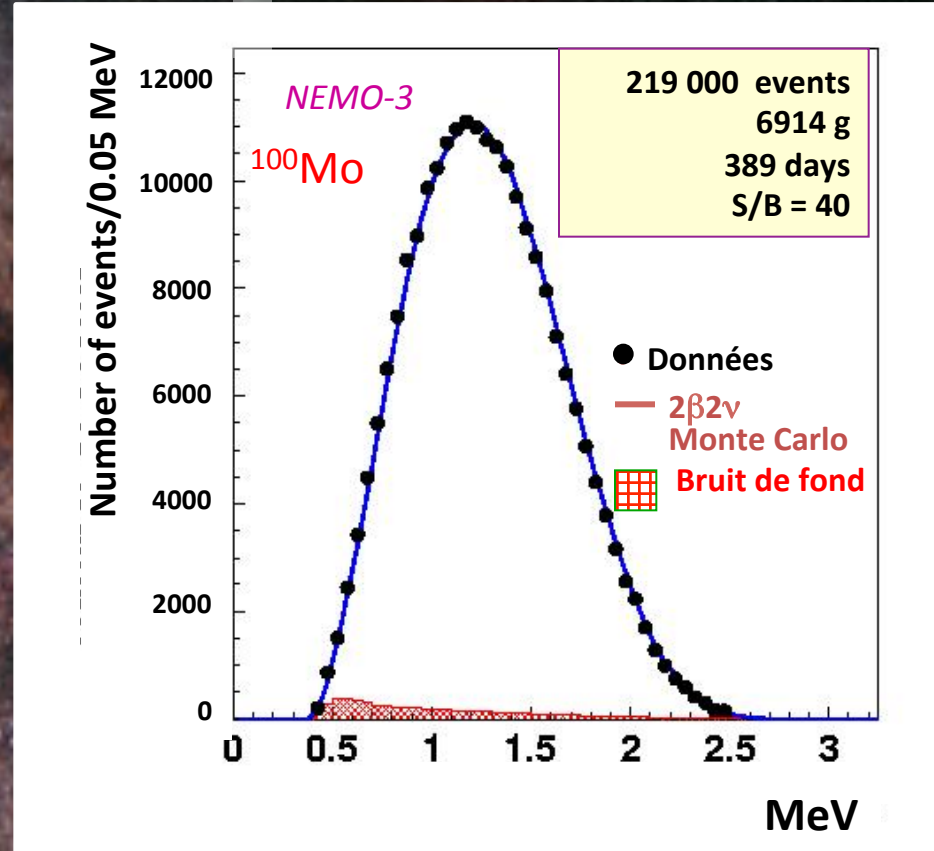


200 tonnes de matériaux : radioactivité totale 1 000 Bq !!  
(corps humain ~ 8000 Bq)

$m_\nu < 0,5 \text{ eV}$

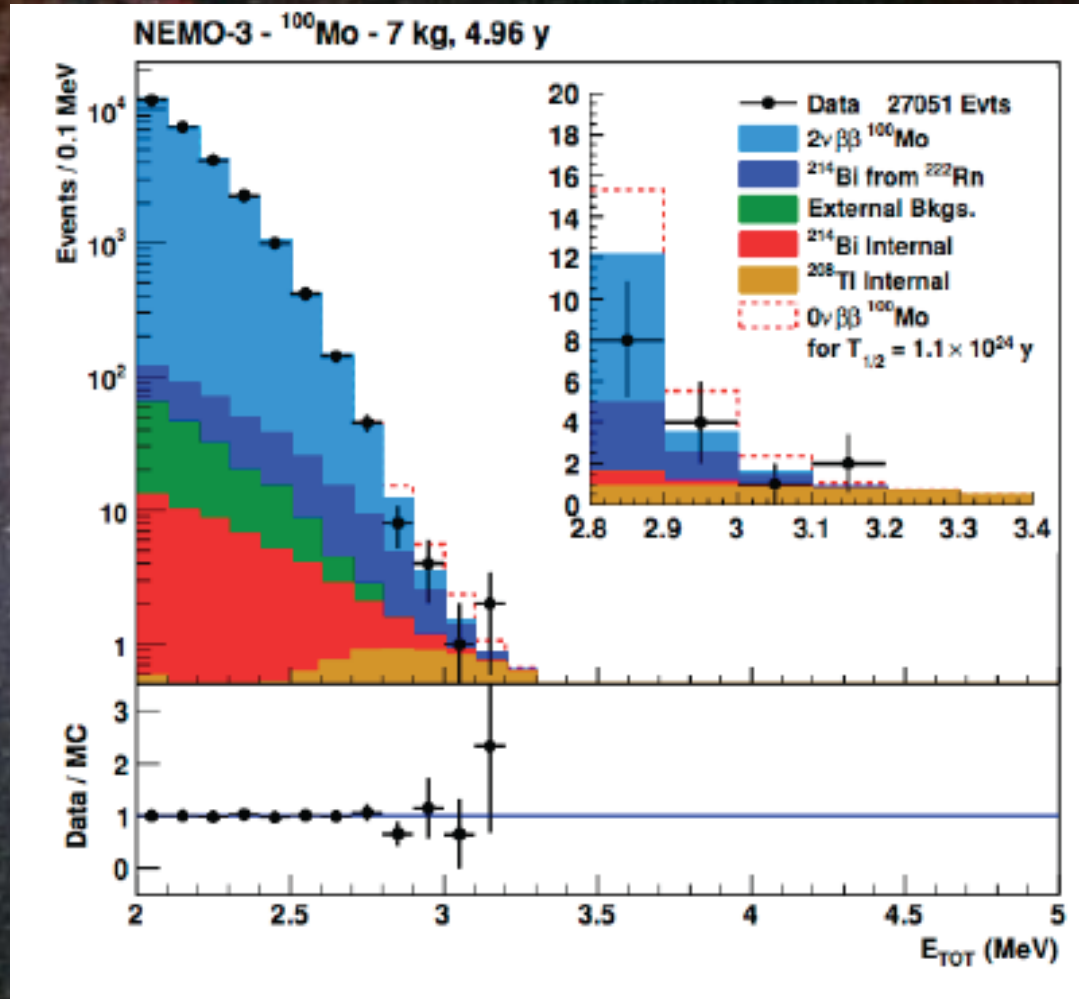


Un évènement dans NEMO3



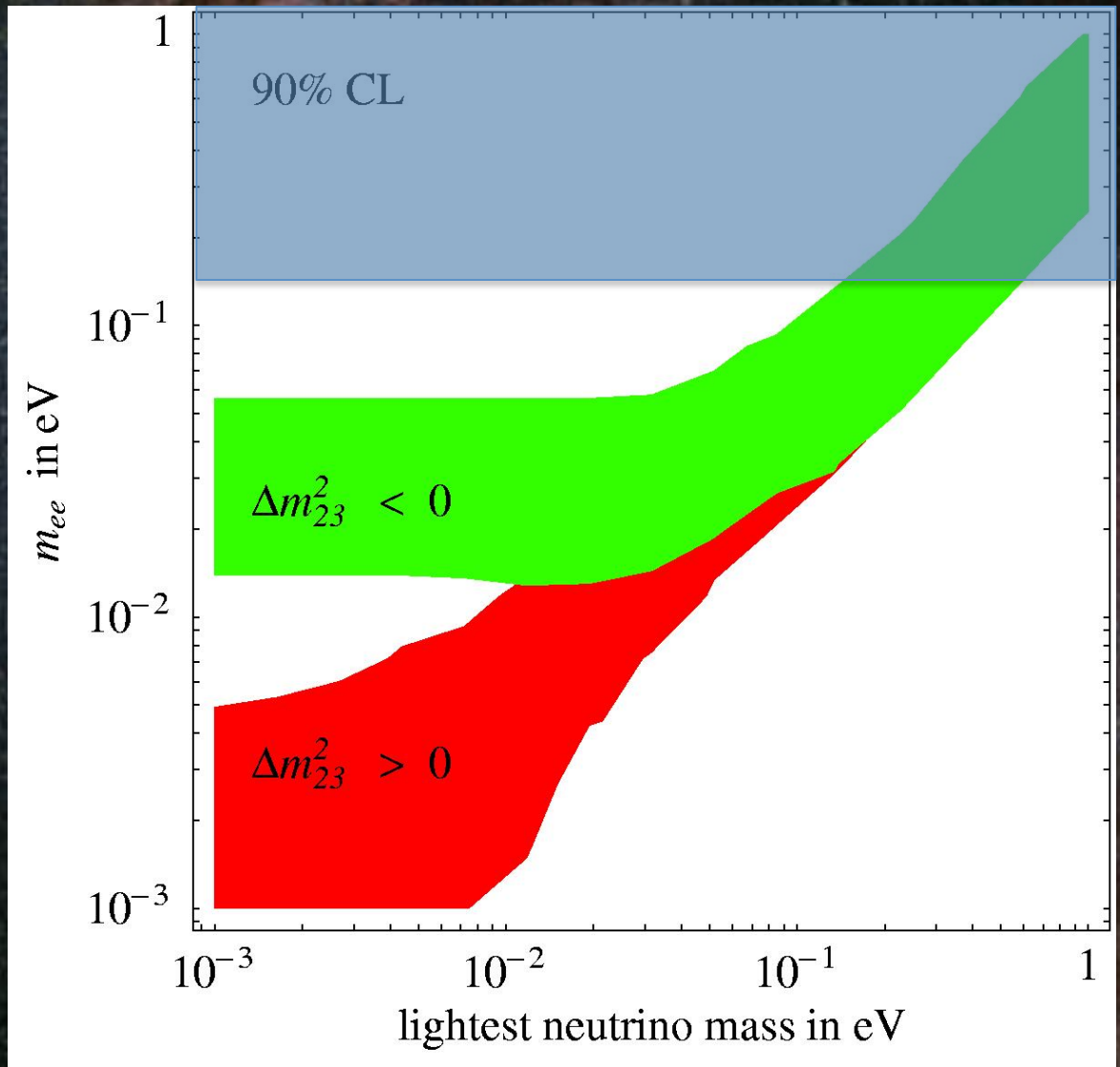
$$T_{1/2}(\beta\beta 2\nu) = 7.11 \pm 0.02 \text{ (stat)} \pm 0.54 \text{ (syst)} \times 10^{18} \text{ years}$$

