Ecole de Physique Distribuée
"Les Messagers de l'Univers"
28-30 Août 2017, APC – Université Paris Diderot

LES NEUTRINOS

Alessandra Tonazzo

Université Paris-Diderot

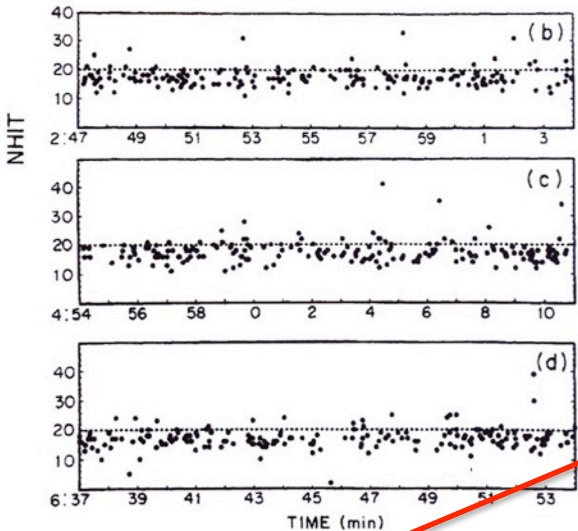
Laboratoire AstroParticule et Cosmologie

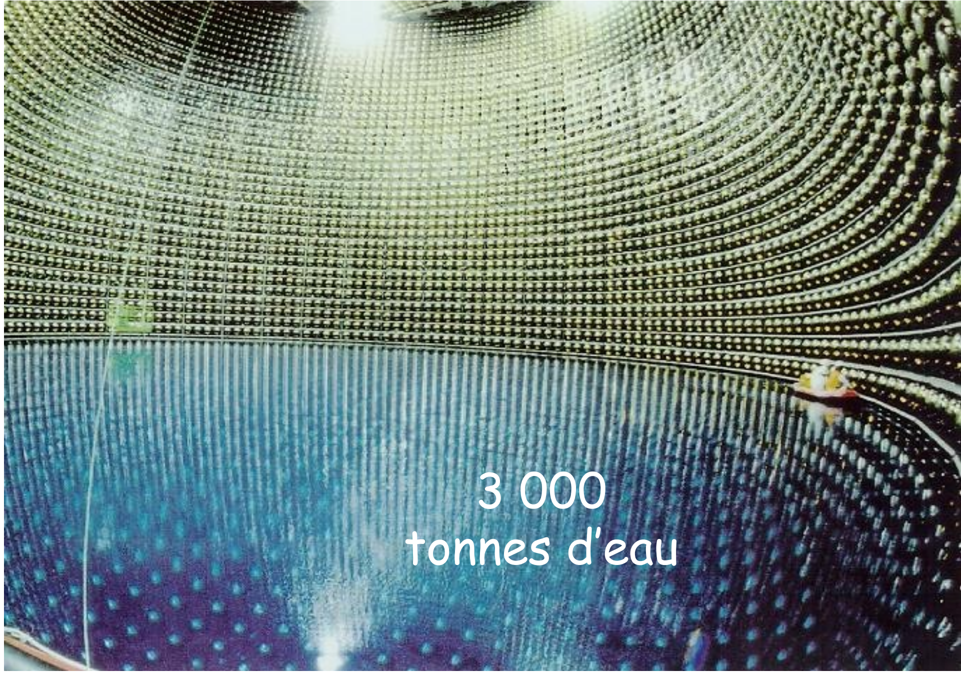
23 février 1987
Mine de Kamioka, Japan
(500 m sous terre)

2:47

4:54

6:37

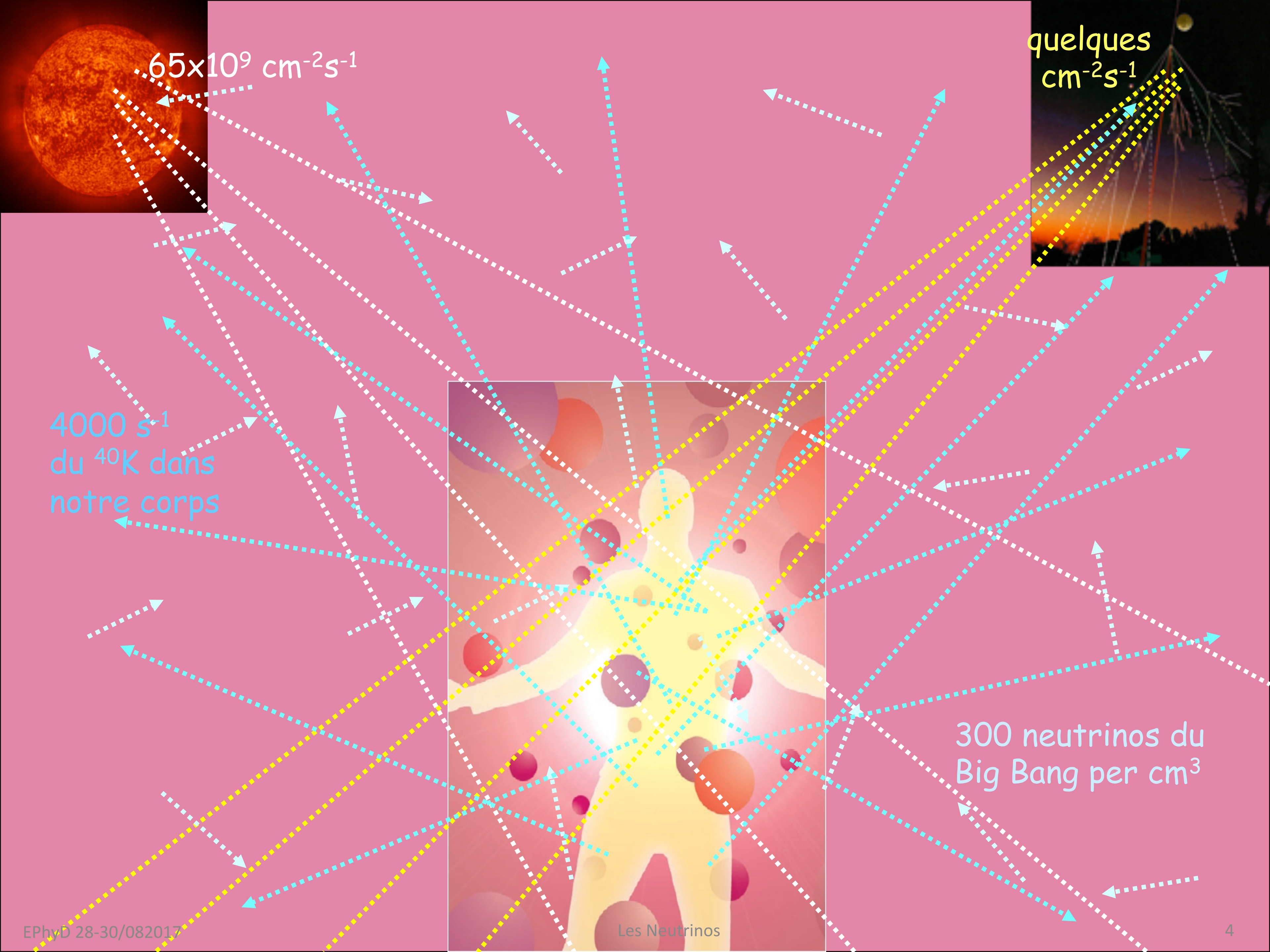




10 signaux en 10 secondes

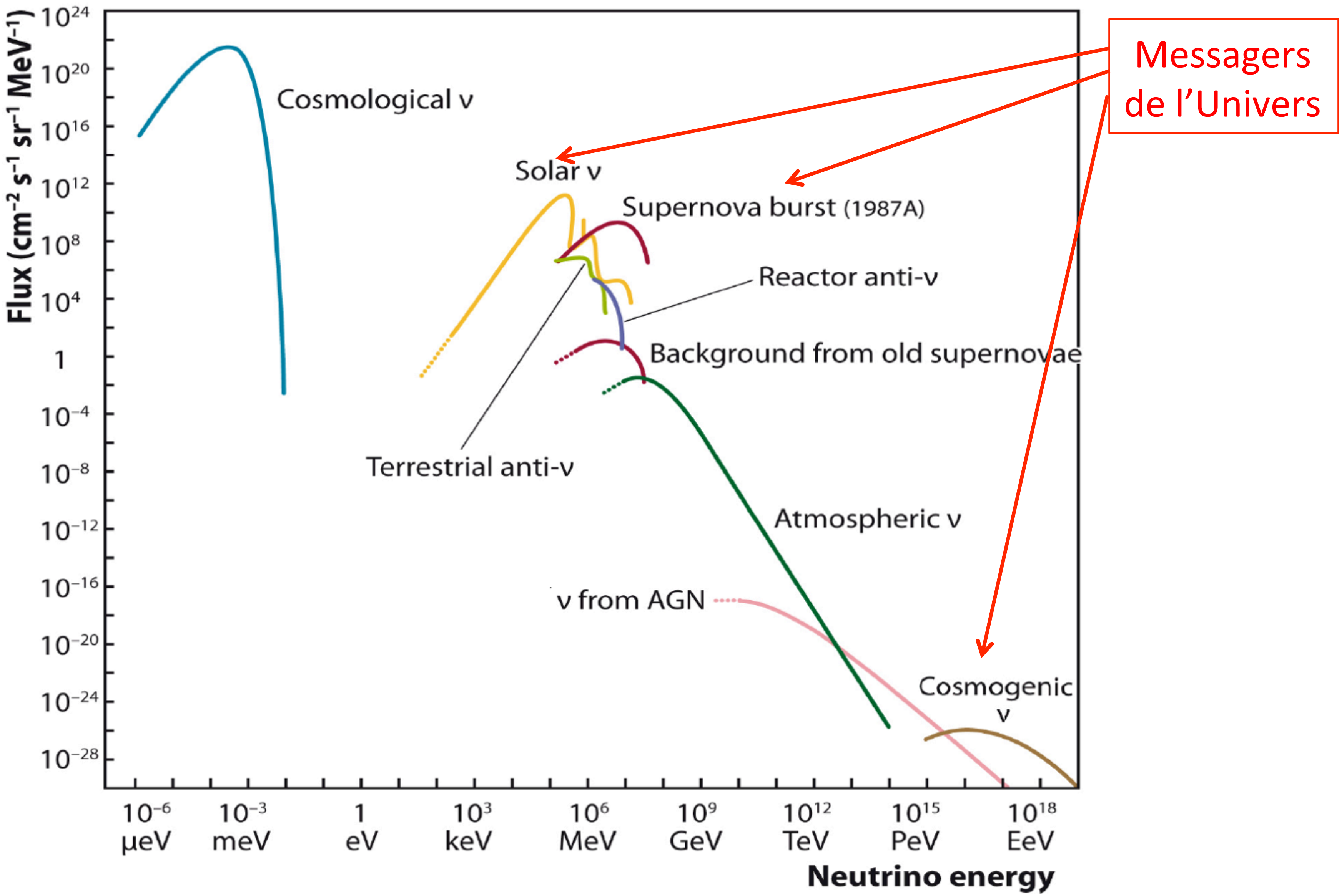
Les neutrinos annoncent
la mort d'une étoile !
(une SuperNova)

Neutrinos de …



65x10⁹ cm⁻²s⁻¹
quelques cm⁻²s⁻¹
4000 s⁻¹ du ⁴⁰K dans notre corps
300 neutrinos du Big Bang per cm³

Les neutrinos sur Terre



Nous allons parler de…

- Un peu d'histoire
- Comment voir les neutrinos

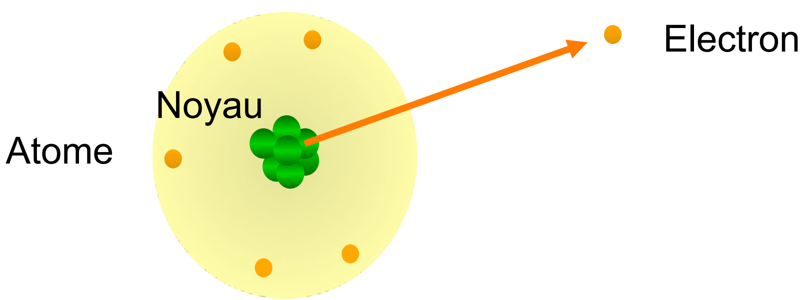
- Ce qu'ils nous disent sur…
  - le Soleil
  - les étoiles
  - et l'Univers

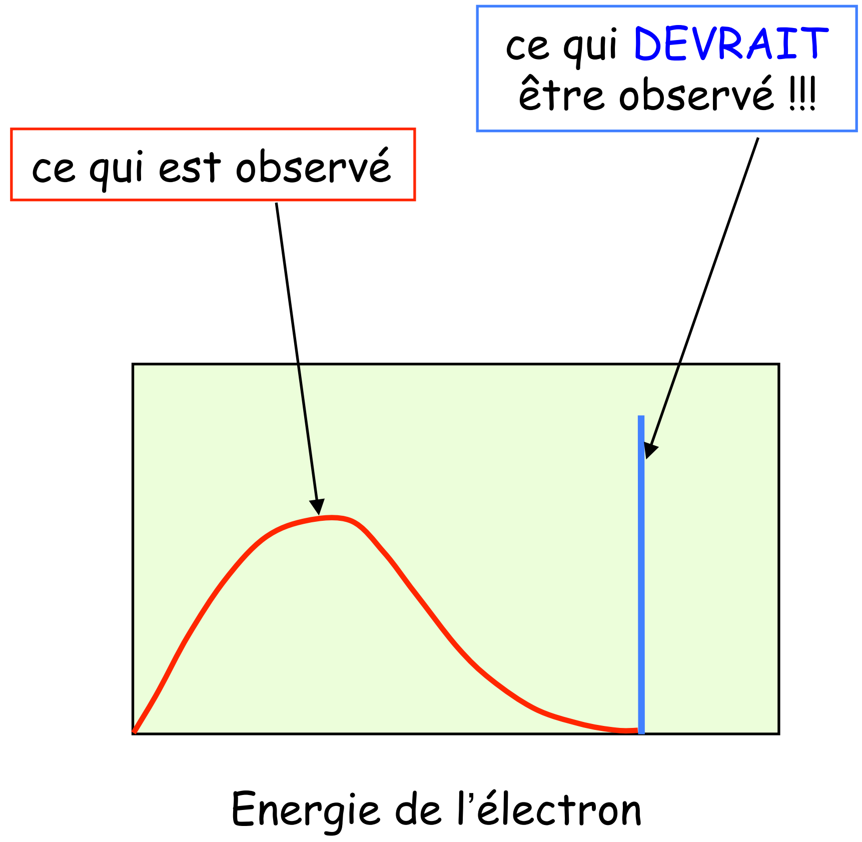
- Ce que nous savons sur les neutrinos
  - les oscillations et la masse

… et ce que nous ne savons pas encore

Pourquoi les neutrinos ?

1930 : La radioactivité β présente une anomalie !





Pourquoi les neutrinos ?

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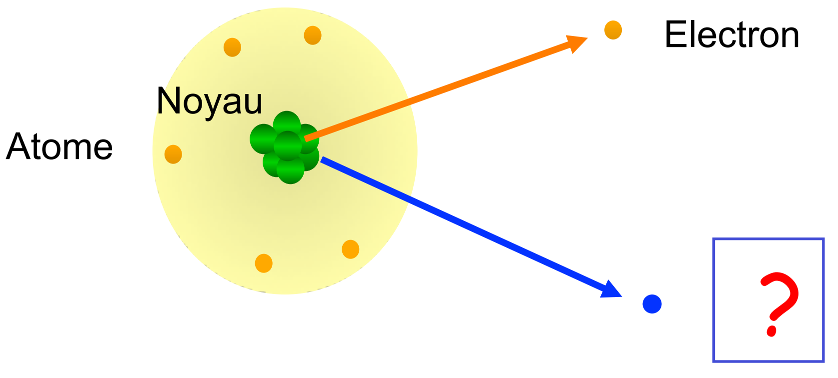
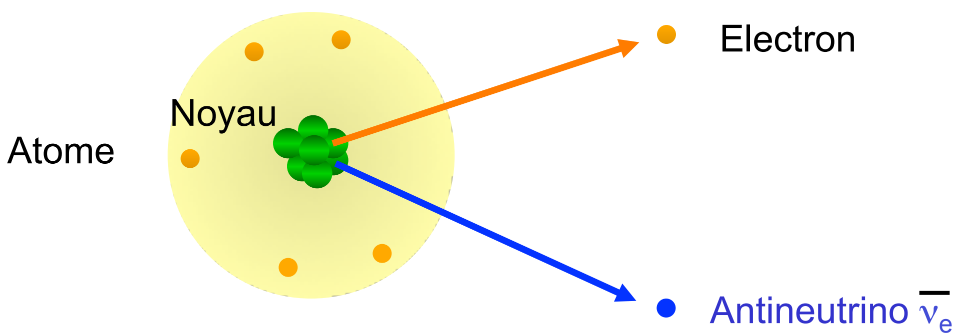


Décembre 1930 : Idée géniale de Wolfgang Pauli !

Il existe une particule inconnue qui emporte l'énergie manquante !

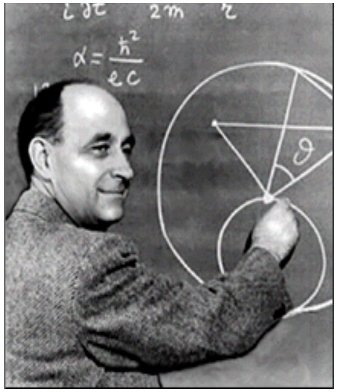
Pourquoi les neutrinos ?

1930 : La radioactivité β présente une anomalie !



$$n \rightarrow p + e^- + \overline{\nu}_e$$

Décembre 1930 : Idée géniale de Wolfgang Pauli !



