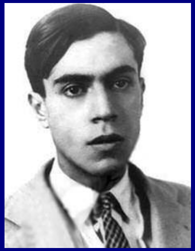
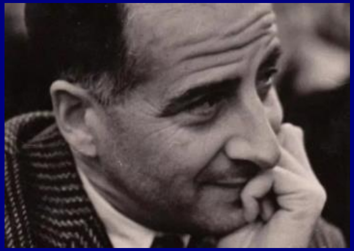
Neutrino Physics and the DUNE Experiment


W. Paulі

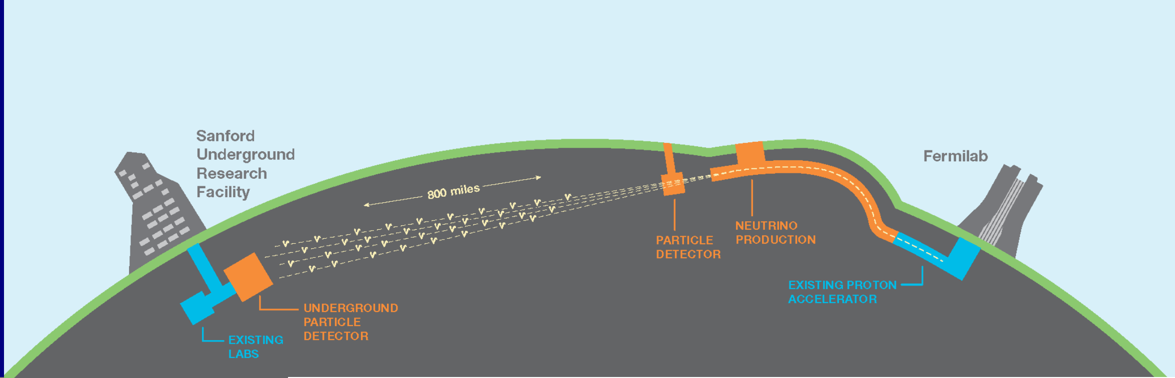

E. Fermi

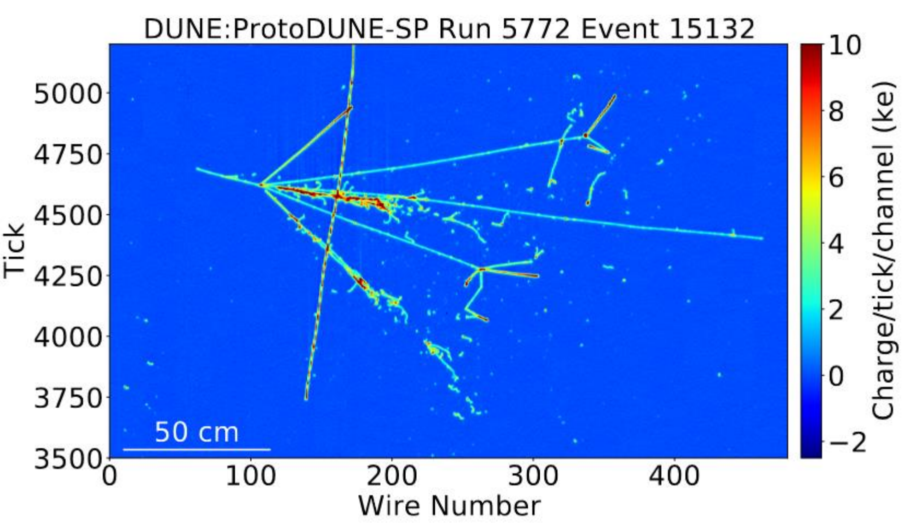

E. Majorana


B. Pontecorvo

30/10/2023
D. Autiero (IP2I)

Journées des deux infinis
30-31/10/2023

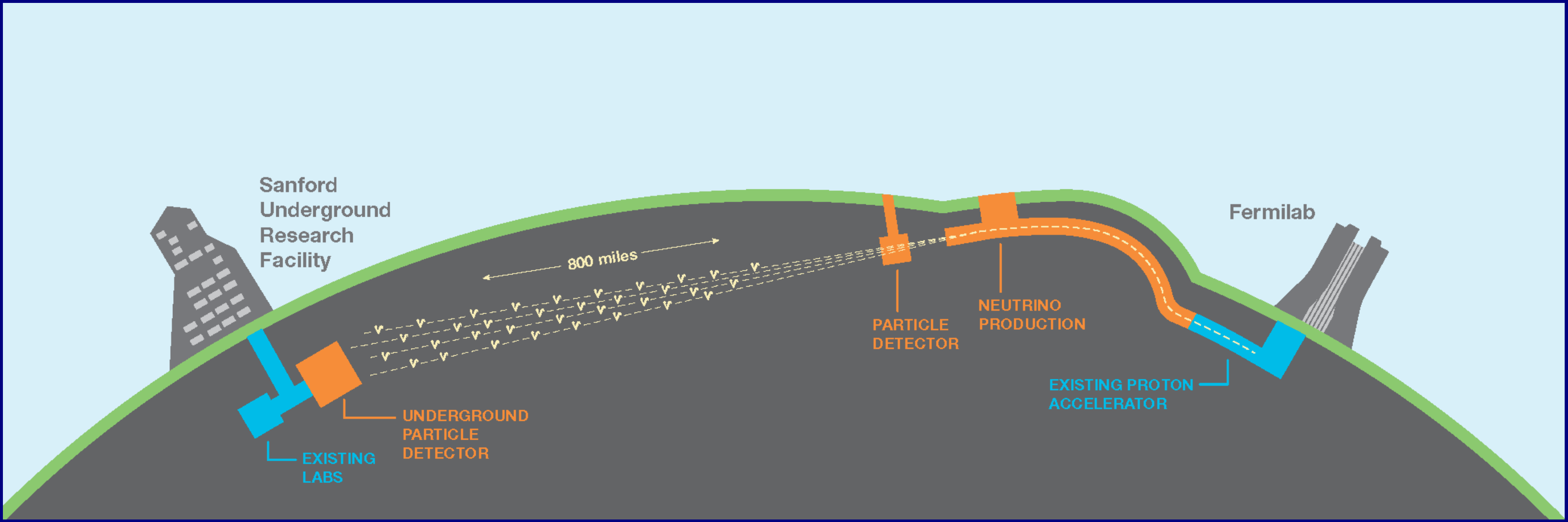




Lectures:

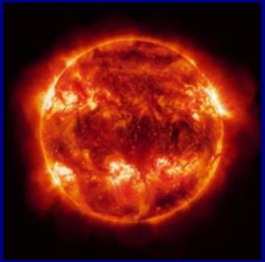
30/10 Lecture 1: Introduction to neutrino physics and neutrino oscillation searches

31/10 Lecture 2: The Deep Underground Neutrino Experiment (DUNE) at LBNF (Long Baseline Neutrino Facility)

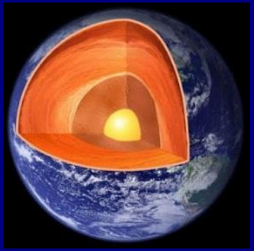


Neutrino sources:

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

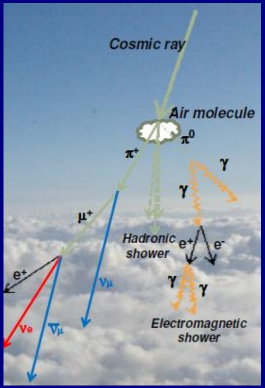


Sun:
65 billions/(cm^2 s)
on the earth surface
~ MeV

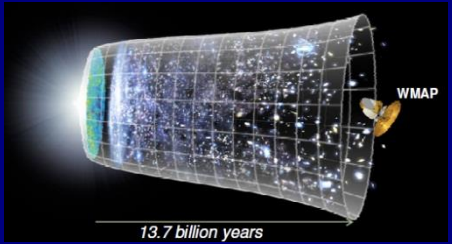


Earth radioactivity
U, Th, K
→Geoneutrinos
4 10^6 /(cm^2 s)
~ MeV

Nuclear reactors:
1 GW → 2 10^{20} anti-nue/s
~ few MeV



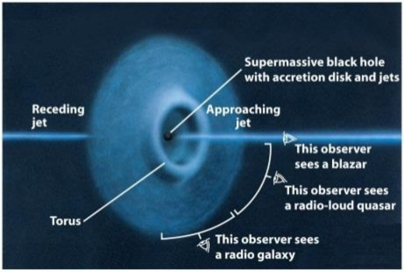
Cosmic rays
~ GeV
~ 1 / (cm^2 minute)



Big Bang
Relic neutrinos
330/cm^3
1.95 K

Human body
20 mg of ^{40}K
340 millions/day

Particle accelerators
~few GeV



Extragalactic:
Active galactic nuclei
Gamma ray bursts
~PeV

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 form of matter in the universe

- Astrophysics:

They are governing the life and death of stars

- Particle Physics:

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

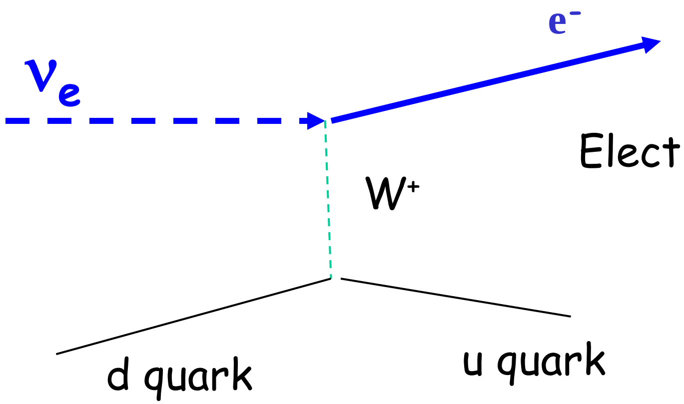
Unfortunately neutrinos are also quite difficult to detect …

→ requiring bright ideas on sources and detectors. This seminar concerns the "Experimental challenges" and also a little bit of history, many neutrino properties were totally unexpected coming out as experimental results

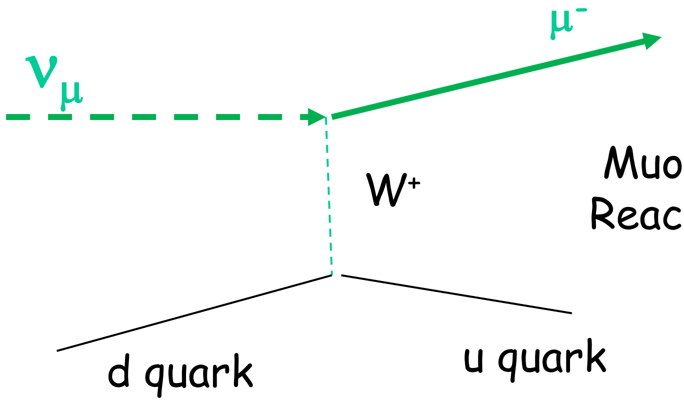
- The history of neutrino physics is a real saga with an <u>extraordinary richness of experimental techniques</u> involved related to the various neutrino sources.

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

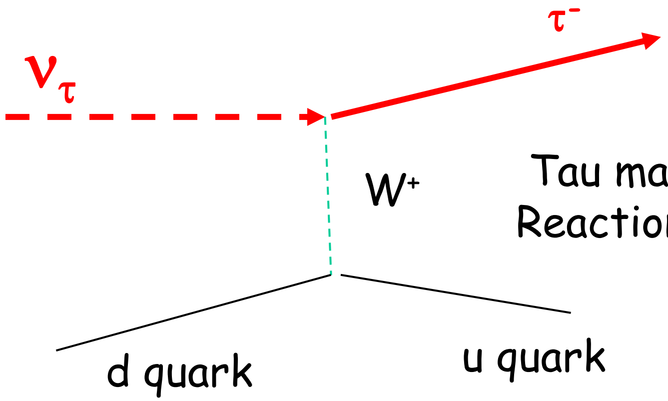
How can we detect different neutrino flavors ? → charged current reactions



Electron mass= 0.511 MeV



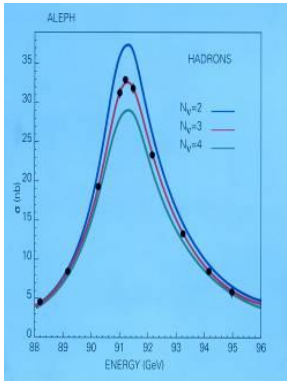
Muon mass= 105.6 MeV
Reaction threshold = 112 MeV



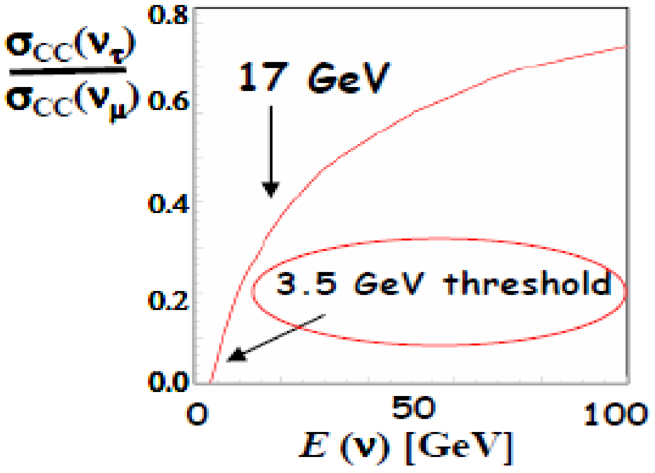
Tau mass= 1777 MeV
Reaction threshold = 3.46 GeV

Standard Model → massless neutrinos:
Neutrino: helicity -1 (+1 not existing)
Antineutrino: +1 (-1 not existing)

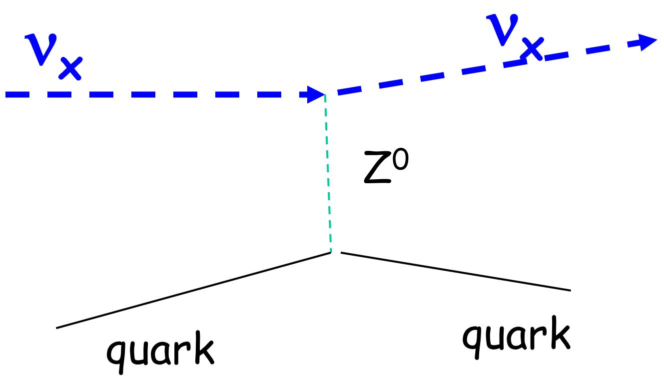
1989 LEP results:
only 3 neutrinos coupled to the Z^0
($M_\upsilon < M_Z/2$)



τ mass kinematic suppression

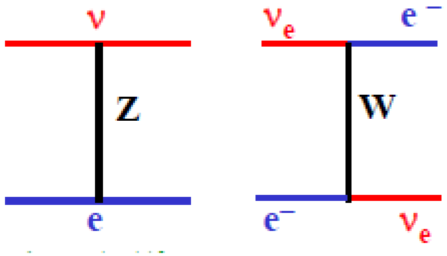


Neutral current reactions (Z exchange) → do not distinguish neutrino flavors, no threshold

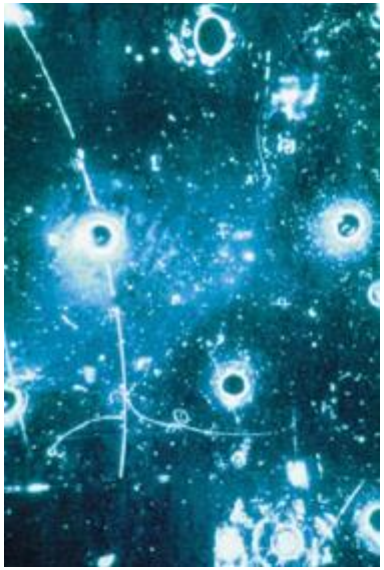


Elastic scattering neutrino-electron

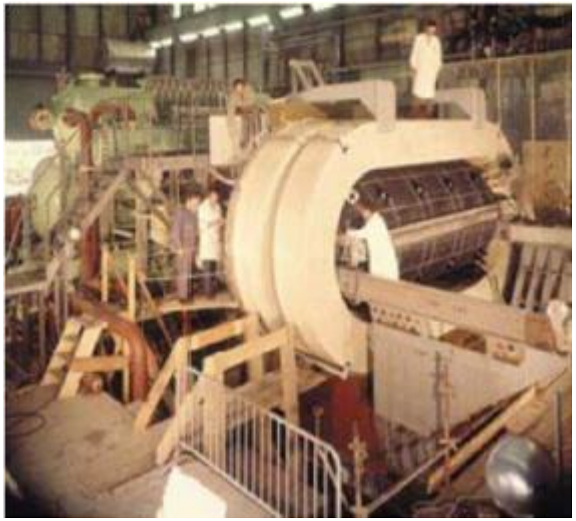
$\nu + e^- \rightarrow \nu + e^-$



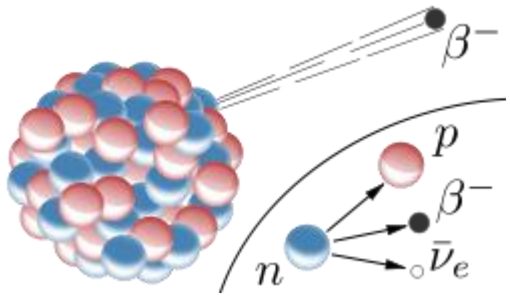
Discovery of neutral currents 1973 (10 years before the discovery of the Z)



Bubble chamber experiment Gargamelle



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



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

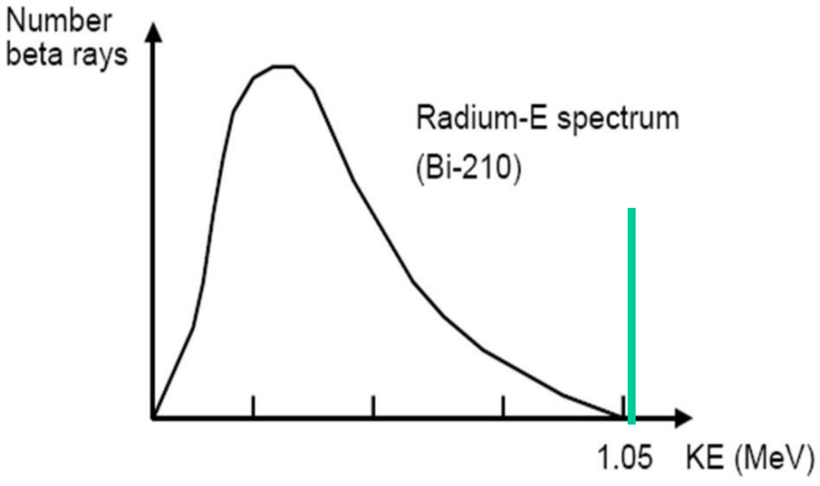
Early 1900s: people thought they were dealing with a two body decay process:

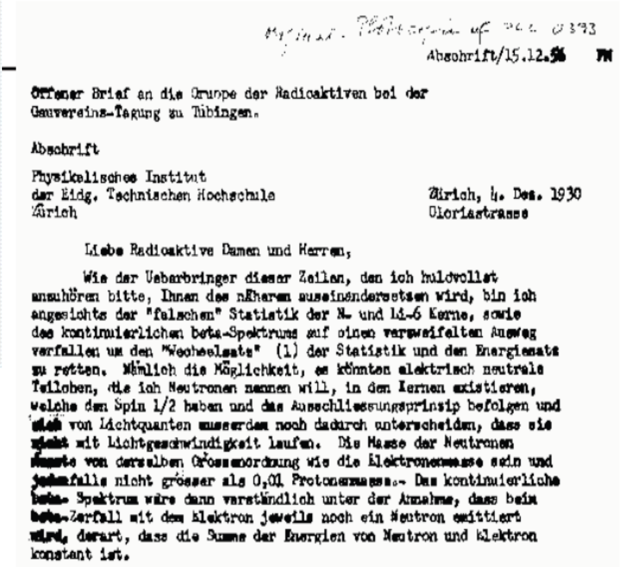
$$(A,Z) \rightarrow (A,Z+1) + e^-$$

→ The energy spectrum of the electrons should be monochromatic:

First measurements of beta spectrum: 1911 Lise Meitner and Otto Hahn, 1914 Ellis and Chadwick → the beta spectrum is continuous !

Meitner: electrons re-interact in the nuclei emitting gamma rays → but no gamma rays detected. Bohr: energy is not conserved in Beta decay !!!





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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.

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

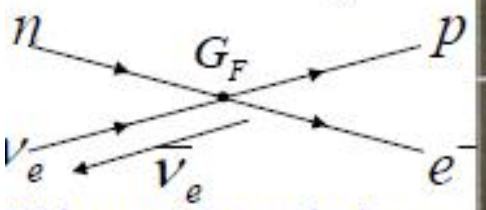
1932 The neutron (as we known today) was discovered, by J. Chadwick, two years after Pauli's proposal

- Solves nuclear spin problem of Li and N nuclei measured to have integer spin:

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):

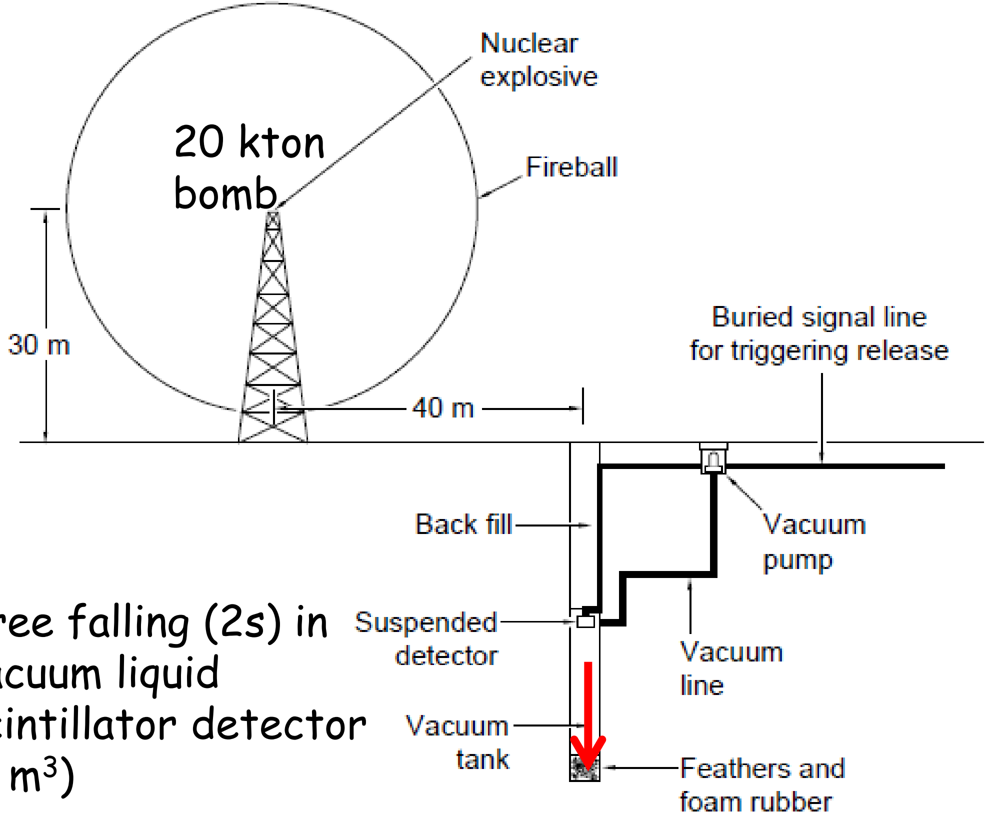
$$\mathcal{L}(x) = -\frac{G_F}{\sqrt{2}}\left[\bar{\phi}_p(x)\gamma^\mu\phi_n(x)\right]\left[\bar{\phi}_e(x)\gamma^\mu\phi_\nu(x)\right]$$

G_F = Fermi coupling constant = (1.16637±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").

How to detect neutrinos by producing them in a nuclear explosion:



20 kton bomb

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.

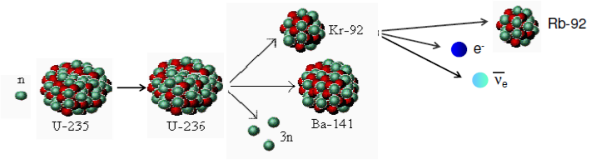
« El Monstro »
Reines and Cowan 1951-1952
Approved after discussing with Fermi and Bethe who were convinced that this was the most promising (anti)neutrino source

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

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

Bomb: flux ~10^{E}4 times larger than with a reactor

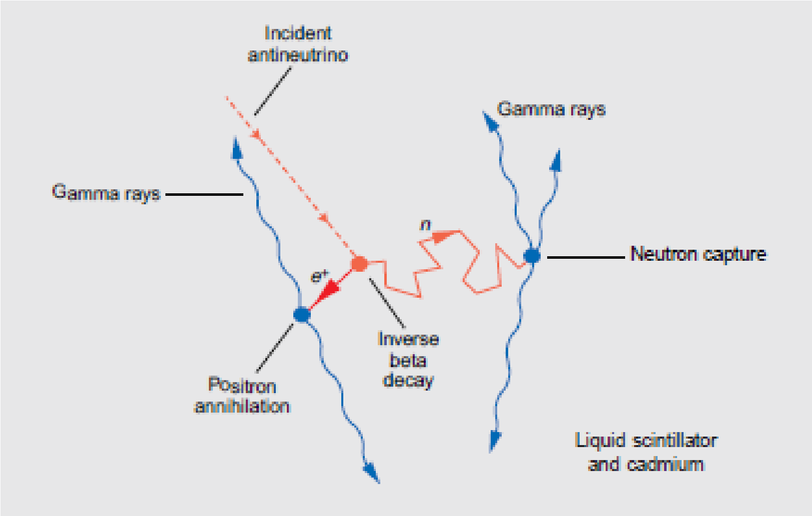
Background from neutrons and gammas similar to reactor
→ But a new idea on how to reduce the background and detect neutrinos over a long time scale with the low reactor flux

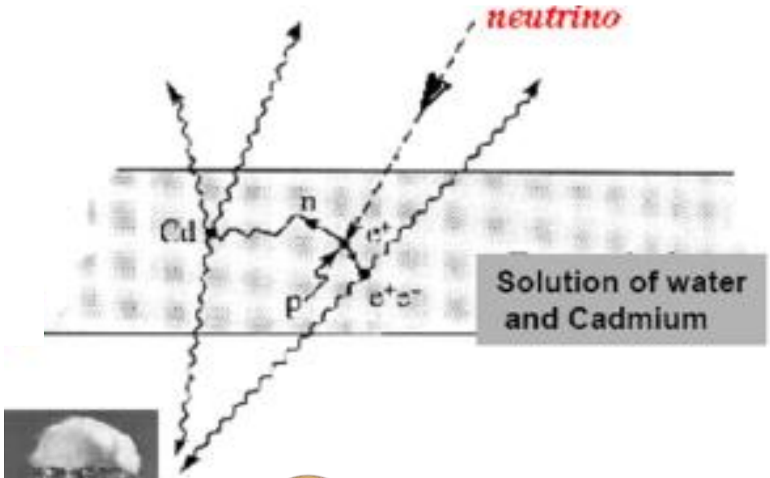


1956 (anti)neutrino detection at the Savannah River reactor, still via inverse beta decay

flux ~$10^{E}13$ neutrino / (cm^2 s)

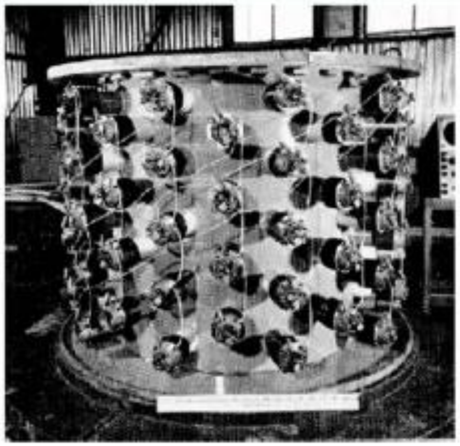
the idea to reduce the background: detect also the delayed neutron capture signal after the positron →





Reines: 1995 Nobel Prize

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



Reines:
« We are happy to inform you (Pauli) that we have definitely detected the neutrino ! »

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

→Nobel 1988

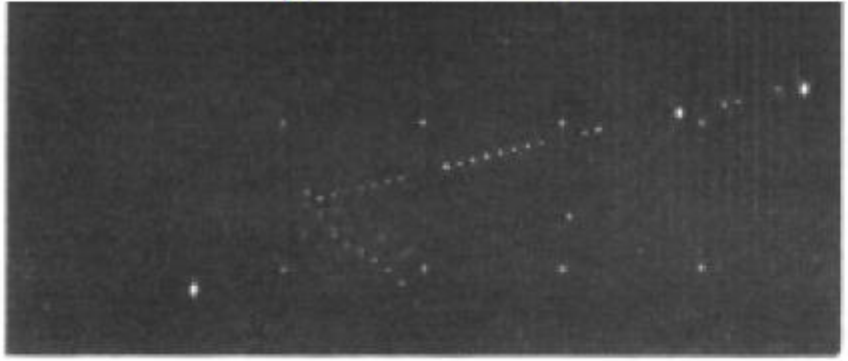
Lederman, Schwarz, Steinberger

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 ($\pi \rightarrow \mu + \nu_\mu$ $K \rightarrow \mu + \nu_\mu$)

- **The "two neutrinos experiment":**

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

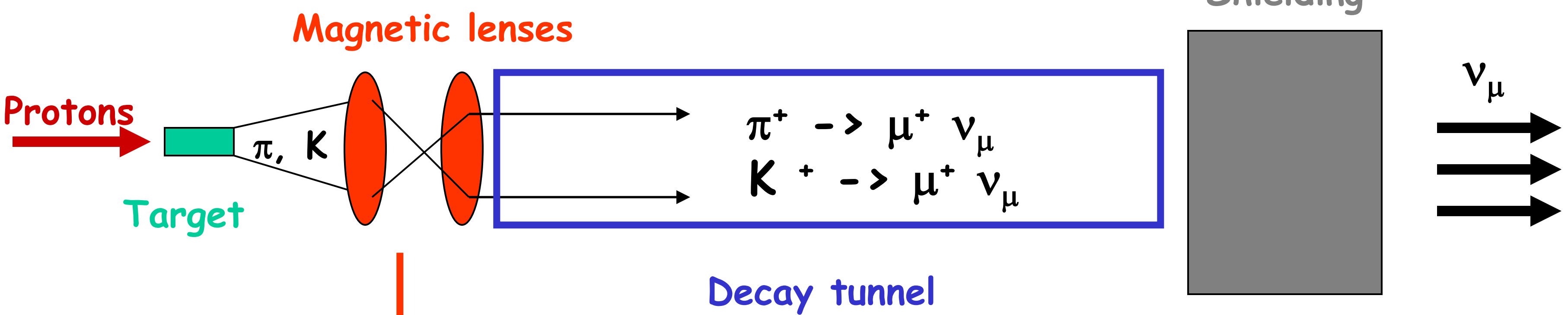


Muonic neutrino is different than electronic neutrino

→ Conservation of leptonic number

Pontecorvo's tombstone Rome

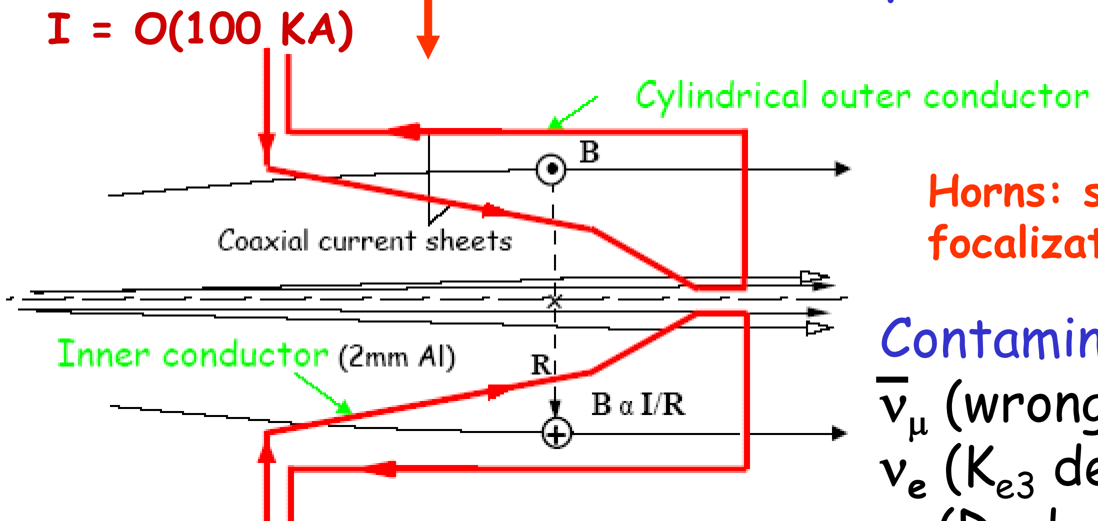
Typical high energy Wide Band neutrino beam