# Résultats de NEMO3



$$T_{1/2}^{0\nu} > 1.1 \times 10^{24} \text{ y}$$

$$\langle m_{\beta\beta} \rangle < 0.33\text{-}0.62 \text{ eV}$$

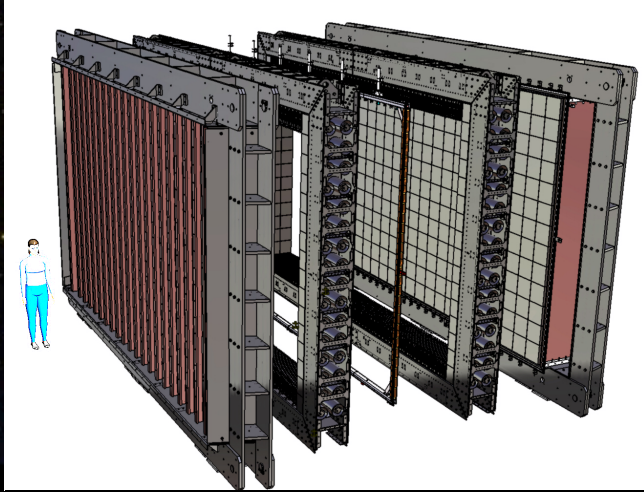


≈ 10 – 100 kg d'isotopes

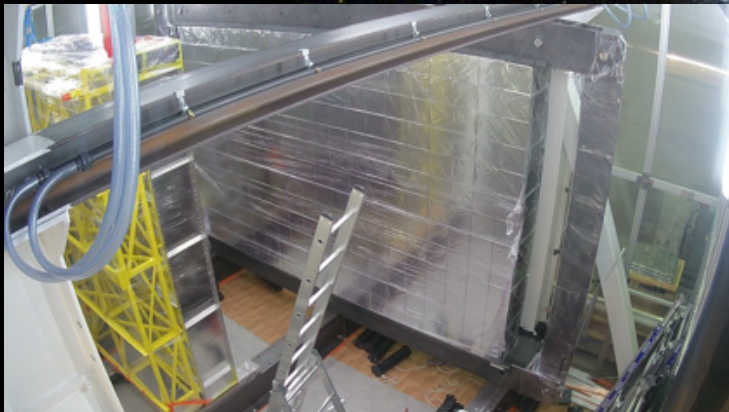
≈ 100 - 1000 kg d'isotopes



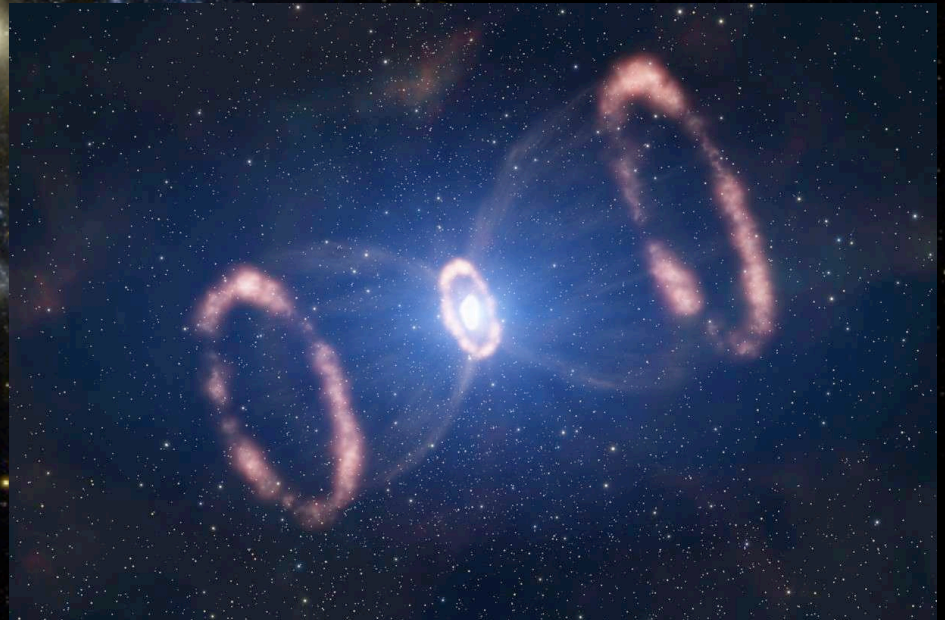
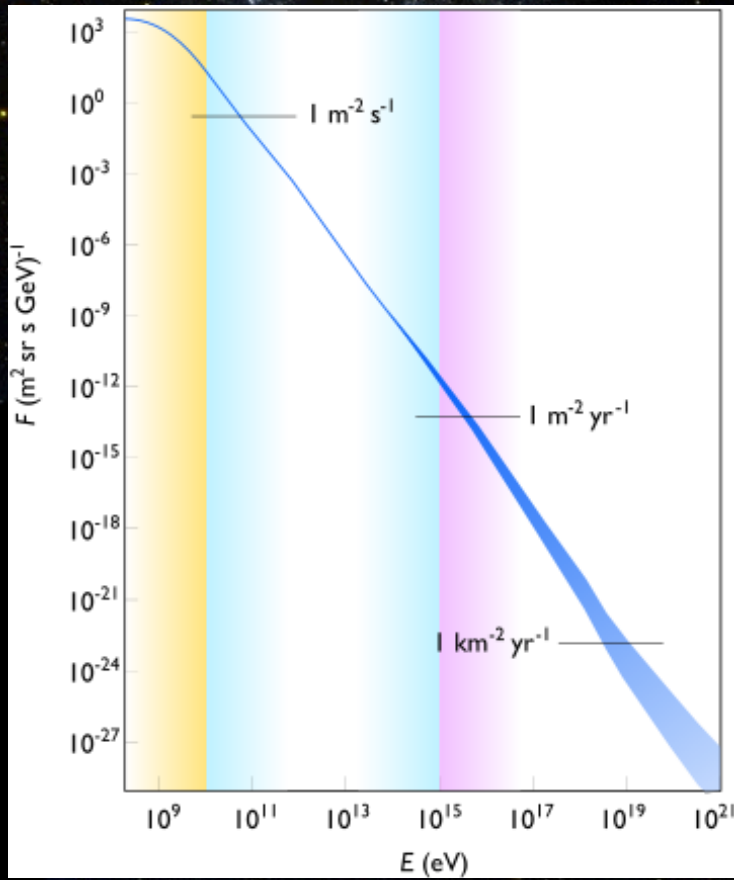
# SuperNEMO



