Neutrinos and Oscillations

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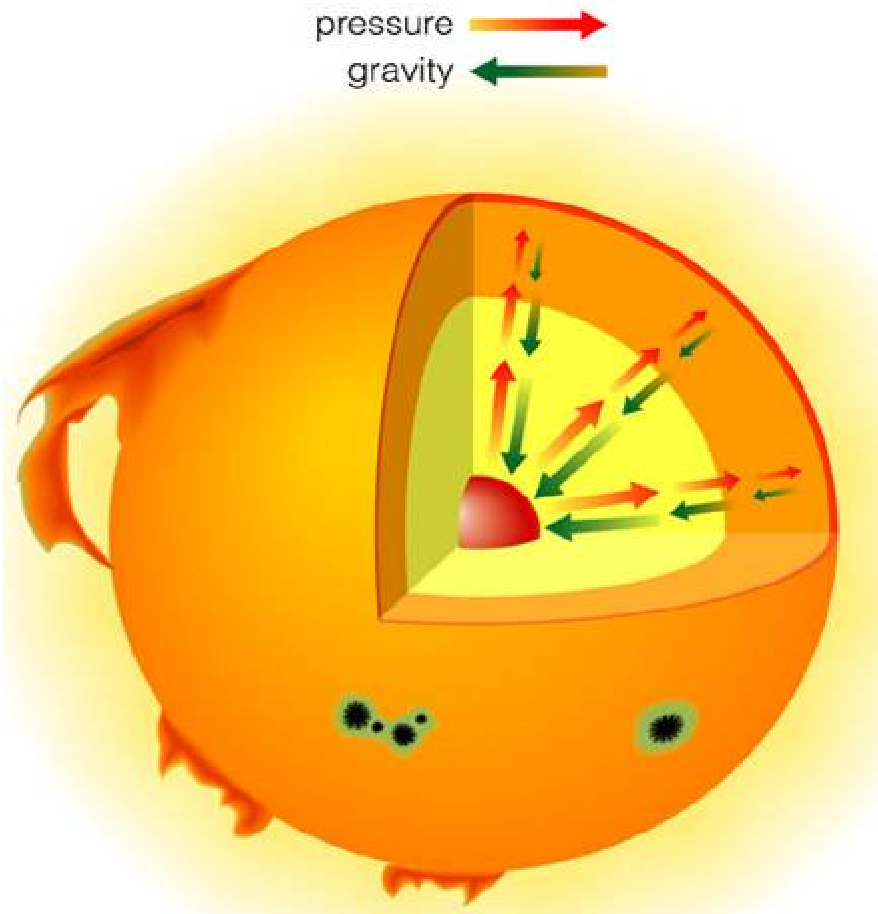
- Solar neutrino problem
- Neutrino history
- Quantum mechanics and neutrino oscillations
- Experimental situation
- Future projects

Solar neutrinos

- How does the sun shine?



equilibrium between gravity and nuclear reaction pressure

Main thermonuclear fusion solar reactions

(pp) $p+p \rightarrow {}^{2}H+e^{+}+\nu_e$

(pep) $p+e^{-}+p \rightarrow {}^{2}H+\nu_e$

99.6%

0.4%

$^{2}H+p \rightarrow {}^{3}He+\gamma$

85%

15%

$2X10^{-5}\%$

$^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$

(hep) $^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu_e$

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

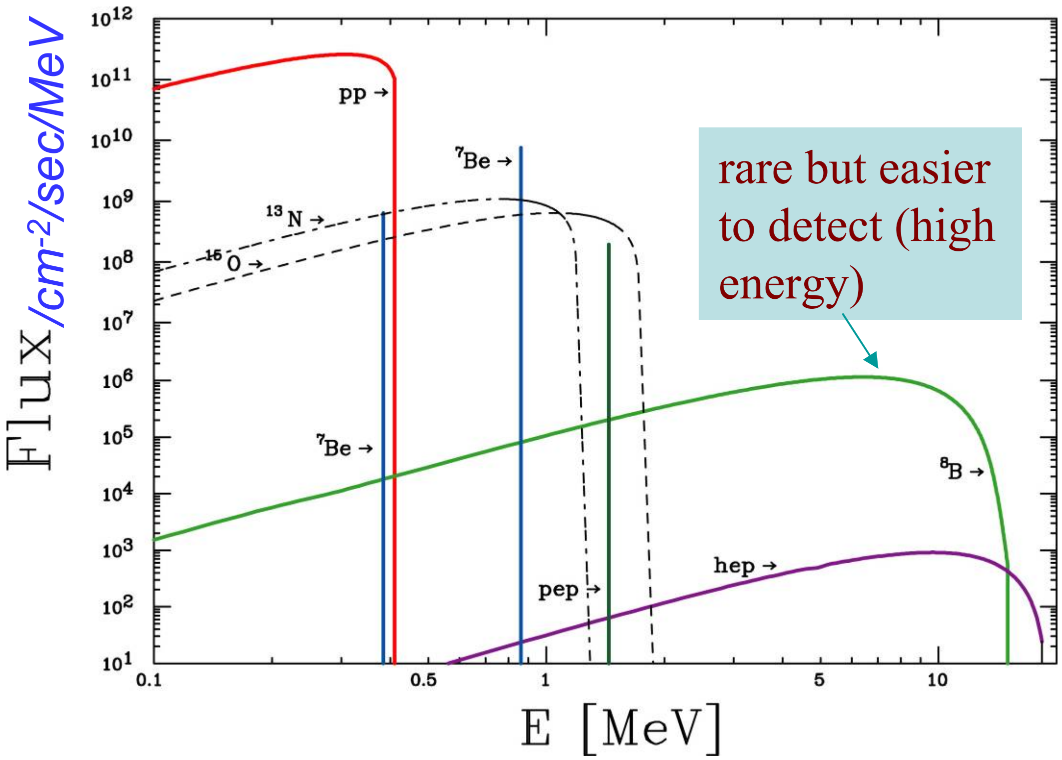
0.13%

99.87%

(^{8}B)
$^{7}Be+p \rightarrow {}^{8}Be+\gamma$
$^{8}B \rightarrow {}^{8}Be^{*} +e^{+} +\nu_e$
$^{8}Be^{*} \rightarrow {}^{4}He+{}^{4}He$

^{7}Be
$^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu_e$
$^{7}Li+p \rightarrow {}^{4}He+{}^{4}He$

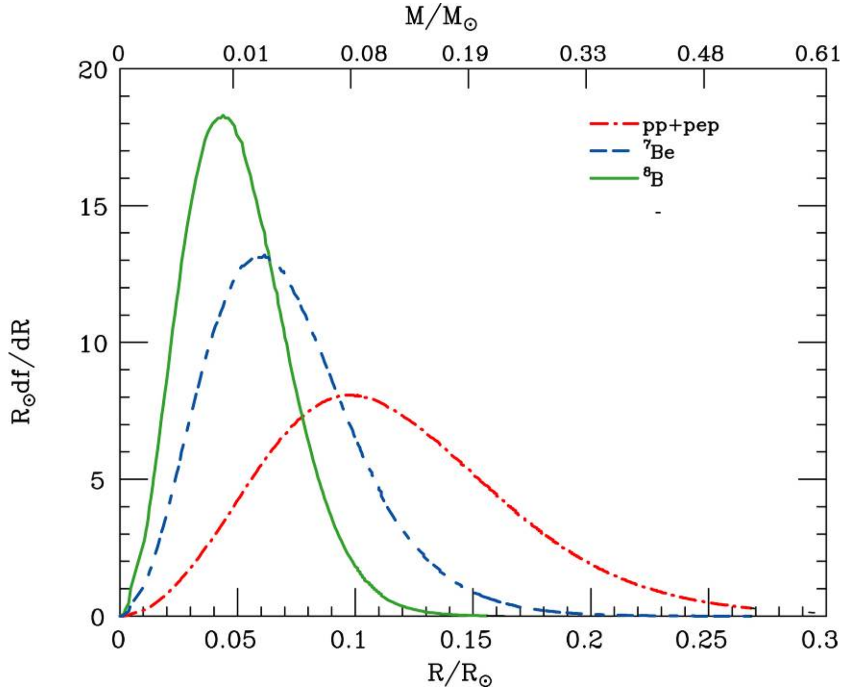
Energy of solar neutrinos



neutrino energy distribution (very important for the neutrino detection)

where the reactions occur inside the sun?

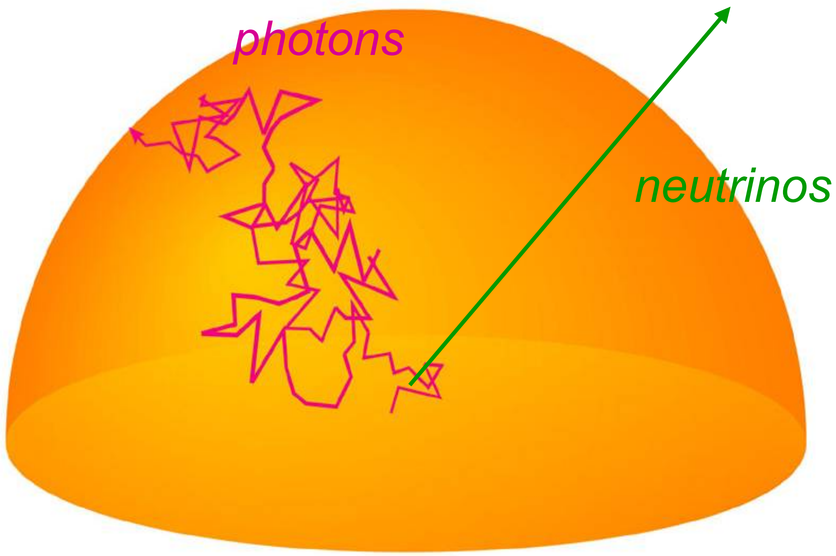
relative solar mass



relative solar radius

Photons and Neutrinos

- The photons take about 1 million years to come at the sun surface (and 8 min. to reach the earth).
- The neutrinos take few sec. to come at the sun surface (and 8 min. to reach the earth).



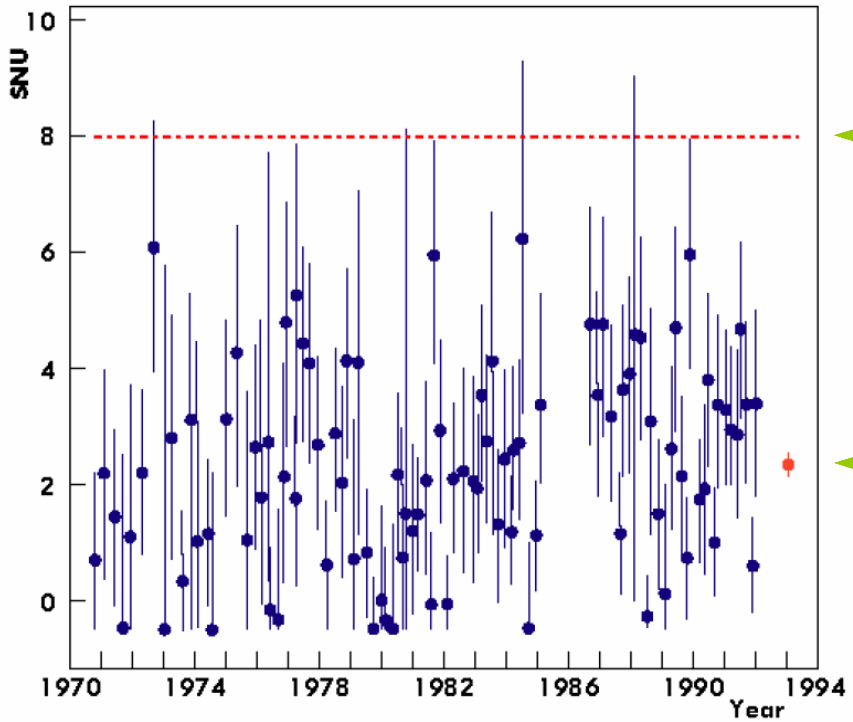
→ *neutrinos good probe of what happens at the heart of the sun*

Homestake Solar Neutrino Detector and solar neutrino problem

- Large tank of C_2Cl_4 (cleaning fluid) in Homestake mine (South Dakota),
- Uses reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$,
- Count Argon atoms produced, expected about 1 a day,
- Started experiment – 1968 Ray Davis- Nobel prize 2002.

Found only 1/3 as many Argon atoms as expected!

Experimental Results



expected flux

mean measured value

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \rightarrow$ flux ~0.33 SSM

Knowing how many neutrinos the proton-proton chain produces, the expected number of neutrinos to be detected by the experiment can be predicted (standard solar model - SSM).

Solar neutrino problem (lasted more than 20 years)

Radiochemical experiments

- First one ever used to detect solar neutrinos - Davis-Pontecorvo reaction:

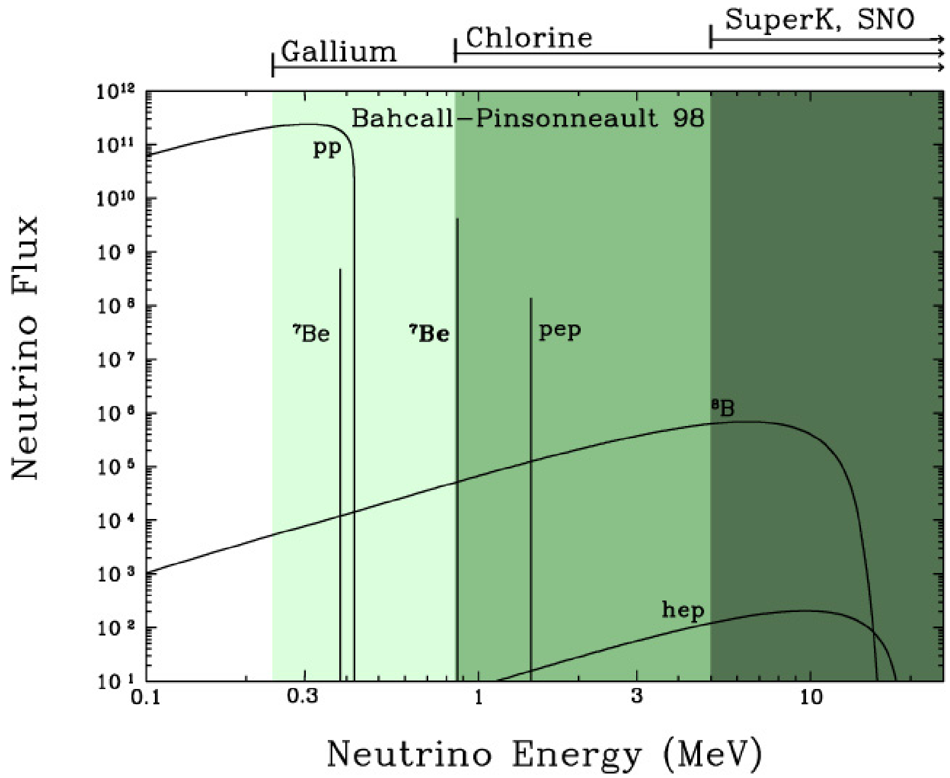
$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

- or the more sensitive one (which has confirmed the previous experiment results):

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{37}Ge$$

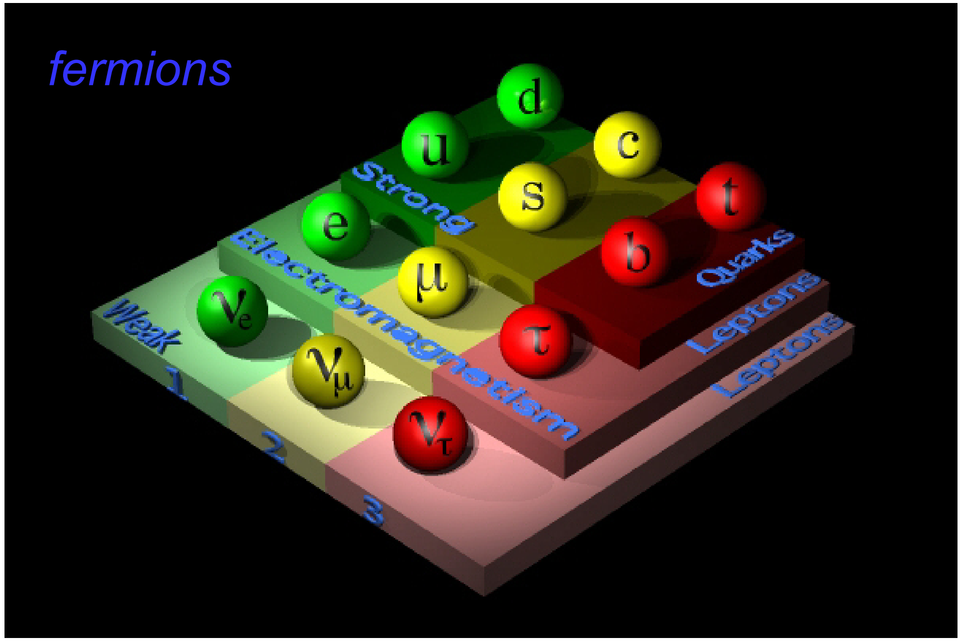
(Threshold at 233 keV, dominant p-p reaction)

ν detection method sensitivity



- Produced isotopes are radioactive with not too long lifetime - they are periodically extracted and counted (non on-line experiment),
- No information on time of interactions or neutrino direction.

What neutrinos are?

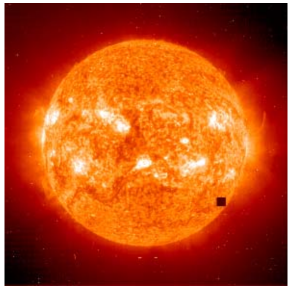


+bosons carrying the interactions

g (8 gluons)	γ (photon)	Z^0 boson	$W^\pm$ boson
strong	*electromagnetic*	*weak*	*weak*

- elementary particles,
- neutral (no electric charge),
- interacting only through weak interaction,
- they have a massive charged partner,
- without mass (this is what the particle Standard Model assumes)?

Main sources of neutrinos



•Solar neutrinos : 2 10^{38} ν/s $\rightarrow$ 40 billions ν/s/cm^2 on earth $\rightarrow$ 400000 billions ν/s/human (<20 MeV).

•Universe :

- Big-Bang : 330 ν/cm^3 (0.0004 eV $\rightarrow$ 2000 km/s if m_ν=10 eV/c^2).
- Stars : 0.000006 ν/cm^3.
- Supernovae : 0.0002 ν/cm^3.

•Earth radioactivity : 50 billions ν/s/human.

•Nuclear reactors : 10-100 billions ν/s/human (1-10 MeV).

•Human body : 340 millions ν/jour (20 mg de potassium 40, β–decay).

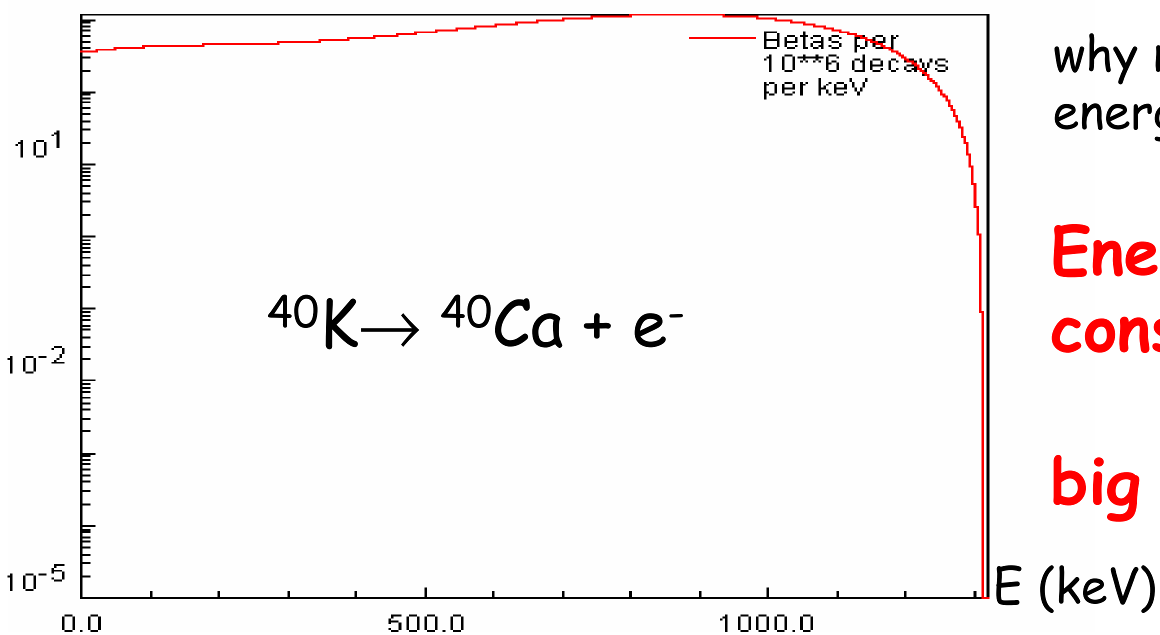
A brief history of neutrino

1886: Pierre Becquerel discovers radioactivity

1897: J.J.Thomson (and others) discover the electron

1902: Pierre and Marie Curie discover that β-rays are electrons

1914 : Lise Maitner, Otto Hahn and James Chadwick measure the energy spectra of the β-rays

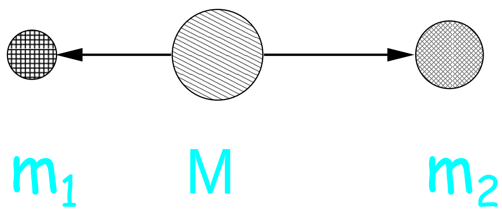


why not a fixed energy?

Energy not conserved?

