# Journée de Rencontres des Jeunes Chercheurs 2022

**Neutrino session**

Thomas Kosc -- Laboratoire de Physique Subatomique & Cosmologie – kosc.thomas@gmail.com

# During this session

1. Study of final-state interactions of protons in neutrino-nucleus scattering with INCL and NuWro cascade models. **Anna Ershova**.

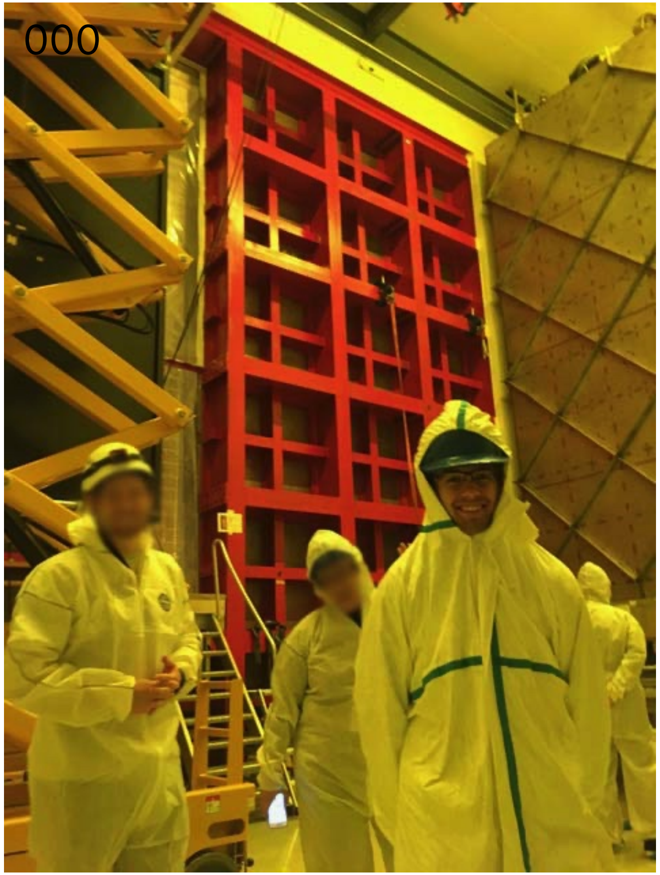
2. The T2K Near Detector ND280 upgrade. **Slava Yevarouskaya.**

3. Recherche de nouvelle physique avec l'expérience RICOCHET via la diffusion cohérente des neutrinos. **Guillaume Chemin**.

# Who am I ?

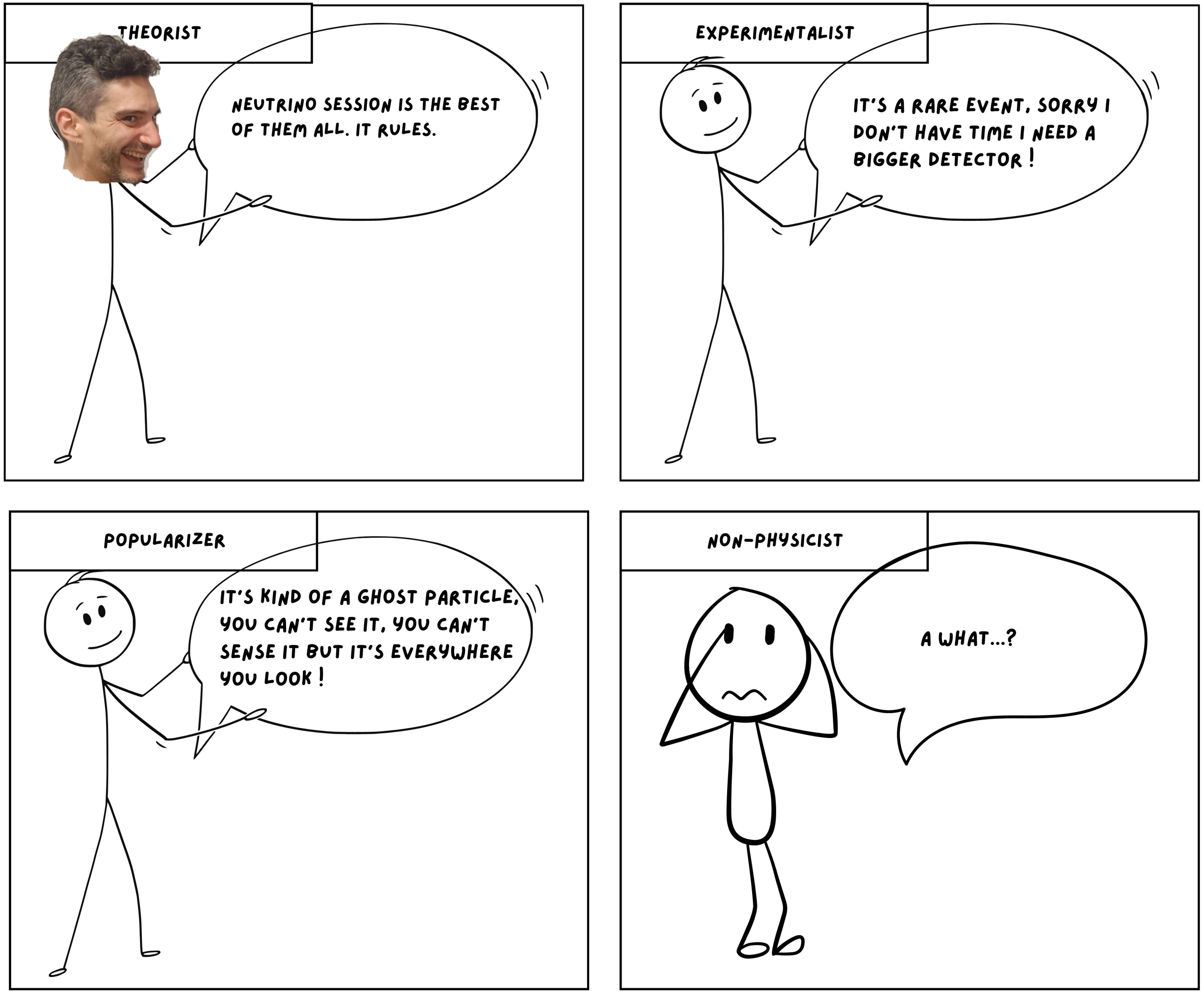
- PhD student (2018-2021) at IP2I (Lyon) : "Kinematic search for tau neutrinos in the DUNE experiment".
- PostDoc position (2021-2023) at Grenoble LPSC in the DUNE experiment.
- **I live in chambéry (Savoie)**

**Tartiflette !**




Thomas Kosc -- Laboratoire de Physique Subatomique & Cosmologie – kosc.thomas@gmail.com

# What's a neutrino ?



# What’s a neutrino ?

- “Matter not in atoms” : my favorite !

# When you say "weak"…?

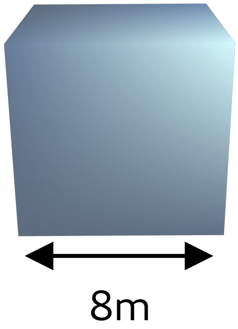
- With an iron stick, you need ~1m to stop half of 1 MeV protons, you need about 1000 light-years to stop half of 1 MeV neutrinos.