1933 : Enrico Fermi baptise cette particule neutrino (le « petit neutre »)

ν

Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

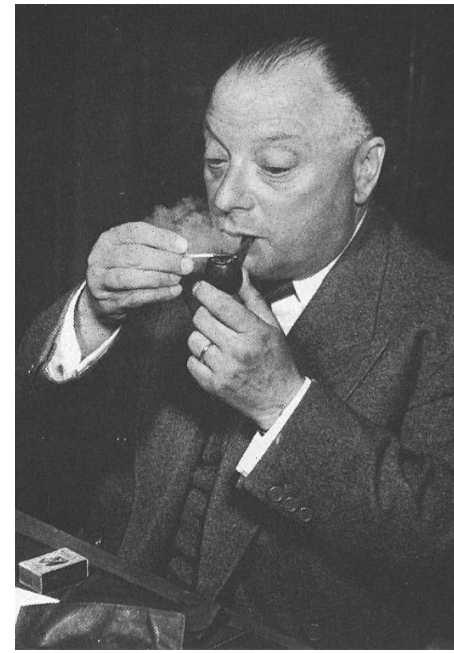
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik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

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli



Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not

allowed to be larger than e • (10^{-13} cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

"I have done a terrible thing, I have postulated a particle that cannot be detected"

La découverte du neutrino

- 1956 : Clyde Cowan et Fred Reines mettent en évidence le neutrino auprès du réacteur nucléaire de Savannah River

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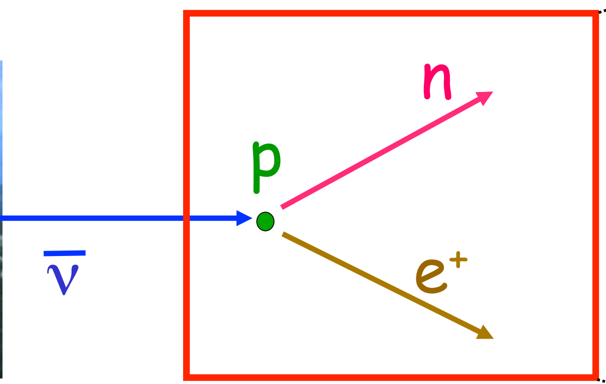
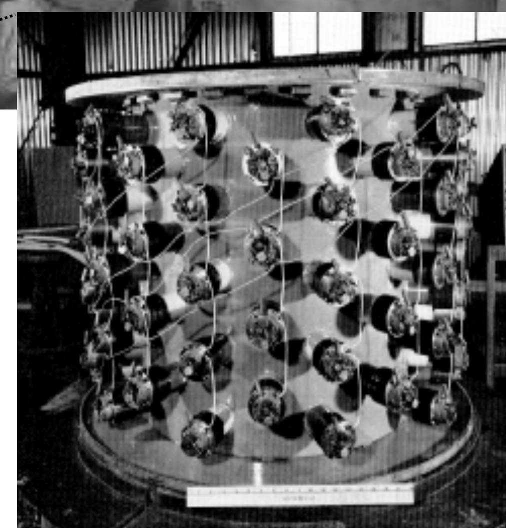
(il s'agit en fait de l'antineutrino électron $\overline{\nu}_e$)

NOBEL PRIZE
1995

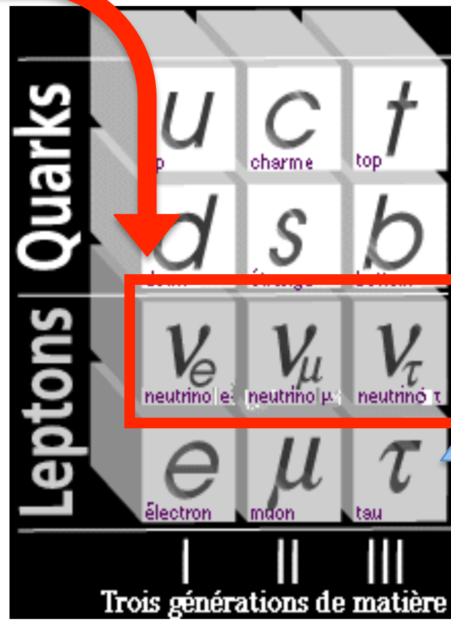




Le monde des particules élémentaires

Neutrinos:
3 “saveurs”

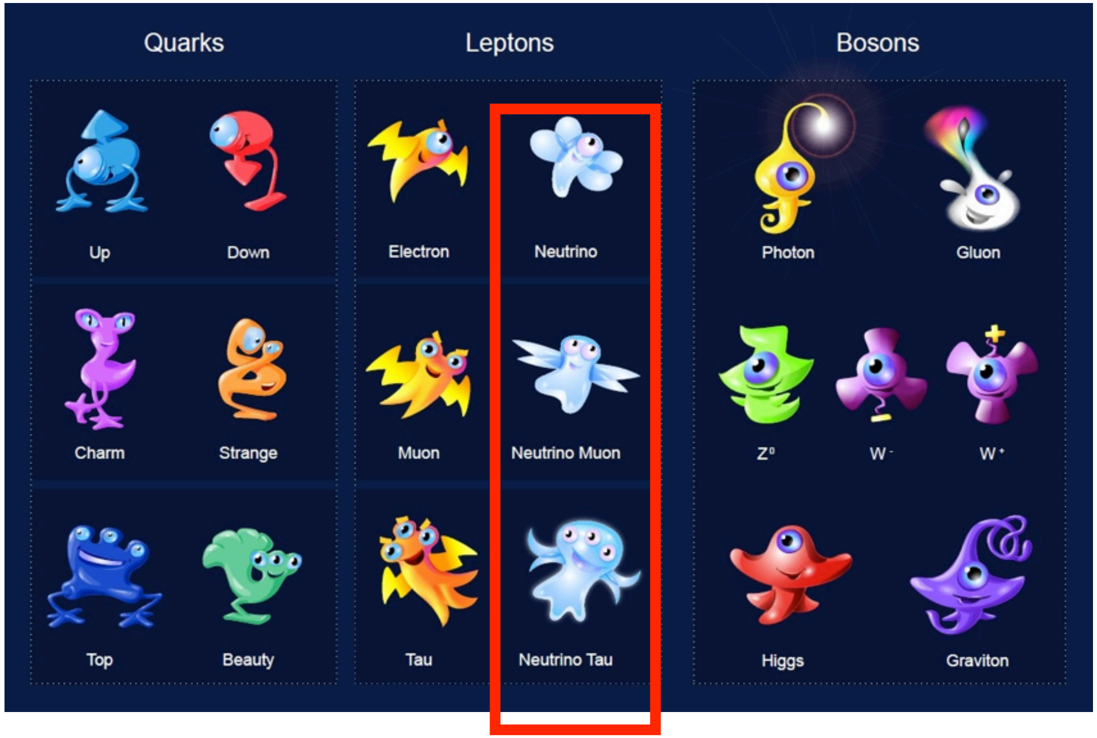
Particules de Matière



Masse
???

Particules de Force

- photon γ (i. électromagnétique)
- W and Z (interaction faible)
- gluons (interaction forte)

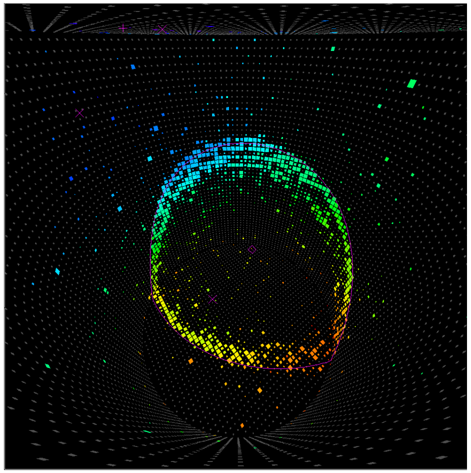


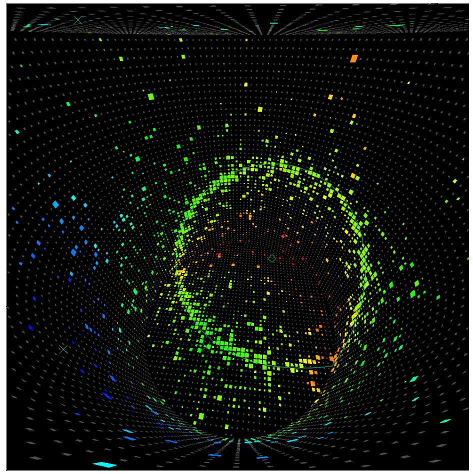
cern.ch

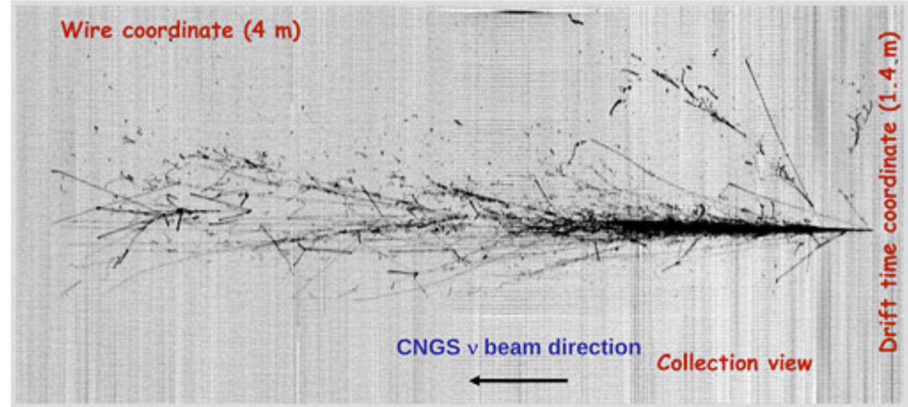
Maman, ils sont comment en vrai, les neutrinos ?

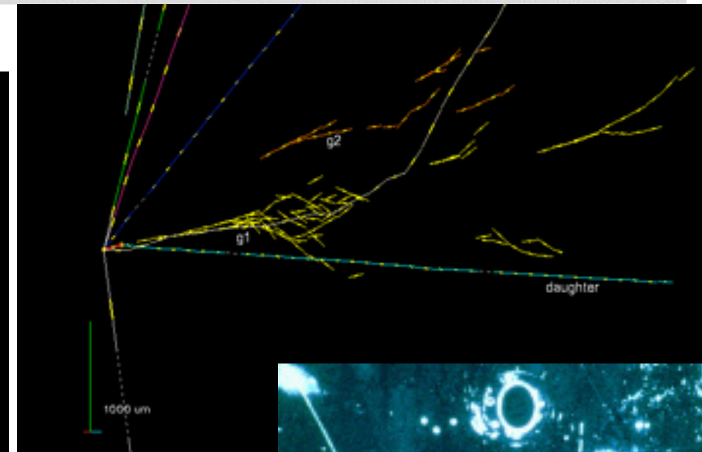
Très difficiles à voir.

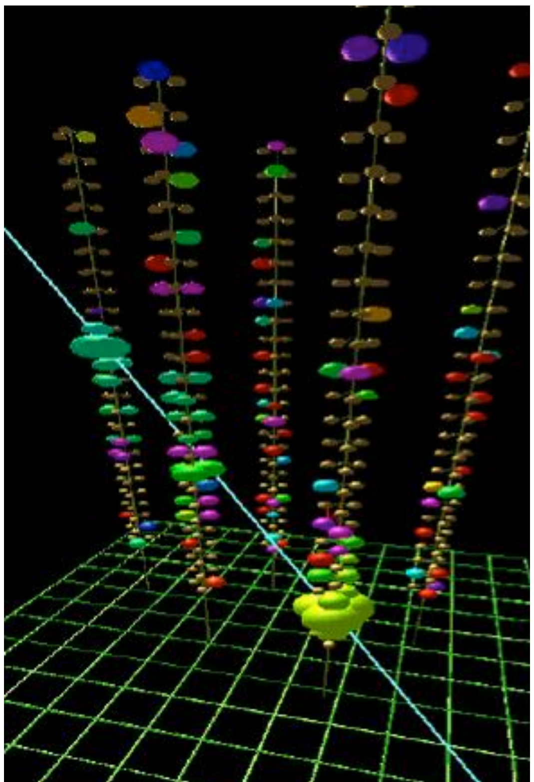
Mais toi, avec l'ordinateur, tu peux les voir !

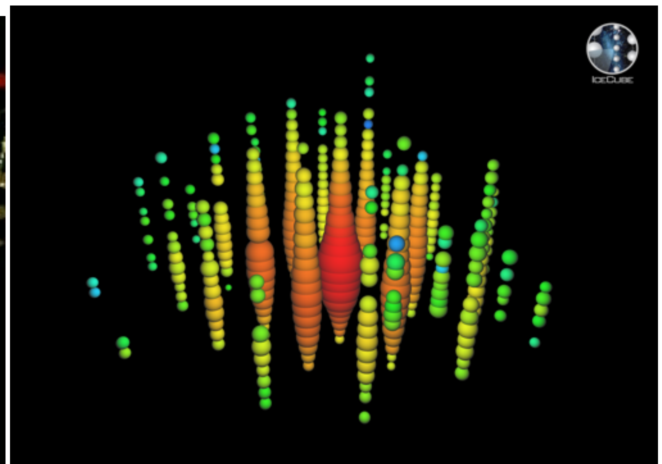


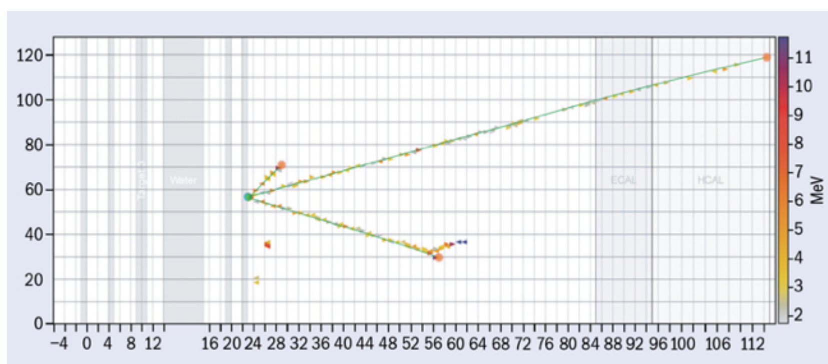


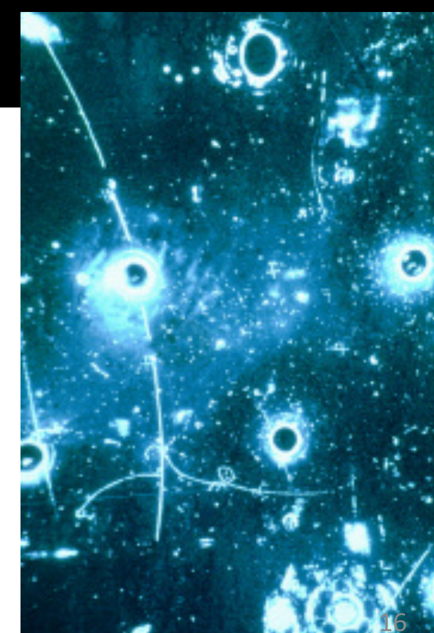

Wire coordinate (4 m)
Drift time coordinate (1.4 m)
CNGS ν beam direction
Collection view


g2
g1
daughter
1000 um



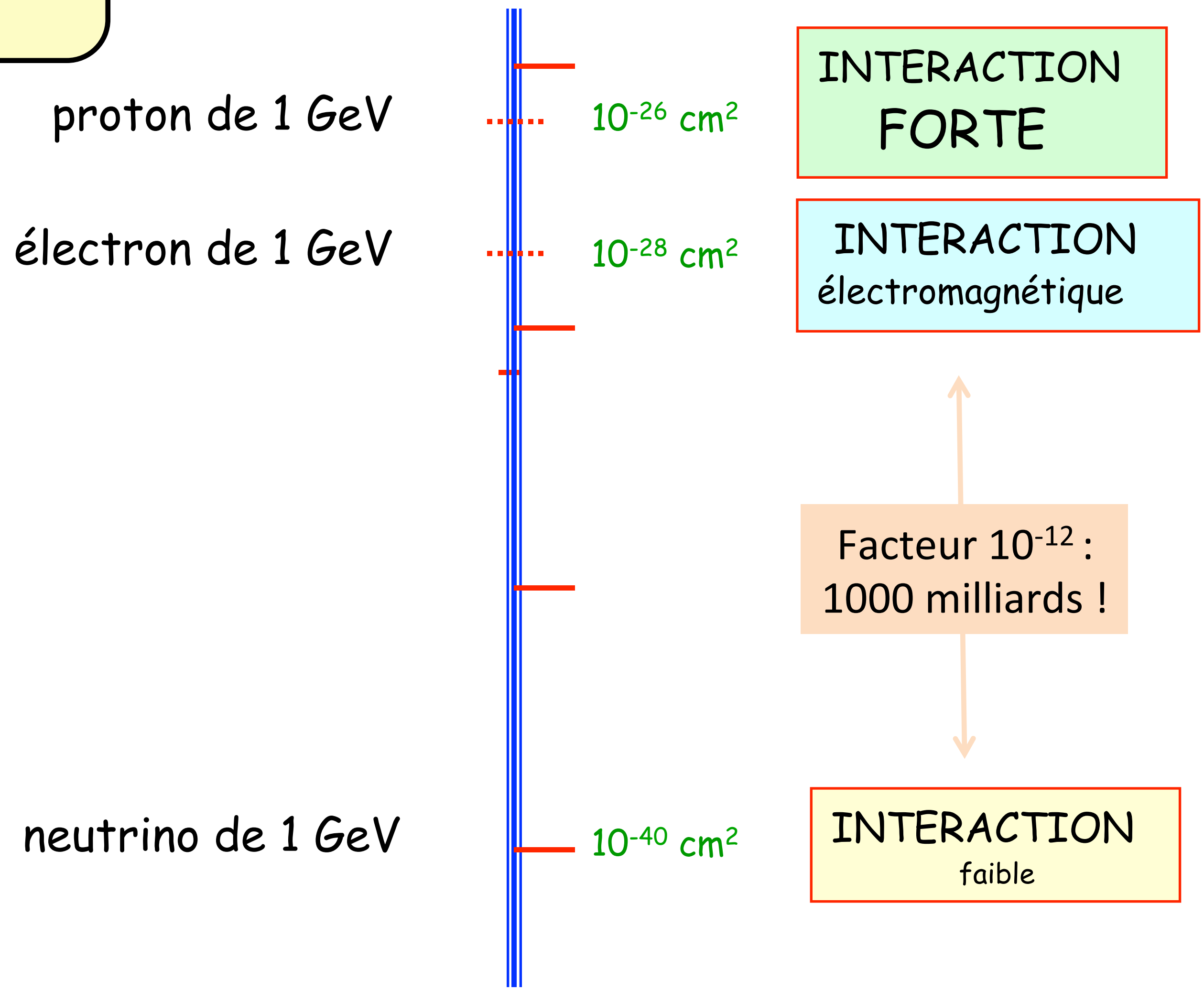



120
100
80
60
40
20
0
−4 0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80 84 88 92 96 100 106 112
11
10
9
8
7
6
5
4
3
2
MeV



Comment interagissent les neutrinos ?

Très faiblement !



Comment interagissent les neutrinos ?

σ : section efficace
(probabilité d'interaction)

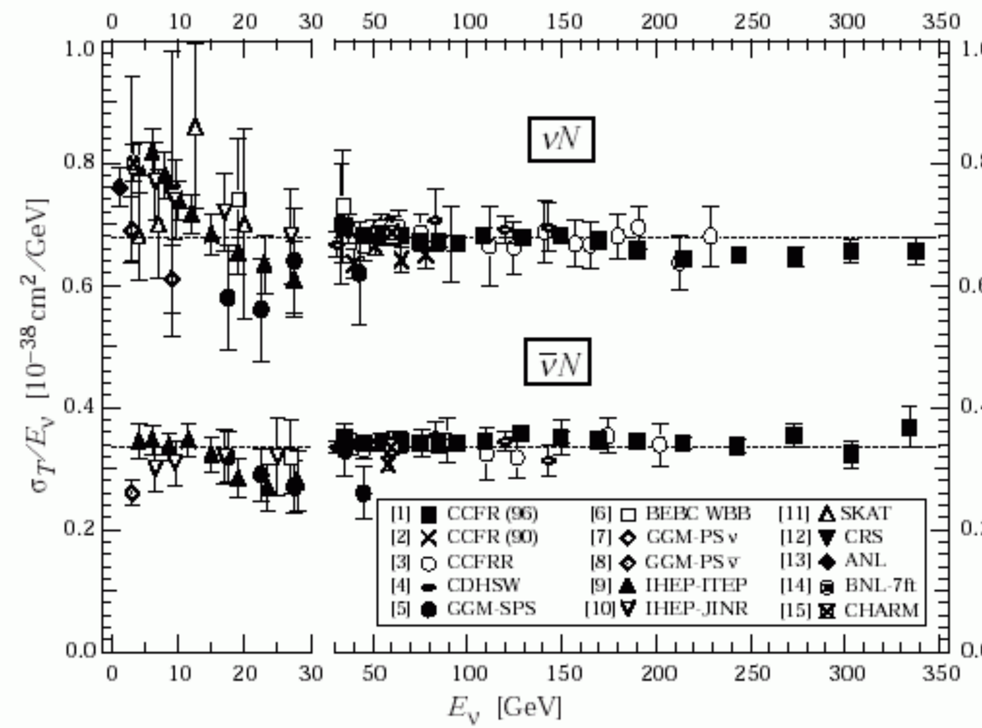


Figure 39.10: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1–4]: $= 0.677 \pm 0.014$ $(0.334 \pm 0.008) \times 10^{-38}$ cm^2/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2001.)

Comment interagissent les neutrinos ?

Ça veut dire quoi, interaction faible ?