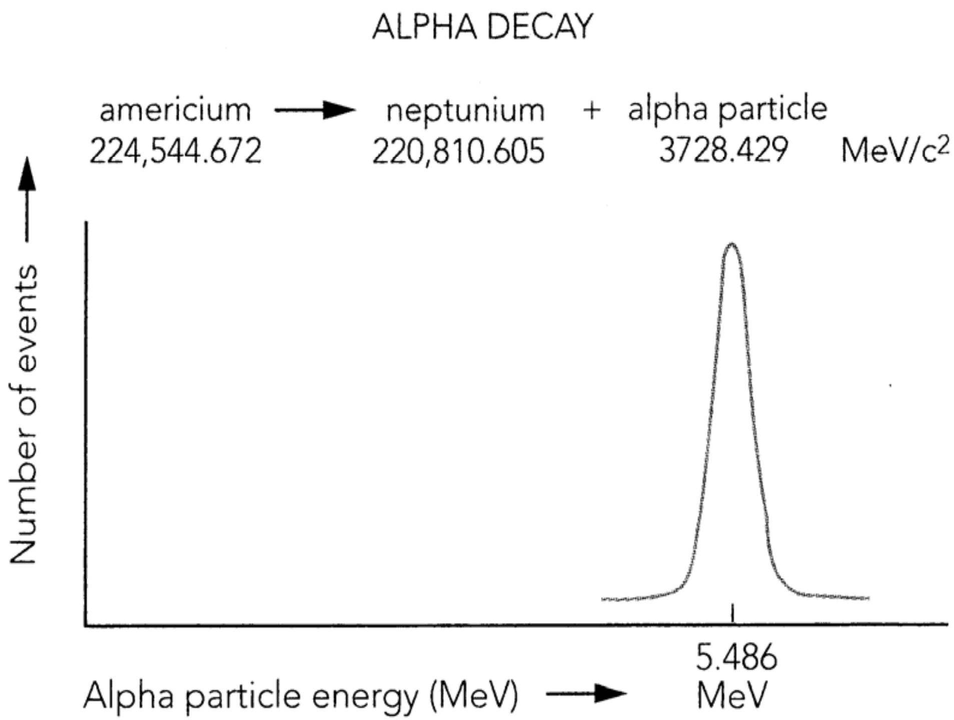
big crisis…

Two body decay



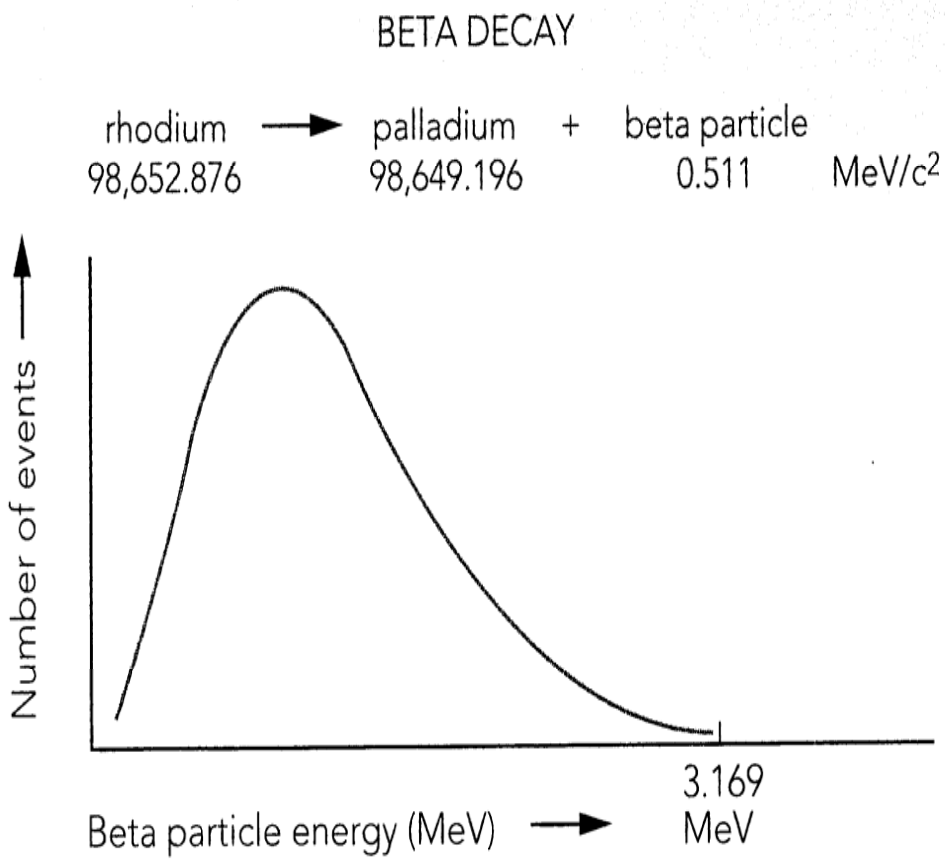
Energy-momentum conservation =>

$$E_2 = \sqrt{m_2^2 + p^2} = \frac{M^2 + m_2^2 - m_1^2}{2M}$$



Energy of the decay products always the same

1913-1930: Puzzle of β decay



Continuous spectrum of b particles (electrons)!

Dec 1930: A Desperate Remedy

Pauli's letter of the 4th of December 1930

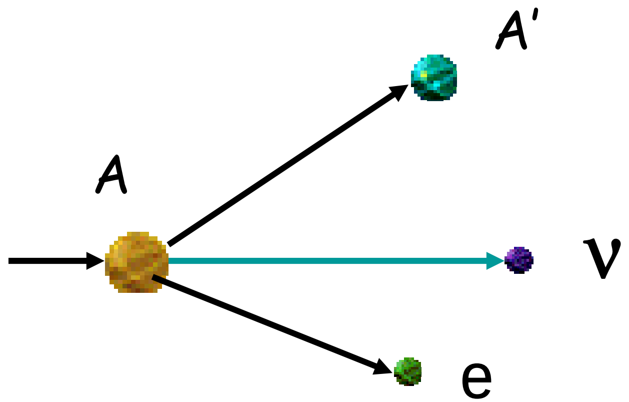
Dear Radioactive Ladies and Gentlemen,

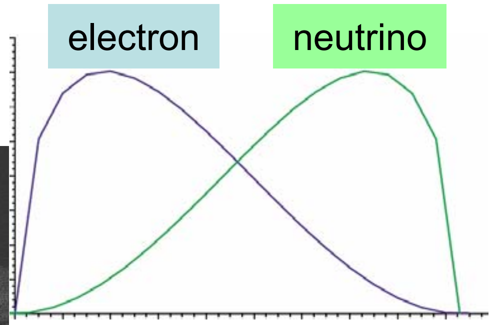
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a ***desperate remedy*** *to save the "exchange theorem" of statistics and the law of conservation of energy. Namely,* ***the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call <u>neutrons</u>, 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 those neutrons very 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 to 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



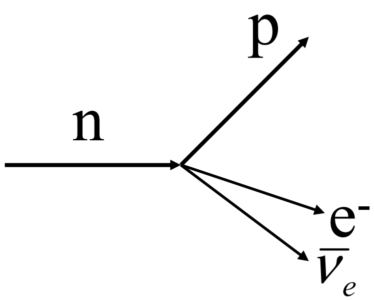


"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." *W.Pauli*

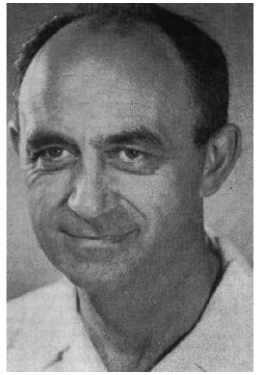
ν history…

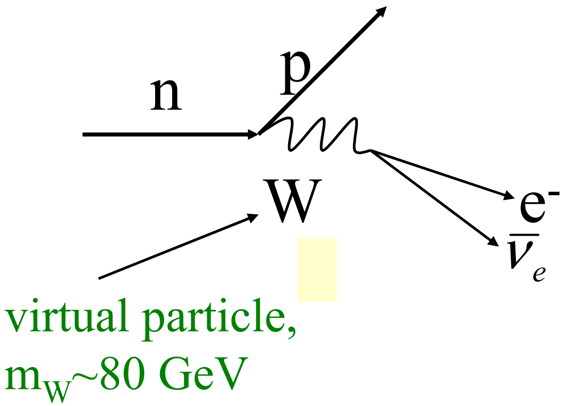
1933 Enrico Fermi develops the β-decay theory (weak interaction) and names the Pauli's "neutron" “neutrino”.

(James Chadwick had discovered the neutron in 1932)



β-decay





intermediate vector boson (IVB, analogue to photon in electromagnetic interaction)

Heisenberg uncertainty principle and virtual particles

$$\Delta x \Delta p \geq \hbar / 2$$

$$\Delta E \Delta t \geq \hbar / 2$$

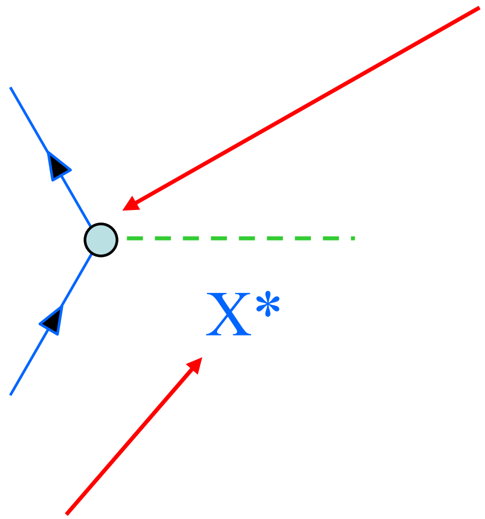
Δt very short

$\Rightarrow$

ΔE very big

$\Rightarrow$

$E^2 - p^2 \neq m^2$



virtual particle

ν history…

1933 : Hans Bethe and Rudolf Peierls

first cross-section calculations (probability of interaction)

$$\sigma_{\nu N} \approx 10^{-10} \sigma_{eN}$$

cross-section very very weak!!!

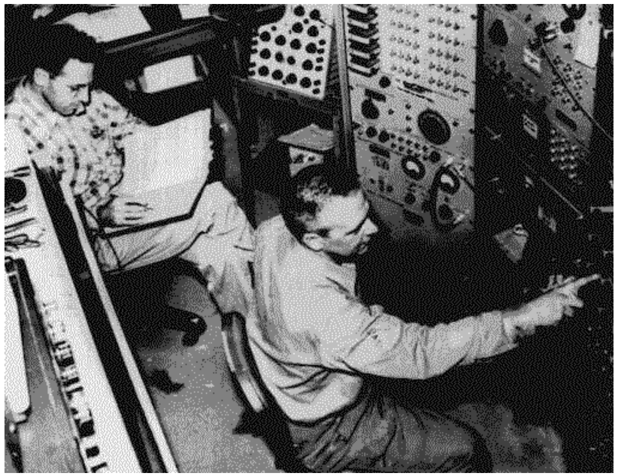
(N for nucleon) cross section= 10^{-44} cm^2

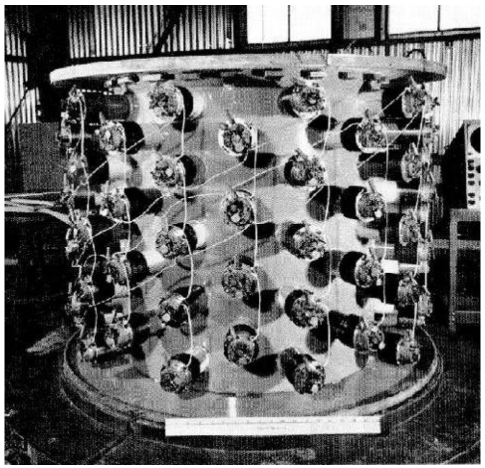
One needs either 10^{16} km of water to absorb a neutrino, or a lot of neutrinos (mean free path longer than a light year of lead).

The beginning of a 26 year quest

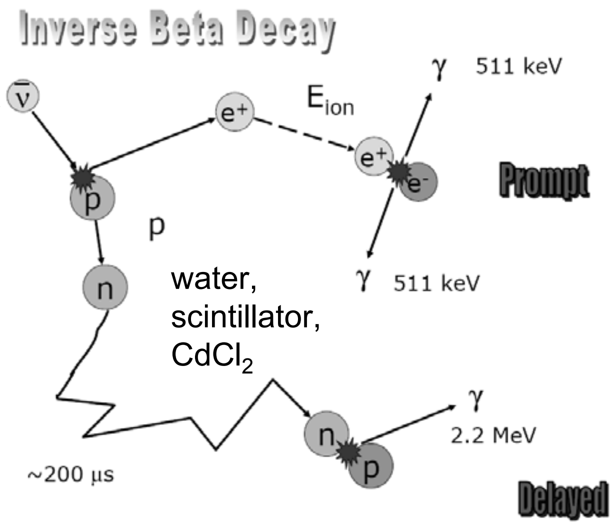
(Fermi: "I offer a case of champagne to whom will detect the first neutrino")

1953-56-58: Fred Reines et Clyde Cowan detect the first neutrino interactions at the Savannah River nuclear power plant





from nuclear reactor



ν history…

1960 : Tsung Dao Lee, Chen Nin Yang, Bruno Pontecorvo, Melvin Shwartz, … π and μ decays to produce intense neutrino beams at accelerators.

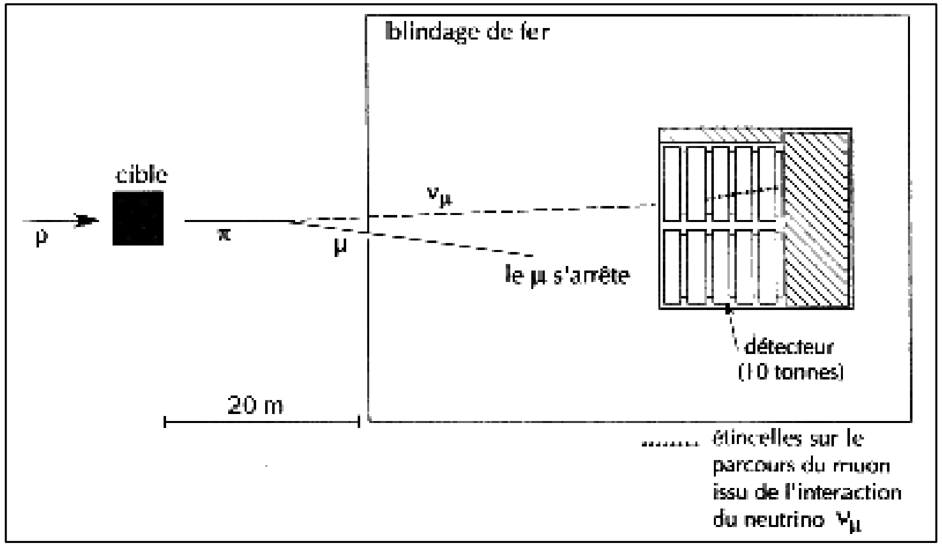
1962 : Leon Lederman, Melvin Schwartz, Jack Steinberger discover ν_μ

ν_μ beam ($\pi^+ \to \mu^+ \nu_\mu$ decays)

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

$$\nu_\mu + N \not\to e^- + X$$

first neutrino beams



1968: Homestake (R. Davis), something wrong with solar neutrinos

2000 : DONUT experiment at FermiLab discovers ν_τ

Trying to find a solution to the solar neutrino problem

- If neutrinos are massive:
  - States participating in weak interactions (flavour eigenstates):
  - States with well defined masses (mass matrix eigenstates):

$$\nu_e \quad \nu_\mu \quad \nu_\tau$$

$$\nu_1 \quad \nu_2 \quad \nu_3$$

Lepton mixing and Quantum Mechanics

- "Known" neutrinos are combinations of mass eigenstate neutrinos, e.g., for electron neutrinos:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- For all neutrinos we can write:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{unitary mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maki-Nakagawa-Sakata matrix

- *change of basis,*
- *U is the transformation operator/matrix,*
- *the hypothetical ν_1, ν_2, ν_3 have unique masses and are the most fundamental neutrino states.*

U-matrix properties

- Unitarity ($UU^{+}=I$): $\langle \nu_\alpha | \nu_\beta \rangle = \delta_i^j$ (=0 for $i \neq j$, =1 for $i = j$)

  α,β=e,μ,τ

$$U^*_{\alpha 1}U_{\alpha 1} + U^*_{\alpha 2}U_{\alpha 2} + U^*_{\alpha 3}U_{\alpha 3} = 1$$

$$(\text{e.g } U^*_{e1}U_{e1} + U^*_{e2}U_{e2} + U^*_{e3}U_{e3} = 1)$$

$$U^*_{\alpha 1}U_{\beta 1} + U^*_{\alpha 2}U_{\beta 2} + U^*_{\alpha 3}U_{\beta 3} = 0 \text{ for } \alpha \neq \beta$$

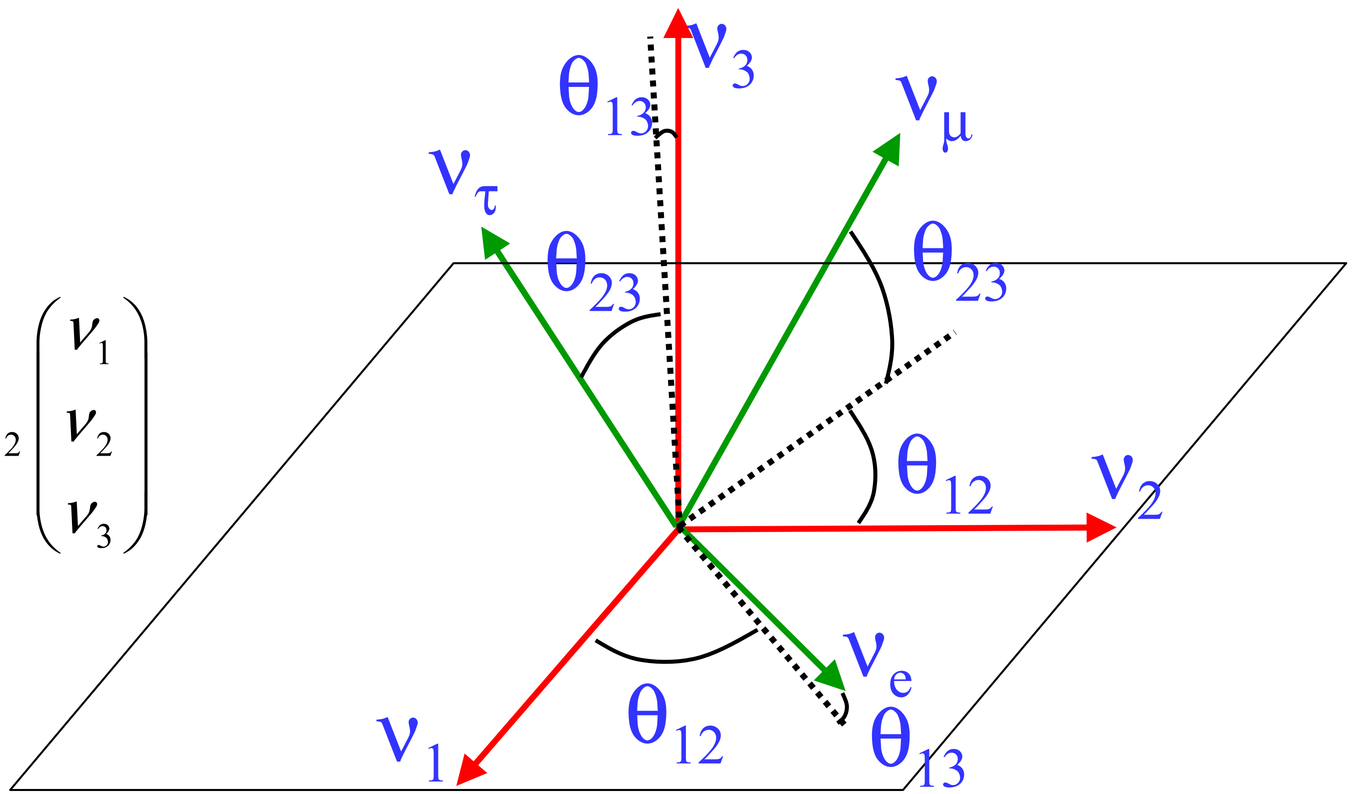
  – or in condensed notation:

$$U^*_{ej}U_{ej} = U^*_{\mu j}U_{\mu j} = U^*_{\tau j}U_{\tau j} = 1$$

$$U^*_{ej}U_{\mu j} = U^*_{ej}U_{\tau j} = U^*_{\mu j}U_{\tau j} = 0$$

Rotation between states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R_{23} R_{13} R_{12} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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

$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$

rotation by: θ_{23} θ_{13} θ_{12}

Final mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Yes but, how can we use all that to explain the solar neutrino problem?

How neutrinos propagate with time?

According to Quantum Mechanics

$$|\nu_j(t)\rangle = e^{-iHt/\hbar}|\nu_j(0)\rangle$$

(H: hamiltonian)

Solutions of Schrödinger equation

For 3 neutrinos with definite energy and mass:

The Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = H\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

for mass states

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_f\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

for flavour states

with: $$H_f = UHU^*$$

How neutrinos propagate with time?

$$|\nu_\alpha(0)\rangle = \sum_{k=1}^{3} U_{\alpha k}^{*} |\nu_k(0)\rangle \qquad \alpha = e,\ \mu,\ \tau$$

time evolution of flavour states: $|\nu_\alpha(t)\rangle = \sum_{k=1}^{3} U_{\alpha k}^{*} e^{-iE_k t} |\nu_k\rangle \quad (\hbar = 1)$

with energy: $E_k = \sqrt{p^2 + m_k^2} \simeq p + \frac{m_k^2}{2p}$ with: $p >> m_k$

$|\nu_k\rangle$ can be expressed as a function of flavour neutrino states $|\nu_\beta\rangle$

$$|\nu_\alpha(t)\rangle = \sum_{\beta} A_{\nu_\alpha \to \nu_\beta}(t) |\nu_\beta\rangle$$

where: $A_{\nu_\alpha \to \nu_\beta}(t) = \sum_{k=1}^{3} U_{\beta k} e^{-iE_k t} U_{\alpha k}^{*}$ the amplitude of $\nu_\alpha \to \nu_\beta$ transitions at the time t (or at distance L)

Transition probability

$$P_{\nu_\alpha \to \nu_\beta} = \left| A_{\nu_\alpha \to \nu_\beta}(t) \right|^2 = \left| \sum_{k=1}^{3} U_{\beta k} e^{-iE_k t/\hbar} U^*_{\alpha k} \right|^2$$

- $U^*_{\alpha k}$: the amplitude to find the neutrino mass eigenstate $|\nu_k>$ with energy E_k in the state of flavour neutrino $|\nu_\alpha>$,
- $e^{-iEkt/\hbar}$ gives the time evolution of the mass eigenstate,
- $U_{\beta k}$: the amplitude to find the flavour neutrino state $|\nu_\beta>$ in the mass eigenstate neutrino $|\nu_k>$.

Using the unitarity condition:

$$\sum_{k=1}^{3} U_{\beta k} U^*_{\alpha k} = \delta_{\alpha\beta}$$

Transition probability

$$P_{\nu_\alpha \to \nu_\beta} = \left| \delta_{\alpha\beta} + \sum_{k=2}^{3} U_{\beta k} U_{\alpha k}^{*} \left[e^{-i\frac{\Delta m_{k1}^2 L}{2E}} - 1 \right] \right|^2$$

(the time has been replaced by the distance)

with: $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

➡ transition probabilities do not depend on particle masses but on squared mass differences

Finally, the transition probability depends on the elements of the mixing matrix, on 2 independent mass-squared differences and on the parameter L/E.