$\pi^+ \to \mu^+ \nu_\mu$

$K^+ \to \mu^+ \nu_\mu$

Decay tunnel



Horns: sign selection, focalization: flux x10

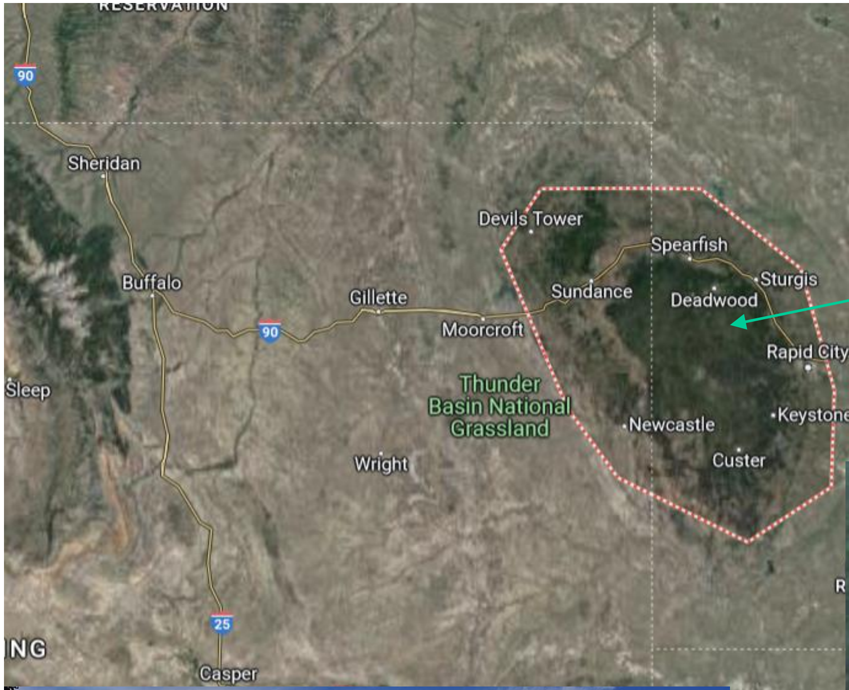
Contaminations:

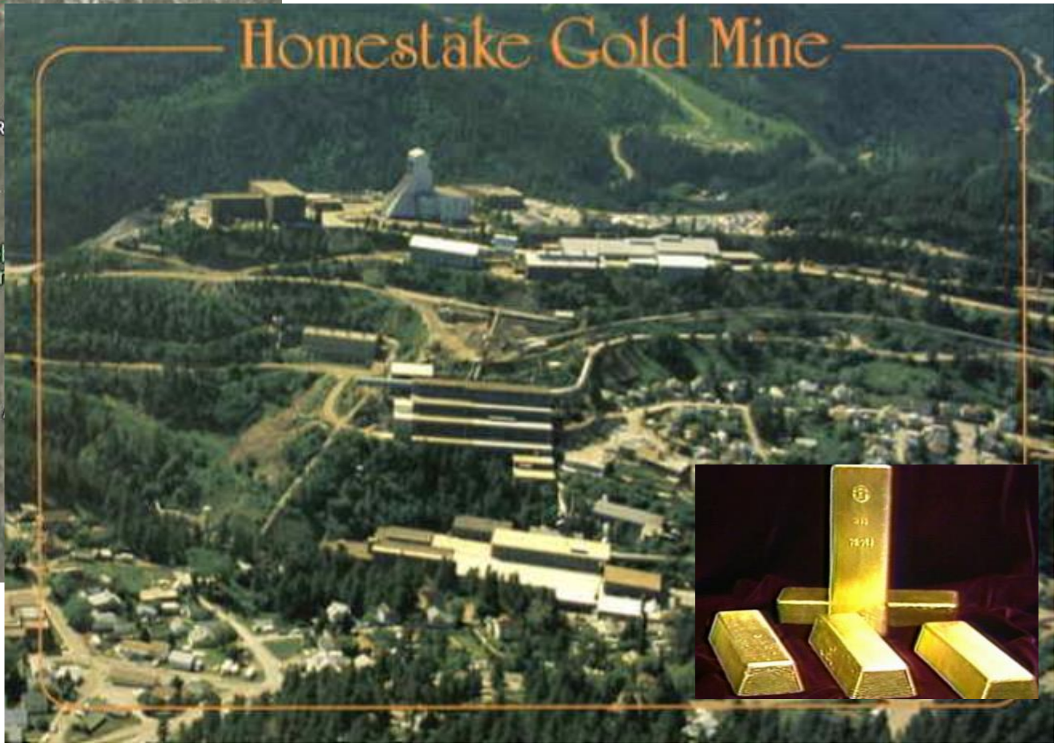
$\bar{\nu}_\mu$ (wrong sign parents)	O(5%)
ν_e (K_{e3} decays, μ decays)	O(1%)
ν_τ (D_s decays)	O(10^{-6})

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, NA61 etc …)

South Dakota, Black Hills, town of Lead (1600 m asl)

Homestake gold mine (1876-2001, 1.24 ktons of gold extracted since the Great Sioux War of 1876)





Since 2007 with the stop of the mine created the Sanford Underground laboratory https://sanfordlab.org/ (the deepest undeground laboratory in USA), now hosting the DUNE experiment

First detection of solar neutrinos 1968: Homestake mine experiment (R. Davis, Nobel 2002)

1500 m 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

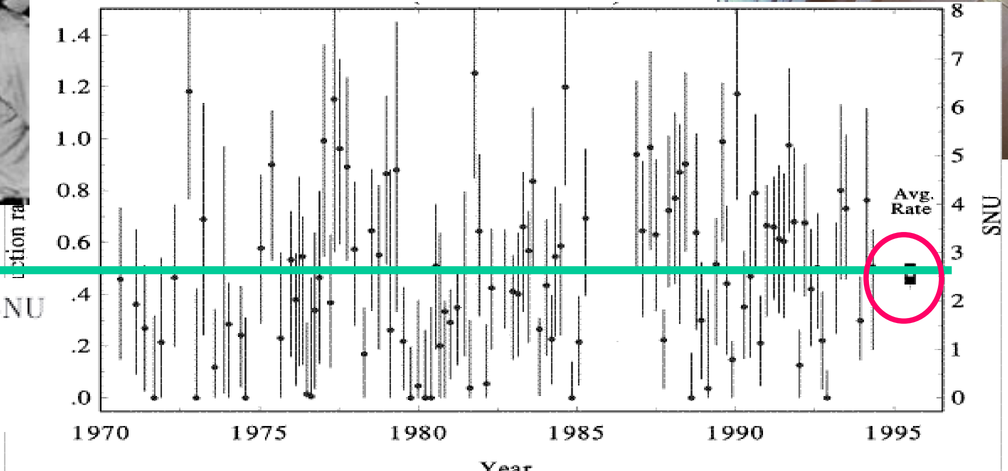
~1.5 Ar atoms/day produced by solar neutrinos
Extracted every 3 months with a flux of N_2

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

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

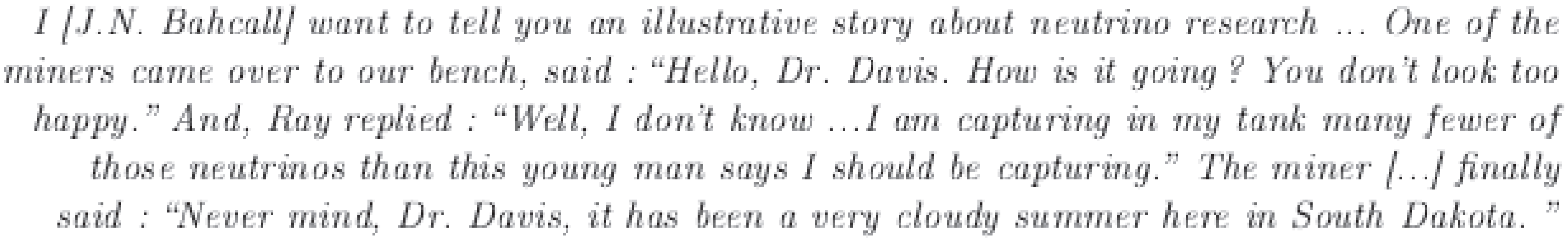
R. Davis and J.Bahcall

1/3 of expected rate
→ Solar neutrinos deficit



$R({}^{37}Cl) = 2.56 \pm 0.16 \pm 0.16$ SNU
$R_{SSM} = 7.6^{+1.3}_{-1.1}$ 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:

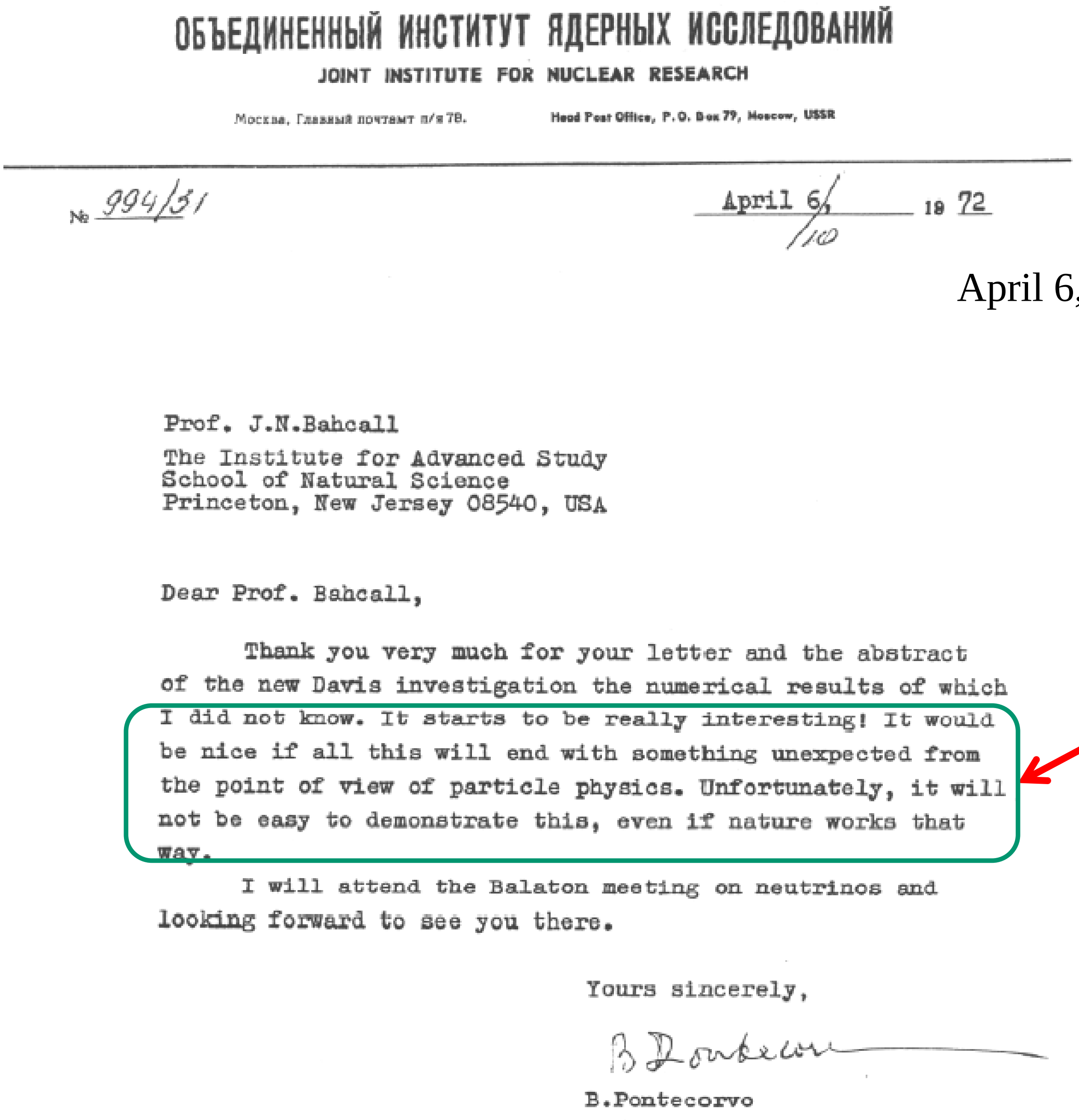
The trivial ones:

- The Homestake experiment, which is quite delicate, has some bias in the neutrino detection
- The Standard Solar Model is not correct (neutrino flux depending on T^{25} !)

The fascinating interpretation by 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 to allow for their charged current interactions → 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 19 72

April 6, 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

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

Neutrino oscillations

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

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:

Simplified case: two neutrinos mixing

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

Only one mixing angle θ is needed

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

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 $m_j \neq m_k$

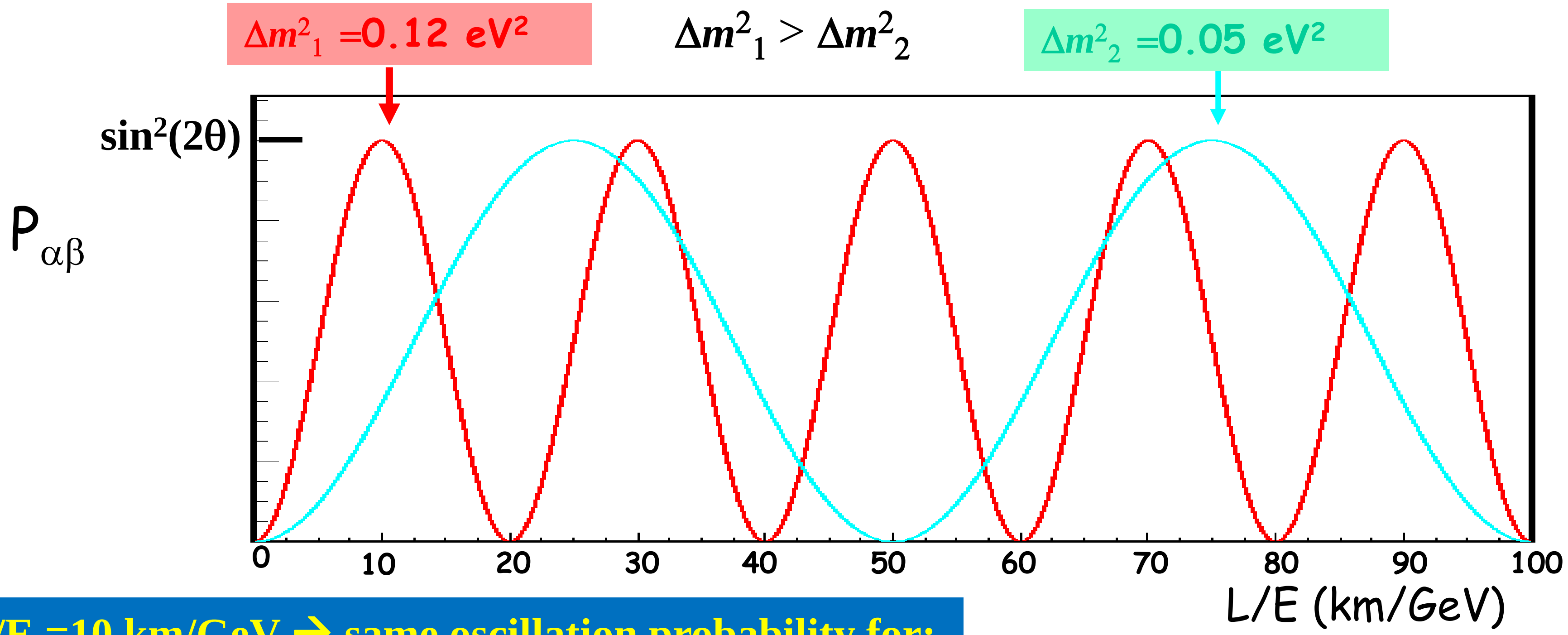
Projecting ν(t) on the flavor basis one can obtain the probability of finding other flavours:

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

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

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

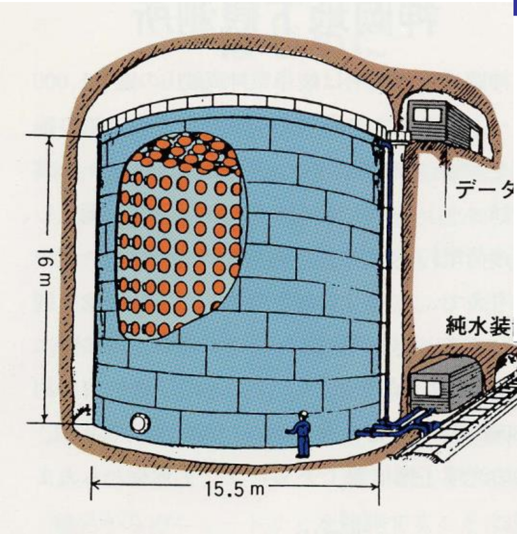
$\Delta m^2 = m_2^2 - m_1^2 [eV^2]$
L [km] (distance among the neutrino source and the detector)
E [GeV] (neutrino energy)

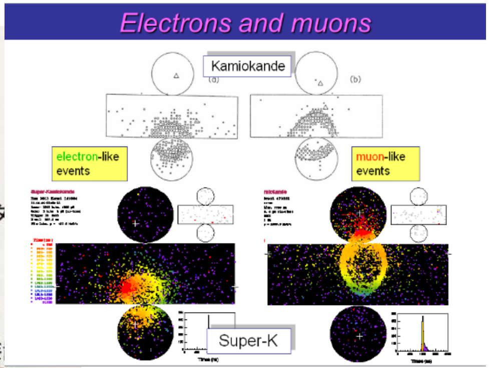


L/E =10 km/GeV → same oscillation probability for:
1 GeV neutrinos after 10 km
1 MeV neutrinos after 10 m

Detection of oscillations: appearance of new neutrino flavors as a function of distance or energy or disappearance of beam neutrinos as a function of distance and energy

Water Cerenkov experiment (Kamiokande 1987-1994)

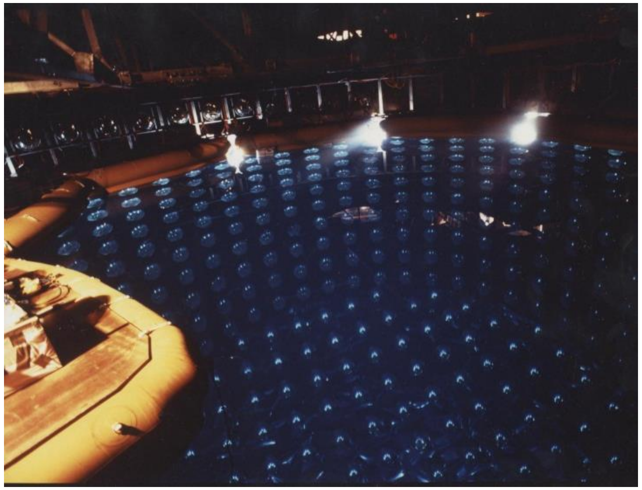




M. Koshiba
Nobel 2002 with R. Davis
(detection of cosmic neutrinos)

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

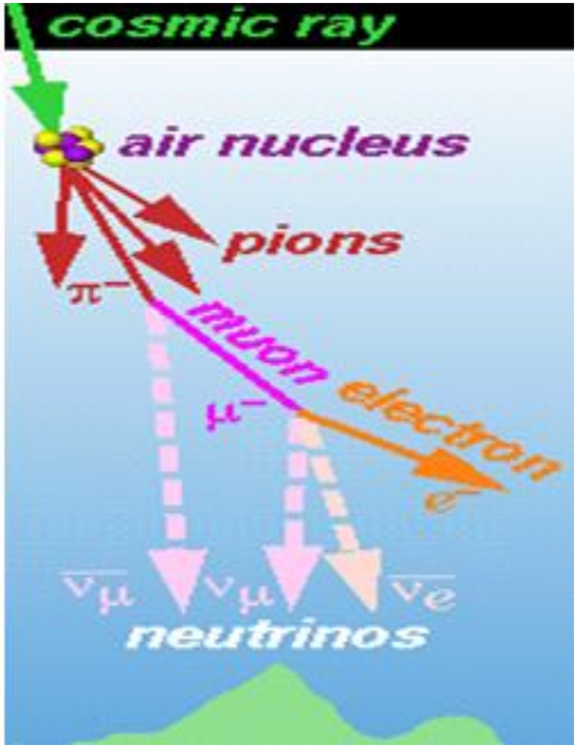
Built for proton decay search (GUT)
Neutrinos produced by cosmic rays in the atmosphere are a background for proton decay (T. Kajita's thesis)
→ Studying the atmospheric neutrinos background they realize that it is different than expectations



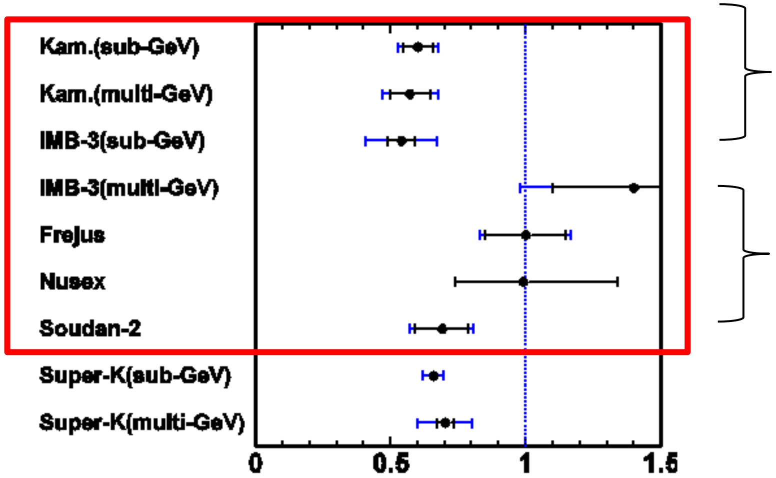
→ Can look at solar neutrinos (high threshold > 5 MeV)
by elastic scattering on electrons (CC+NC reactions) (emitted electron at 5 MeV stops in ~2 cm in water)
$\nu + e^- \rightarrow \nu + e^-$ electron has still some correlation with neutrino direction

→ Deficit of solar neutrinos ~50%
→ Detection of neutrinos from supernova SN1987A !

Atmospheric neutrinos anomaly

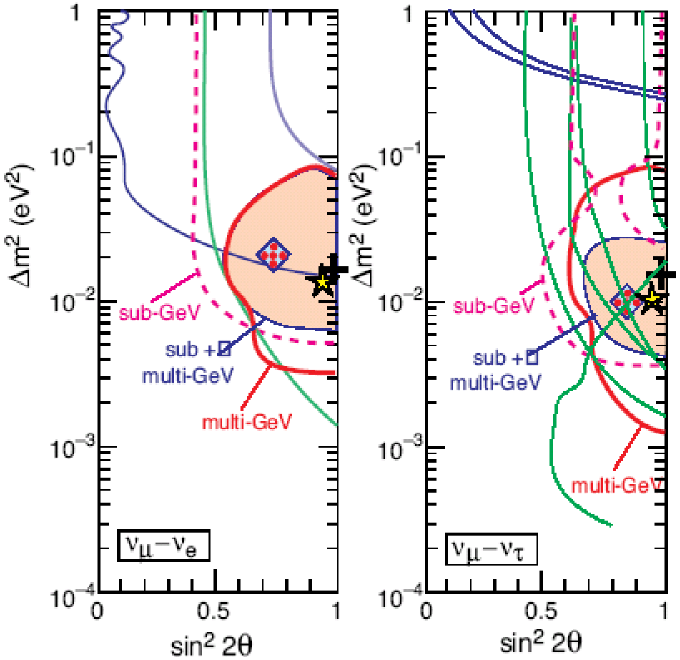


Let's write the atmospheric ν_μ deficit by (μ/e)data/(μ/e)MC

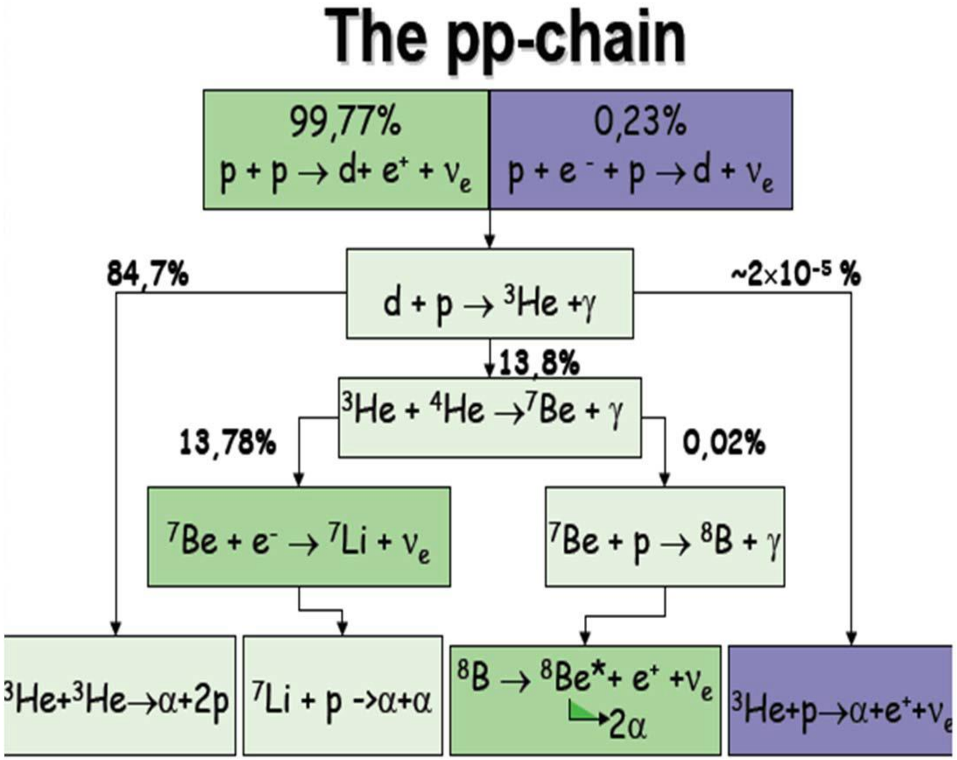


Water Cerenkov experiments

Iron calorimeters



- Unclear situation among different experiments (water Cerenkov, calorimeters)
- Interpretation in terms of neutrino oscillations (possible in terms of both $\nu\mu \rightarrow \nu e$ and $\nu\mu \rightarrow \nu\tau$) with $\Delta m^2 \sim 10^{-2}$ eV^2
- Some first hints of dependence on the zenith angle but not yet convincing



The pp-chain

99,77% $p + p \rightarrow d + e^+ + \nu_e$

0,23% $p + e^- + p \rightarrow d + \nu_e$

$d + p \rightarrow {}^3He + \gamma$

84,7%

~2×10⁻⁵ %

13,8%

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

13,78%

0,02%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

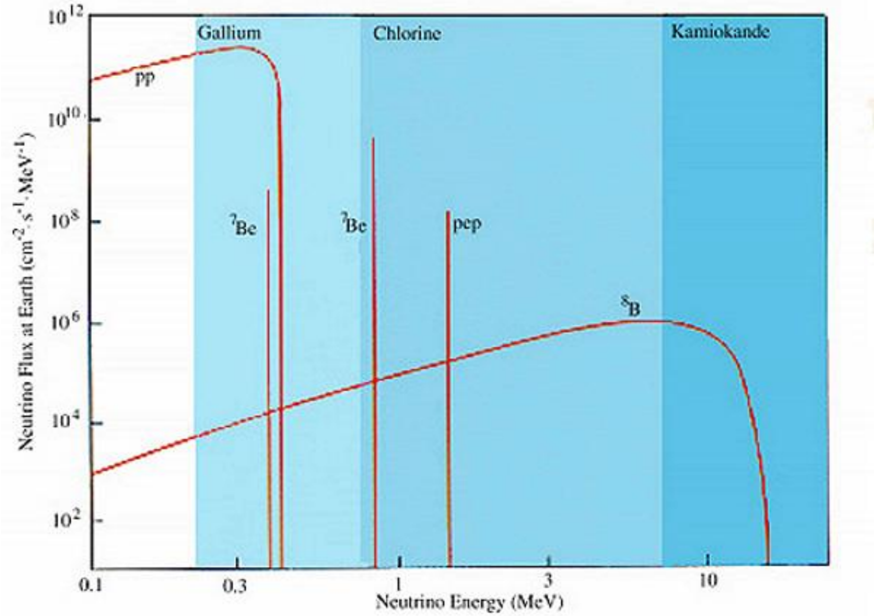
${}^7Be + p \rightarrow {}^8B + \gamma$

${}^3He + {}^3He \rightarrow \alpha + 2p$

${}^7Li + p \rightarrow \alpha + \alpha$

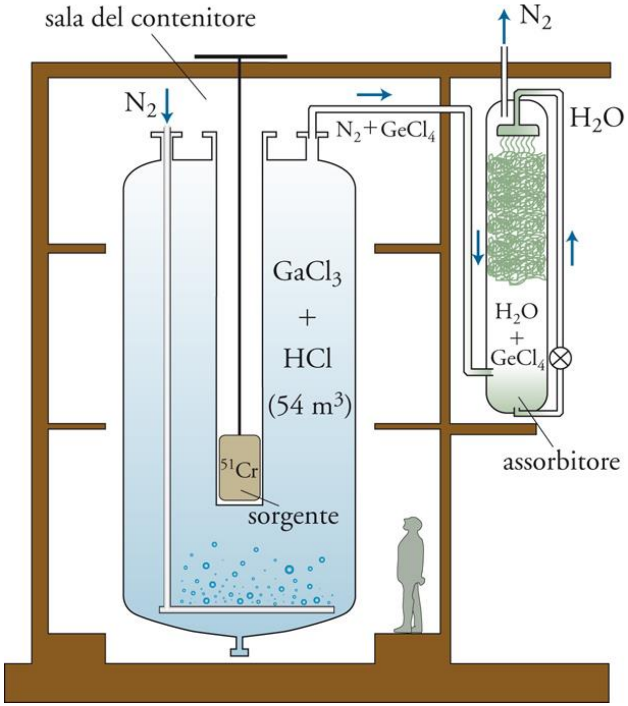
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e \rightarrow 2\alpha$

${}^3He + p \rightarrow \alpha + e^+ + \nu_e$



1% uncertainty

20% uncertainty



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

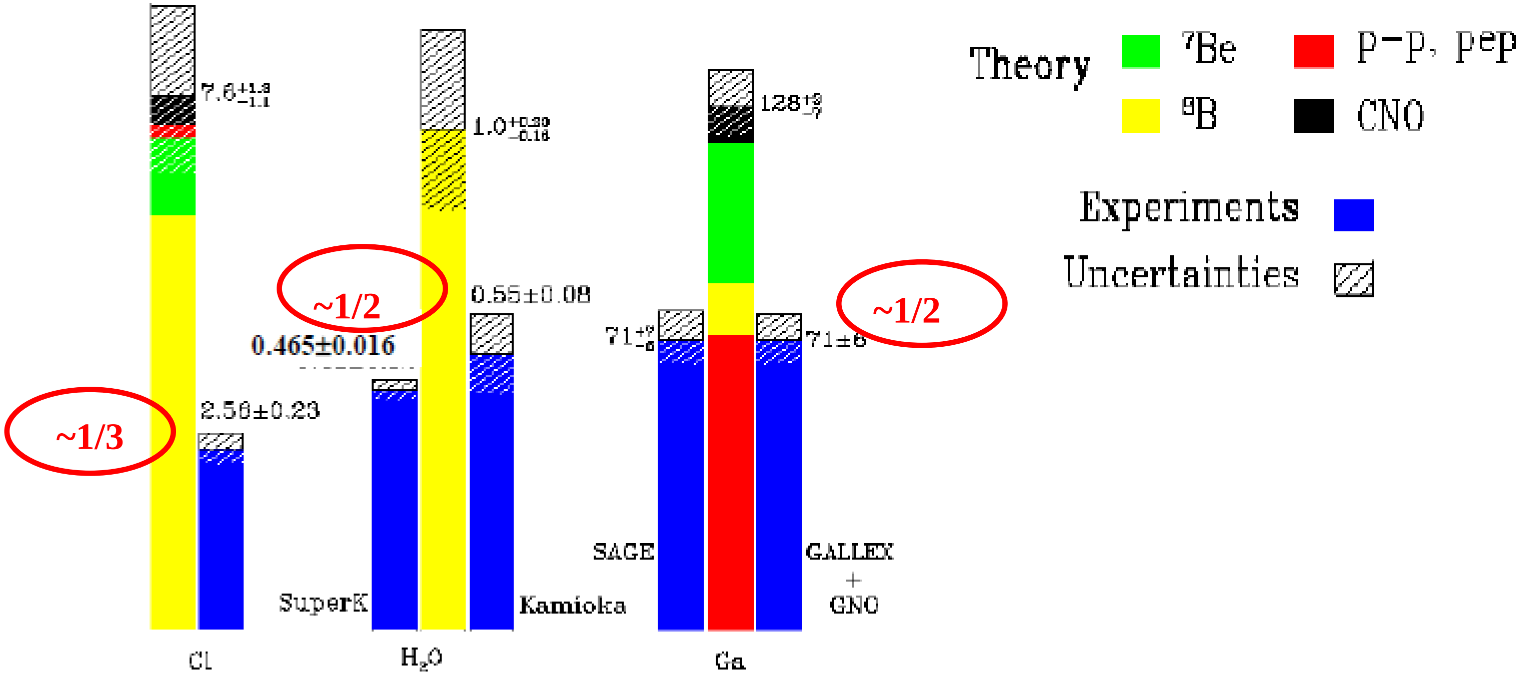
$$\nu_e + {}^{71}Ga_{31} \rightarrow e^- + {}^{71}Ge_{32}$$

→ **Confirms the deficit but: Data/SSM = 0.56**

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

Is there an energy dependence of the solar neutrino deficit?