Longueur d'absorption ou parcours libre moyen

$$\lambda = \frac{1}{n\sigma}$$

Densité de cibles (n)

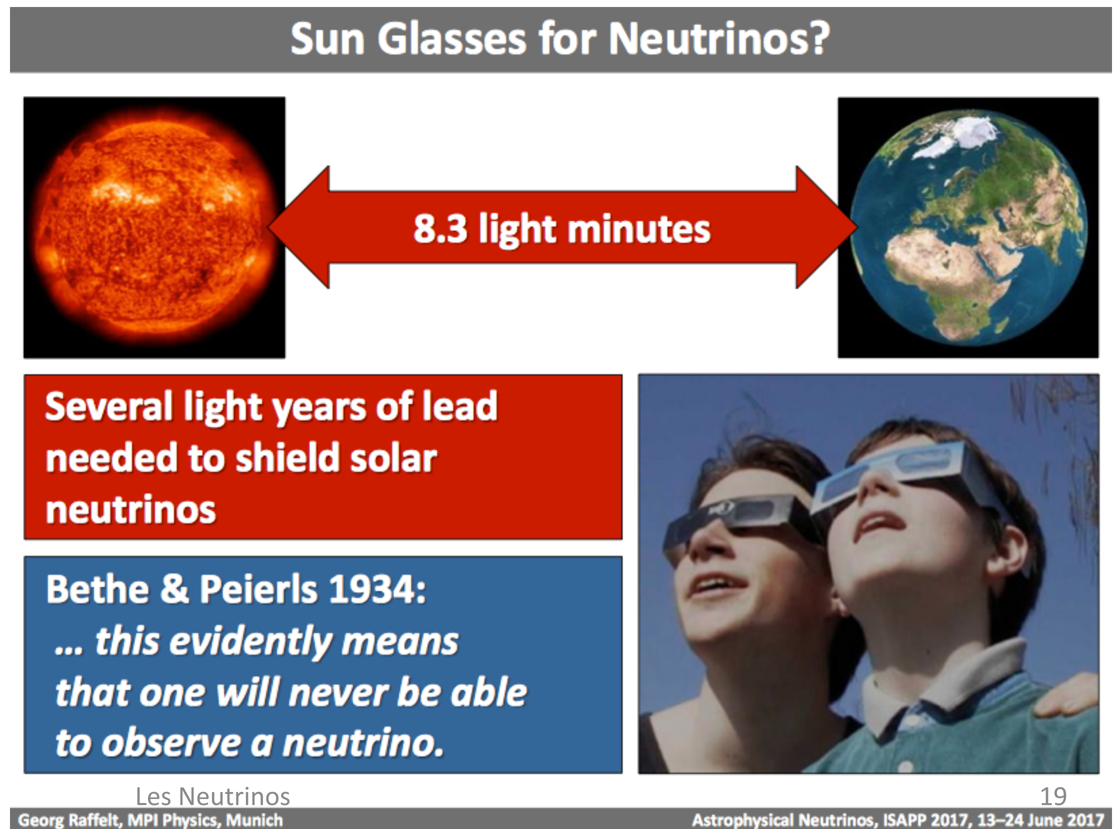
Section efficace d'interaction (σ)

$$\lambda = \frac{1}{n\sigma} =$$

$$\frac{1}{\left(6.7\times 10^{22}\,cm^{-3}\right)\cdot\left(10^{-43}\,cm^{2}\right)} =$$

$$1.5\times 10^{20}\,cm =$$

150 années lumière



Comment interagissent les neutrinos ?

Ça veut dire quoi, interaction faible ?

Combien d'interactions de neutrinos solaires dans 1 tonne d'eau en 1 jour ?

Flux de neutrinos (> 5 MeV)

Section efficace d'interaction $\nu_e e^- \rightarrow \nu_e e^-$

Nombre de cibles (electrons) $N_T = 18 \times N_{Avogadre} \times 1t / 18g$

$$N_{\text{int}} = \Phi_\nu \cdot \sigma \cdot N_T$$

$$= \left(2x10^6 cm^{-2} s^{-1}\right) \cdot \left(10^{-43} cm^2\right) \cdot \left(6 \times 10^{29}\right) \cdot 86400 s / j$$

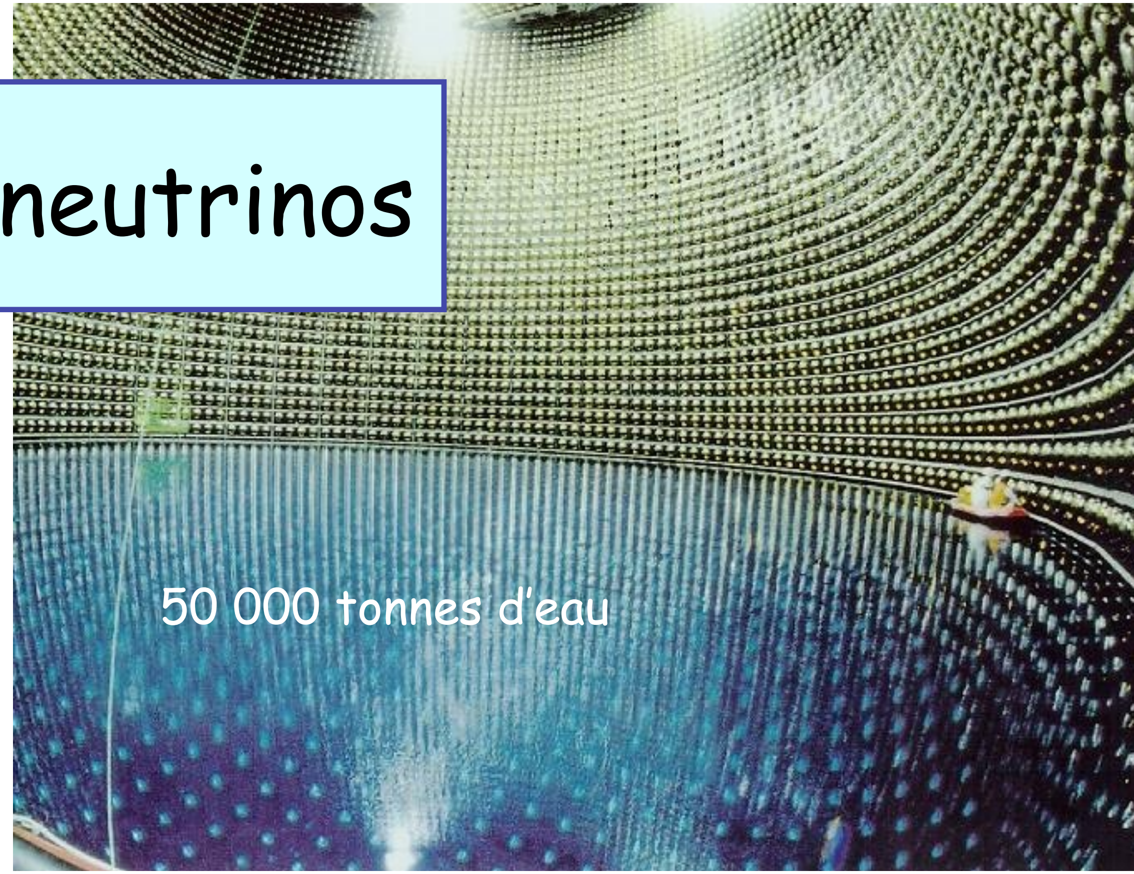
$$\sim 0.1 \ \text{ par jour}$$

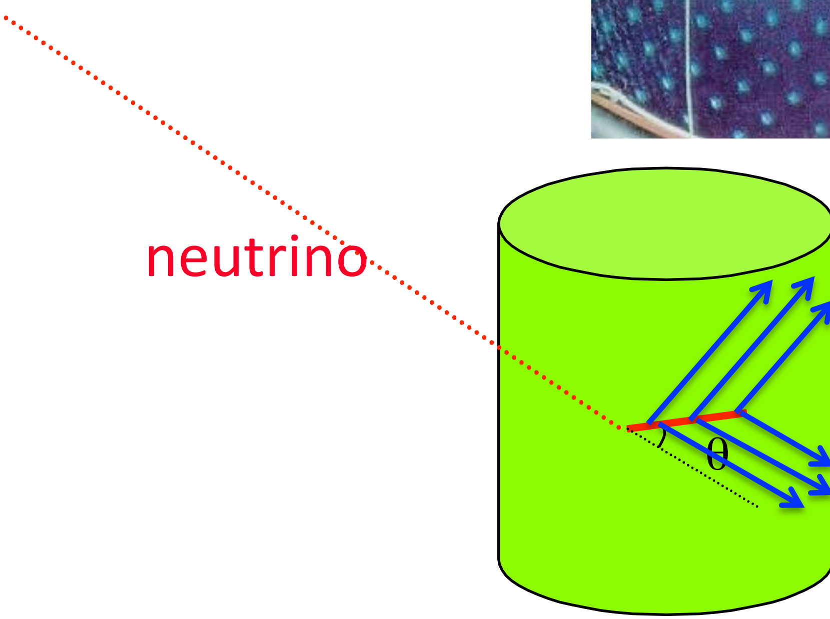
Pour piéger les neutrinos, il faut

- ***beaucoup de neutrinos***
- ***de grands détecteurs***

Détecteurs de neutrinos

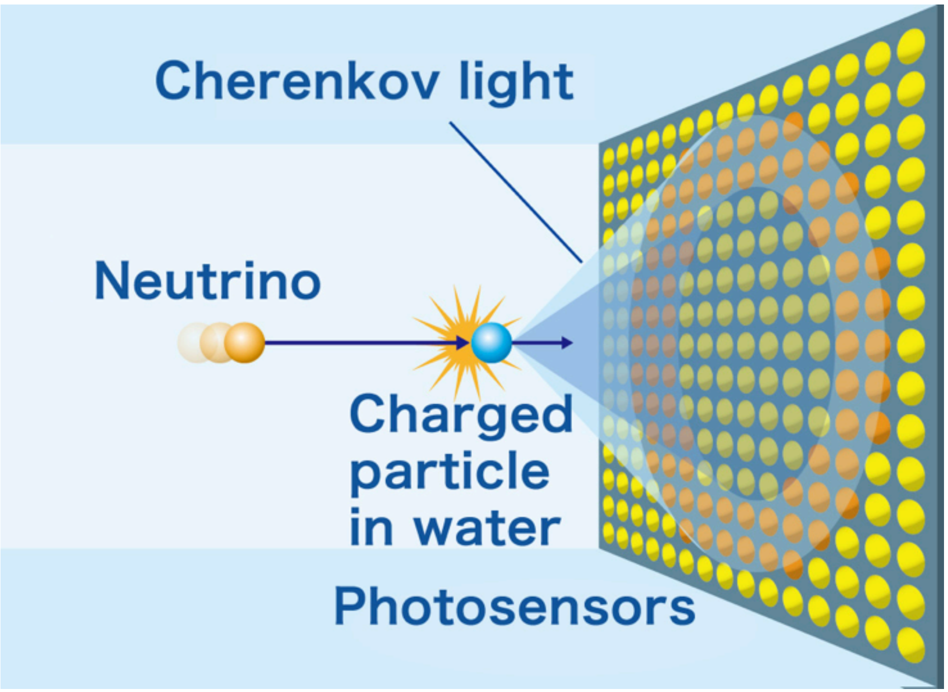
SuperKamiokande
(Mine de Kamioka,
Japon)

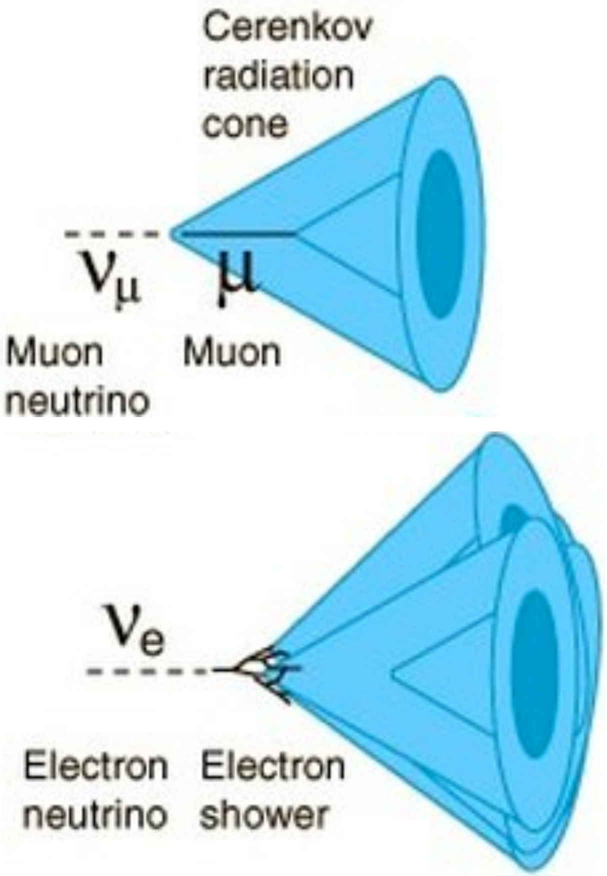




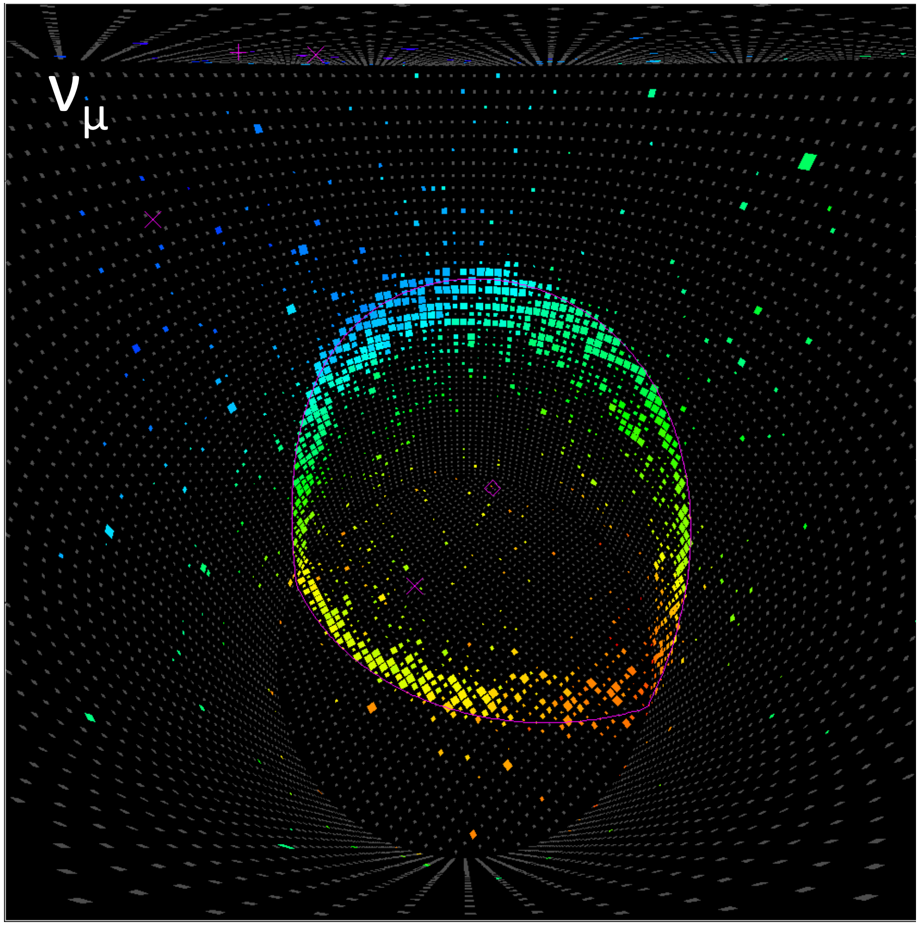
électron
ou muon → **LUMIERE !**
= SIGNAL

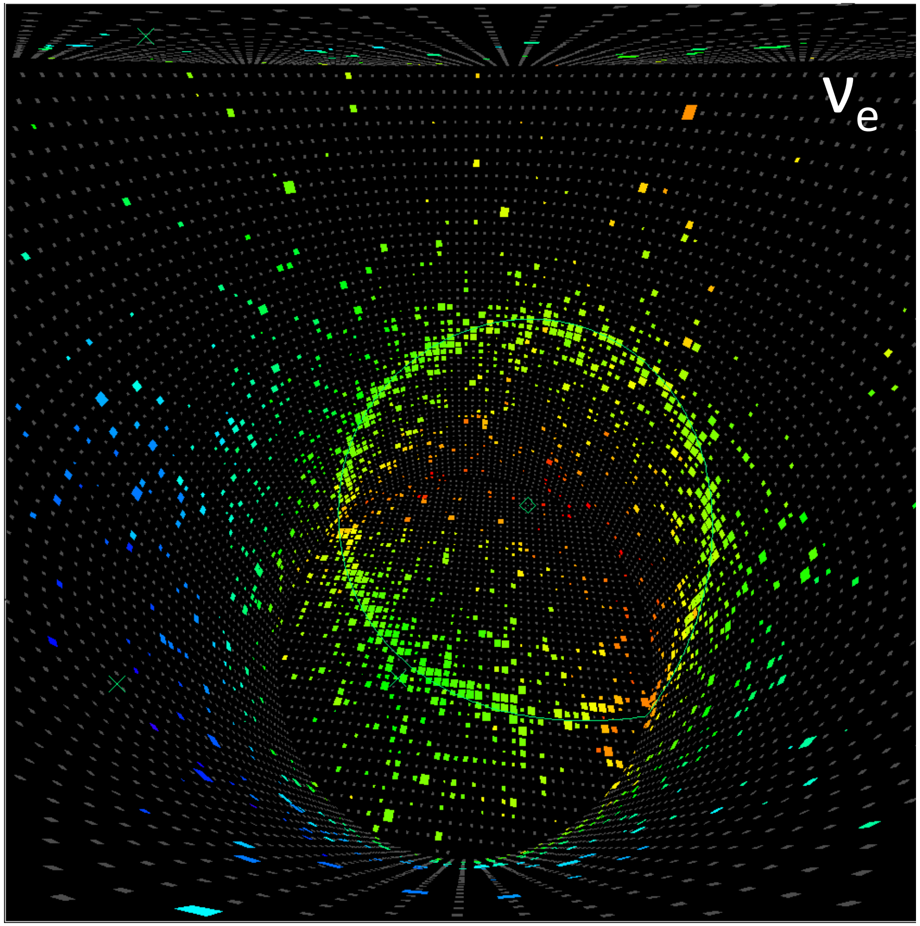
Détecteurs de neutrinos : effet Cherenkov