No transitions are observed when: $\Delta m_{k1}^2 L / E \ll 1$

with Δm^2 given in eV^2, *L* in km and *E* in GeV

Probability as a function of the mixing angles

$$P(\nu_\alpha \xrightarrow{\alpha\neq\beta} \nu_\beta) = -4\sum_{i>j}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) =$$

$$= -2\sum_{i=1}^{3}\sum_{j=1, j\neq i}^{3}(U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j})\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) =$$

$$= -4\left[\underbrace{U_{\alpha 1}U_{\beta 1}U_{\alpha 2}U_{\beta 2}}_{c_{12}}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E}\right) + \underbrace{U_{\alpha 1}U_{\beta 1}U_{\alpha 3}U_{\beta 3}}_{c_{13}}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E}\right) + \underbrace{U_{\alpha 2}U_{\beta 2}U_{\alpha 3}U_{\beta 3}}_{c_{23}}\sin^2\left(\frac{1.27\Delta m^2_{23}L}{E}\right)\right]$$

$(\hbar c = 197\, MeV\ fm)$

transitions only if the neutrino masses are non-zero and not the same

Oscillation Probability and approximations

$$P(\nu_\alpha \to \nu_\beta) = -4\left[c_{12}\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E}\right) + c_{13}\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E}\right) + c_{23}\sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right)\right]$$

Let's assume: $\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m \qquad \Delta m_{12} \equiv \delta m$ (justified by experimental results)

$$\Delta m \gg \delta m$$

Let's consider two types of experiments:

Case A – small L/E: $\sin^2\left(\frac{1.27\delta m^2 L}{E}\right) \approx 0$

$$P(\nu_\alpha \to \nu_\beta) = -4(c_{13} + c_{23})\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

not anymore sensitive to θ_{12} and δm

Oscillation Probability

Case B – large L/E:

$$\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right) \approx \frac{1}{2}$$

⇒

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4\left[c_{12}\sin^2\left(\frac{1.27\delta m^2 L}{E}\right) + 0.5(c_{13} + c_{23})\right]$$

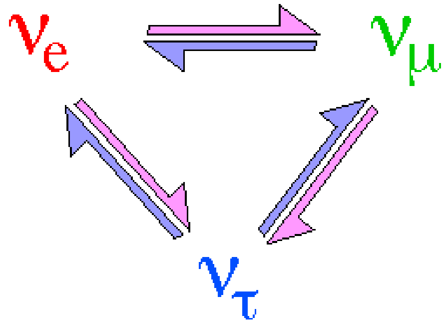
not anymore sensitive to Δm while the amplitude of the oscillation depends only on θ_{12}

Case A: small L/E

$$P(\nu_\mu \to \nu_\tau) \approx \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

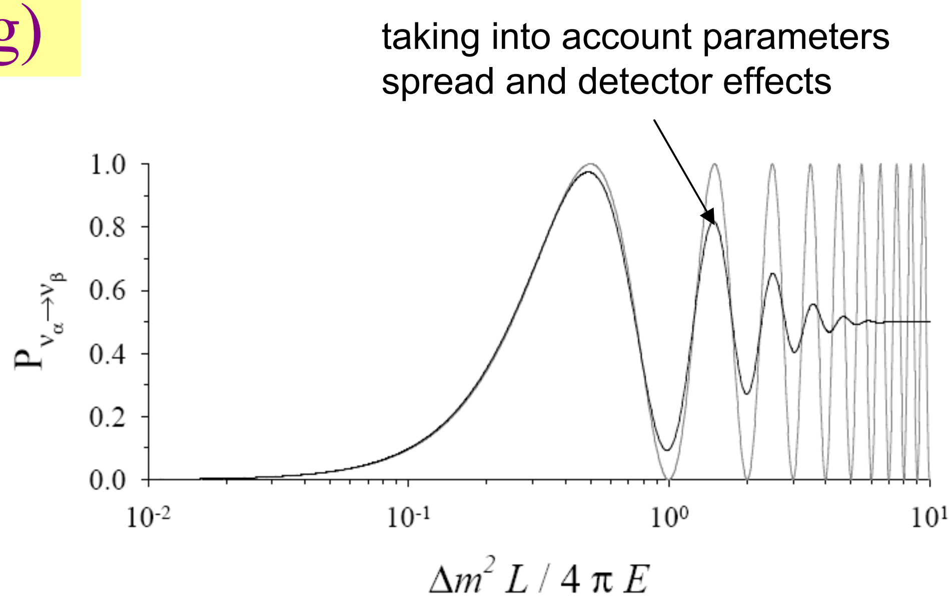
$$P(\nu_e \to \nu_\tau) \approx \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



oscillation

(for θ_{13}=0 only 2 flavours mixing)

Case of atmospheric neutrinos



Case A: large L/E

$$P\left(\nu_e \to \nu_{\mu\tau}\right) = \cos^2\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\delta m^2 L}{E_\nu}\right) + 0.5 \sin^2 2\theta_{13}$$

Case of solar neutrinos

Oscillation parameters

mixing angles $\theta_{13}, \ \theta_{12}, \ \theta_{23}$

mass differences
(only 2 are free) $\Delta m_{13}, \ \Delta m_{23}, \ \Delta m_{12}$

what can be varied by humans in order to study neutrino oscillations $E_\nu, \ L$

$$\sin\left(\frac{1.27\Delta m^2 L}{E_\nu}\right) = \sin(\pi \frac{L}{L_{osc}})$$

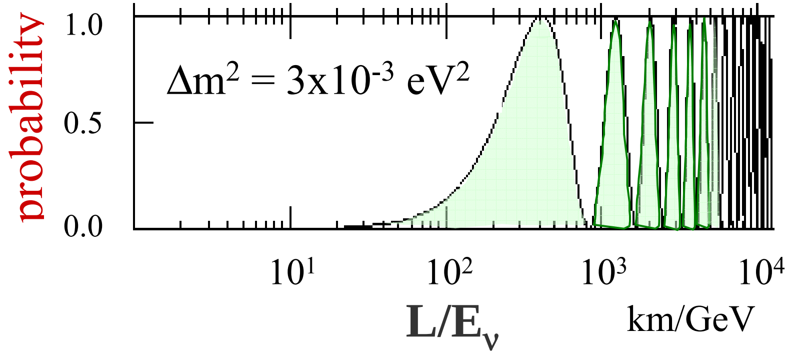
Very often used: Oscillation length (length after which all neutrinos reappear):

$$L_{osc} = \frac{2.5 E_\nu}{\Delta m^2}$$

Appearance and disappearance experiments

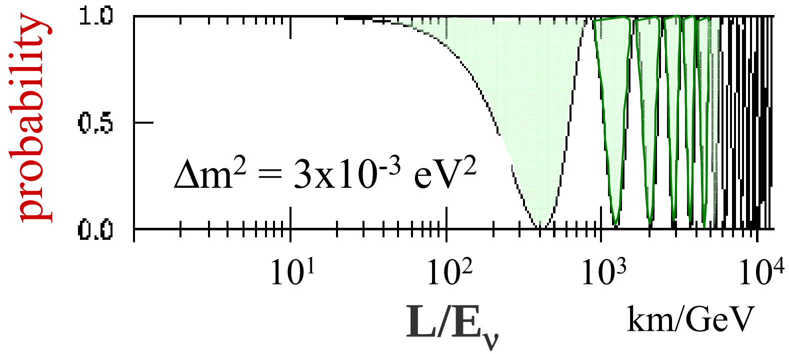
In a disappearance experiment one counts how many of the initial neutrinos ν_α are left after passing a distance *L*:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



In an appearance experiment one searches for neutrinos ν_β in an initial beam of ν_α :

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



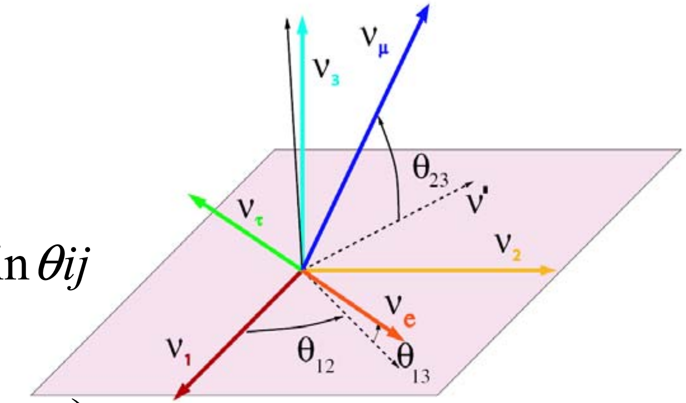
Back to solar neutrino problem

Radiochemical experiments were only sensitive to ν_e

Neutrino Oscillations and mixing matrix

Matrix MNSP (Maki, Nakagawa, Sakata, Pontecorvo)

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \qquad c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta ij$$



$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

solar, reactors

atmospheric, accelerators

reactors
accelerators
CP violation

Majorana phases

sensitive to CP violation if $\theta_{13}>0$

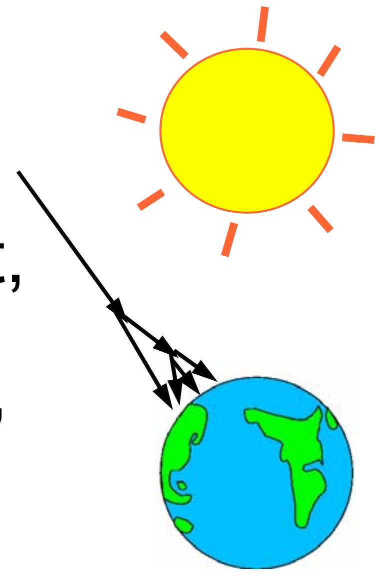
To Make a Precision Measurement of Neutrino Properties

How do you design a neutrino experiment?

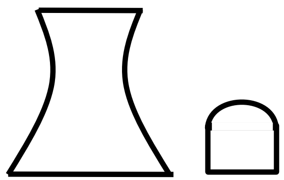
- An intense source of neutrinos (Reactors, sun, ν-beams…)
- Right type and energy,
- The ability to do precise energy measurements.
- Large detectors at the optimal distances from the source,
- Distance from the neutrino source,
- Protection from cosmic rays (Deep Underground)

Neutrino experiments

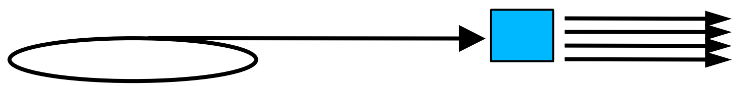
Using:



- solar neutrinos (distance fixed, energy fixed), good for (Δm^2_{12}, θ_{12}) measurement,
- atmospheric neutrinos (distance can vary, energy fixed), good for (Δm^2_{23}, θ_{23}) measurement

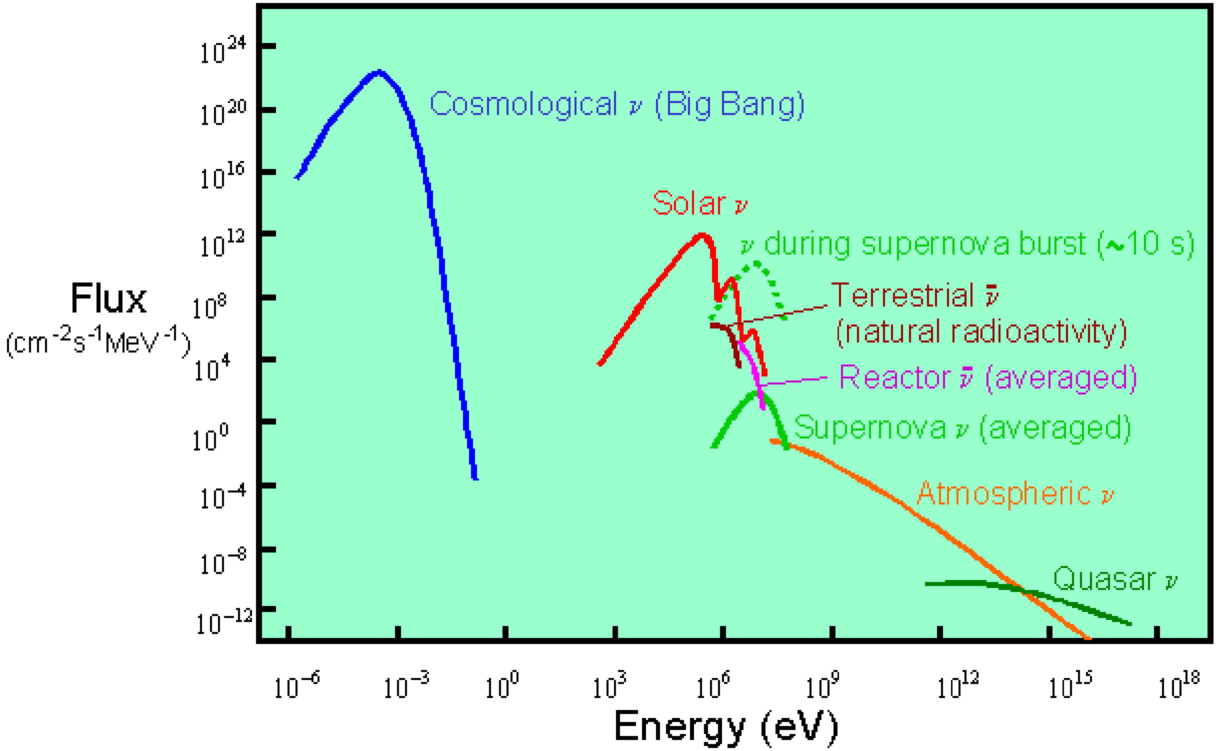


- reactor neutrinos (distance can be tuned, energy fixed), good for (Δm^2_{13}, θ_{13})
- accelerator neutrinos (distance can be tuned, energy can be tuned).

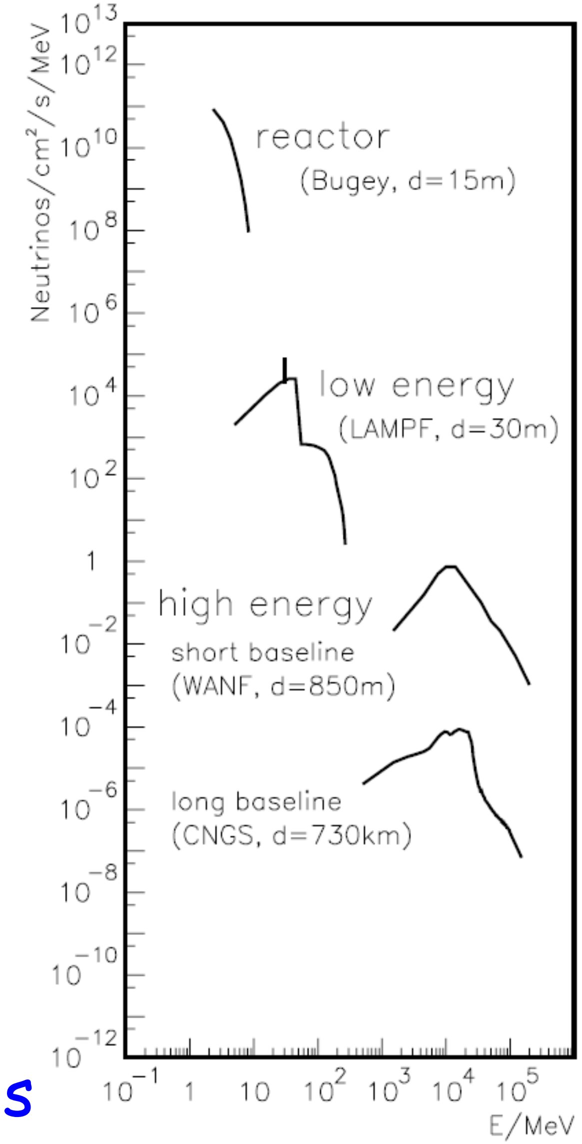


on top of that the experiment neutrino detection sensitivity has to be taken into account

Neutrino energy spectra



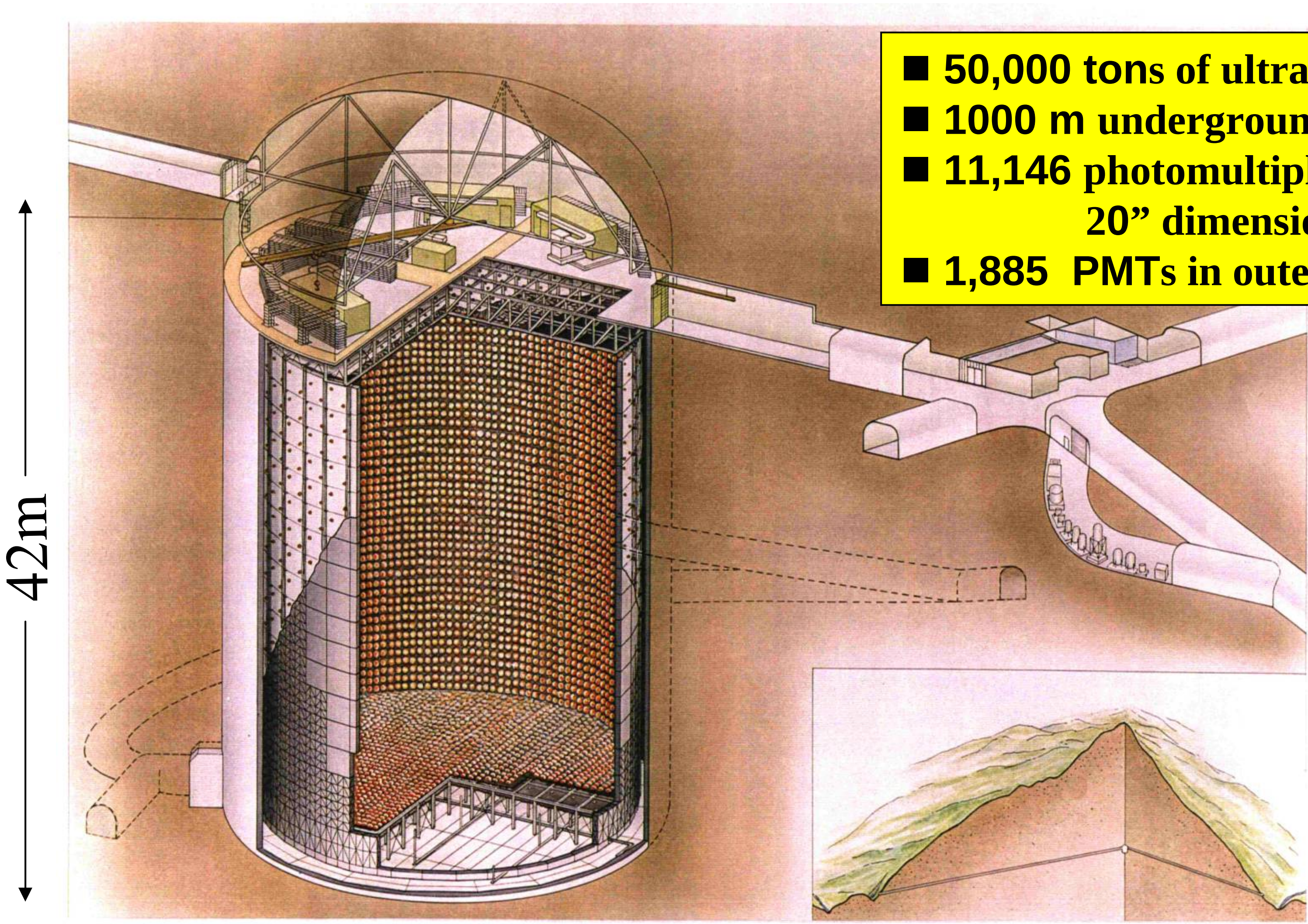
"natural" neutrinos



"human" neutrinos

Confirmation of neutrino oscillations

Super-Kamiokande detector

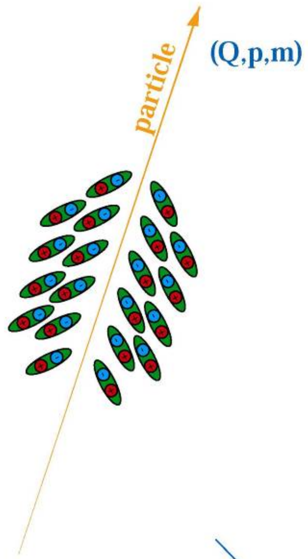


- 50,000 tons of ultra-pure water
- 1000 m underground
- 11,146 photomultipliers (PMT)
  20” dimension
- 1,885 PMTs in outer layer

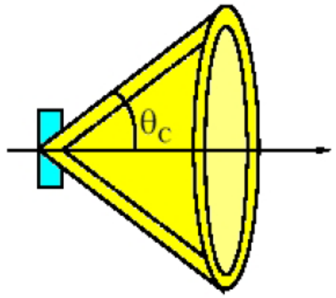
Japan

Detection technique used at SK

Cerenkov radiation



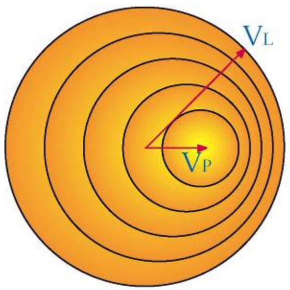
Light emission only if the particle is faster than light in the crossed medium (radiator)



Cerenkov angle:

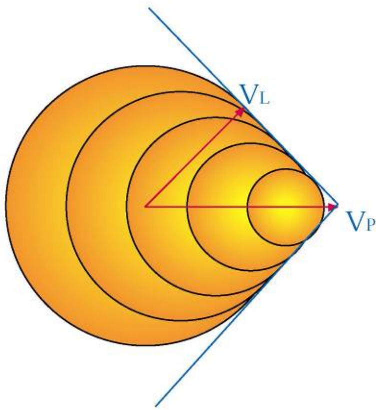
$$\cos\theta_C = \frac{1}{\beta n}$$

β=particle velocity (v/c)
n=index of refraction



$V_P<V_L$

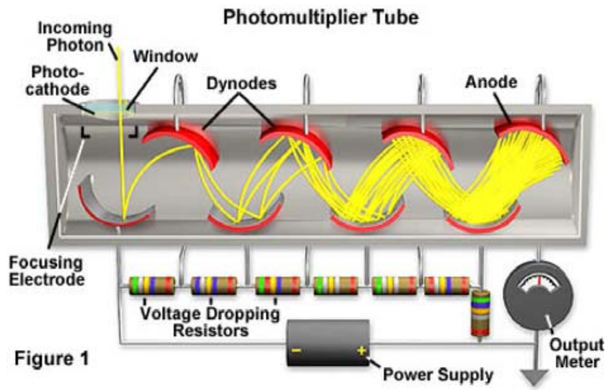
no light emission



$V_P>V_L$

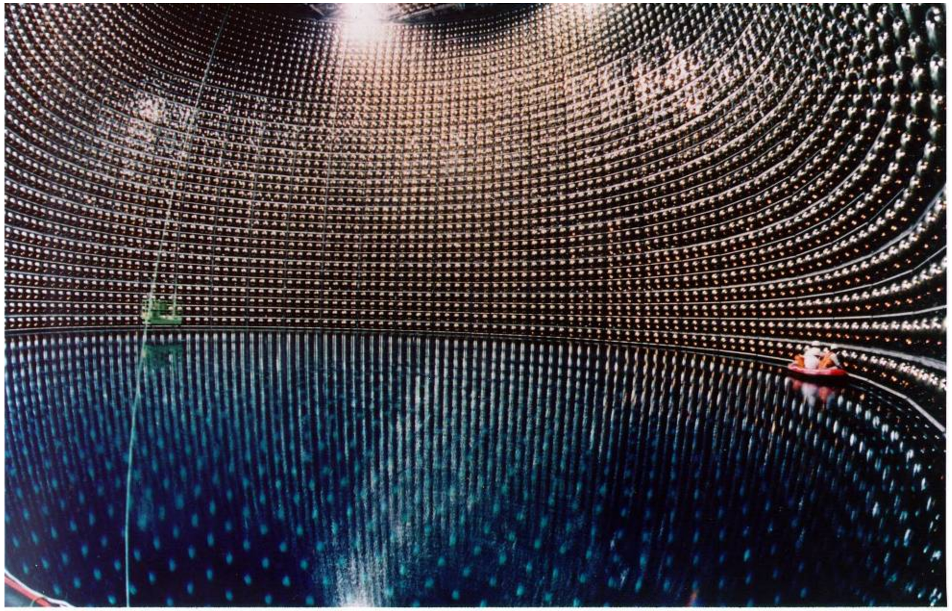
light emission

Light detection technique: Photomultipliers

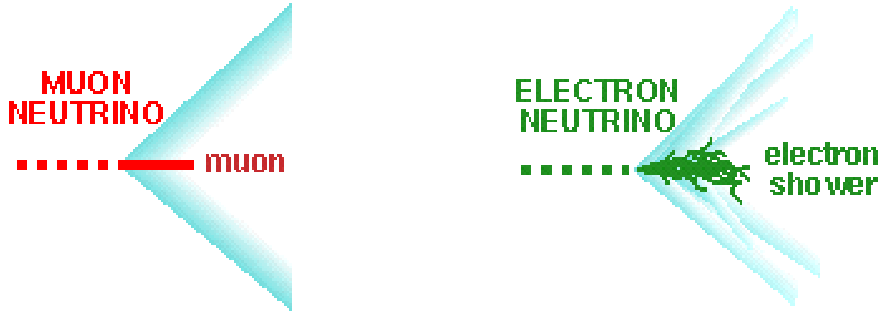


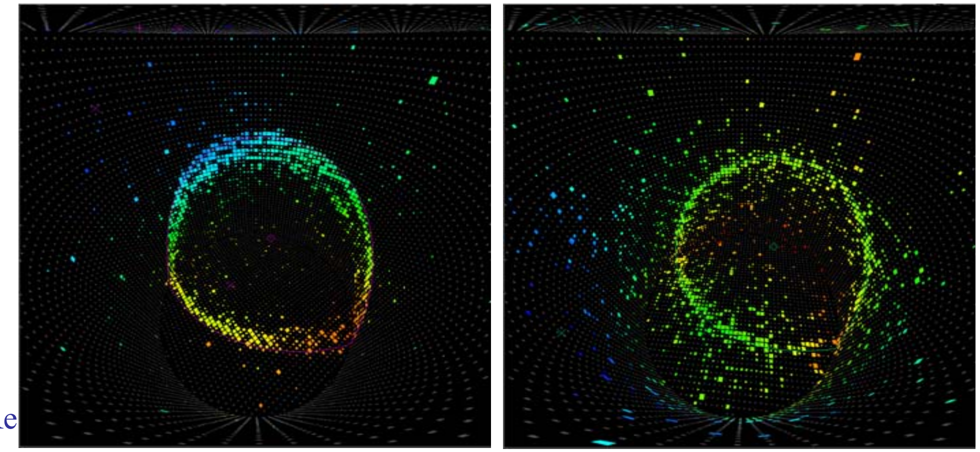
Super Kamiokande Detector

Less efficient technique for solar neutrinos than Gallium and Chlorine but on-line experiment with directionality information.

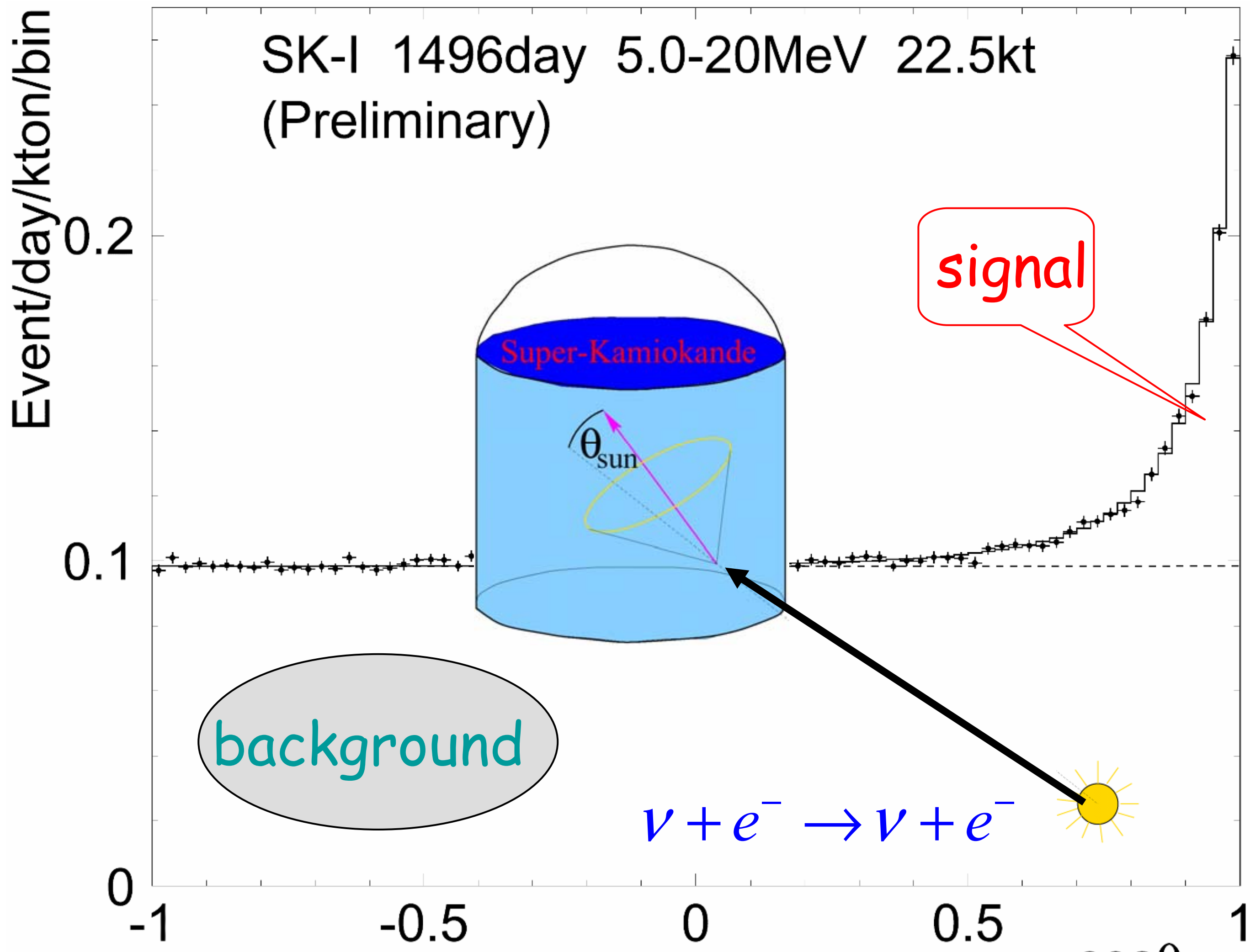


Cleaning detector during filling
- no radioactive dust allowed

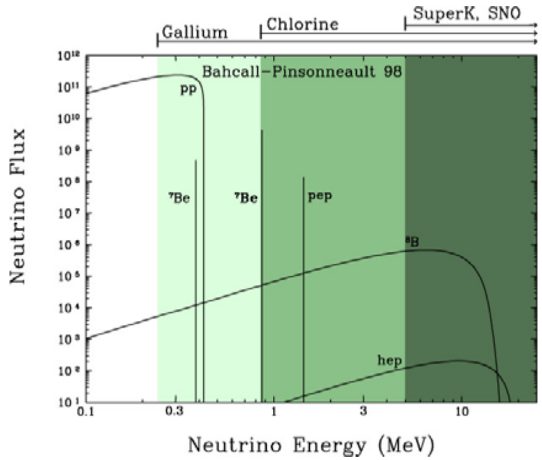




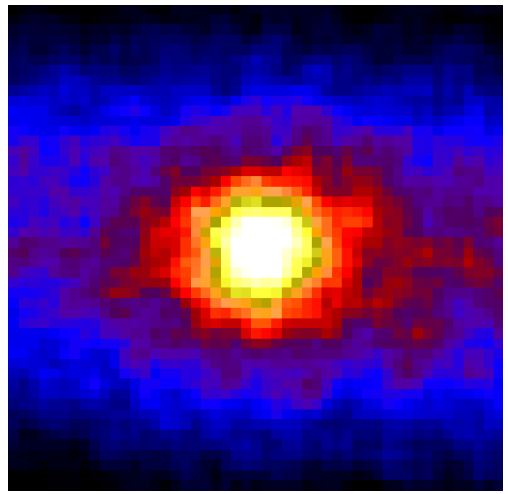
Super-Kamiokande: Solar neutrinos



the sun is "here"



the sun shining with neutrinos!



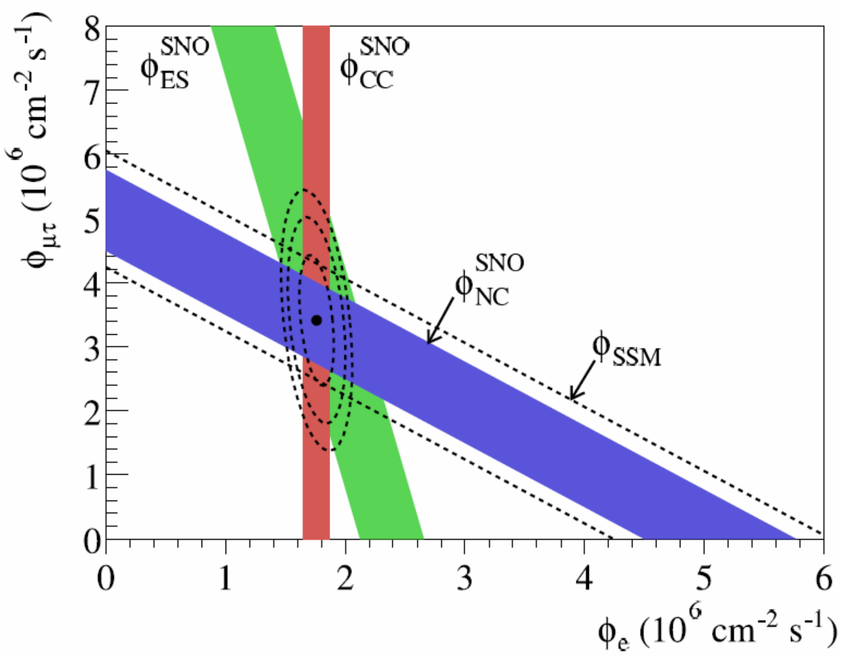
confirmation of solar neutrino results of radiochemical experiments

SNO

(Sudbury Neutrino Observatory)

Water detector with a difference:

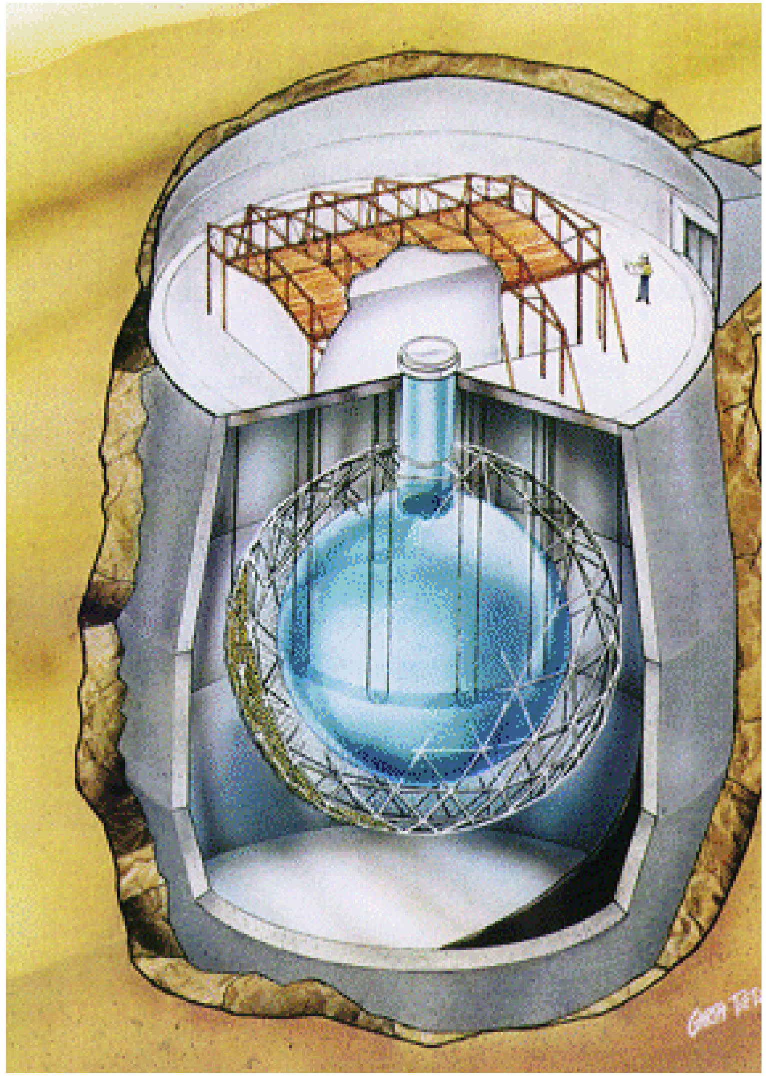
- **2 km underground**
- **1000 tons D_2O**
- **10^4 - 8” PMTs**
- **6500 tons H_2O**
- **sensitive to all neutrino families**



