



NEUTRINO OSCILLATIONS

A.Meregaglia (IPHC / IN2P3-CNRS)

European summer campus 2011 - Between two infinities

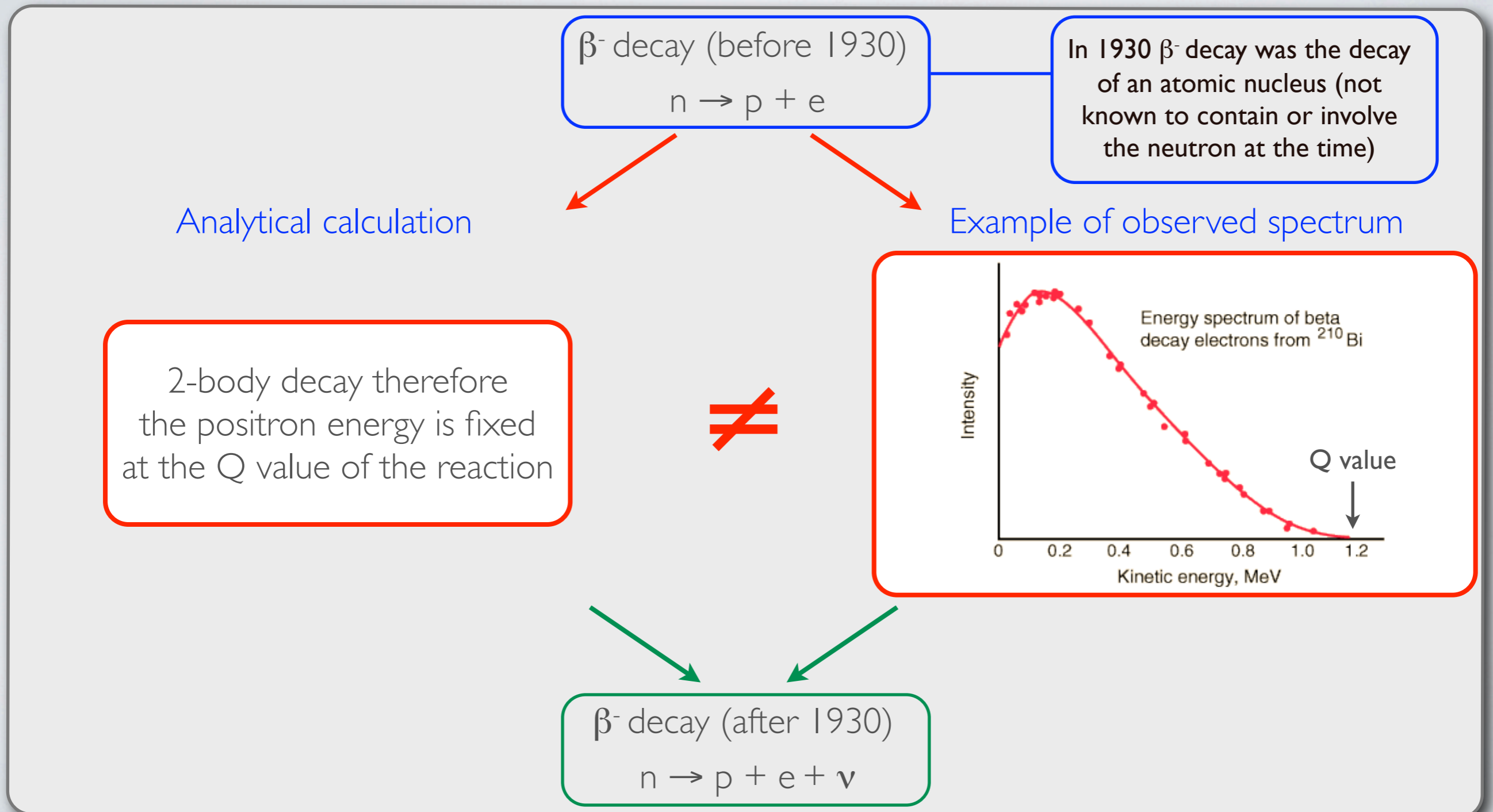
OUTLINE

- **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.



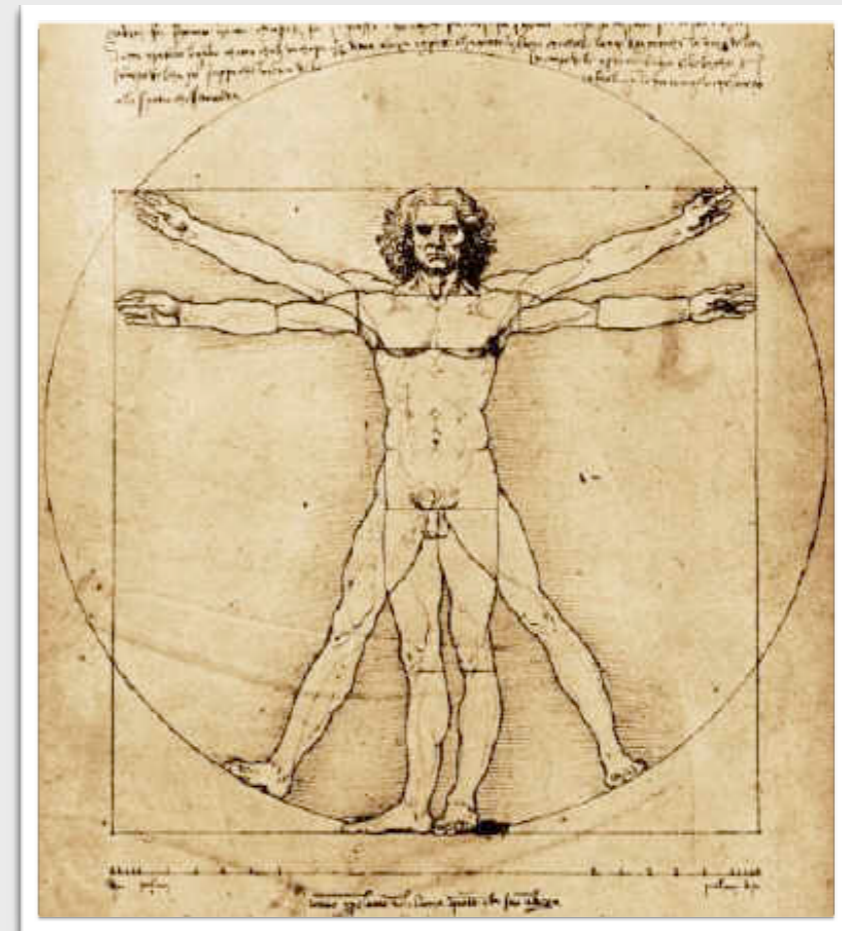
WHAT IS A NEUTRINO?

- 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} cm² 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?

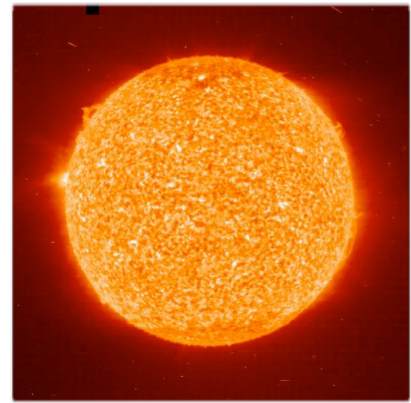
- The neutrino is a particle “**invented**” by Pauli in **1930** in order to conserve the energy and the momentum in β decays.
- This particle was **observed** for the first time by Cowan e Reines in **1956**.
- In **1962** it was discovered that neutrinos exist in (3) **different flavours**.
- In **2000** 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.

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.

Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u up	c charm	t top	γ photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	e electron	μ muon	τ tau	W[±] weak force
				Bosons (Forces)

NEUTRINO SOURCES

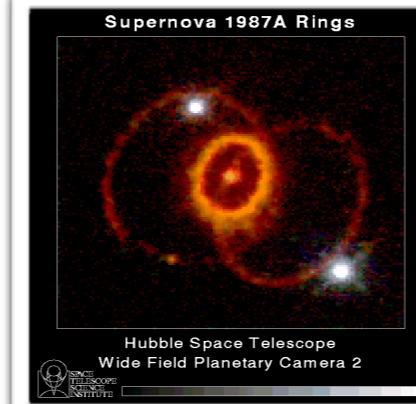
- There are many sources of neutrinos: they can be divided into **natural** (sun, natural radioactivity, etc.) and **human-made** (accelerators and reactors).



Solar ν
 $6 \times 10^{10} \nu \text{ s}^{-1} \text{ cm}^{-2}$
on earth



Atmospheric ν
 $1 \nu \text{ s}^{-1} \text{ cm}^{-2}$
on earth



Supernova ν



Big Bang ν
 $(330 \nu \text{ cm}^{-3})$



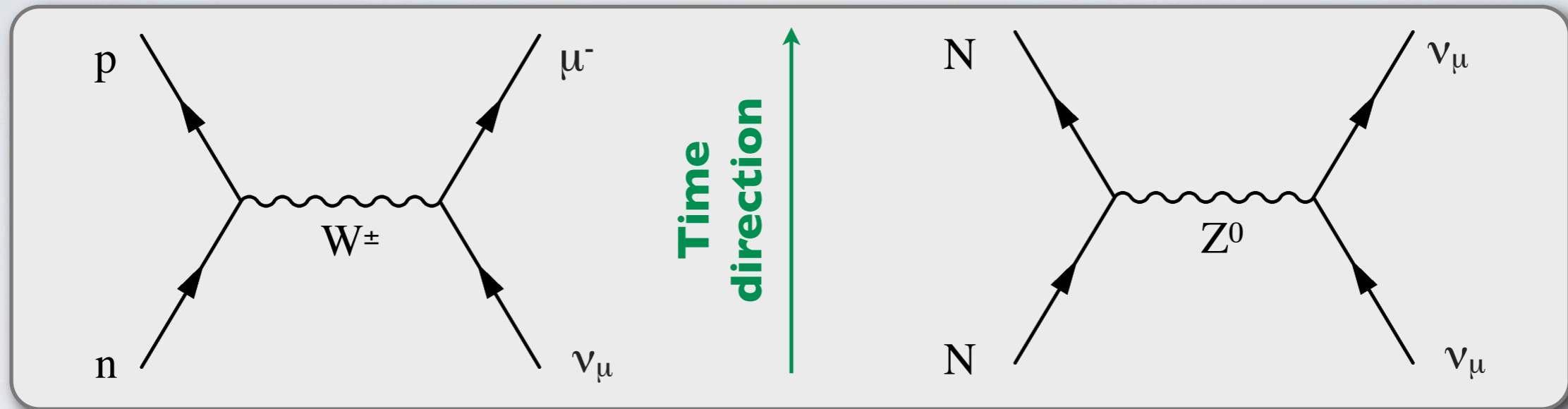
Accelerator ν



Reactor ν
 $10^{21} \nu \text{ s}^{-1}$
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 →

$$Q^2 = 4E_\nu E_\mu \sin^2(\theta/2)$$

Angle between incoming neutrino and outgoing lepton

hadronic invariant mass →

$$W^2 + Q^2 = 2M\nu + M^2$$

Nucleon mass

transferred energy →

$$\nu = E_{had} - M = E_\nu - E_\mu$$

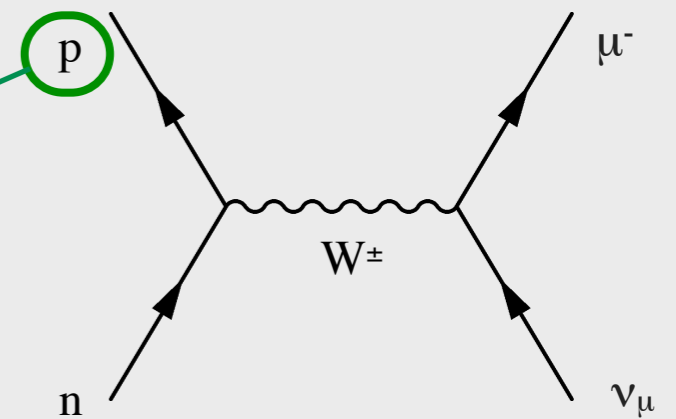
NEUTRINO INTERACTION

- 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:
 $W \approx M$

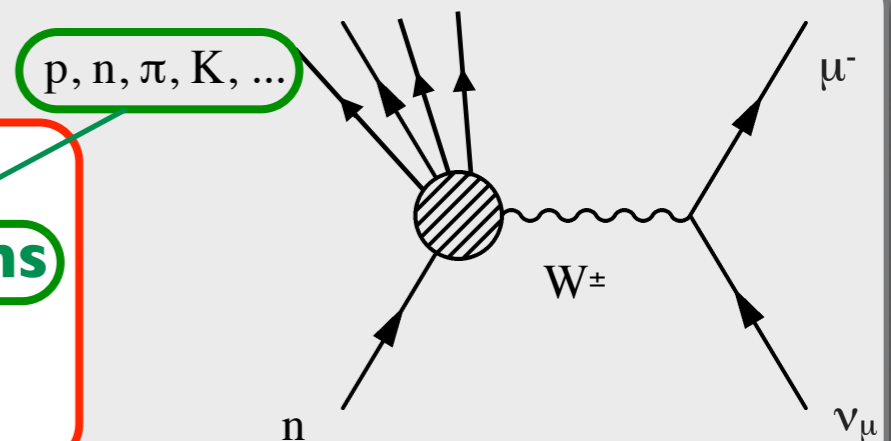
“soft collision”: **only a nucleon** is emitted (before nuclear reinteractions)



DIS

The invariant mass is much larger than the nucleon mass:
 $W \gg M$

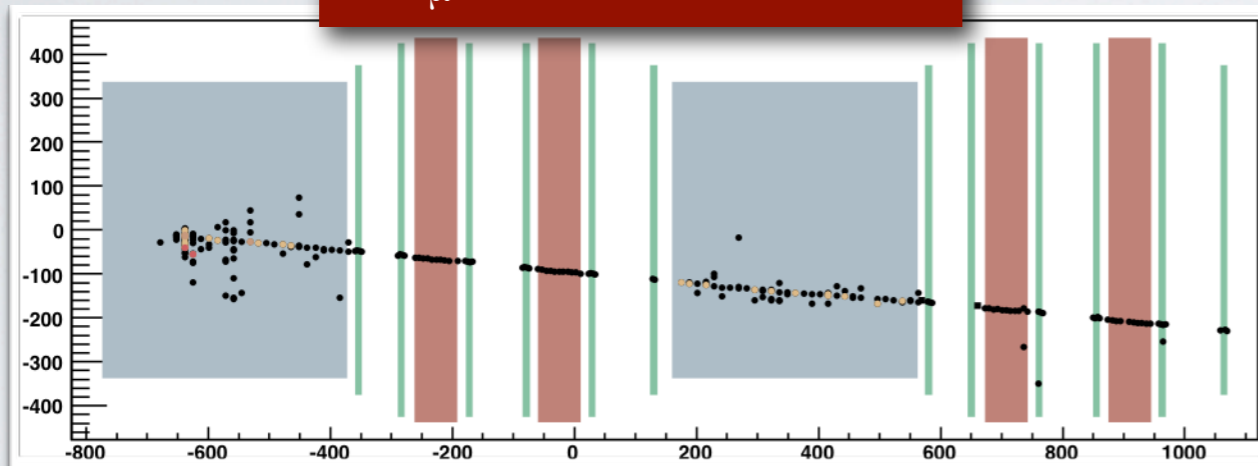
“hard collision”: **many hadrons** are emitted



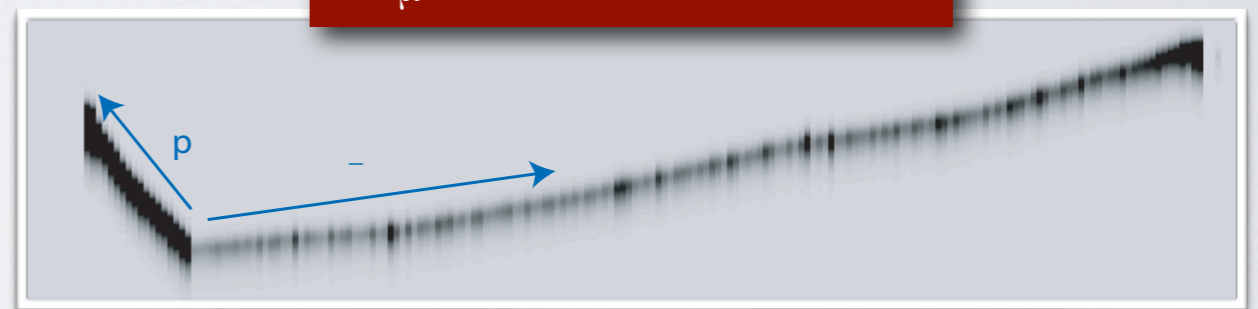
NEUTRINO DETECTION

- 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.

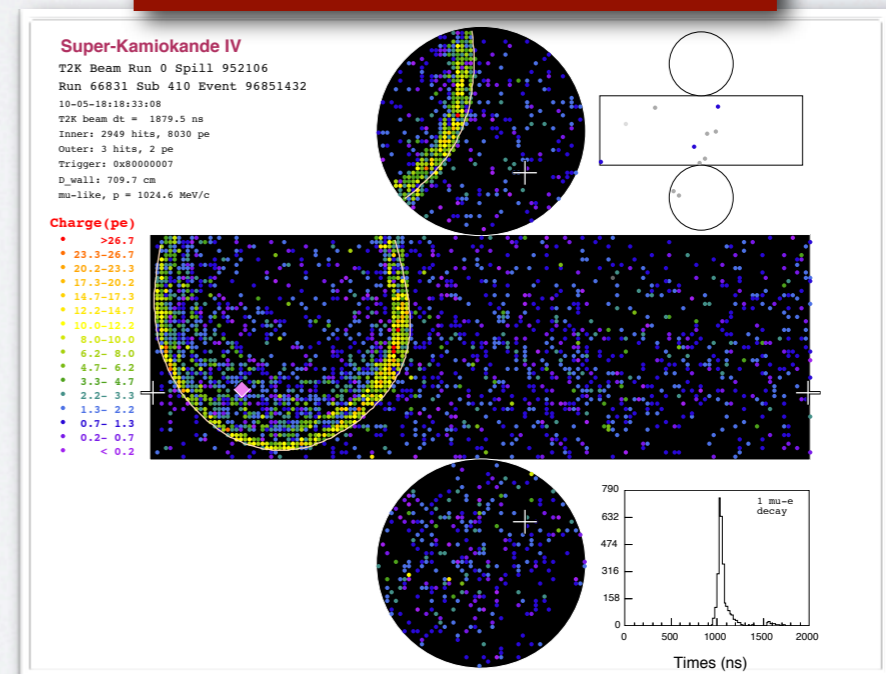
ν_μ CC in OPERA



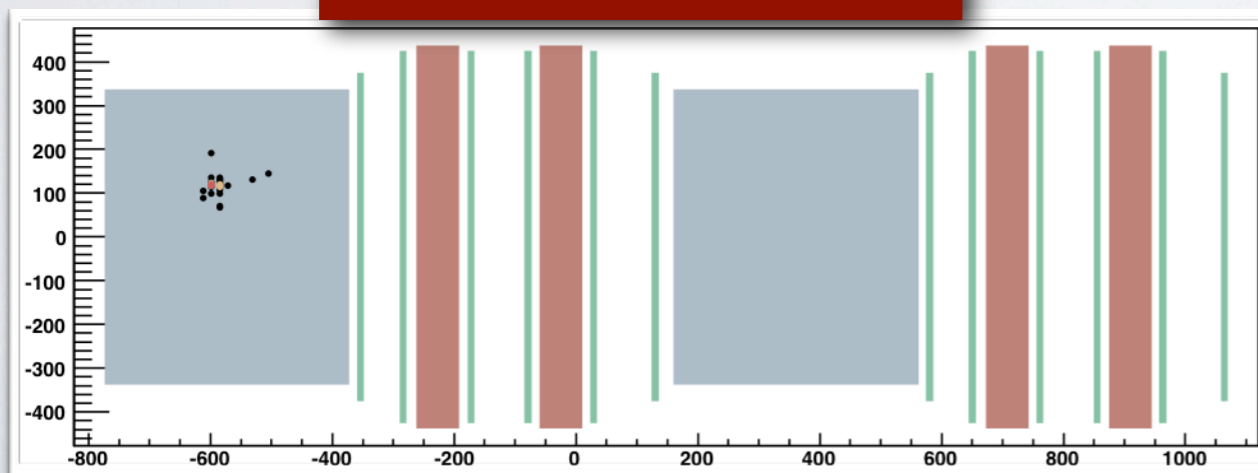
ν_μ CC in LAr TPC



ν_μ CC in SK



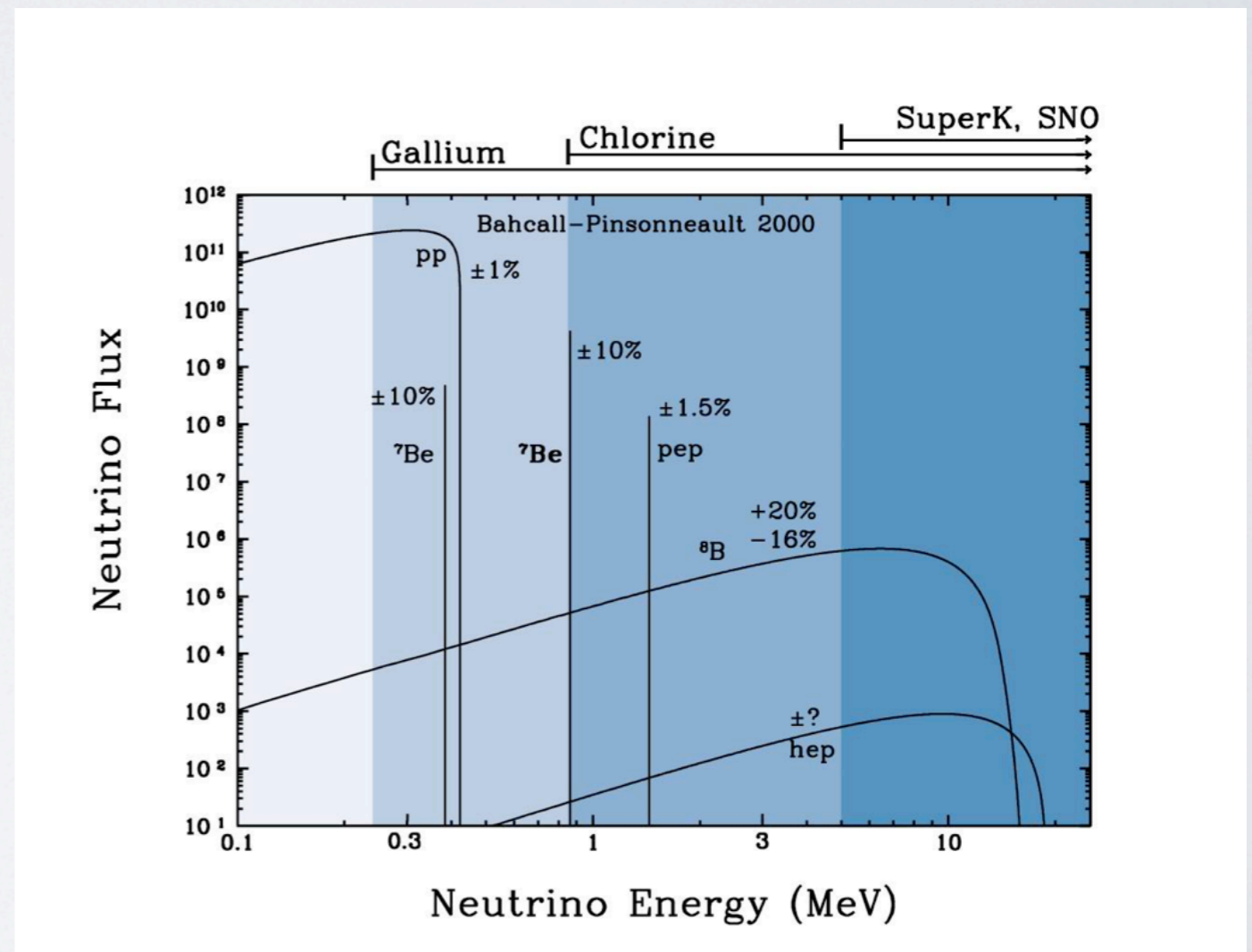
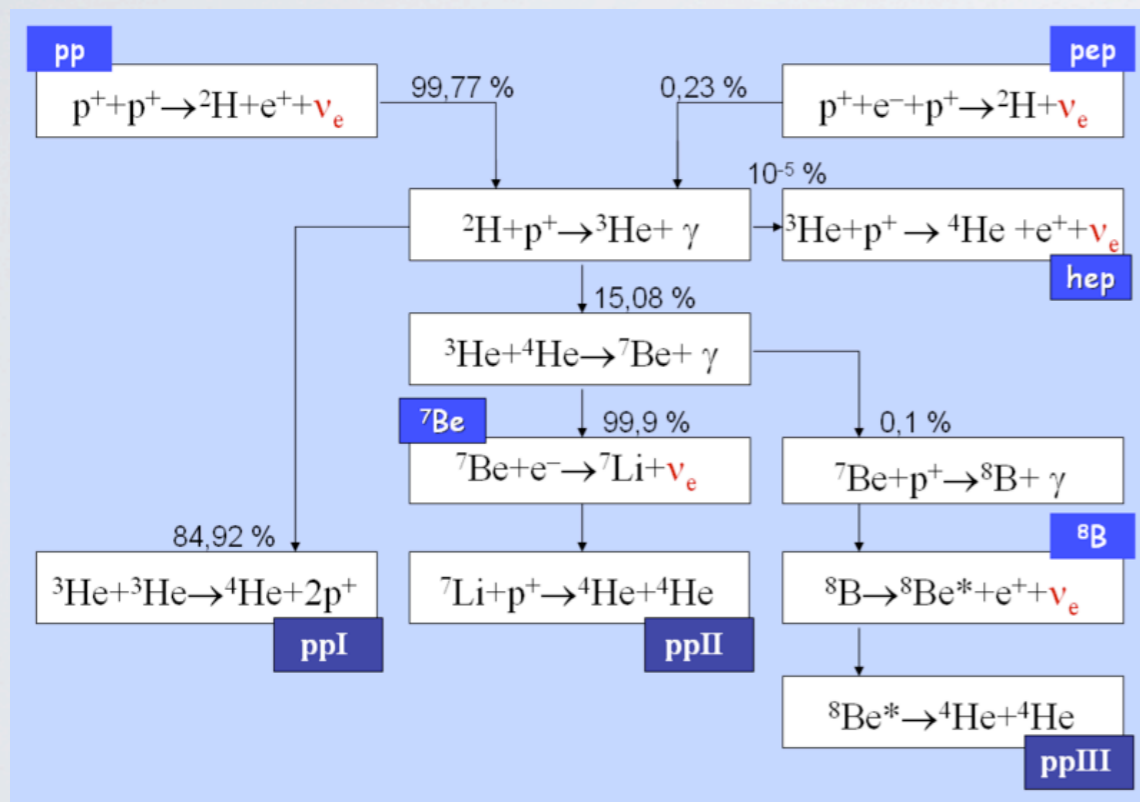
ν NC in OPERA