- What volume of water needed to measure an interaction rate of 1 solar neutrino event per second, given a flux of about 60 billion neutrinos/cm²/s ?

$$\Gamma = \underbrace{\phi}_{60\times10^{9}\ \nu/cm^{2}/s} \times \underbrace{\sigma}_{10^{-42}\ cm^{2}} \times \frac{\rho_{H_2O}\times V}{M\left(H_2 0\right)} \underbrace{N}_{6\times10^{23}\,mol^{-1}}$$

- Invert the relation to calculate V :

**~500 m³**

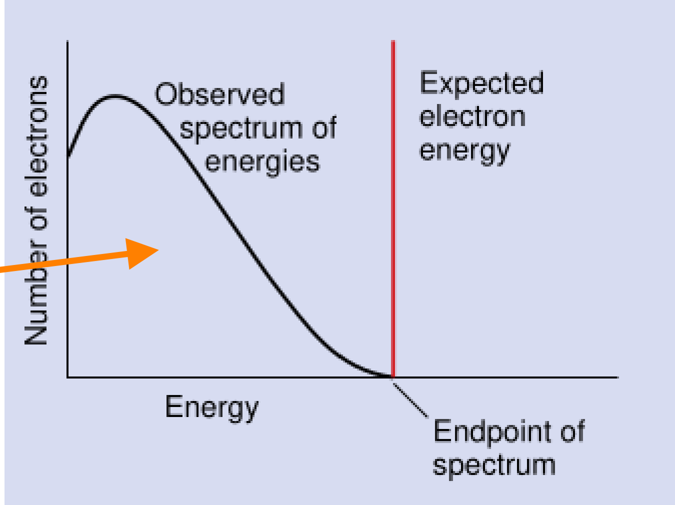



Thomas Kosc -- Laboratoire de Physique Subatomique & Cosmologie – kosc.thomas@gmail.com

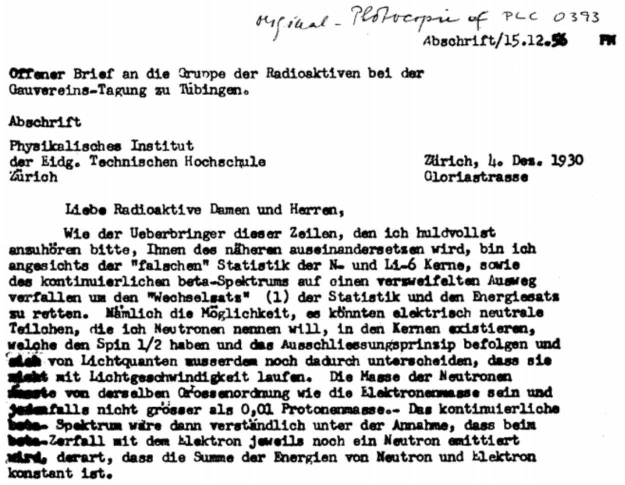
# Historical considerations

# It started with an anomaly

- The observation of beta decay showed apparent non conservation of energy in the process.




- W. Pauli suggests in 1930 the missing energy is shared with an escaping neutral particle : the neutrino.



Original - Photocopie of PLC 0393
Abschrift/15.12.56 PM

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

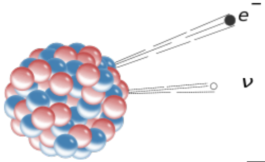
Abschrift

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.




- Fermi 1933 : theorie of beta decay. Still taught as correct approximation !

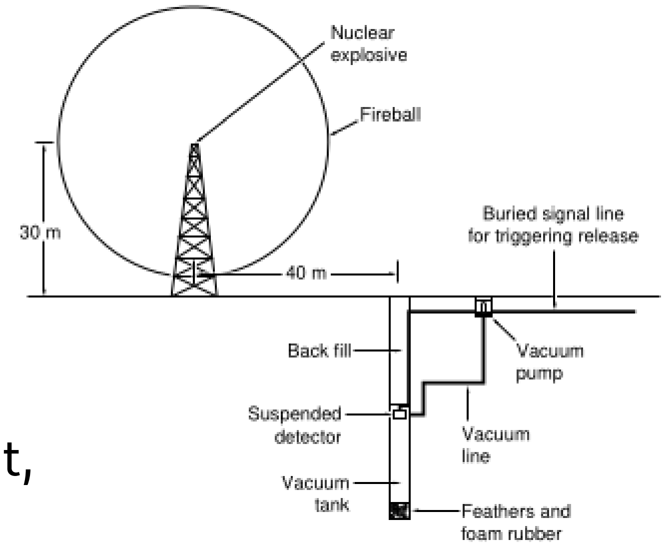
*"it contains speculations too remote from reality to be of interest to the reader"*

# F. Reines & C. Cowan

Reines : "Life was much simpler in those days".

- Initial plan was to use an atomic bomb as intense (anti)neutrino source.
- Later idea to detect positron and neutron in coincidence made the use of atomic bomb less needed.

- The Hanford experiment (1953) : Hanford experiment, low S/N.
- The Savannah River experiment (1956) : definite evidence for neutrino detection.