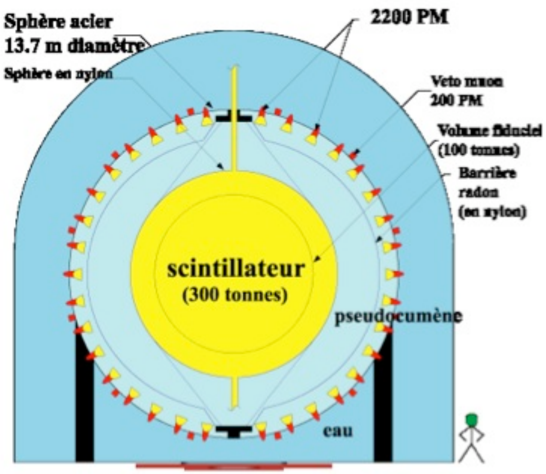
Des neutrinos dans Super-K



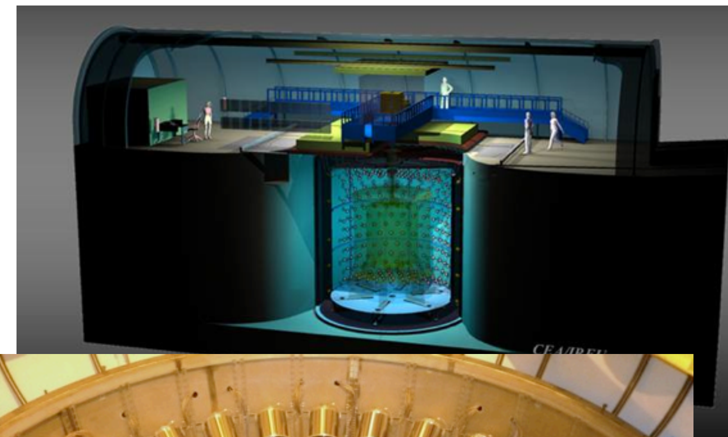


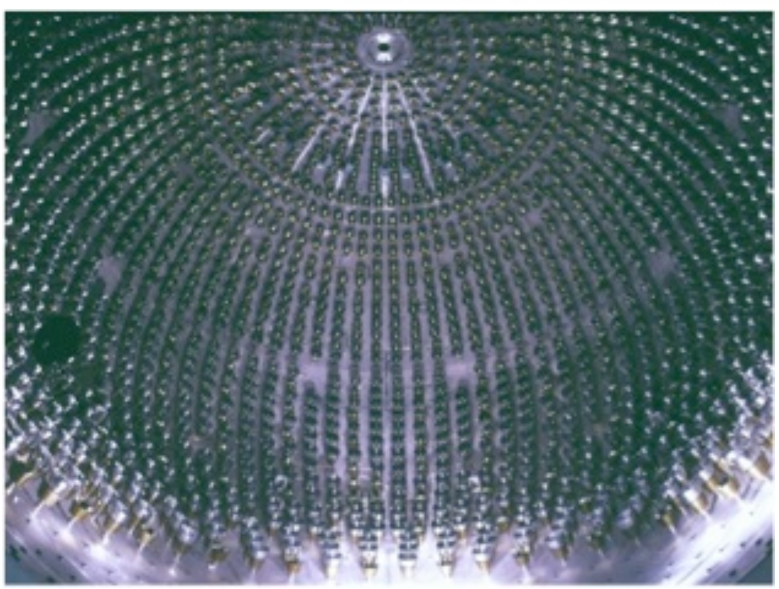
Autres détecteurs de neutrinos

Borexino
(Laboratori Nazionali del Gran Sasso)



Double Chooz
(Ardennes, France)





Que peuvent nous dire les neutrinos?

comment fonctionne le Soleil,

comment les étoiles finissent d'existter,

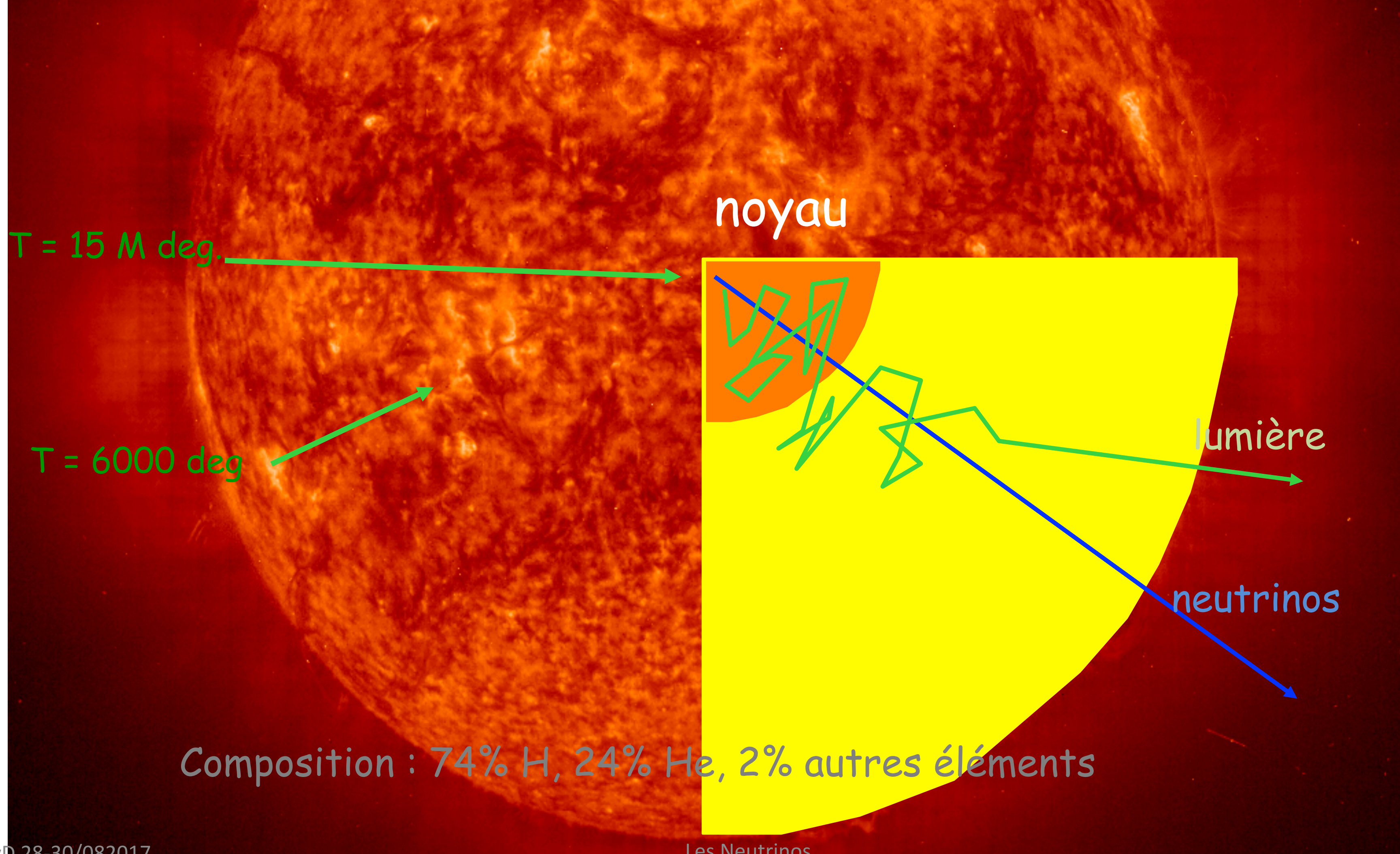
ce qu'il se passe dans l'Univers…

Dans le Soleil

Masse : 2 10^{30} kg

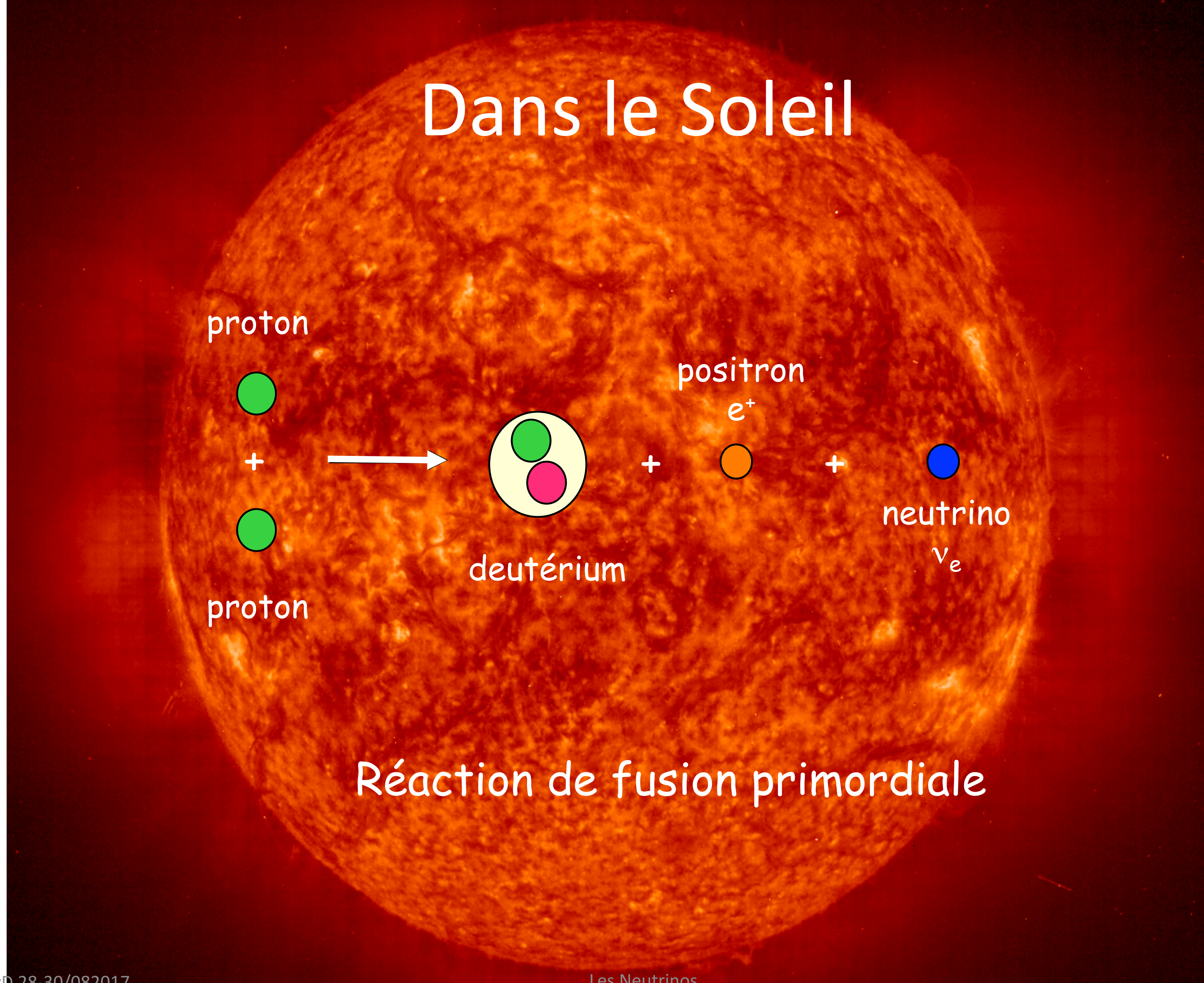
Diamètre : 1 400 000 km

150 M km de la Terre
(8 minutes lumière)

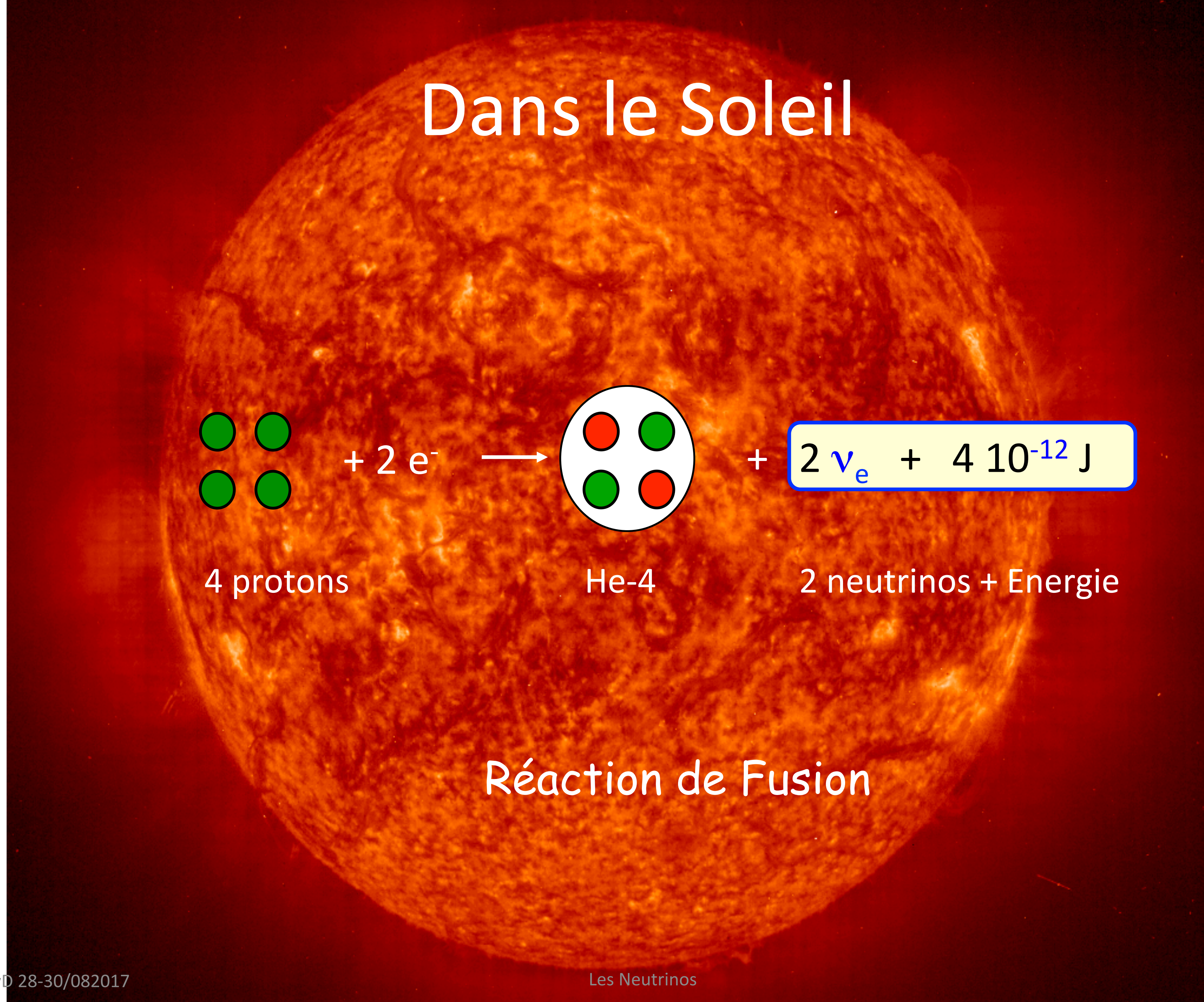


Composition : 74% H, 24% He, 2% autres éléments

Dans le Soleil



Réaction de fusion primordiale



Dans le Soleil

$+ 2\,e^- \longrightarrow$

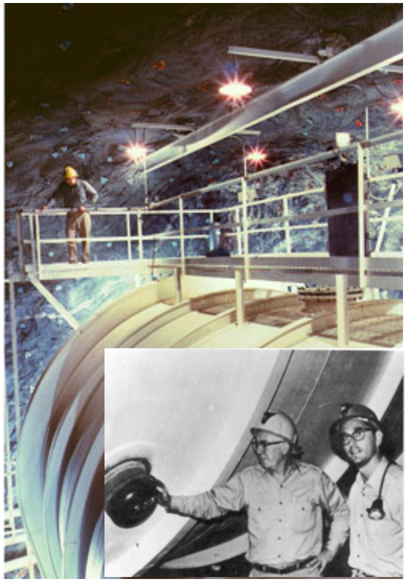
$+ \; 2\,\nu_e \; + \; 4\,10^{-12}$ J

4 protons — He-4 — 2 neutrinos + Energie

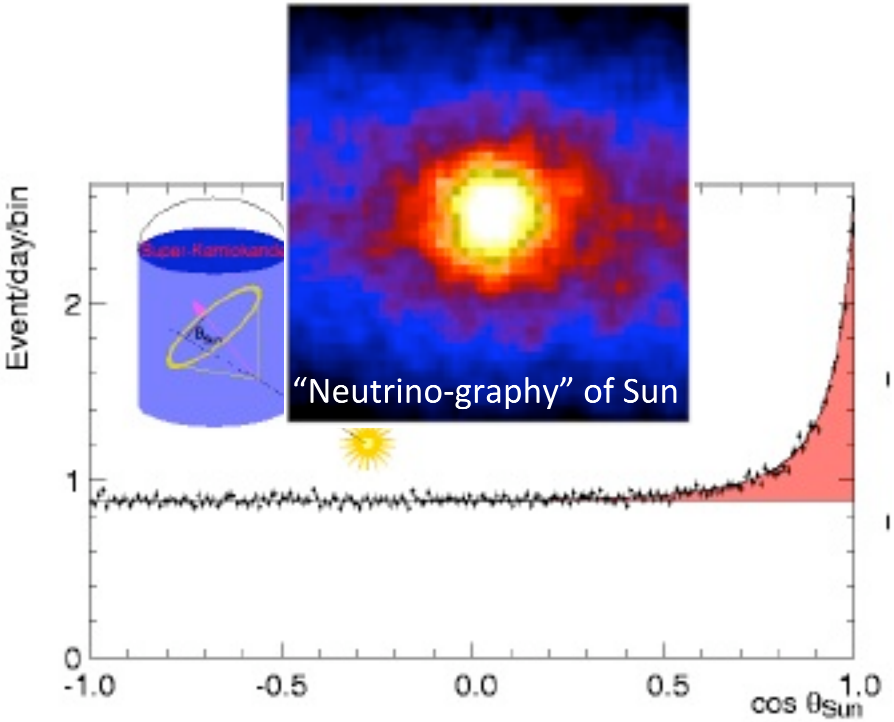
Réaction de Fusion

Nous avons vu les neutrinos du Soleil !

