Neutrino Physics

Italian Teachers Programme 2012, CERN 14/9/2012

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Why are neutrinos so interesting ?

- Cosmology:

They played an important role during the Big Bang, they could explain the asymmetry among matter and anti-matter, they are the most abundant particles in the universe

- Astrophysics:

They are ruling the life and death of stars

- Particle Physics:

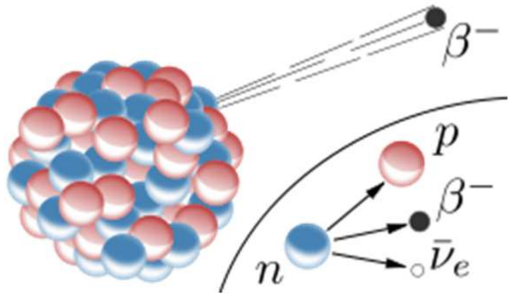
They are a window on physics beyond the Standard Model of particle physics: presently they represent the only experimental hint in that direction

Many properties of neutrinos were totally unexpected coming out as experimental results:

> The history of neutrino physics is a real saga with an extraordinary richness of experimental techniques involved

There are still a lot of open questions in neutrino physics …

The birth of the neutrino as a « desperate remedy » to solve apparent energy non-conservation in β decays (W. Pauli 1930)



Radioactivity: β- decay $^A_ZN \rightarrow \; ^{\;\;\;A}_{Z+1}N' + e^- + \bar{\nu}_e,$

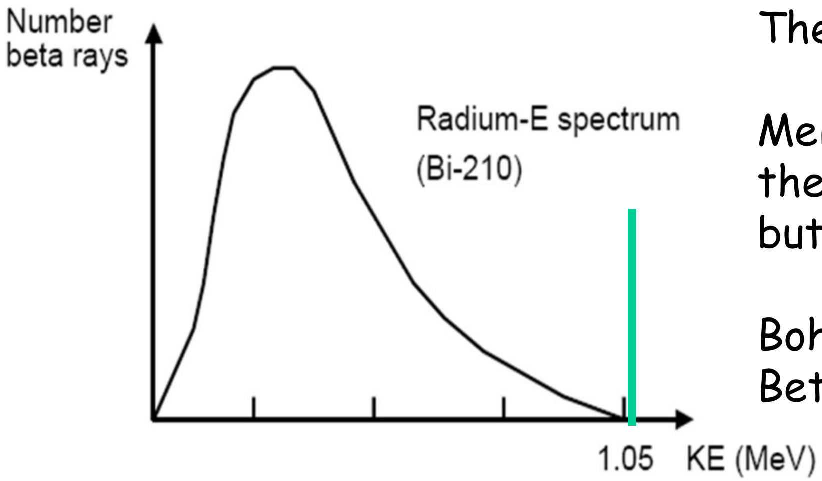
Early 1900s: people thought they were dealing with a two body decay process:

$$(A,Z) \rightarrow (A,Z+1) + e^-$$

→ The energy spectrum of the electrons should be monochromatic:

$$p = \frac{1}{2M}\sqrt{\left[M^2-(m_1-m_2)^2\right]\left[M^2-(m_1+m_2)^2\right]}$$ with $M=M(A,Z)$, $m_1=M(A,Z+1)$ and $m_2=m_e$

First measurements of beta spectrum:
1911 Lise Meitner and Otto Hahn, 1914 Ellis and Chadwick



The beta spectrum is continuous

Meitner: electrons reinteract in the nuclei emitting gamma rays → but no gamma rays detected

Bohr: energy is not conserved in Beta decay !!!

Additional problem: the model of the nucleus (made of protons+electrons) and the spin of nuclei (Li and N) measured to be integer

Li nucleus: 6 protons + 3 electrons = 9 fermions
N nucleus: 14 protons + 7 electrons = 21 fermions

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.

1930: W. Pauli makes the hypothesis of an undetectable particle sharing the energy of beta decay with the emitted electron.

From Pauli's letter of the 4th of December 1930

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, how 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" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which 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 masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant... I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think about this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant,
W. Pauli

Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally

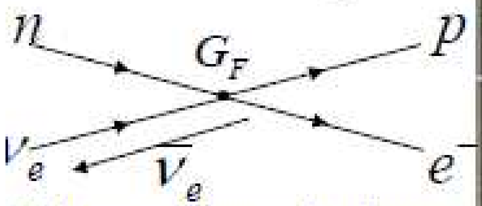
1932 The neutron (as we know it today) was discovered, by J. Chadwick, two years after Pauli's proposal

- Solves nuclear spin problem: A= Z(protons)+N(neutrons)

But the mass of the neutron is similar to the proton mass

→ cannot be the Paulis's particle

Fermi, 1933: coherent theory of beta decay



"Abstract speculations too far from physical reality to be of any interest to the readers"

Nature, rejecting the paper!

E. Fermi, *La Ricerca Scientifica* 4 (II), (1933), 491-495; and Z.Physik, 88 (1934) 161

Pauli thought his proposal of the "neutron" was too speculative, he did not publish it in a scientific journal until 1934, by which time Fermi had already developed his theory of beta decay incorporating the neutrino.

Fermi 4-fermion contact interaction, Lagrangian of interaction (in analogy with electrodynamics):

$$\mathcal{L}(x) = -\frac{G_F}{\sqrt{2}}\left[\bar{\phi}_p(x)\gamma^\mu\phi_n(x)\right]\left[\bar{\phi}_e(x)\gamma^\mu\phi_\nu(x)\right]$$

G_F = Fermi coupling constant = $(1.16637 \pm 0.000001)\ 10^{-5}\ GeV^{-2}$

In 1934, at a seminar Fermi was asked whether the neutral particle emitted in the nuclear beta-decay was the same as Chadwick's neutron.

Fermi clarified that he was talking about a different particle which he referred to as neutrino ("little neutral one").

Inverse beta decay process as a tool for neutrino detection:

$$\bar{\nu} + N(n, p) \rightarrow e^{+} + N(n+1, p-1) \; ,$$

where n equals the number of neutrons and p equals the number of protons. If the nucleus happens to be that of hydrogen (a single proton), then the interaction produces a neutron and a positron:

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

Bethe & Peierls, computing its cross section, 1934:

Few MeV neutrinos resulted to have an interaction length of about one light year of lead: "..this meant that one obviously would never be able to see a neutrino."

1946 Pontecorvo proposes the following reaction for neutrino detection

$\nu + {}^{37}Cl \rightarrow \beta^{-} + {}^{37}Ar$, ${}^{37}Ar \rightarrow {}^{37}Cl$ **(34 days, K-capture)**

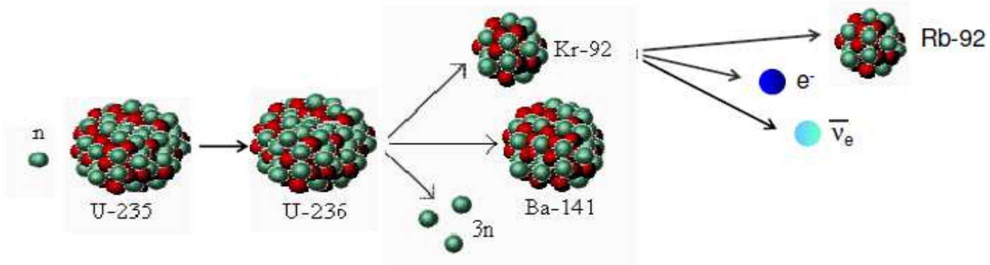
Davis exploits the Pontecorvo reaction $\nu + {}^{37}Cl \rightarrow \beta^{-} + {}^{37}Ar$:

- 1955-58, antineutrinos from reactor (Brookhaven, Savannah River)

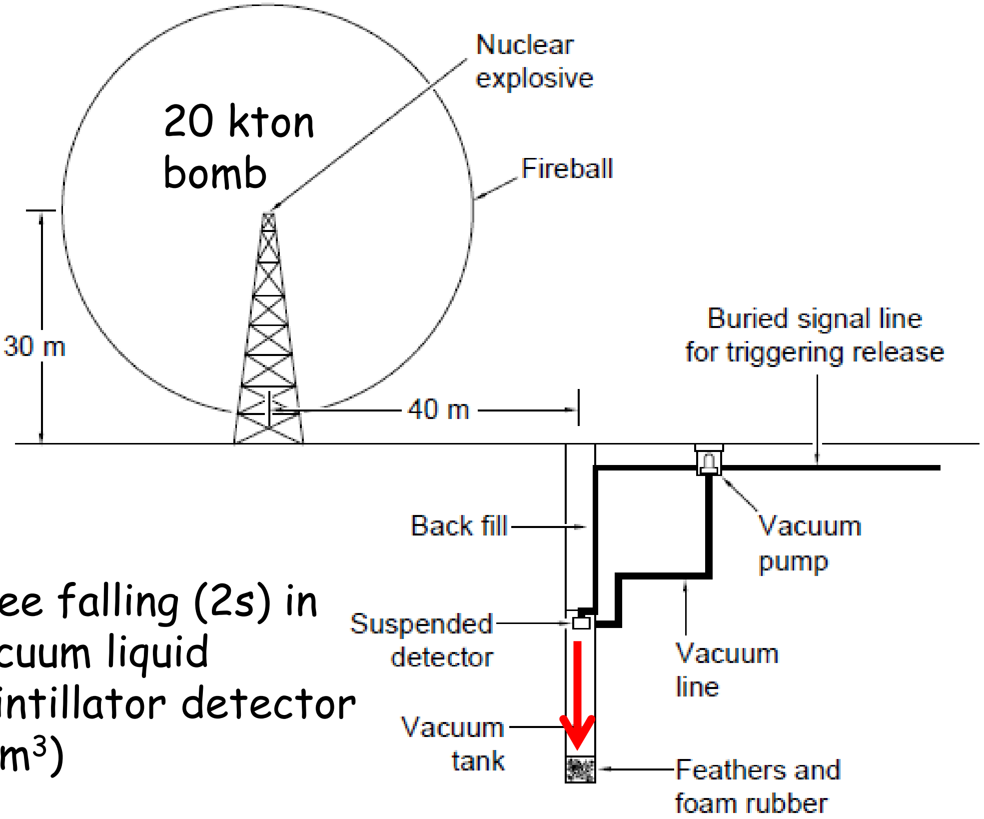
no signal => lepton number

- 1968, solar neutrinos detection

Neutrinos from decays of nuclear fission Products →



How to detect neutrinos: producing them in a nuclear explosion



Free falling (2s) in vacuum liquid scintillator detector (1 m^3)

Figure 1. Detecting Neutrinos from a Nuclear Explosion
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

« El Monstro »
Reines and Cowan 1951-1952
Approved after discussing with Fermi and Bethe who were convinced that this was the most promising (anti)neutrino source

- ✓ Intense
- ✓ Short flash (less environmental background)

but then abandoned in favour of the detection at a nuclear reactor:

Bomb: flux ~10E4 times larger than with a reactor

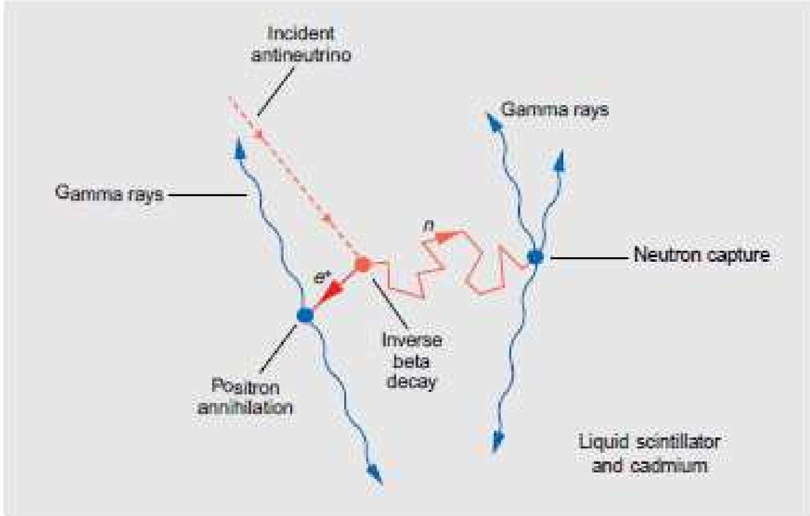
Background from neutrons and gammas similar to reactor

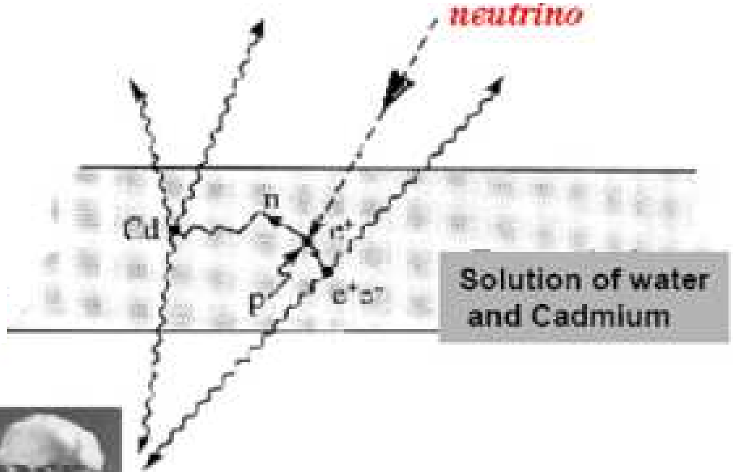
→ But a new idea on how to reduce the background and detect neutrinos over a long time scale with the low reactor flux

1956 (anti)neutrino detection at the Savannah River reactor

flux ~10^E13 neutrino / (cm2 s)

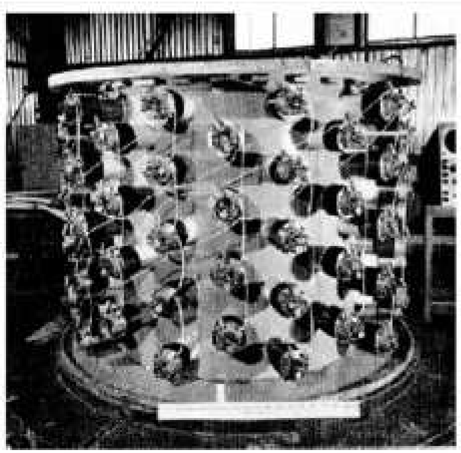
the idea: detect also the delayed neutron capture signal after the positron →





Reines: 1995 Nobel Prize

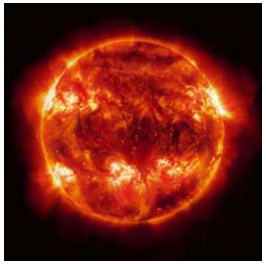
Detector 12 m underground and 11 m from reactor
~3 neutrinos detected/hour



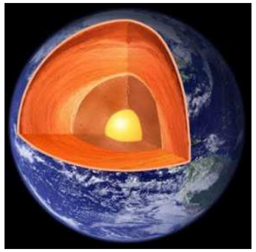
We are happy to inform you (Pauli) that we have definitely detected the neutrino

Neutrino sources:

Supernova explosion
99% of collapse energy in neutrinos
10-30 MeV

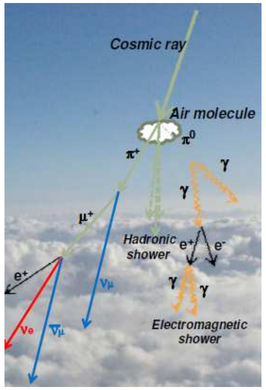


Sun:
65 billions/s/cm2
on the earth surface
~ MeV

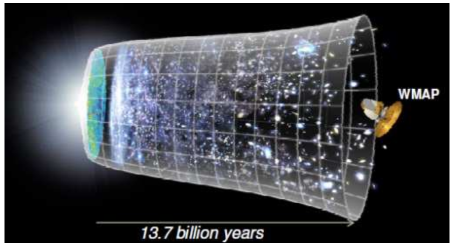


Earth radioactivity
U, Th, K
→Geoneutrinos
$4^{E}6$ /(cm2 s)
~ MeV

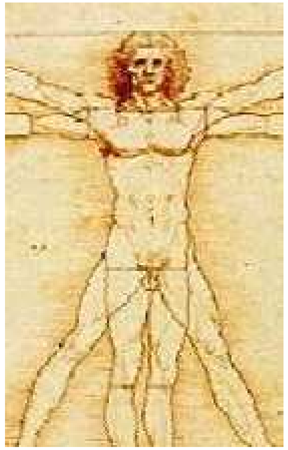
Nuclear reactors:
1 GW → $2^{E}20$ anti-nue/s
~ few MeV



Cosmic rays
~ GeV
~ 1 / (cm2 minute)

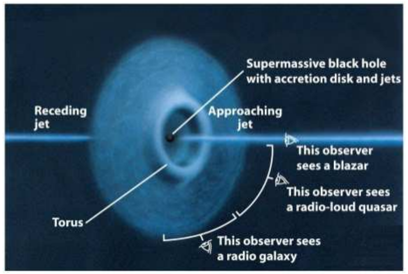


Big Bang
Relic neutrinos
330/cm3
1.95 K



Human Body
20 mg of K 40
340 millions/day

Particle accelerators
~few GeV

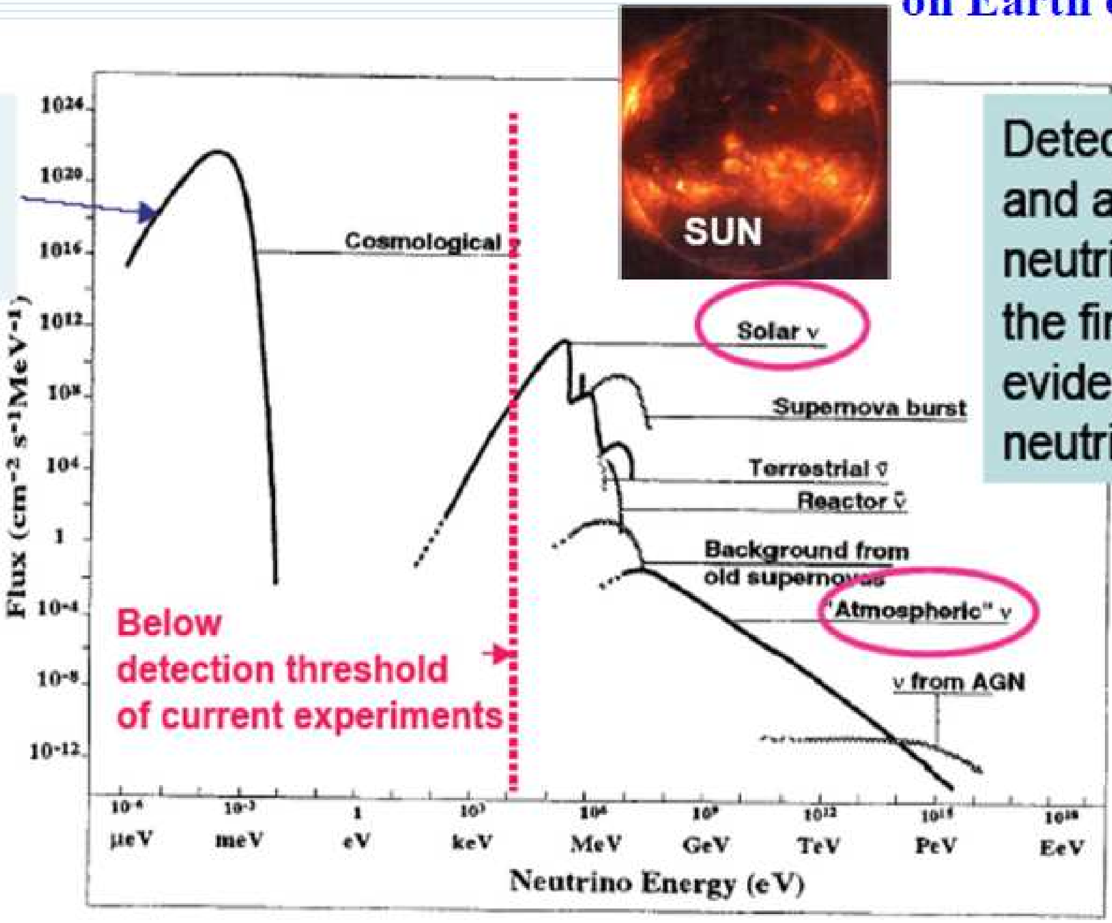


Extragalactic:
Active galactic nuclei
Gamma ray bursts
PeV

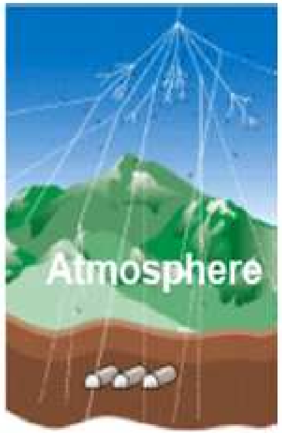
Sources of neutrinos

The Sun is the most intense detected source with a flux on Earth of $6\ 10^{10}\ \nu/cm^2s$