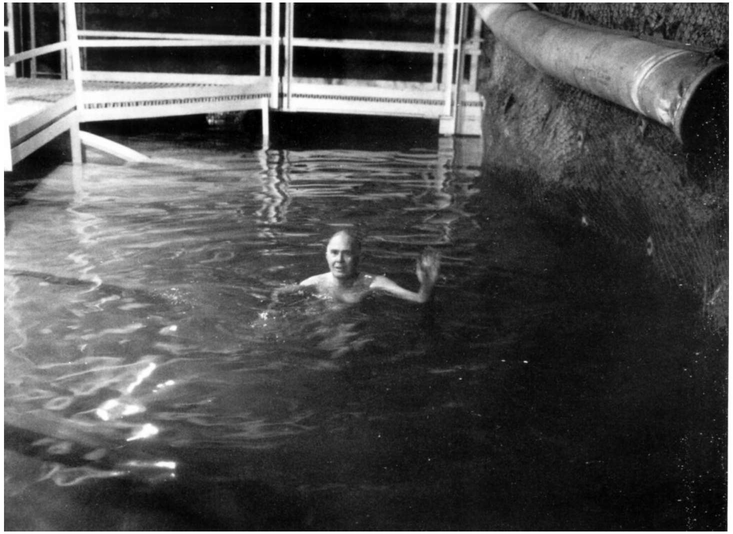


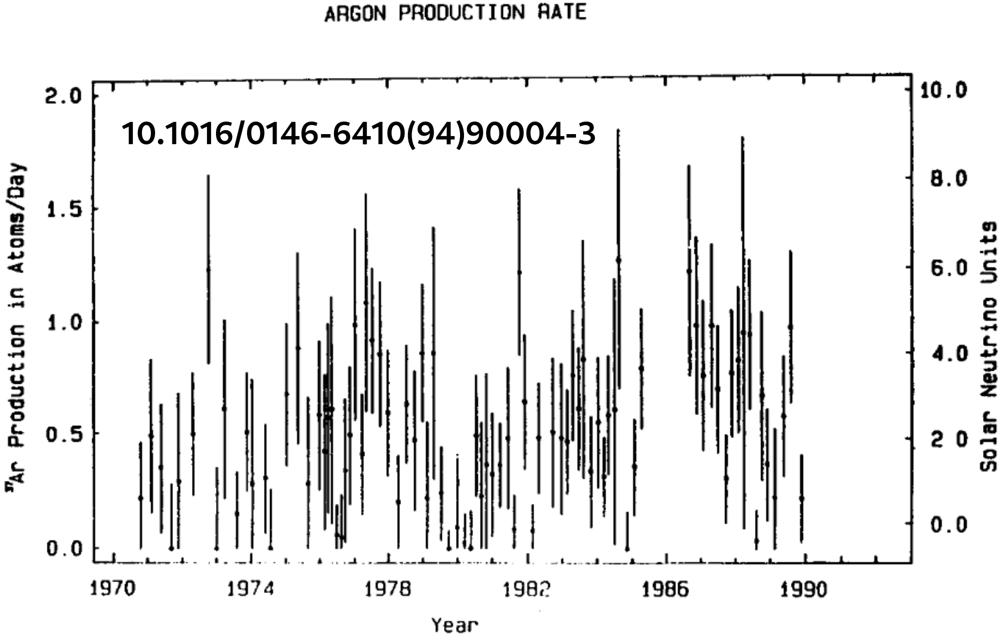

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Question from a student : "they only detected the positron and the neutron, not the neutrino ? How to be sure it was a neutrino ?"

# R. Davis experiment (solar neutrino problem)

- Inverse beta decay $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$
- Measure the radioactivity associated to argon 37 (half life ~30 days).






- Triggered **solar neutrino problem** which remained for 30 years !
  **Where are the dawn neutrinos ?**

# Atmospheric neutrino problem (1988)

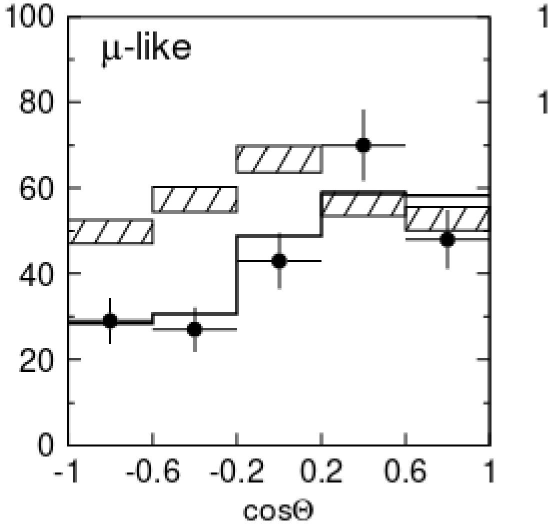
- Kamiokande = Kamioka **Nucleon Decay Experiment.**
- Atmospheric muon neutrinos as background for proton decay signal.
- **Where are the dawn neutrinos** ?

We have observed 277 fully contained events in the KAMIOKANDE detector. The number of electron-like single-prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single-prong events is $59 \pm 7\%$ (statistical error) of the predicted number of the Monte Carlo calculation. We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.

# Evidence for neutrino oscillations

- Two episodes : evidence for oscillations of atmospheric and then solar neutrinos

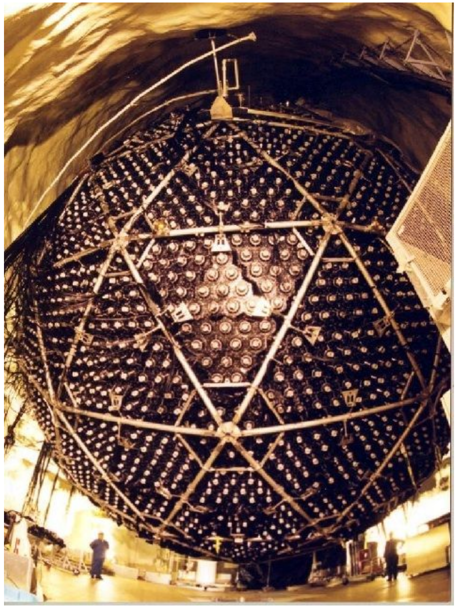
**Super-Kamiokande 1998**
(Neutrino Detection Experiment) :
Numu depletion is zenith angle dependant !





**SNO 2001** (Sudbury Neutrino Observatory) :

- electron neutrino solar flux is smaller.
- All flavour neutrinos flux is consistent with predictions !



# Neutrinos oscillate !

# Neutrino oscillations ?

- For ~20 years we entered a so-called precision neutrino oscillations era. What do we mean ?
- Flavour states don't diagonalize mass lagrangian.

$$j^{\rho}_{W,L} = 2\,\bar{\mathbf{n}}_L\, U^{\dagger}\gamma^{\rho}\mathbf{l}_L = 2\sum_{\alpha=e,\mu,\tau}\sum_{i=1}^{3}\bar{\nu}_{iL}U^{\star}_{\alpha i}\gamma^{\rho}l_{\alpha L},$$

- Leptonic mixing matrix (PMNS matrix) with four parameters to measure, in addition to two independant mass splittings.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{atmospheric}\underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{reactor}\underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{solar}$$

Thomas Kosc -- Laboratoire de Physique Subatomique & Cosmologie – kosc.thomas@gmail.com

# Mixing and oscillations : subtleties...

- Ever noticed

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\, \nu_i \longrightarrow |\nu_\alpha\rangle = \sum_{i=1}^{3} U^{\star}_{\alpha i} |\nu_i\rangle .$$

**What the *** ?**

- 2 flavour approximation :

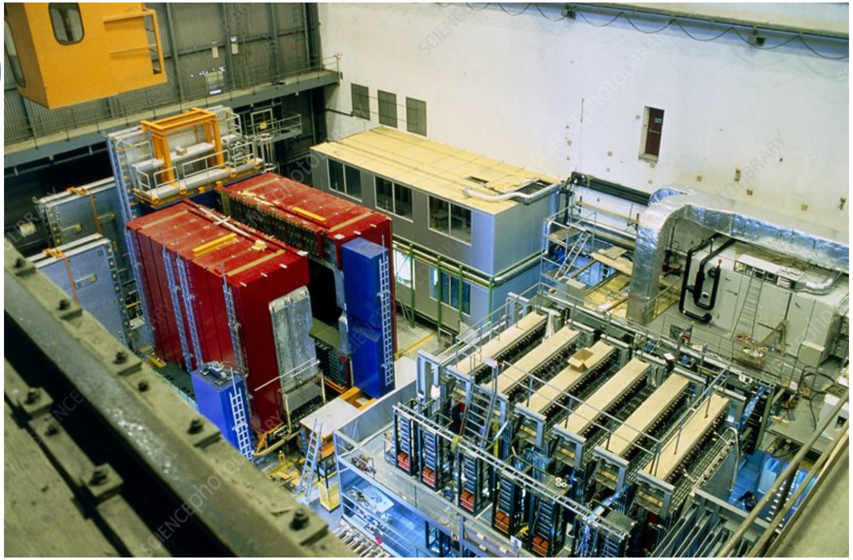
$$p(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta) \sin^2 \frac{\Delta m^2 L}{4E}$$

- Mixing is not oscillations !