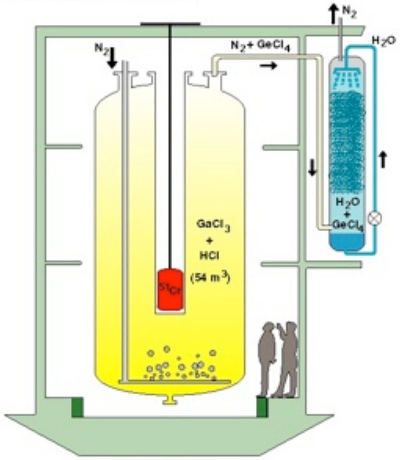
SAGE (Canada)



(SUPER-)KAMIOKANDE
(Japan)

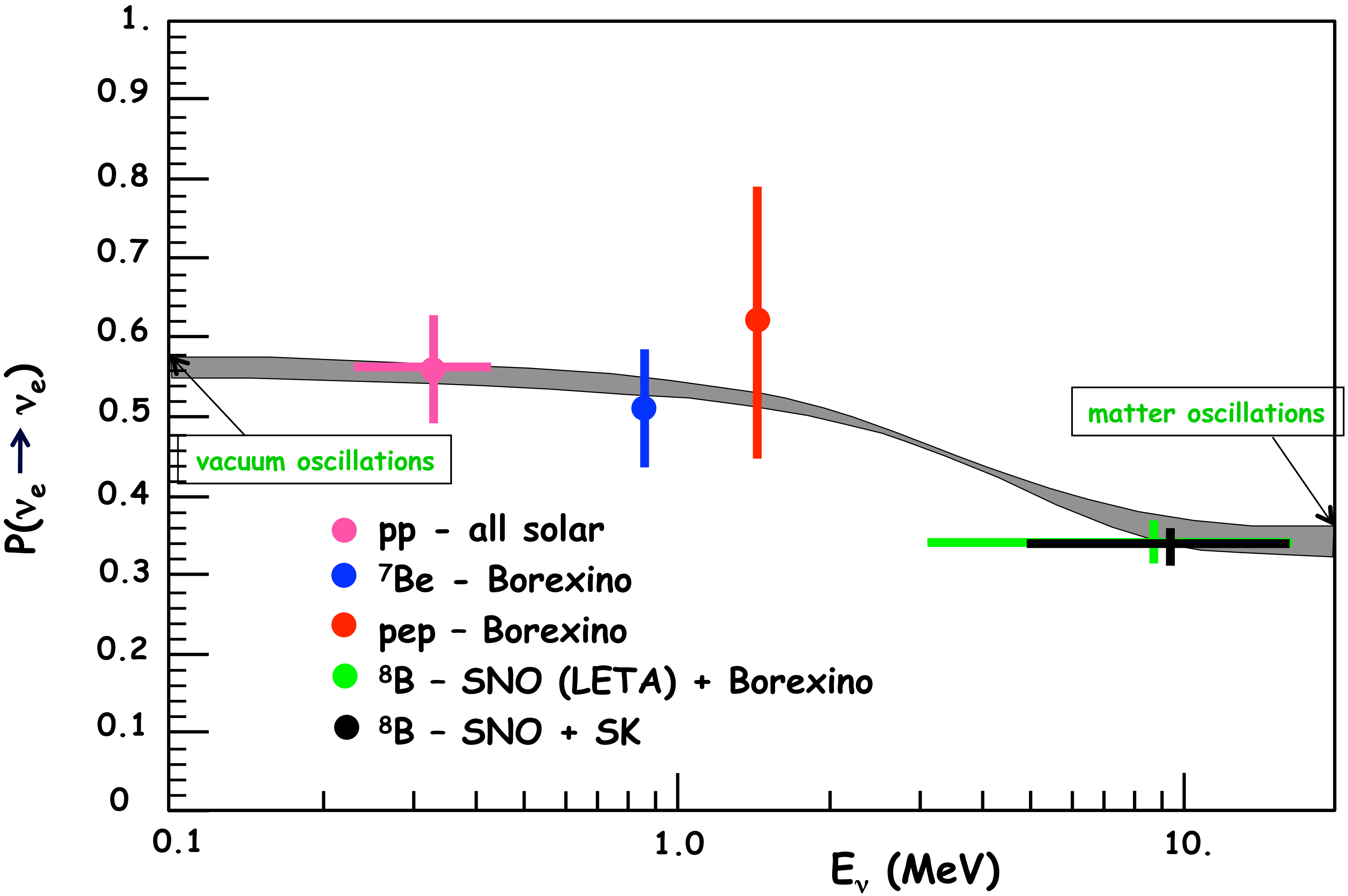


GALLEX
(Gran Sasso)



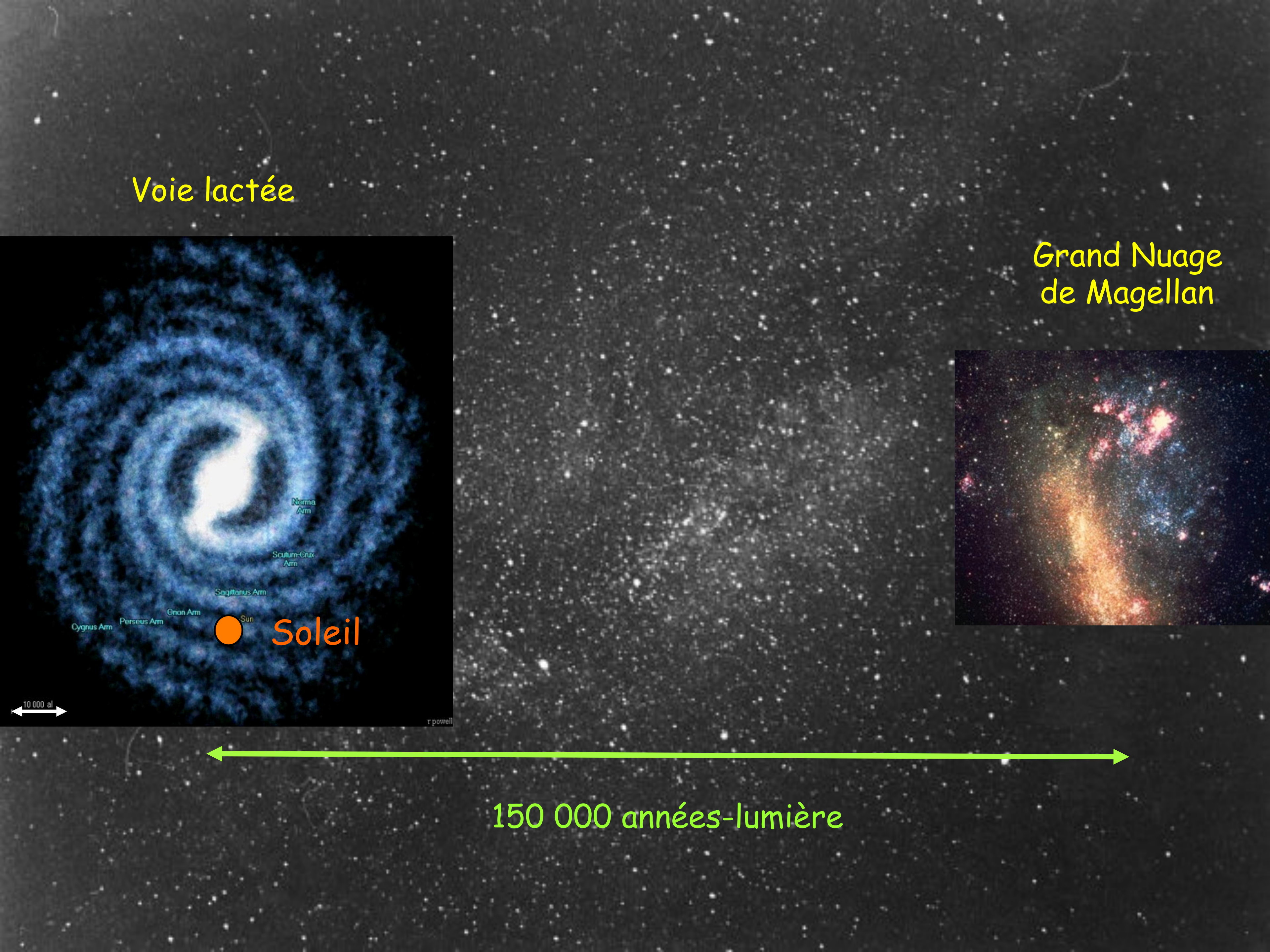
=> Preuve du mécanisme de fonctionnement du Soleil !

Les neutrinos solaires aujourd'hui



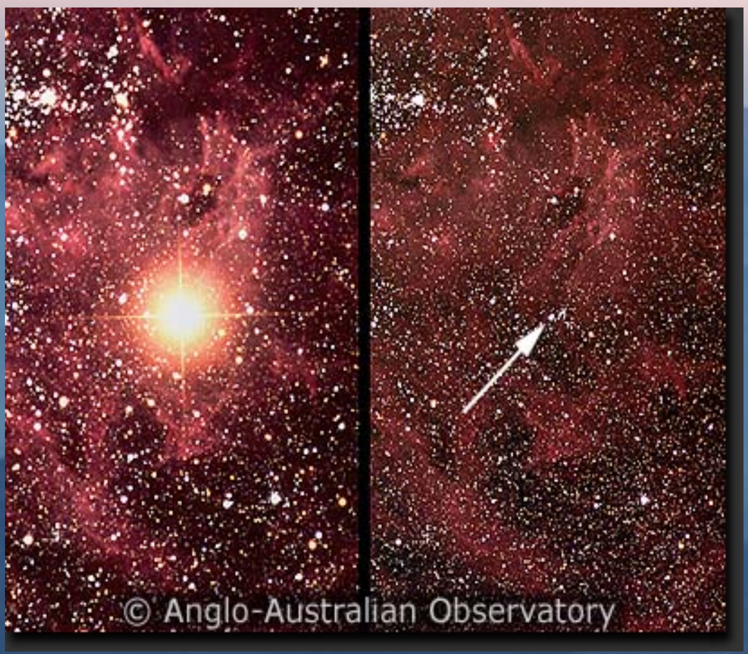
Confirmation du modèle de fonctionnement du Soleil


60 000 a.l.
30 000 a.l.
La Voie Lactée, Notre Galaxie
Eloignons-nous un peu !
© Mark A. Garlick / space-art.co.uk


Voie lactée
Norma Arm
Scutum-Crux Arm
Sagittarius Arm
Orion Arm
Perseus Arm
Cygnus Arm
Sun
Soleil
10 000 al
r powell
Grand Nuage de Magellan
150 000 années-lumière

Large Magellanic Cloud
150 000 years ago
Sanduleak -69°202

Observatoire de Las Campanas (Chili)

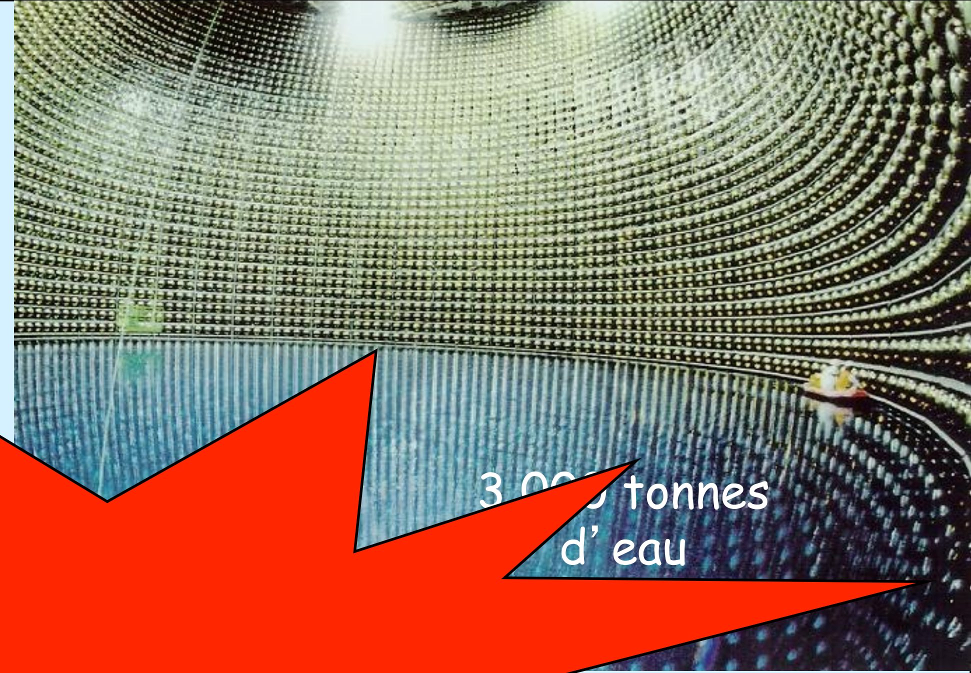


23 février 1987

Découverte de SN1987A
à l’œil nu !

… et avec un télescope !

23 février 1987
Mine de Kamioka

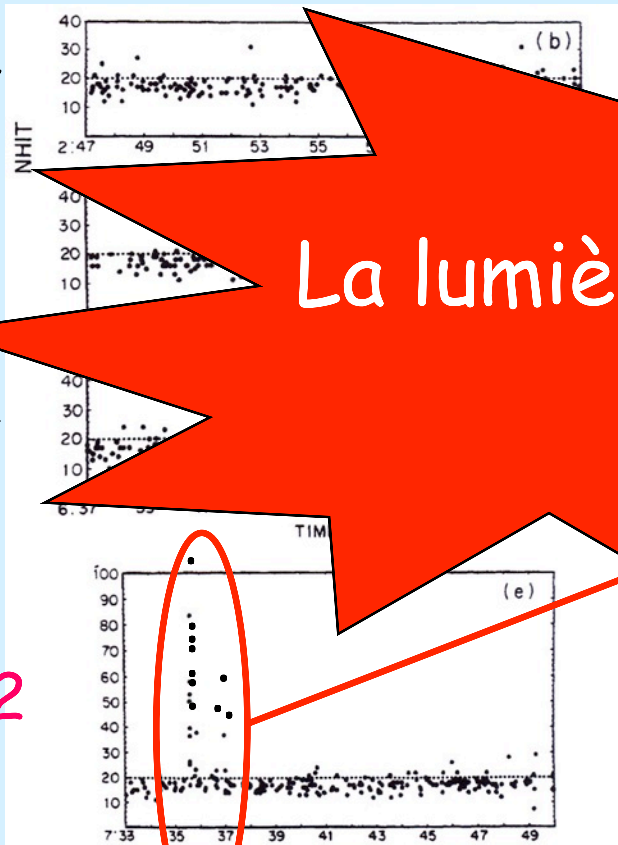


2h47

4h34

6h37

7h32



La lumière des neutrinos !

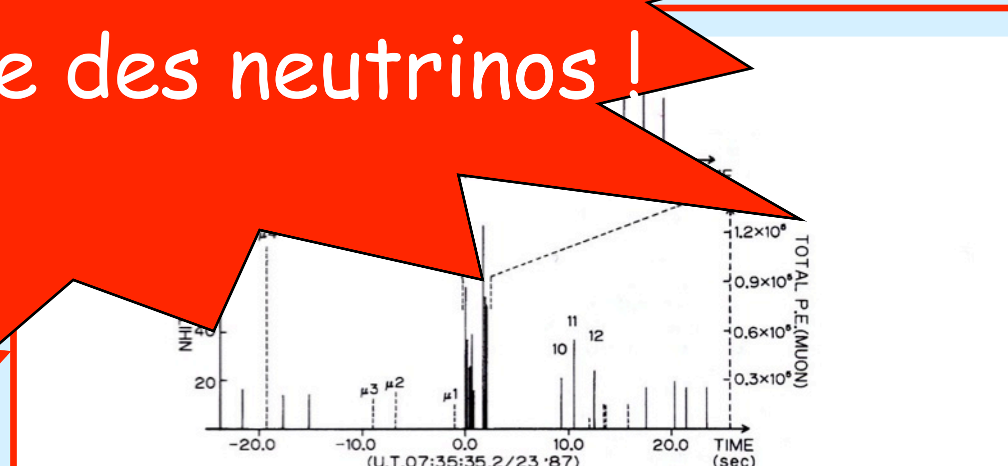


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu 1$–$\mu 4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

➢ 10 interactions en 10 secondes !