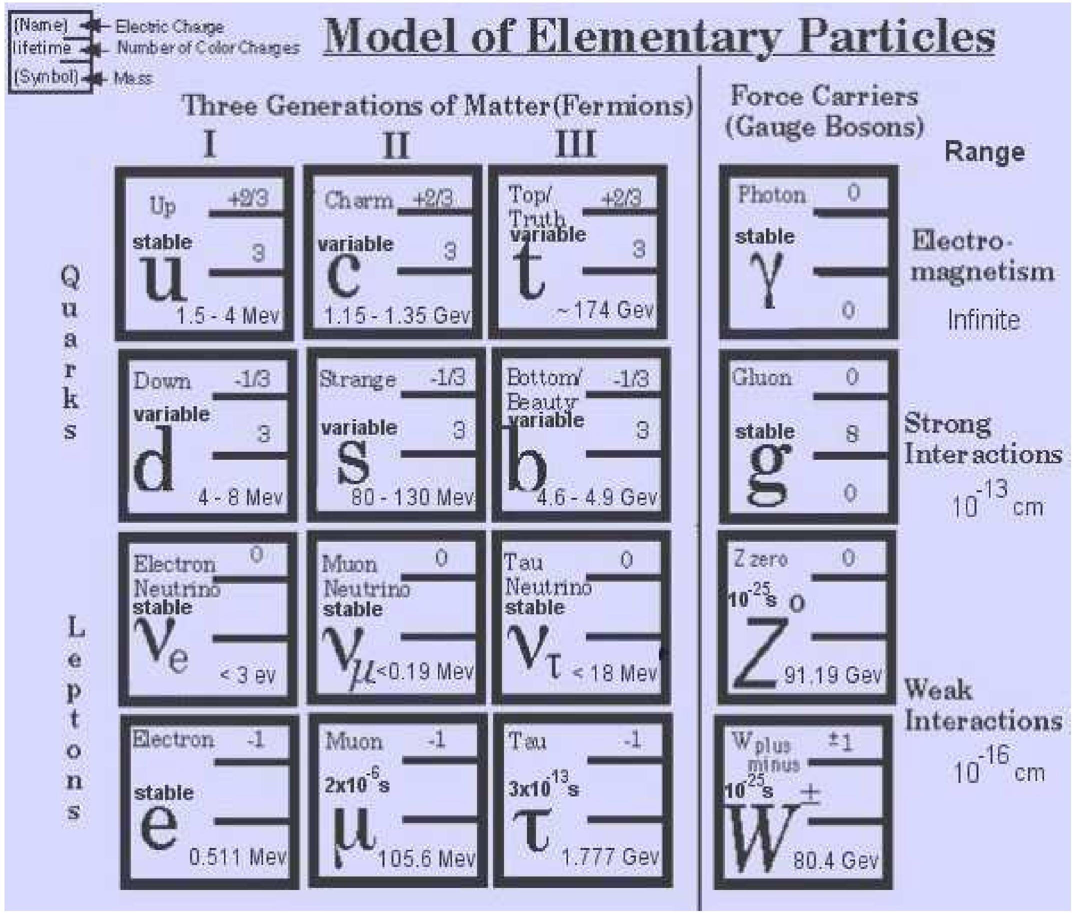
Abundant but challenging detection

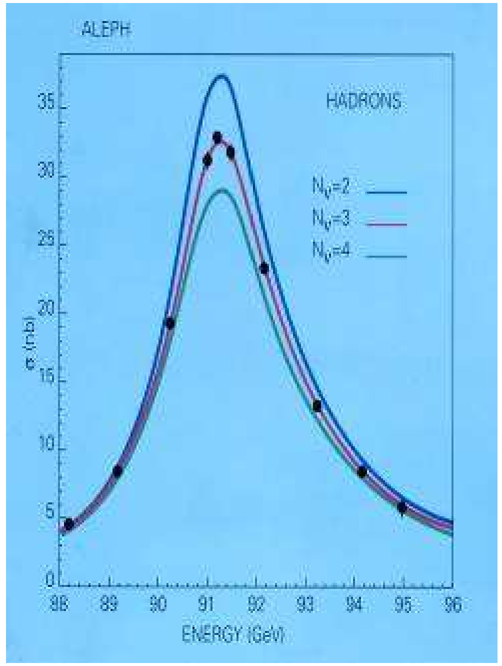


Detection of solar and atmospheric neutrino has provided the first compelling evidence of neutrino oscillations



Standard Model of Elementary particles

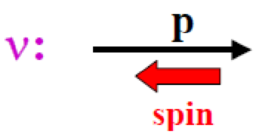


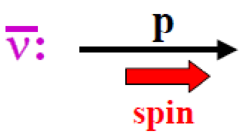


1989 LEP results:
only 3 neutrinos coupled to the Z^0
($M_\upsilon < M_Z/2$)

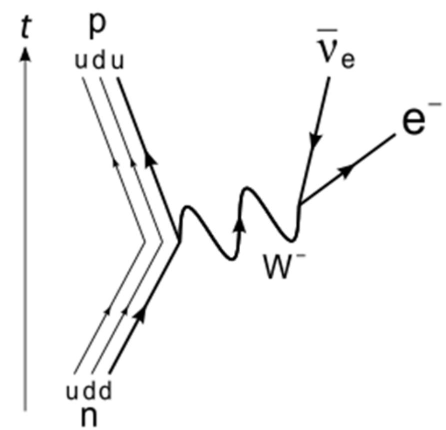
Why 3 families ?
Why so different masses ?

In SM massless neutrinos:
Neutrino: helicity -1 (+1 not existing)
Antineutrino: +1 (-1 not existing)

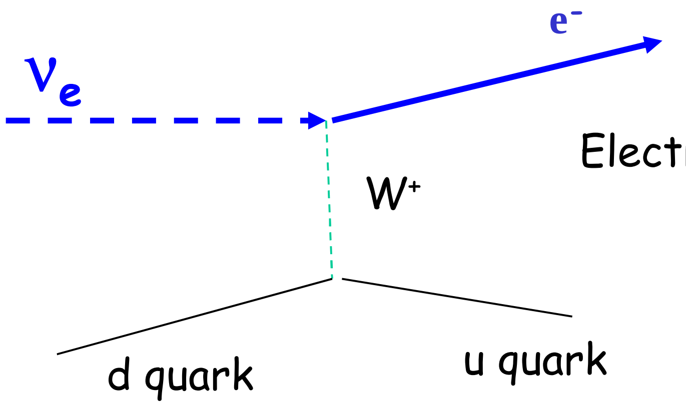




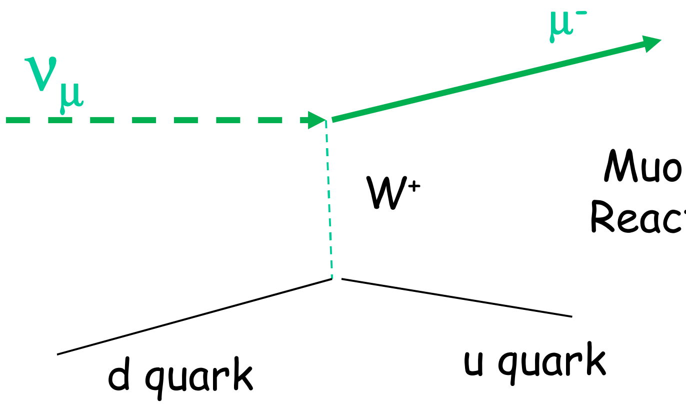
Modern description of the Beta decay



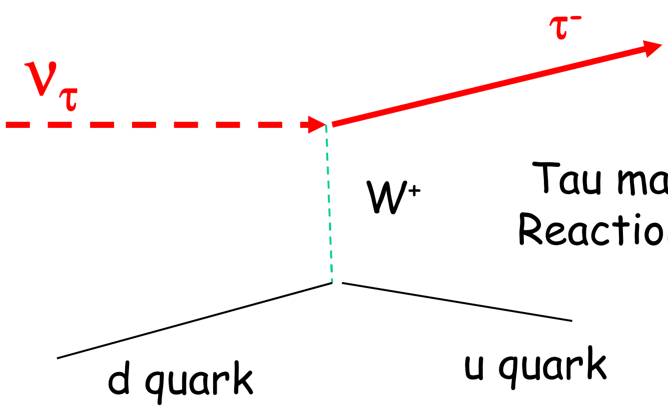
How can we detect different neutrinos: Charged Current reactions



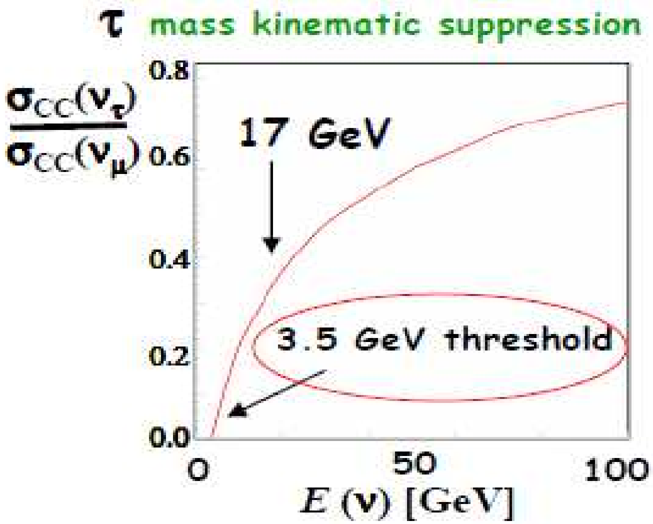
Electron mass= 0.511 MeV



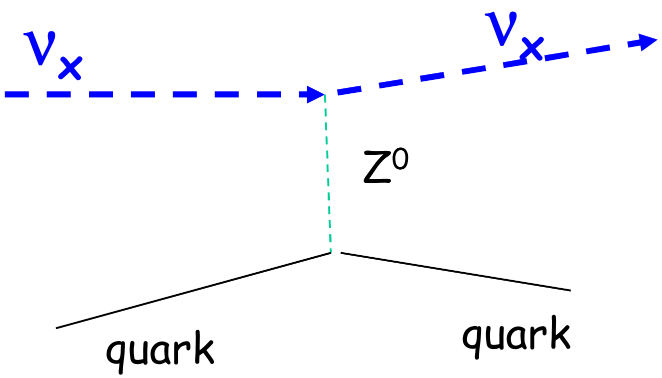
Muon mass= 105.6 MeV
Reaction threshold = 112 MeV



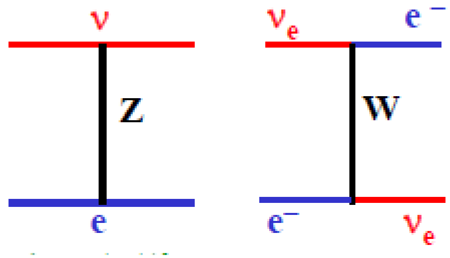
Tau mass= 1777 MeV
Reaction threshold = 3.46 GeV



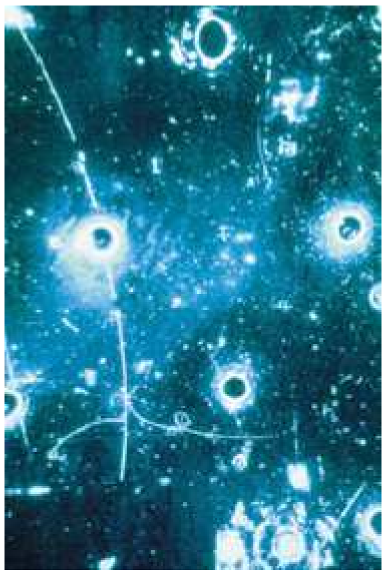
Neutral current reactions (Z exchange), do not distinguish neutrinos, no threshold



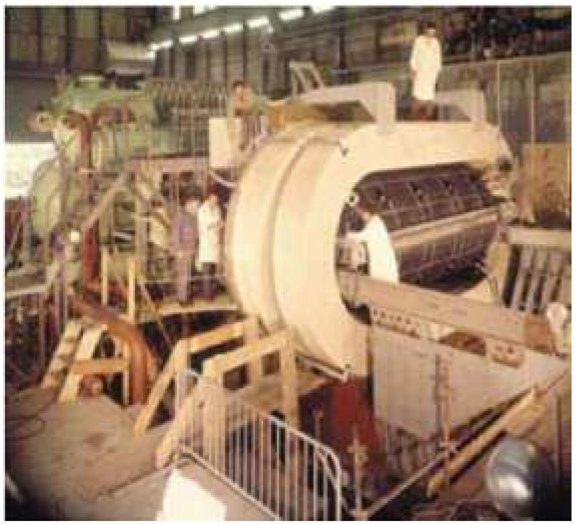
Elastic scattering neutrino-electron



Discovery of neutral currents 1973 (10 years before the discovery of the Z)



Bubble chamber experiment Gargamelle



1962 Discovery of the muonic neutrino with the first neutrino beam produced with an accelerator (pion decays)

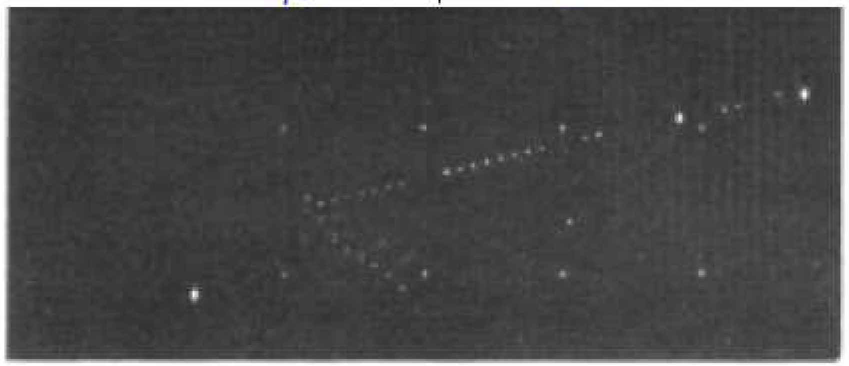
Nobel 1988

Lederman, Schwarz, Steinberger

1959 Pontecorvo raised the question whether ν from β-decay processes is identical with ν from pion decay (Sov. Phys. JETP 10 (1960) 1236)

1960 Pontecorvo and Schwartz (PRL 4 (1960) 306) suggested to study neutrino reactions with high energy muons coming from proton accelerator ($\pi \rightarrow \mu + \nu_\mu$ $K \rightarrow \mu + \nu_\mu$)

$$\nu_\mu + N \rightarrow \mu^- + X$$

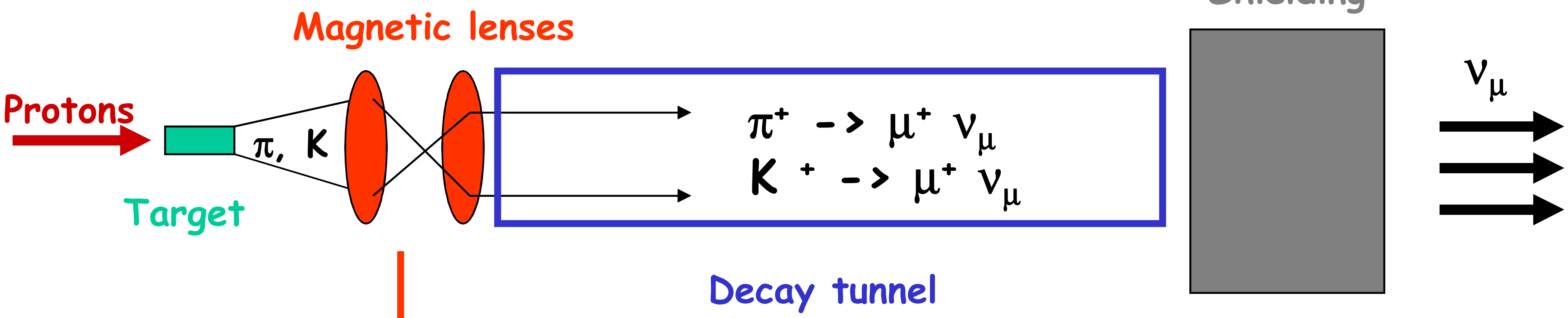


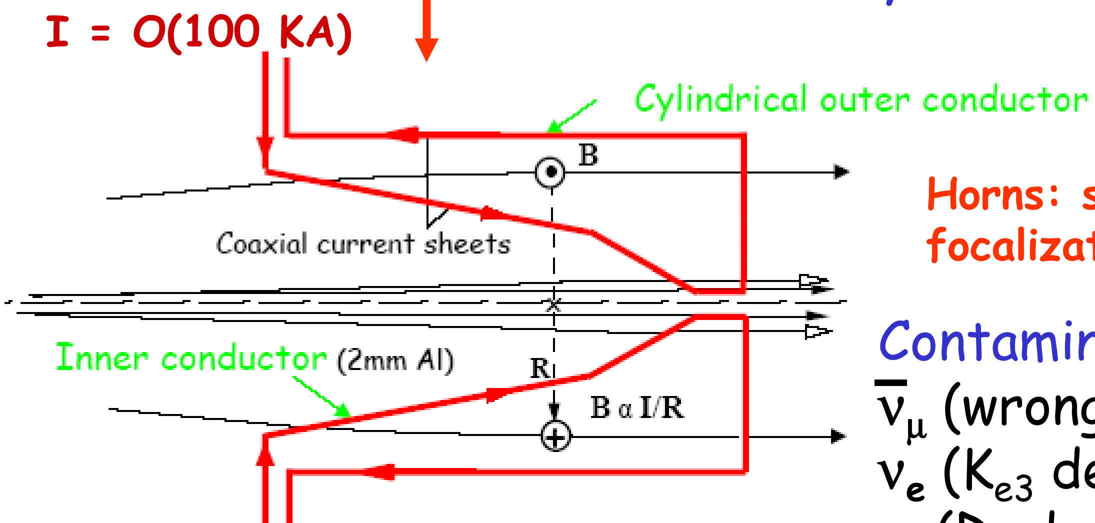
The two neutrinos experiment:

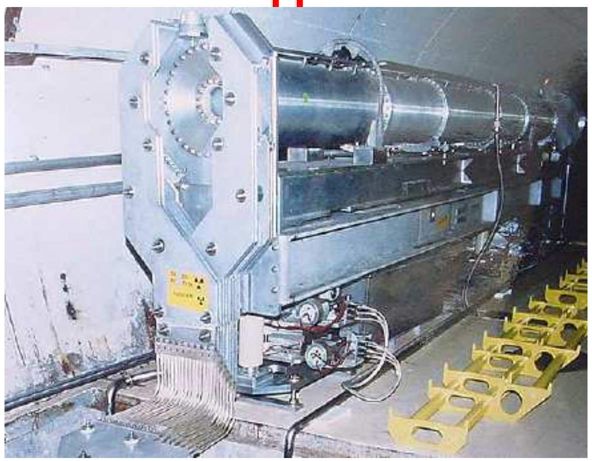
Muonic neutrino different than electronic neutrino

→ Conservation of leptonic number

Typical high energy Wide Band neutrino beam







Horns: sign selection, focalization: flux x10

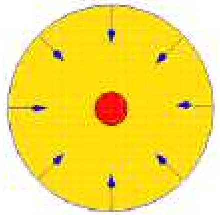
Contaminations:

$\bar{\nu}_\mu$ (wrong sign parents)	O(5%)
ν_e (K_{e3} decays, μ decays)	O(1%)
ν_τ (D_s decays)	O(10^{-6})

Note that the π/K abundances and spectra at the target are not easy to predict: to reduce systematics perform ad hoc hadron-production experiments (Spy, Harp etc …)

Solar Neutrinos

Sun birth for the gravitational collapse of a primordial gas cloud (~75%H2, ~25%He)
→ Increase of density and temperature in the core → nuclear fusion reactions



→ Idrostatic equilibrium between pressure from fusion reactions and gravitational attraction

Final result of chain of fusion reactions: $4p \rightarrow He^4 + 2e^+ + 2\nu_e$

Average energy emitted under the form of **electromagnetic radiation**:

$$Q = (4M_p - M_{He^4} + 2m_e)c^2 - \langle E(2\nu_e)\rangle \approx 26.1 \text{ MeV}$$

