NEUTRINO OSCILLATIONS

A.Meregaglia (IPHC / IN2P3-CNRS)

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OUTLINE

- **Introduction on neutrinos:**
  - What is a neutrino?
  - Neutrino sources and fluxes.
  - Interactions and detection techniques.
- **Neutrino oscillations:**
  - Phenomena of oscillation.
  - Vacuum Vs. matter.
- **Neutrino experiments:**
  - Experimental evidences.
- **Conclusions**

INTRODUCTION ON NEUTRINOS

WHAT IS A NEUTRINO?

- The neutrino is a particle "**invented**" by Pauli in **1930** in order to conserve the energy and the momentum in β decays.

β^- decay (before 1930)

$n \rightarrow p + e$

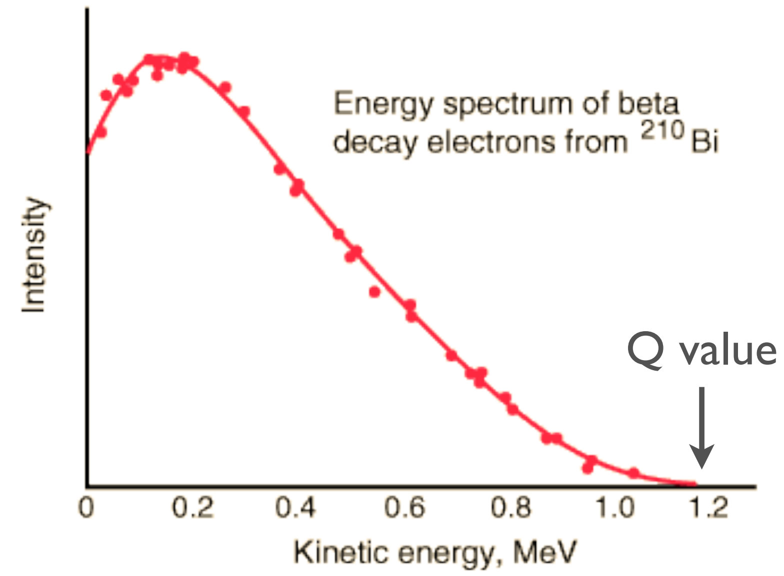
In 1930 β^- decay was the decay of an atomic nucleus (not known to contain or involve the neutron at the time)

Analytical calculation

2-body decay therefore the positron energy is fixed at the Q value of the reaction

$\neq$

Example of observed spectrum



β^- decay (after 1930)

$n \rightarrow p + e + \nu$

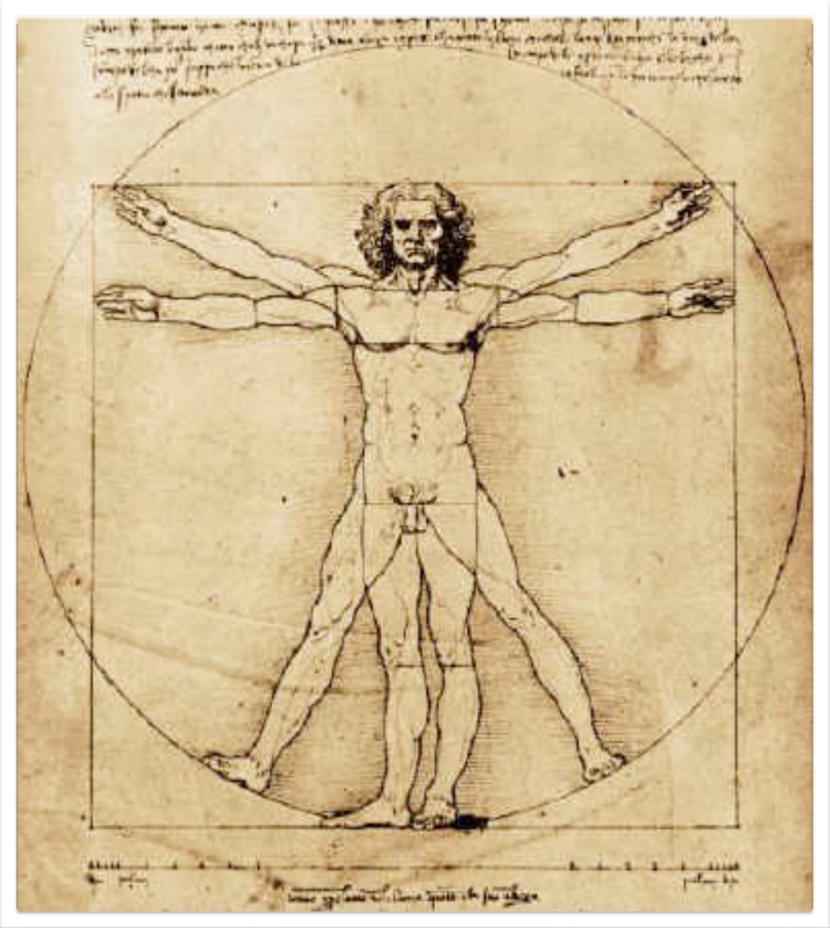
WHAT IS A NEUTRINO?

- The neutrino is a particle "**invented**" by Pauli in **1930** in order to conserve the energy and the momentum in β decays.
- This particle was **observed** for the first time by Cowan and Reines in **1956**.

Why did it take that long?

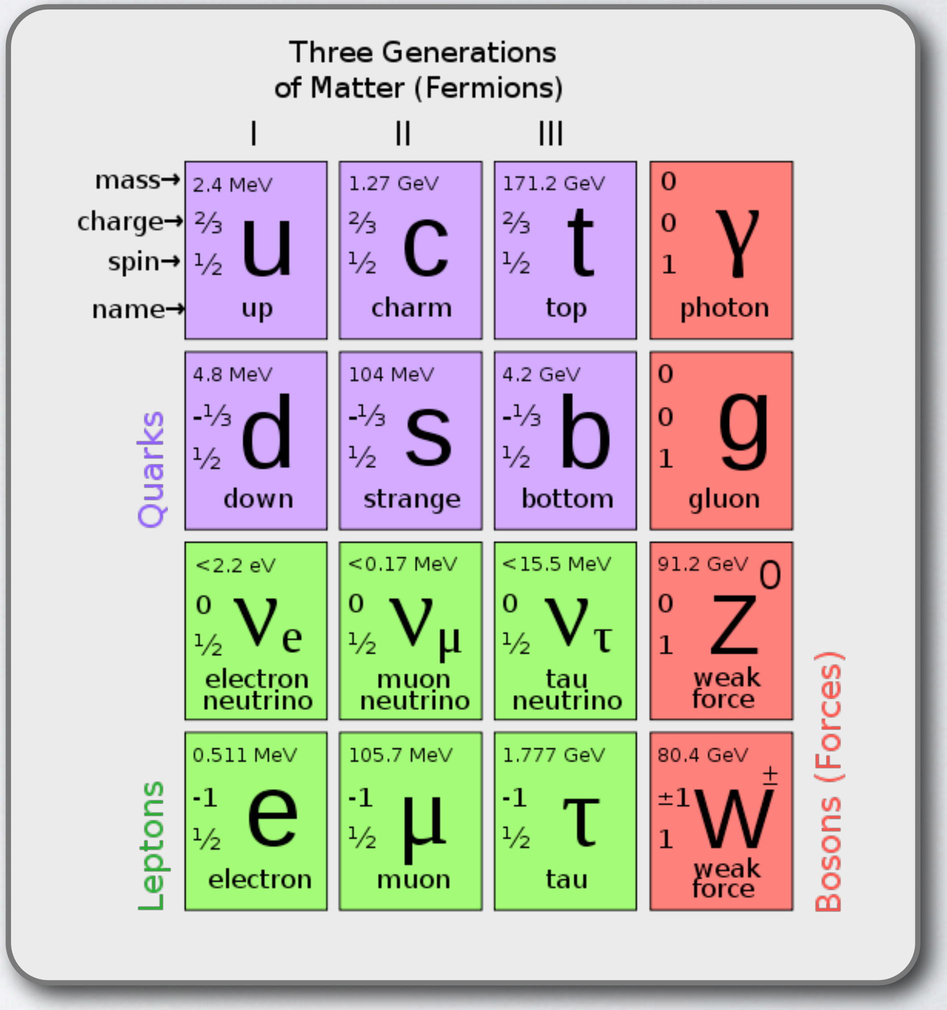
The interaction probability (cross section) is very low (order of 10^{-38} cm^2 at 1 GeV).

Every day 4×10^{19} ν pass through our body and on average only 1 interacts in our life



WHAT IS A NEUTRINO?

- The neutrino is a particle "**invented**" by Pauli in **1930** in order to conserve the energy and the momentum in β decays.
- This particle was **observed** for the first time by Cowan e Reines in **1956**.
- In **1962** it was discovered that neutrinos exist in (3) **different flavours**.
- In **2000** the last neutrino (ν_τ) foreseen in the Standard Model (SM) has been observed.
- Neutrinos have been assumed to be massless in the Standard Model, however strong evidences point to small but non zero values of the neutrino masses.



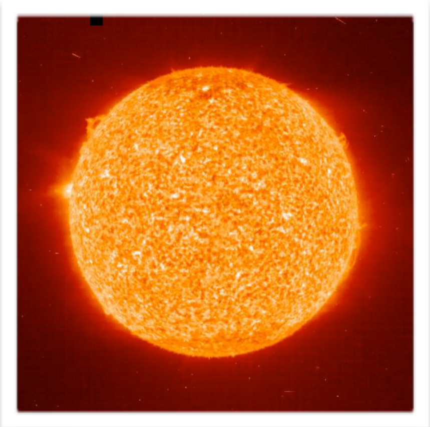
Three Generations of Matter (Fermions)

		I	II	III		
Quarks	mass→ charge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon	Bosons (Forces)
		4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon	
Leptons		<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force	
		0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force	

In this lecture we will discuss neutrino masses related to oscillations.
For a discussion on Dirac Vs Majorana and absolute masses see lecture by G.Drexlin.

NEUTRINO SOURCES

- There are many sources of neutrinos: they can be divided into **natural** (sun, natural radioactivity, etc.) and **human-made** (accelerators and reactors).



Solar ν

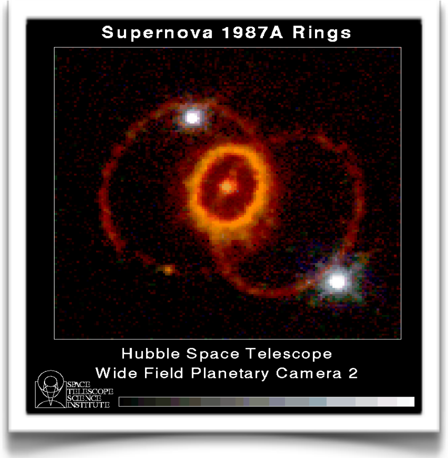
$6 \times 10^{10}\ \nu s^{-1} cm^{-2}$

on earth

Atmospheric ν

$1\ \nu s^{-1} cm^{-2}$

on earth



Supernova ν

Big Bang ν

($330\ \nu cm^{-3}$)

Accelerator ν

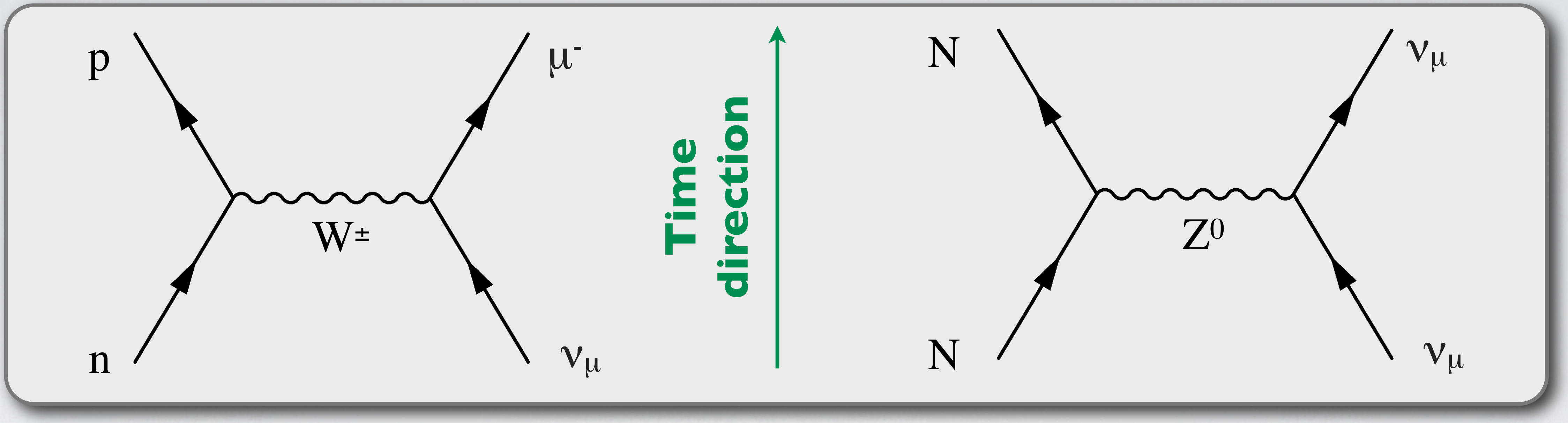
Reactor ν

$10^{21}\ \nu s^{-1}$

produced

NEUTRINO INTERACTION

- Neutrinos are subject only to **weak interaction**.
- The interaction is therefore given by the exchange of a **W** boson (**charge current** interaction) or a **Z** boson (**neutral current** interaction).



- The interactions can be described using some kinematical variables:

4-momentum transferred → $Q^2 = 4E_\nu E_\mu \sin^2(\boxed{\theta}/2)$

hadronic invariant mass → $W^2 + Q^2 = 2M\nu + \boxed{M^2}$

transferred energy → $\nu = E_{had} - M = E_\nu - E_\mu$

Angle between incoming neutrino and outgoing lepton

Nucleon mass

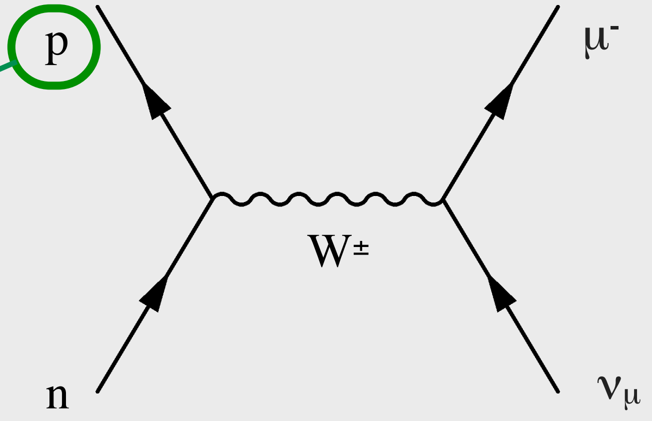
NEUTRINO INTERACTION

- The interactions can be divided into quasi-elastic (**QE**) and deep-inelastic (**DIS**). The intermediate regime is given by resonant interactions (**RES**).
- This classification has a strong impact what can be observed i.e. on the detection.

QE

The invariant mass is almost only the nucleon mass: W≈M

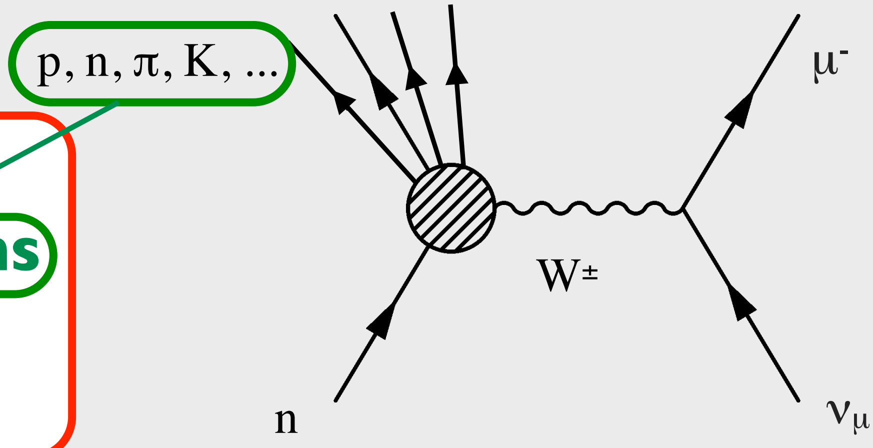
"soft collision": **only a nucleon** is emitted (before nuclear reinteractions)



DIS

The invariant mass is much larger than the nucleon mass: W>>M

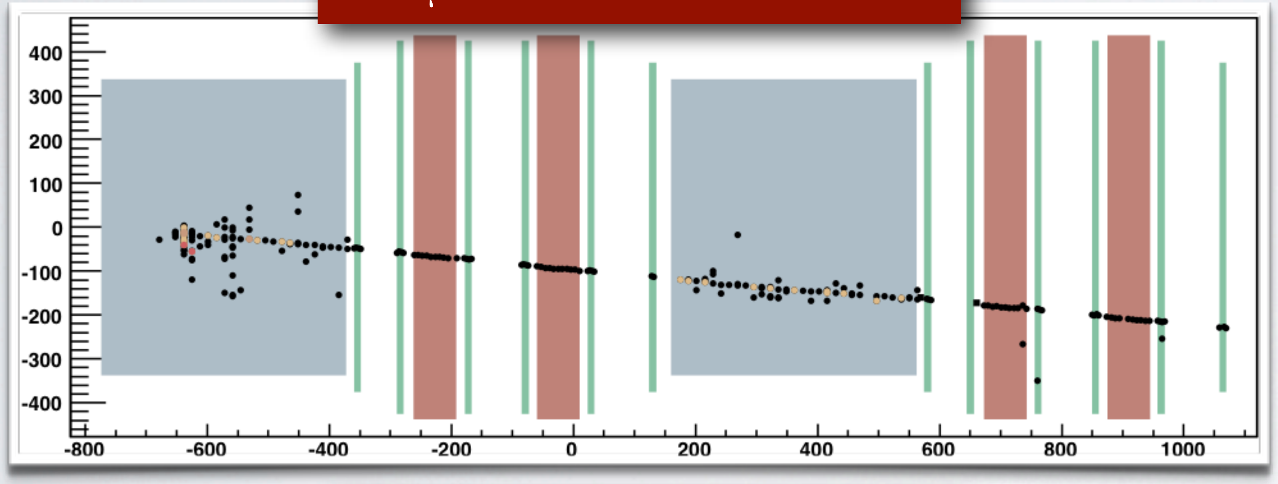
"hard collision": **many hadrons** are emitted



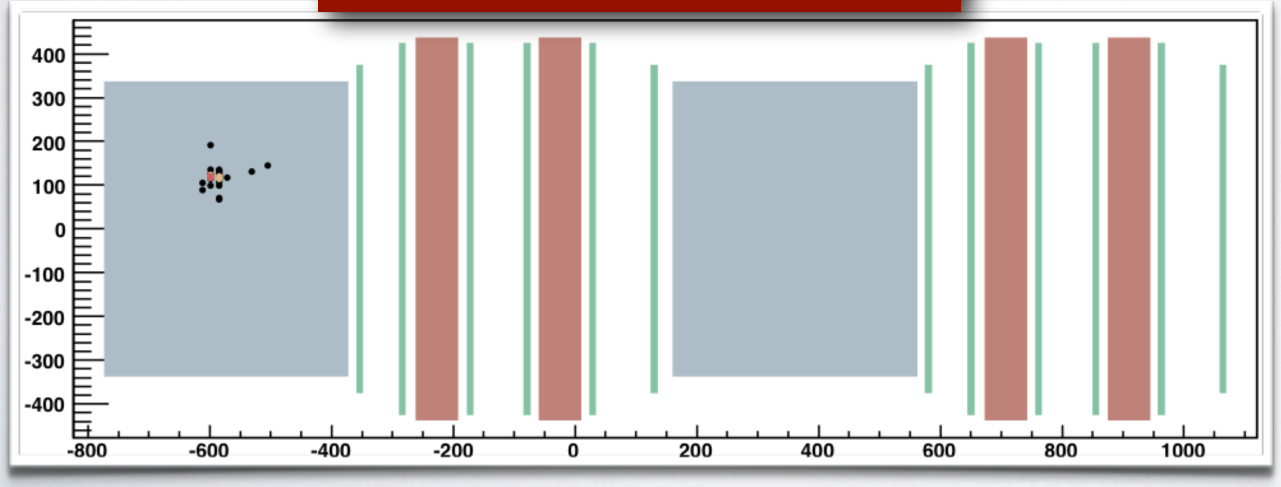
NEUTRINO DETECTION

- Neutrinos can be detected only looking at the products of their interactions.
- For **NC** events the **nucleon/hadronic shower** produced can be detected.
- For **CC** events both the **lepton** and the **nucleon/hadronic shower** can be measured.
- The resolutions, thresholds and types of measurement depend on the detector used.

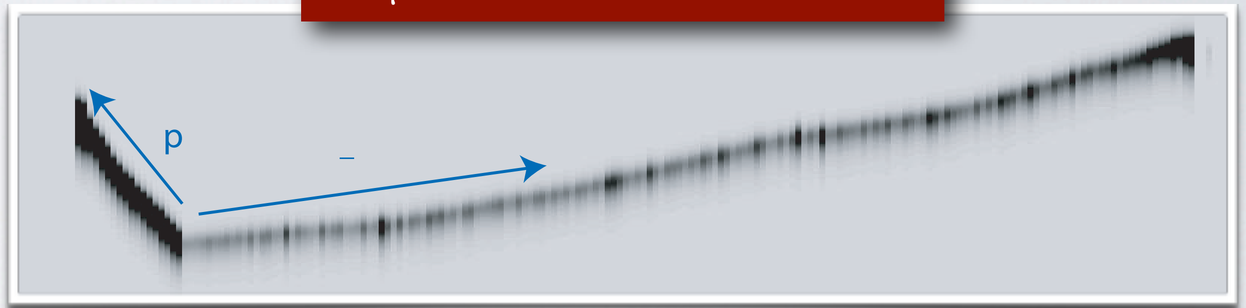
ν_μCC in OPERA



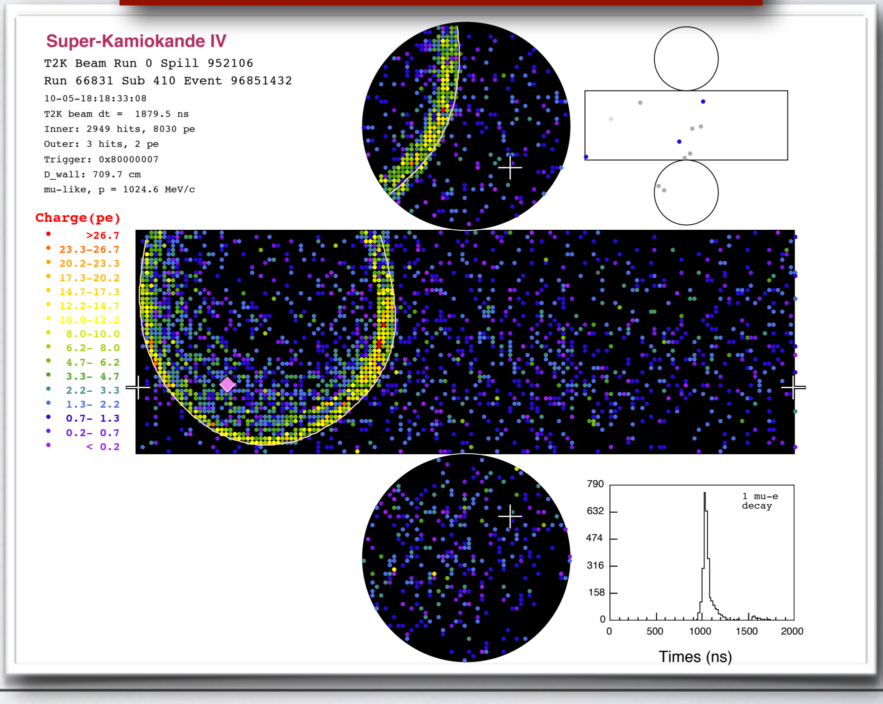
νNC in OPERA



ν_μCC in LAr TPC



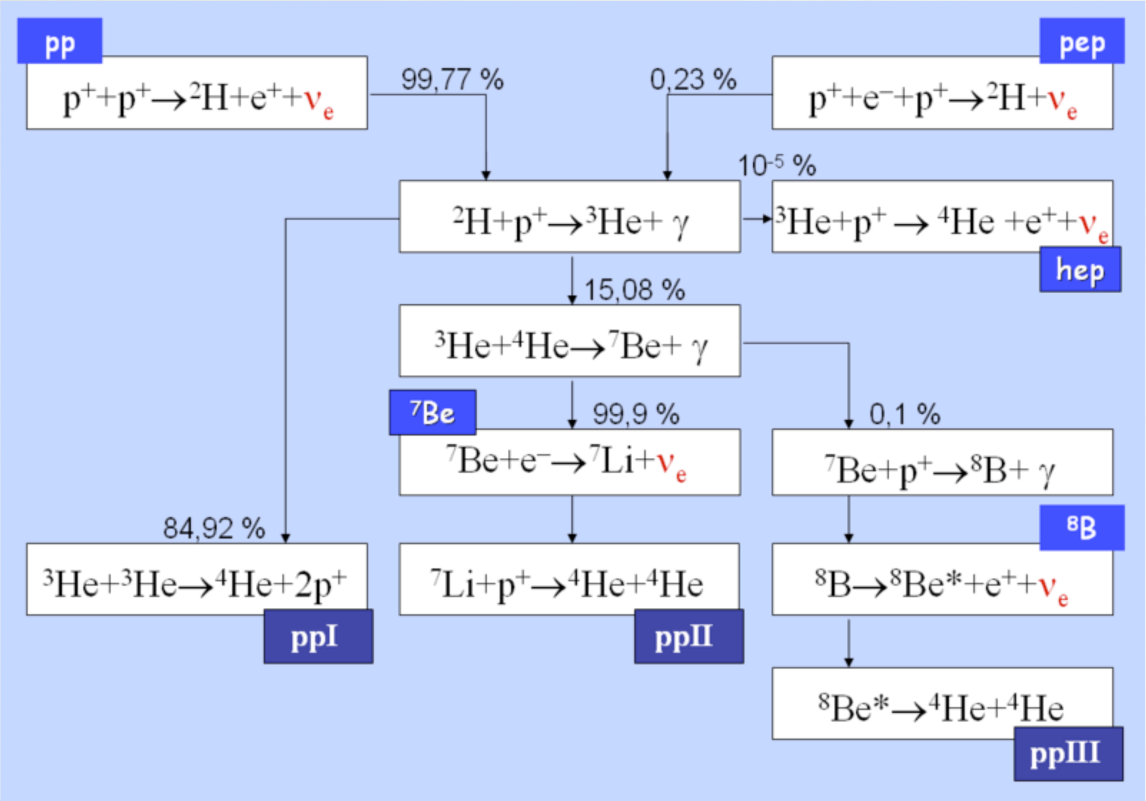
ν_μCC in SK

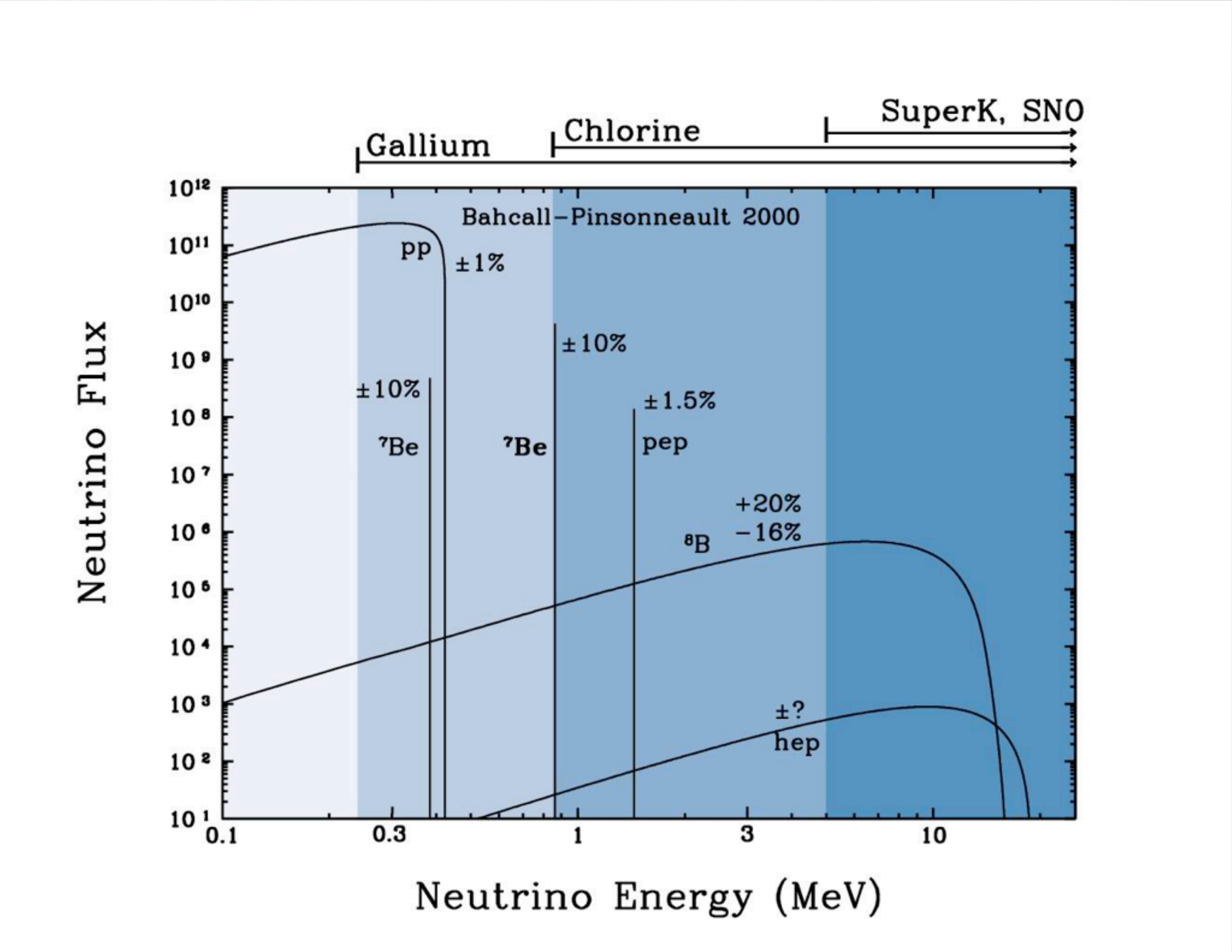


NEUTRINO OSCILLATIONS

SOLAR NEUTRINO PROBLEM

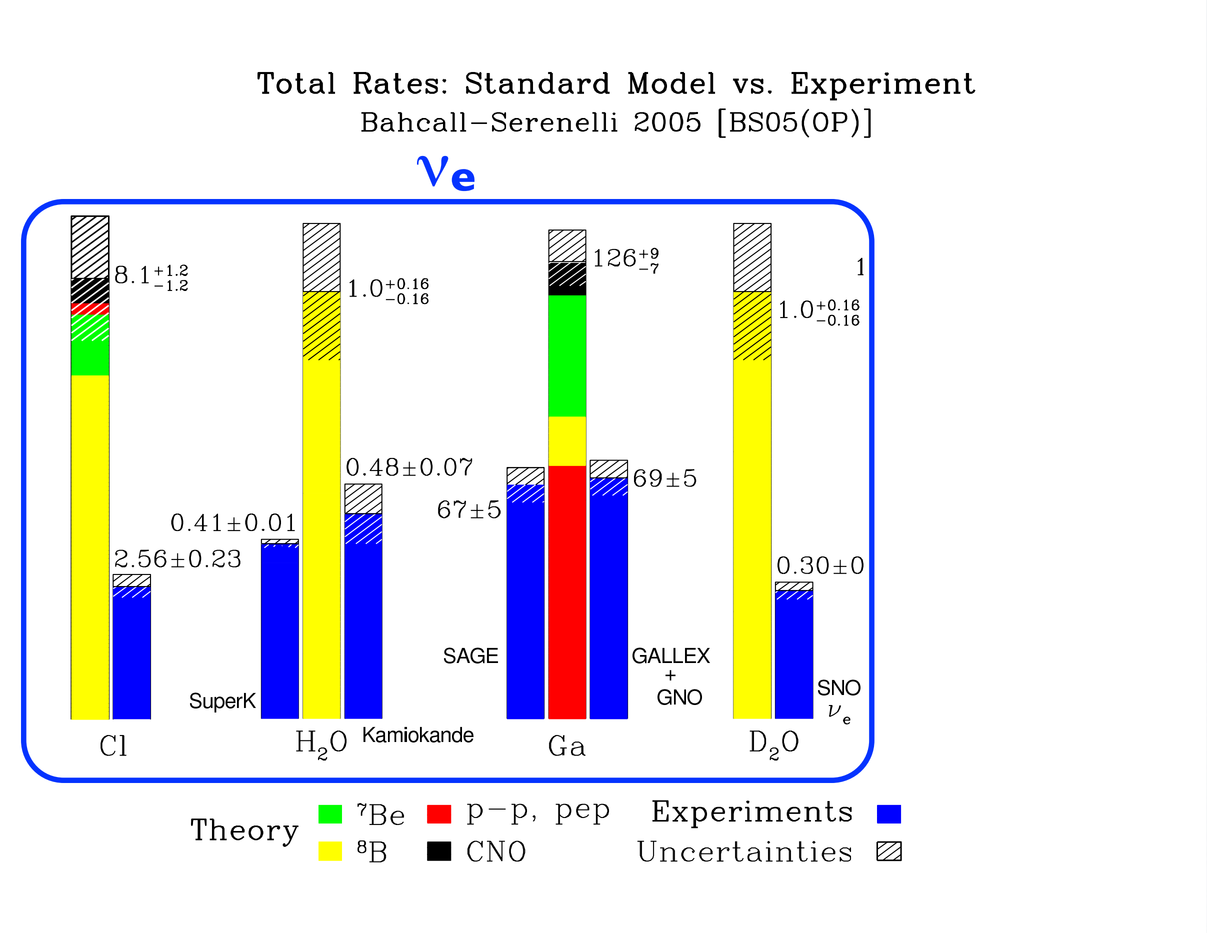
- The sun emits a huge number of neutrinos and the energy and flux have been computed by Bahcall starting in the1960's.
- These fluxes are computed according to our knowledge on the solar model.





SOLAR NEUTRINO PROBLEM

- Experiments **measured** however about **half** of the **expected** neutrino flux.