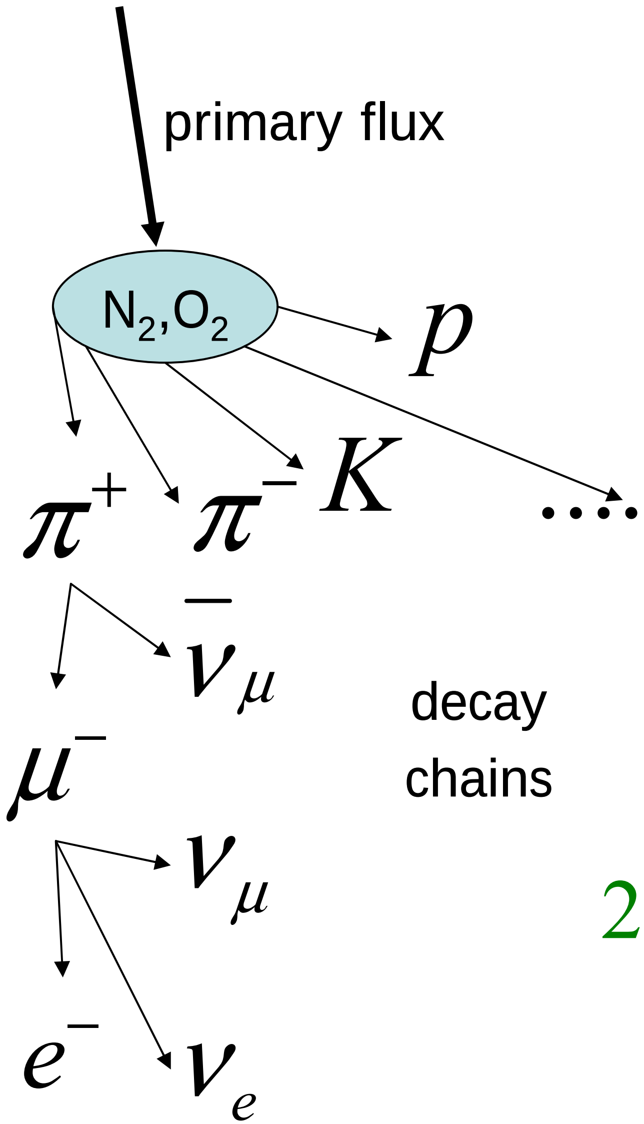
combined results

all solar neutrinos are there

Canada



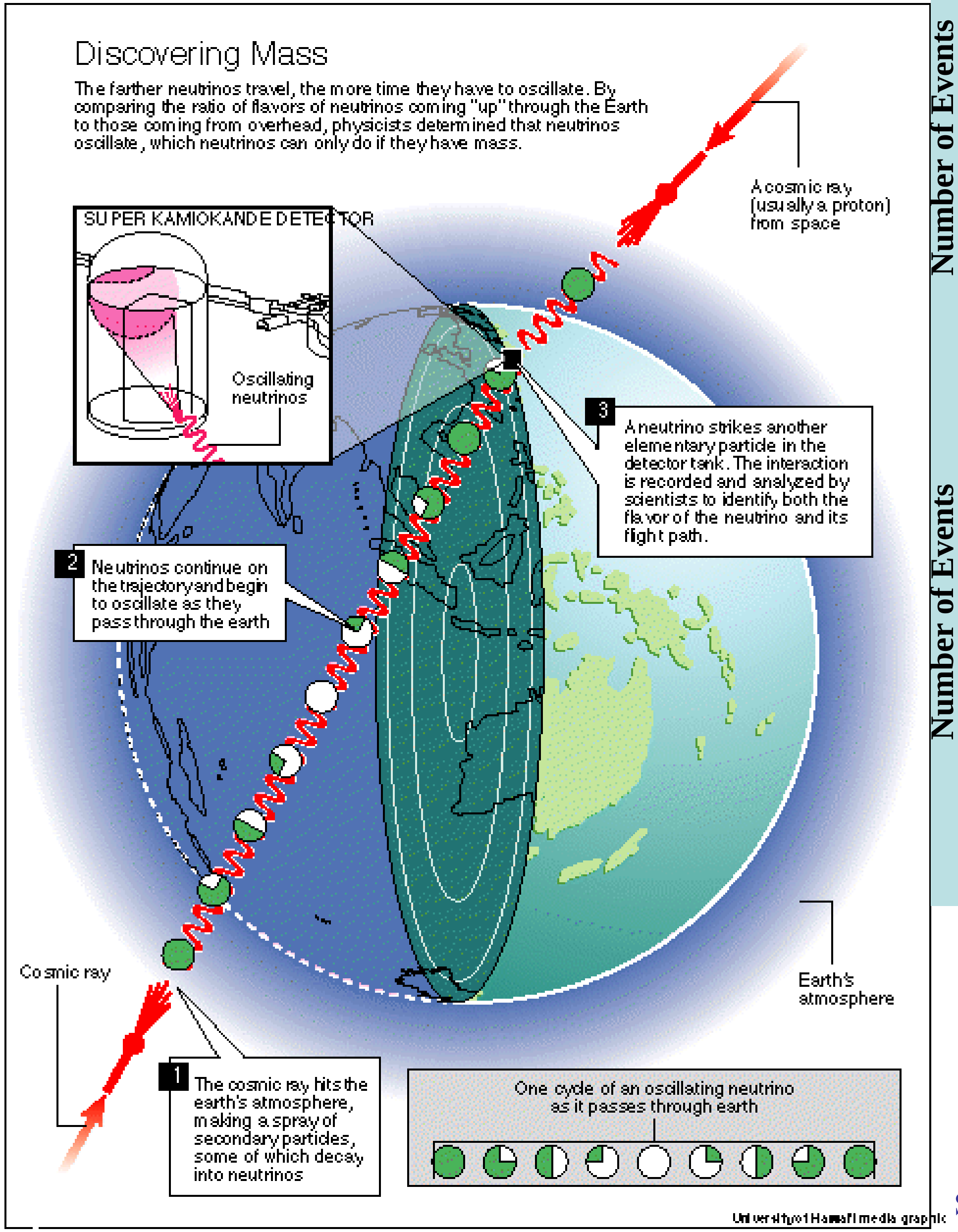
Atmospheric neutrinos

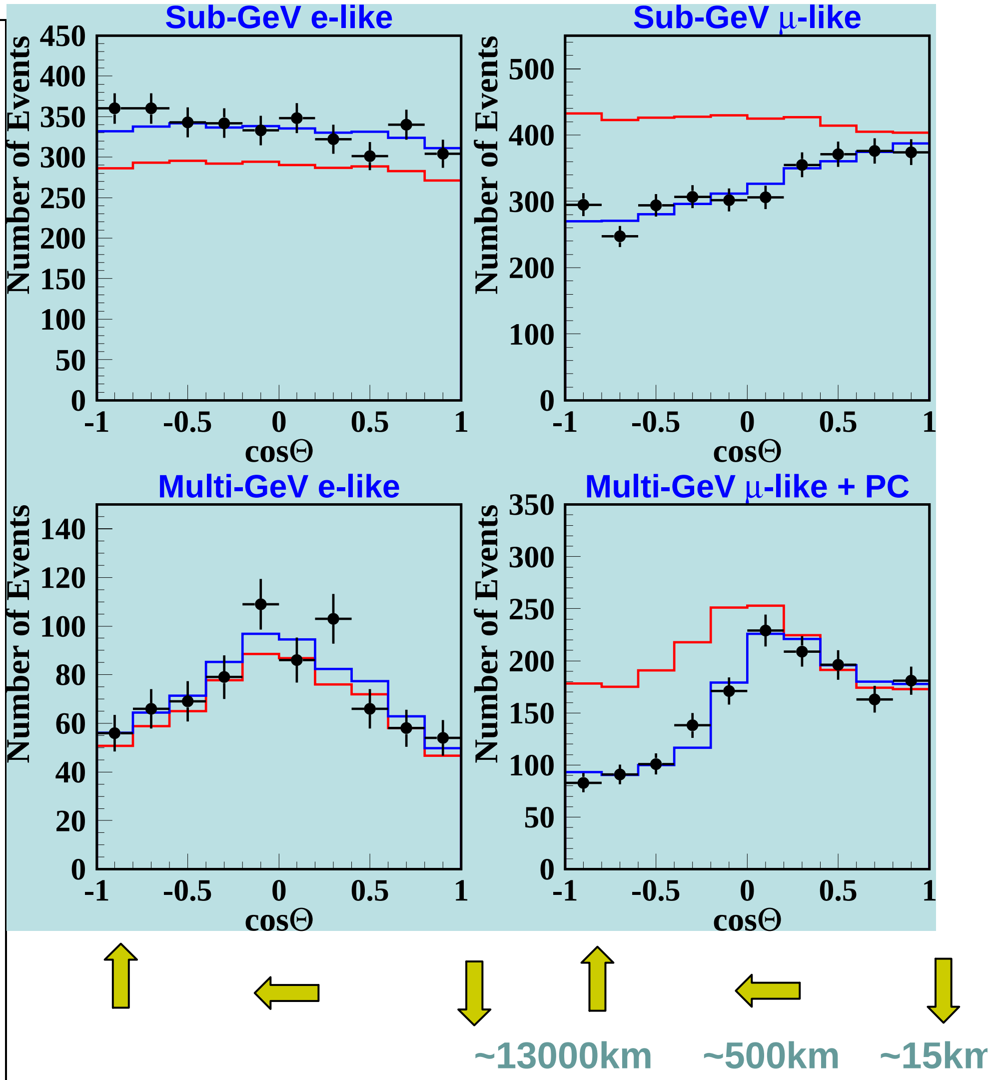


2x more ν_μ than ν_e

Atmospheric neutrinos and confirmation of oscillations

SuperK



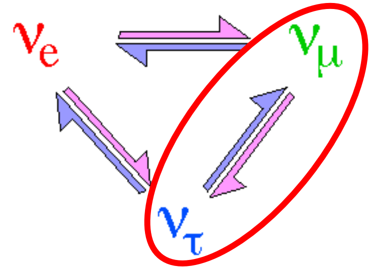


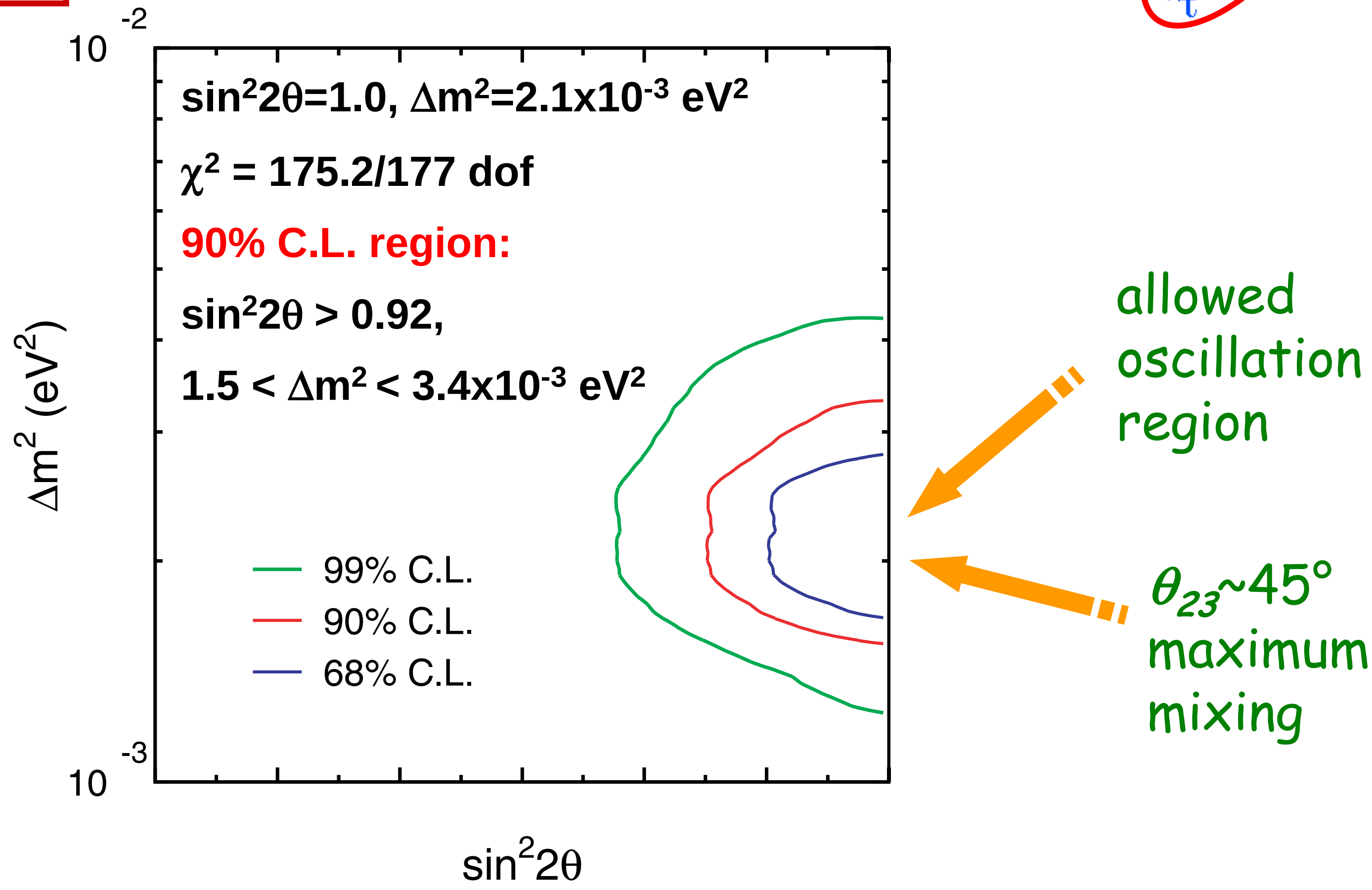
Null oscillation

Best fit

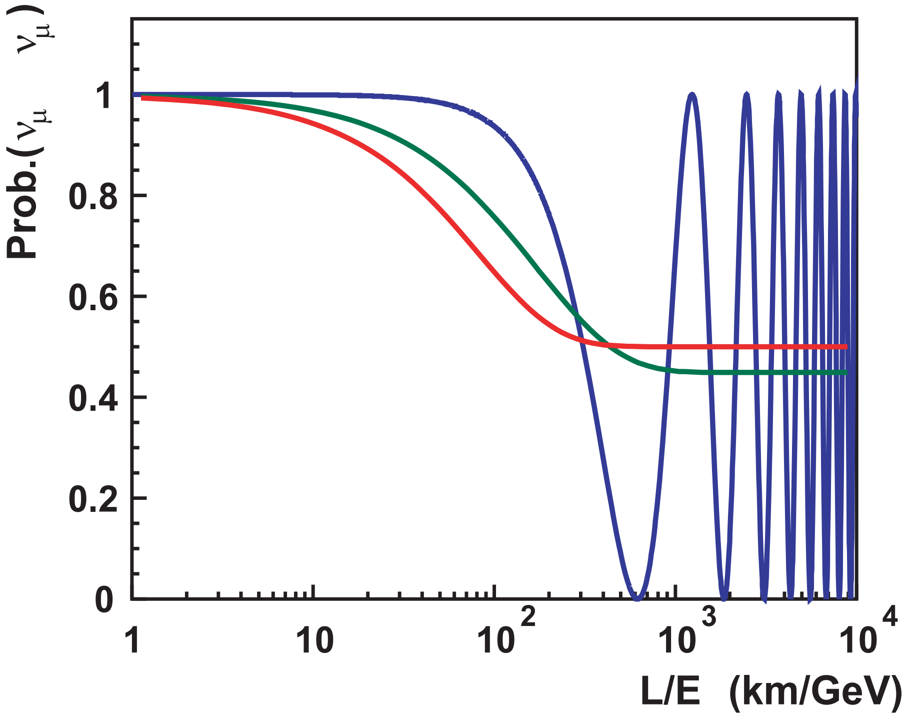
Atmospheric neutrinos and confirmation of oscillations

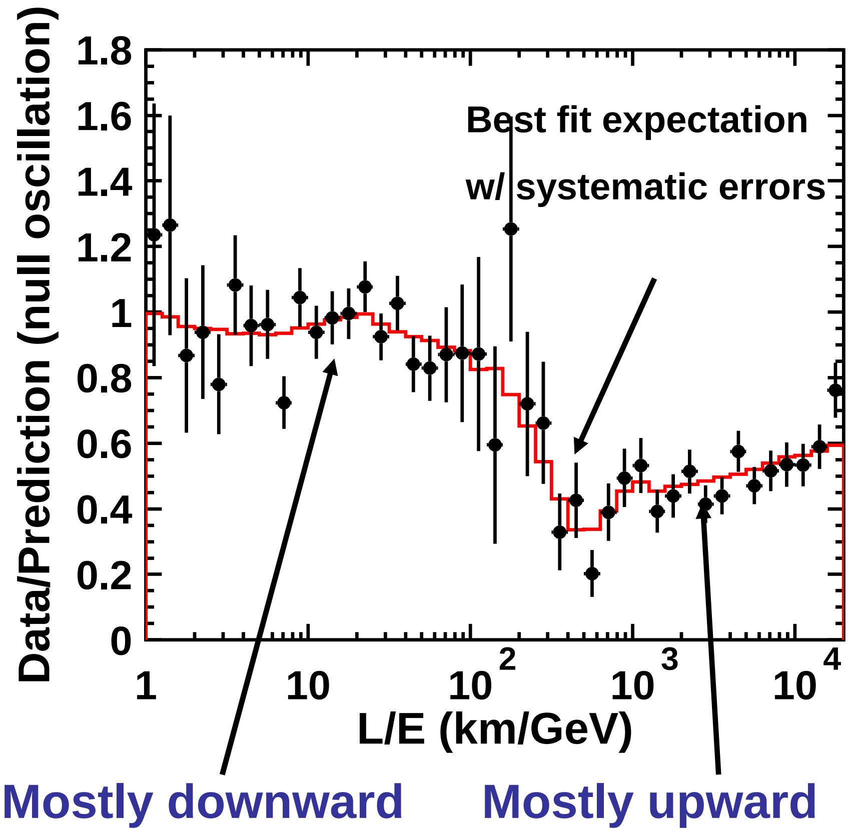
$\nu_\mu \leftrightarrow \nu_\tau$
2-flavor oscillations



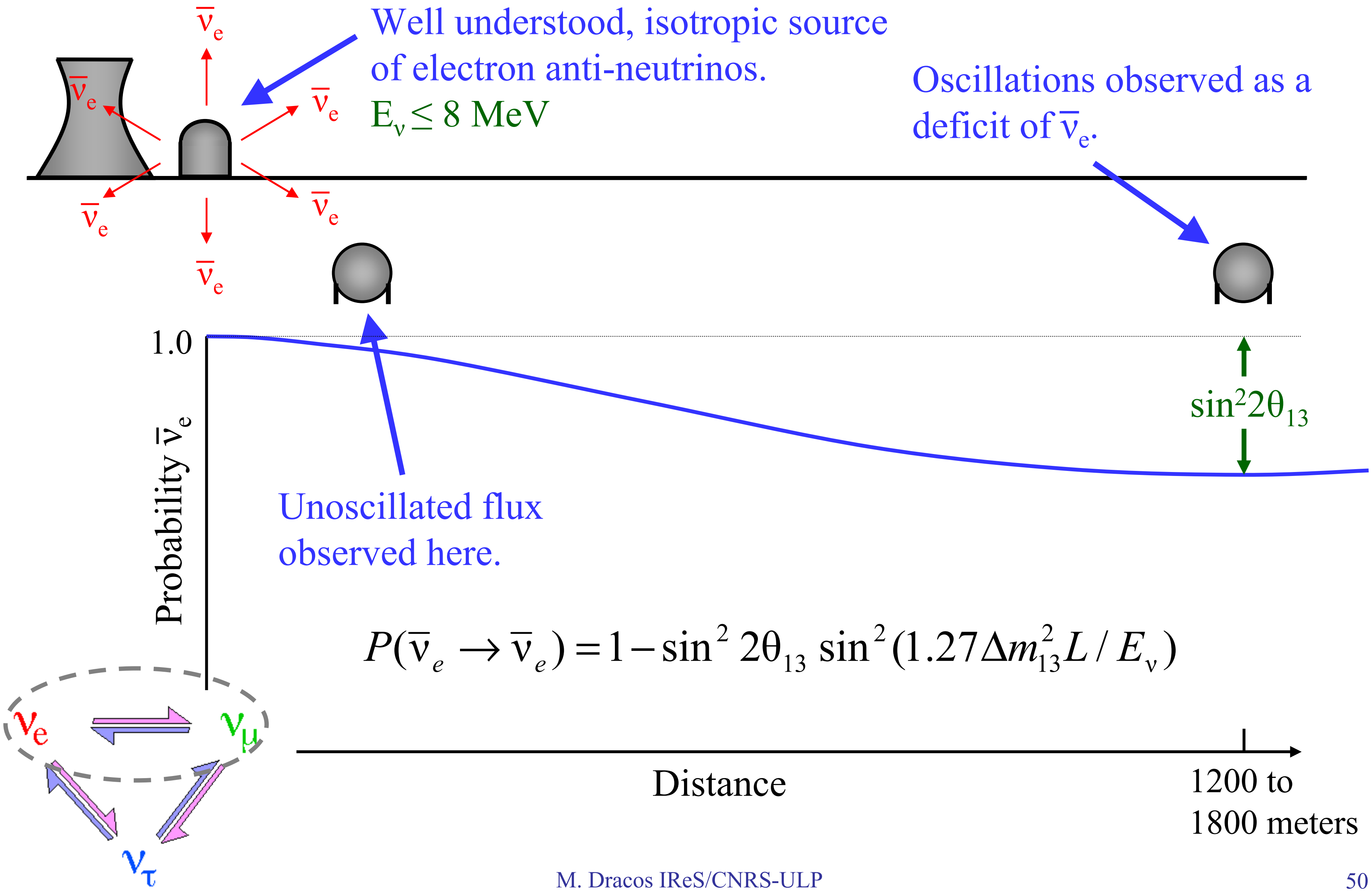


L/E Oscillation result





$\mathrm{Sin}^2 2\theta_{13}$ and Reactor Experiments



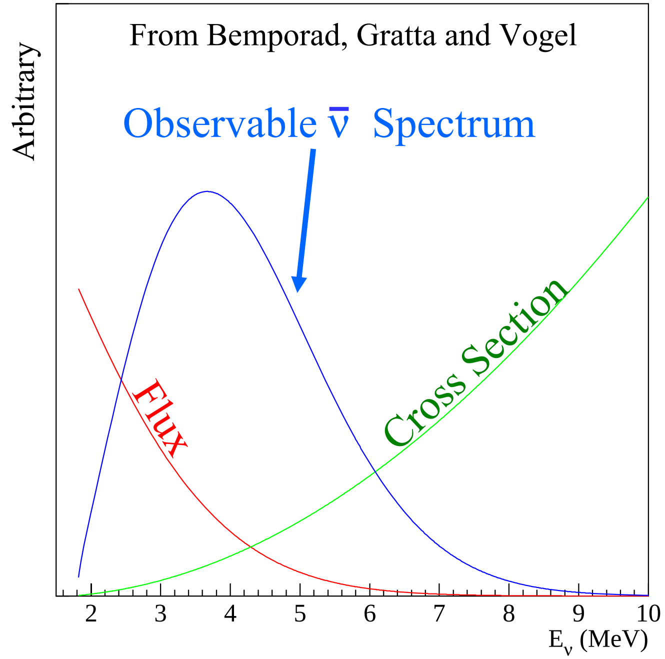
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{13} L / E_\nu)$$

Nuclear Reactors as a Neutrino Source

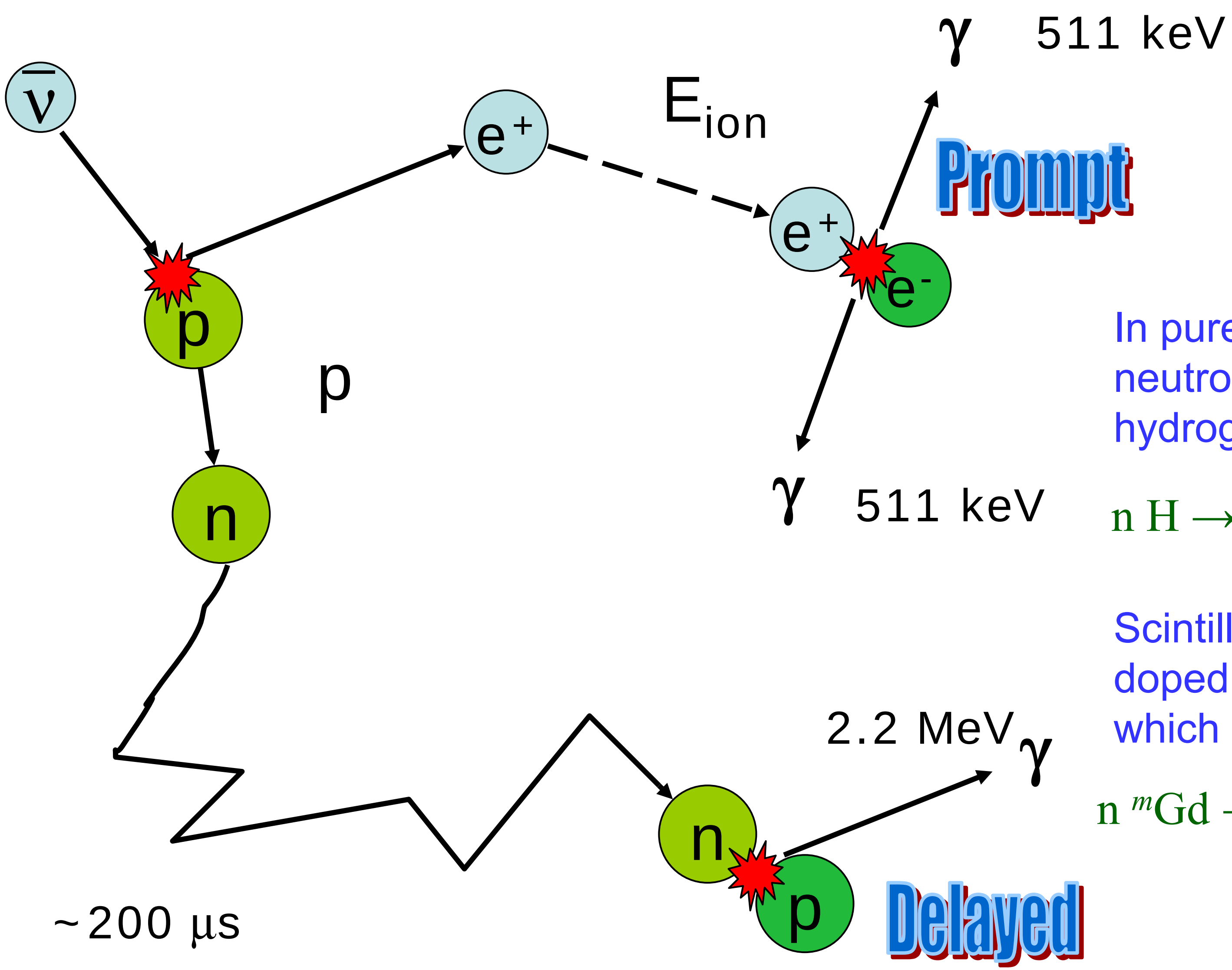
- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ deriving from the β-decay of the neutron-rich fission fragments.
- Each fission liberates about 200 MeV of energy and generates about 6 electron anti-neutrinos. So for a typical commercial reactor (3 GW thermal energy)

$$3\ \text{GW} \approx 2\times10^{21}\ \text{MeV/s} \rightarrow 6\times10^{20}\ \bar{\nu}_e/\text{s}$$

- The observable $\bar{\nu}$ spectrum is the product of the flux and the cross section.
- The spectrum peaks at ~3.7 MeV.



Inverse Beta Decay



In pure scintillator the neutron would capture on hydrogen

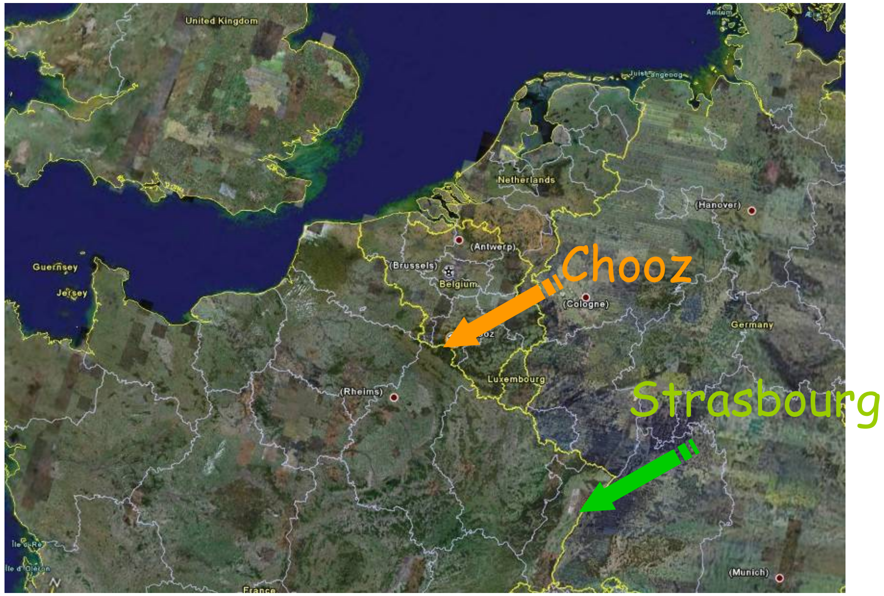
$$n\,H \rightarrow D\,\gamma \;\; (2.2 \text{ MeV})$$

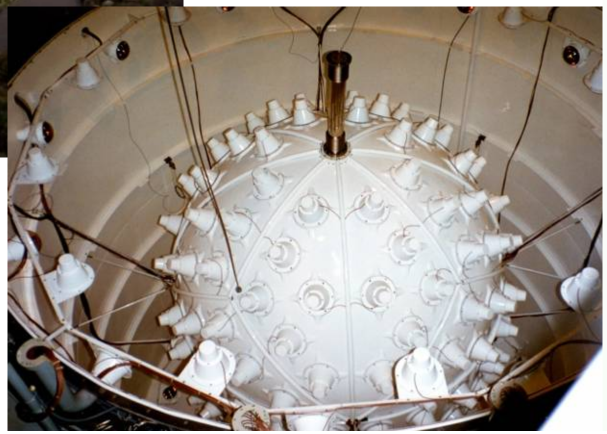
Scintillator very often is doped with gadolinium which enhances capture

$$n\,{}^{m}Gd \rightarrow {}^{m+1}Gd\ \gamma\text{'s}\ (8 \text{ MeV})$$

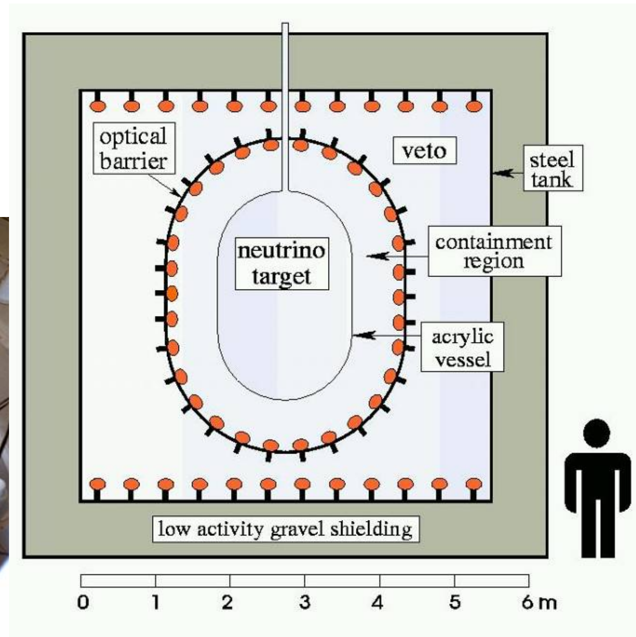
CHOOZ detector

- Site: CHOOZ reactor, Ardennes (France)
- 2 cores: 2x4200 MW
- Depth: 300 mwe
- 5 tons of liquid scintillator (gadolinium loaded)
- <L> ~ 1 km