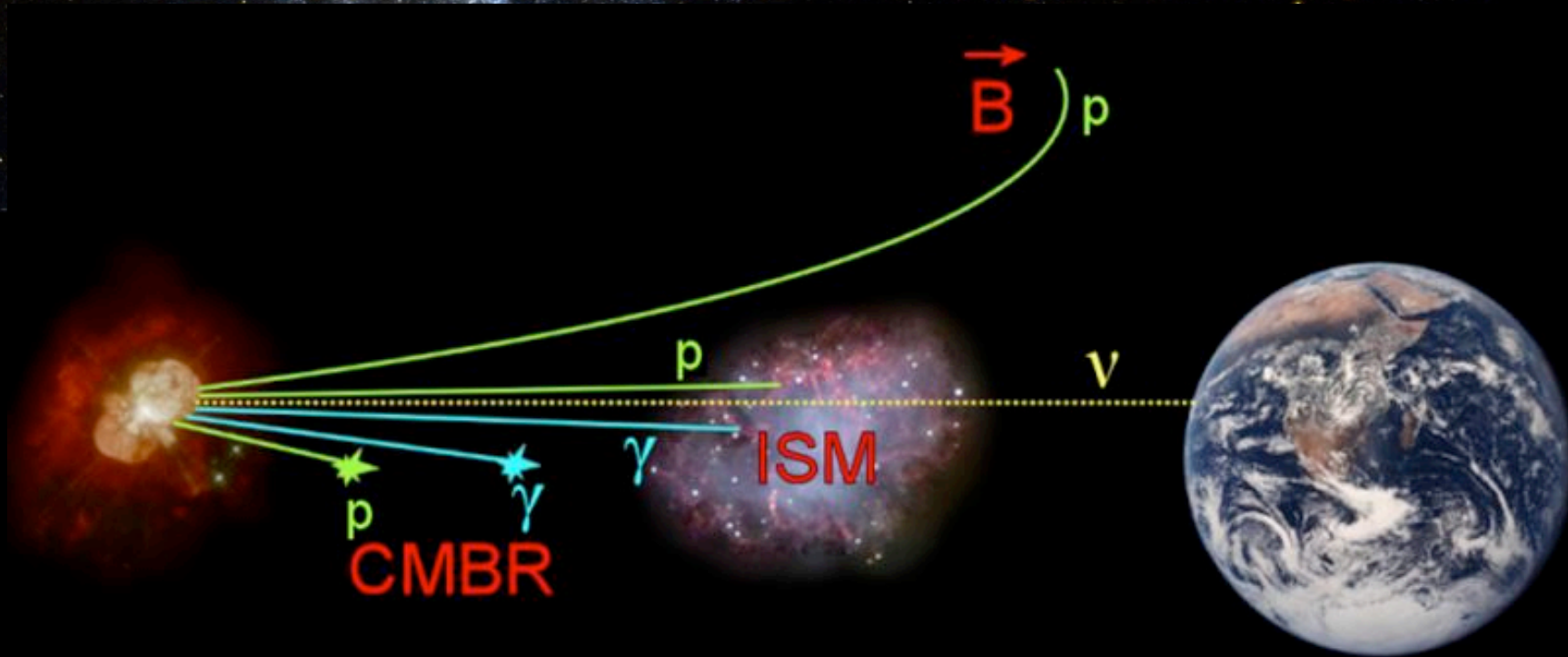
5 kg d'isotopes double bêta \* 20



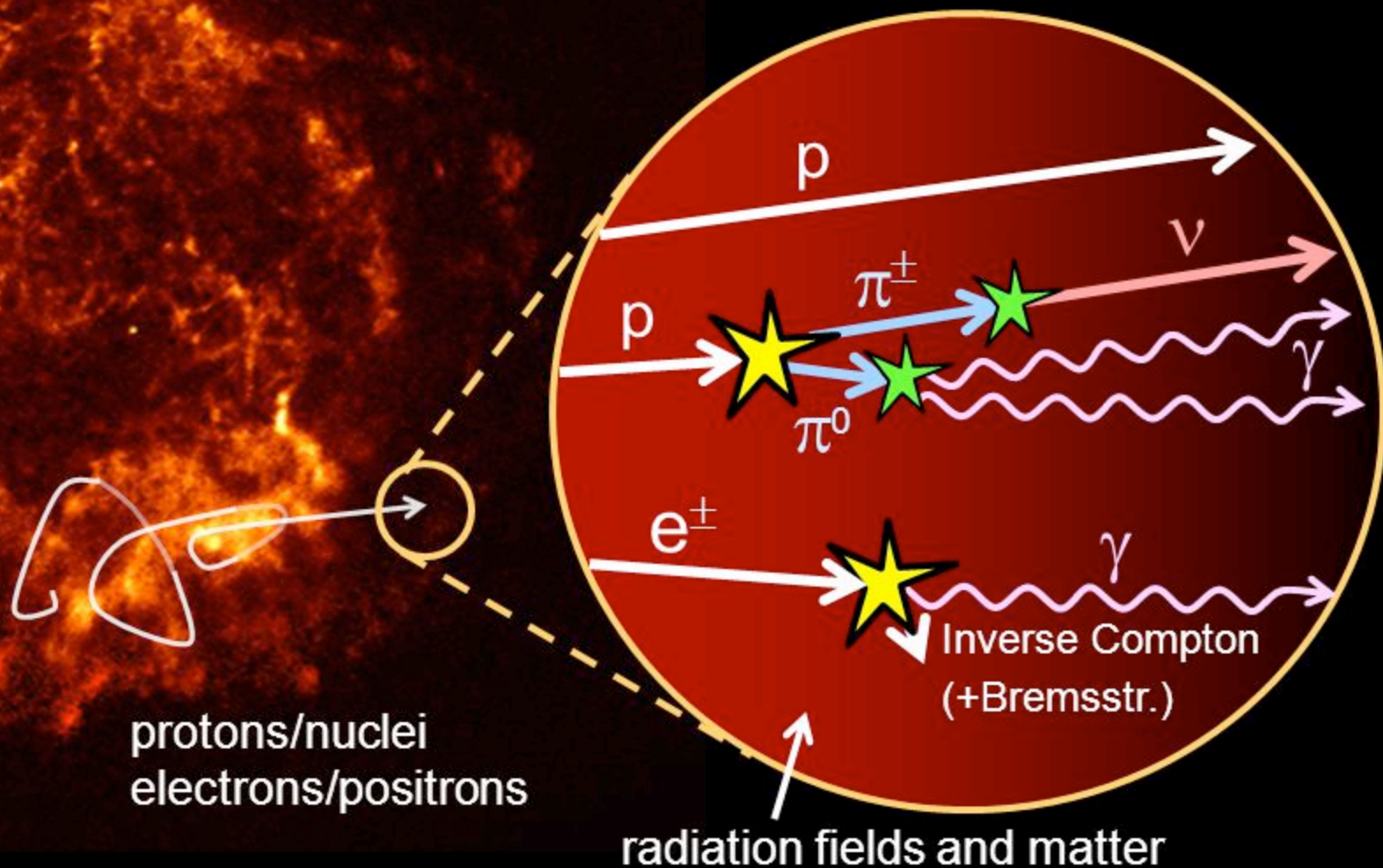
# Rayonnement cosmique

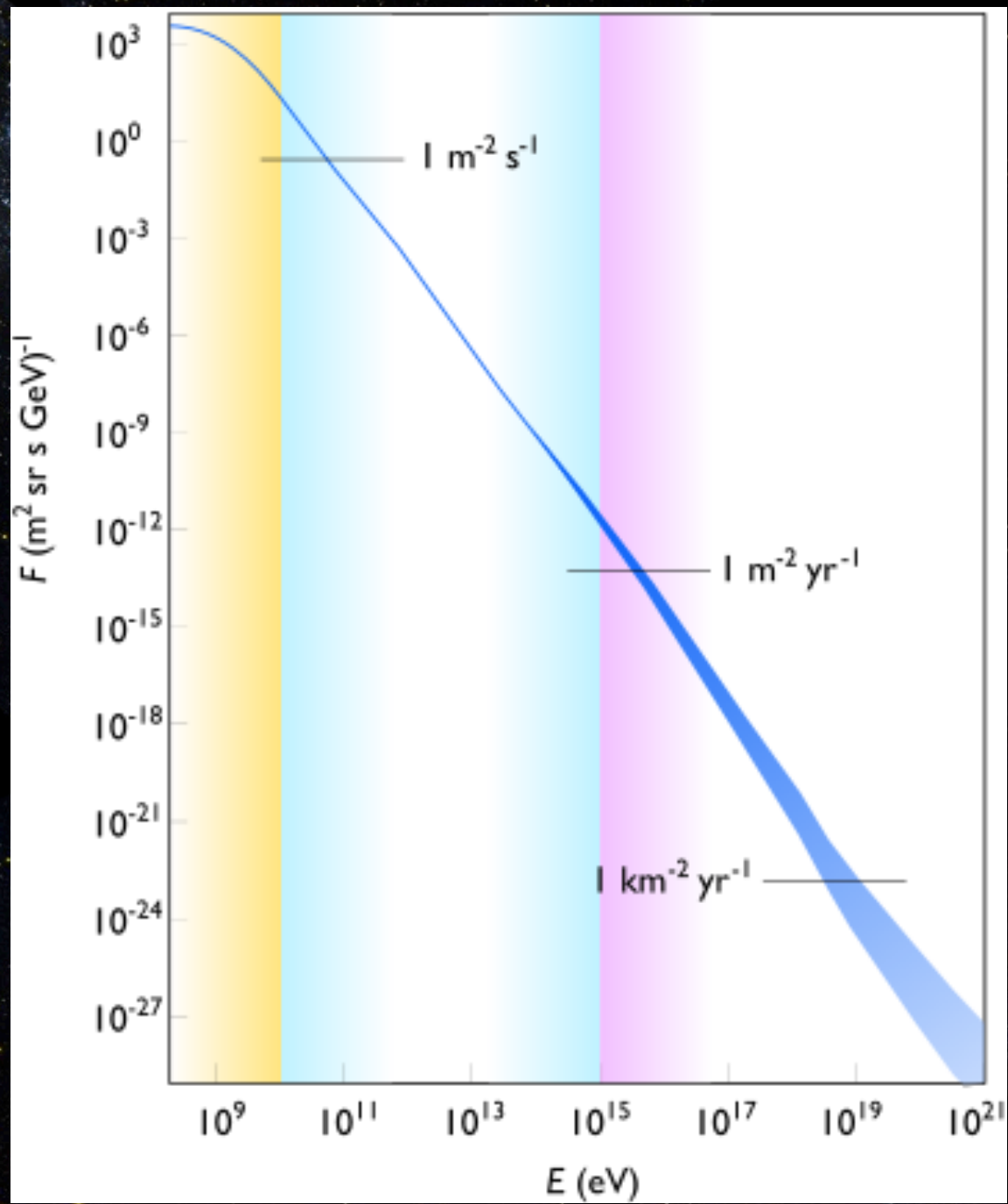


# Le neutrino un messenger cosmique ?

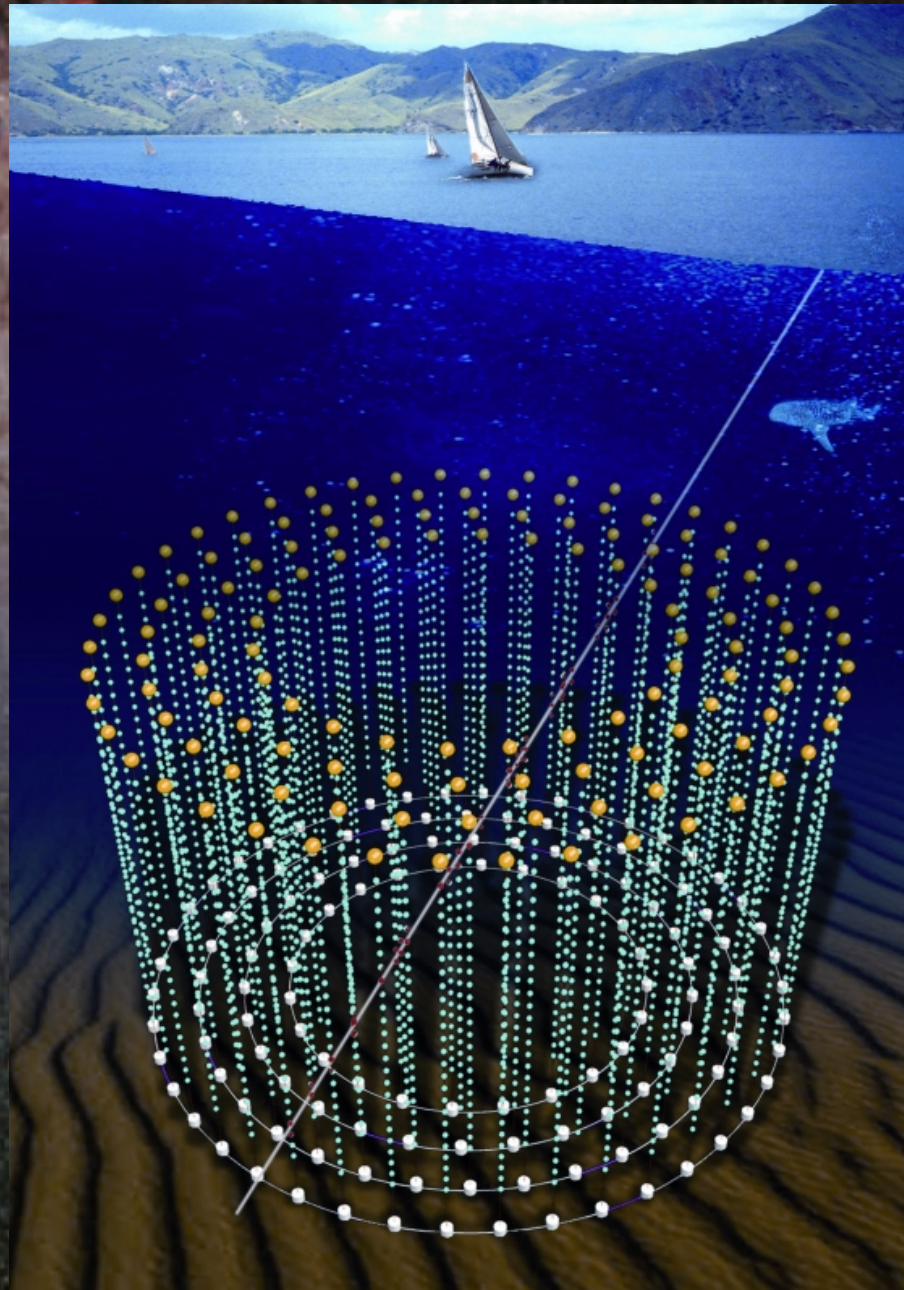