Experiment	Threshold (MeV)	Ratio exp/theory
Homestake (1968)	0.814	0.32
Kamiokande (1989)	6.5	0.48
Gallex (1992)	0.233	0.55
SAGE (1990)	0.233	0.53
SK (1996)	6.5	0.41
SNO (1999)	5 (CC events)	0.30

1 SNU= 10^{-36} capture per target atom per second

- Possible explanations:

1. The solar model is not well enough understood?

2. The neutrinos are not well enough known?

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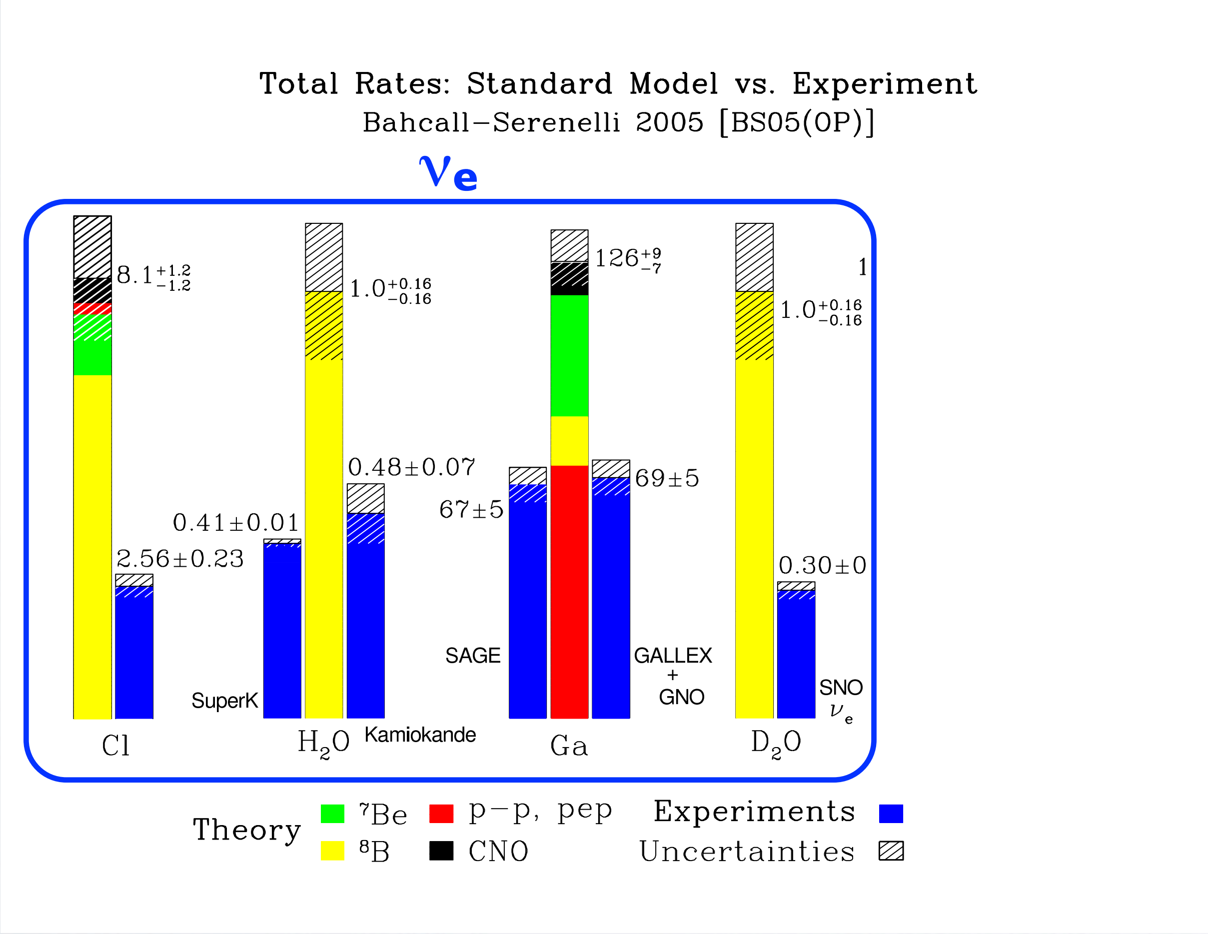

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Neutrino oscillation? Idea of Pontecorvo back in 1957

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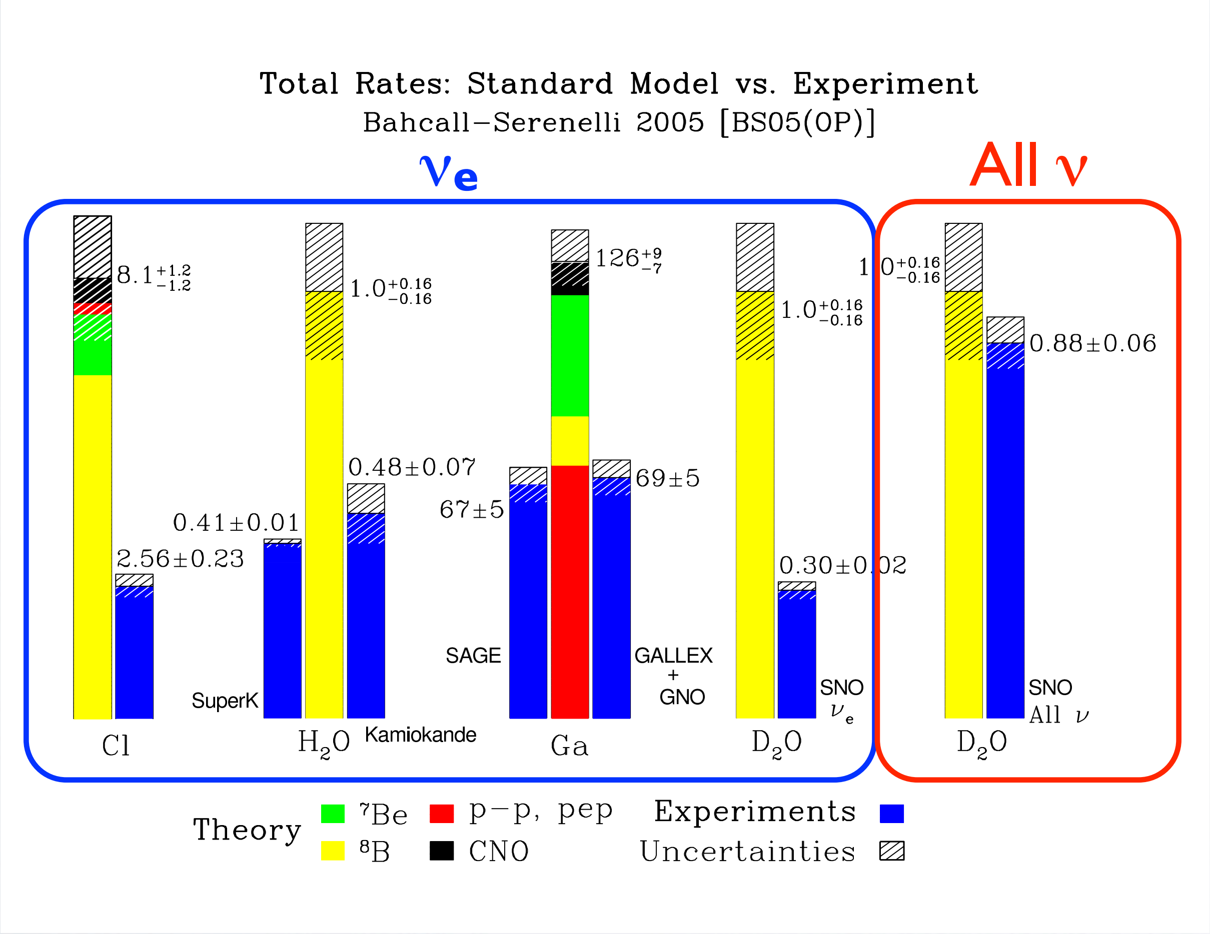

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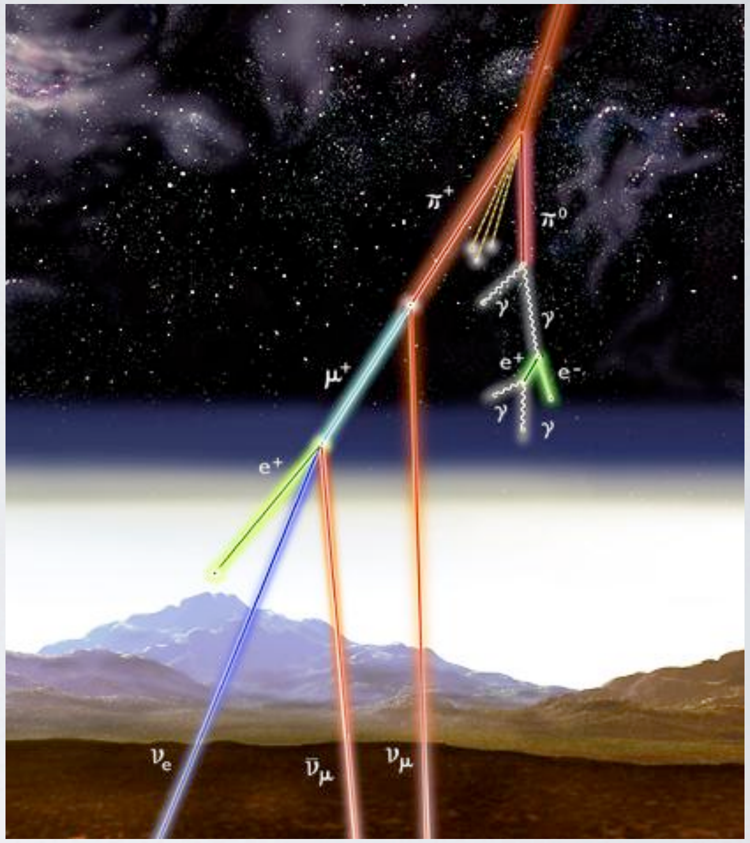
ATMOSPHERIC NEUTRINO PROBLEM



- **Cosmic rays** hitting the atmosphere produce hadronic showers:

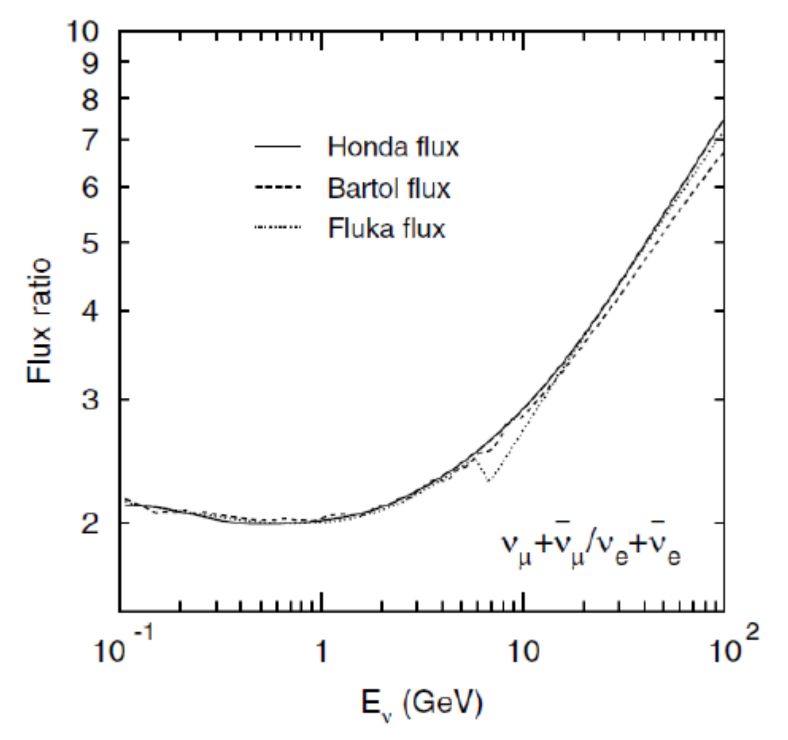
$$\mathrm{p} + \mathrm{N} \rightarrow X + \pi/K's$$

- Due to low density of the atmosphere most of the **hadrons decay** before interacting and also a large fraction of the **muons** produced by the secondary particles **decay** before reaching the ground.

- The most relevant chain is:

$$\begin{tikzcd} \pi^- \rightarrow \mu^- \bar{\nu}_\mu \arrow[d] & \pi^+ \rightarrow \mu^+ \nu_\mu \arrow[d] \\ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu & \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \end{tikzcd}$$

- We might naively expect that the ratio $\dfrac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e}$ is ≈ 2, however this is true only at low energies (E_μ < 1 GeV) since at high energies muons reach the ground before decaying and the fraction of ν_e is therefore reduced.



ATMOSPHERIC NEUTRINO PROBLEM

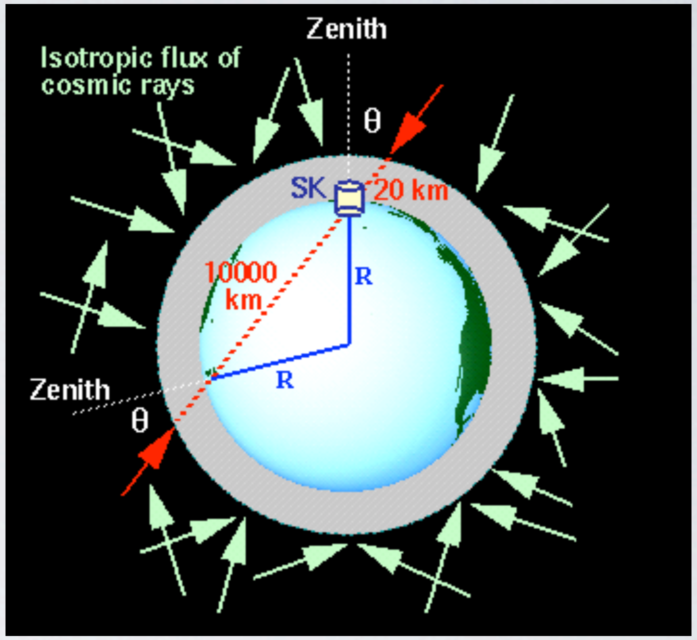
- Many experiments measured the ratio: $RR = \frac{(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)_{Observed}}{(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)_{Expected}}$

Experiment	Ratio
Frejus (1988)	1.00 ± 0.15 ± 0.08
IMB (1991)	0.54 ± 0.05 ± 0.11
Kamiokande $_{\text{sub GeV}}$ (1994)	0.60 ± 0.05 ± 0.05
Kamiokande $_{\text{multi GeV}}$ (1994)	0.57 ± 0.08 ± 0.07
Soudan2 (1997)	0.64 ± 0.11 ± 0.06
SK $_{\text{sub GeV}}$ (1997)	0.65 ± 0.02 ± 0.05
SK $_{\text{multi GeV}}$ (1997)	0.67 ± 0.04 ± 0.08

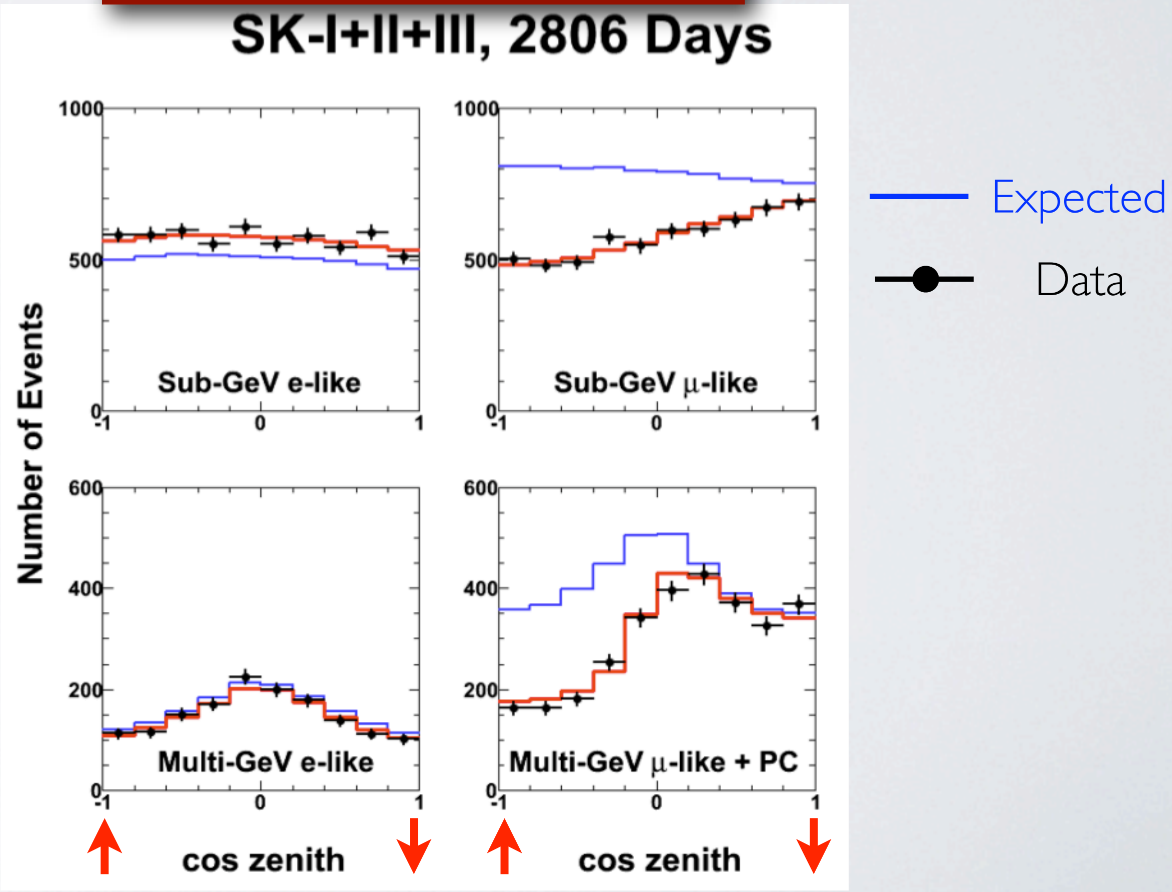
- **Are the electrons too many or the muons too few?**

ATMOSPHERIC NEUTRINO PROBLEM

- Super Kamiokande (SK) studied the dependence of electrons and muons (outgoing leptons of neutrino interactions) from the zenith angle.
- A "**disappearance**" of muon was observed in particular for up-going muons (i.e. neutrino that travelled through the earth to reach the detector).
- This was a strong evidence for **neutrino oscillation** ($\nu_\mu \rightarrow \nu_x$ with $\nu_x \neq \nu_e$).
- It also proved that the oscillation phenomenon has a **dependence on the baseline** (i.e. the distance between the neutrino source and the detector).



SK latest results



NEUTRINO MIXING

- Neutrino 3-flavour oscillation is now well established both at the solar and atmospheric scale.
- This means that mass eigenstates and flavour eigenstates are different.
- Neutrinos are produced in weak interactions i.e. as flavour eigenstates and propagate as mass eigenstates (Hamiltonian eigenstates).
- The relationship between the two eigenstate bases can be expressed using the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U_{e1}} & \mathrm{U_{e2}} & \mathrm{U_{e3}} \\ \mathrm{U}_{\mu 1} & \mathrm{U}_{\mu 2} & \mathrm{U}_{\mu 3} \\ \mathrm{U}_{\tau 1} & \mathrm{U}_{\tau 2} & \mathrm{U}_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- This means that the neutrino of a given flavour α can be expressed as a combination of mass states *i* :

$$| \nu_\alpha \rangle = \sum_{i=1}^{n} U^*_{\alpha i} \, | \nu_i \rangle$$

NEUTRINO OSCILLATIONS

- The **mass eigenstates** are eigenstate of the Hamiltonian and their **propagation** can be described by **plane wave** solutions as:

$$\boxed{\mid \nu_i(\vec{x},t)\rangle = e^{-i(E_i t - \vec{p}_i \cdot \vec{x})} \mid \nu_i(0,0)\rangle}$$

- The probability that a neutrino of a flavour α at a certain position and at a certain instant is measured as a neutrino of flavour β is called **oscillation probability** and can be computed as:

$$\boxed{P_{\alpha\beta} = \mid \langle \nu_\beta \mid \nu_\alpha(\vec{x},t)\rangle \mid^2}$$

- Under the assumption that the mass eigenstates have the same energy but different momentum due to a non zero value of their mass,

$$\boxed{E = \sqrt{p_i^2 + m_i^2}}$$

the development of the computation gives raise to terms of the form:

$$\boxed{\sin^2(\Delta m^2_{ij} L/4E)} \xrightarrow[\text{where}]{}$$

$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

L = baseline (normally distance between ν source and detector)

See exercise by C.Jollet

NEUTRINO OSCILLATIONS

- The oscillation term has been given in natural units, i.e. $c = \hbar = 1$
- Once the units are restored we have:

$$\sin^2(\Delta m^2_{ij} L/4E) \longrightarrow \sin^2(1.27\Delta m^2_{ij} L/E)$$

L = [km]
E = [GeV]
Δm^2 = [eV^2]

See exercise by C.Jollet

- **Note** that **oscillations** are possible **only** if at least two **masses** are **different**!

- The full oscillation probability in case of 3 flavours can be written as:

$$\begin{aligned} P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(1.27\Delta m^2_{ij}L/E) \\ +2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(2.54\Delta m^2_{ij}L/E) \end{aligned}$$

A SIMPLE PICTURE: 2 FLAVOURS

- As an example we take the 2-flavour case. The mixing matrix can be written as:

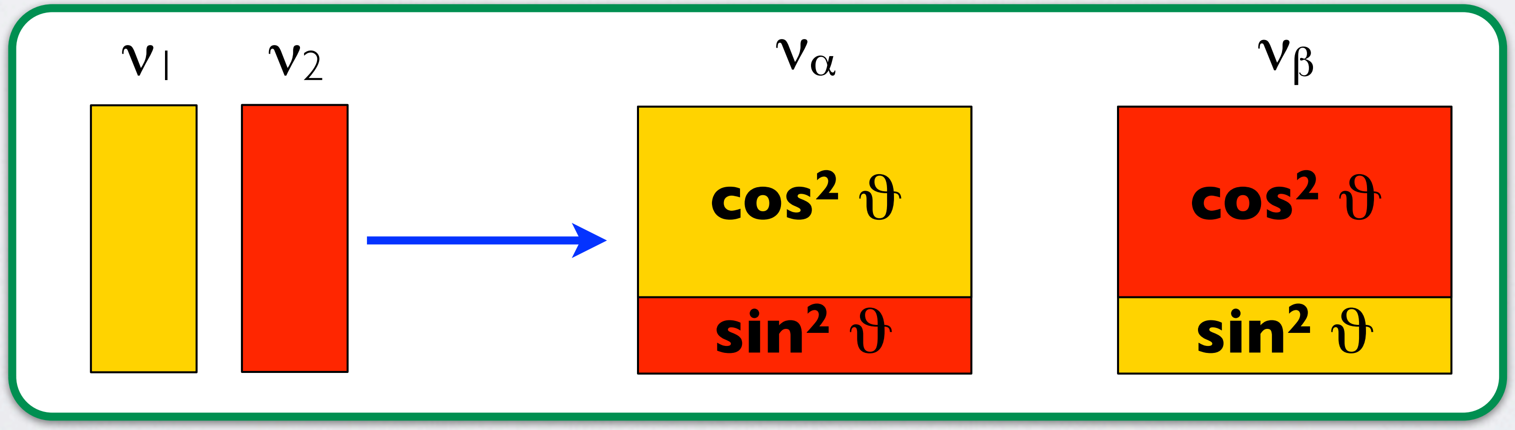
$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

- This means that we can write the flavour eigenstates as:

$$\begin{aligned} \mid \nu_\alpha\rangle &= \cos\theta \mid \nu_1\rangle + \sin\theta \mid \nu_2\rangle \\ \mid \nu_\beta\rangle &= -\sin\theta \mid \nu_1\rangle + \cos\theta \mid \nu_2\rangle \end{aligned}$$

- For example the fraction of ν_α made of ν_1 is :

$$\mid \langle \nu_\alpha \mid \nu_1 \rangle \mid^2 = \cos^2\theta$$



A SIMPLE PICTURE: 2 FLAVOURS

- Although in experiments the time is not measured and the fixed parameter is the baseline, for a better understanding let's look at the time evolution only:

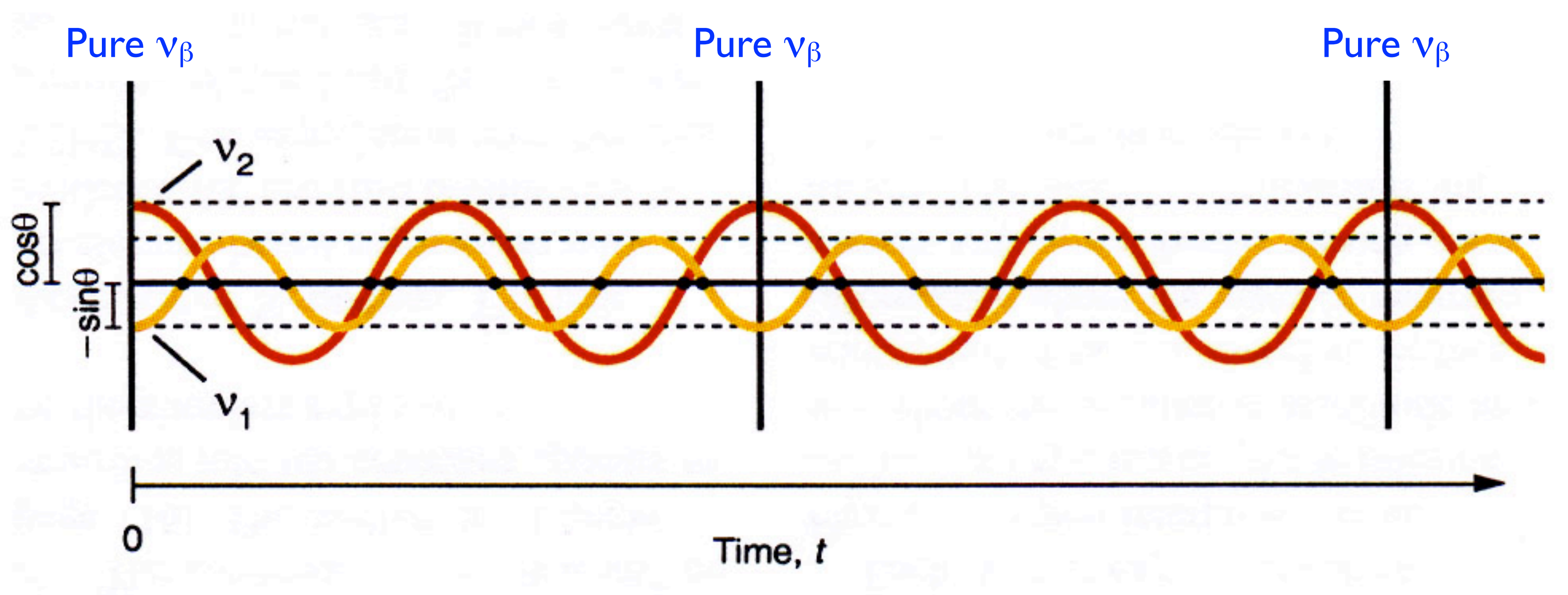
$$\boxed{\mid \nu_i(t)\rangle = e^{-iE_it} \mid \nu_i(0)\rangle}$$

- The time evolution of flavour eigenstates can be written as:

$$\boxed{\mid \nu_\beta(t)\rangle = -\sin\theta e^{-iE_1t} \mid \nu_1(0)\rangle + \cos\theta e^{-iE_2t} \mid \nu_2(0)\rangle}$$

$$\boxed{\mid \nu_\alpha(t)\rangle = \cos\theta e^{-iE_1t} \mid \nu_1(0)\rangle + \sin\theta e^{-iE_2t} \mid \nu_2(0)\rangle}$$

- The oscillation pattern can be graphically described as:



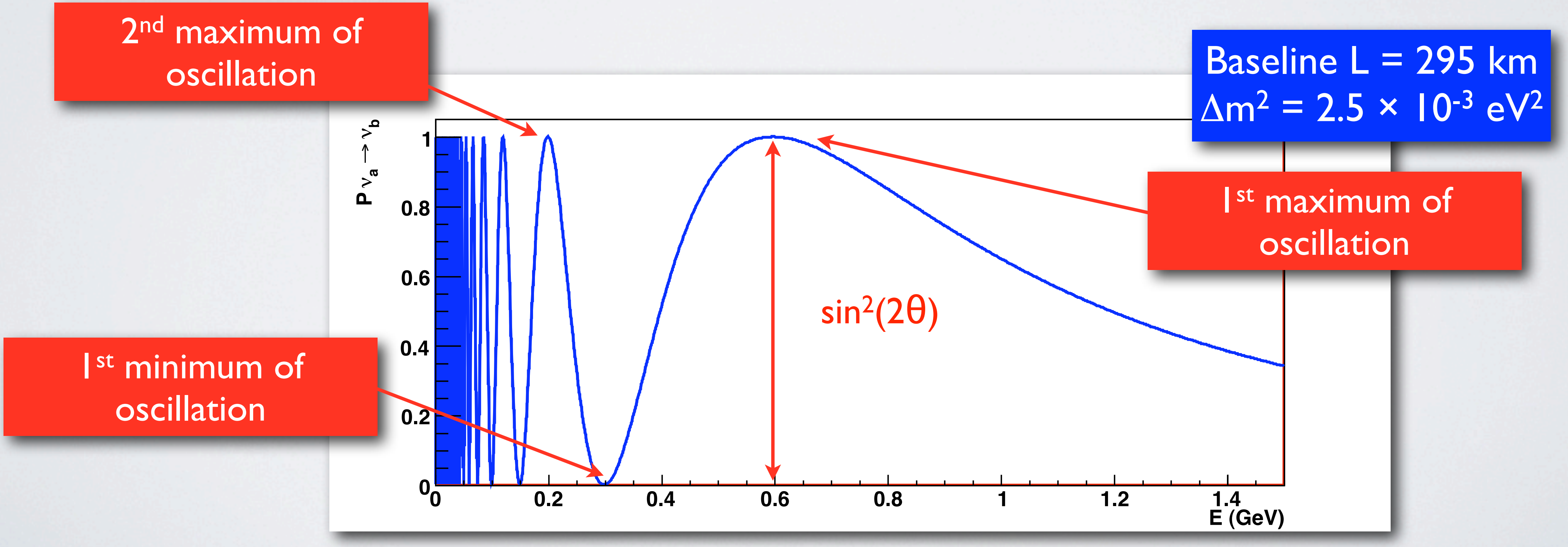
A SIMPLE PICTURE: 2 FLAVOURS

- In the 2 flavour case the oscillation probability can be written as:

$$\boxed{P_{\alpha\beta} = \sin^2 2\theta \sin^2(1.27\frac{\Delta m^2 L}{E})}$$

See exercise by C.Jollet

- If we take as an example a baseline of 295 km and the atmospheric mass splitting we can compute the oscillation probability from a flavour α to a flavour β as a function of the neutrino energy:



2nd maximum of oscillation

Baseline L = 295 km
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

1st maximum of oscillation

1st minimum of oscillation

WHAT ABOUT ANTINEUTRINOS?

- In the SM every particle has its own antiparticle.
- In physics we have a theorem stating that **CPT symmetry** (Charge, Parity and Time) is conserved.
- CPT symmetry guarantees that the particle and its antiparticle have the same mass and opposite quantum numbers.

- It can be easily seen in the oscillation probability equation that:

$$\boxed{P(\nu_\alpha \to \nu_\beta; U) = P(\nu_\beta \to \nu_\alpha; U^*)}$$

T transformation

- From the conservation of CPT we can therefore infer that:

$$\boxed{P(\nu_\alpha \to \nu_\beta; U) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta; U^*)}$$

CP transformation

- If the mixing matrix is complex the probability of oscillation for neutrinos and antineutrinos will be in general different: this would lead to **CP violation**.

MORE ON THE MIXING MATRIX

- For **N** neutrinos the most general mixing matrix is a **complex** matrix **N** × **N**. This gives **$2N^2$ free parameters**.

- In order to conserve probability the matrix has to be **unitary** (the inverse matrix is equal to the conjugate transpose):

$$\boxed{\begin{array}{l} \sum_\alpha \mid U_{\alpha i} \mid^2 = 1 \\ \sum_\alpha U^*_{\alpha i} U_{\alpha j} = 0 \quad \text{for } \; i \neq j \end{array}}$$

N constraints

N(N-1) constraints

- We can **redefine** our **flavour states** to absorb some phases:

$$\boxed{\langle l_\alpha \mid \rightarrow \langle l'_\alpha \mid = \langle l_\alpha \mid e^{-i\phi_\alpha} \Rightarrow U_{\alpha i} \rightarrow U'_{\alpha i} = e^{-i\phi_\alpha} U_{\alpha i}}$$

N constraints

- The same can be done on the **mass states** to add **N-1 constraints** (one global phase will remain). **NOTE** that this is true for **Dirac neutrinos** which means that neutrinos and antineutrinos are different particles.

See talk by G.Drexlin

- This leaves **$(N-1)^2$ free parameters**.

MORE ON THE MIXING MATRIX

- **If CP is conserved** the oscillation probability for neutrinos and antineutrinos are identical and the matrix can be formed by **real parameters** only giving **N^2 free parameters**.
- Taking into account the orthogonality constraints we have **N(N-1)/2 free parameters conserving CP**.
- The number of **complex phases** is instead **(N-1)(N-2)/2**.

	General (Dirac case)	**SM case (N=3)**
Mixing angles (CP conserving)	N(N-1)/2	3
Complex phases (CP violating)	(N-1)(N-2)/2	1
Total free parameters	$(N-1)^2$	4

MORE ON THE MIXING MATRIX

- In the case of **3 neutrino families** we have **3** real parameters (**mixing angles**) and **1** complex one (**complex phase**).

- Various parameterisations exist but the most common one is:

$$\begin{pmatrix} \mathrm{U}_{e1} & \mathrm{U}_{e2} & \mathrm{U}_{e3} \\ \mathrm{U}_{\mu 1} & \mathrm{U}_{\mu 2} & \mathrm{U}_{\mu 3} \\ \mathrm{U}_{\tau 1} & \mathrm{U}_{\tau 2} & \mathrm{U}_{\tau 3} \end{pmatrix} \longrightarrow \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}\, c_{23} - c_{12}\, s_{13}\, s_{23}\, e^{i\delta_{\mathrm{CP}}} & c_{12}\, c_{23} - s_{12}\, s_{13}\, s_{23}\, e^{i\delta_{\mathrm{CP}}} & c_{13}\, s_{23} \\ s_{12}\, s_{23} - c_{12}\, s_{13}\, c_{23}\, e^{i\delta_{\mathrm{CP}}} & -c_{12}\, s_{23} - s_{12}\, s_{13}\, c_{23}\, e^{i\delta_{\mathrm{CP}}} & c_{13}\, c_{23} \end{pmatrix}$$

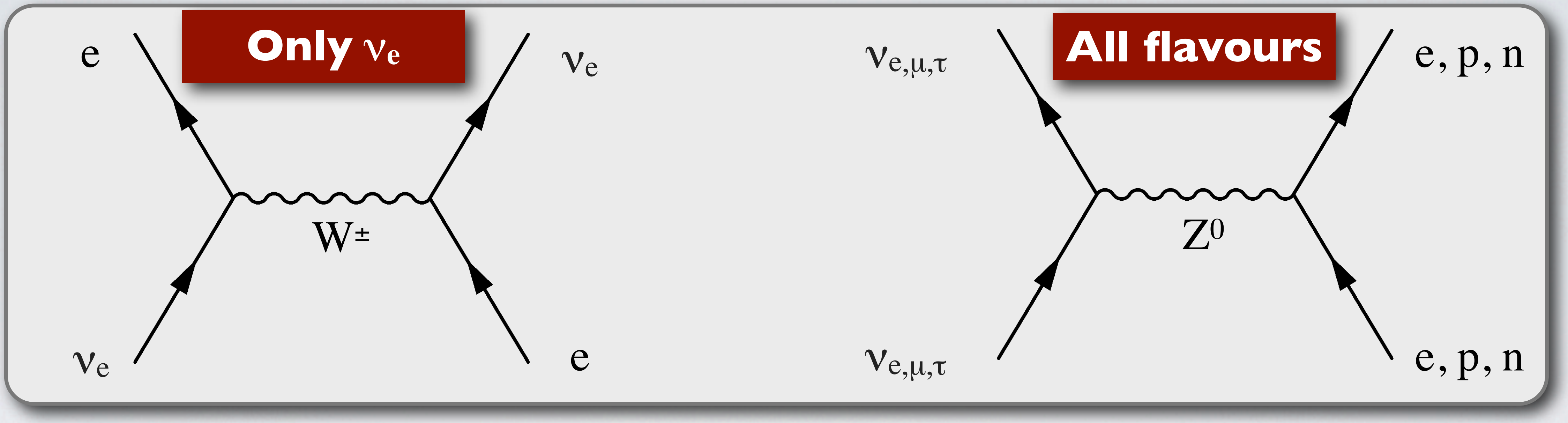
where "c_{ij}" stands for "*cos* ϑ_{ij}" and "s_{ij}" for "*sin* ϑ_{ij}" with ϑ_{ij} a mixing angle.