NEUTRINO OSCILLATIONS

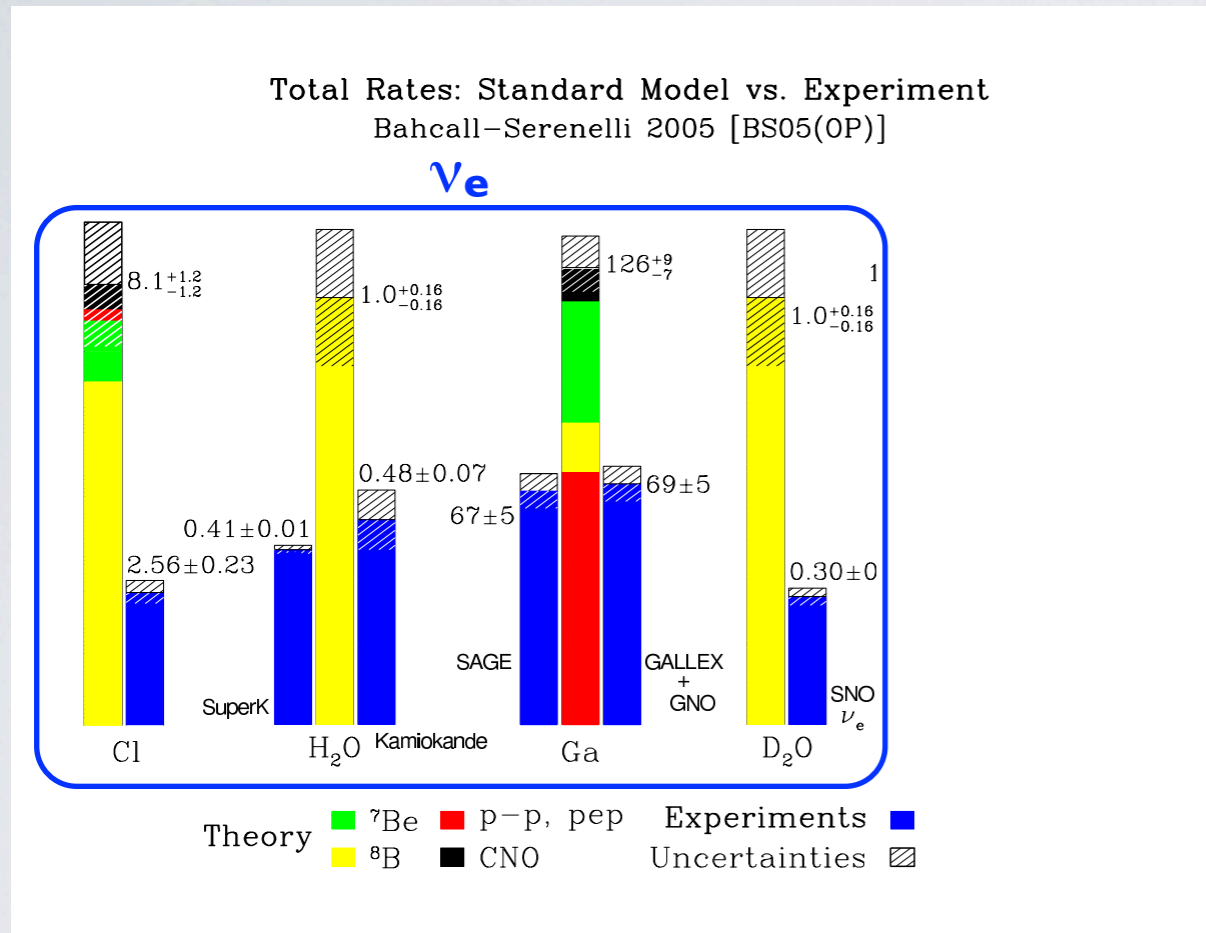
SOLAR NEUTRINO PROBLEM

- The sun emits a huge number of neutrinos and the energy and flux have been computed by Bahcall starting in the 1960'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

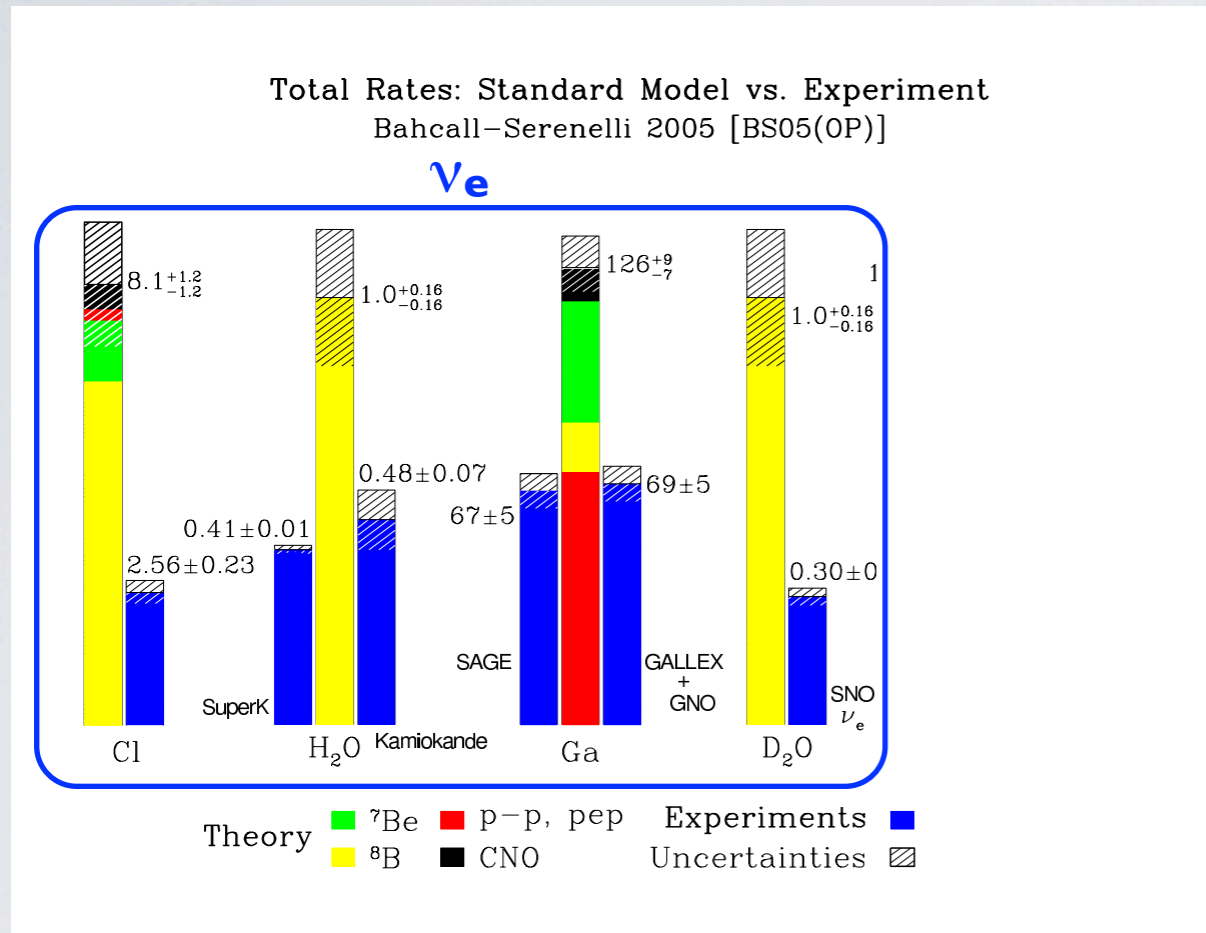
- Possible explanations:

1. The solar model is not well enough understood?

2. The neutrinos are not well enough known?

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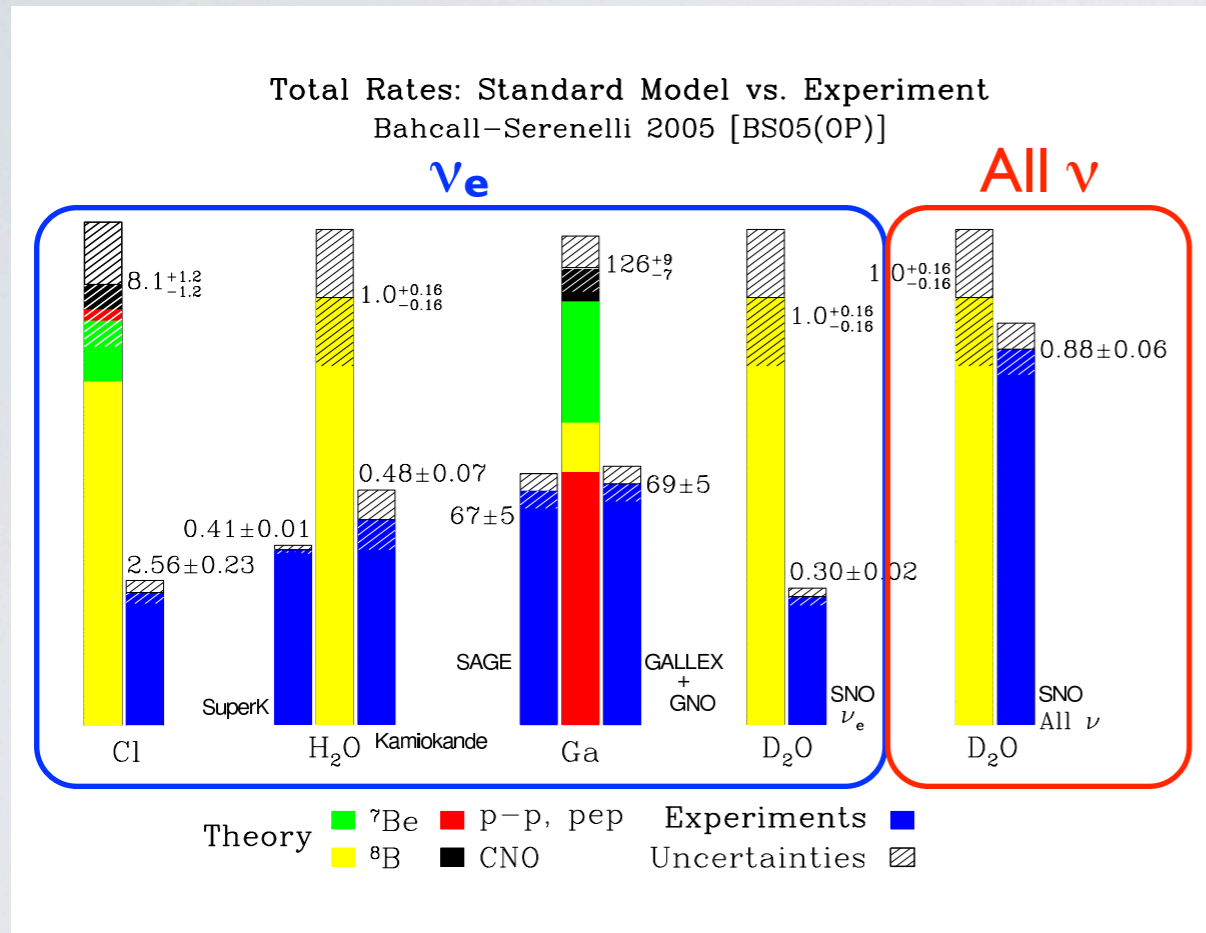
Disfavoured by good agreement with helioseismology measurements

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Neutrino oscillation? Idea of Pontecorvo back in 1957

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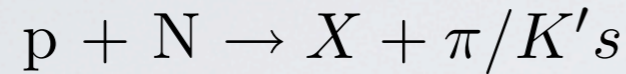
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Neutrino oscillation? Idea of Pontecorvo back in 1957

ATMOSPHERIC NEUTRINO PROBLEM

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

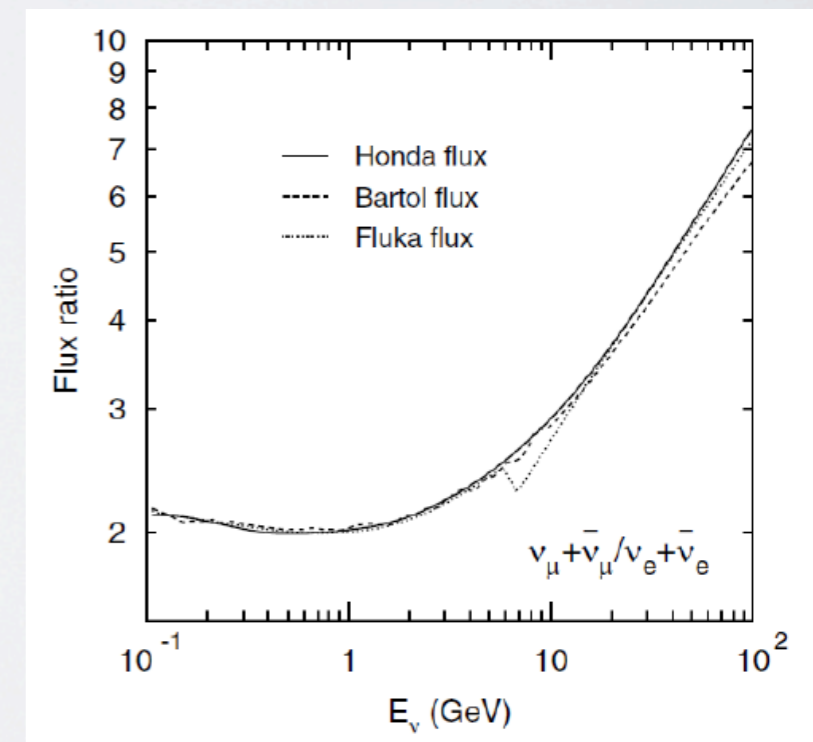
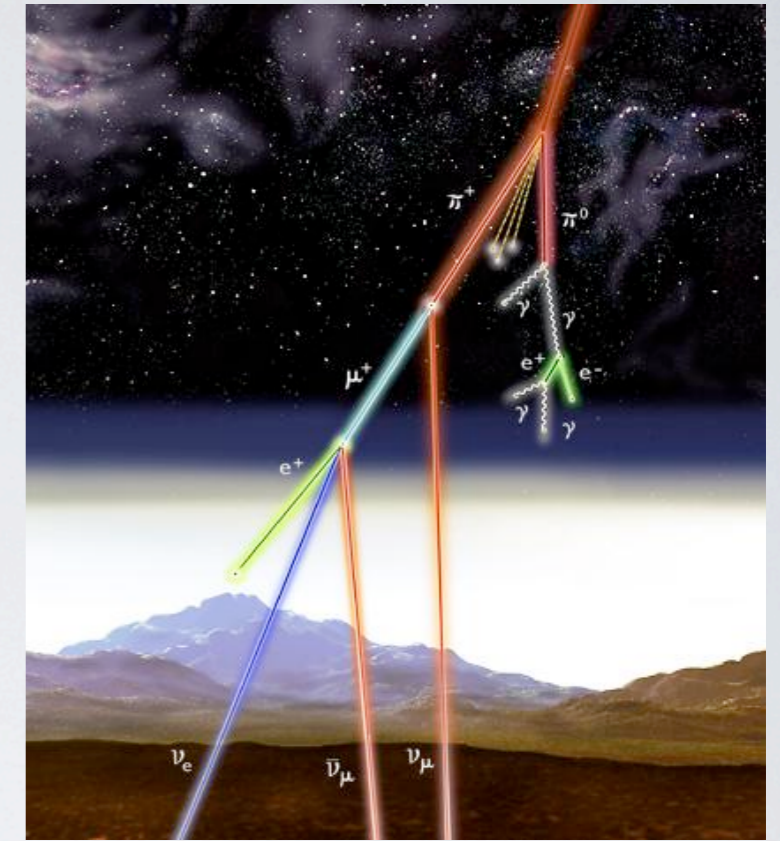


- Due to low density of the atmosphere most of the **hadrons decay** before interacting and also a large fraction of the **muons** produced by the secondary particles **decay** before reaching the ground.

- The most relevant chain is:

$$\begin{array}{ll} \pi^- \rightarrow \mu^- \bar{\nu}_\mu & \pi^+ \rightarrow \mu^+ \nu_\mu \\ \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu & \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \end{array}$$

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



ATMOSPHERIC NEUTRINO PROBLEM

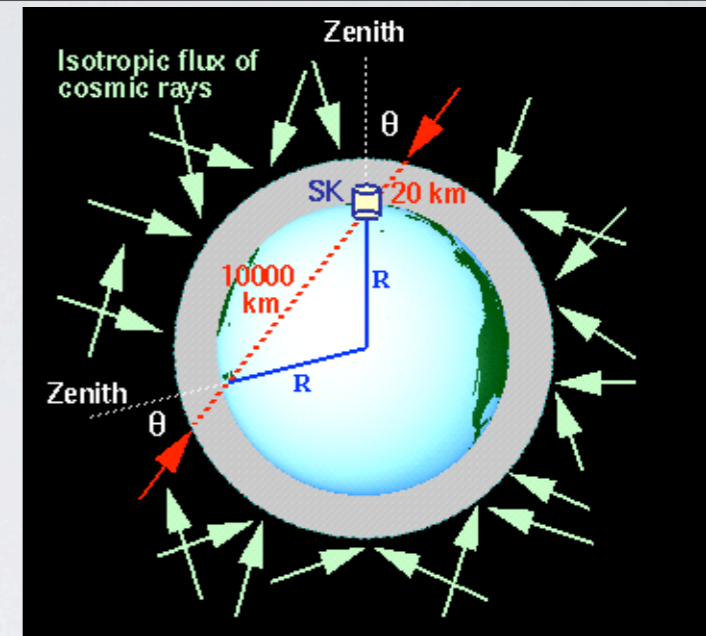
- Many experiments measured the ratio:
$$RR = \frac{(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)_{Observed}}{(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)_{Expected}}$$

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

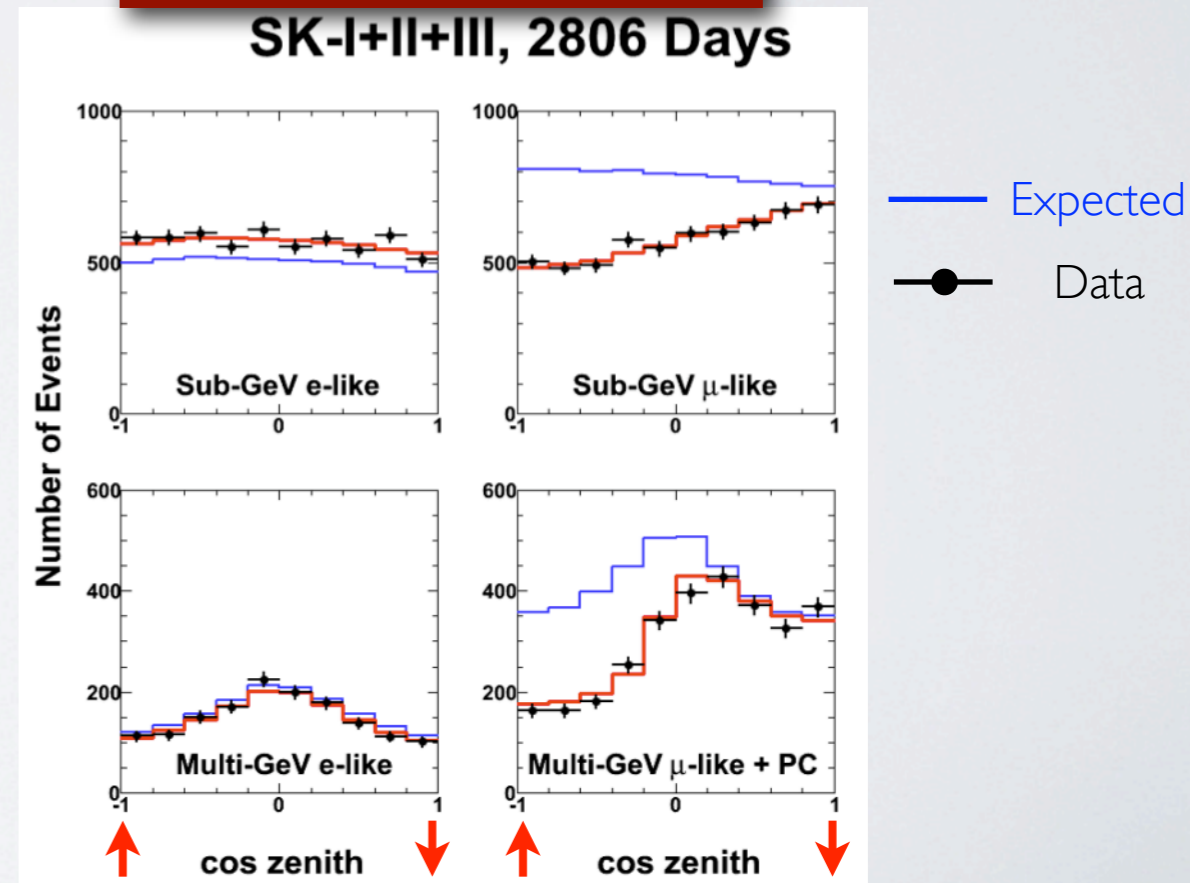
- **Are the electrons too many or the muons too few?**

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:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- 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:

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

- 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:

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

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

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

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

$$\sin^2(\Delta m_{ij}^2 L / 4E)$$

where

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

L = baseline (normally distance between
v 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:

$$\sin^2(\Delta m_{ij}^2 L / 4E)$$



$$\sin^2(1.27 \Delta m_{ij}^2 L / E)$$

$$\begin{aligned} L &= [\text{km}] \\ E &= [\text{GeV}] \\ \Delta m^2 &= [\text{eV}^2] \end{aligned}$$