- Oscillations are a pure fascinating quantum mechanical effect : the more you look at it, the less you get it !

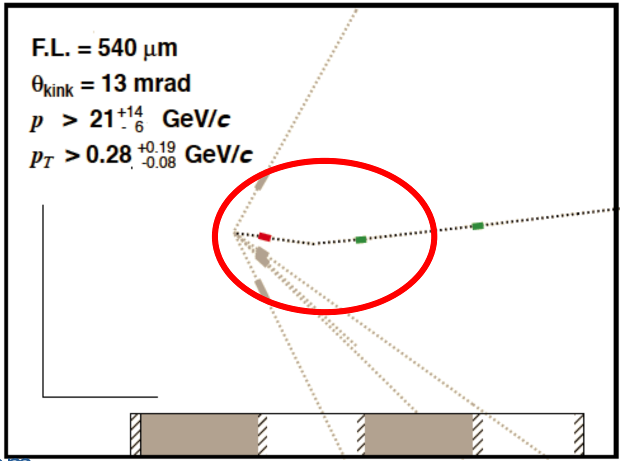
# Back to history !

# Tau neutrino observation (2001)



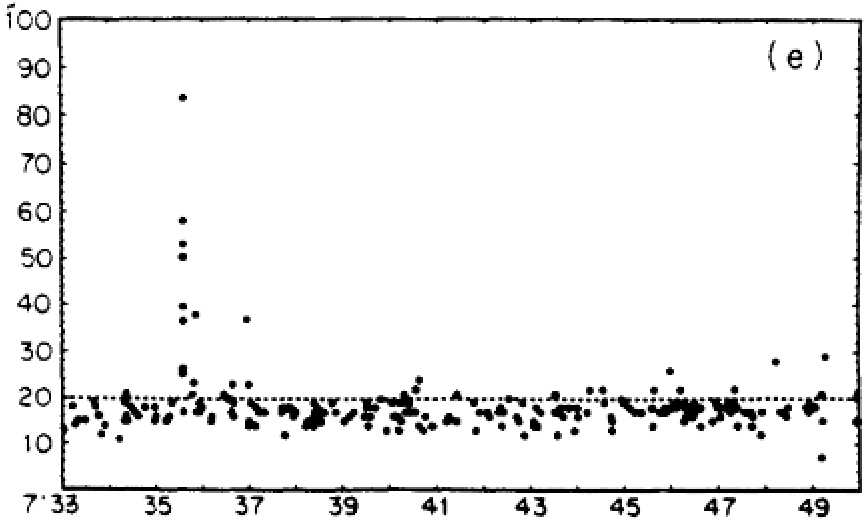
- In the 90's, CHORUS and NOMAD attempted to measure tau neutrino interactions at short baselines (few 100m) at CERN : dark matter candidate ! **Negative result**

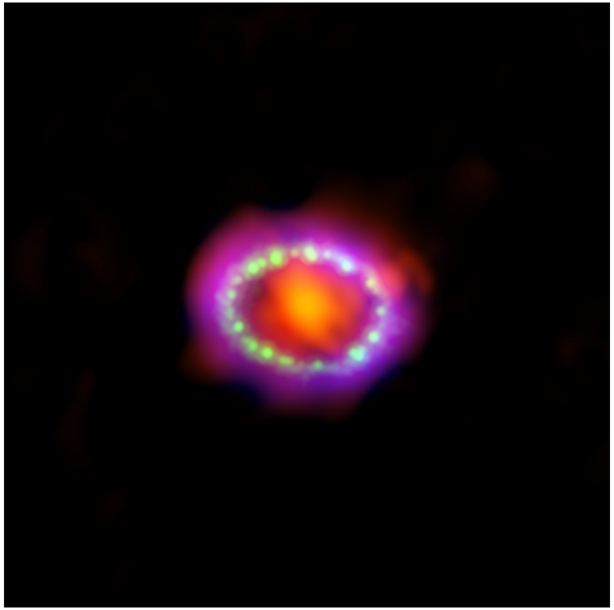
- In 2001 DONUT definitely observes the tau neutrino by using Tevatron 800 GeV protons to create a beam of neutrinos (containing tau neutrinos).



# Supernovae neutrinos

- Kamiokande captured 12 electron neutrino like event at the tile corresponding to the burst of the SN1987A supernovae. First supernovae ever detected with neutrinos !



- Many neutrino experiments today have a dedicated scientific program in case of a supernovae burst.

# Betelgeuse playing with physicist nerves…

**Bételgeuse : que verrons-nous quand elle explosera en supernova ?**

Mis à jour le 02 juillet 2021 à 17h45

**Quelles sont les chances de voir l'étoile Bételgeuse exploser de notre vivant ?**

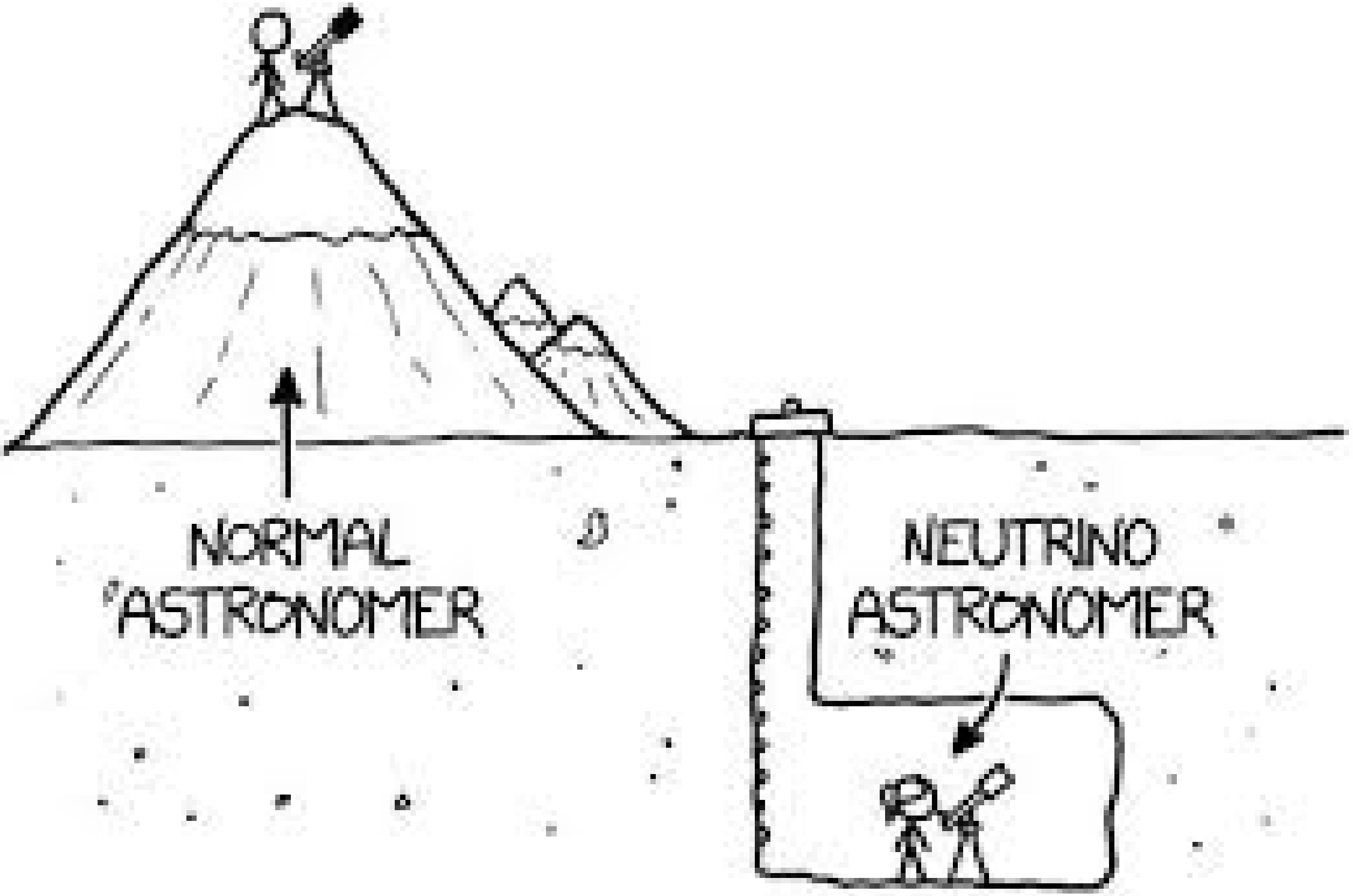
**Bételgeuse: pour quand la spectaculaire supernova ?**

