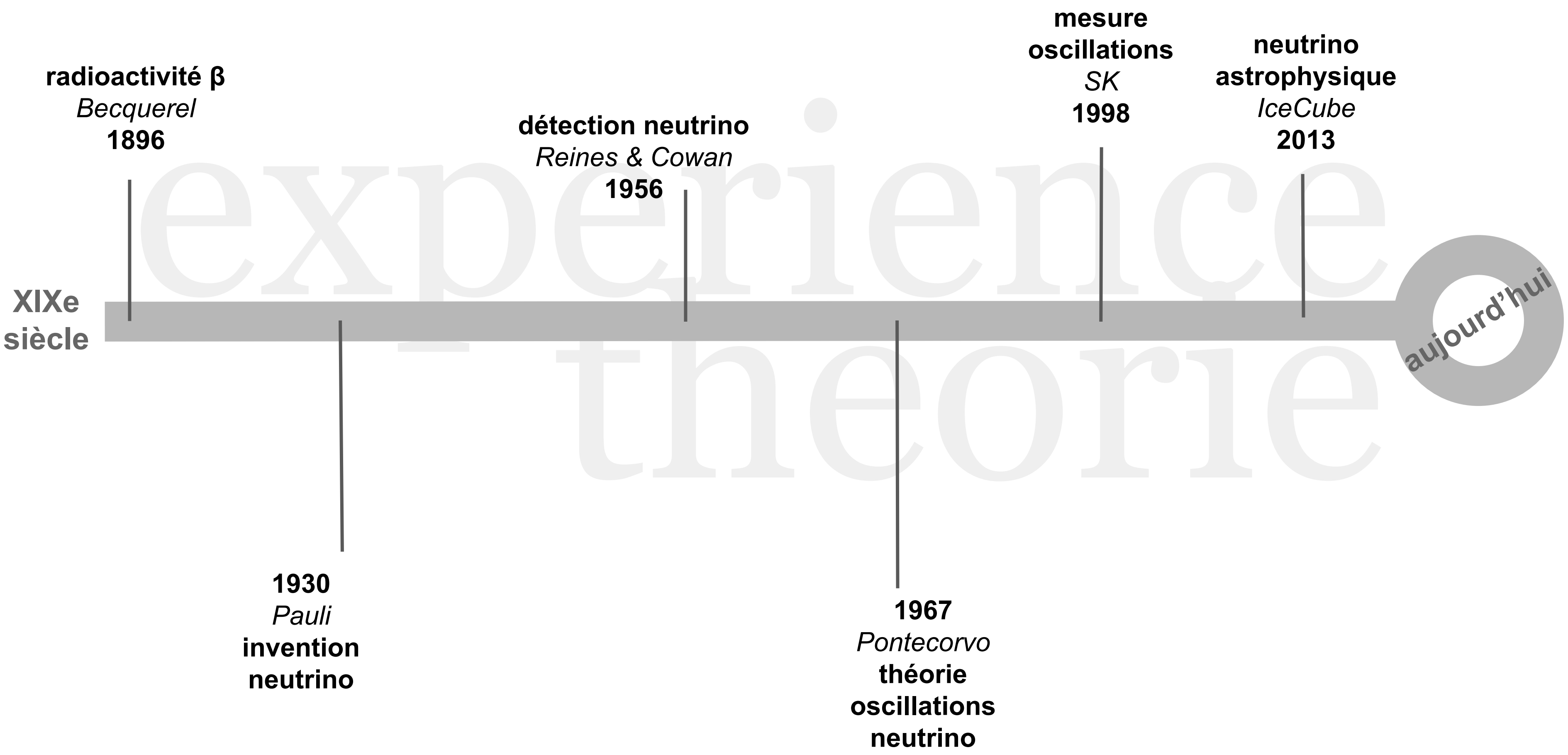
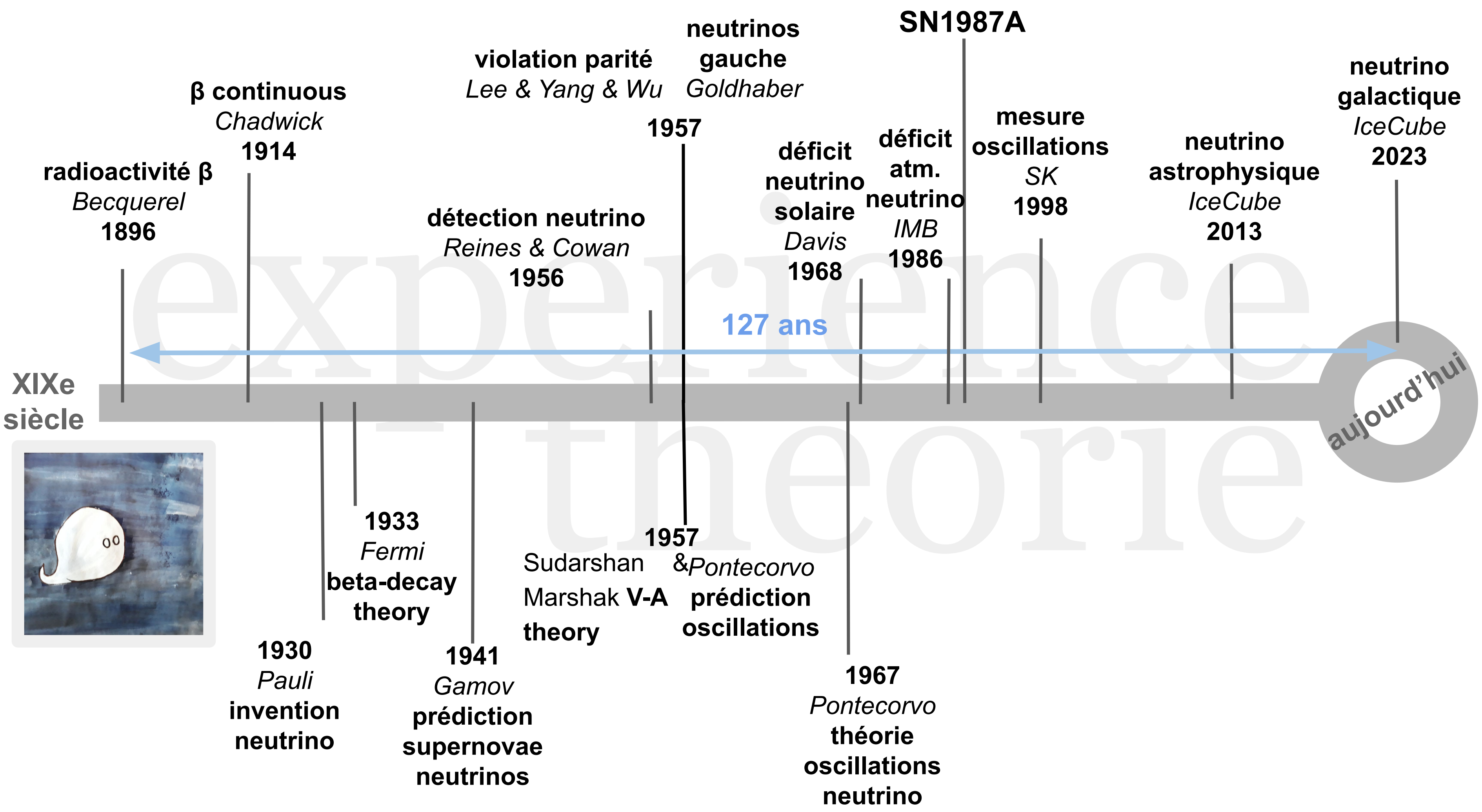
# Histoire du neutrino

Luc C. · 30/09/2023 · La Seyne



radioactivité β
*Becquerel*
1896
détection neutrino
*Reines & Cowan*
1956
mesure oscillations
*SK*
1998
neutrino astrophysique
*IceCube*
2013
expérience
XIXe siècle
théorie
aujourd'hui
1930
*Pauli*
invention neutrino
1967
*Pontecorvo*
théorie oscillations neutrino



XIXe siècle
radioactivité β
Becquerel
1896
β continuous
Chadwick
1914
1930
Pauli
invention neutrino
1933
Fermi
beta-decay theory
1941
Gamov
prédiction supernovae neutrinos
détection neutrino
Reines & Cowan
1956
violation parité
Lee & Yang & Wu
1957
neutrinos gauche
Goldhaber
Sudarshan Marshak V-A theory
1957
& Pontecorvo
prédiction oscillations
1967
Pontecorvo
théorie oscillations neutrino
déficit neutrino solaire
Davis
1968
déficit atm. neutrino
IMB
1986
SN1987A
mesure oscillations
SK
1998
neutrino astrophysique
IceCube
2013
neutrino galactique
IceCube
2023
127 ans
aujourd'hui
expérience
théorie

# découverte du neutrino

**spectre β continuous**
*Chadwick*
**1914**

**radioactivité β**
*Becquerel*
**1896**

**détection neutrino**
*Reines & Cowan*
**1956**

experience

**XIXe siècle**

aujourd'hui

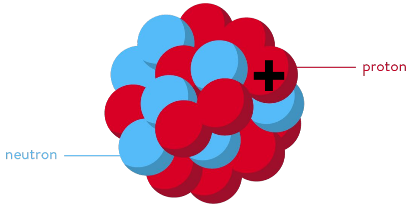
theorie

**1933**
*Fermi*
**beta-decay theory**

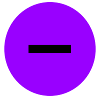
**1930**
*Pauli*
**invention neutrino**

# particules

mass : propriété intrinsèque → résistance à l'inertie
unité : 1 MeV = 1 000 000 eV

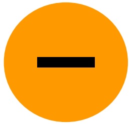



electron



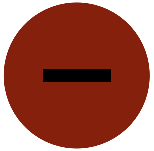
**0.5 MeV**

muon



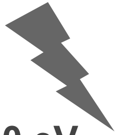
**100 MeV**

tau



**1700 MeV**

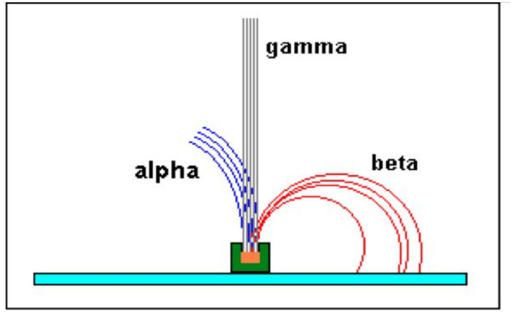
photon

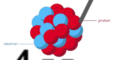


**0 eV**

# radioactivité

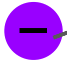
*Becquerel*
**1896**
.
*Chadwick*
**1914**



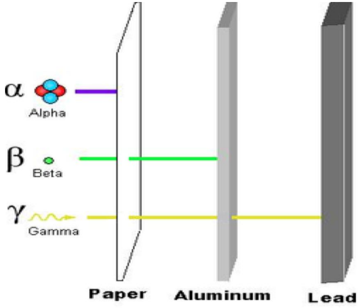



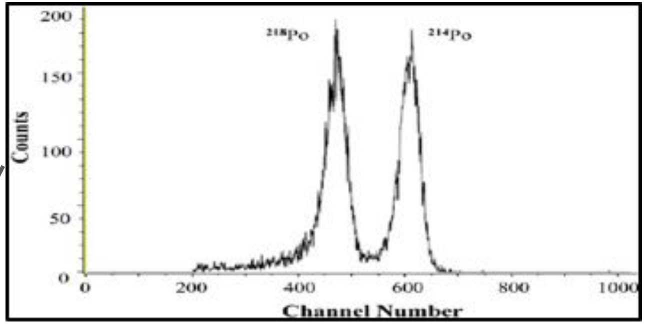
$$\alpha : \quad {}^{222}_{86}Rn \longrightarrow {}^{218}_{84}Po + {}^{4}_{2}He$$

$$\beta : \quad {}^{210}_{83}Bi \longrightarrow {}^{210}_{84}Po + e^{-}$$

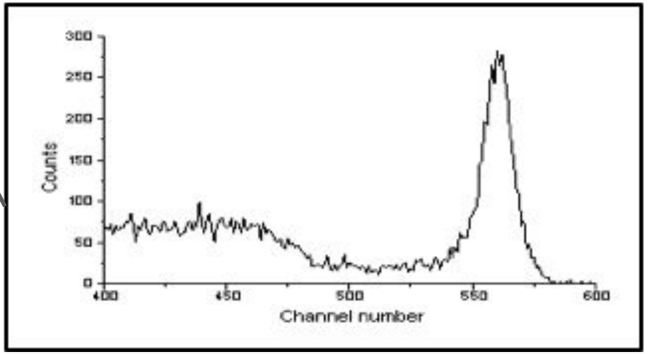


$$\gamma : \quad {}^{137m}_{56}Ba \longrightarrow {}^{137}_{56}Ba + \gamma$$



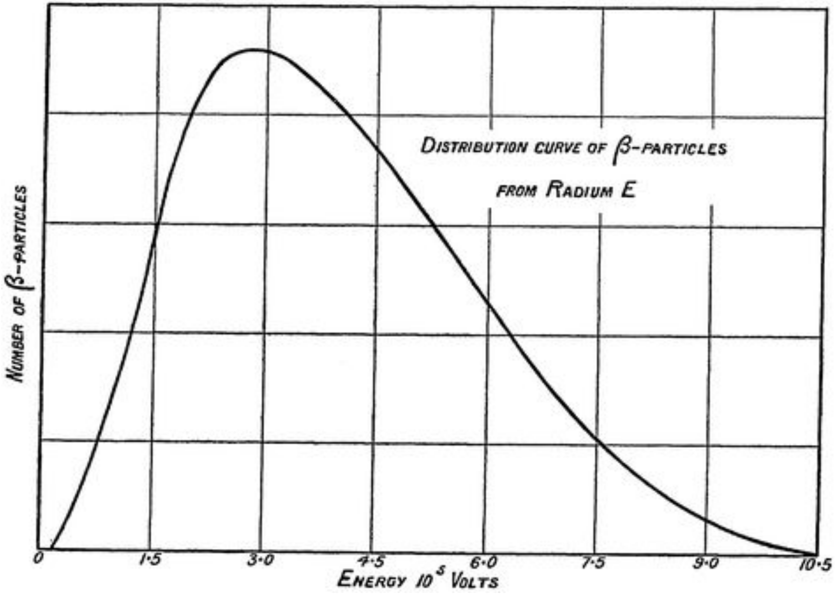

?