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:

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

A SIMPLE PICTURE: 2 FLAVOURS

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

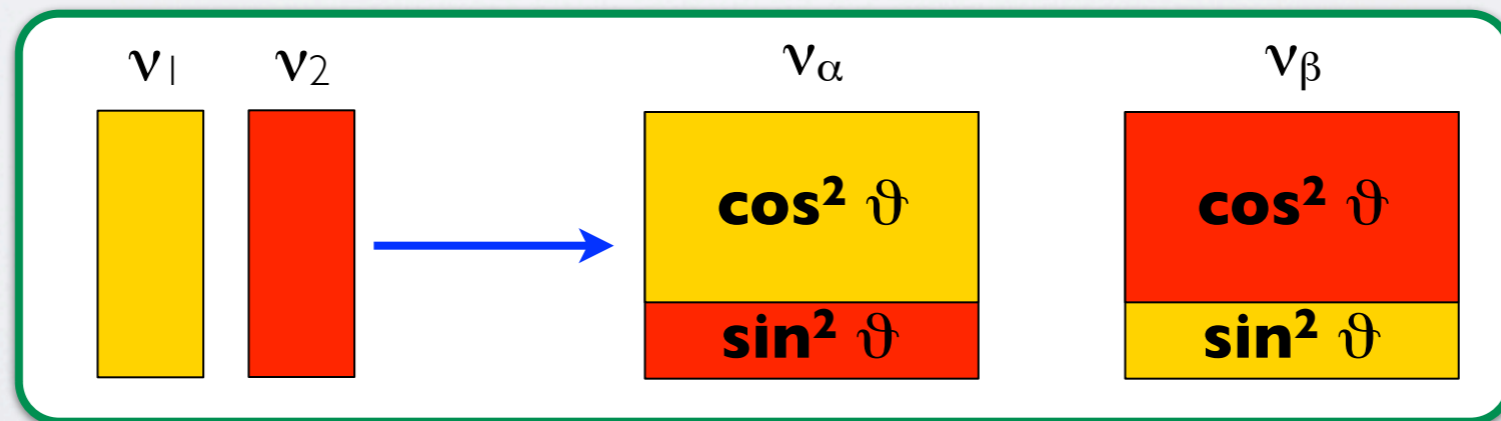
$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

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

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

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

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



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:

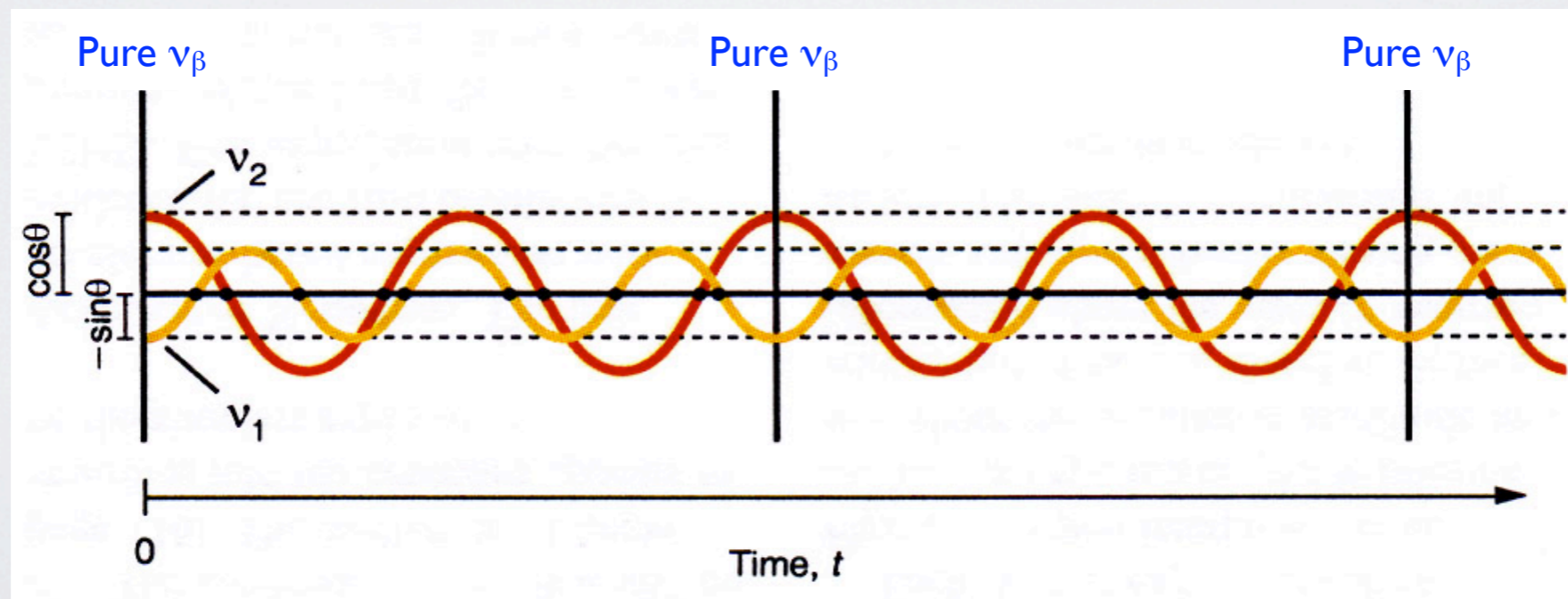
$$|\nu_i(t)\rangle = e^{-iE_i t} |\nu_i(0)\rangle$$

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

$$|\nu_\beta(t)\rangle = -\sin\theta e^{-iE_1 t} |\nu_1(0)\rangle + \cos\theta e^{-iE_2 t} |\nu_2(0)\rangle$$

$$|\nu_\alpha(t)\rangle = \cos\theta e^{-iE_1 t} |\nu_1(0)\rangle + \sin\theta e^{-iE_2 t} |\nu_2(0)\rangle$$

- The oscillation pattern can be graphically described as:



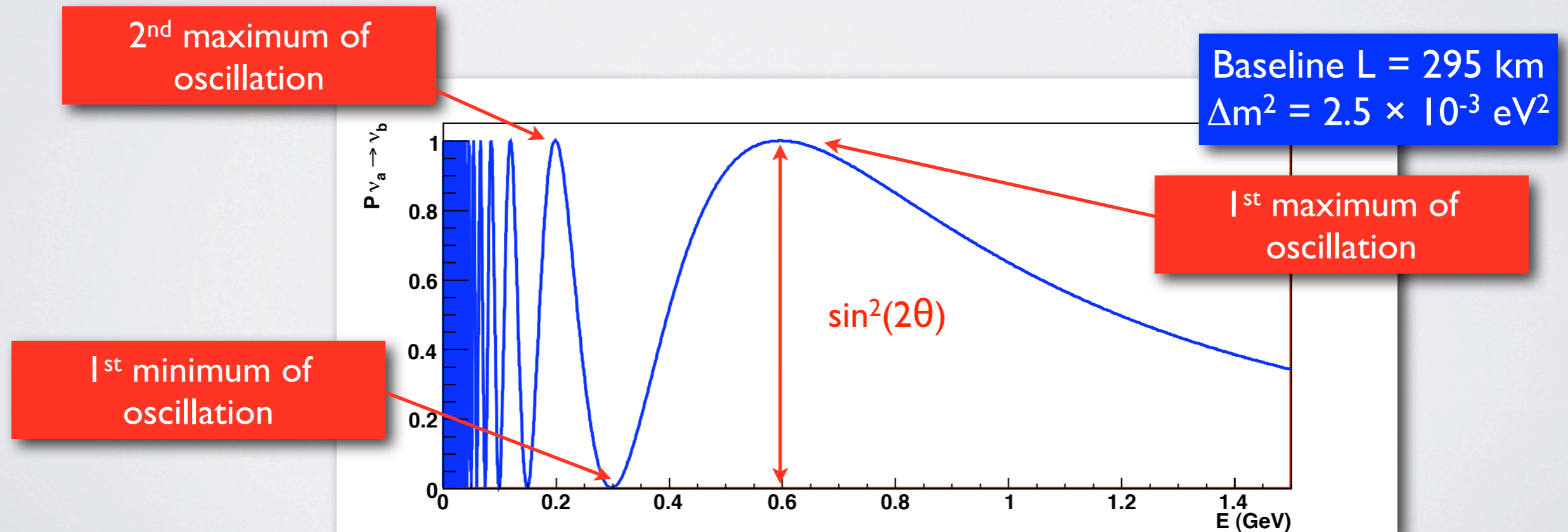
A SIMPLE PICTURE: 2 FLAVOURS

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

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

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:



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:

$$P(\nu_\alpha \rightarrow \nu_\beta; U) = P(\nu_\beta \rightarrow \nu_\alpha; U^*)$$

T transformation

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

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

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 **2N² free parameters**.
- In order to conserve probability the matrix has to be **unitary** (the inverse matrix is equal to the conjugate transpose):

$$\sum_{\alpha} |U_{\alpha i}|^2 = 1 \quad \leftarrow \text{N constraints}$$
$$\sum_{\alpha} U_{\alpha i}^* U_{\alpha j} = 0 \quad \text{for } i \neq j \quad \leftarrow \text{N(N-1) constraints}$$

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

$$\langle l_{\alpha} | \rightarrow \langle l'_{\alpha} | = \langle l_{\alpha} | e^{-i\phi_{\alpha}} \Rightarrow U_{\alpha i} \rightarrow U'_{\alpha i} = e^{-i\phi_{\alpha}} U_{\alpha i} \quad \leftarrow \text{N constraints}$$

- 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:

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

where “ c_{ij} ” stands for “ $\cos \vartheta_{ij}$ ” and “ s_{ij} ” for “ $\sin \vartheta_{ij}$ ” 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:

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

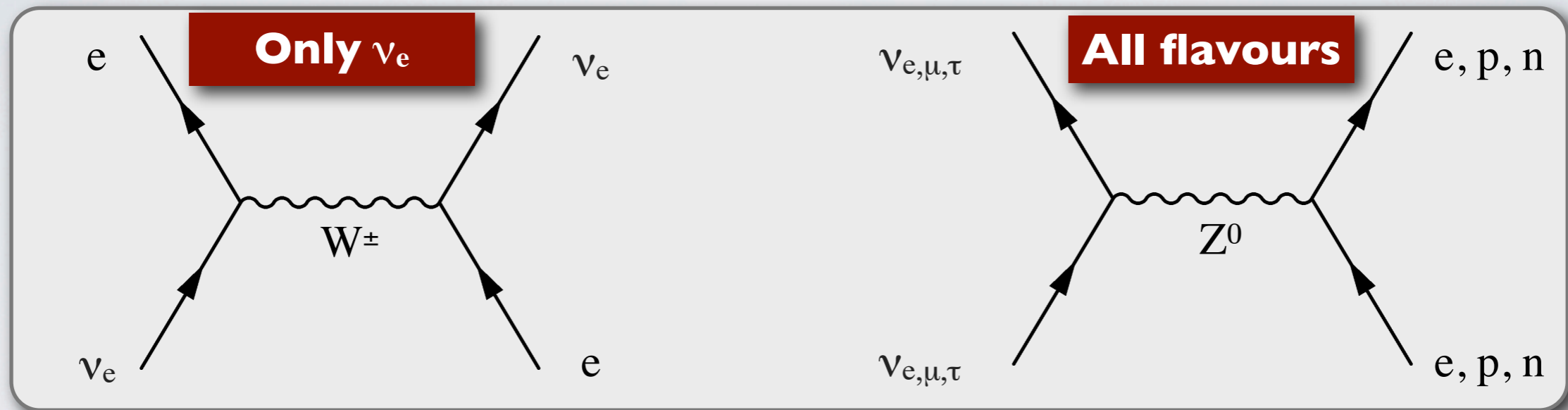
Atmospheric scale

Interference

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:

$$V = V_e - V_X = \sqrt{2}G_F n_e$$

where

$$2\sqrt{2}G_F n_e = 7.56 \times 10^{-5} eV^2 \rho (g/cm^3)$$

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:

$$H_0 \rightarrow H = H_0 + V$$

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:

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

where

$$A = 2E(V_e - V_X)$$

- The mixing angle can be written as:

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

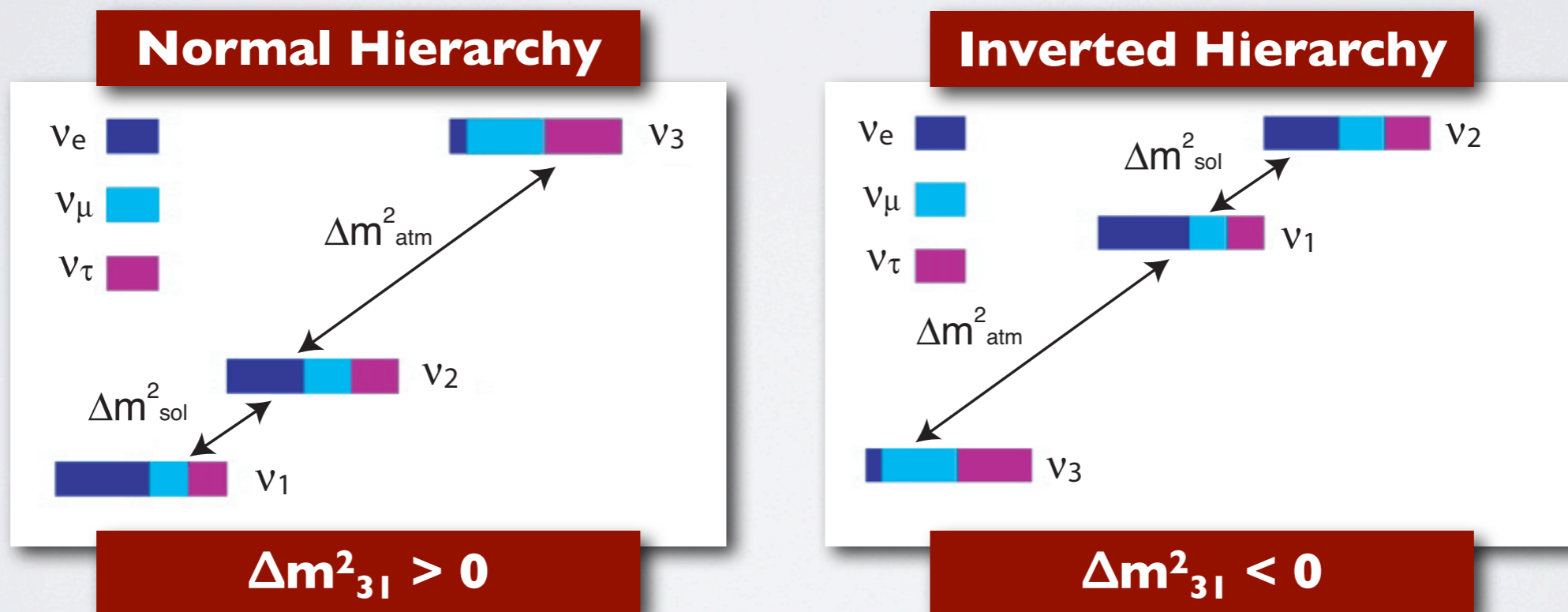
- We note some important features:

1. As expected if $A \rightarrow 0$ (vacuum) $\theta_m \rightarrow \theta$.

2. If $A = \Delta m^2 \cos(2\theta)$ 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

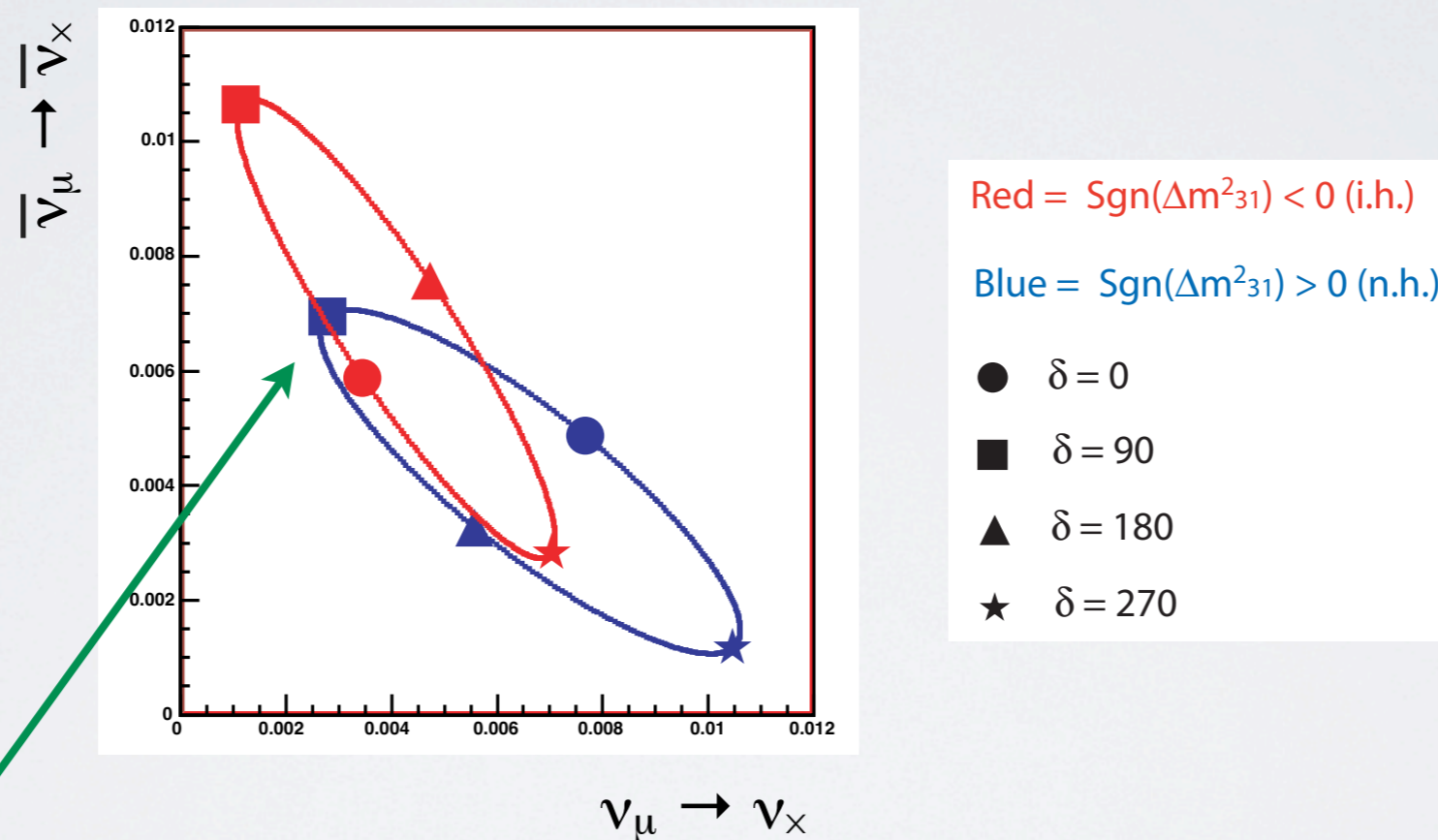
- We have seen that the ingredients for the description of neutrino oscillations are: the 3 mixing angles (θ_{12} , θ_{13} , θ_{23}), possibly the complex phase (δ_{CP}), and two mass differences (Δm^2_{21} , $\Delta m^2_{31} \approx \Delta m^2_{32}$).
- Another important ingredient is the **sign** of 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.



- 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** ($\delta_{\text{CP}} = 90$) **OR I.H. and CP conserved** ($\delta_{\text{CP}} \approx 0$).

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

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

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

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

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

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

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

Atmospheric term

Solar term

Interference terms

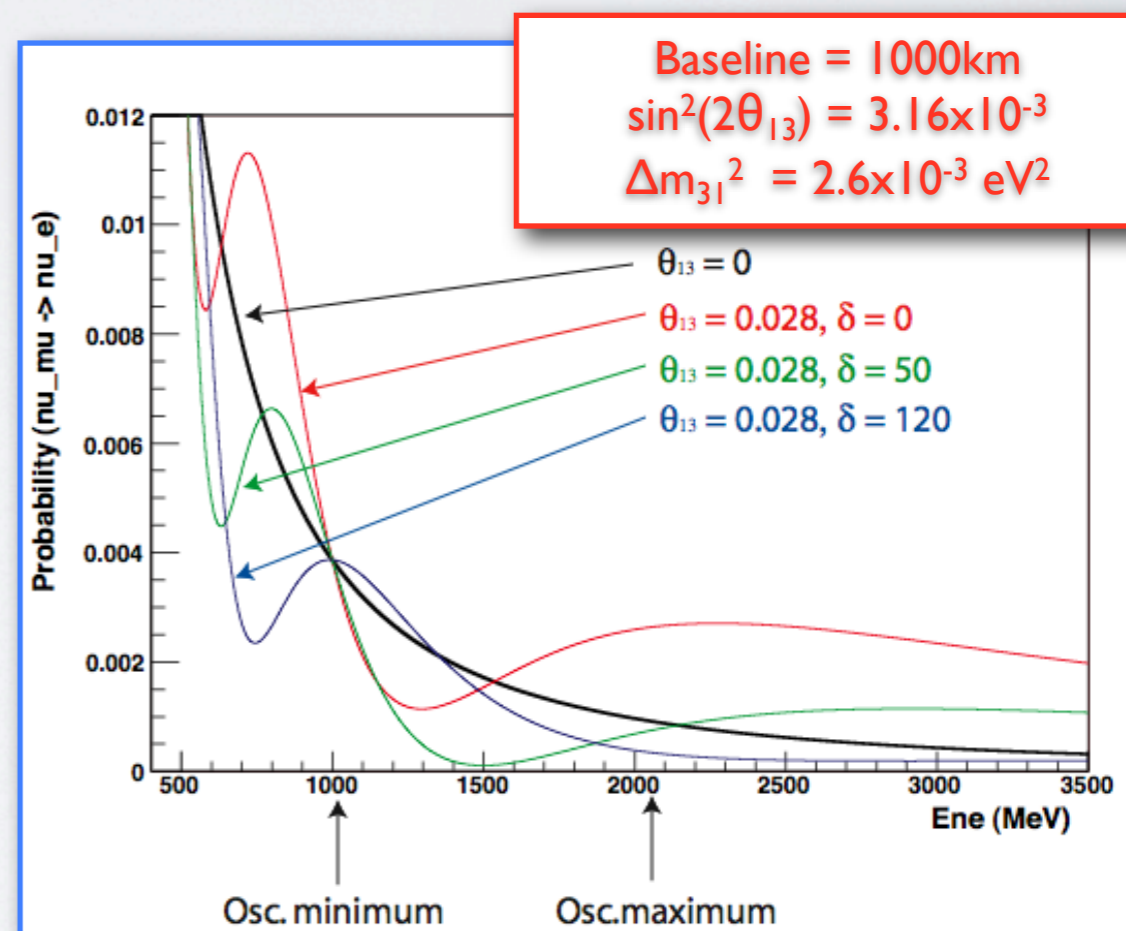
$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu}$$

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

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

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

- 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_{31}^2 also affects the oscillation probability (**only in matter**) and mass hierarchy must be determined.