(from $2e^+ + 2e^- \rightarrow 4\gamma$)

$(\langle E(2\nu_e)\rangle \approx 0.59 \text{ MeV})$

2.2% of the total

Solar luminosity: $L_\odot = 3.846\text{x}10^{26} \text{ W} = 2.401\text{x}10^{39} \text{ MeV/s}$

Rate of neutrino emission: $dN(\nu_e)/dt = 2\, L_\odot/Q \approx 1.84\text{x}10^{38} \text{ s}^{-1}$

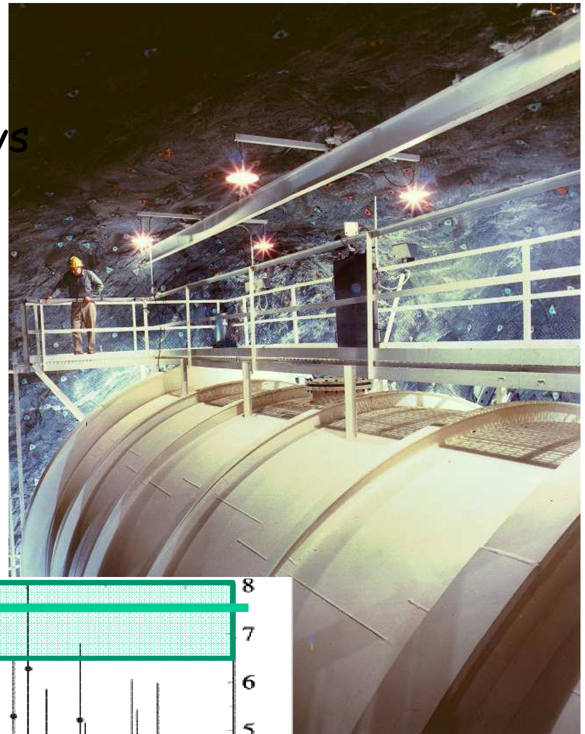
Flux of neutrinos on earth: $\Phi(\nu_e) \approx 6.4\text{x}10^{10} \text{ cm}^{-2} \text{ s}^{-1}$

First detection of solar neutrinos 1968: Homestake mine experiment R. Davis
Depth equivalent to 4100 m of water

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (34 days, K-capture) $e^- + {}^{37}Ar \rightarrow \nu_e + {}^{37}Cl$

E(neutrino)> 0.814 MeV

Tank with 390 **m**^{3} of C_2Cl_4
${}^{37}Cl$ ~24% of natural Cl

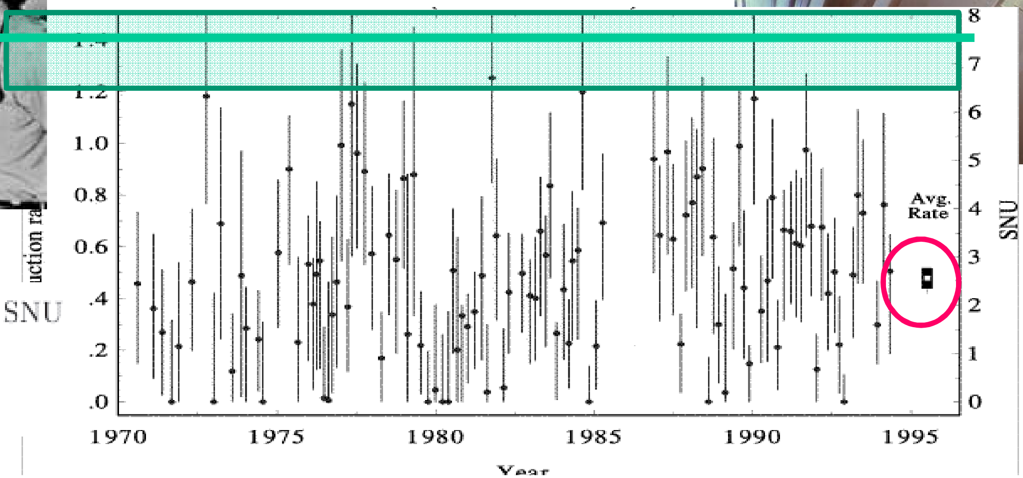


~1.5 Ar atoms/day produced by solar neutrinos
Extracted every 3 months with a flux of N

Final state ${}^{37}Cl$ excited emitting Augier electrons e/o x rays

Results compared to the neutrino flux predicted by the Standard Solar Model (J. Bahcall)

→ 1/3 of expected rate
Solar neutrinos deficit



$$R({}^{37}Cl) = 2.56 \pm 0.16 \pm 0.16 \text{ SNU}$$
$$R_{SSM} = 7.6^{+1.3}_{-1.1} \text{ SNU}$$
$$R_{Données/SSM} = 0.33 \pm 0.03$$

Interpretations:

> *I [J.N. Bahcall] want to tell you an illustrative story about neutrino research … One of the miners came over to our bench, said : "Hello, Dr. Davis. How is it going ? You don't look too happy." And, Ray replied : "Well, I don't know …I am capturing in my tank many fewer of those neutrinos than this young man says I should be capturing." The miner […] finally said : "Never mind, Dr. Davis, it has been a very cloudy summer here in South Dakota. "*

More seriously debated for long … long time:

The trivial ones:

- The Homestake experiment which is quite delicate has a bias in the neutrino detection
- The Standard Solar Model is not correct

The fascinating one:
Pontecorvo: the Davis experiment and the SSM are both correct it is new physics: neutrinos change their nature during their trip to the earth

→ Neutrino oscillations
Electronic neutrinos from the sun become muonic neutrinos
The energy of the muonic neutrinos is too low for the charged current reaction → neutrino disappearance
But neutrinos must be massive particles

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79.   Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/31   April 6/10 1972

Prof. J.N.Bahcall

The Institute for Advanced Study
School of Natural Science
Princeton, New Jersey 08540, USA

Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

I will attend the Balaton meeting on neutrinos and looking forward to see you there.

Yours sincerely,

B. Pontecorvo

B.Pontecorvo

Pontecorvo was predictive:
It took 30 years for the demonstration !

Neutrino oscillations

Neutrino mixing (Pontecorvo 1958; Maki, Nakagawa, Sakata 1962):

3 neutrinos framework, neutrinos are massive particles and they mix similarly to quarks; the flavour eigenstates ν_e, ν_μ, ν_τ are not mass eigenstates but linear superpositions of the mass eigenstates ν_1, ν_2, ν_3 with eigenvalues m_1, m_2, m_3:

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

$\alpha = e, \mu, \tau$ (flavor index)

$i = 1, 2, 3$ (mass index)

$U_{\alpha i}$= **unitary mixing matrix**

Today favorite parametrization of U: in terms of 3 mixing angles $\theta_{12}\ \theta_{23}\ \theta_{13}$ and one Dirac-like CP phase δ (two extra phases in case of Majorana neutrinos):

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

Atmospheric ν oscillations **Solar ν oscillations**

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

where: $s_{ij} \equiv \sin\theta_{ij}$, $c_{ij} \equiv \cos\theta_{ij}$.

Considering the time evolution of a flavour eigentstate ν_α produced at t = 0:

$$|\nu(t)\rangle = e^{i\mathbf{p}\cdot\mathbf{r}} \sum_k U_{\alpha k} e^{-iE_k t} |\nu_k\rangle \qquad E_k = \sqrt{p^2 + m_k^2}$$

The phases: $e^{-iE_k t}$ will be different if $m_j \neq m_k$

Projecting ν(t) on the flavor basis one can obtain the probability of finding other flavours:

→ **Appearance of the flavour $\nu_\beta \neq \nu_\alpha$ for t > 0**

Simplified case: two neutrinos mixing

Only one mixing angle θ is needed

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_\beta\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

If $\nu = \nu_\alpha$ at (t = 0):

$$|\nu(t)\rangle = e^{i(\mathbf{p}\cdot\mathbf{r} - E_1 t)}\left[\cos\theta|\nu_1\rangle + e^{-i(E_2 - E_1)t}\sin\theta|\nu_2\rangle\right]$$

Probability of detecting ν_β at the instant t if $\nu(0) = \nu_\alpha$:

$$\mathcal{P}_{\alpha\beta}(t) = \left|\langle \nu_\beta | \nu(t)\rangle\right|^2 = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 t}{4E}\right)$$

$$\hbar = c = 1$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Oscillatory behaviour of $P_{\alpha\beta}$ with time ruled by two parameters:

θ is related to the amplitude of the oscillation

Δm^2 is related to the wavelength

$$E_2 - E_1 \approx \frac{m_2^2 - m_1^2}{2p} \approx \frac{m_2^2 - m_1^2}{2E} \equiv \frac{\Delta m^2}{2E}$$

For m<<p, and assuming propagation in vacuum:

$$E = \sqrt{p^2 + m^2} \approx p + \frac{m^2}{2p}$$

In more empirical units:

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(1.267\Delta m^2 \frac{L}{E}\right)$$

Δm^2 [eV^2]

$L=ct$ [km] (distance among the neutrino source and the detector)

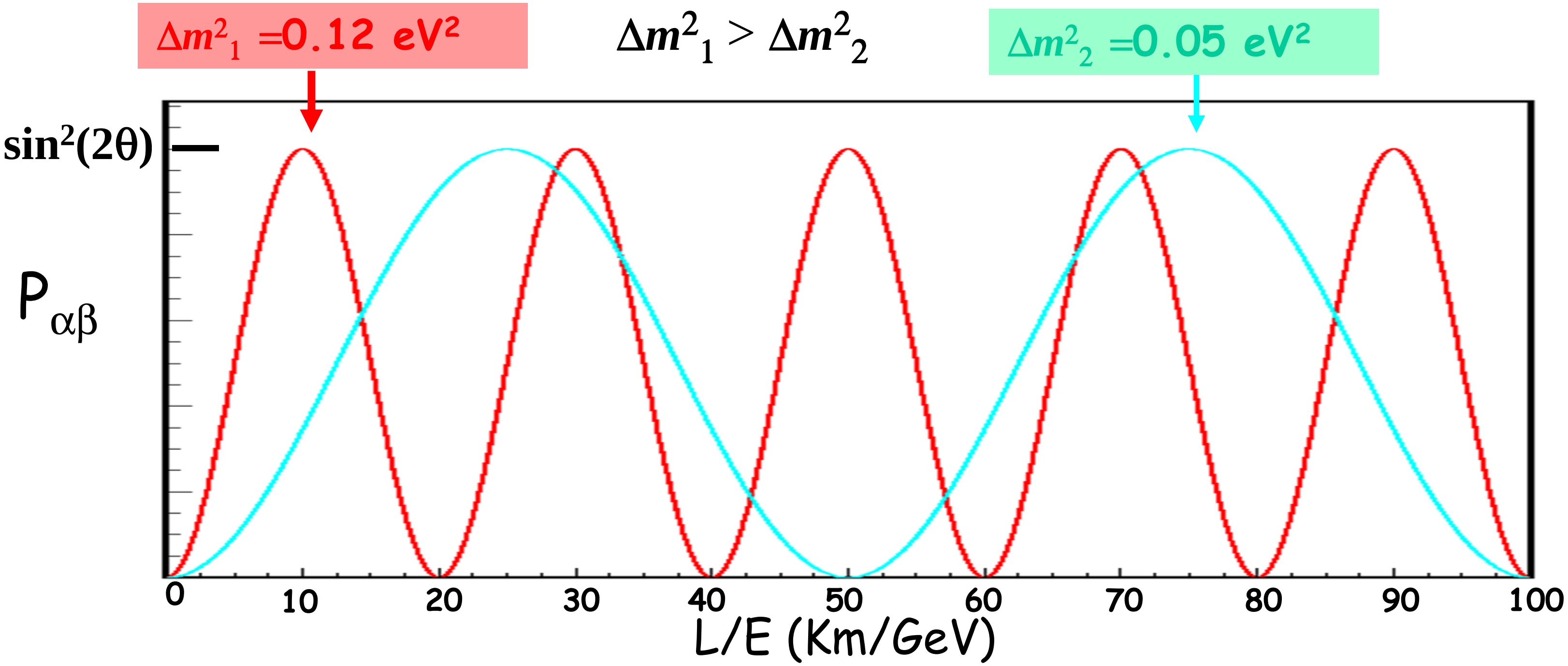
E [GeV] (neutrino energy)

Given Δm^2 the experimental quantity for the study of neutrino oscillations is the ratio L/E [km/GeV]: first oscillation maximum at L/E ~ 1.24 / Δm^2

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2\left(\pi\frac{L}{\lambda}\right)$$

$$\lambda = 2.48\frac{E}{\Delta m^2}$$

Oscillation wavelength



For very large Δm^2 the oscillations become very fast and average over the dimensions of the source and of the detector:

$$\rightarrow \quad \langle \sin^2(1.267\ \Delta m^2\ L/E)\rangle = 1/2 \qquad P=(1/2)\sin^2(2\theta)$$

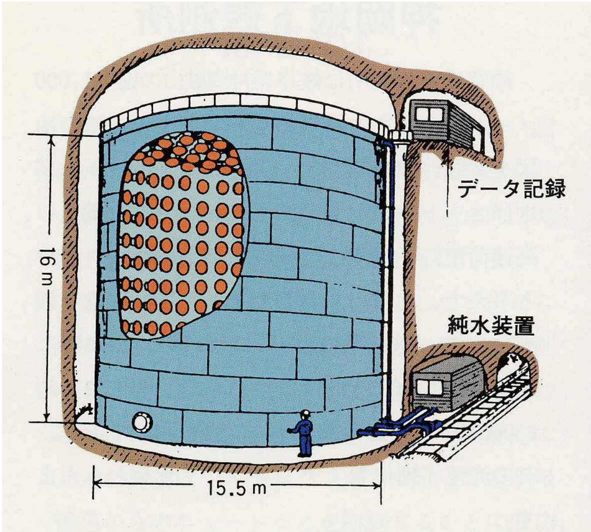
The baseline is related to the L/E ratio of the experimental setup:

Short Baseline experiments: sensitive to large Δm^2 (> 1 eV^2)

Long Baseline experiments: sensitive at least to Δm^2 of interest for the atmospheric neutrino anomaly (<10^{-2} eV^2), L/E > 100 Km/GeV

Reactors: L>0.3 Km, E~3 MeV
Accelerators: L>100 Km, E~1 GeV

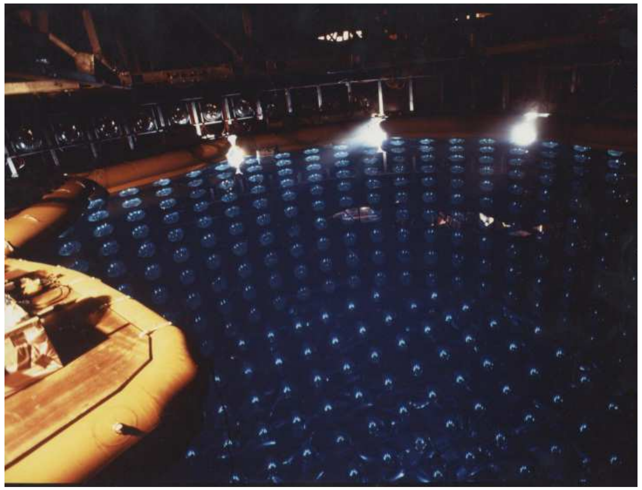
Water Cerenkov experiment (Kamiokande 1987-1994)

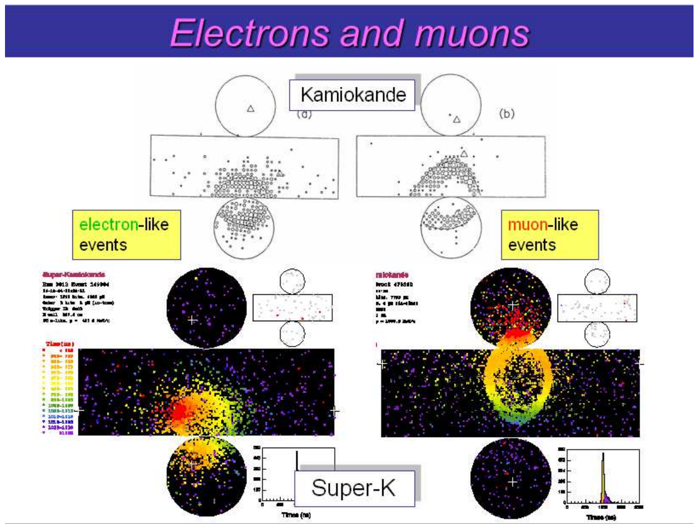


Particle detection by emission of Cerenkov light in water (680 tons) → (electrons, muons)

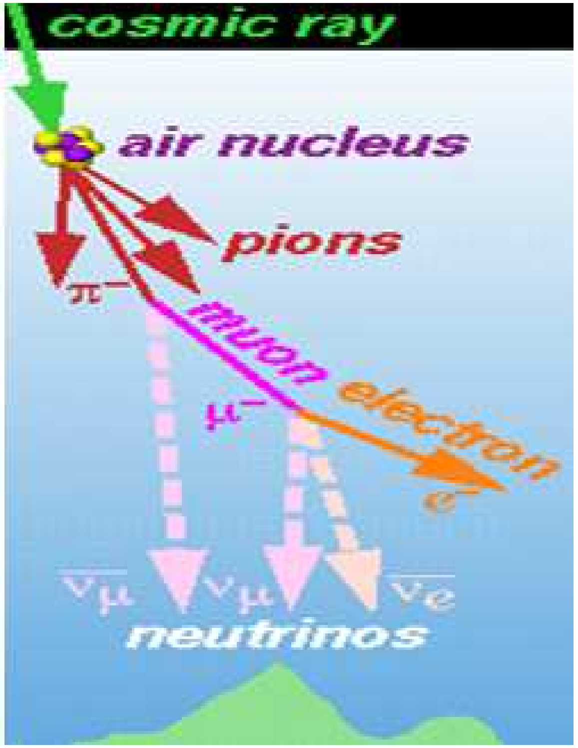
Built for proton decay search
Neutrinos produced by cosmic rays in the atmosphere are a background for cosmic rays
→ Studying this background people realize that it is different than expectations

→ Can look at solar neutrinos (high threshold > 5 MeV) by elastic scattering on electrons (emitted electron at 5 MeV stops in ~2 cm in water)
→ Deficit of solar neutrinos ~50%

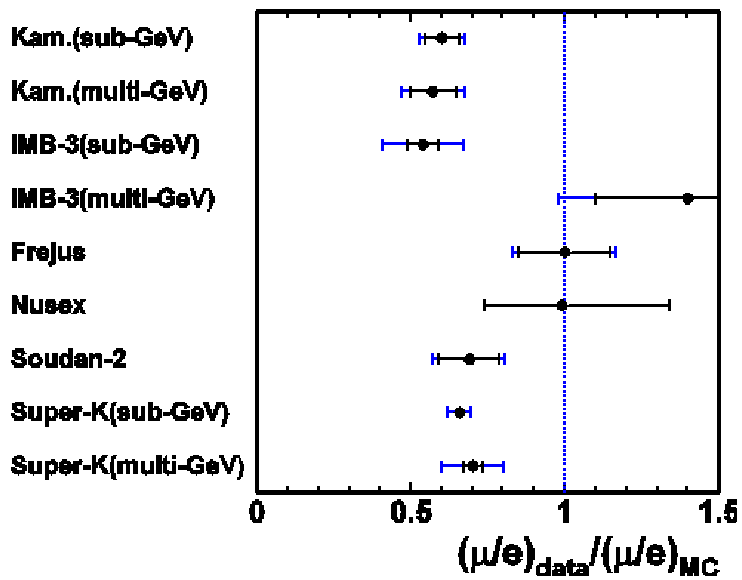




Atmospheric neutrinos anomaly



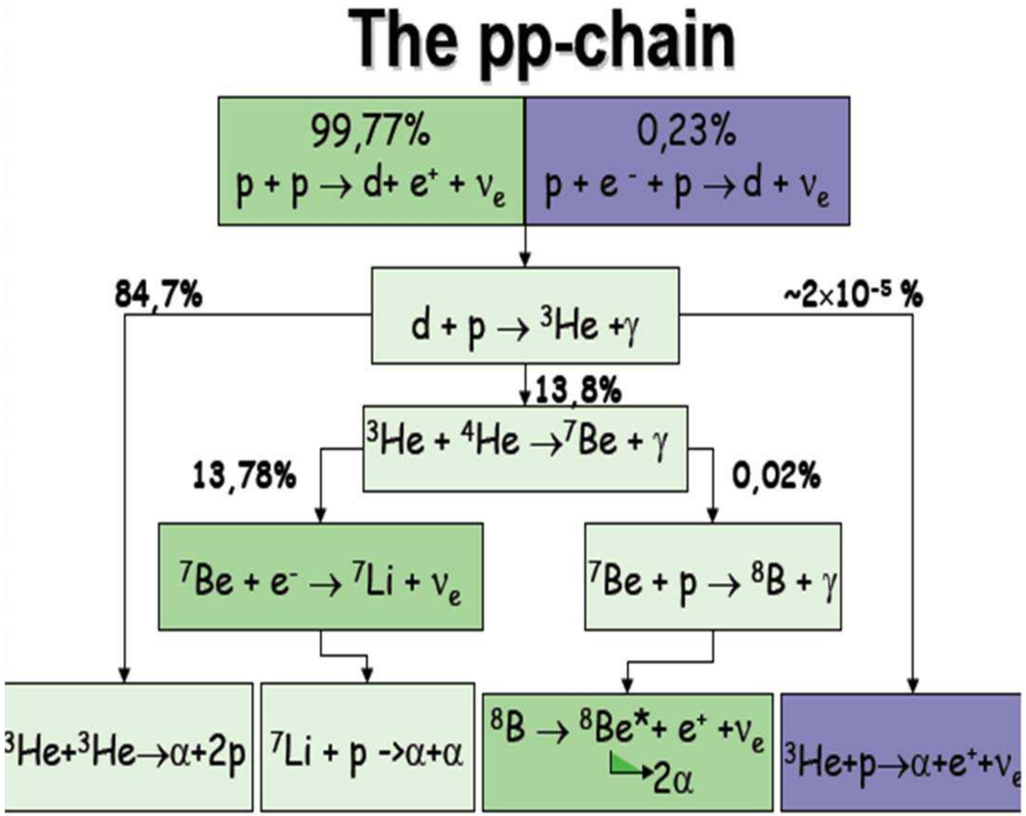
Let's write the atmospheric ν_μ deficit by $(\mu/e)data/(\mu/e)MC$