Neutrinos de SuperNovae

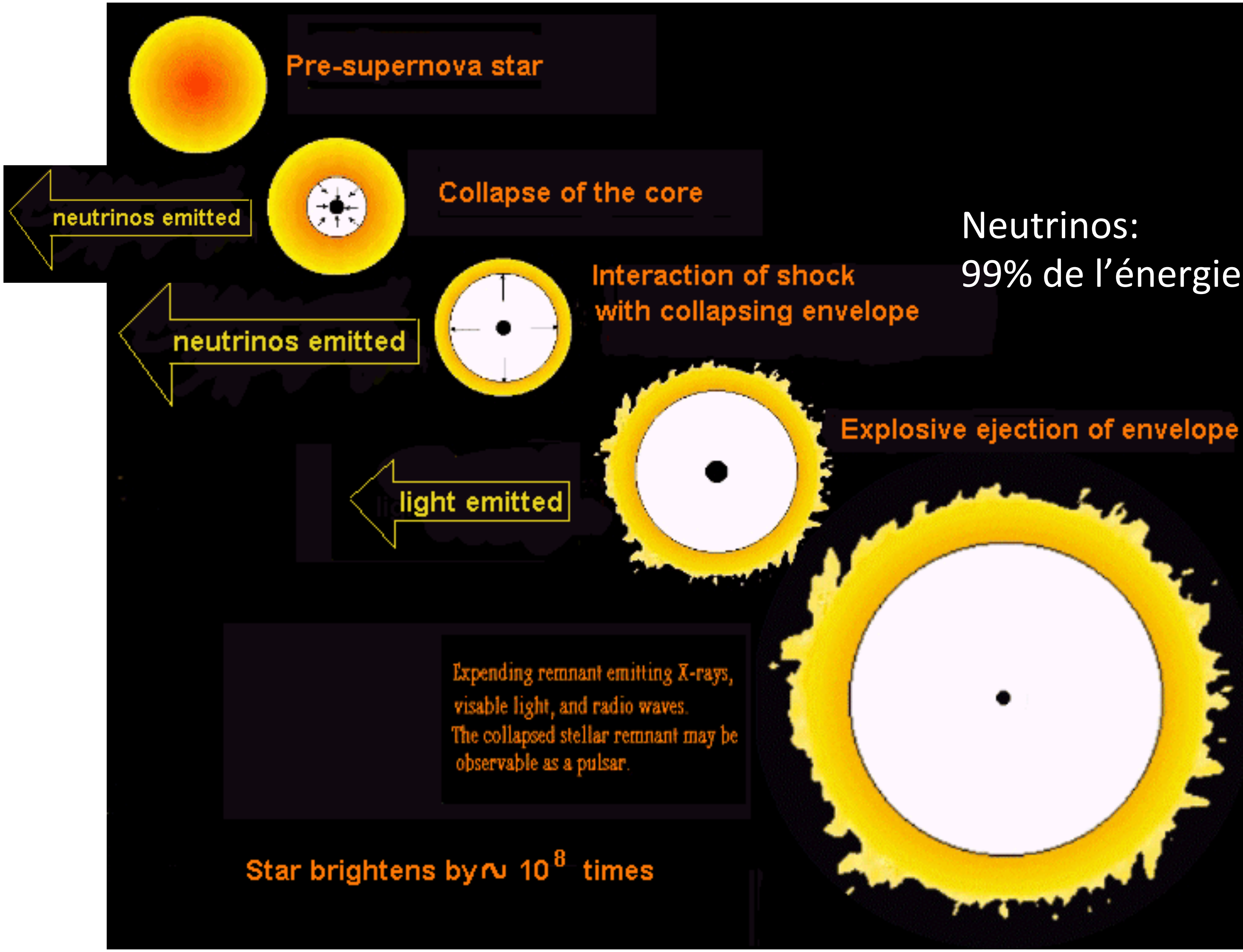
temps

0.1 s

0.5 s

2 hrs

~mois

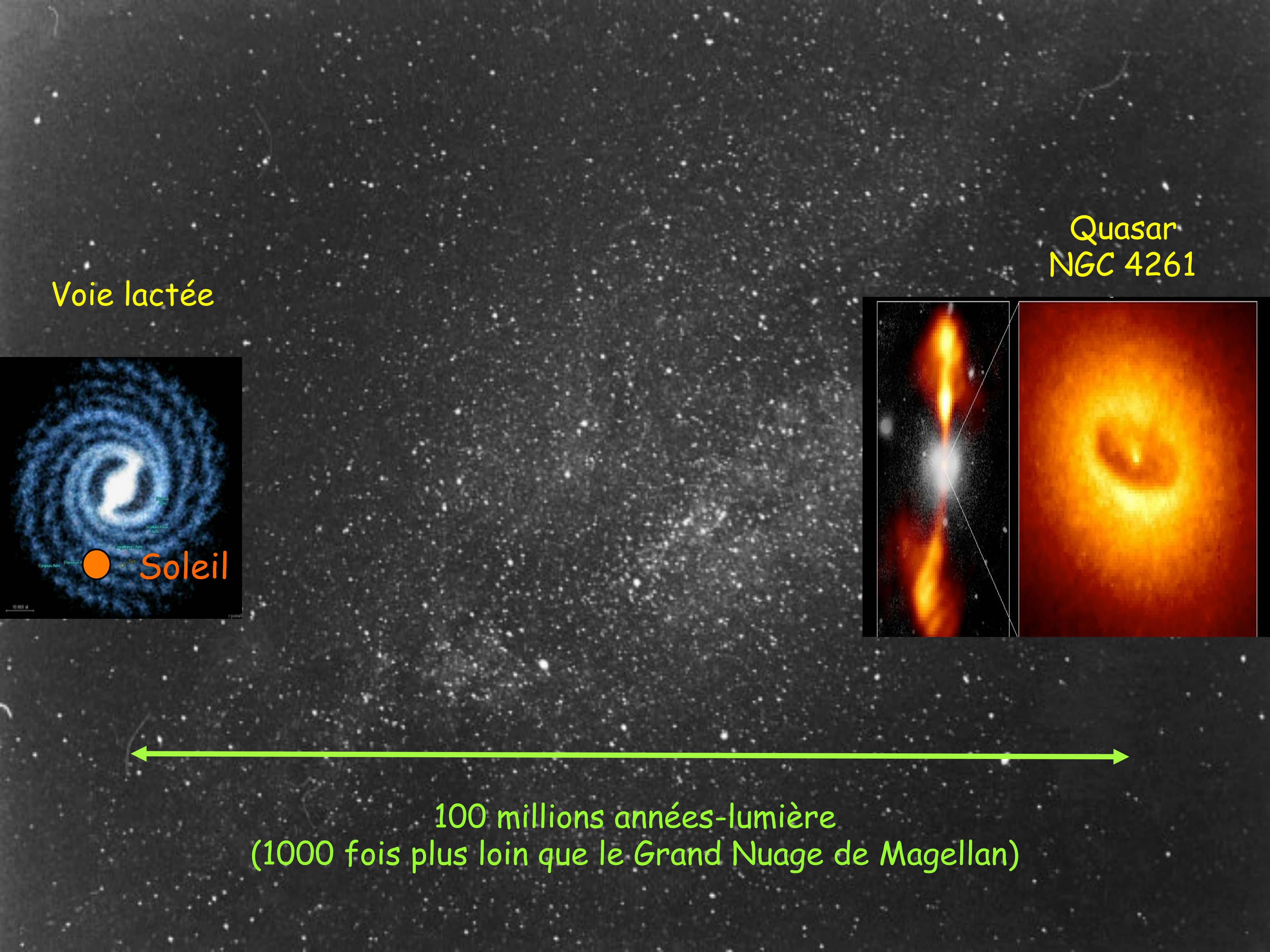


Neutrinos:
99% de l'énergie

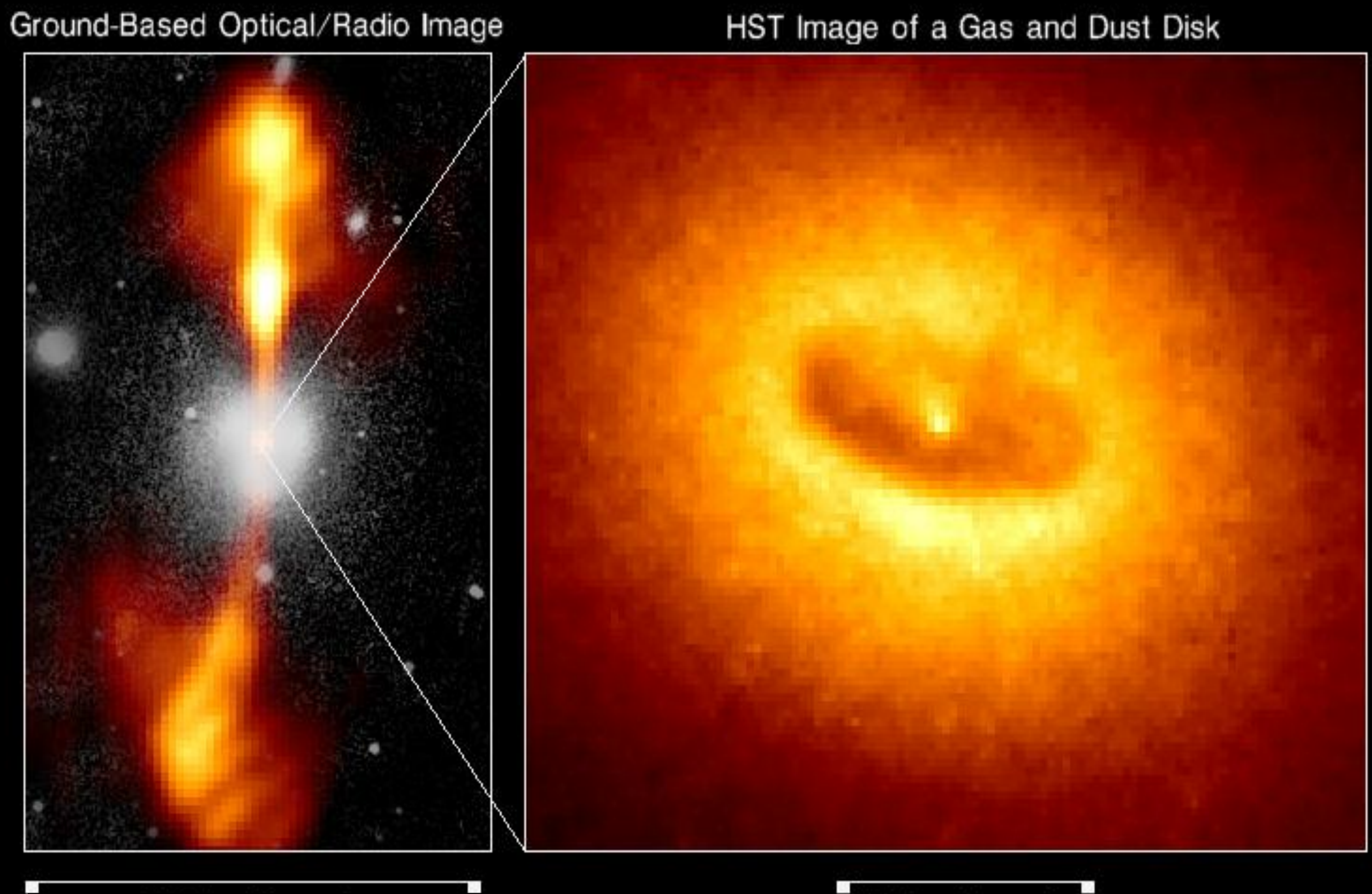
En attendant la prochaine SuperNova…

Les neutrinos, messagers de la vie et de la mort des étoiles

NOBEL PRIZE FOR PHYSICS 2002
one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"*


Voie lactée
Soleil
Quasar
NGC 4261
100 millions années-lumière
(1000 fois plus loin que le Grand Nuage de Magellan)

Quasar NGC 4261
100 millions années-lumière



80 000 années-lumière

400 années-lumière

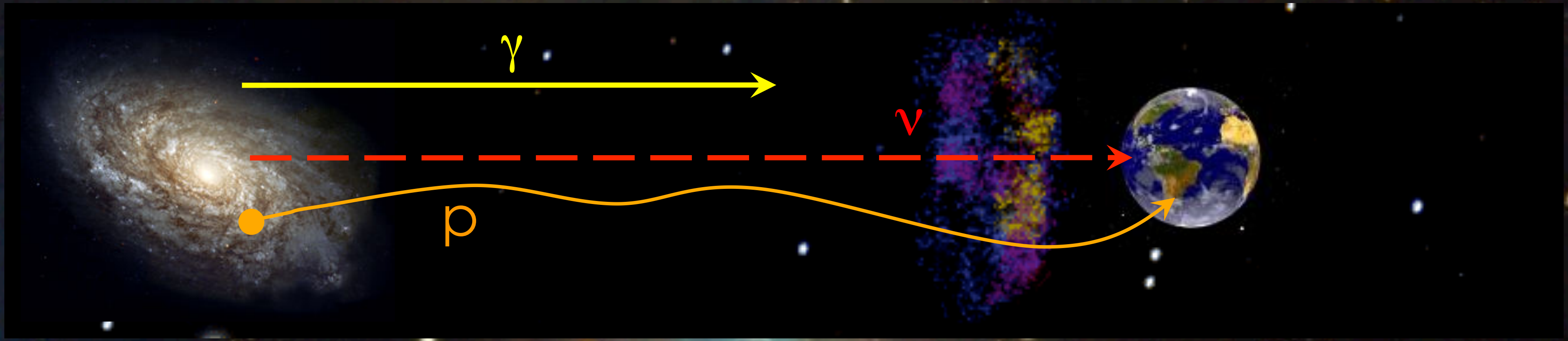
Neutrinos de très haute énergie

- Rayons cosmiques interagissant dans le disque de gaz interstellaire dans la Voie Lactée (p+p)

- Rayons cosmiques de très haute énergie interagissant avec la radiation intergalactique, puis désintégration des pions
  $p + \gamma \rightarrow \pi^+ + n \rightarrow \mu^+ + \nu_\mu + n$

- Collisions p+p ou p + γ puis désintégration de π “in situ” dans plusieurs sources: Active Galcatic Nuclei (AGN), Gamma Ray Bursts (GRB), Star Burst Galaxies…

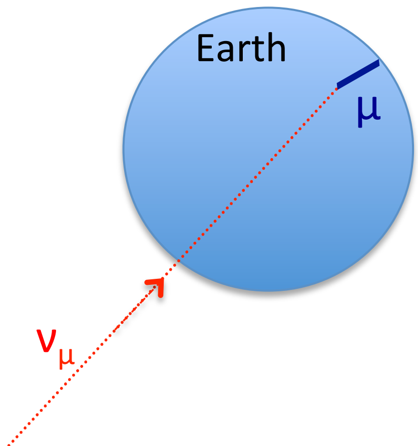
Neutrinos, new messengers of the Universe



ANTARES
Observing the sky 2500m underwater
(off Toulon)

ANTARES

interaction of a ν_μ

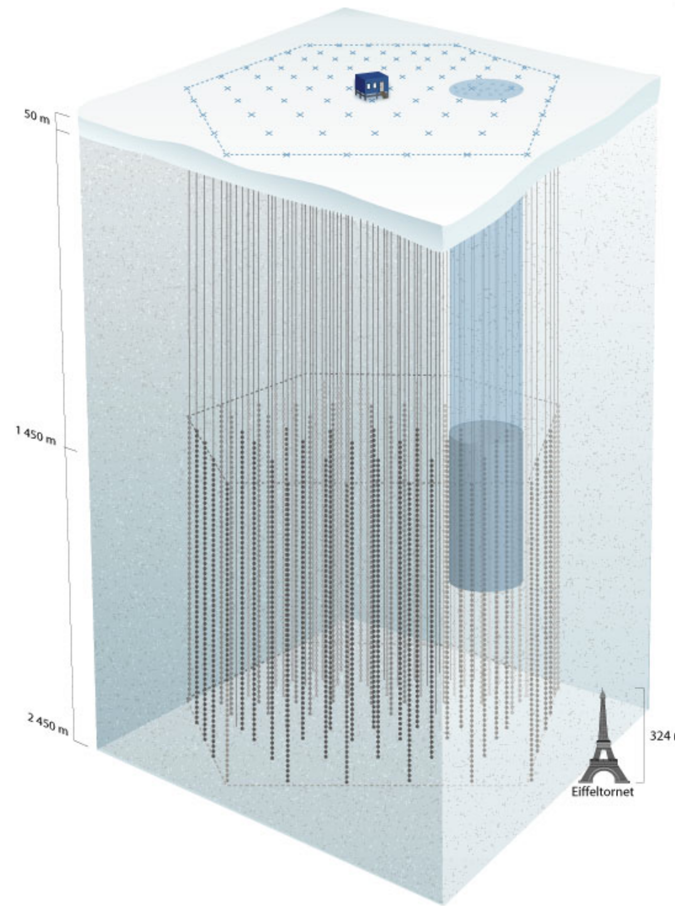



THE ANTARES UNDERWATER TELESCOPE

Pour observer tout le ciel ?

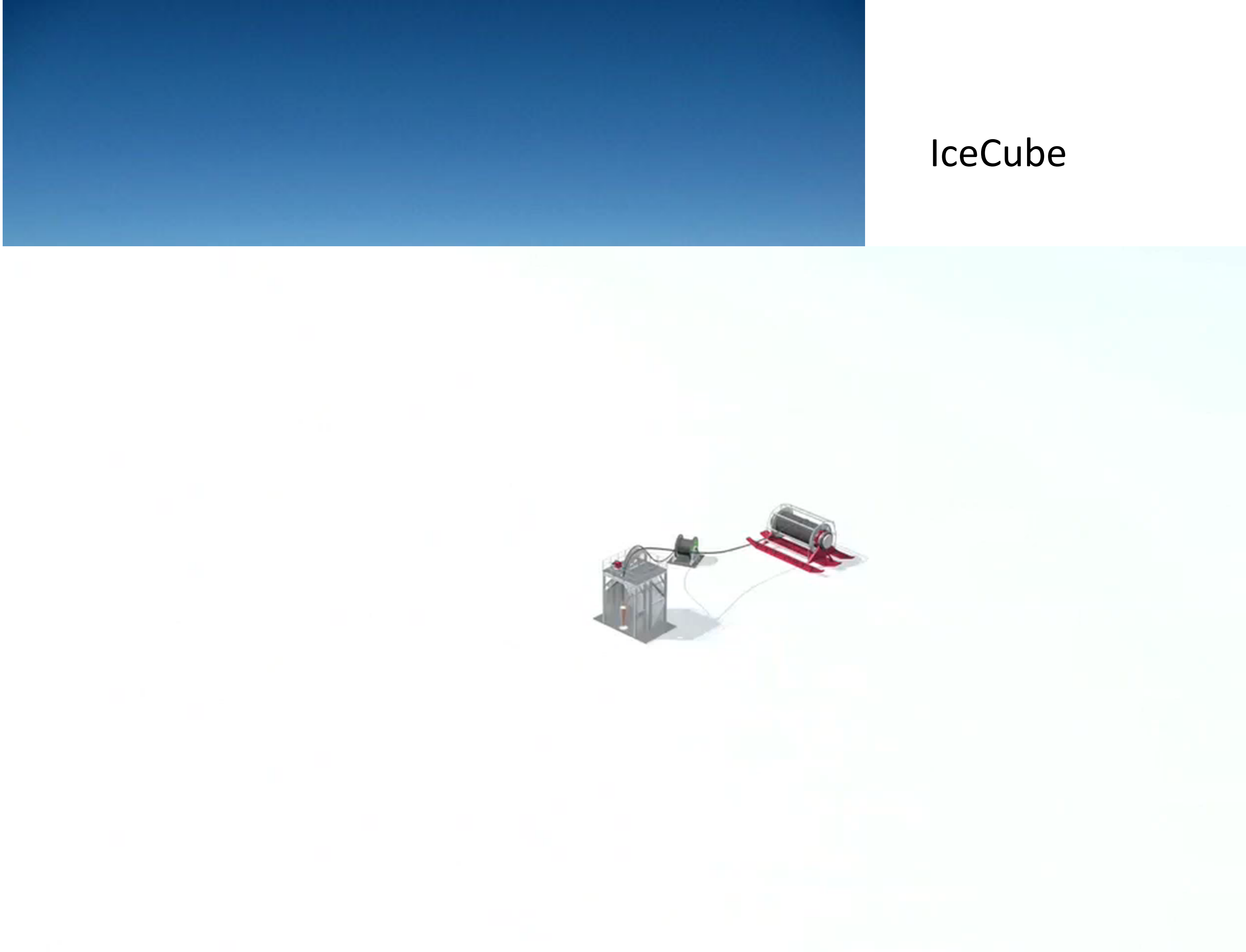
ANTARES au large de Toulon

IceCube au Pôle Sud

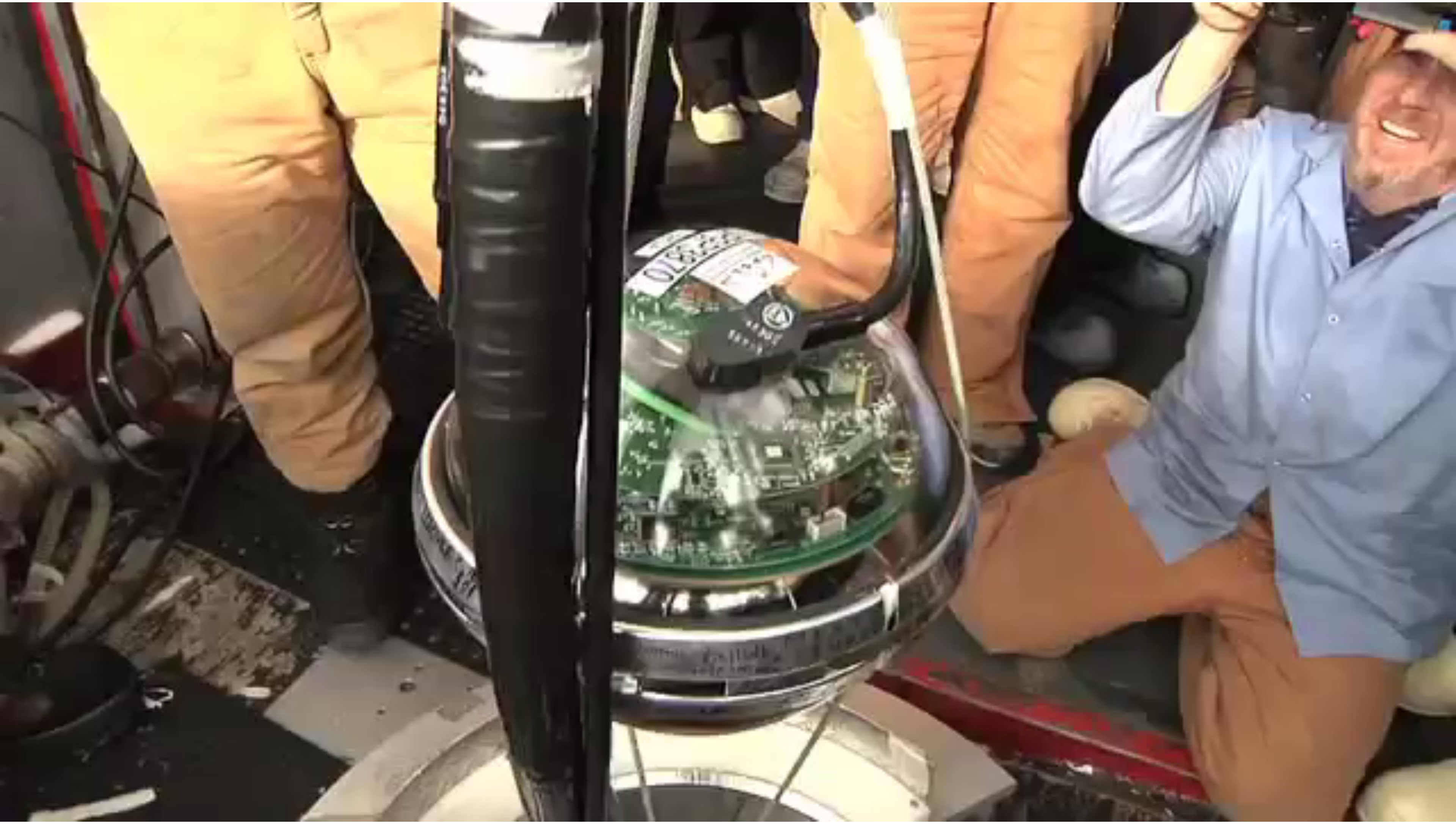


ceCube

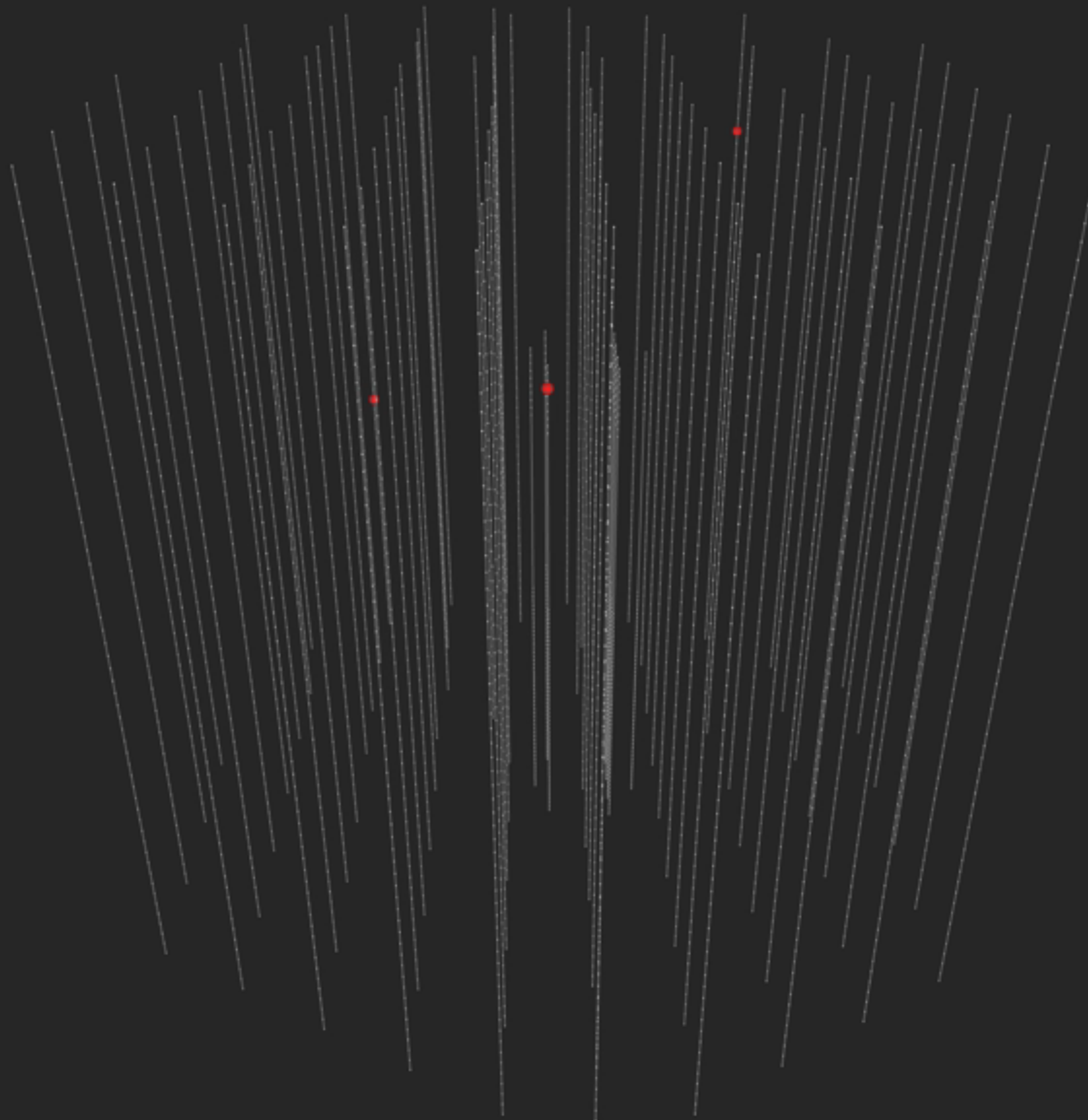
IceCube



Modules optiques d'IceCube

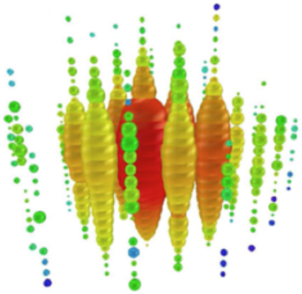


Modules optiques d'IceCube

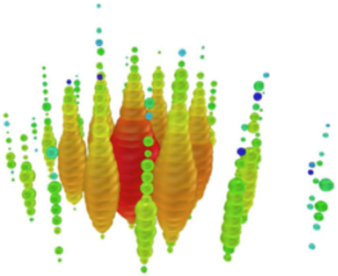


Excès de neutrinos à très haute énergie

L'histoire… (2010-2012)