- In 2020 Betelgeuse luminosity dimmed drastically. There were hopes that it was "about to" explode.

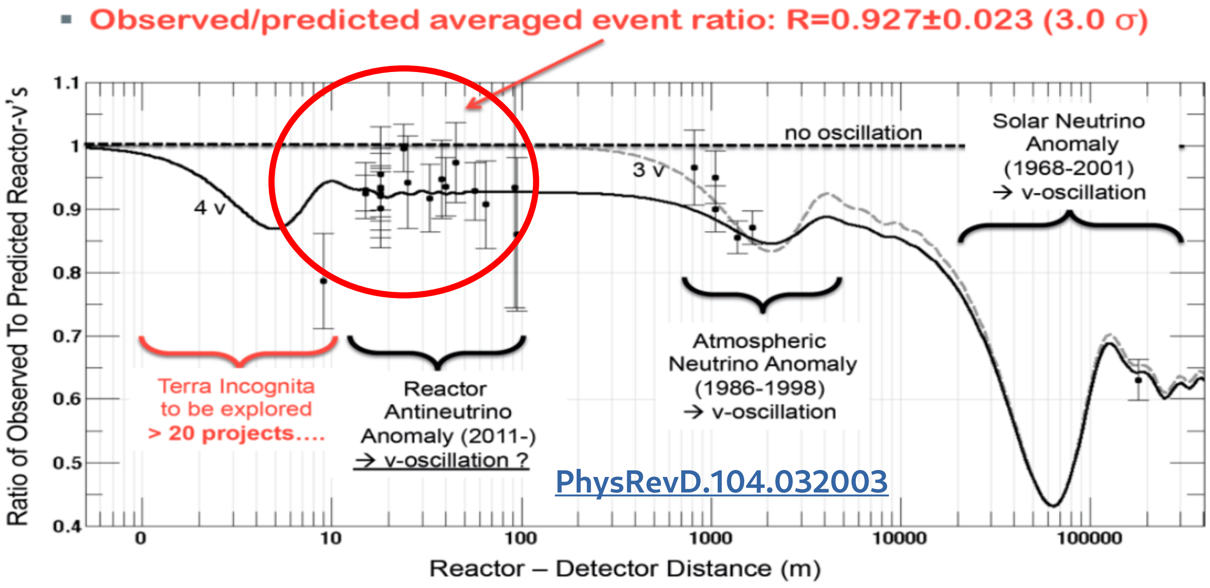
???

Thomas Kosc -- Laboratoire de Physique Subatomique & Cosmologie – kosc.thomas@gmail.com

# Some current hot topics

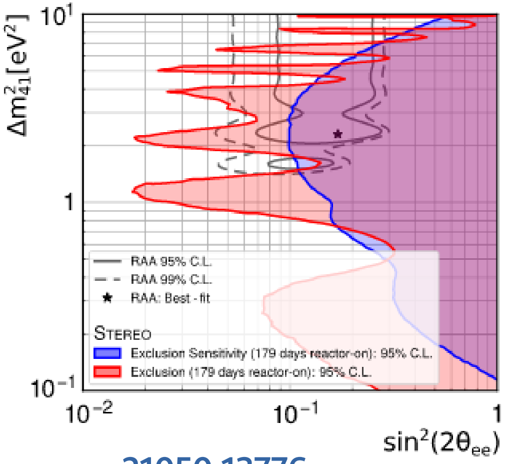


# A fourth neutrino...?



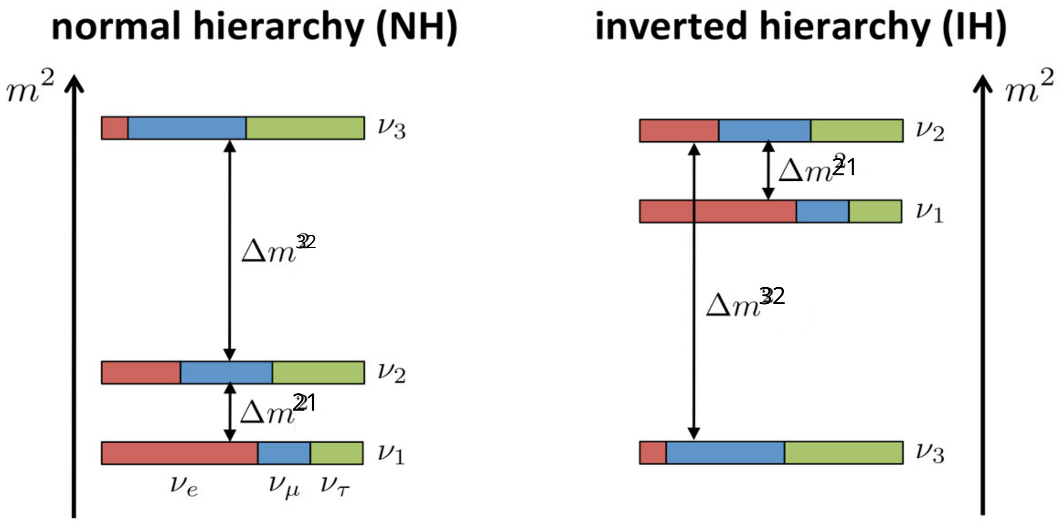

- Several experiments have investigated the reactor neutrino anomaly (missing neutrinos at short baselines ~10m).
- $\Delta m^2 \sim eV^2$

- Oscillation hypothesis ruled out by PROSPECT, STEREO and DANSS, observe by NEUTRINO-4.