- This parametrisation allows for a rewriting of the matrix in 3 different ones, separating the oscillations according to the experimental evidences:

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric scale}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Interference}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar scale}}$$

MATTER

- So far we have considered the neutrino propagation and oscillations in vacuum.
- When they travel in matter the hamiltonian of the system is different according to the flavours since **only ν_e** can do **charge current scattering on electrons**.



- The difference of potential seen by the electron neutrinos with respect to other flavours can be written as:

$$\boxed{V = V_e - V_X = \sqrt{2} G_F n_e} \xrightarrow{\text{where}} \boxed{2\sqrt{2} G_F n_e = 7.56 \times 10^{-5} eV^2 \rho(g/cm^3)}$$

where X stands for μ or τ, G_F is the Fermi coupling constant and n_e the electron density.

- If H_0 is the Hamiltonian in Vacuum, the new Hamiltonian H becomes therefore:

$$\boxed{H_0 \rightarrow H = H_0 + V}$$

MATTER

- If the Hamiltonian changes, the eigenstates and the eigenvalues change as well i.e. **effective masses and mixing are different in matter** and they change along the neutrino trajectory if the matter density changes.
- In the simple 2 flavour case, the mass eigenstates can be written as:

$$\boxed{\mu_{1,2}^2 = \frac{m_1^2 + m_2^2}{2} + E(V_e + V_X) \pm \frac{1}{2}\sqrt{(\Delta m^2 \cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}} \xrightarrow[\text{where}]{} \boxed{A = 2E(V_e - V_X)}$$

- The mixing angle can be written as:

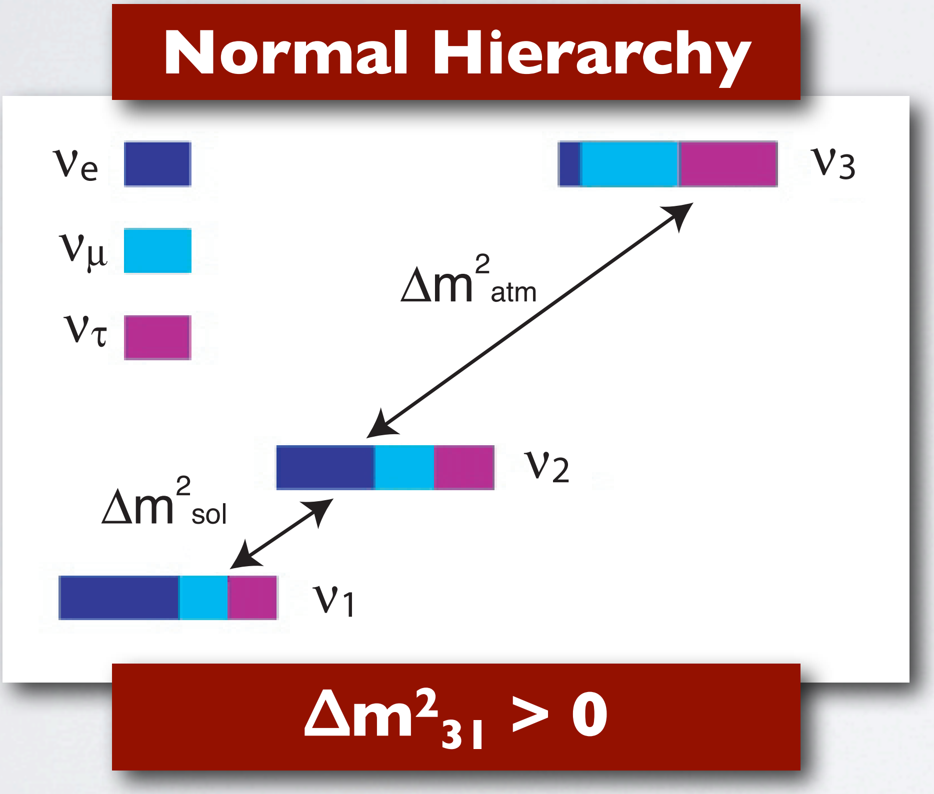
$$\boxed{\tan(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2 \cos(2\theta) - A}}$$

- We note some important features:

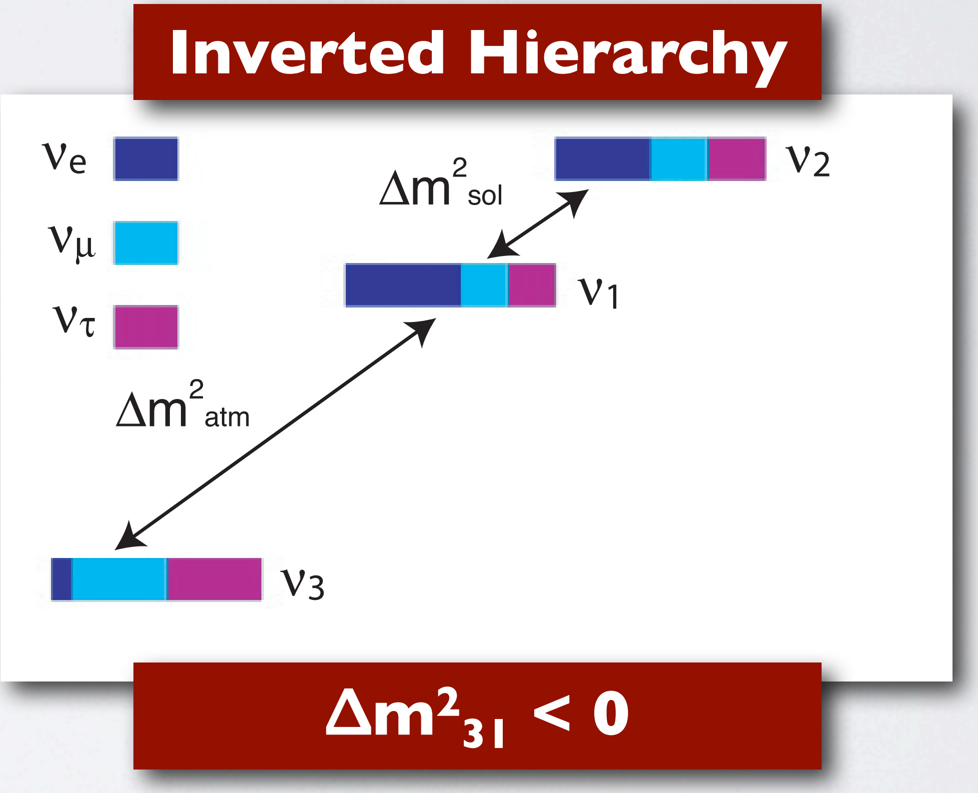
1. As expected if A → 0 (vacuum) $\theta_m \to \theta$.
2. If $\boxed{A = \Delta m^2 \cos(2\theta)}$ we have a **resonant condition**: no matter how small the mixing value is in vacuum (provided it is not zero), the **mixing in matter is maximal**.

MASS HIERARCHY

- We have seen that the ingredients for the description of neutrino oscillations are: the 3 mixing angles (θ_{12}, θ_{13}, θ_{23}), possibly the complex phase (δ_{CP}), and two mass differences (Δm^2_{21}, $\Delta m^2_{31} \approx \Delta m^2_{32}$).
- Another important ingredient is the **sign** of the **mass difference**.
- For Δm^2_{21} the sign is known by the solar oscillation measurements (see later) but the **sign of Δm^2_{31}** is **unknown**. This is called **mass hierarchy** degeneracy.


Normal Hierarchy

$\Delta m^2_{31} > 0$

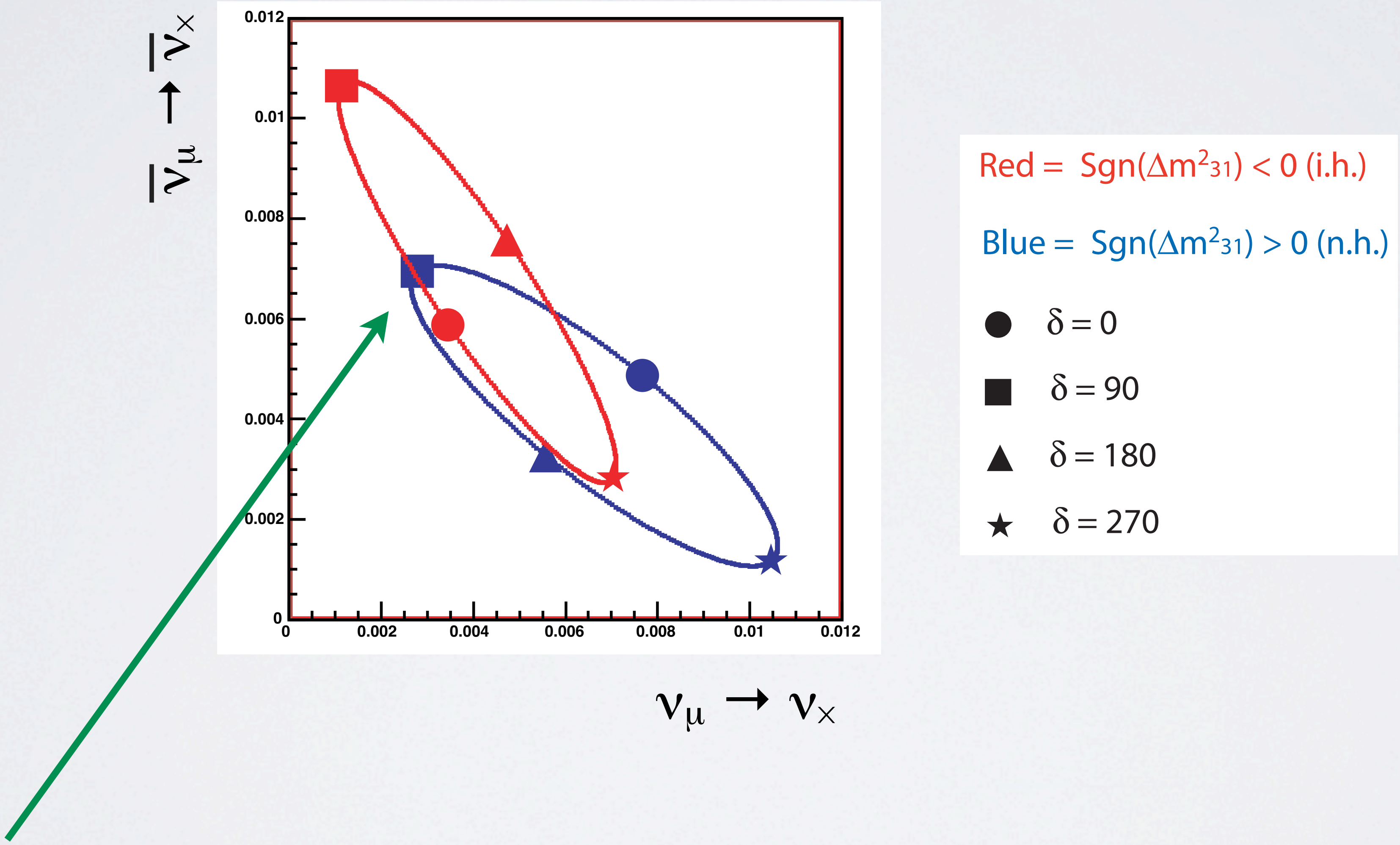

Inverted Hierarchy

$\Delta m^2_{31} < 0$

- The sign has an effect on the oscillation probability in matter and this indetermination has an effect on the measurement of CP violation.

HIERARCHY VS CP

- To understand how mass hierarchy and CP violation effects mix let's take an example: a baseline of 1050 km and an energy of 2.5 GeV, for the measurement of $\nu_\mu \rightarrow \nu_x$ transition (atmospheric sector).
- To measure CP violation we have to observe a difference in the oscillation probability of neutrino and antineutrinos.



- The same spectrum can be fitted with **N.H. and CP violation** ($\delta_{CP} = 90$) **OR I.H. and CP conserved** ($\delta_{CP} \approx 0$).

EXAMPLE: $\nu_\mu \rightarrow \nu_e$

- The full 3-flavour neutrino oscillation probability for $\nu_\mu \rightarrow \nu_e$ in matter is given by:

$$P(\nu_\mu \rightarrow \nu_e) = \Sigma_{i=1,4} P_i$$

$$P_1 = \sin^2\theta_{23}\sin^2(2\theta_{13})\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

Atmospheric term

$$P_2 = \cos^2\theta_{23}\sin^2(2\theta_{12})\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

Solar term

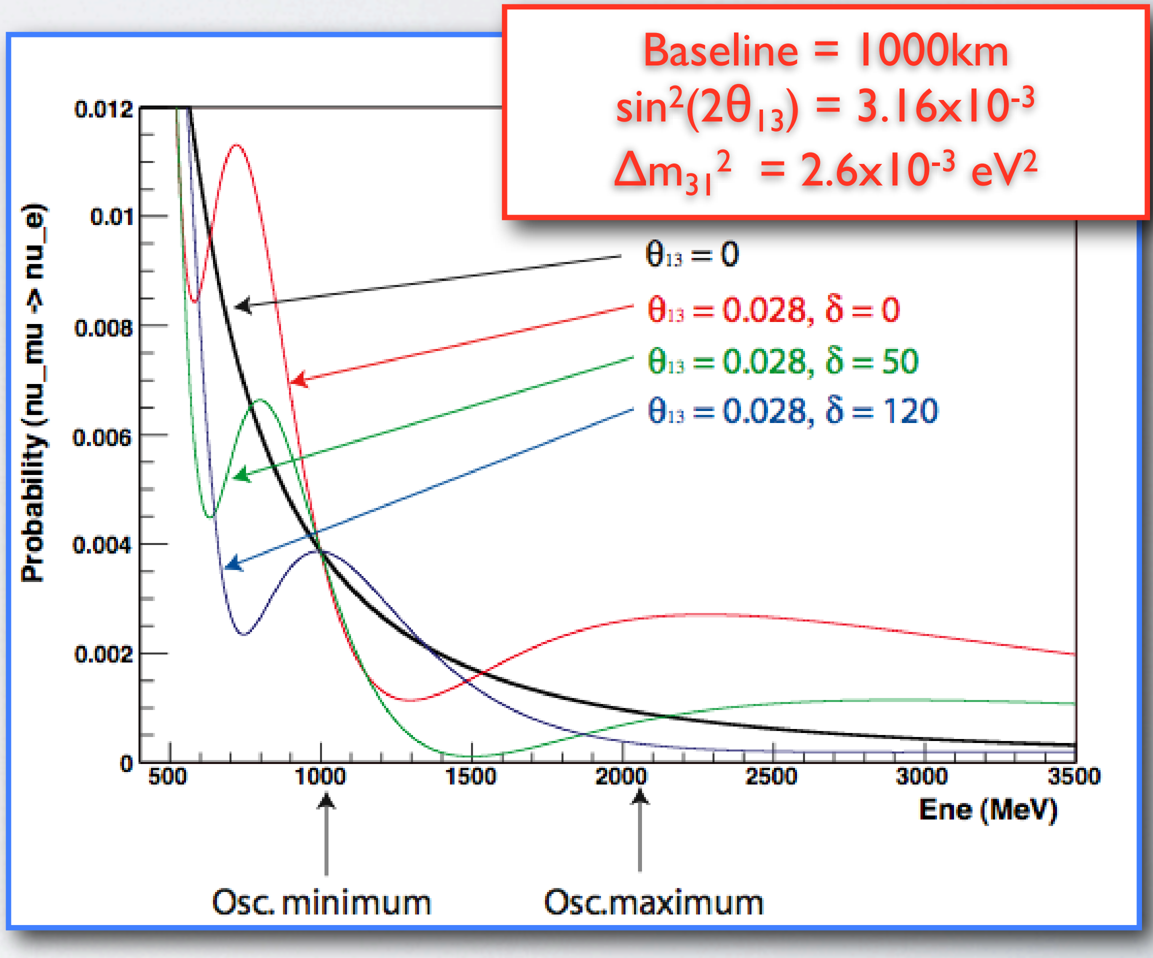
$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

Interference terms

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$
$$B_\pm = |A \pm \Delta_{13}|$$
$$J = \cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})$$

- **θ_{13}** is crucial for the atmospheric part of the oscillation, and it must be proved to be non-zero.
- In case of a value of θ_{13} different from zero, the oscillation probability depends strongly on the value of **δ**.
- The so far unknown sign of **Δm^2_{31}** also affects the oscillation probability (**only in matter**) and mass hierarchy must be determined.



Baseline = 1000km
$\sin^2(2\theta_{13}) = 3.16\times10^{-3}$
$\Delta m_{31}^2 = 2.6\times10^{-3}$ eV^2

PARAMETERS

- These are the parameters needed to describe neutrino oscillations in the 3 flavour scheme.

Parameter	**Present knowledge (90% C.L.)**	**Channel**	**Experiments**	**Future**
θ_{23}				
θ_{12}				
θ_{13}				
$\lvert\Delta m^2_{21}\rvert$				
Sign (Δm^2_{21})				
$\lvert\Delta m^2_{31}\rvert$				
Sign (Δm^2_{31})				
δ_{CP}				

NEUTRINO EXPERIMENTS

This is **NOT** a full review of all the experiments that played a role in neutrino history!

NEUTRINO EXPERIMENTS

It is just an highlight on **some** detection techniques and important results related to neutrino oscillation, but it is far from being complete.

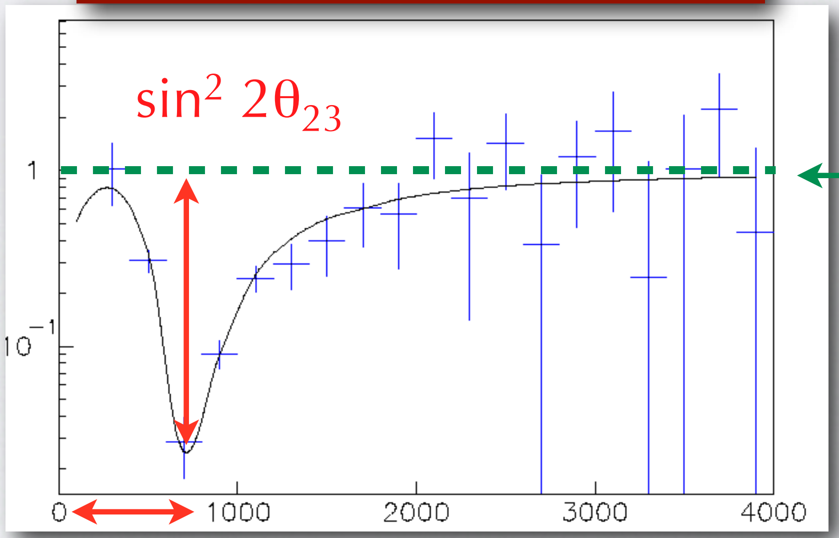
ATMOSPHERIC SECTOR

- To measure the parameters of the atmospheric sector (**θ_{23}**, **$\Delta m_{32}^2 \approx \Delta m_{31}^2$**) a good channel to study is the $\nu_\mu \rightarrow \nu_x$ **transition**.
- An approximation of the oscillation probability can be written as:

$$P(\nu_\mu \rightarrow \nu_x) \sim \cos^4\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m_{32}^2 L/4E_\nu)$$

- To observe such an oscillation, the experiments **compare** the **expected** ν_μ **flux** with the **measured one**.

ν_μ flux measured / ν_μ flux predicted



No oscillation

Δm^2_{32}

E_ν (MeV)

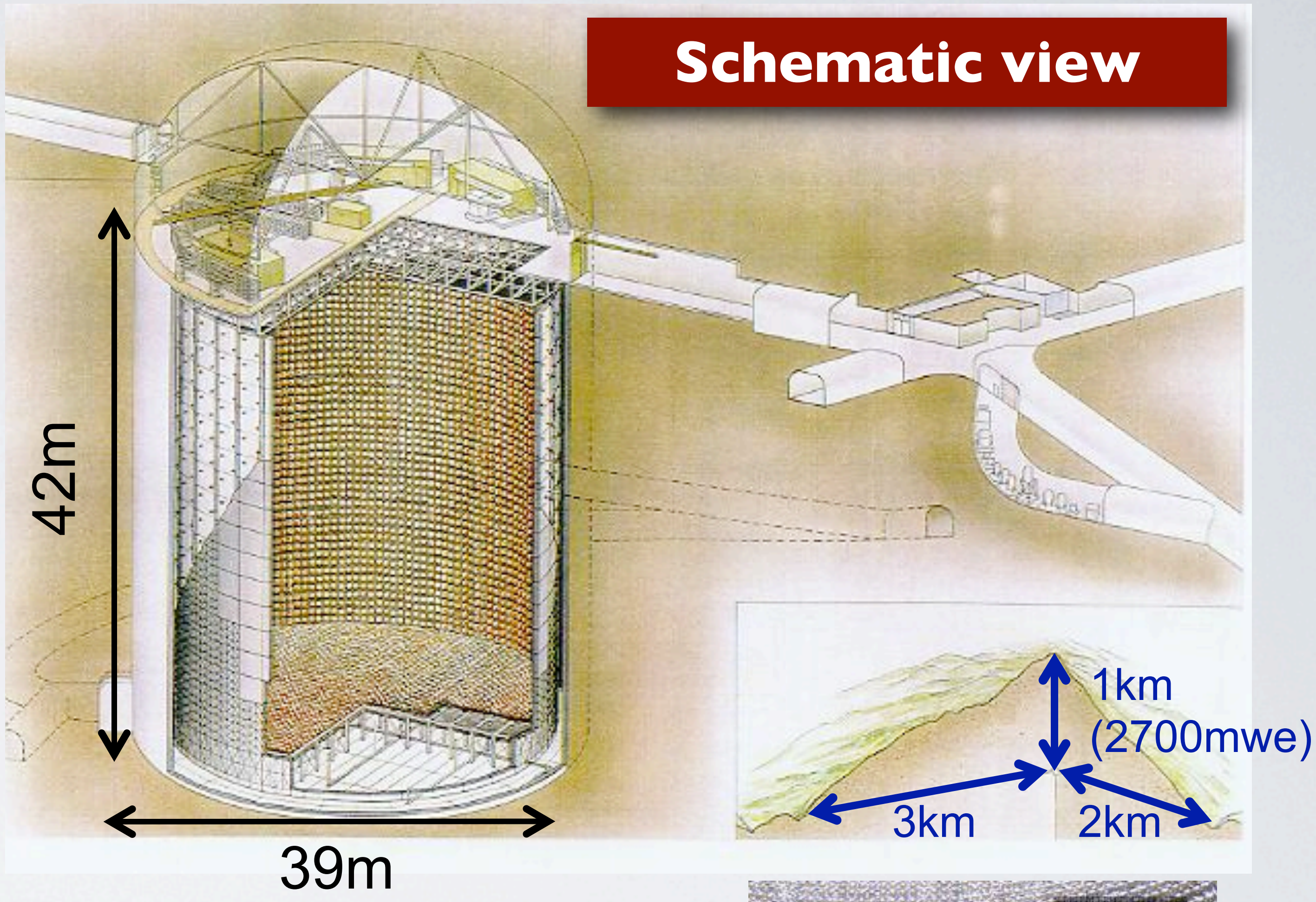
- The experiments that play(ed) a crucial role in these measurements are: **Super Kamiokande** (SK), **K2K**, **MINOS** and **T2K**.

SUPER KAMIOKANDE

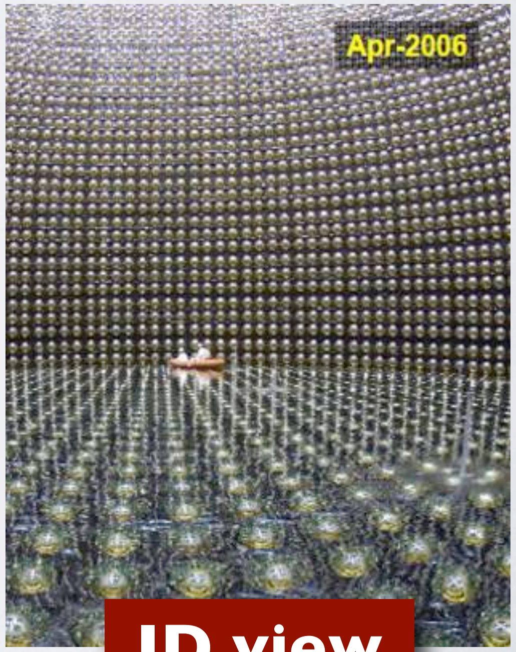
- SK is a **50 kton water Cherenkov** detector with a **fiducial volume of 22.5 kton**.
- It is located about 1 km underground.
- The inner detector is made of about 11146 PMTs with a diameter of 50 cm.
- The veto (2m of water) is made of about 1885 PMTs with a diameter of 20 cm.
- The event rate is about **10 ν/day** both for solar and atmospheric neutrinos.

The detector started data taking in 1996 and it is a **multi purpose observatory**: atm, solar and SN ν observation, far detector for K2K and T2K, proton decay search.

Schematic view



PMTs

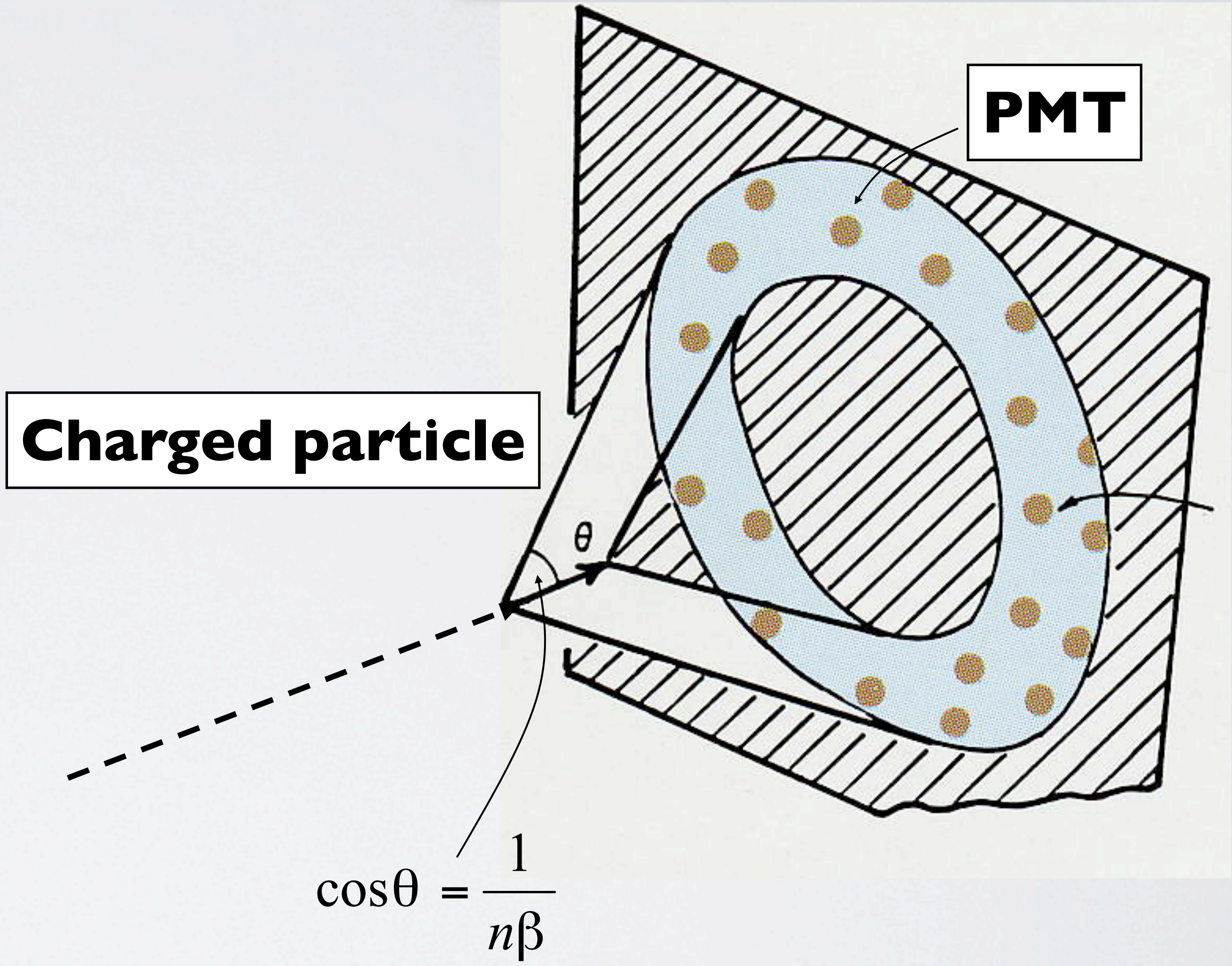


ID view

SK DETECTION PRINCIPLE

- The particle detection is based on the emission of Cherenkov radiation.
- **Charged particles** travelling through a medium at a **velocity larger** than the **speed of light in that medium** emit light (**Cherenkov light**).
- The angle ϑ depends on the refractive index of the medium ***n*** and the velocity of the particle with respect to the speed of light in vacuum β.
- The number of **emitted photons** with a wavelength between 300 and 600 nm (typical range of good efficiency of PMT) is **only about 340 per cm**. This is the reason for using large PMTs.

Schematic view



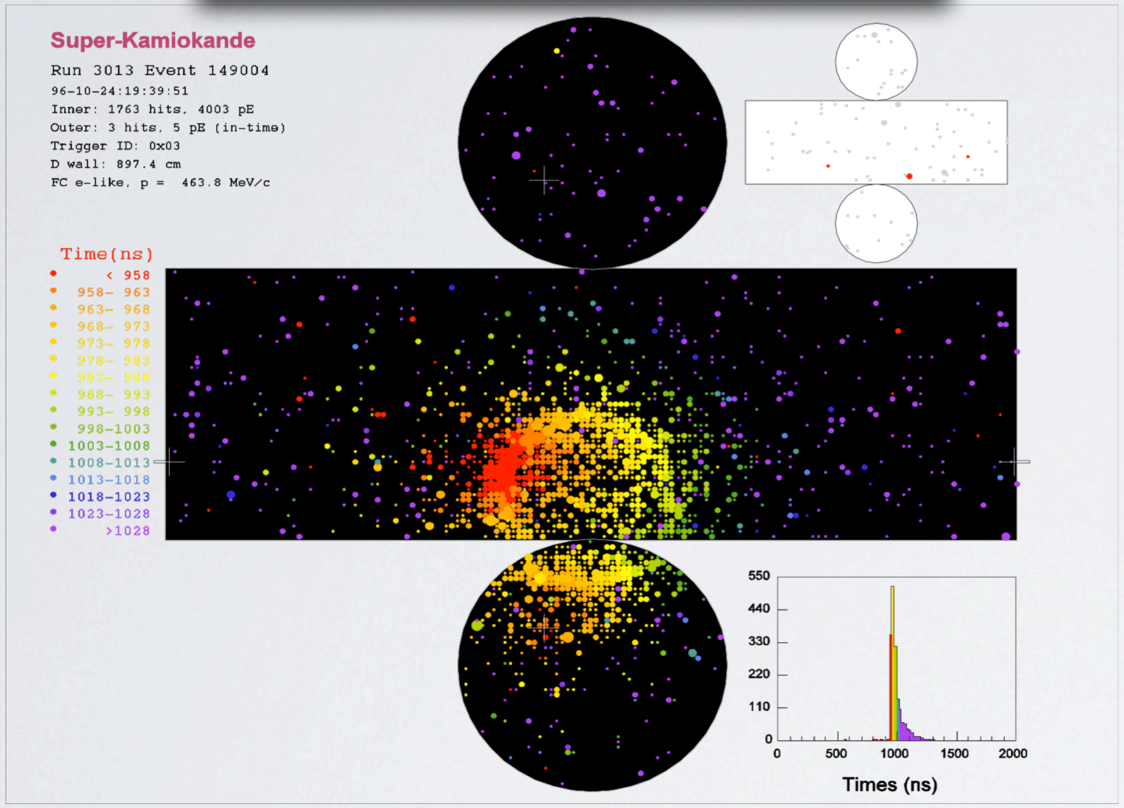
$$\cos\theta = \frac{1}{n\beta}$$

In **water n = 1.34** therefore **for β = 1, ϑ = 42 deg**.

SK PARTICLE ID

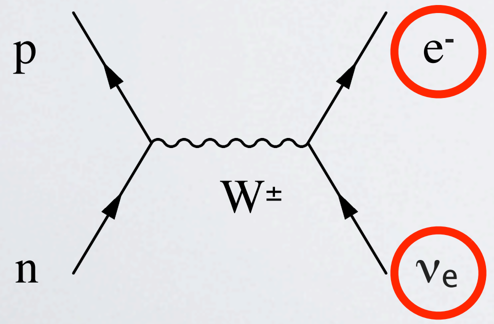
- The **particle identification** (important for the lepton to **distinguish** between the different **neutrino flavours**) is done using algorithms that study the **ring shape**.