# désintégration β sprectre continu

$$\beta \ : \ {}^{210}_{83}Bi \longrightarrow {}^{210}_{84}Po + e^-$$

*Ellis & Wooster 1927*



# invention d’une nouvelle particule

**1930**
*Pauli*

- neutre
- masse faible
  < 0.01 proton
- “neutron”
- $E_p + E_n = cst$

Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben 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 $\mu$ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann $\mu$ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

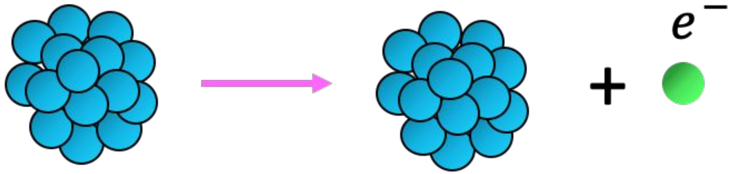
Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen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

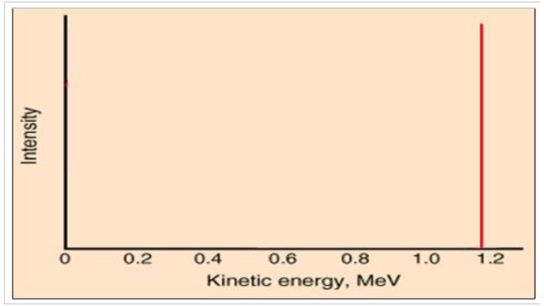
Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten 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

# conservation de l'energie

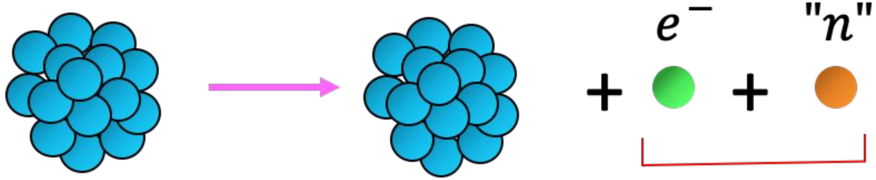
$^{210}_{83}Bi \qquad ^{210}_{84}Po \qquad e^-$



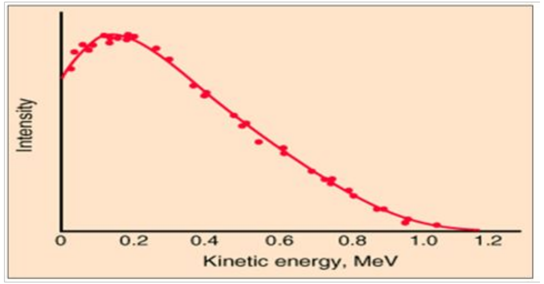



Non observable

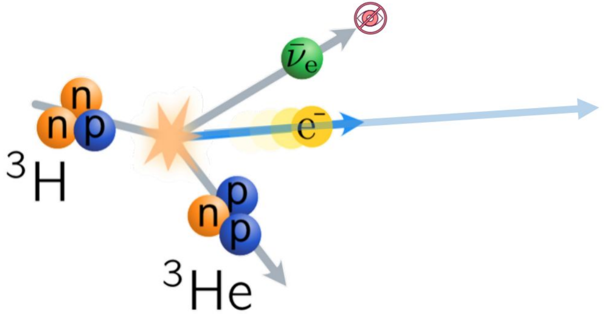
$^{210}_{83}Bi \qquad ^{210}_{84}Po \qquad e^- \qquad "n"$



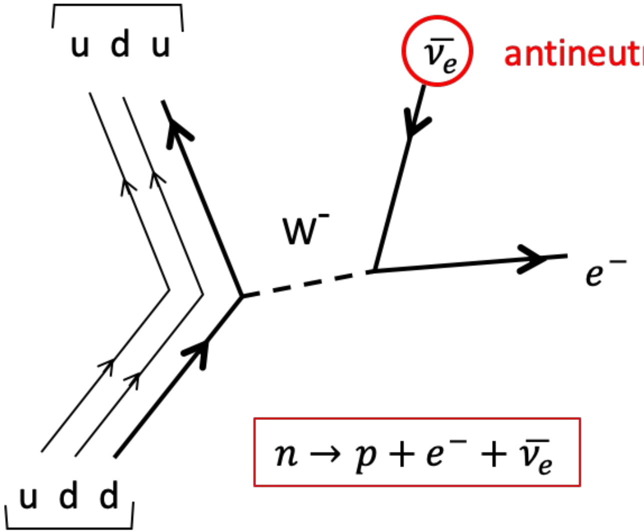
$E_e + E_{«n»} = C^{te}$



# désintégration β

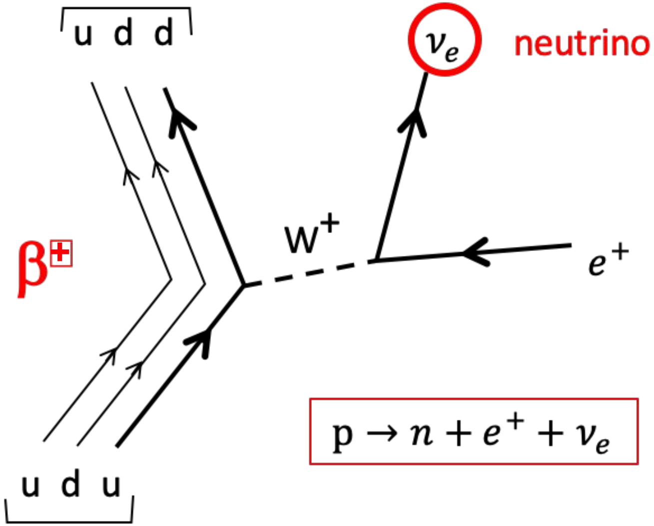



β⁻




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

β⁺




$$p \rightarrow n + e^+ + \nu_e$$

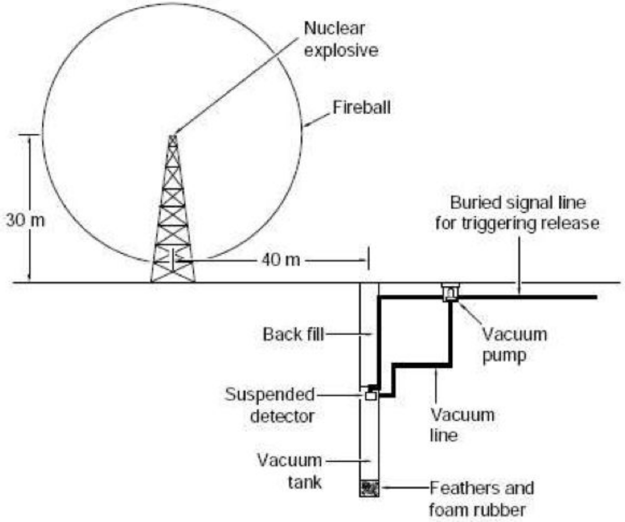
# détection neutrino

*1934 Bethe & Peierls*

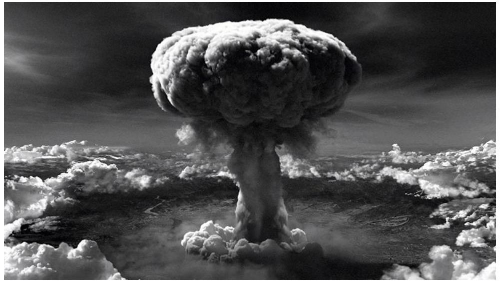
$\sigma \approx 10^{-44}$ $cm^2$ @ 2 MeV ⇒  distance d'intéraction = **1600 a.l.**


→ **indétectable**

# détection neutrino



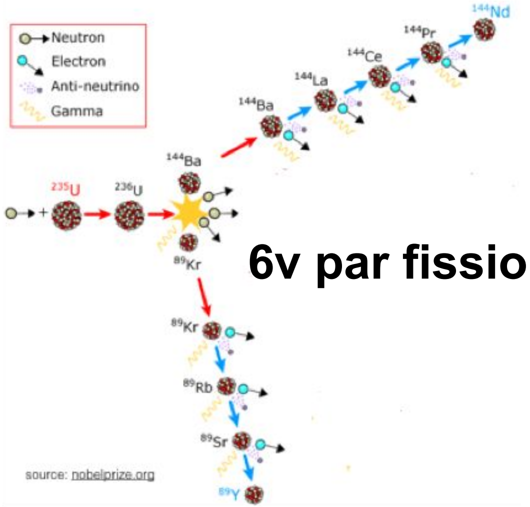

- idée de Fermi
- bombe nucléaire
- flux intense de neutrinos
- plus près de la source



# détection neutrino

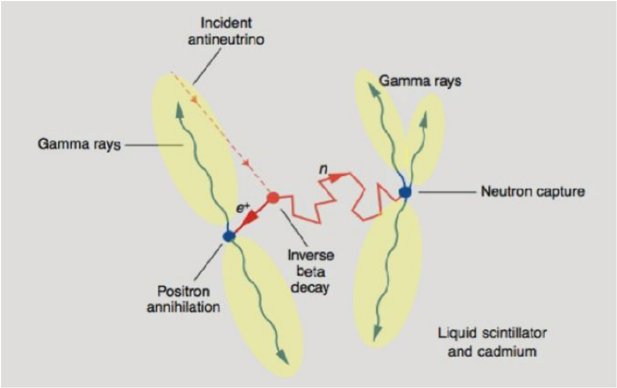
*1953 Reines & Cowan*
Handford experiment

**réacteur nucléaire d'Hanford**


**6ν par fission**

$$\nu + p \rightarrow n + e^{+}$$

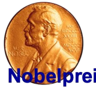



bruit = muons atmosphériques

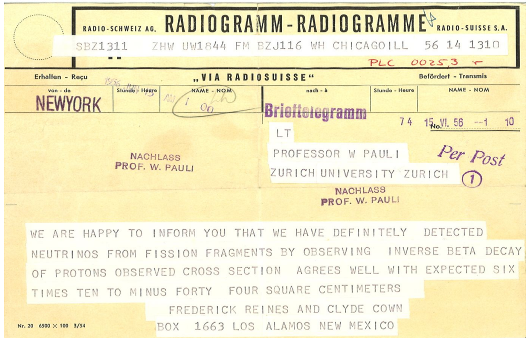
résultats insuffisant → 0.41 ± 0.20 events / min (Réacteur ON – OFF)

# détection neutrino

*1956 Reines & Cowan*
Savannah river


Nobelpreis 1995


- réduction du bruit cosmique
- signal/bruit = 3/1
- annonce à Pauli 15 juin 1956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LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