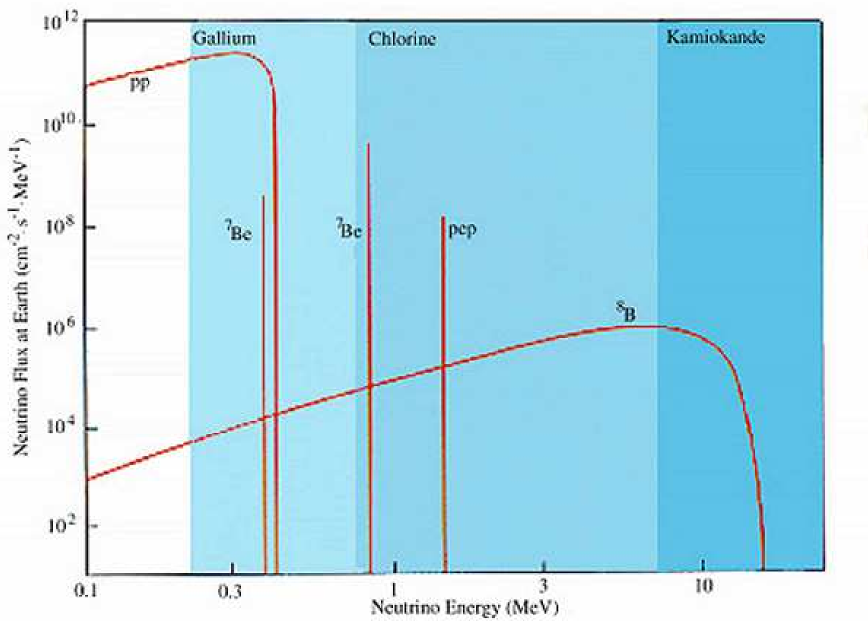


Unclear situation among different experiments

Interpretation in terms of neutrino oscillations (both $\nu\mu \rightarrow \nu e$ and $\nu\mu \rightarrow \nu\tau$) with $\Delta m^2 \sim 10^{-2}\ eV^2$

Some hints of dependence on the zenith angle





1% uncertainty

20% uncertainty

Gallex (1991-2002): radiochemical experiment with Gallium looking at low energy neutrinos (>0.233 MeV) from pp cycle

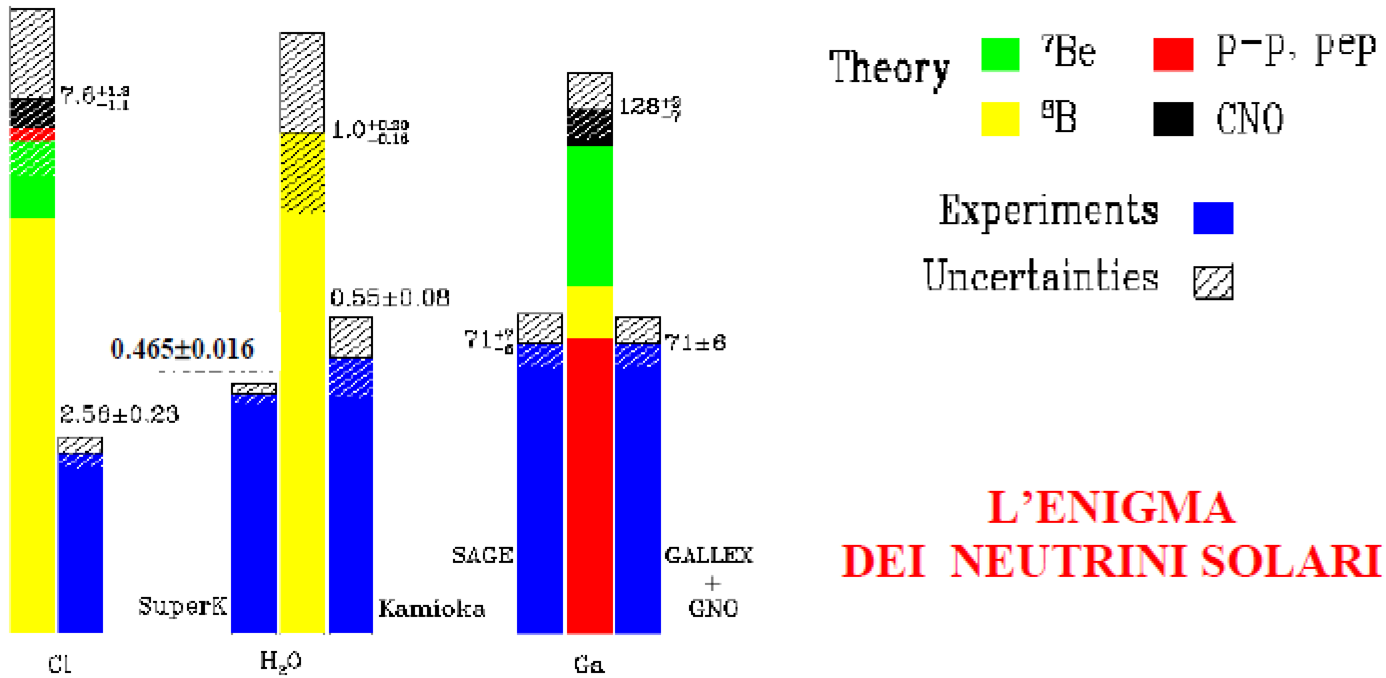
→ Confirms the deficit but:
Data/SSM = 0.56

$$\nu_e + {}^{71}\mathrm{Ga}_{31} \rightarrow e^- + {}^{71}\mathrm{Ge}_{32}$$

In parallel many checks are performed also on the Standard Solar Model

The 3 experiments give different results (in particular Homestake) even considering neutrino oscillations as an explanation

Is there an energy dependence of the solar neutrino deficit?



L'ENIGMA DEI NEUTRINI SOLARI

A more complex mechanism MSW which includes in the oscillations mechanism resonant effects of neutrino interactions with matter can explain the 3 results

Neutrino oscillation searches at the beginning of 90s

(long time ago in neutrino physics, not so much in everydays life …)

U.S. new president in 1993

- The long standing (since 1968) problem of the solar neutrino deficit opened by the Homestake measurements (+ Kamiokande since 1986)
In 1992 first Gallex results confirm the deficit also for neutrinos from the pp cycle

- Atmospheric neutrino anomaly still quite weak

The controlled observation of neutrino oscillations with an accelerator neutrino beam would have been a great discovery, where to search ?

Prejudice towards small mixing angles and large Δm^2

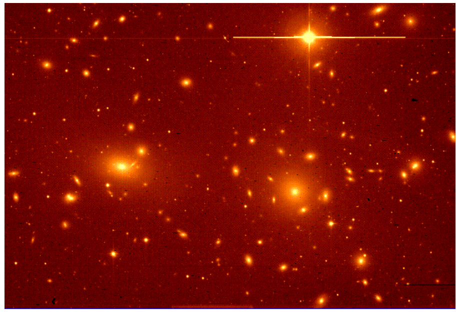
✓Take the MSW solution of the solar neutrino deficit: $\Delta m^2_{\mu e} \sim 10^{-5}$ eV^2

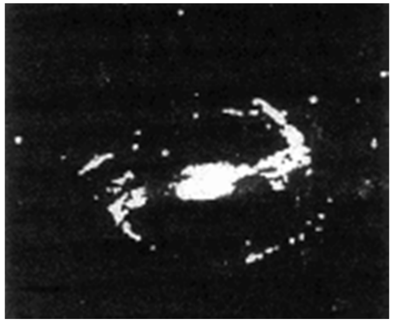
✓Assume a strong hierarchy: $m_{\nu e} \ll m_{\nu\mu} \ll m_{\nu\tau} \rightarrow m_{\nu\mu} \sim 3\times10^{-3}$ eV

✓Assume the See-Saw mechanism: $m(\nu_i)=m^2(f_i)/M$
M=very large Majorana mass $m(f_i)$= e.g. quark masses

Then: $m_{\nu\tau} \sim 30$ eV (Cosmological relevance)

Dark matter

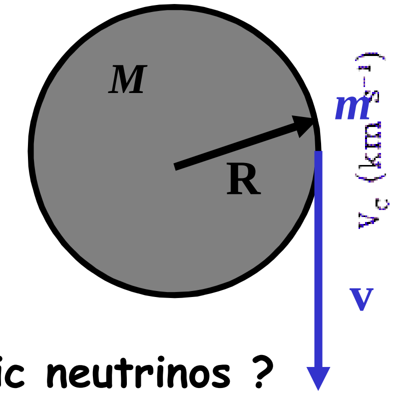


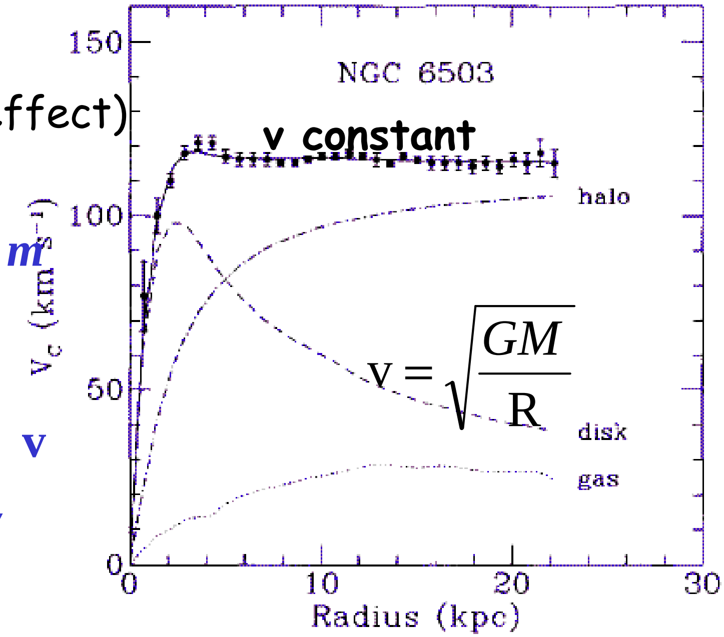


Coma cluster of galaxies, application of the virial theorem by F. Zwicky (1933)
velocity dispersion, geometric size → **total mass (x400 luminous mass)**

Rotational velocity curves of galaxies (Hydrogen, doppler effect)

$$m\frac{v^2}{R} = \frac{GMm}{R^2}$$





Could it be due to the BIG BANG relic neutrinos ?
112 ν/ cm³ per flavour

if $\sum m_i \approx 52$ eV then $\Omega_\nu = 1$

« ν are an important component of the dark matter » ~ a few 10 eV
Harari PLB 1989

1992 first measurements from the COBE satellite $\Omega \sim 1$

J. Ellis PLB 292 1992 $\Omega_{HDM} = 0.3$, $\Omega_{CDM} = 0.7$

Recent cosmological results: $\sum m\nu < 0.26 eV$ 95% CL

With $m_{\nu\tau}$ ~ 30 eV cosmological neutrinos important component of dark matter $\Delta m^2_{\mu\tau}$ O(100 eV²)

Look for $\nu_\mu \rightarrow \nu_\tau$ with short baseline experiments at accelerators, high energy beam

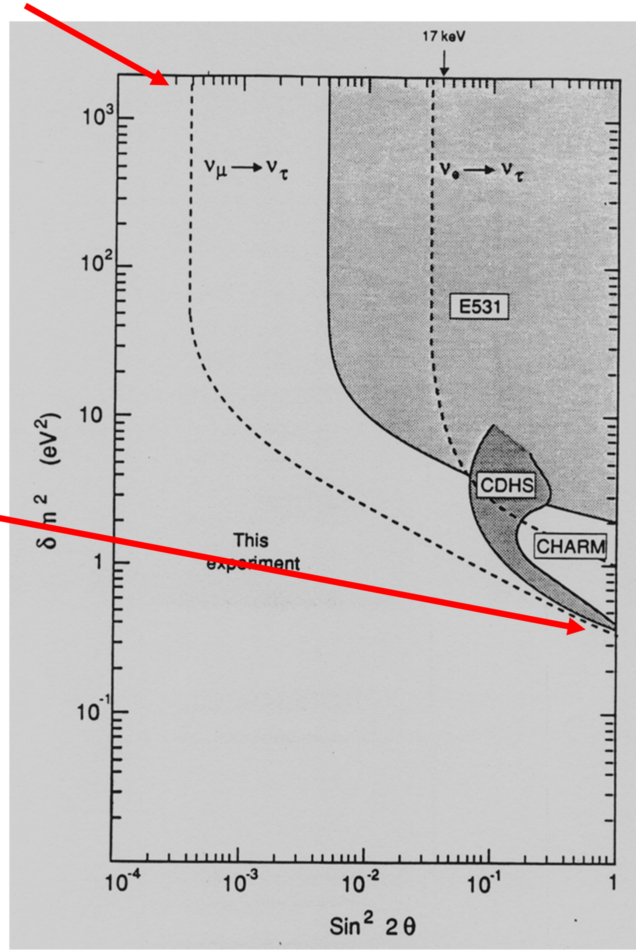
CERN ν_τ appearance experiments:

Search for ν_τ appearance from oscillations in the CERN wide band neutrino beam (WANF)

Pioneers of the technique also for long baseline experiments, important samples of neutrino interactions well measured

sensitive down to:

$P_{\mu\tau}$~ 1.5x10^{-4} (90% CL) **(x10) improvement**



$\langle E_\nu \rangle$=24 GeV
$\langle L \rangle$=600 m
sensitive to:
1 eV² < Δm^2

NOMAD:

- Proposal 1991
- Detector 1995
- Data-taking 95-98 (1.35 M ν_μ CC)

CHORUS:

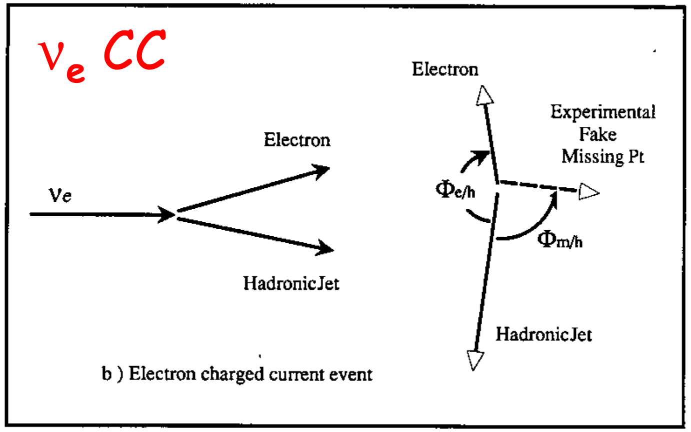
Data-taking 1994-1997 (0.71 M ν_μ CC)

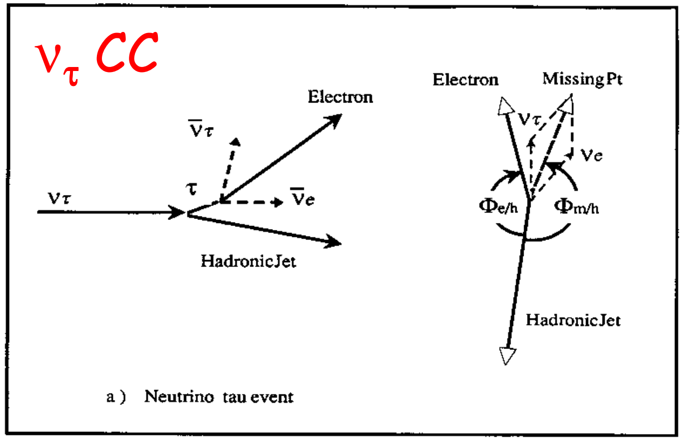
Use of kinematics to extract a ν_τ signal:

(First proposed by Albrigth and Shrock P.L.B. 1979)

NOMAD: fully reconstruct 1.7 M neutrino interactions, with good resolution, at single particles level:

→ Kinematics closure on the transverse plane





Find ντ down to Pμτ~ 10^{-4} in a large background:

1.3 M νμ CC

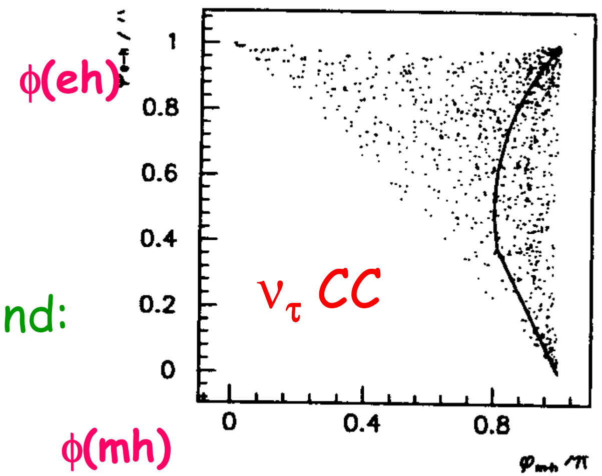
0,4 M νμ NC

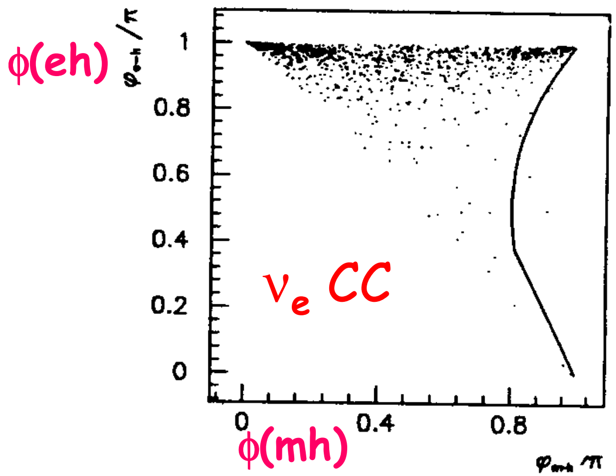
13 K νe CC

Exploit the small νe background:

τ->e channel: electron id

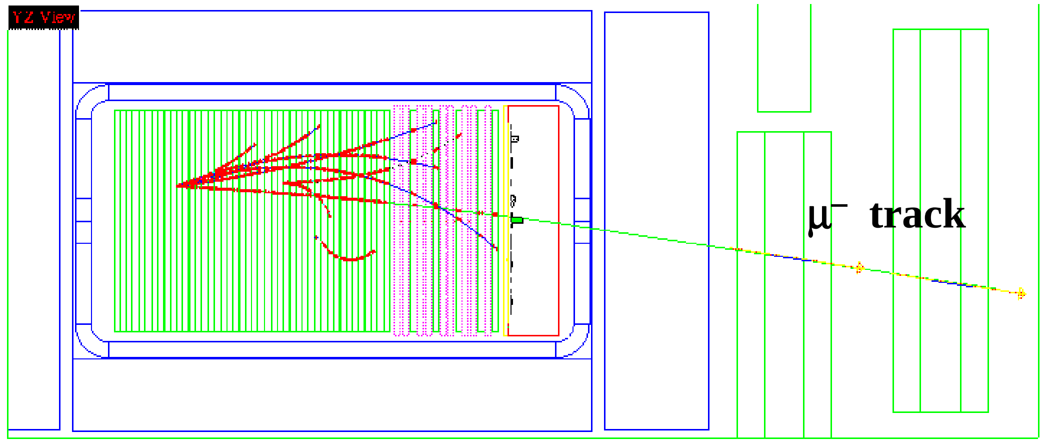
The ϕ- ϕ plot:



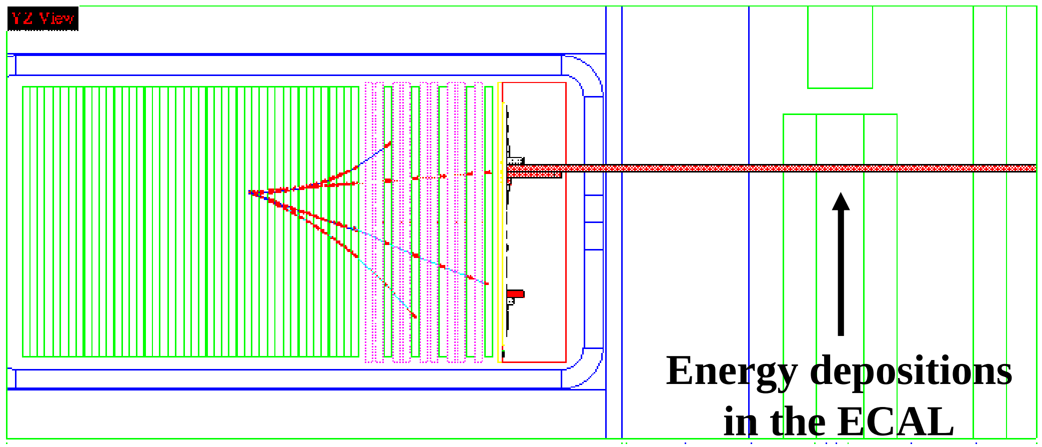


Nomad typical events:

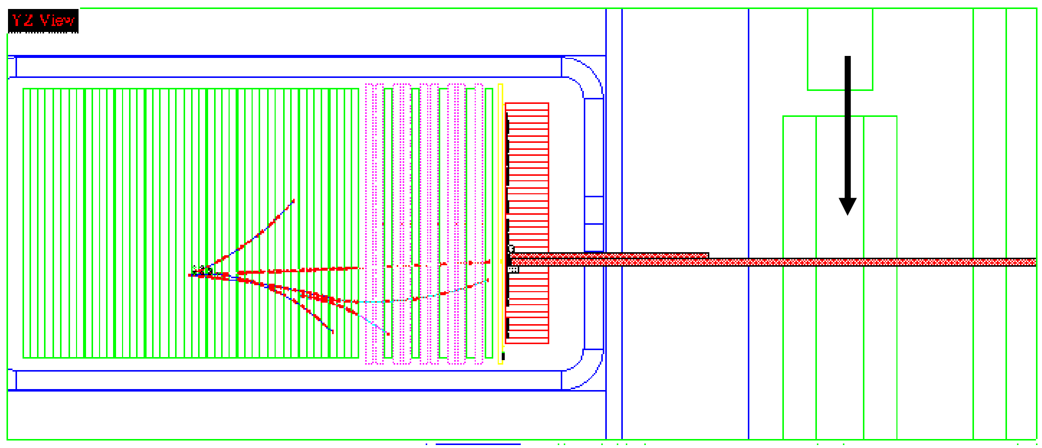
$$\nu_\mu + N \rightarrow \mu^- + X$$



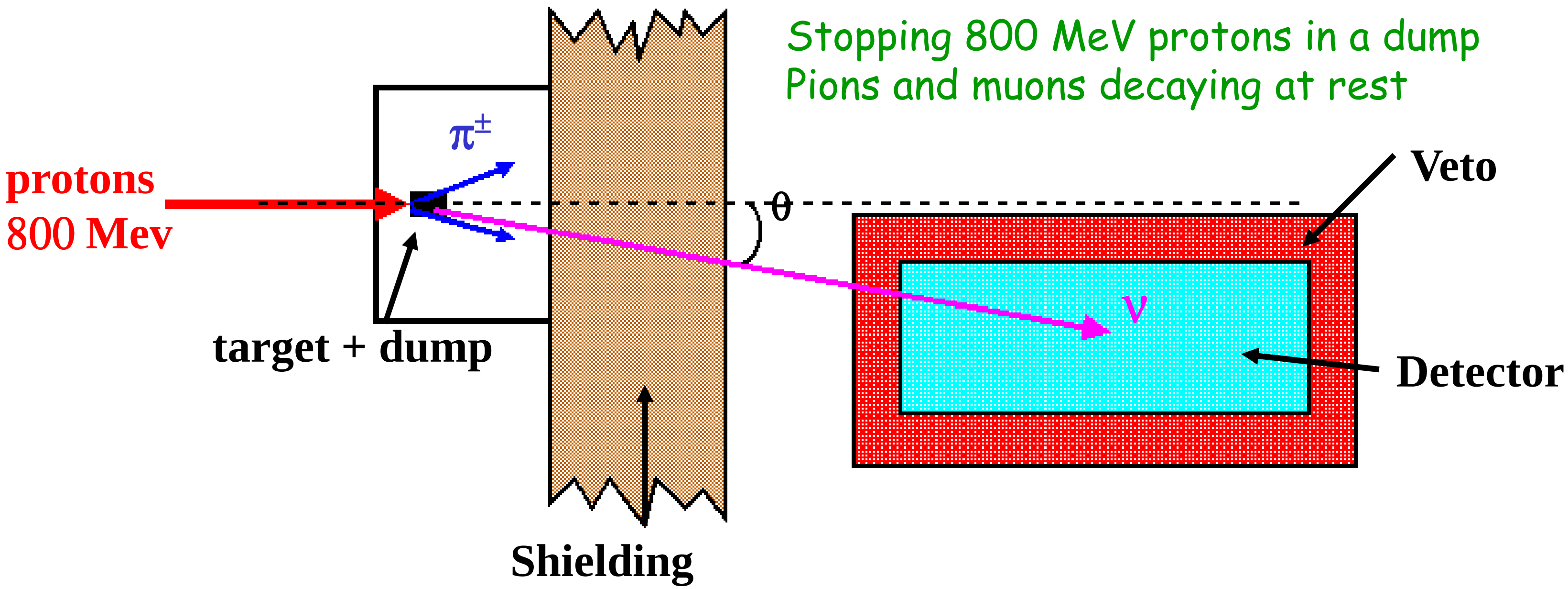
$$\nu_e + N \rightarrow e^- + X$$

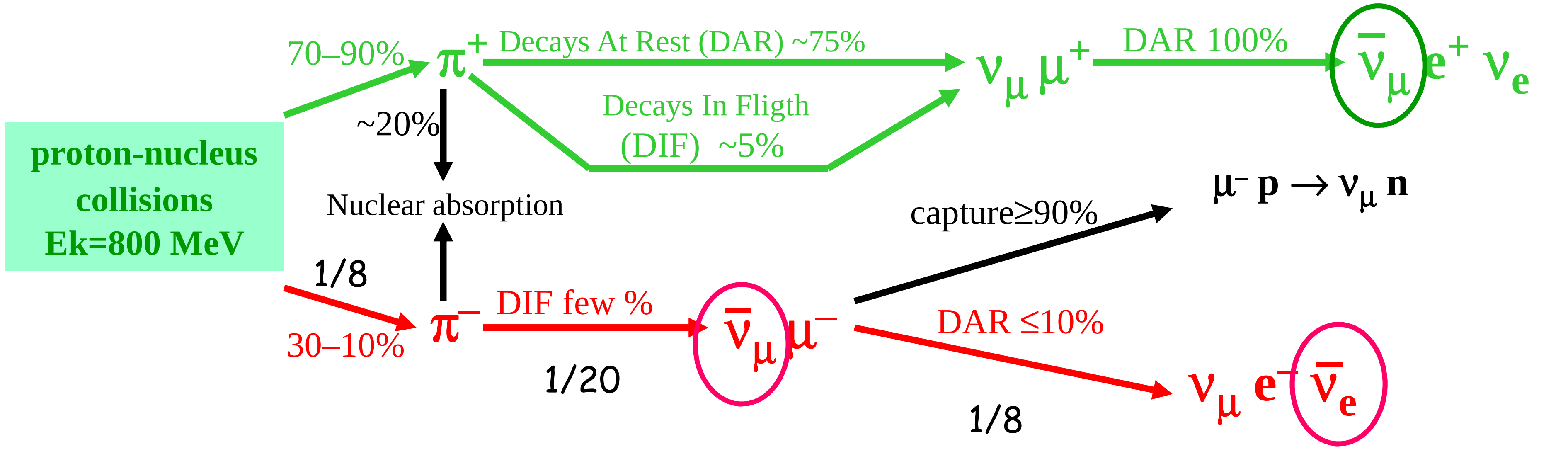


$$\bar{\nu}_e + N \rightarrow e^+ + X$$



The LSND experiment (1993-2001)





The only source of $\bar{\nu}_e$

$$\frac{\bar{\nu}_e}{\nu_e} \le 10^{-3}$$

Goal: search for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

LSND result: evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

Signal: Positrons with 20 < *E* < 200 MeV correlated in space and in time with the γ rays of 2.2 MeV expected from the neutron capture:

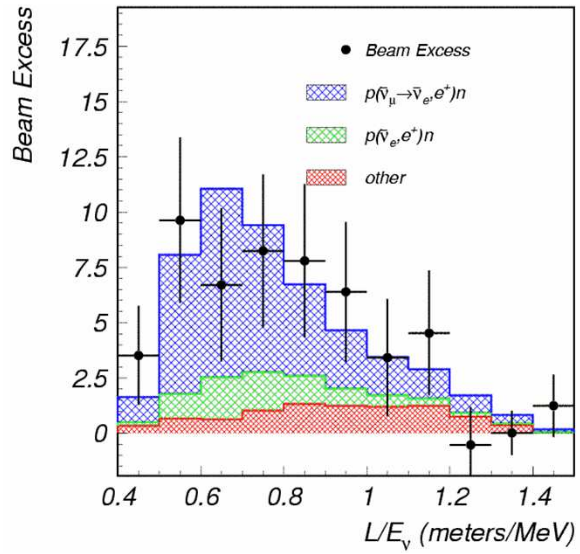
N("beam-on") – N("beam-off") = 117. 9 ± 22.4 events

Background due to μ^- DAR = 19.5 ± 3.9

Background from π^- DIF + ($\bar{\nu}_\mu + p \rightarrow \mu^+ + n$) = 10.5 ± 4.6

Signal $\bar{\nu}_e$ = 87. 9 ± 22.4 ± 6.0 events 3.8 σ effect
(stat.) (syst.)

$$\mathcal{P}_{osc}(\bar{\nu}_\mu - \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045) \times 10^{-2}$$



LSND has not been confirmed by dedicated experiment MINIBOONE (2001-2008)

However some small anomalies are still floating around in this domain feeding speculations and additional experimental activity

The oscillation signal $\bar{\nu}_\mu - \bar{\nu}_e$ in LSND complicates the global scenario: with 3 neutrinos only two independent Δm^2 are possible:

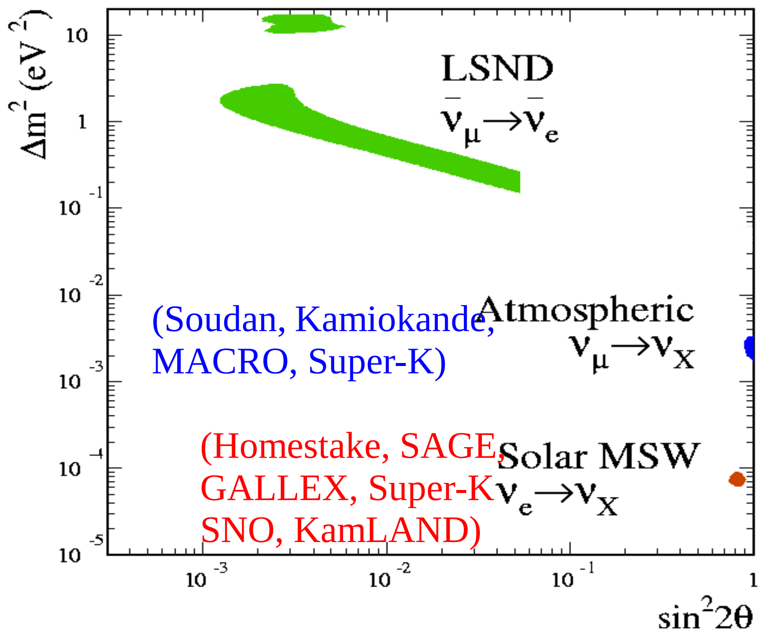
$$\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

$$\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$$

Oscillation signals:

- **Solar:** $\Delta m_{12}^2 \approx 7 \times 10^{-5}\ \mathrm{eV}^2$
- **Atmosperic:** $\Delta m_{23}^2 \approx 2.5 \times 10^{-3}\ \mathrm{eV}^2$
- **LSND:** $|\Delta m_{31}^2| = 0.2 — 2\ \mathrm{eV}^2$

$$|\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2| = 0.2 — 2\ \mathrm{eV}^2$$

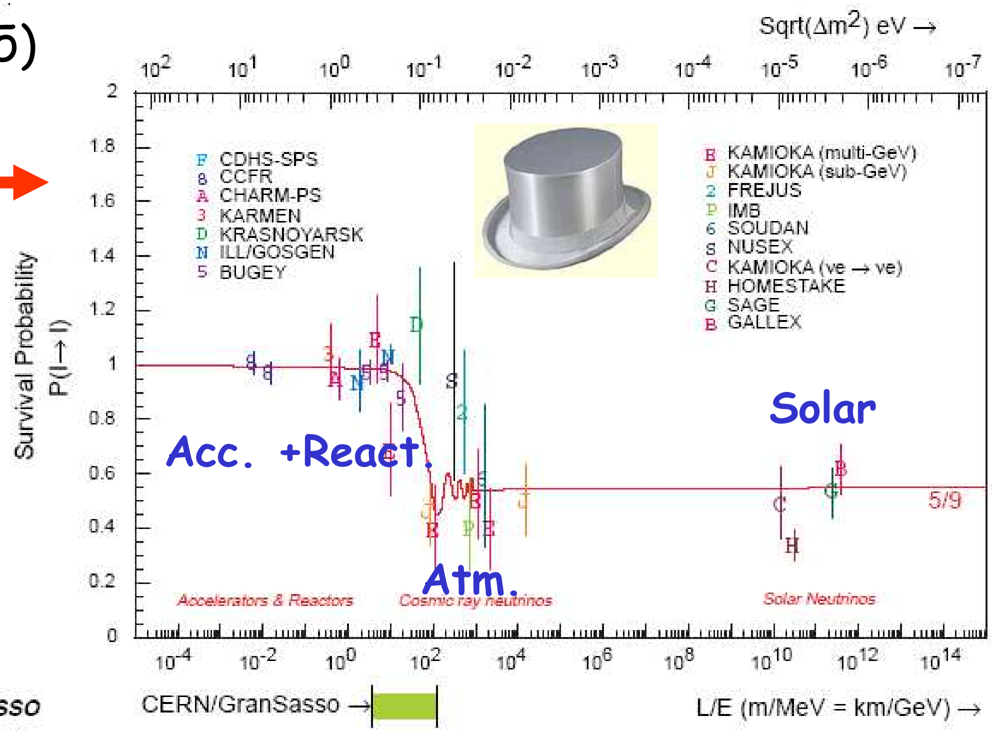


➢ At least 4 neutrinos are needed to reconcile all the results, from LEP it is known that the number of active light neutrinos is 3, so the other neutrinos must be sterile

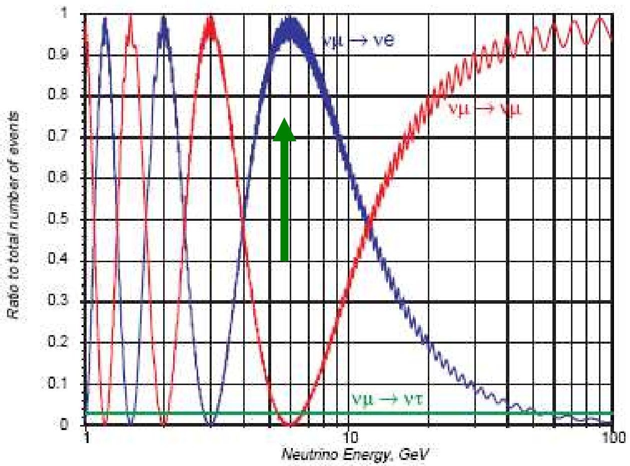
➢ Even under this assumption the global fit of oscillation signals is poor:oscillations involving sterile neutrinos are disfavoured for the Atmospheric and Solar neutrinos, more sophisticate mechanisms like CPT violation must be advocated

The Perkins plot (PLB 349 1995)

Interpretation of solar + atmospheric data in terms of just one $\nu_\mu \to \nu_e$ oscillation with $\Delta m^2 \sim 10^{-2}$ eV^2



The Acker-Pakvasa 3 flavours model **hep-ph/9611423** included also LSND ($\Delta m^2 \sim 1$ eV^2)

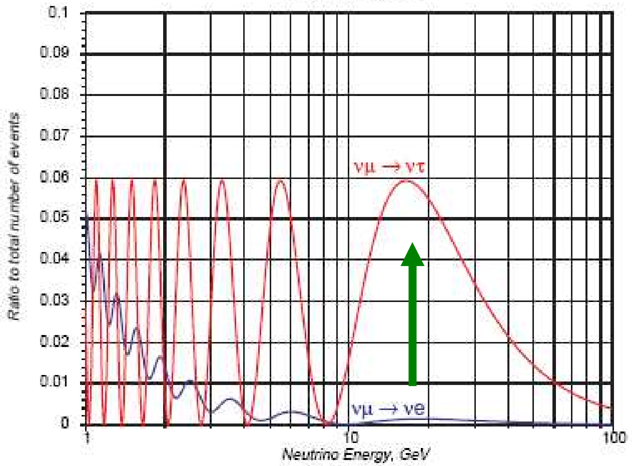


(C)
Gran Sasso
(735 km)

Icarus SPSLC 96/58 P304 19/12/1996

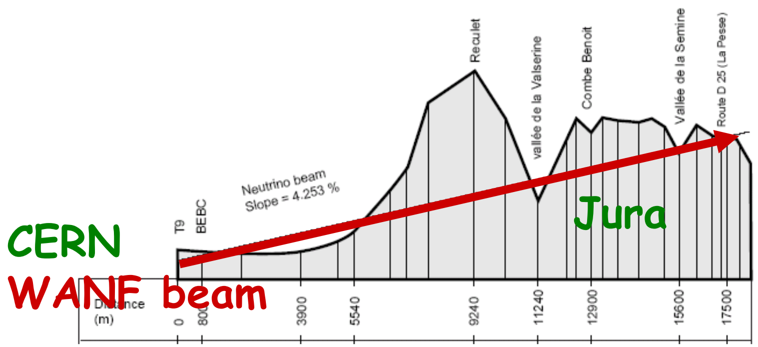
6. Conclusion

There is a substantial body of data leading to a theoretical prejudice which suggests that most probably the Gran Sasso and possibly the Jura locations, coupled with the SPS neutrino beam could be the real 'focal point' of the neutrino oscillation search. Spectacular $\nu_\mu \leftrightarrow \nu_\tau$ conversion is expected to be visible behind the Jura and a monumental $\nu_\mu \leftrightarrow \nu_e$ conversion is expected to be observed at the Gran Sasso position.