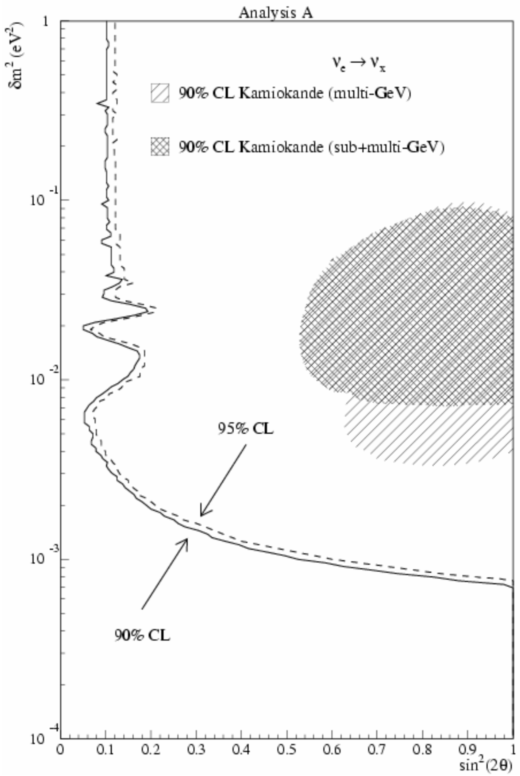


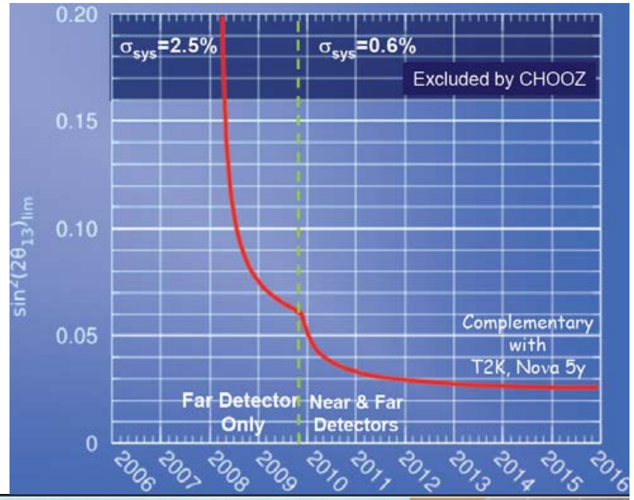
5-ton target



CHOOZ detector

future (>2008)

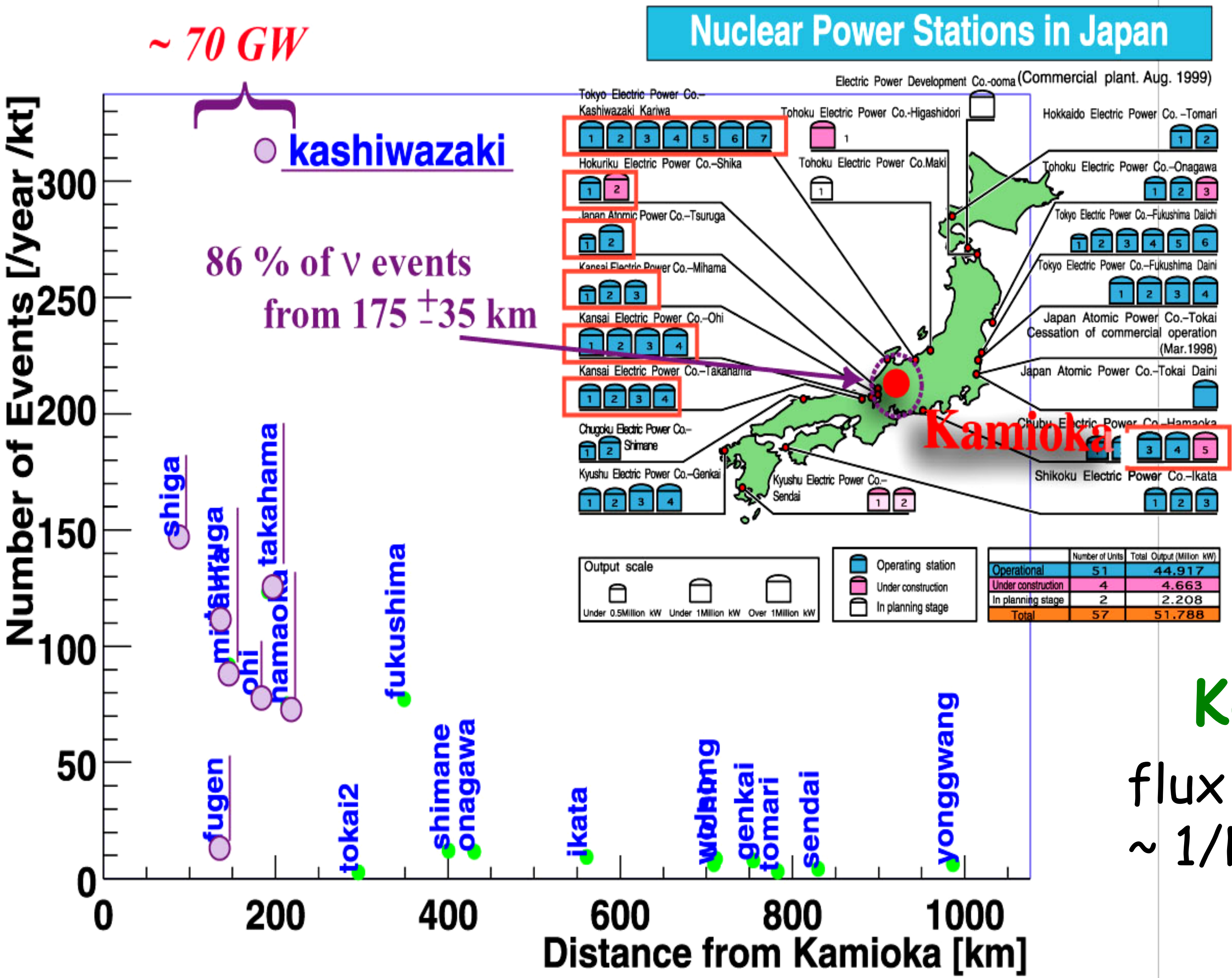




•Exclusion $\nu_\mu \rightarrow \nu_e$: $\Delta m^2_{sol} < 7\times10^{-4}$ eV^2 (90% CL)
Best constraint on $\sin^2(2\theta_{13}) < 0.14$

Reactor experiments

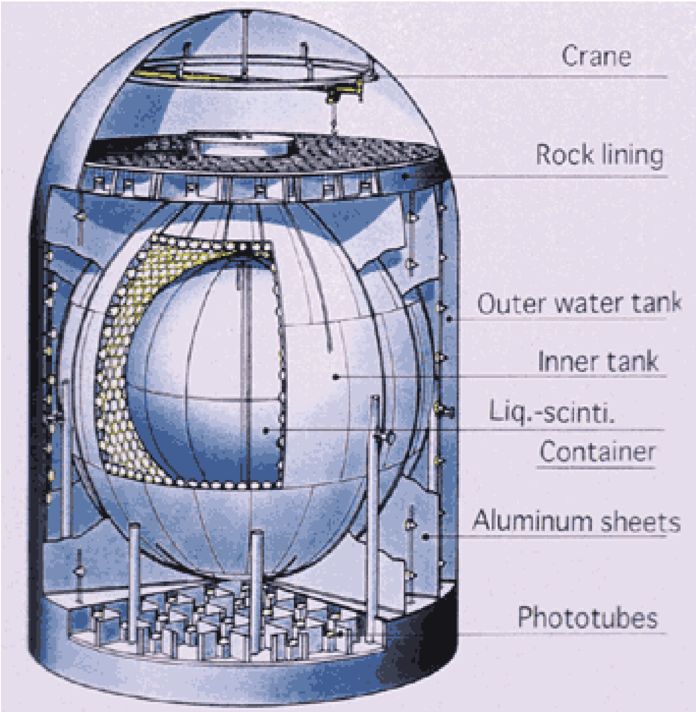
20 % of world nuclear power



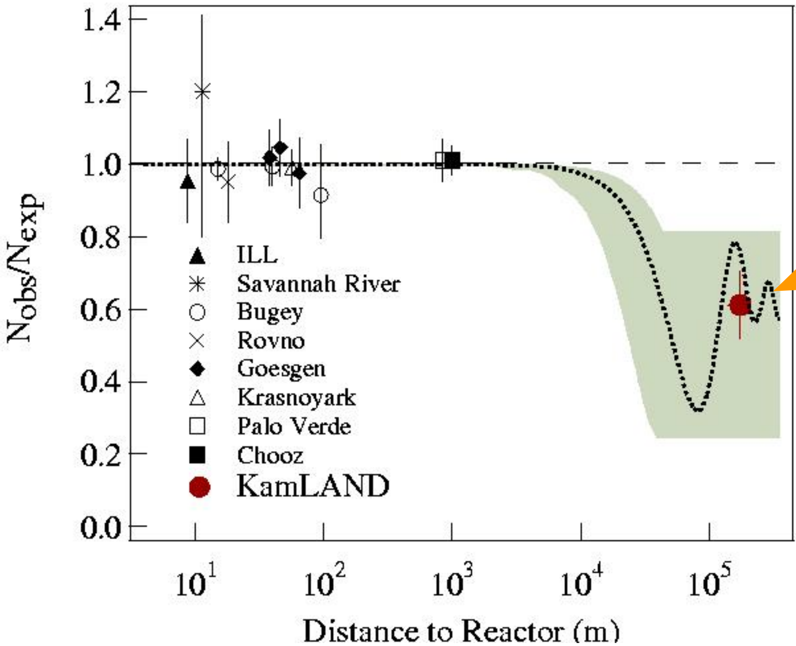
KamLAND

flux $\sim 1/R^2$

KamLAND detector

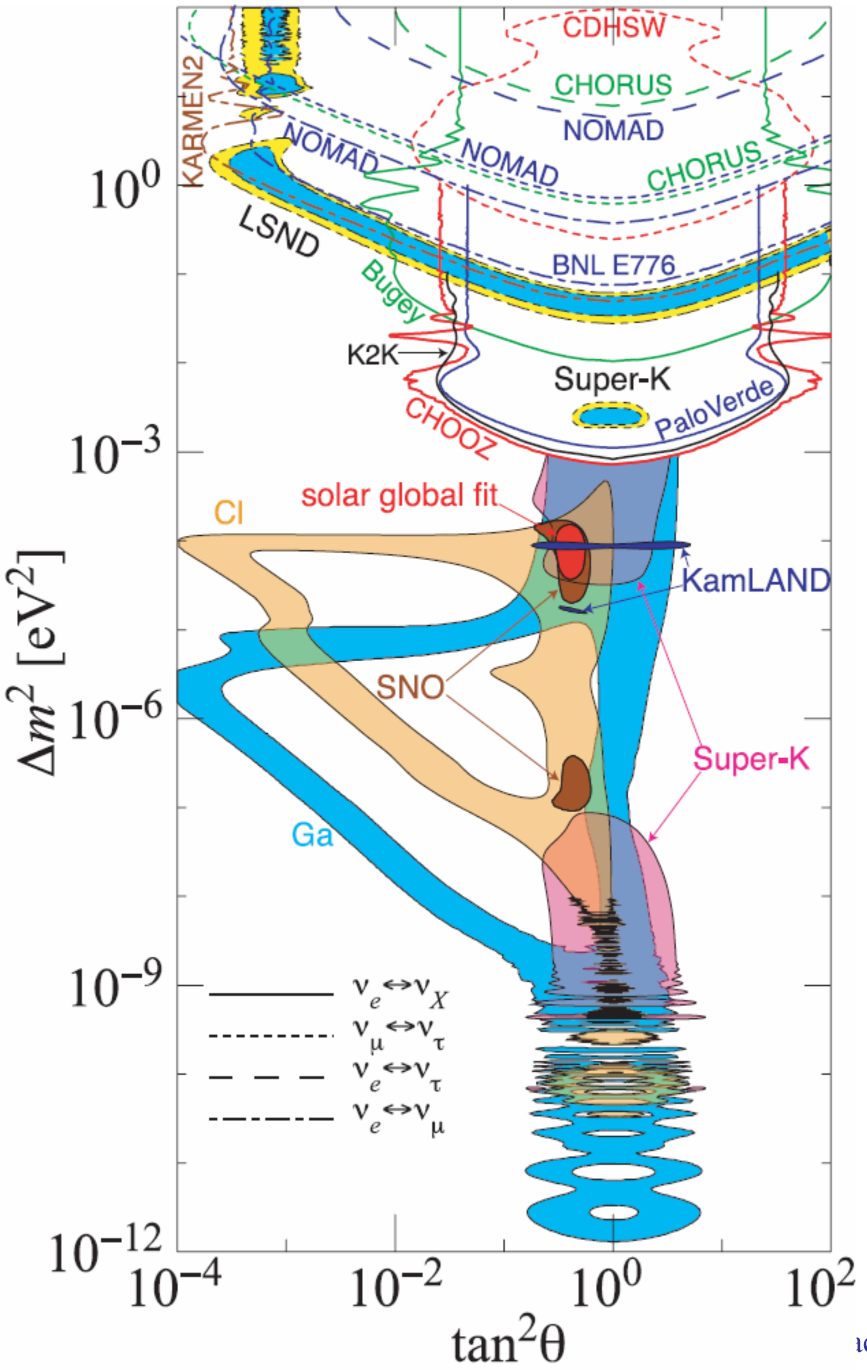


- external container filled with 3.2 ktons of water
- inner spherical container filled with 2 ktons of mineral oil
- inside a transparent baloon filled with **1 kt of liquid scintillator**
- 2100 photomultipliers to measure scintillation light
- located in Kamioka mine at **depth of 1 km**



compatible with oscillation hypothesis

Proposed Reactor Neutrino Experiments



Combined results from all experiments

from solar neutrinos

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$

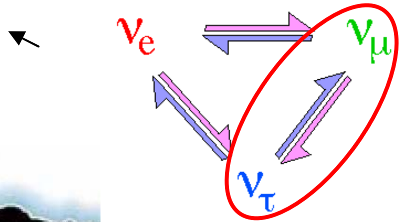
from atmospheric neutrinos and neutrino beams

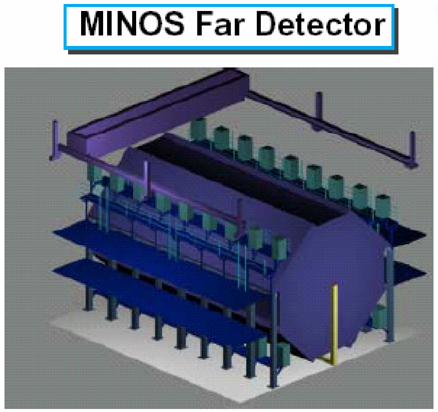
$1.9\times10^{-3} < \Delta m^2_{23} < 3.0\times10^{-3}$ eV^2
$0.90 < \sin^2 2\theta_{23}$ @ 90% C.L.

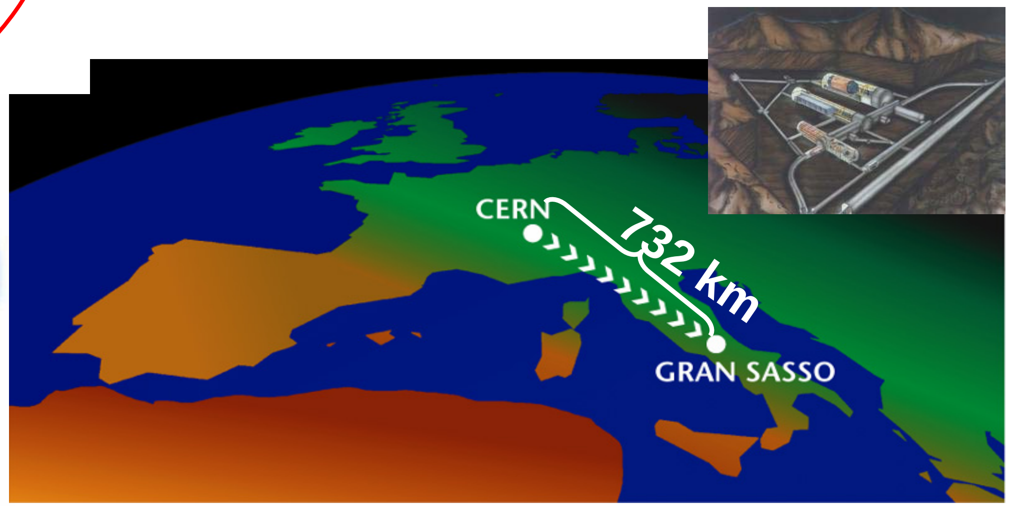
from reactors

$\sin^2 2\theta_{13} < 0.15$

Long Base Line Experiments







Numi ν_μ beam Fermilab-Minesota 730 km

disappearance experiment

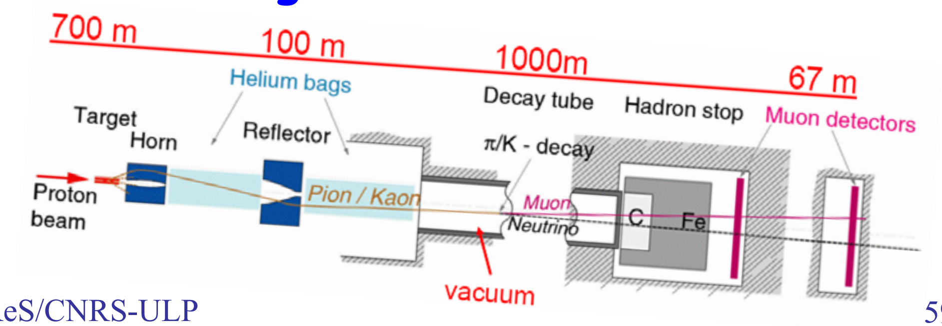
has just gave the first results…

$$|\Delta m^2_{32}| = 2.72^{+0.38}_{-0.25}\,(\text{stat}) \pm 0.13\,(\text{stat}) \times 10^{-3}\,\text{eV}^2$$
$$\sin^2 2\theta_{23} = 1.00\,_{-0.13}\,(\text{stat}) \pm 0.04\,(\text{syst})$$