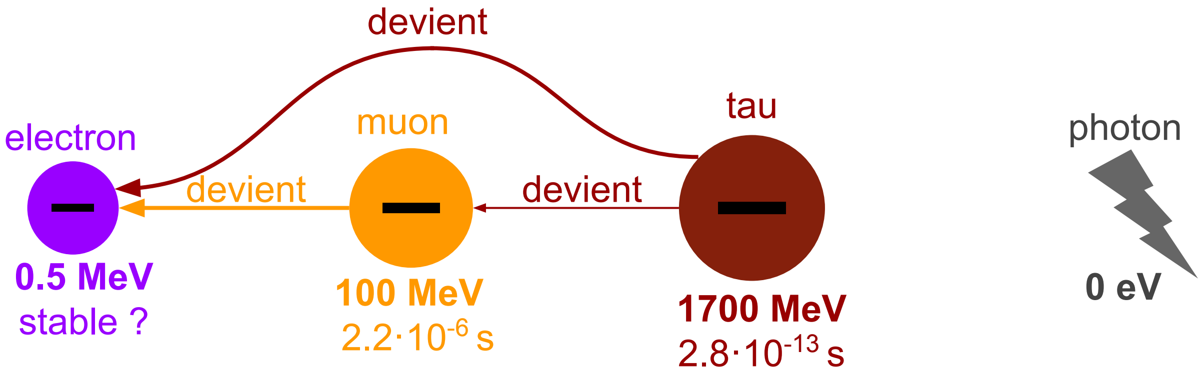
Per Post

NACHLASS PROF. W. PAULI

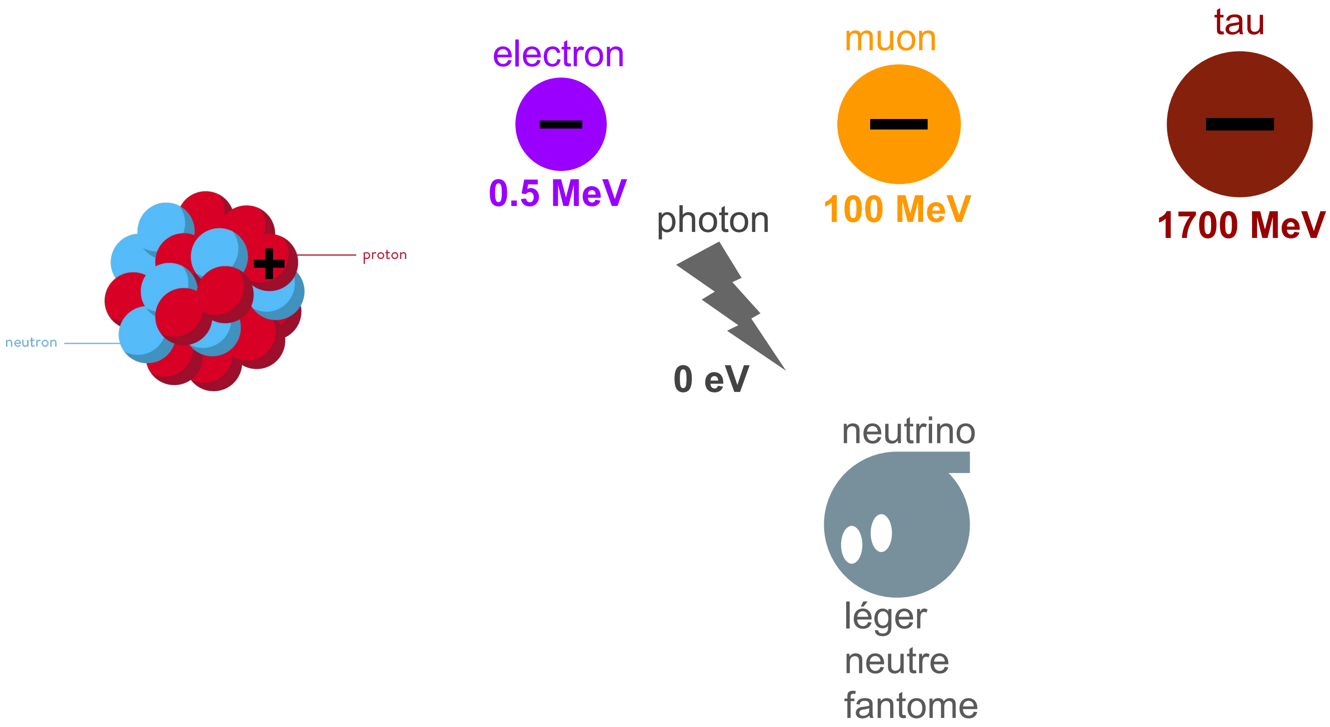
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN
BOX 1663 LOS ALAMOS NEW MEXICO

# particules


devient
electron
muon
tau
photon
devient
devient
0.5 MeV
stable ?
100 MeV
2.2·10-6 s
1700 MeV
2.8·10-13 s
0 eV

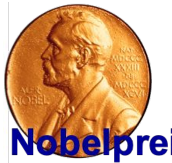
# particules



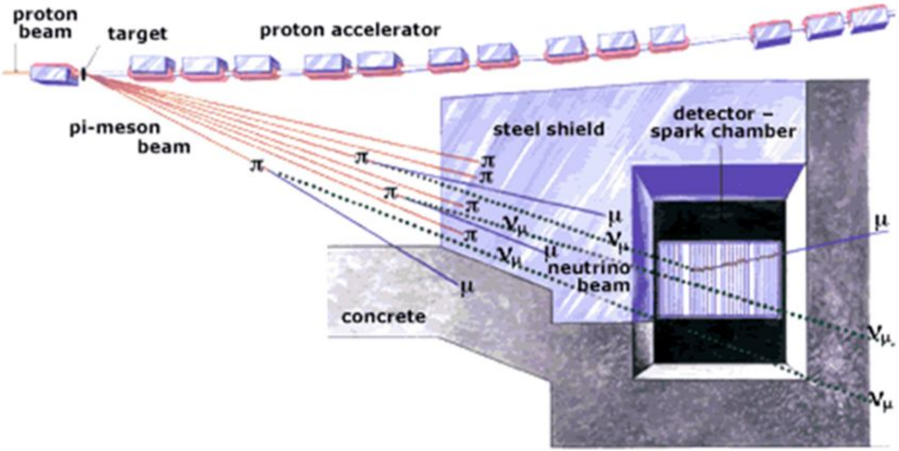
proton
neutron
electron
0.5 MeV
muon
100 MeV
tau
1700 MeV
photon
0 eV
neutrino
léger
neutre
fantome

# neutrino muonique

*1962*
*Schwartz Lederman*
*Steinberge*

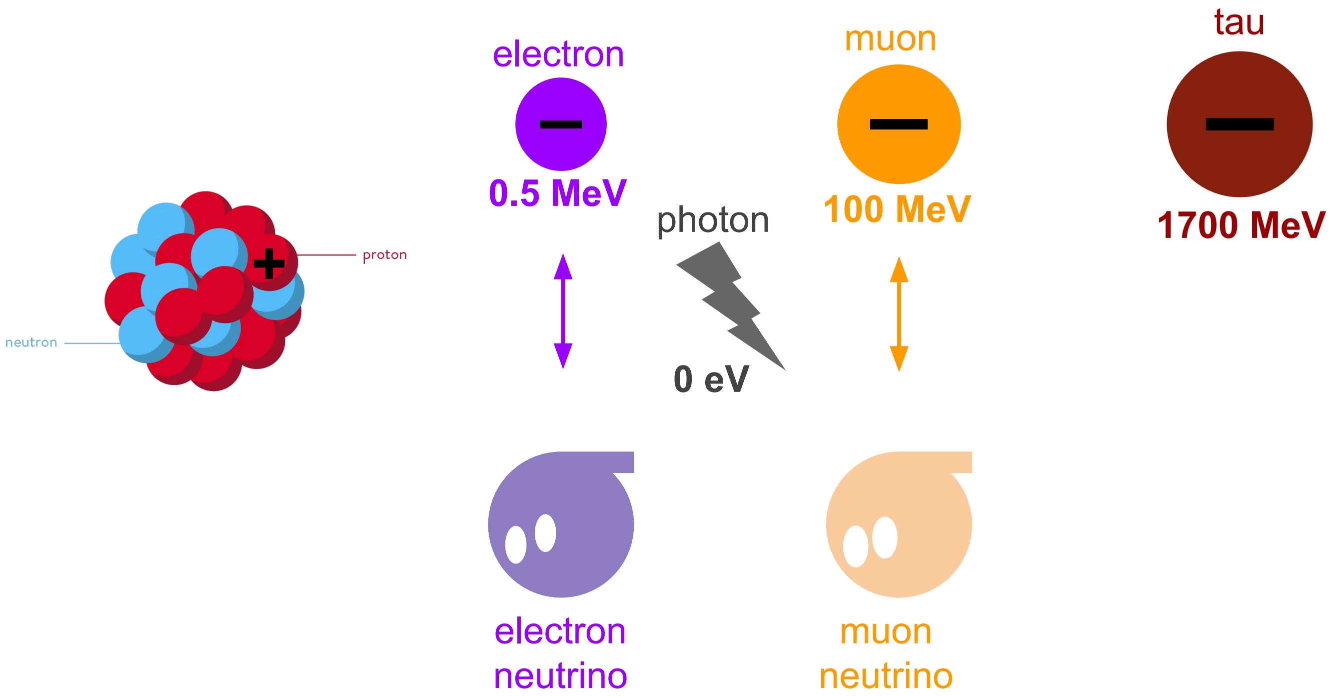


**Nobelpreis 1988**



# particules

spin : corp chargé tourne → moment magnétique → dipole → moment angulaire intrinsèque



# ré-écriture de l'interaction faible

**violation parité**
*Lee & Yang & Wu*

**neutrinos gauche**
*Goldhaber*

**1957**

experience

**XIXe siècle**

**aujourd'hui**

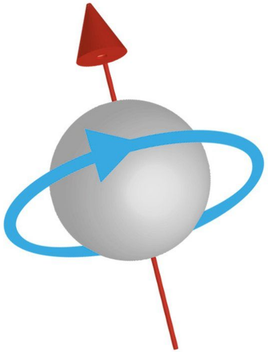
theorie

**1957**
Sudarshan & Marshak **V-A theory**

# spin

**classique**
corp chargé tourne
→ moment magnétique
→ dipôle ou aimant

**quantique**
→ même propriété
→ sans tourner
→ moment angulaire intrinsèque
→ dévié par champ électromagnétique
( → seulement valeurs discretes )

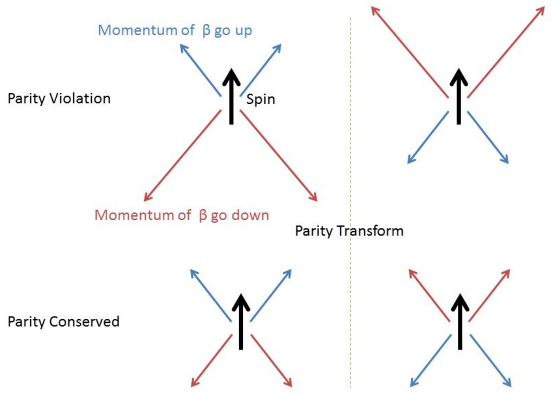


# violation de parité

**violation parité**
*Lee & Yang & Wu*

$${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$$

- désintégration cobalt
- vérifier la direction d'émissions des e⁻
  → symétrie P dans l'interaction faible



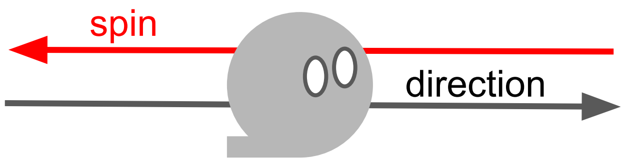

If Parity conserved, the 2 pictures must be the same. That forcing the momentum of red and blue arrows are the same