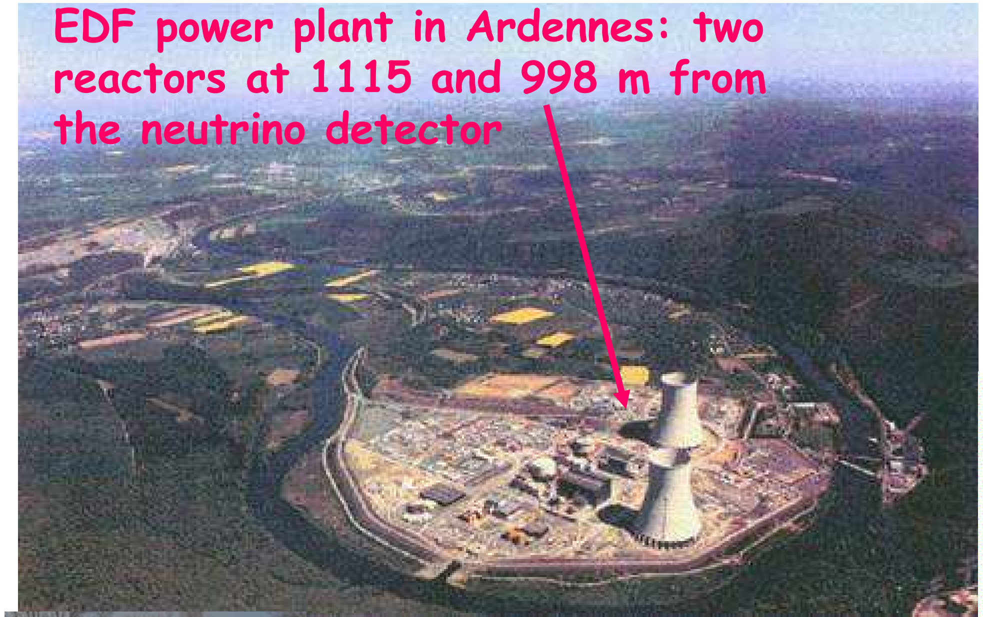


(B)
Behind Jura
(17 km)

Medium-baseline
L/E~1Km/GeV



CHOOZ (the first long baseline experiment) 1997-1998



$\bar{\nu}_e \rightarrow \bar{\nu}_e$ (disappearance experiment at nuclear reactor)

P_{th}= 8.5 GW_{th}, 1 detector at L ~ 1 km, overburden equivalent to 300 m H_2O, Reactor neutrino flux known at 2.7 %, L/E ~ 330 Km/GeV

Target: 5 ton liquid scintillator target with 0.09% Gadolinium

Prompt annihilation signal (γ rays)

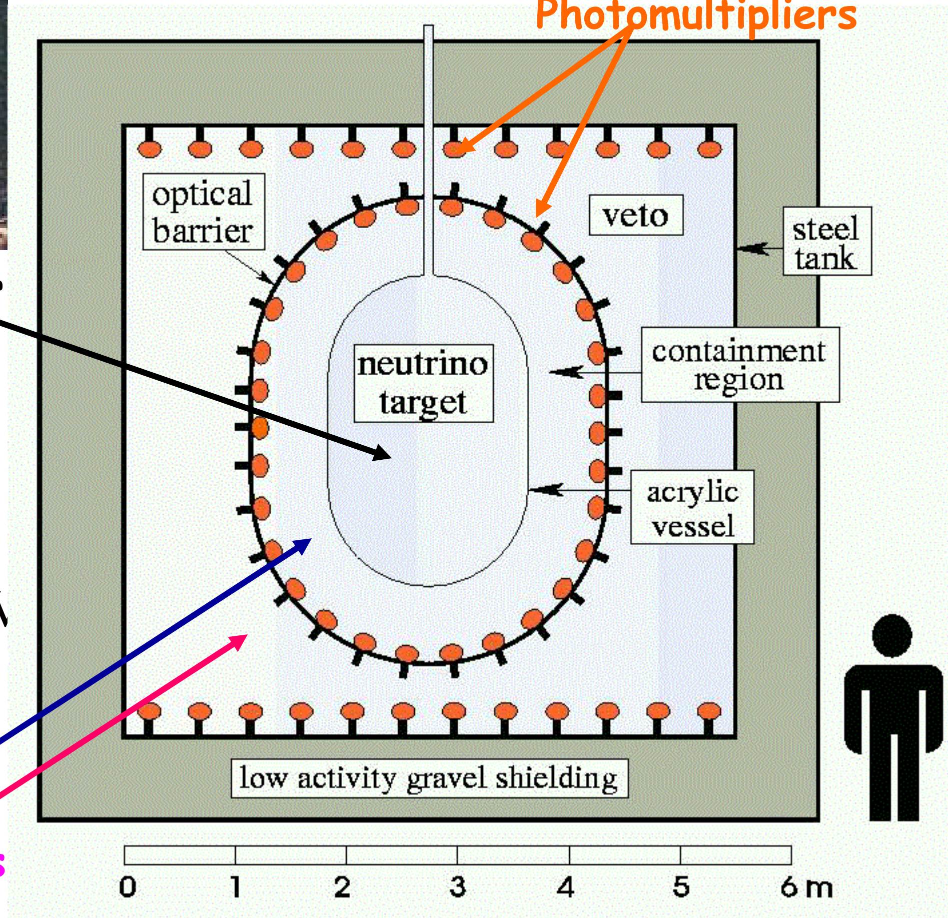
$\bar{\nu}_e + p \rightarrow e^+ + n$

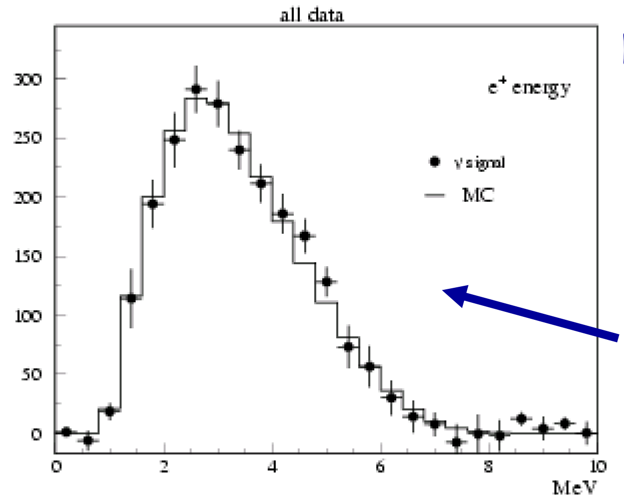
$n + Gd \rightarrow \gamma$ rays (E_{tot} 8.1 MeV

n capture on Gd after thermalization ~30μs

17 ton liquid scint. without Gd (containement of γ rays)

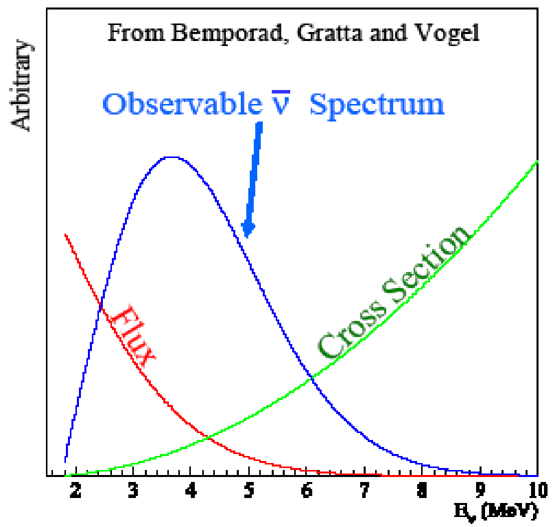
90 ton liquid scint. cosmic rays





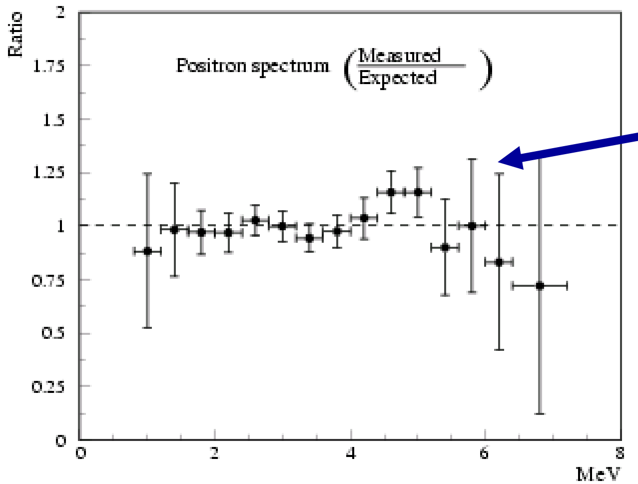
$N(\overline{\nu}_e) \sim 2\ 10^{20}\ s^{-1}/\ GW_{th}$

Signal ~ 25 events/day, background (reactors off) ~ 1.2 events/day



Energy spectrum of the positrons compared with the predicted one (no oscillations)

$E(\overline{\nu}_e) = E(e^+) + 1.8$ MeV



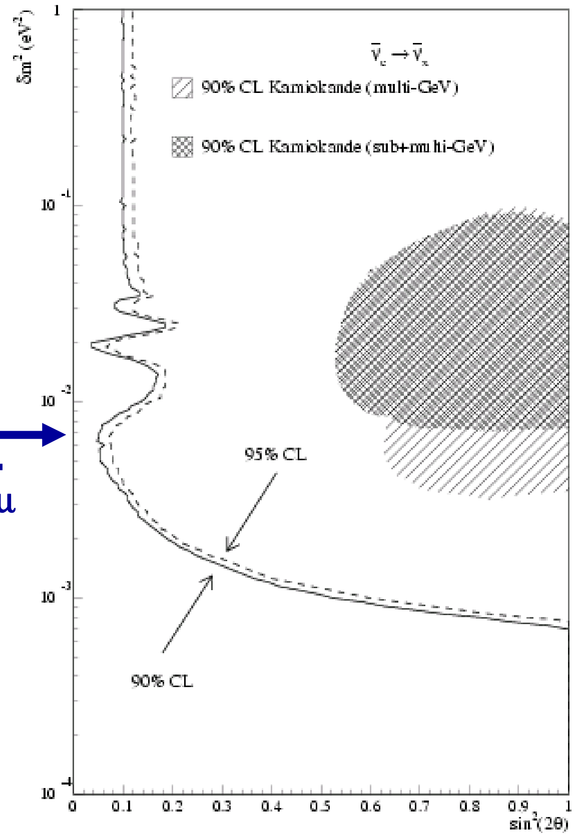
Ratio measured/expected

Integrated ratio = $1.01 \pm 0.028 \pm 0.027$

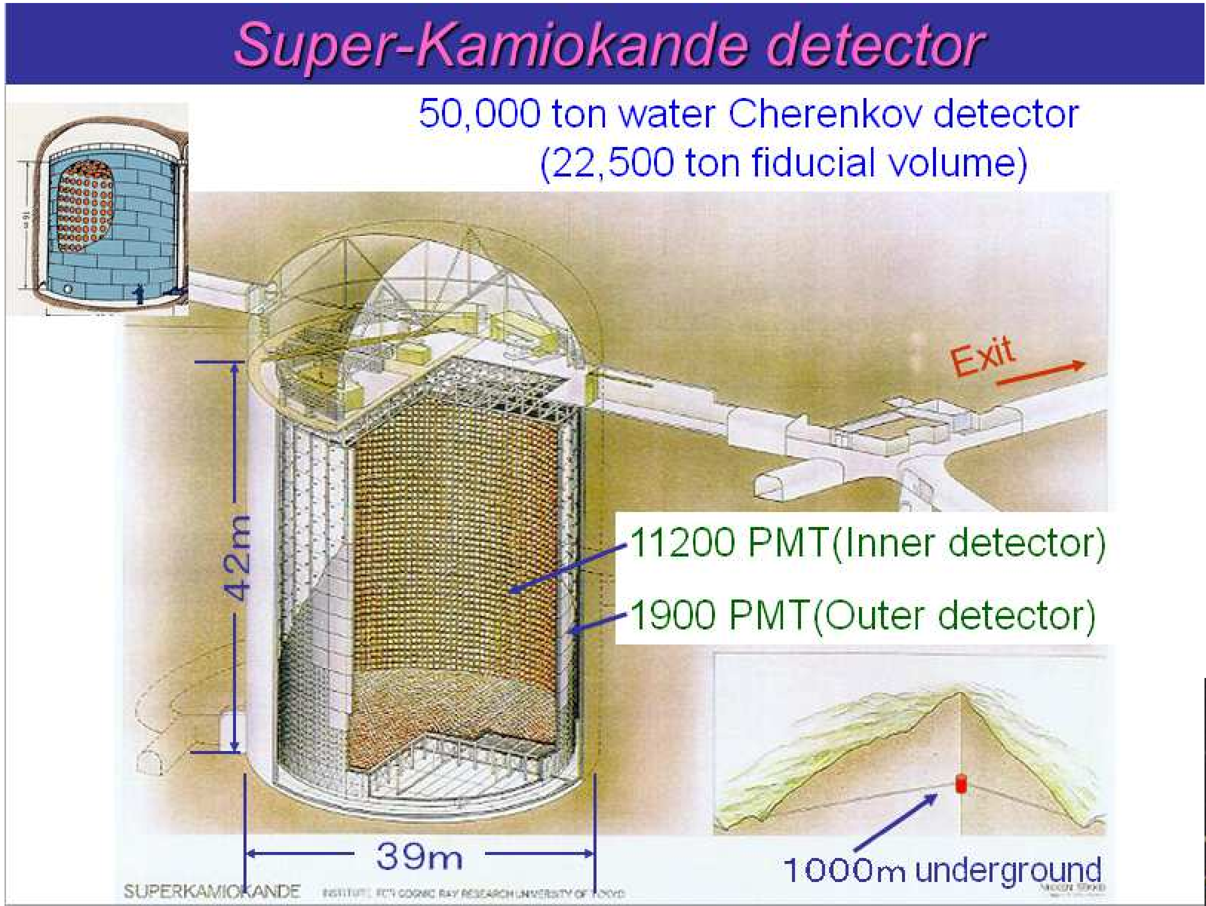
Positron energy (MeV)

CHOOZ did not observe a significative deficit of ν_e

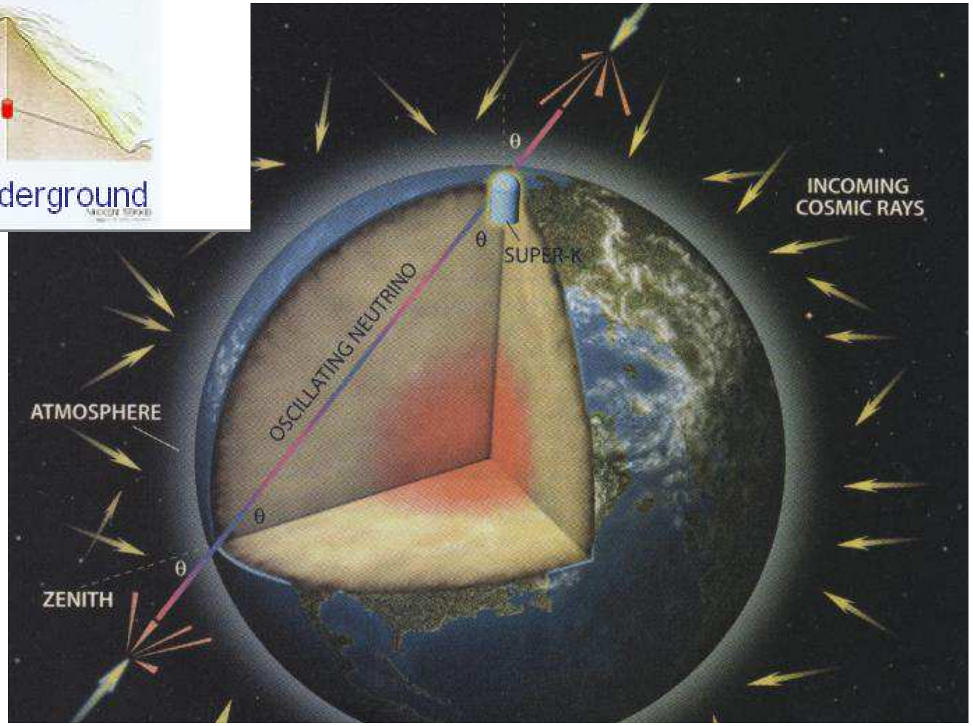
NO « monumental » $\overline{\nu}_e \rightarrow \overline{\nu}_\mu$ conversion



This result was published in 1998 before the Super-Kamiokande results and excluded the atmospheric neutrino anomaly interpretation in terms of $\nu_\mu \rightarrow \nu_e$ oscillations

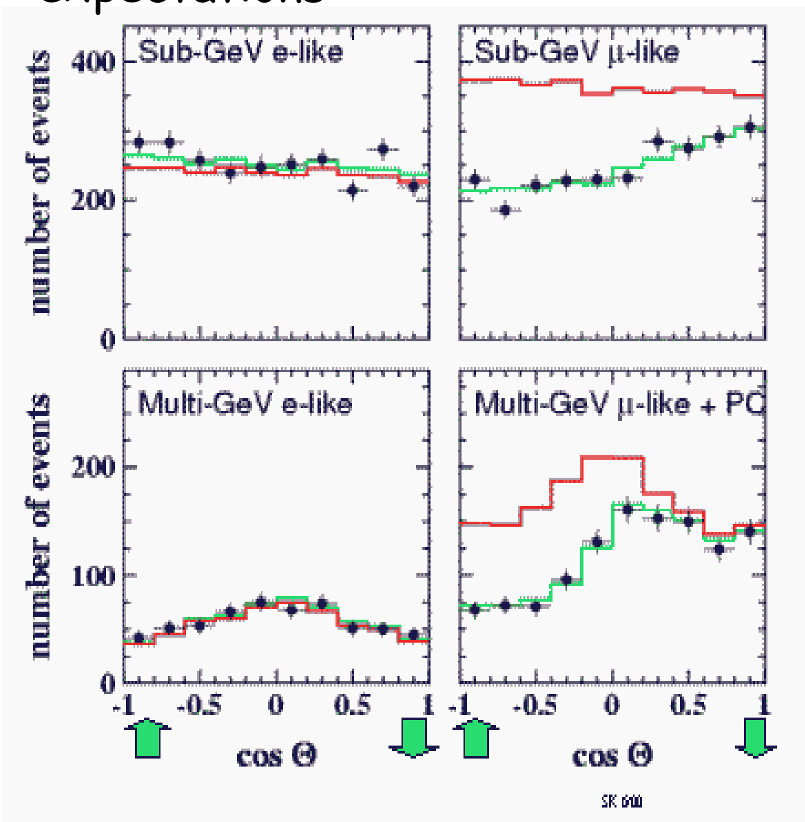


SuperKamiokande
1996- …. now



Neutrino 98 Conference in Takayama (June 1998)

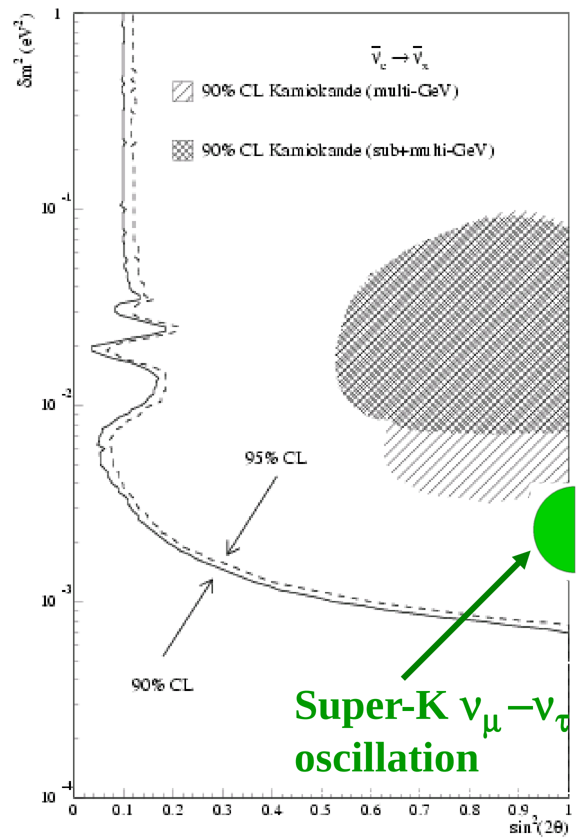
First results from Super-Kamiokande on atmospheric neutrinos, evidence of a zenith angle dependence of ν_μ disappearance, ν_e in agreement with expectations