The 3 experiments Homestake, Gallium and SuperK have different results (in particular Homestake) even considering neutrino oscillations as an explanation



A more complex mechanism MSW (Mikheyev-Smirnov-Wolfenstein 1978-1986) which includes in the oscillations mechanism the effect of neutrino interactions with electrons in matter (νe additional charged current forward scattering)

→ It changes the effective neutrino masses (analogy with refractive index for light)
→ It can introduce an energy dependence which explains the 3 results

Neutrino oscillation searches at the beginning of 90s

- 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

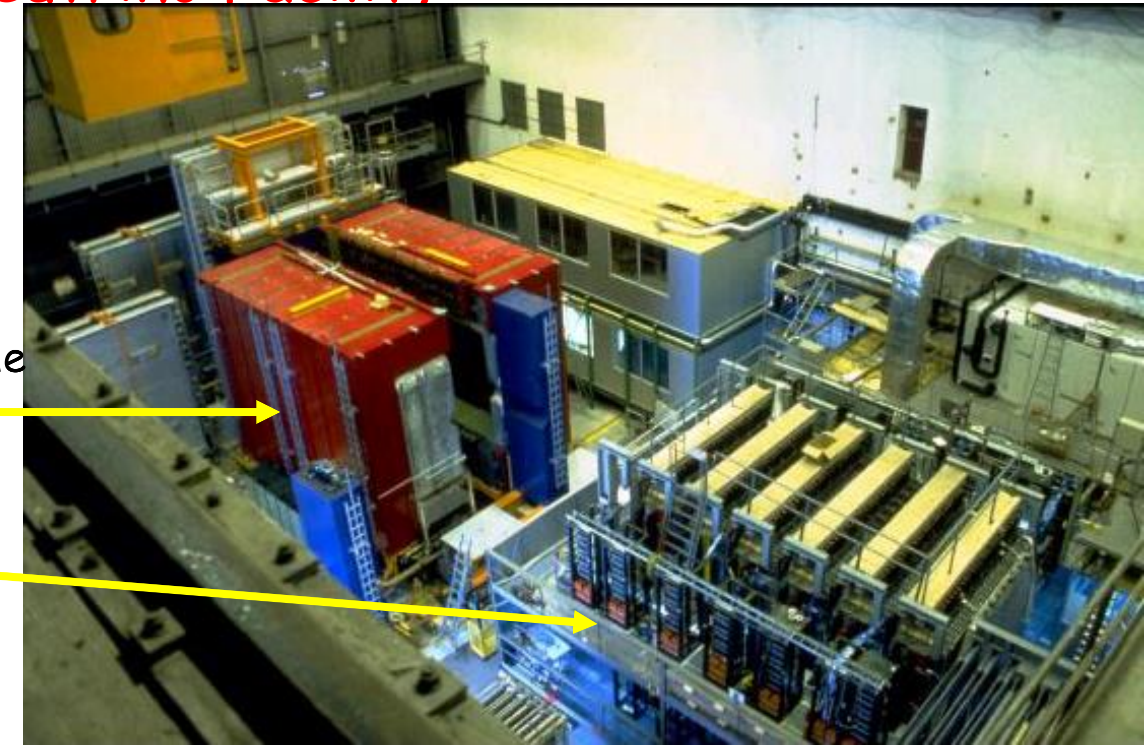
Then: $m_{\nu\tau} \sim 30$ eV (Cosmological relevance)

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

The NOMAD/CHORUS experiments at the CERN West Area Neutrino Facility

Short-baseline search for
$\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations

Running in 1994-1998



The NOMAD experiment hosted in the UA1/NOMAD/T2K magnet

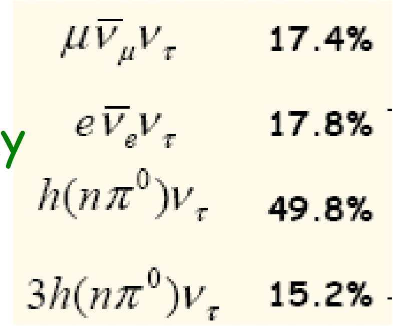
The CHORUS experiment

NOMAD: measurement of τ decay kinematics:

Presence of neutrino(s) in the final state, missing P_t , visible decay daughters
→ (tracking, calorimetry) → main channel: electronic tau decay

Collected samples:
1.3 M νμ CC
0.4 M νμ NC
13 K νe CC

τ decay modes



$\mu\bar{\nu}_\mu\nu_\tau$	17.4%
$e\bar{\nu}_e\nu_\tau$	17.8%
$h(n\pi^0)\nu_\tau$	49.8%
$3h(n\pi^0)\nu_\tau$	15.2%

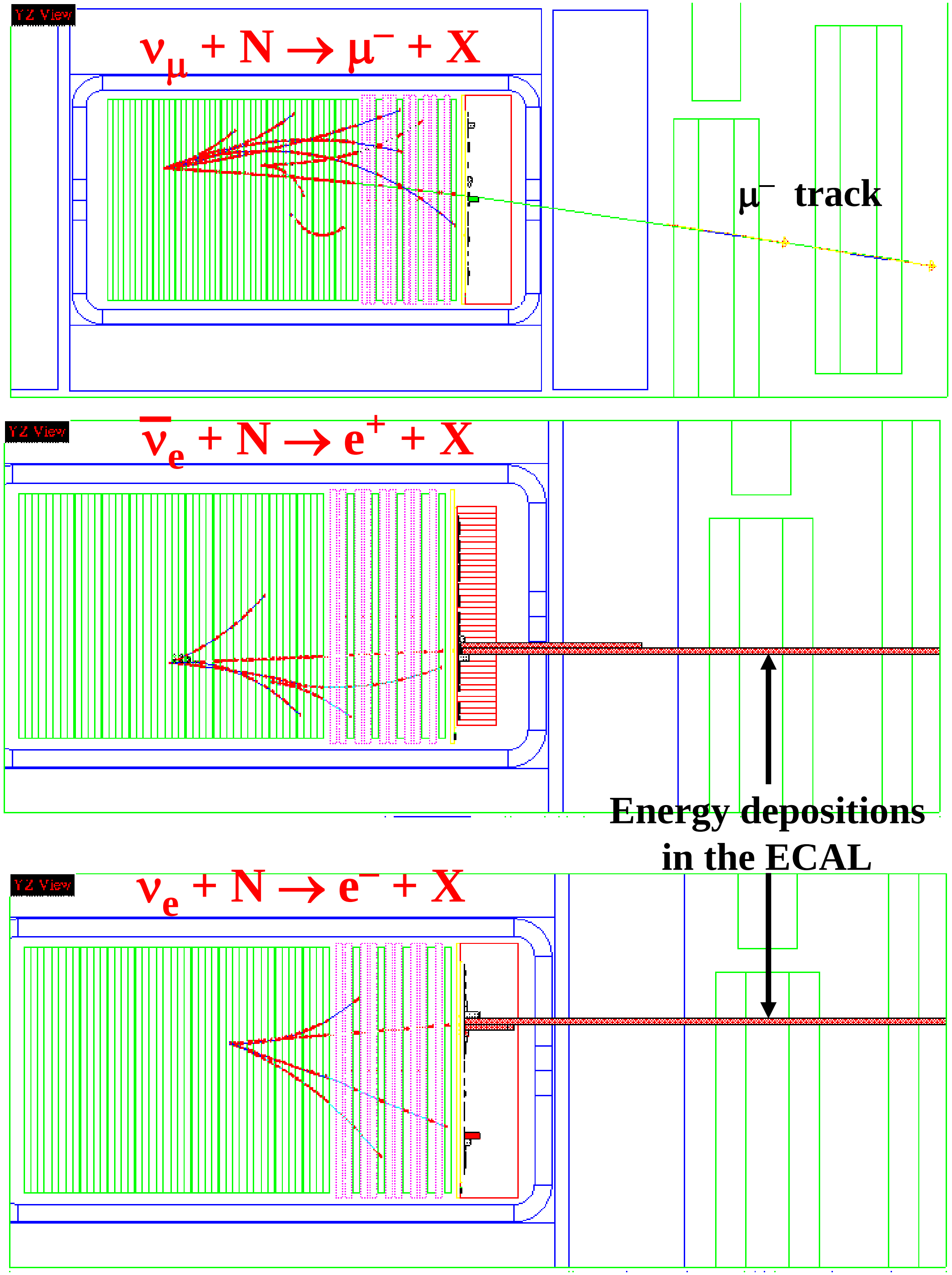
Exploit the small νe background (~1%):
τ->e channel: electron id

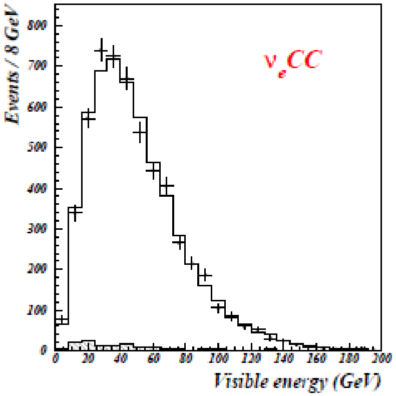
Go down to $P_{\mu\tau} \sim 10^{-4}$

Nomad typical events →

Nomad:

- Modern bubble chamber version
- Very good for electron identification and kinematical measurements
- 3 ton detector, technology not exportable to the kton scale
- Still very good as near detector in a LBL experiment, Nomad-like detector considered for the next LBL experiment in the USA (DUNE)



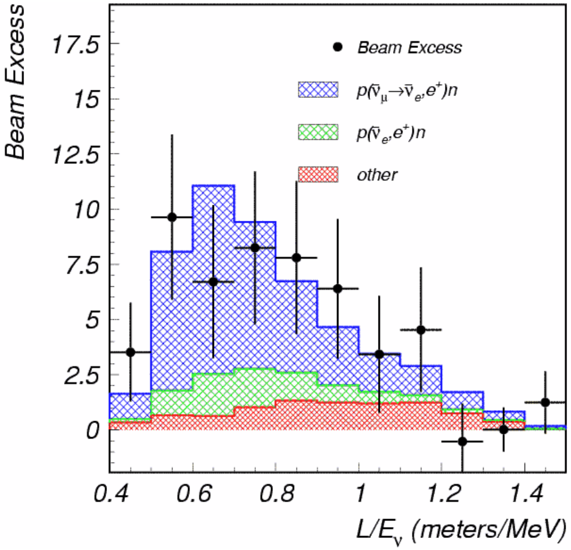


$\nu_\mu \rightarrow \nu_e$ analysis:

5600 ν_e CC events
44% efficiency
98% purity

LSND result: evidence for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations (1994)

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.)

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

Δm^2 in the ~eV² region

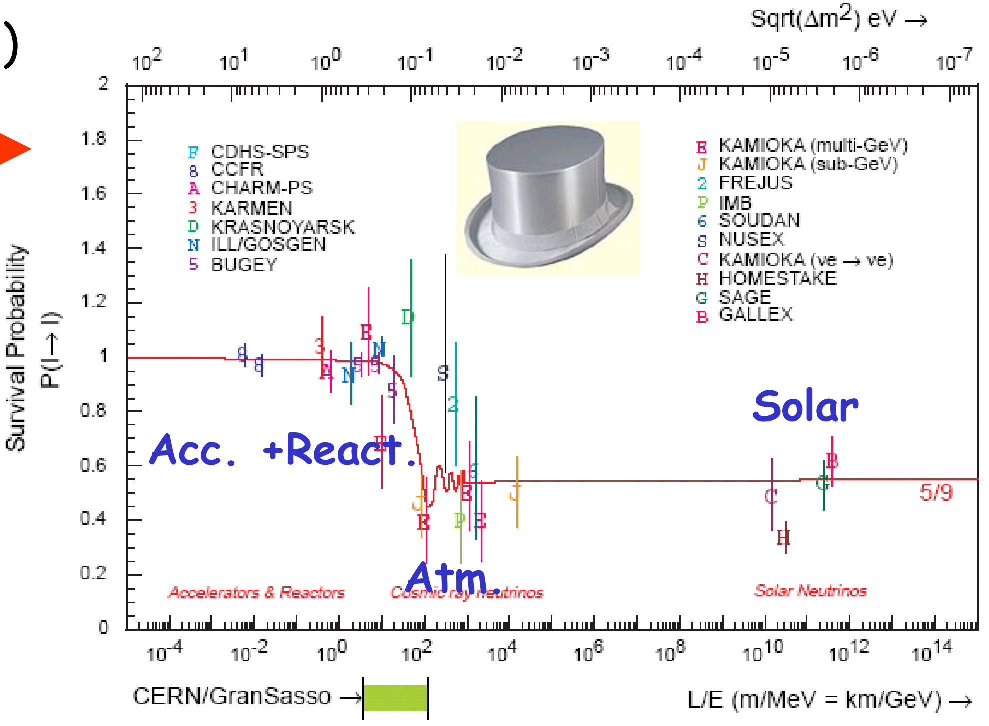
LSND not really confirmed by the dedicated experiment MINIBOONE (2001-2008)

However several ~3 sigma anomalies (LSND, MINIBOONE low energy, Reactor anomaly, Cr source) not completely coherent among themselves) are still floating around in the field, feeding theoretical models and additional experimental activity.
These results require more than 3 neutrino flavors to be explained → sterile neutrinos but even models with additional sterile neutrinos do not fit data well

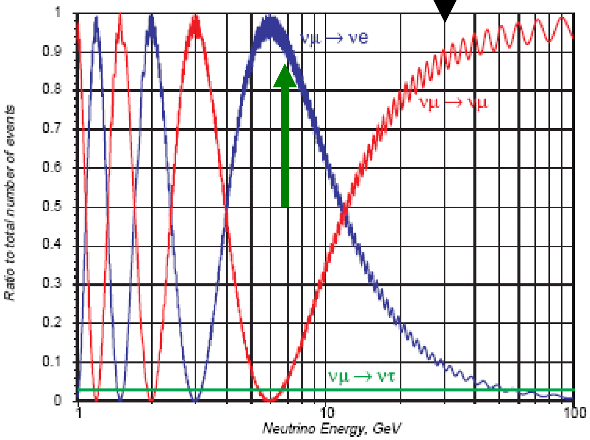
→ Very intensive effort ongoing now at FERMILAB with the short-baseline program + experiments at nuclear reactors and with radioactive sources performed in last years)

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

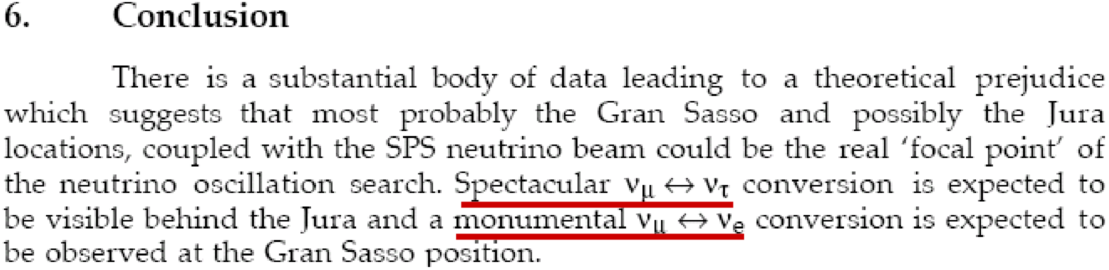


The Acker-Pakvasa
3 flavours model **hep-ph/9611423** included
also LSND (**$\Delta m^2 \sim 1$ eV^2**)



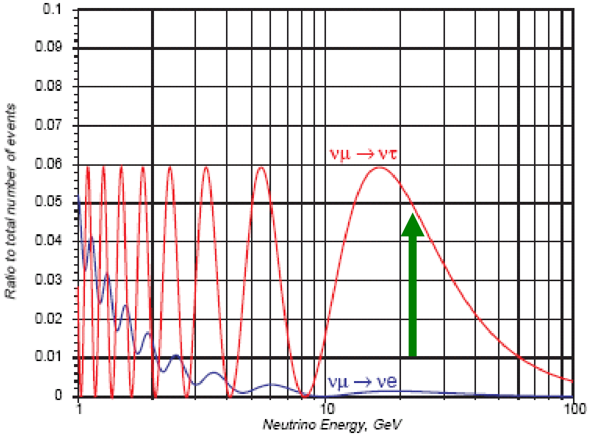
(C)
Gran Sasso
(7…

Icarus SPSLC 96/58 P304 19/12/1996



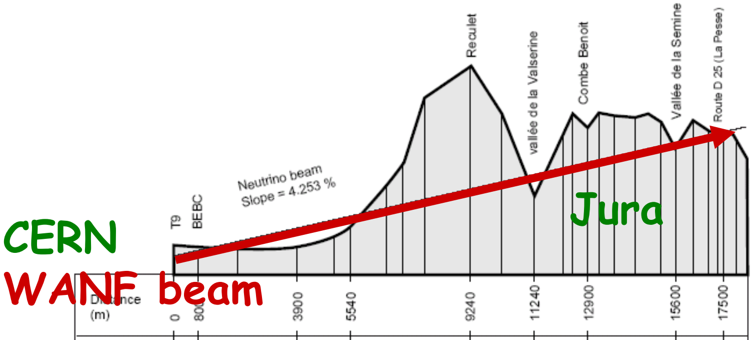
6. Conclusion

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)

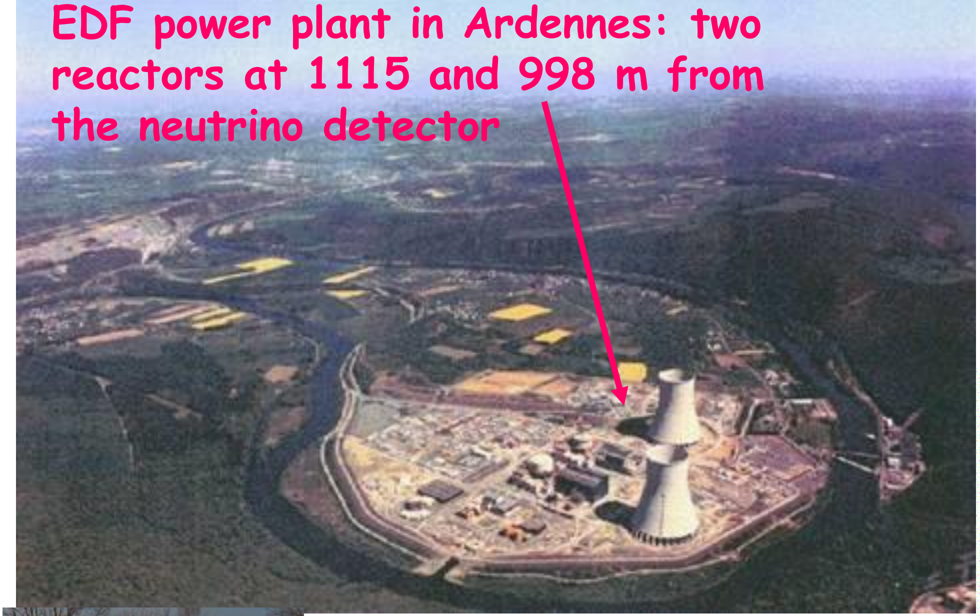
Medium-baseline
L/E~1Km/GeV



CHOOZ (the first long-baseline experiment) 1997-1998

$\overline{\nu}_e \rightarrow \overline{\nu}_e$ (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



EDF power plant in Ardennes: two reactors at 1115 and 998 m from the neutrino detector

Target: 5 ton liquid scintillator target with 0.09% Gadolinium

Prompt annihilation signal (γ rays)

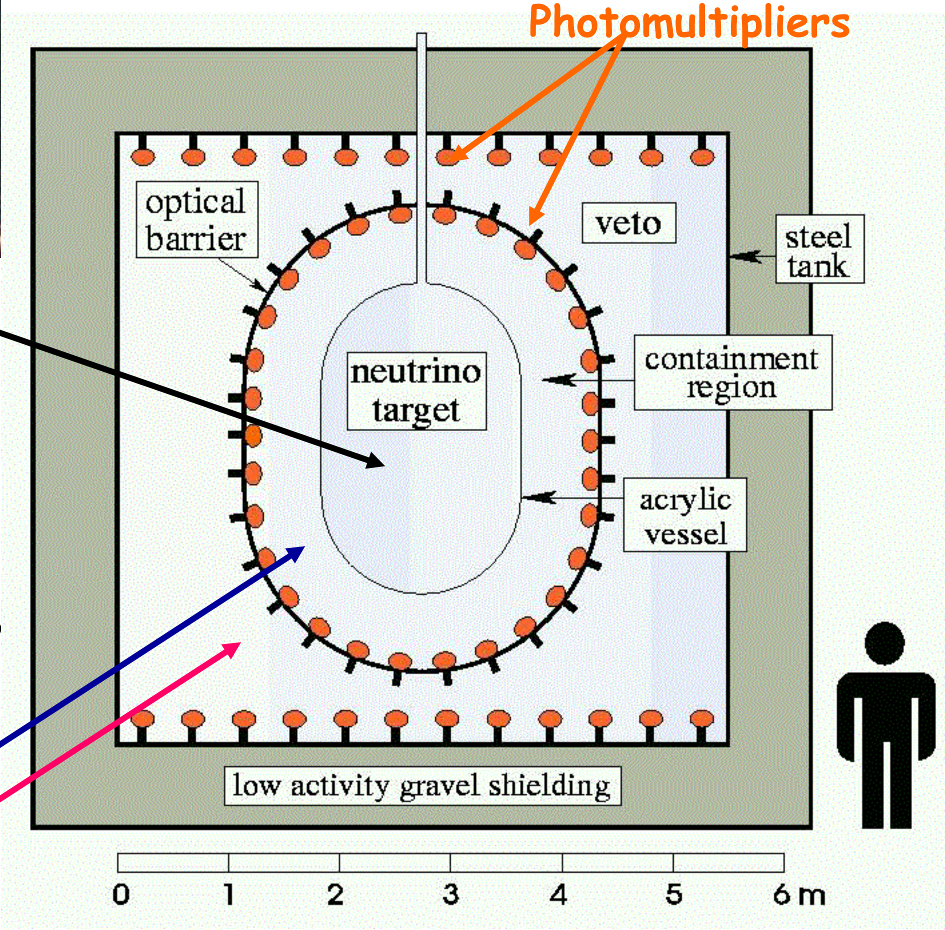
$\overline{\nu}_e + p \rightarrow e^+ + n$

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

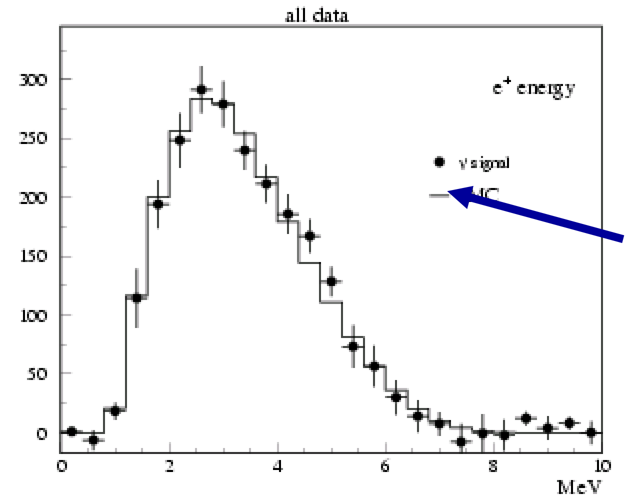
n capture on Gd after thermalization ~30μs

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

90 ton liquid scint. cosmic rays



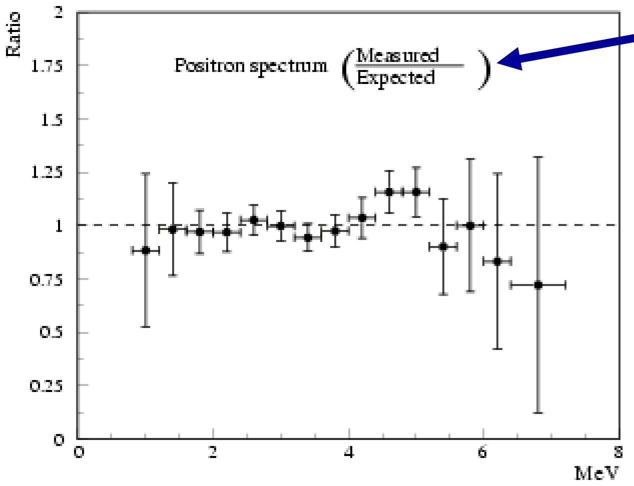
CHOOZ (the first long-baseline experiment) 1997-1998



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



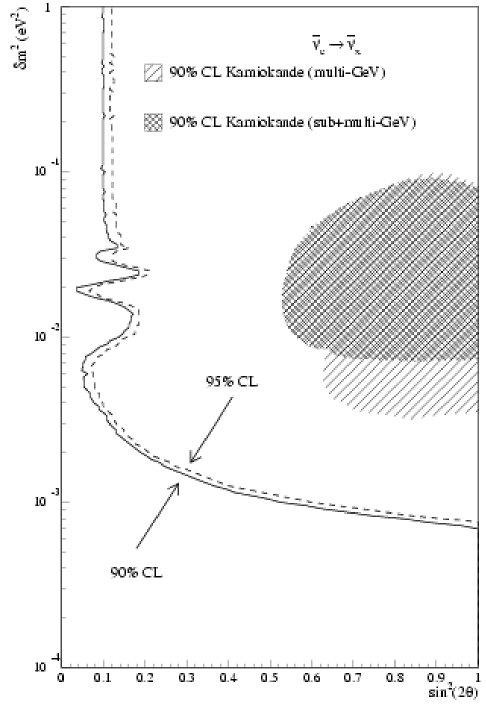
Positron energy (MeV)