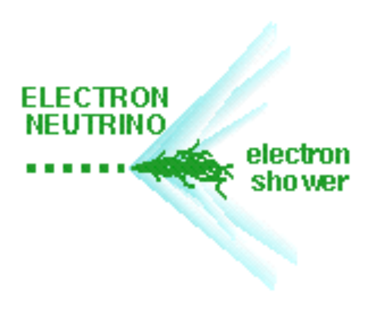
stopping electron ring



Super-Kamiokande

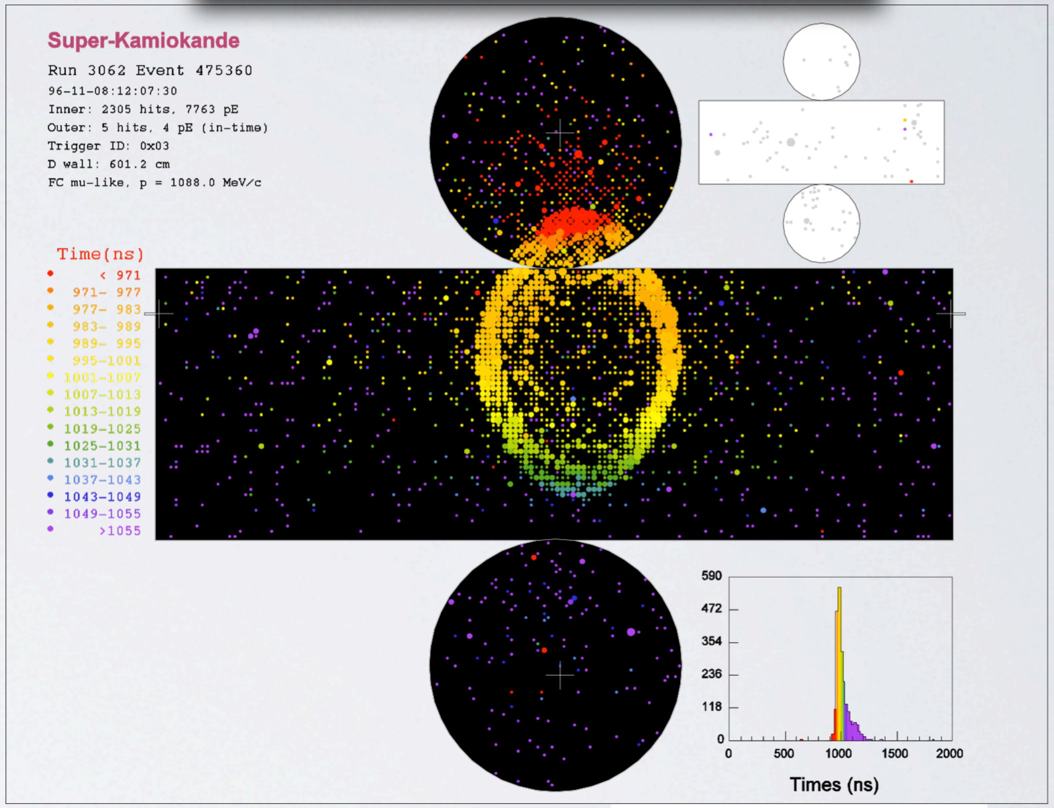
```
Run 3013 Event 149004
96-10-24:19:39:51
Inner: 1763 hits, 4003 pE
Outer: 3 hits, 5 pE (in-time)
Trigger ID: 0x03
D wall: 897.4 cm
FC e-like, p =  463.8 MeV/c
```





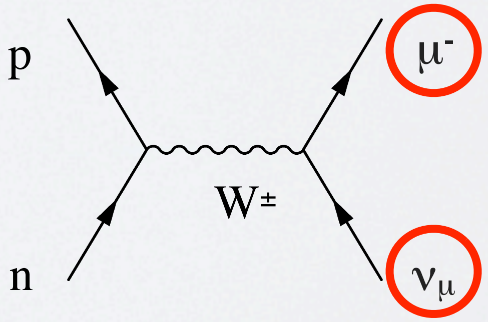
Not well defined cone

stopping muon ring



Super-Kamiokande

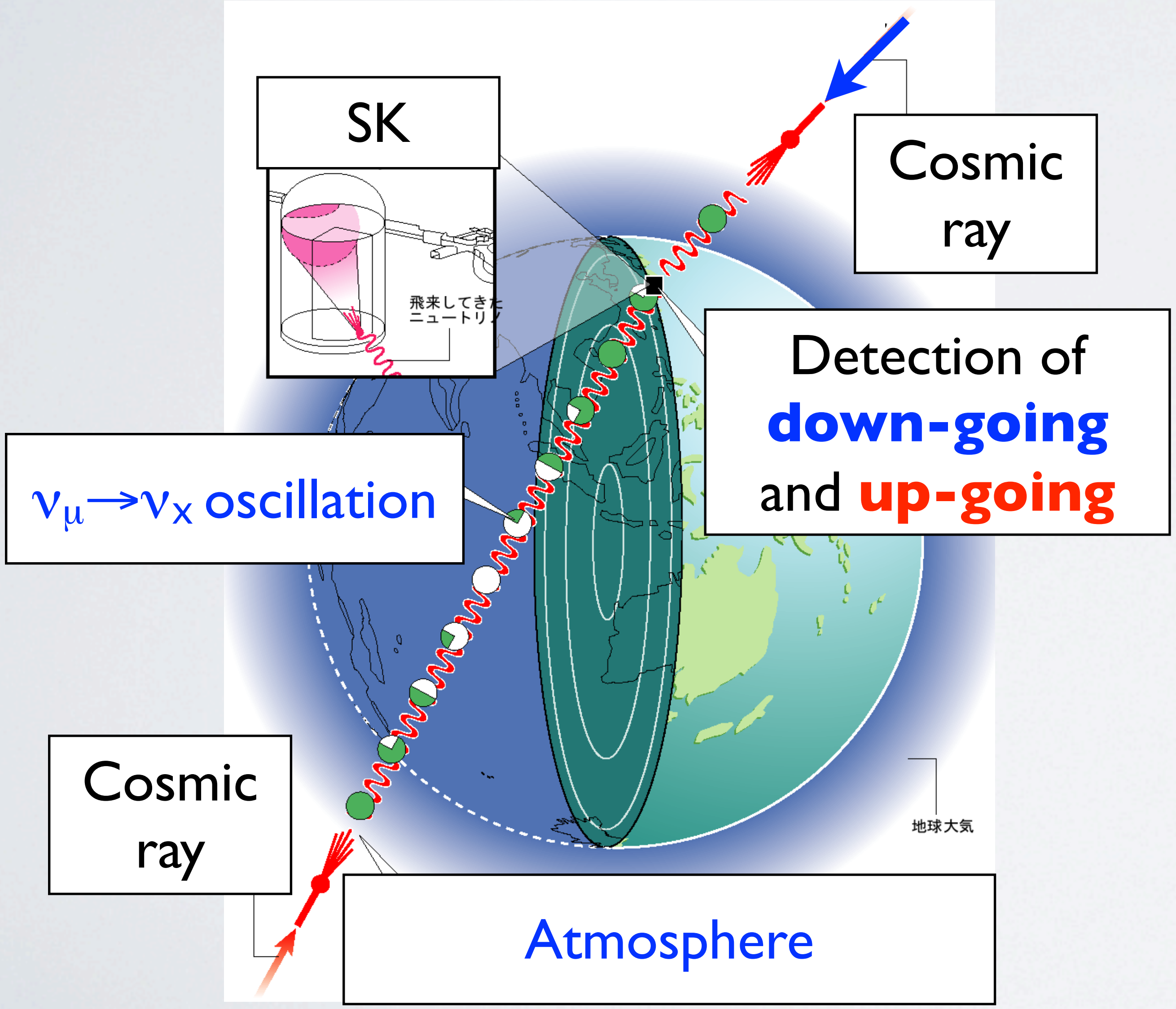
```
Run 3062 Event 475360
96-11-08:12:07:30
Inner: 2305 hits, 7763 pE
Outer: 5 hits, 4 pE (in-time)
Trigger ID: 0x03
D wall: 601.2 cm
FC mu-like, p = 1088.0 MeV/c
```



Well defined cone

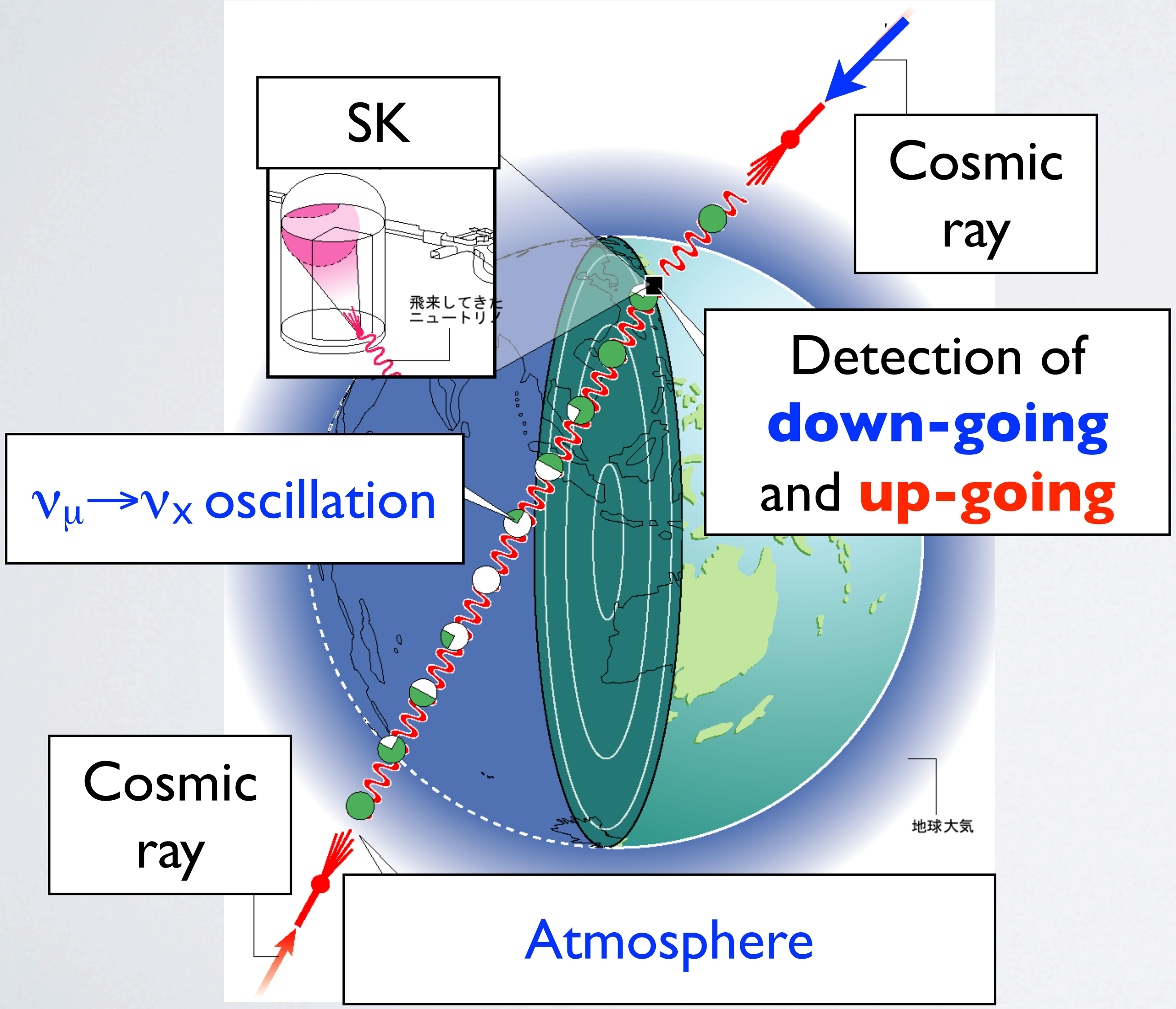
OSCILLATION OBSERVATION

- **Up-going** and **down-going** neutrinos travel difference distances between the production point and the detector (i.e. they have **different baselines**).



OSCILLATION OBSERVATION

- **Up-going** and **down-going** neutrinos travel difference distances between the production point and the detector (i.e. they have **different baselines**).
- The oscillation probability is therefore different: **oscillations** can be seen for the **up-going** neutrinos.



SK

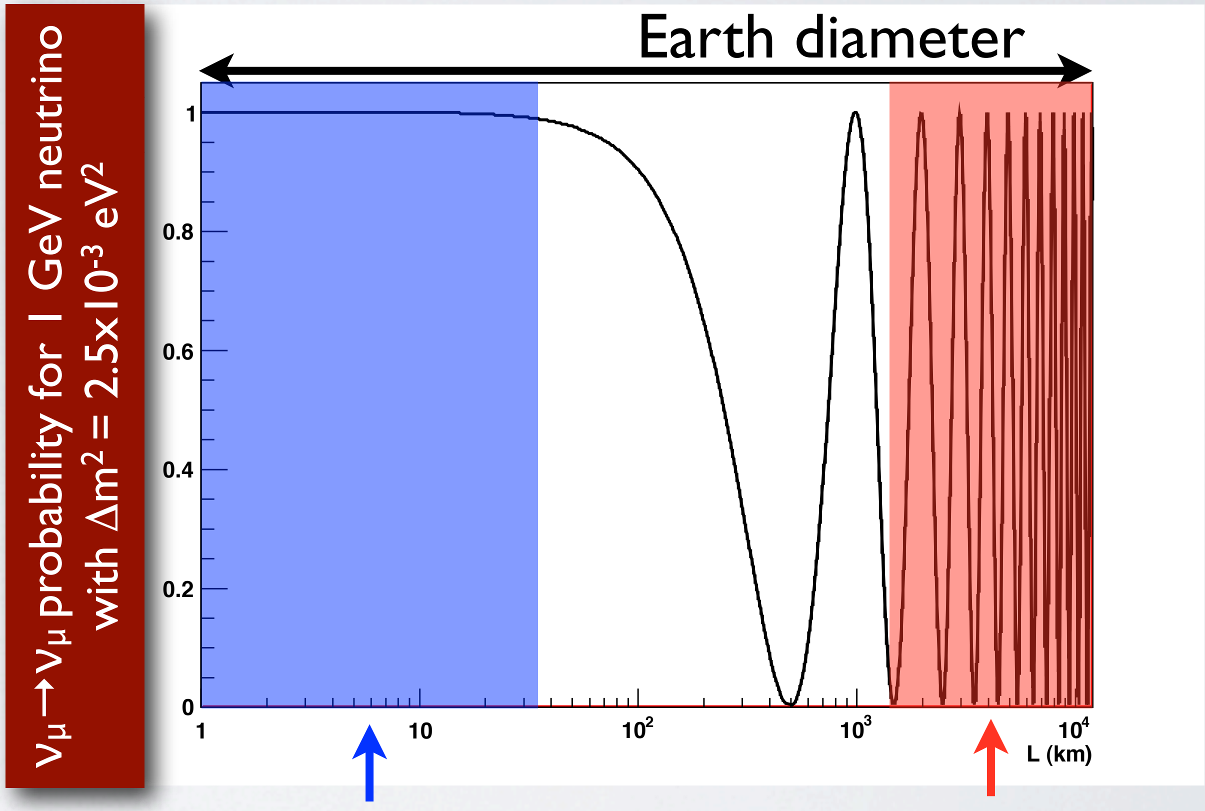
Cosmic ray

Detection of **down-going** and **up-going**

$\nu_\mu \rightarrow \nu_X$ oscillation

Cosmic ray

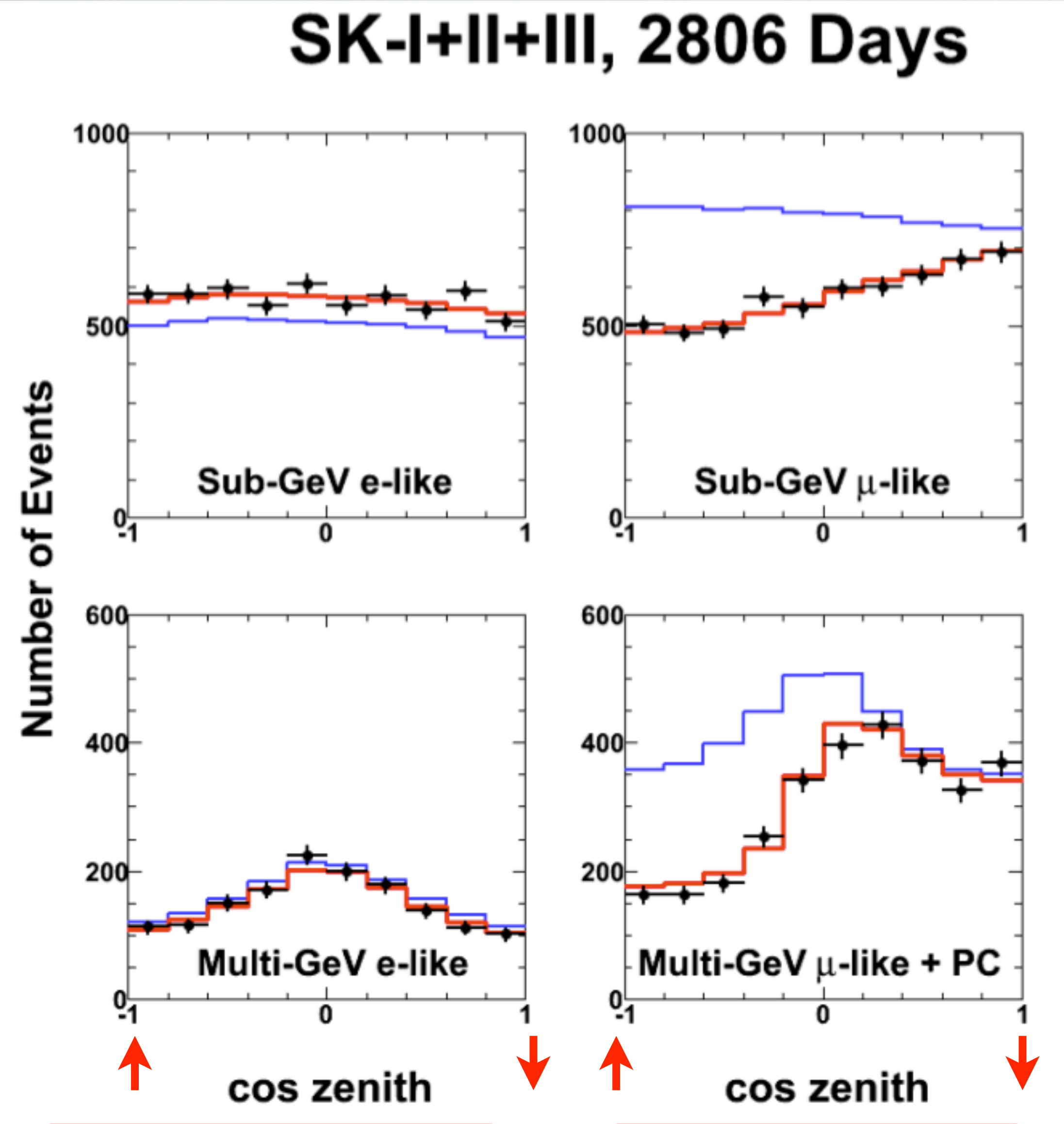
Atmosphere



down-going
NO OSCILLATION

up-going
OSCILLATION

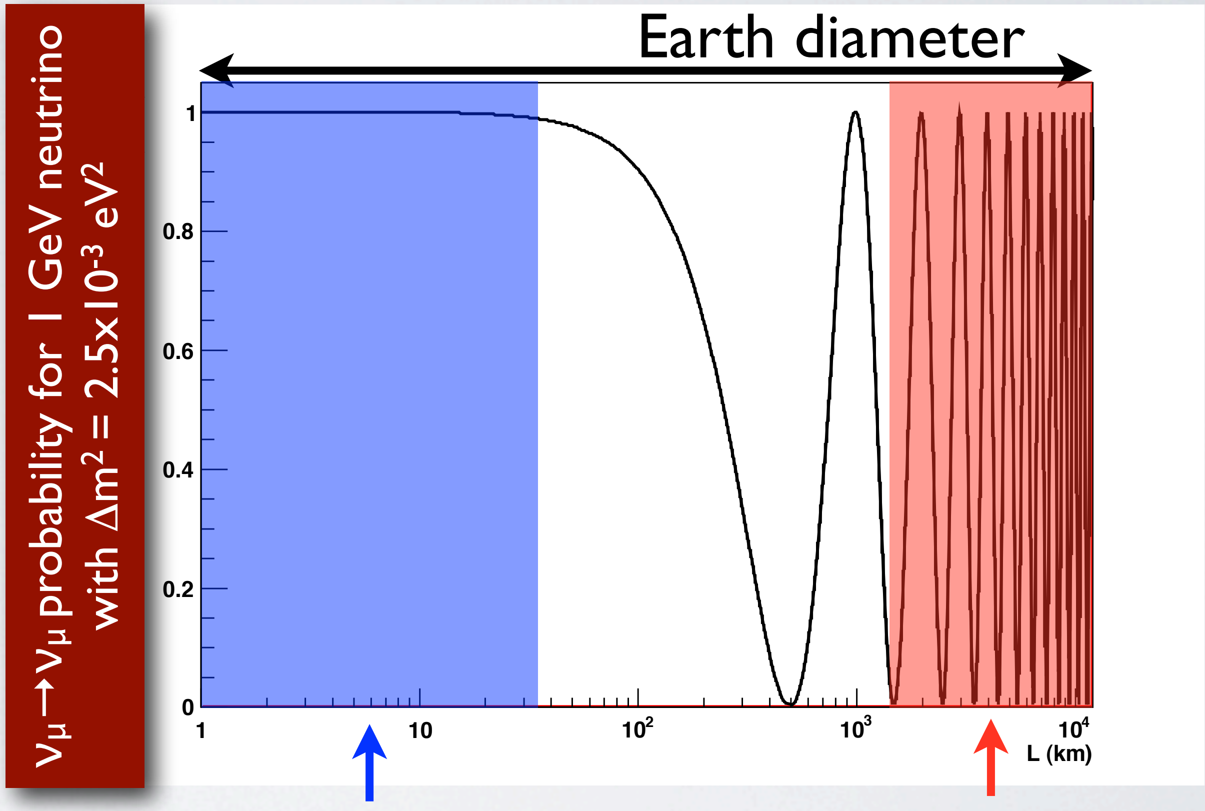
SK RESULTS



— Expected (NO OSCILLATION)

—●— Data

— Best fit (OSCILLATION)



down-going
NO OSCILLATION

up-going
OSCILLATION

No ν_e appeared

ν_μ disappeared

Indirect $\nu_\mu \rightarrow \nu_\tau$ oscillation observation (3 flavours model)

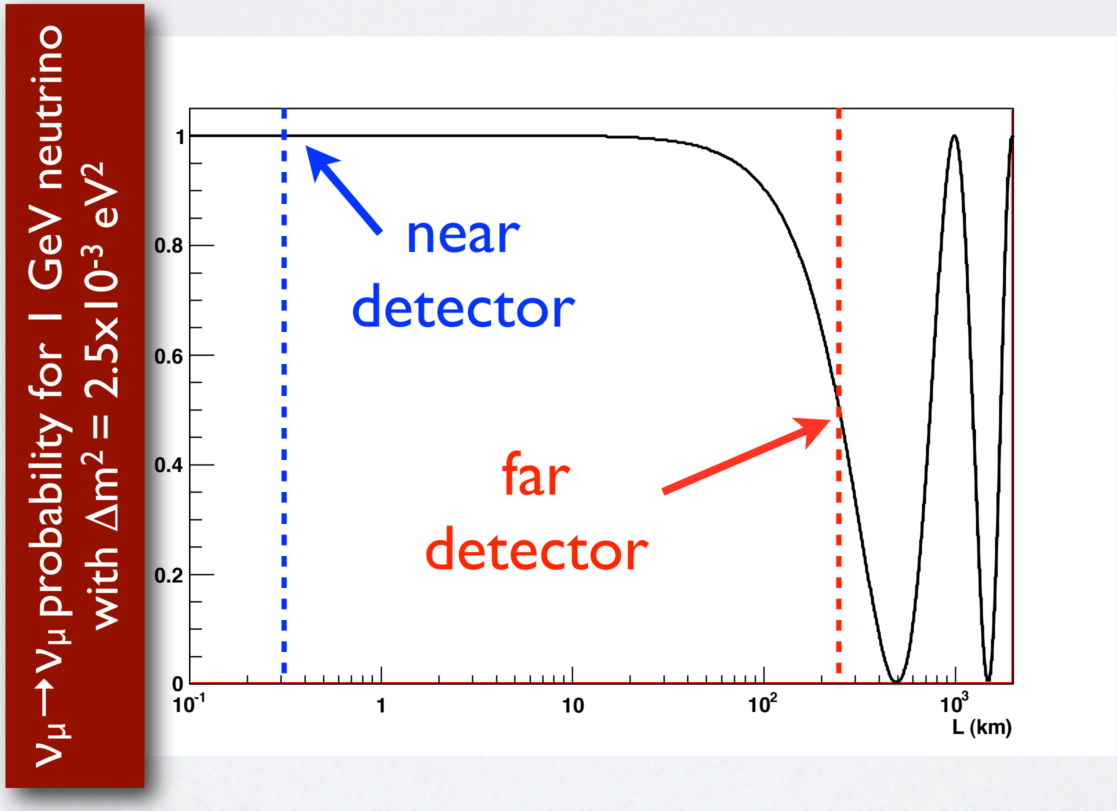
Best fit

$\sin^2(2\theta_{23}) \geq 0.92$

$1.9 \leq |\Delta m^2_{31}| \, / \, 10^{-3} \text{ eV}^2 \leq 2.6$

LONG BASELINE EXPERIMENTS

- **Long baseline** neutrino oscillation experiments aim at the precise measurement of the oscillation parameters using a neutrino beam.
- The advantage is that the **neutrino energy** can be **tuned** to match the baseline and the expected mass splitting.
- The neutrino spectra are measured near the source **before the oscillation** (**near detector**) and at the foreseen baseline **after the oscillation** (**far detector**).

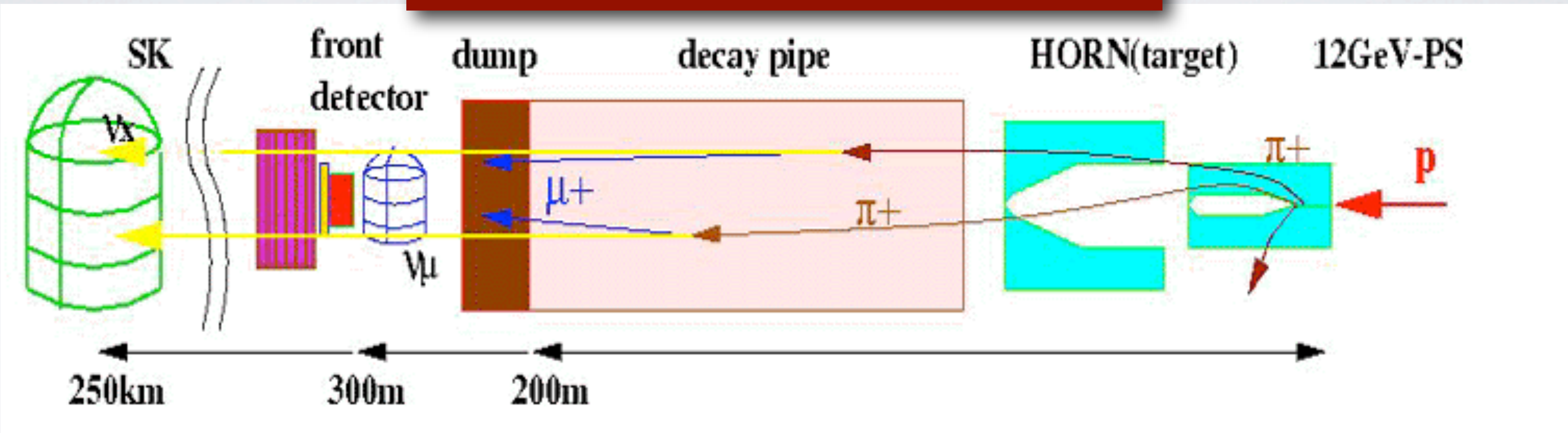


NEUTRINO BEAM

- **Standard neutrino beams** are used to **produce** ν_μ and typically the chain is the following:

1. Protons are accelerated and shot on a Carbon target.
2. Pions (and kaons) are focused by electromagnetic fields in the "horns".
3. Pions decay producing muons and neutrinos.

Scheme of the K2K beam



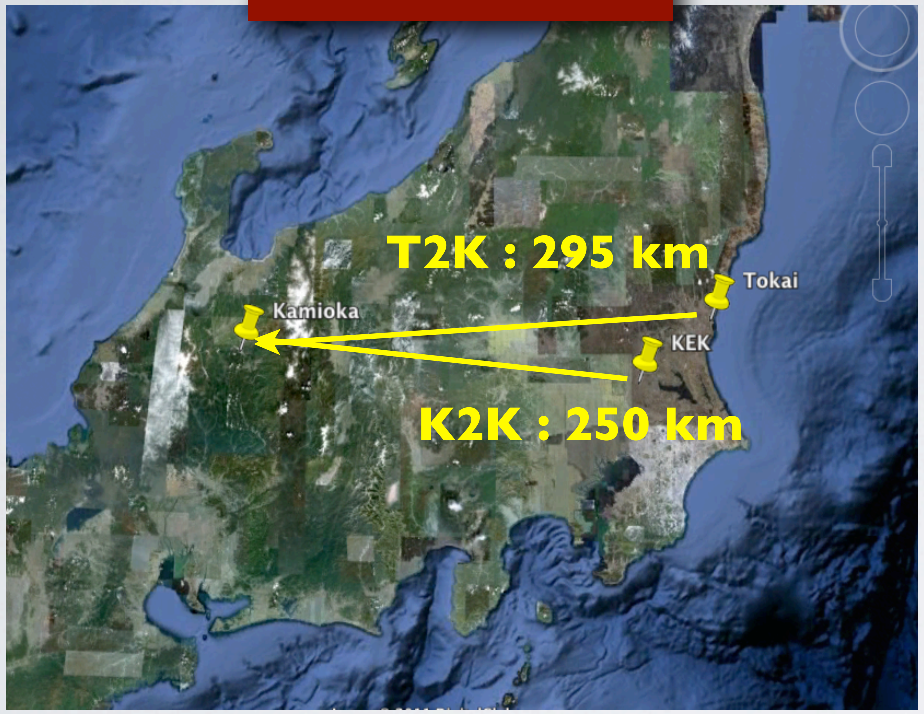
- The length of the decay pipe is tuned to optimised the decay of the pions and avoid the decay of the muons which would contaminate the beam with ν_e.

$$\boxed{\pi^+ \to \mu^+\nu_\mu}$$

$$\xcancel{\mu^+ \to e^+\nu_e\bar{\nu}_\mu}$$

LONG BASELINE EXPERIMENTS

K2K - T2K



- SK as far detector.
- **K2K** took data between 1999 and 2005.
- **T2K** started in January 2010: unfortunately the recent earthquake might retard the final results.

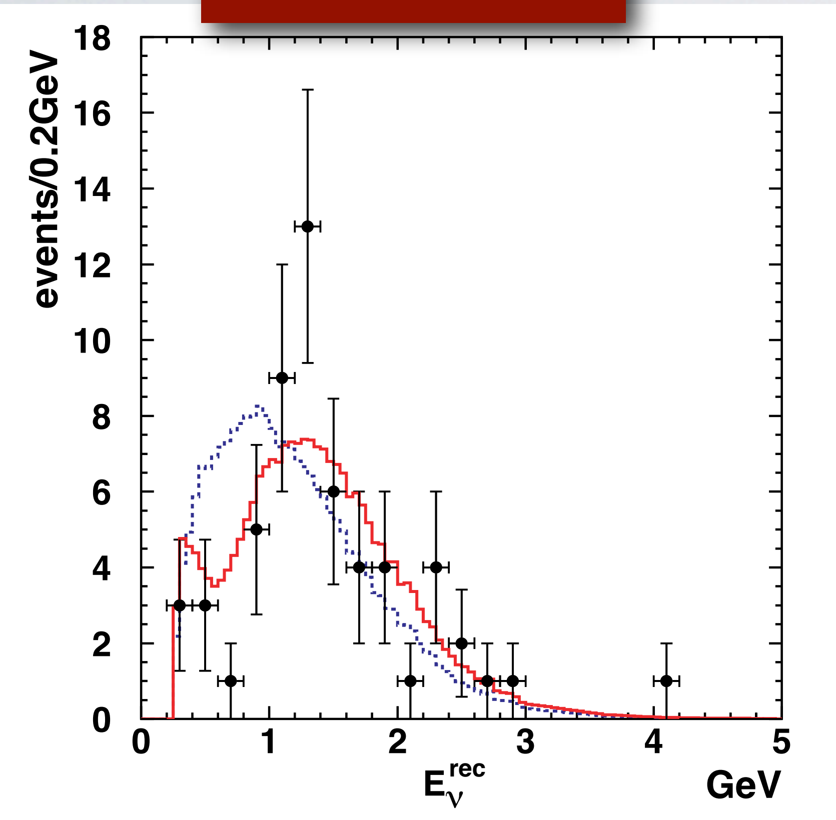
MINOS

- The detection technology of **MINOS** (both for far and near detectors) is based on scintillation strips interleaved by magnetised steel.
- MINOS started data taking in 2002.

Experiment	Baseline	ν_μ E (peak)	L/E (km/GeV)	optimal Δm^2 (eV^2)
K2K	250 km	~ 1 GeV	~ 250	4.9E-3
T2K	295 km	~ 600 MeV	~ 490	2.5E-3
MINOS	730 km	~ 3 GeV	~ 250	4.9E-3

RESULTS (90% C.L.)

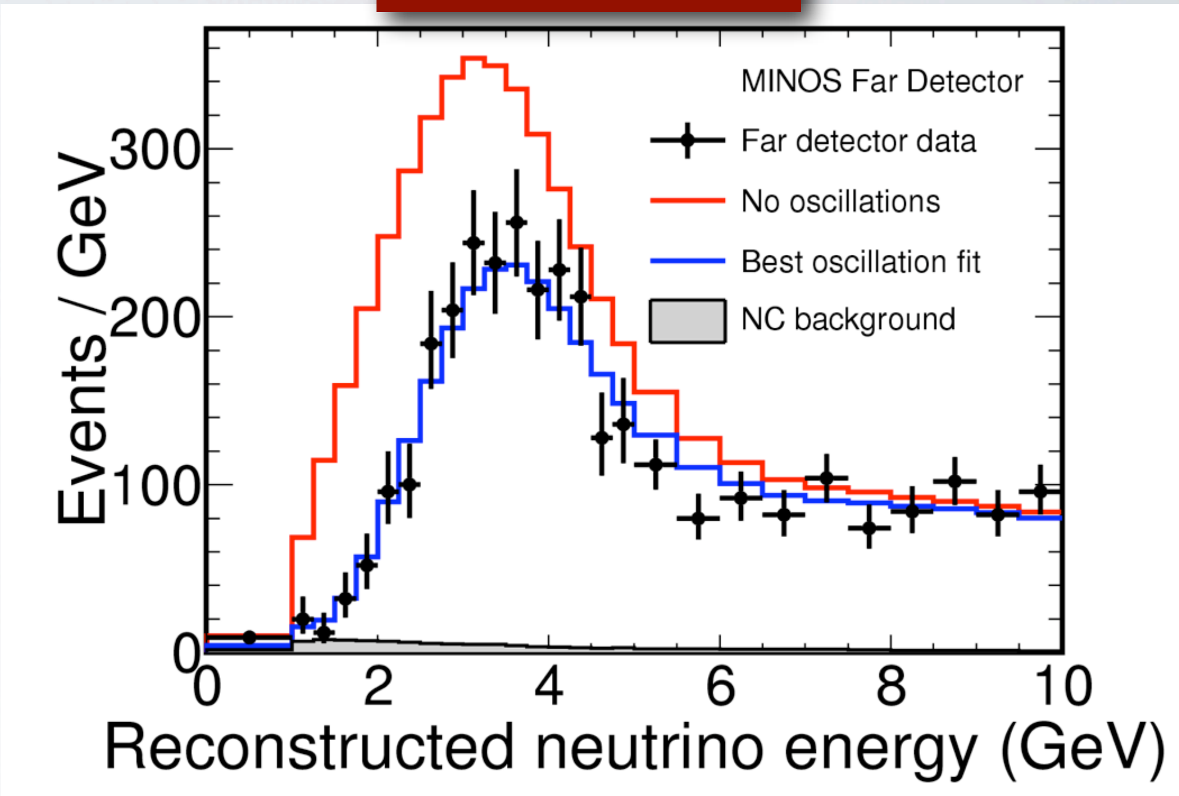
K2K



$\sin^2(2\theta_{23}) \geq 0.6$

$1.9 \leq |\Delta m^2_{31}| / 10^{-3}\ \mathrm{eV}^2 \leq 3.5$

MINOS



$\sin^2(2\theta_{23}) \geq 0.87$

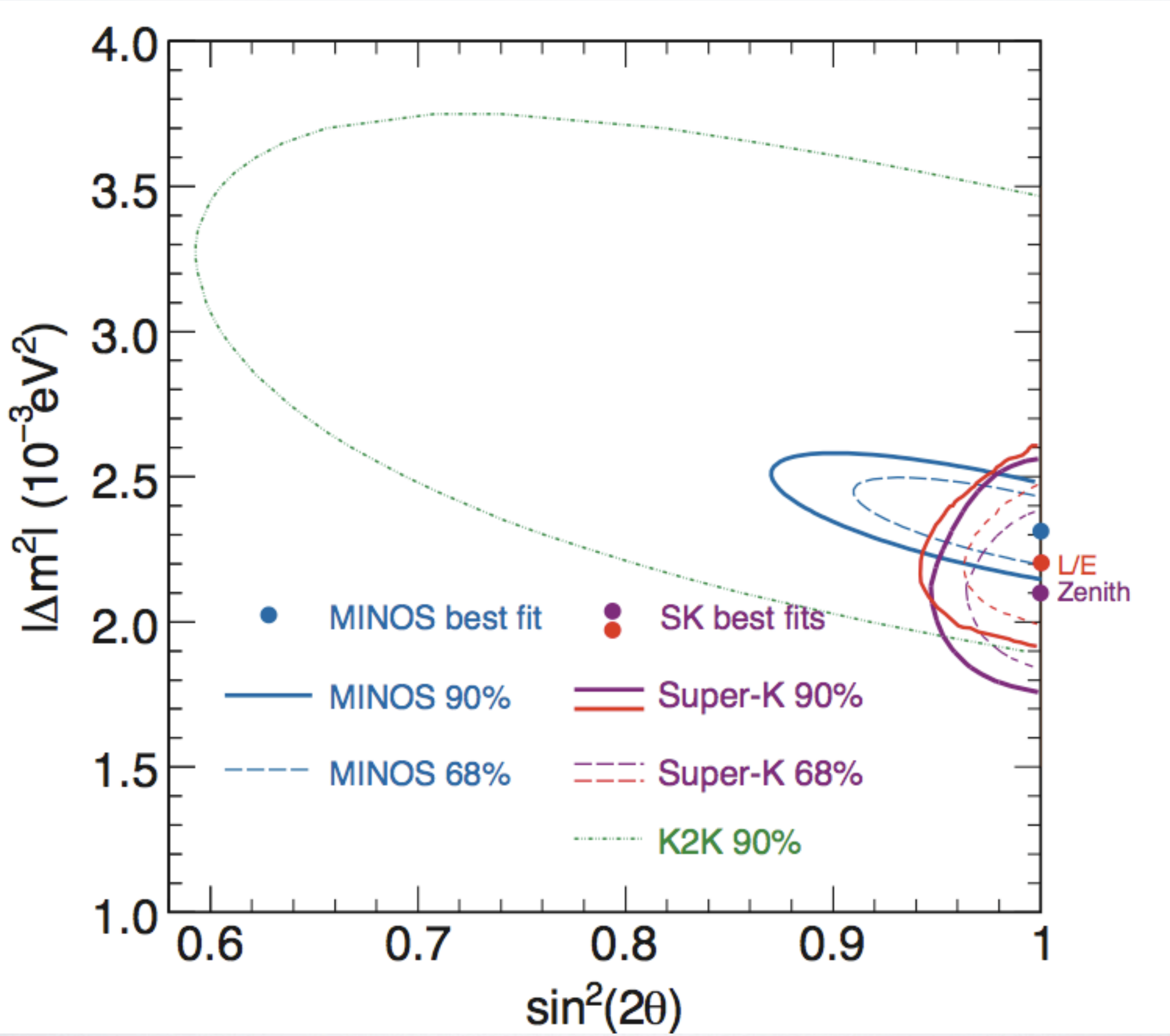
$2.24 \leq |\Delta m^2_{31}| / 10^{-3}\ \mathrm{eV}^2 \leq 2.44$