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}				
$ \Delta m^2_{21} $				
Sign (Δm^2_{21})				
$ \Delta m^2_{31} $				
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

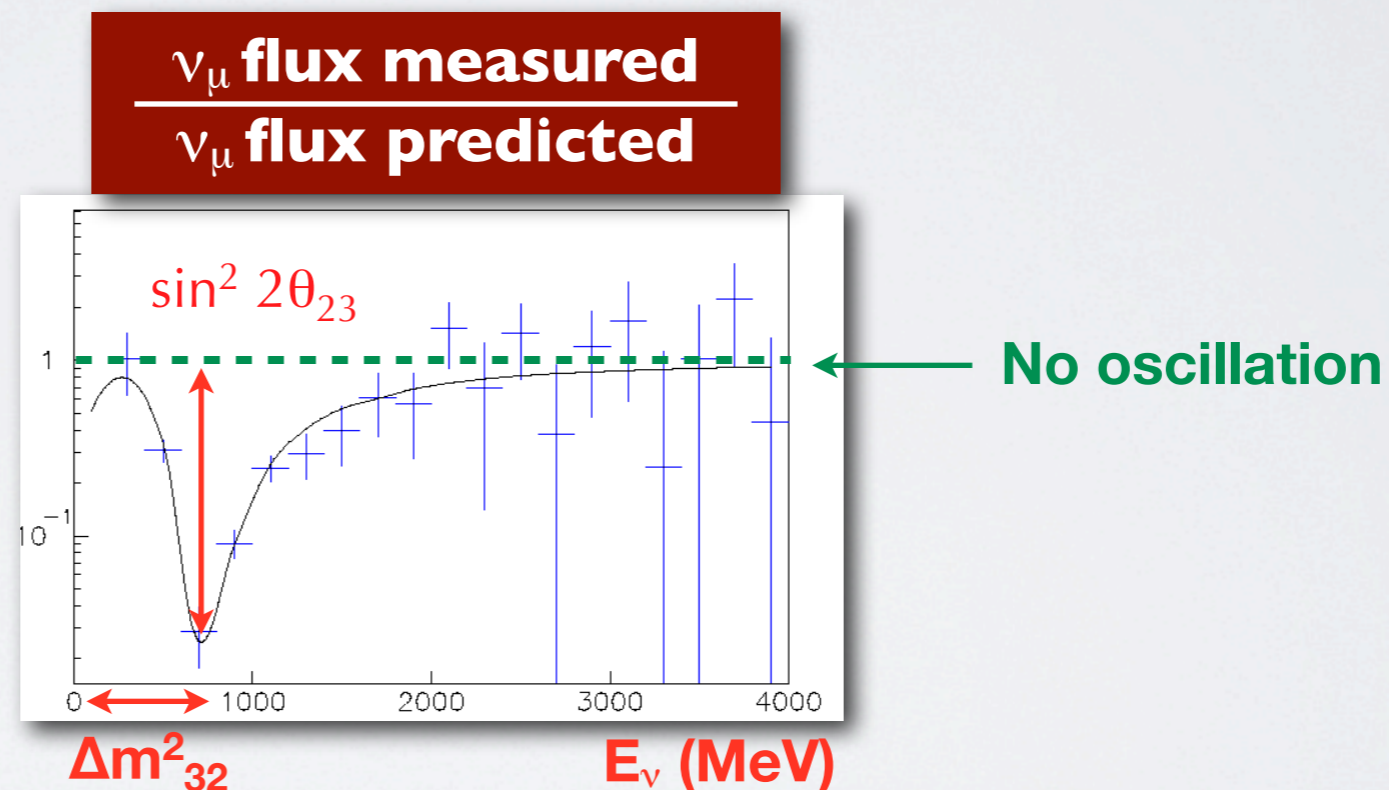
It is just an highlight on **some** detection techniques and important results related to neutrino oscillation, but it is far from being complete.

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**.

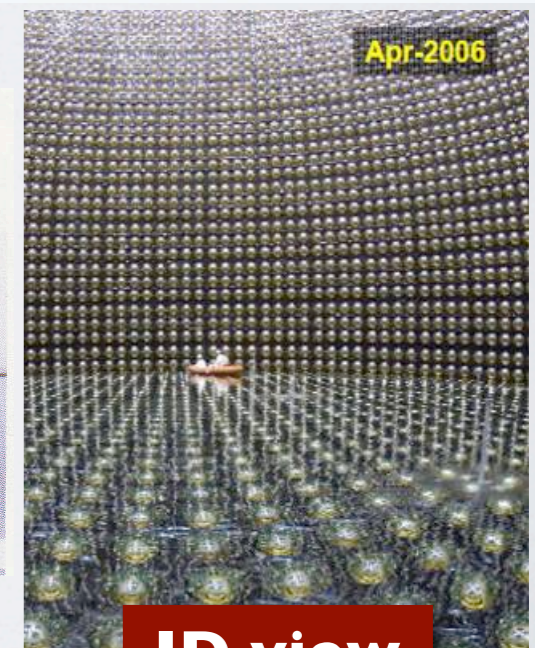
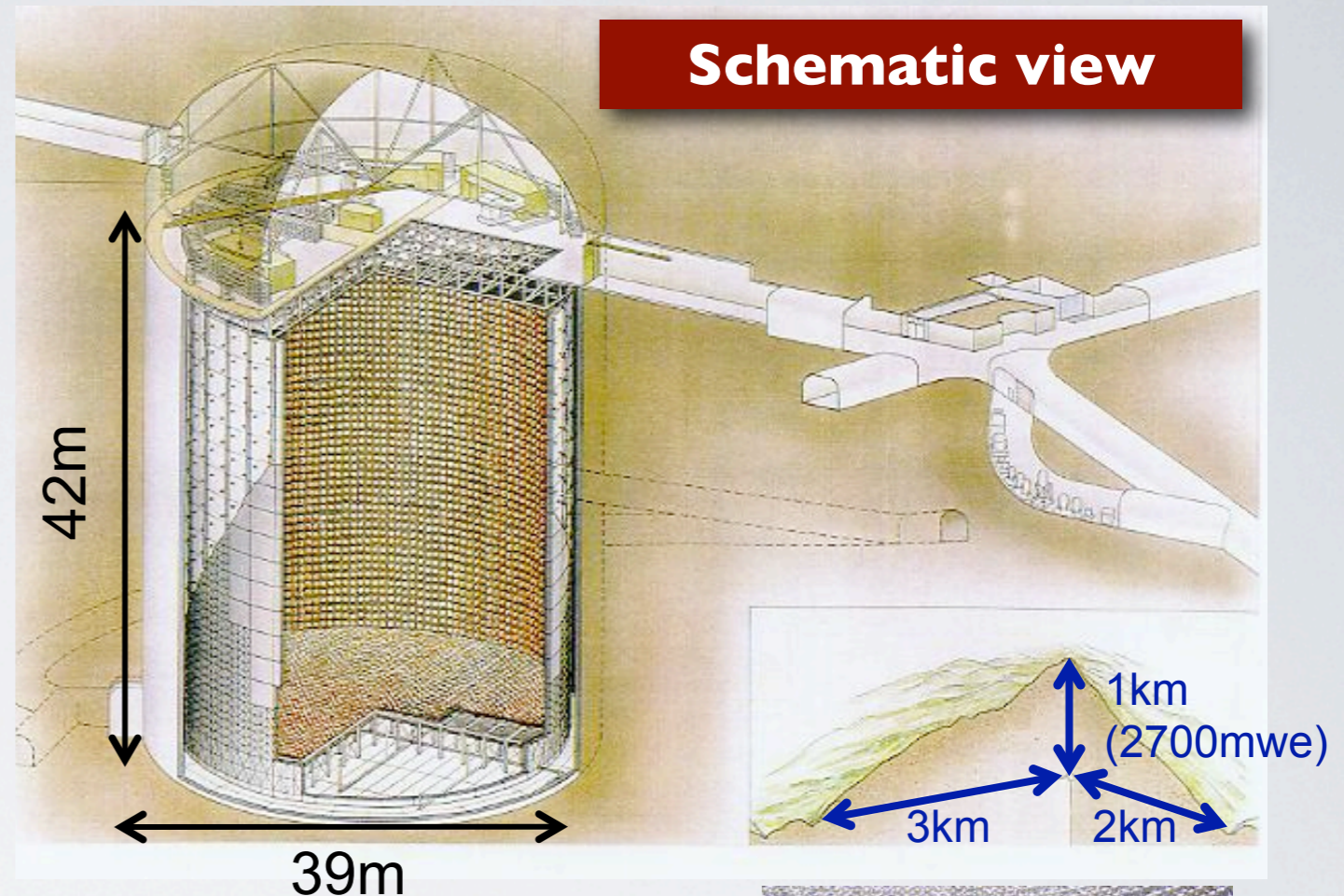


- The experiments that play(ed) a crucial role in these measurements are: **Super Kamiokande** (SK), **K2K**, **MINOS** and **T2K**.

SUPER KAMIOKANDE

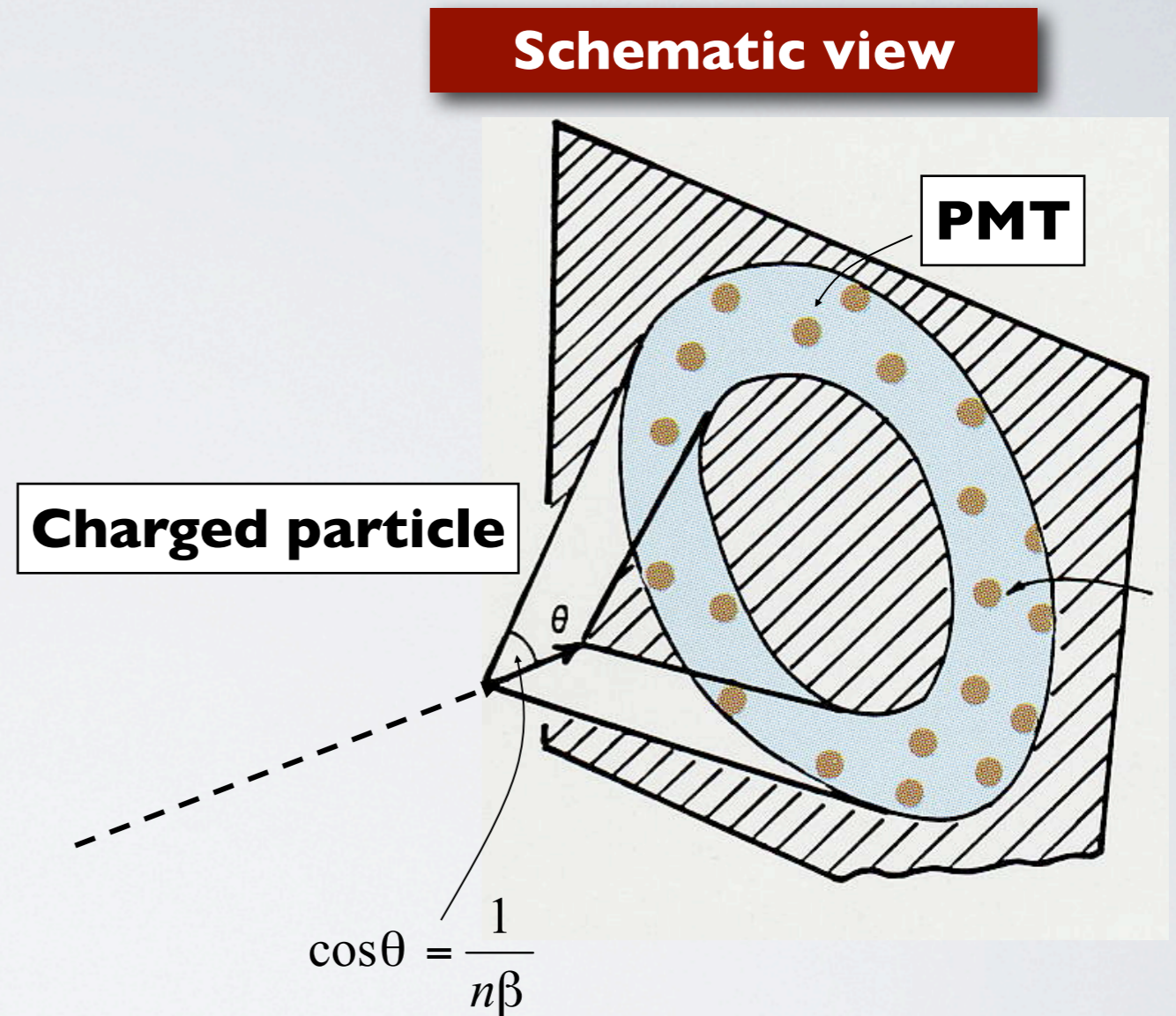
- SK is a **50 kton water Cherenkov** detector with a **fiducial volume of 22.5 kton**.
- It is located about 1 km underground.
- The inner detector is made of about 11146 PMTs with a diameter of 50 cm.
- The veto (2m of water) is made of about 1885 PMTs with a diameter of 20 cm.
- The event rate is 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.



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.

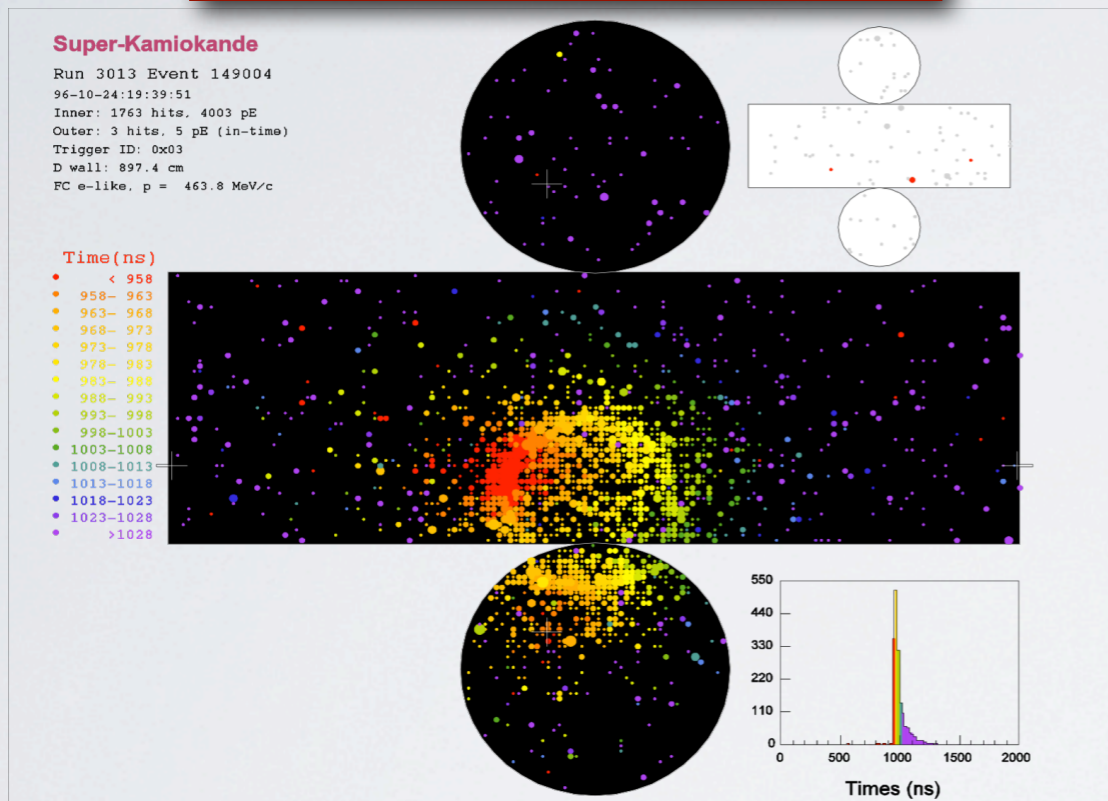


In **water $n = 1.34$** therefore
for $\beta = 1$, $\vartheta = 42$ deg.

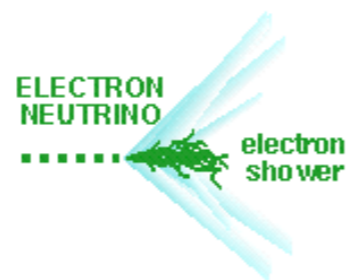
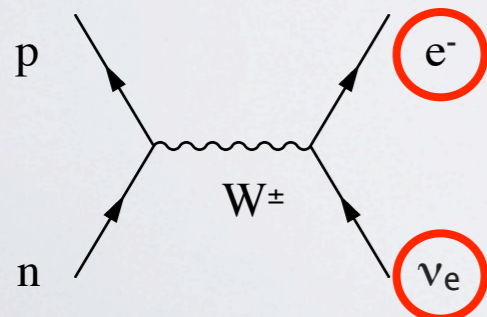
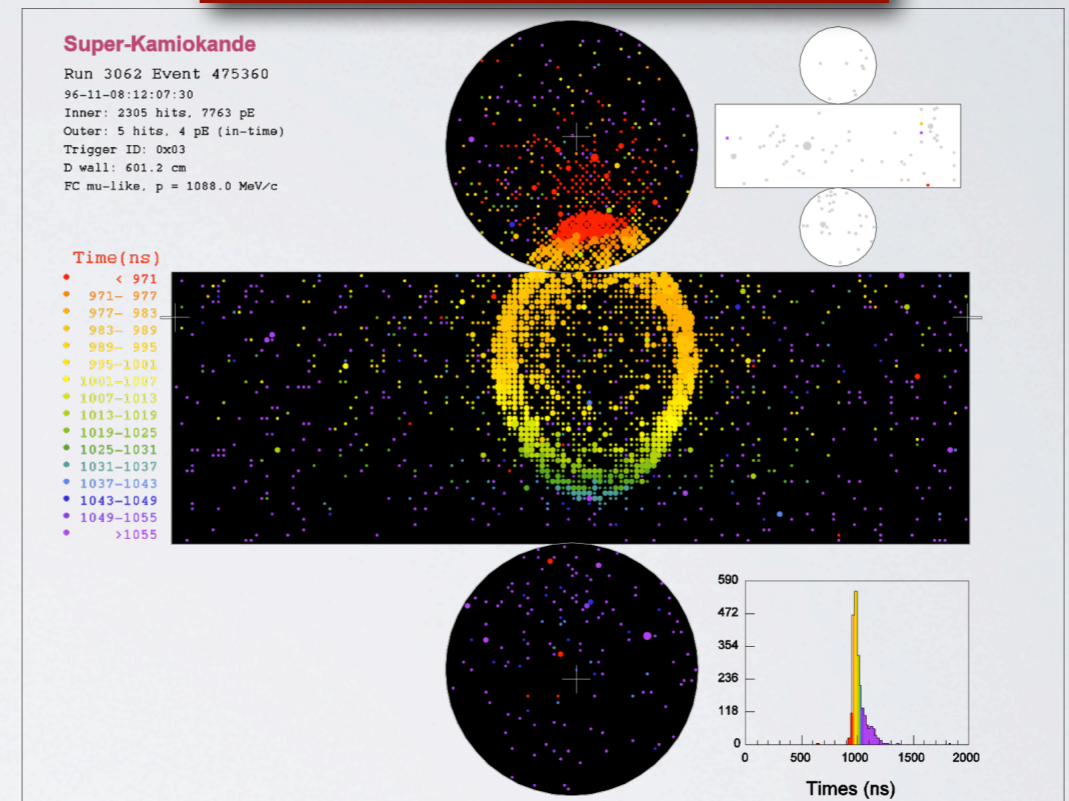
SK PARTICLE ID