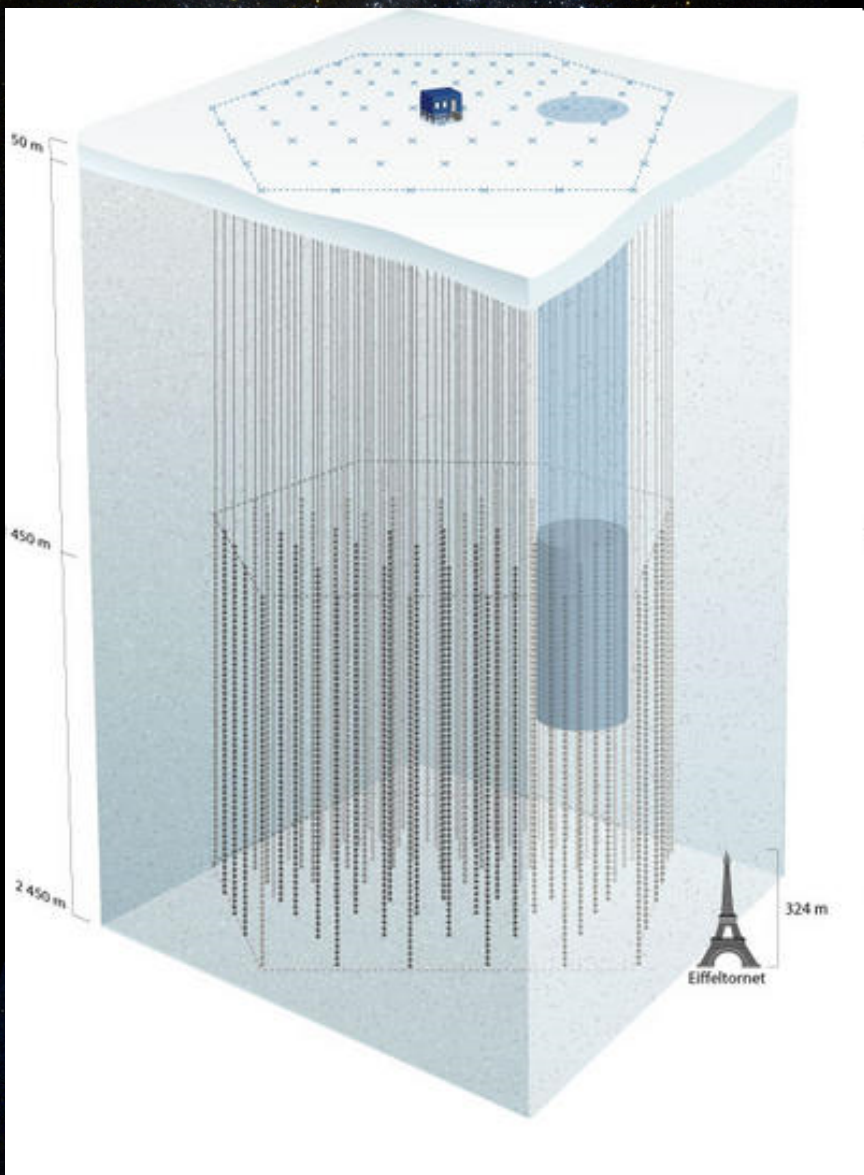
# Production in Cosmic Accelerators

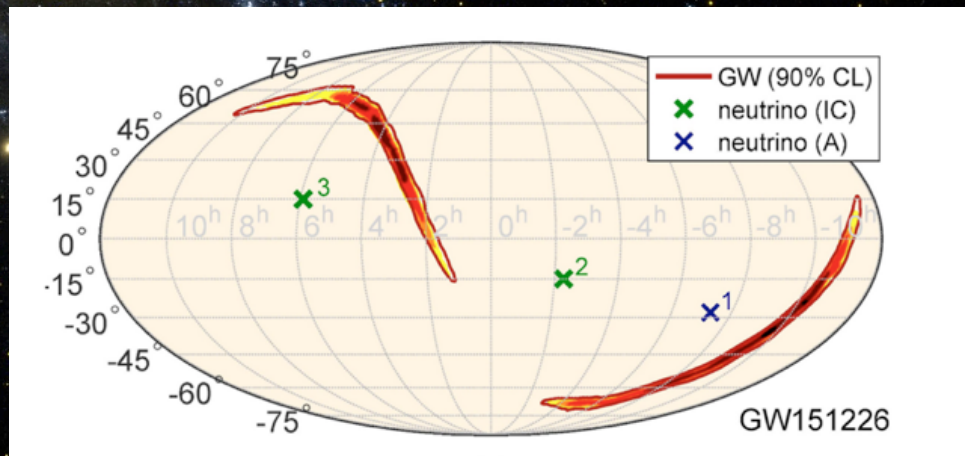
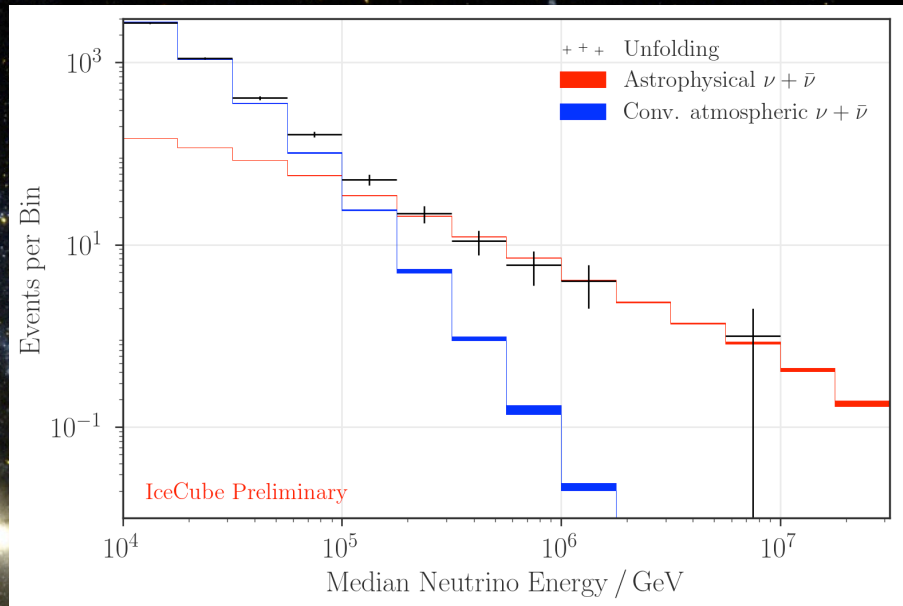
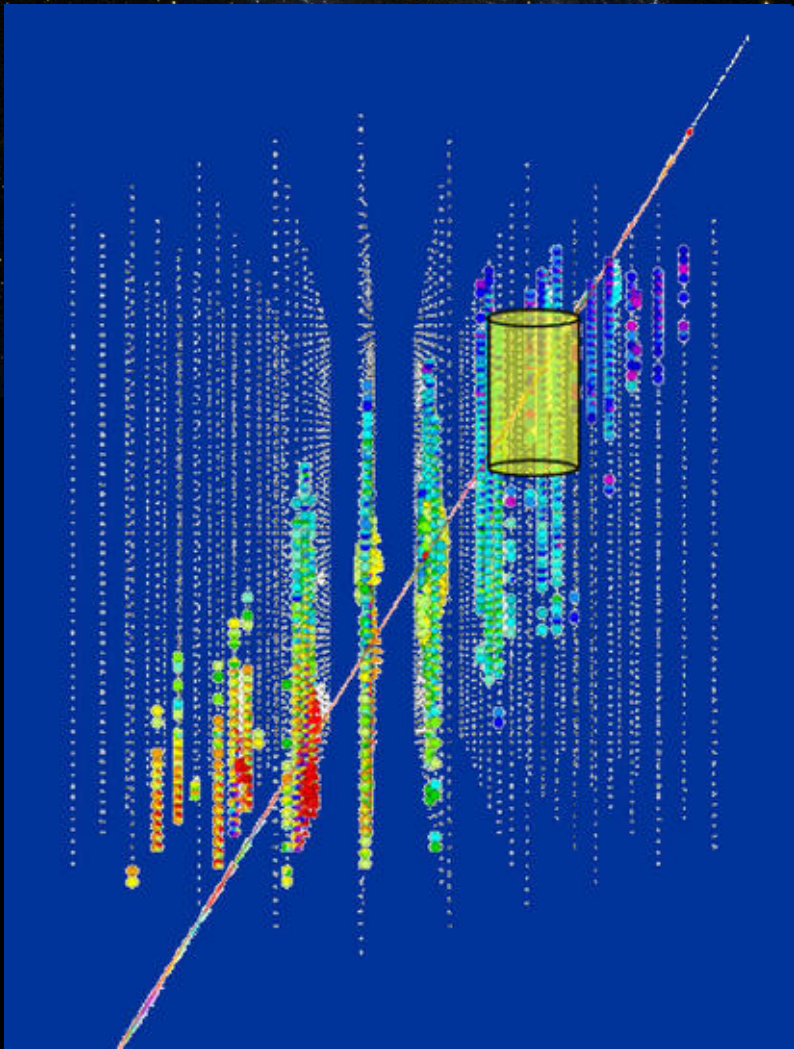