**1957**

**neutrinos gauche**
*Goldhaber*

$$A(J=0) + e^- \rightarrow B^*(J=1) + \nu \rightarrow B(J=0) + \gamma + \nu$$

**spin :**
corp chargé tourne
→ moment magnétique
→ dipôle
→ moment angulaire intrinsèque



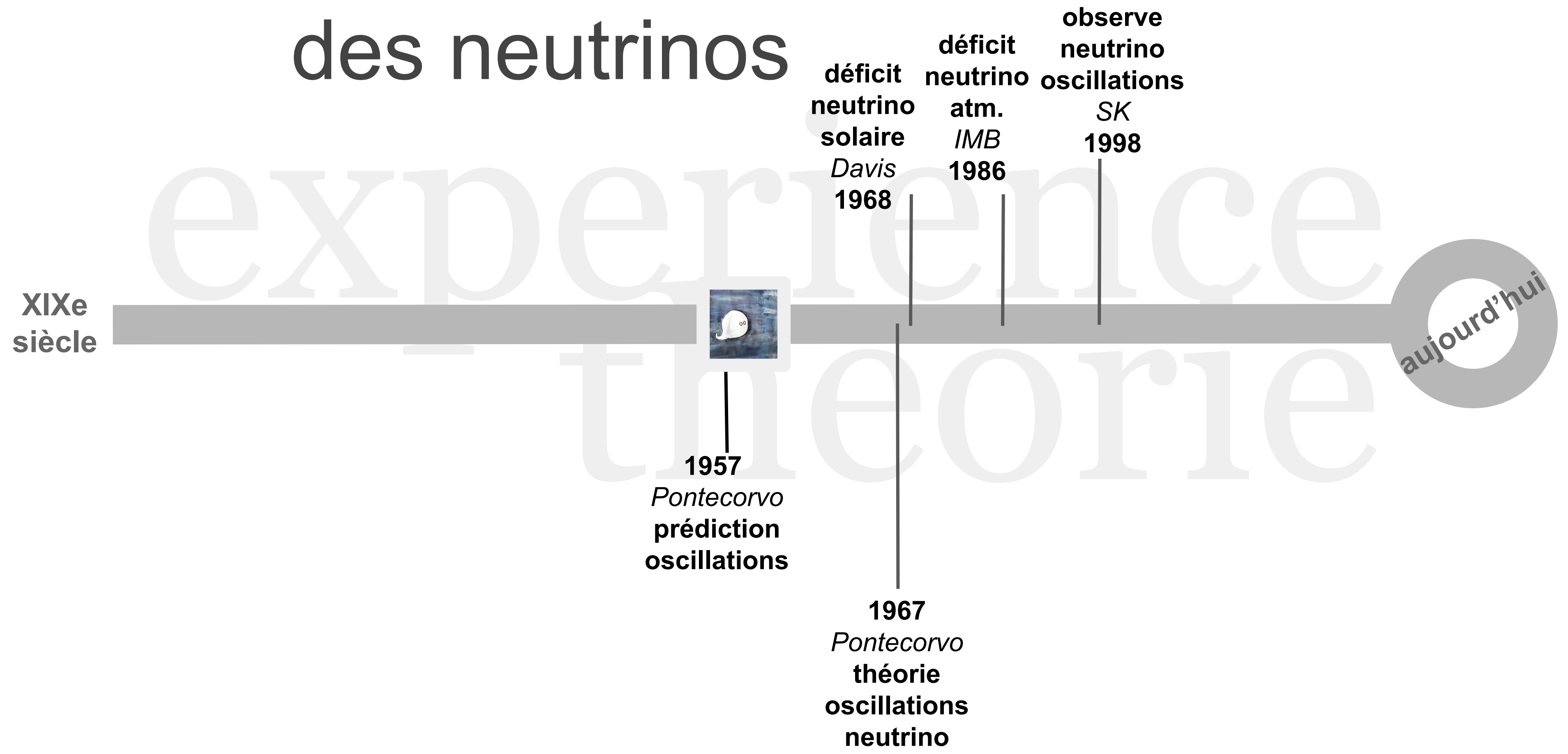

**neutrino sont gaucher**

# violation de parité

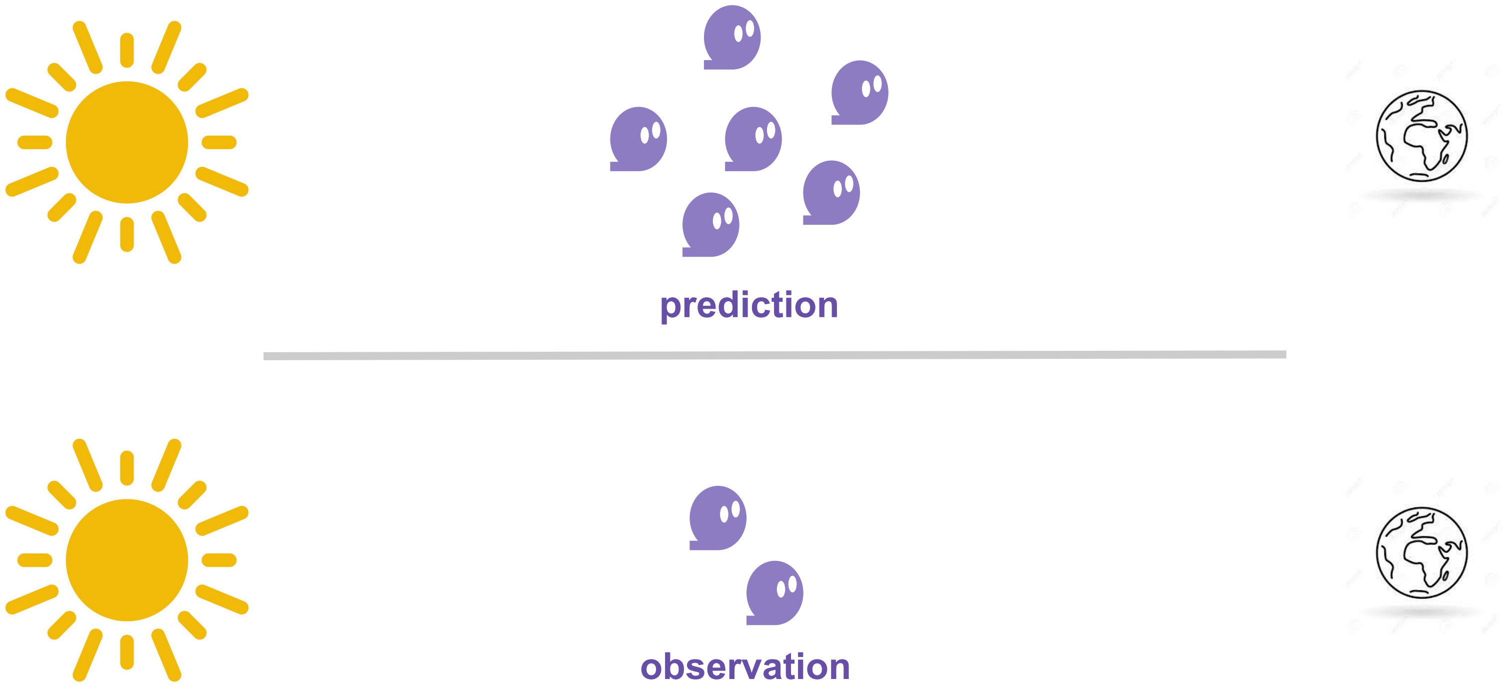
Sudarshan &
Marshak
1957
**V-A theory**

- **révision modèle standard**
- interaction faible
- influence **direct** de découverte expérimentale sur la théorie
- théorie insère **masse neutrino nulle**
- pas de raison d'ajouter une masse aux neutrinos
- pour cela il faudrait inclure un neutrino droit dans la théorie