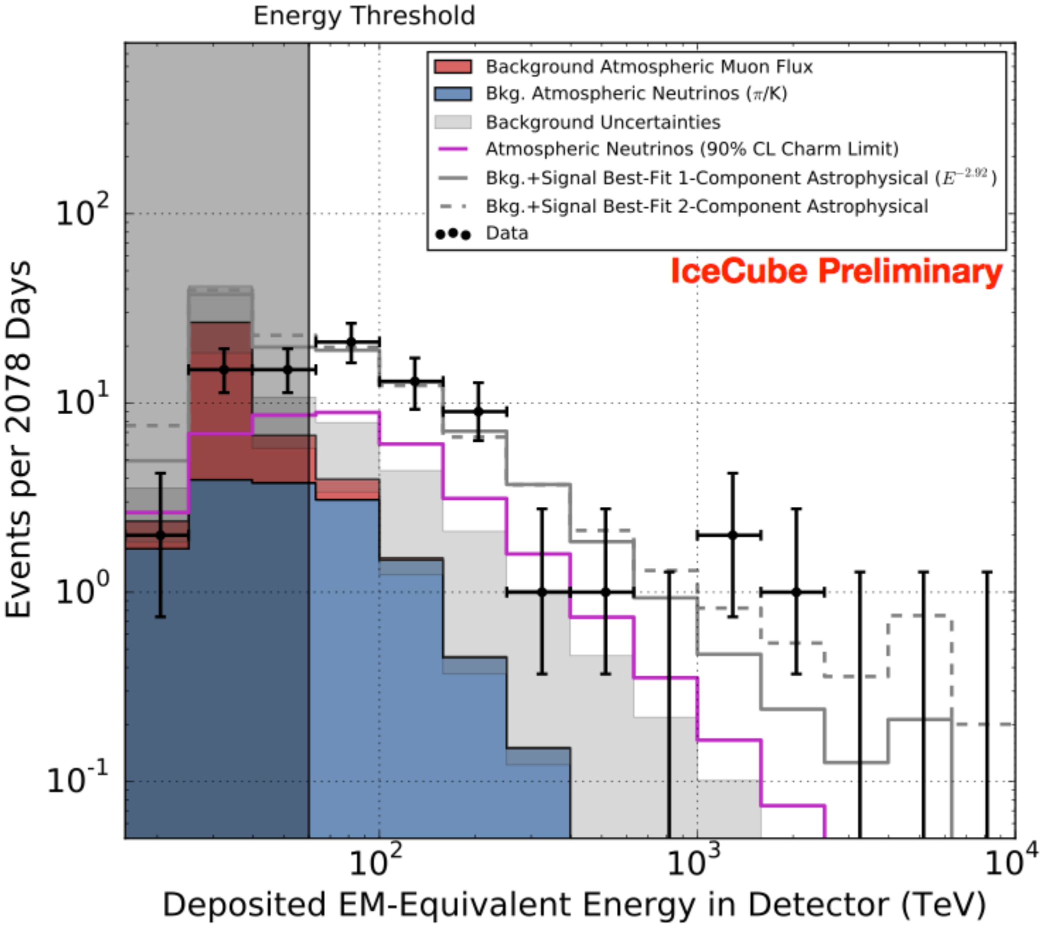


1.04±0.16 PeV



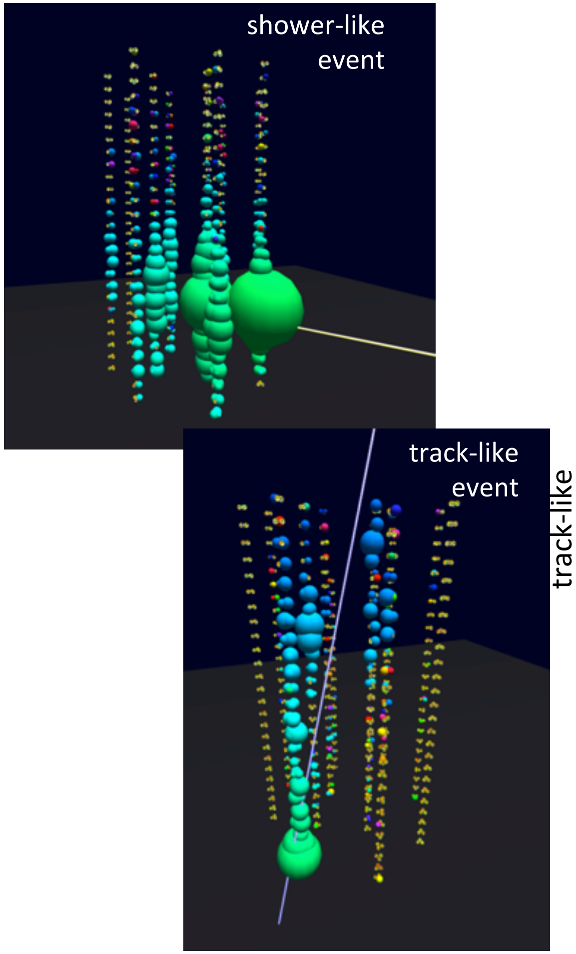
1.14±0.17 PeV

IceCube, 6 ans

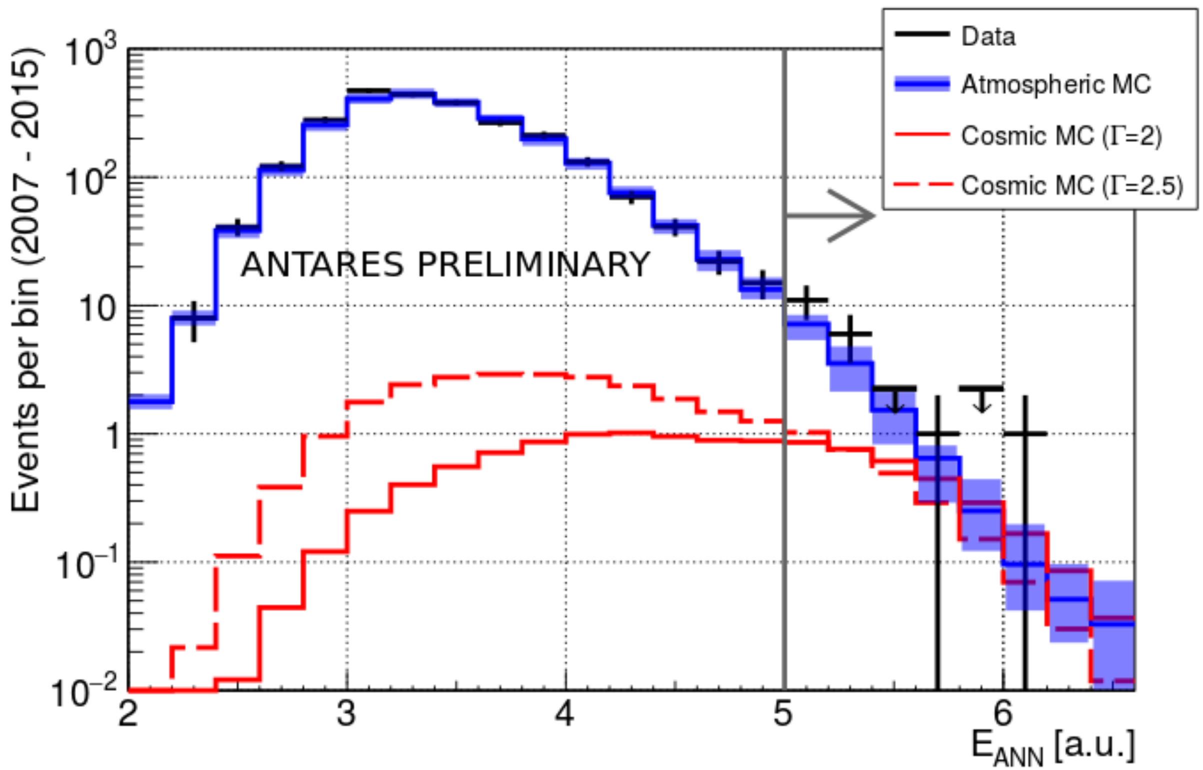


Quelle est leur origine ?

Excès de neutrinos à très haute énergie



ANTARES, 9 ans



Quelle est leur origine ?

Astronomie Multi-Messagers

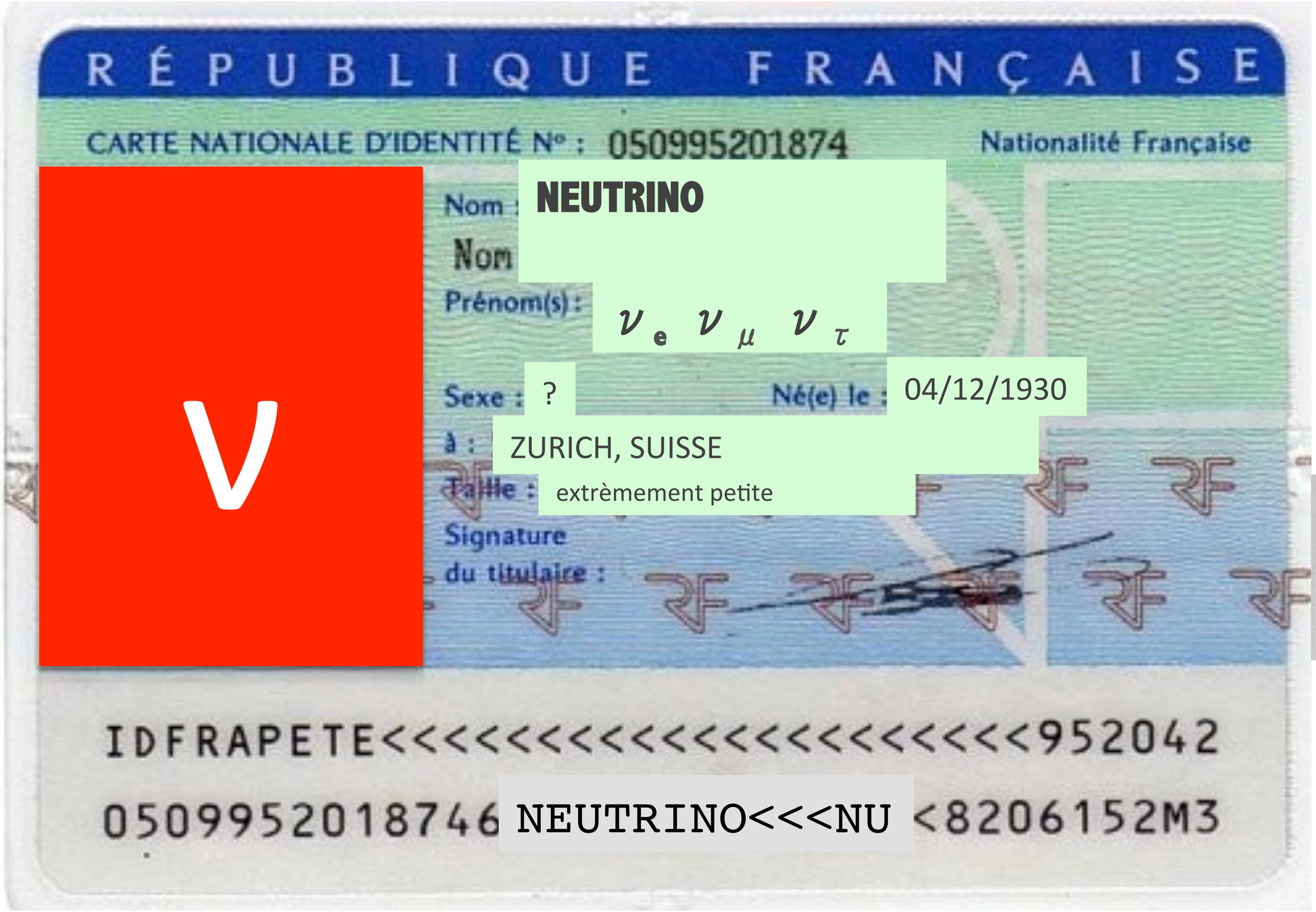
Phys.Rev. D96 (2017) no.2, 022005

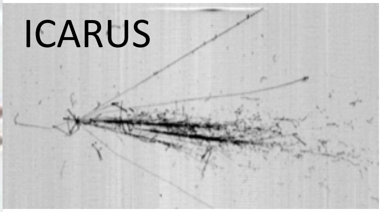
Search for High-energy Neutrinos from Gravitational Wave Event GW151226 and Candidate LVT151012 with ANTARES and IceCube

ANTARES Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration*

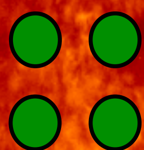
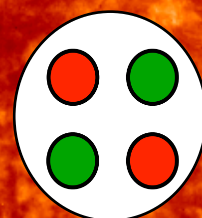
The Advanced LIGO observatories detected gravitational waves from two binary black hole mergers during their first observation run (O1). We present a high-energy neutrino follow-up search for the second gravitational wave event, GW151226, as well as for gravitational wave candidate LVT151012. We find 2 and 4 neutrino candidates detected by IceCube, and 1 and 0 detected by ANTARES, within ±500 s around the respective gravitational wave signals, consistent with the expected background rate. None of these neutrino candidates are found to be directionally coincident with GW151226 or LVT151012. We use non-detection to constrain isotropic-equivalent high-energy neutrino emission from GW151226 adopting the GW event's 3D localization, to less than $2 \times 10^{51} - 2 \times 10^{54}$ erg.

Les Neutrinos : que savons nous ?





Retour dans le soleil…

 + 2 e$^-$ ⟶  + $2\,\nu_e$ + 4 10^{-12} J

4 protons — He-4 — 2 neutrinos + Energie

Flux des neutrinos solaires sur Terre :

$$\Phi_\nu = 2\,\frac{\text{Luminosité du Soleil}}{\text{Energie par réaction}}\,\frac{1}{4\pi d^2}$$

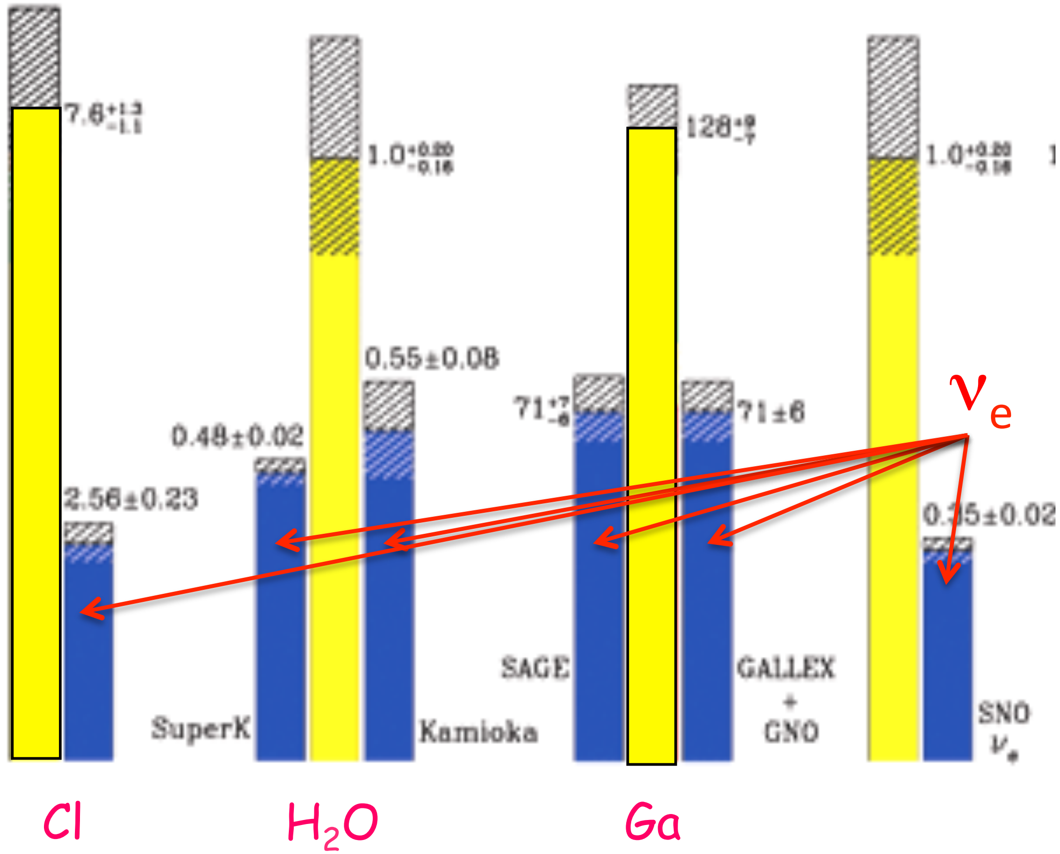
Luminosité du Soleil : 3,8 10^{26} W

Energie par réaction : 4 10^{-12} J

d : 1,5 10^{11} m

6.5 10^{10} cm^{-2}s^{-1}

Neutrinos solaires :
mesures et prévisions



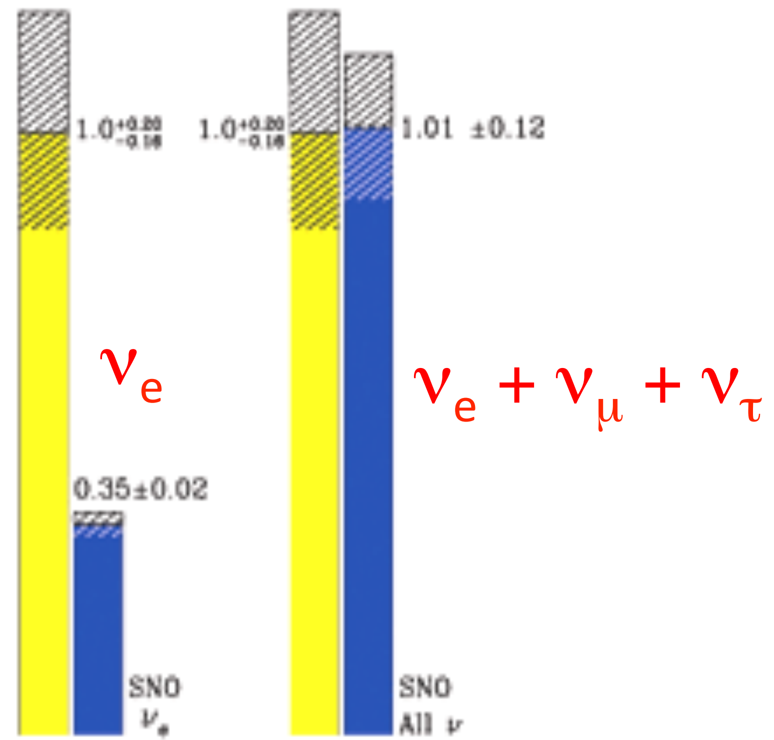
THE PUZZLE…

SNO (2002)