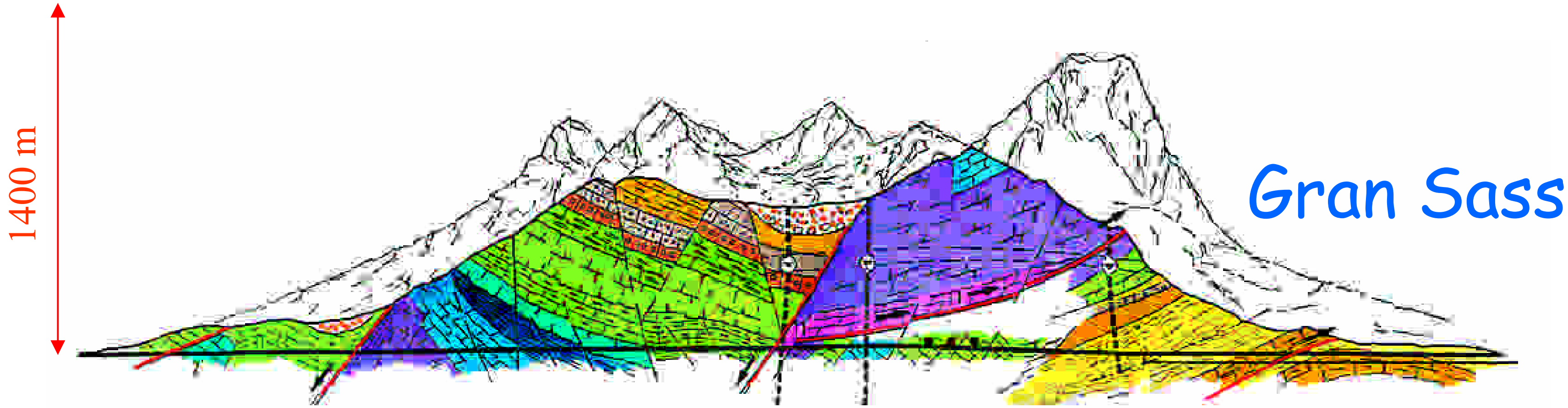
CNGS ν_μ beam CERN-Gran Sasso 732 km

first appearance experiment

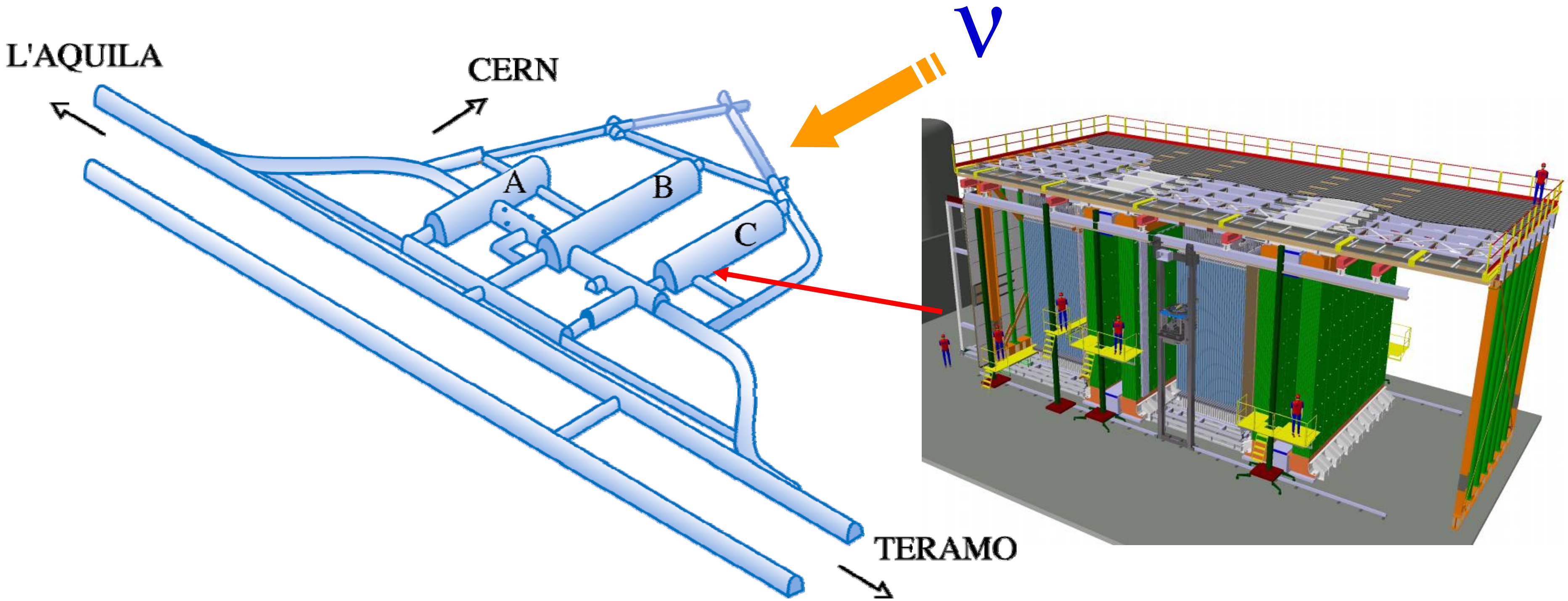
is starting now…



The OPERA detector



Gran Sasso

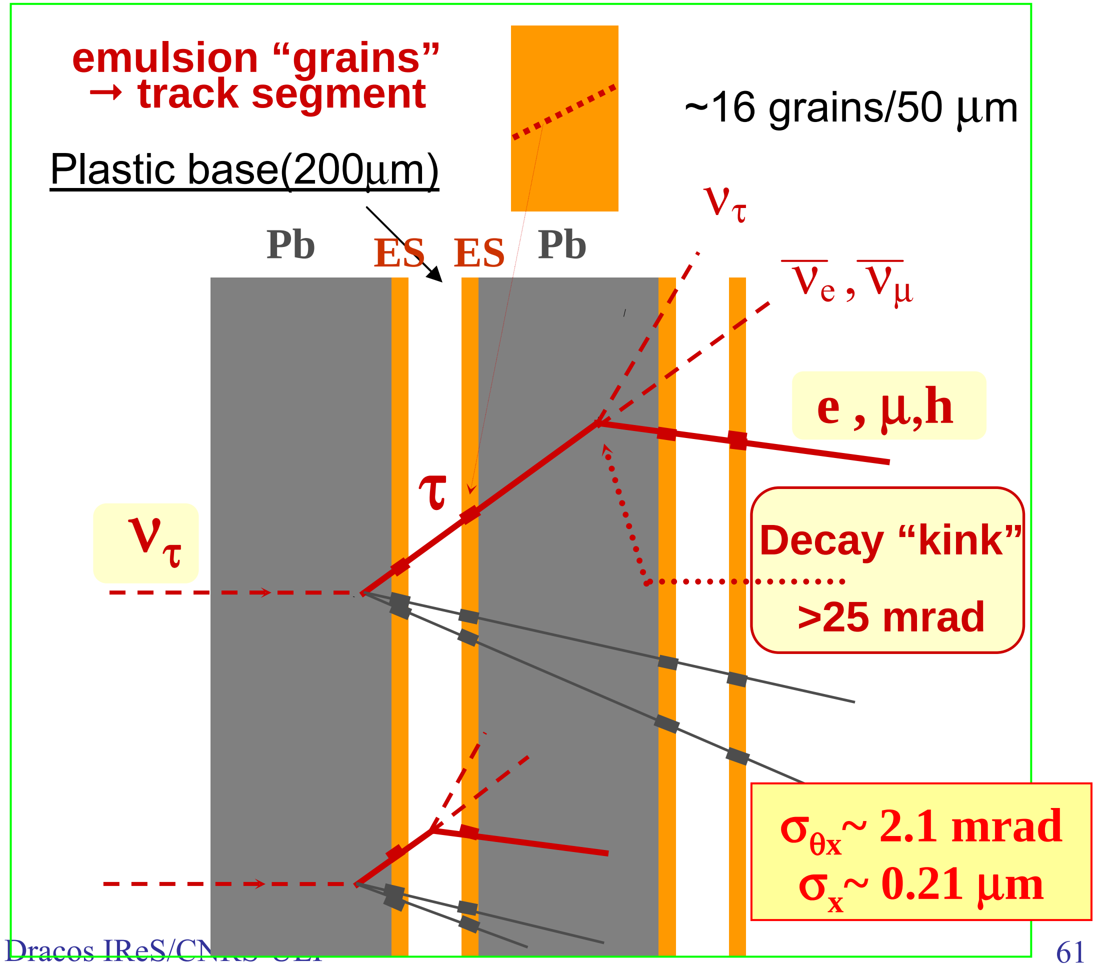


OPERA experiment

μm resolution
⇒ photographic emulsions (DONUT)

Large target mass
⇒ lead materials

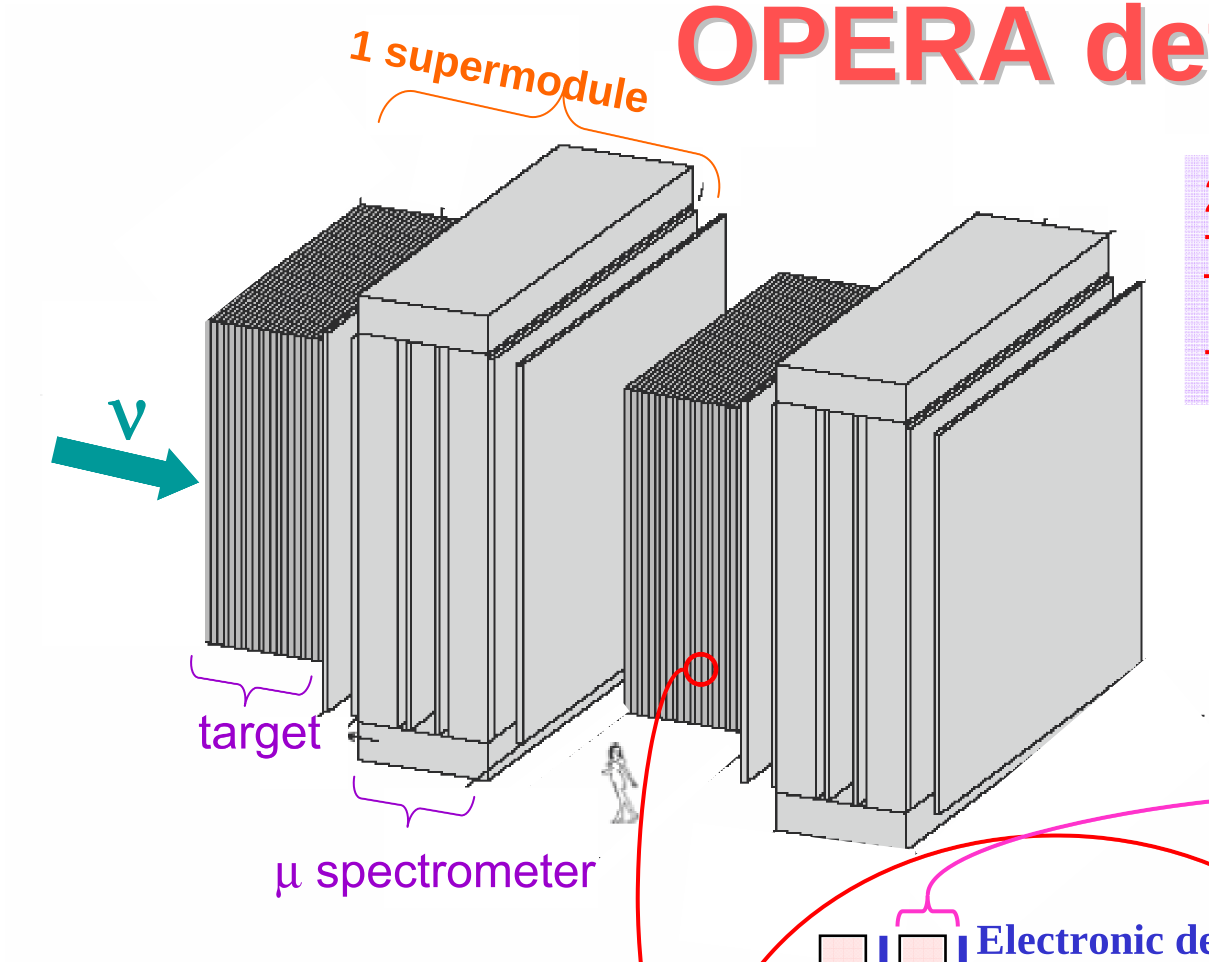
⇒Detector based on bricks :
Sandwich of 56 (1mm) Pb sheets
+56 emulsion layers

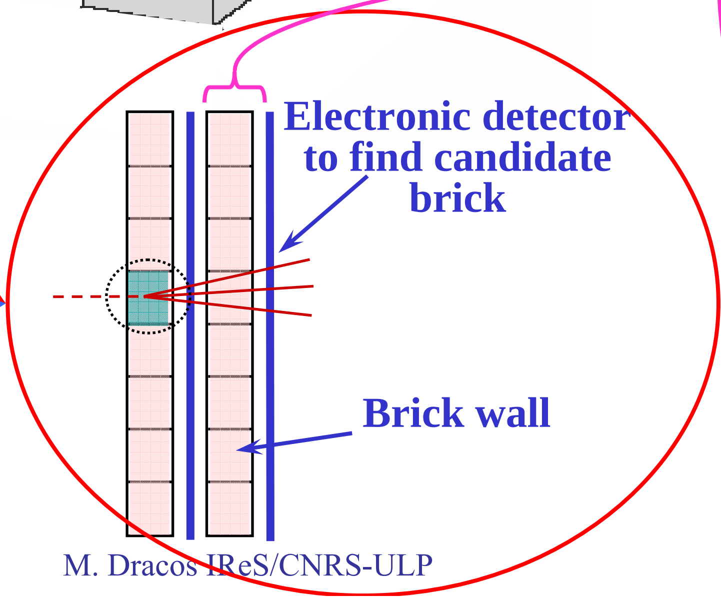


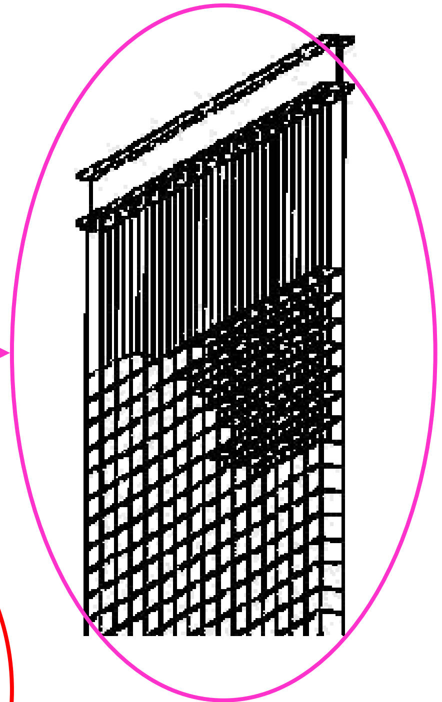
OPERA detector

Gran Sasso, Hall C

2 Supermodules
Target: **31 walls/supermodule**
with **3328 bricks** each
Target mass: 1.8 ktons





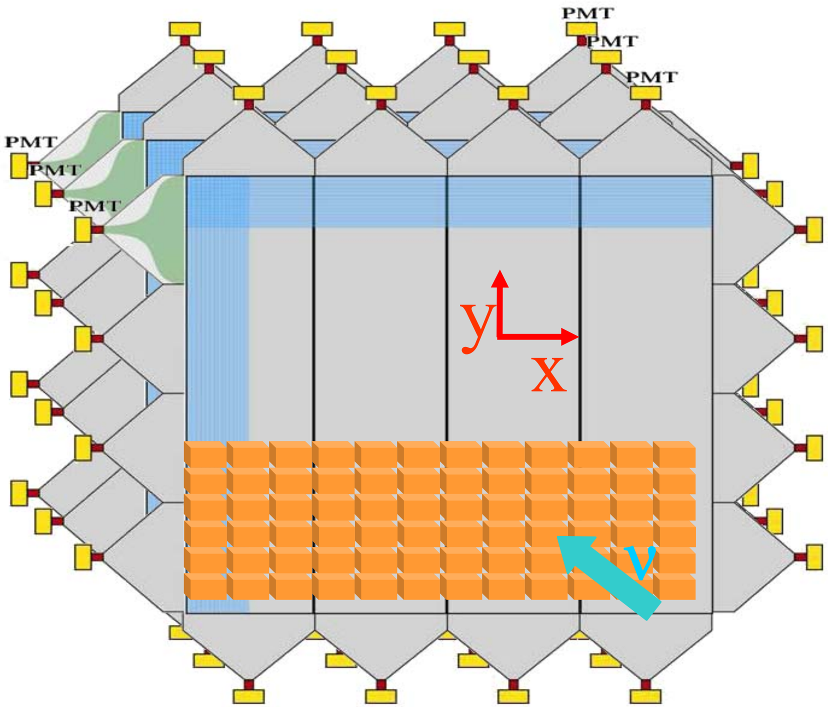


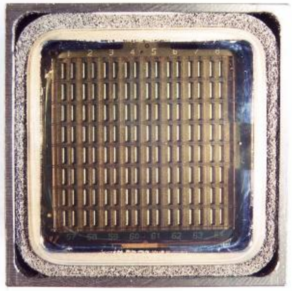
- **Robot to remove the candidate brick**
- **Scan by automatic microscope**

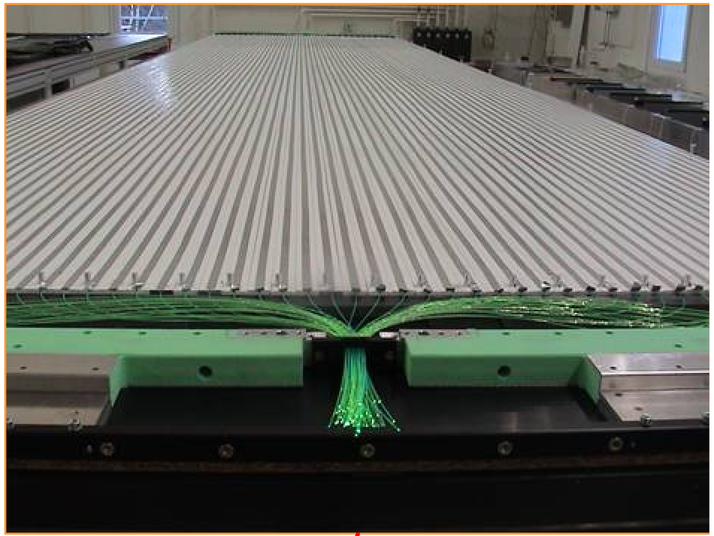
Target Tracker

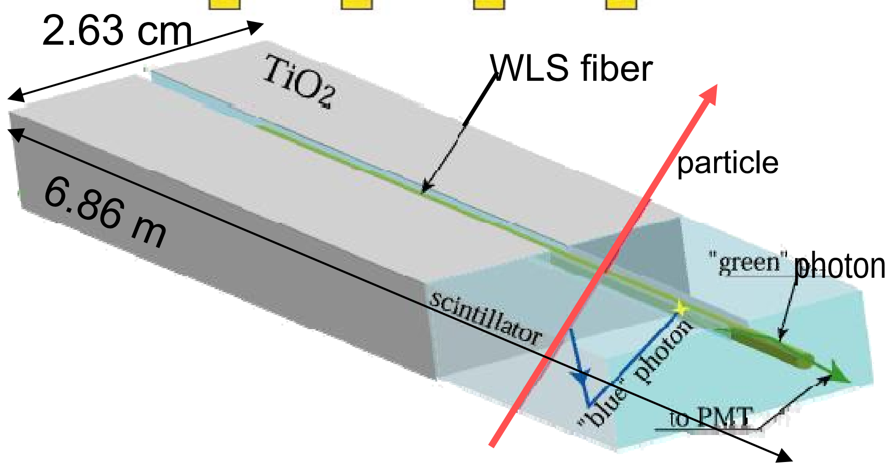
⇒ Find the right brick to extract

Plastic scintillator + wave length shifting fiber
+ 64 channel multi-anode Hamamatsu PM









- N_{pe}>5 p.e. for a mip (2.15 MeV)

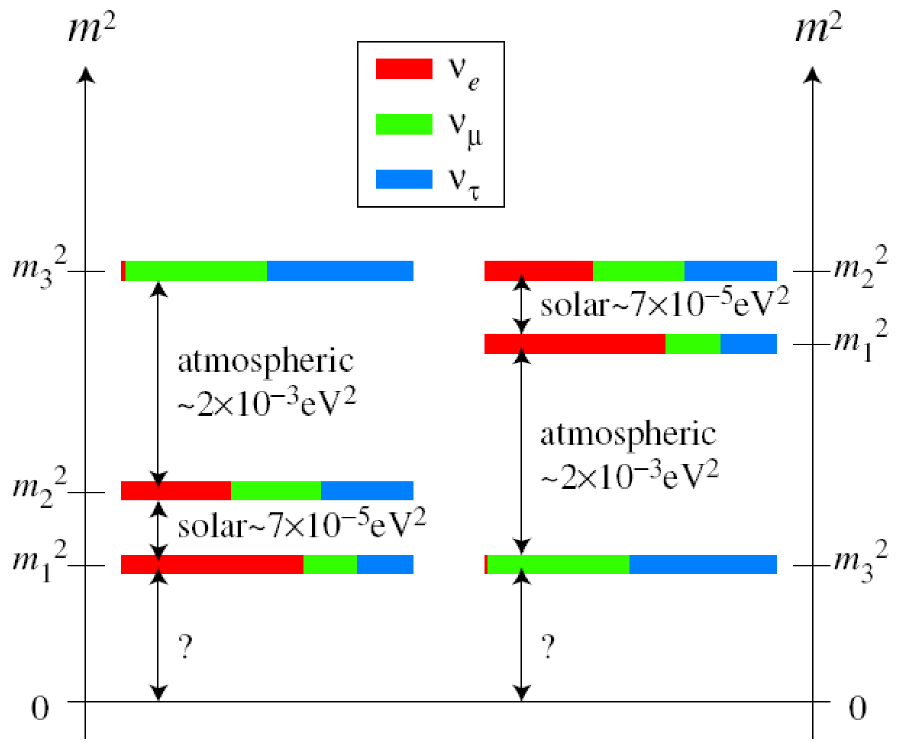
~99% detection efficiency ⇒ trigger

- brick finding: $\varepsilon_{brick} \sim 80\%$

Few of many pending questions

- θ_{13}?
- CP violation?
- normal or inverted hierarchy
- absolute masses?

...



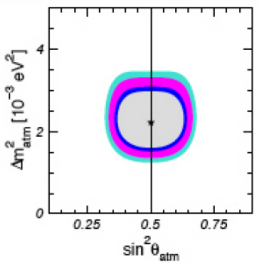
Future Neutrino Oscillation Projects

(mainly to discover $\nu_e \leftrightarrow \nu_\mu$ oscillation and measure θ_{13})

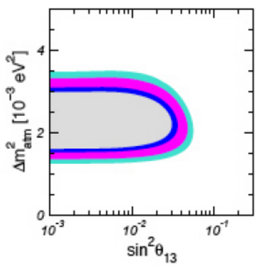
T2K

$$|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$$

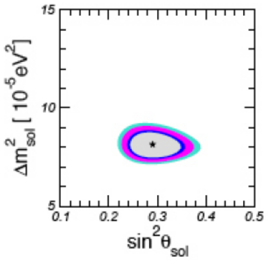
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