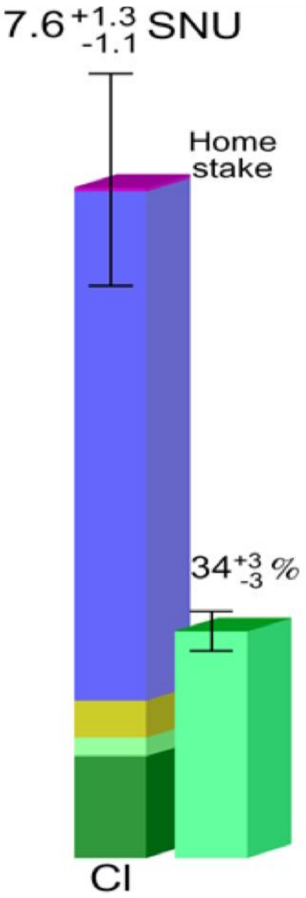
# oscillation des neutrinos



# problème des neutrinos solaires



# problème des neutrinos solaires

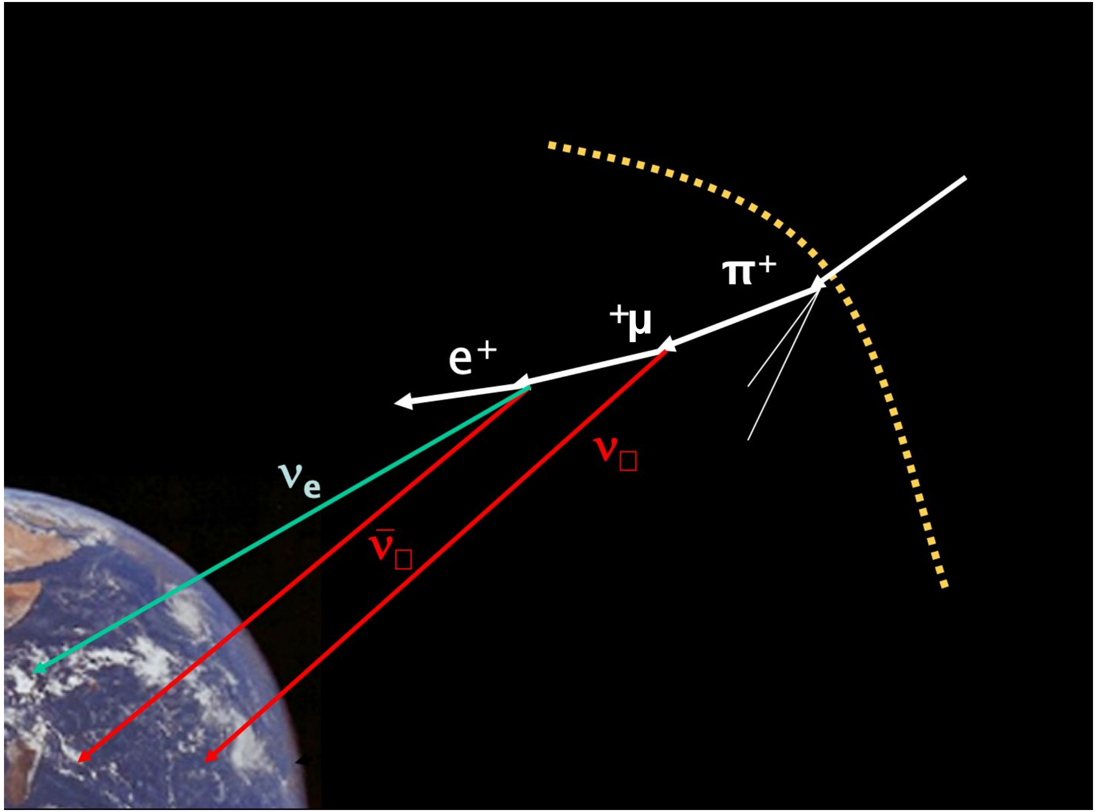



- **exp/théo = 34% déficit solaire**
- *Davis* **1968**

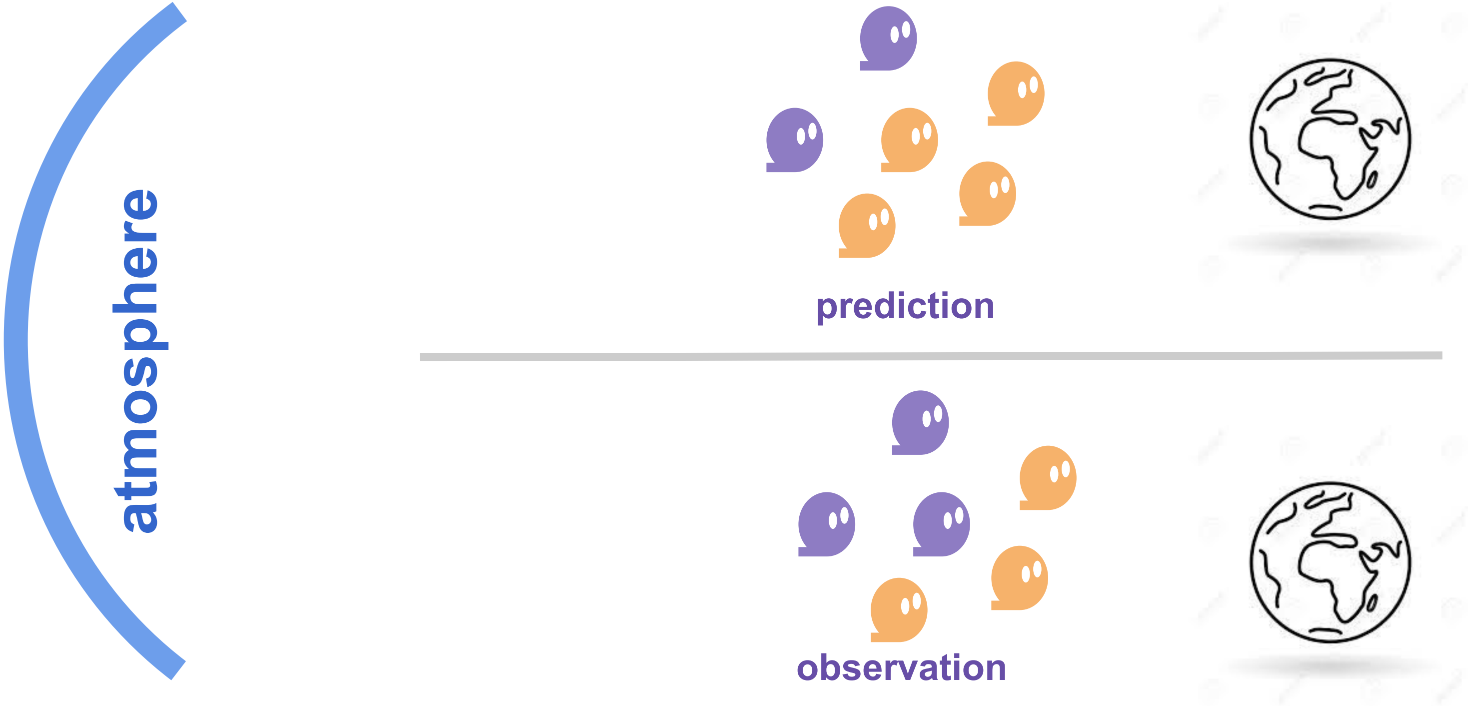
*(380 000 L. de* tétrachloroéthylène*)*

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar},$$

# neutrino atmosphériques



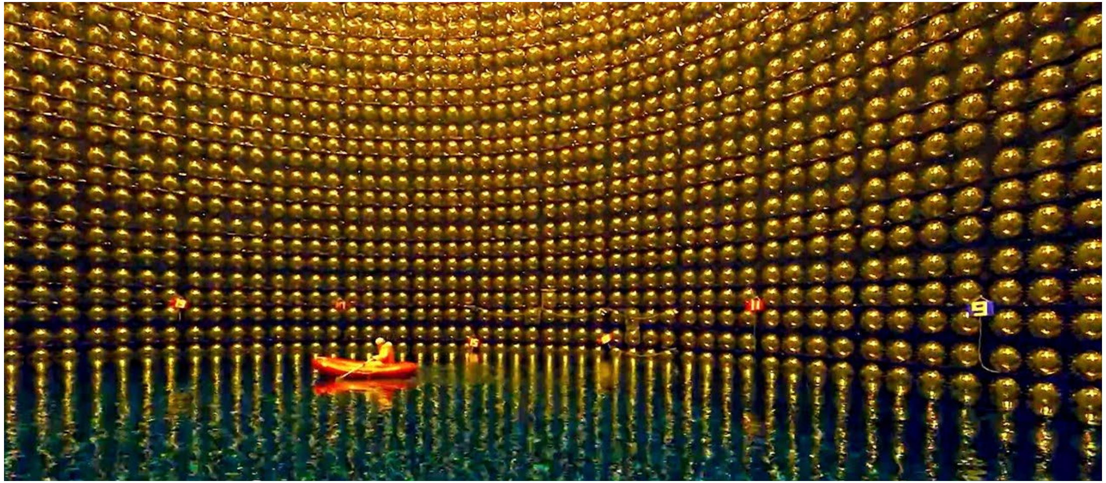
# anomalie des neutrinos atmosphériques

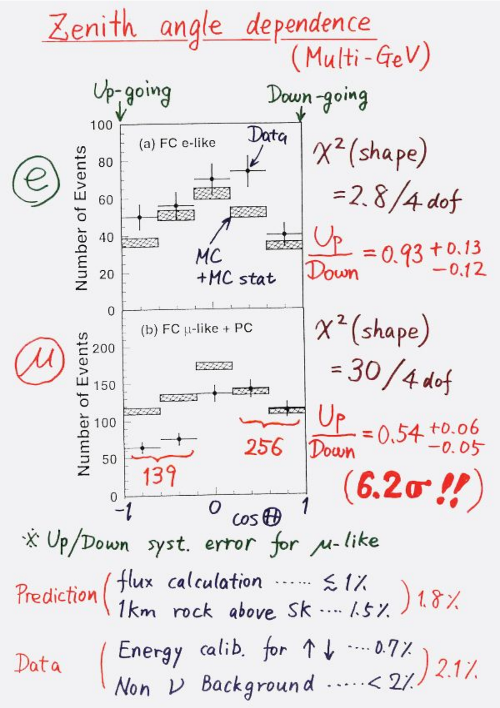


# preuve des oscillation
# Super-Kamiokande

**1998**

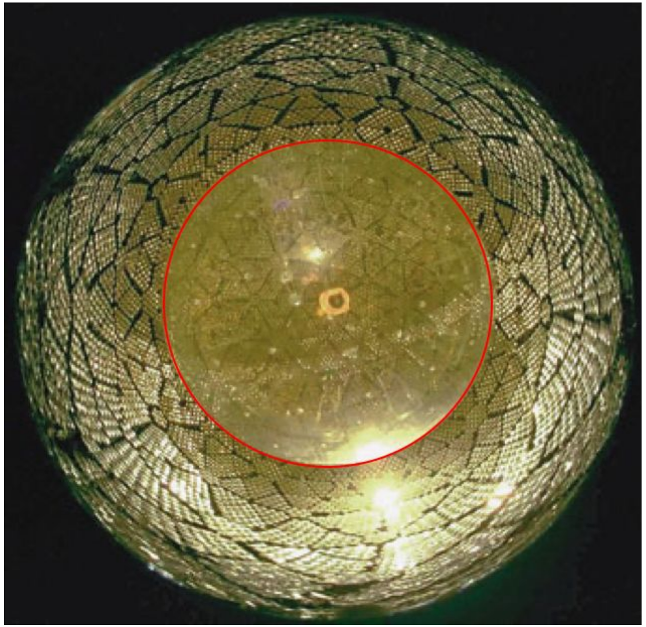
**50 000 tonnes d'eau ultrapure**





# oscillation neutrinos solaires

**SNO 2001**



$$\nu_{e,\mu,\tau} + {}^2H \xrightarrow{Z^0} p + n + \nu_{e,\mu,\tau}$$

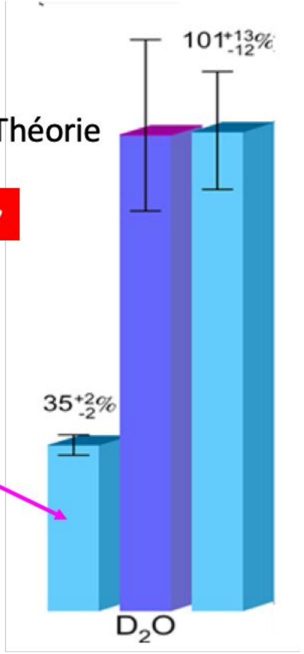
Sensible à tous les ν

Particule détectée

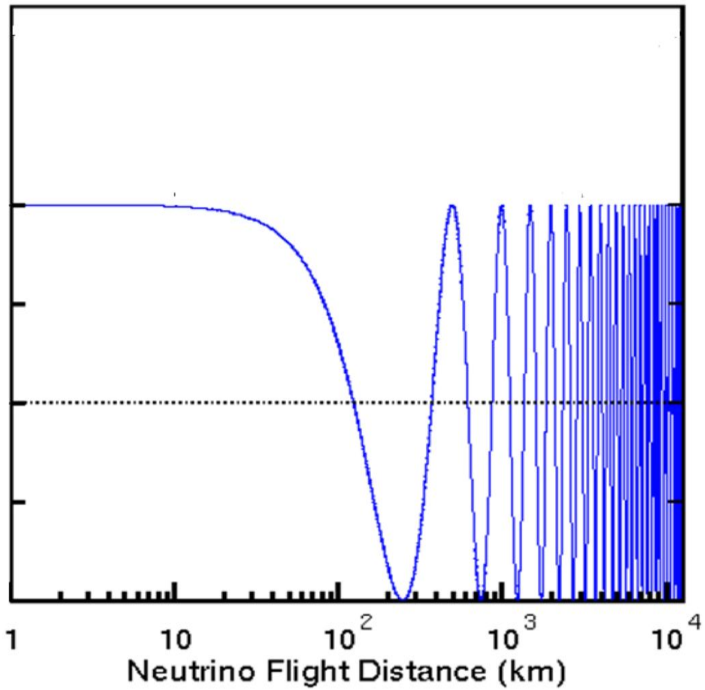
$$\nu_e + {}^2H \xrightarrow{W^-} p + p + e^-$$

$D_2 0$

Sensible aux les $\nu_e$



# probabilité d'oscillation



# théorie de l’oscillation des neutrino

seulement impliquant **neutrino électronique et muonique**

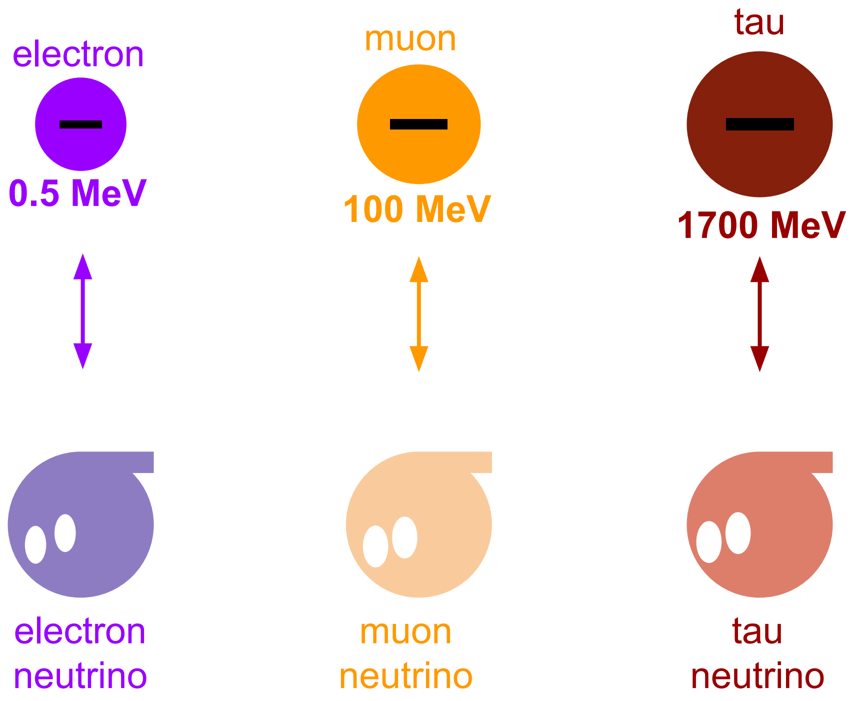
NEUTRINO ASTRONOMY AND LEPTON CHARGE

V. GRIBOV * and B. PONTECORVO
*Joint Institute for Nuclear Research, Dubna, USSR*

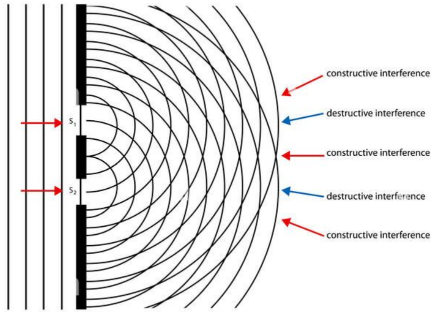
Received 20 December 1968

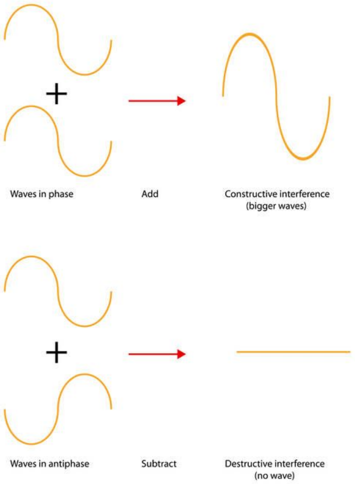
It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^o \rightleftarrows \tilde{K}^o$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

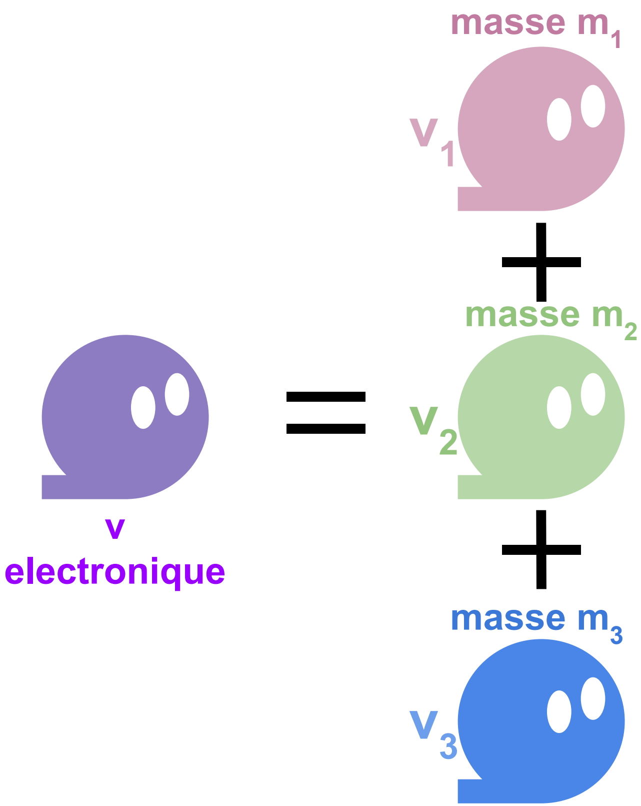
# particules

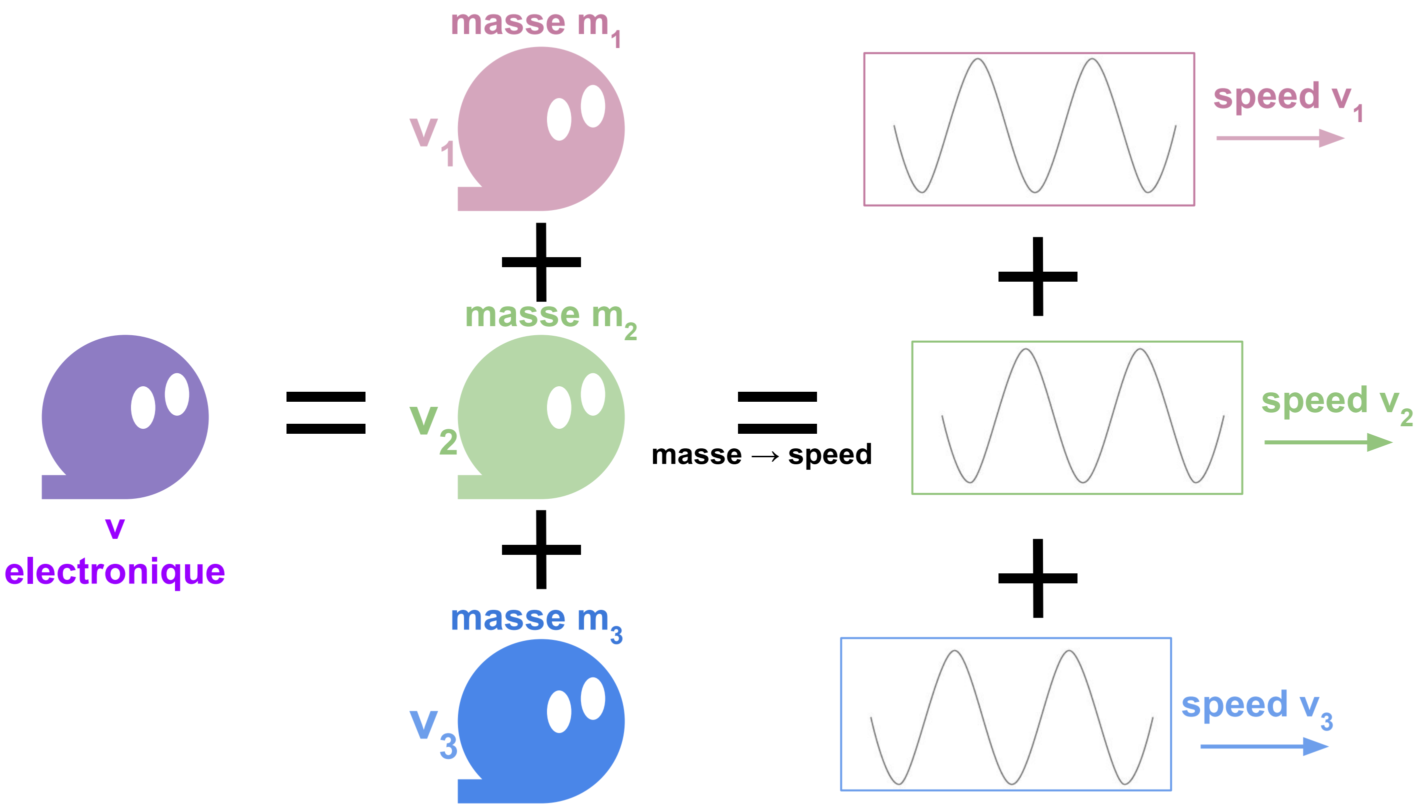

electron
0.5 MeV
muon
100 MeV
tau
1700 MeV
electron
neutrino
muon
neutrino
tau
neutrino