21050.13776

# Mass hierarchy

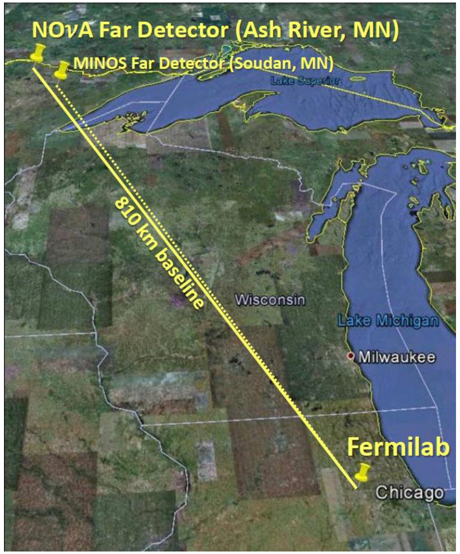



- Ambiguity in the sign of $\Delta m^2_{31}$
- Normal hierarchy currently favoured at ~$2\sigma$
- Future experiments (JUNO, DUNE, HYPERK) will definitely measure mass hierarchy.

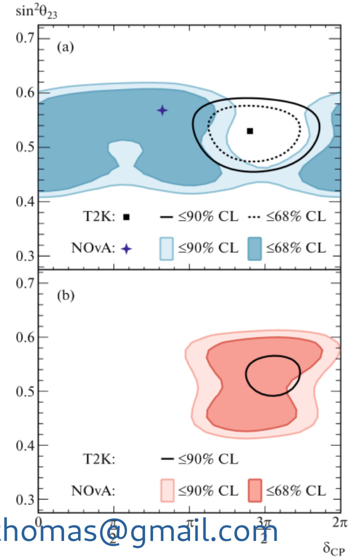
# Long baselines and CP violation

- T2K and NOvA are the two current long-baseline worldleading experiments.

$$p(\nu_\alpha \rightarrow \nu_\beta) - p(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \propto c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin(\delta_{CP})$$

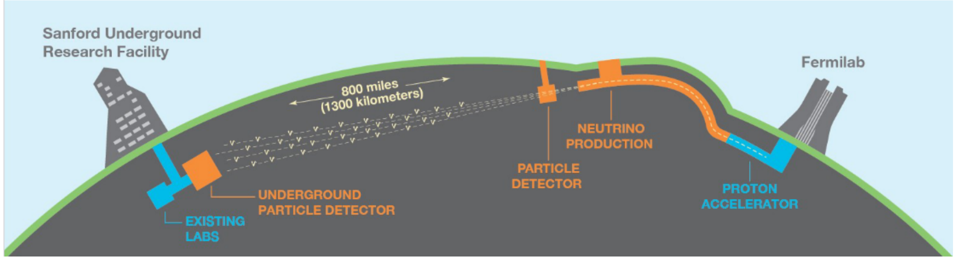




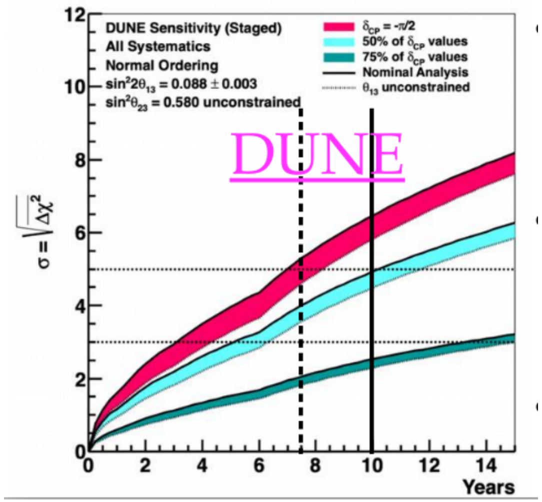

- Slight tension between the two : nothing is set !

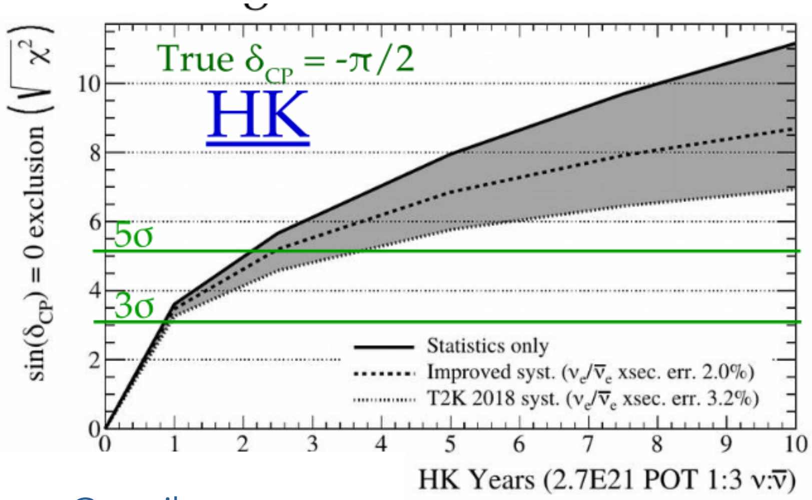
# Next generation of long baselines

- T2HK (evolution of T2K) and DUNE/LBNF are the next competing long-baseline neutrino experiments



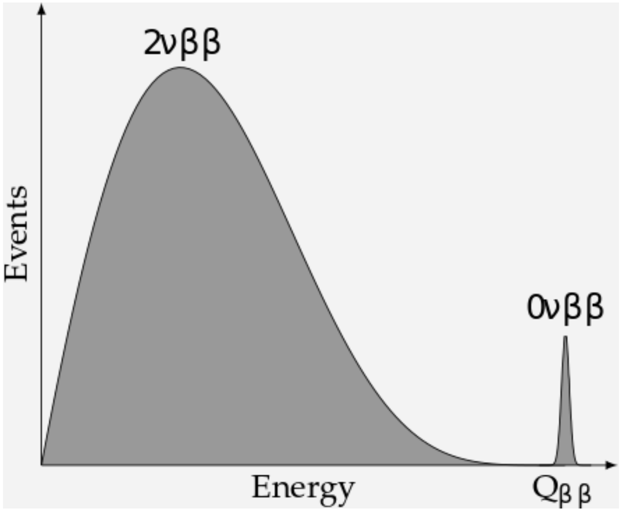

- Race to $5\sigma$ exclusion of CP-conservative value of $\delta_{CP}$ has started !