Ratio measured/expected

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

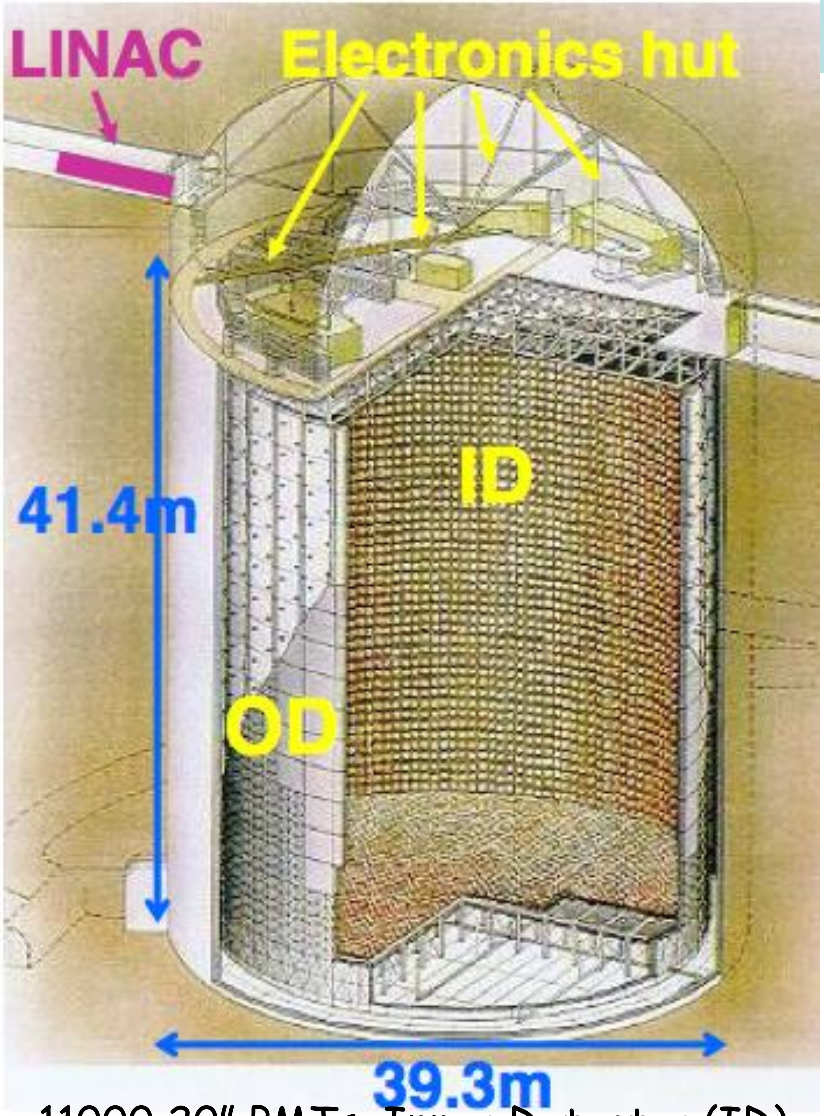
CHOOZ did not observe a significative deficit of ν_e

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



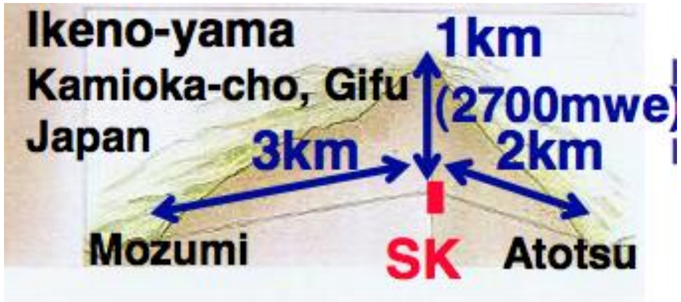
This result was published in 1998 before the Super-Kamiokande results and excluded the atmospheric neutrino anomaly interpretation in terms of $\nu_\mu \rightarrow \nu_e$ oscillations

The Super-Kamiokande detector



~11000 20" PMTs Inner Detector (ID) (40% coverage)

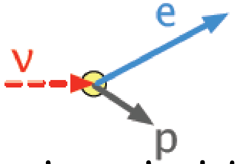
Proton decay, solar neutrinos, atmospheric neutrinos, supernovae neutrinos + accelerator neutrinos (K2K, T2K)



- 50 Kton Water Cherenkov detector (fiducial volume 22.5 Kton)
- Operation since April 1996 (accident in 2001 recovered in 2006)
- Dead-time less DAQ system (since 2008~)

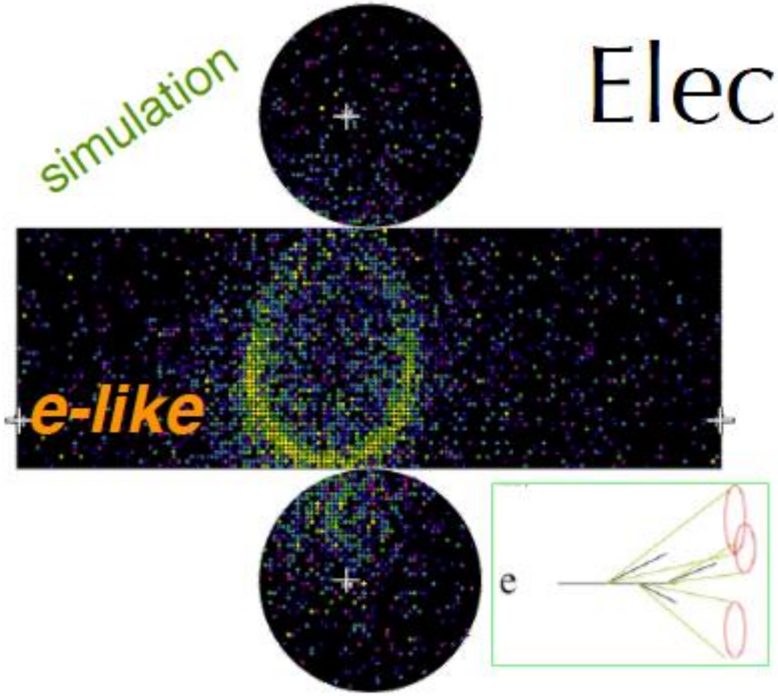
- Detector performance well-matched to sub-GeV neutrinos:
  - Excellent performance for single particle events
  - Good e-like(shower ring) / μ-like separation
  - Quasi-elastic scattering dominant in sub-GeV region.

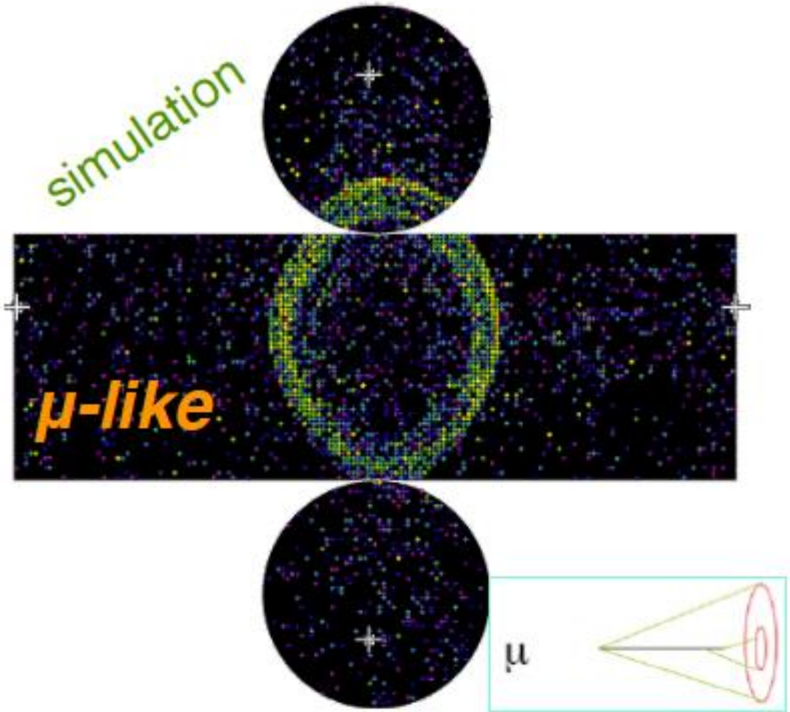
νe signal: $\nu_e + n \to e + p$



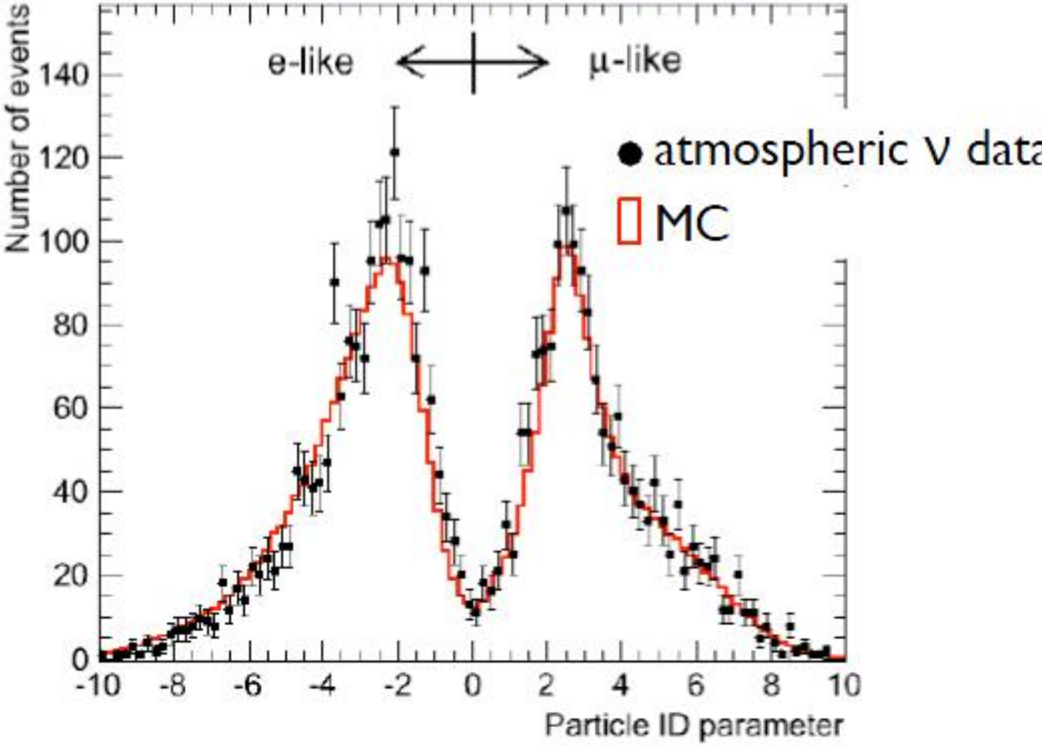
proton not detected (below Cerenkov threshold)

Electron-like and muon-like event at SK





Particle identification using ring shape & opening angle

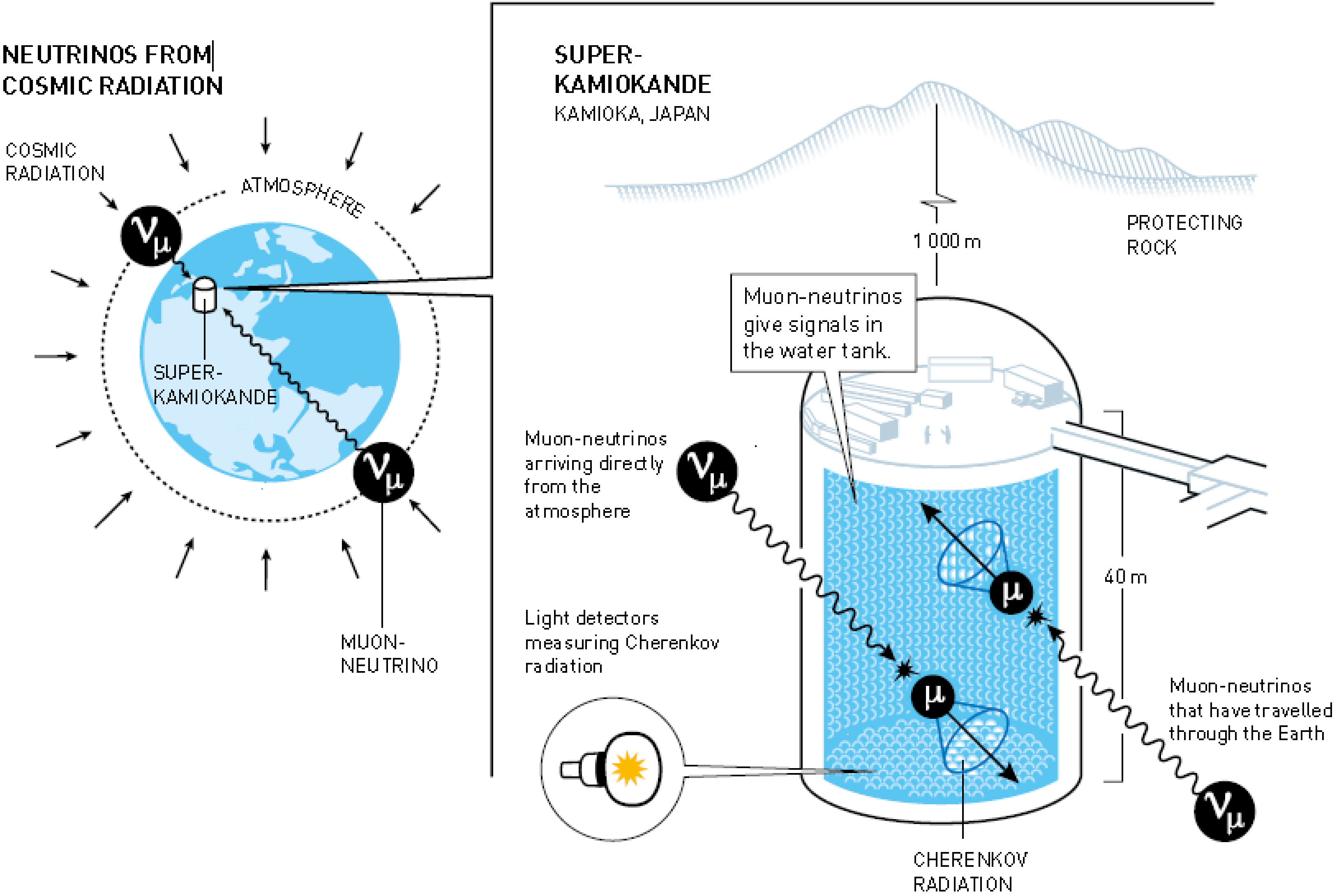


Probability that μ is mis-identified as electron is ~1%

NEUTRINOS FROM COSMIC RADIATION

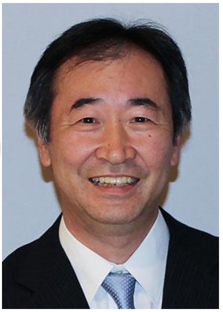
SUPER-KAMIOKANDE

KAMIOKA, JAPAN

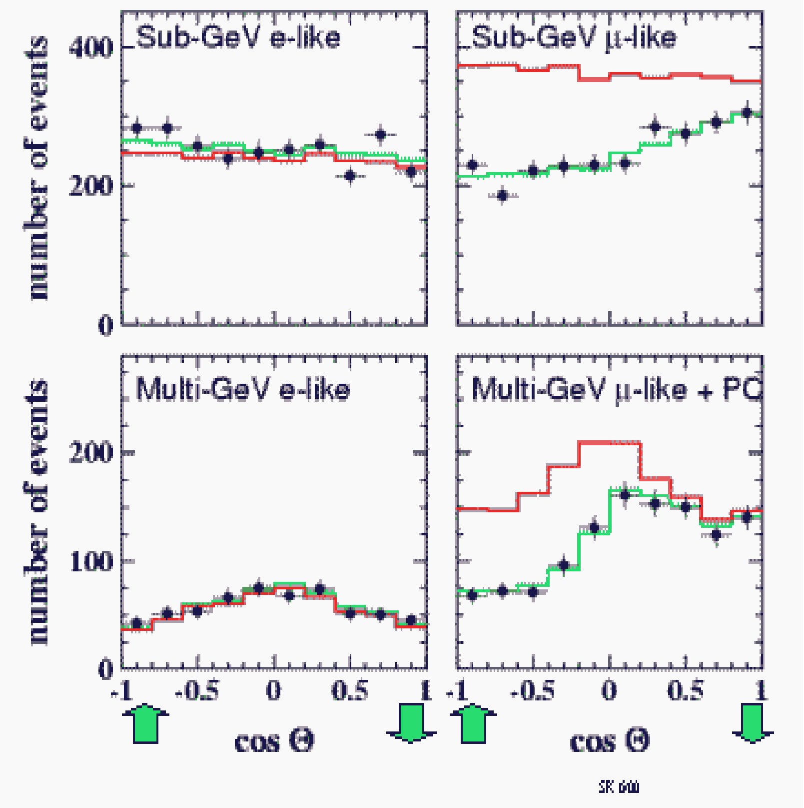


Neutrino 98 Conference in Takayama (June 1998)

Nobel 2015



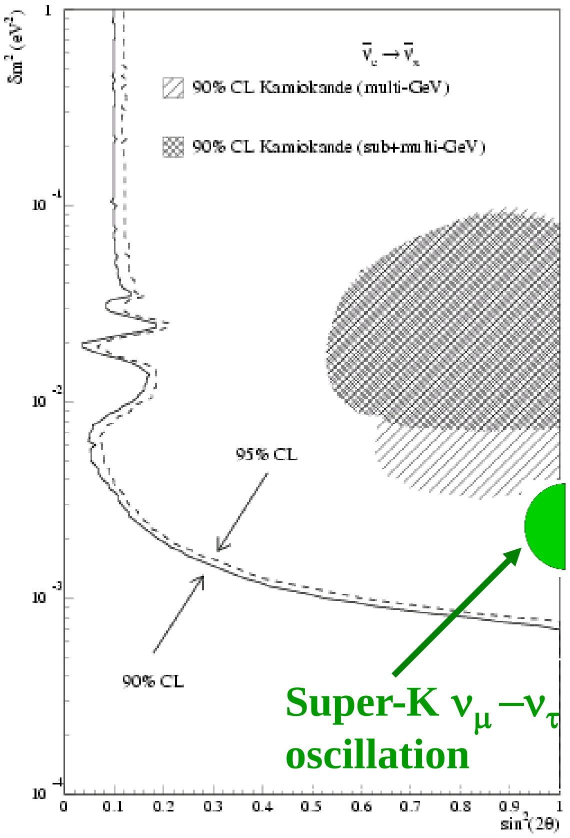
First results from Super-Kamiokande on atmospheric neutrinos, evidence of a zenith angle dependence of ν_μ disappearance, ν_e in agreement with expectations



SK: Atmospheric neutrinos anomaly

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

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



Super-K $\nu_\mu - \nu_\tau$ oscillation

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

→Opens the campaign for long baseline experiments to reproduce the phenomenon with accelerator neutrinos

SNO and Kamland at the close horizon
LBL experiments K2K, MINOS launched

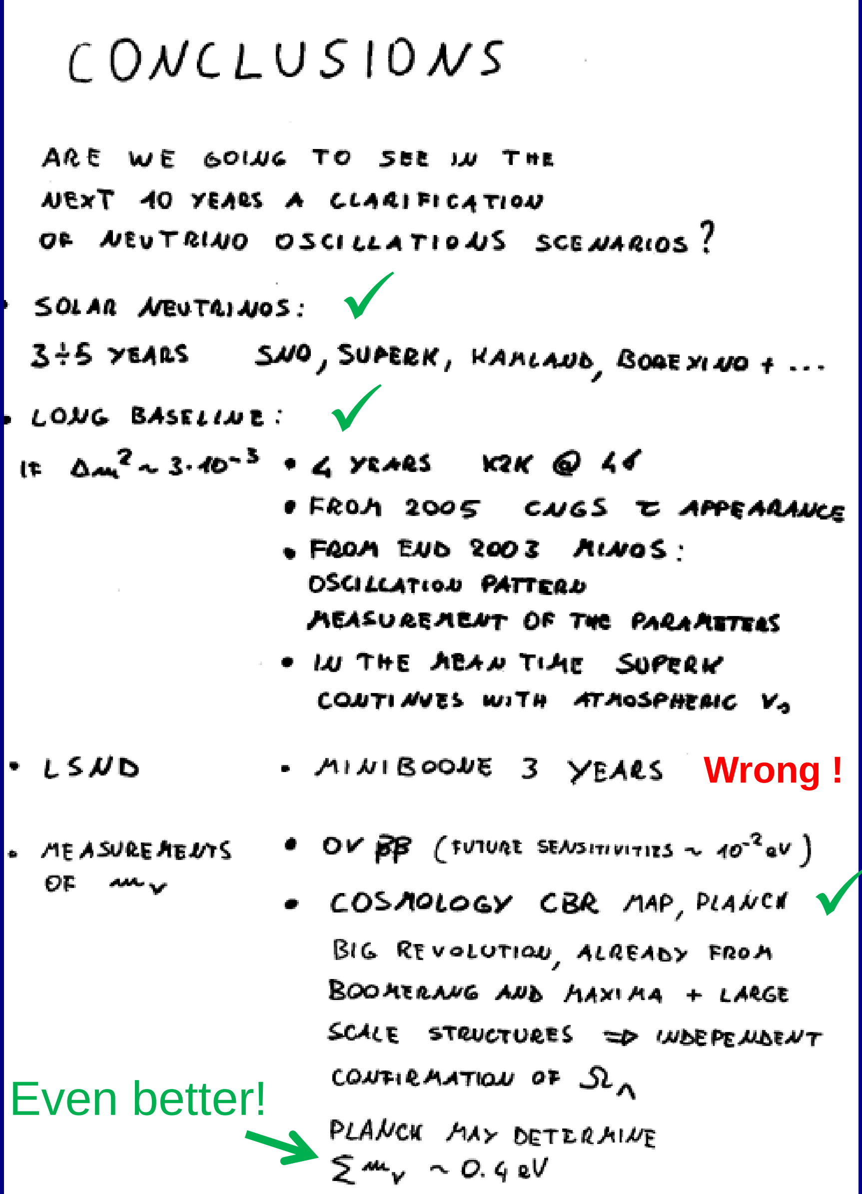
CERN 4/7/2000

HIGHLIGHTS OF THE

NEUTRINO 2000 CONFERENCE

SUDBURY JUNE 16-21 2000

D. AUTIERO
CERN/EP



CONCLUSIONS

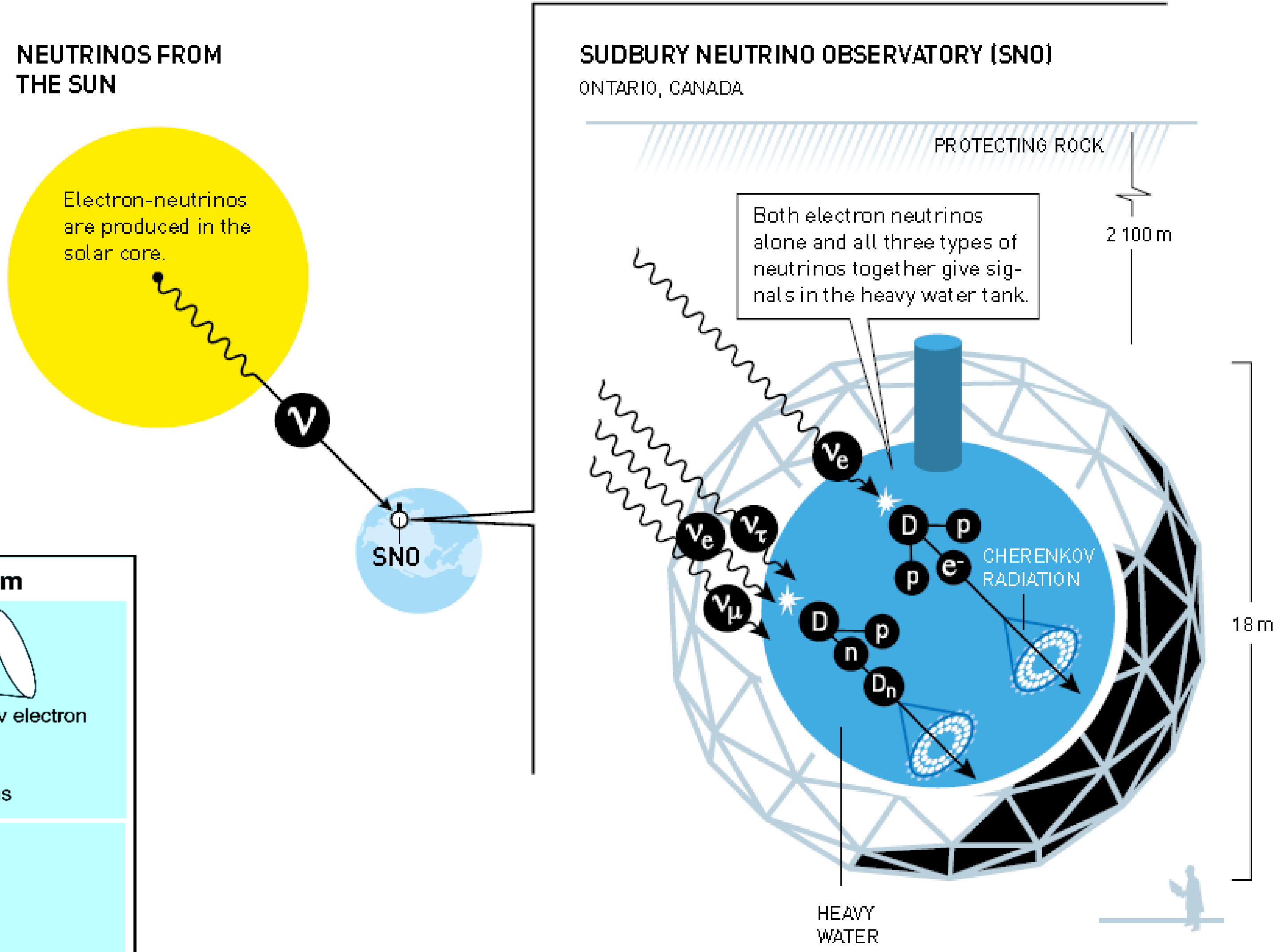
ARE WE GOING TO SEE IN THE NEXT 10 YEARS A CLARIFICATION OF NEUTRINO OSCILLATIONS SCENARIOS?

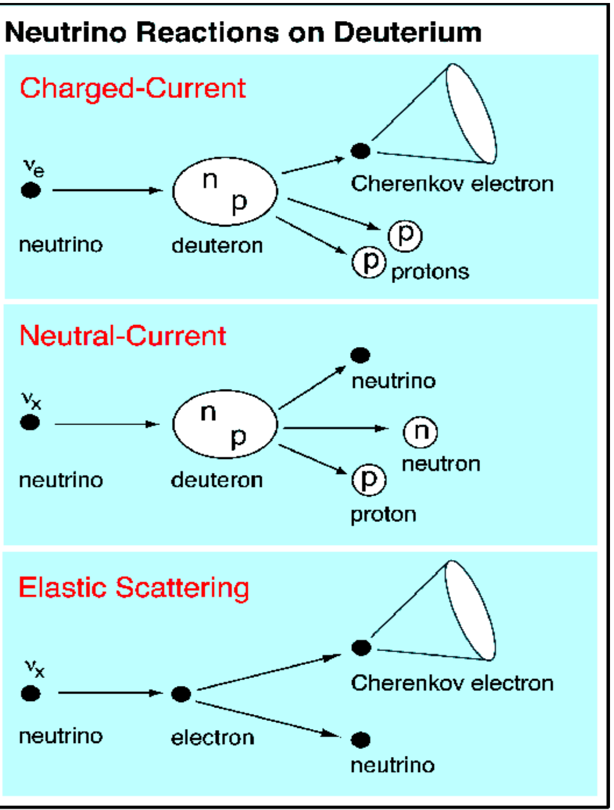
- SOLAR NEUTRINOS: ✓
  3÷5 YEARS SNO, SUPERK, KAMLAND, BOREXINO + ...
- LONG BASELINE: ✓
  IF $\Delta m^2 \sim 3 \cdot 10^{-3}$
  - 4 YEARS K2K @ 4σ
  - FROM 2005 CNGS τ APPEARANCE
  - FROM END 2003 MINOS: OSCILLATION PATTERN MEASUREMENT OF THE PARAMETERS
  - IN THE MEAN TIME SUPERK CONTINUES WITH ATMOSPHERIC ν_s
- LSND
  - MINIBOONE 3 YEARS **Wrong !**
- MEASUREMENTS OF m_ν
  - $0\nu\beta\beta$ (FUTURE SENSITIVITIES $\sim 10^{-2}$ eV)
  - COSMOLOGY CBR MAP, PLANCK ✓
    BIG REVOLUTION, ALREADY FROM BOOMERANG AND MAXIMA + LARGE SCALE STRUCTURES ⇒ INDEPENDENT CONFIRMATION OF Ω_Λ

Even better! →

PLANCK MAY DETERMINE $\sum m_\nu \sim 0.4$ eV

Nobel 2015





Neutrino Reactions on Deuterium

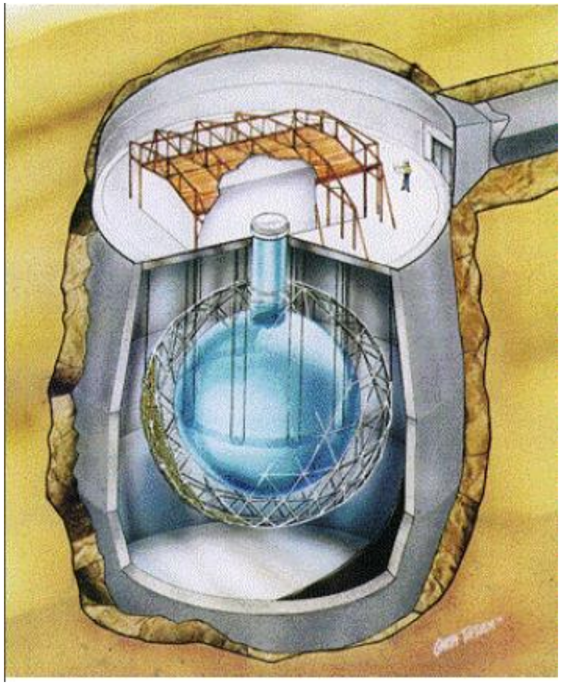
SNO: 1000 tons of heavy water, sensitive to neutral current reactions → measure the total neutrino flux independently from their flavor

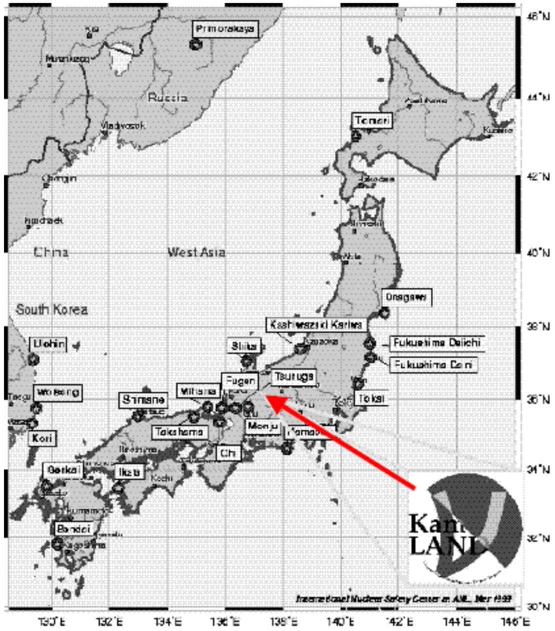
The final proof for solar neutrinos:

2001: SNO Measurement of the total neutrino flux independently from their flavor

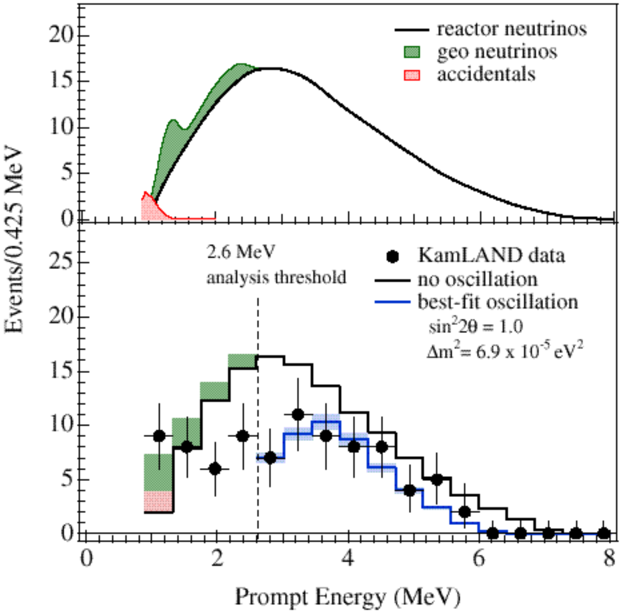
(NC) ν+d→ν+p+n

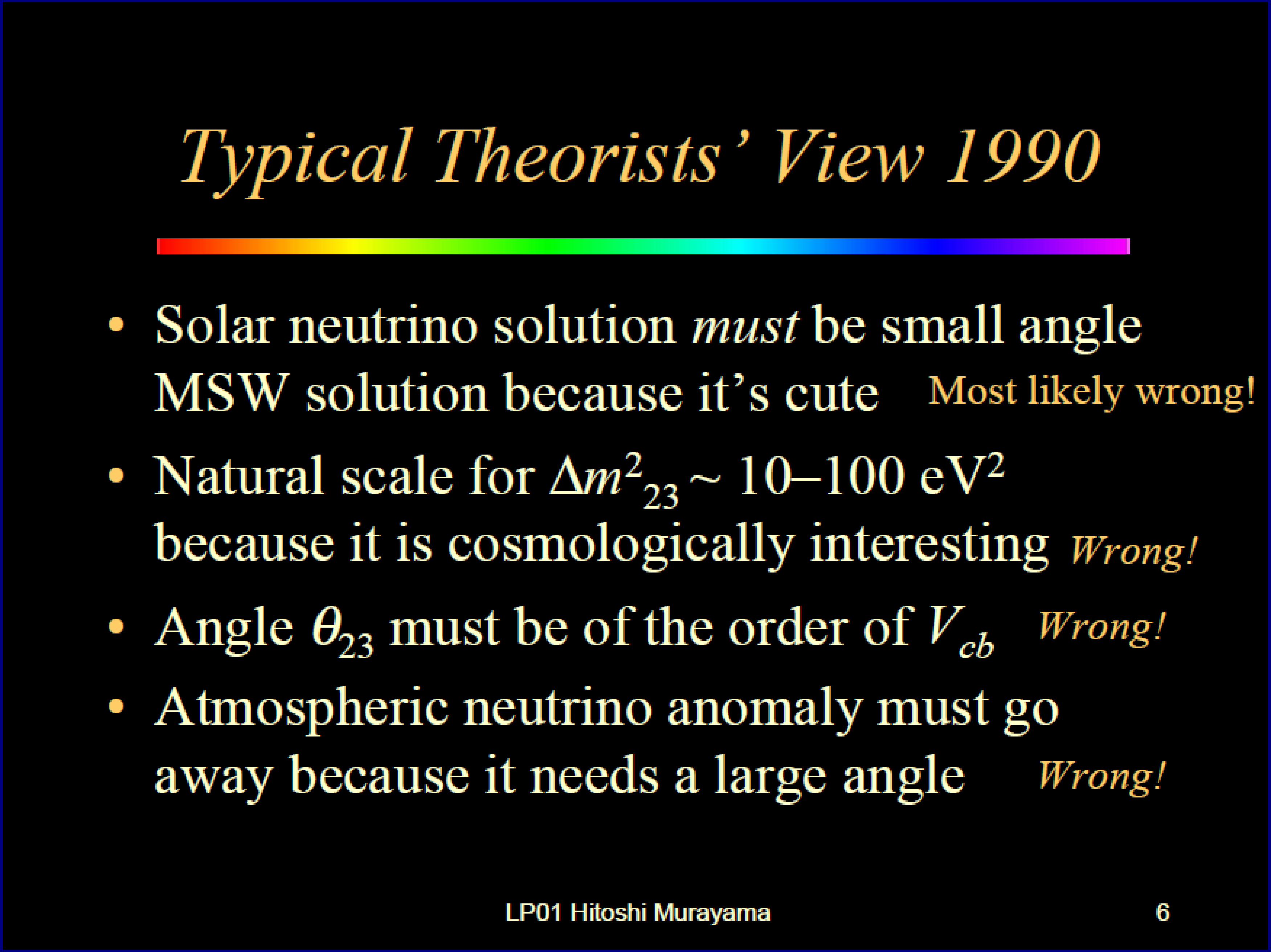
The total neutrino flux agrees with the SSM !
→ Electron neutrinos change into other neutrino flavors





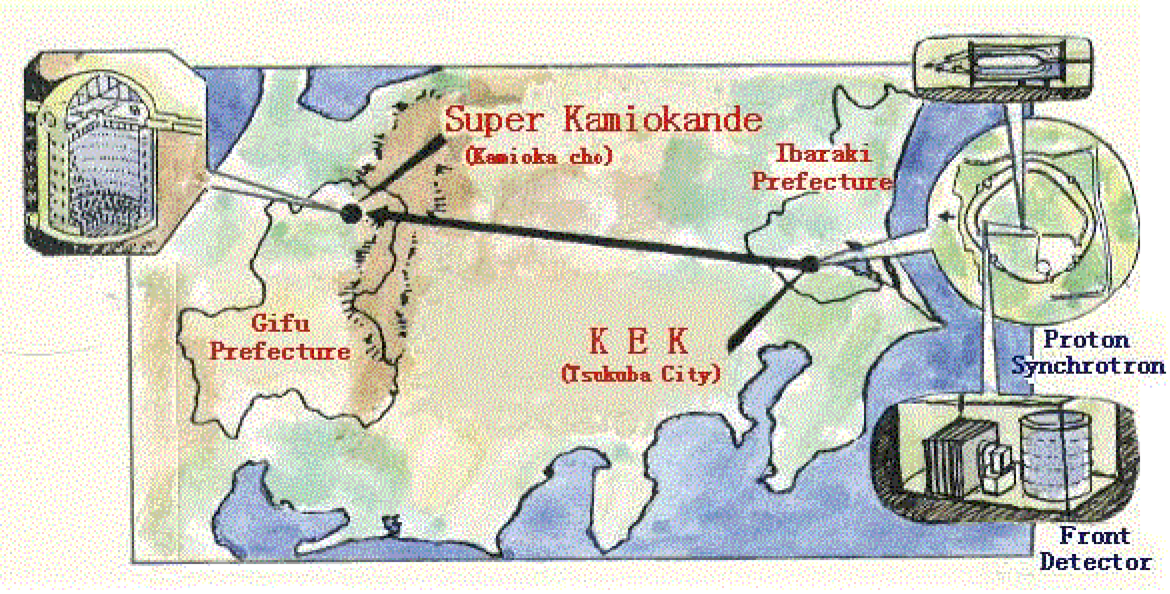
2002: Kamland
reactor experiment
1000 ton liquid scintillator
reproduces the solar neutrino oscillations on earth using antineutrinos from far reactors (on average 180 km)





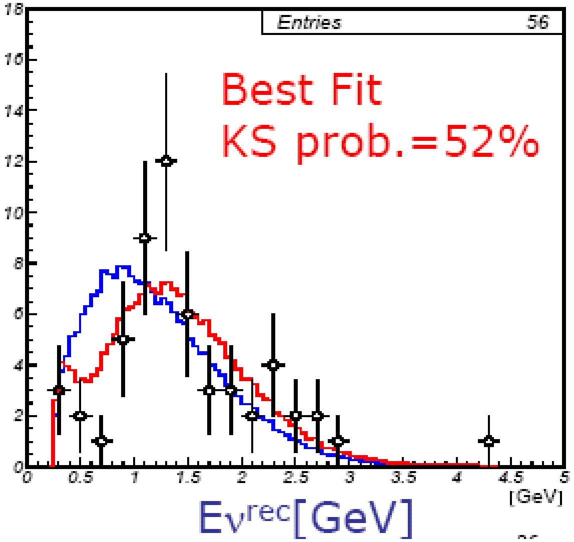
Typical Theorists' View 1990

- Solar neutrino solution *must* be small angle MSW solution because it's cute Most likely wrong!
- Natural scale for $\Delta m^2_{23} \sim 10\text{–}100\ \text{eV}^2$ because it is cosmologically interesting *Wrong!*
- Angle θ_{23} must be of the order of V_{cb} *Wrong!*
- Atmospheric neutrino anomaly must go away because it needs a large angle *Wrong!*

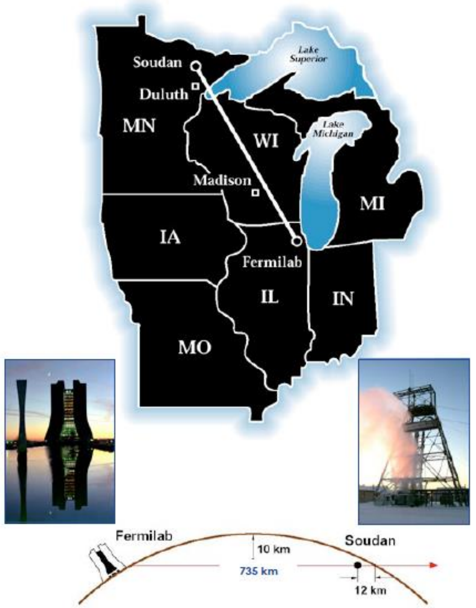


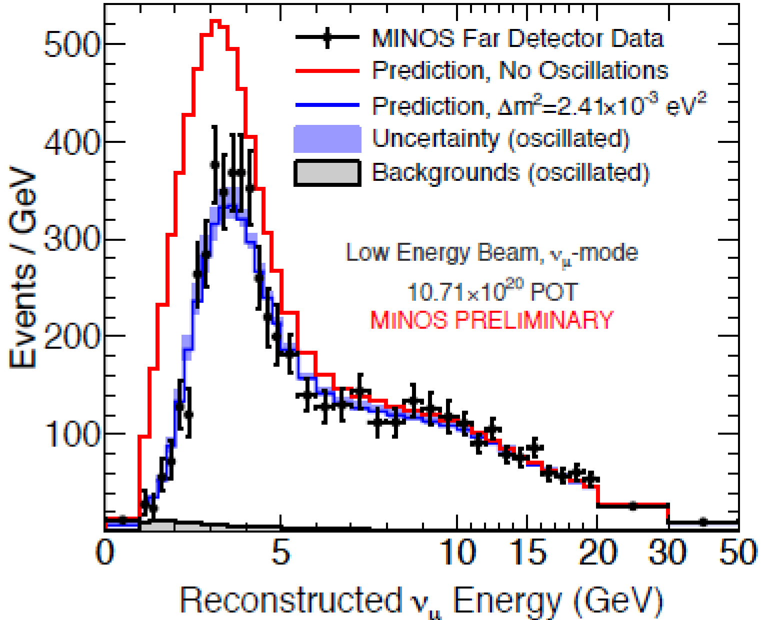
K2K results in 2004

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



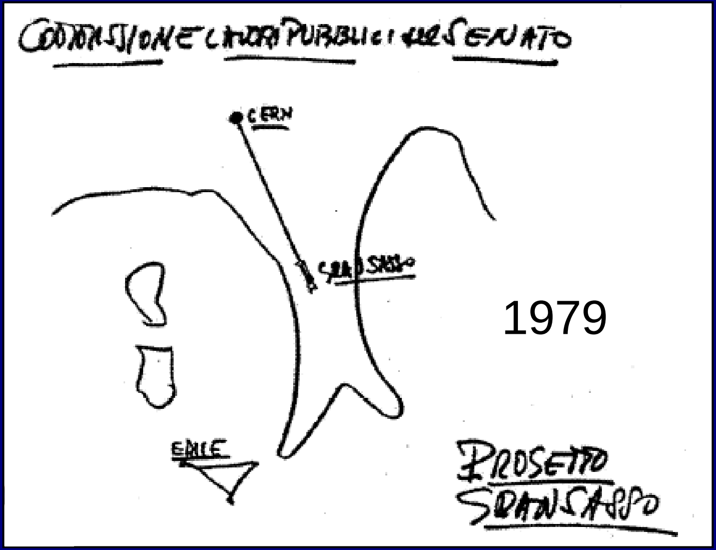
MINOS (U.S.) results in 2006





→ Confirmation of SuperKamiokande atmospheric neutrino results with accelerator neutrinos

Cern Neutrinos to Gran Sasso



1979

- 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 subleading $\nu_\mu \rightarrow \nu_e$ oscillations

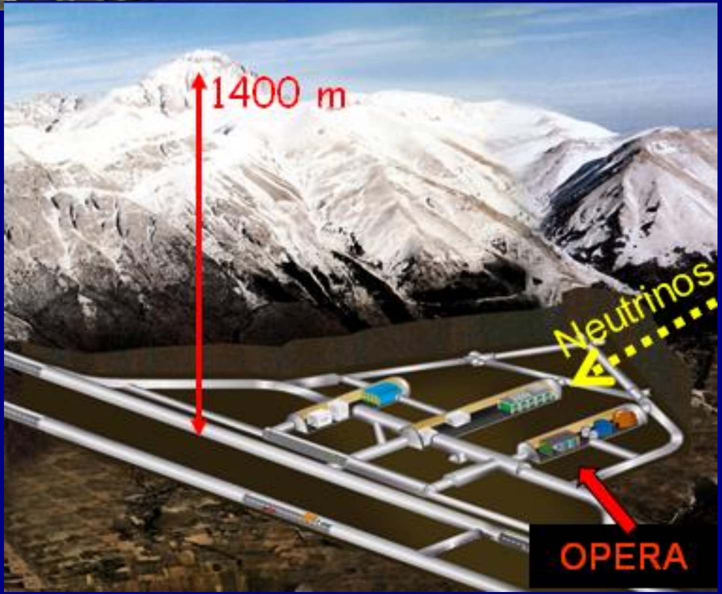
- Beam: CNGS (1999)
- ν_τ appearance experiments at LNGS
- No near detectors needed in appearance mode

CNGS1 (2000)

OPERA

CNGS2 (2002)

Imaging Cosmic And Rare Underground Signals

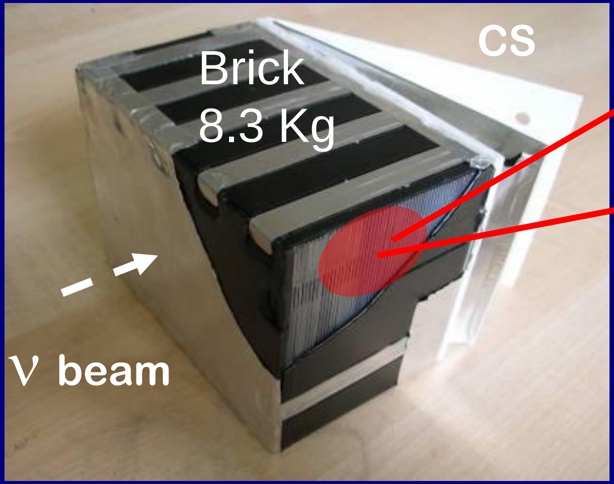


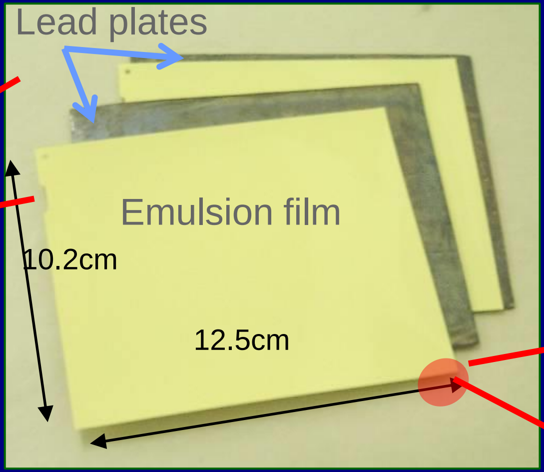
OPERA basic unit: the « Brick »

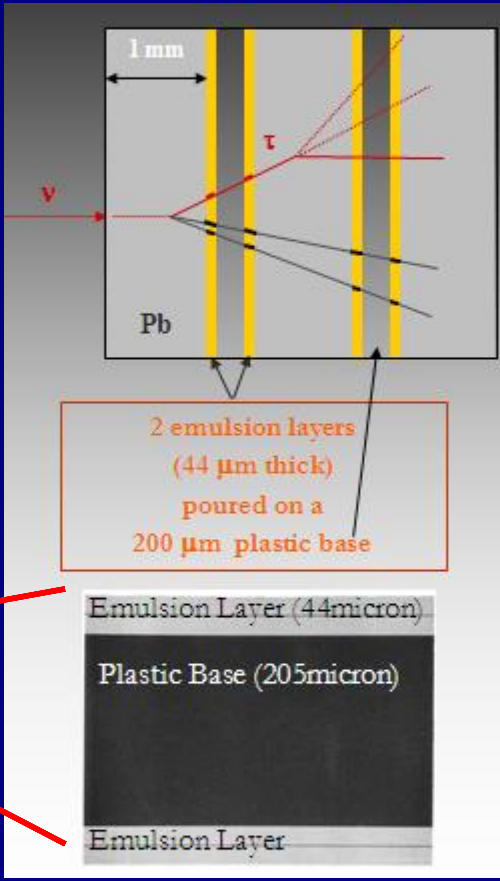
Based on the concept of the **E**mulsion **C**loud **C**hamber :

- 57 emulsion films + 56 Pb plates
- interface to electronic detectors: removable box with 2 films (Changeable Sheets)

→ High space resolution in a large mass detectors with a completely modular scheme





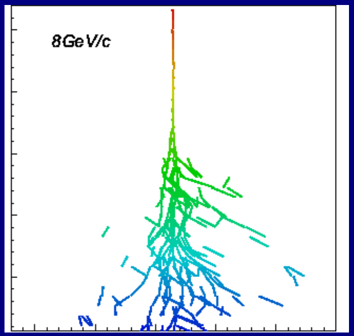


Tracks reconstruction accuracy in emulsions:

$\Delta x \approx 0.3\ \mu m$ $\Delta\theta \approx 2$ **mrad**

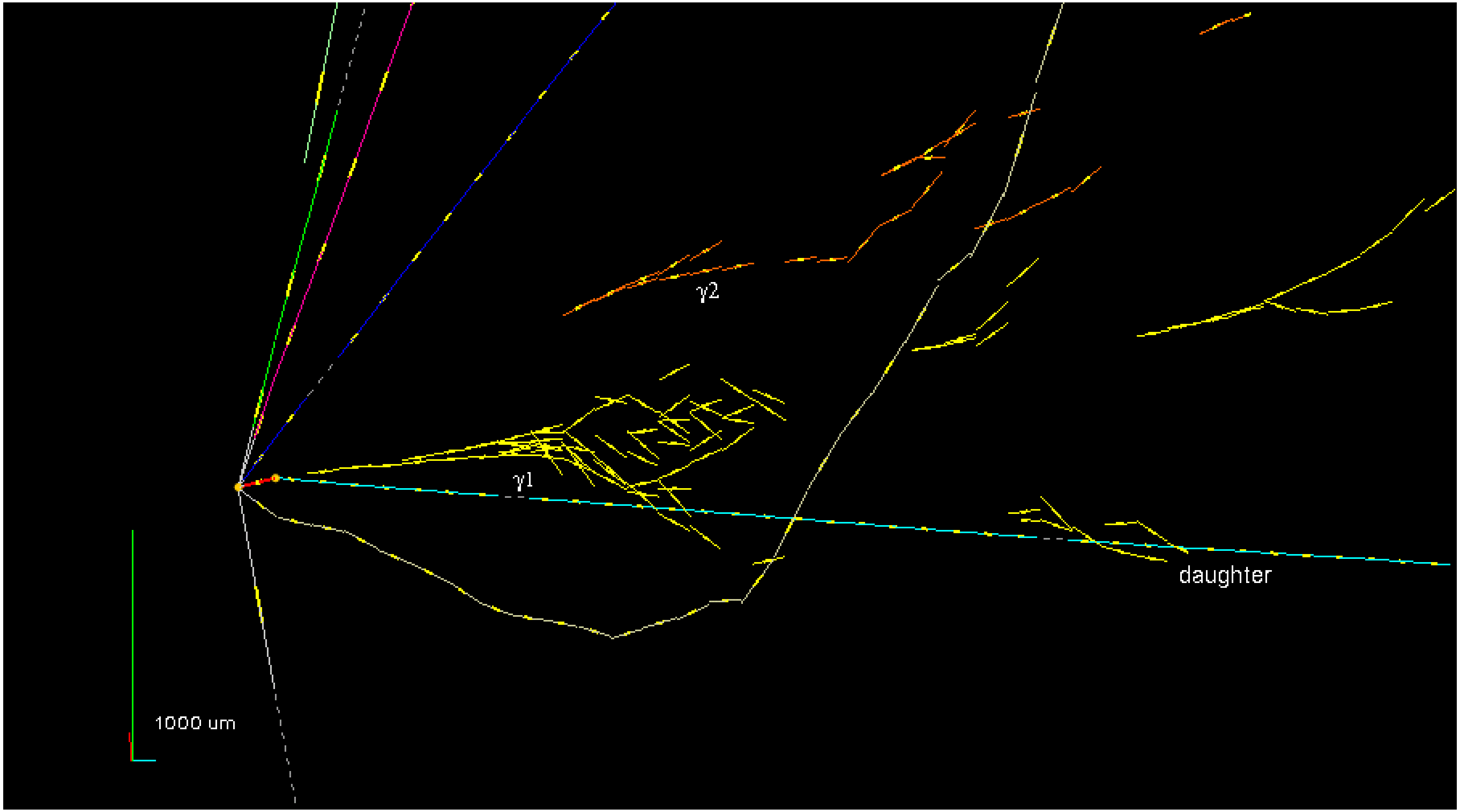
Bricks are complete stand-alone detectors:

- ✓ Neutrino interaction vertex and kink topology reconstruction
- ✓ Measurement of hadrons momenta by multiple Coulomb scattering
- ✓ dE/dx: pion/muon separation at low energy (at end of range)
- ✓ Electron identification and measurement of the energy of electrons and gammas (electromagnetic calorimetry)



First OPERA ν_τ candidate
(single hadronic prong τ decay)

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



$$\nu_\tau + N \rightarrow \tau^- + X$$
$$\tau^- \rightarrow \rho^- + \nu_\tau$$
$$\rho^- \rightarrow \pi^- + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

Visible tau decay topology with kink and two gammas

Standard 3 ν framework (ignoring LSND, Miniboone anomaly, Reactors anomaly, Cr source anomaly …)

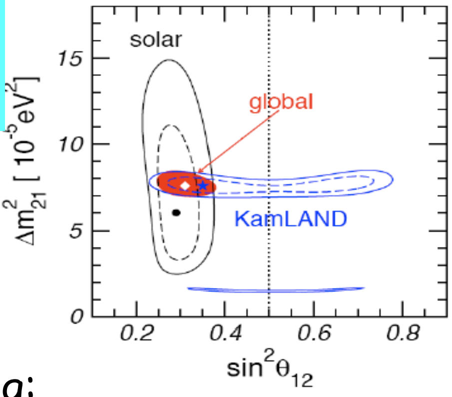
Two almost independent oscillations describing;

solar neutrinos: Δm^2_{21} $(7.65^{+0.23}_{-0.20})\,10^{-5}\,\mathrm{eV}^2$, $\sin^2\theta_{12}$ $0.304^{+0.022}_{-0.016}$

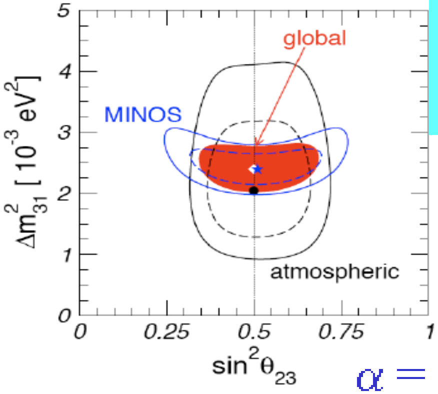
and atmospheric neutrinos: $|\Delta m^2_{31}|$ $(2.40^{+0.12}_{-0.11})\,10^{-3}\,\mathrm{eV}^2$, $\sin^2\theta_{23}$ $0.50^{+0.07}_{-0.06}$

Solar neutrinos
+ Kamland
ν_e, anti-ν_e disappearance

L/E~15 Km/MeV



L/E~500 Km/GeV



Atmospheric neutrinos
+ accelerators
ν_μ disappearance

3 neutrino flavours mixing:
favorite parametrization of U:
in terms of 3 mixing angles θ_{12} θ_{23} θ_{13} and one Dirac-like CP phase δ :

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

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

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

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

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

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

Bridge

θ_{13}, CP violation?

Key measurements of neutrino mixing via the study of $\nu_\mu \rightarrow \nu_e$ oscillations:

Direct evidence for CP violation must be searched in with the sub-leading $\nu_\mu \rightarrow \nu_e$ oscillation at the Δm^2 of the atmospheric neutrinos ($\Delta m^2 \sim 10^{-3}$ eV^2)

Matter effect

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

Leading term

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

CP-terms

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

Solar term

CPV

$$J_{CP} = 1/8 \sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31} L/4E$$

E_ν dependence

$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

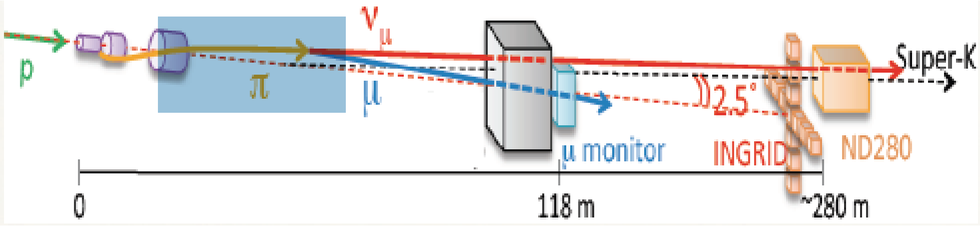
The same oscillation channel provides infos on:

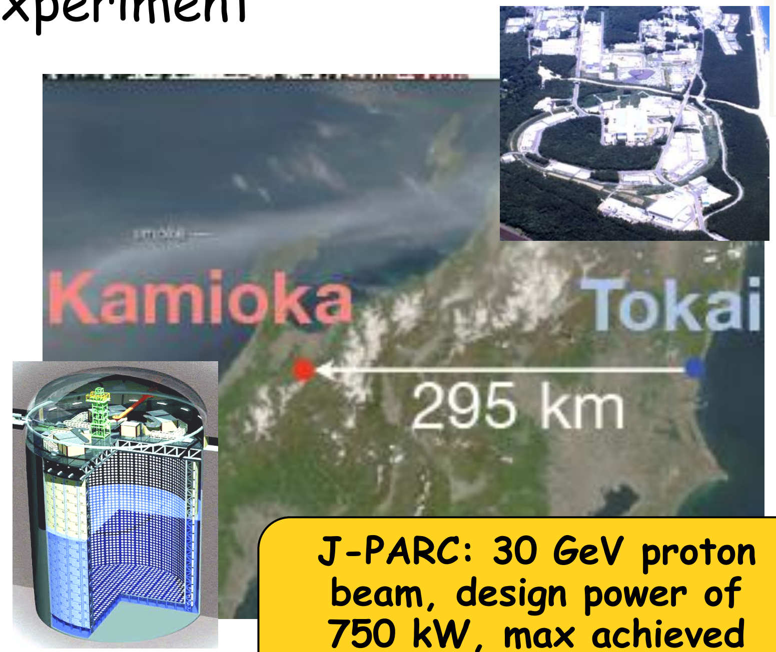
- θ_{13}
- Matter effects and mass hierarchy
- CP violation

Large θ_{13} → next steps accessible with standard beams !