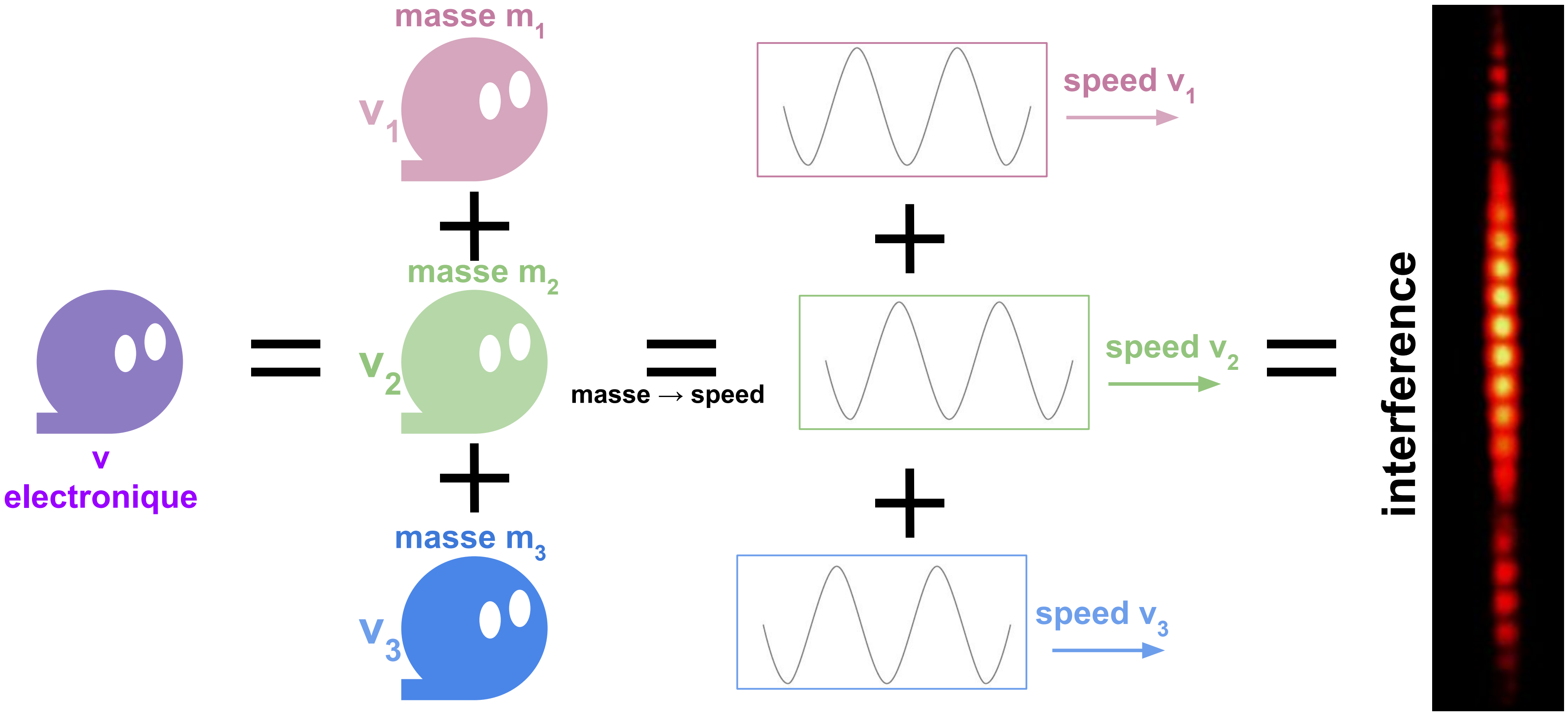
# ondes


constructive interference
destructive interference
constructive interference
destructive interference
constructive interference

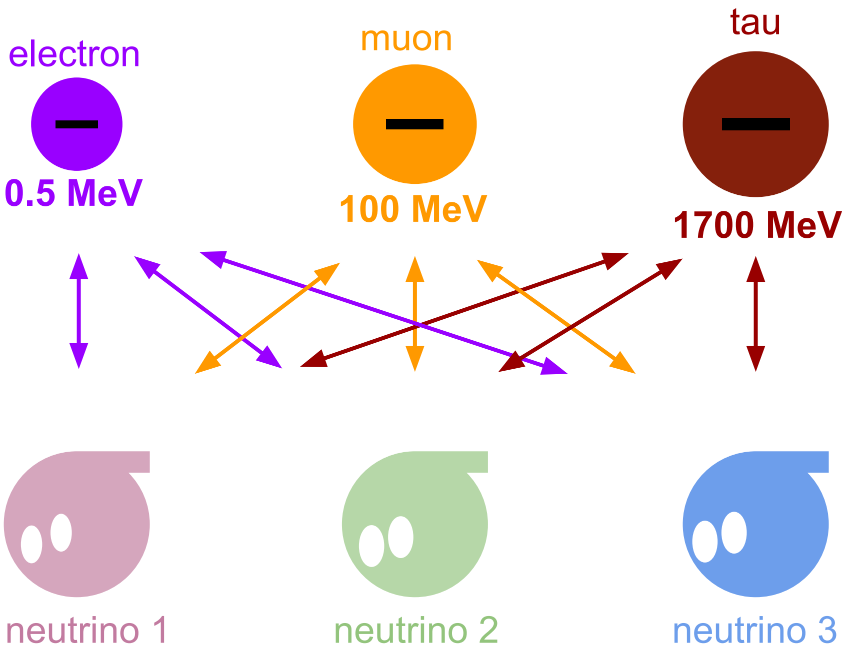

Waves in phase
Add
Constructive interference
(bigger waves)
Waves in antiphase
Subtract
Destructive interference
(no wave)


masse m1
v1
masse m2
v2
masse m3
v3
v
electronique

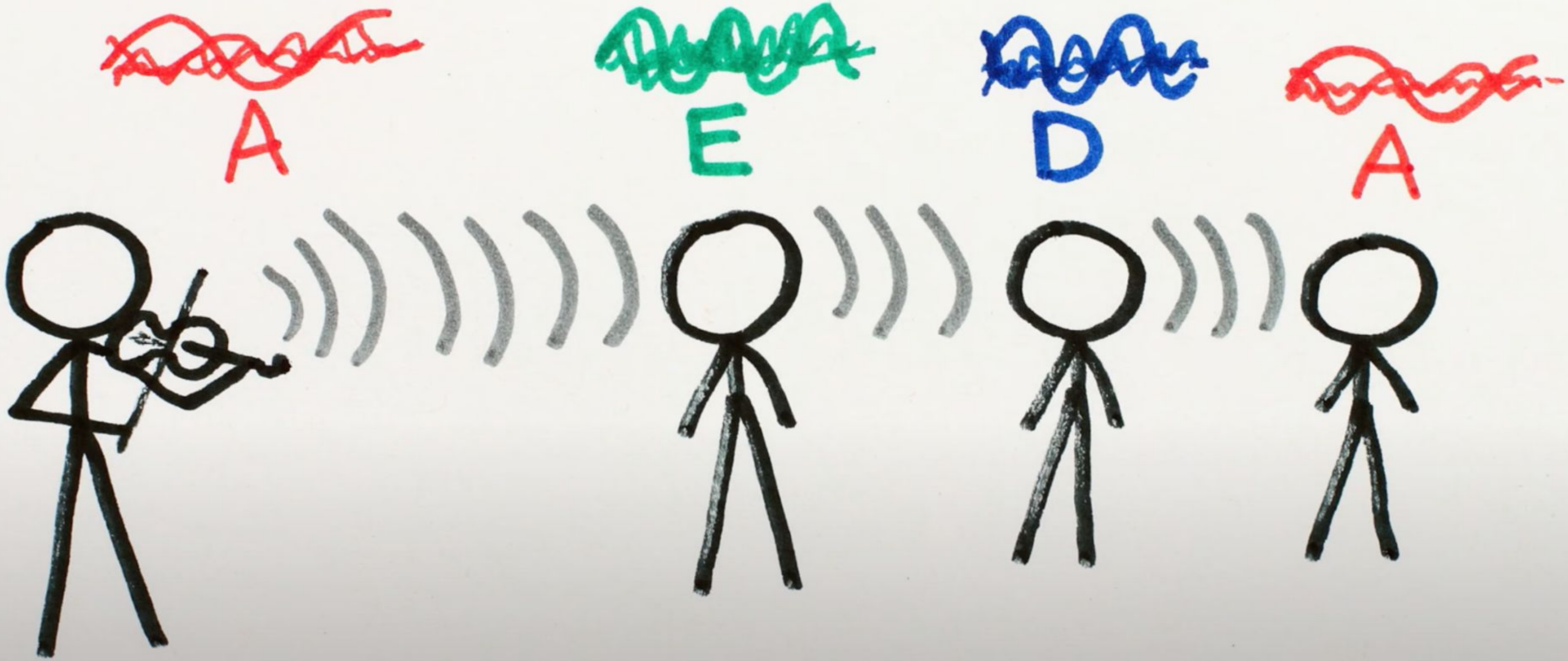

masse $m_1$
$v_1$
masse $m_2$
$v_2$
masse $m_3$
$v_3$
v
electronique
masse → speed
speed $v_1$
speed $v_2$
speed $v_3$

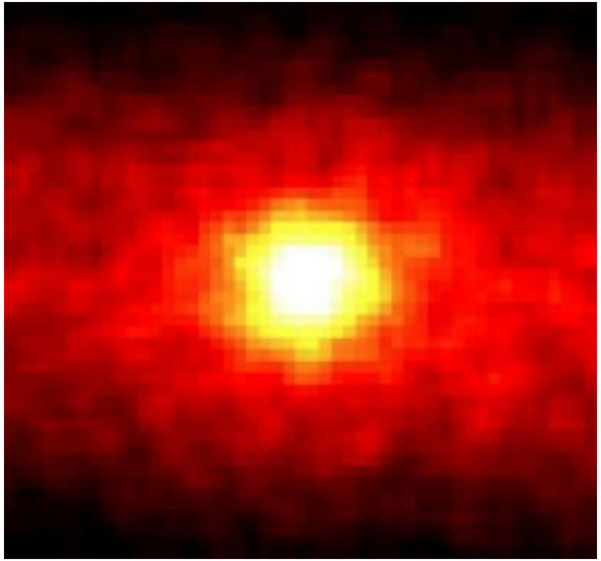

masse $m_1$
$v_1$
masse $m_2$
$v_2$
masse $m_3$
$v_3$
v
electronique
masse → speed
speed $v_1$
speed $v_2$
speed $v_3$
interference

# particules



electron
0.5 MeV
muon
100 MeV
tau
1700 MeV
neutrino 1
neutrino 2
neutrino 3


A
E
D
A



# oscillation des neutrinos

experience
théorie

**XIXe siècle**

**1957**
*Pontecorvo*
**prédiction oscillations**

**1967**
*Pontecorvo*
**théorie oscillations neutrino**

**déficit neutrino solaire**
*Davis*
**1968**

**déficit neutrino atm.**
*IMB*
**1986**

**observe neutrino oscillations**
*SK*
**1998**

**mesure angle mélange oscillations**
*KM3NeT*
**2019**

**aujourd'hui**

# KM3NeT

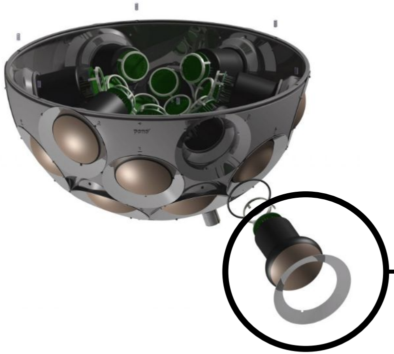


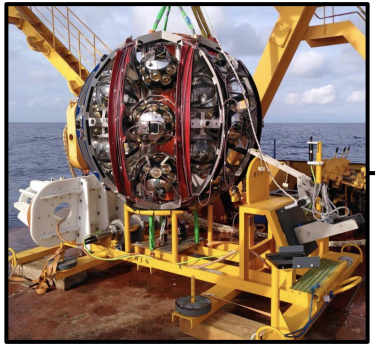
**Photo-multiplier tubes (PMT)**

detect cherenkov light from the charged products of neutrino interactions in sea-water