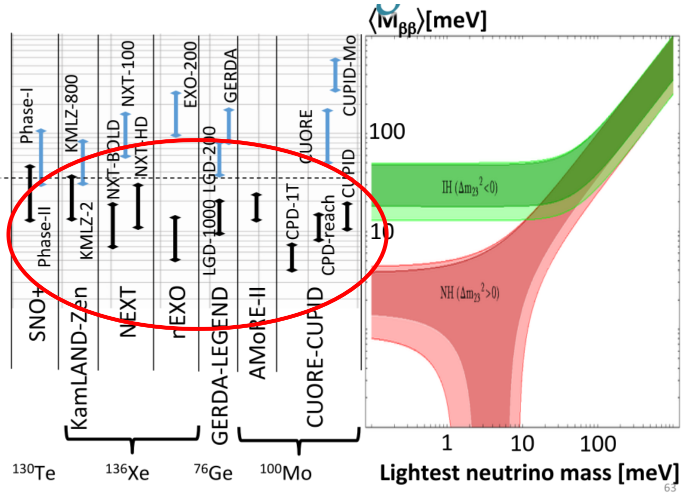



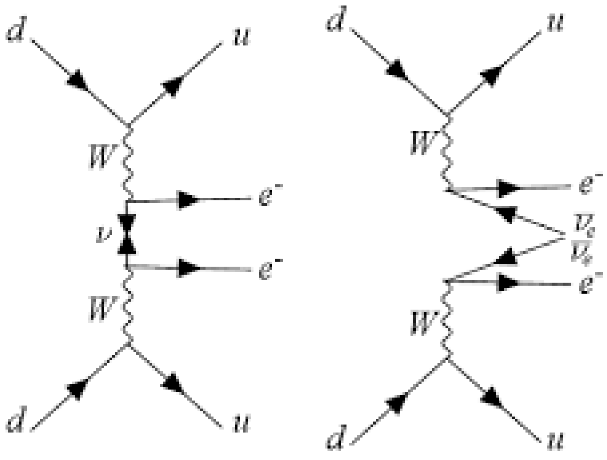
# Neutrinoless double beta decay

- Double beta decay is a rare decay process : (A,Z) → (A,Z+2) + $2e^{-}$ + ***
- Many competing experiments searching for the low signal of neutrinoless double beta decay.
- Important features : absolute neutrino mass scale, Majorana nature of neutrino (i.e nu = nubar), mass hierarchy.




**Next generation**

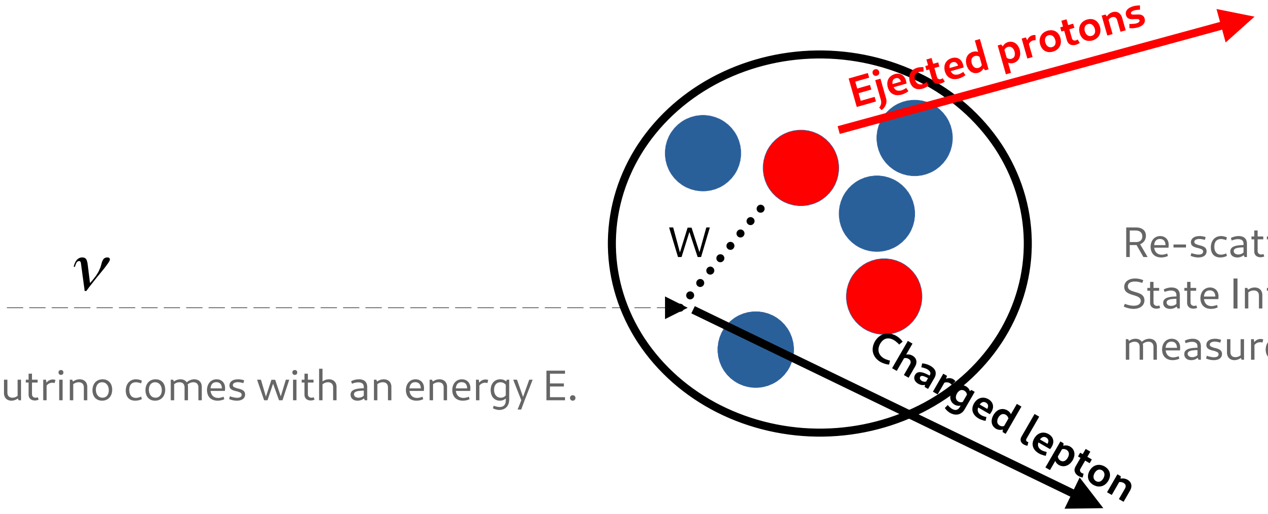


# A typical limitation in neutrino physics

- I want my experiment to run within 10 years maximum and acquire sufficient statistics : pick heavy target to increase event rate !

- But when we measure neutrino cross sections, we actually measure strongly biaised cross sections. Pick a quasi elastic scattering nu + n → p + alpha :

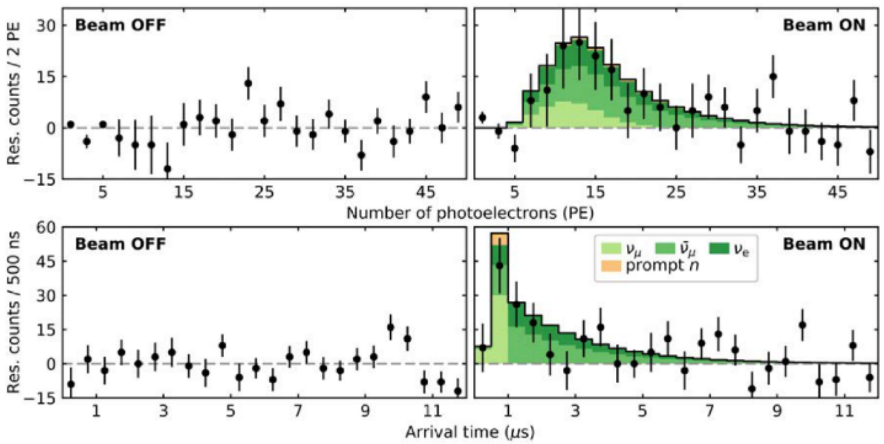



The neutrino comes with an energy E.

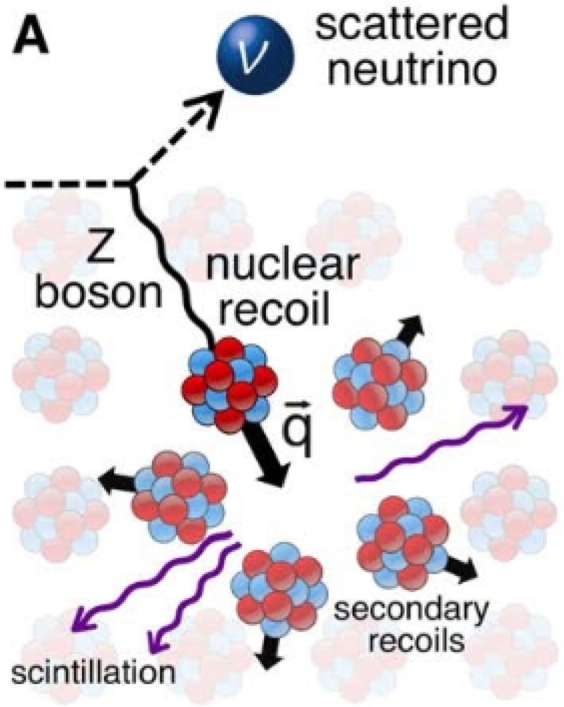
Re-scattering inside nucleus (Final State Interaction) : biais energy measurement !

# Last but not least (2017) !

- COHERENT first observed coherent elastic neutrino nucleus scattering.




1708.01294




- Promising for probing new physics

Thank you !