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

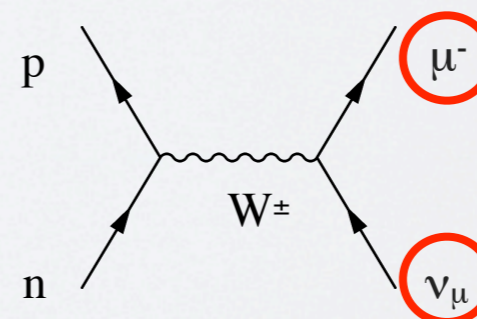
stopping electron ring



stopping muon ring



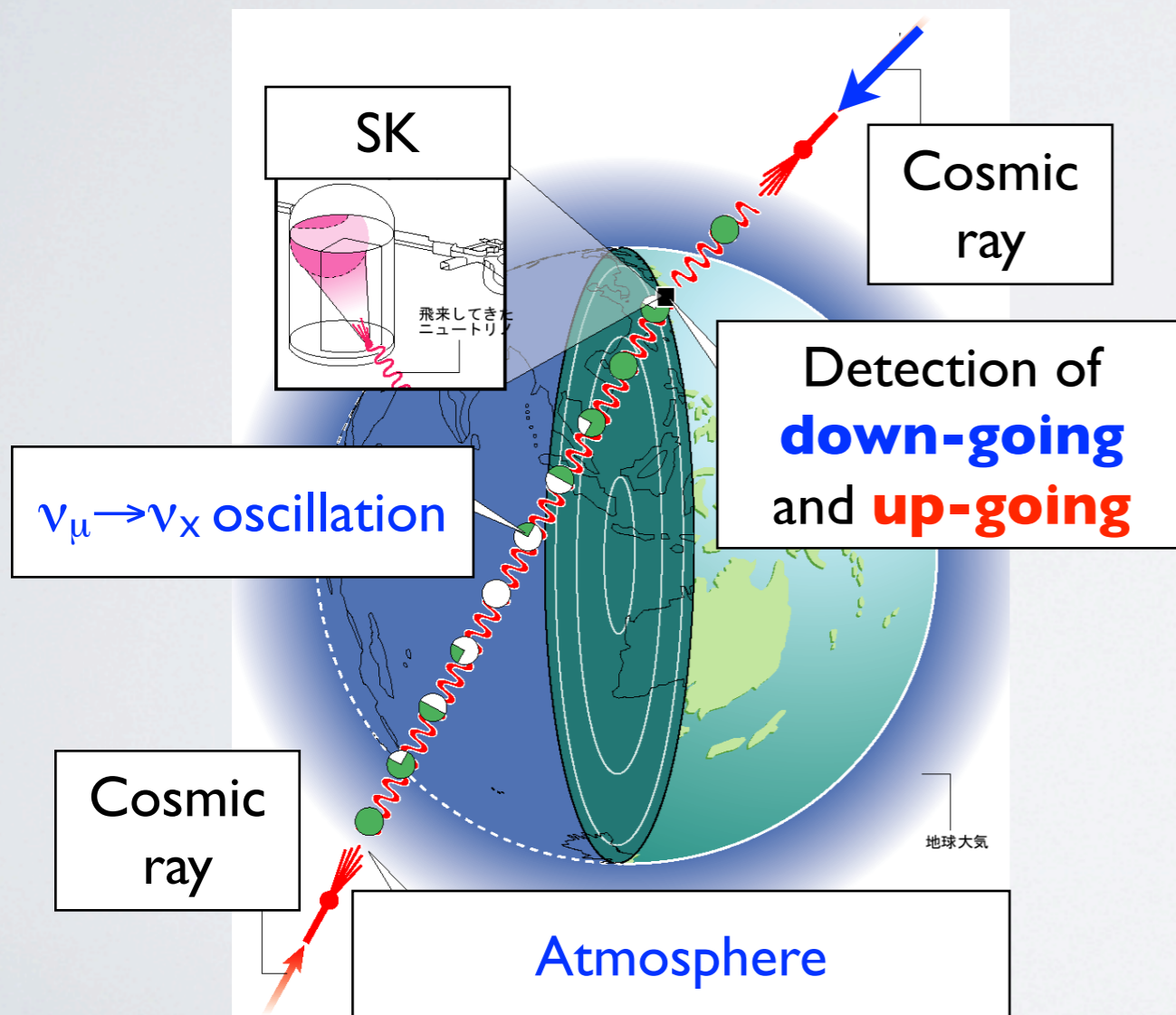
Not well defined cone



Well defined cone

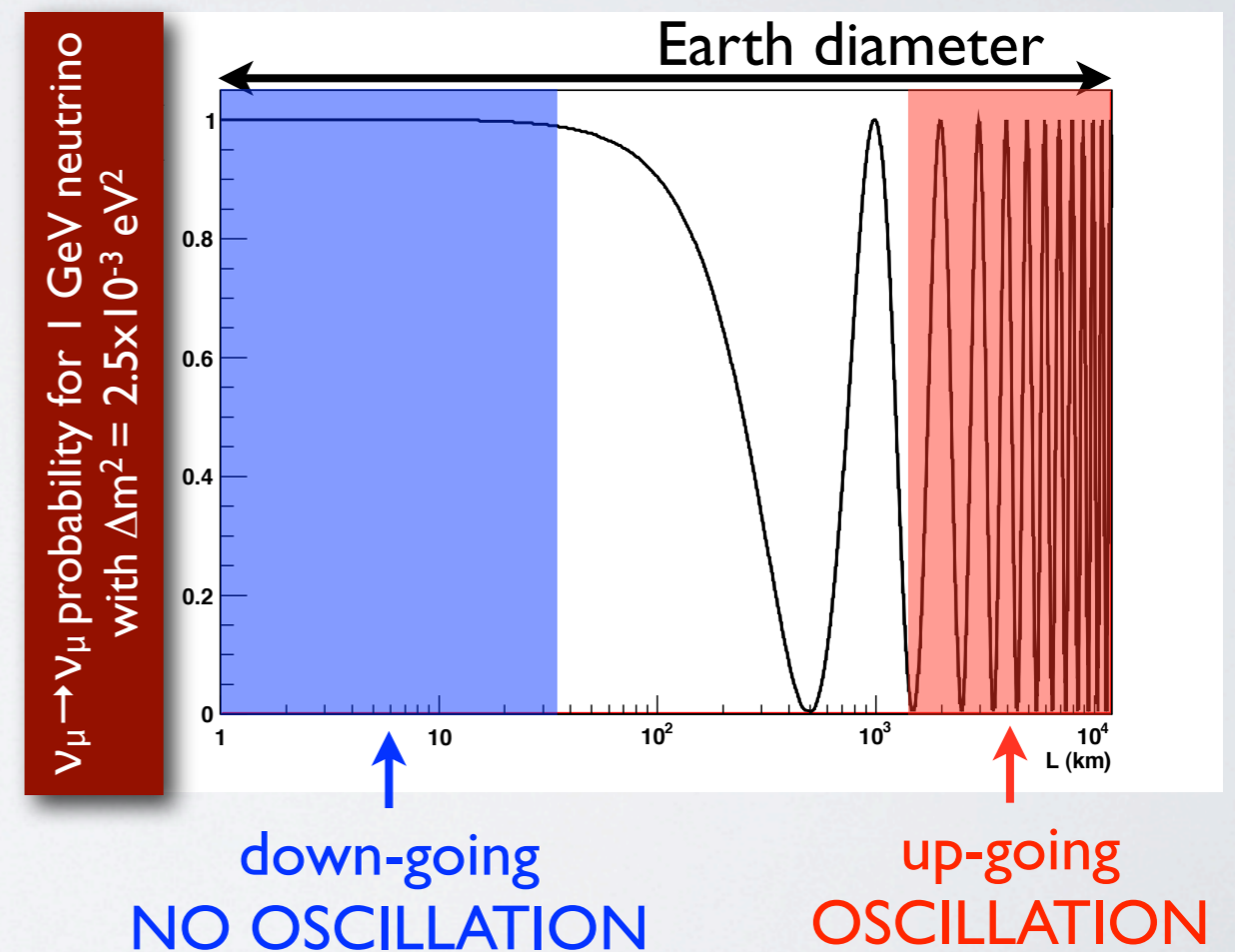
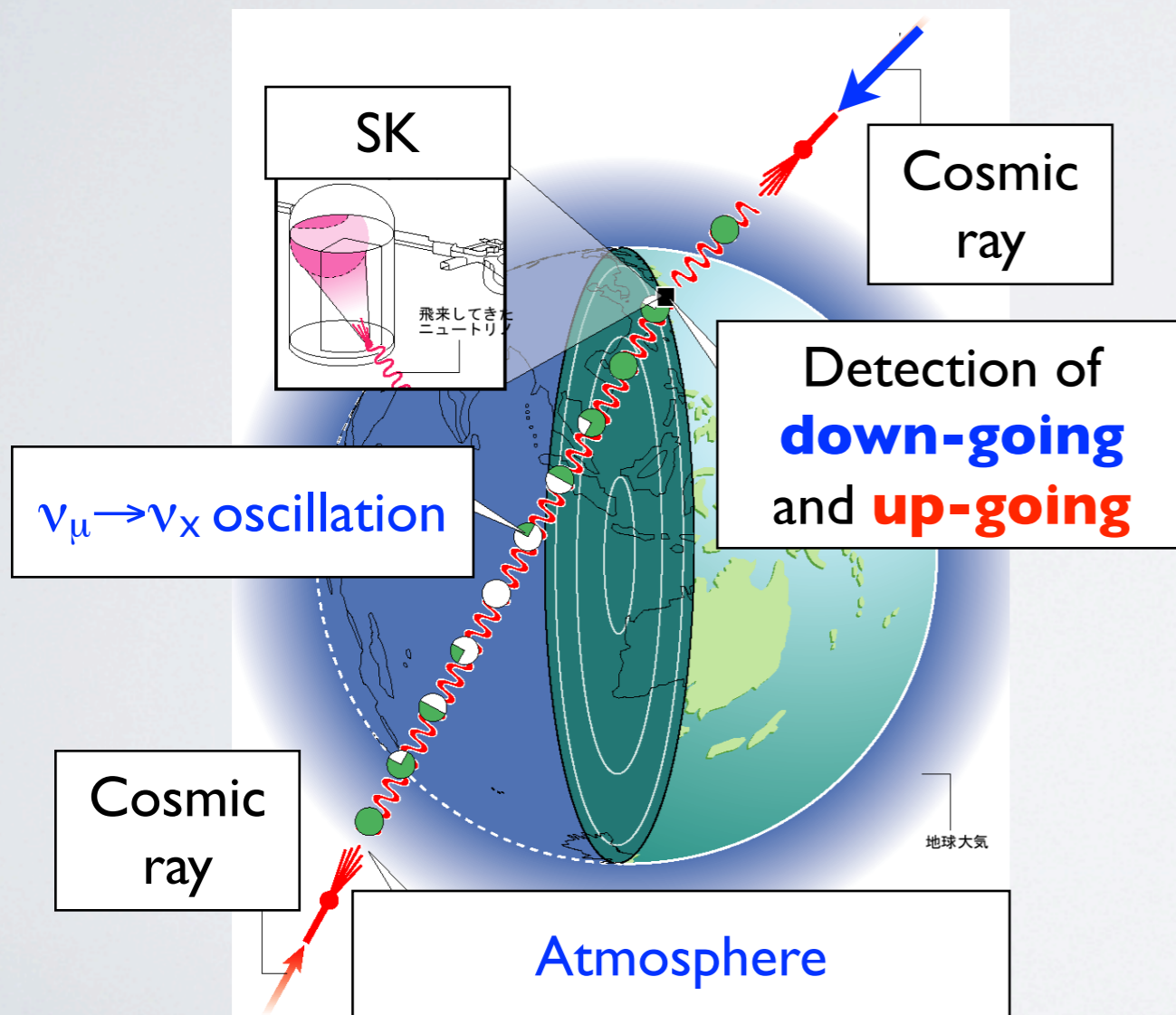
OSCILLATION OBSERVATION

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



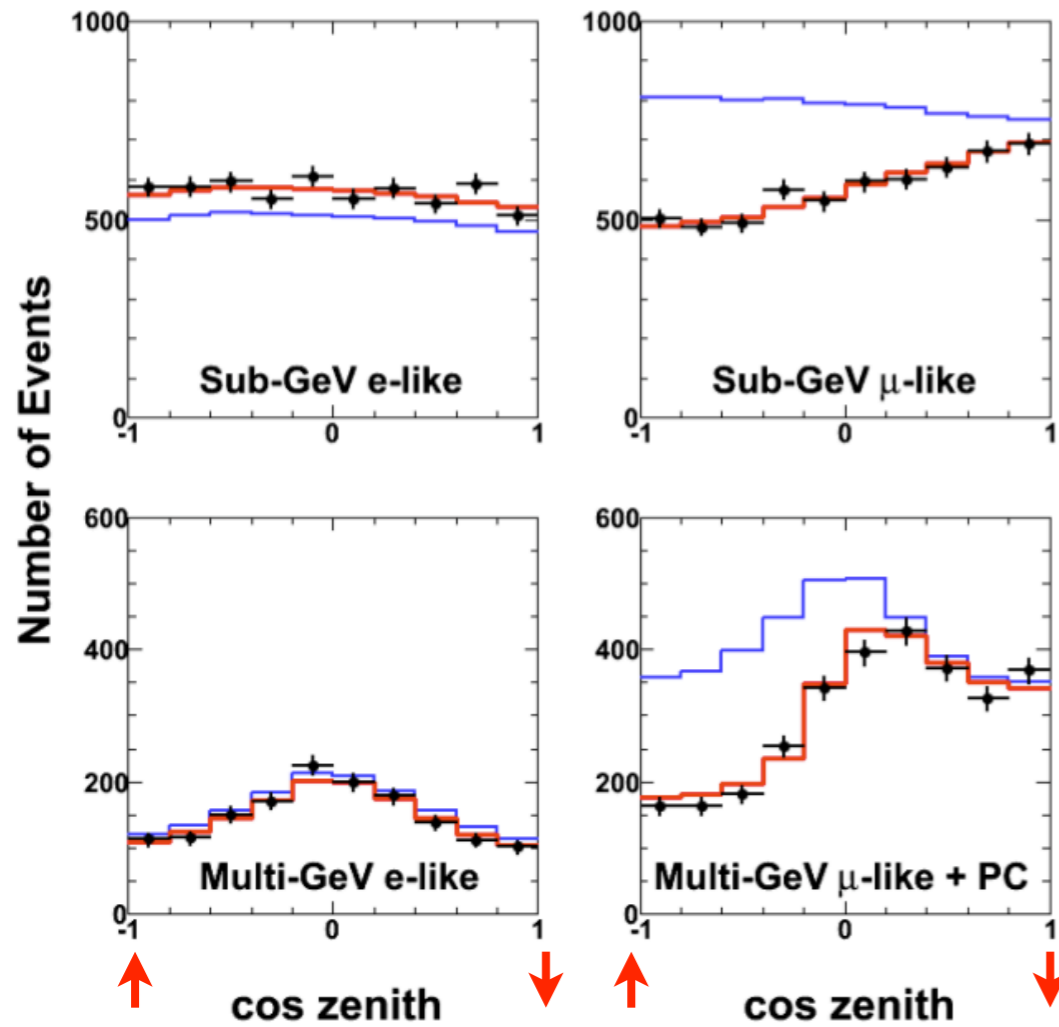
OSCILLATION OBSERVATION

- **Up-going** and **down-going** neutrinos travel different 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 RESULTS

SK-I+II+III, 2806 Days



No ν_e appeared

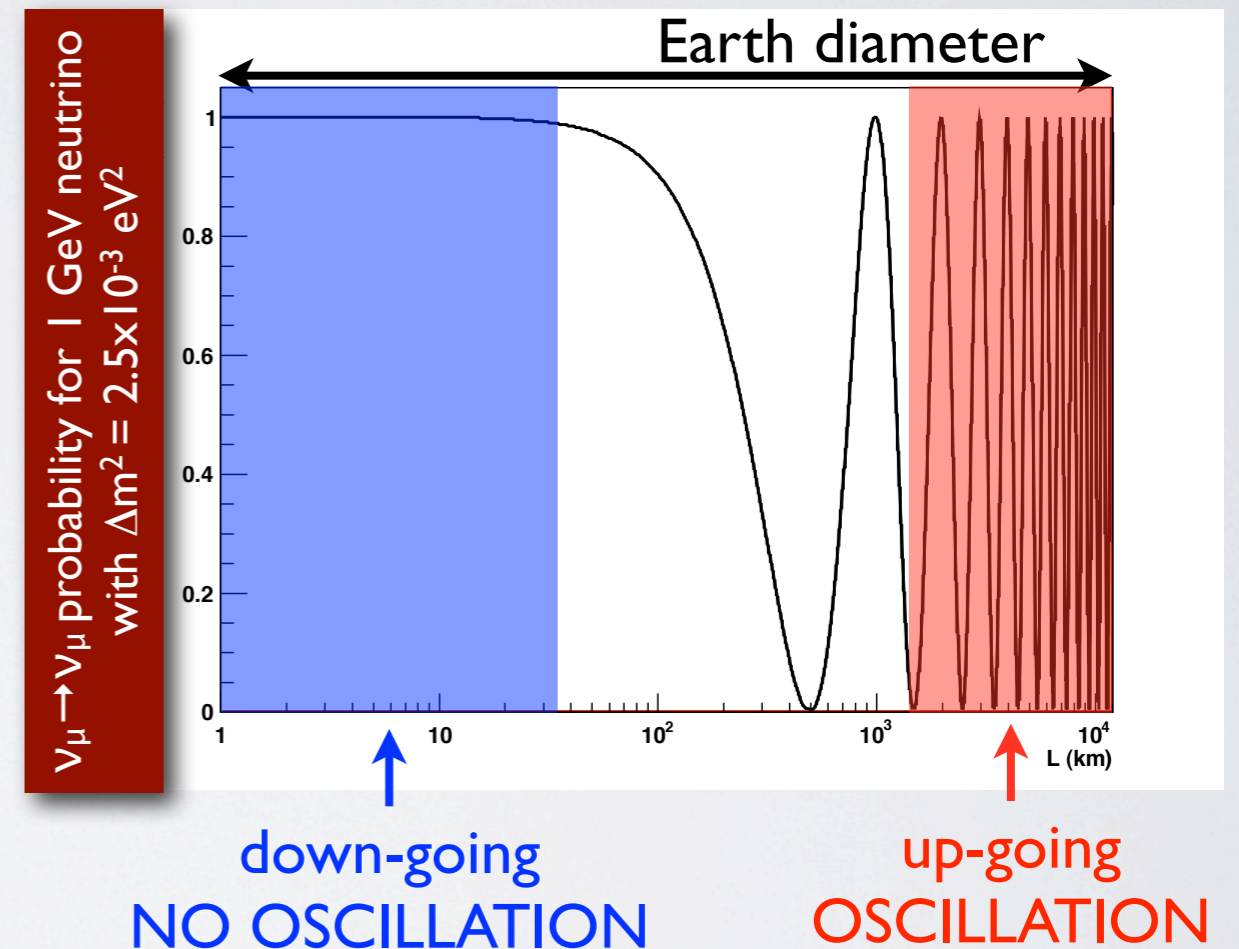
ν_μ disappeared

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

Best fit

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

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

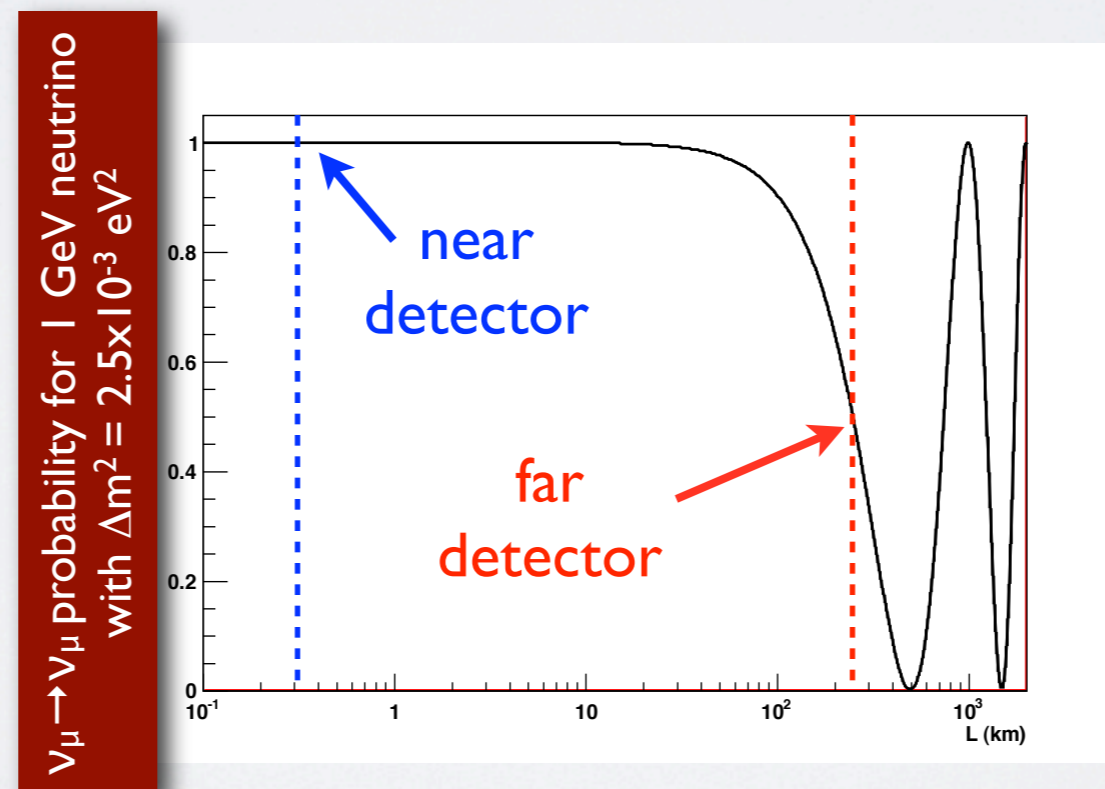


down-going
NO OSCILLATION

up-going
OSCILLATION

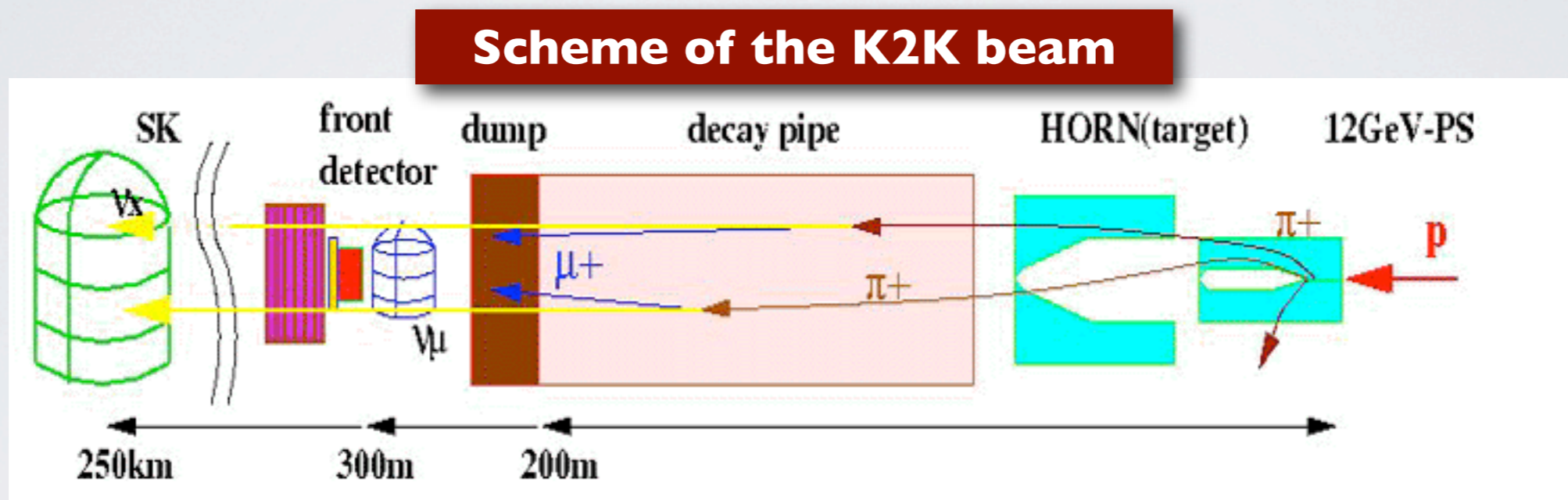
LONG BASELINE EXPERIMENTS

- **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**).

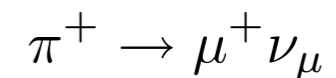


NEUTRINO BEAM

- **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.

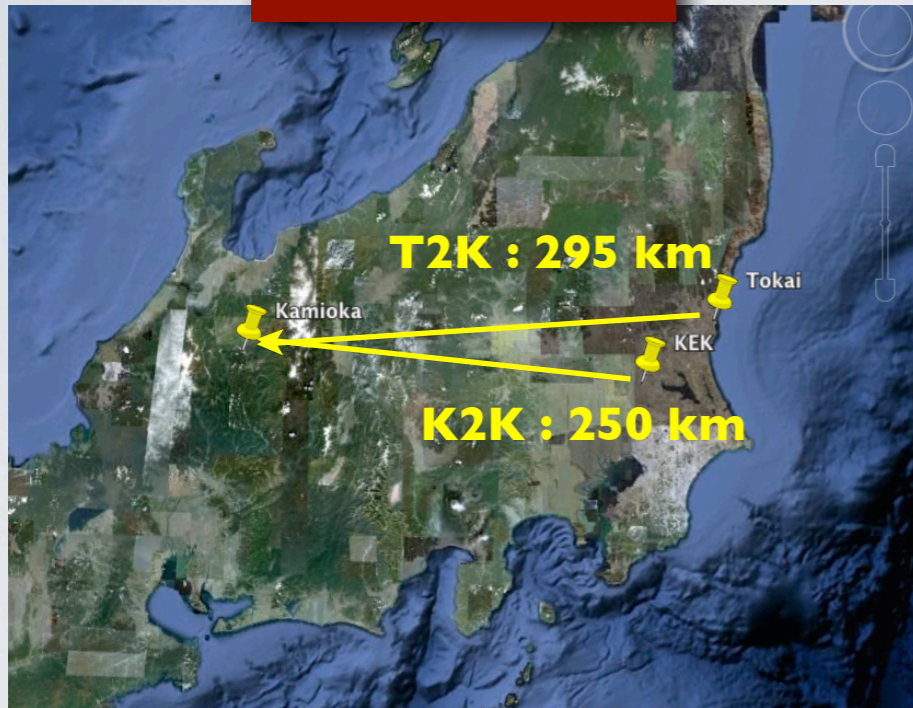


- The length of the decay pipe is tuned to optimised the decay of the pions and avoid the decay of the muons which would contaminate the beam with ν_e .



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

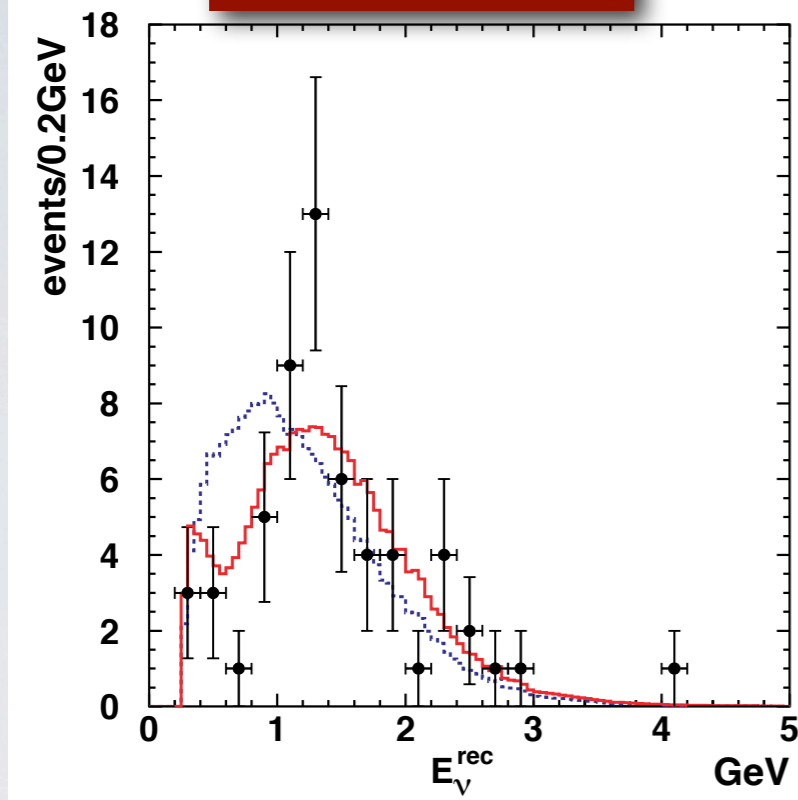


- The detection technology of **MINOS** (both for far and near detectors) is based on scintillation strips interleaved by magnetised steel.
- MINOS started data taking in 2002.

Experiment	Baseline	$\nu_\mu E$ (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.)