SK: *Atmospheric neutrinos anomaly*

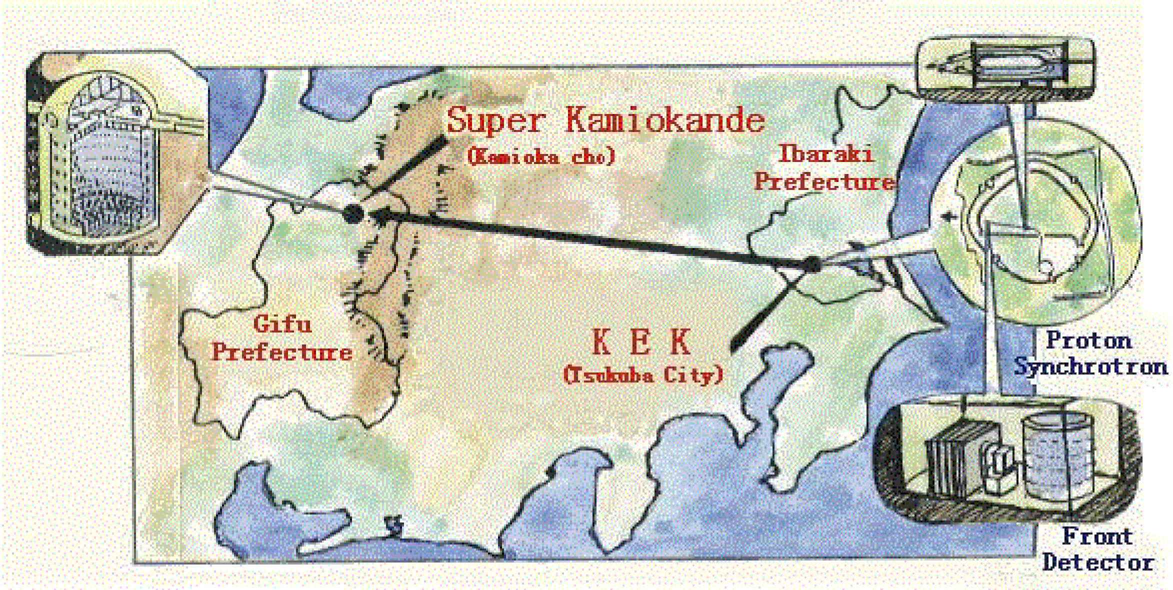
intepretable in terms of $\nu_\mu \rightarrow \nu_\tau$ oscillations with a $\Delta m^2 \sim$ a few 10^{-3} eV^2

CHOOZ: no $\nu_\mu \rightarrow \nu_e$ oscillations, Θ_{13}<11°



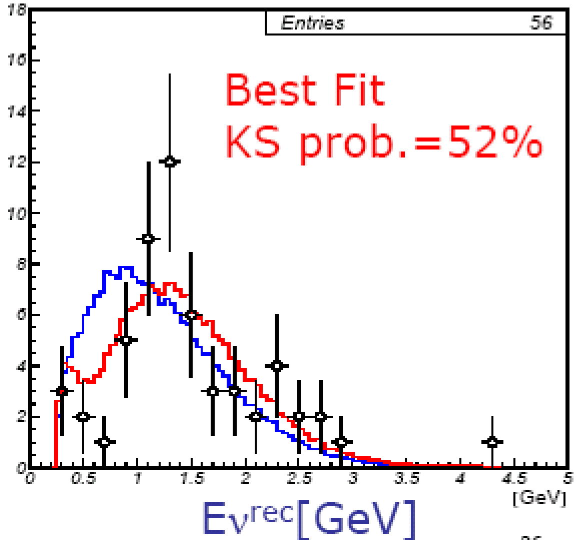
Neutrino oscillations start to be taken seriously as explanation of the atmospheric neutrinos anomaly

Opens a campaign for a new generation of long baseline experiments to provide a final proof

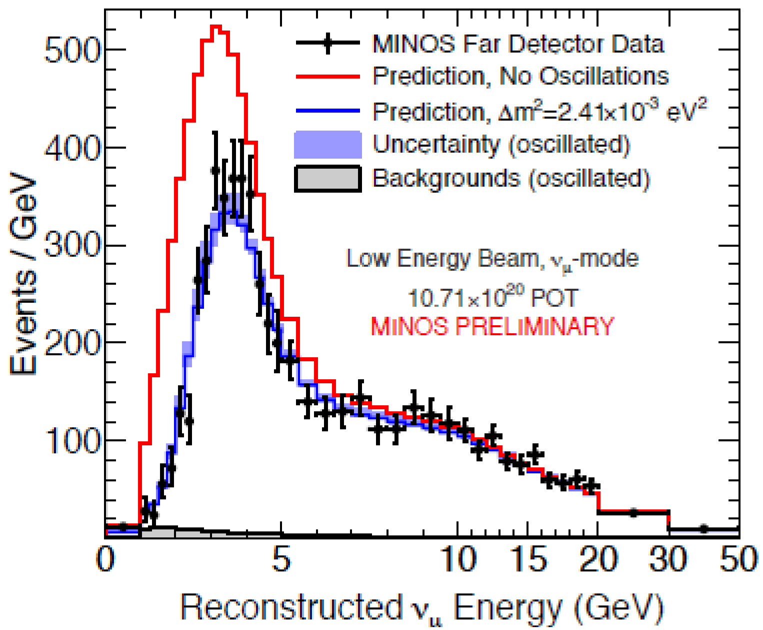


K2K results in 2004

- $N_{SK}^{obs}=108$
- N_{SK}^{exp} (best fit) $=104.8$



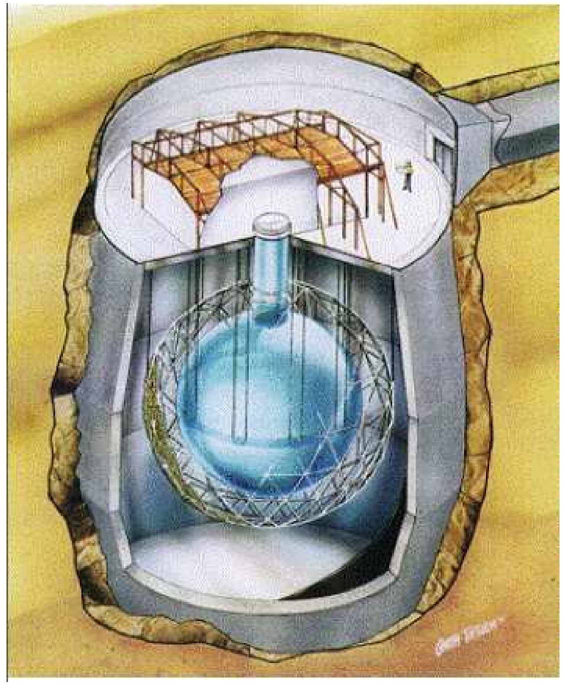
MINOS (U.S.) results in 2006



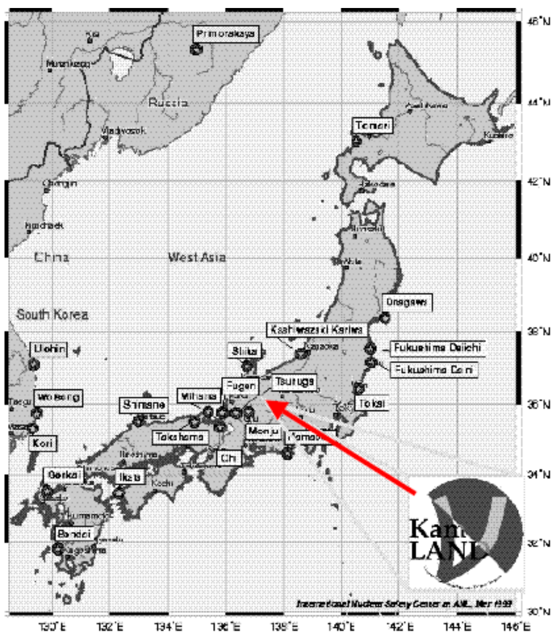
The final proof for solar neutrinos:

2001: SNO 1000 tons of heavy water, sensitive to neutral current reactions → measure the total neutrino flux independently from their flavor

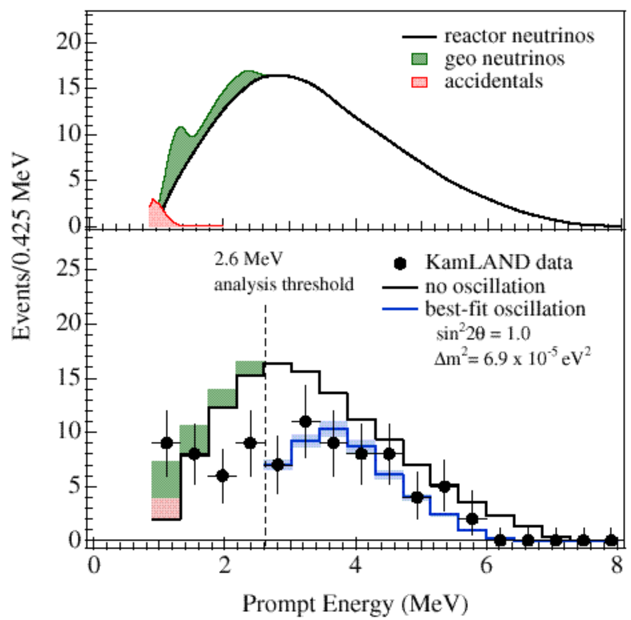
(NC) ν**+ d**$\rightarrow$$\nu$**+ p + n**

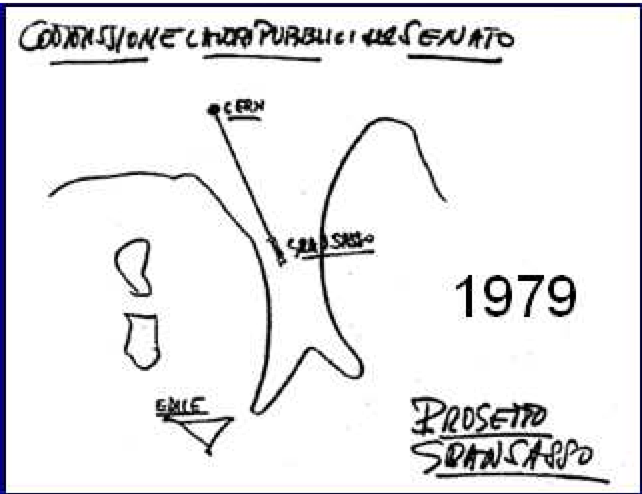


The total neutrino flux agrees with the SSM !
Electron neutrinos change into other neutrinos



2002: Kamland reactor experiment 1000 ton liquid scintillator reproduces the solar neutrino oscillations on earth using antineutrinos of far reactors (on average 180 km)





Cern Neutrinos to Gran Sasso

- Unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for ν_τ appearance in a pure ν_μ beam
- Search for the subleading $\nu_\mu \rightarrow \nu_e$ oscillations

- Beam: CNGS (1999)
- ν_τ appearance experiments at LNGS
- No near detectors needed in appearance mode

CNGS1 (2000) OPERA

CNGS2 (2002) ICARUS

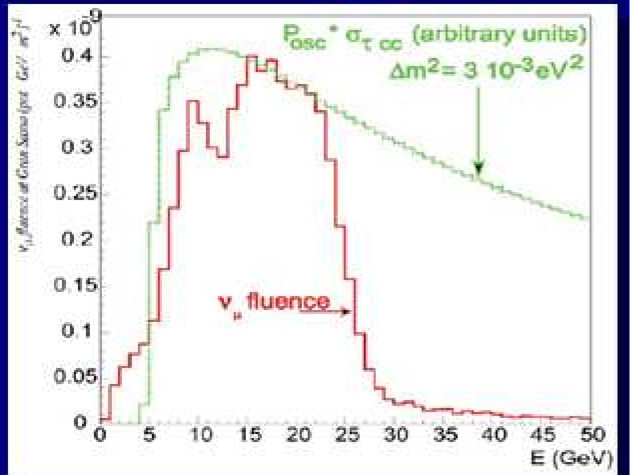
$$N_\tau \approx 1.61 \sin^2(2\theta)(\Delta m^2)^2 L^2 \int_{3.5\,GeV}^{E_{max}} \Phi_\mu(E) \frac{\sigma_\tau(E)}{E^2} dE$$

Dependence of the events rate on $(\Delta m^2)^2$

Signal constant as a function of L for L << λ
Φ_μ contains a factor $1/L^2$

Quantity to be optimized playing with the beam spectrum:
ν_μ flux vs $\sigma(\tau)/E^2$

→ produce the max. number of $\nu\tau$ CC



CNGS fluxes

<E (ν_μ)>	17 GeV
L	730 km
L/E	43 Km/GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$ CC	0.87%
$\bar{\nu}_\mu / \nu_\mu$ CC	2.1%
ν_τ prompt	negligible

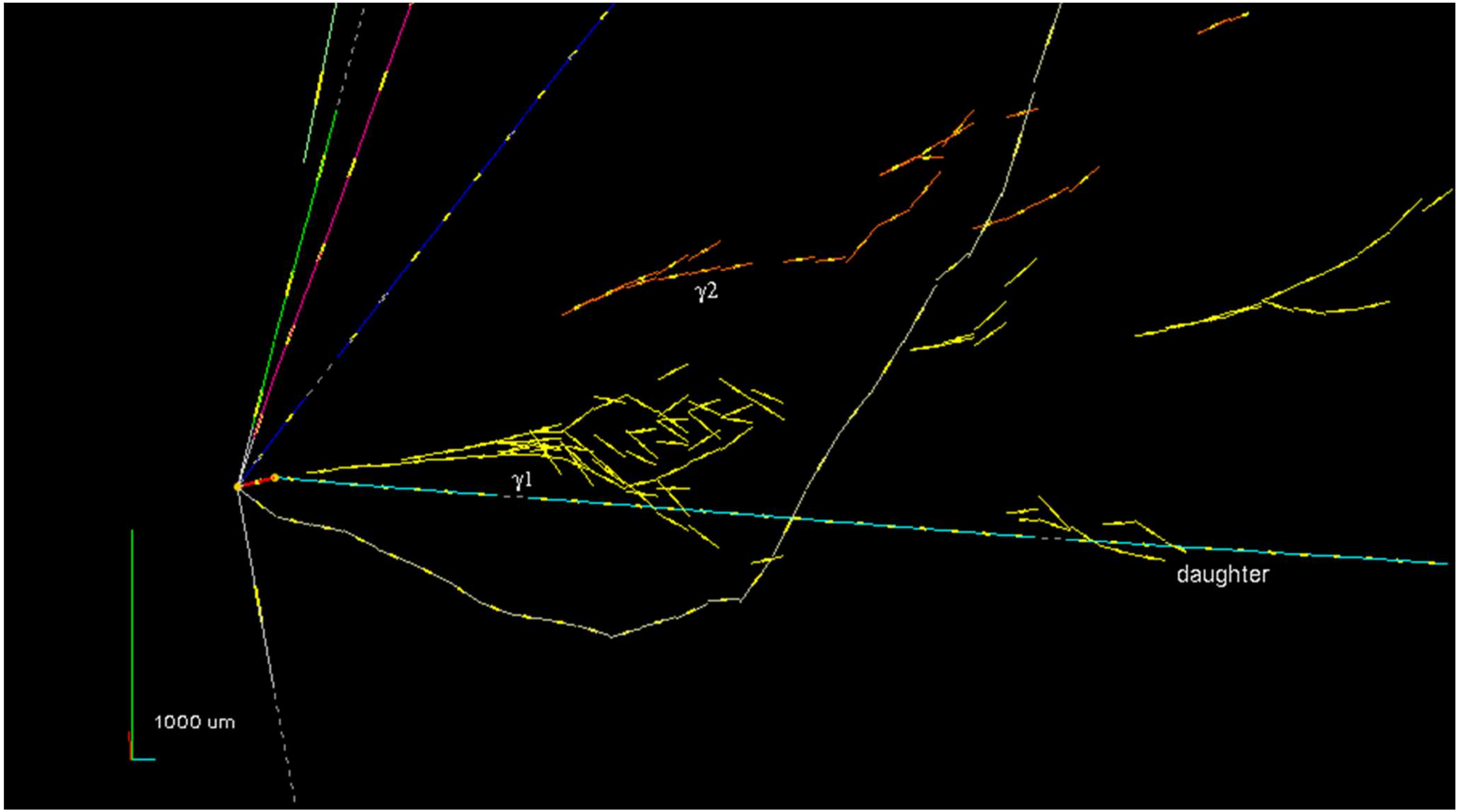
- Nominal beam performance (4.5 10^{19} pot/y)
- OPERA Target mass of 1.25 kton

→ Expected number of interactions in 5 years :
~ 23600 ν_μ CC+NC
~ 170 ν_e + $\bar{\nu}_e$ CC
~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV²)

After efficiencies, 8 tau decays are expected, with <1 background events

First OPERA ν_τ candidate
(single hadronic prong τ decay)

http://arxiv.org/abs/1006.1623
Physics Letters B (PLB-D-10-00744)



ν_τ + N → τ^- + X

$\tau^- \rightarrow \rho^- + \nu_\tau$

$\rho^- \rightarrow \pi^- + \pi^0$

$\pi^0 \rightarrow \gamma + \gamma$

Visible tau decay topology
with kink and two gammas

Neutrino velocity measurement

Time — Neutrinos production time (CERN)
Neutrinos interaction time (OPERA detector)

Space — Accurate determination of the distance (Geodesy)

→ Massive application of metrology techniques in HEP

2009-2011 measurement with standard CNGS beam → Blind analysis: "box" opened after assessment of delays, previously fixed to arbitrary values:

- High neutrino energy - high statistics ~15000 events
- Precise measurement of neutrino time distribution at CERN through proton waveforms
- Sophisticated timing system: ~1 ns CNGS-OPERA synchronization
- Calibrations techniques of CNGS and OPERA timing chains: ~ 1 ns level
- Measurement of baseline by global geodesy: 20 cm accuracy over 730 km (longest neutrino baseline actually available)

→ Result: ~10 ns overall accuracy on TOF with similar stat. and sys. errors

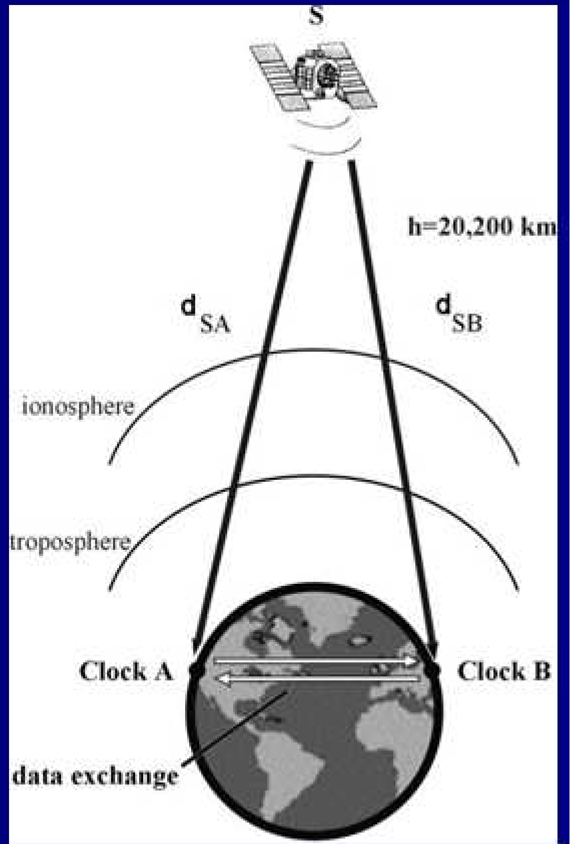
GPS common-view mode

R. Garwin
one of the fathers of GPS

Standard GPS operation:

resolves x, y, z, t with ≥ 4 satellite observations

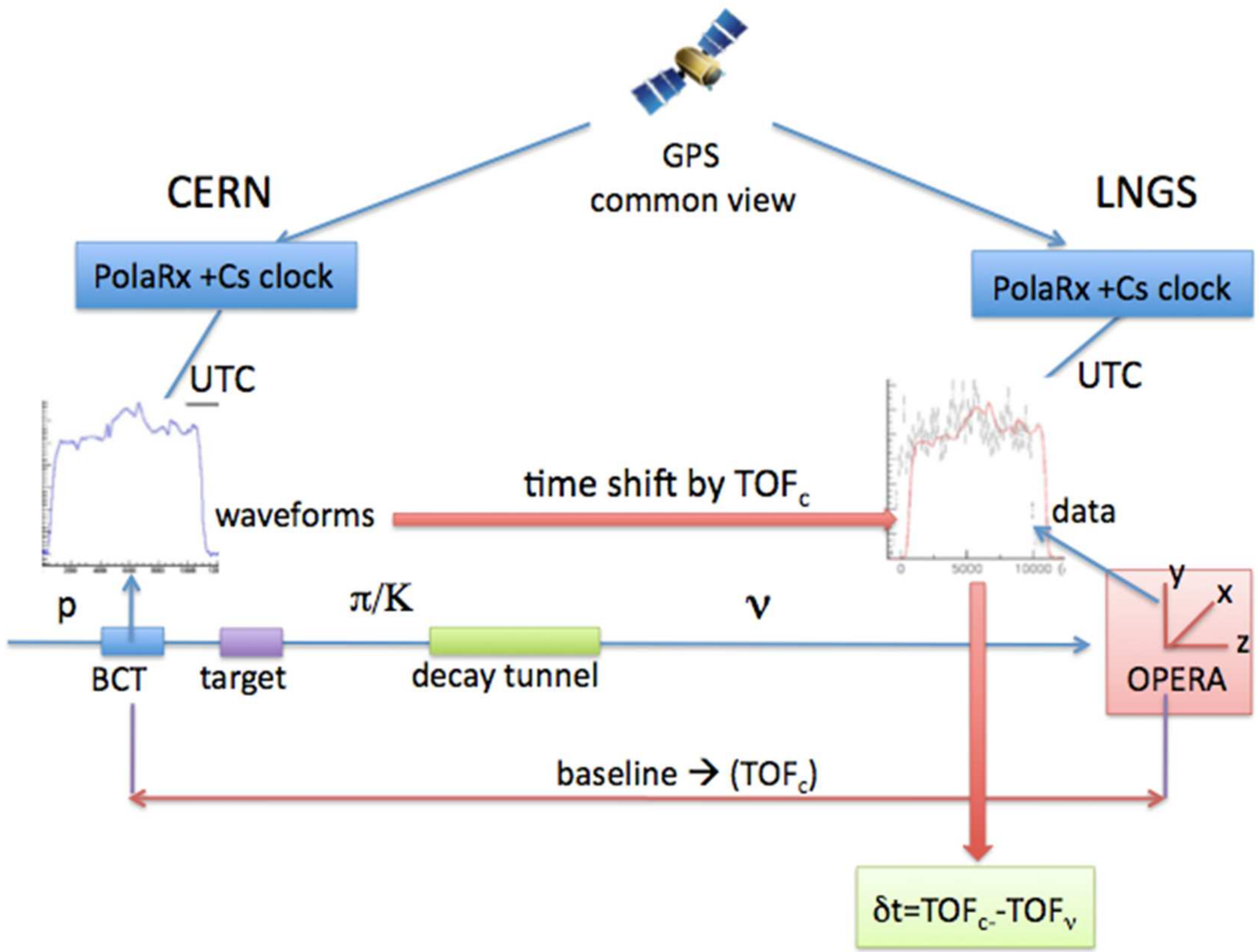
Common-view mode (the same satellite for the two sites, for each comparison): →