To study this channel it is crucial to use a detector capable of providing a very good measurement of electrons (electron identification, background rejection) and energy resolution

The search for θ_{13}: The T2K (Tokai to Kamioka) experiment





J-PARC: 30 GeV proton beam, design power of 750 kW, max achieved 371 KW

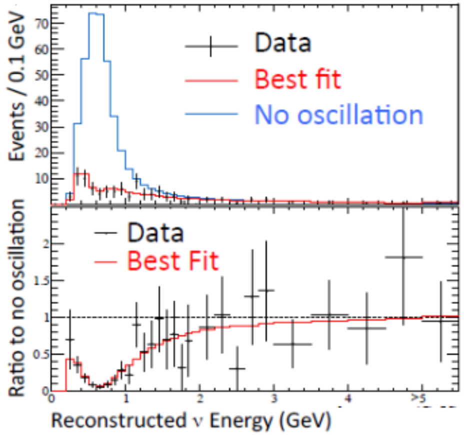
- Baseline 295km, 2.5° off-axis beam tuned to oscillation maximum, <E> ~ 0.6 GeV
- Search for/measure neutrino oscillations:

  $\nu_\mu \rightarrow \nu_e$

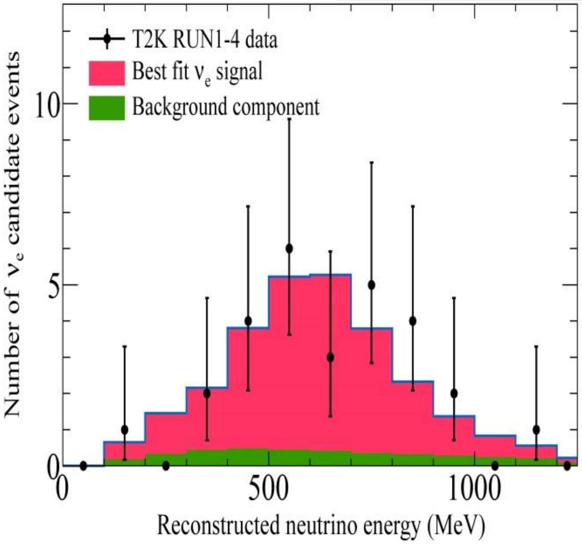
  $\nu_\mu \rightarrow \nu_\tau$
- Measurement of θ_{13} in appearance mode
- Disappearance mode: improve measurement of θ_{23}, Δm^2_{23} → is θ_{23} maximal?

$$\boxed{\begin{array}{l}\sin^2\theta_{23} = 0.514^{+0.0055}_{-0.0056}\ \text{(N.H.)}\\ \sin^2\theta_{23} = 0.511^{+0.0055}_{-0.0055}\ \text{(I.H.)}\end{array}}$$

Θ_{23} measurement further improved in 2015 …



- Most precise measurement of θ_{23} (11%)
- *Phys.Rev.Lett.* **112**,181801 (2014)



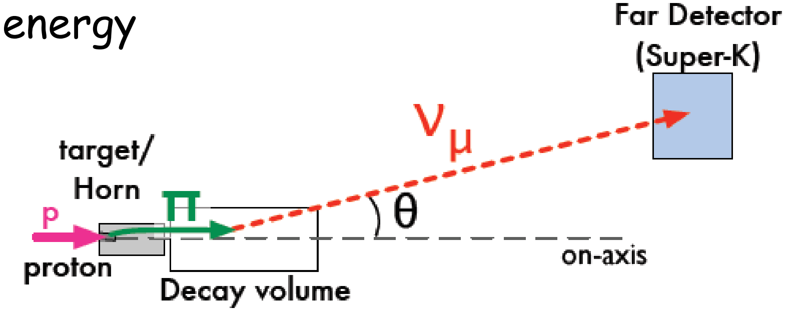
T2K: July 2013
conclusive observation of ν_e appearance from a ν_μ beam:

- **28 ν_e candidate events observed**
- **background 4.64±0.53 events**

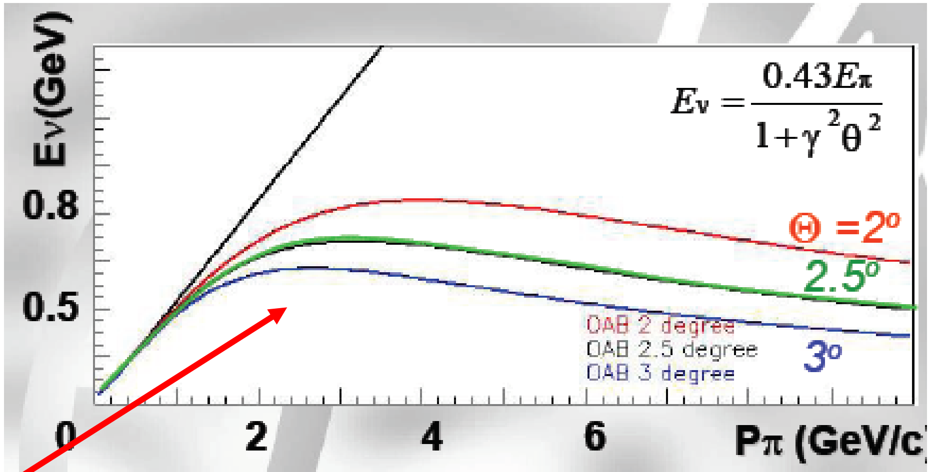
7.5 σ significance for non-zero θ_{13}

The off-axis neutrino beam:

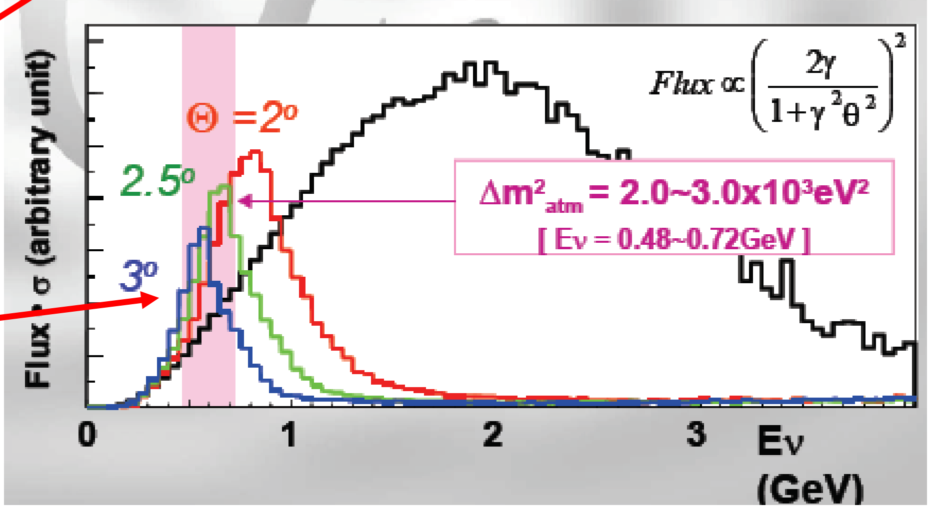
A very brigth idea to produce a tunable intense and narrow-band beam at low energy



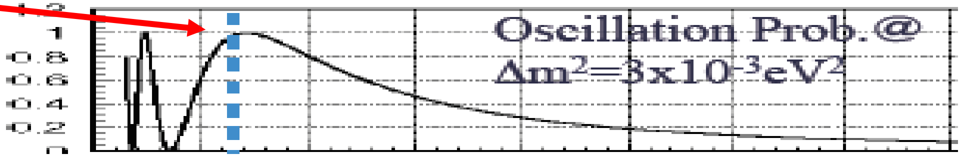
Given the pion decay kinematics at off-axis the relation between the pion momentum and the neutrino energy saturates



The flux at low energy is narrow-band and higher than the on-axis flux at the same energy



The energy can be tuned to the first oscillation maximum E~0.6 GeV for 2.5°



→ Most of the beam oscillates, very few ν_μ CC recorded: max disappearance

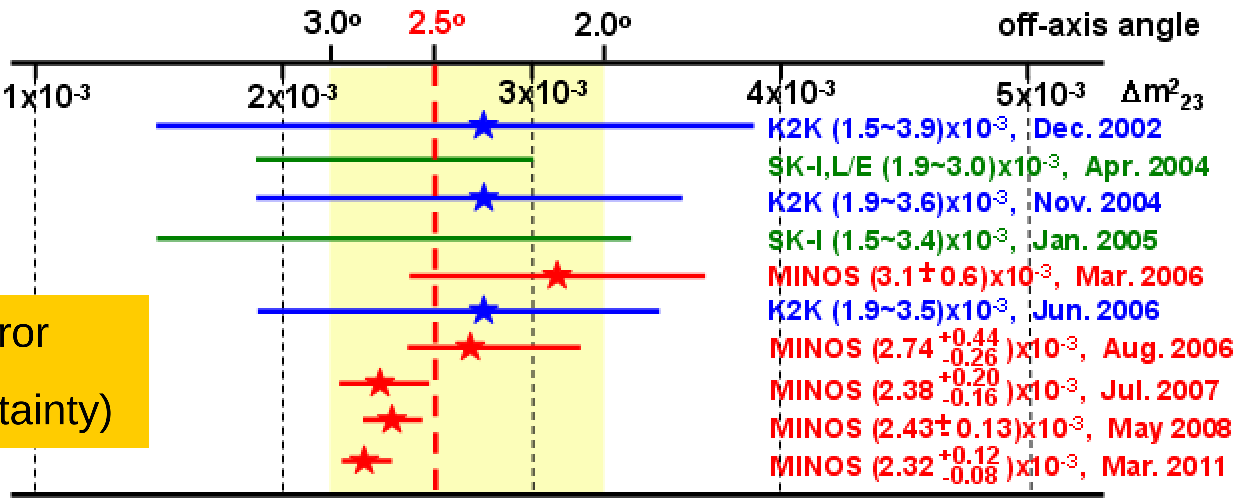
Small energy tail → low background from NC and ν_e
0.2% ν_e contamination and π° BG

→ max S/B ratio for ν_e search

Important to keep the beam direction stable to have the peak energy stable

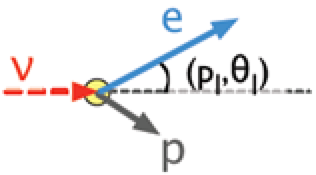
ν_μ disapperance

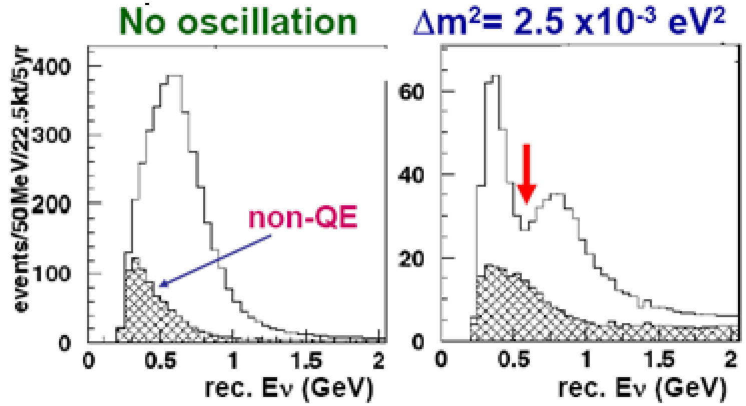
Off-axis angle fixed in 2007

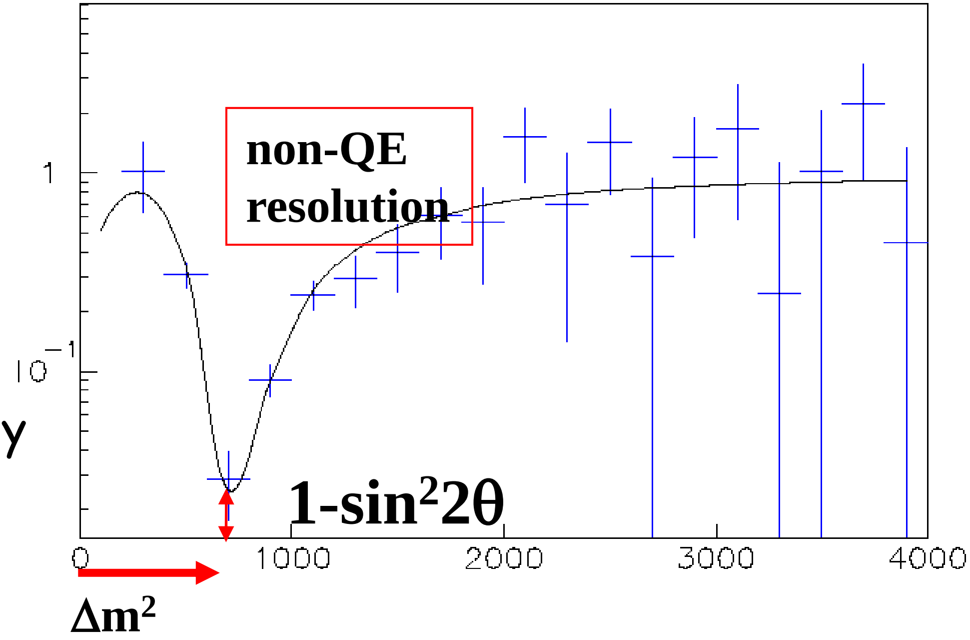


- measure Δm^2_{23} with **10^{-4} eV^2** error
- know if $\sin^2 2\theta_{23} = 1$ (**0.01** uncertainty)

$$E_\nu = \frac{ME_\mu - 0.5m_\mu^{\ 2}}{M - E_\mu + p_\mu \cos\theta}$$





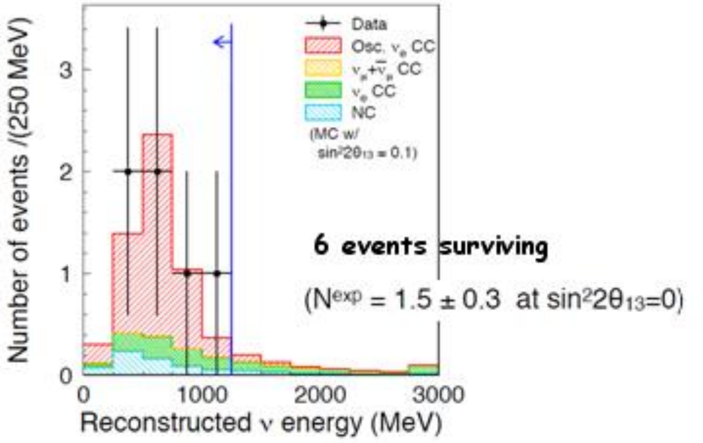


Systematic uncertainty dominated by QE/non-QE ratio (20% syst) which affects the neutrino energy reconstruction in SK

→Near detector has a fundamental role in assessing this ratio

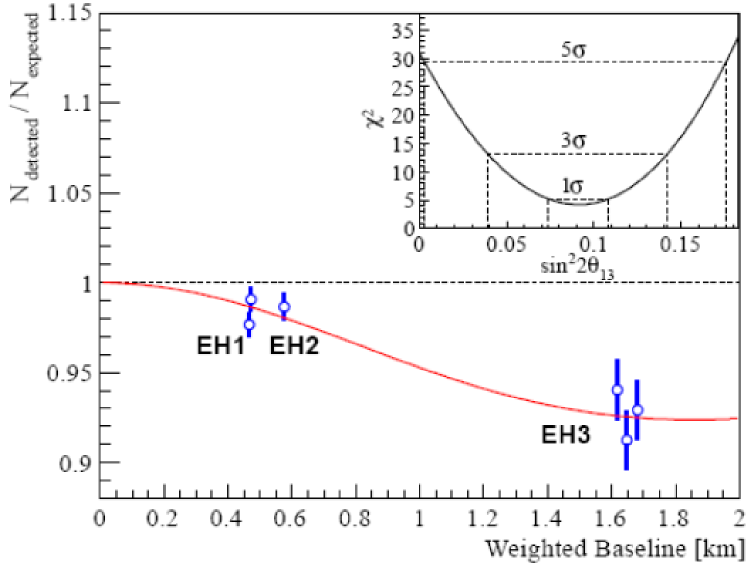
2012: the turning point, $\nu_\mu \rightarrow \nu_e$ oscillations and θ_{13}

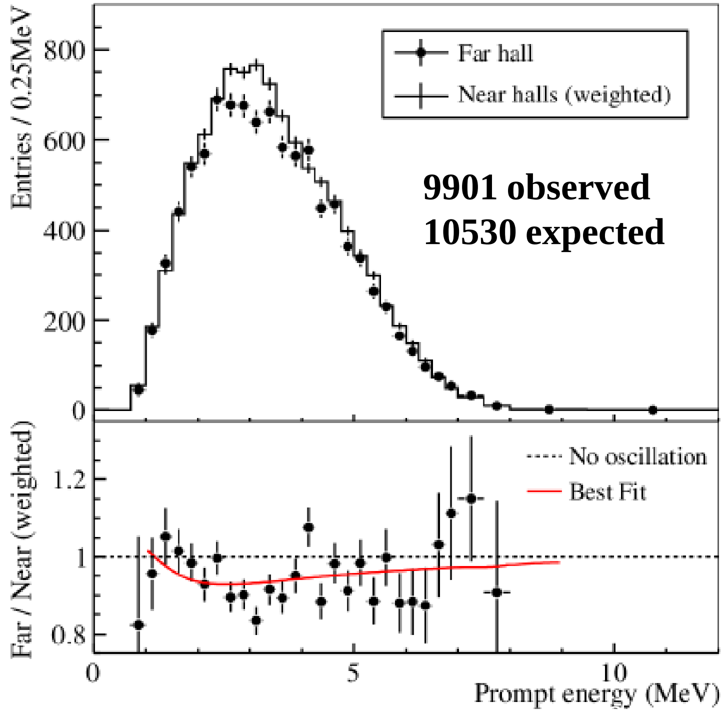
T2K off-axis beam (tuned for osc. max.)
$\nu_\mu \rightarrow \nu_e$ appearance
First result on θ_{13} (June 2011):
6 events observed, 1.5 events bck. → 2.5 σ



March 8th 2012:
Daya Bay reactor anti-neutrinos
$\nu_e \rightarrow \nu_\mu$ (ν_e disappearance)

$\mathbf{Sin^2 2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst)}$



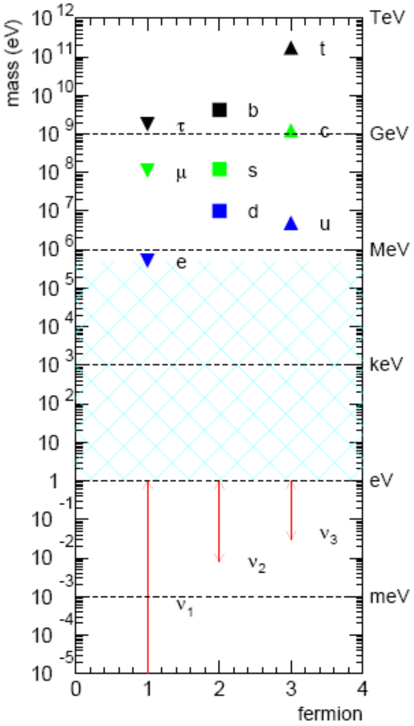


5.2 σ for non-zero θ_{13}

In March 2012 we entered in a new era !!!

Neutrino oscillations are presently in particle physics the only evidence for BSM physics → Neutrinos: a window beyond the S.M. to G.U.T.

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

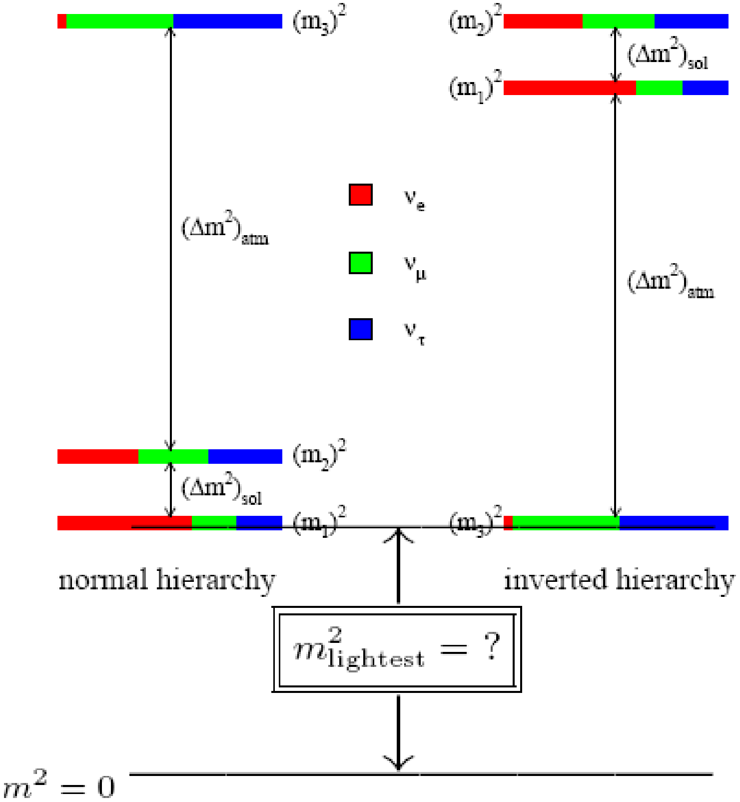


- ➢Why are neutrino masses so small ?
- ➢Why is the mixing matrix so different than the one of the quarks ?

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 ?

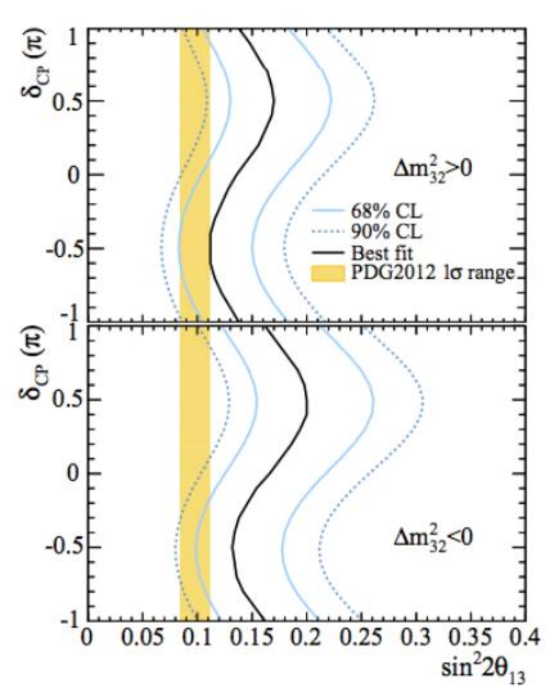


CP violation in the neutrino sector can explain the matter/antimatter asymmetry in the universe

An experimental program for the next 20 years (like for CP in quark sector):

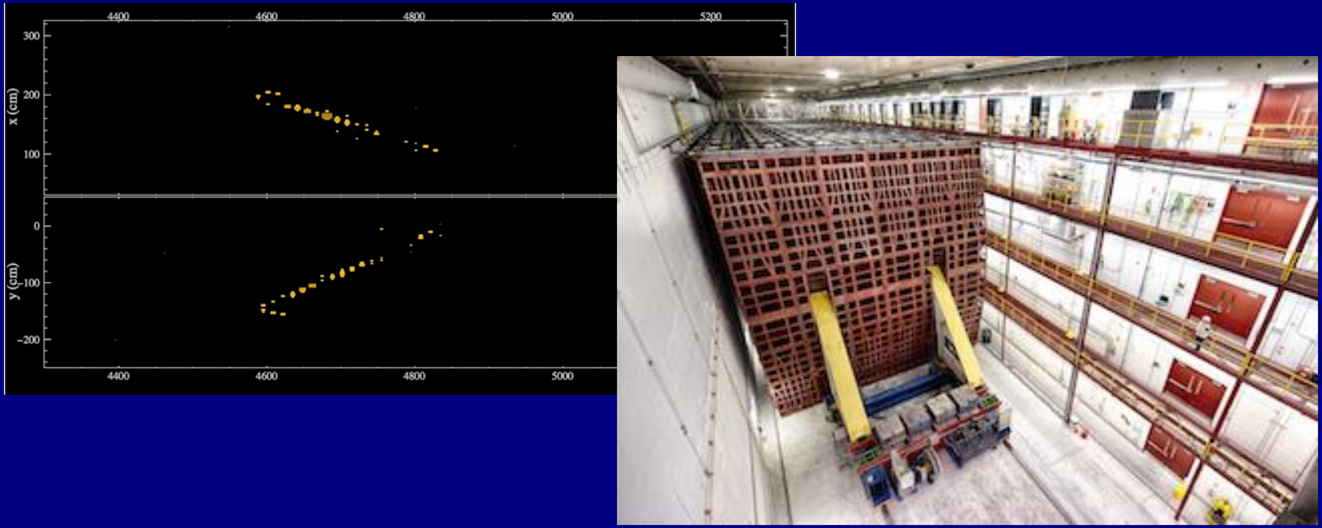
Comparing T2K apperance results, as a function of δ CP with disappearance at reactors (insensitive to CP)

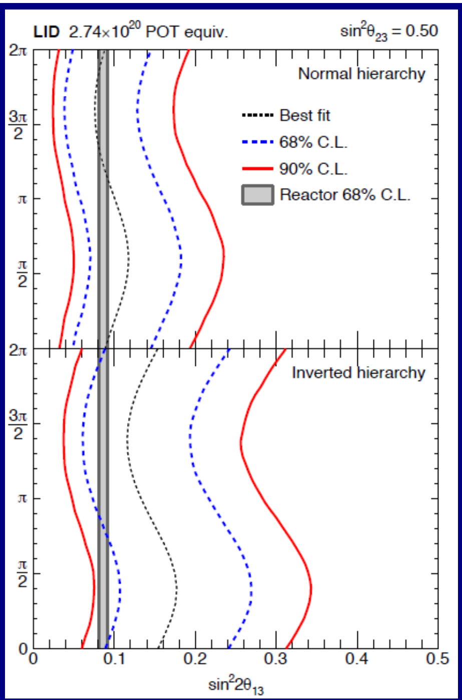
→ Some hint in the direction of $\delta \sim -1/2\pi$ (aka $3/2\pi$)
T2K running in anti-neutrino mode



NOVA 14 kton finely segmented liquid scintillator experiment (65% active mass) at 810 km from Fermilab, off-axis 0.84°
Run with neutrinos and anti-neutrinos ~2 GeV

Some complementarities to T2K:
Detector systematics: liquid scintilllator vs WC
Larger matter effects and different interplay among parameters

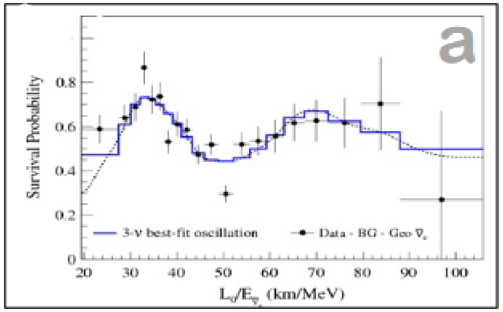




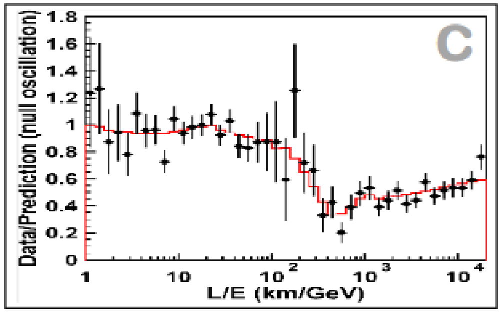
The combination of Reactors+T2K+NOVA in the next years may yield CP significance at the level of 2-3 σ

3ν oscillations probed by many experiments in different flavor channels..

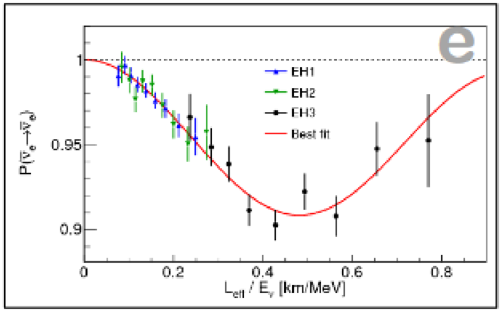
e→e (KamLAND, KL)



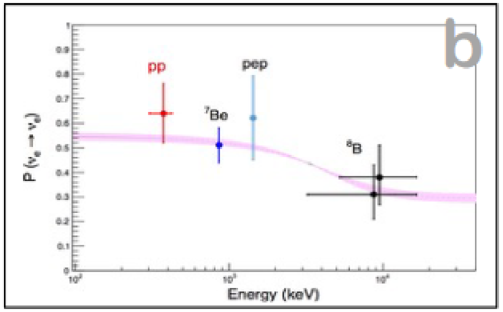
μ→μ (Atmospheric)



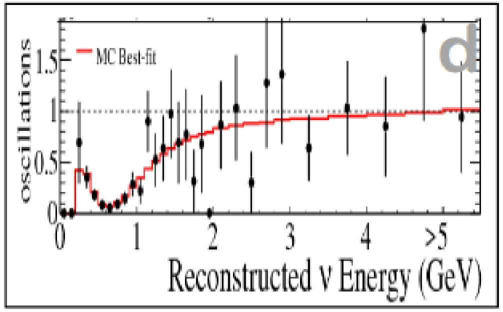
e→e (SBL Reac.)



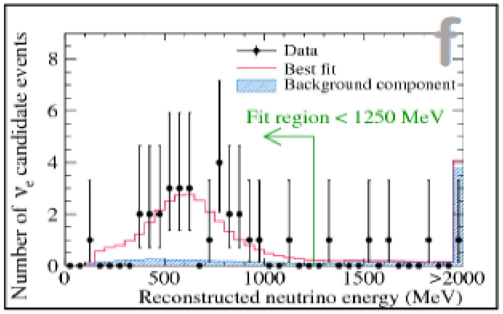
e→e (Solar)



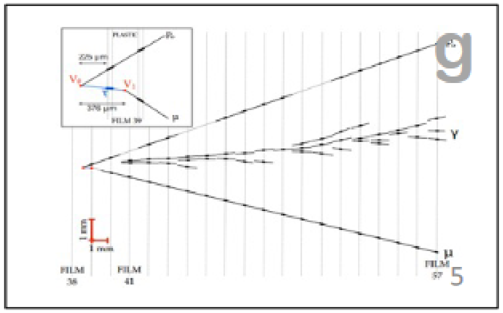
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)



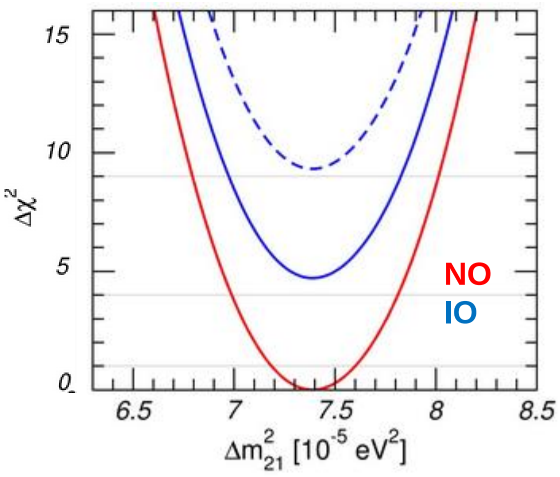
LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

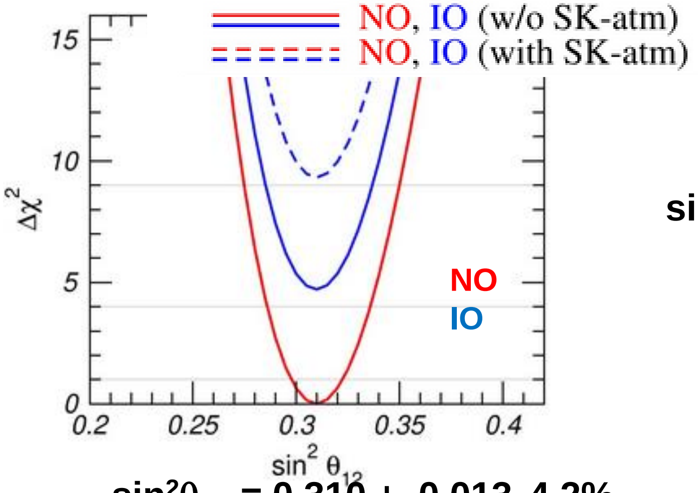
E. Lisi Recent topics in the analysis of neutrino mass-mixing parameters, Corfu July 2023

Most of the 3 angles and 2 Δm^2 parameters are known by global fits with <5% accuracy

NuFIT 4.0 (2018)

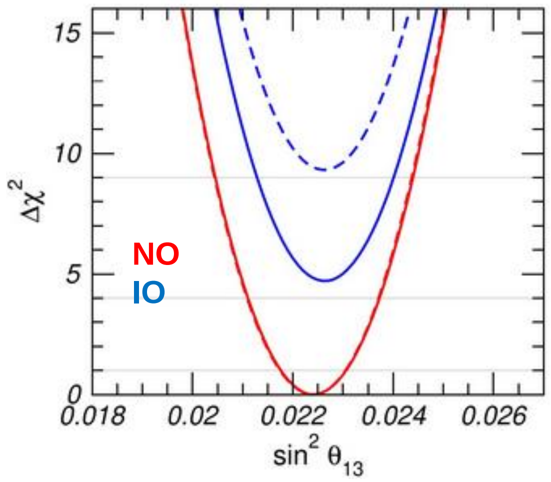


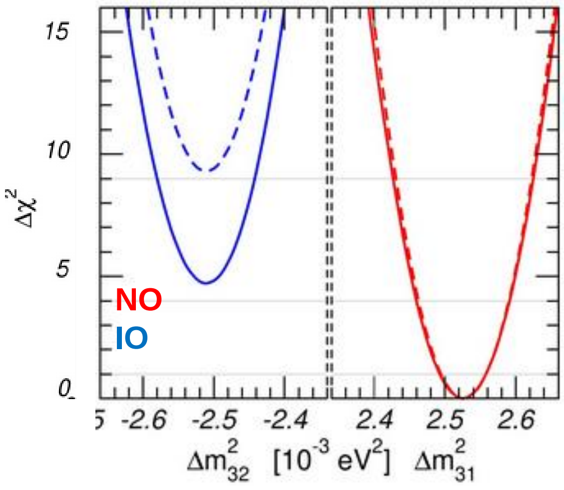
Δm^2_{21} = 7.4 +_0.20 eV^2 2.4%



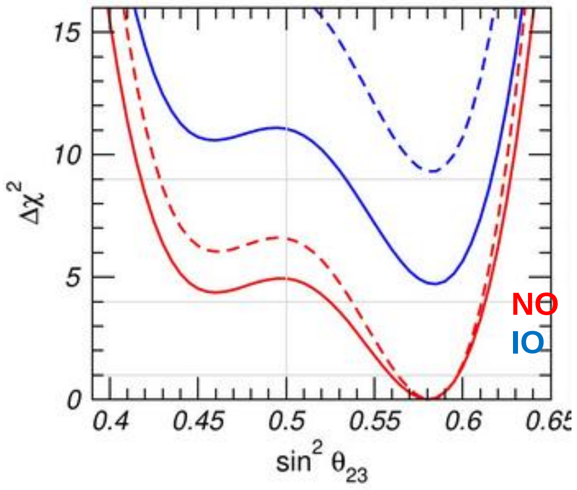
$\sin^2\theta_{12}$ = 0.310 +_0.013 4.2%