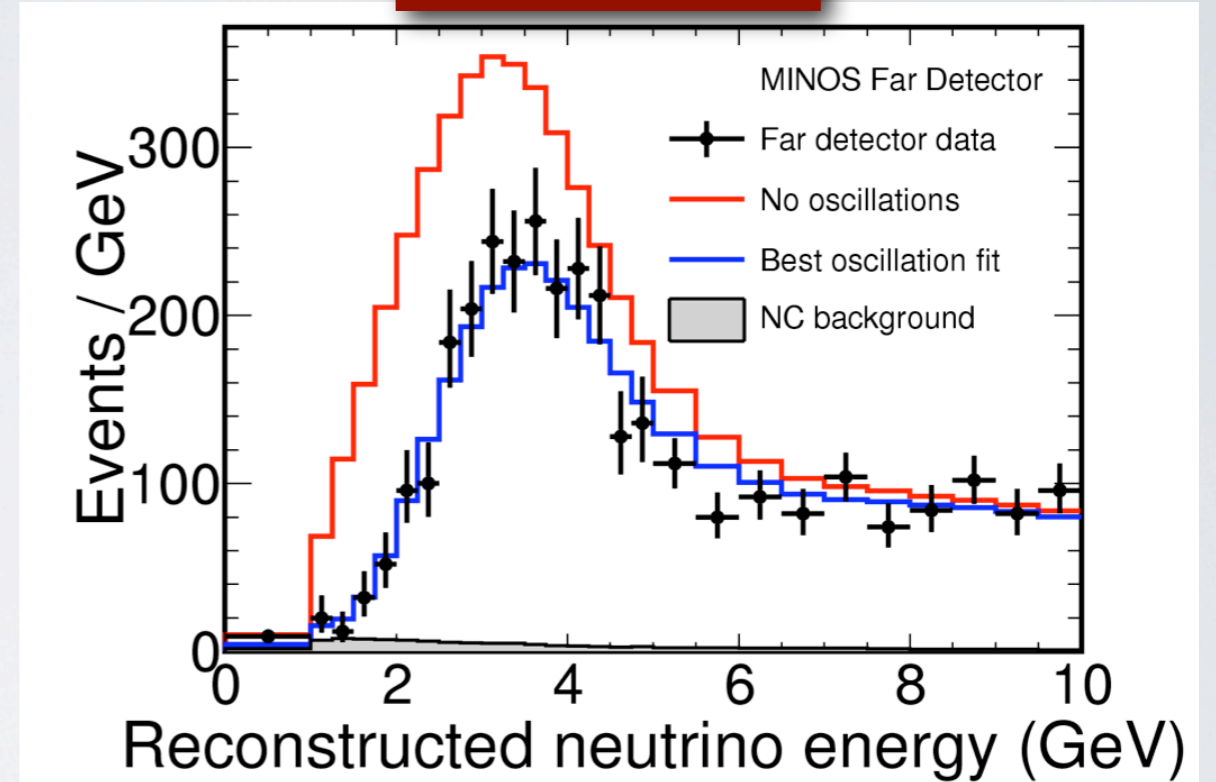
K2K



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

$$1.9 \leq |\Delta m_{31}^2| / 10^{-3} \text{ eV}^2 \leq 3.5$$

MINOS



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

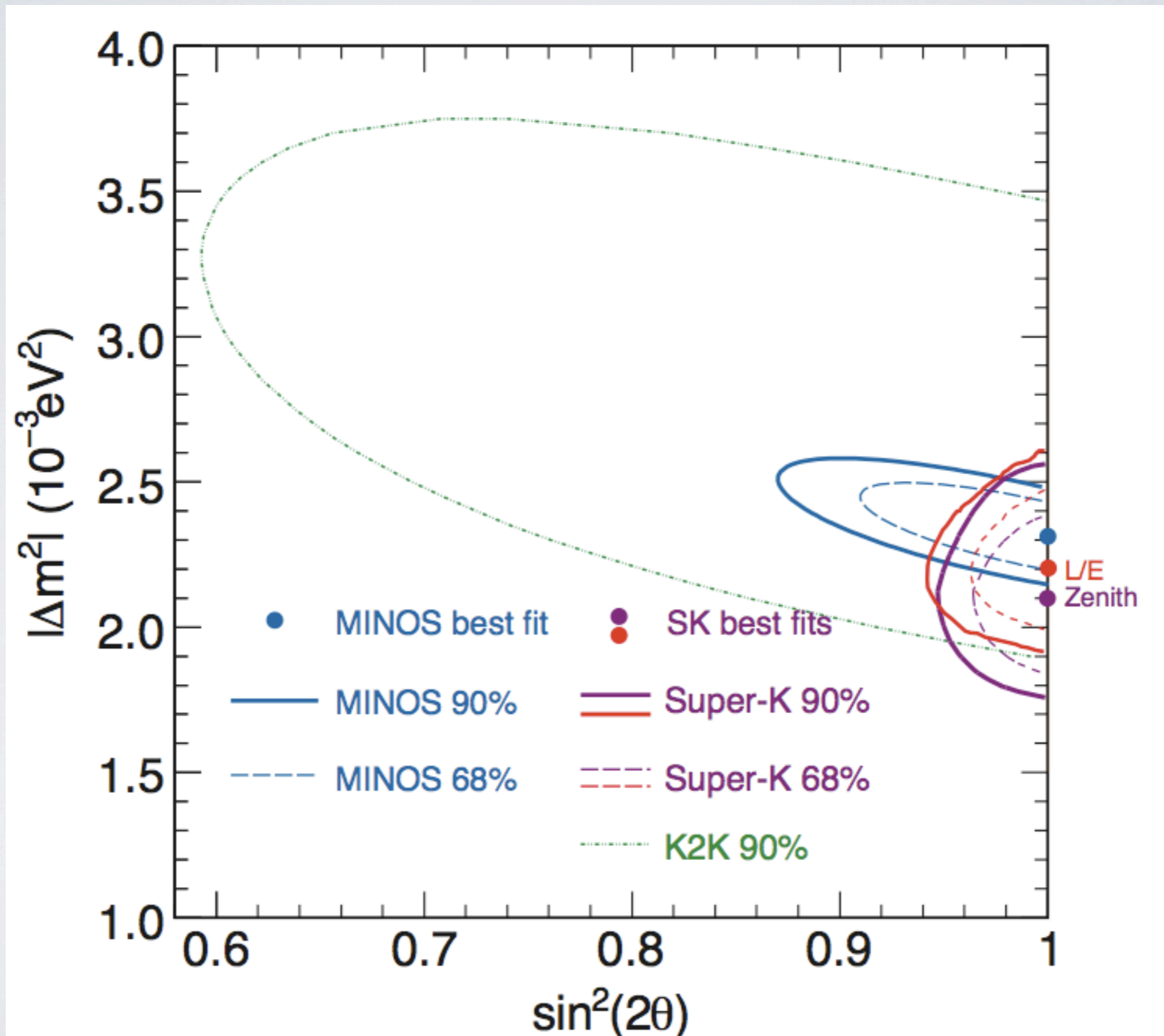
$$2.24 \leq |\Delta m_{31}^2| / 10^{-3} \text{ eV}^2 \leq 2.44$$

T2K Goals

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

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

RESULTS



PARAMETERS

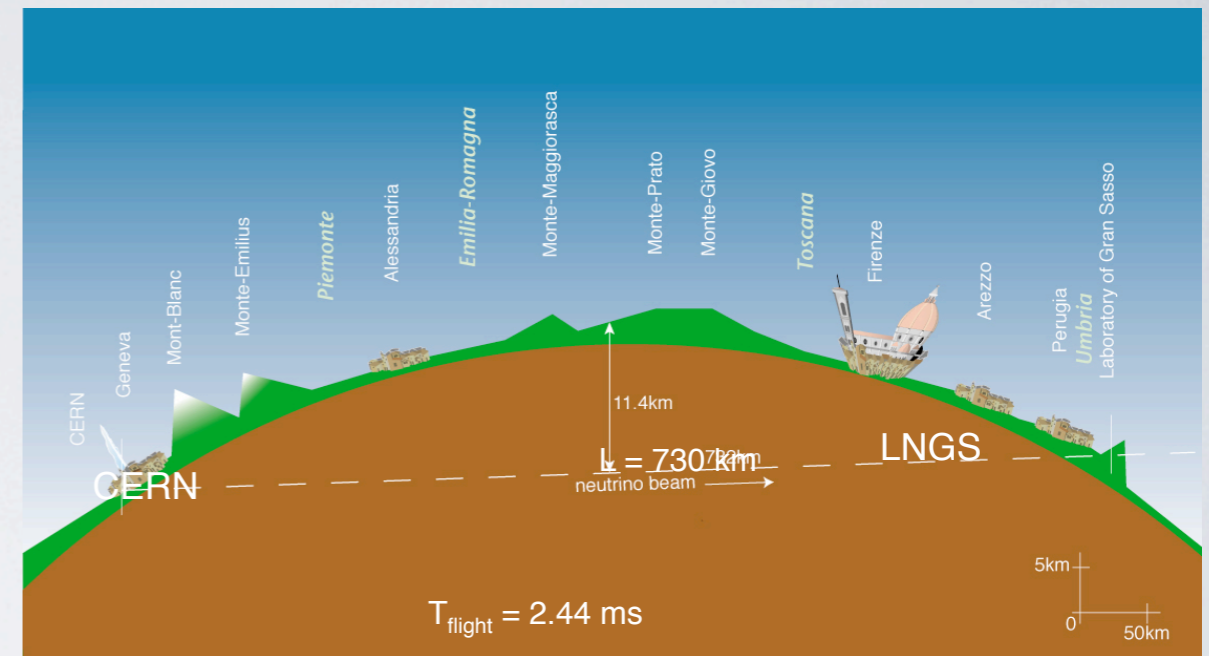
Parameter	Present knowledge (90% C.L.)	Channel	Experiments	Future
θ_{23}				
θ_{12}				
θ_{13}				
$ \Delta m^2_{21} $				
Sign (Δm^2_{21})				
$ \Delta m^2_{31} $				
Sign (Δm^2_{31})				
δ_{CP}				

PARAMETERS

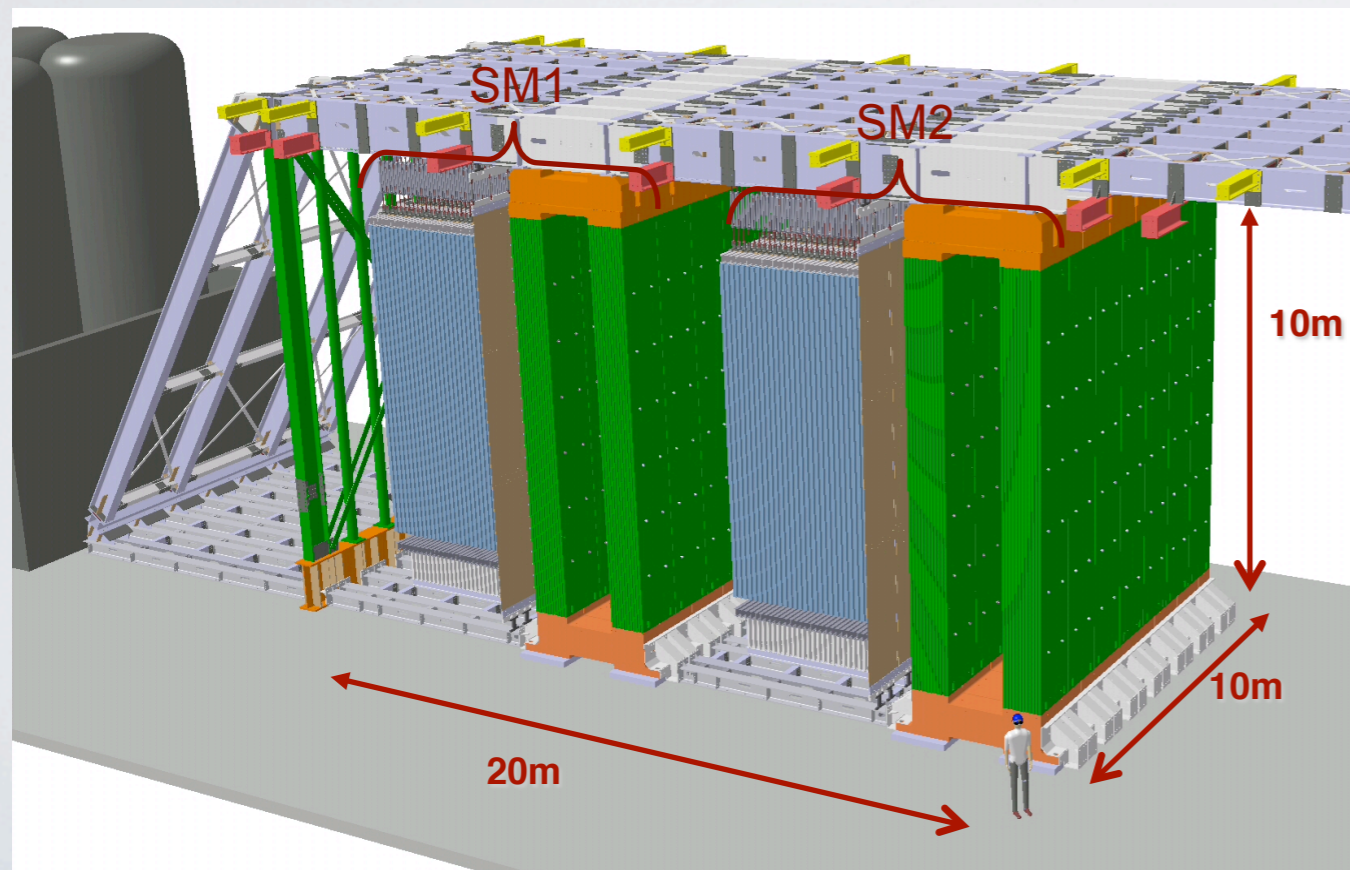
Parameter	Present knowledge (90% C.L.)	Channel	Experiments	Future
θ_{23}	$\sin^2(2\theta_{23}) \geq 0.96$	$P(\nu_\mu \rightarrow \nu_\mu)$	SK, (K2K, MINOS)	T2K
θ_{12}				
θ_{13}				
$ \Delta m^2_{21} $				
Sign (Δm^2_{21})				
$ \Delta m^2_{31} $	$2.24 \leq \Delta m^2_{31} / 10^{-3} \text{ eV}^2 \leq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

OPERA

- So far in the atmospheric sector only disappearance has been measured i.e. $\nu_{\mu} \rightarrow \nu_{\tau}$.
- 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.



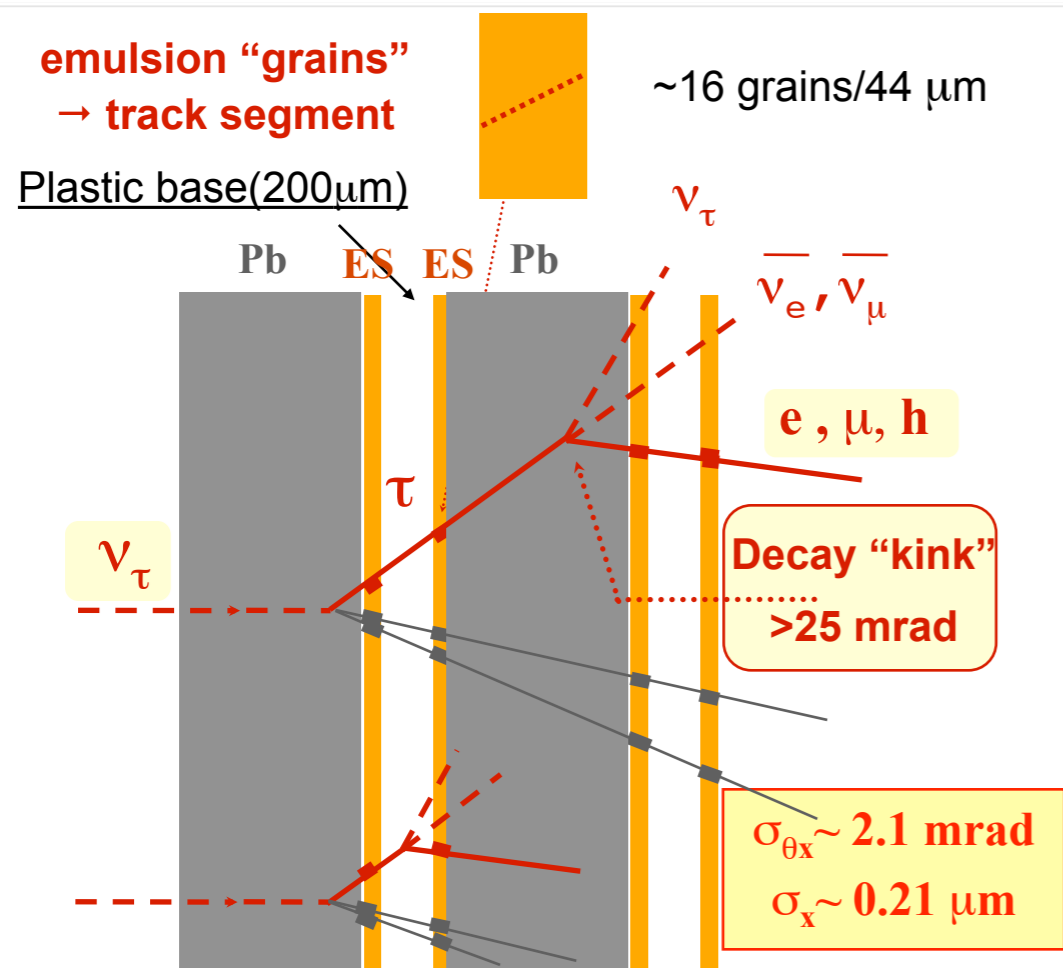
ν_{μ} \longrightarrow Oscillation \longrightarrow ν_{τ}



- The τ lepton decays rapidly ($\sim 10^{-13} \text{ s}$) 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 v_μ CC of events) the electronic detectors made of plastic scintillators and RPC planes are used.



Brick weight: 8.3 kg



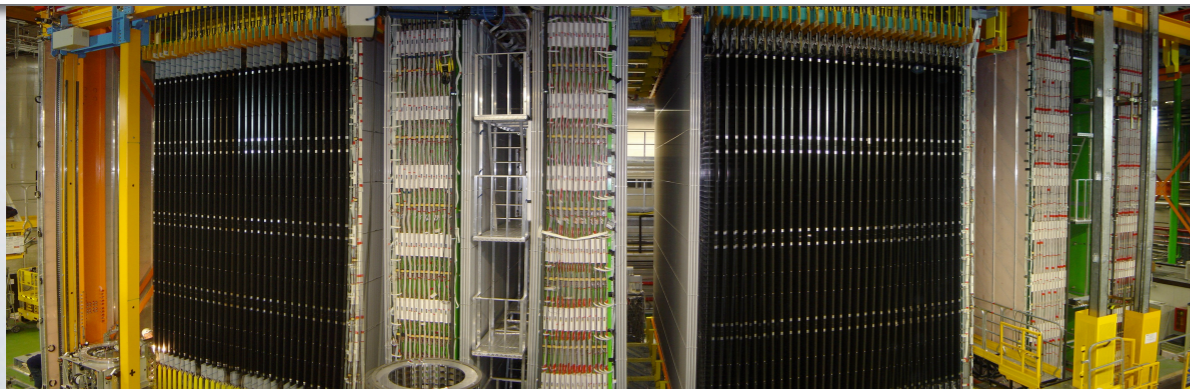
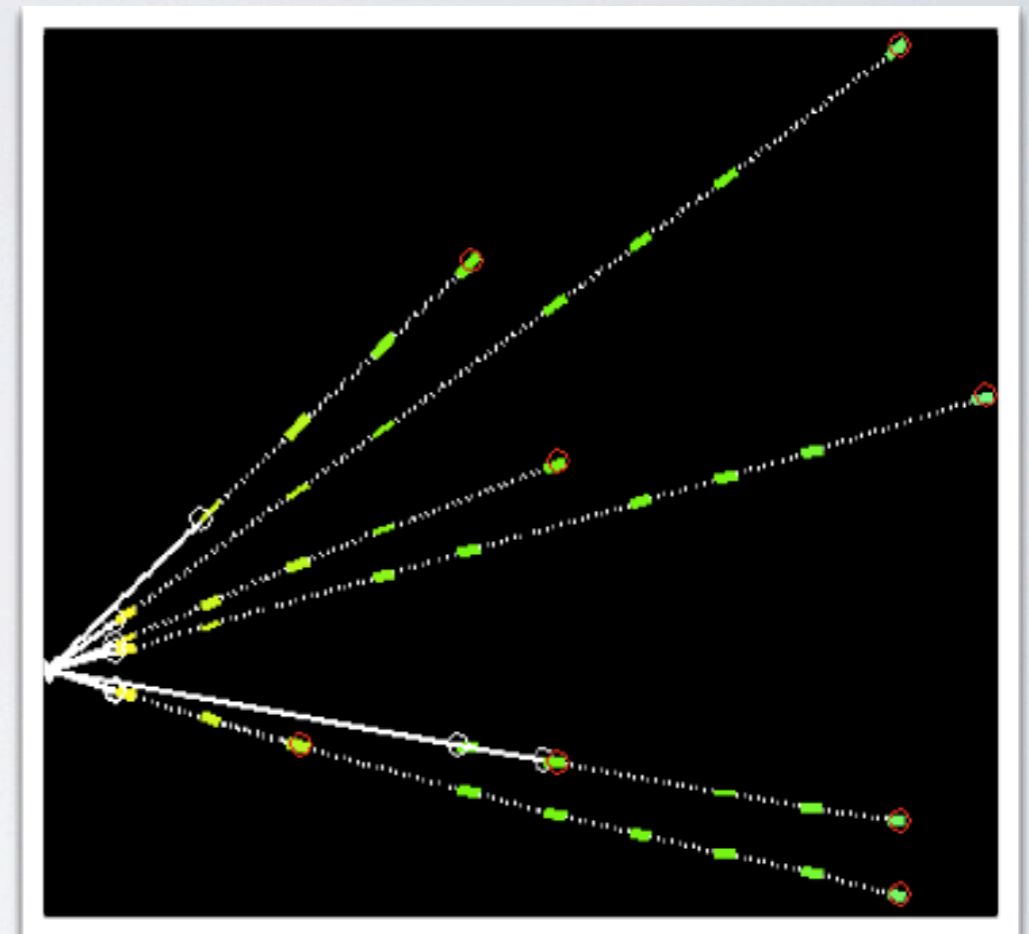
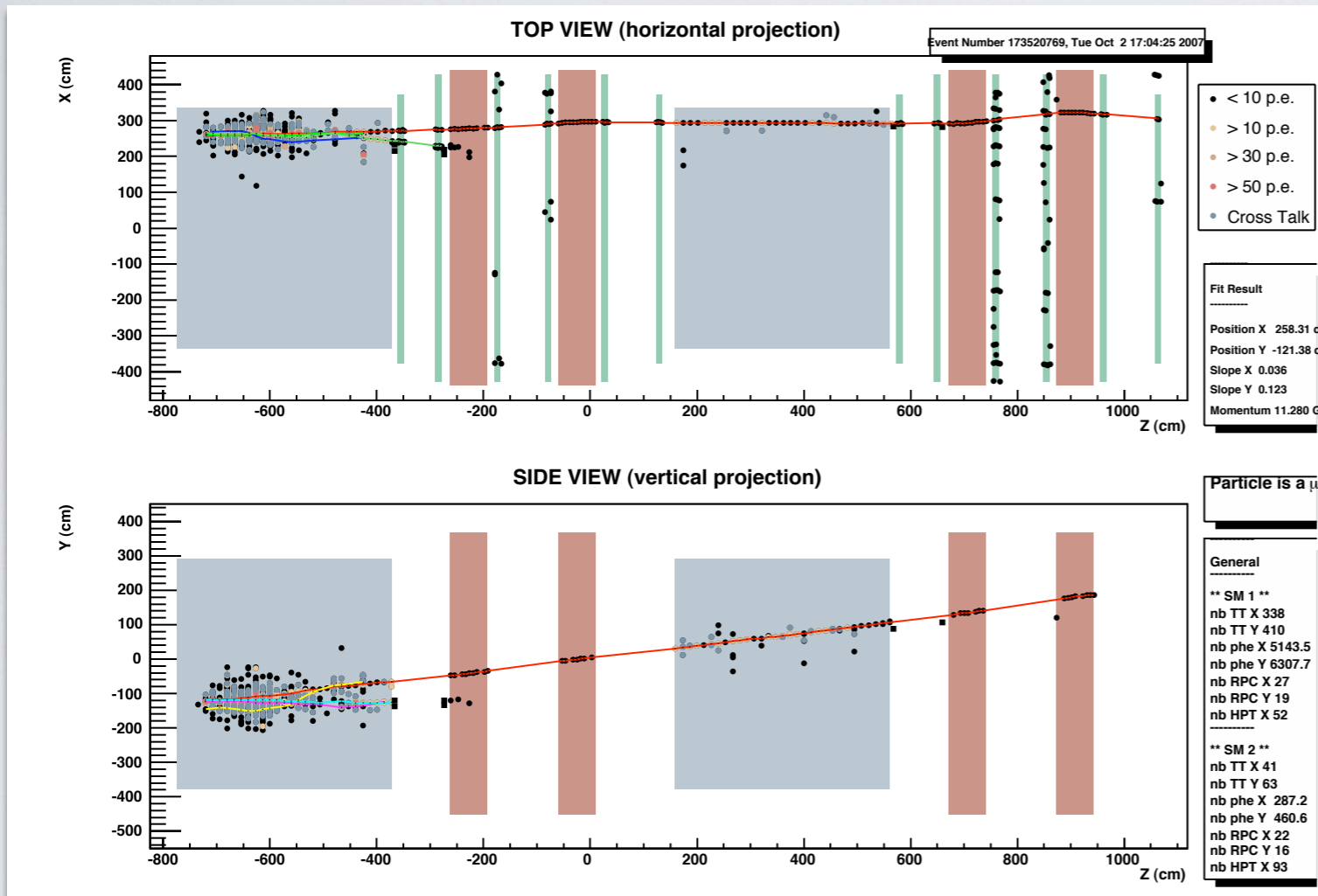
Sandwich of 56 (1 mm) Pb sheets
+ 57 FUJI emulsion layers
+ 1 changeable sheet