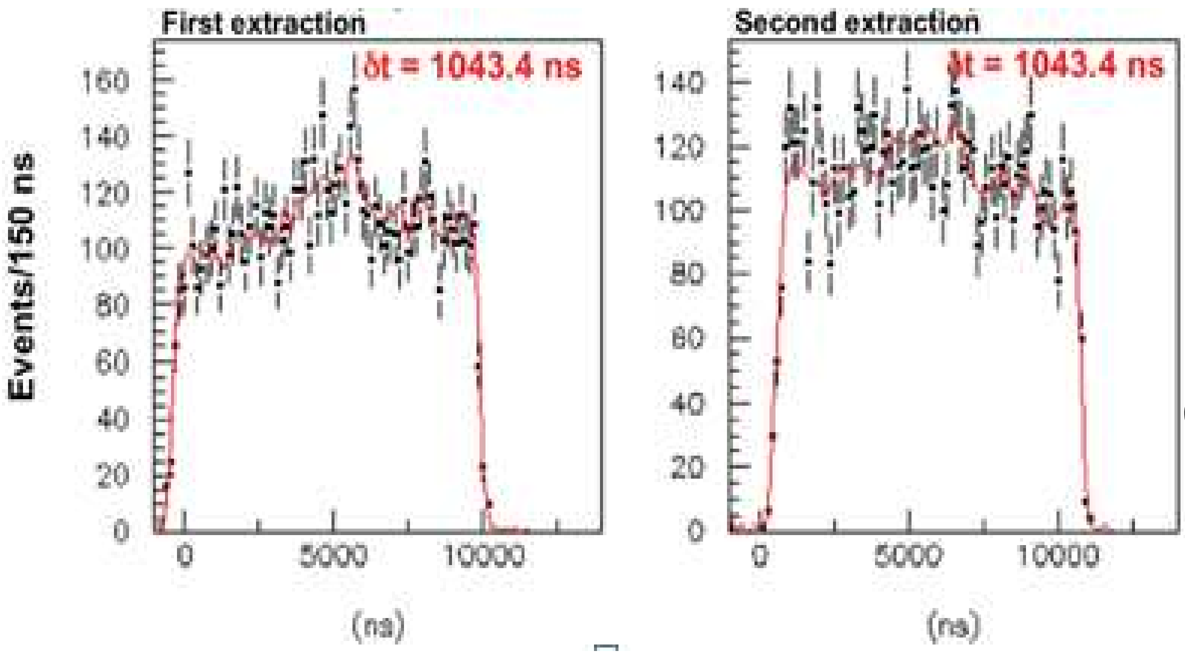
- x, y, z known from former dedicated measurements
- determine time differences of local clocks (both sites) w.r.t. the satellite, by offline data exchange
- 730 km << 20000 km (satellite height) → similar paths in ionosphere

Twin geodetic GPS receiver PolaRx2e +
Cs clock → Time-transfer (~1 ns accuracy)

Standard technique used in TAI (International Atomic Time) by BIPM



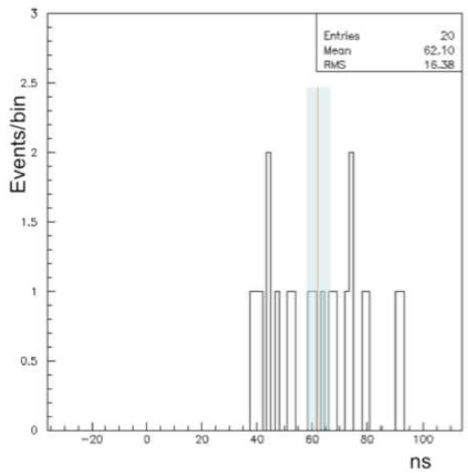
GPS
common view
CERN
LNGS
PolaRx +Cs clock
PolaRx +Cs clock
UTC
UTC
time shift by TOF$_c$
waveforms
data
p
π/K
ν
BCT
target
decay tunnel
OPERA
y
x
z
baseline → (TOF$_c$)
$\delta t = TOF_c - TOF_\nu$



Neutrino data vs protons: after delay determination (2009-2011) ~15000 neutrinos (September 2011)

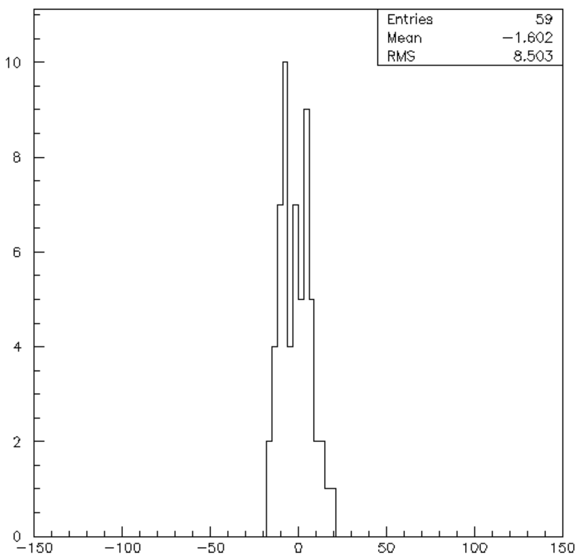
UNBLIND: $\delta t = TOF_c - TOF_{\nu=}$

(57.8 ± 7.8 (stat.) -5.9 +8.3 (sys.)) n



November 2011 (20 neutrinos measured individually)

δt = (62.1 ± 3.7 (stat.)) ns



December-February 2012
Two unknow sources of bias identified

May 2012 (59 neutrinos measured individually)

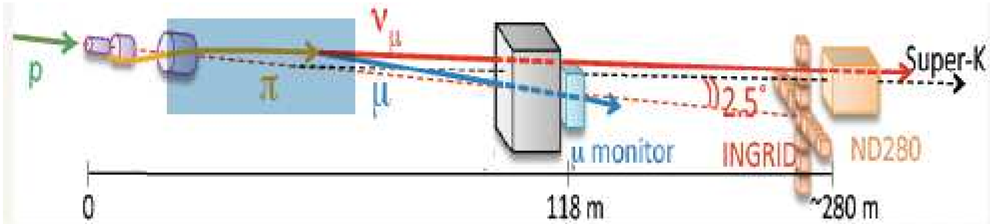
$$\delta t = \left(-1.6 \pm 1.1\ (stat.)^{+6.1}_{-3.7}\ (sys)\right)\ \mathrm{ns}$$

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

The search for θ13:

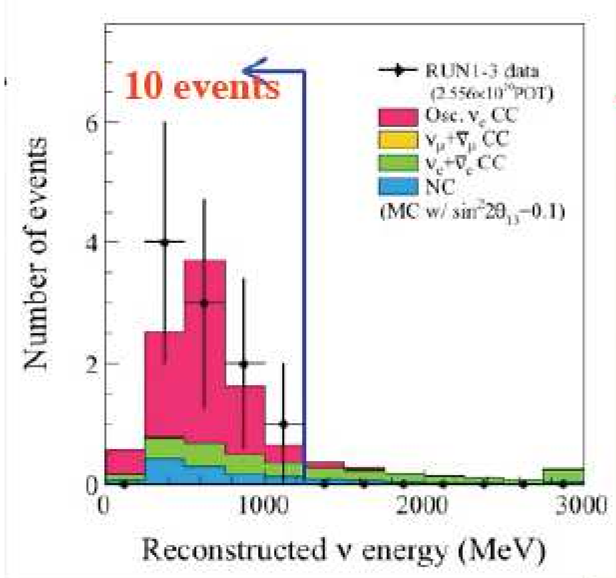
If the angle θ13 is different than zero at the same L/E of the atmospheric neutrino oscillation there should be a subleading oscillation between the muonic neutrino and the electron neutrino

The determination θ13 of is fundamental for the next steps in neutrino physics (study of CP violation)



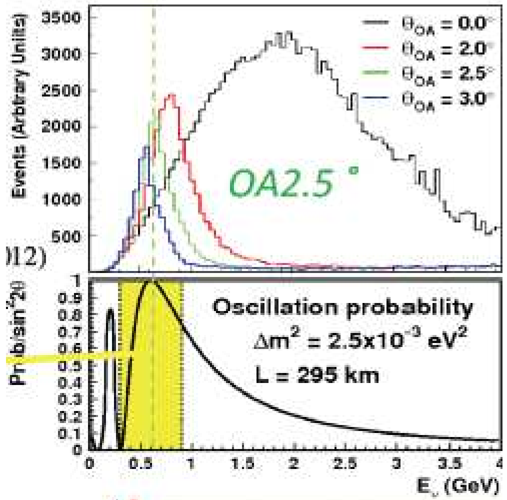
The off-axis neutrino beam

First hint of electron neutrino appearance signal in March 2011 before the earthquake

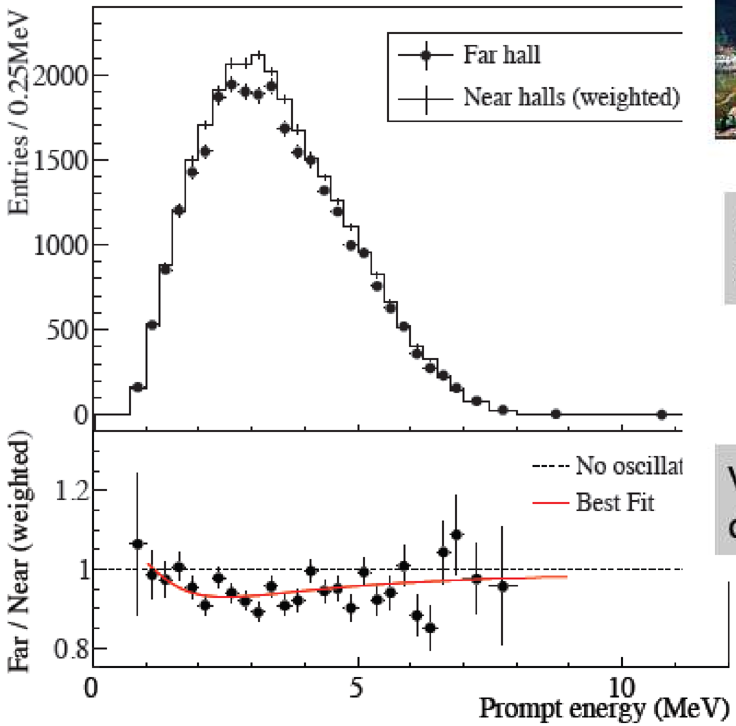


10 events of electron neutrino appearance observed with a background of 2.7

3.2 sigmas



2012 the Daya Bay experiment

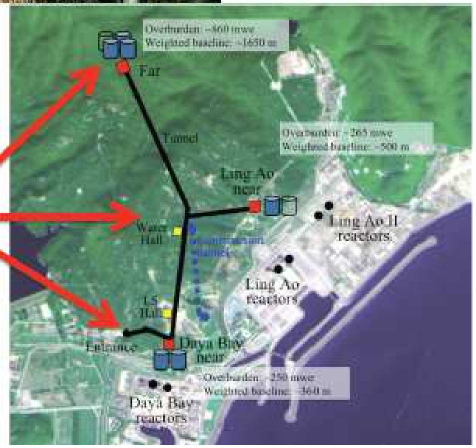


Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

6 commercial reactor cores with 17.4 GW_{th} total power.

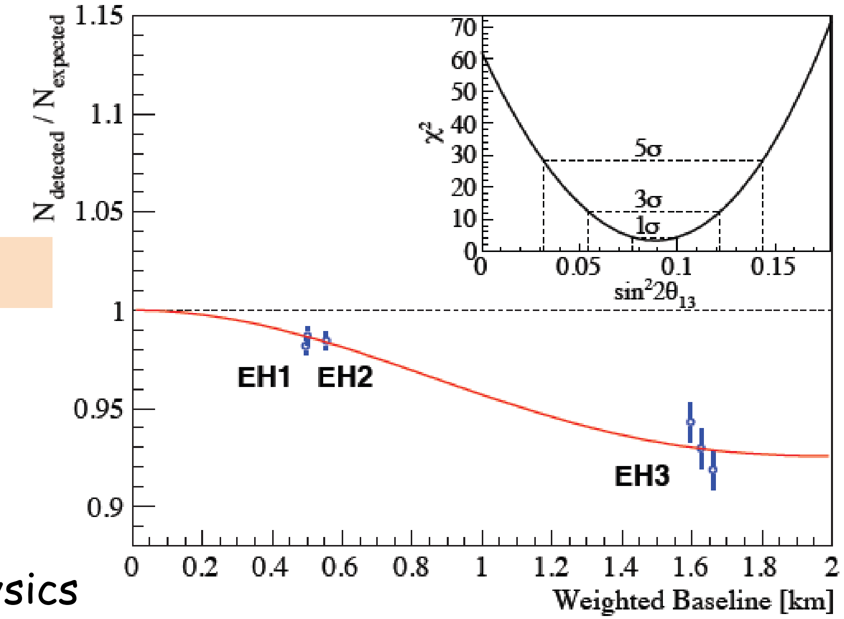
6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

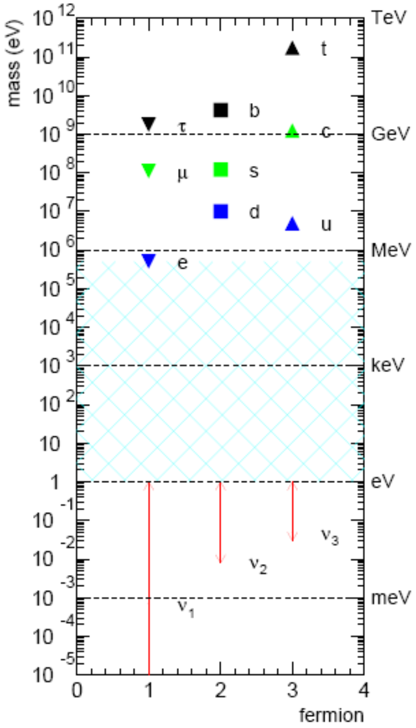
$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)



The value of is just below the CHOOZ limit
Confirmed by other two reactor experiments:
Double-CHOOZ and RENO
A huge boost to future neutrino oscillations physics

Neutrinos: a window beyond the S.M. → G.U.T.

Fundamental questions related to a deeper description of physics and to the evolution of the universe



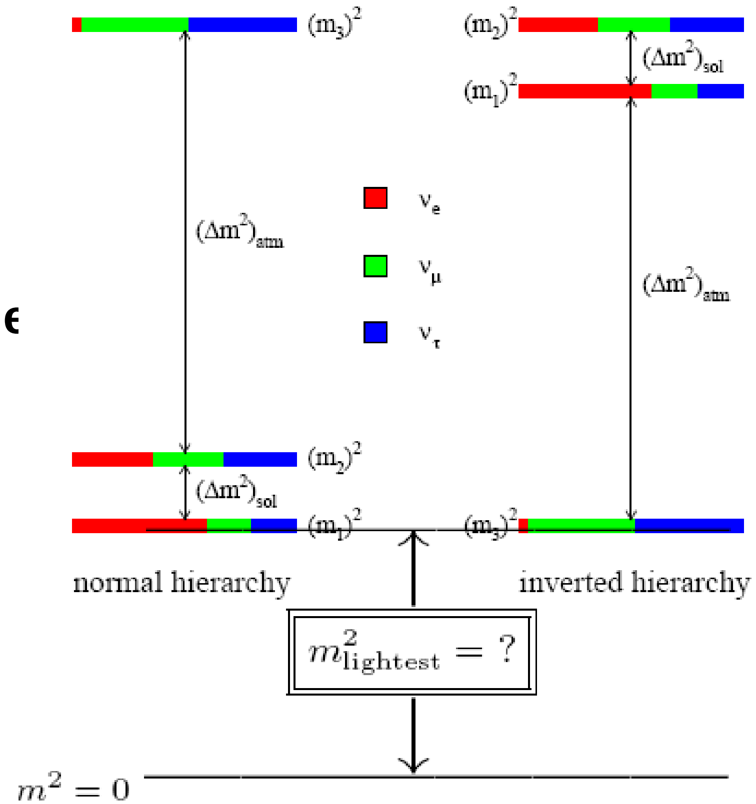
- Why are neutrino masses so small ?
- Why is the mixing matrix so different than the one of the quarks ?

What is this very strange puzzle suggesting us ?

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- **Which is the mass of the lightest state**
- **Are neutrinos Majorana particles ?**

- **Which is the hierarchy of the mass eigenstates ?**
- **Is there CP violation in the neutrino sector ?**



CP violation in the neutrino sector can explain the matter/antimatter asymmetry in the universe

Several projects are being proposed and discussed for the next steps
An example in Europe submitted to CERN in June 2012

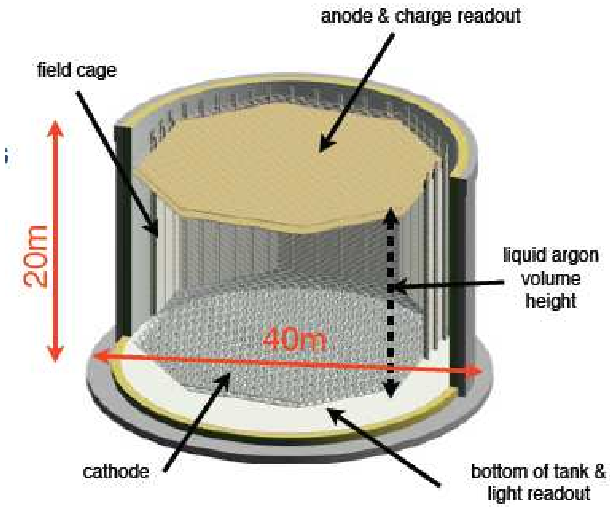
2100 km from RAL, 1500 km from DESY, and 1160 km from Protvino.

LBNO:

Beam from CERN to Finland over 2300 km

Profits of the study of underground sites performed by the european program LAGUNA

50 kton Liquid Argon detector for the determination of neutrino mass hierarchy, search for CP violation, search for proton decay and for supernova neutrinos



I hope you will find neutrino physics interesting

Thanks for your attention