T2K Goals

$\delta(\sin^2(2\theta_{23})) \sim 0.01$

$\delta(\Delta m^2_{23}) \leq 3 \times 10^{-5}$

RESULTS


4.0
3.5
3.0
2.5
2.0
1.5
1.0
$|\Delta m^2|$ (10^{-3}eV^2)
0.6
0.7
0.8
0.9
1
$\sin^2(2\theta)$
L/E
Zenith
MINOS best fit
SK best fits
MINOS 90%
Super-K 90%
MINOS 68%
Super-K 68%
K2K 90%

PARAMETERS

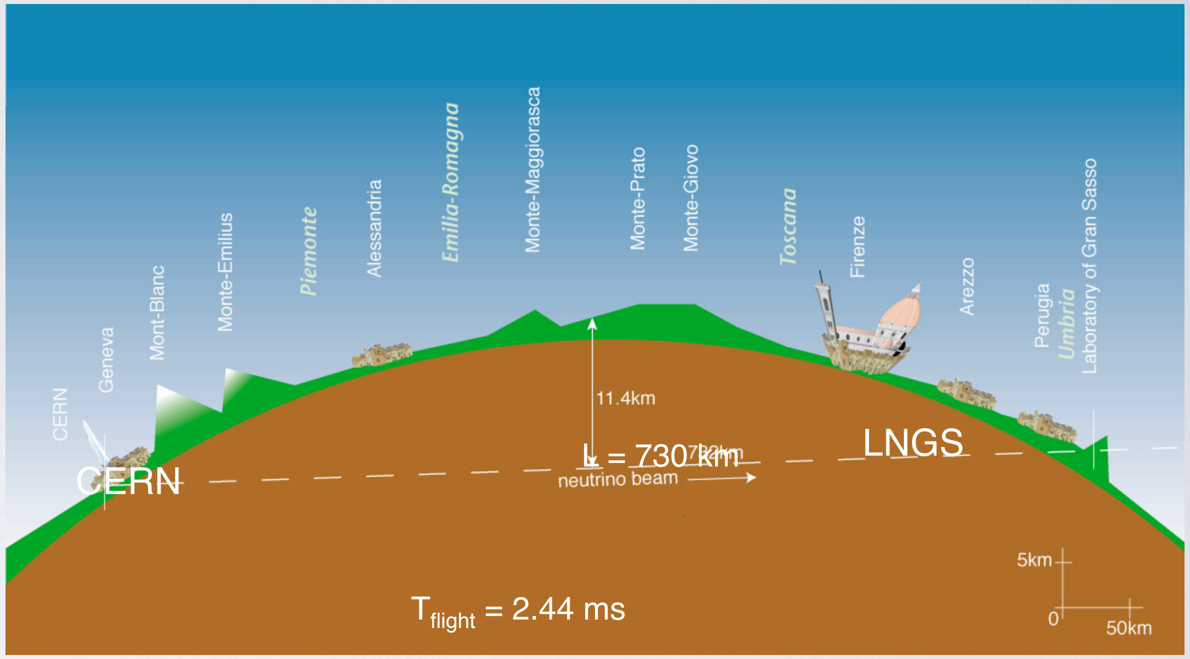
Parameter	**Present knowledge (90% C.L.)**	**Channel**	**Experiments**	**Future**
θ_{23}				
θ_{12}				
θ_{13}				
$\|\Delta m^2_{21}\|$				
Sign (Δm^2_{21})				
$\|\Delta m^2_{31}\|$				
Sign (Δm^2_{31})				
δ_{CP}				

PARAMETERS

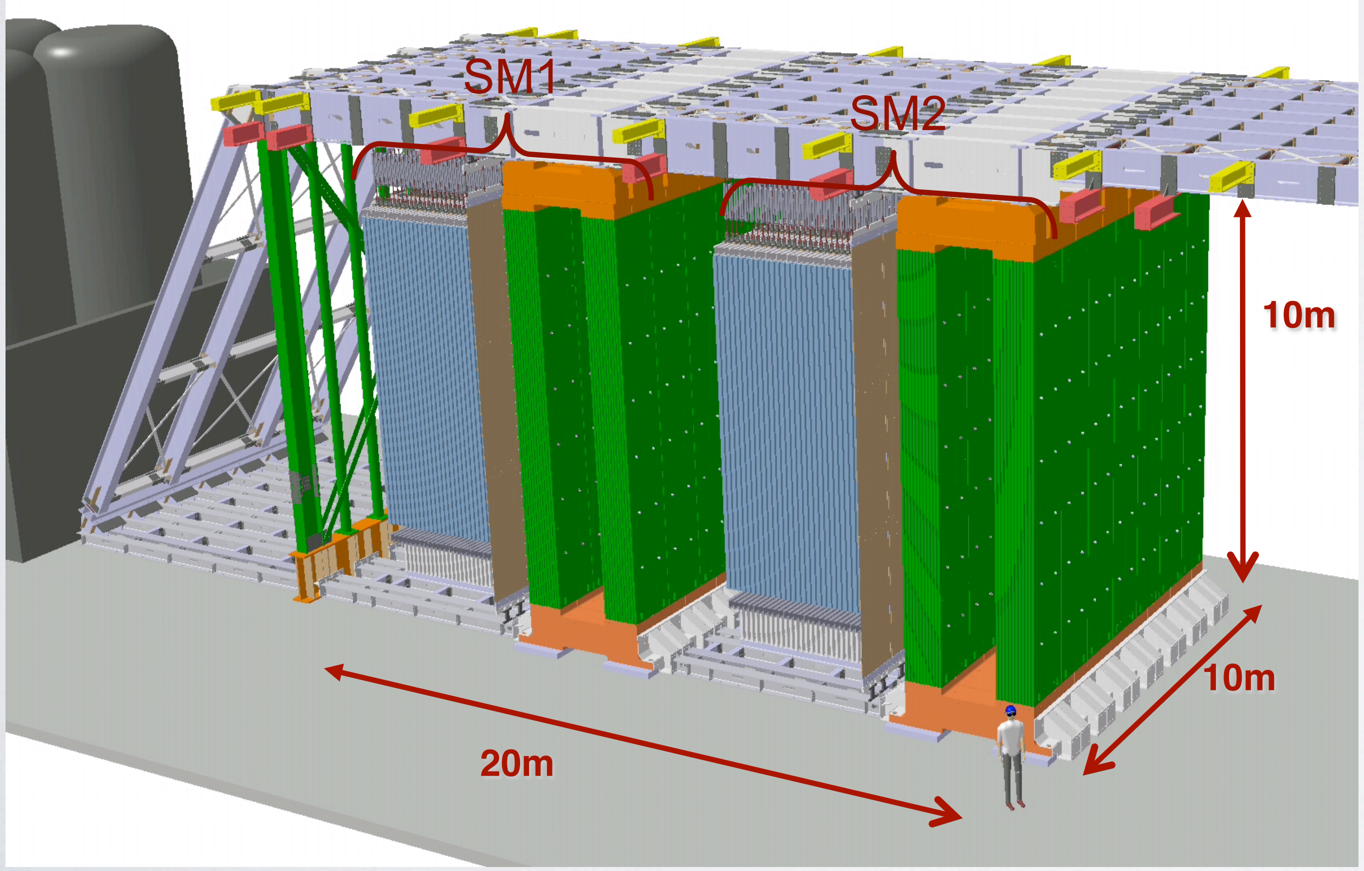
Parameter	**Present knowledge (90% C.L.)**	**Channel**	**Experiments**	**Future**
θ_{23}	$\sin^2(2\theta_{23}) \geq 0.96$	$P(\nu_\mu \rightarrow \nu_\mu)$	SK, (K2K, MINOS)	T2K
θ_{12}				
θ_{13}				
$\lvert\Delta m^2_{21}\rvert$				
Sign (Δm^2_{21})				
$\lvert\Delta m^2_{31}\rvert$	$2.24 \leq \lvert\Delta m^2_{31}\rvert$ / 10^{-3} eV$^2 \leq 2.44$	$P(\nu_\mu \rightarrow \nu_\mu)$	(SK, K2K), MINOS	MINOS, T2K
Sign (Δm^2_{31})				
δ_{CP}				

OPERA

- So far in the atmospheric sector only disappearance has been measured i.e. $\nu_\mu \rightarrow \nu_x$.
- To prove that the transition observed is actually $\nu_\mu \rightarrow \nu_\tau$, another long baseline (from CERN to Gran Sasso) experiment is taking data: **OPERA**.
- The goal is the first observation of the oscillation in the appearance mode, detecting the τ lepton.



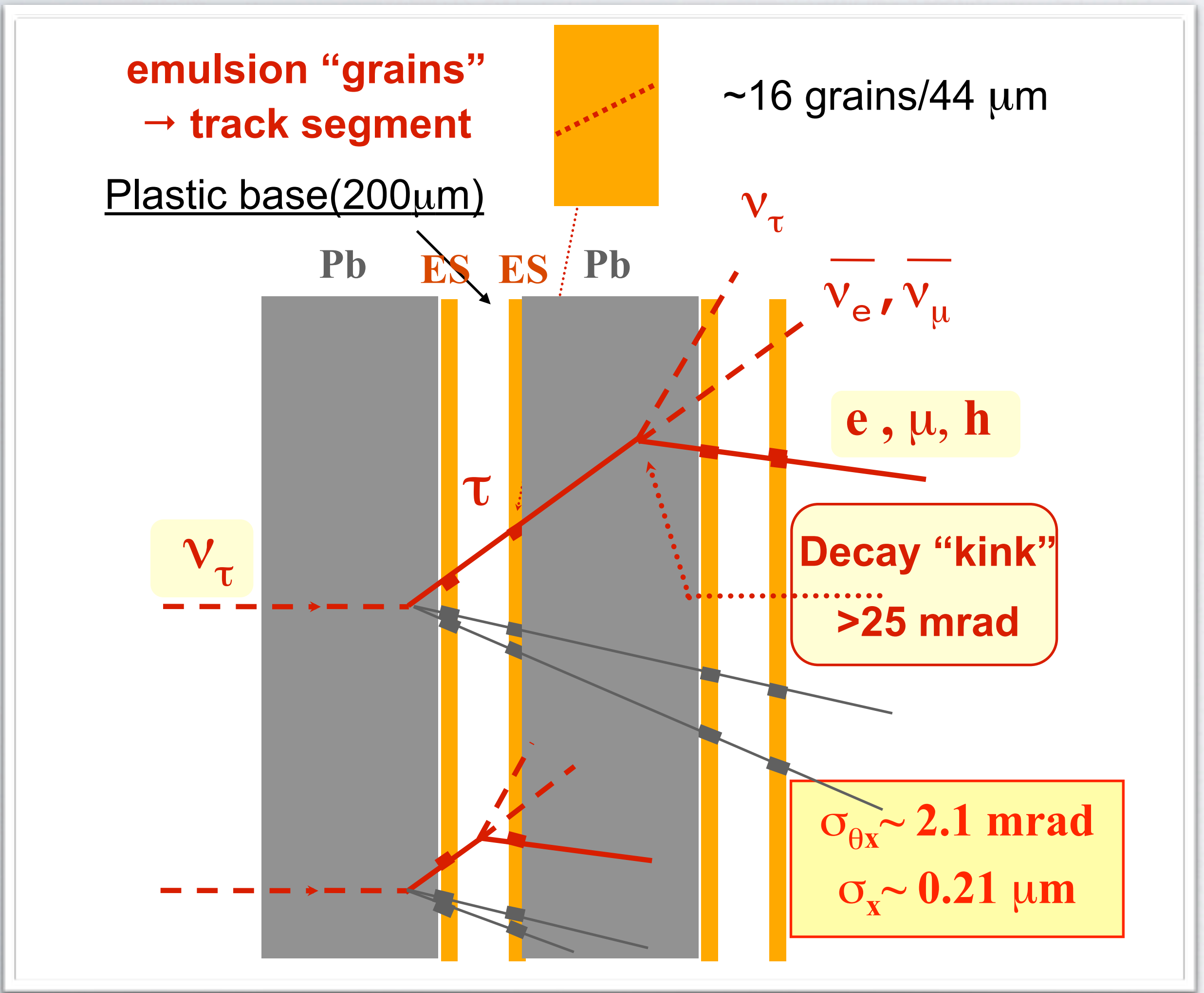
ν_μ ⟶ Oscillation ⟶ ν_τ



- The τ lepton decays rapidly ($\sim 10^{-13}$ s) and travels about a hundred μm.
- To observe it a huge spacial resolution is needed: this is achieved using photographic emulsions.

DETECTION TECHNIQUE

- The basic detection unit is the brick, made of sheets of lead and emulsions.
- The signal signature is the **kink decay** topology.
- To extract the correct brick and for the muon identification (selection ν_μ CC of events) the electronic detectors made of plastic scintillators and RPC planes are used.



Brick weight: 8.3 kg

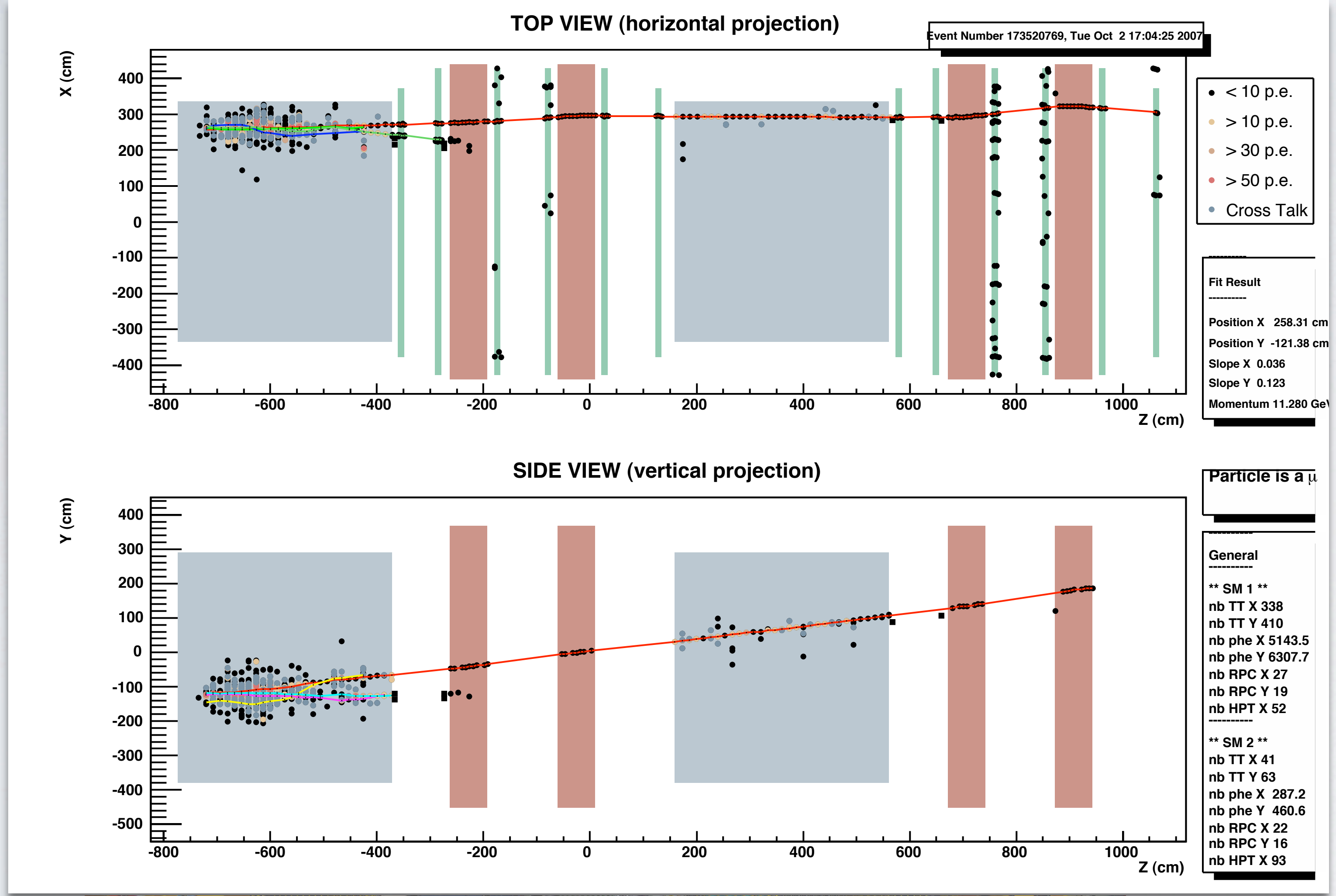
Sandwich of 56 (1mm) Pb sheets
+ 57 FUJI emulsion layers
+ 1 changeable sheet

TYPICAL EVENT

ν_μ CC interaction

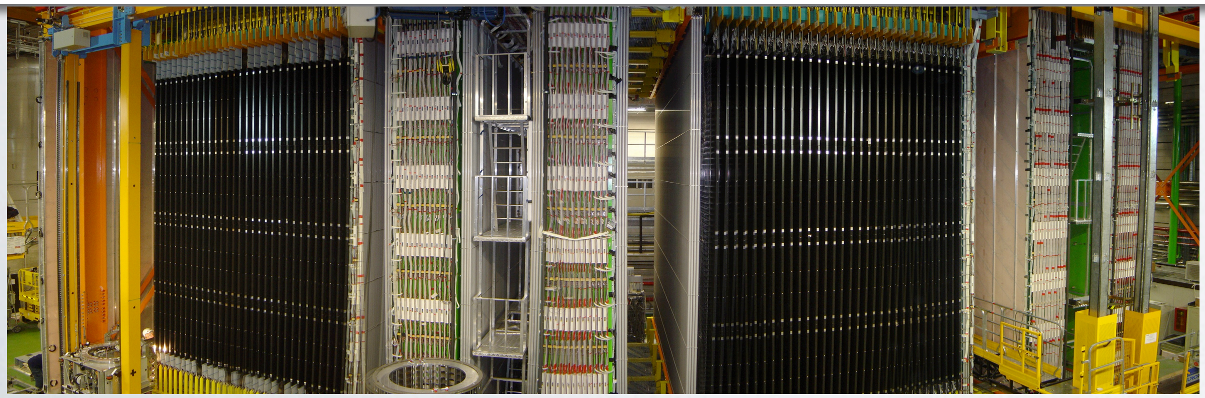
Reconstruction in electronic detectors

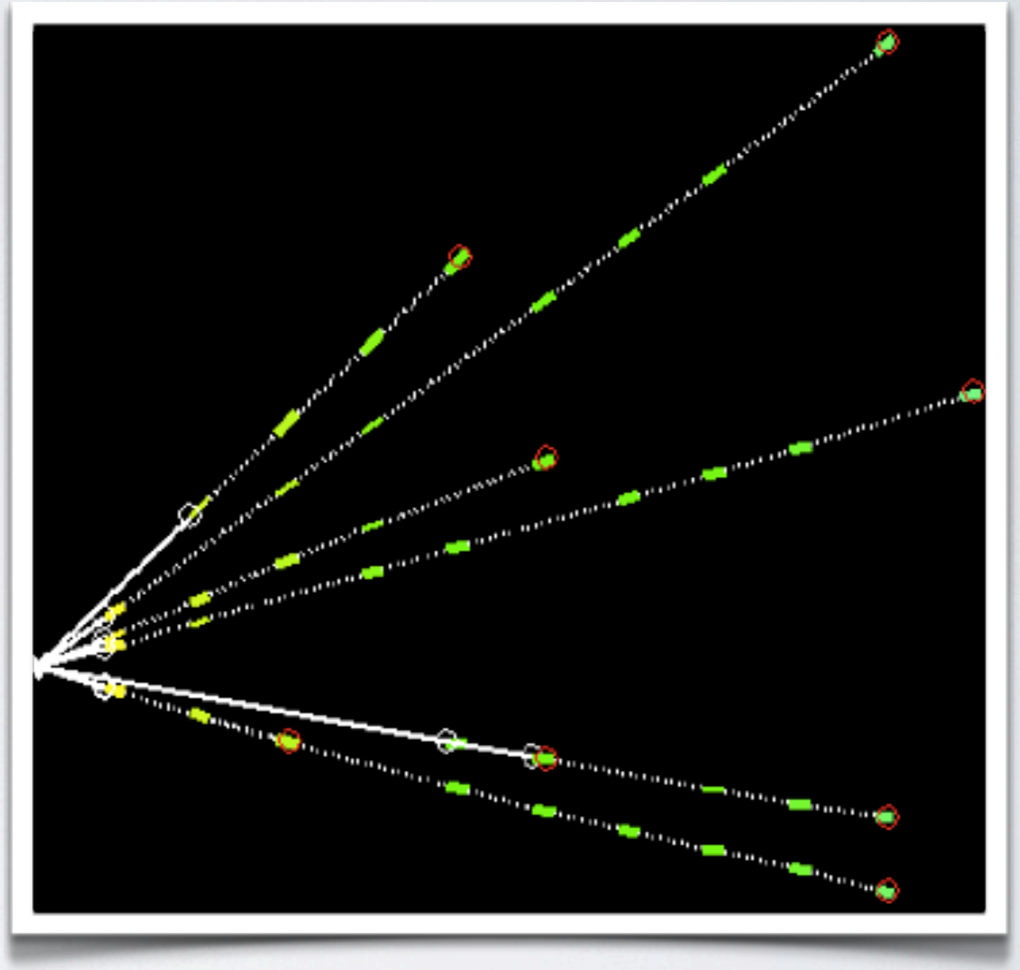
Reconstruction in emulsions



```
----------
Fit Result
----------
Position X   258.31 cm
Position Y  -121.38 cm
Slope X  0.036
Slope Y  0.123
Momentum 11.280 Ge
```

```
----------
General
----------
** SM 1 **
nb TT X 338
nb TT Y 410
nb phe X 5143.5
nb phe Y 6307.7
nb RPC X 27
nb RPC Y 19
nb HPT X 52
----------
** SM 2 **
nb TT X 41
nb TT Y 63
nb phe X  287.2
nb phe Y  460.6
nb RPC X 22
nb RPC Y 16
nb HPT X 93
```





Data taking ongoing since 2007 and **1 signal candidate** has been observed.

SOLAR SECTOR

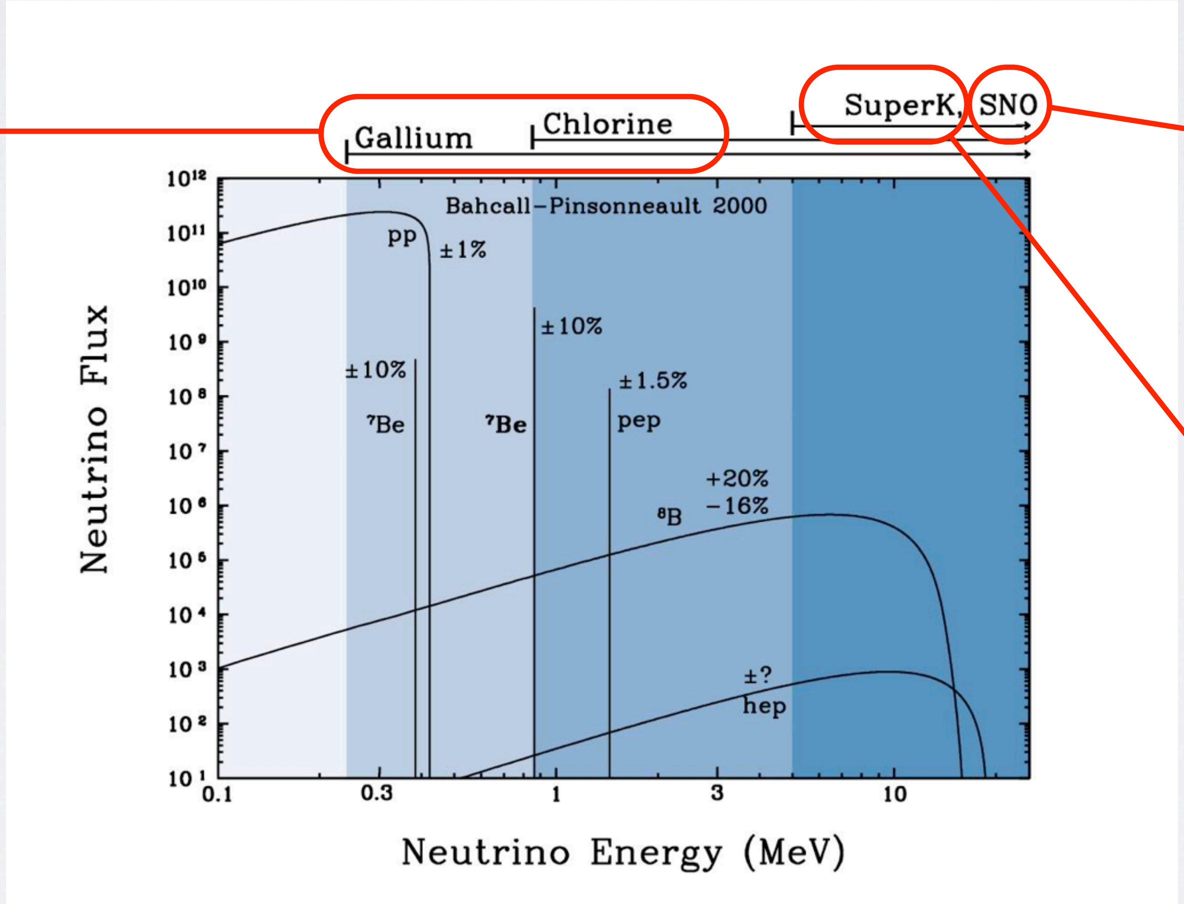
- To measure the parameters of the solar sector ($\boldsymbol{\theta_{12}}$, $\boldsymbol{\Delta m_{21}^2}$) a good channel to study is the $\nu_e \rightarrow \nu_x$ **transition**.

- Even in this case the idea is to compare the measured flux with the expected one, which relies on our knowledge on the standard solar model.

- According to the detection technology the different experiments are sensitive to different energies and therefore production chains in the sun.

Radio chemical

Homestake
SAGE
GALLEX
GNO



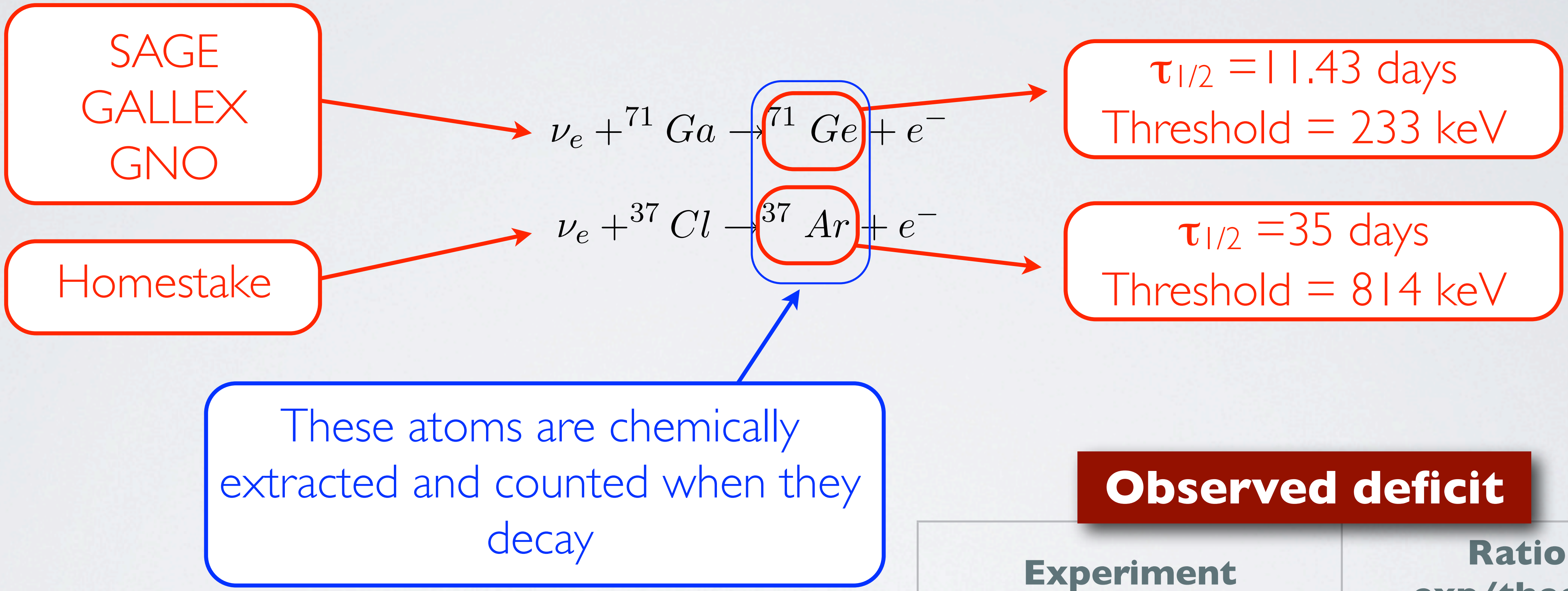
Cherenkov + scintillation

Cherenkov radiation

- In addition, the $\bar{\nu}_e \rightarrow \bar{\nu}_x$ **transition** can be studied using reactor neutrinos as it is done in the KamLAND experiment (scintillation).

RADIO CHEMICAL EXPERIMENTS

- These are the first experiments on solar neutrinos: the Homestake experiment (also known as Davis experiment) started in 1960.
- The detection principle is the following:



SAGE
GALLEX
GNO

Homestake

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

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

$\tau_{1/2}$ =11.43 days
Threshold = 233 keV

$\tau_{1/2}$ =35 days
Threshold = 814 keV

These atoms are chemically extracted and counted when they decay

- The advantage is the low threshold and the possibility to explore neutrinos coming from the pp chain.
- The disadvantage is the complex counting of the interactions and the fact that it is not real time detection.

Observed deficit

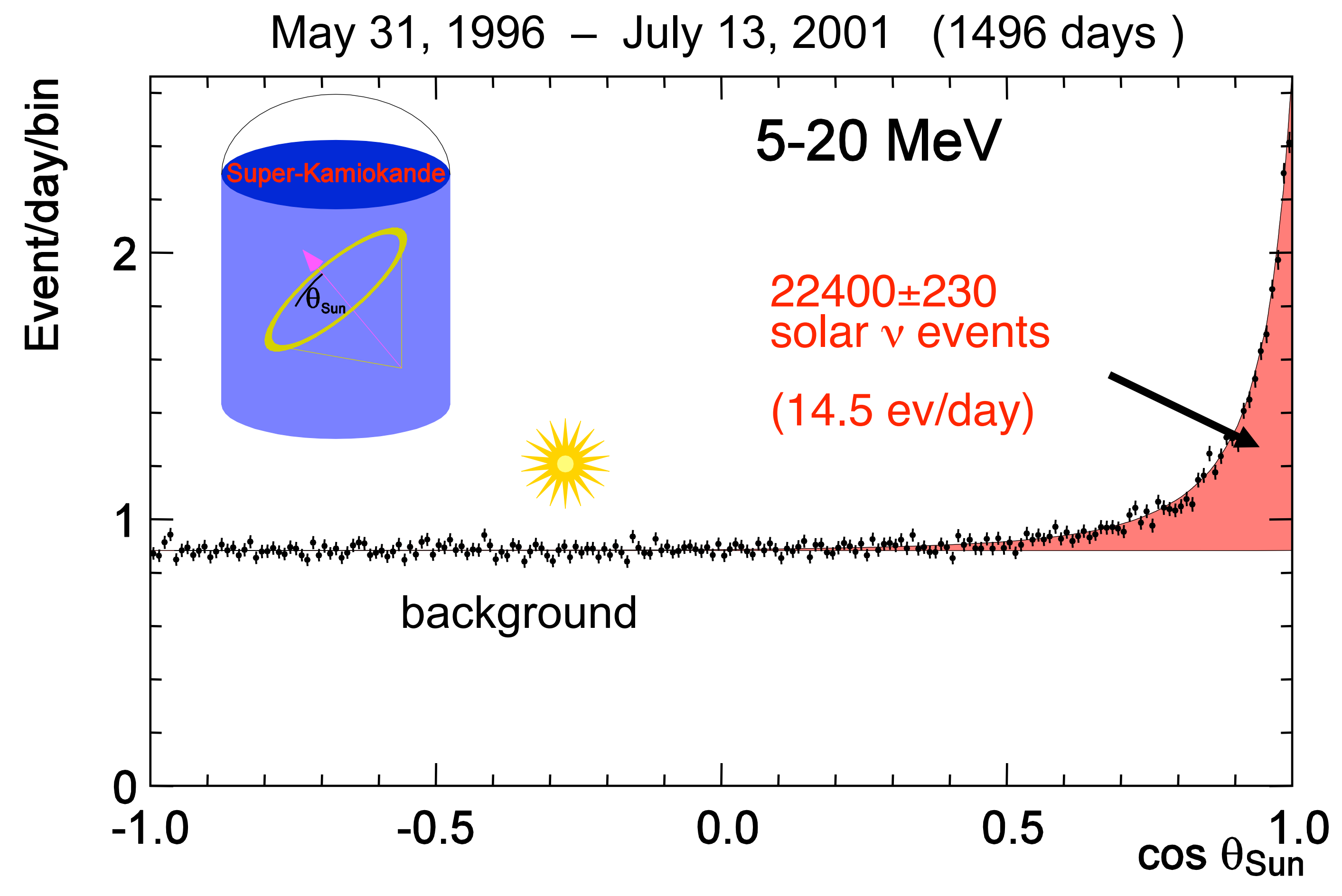
Experiment	**Ratio exp/theory**
Homestake (1968)	0.32
SAGE (1990)	0.53
Gallex (1992)	0.55

SUPER KAMIOKANDE

- The working principle of SK has been described in relation to atmospheric neutrinos.
- The signal that can be observed is the elastic scattering on electrons:

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

Threshold = 6.5 MeV



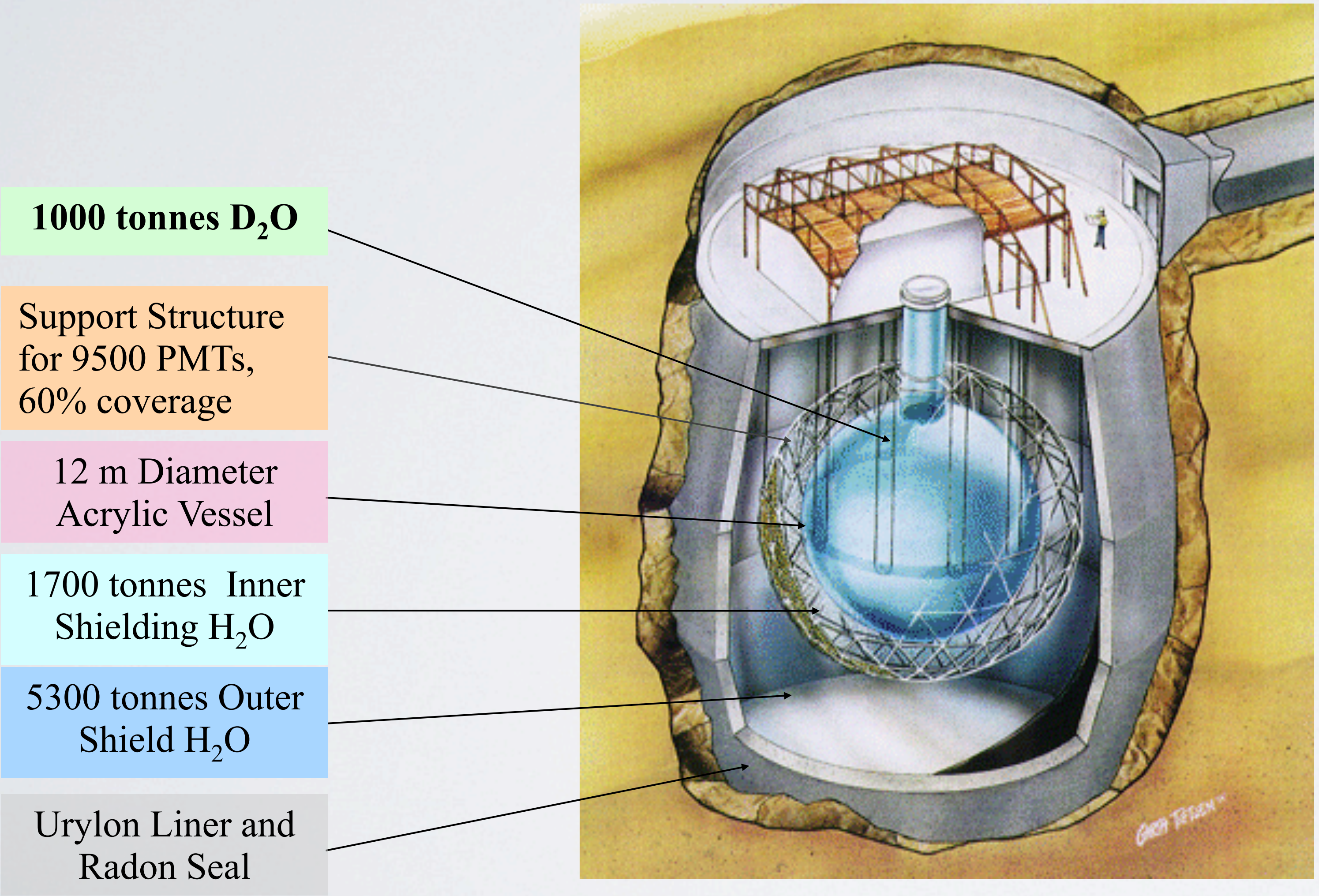
Observed deficit

Experiment	Ratio exp/theory
SK (1998)	0.41

NOTE: no evidence for spectrum distortion.