# ANTARES et KM3Net





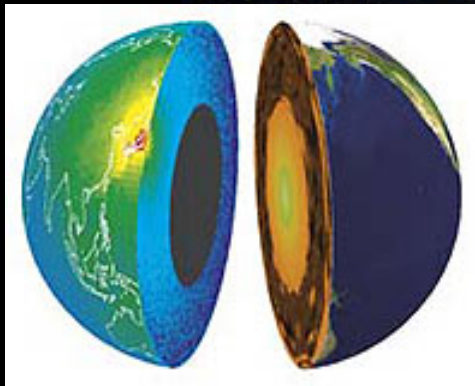
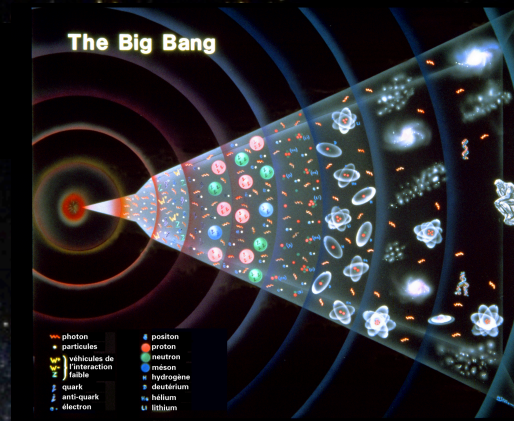




Masse, nature, oscillation,  
violation CP, neutrino stérile,...

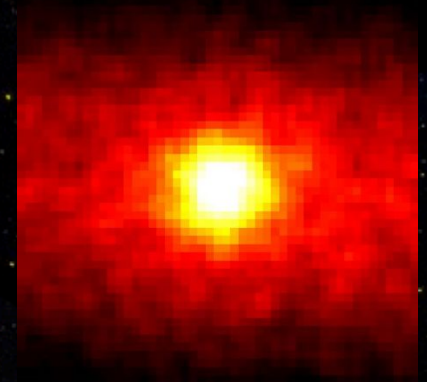
Rôle en cosmologie ?