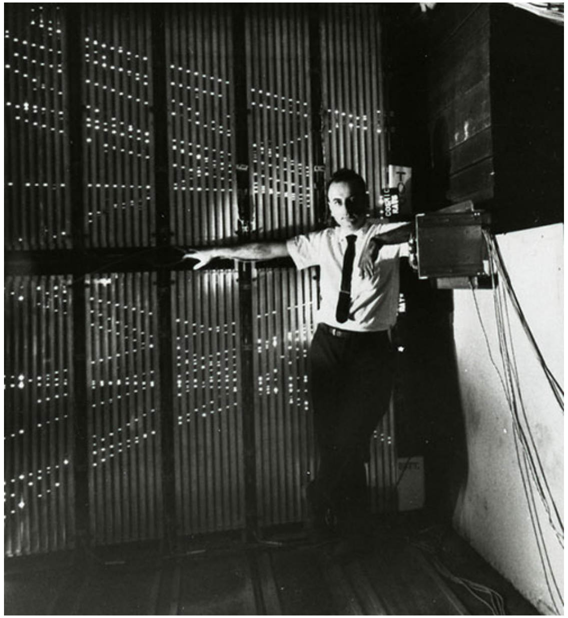
# Muon neutrino discovery (1962)

- Produce a neutrino beam and show a second type of neutrino.
- We still use the same process to create artificial neutrino beams !

$$\pi \rightarrow \mu + \nu_\mu / \bar{\nu}_\mu$$

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

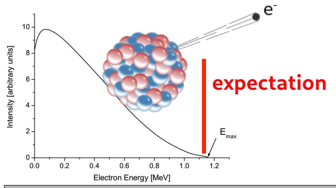
G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

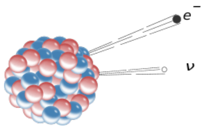


**M. Schwartz in front of spark chamber used for experiment.**

# From a historical point of view

Add sternbeerger




*"it contains speculations too remote from reality to be of interest to the reader"*

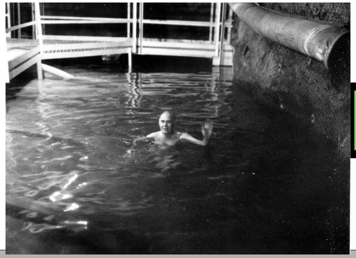
Bêta spectrum is not monochromatic (Chadwick, 1914)

W. Pauli (1930) suggests energy is shared with second particle.

Theory of Bêta decay by Fermi (1933).

Reines & Cowan 1956

1962 second neutrino type : muon neutrino.



Solar Neutrino Problem

Atmospheric Neutrino Problem

**2015 physics Nobel Prize.**

Precision neutrino oscillations program

R. Davis observes 1/3 of expected Solar neutrino flux (1969)

Kamiokande : deficit in atmospheric muon neutrinos (1988)

Super-Kamiokande : evidence for atmospheric neutrino oscillations (1998)

SNO : evidence for solar neutrino oscillations.

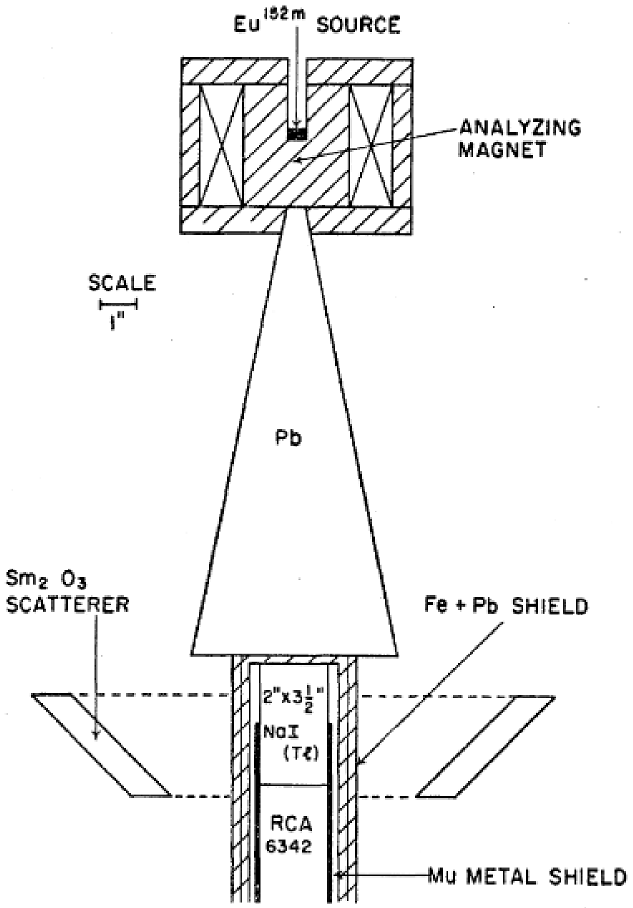
2017 : Coherent elastic neutrino-nucleus scattering

# Helicity of neutrinos ?

- M. Goldhaber's experiment in 1957.
- Elegant idea to measure the helicity of a photon following orbital electron capture.

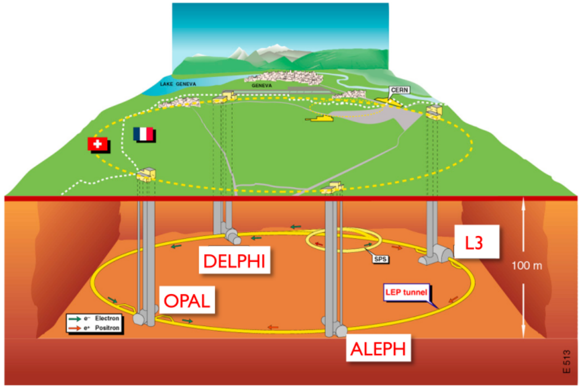
$$A(J=0)+e^{-}\rightarrow B^{*}(J=1)+\nu\rightarrow B(J=0)+\gamma+\nu$$

Eu(152) produisant Sm(152)



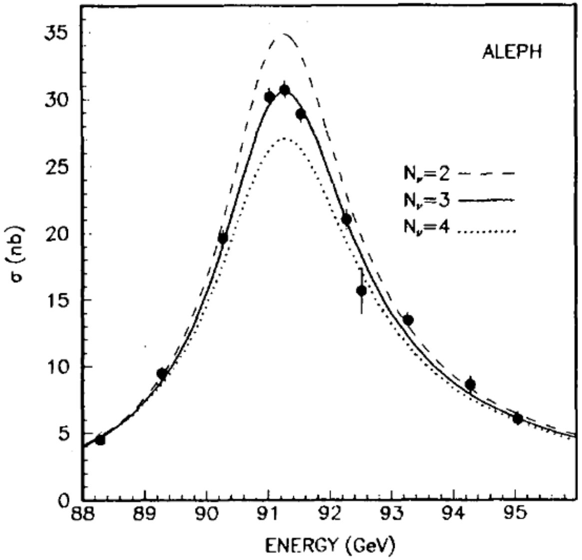
# ALEPH result

- ALEPH was an experiment running on LEP at CERN in the 90's.




- In particular it studied the decay of Z bosons.

- ALEPH collaboration showed evidence that number of families below 45 GeV is 3, as the decay width is function of number of active neutrino families below 45 GeV.




$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + N_\nu \times \Gamma_{\nu\nu}$$