SNO

- **SNO** was an experiment located in Canada that uses Cerenkov detection method.
- The target is heavy water (D_2O) and the **experiment can detect all flavours of neutrinos** (depending on the channel studied).



1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

- The advantage is that it measures a **deficit** of the ν_e but also it **confirms** that the **total flux** of ν is in agreement with the SSM.

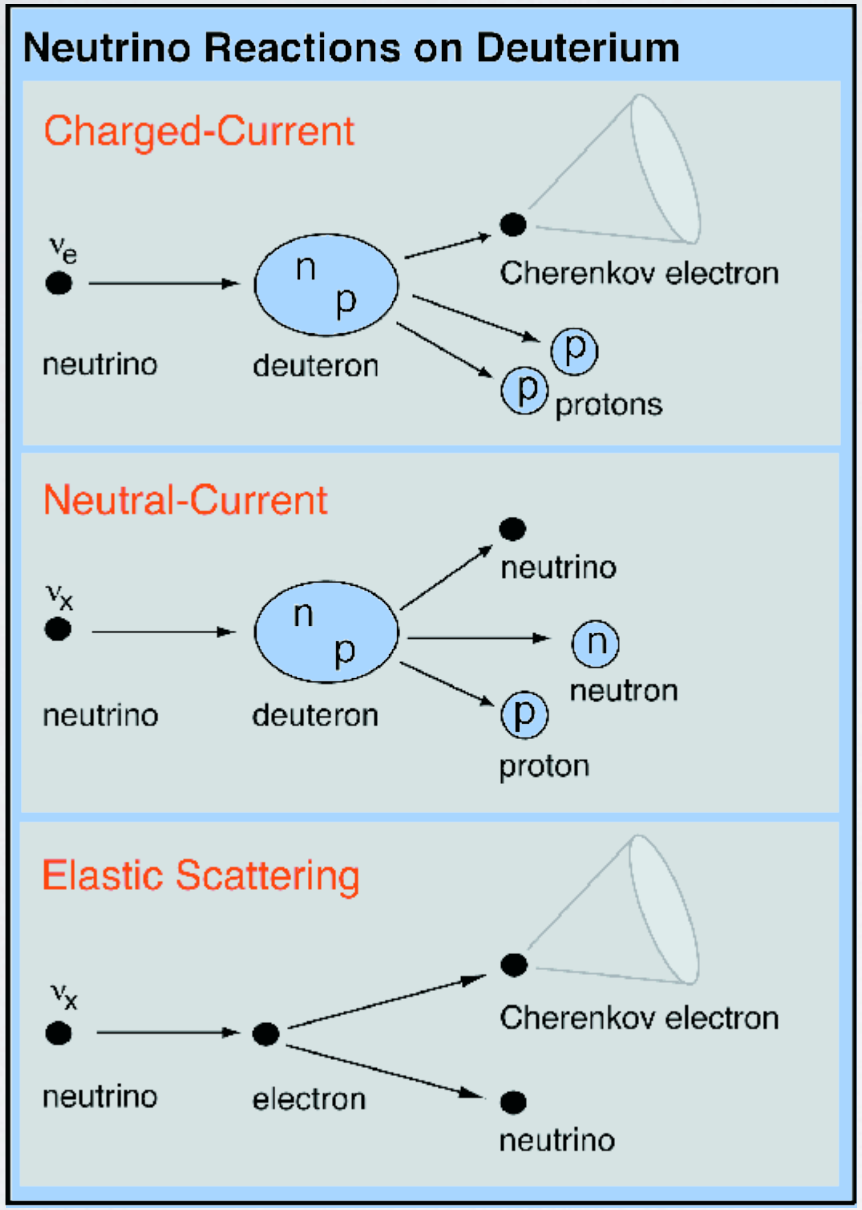
SNO

- The three reactions used are the following:

$$\nu_e + d \rightarrow p + p + e^-$$

$$\nu_x + d \rightarrow p + n + \nu_x$$

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



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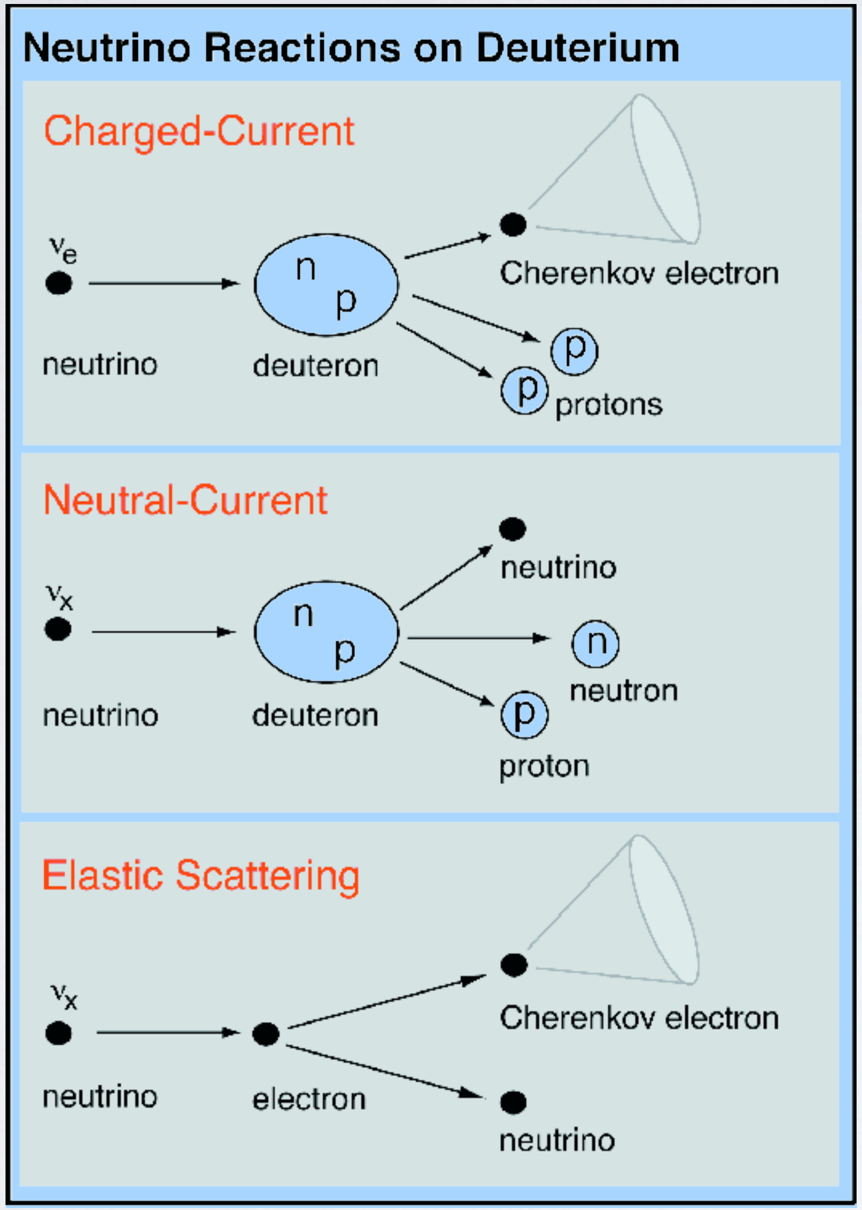

How is the neutron detected?

SNO

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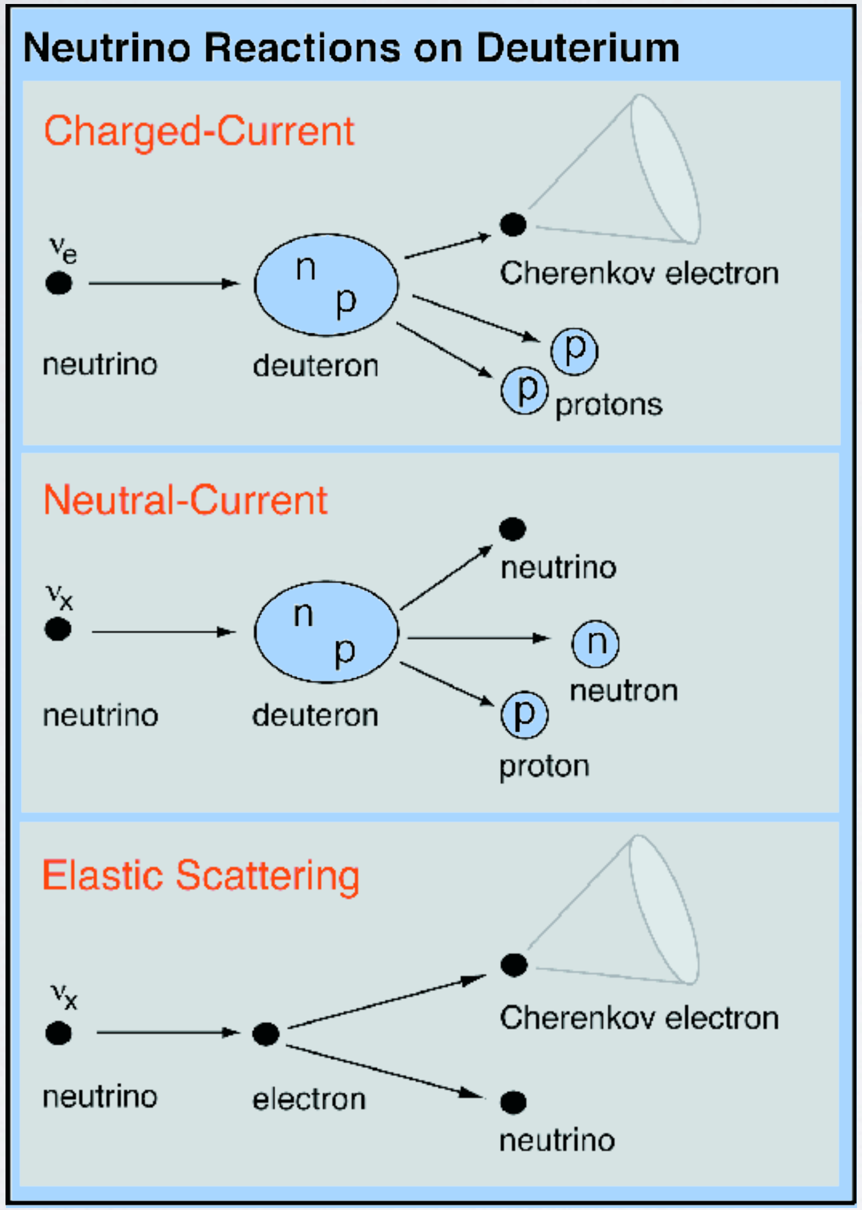

How is the neutron detected?

phase I

$$n +^2 H \rightarrow \gamma +^3 H$$

6.25 MeV

SNO

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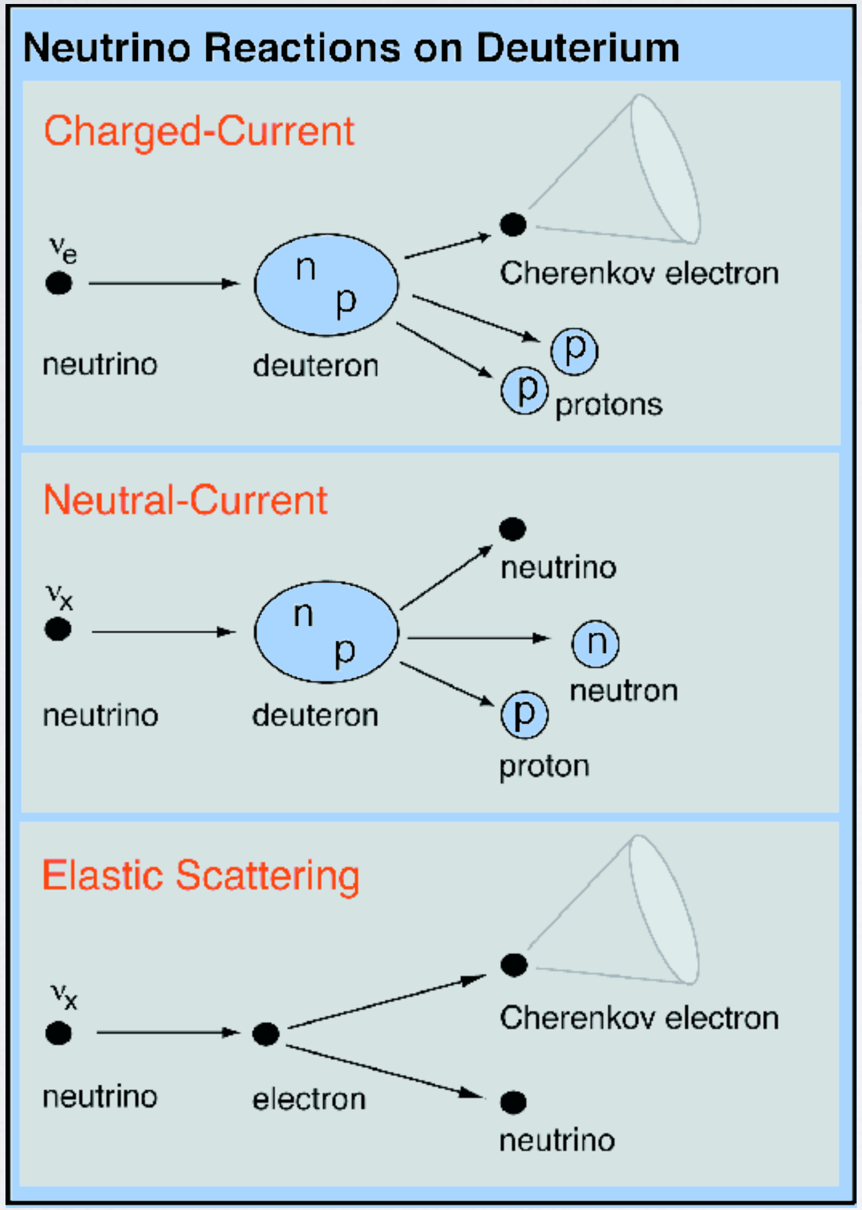


How is the neutron detected?

phase 1

$$n +^2 H \rightarrow \gamma +^3 H$$

6.25 MeV

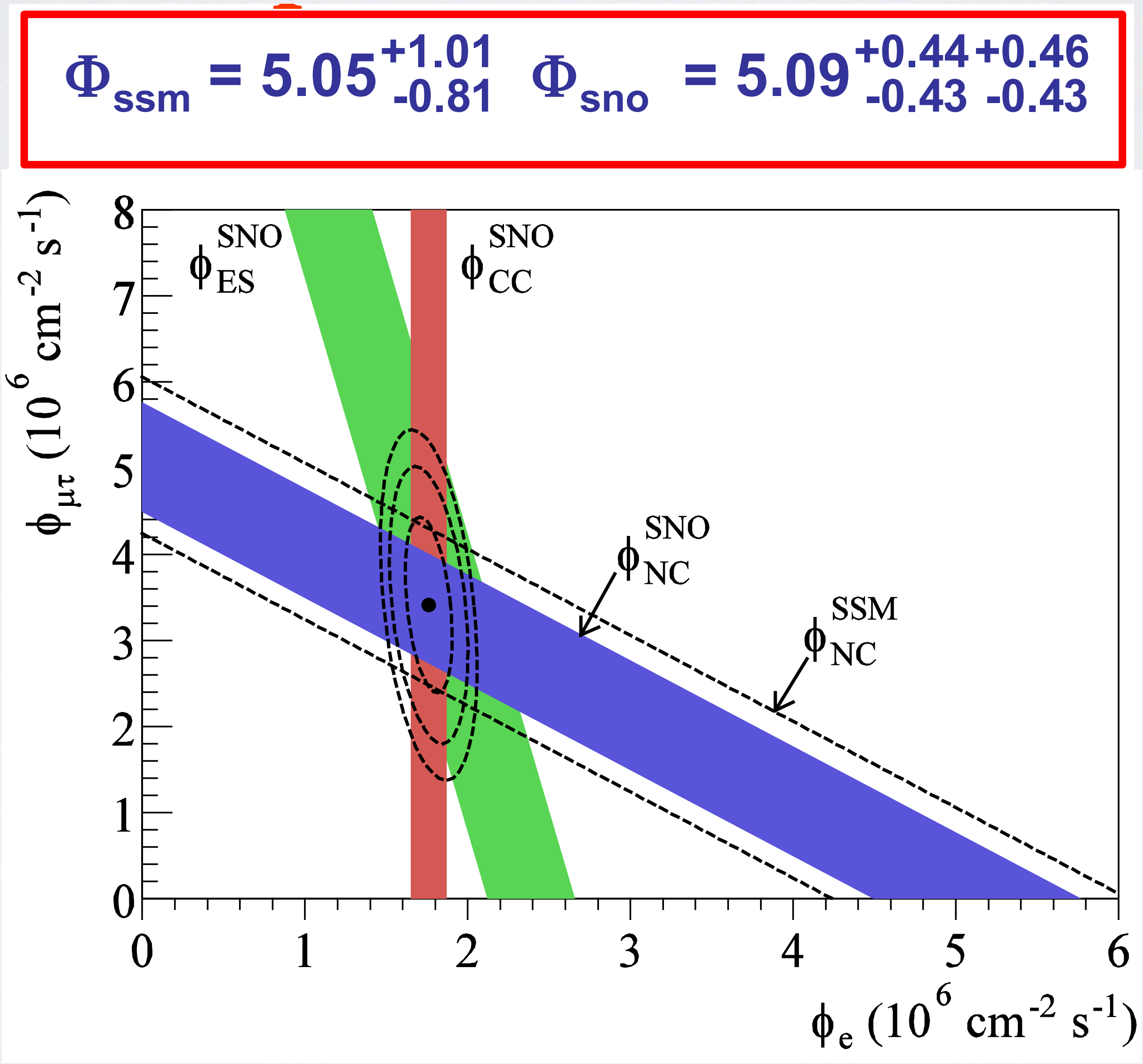
phase 2
2 ton of NaCl

$$n +^{35} Cl \rightarrow \gamma +^{36} Cl$$

8.6 MeV

SNO

- Using all the channels SNO found:
  1. About **30%** of the **expected ν_e flux** (in case of no oscillation).
  2. A **total flux in agreement with the SSM prediction**.
- The non oscillation hypothesis is ruled out at 5.3 σ C.L.



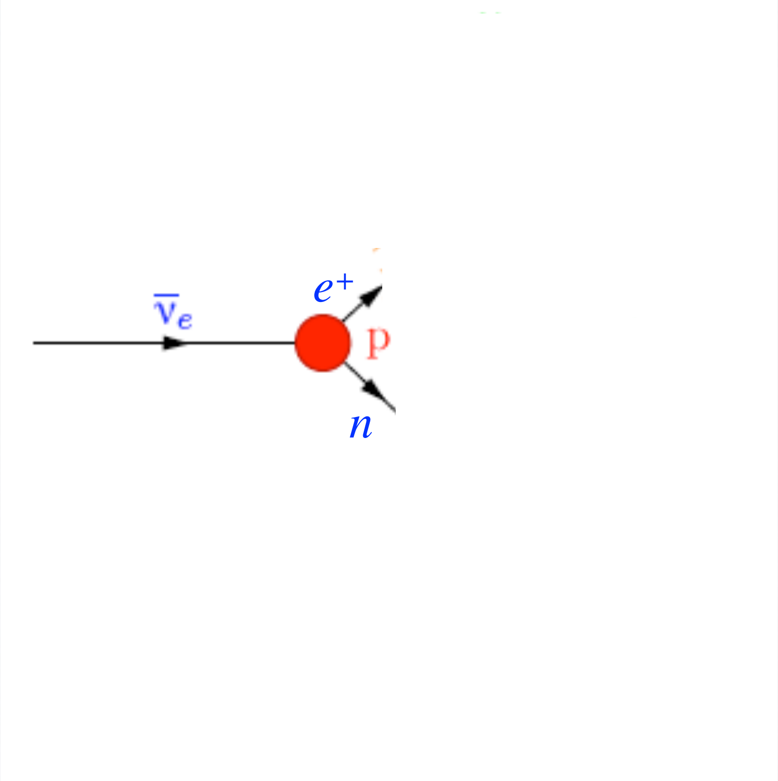
$$\Phi_{ssm} = 5.05^{+1.01}_{-0.81} \quad \Phi_{sno} = 5.09^{+0.44\,+0.46}_{-0.43\,-0.43}$$

KAMLAND

- KamLAND is a **liquid scintillator** detector located in Japan that measures $\overline{\nu}_e$ coming from nuclear reactors (equivalent of long baseline experiments for the solar sector).

- The reaction used is the following:

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



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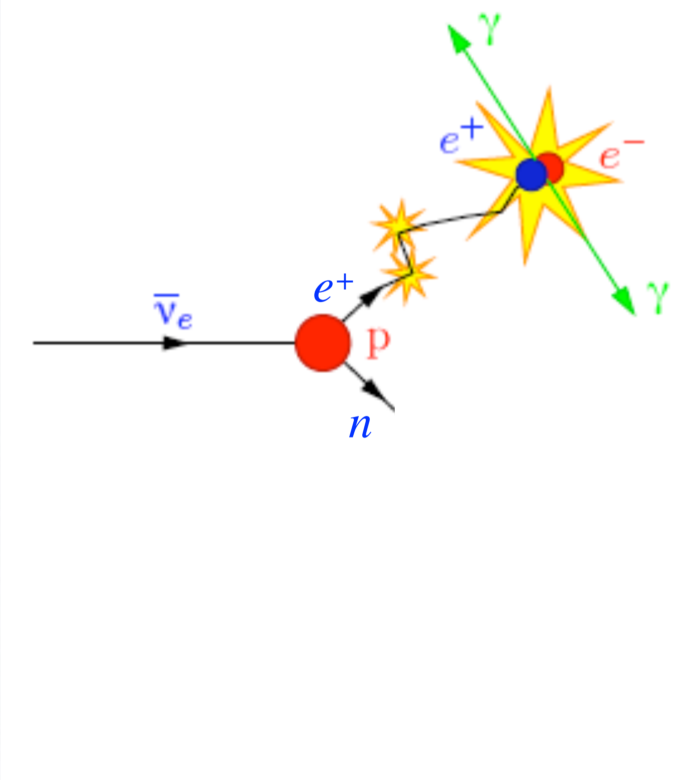
Charged particles passing through a liquid scintillator **emit light** (no directionality) that can be detected with PMT

The **positron annihilates** producing gammas at 1.022 MeV

Prompt signal (~10 ns)



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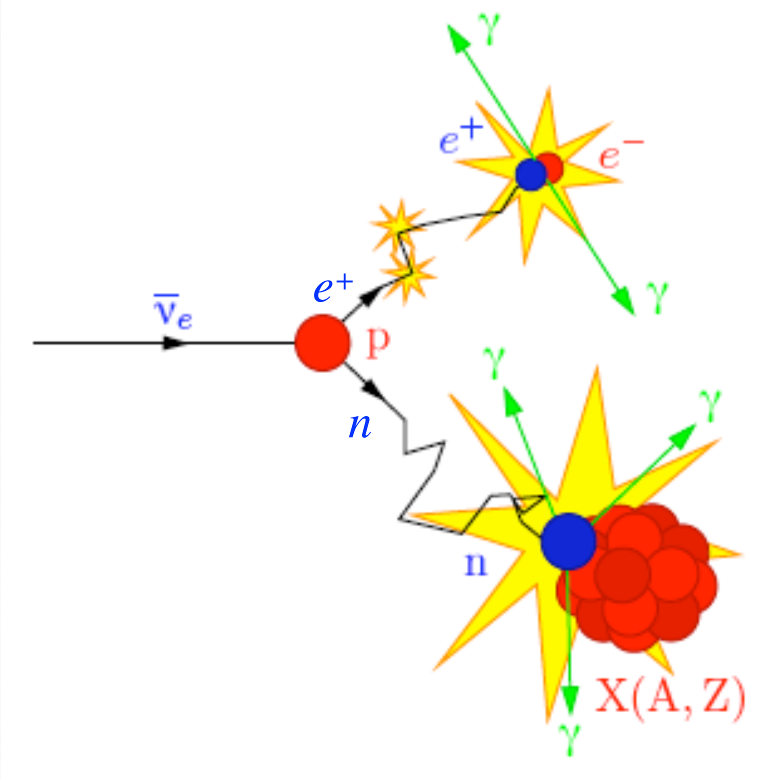


The neutrons are absorbed on H:

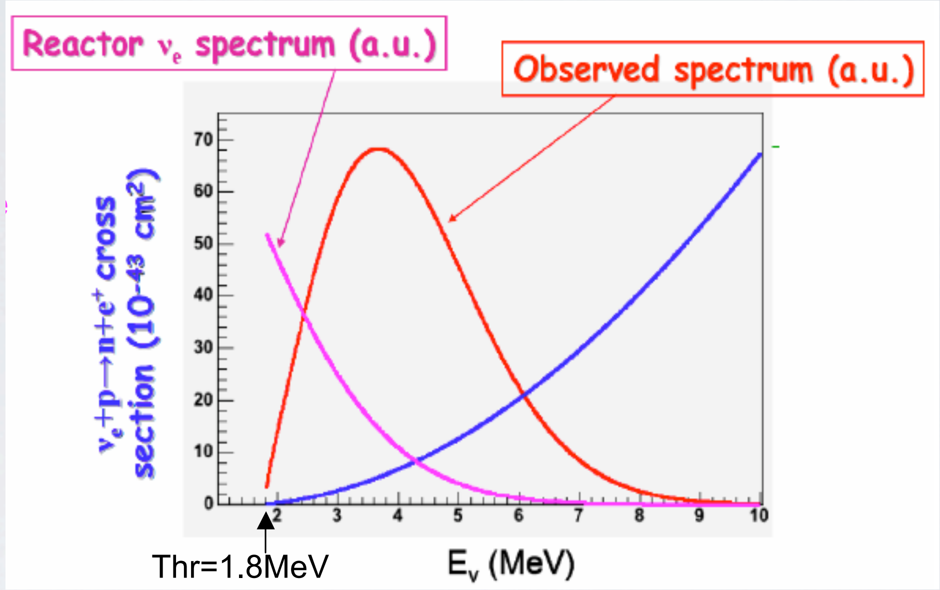
$$n + p \rightarrow^2 H + \gamma$$

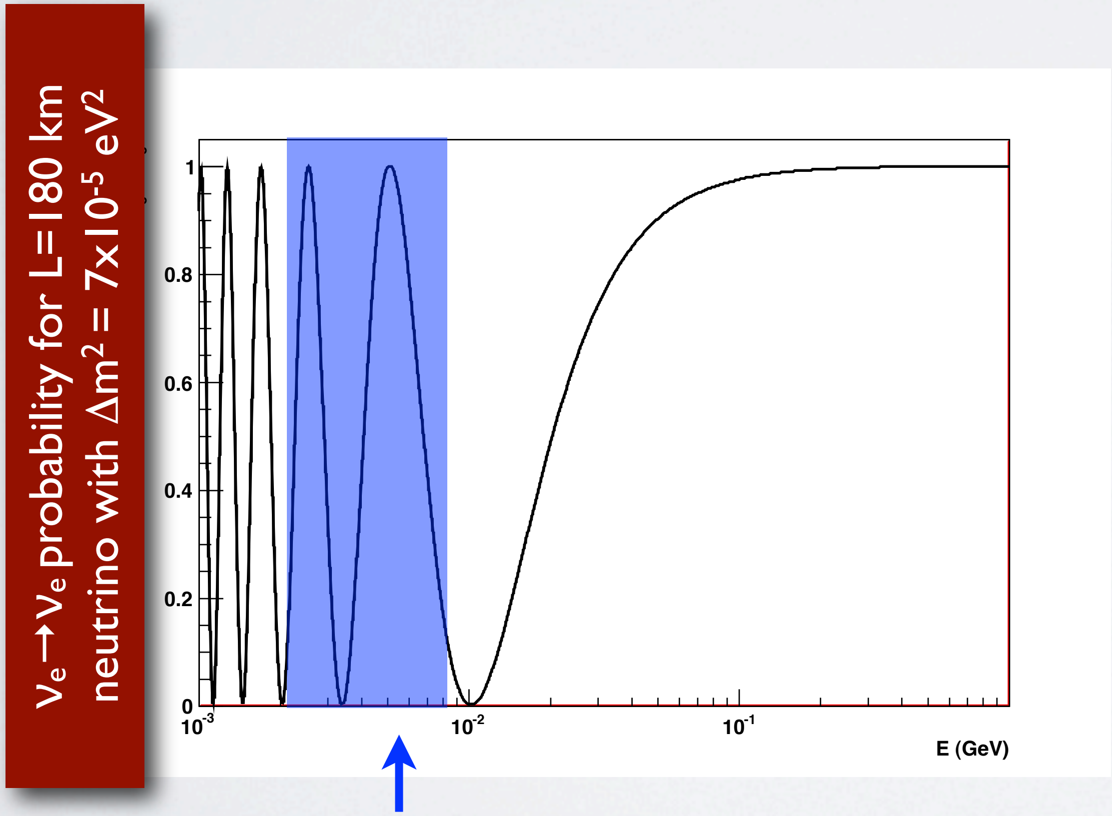
producing gammas at 2.2 MeV

Delayed signal (~200 μs)

KAMLAND

- The **antineutrinos** come from reactors and they have a spectra (flux times cross section) **between 1 and 10 MeV**.
- The antineutrinos come from many reactors and the **average baseline** (weighted on the flux) is about **180 km**.