Preuve de physique au-delà du  
Modèle standard



Sonder la terre

Astronomie neutrino  
Etoile, Supernova,...



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





270 000 000 000 000 000





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

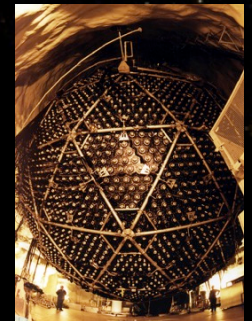
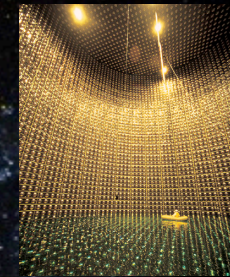
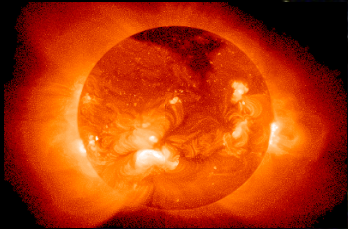
Question de la repression des fraudes: comment expertiser ces bouteilles ?

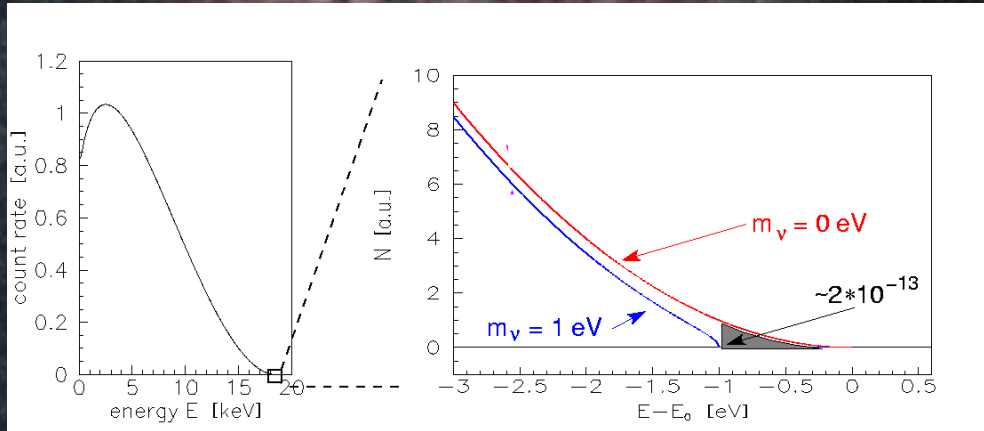
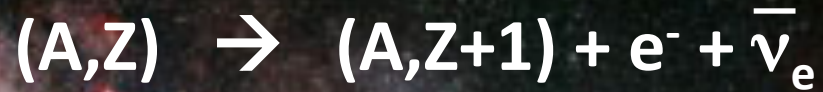
# Piège à neutrino