x31

**Digital Optical Module (DOM)**

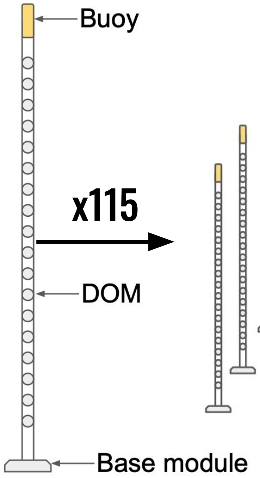
x18



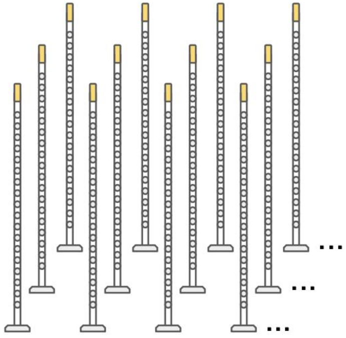
**Launcher Optical Modules (LOM)**

unfurl

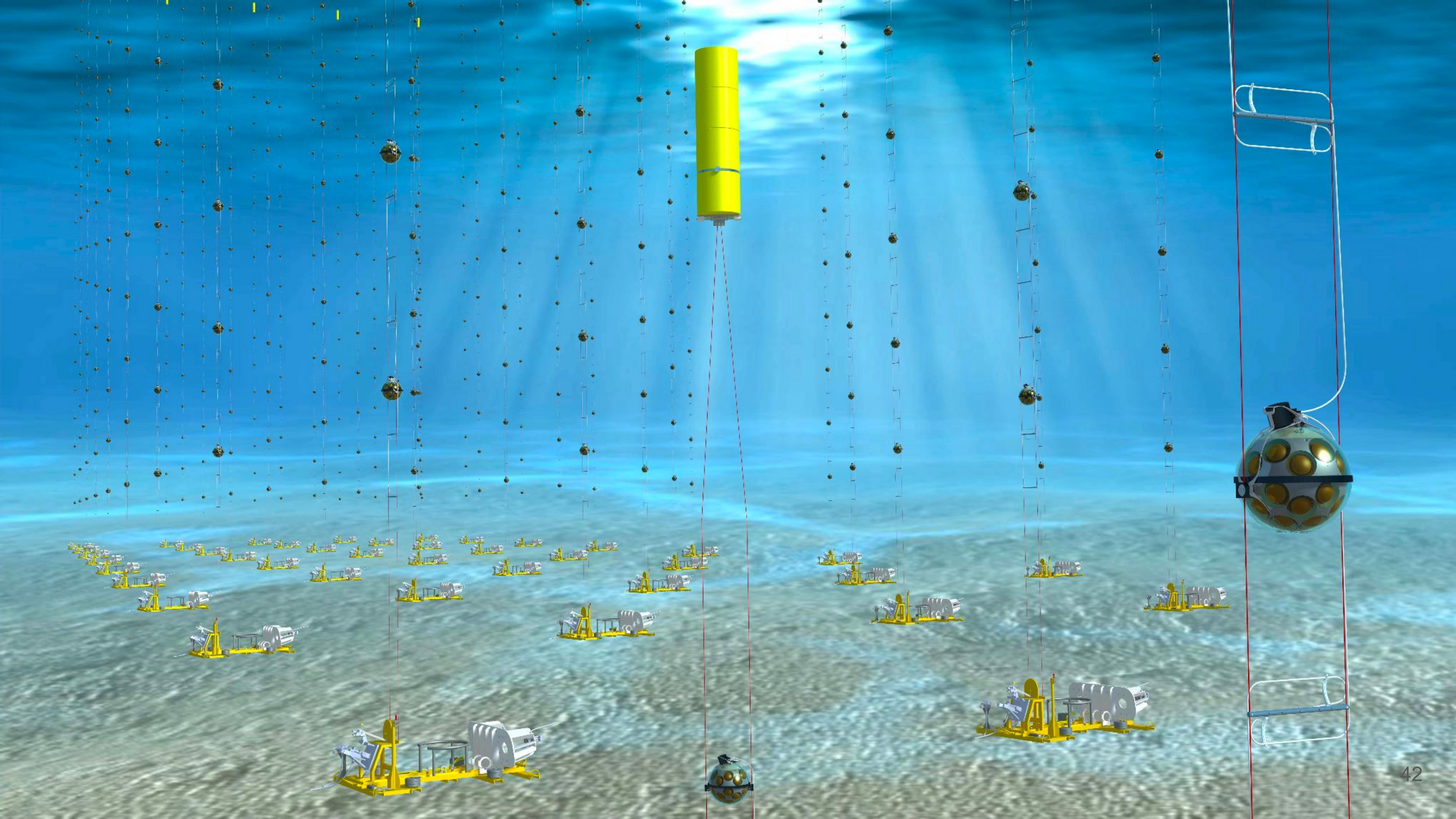
**Detection Unit (DU)**




x115

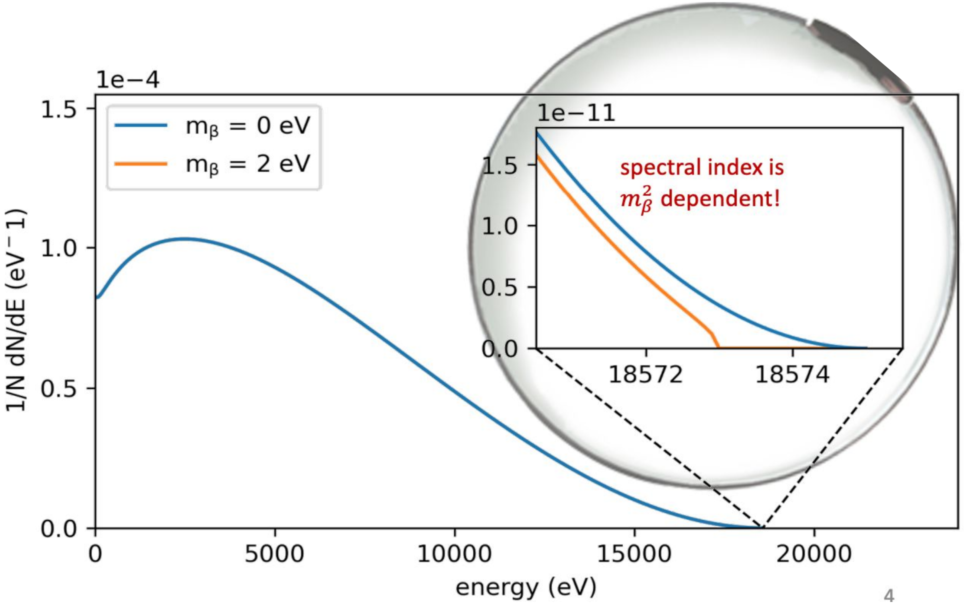



**Building Block (BB)**



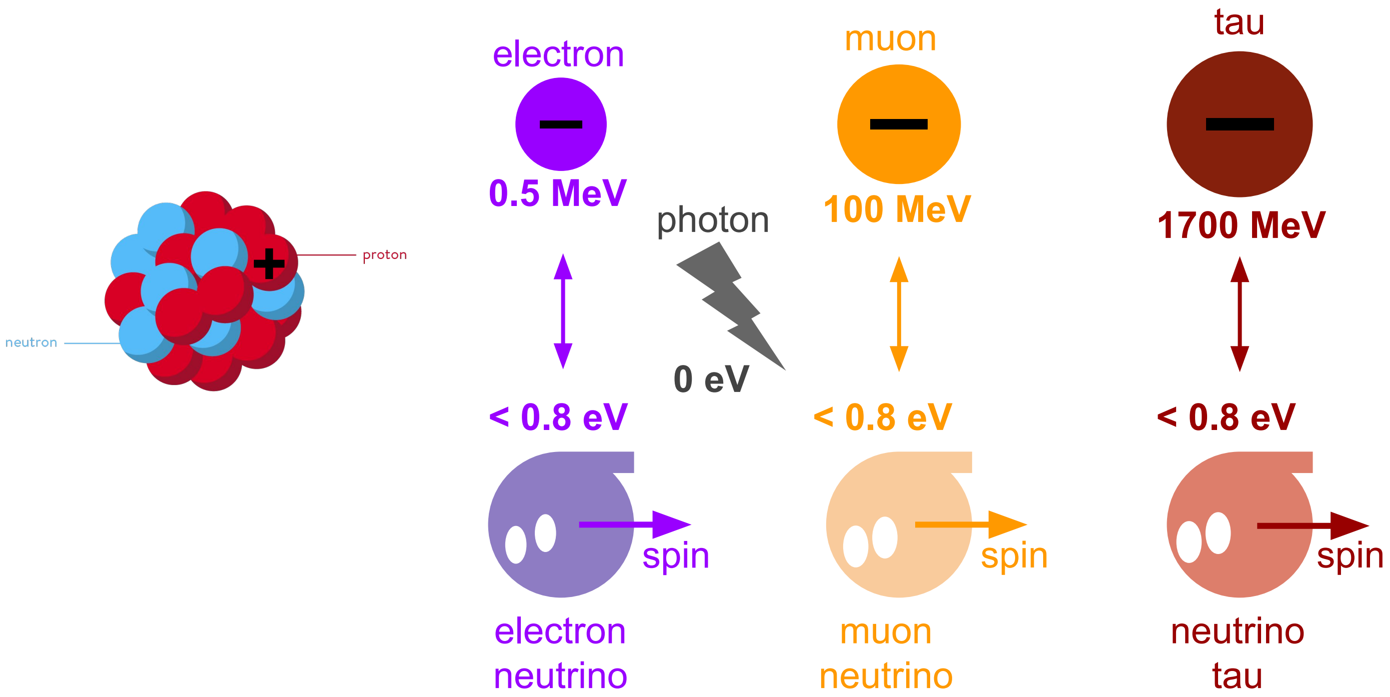
# KATRIN

spectre continu
→ forme change selon la masse
masse neutrino électronique < 0.8 eV

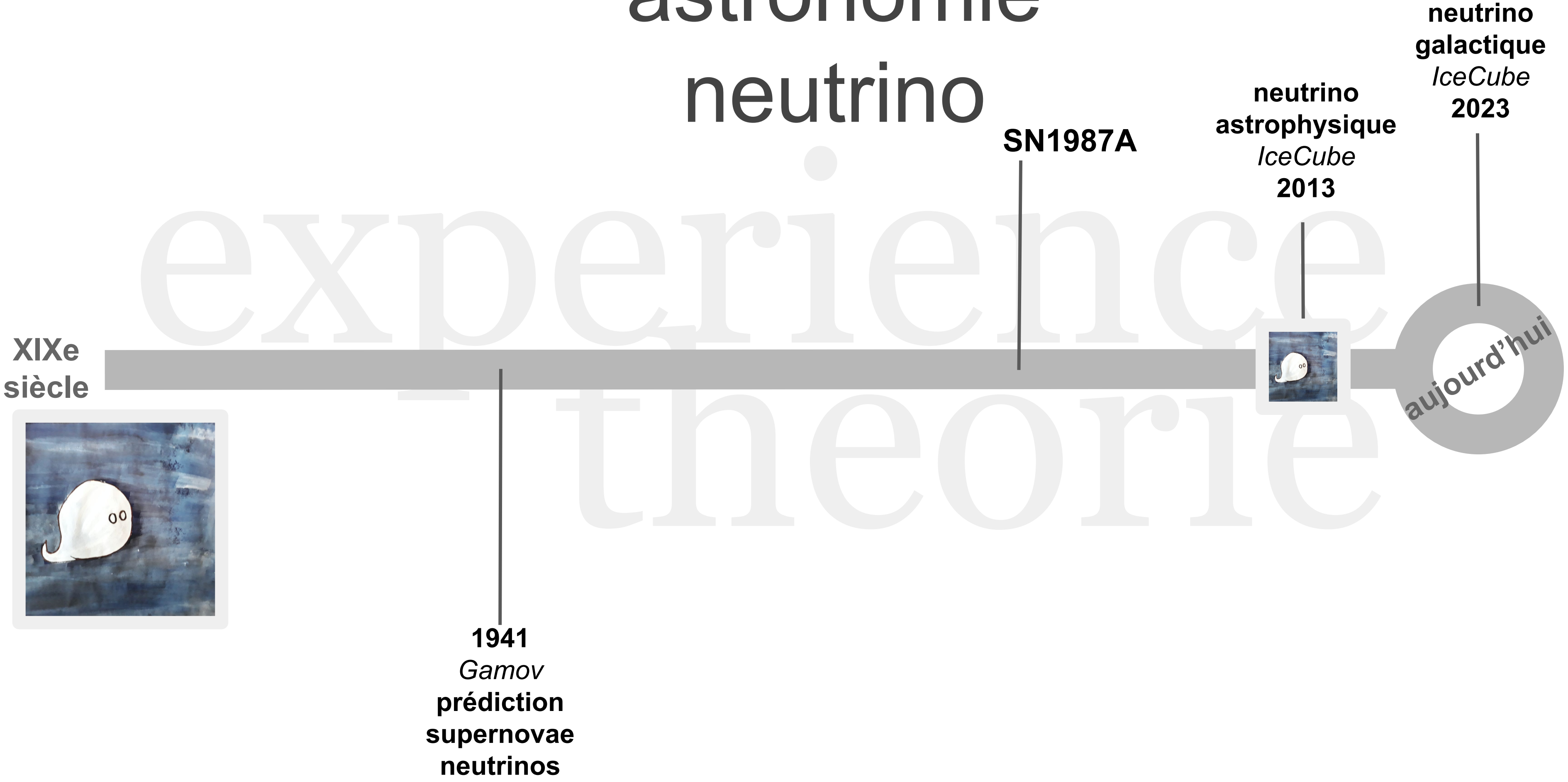


# particules

spin : corp chargé tourne → moment magnétique → dipole → moment angulaire intrinsèque



# astronomie neutrino



# astronomie neutrino

experience
theorie

**XIXe siècle**

**1941**
*Gamov*
**prédiction supernovae neutrinos**

**SN1987A**

**neutrino astrophysique**
*IceCube*
**2013**

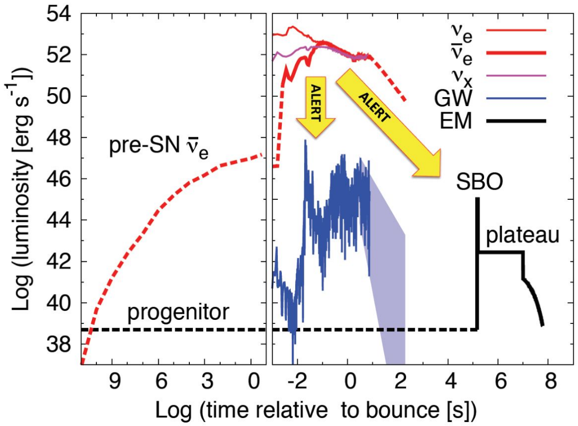
*KM3NeT*
**2019**

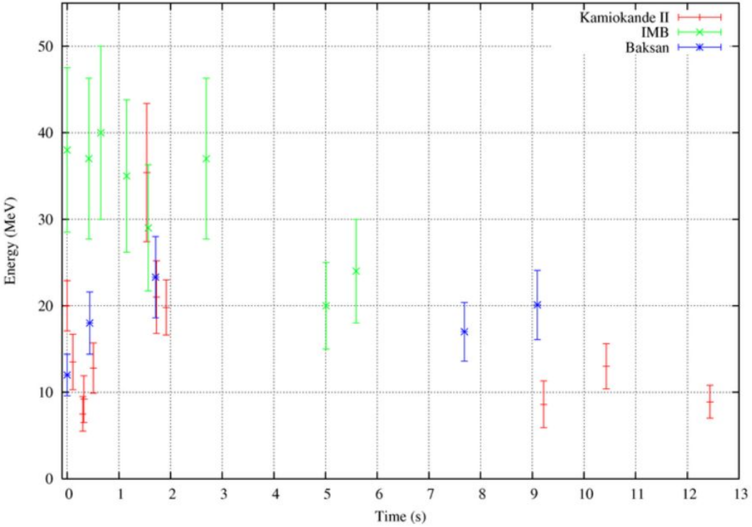
**neutrino galactique**
*IceCube*
**2023**