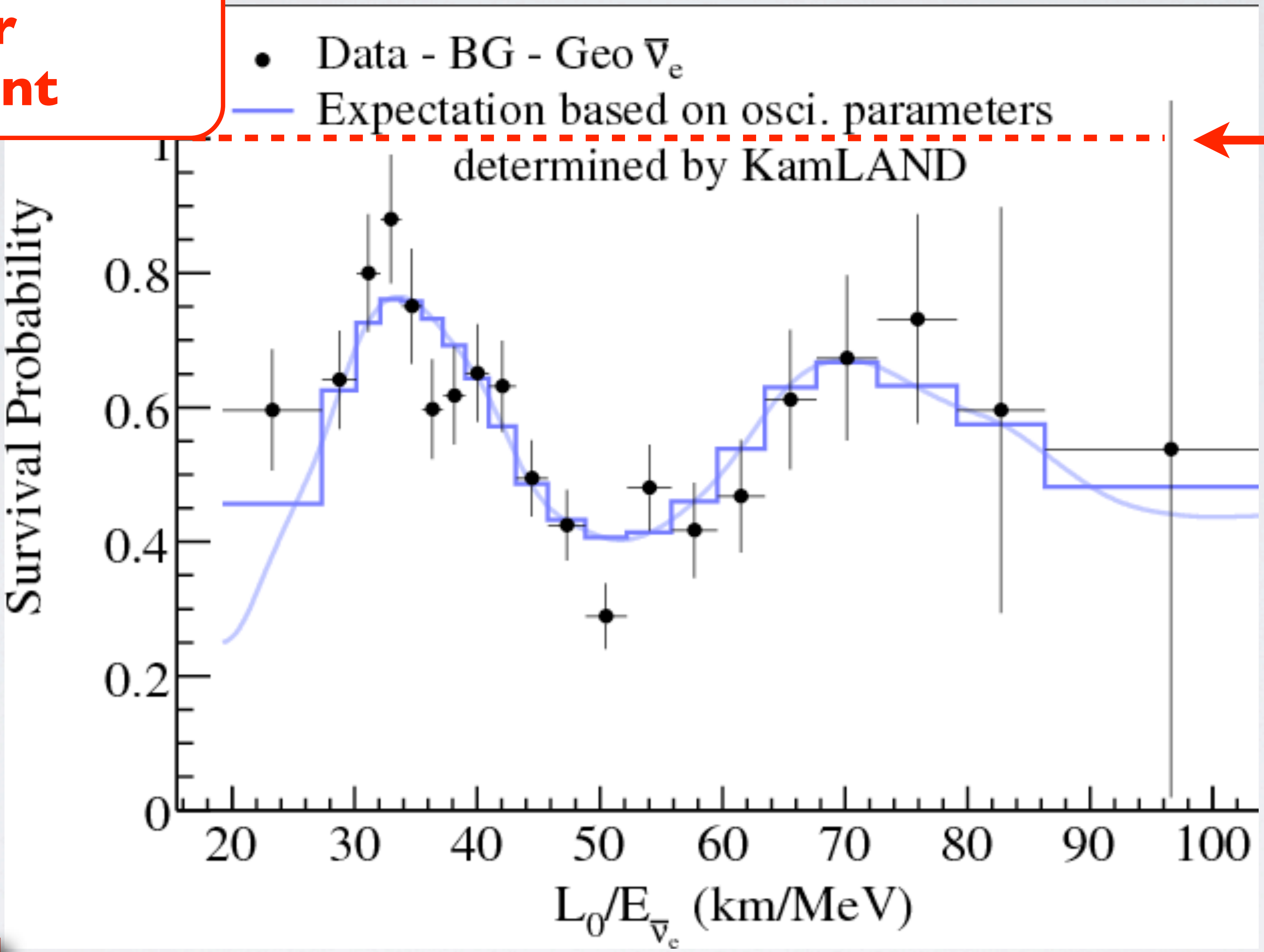




Reactor neutrinos

KAMLAND

Clear evidence of oscillation and parameter measurement



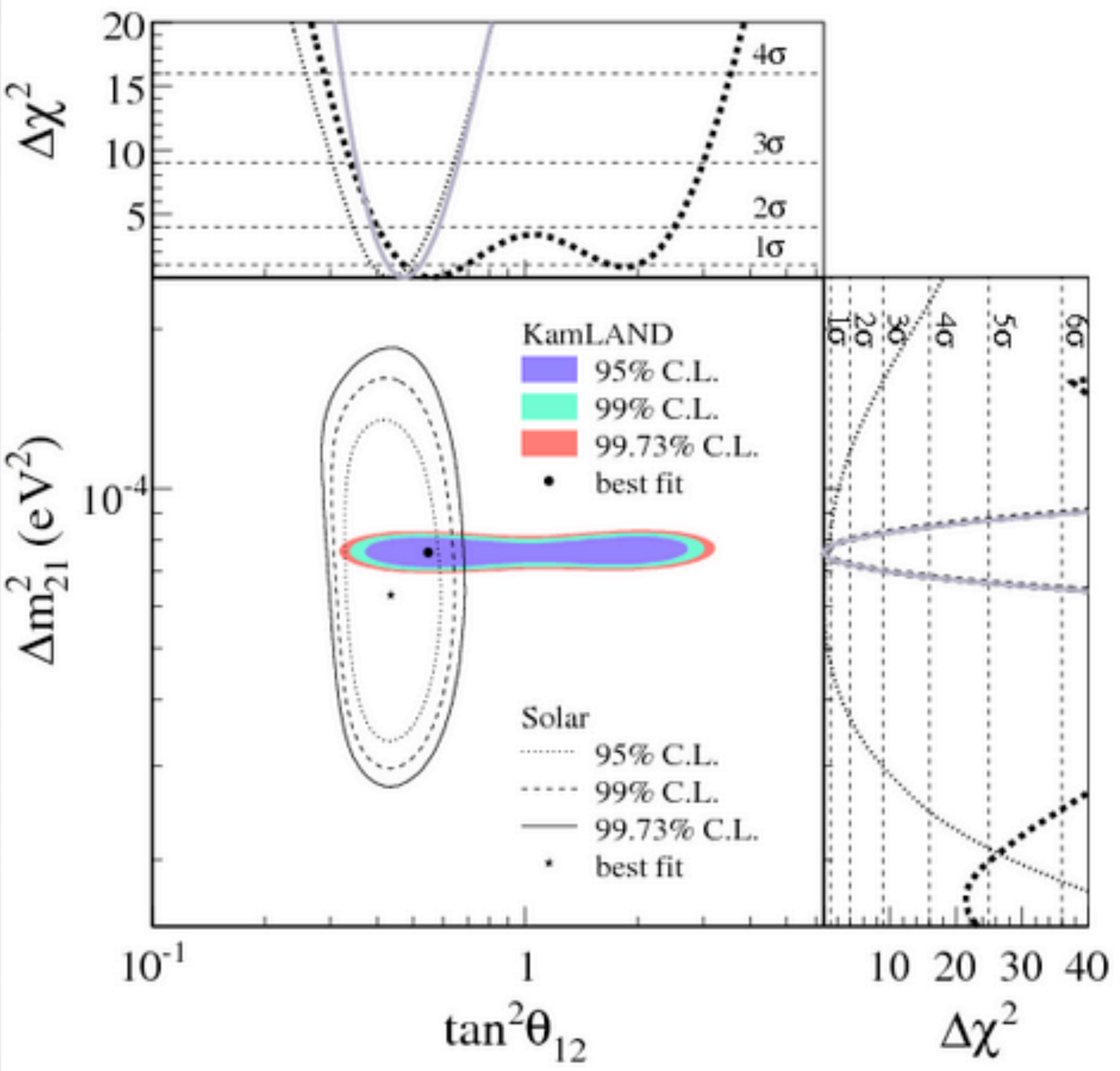
No oscillation expectation

Energy (MeV) corresponding to a baseline of 180 km

9 6 4.5 3 2

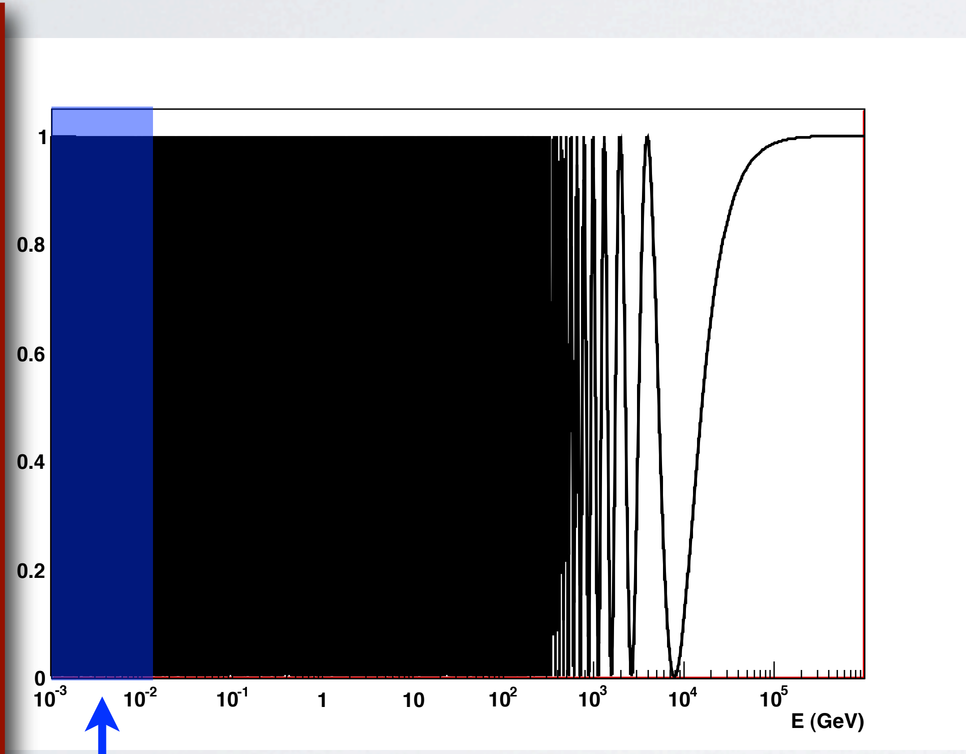
RESULTS

- **KamLAND** has a great precision on the **mass splitting** since the positions of the maxima of oscillation are well measured.
- However the normalisation is less precise and the **solar measurements** give more stringent constraints on the **mixing angle**.



SOLAR OSCILLATIONS

- As in the atmospheric case, a best value for the mixing angle and the mass splitting has been found combining all experiments.
- With this value of **Δm_{21}^2** and the known baseline (the distance sun - earth is about 1.5×10^8 km) it is clear that no oscillation pattern can be measured and only the average of $\sin^2(\theta_{12})$ can be seen (i.e. 0.5).



$\nu_e \rightarrow \nu_e$ probability for $L=1.5\times10^8$ km neutrino with $\Delta m^2 = 7\times10^{-5}$ eV2

Solar neutrinos

- It is clear that if the mixing angle is maximal, we expect half of the neutrinos, otherwise we expect more than half:

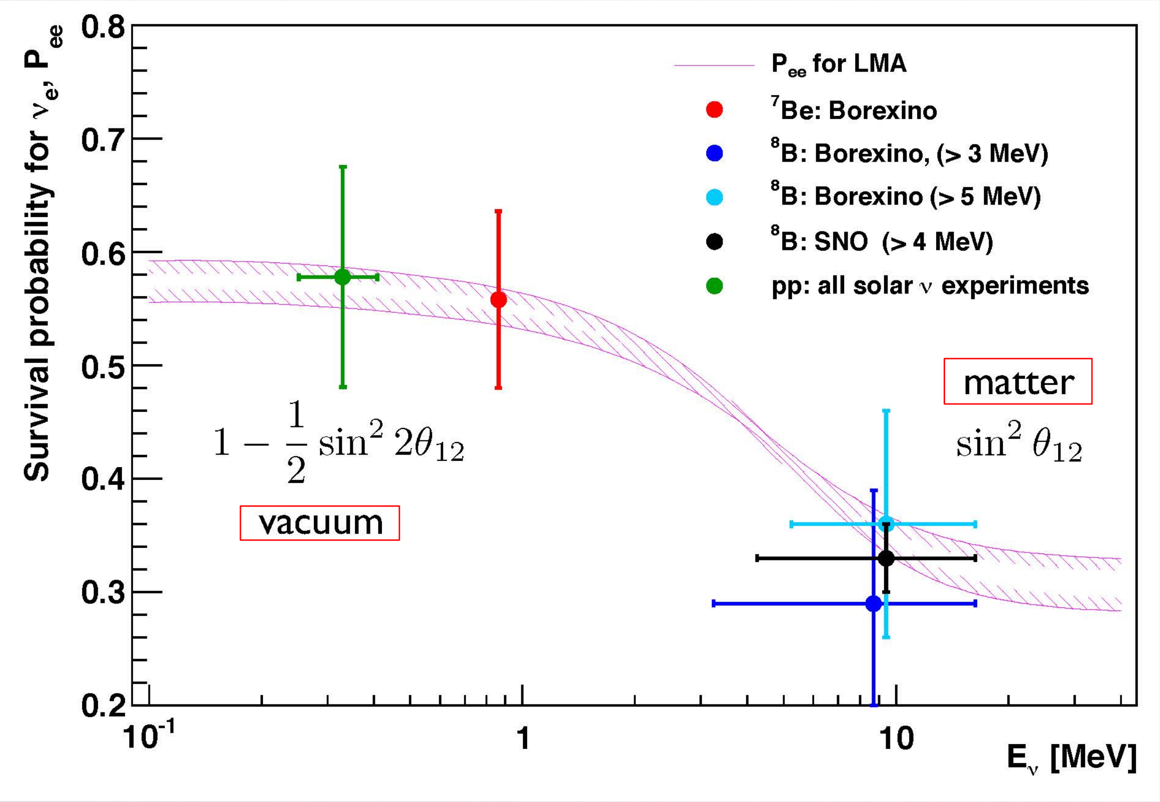
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{12} \boxed{\sin^2(1.27\frac{\Delta m_{12}^2 L}{E})}$$

$$P(\nu_e \rightarrow \nu_e) = 1 - \boxed{\frac{1}{2}} \sin^2 2\theta_{12} \quad \boxed{\geq 0.5}$$

- However, the **deficit** found by some experiments is **larger than 0.5**. The **answer** comes from the **MSW effect**.

MSW EFFECT FOR SOLAR NEUTRINOS

- We have seen that in matter the oscillation is modified.
- Solar neutrinos are produced inside the sun and therefore travel through a **medium with varying density**.
- This is quite complicated since instantaneous eigenstates of the hamiltonian are not the eigenstate of propagation.
- The flavour transformation of neutrinos from one flavour to another in a medium of varying density is called MSW (Mikheyev-Smirnov-Wolfenstein) and it depends on the neutrino energy.



Neutrino Energy	Transition	Survival probability
< 2 MeV	Vacuum oscillations	$1-\frac{1}{2}\sin^2 2\theta_{12}$
2 - 10 MeV	Interplay between vacuum oscillations and adiabatic transition	↕
>10 MeV	adiabatic transition	$\sin^2 2\theta_{12}$

NOTE: Matter effects in the Sun have uniquely determined the **positive sign Δm^2_{21}**.

PARAMETERS

Parameter	**Present knowledge (90% C.L.)**	**Channel**	**Experiments**	**Future**
θ_{23}	$\sin^2(2\theta_{23}) \geq 0.96$	$P(\nu_\mu \to \nu_\mu)$	SK, (K2K, MINOS)	T2K
θ_{12}				
θ_{13}				
$\lvert\Delta m^2_{21}\rvert$				
Sign (Δm^2_{21})				
$\lvert\Delta m^2_{31}\rvert$	$2.24 \leq \lvert\Delta m^2_{31}\rvert$ / 10^{-3} eV$^2 \leq 2.44$	$P(\nu_\mu \to \nu_\mu)$	(SK, K2K), MINOS	MINOS, T2K
Sign (Δm^2_{31})				
δ_{CP}				

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θ_{13}				
$\lvert\Delta m^2_{21}\rvert$	$7.2 \leq \Delta m^2_{21}$ / 10^{-5} eV$^2 \leq 7.9$	Solar ν + P(anti $\nu_e \rightarrow$ anti ν_e)	SK, SNO, KamLAND	
Sign (Δm^2_{21})	+	Solar ν + P(anti $\nu_e \rightarrow$ anti ν_e)	SK, SNO, KamLAND	
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Sign (Δm^2_{31})				
δ_{CP}				

INTERFERENCE SECTOR

- To measure the mixing angle of the interference sector (**θ_{13}**) there are two possibilities:

$\nu_\mu \rightarrow \nu_e$ **transition** (appearance channel)

$$P(\nu_\mu \rightarrow \nu_e) = \Sigma_{i=1,4} P_i$$

$$P_1 = \sin^2\theta_{23}\sin^2(2\theta_{13})\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23}\sin^2(2\theta_{12})\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

$$A = \sqrt{2}G_F n_e$$

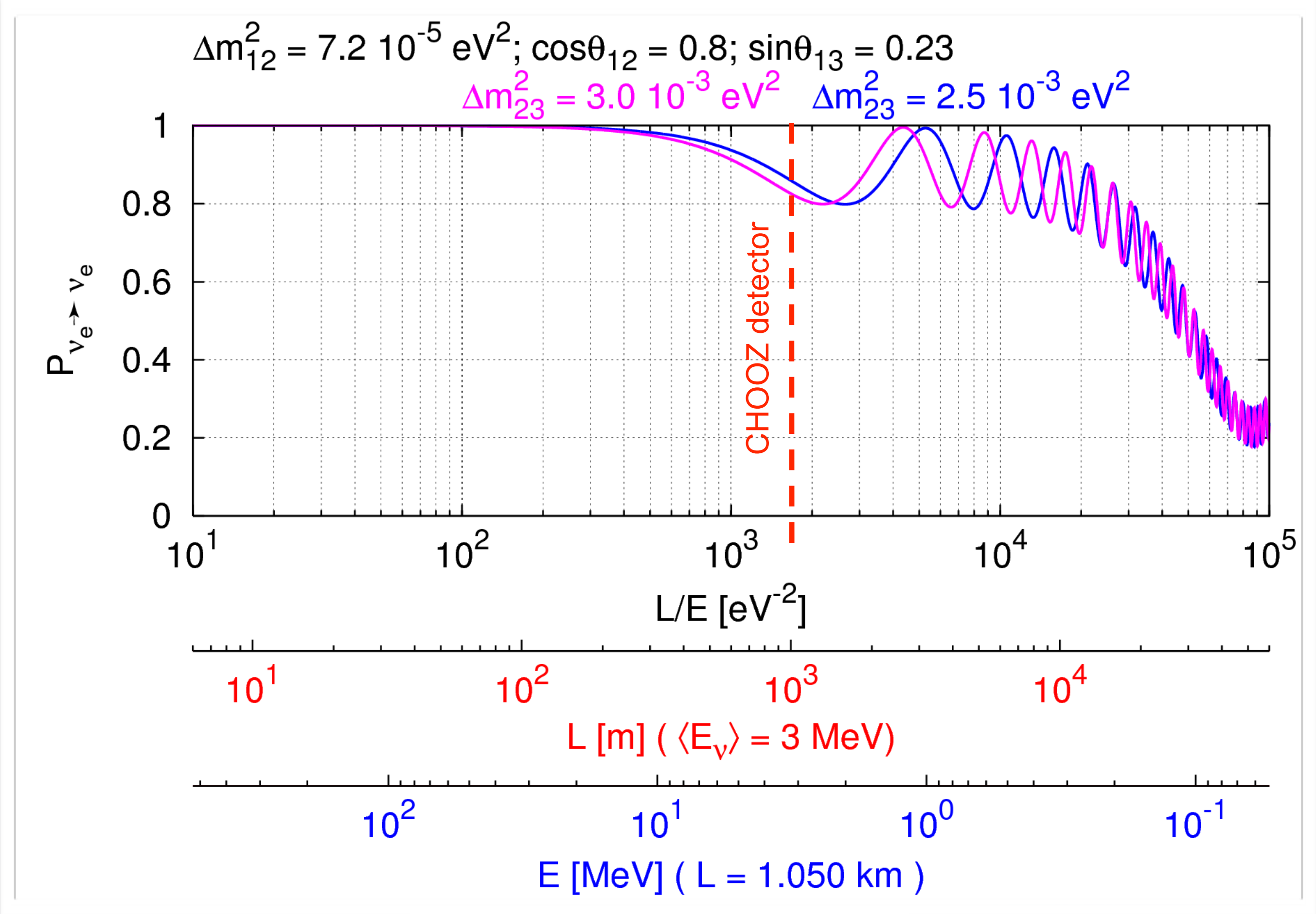
$$B_\pm = |A \pm \Delta_{13}|$$

$$J = \cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})$$

This channel is investigated by the **T2K** experiment and it will be investigated by future LBL such as **NOvA**.

$\overline{\nu}_e \rightarrow \overline{\nu}_x$ **transition** (disappearance channel)

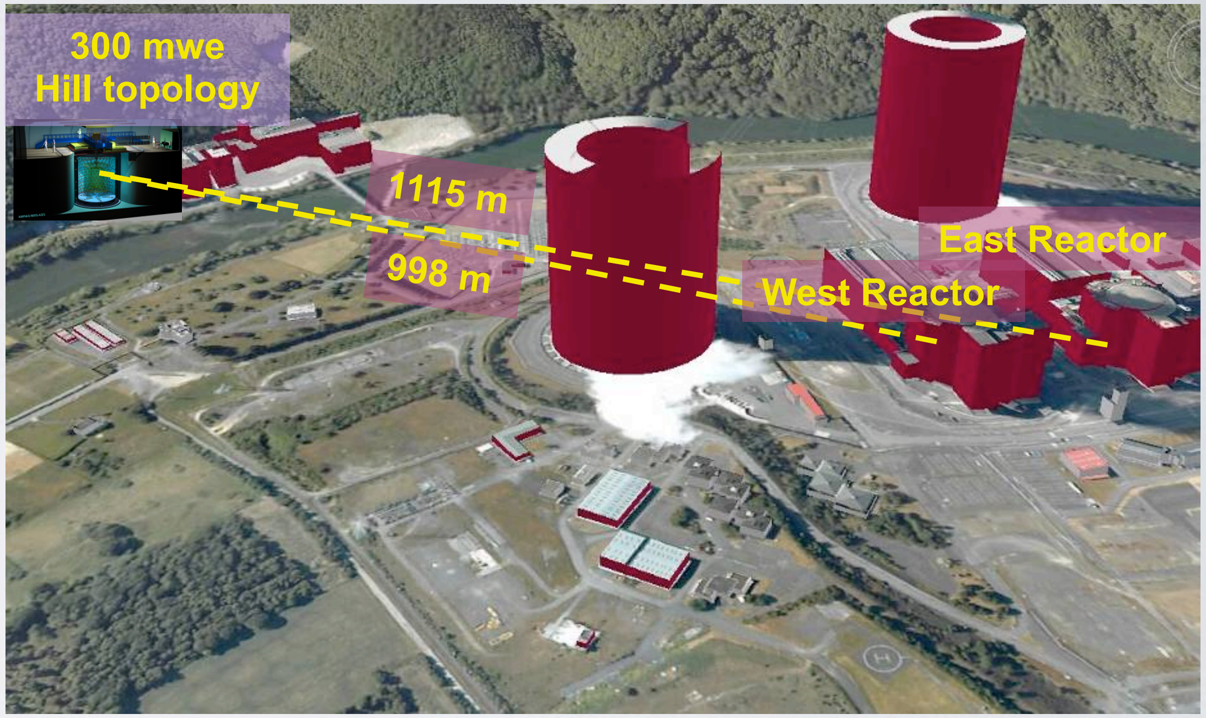
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \cong 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{23}L}{4E}\right)$$



This channel was investigated by the **Chooz** experiment and it is now studied by other reactors experiments, one of which is the **Double Chooz** experiment.

CHOOZ

- **Chooz** was an experiment that uses the detection principle of the liquid scintillator.



- The neutrino source consists of two nuclear reactors (produced $\overline{\nu}_e$ and observation of the $\overline{\nu}_e \rightarrow \overline{\nu}_x$ transition).

- As described for the KamLAND experiment, the reaction observed is:

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

- The scintillator is doped with Gadolinium (Gd) and the signature of the delayed signal (neutron absorption) is given by:

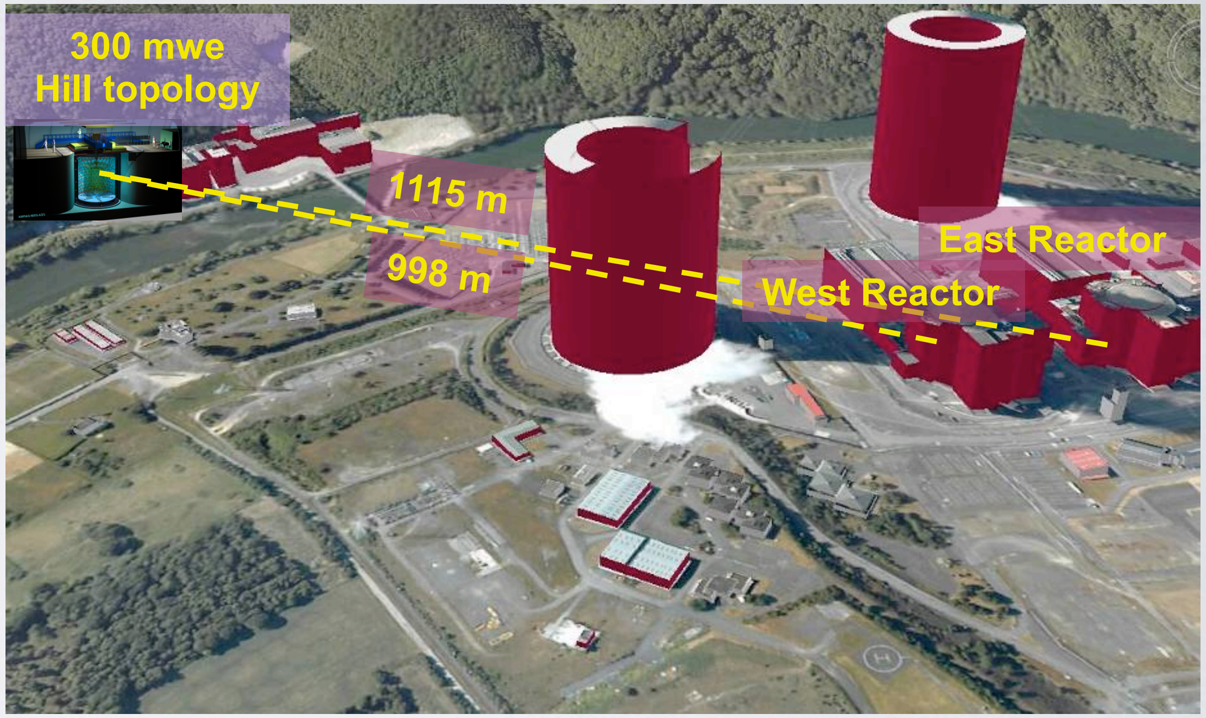
$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$$

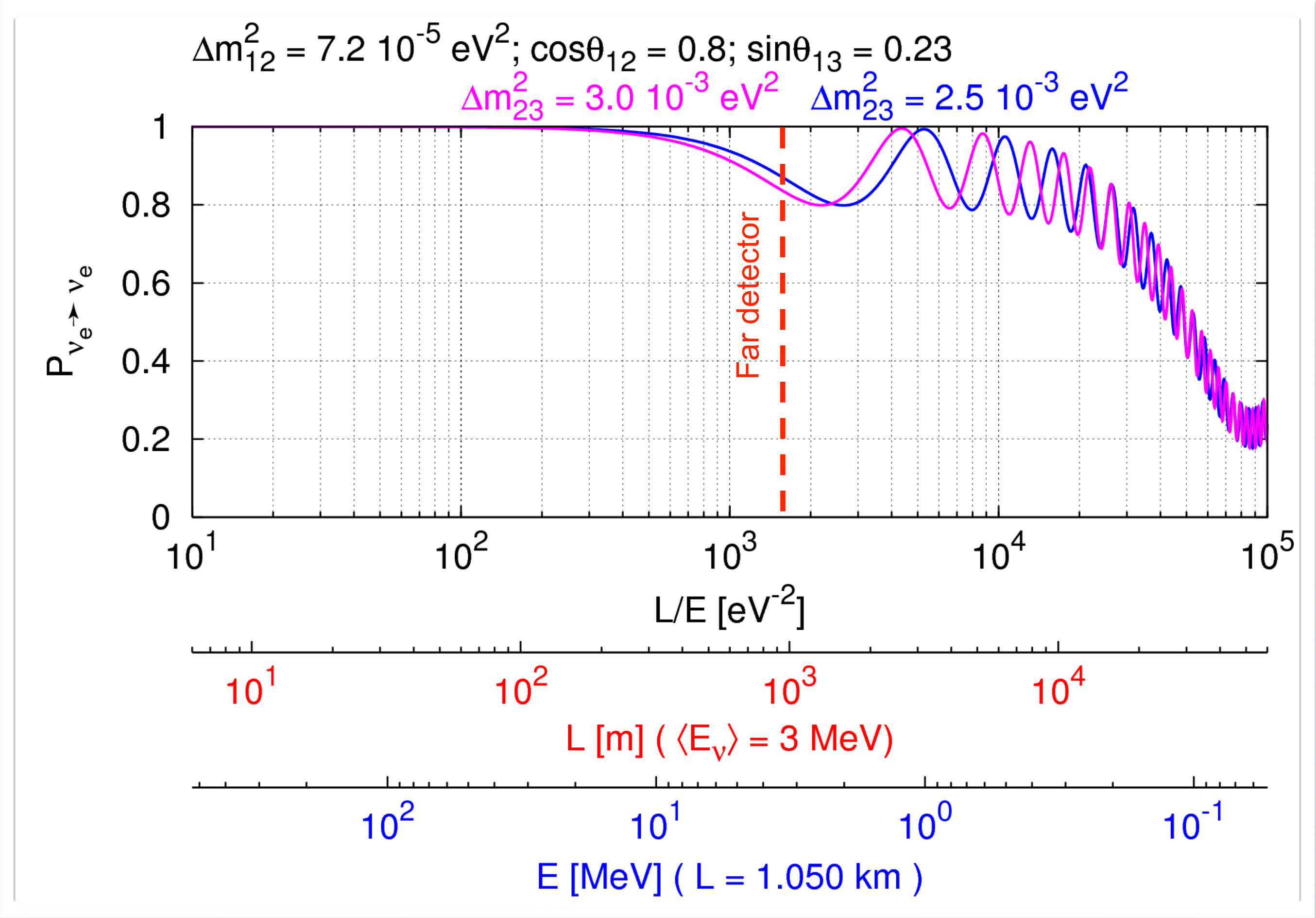
producing gammas at
8 MeV

Delayed signal (~30 μs)

DOUBLE CHOOZ

Double Chooz uses the same technique but two detectors in order to measure the flux before oscillations and reduce the systematics.





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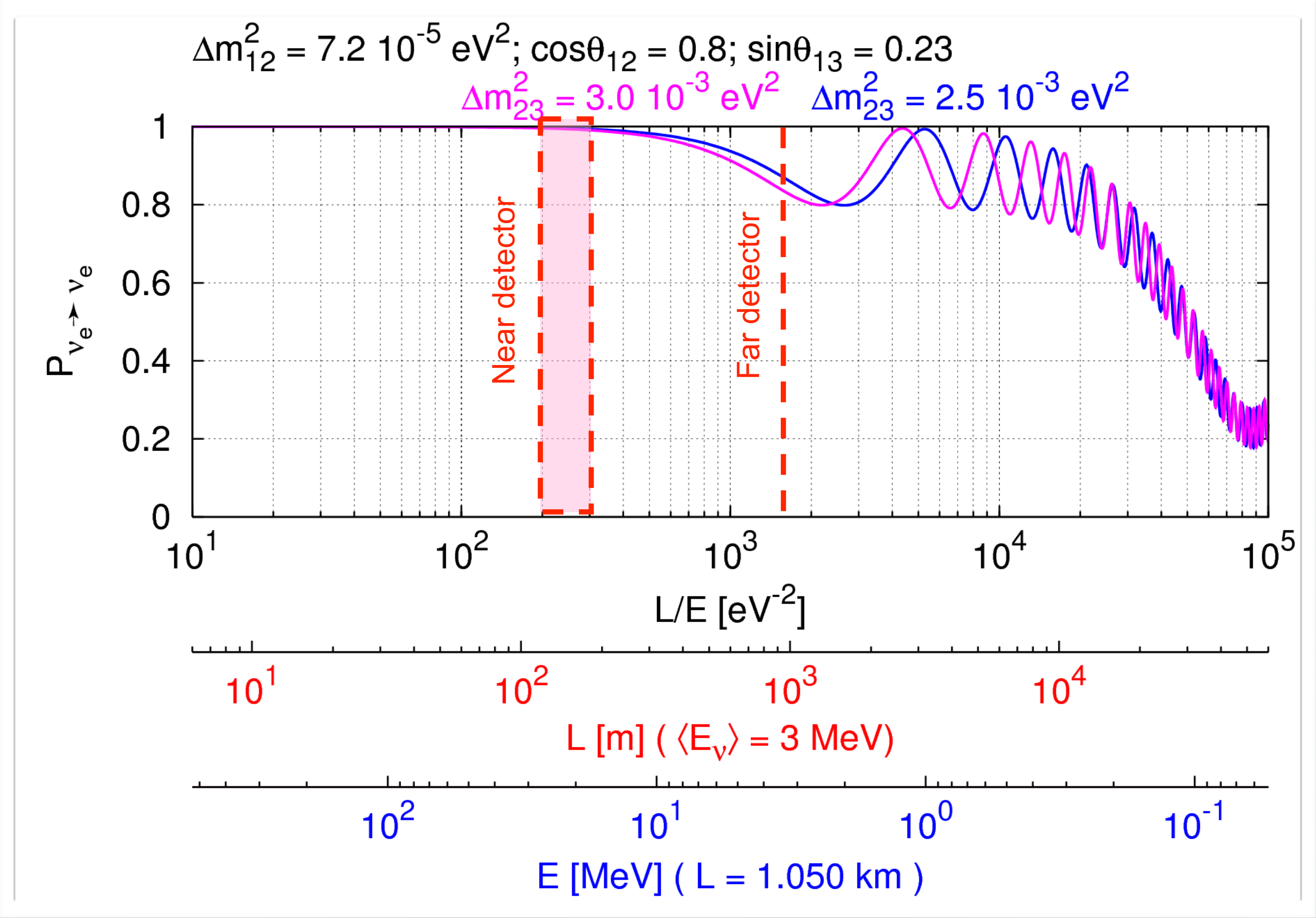
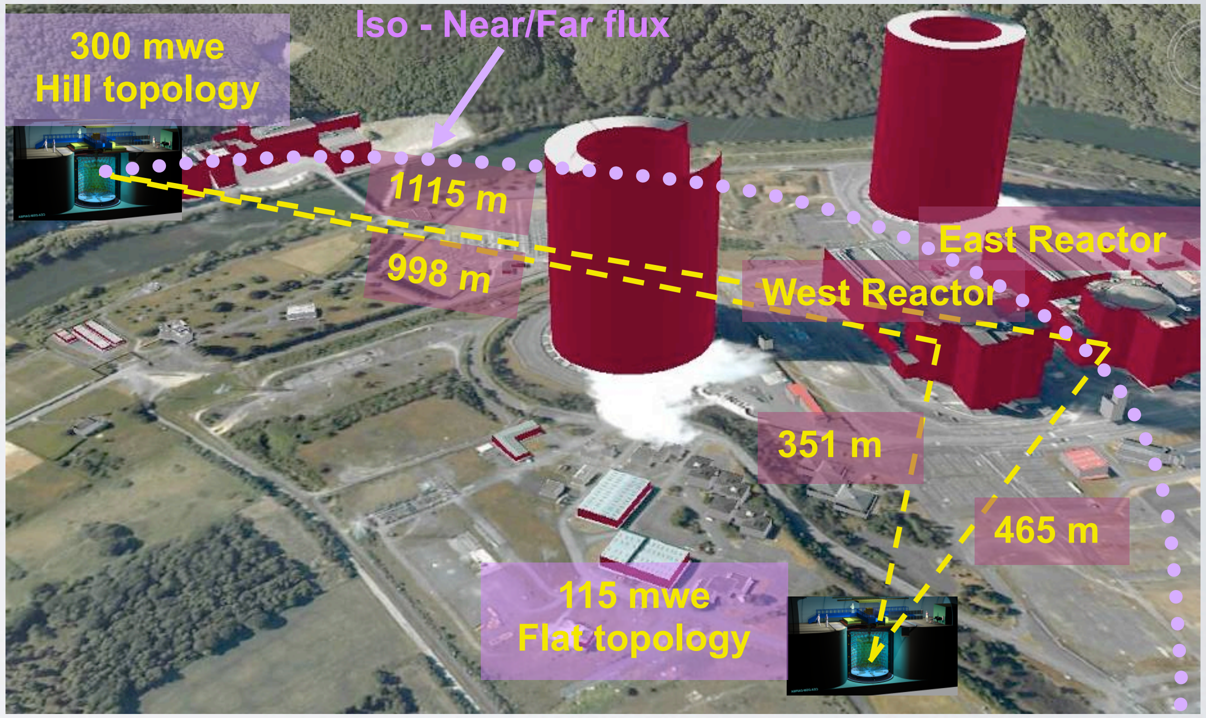
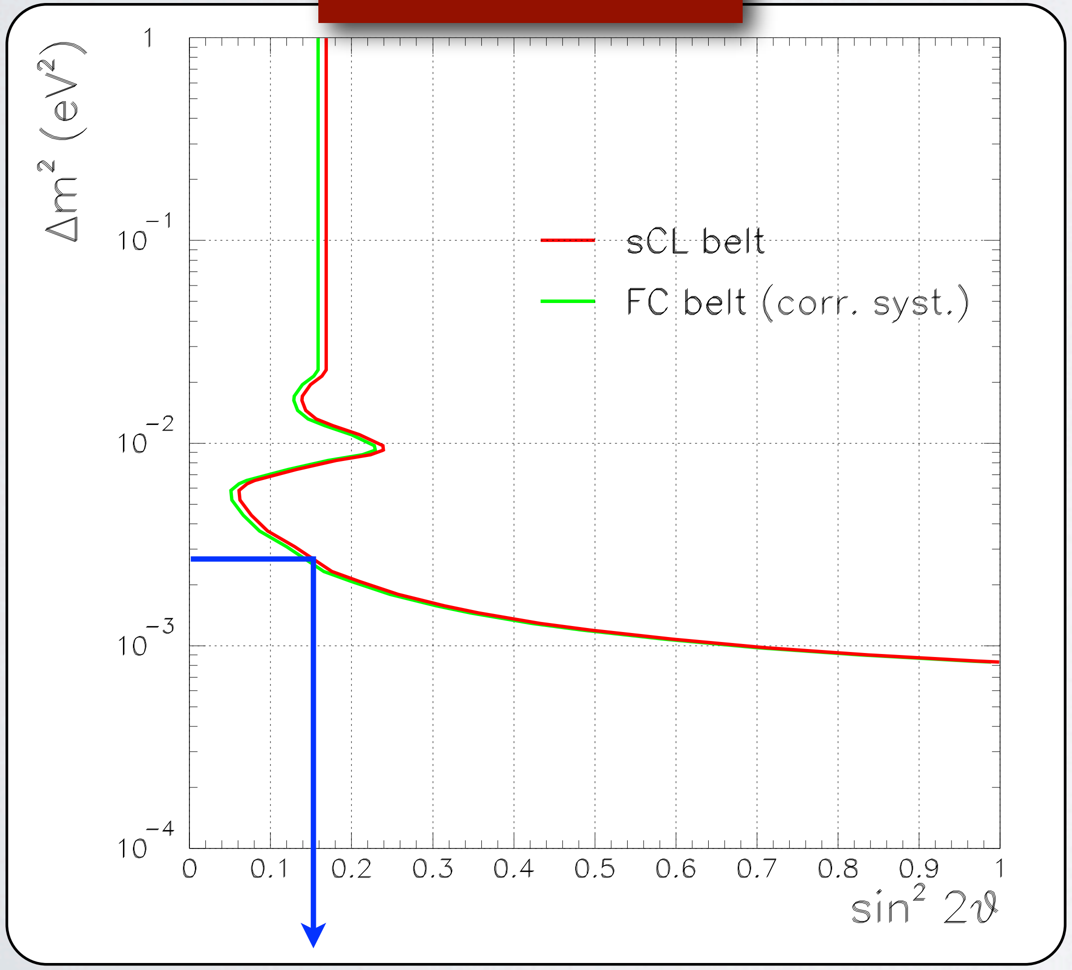




(DOUBLE) CHOOZ

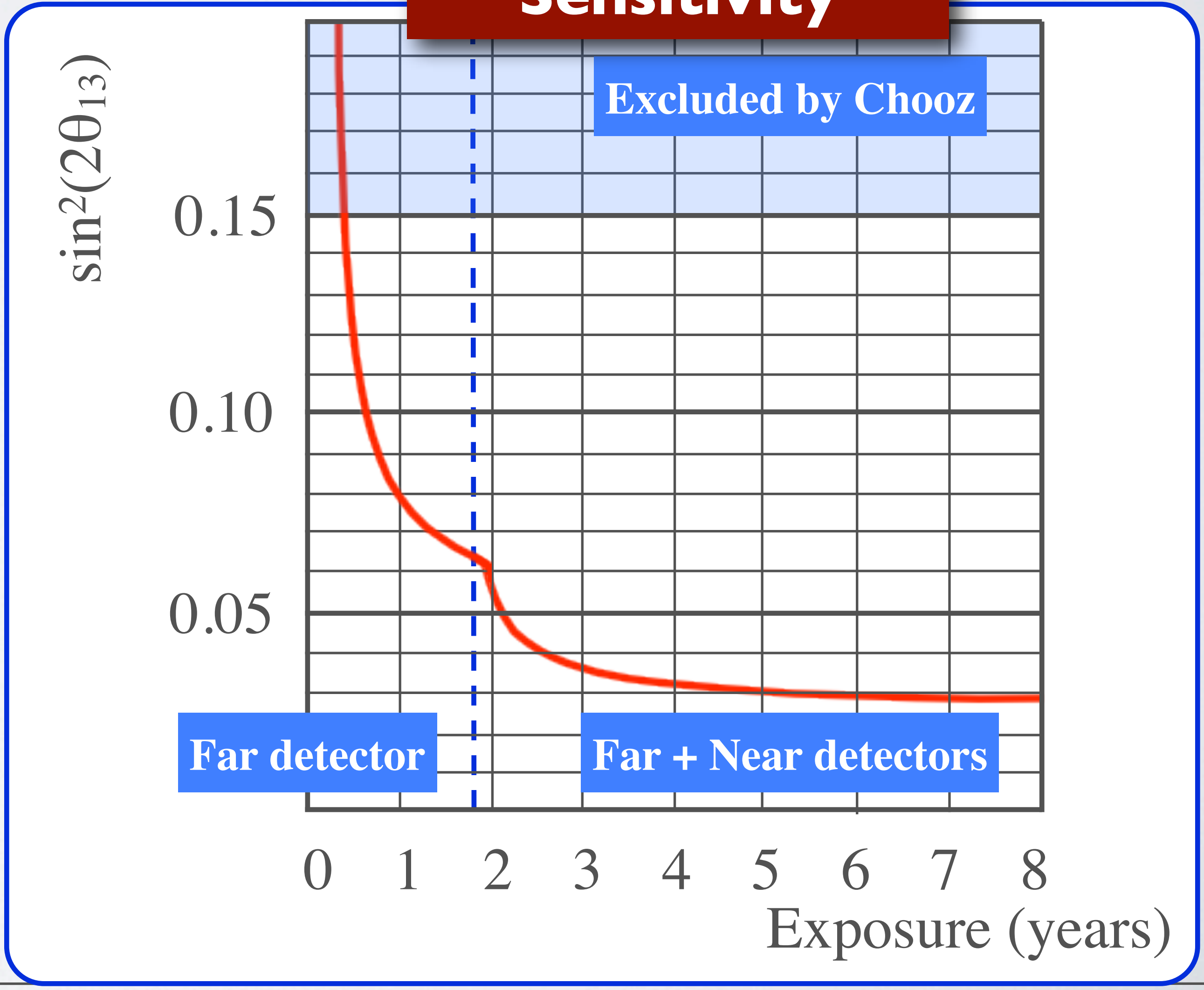
- **Chooz** did not measure any oscillation and gave a limit on the value of the mixing angle **θ_{13}**.
- **Double Chooz** has just started and it should provide in a few years a limit 5 times better than Chooz or in a good scenario observe the oscillations.
- Other reactor experiments such as **RENO** and **Daya Bay** will also give results in a near future.