← 30 000 000 000 000 000 000 km de plomb →



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



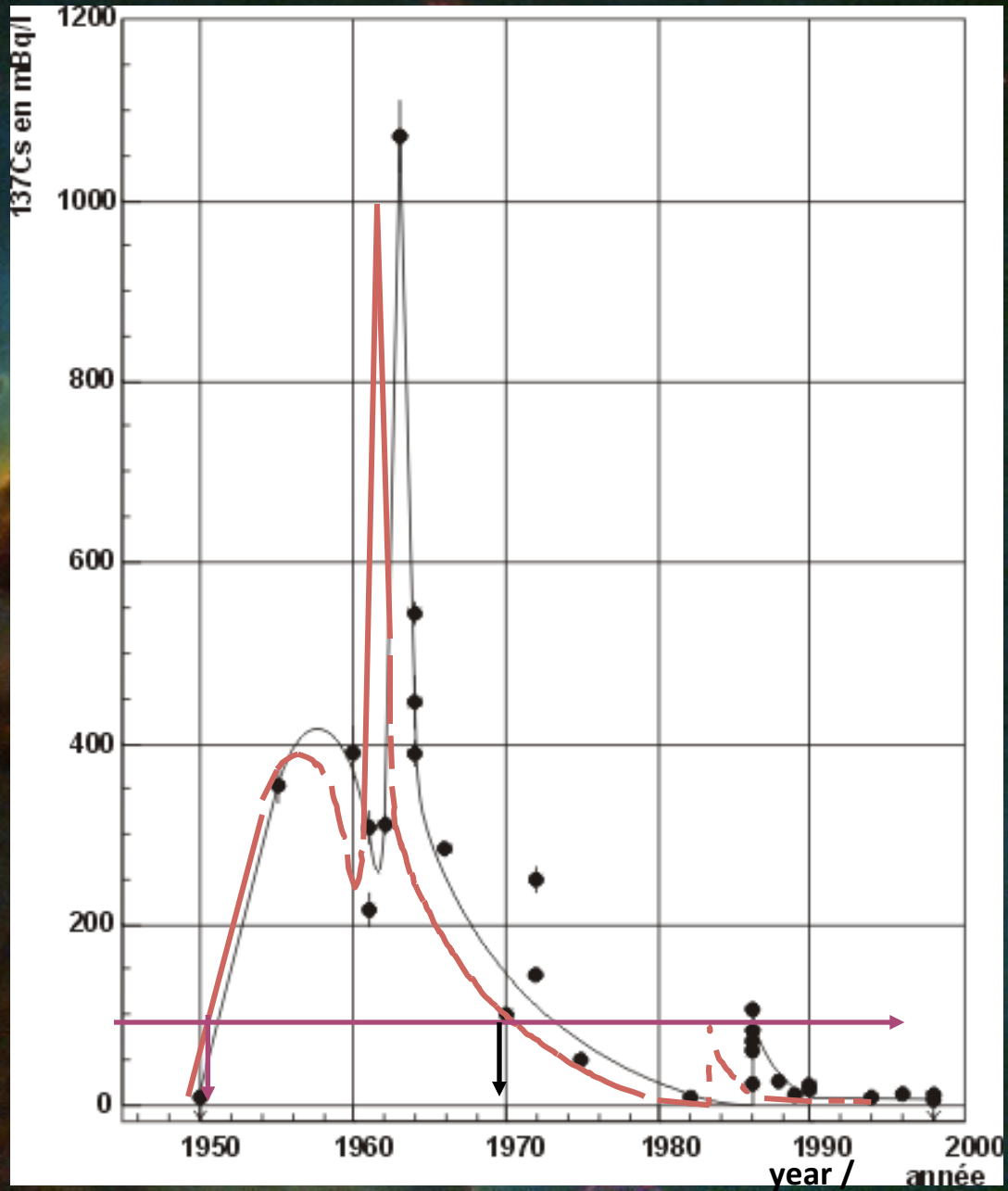


**$m_\nu < 2,3$  eV (95% C.L.)**



**Vers 2020  $m_\nu < 0,2$  eV (95% C.L.)**

# Mesure du $^{137}\text{Cs}$ en fonction de temps

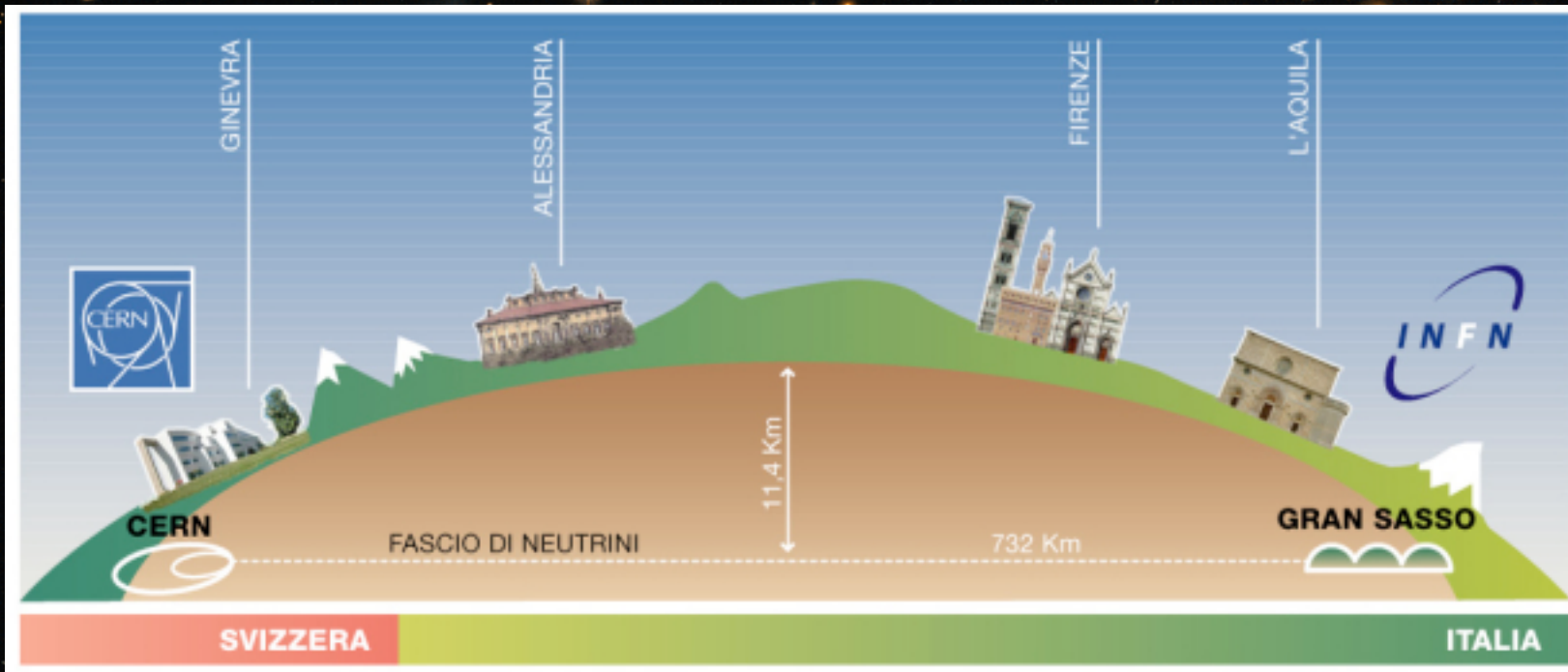


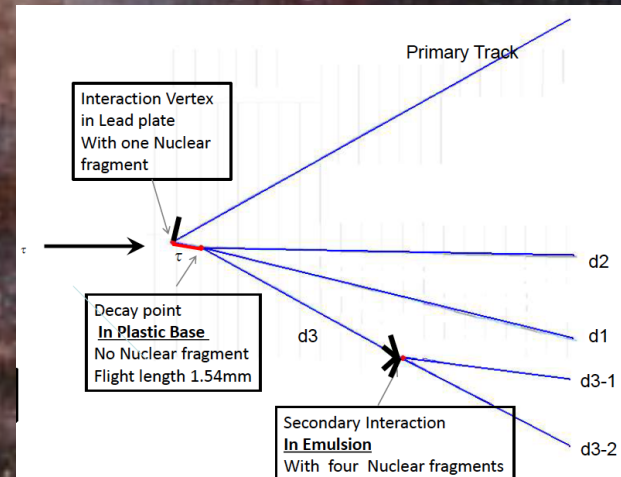
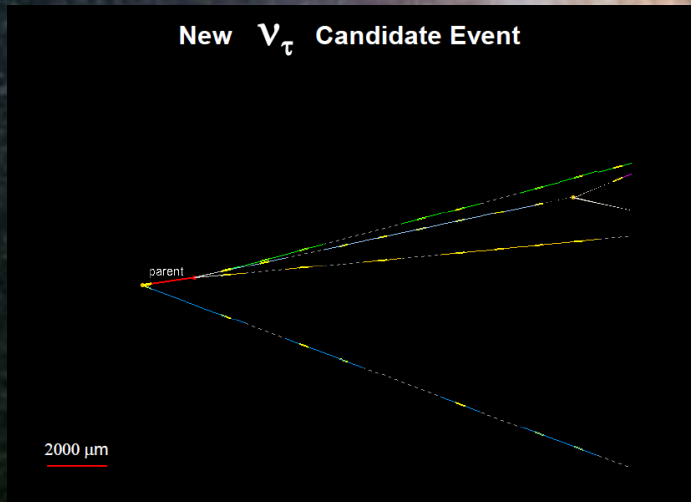
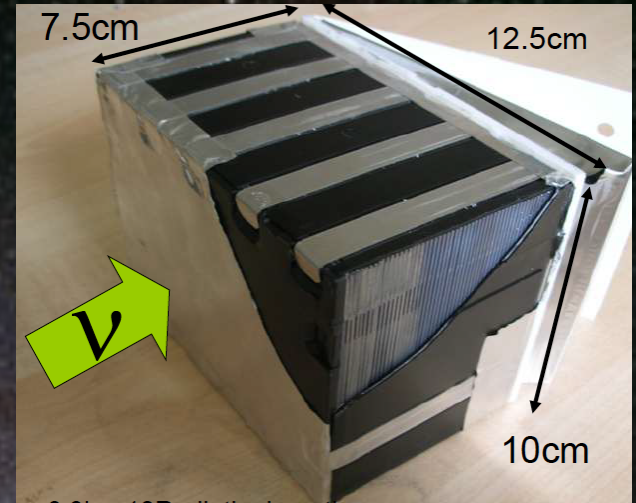
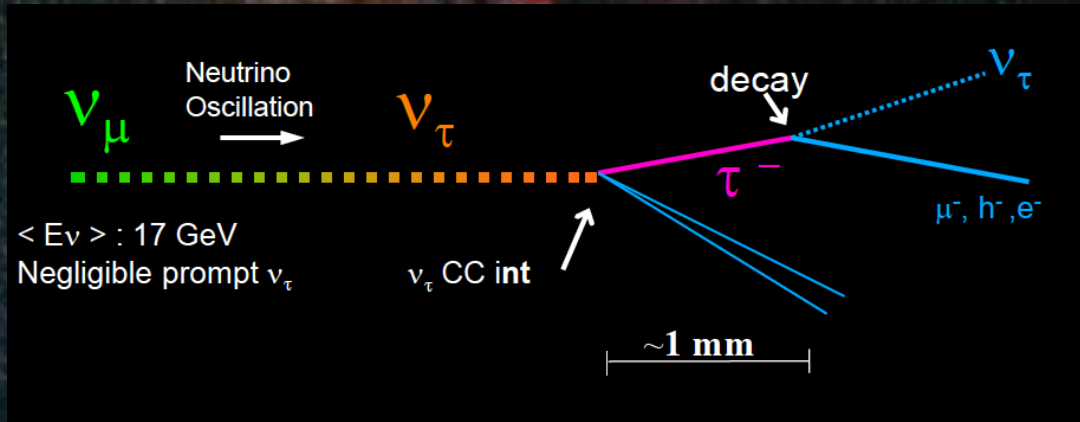


Photography of the expected Thomas Jefferson bottles of wine from 1784 and 1787. Two bottles are from Chateau Lafite, the two other are from Branne Mouton, which nowadays is called Mouton Rothschild