$\sin^2\theta_{13}$ = 0.02241 +_0.00065 2.9%



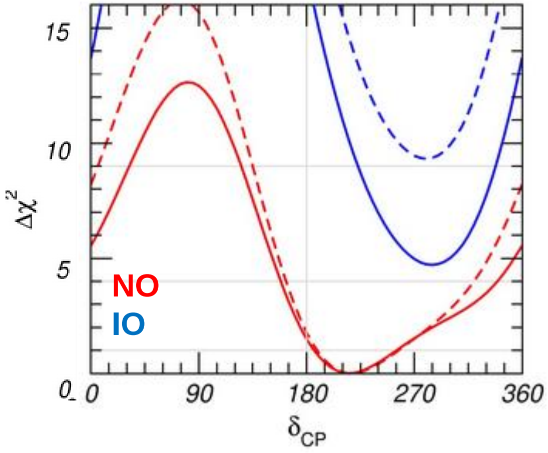


Δm^2_{32} = +2.525 +_0.033 eV^2 1.3%



$\sin^2\theta_{23}$: Octant instability

$\sin^2\theta_{23}$ = 0.582+0.015-0.019

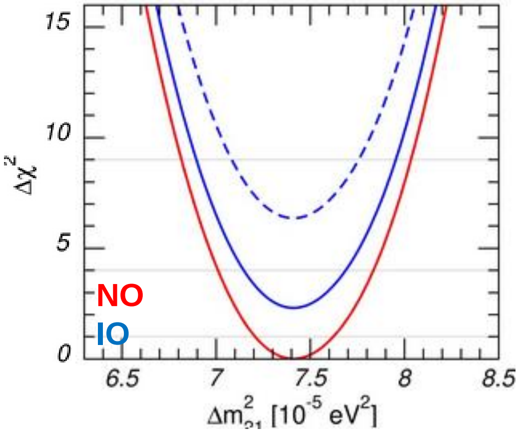


IO disfavored with respect to NO at ~2σ level. (~3σ level with SK)

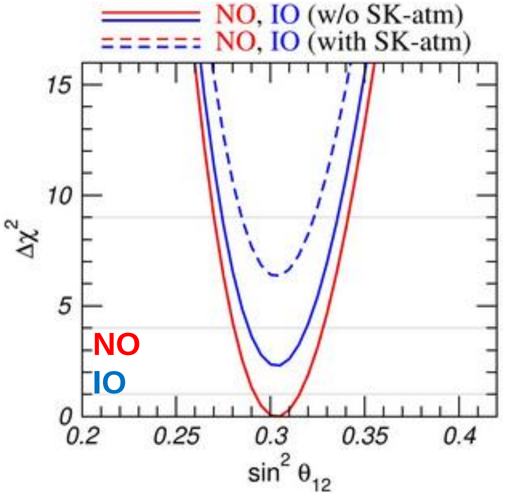
Largest mixing angle close to π/4, but octant undetermined : sin2 θ_{23} <0.5 disfavored at ~2.5σ level including SK

CPV delta ~217° favored , CP conservation still compatible within ~1.3σ in NO (including SK)

NuFIT 5.2 (2022)

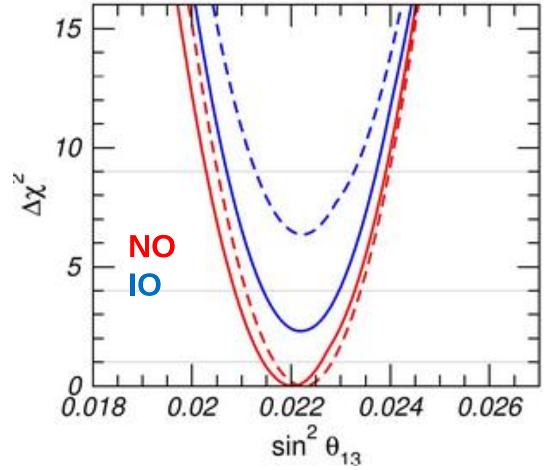


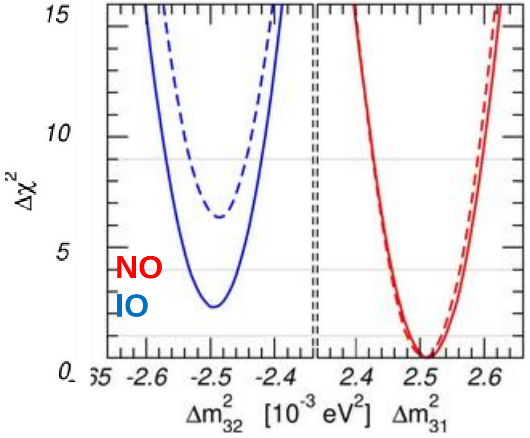
Δm^2_{21} = 7.41 +_0.20 eV^2 2.7%



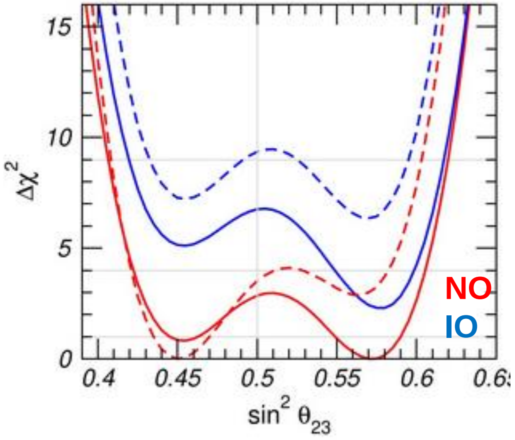
$\sin^2\theta_{12}$ = 0.303 +_0.012 4.0%

$\sin^2\theta_{13}$ = 0.02225 +_0.00059 2.6%



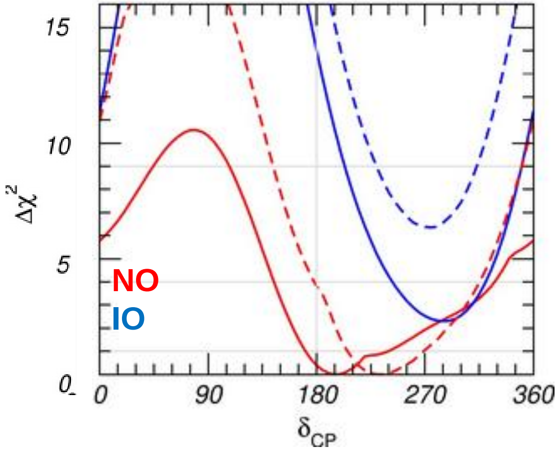


Δm^2_{32} = +2.507 +_0.027 eV^2 1.1%

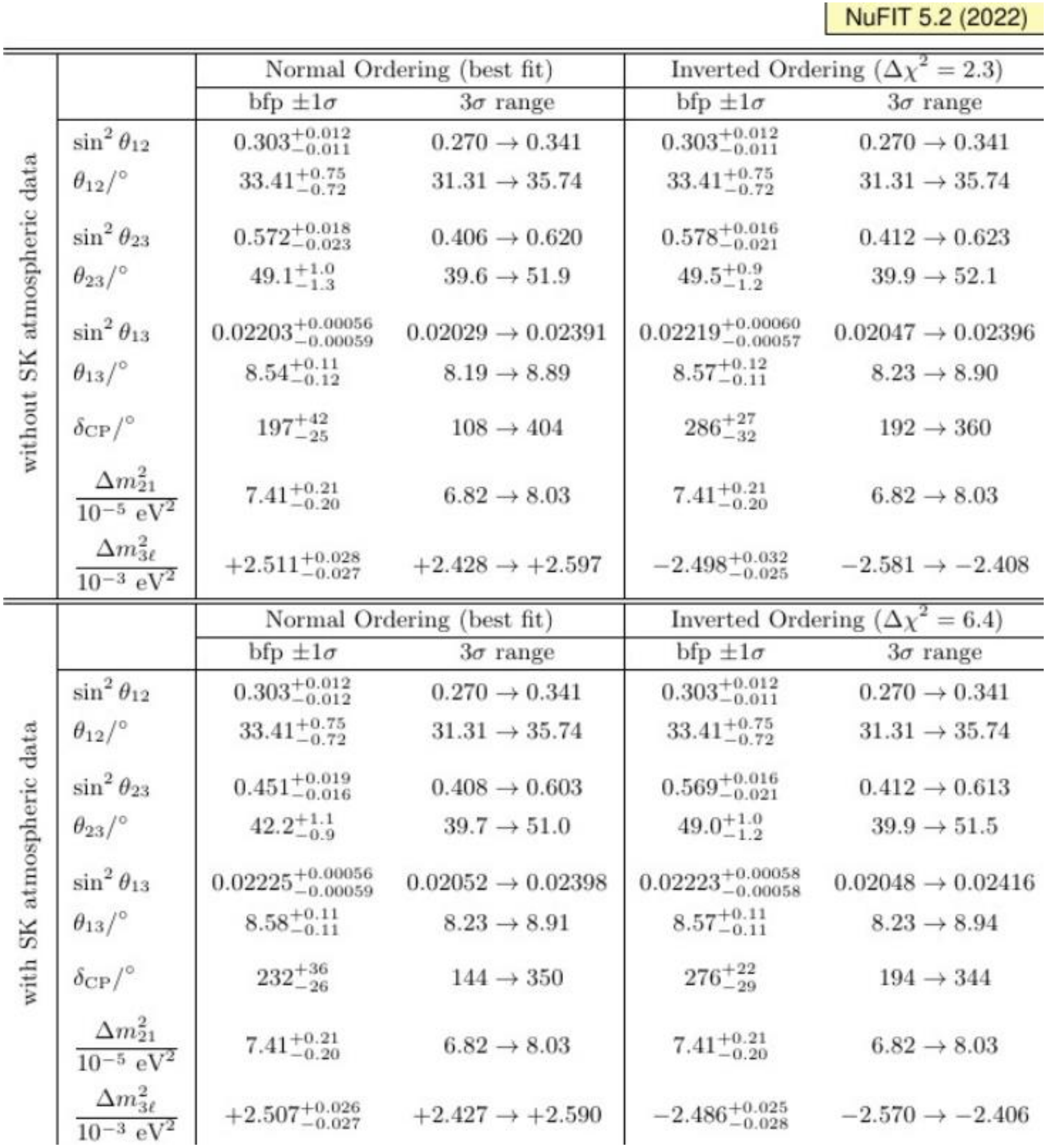


$\sin^2\theta_{23}$: Octant instability

$\sin^2\theta_{23}$ = 0.451+0.019-0.016



IO disfavored with respect to NO at ~1.5σ level. (~2.5σ level with SK)
Largest mixing angle close to π/4, but octant undetermined
CPV delta ~232° favored , CP conservation 180° still compatible within ~2σ in NO (including SK)



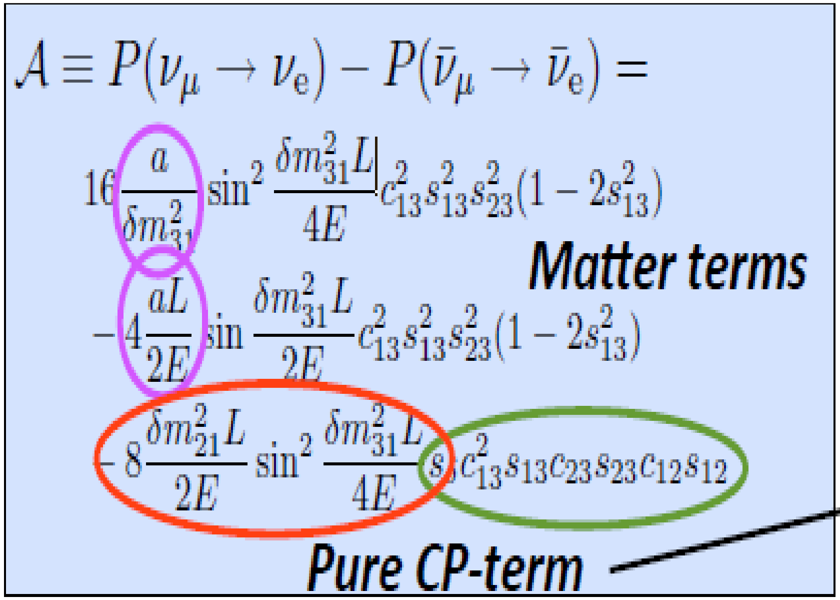
NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{\rm CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{\rm CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

CP asymmetry as a function of L/E

CP violation can be measured by comparing ν and anti-ν oscillation probabilities in an asymmetry variable



$$\mathcal{A} \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

$$16\frac{a}{\delta m^2_{31}}\sin^2\frac{\delta m^2_{31}L}{4E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

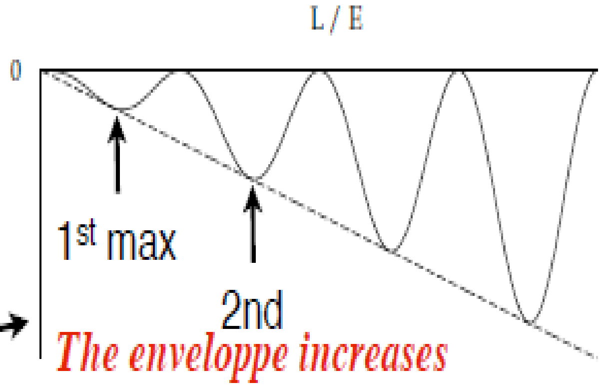
$$-4\frac{aL}{2E}\sin\frac{\delta m^2_{31}L}{2E}c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

$$-8\frac{\delta m^2_{21}L}{2E}\sin^2\frac{\delta m^2_{31}L}{4E}s_\delta c^2_{13}s_{13}c_{23}s_{23}c_{12}s_{12}$$

Matter terms

Pure CP-term

$$\left.\frac{P(\nu)-P(\bar{\nu})}{P(\nu)+P(\bar{\nu})}\right|_{a=0} \approx -\frac{2s_\delta c_{12}s_{12}}{s_{13}}\cot\theta_{23}\frac{\delta m^2_{21}L}{2E}$$



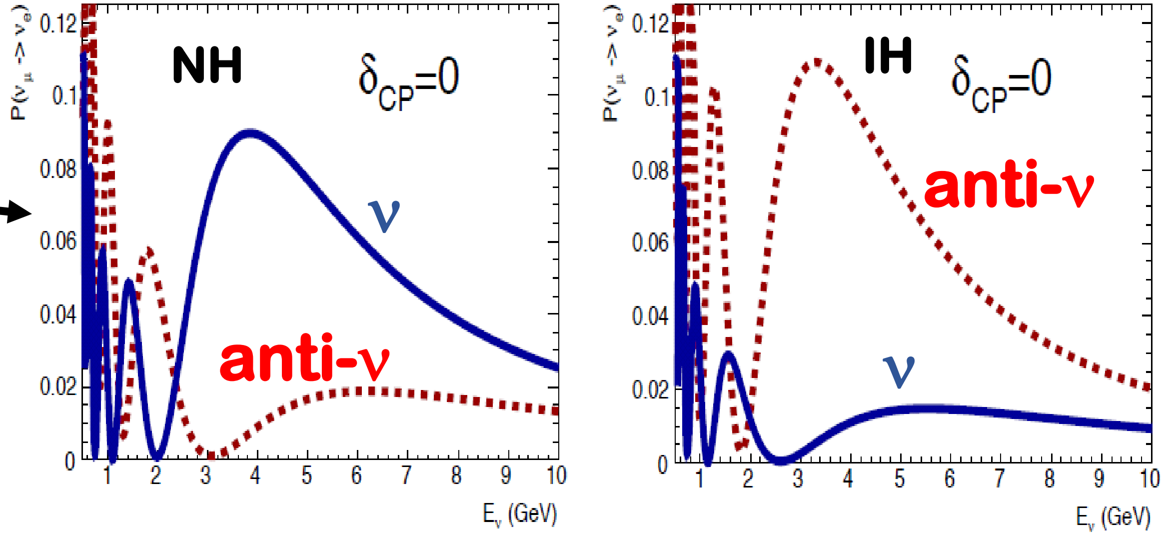
The envelope increases linearly with L/E

The amplitude of the pure CP term increases with L/E → this effect is stronger at the second oscillation maximum.

Measurements at the second oscillation maximum are very important and possible only with a detector with very good energy resolution

Matter effects and CP violation effects degeneracy

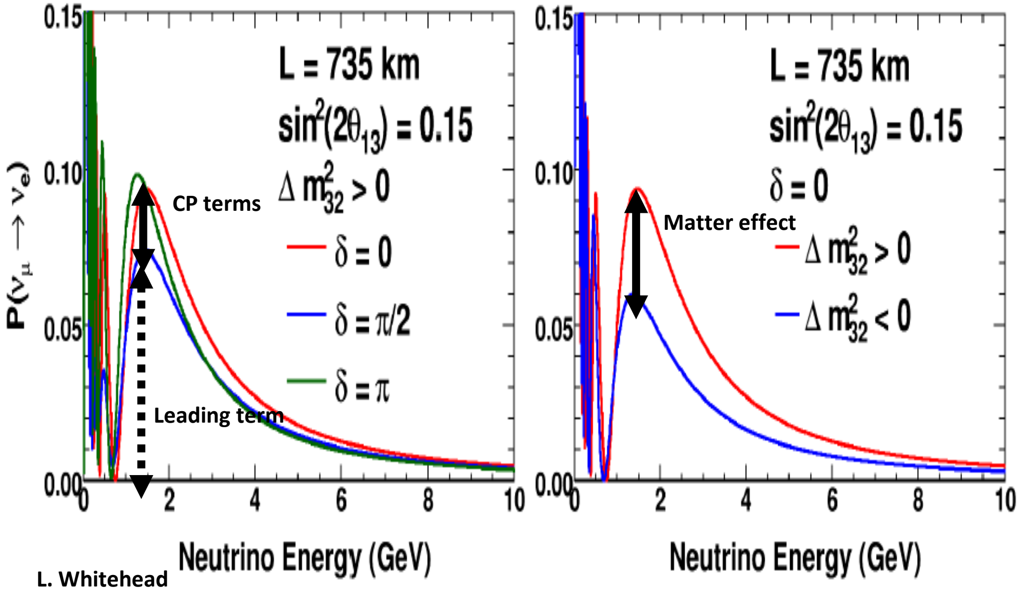
Matter effects on the oscillation probability at L = 2300 km for ν and anti-ν in the case of Normal (NH) or Inverted (IH) hierarchy



Since CP violation is also measured by comparing ν and anti-ν oscillation probabilities matter effects mimic CP violation if the mass hierarchy is not known

- **It is needed to accurately measure and subtract the matter effects in order to look for CP**

- **Matter effects dominate around the first maximum**



L. Whitehead

Effects on oscillation probabilities as a function of δ CP

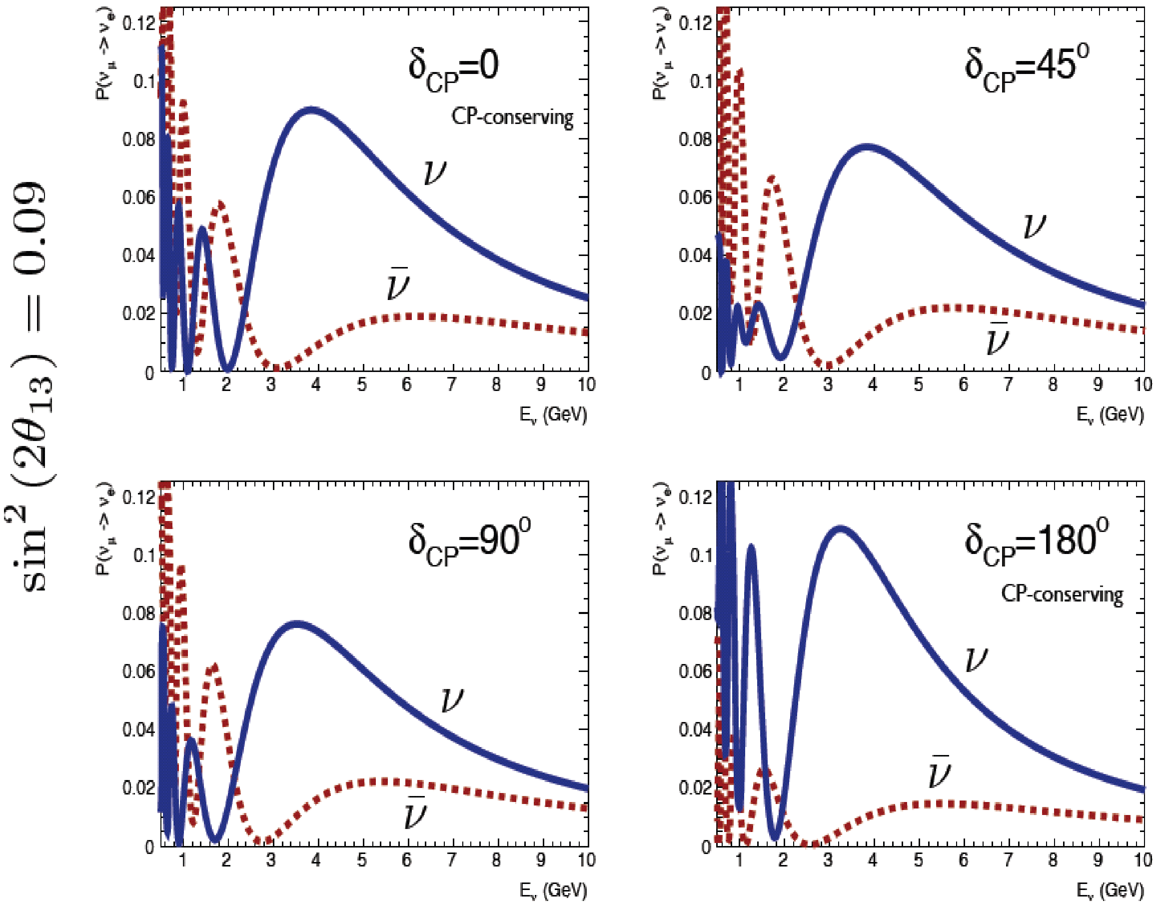
Once the mass hierarchy is determined, it is possible to study the CP-violation and determine the value of δ by measuring the ν and anti-ν oscillation probabilities

A lot of information is contained in the shape around the first and second maximum

→Direct measurement of the energy dependence (L/E behavior) induced by matter effects and CP-phase terms, independently for ν and anti-ν, by measurement of events energy spectrum

CERN-Pyhäsalmi: spectral information $\nu_\mu \rightarrow \nu_e$

★Normal mass hierarchy L=2300 km

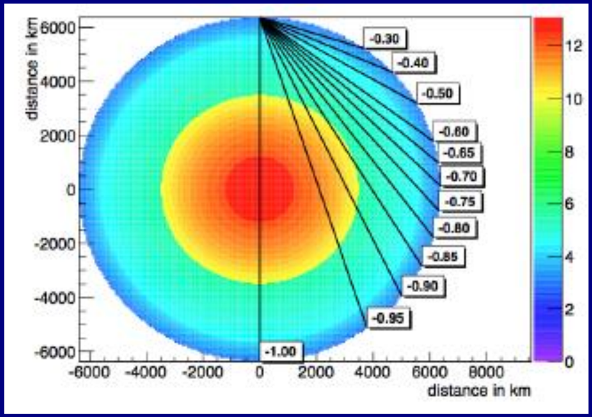


Addressing mass hierarchy with non-accelerator experiments:

Matter effects in atmospheric neutrinos:

Study upward going neutrino flux in bins of energy and cos(θ)

→ Different patterns at low energy

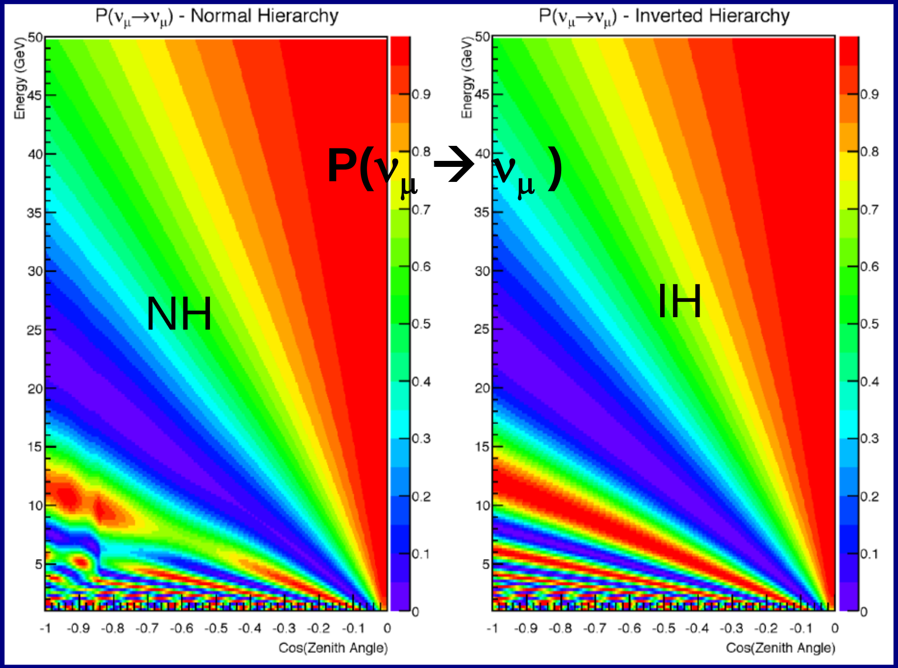


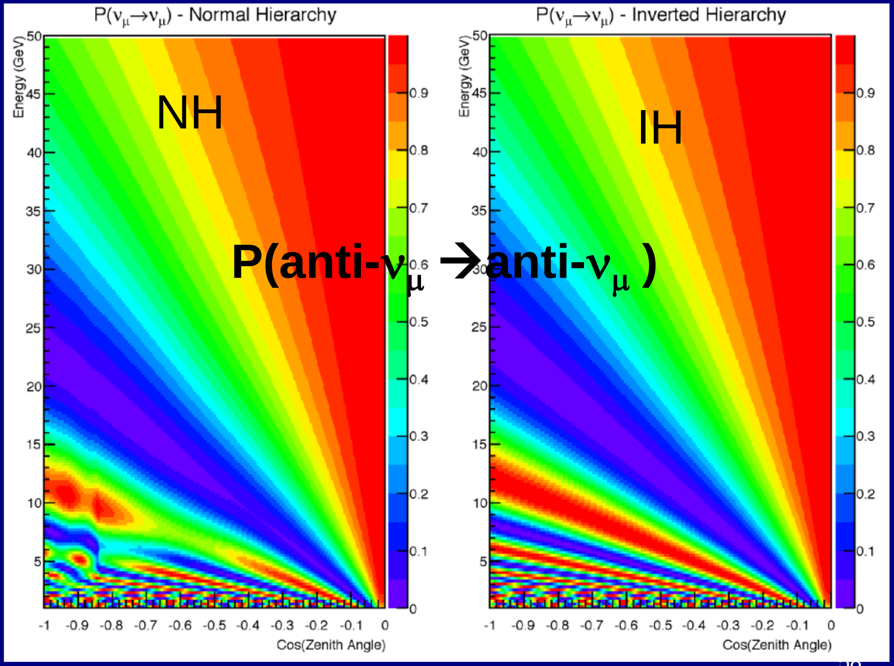
Oscillations probabilities for NH and IH are similar for neutrinos and antineutrinos → if the charge of the muons is not measured the effect is diluted

However there are differences in fluxes and cross sections for neutrinos and antineutrinos and a few % effects can be still measured

Adaptation of the high energy neutrino observatories Icecube and Antares at low energy → Pingu, Orca, higher density of photomultiplier strings

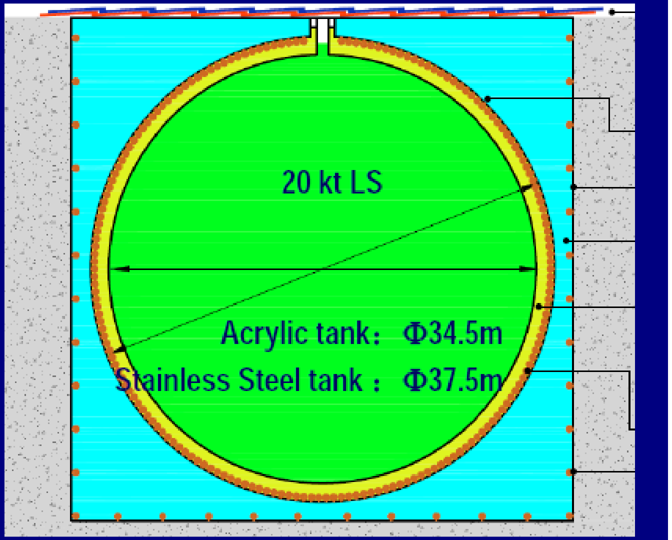
Difficult measurement for flux modelling and detector response to reach ~3σ significance