**aujourd'hui**

# SN1987A

- lumière visible 23/02/1987, **~10:00** UTC
- neutrinos détectés **23/02/1987**, **07:35** UTC
- in the LMC, ~55 kpc → proche galaxie
- explosion of a blue supergiant -> **Type II SN**
- only **~25 neutrinos** détectés
- ~10^58 émis




- Kamiokande

$E_{th}$ = 8.5 MeV
M = 2.9kt
=> 11 neutrinos

- IMB

$E_{th}$ = 29 MeV
M = 6kt
=> 8 neutrinos

- Baksan

$E_{th}$ = 10 MeV
M=130t
=> 3-5 neutrinos

- Mont Blanc

$E_{th}$ = 7 MeV
M = 90t
=> 5 neutrinos **???**
(delay -3h)

# $1^{ers}$ neutrinos cosmiques

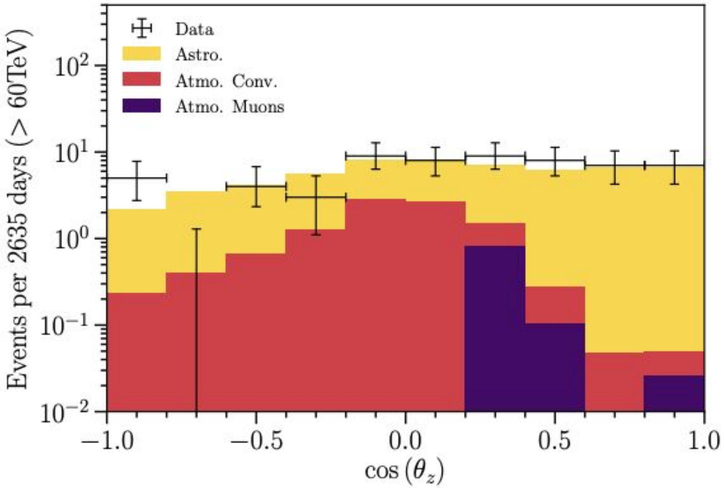
2013

**ne provenant**

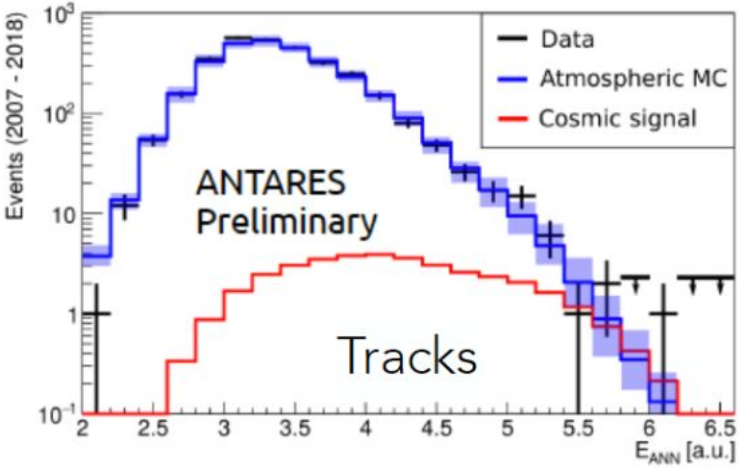
- ni de la terre
- ni du soleil
- ni de l'atmosphère

→ **d'où proviennent ils ?**

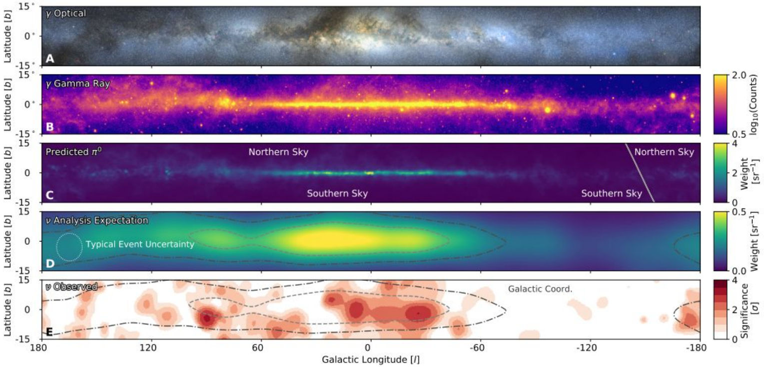
IceCube

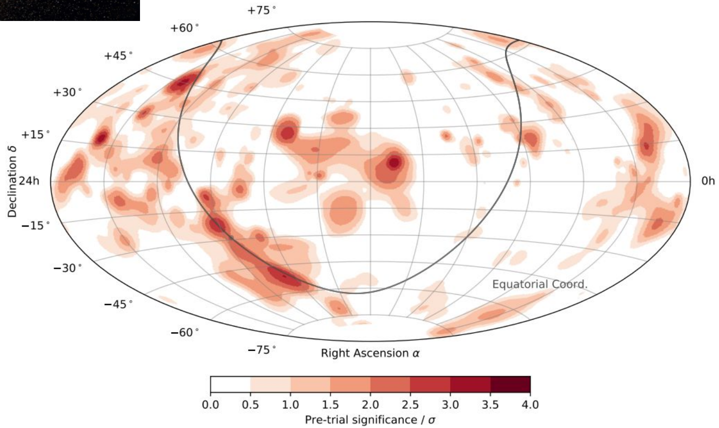



ANTARES



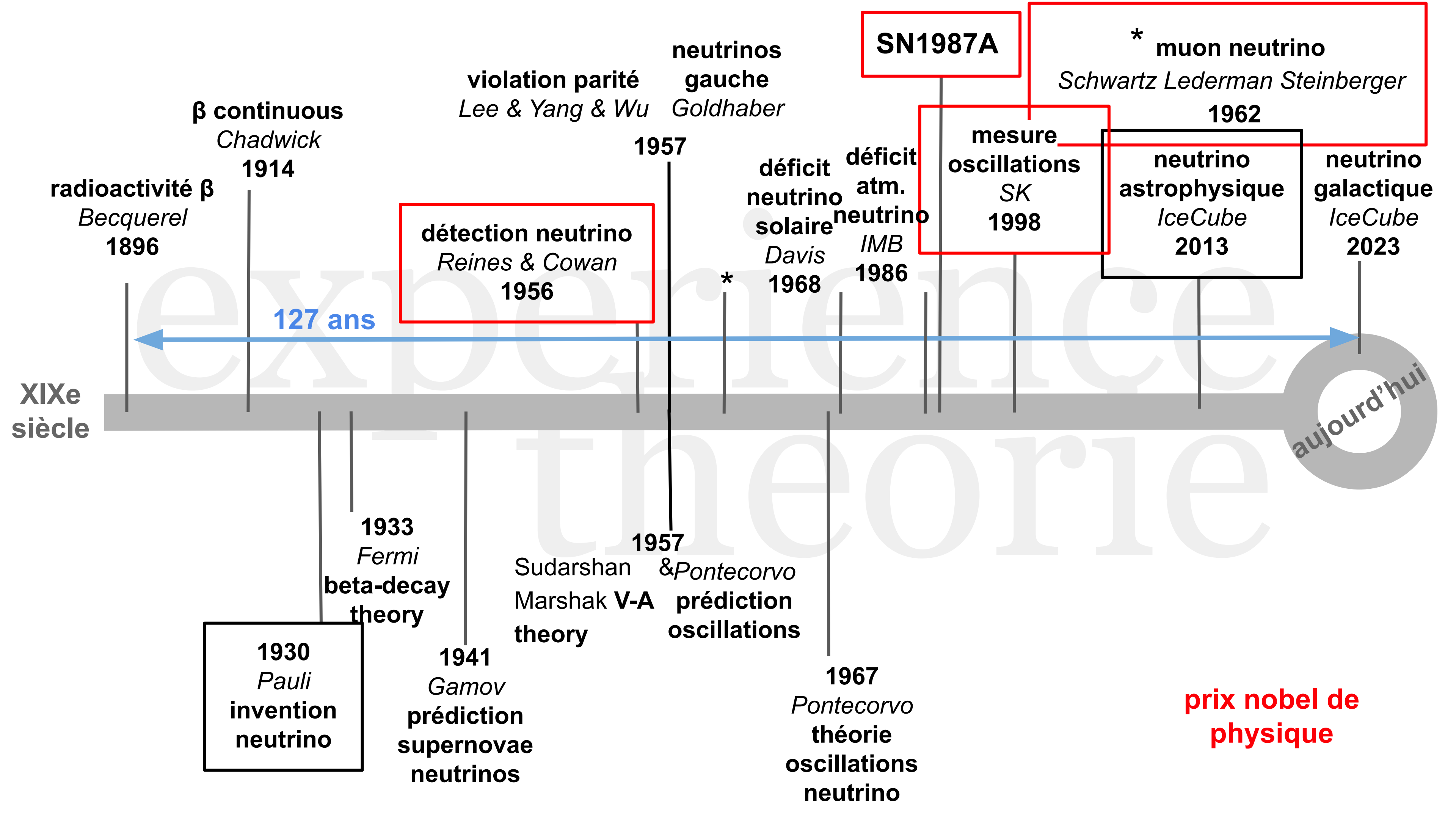
# neutrinos du plan galactique




arXiv:2307.04427v1 [astro-ph.HE]

**ICECUBE** *10 Jul 2023*



SN1987A
* muon neutrino
Schwartz Lederman Steinberger
1962
neutrinos gauche
Goldhaber
violation parité
Lee & Yang & Wu
1957
β continuous
Chadwick
1914
radioactivité β
Becquerel
1896
détection neutrino
Reines & Cowan
1956
*
déficit neutrino solaire
Davis
1968
déficit atm. neutrino
IMB
1986
mesure oscillations
SK
1998
neutrino astrophysique
IceCube
2013
neutrino galactique
IceCube
2023
127 ans
XIXe siècle
aujourd'hui
expérience
théorie
1933
Fermi
beta-decay theory
1930
Pauli
invention neutrino
1941
Gamov
prédiction supernovae neutrinos
Sudarshan
Marshak V-A
theory
1957
&Pontecorvo
prédiction oscillations
1967
Pontecorvo
théorie oscillations neutrino
prix nobel de physique

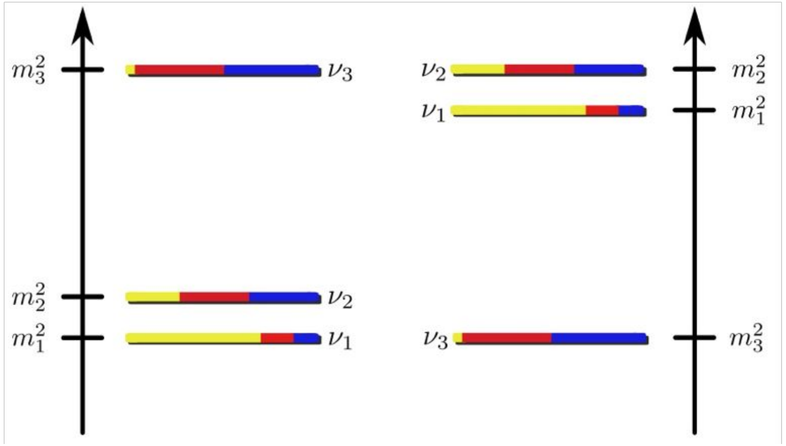
# sources

- History of the neutrino, 2018, Michel C., Jacques D. Daniel. V
- Jose Busto, CPPM
- Jurgen Brunner, CPPM
- minute physics, oscillations

# backup

# Possible mass pattern

- Naming/Color convention
  - Index 1, 2, 3 : increasing contribution of electron state
  - Electron | Muon | Tau
- Matter effect in sun fixes $m_2 > m_1$
- No matter effects to measure $\Delta m_{31}^2 \rightarrow$ sign unconstraint
- 2 schemes survive

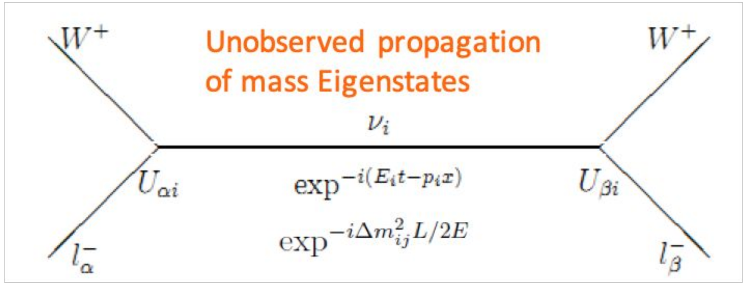


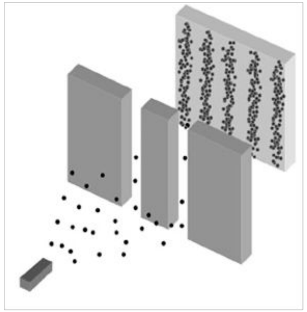
# Neutrino Oscillations

- Weak Eigenstates are superposition of mass Eigenstates

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Neutrino detection
via CC interaction



Neutrino flavour defined via charged leptons

Coherent sum

$$P(\alpha \to \beta) = |\sum_i U_{\beta i} \ \exp^{-i(E_i t - \vec{p_i}\vec{x})} \ U^*_{\alpha i}|^2.$$

Classic: incoherent sum

$$P(\alpha \to \beta) = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$