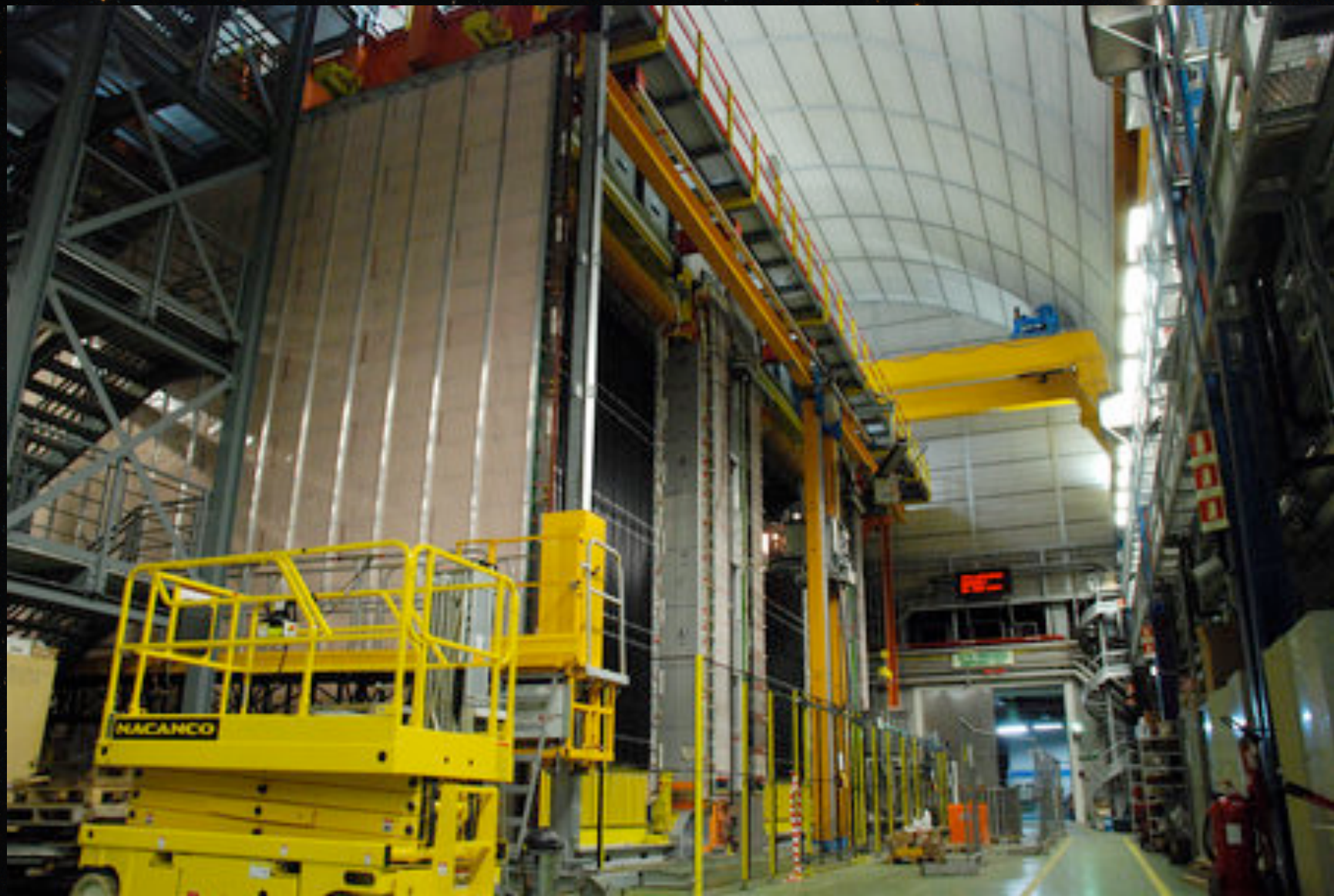








2 événements détectés



## Cern test 'breaks speed of light'

**0.0024 seconds**

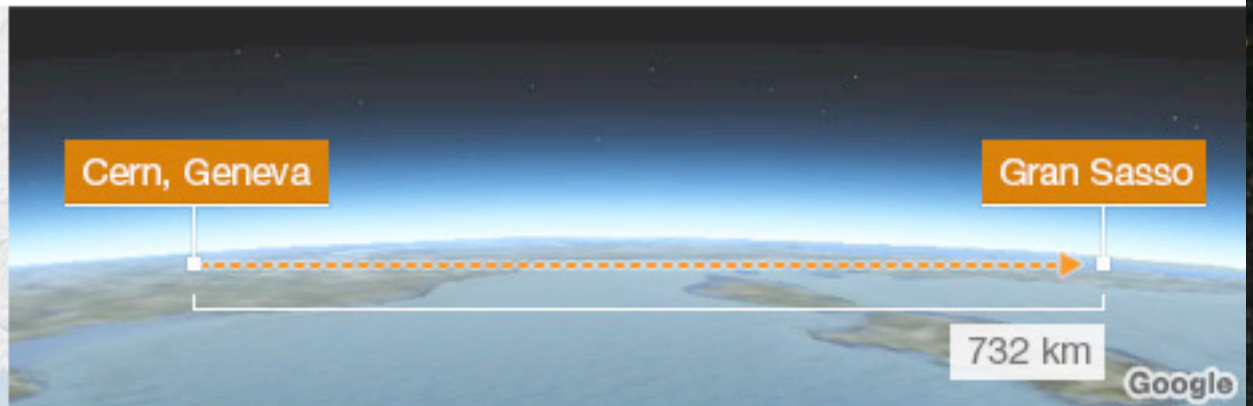
time taken by neutrinos

**0.00000006 seconds**

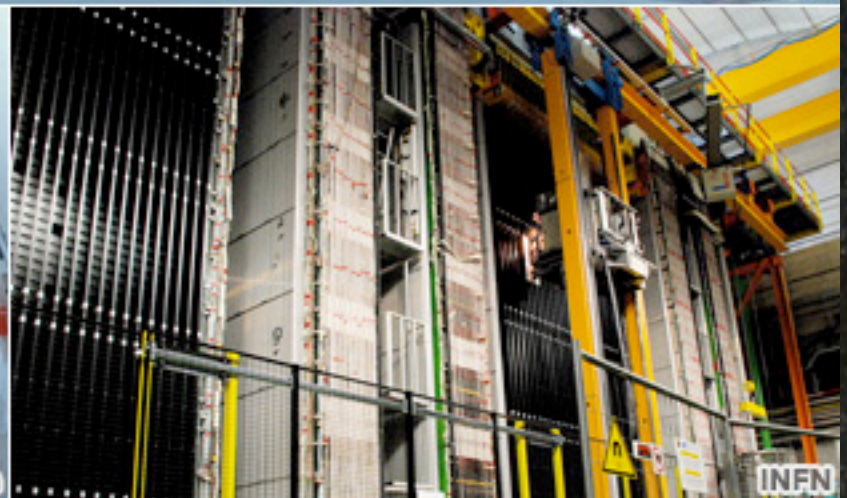
faster than the expected time

**732 km**

distance travelled through rock



**Cern, Switzerland:** A beam of neutrino particles is sent through rock towards Italy



**Gran Sasso, Italy:** Bricks with ultrasensitive covering at underground laboratory detect arrival

Des problemes ont été trouvés dans la synchronisation avec le système GPS et avec la connection d'une fibre optique transmettant le signal temps.



## Conclusions

- OPERA has updated the already announced result.
- The two issues found affecting the previous analysis have been understood and new systematic errors have been evaluated.
- A new short-bunch narrow-spacing proton beam run has just finished.
- The new preliminary result from 2012 data is:

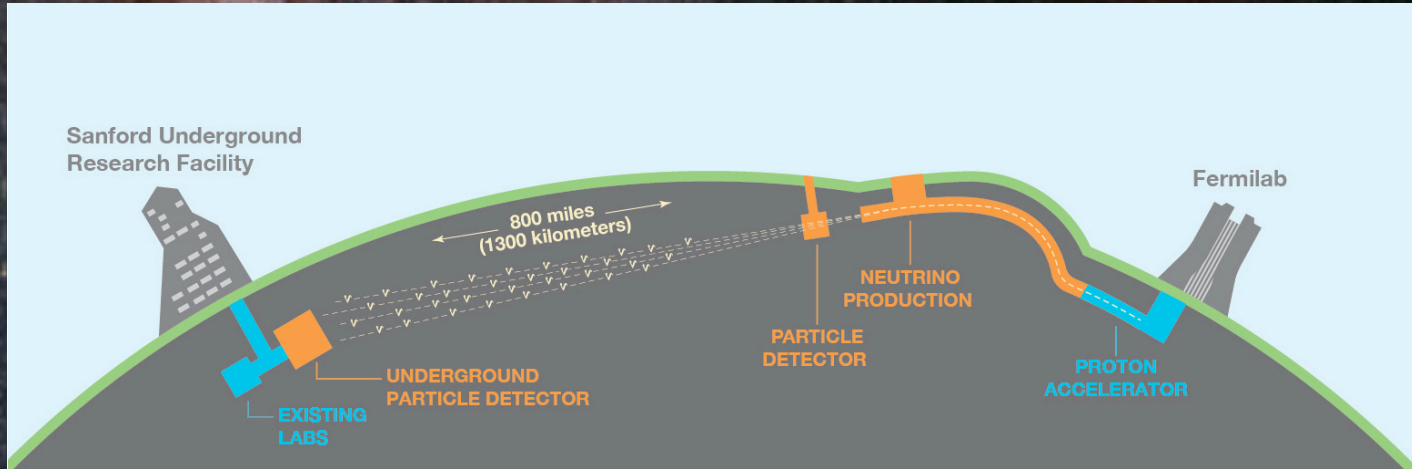
$$\delta t = (-1.6 \pm 1.1 \text{ (stat.)}_{-3.7}^{+6.1} \text{ (sys.)}) \text{ ns}$$

$$\frac{v-c}{c} = \frac{\delta t}{TOF_c - \delta t} = (-0.7 \pm 0.5 \text{ (stat.)}_{-1.5}^{+2.5} \text{ (sys.)}) \times 10^{-6}$$

compatible with the 2011 revised results.

- Results to be published soon.

# DUNE : Violation de CP



$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin aL}{aL} \Delta_{21} \cos(\Delta_{31} - \delta_{CP}) \\
 & + \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 aL}{aL^2} \Delta_{21}^2,
 \end{aligned}$$

$$a = G_F N_e / \sqrt{2}$$

$$D_{ij} = \frac{Dm_{ij}^2 L}{4E}$$

(For antineutrinos,  $a \rightarrow -a$  and  $\delta \rightarrow -\delta$ )