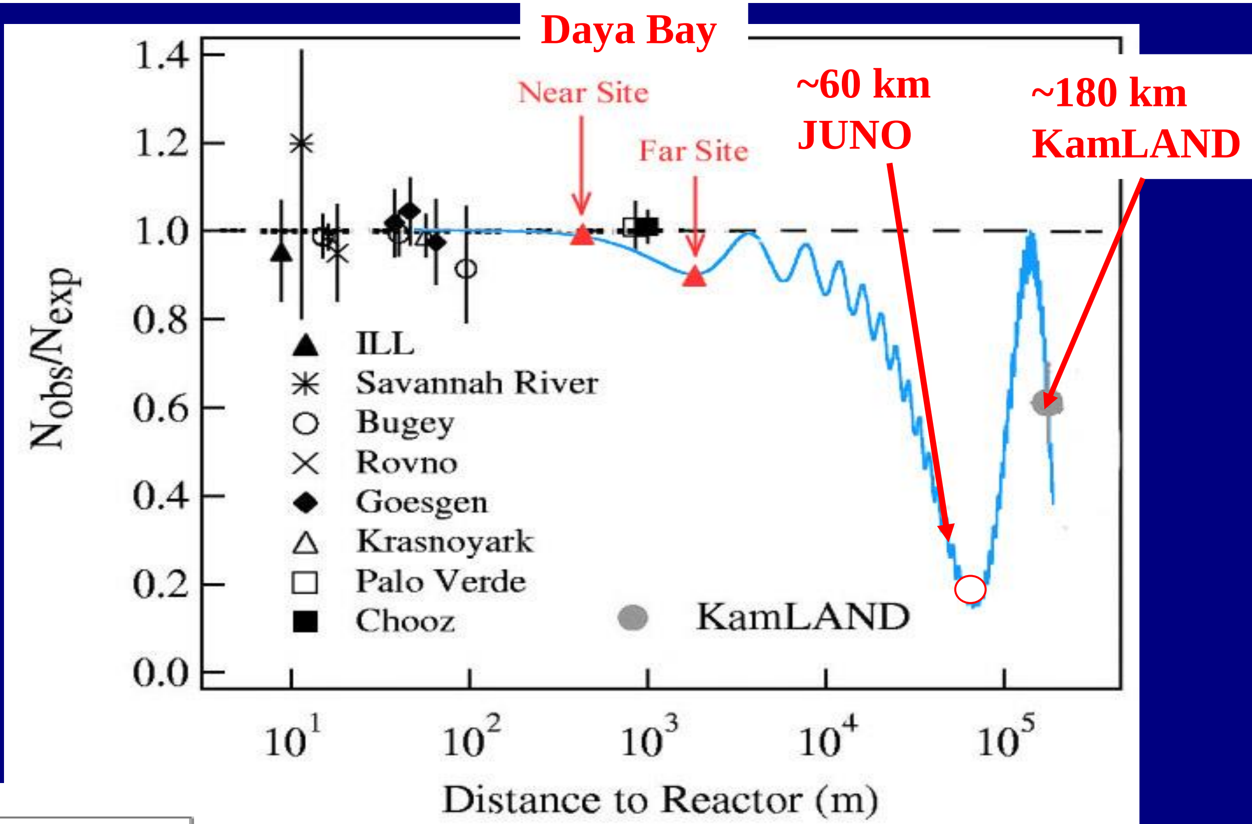


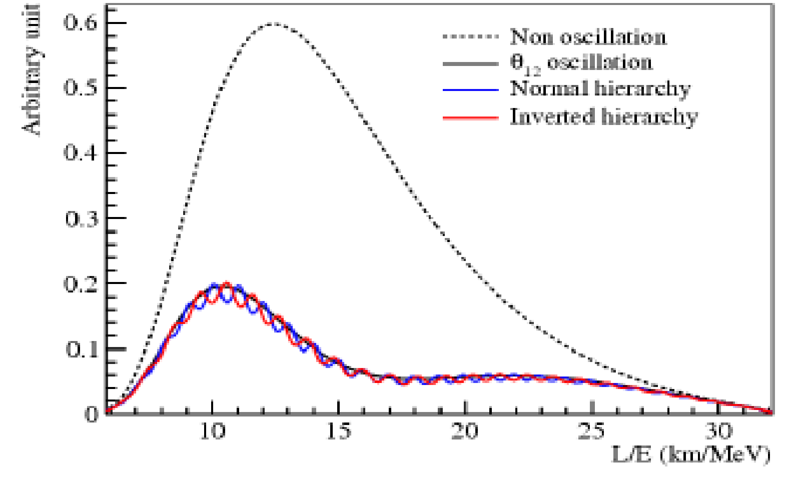
Reactor experiments tuned on solar oscillations wavelength $\Delta m^2_{12} + \theta_{12}$ (JUNO –RENO50)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2 2\theta_{12}\sin^2\frac{\Delta m^2_{13}L}{4E} + \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{23}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E}$$



JUNO, expected start after 2021



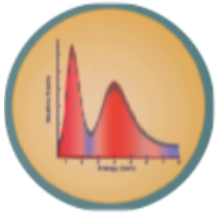


Study of anti-nue disappearance exploiting the interference between the atmospheric and solar terms

→ Shifted patterns in measured neutrino energy spectrum

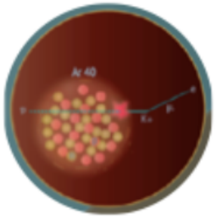
Requiring exceptional resolution and linearity (<1% precision) to reach ~3σ significance

The Primary DUNE Scientific Goals



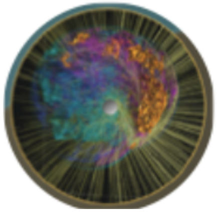
Neutrino oscillations

- CP violation in the ν sector
- Neutrino mass hierarchy
- Precision oscillation measurements
- Testing of 3ν paradigm



Proton decay

- Predicted by BSM theories, but not yet seen
- Unique sensitivity to SUSY-favored modes ($p \to \bar{\nu} K^{+}$)



Supernova neutrinos

- Neutrino burst from galactic core-collapse supernova
- Unique sensitivity to supernova ν_e's

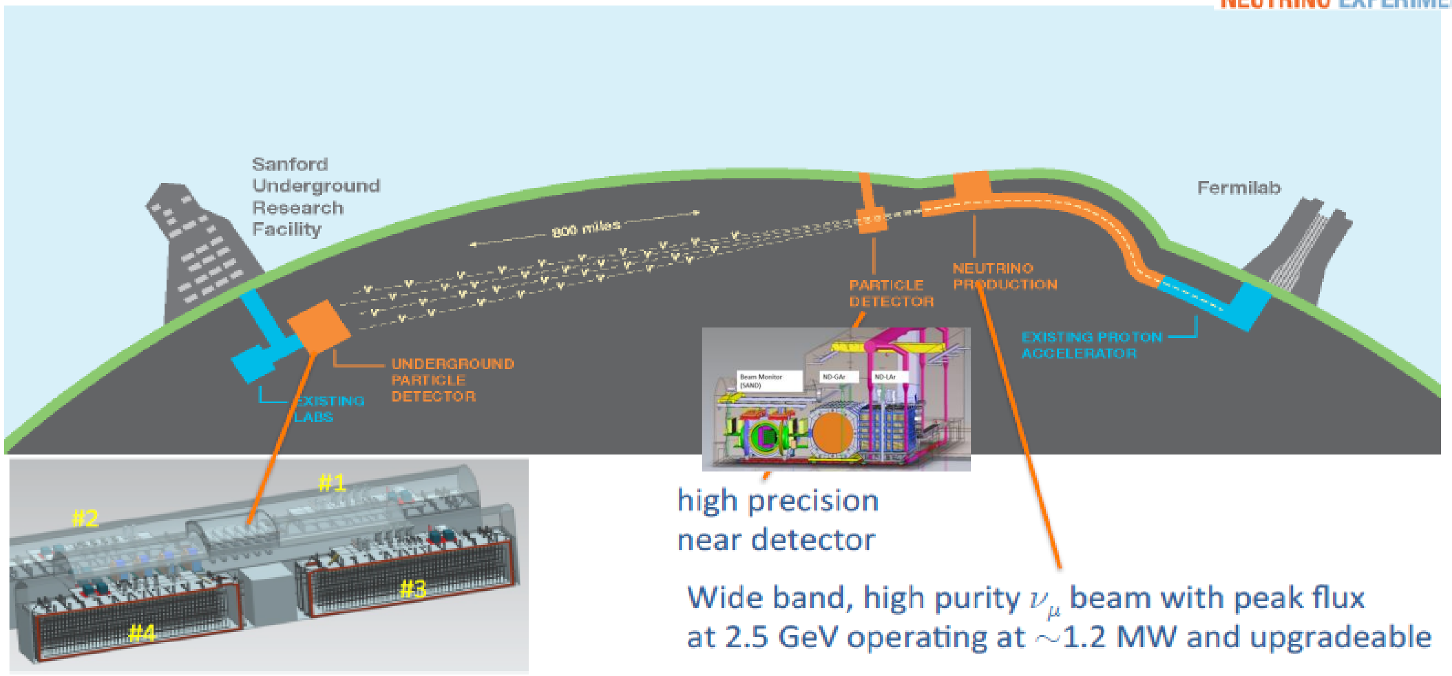
- **DUNE experiment: started in 2014/5 by an international *worldwide* collaboration including EU countries and CERN**
- **Strong french participation supported by a IR* program and 6 IN2P3 laboratories (APC, IJCLAB, IP2I, LAPP, LP2I, LPSC)**

- **Infrastructure based in the USA:**
- Neutrino Beam from Fermilab Chicago, Illinois
- Underground (1500m depth) far detector infrastructure in Lead, South Dakota, SURF laboratory (in former Homestake mine) at 1300 km from Fermilab

→ Needs sophisticated massive detectors **O(10 kton)** in order to study tiny effects :
- Accurate identification of neutrino flavors via final state lepton (**muon, electron, tau**)
- Precise measurement of **neutrino energy**

→ Electronic version of **Bubble Chambers**: **The Liquid Argon Time Projection Chamber (TPC)**

Overall Experimental Layout



high precision
near detector

Wide band, high purity ν_μ beam with peak flux
at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

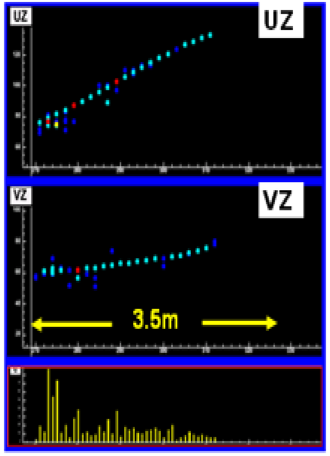
- Four liquid argon far detector modules of ~10 kton LAr mass each located in the mine at 1500m depth
- First two detector modules constructed by 2028

- ➢ Neutrino Beam: 1.2 – 2.4 MW proton beam intensity on target
- ➢ ~40 kton Far Detector mass

Typical neutrino interactions events in fine grained detectors

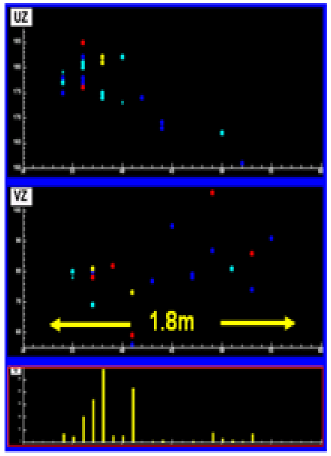
MINOS (sandwich of 2.54 cm magnetized steel and 1 cm scintillator plates)

ν_μ CC Event



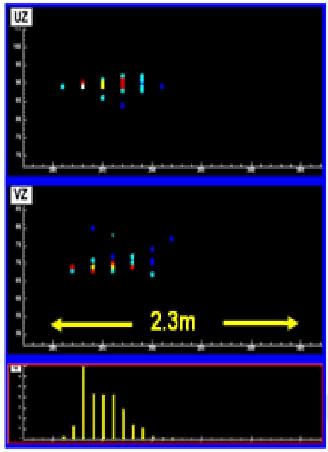
- Long muon track + hadronic activity at vertex

NC Event



- Short showering event, often diffuse

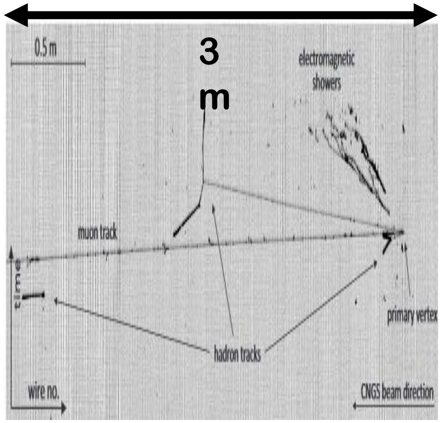
ν_e CC Event



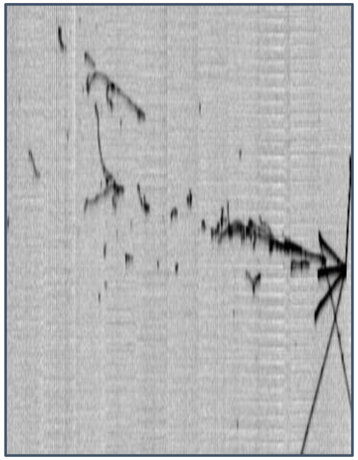
- Short event with typical EM shower profile

ICARUS **LAr TPC neutrino interactions from CNGS beam**

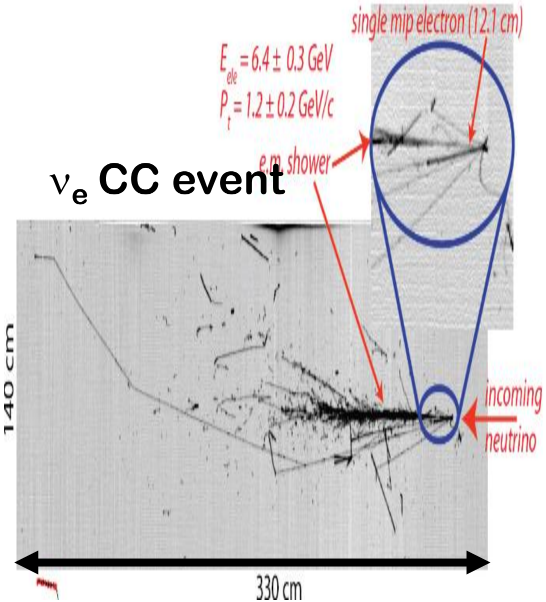
ν_μ CC event with π^0 production



ν_μ NC event with π^0 production



ν_e CC event



The Liquid Argon Time Projection Chamber *(C. Rubbia 1977)*

- Homogeneous massive target and ionization detector → electronic bubble chamber

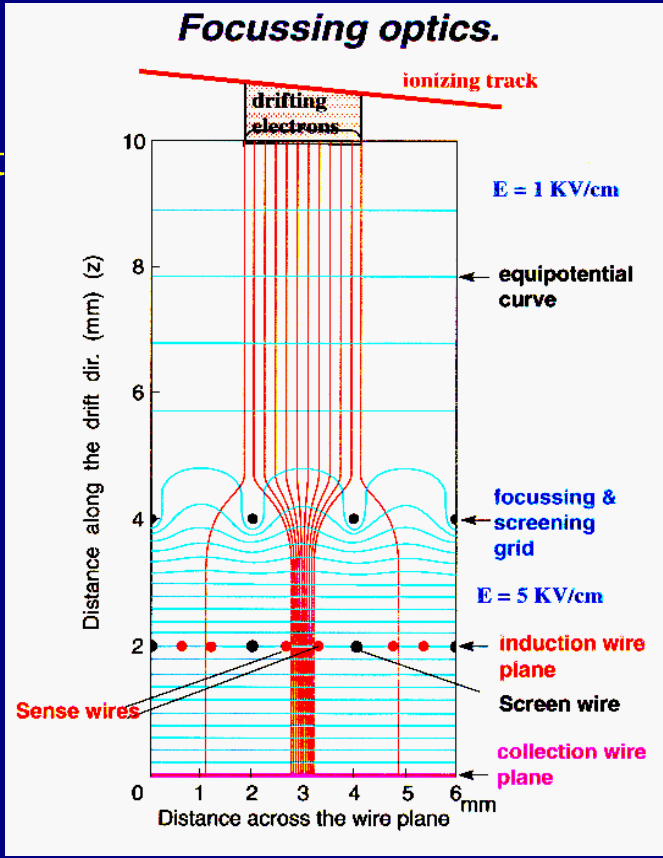
- 3D event reconstruction with ~1 mm resolution, surface readout

- High resolution calorimetry (electromagnetic and hadronic showers)

- Primary ionization in LAr: 1 m.i.p ~ 20000 e- on 3 mm

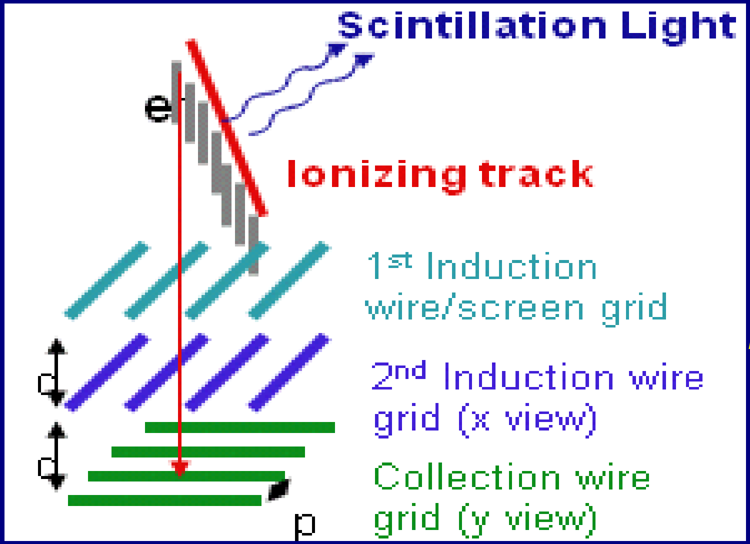
- Detection of UV scintillation light in Argon (5000 photons/mm @128 nm) to provide t = 0 signal of the event

Ideal detector for neutrino oscillations, supernovae neutrinos and proton decay



z = drift time

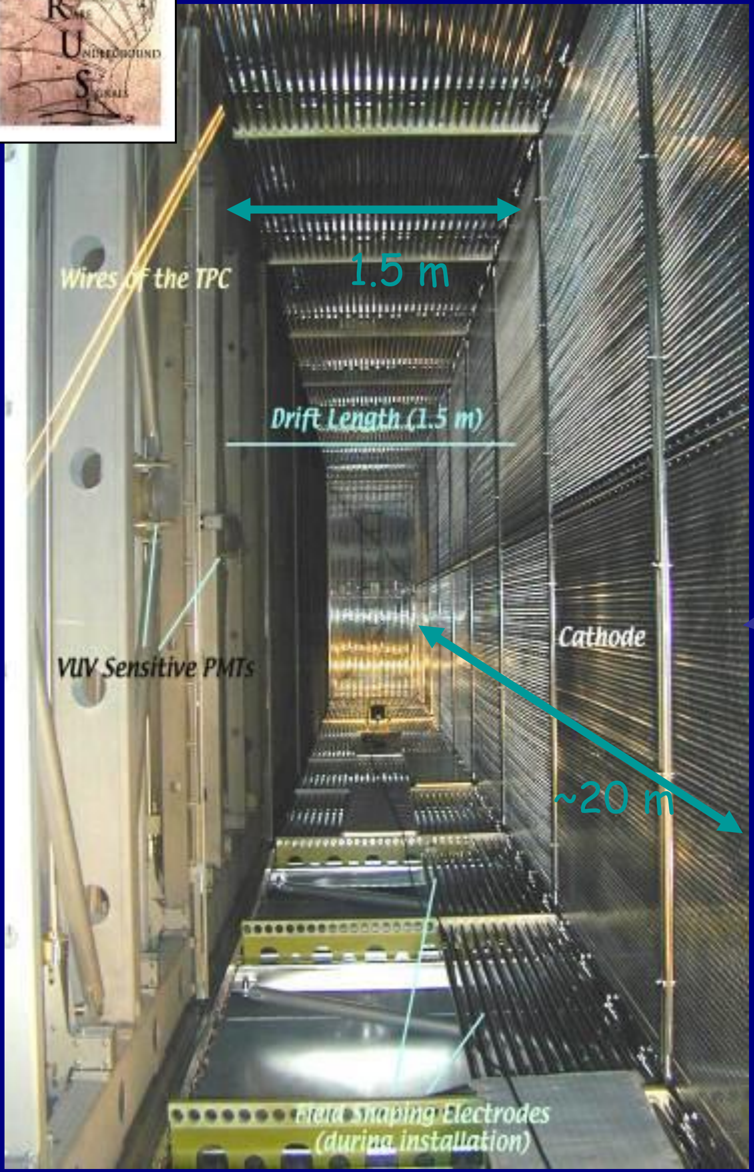
Drift Field: 0.5-1 kV/cm
Drift time:
1.5ms/3m @1 kV/cm

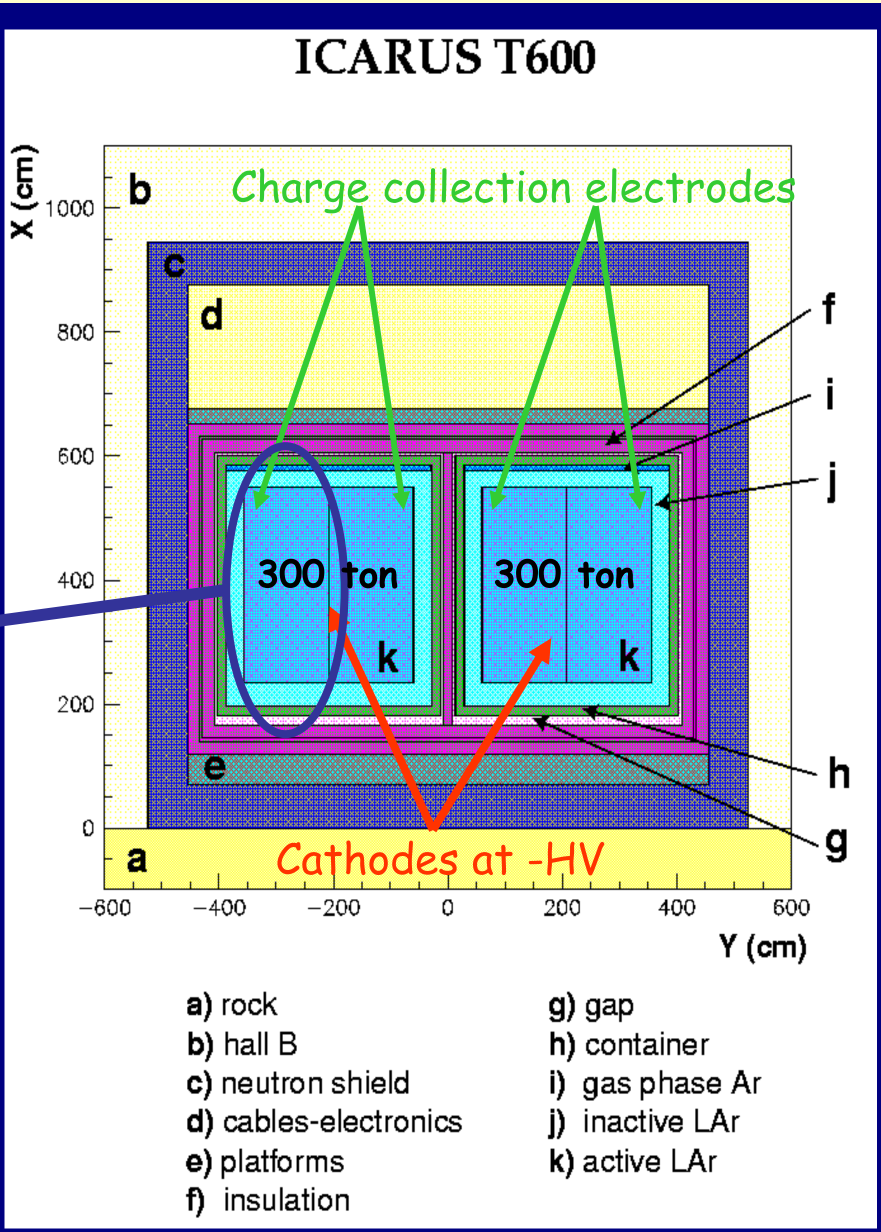


Non-destructive multiple readout with induction planes

→ drift requiring < 0.1 ppb O_2 equiv. impurities

ICARUS T600 prototype (2001) exploited at LNGS and now at FNAL for the short-baseline program





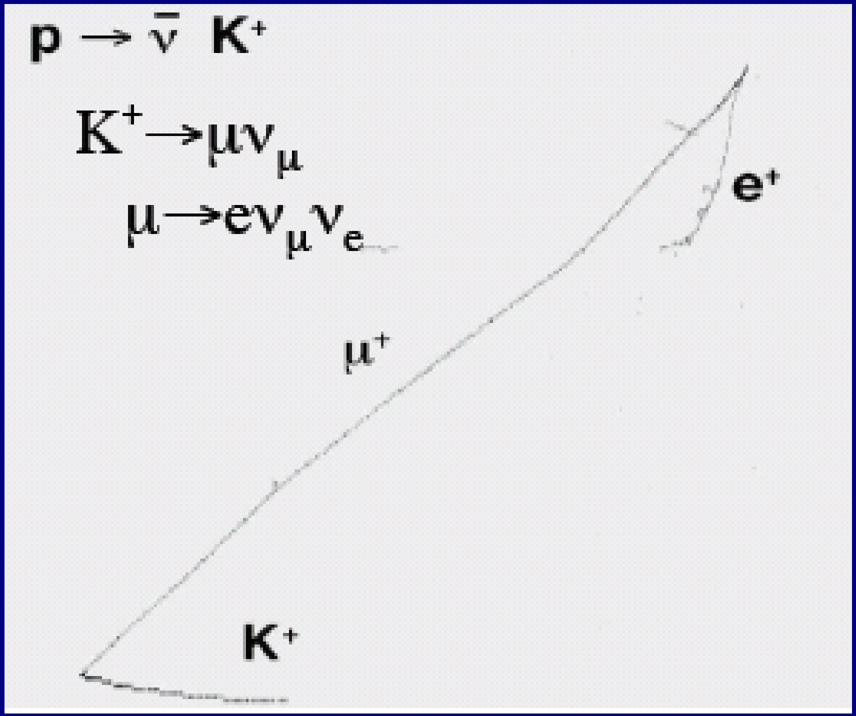
The liquid argon TPC as an electronic bubble chamber

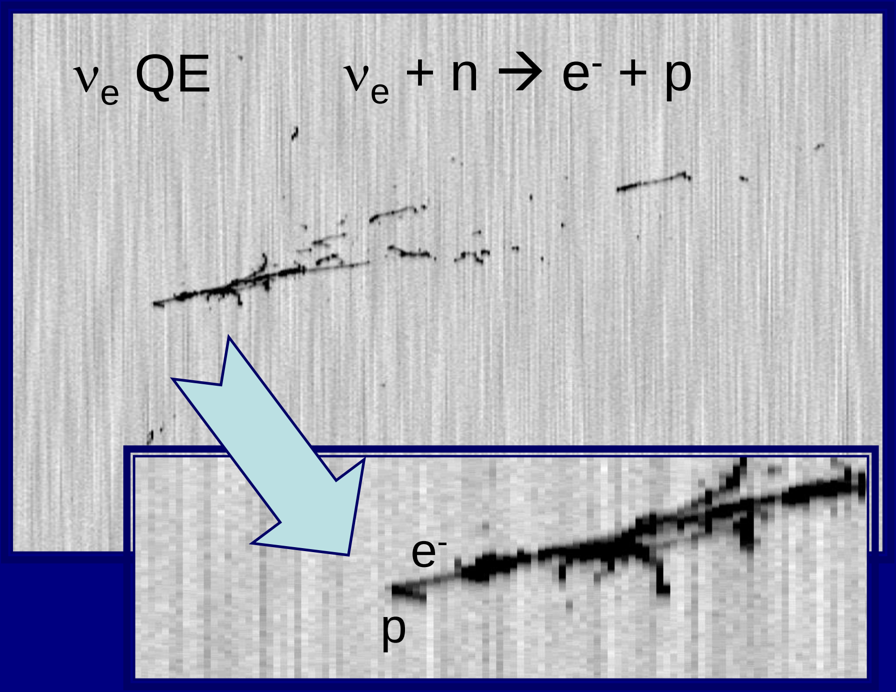
- Large mass, homogeneous detector, low thresholds, exclusive final states
- Tracking + calorimetry (0.02 X0 sampling)
- **Electron** identification, π^0 rejection, particles **identification with dE/dx**

→ Neutrino physics (electron identification, reconstruction of event kinematics, identification of exclusive states, excellent energy resolution from sub GeV to multi GeV)

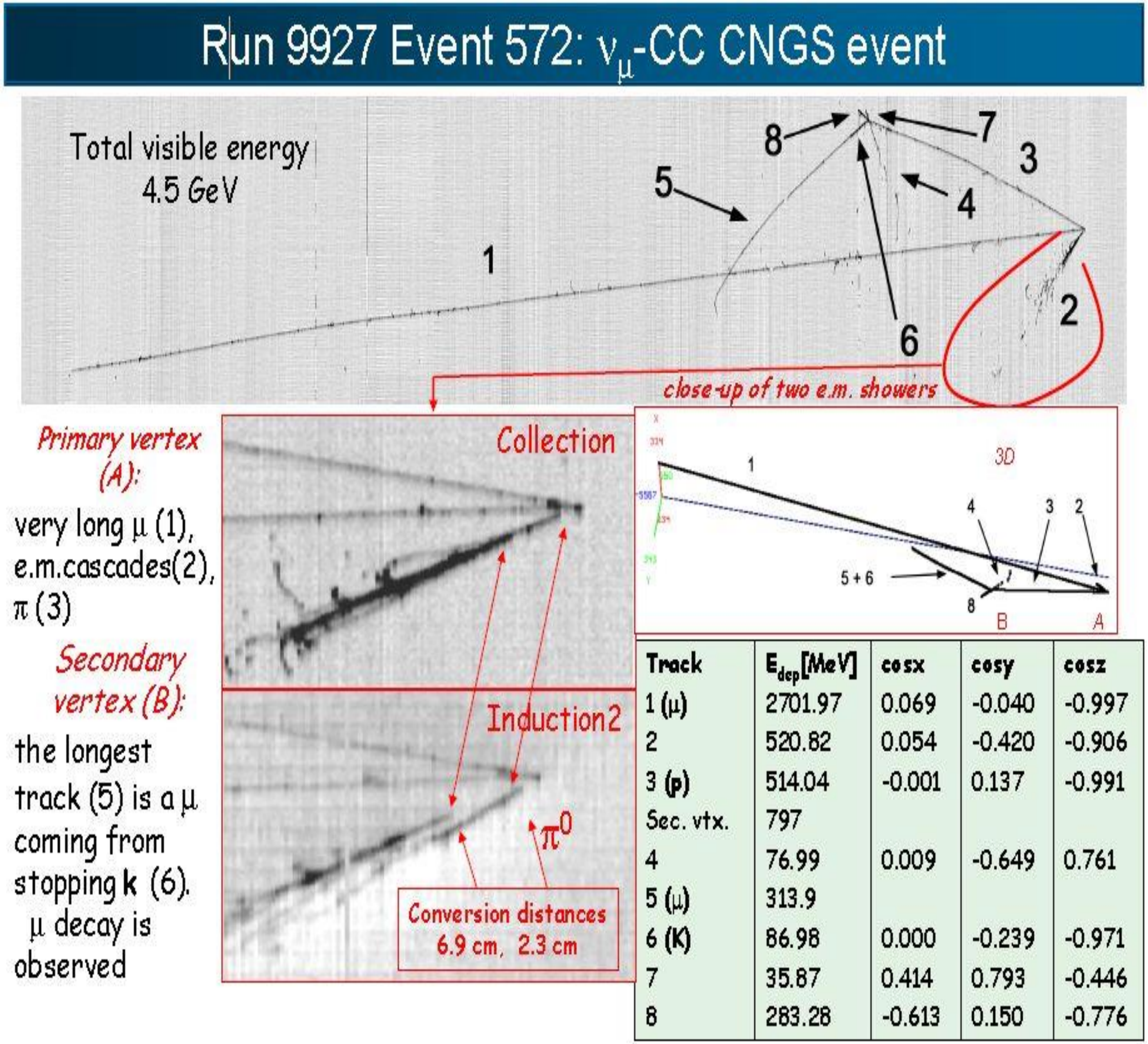
→ Supernovae neutrinos

→ Proton decay search (large mass, particles id.)





The liquid argon TPC as an electronic bubble chamber



Run 9927 Event 572: ν_μ-CC CNGS event

Total visible energy
4.5 GeV

Primary vertex (A):
very long μ (1), e.m.cascades(2), π (3)

Secondary vertex (B):
the longest track (5) is a μ coming from stopping **k** (6).
μ decay is observed

Conversion distances
6.9 cm, 2.3 cm

Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

→ Continuation in the second lecture tomorrow