Chooz



$\sin^2(2\theta_{13}) \leq 0.15$

Double Chooz Sensitivity

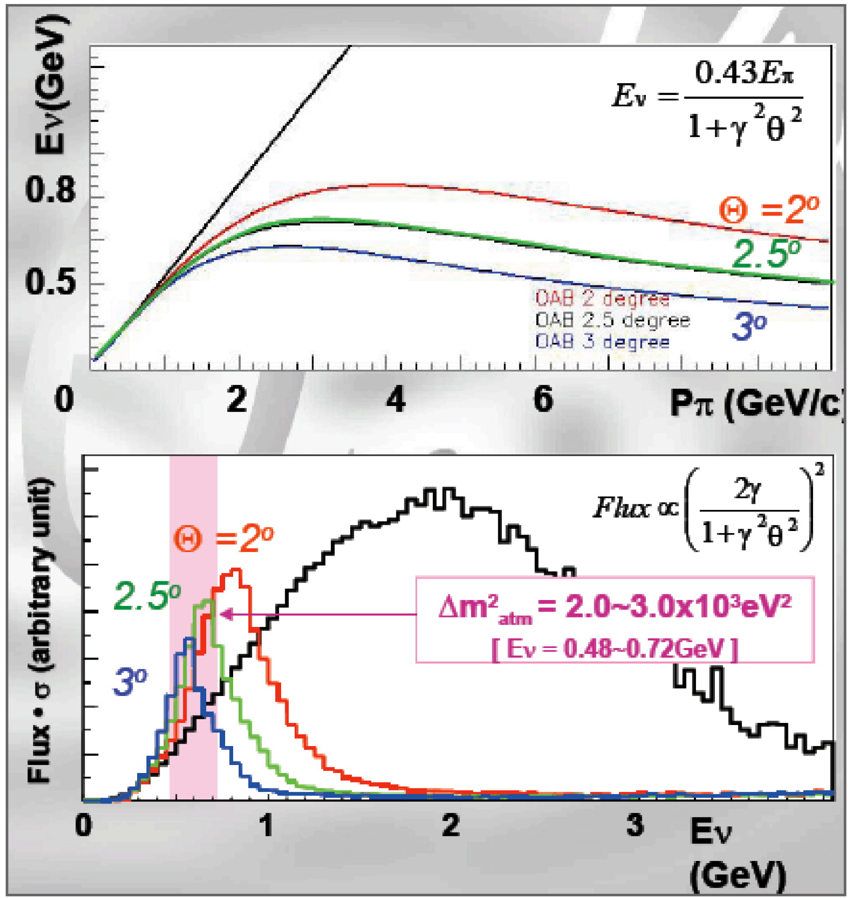


T2K

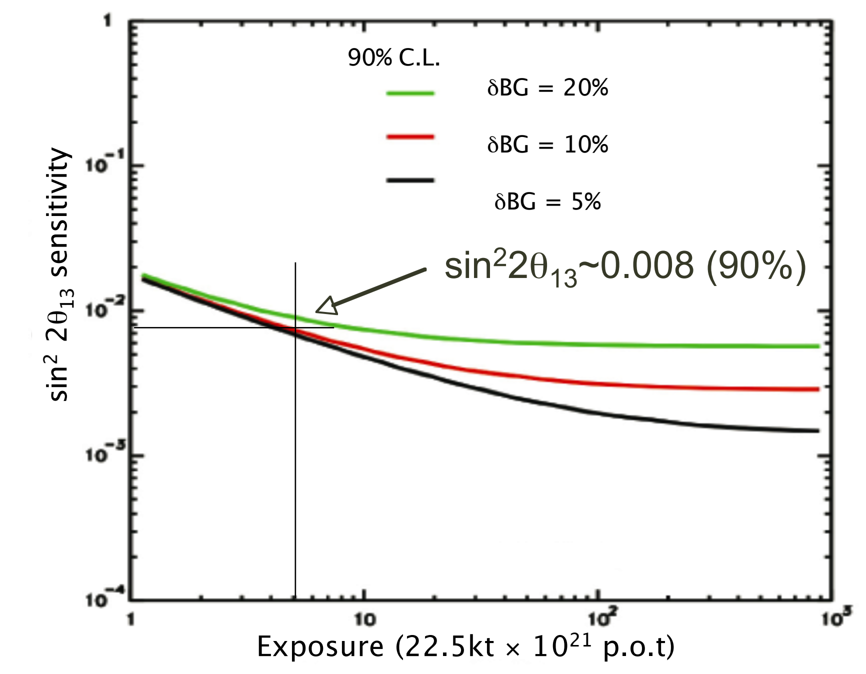
- **T2K** experiment has been presented in the framework of the atmospheric sector for the measurement of the $\nu_\mu \rightarrow \nu_x$ transition.

- The main goal of the experiment is the observation of the $\nu_\mu \rightarrow \nu_e$ **transition** for the measurement of the θ_{13} mixing angle.

- T2K uses a neutrino super beam (high intensity) and the neutrino energy is focused using the "**off-axis**" technique to the maximum of oscillation corresponding to the atmospheric mass splitting.

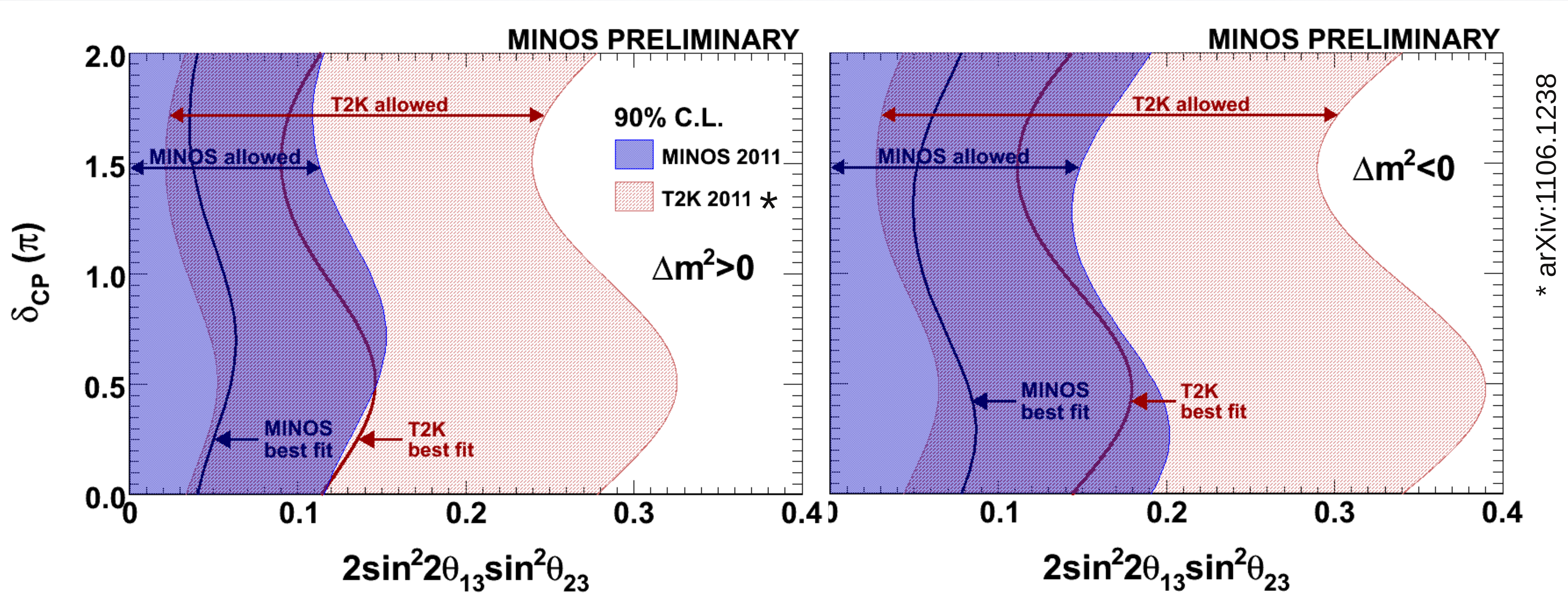


- The **goal** in case of no oscillation is a limit on **$\sin^2(2\theta_{13})$** of **8×10^{-3} (90% C.L.)** (factor of 20 better than CHOOZ).

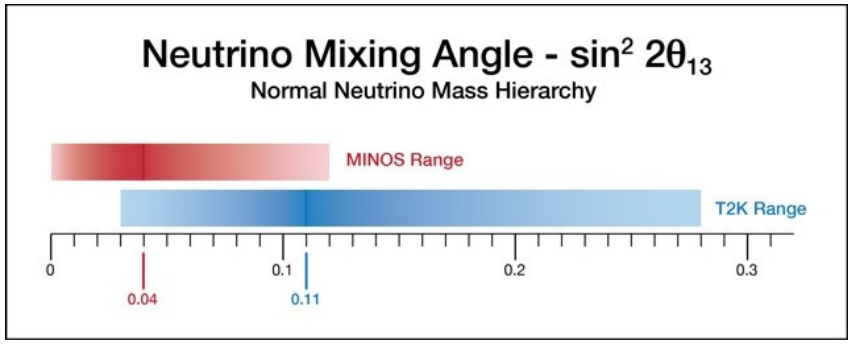


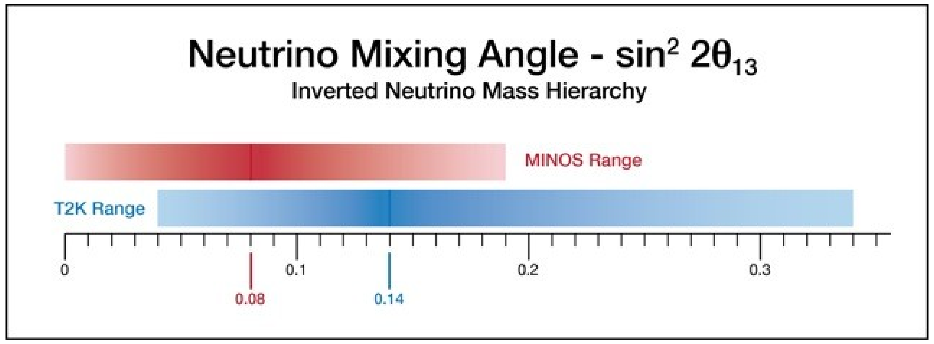
RECENT RESULTS

- **T2K** and **MINOS** have recently published some results that strongly disfavour the possibility of a vanishing θ_{13} mixing angle.
- The two experiments found an excess of events over the background of 2.5 and 1.7 sigma respectively.



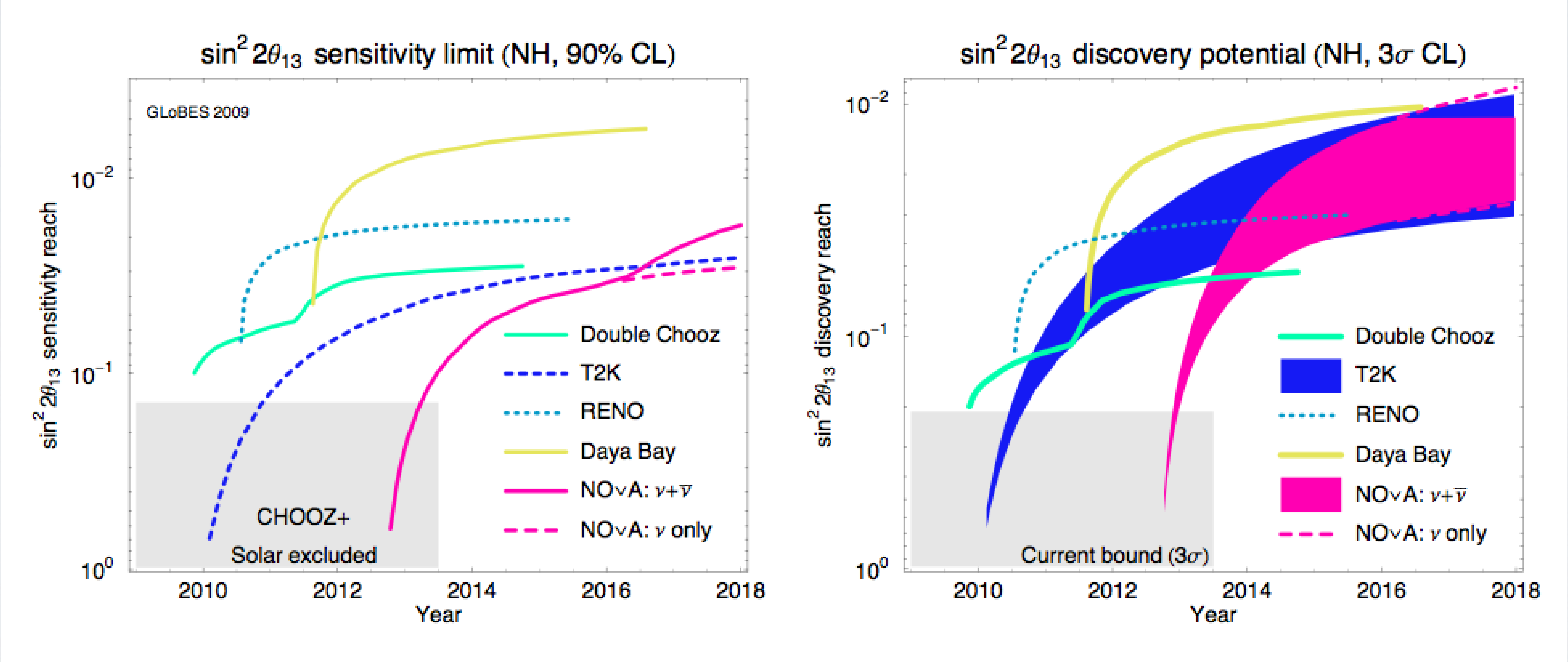
* arXiv:1106.1238





RESULTS

- **Chooz** is still the experiment with the best limit on **θ_{13}** but in the near future we expect much **better sensitivities** both **from reactor experiment** and **from long baseline** neutrino oscillation experiments.



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θ_{13}	$\sin^2(2\theta_{13}) \leq 0.15$	$P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$ $P(\nu_\mu \rightarrow \nu_e)$	Chooz	T2K, Double Chooz, RENO, Daya Bay Future LBL
$\lvert\Delta m^2_{21}\rvert$	$7.2 \leq \Delta m^2_{21}$ / 10^{-5} $\text{eV}^2 \leq 7.9$	Solar ν + $P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$	SK, SNO, KamLAND	
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$\lvert\Delta m^2_{31}\rvert$	$2.24 \leq \lvert\Delta m^2_{31}\rvert$ / 10^{-3} $\text{eV}^2 \leq 2.44$	$P(\nu_\mu \rightarrow \nu_\mu)$	(SK, K2K), MINOS	MINOS, T2K
Sign (Δm^2_{31})				
δ_{CP}				

OPEN QUESTIONS

- The past and present generation of neutrino oscillation experiments allowed to **almost complete our knowledge on the mixing matrix**. However there are still two ingredients completely **unknown**: the sign of the atmospheric mass splitting i.e. the mass hierarchy (**sign Δm_{31}^2**) and the value of the complex phase δ_{CP}.
- Out of these two, δ_{CP} is the most interesting measurement in neutrino physics since if it is different from the conserving values (0, π) it would cause **CP violation in the leptonic sector**, which would be an important ingredient in the explanation of the **matter-antimatter asymmetry in our universe**.
- Unfortunately, as explained before, mass hierarchy degeneracy and CP violation effects are difficult to disentangle, since both give a difference between neutrinos and antineutrinos.
- Moreover the intrinsic **CP violation can be observed ONLY if the mixing angle θ_{13} is not zero**.

CP VIOLATION

- Future long baseline experiments aim at the measurement of CP violation comparing neutrino and antineutrino oscillation probabilities.
- The **mass hierarchy** can be observed when the baseline is long enough (i.e. ≥ ~ 1000 km) and **matter effects** become measurable (**effect dependent on the baseline**).
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- A way to disentangle the two effects is to **measure neutrino oscillations at different baselines** (always comparing neutrino and antineutrino oscillation probabilities).

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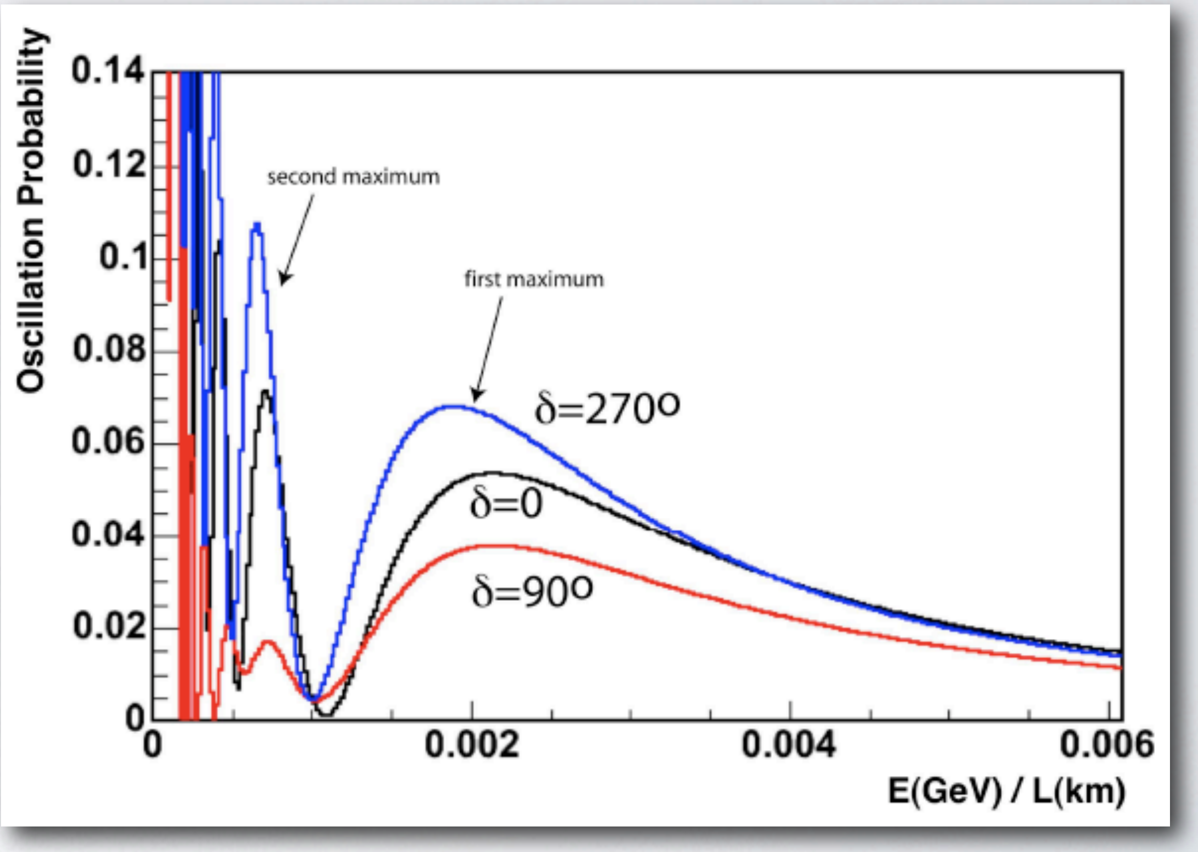
- Another possibility is to compare the **different maxima of oscillations** since their **ratio has a difference dependence** on the value of δ_{CP}.



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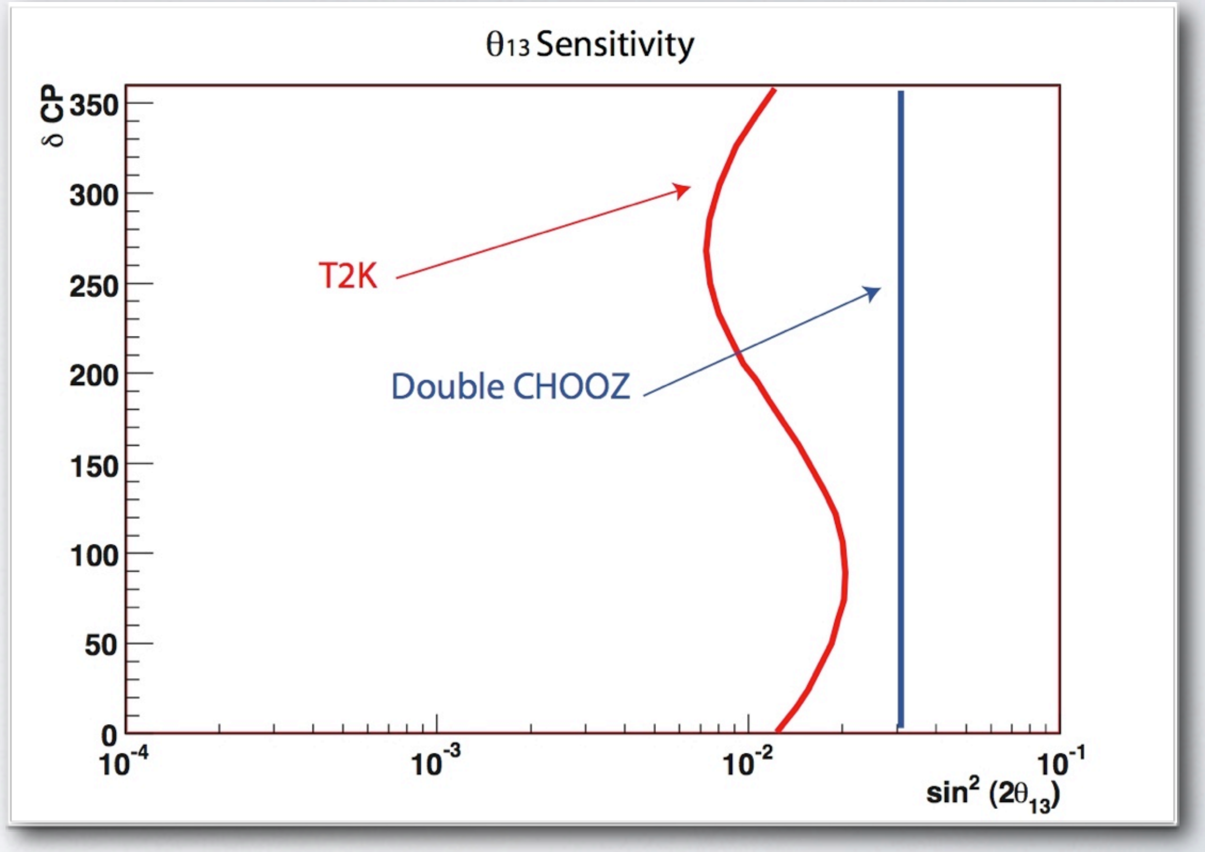
- A way to disentangle the two effects is to **measure neutrino oscillations at different baselines** (always comparing neutrino and antineutrino oscillation probabilities).
- A third way consists in **comparing results of appearance and disappearance experiments** since **disappearance experiments are CP conserving**:

$$P(\nu_\alpha \to \nu_x) = 1 - \boxed{P(\nu_\alpha \to \nu_\alpha)}$$

CPT conserved + T conserved

↓

CP conserved



PARAMETERS

Parameter	**Present knowledge (90% C.L.)**	**Channel**	**Experiments**	**Future**
θ_{23}	$\sin^2(2\theta_{23}) \geq 0.96$	$P(\nu_\mu \rightarrow \nu_\mu)$	SK, (K2K, MINOS)	T2K
θ_{12}	$0.82 \leq \sin^2(2\theta_{12}) \leq 0.89$	Solar ν + P(anti ν_e → anti ν_e)	SK, SNO, KamLAND	
θ_{13}	$\sin^2(2\theta_{13}) \leq 0.15$	P(anti ν_e → anti ν_e) $P(\nu_\mu \rightarrow \nu_e)$	CHOOZ	T2K, Double CHOOZ Future LBL
$\lvert\Delta m^2_{21}\rvert$	$7.2 \leq \Delta m^2_{21}$ / 10^{-5} eV$^2 \leq 7.9$	Solar ν + P(anti ν_e → anti ν_e)	SK, SNO, KamLAND	
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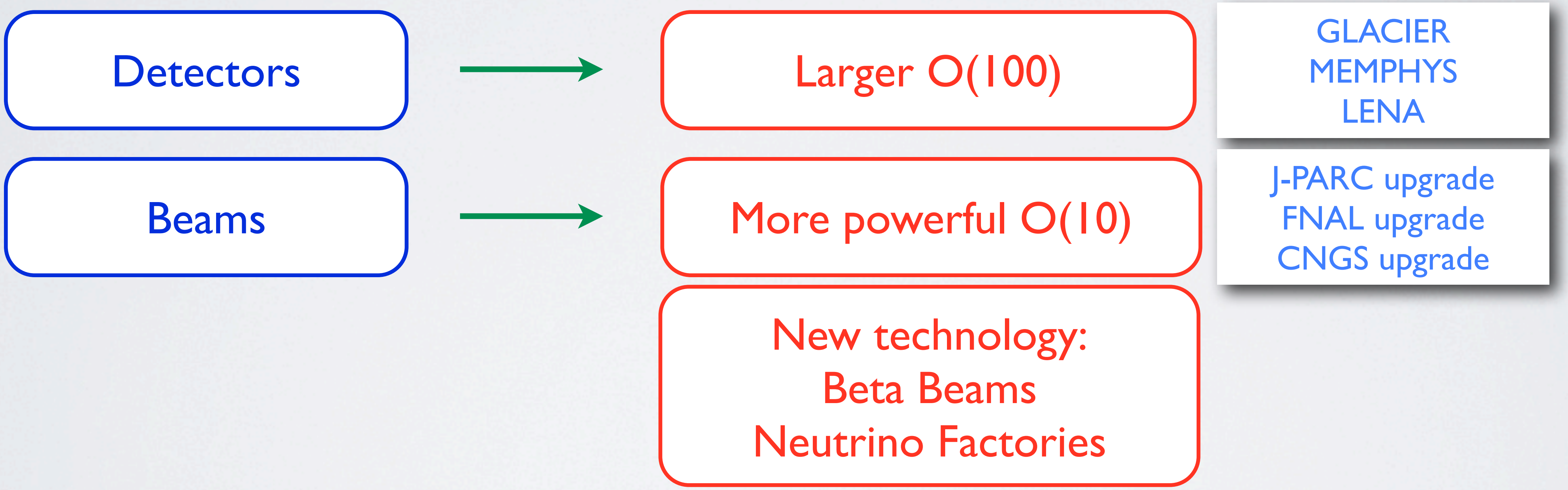
Sign (Δm^2_{31})	Unknown	$P(\nu_\mu \to \nu_e)$ Vs P(anti ν_e → anti ν_e)		Future LBL
δ_{CP}	Unknown	$P(\nu_\mu \to \nu_e)$ Vs P(anti ν_e → anti ν_e)		T2K+Reactor Future LBL

CONCLUSIONS

FUTURE OF NEUTRINO PHYSICS

- The present generation of neutrino oscillation experiments will allow to reach a limit on **$\sin^2(2\theta_{13}) \leq 8 \times 10^{-3}$**.
- According to the fact that θ_{13} is different from zero or not (**strong evidences recently obtained**), the next generation of experiment will aim to a **reduction of such a limit**, or to the search of **CP violation in the leptonic sector**.
- The future can be schematically summarised as:



Detectors → Larger O(100)

GLACIER
MEMPHYS
LENA

Beams → More powerful O(10)

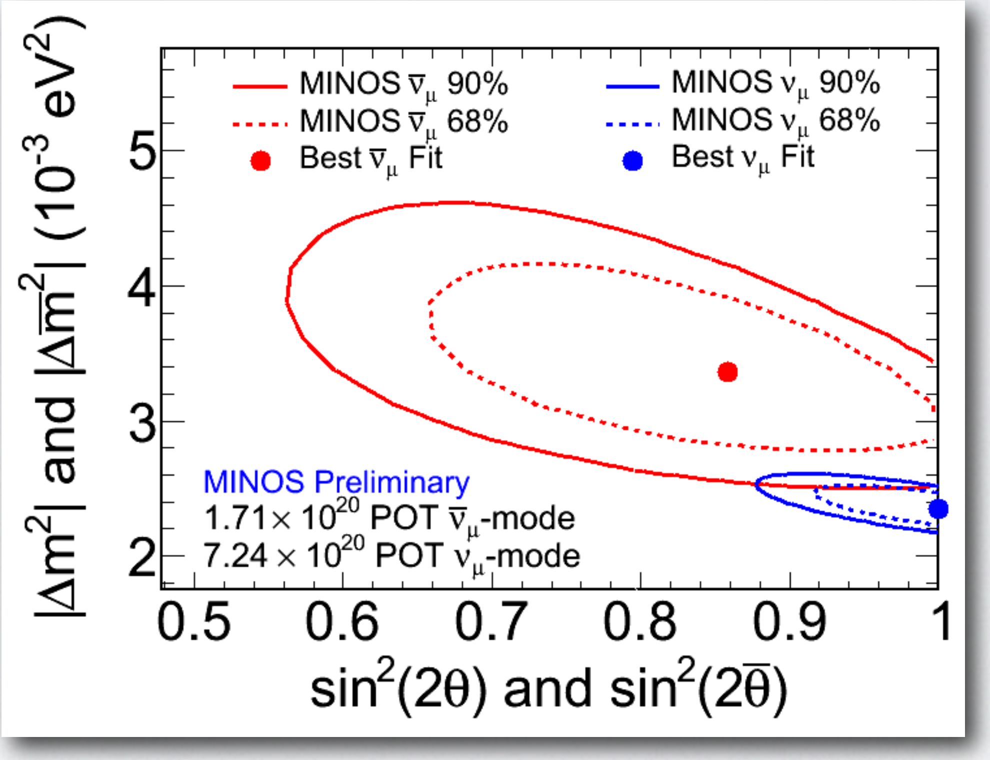
J-PARC upgrade
FNAL upgrade
CNGS upgrade

New technology:
Beta Beams
Neutrino Factories

All these projects require a huge amount of money and R&D.
The neutrino community is evaluating all the different options (projects such as **LAGUNA** or **EUROν**) to have a joint effort on the next generation experiments.

NEW PHYSICS?

- What has been presented is what is normally called "**standard**" neutrino physics.
- In 1996 **LSND** experiment saw an excess of antineutrinos in a new region of parameters incompatible with other flavour trnasitions: more than 3 neutrinos? **Sterile neutrinos?**
- **MiniBooNE** did not see the excess studying neutrino oscillations, but has some hints of an excess in the antineutrino mode.
- **MINOS** has shown hints for a difference in the oscillation parameters of neutrinos and antineutrinos: **how to explain this?**



There are some hints of "**new physics**" in the neutrino sector. If proved to be true many things about neutrinos that we think we understand are to be rethought...

...TO BE CONTINUED...