TYPICAL EVENT

ν_μ CC interaction

Reconstruction in electronic detectors

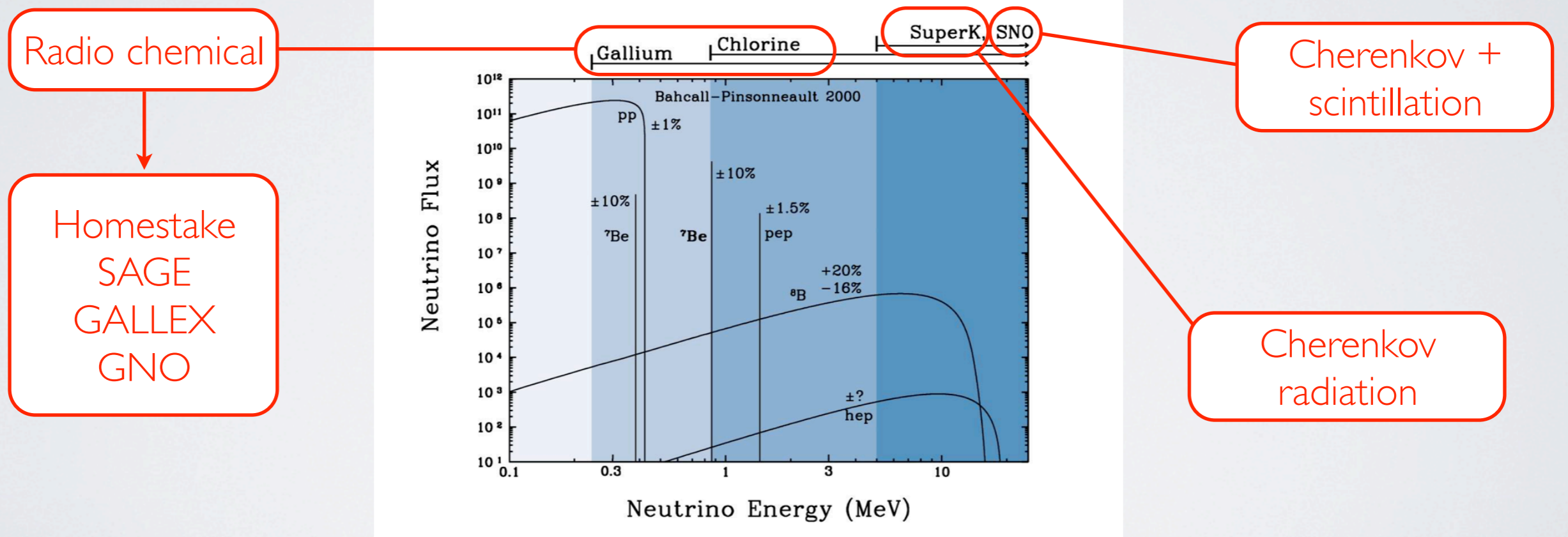
Reconstruction in emulsions



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

SOLAR SECTOR

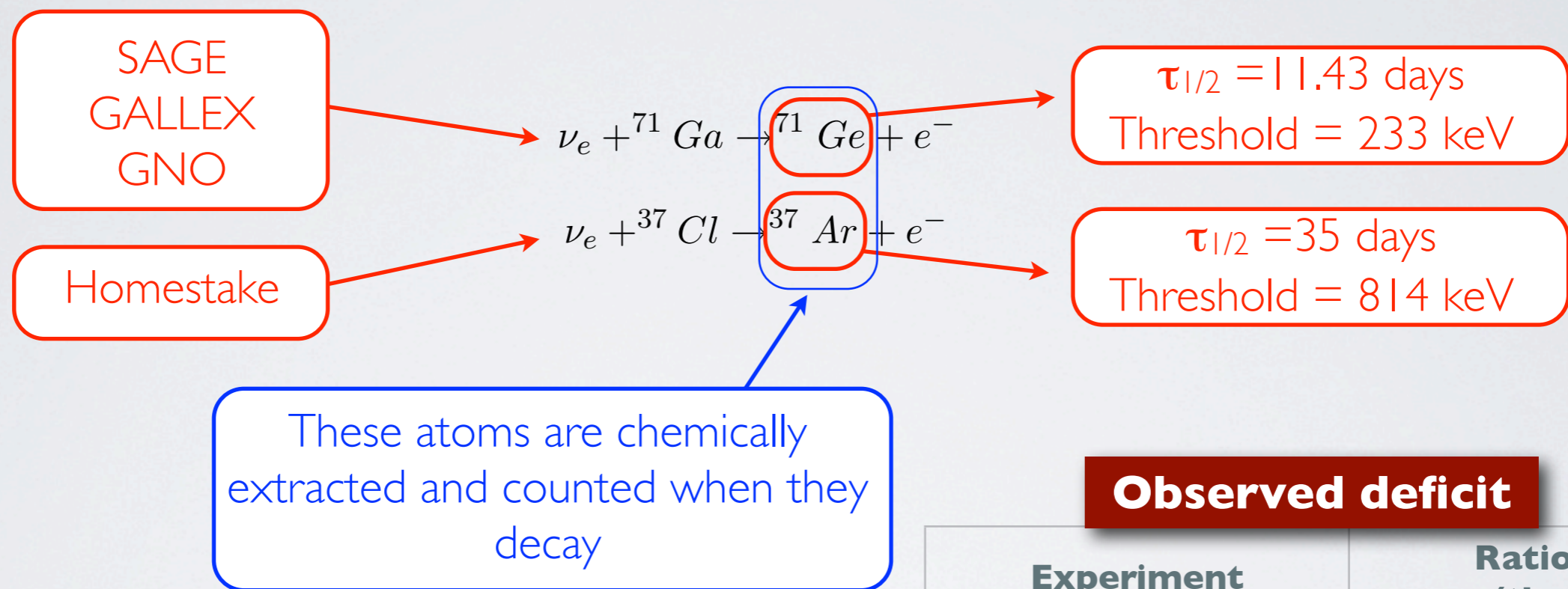
- To measure the parameters of the solar sector (θ_{12} , Δm_{21}^2) a good channel to study is the $\nu_e \rightarrow \nu_x$ **transition**.
- Even in this case the idea is to compare the measured flux with the expected one, which relies on our knowledge on the standard solar model.
- According to the detection technology the different experiments are sensitive to different energies and therefore production chains in the sun.



- 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:



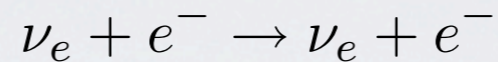
- The advantage is the low threshold and the possibility to explore neutrinos coming from the pp chain.
- The disadvantage is the complex counting of the interactions and the fact that it is not real time detection.

Observed deficit

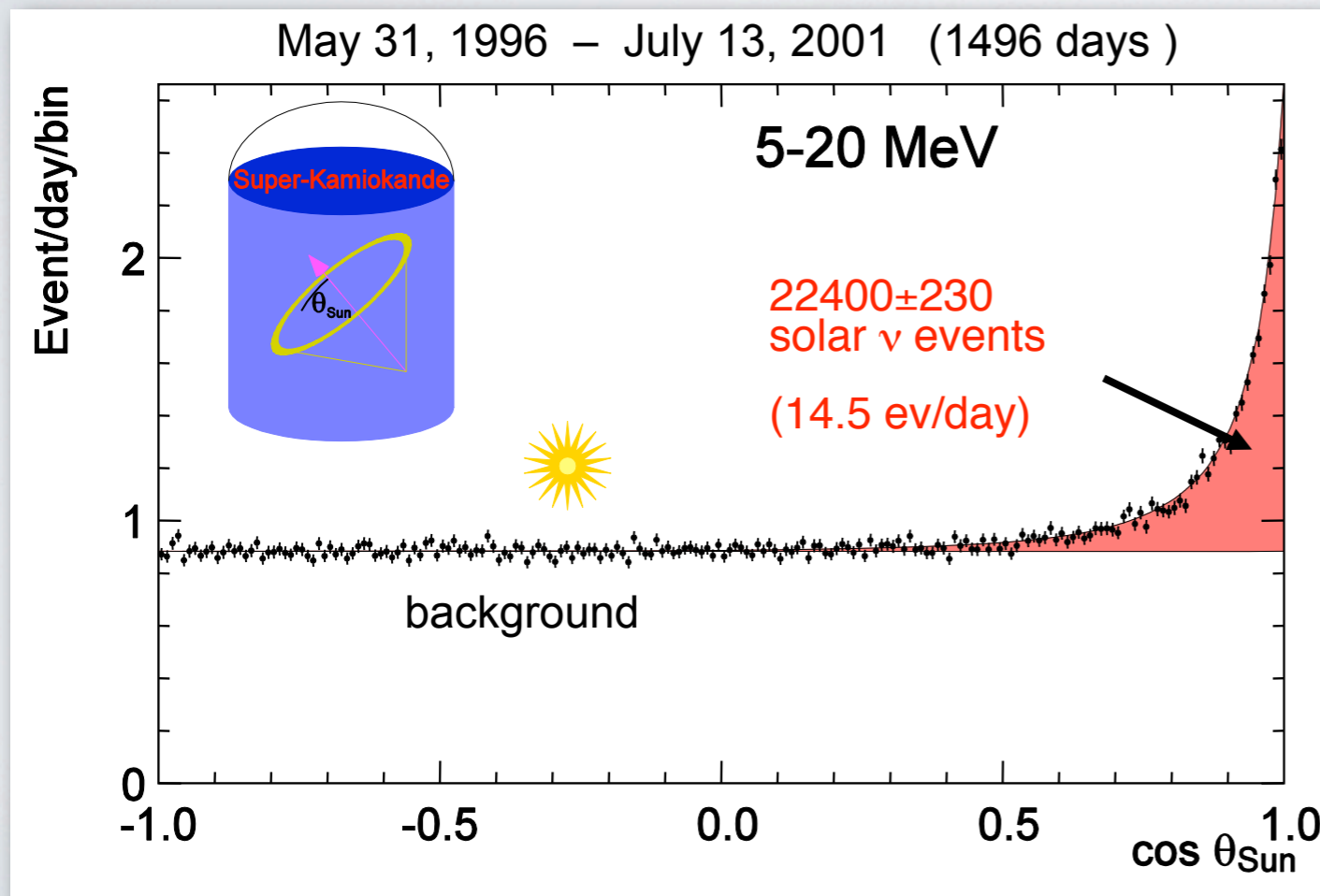
Experiment	Ratio exp/theory
Homestake (1968)	0.32
SAGE (1990)	0.53
Gallex (1992)	0.55

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:



Threshold = 6.5 MeV



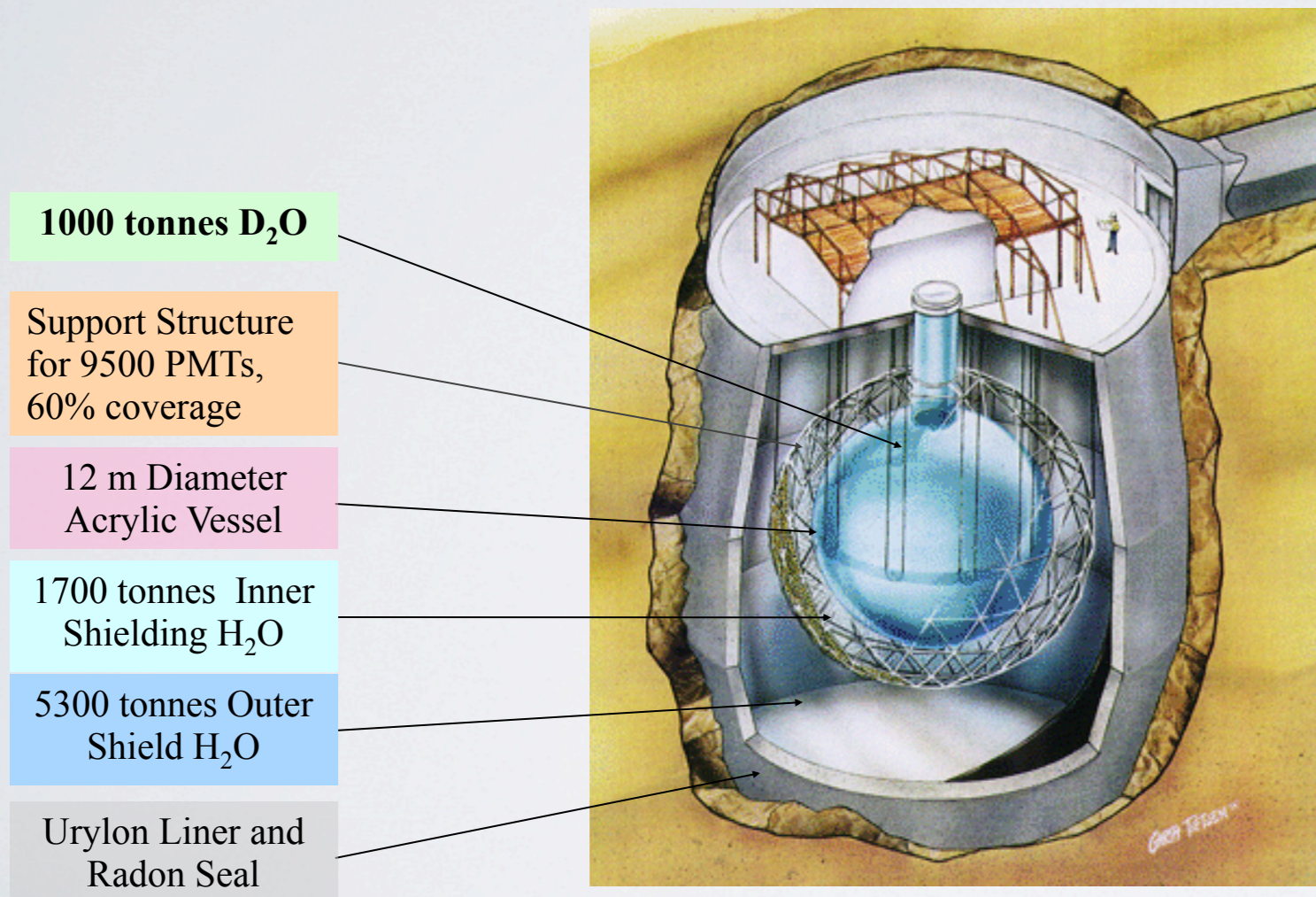
Observed deficit

Experiment	Ratio exp/theory
SK (1998)	0.41

**NOTE: no evidence for
spectrum distortion.**

SNO

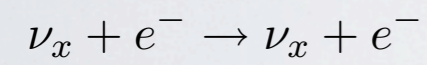
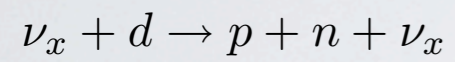
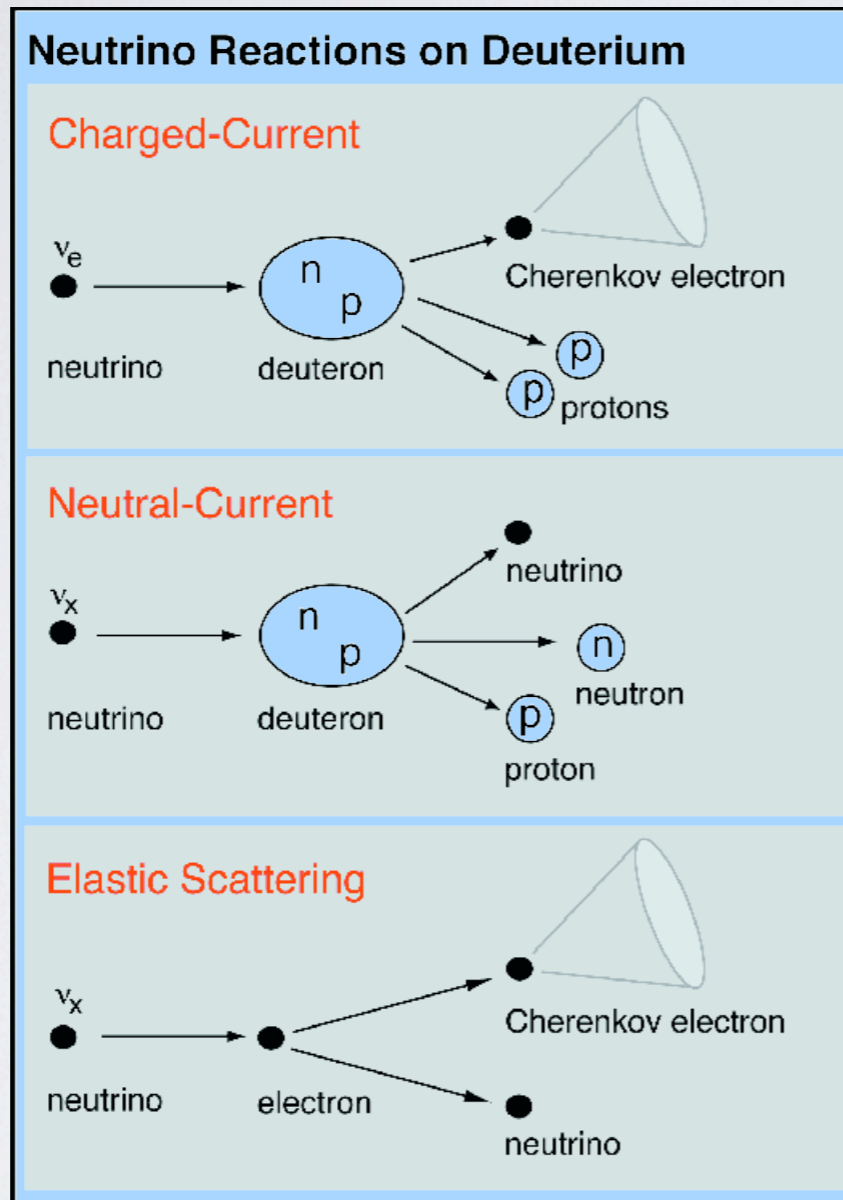
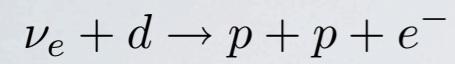
- **SNO** was an experiment located in Canada that uses Cerenkov detection method.
- The target is heavy water (D_2O) and the **experiment can detect all flavours of neutrinos** (depending on the channel studied).



- 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.

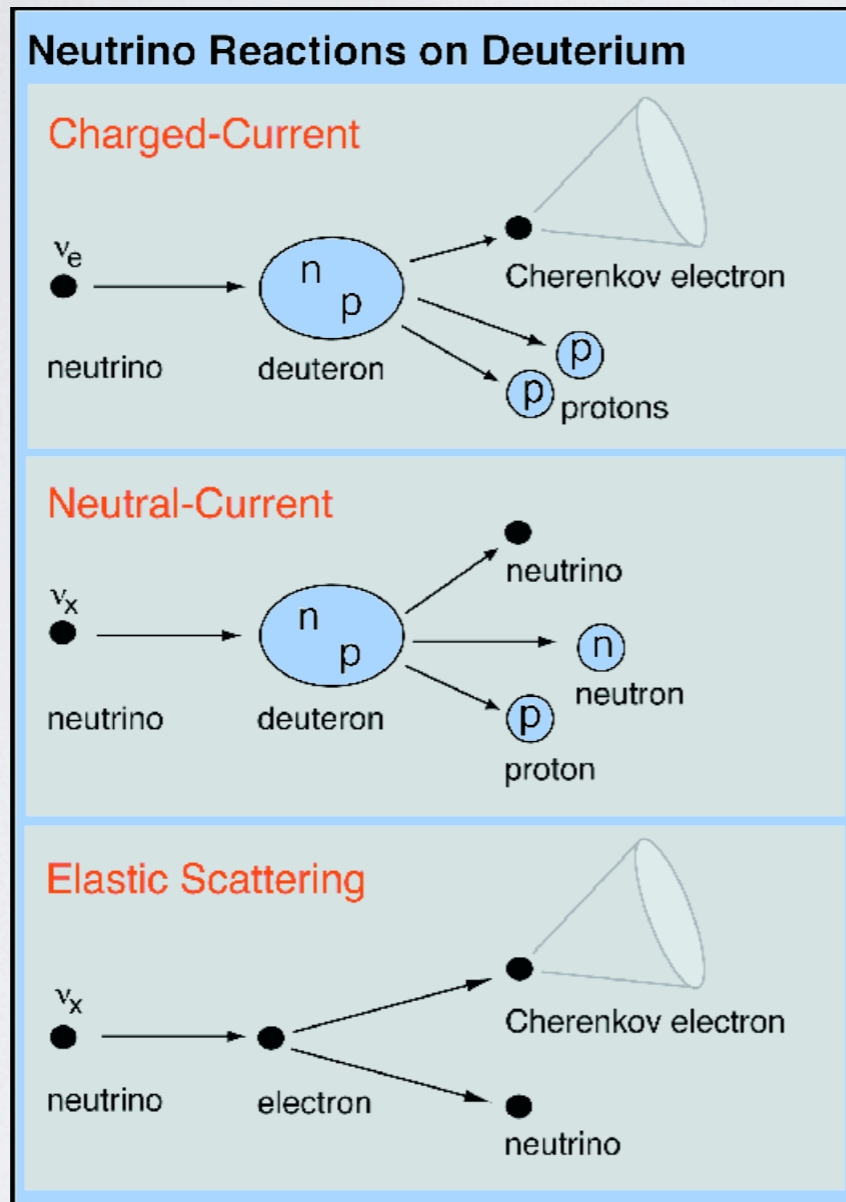
SNO

- The three reactions used are the following:



SNO

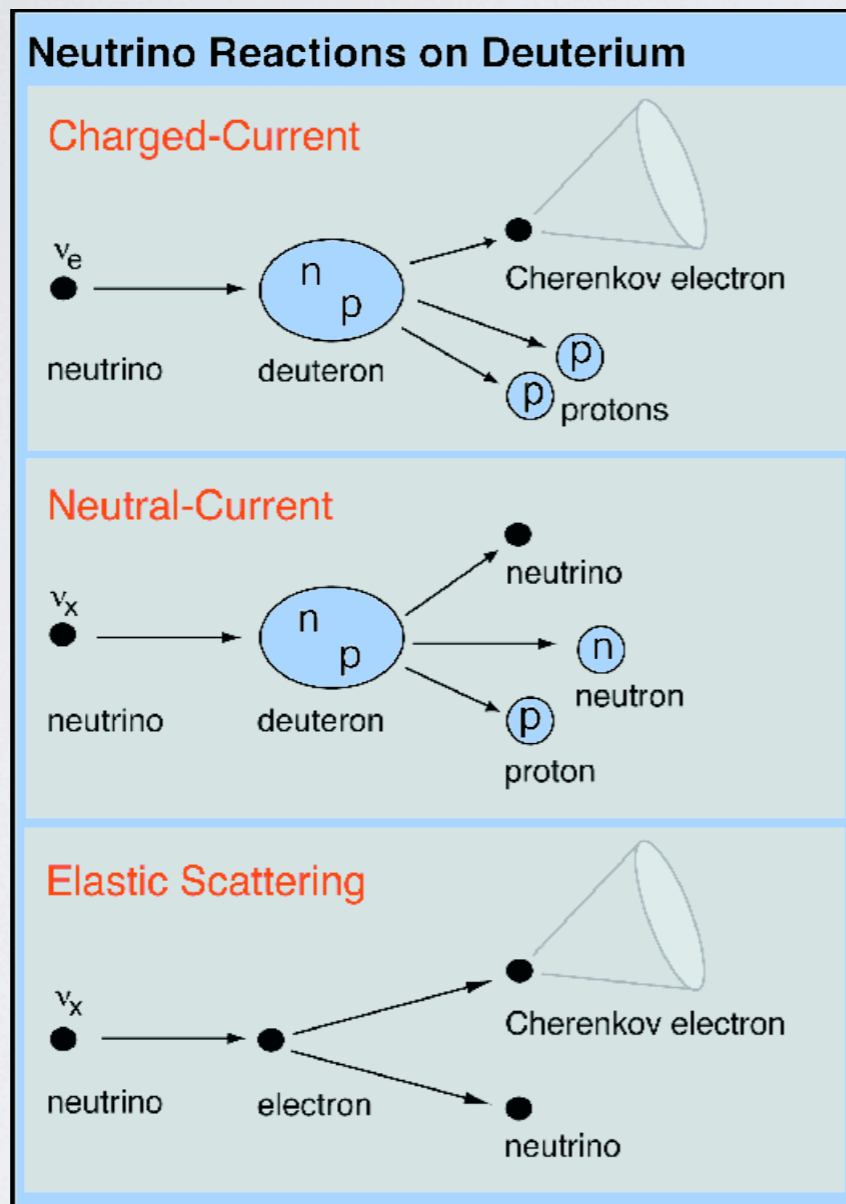
- The three reactions used are the following:



How is the neutron detected?