Neutrinos solaires : mesures et prévisions

1. Preuve que les neutrinos (ν_e) se manifestent differemments (ν_μ ou ν_τ) après la propagation

2. Preuve des modèles solaires



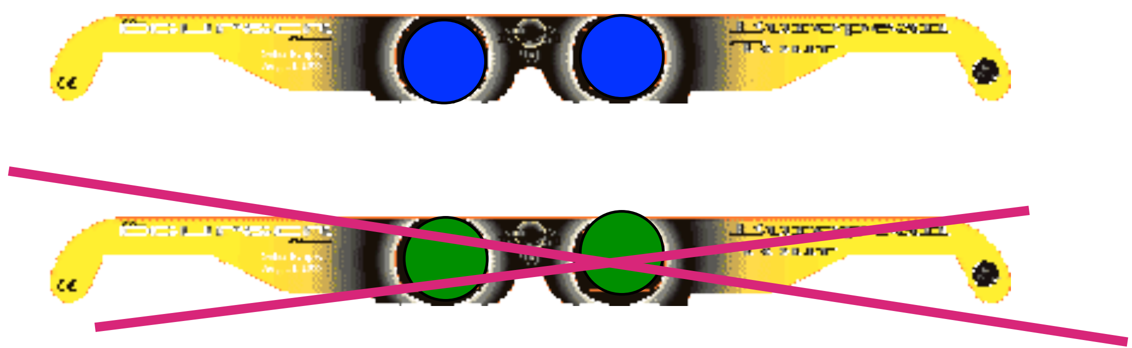
SNO (2002)

The solution to the puzzle: oscillation $\nu_e \rightarrow \nu_{\mu,\tau}$

L'enigme des neutrinos solaires explique par les oscillations

- Les neutrinos se manifestent avec différentes saveurs le long de leur chemin

- Mais, avant SNO, nos détecteurs n'étaient sensibles qu'à la saveur de départ !



Les oscillations des neutrinos

Etats propres de saveur (interaction)

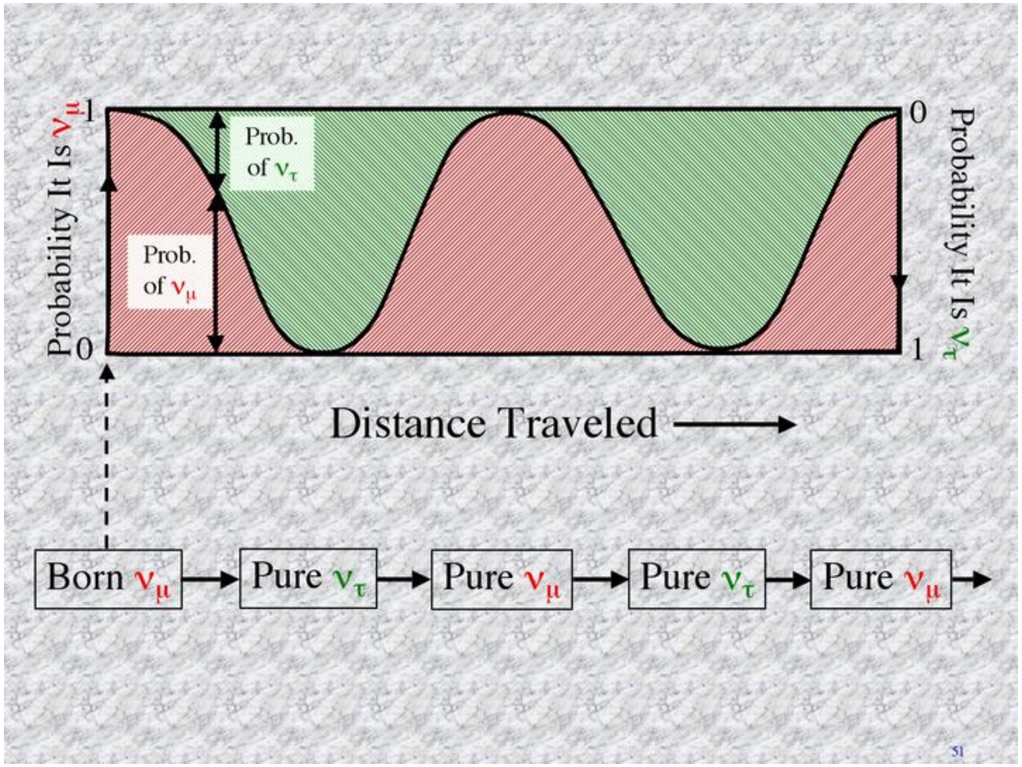
Etats propres de masse (propagation)

$$P(\nu_i \rightarrow \nu_j) =$$

$$\sin^2(2\theta) \cdot \sin^2\left(\pi \cdot L(m)\frac{\Delta m^2 (eV^2)}{2.5\,E_\nu (MeV)}\right)$$

Angle de mélange

Différence de masse



Les oscillations des neutrinos

C. Giunti

Fields $\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{kL}$ $\Longrightarrow$ $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$ States

initial flavor: $\alpha = e$ or μ or τ

$$|\nu_k(t,x)\rangle = e^{-iE_k t + ip_k x} |\nu_k\rangle \Rightarrow |\nu_\alpha(t,x)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t + ip_k x} |\nu_k\rangle$$

$$|\nu_k\rangle = \sum_{\beta=e,\mu,\tau} U_{\beta k} |\nu_\beta\rangle \Rightarrow |\nu_\alpha(t,x)\rangle = \sum_{\beta=e,\mu,\tau} \underbrace{\left(\sum_k U^*_{\alpha k} e^{-iE_k t + ip_k x} U_{\beta k} \right)}_{\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t,x)} |\nu_\beta\rangle$$

$$\mathcal{A}_{\nu_\alpha \to \nu_\beta}(0,0) = \sum_k U^*_{\alpha k} U_{\beta k} = \delta_{\alpha\beta} \qquad \mathcal{A}_{\nu_\alpha \to \nu_\beta}(t>0, x>0) \neq \delta_{\alpha\beta}$$

$$P_{\nu_\alpha \to \nu_\beta}(t,x) = |\mathcal{A}_{\nu_\alpha \to \nu_\beta}(t,x)|^2 = \left| \sum_k U^*_{\alpha k} e^{-iE_k t + ip_k x} U_{\beta k} \right|^2$$

ultra-relativistic neutrinos $\Longrightarrow$ $t \simeq x = L$ source-detector distance

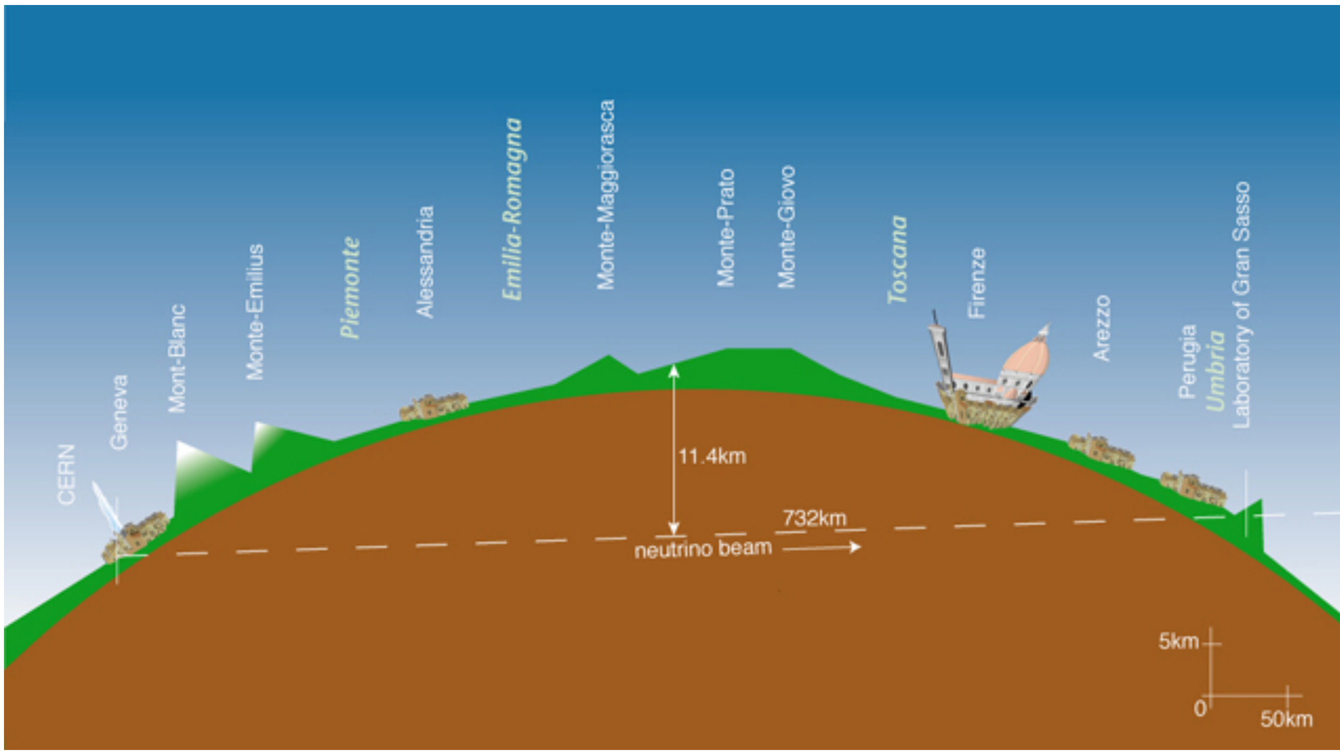
$$E_k t - p_k x \simeq (E_k - p_k) L = \frac{E_k^2 - p_k^2}{E_k + p_k} L = \frac{m_k^2}{E_k + p_k} L \simeq \frac{m_k^2}{2E} L$$

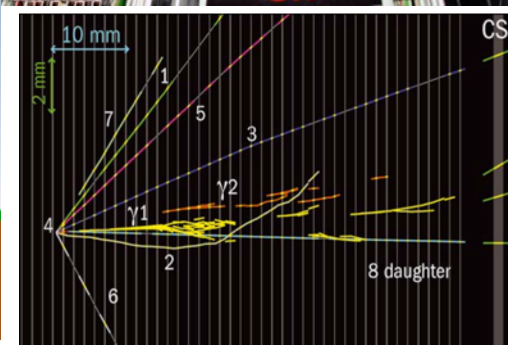
$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \left| \sum_k U^*_{\alpha k} e^{-i m_k^2 L / 2E} U_{\beta k} \right|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E} \right)$$

$\Delta m^2_{kj} = m_k^2 - m_j^2$

Les oscillation des neutrinos : évidence directe

CNGS: a neutrino beam from CERN to Gran Sasso

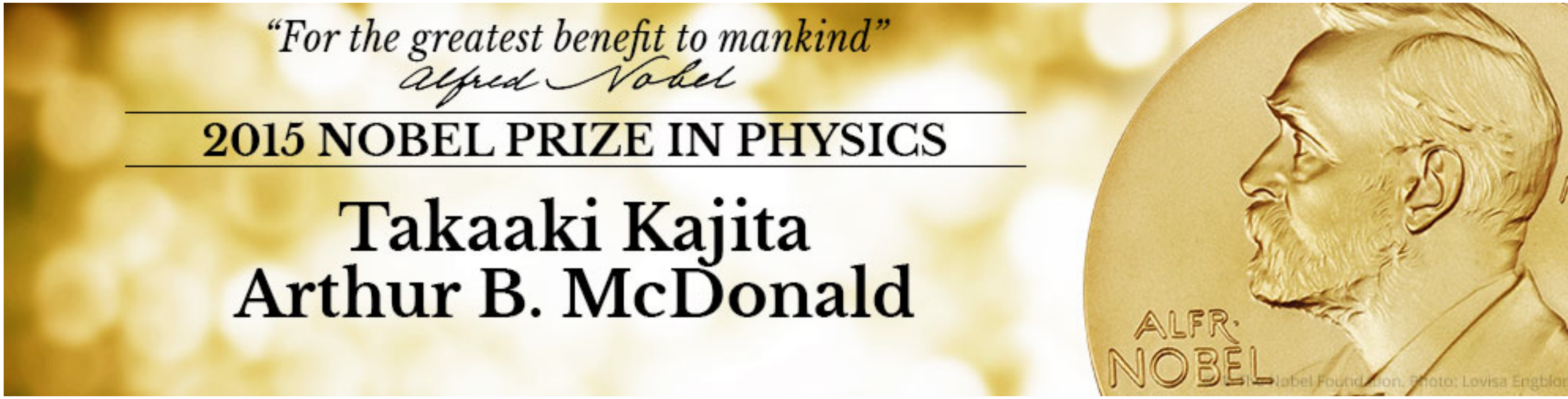




CERN:
ν_μ produced

OPERA:
ν_τ detected

Les oscillations des neutrinos

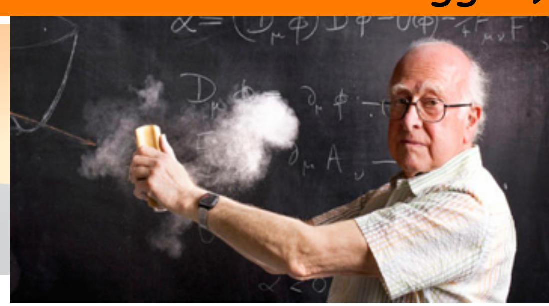



Ill: N. Elmehed. © Nobel Media 2015

2015 Nobel Prize in Physics

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 neutrinos oscillent => ont une masse
("parlent" avec le boson de Higgs !)



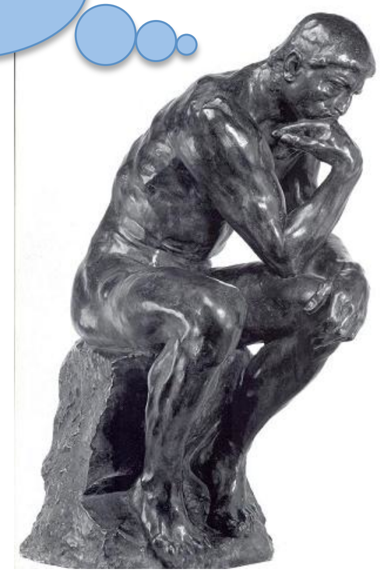
Mais alors… nous savons tout ?

Neutrinos et anti-neutrinos se comportent de la même facon ?

Si non, pouvons-nous comprendre la différence entre matière et anti-matière dans l'Univers … ?

Quel neutrino est le plus lourd ?

3 ou plus ?



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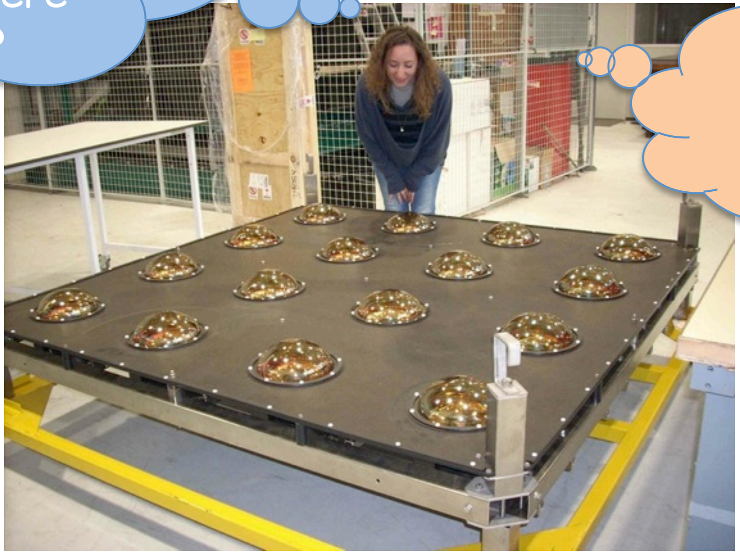
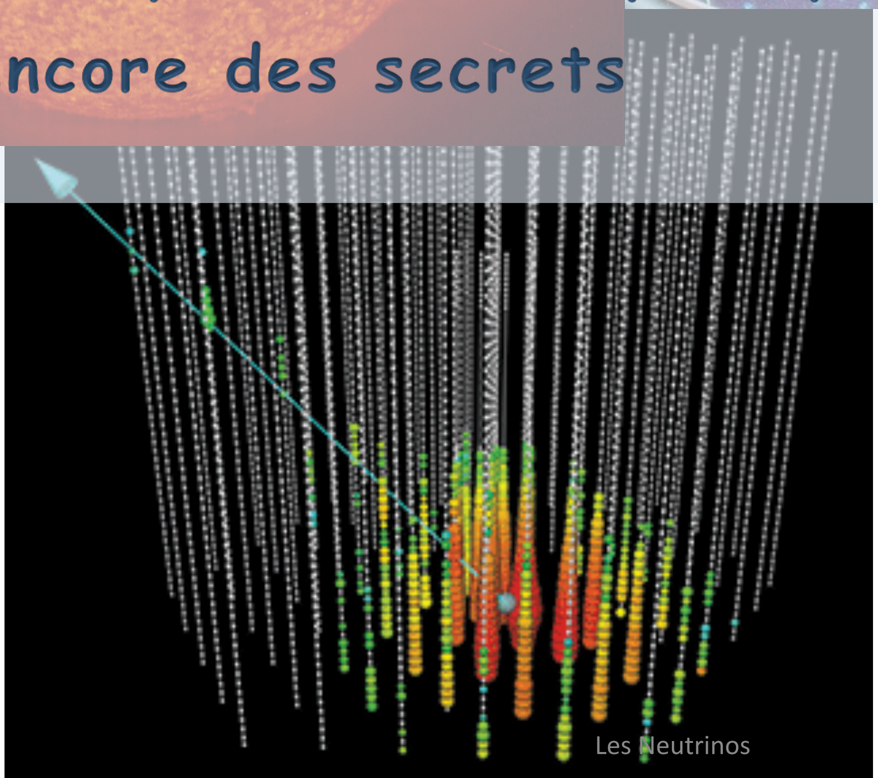


Les Neutrinos

- Sont difficiles à piéger
- Sont des messagers uniques de leurs sources
  - le Soleil, les étoiles, l'Univers…
- Sont des particules un peu spéciales
- Ont encore des secrets



MERCI!