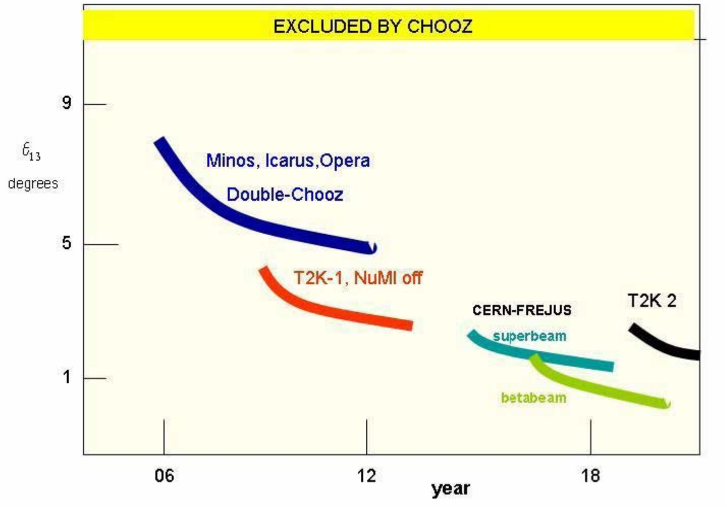
atmospheric + K2K
$|\Delta m^2_{31}|$

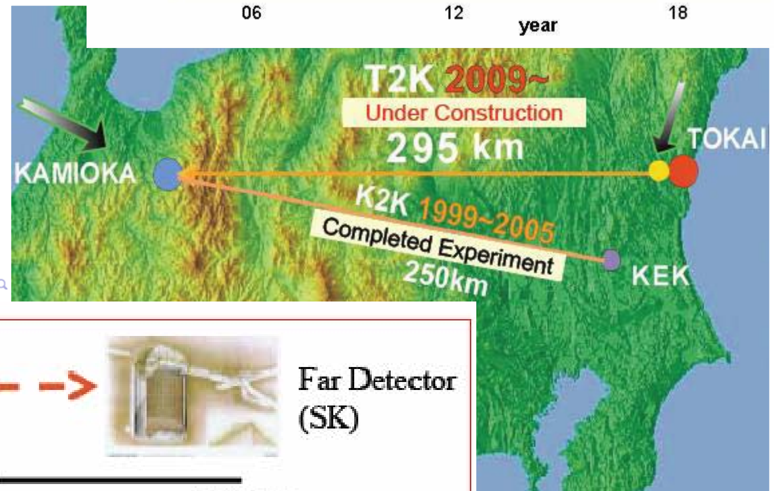


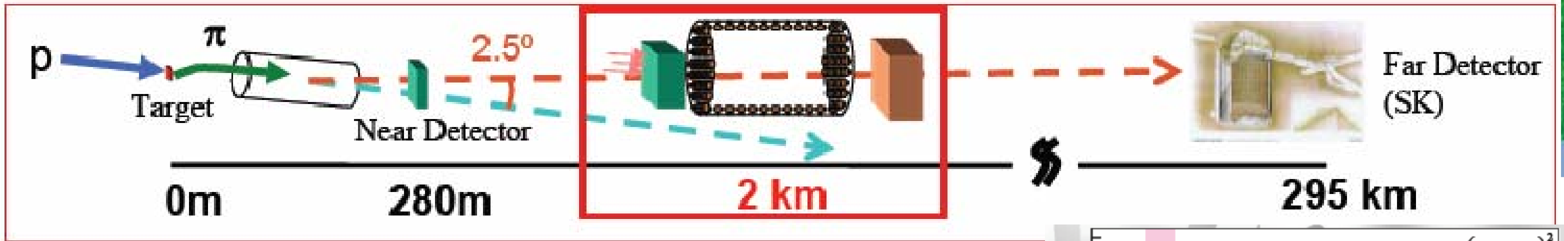
CHOOZ



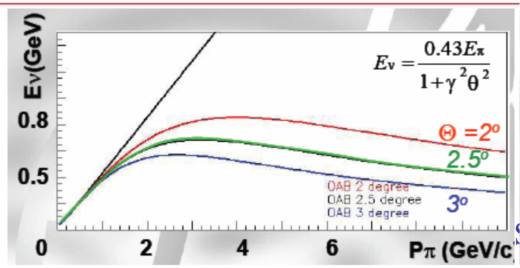
solar + KamLAND
Δm^2_{21}

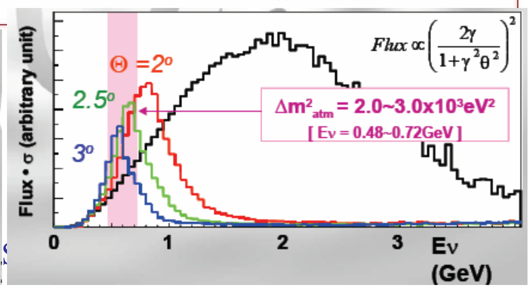




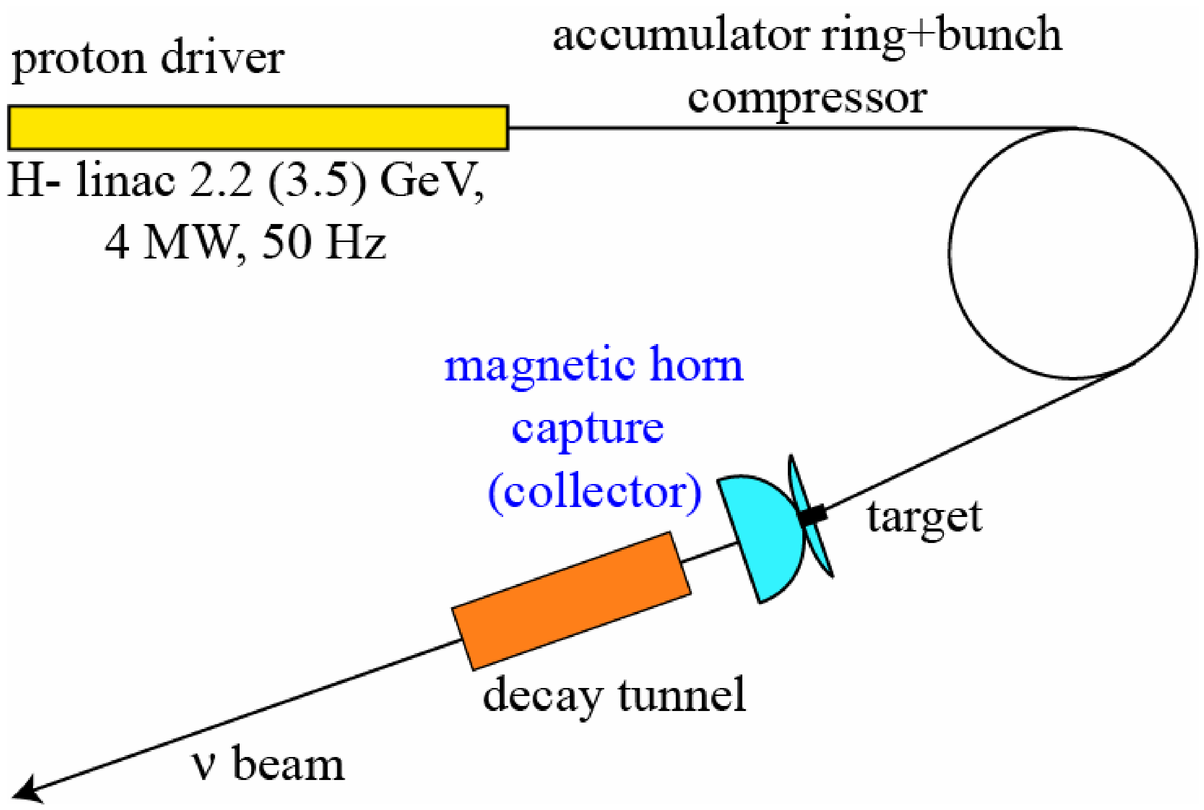


Very intense proton beam (0.7 MW)
Off-axis (2-3 deg.)
$< E >$ 0.7 GeV





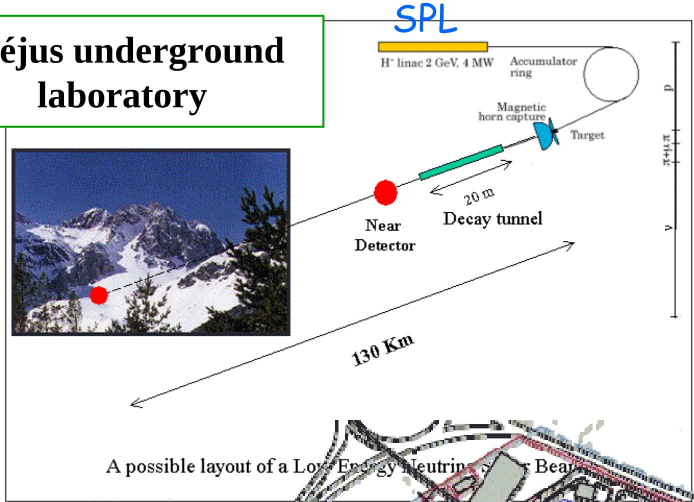
Super-Beams

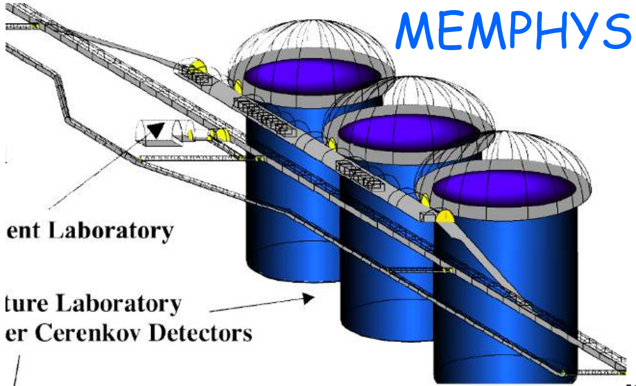


~300 MeV ν_μ Neutrinos
small contamination
from ν_e (no K at 2 GeV!)

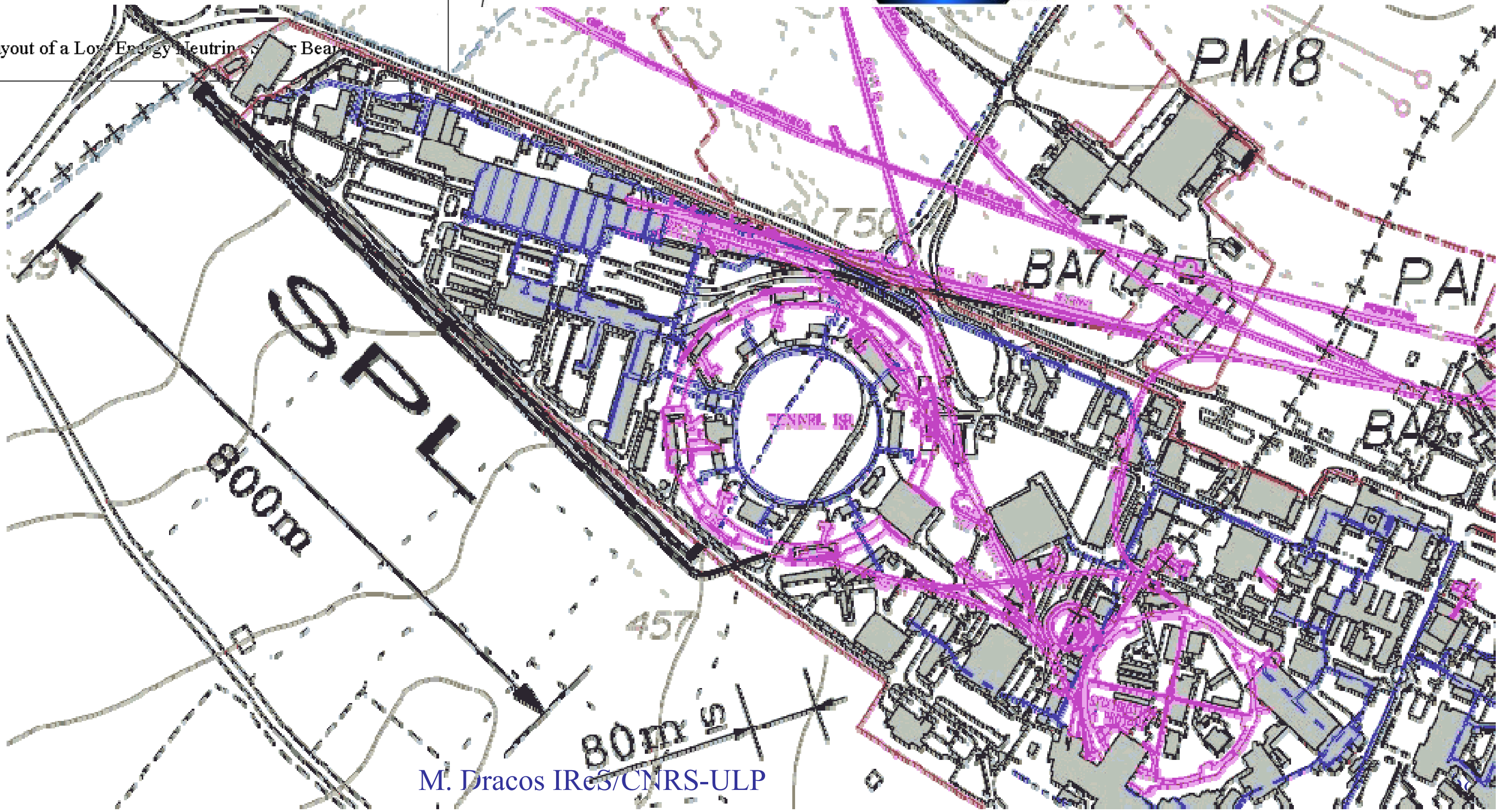
Super-Beam project at CERN

Fréjus underground laboratory





Megaton Cerenkov Detector
also : proton decay, supernovae, solar and atmospheric neutrinos.

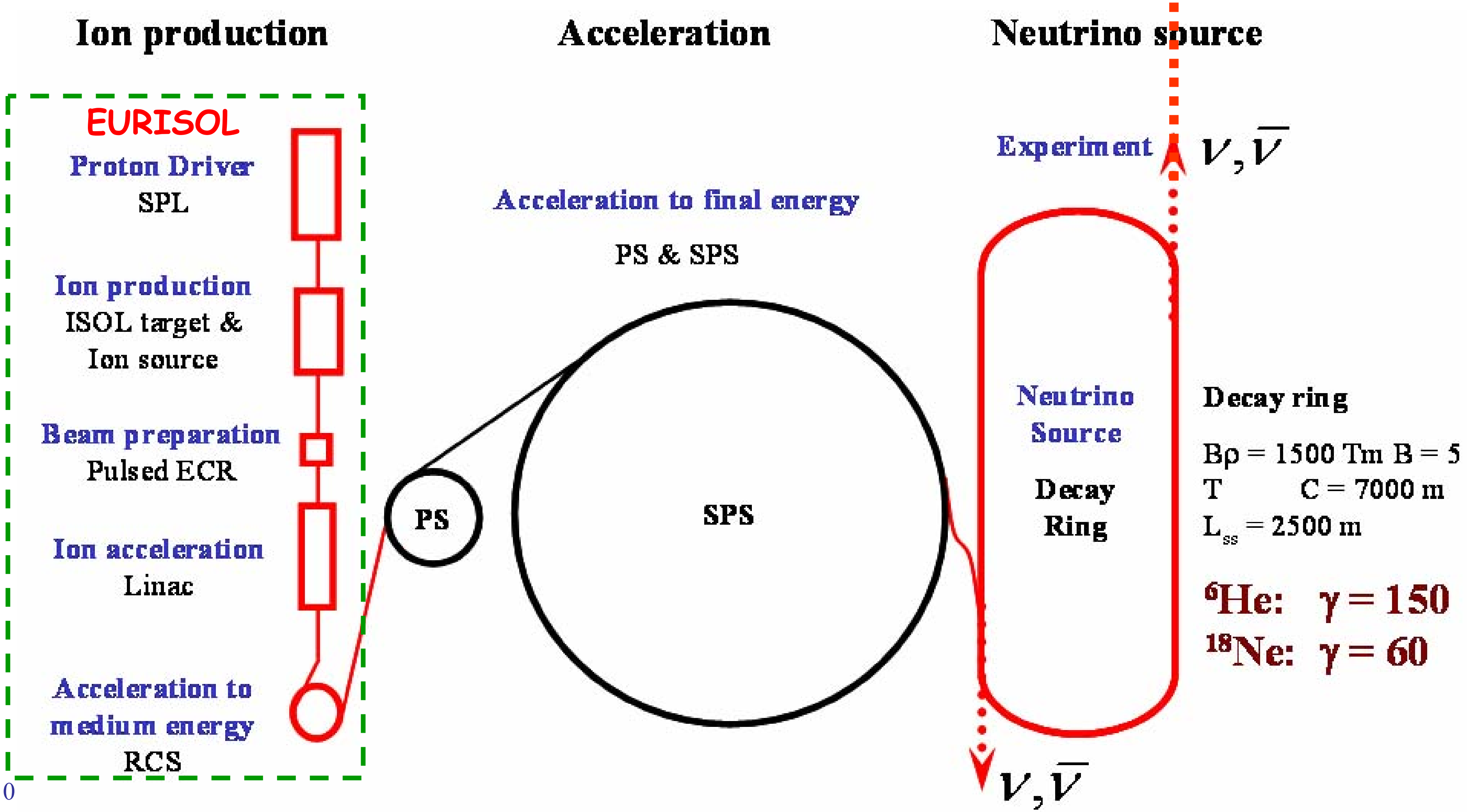


Beta-Beams

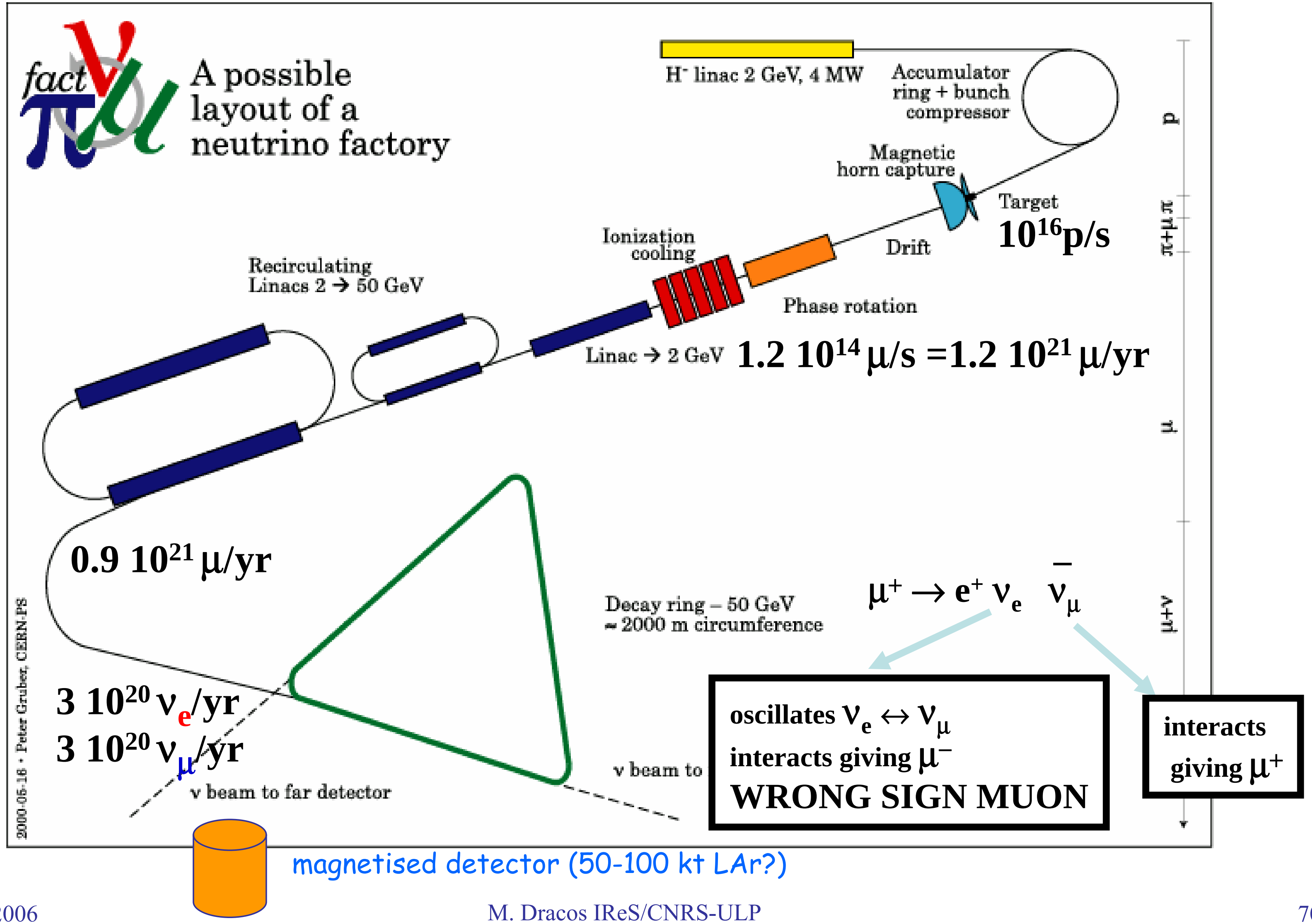
Detector at Fréjus

Same detector than for SB !

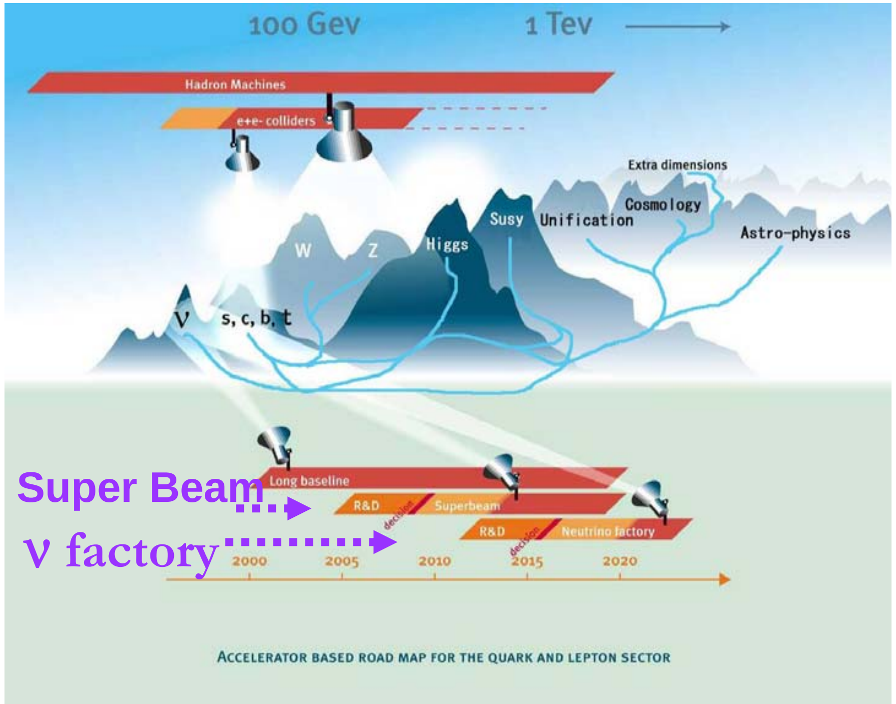
Accumulate ^{18}Ne, ^{6}He to produce pure beams of ν_e et $\bar{\nu}_e$

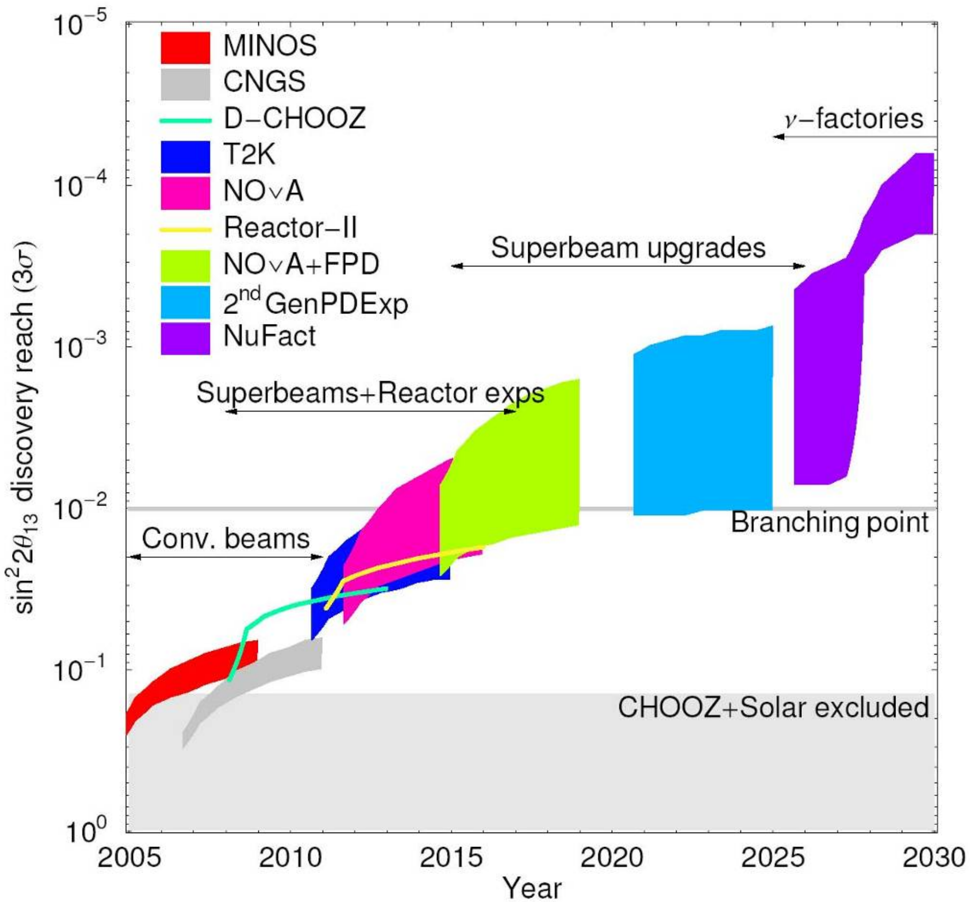


Neutrino Factory at CERN



Future Neutrino Facilities





Summary

- **Quantum Mechanics predict particle oscillations,**
- **Neutrino oscillations established,**
- **Many questions pending like, absolute neutrino masses, why so small masses, how small is θ_{13} etc…,**
- **Future experiments will try to answer the main questions and probably make unexpected discoveries,**
- **Neutrino physics is very fascinating.**

much more on neutrinos at neutrino oscillation industry:
http://www.hep.anl.gov/ndk/hypertext/nuindustry.html

Is that all?