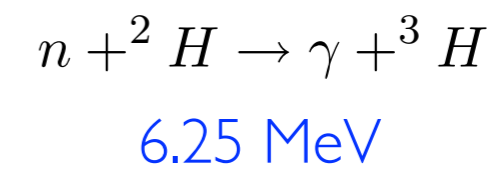
SNO

- The three reactions used are the following:



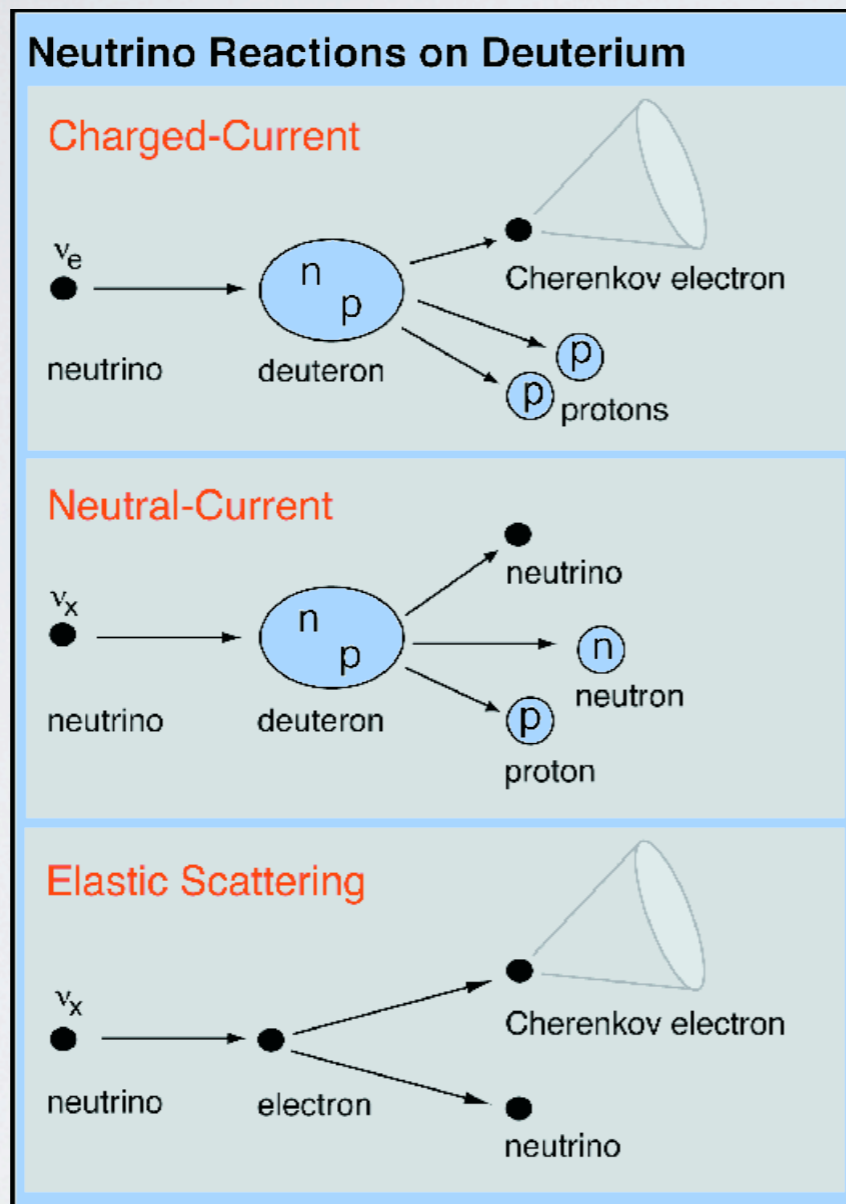
How is the neutron detected?

phase I



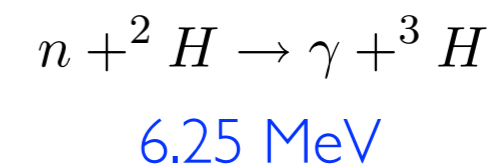
SNO

- The three reactions used are the following:

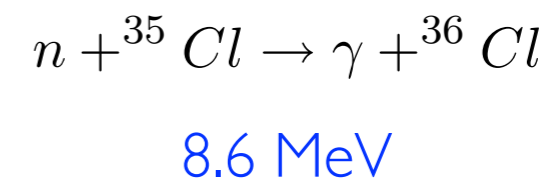


How is the neutron detected?

phase I



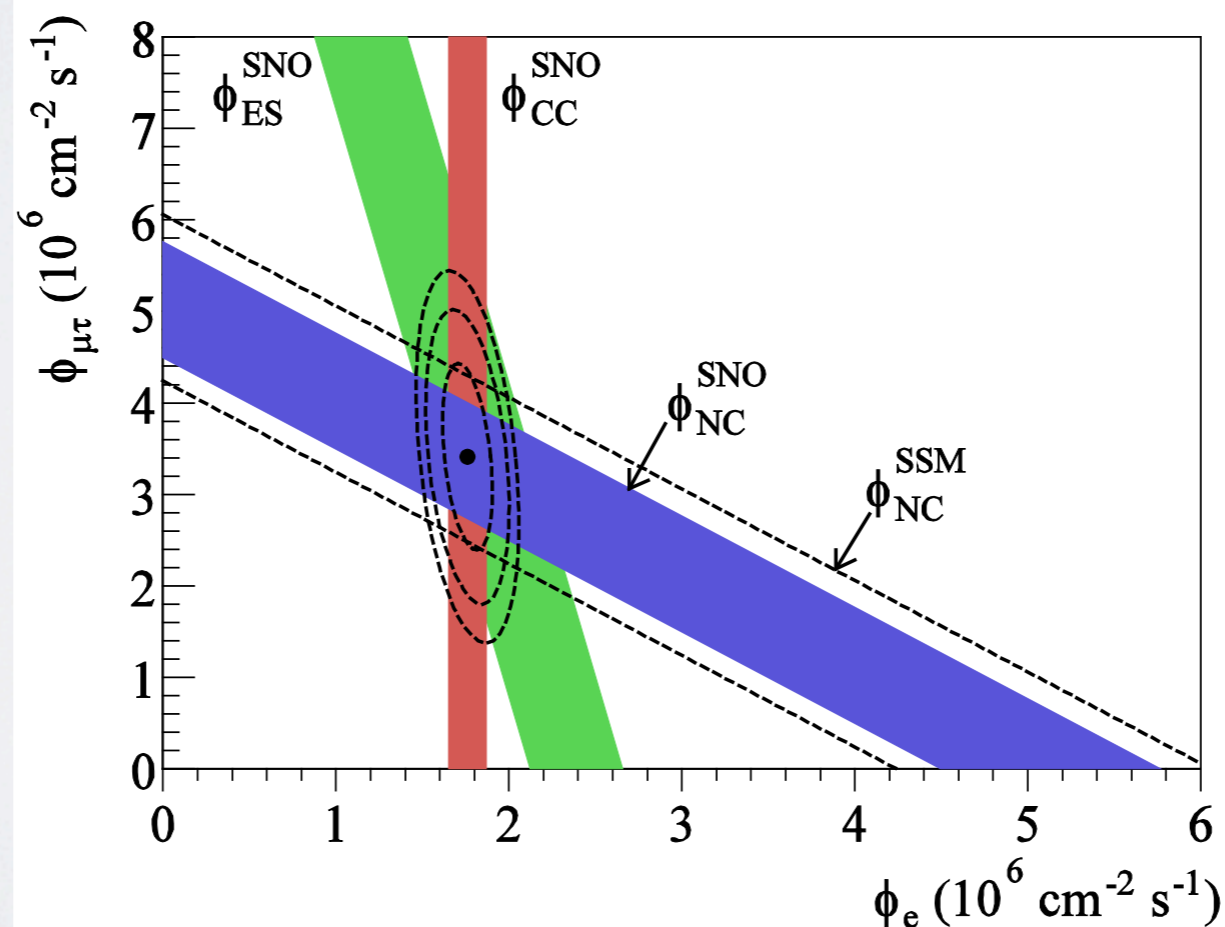
phase 2
2 ton of NaCl



SNO

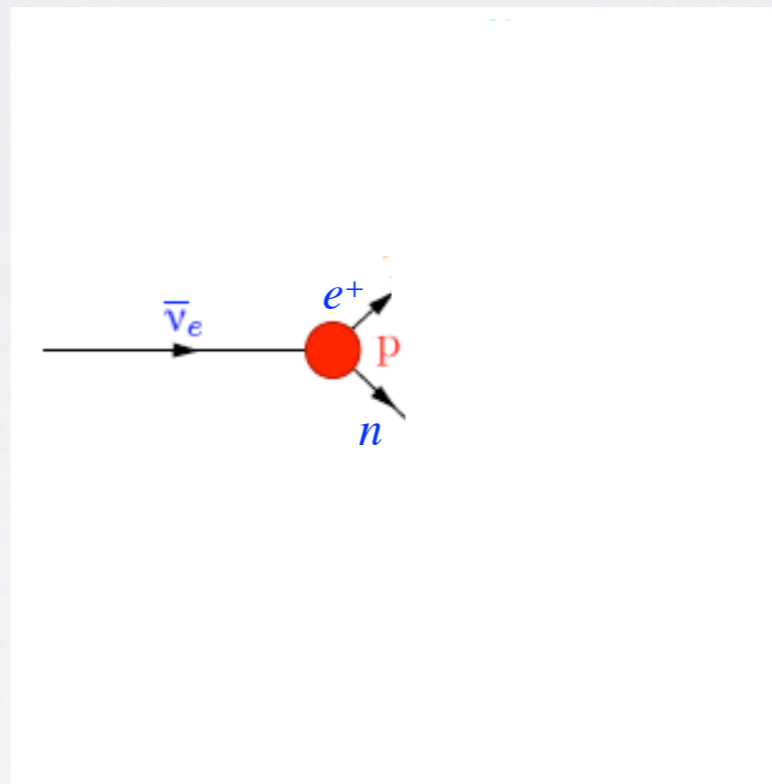
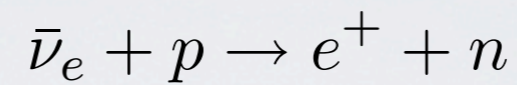
- Using all the channels SNO found:
 - About **30%** of the **expected ν_e flux** (in case of no oscillation).
 - A **total flux in agreement with the SSM prediction**.
- The non oscillation hypothesis is ruled out at 5.3σ C.L.

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



KAMLAND

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



KAMLAND

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

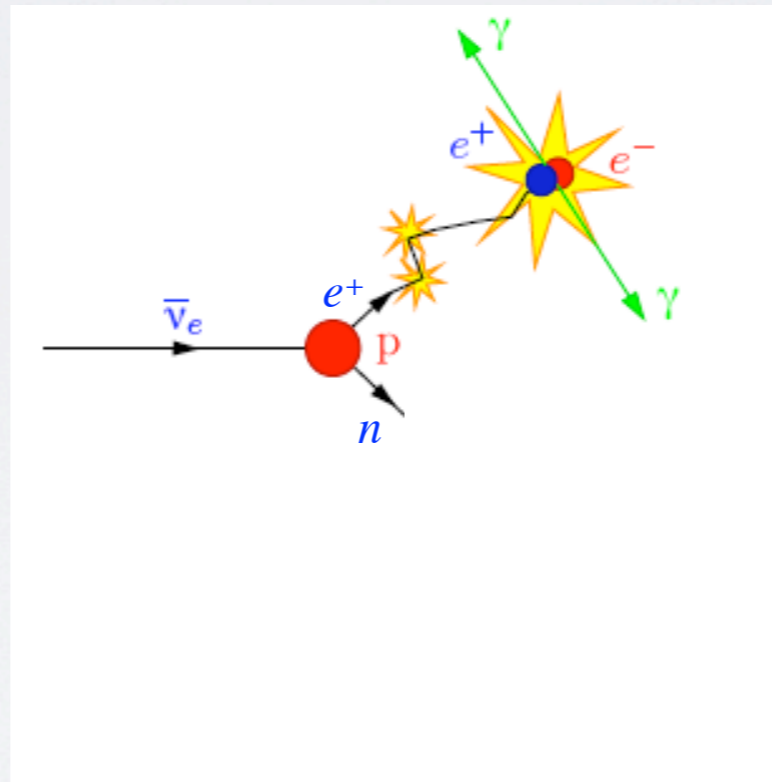


Charged particles

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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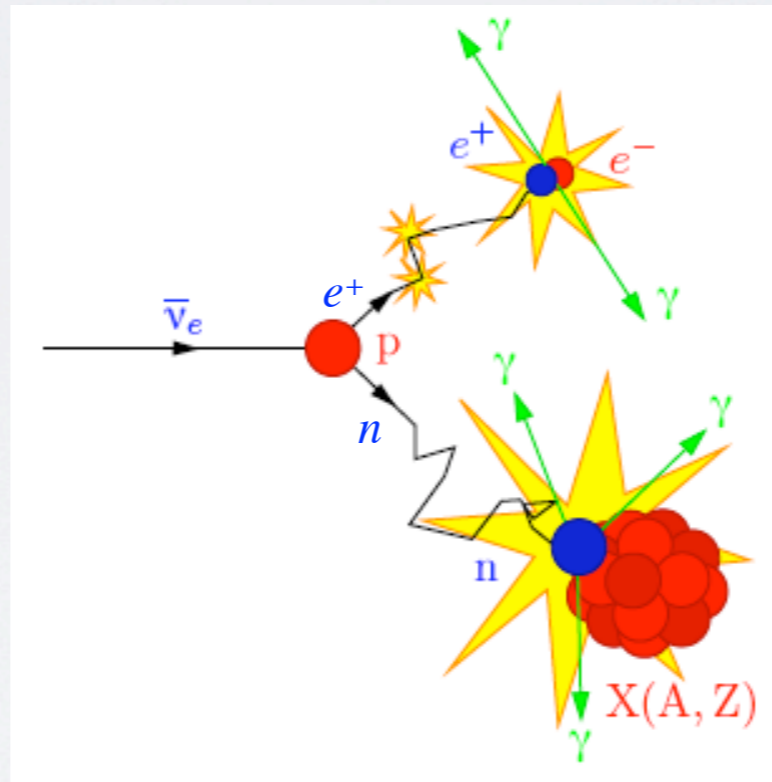


Charged particles

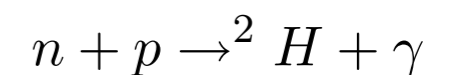
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The neutrons are absorbed on H:

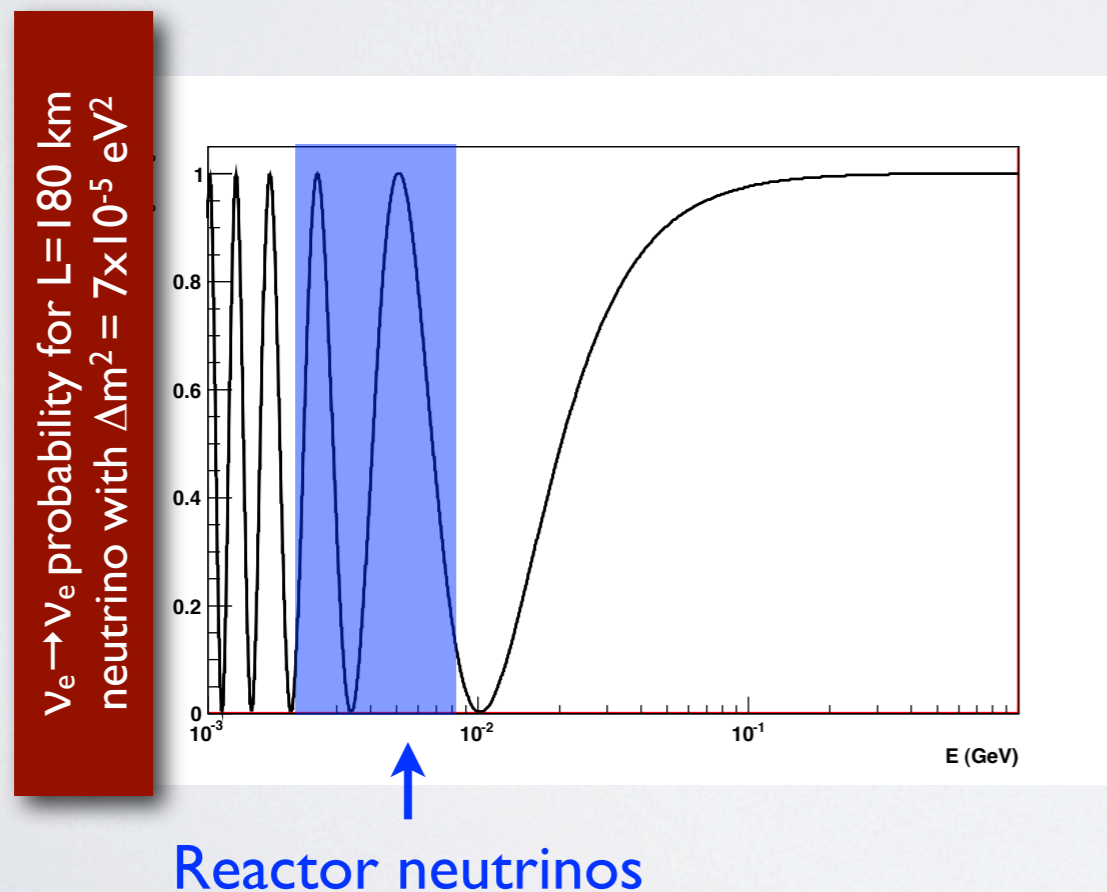
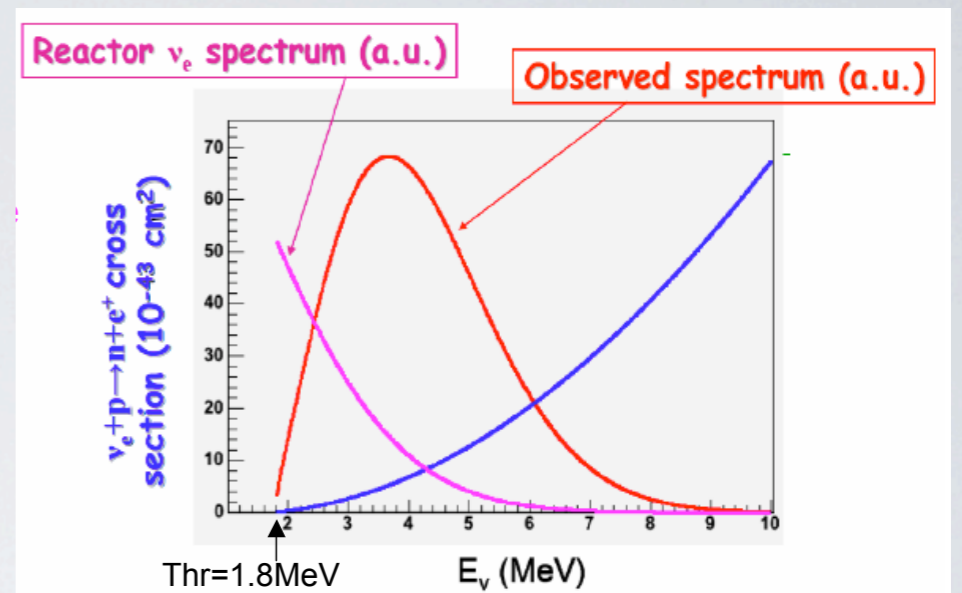


producing gammas at 2.2 MeV

Delayed signal (~200 μs)

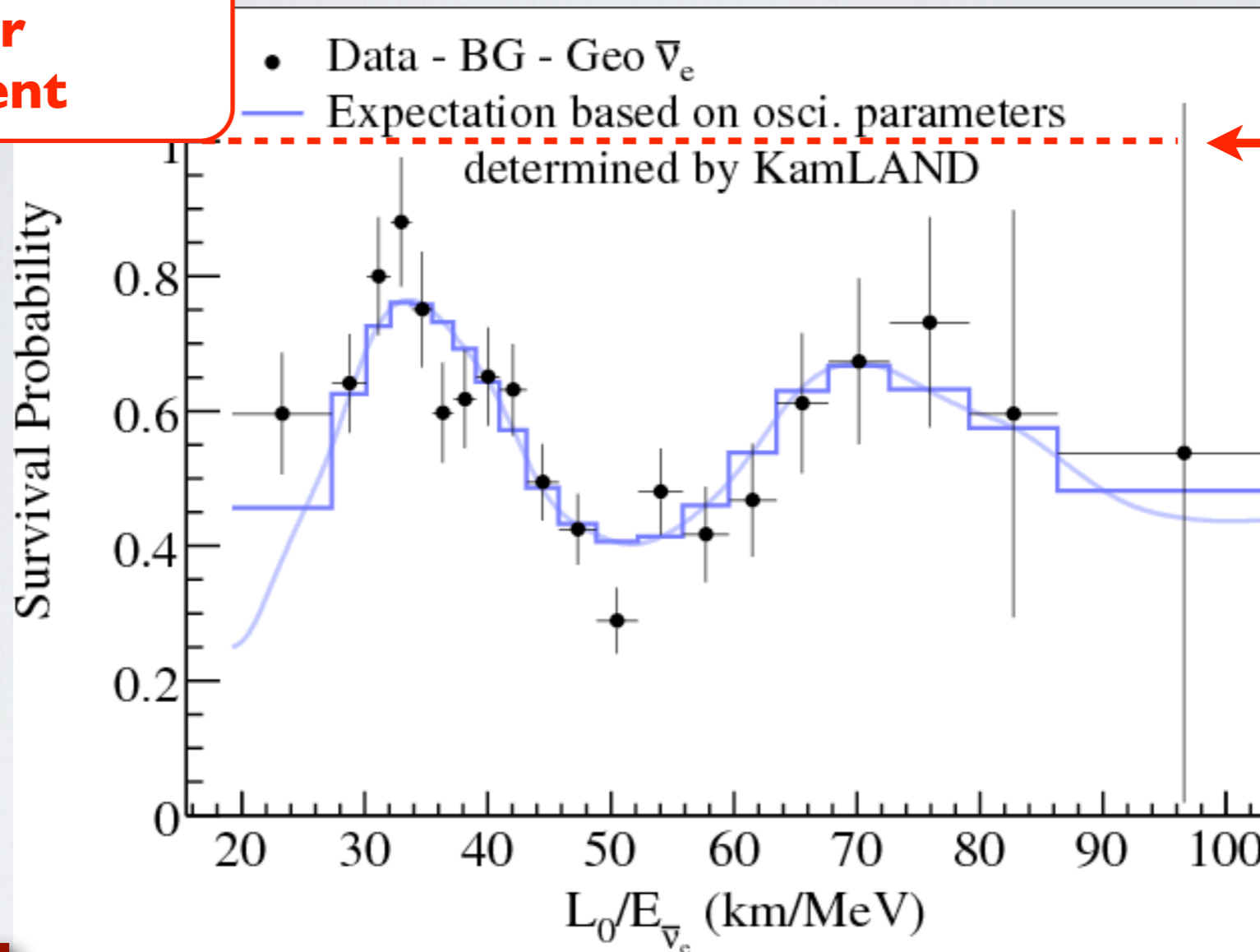
KAMLAND

- 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**.



KAMLAND

Clear evidence of oscillation and parameter measurement



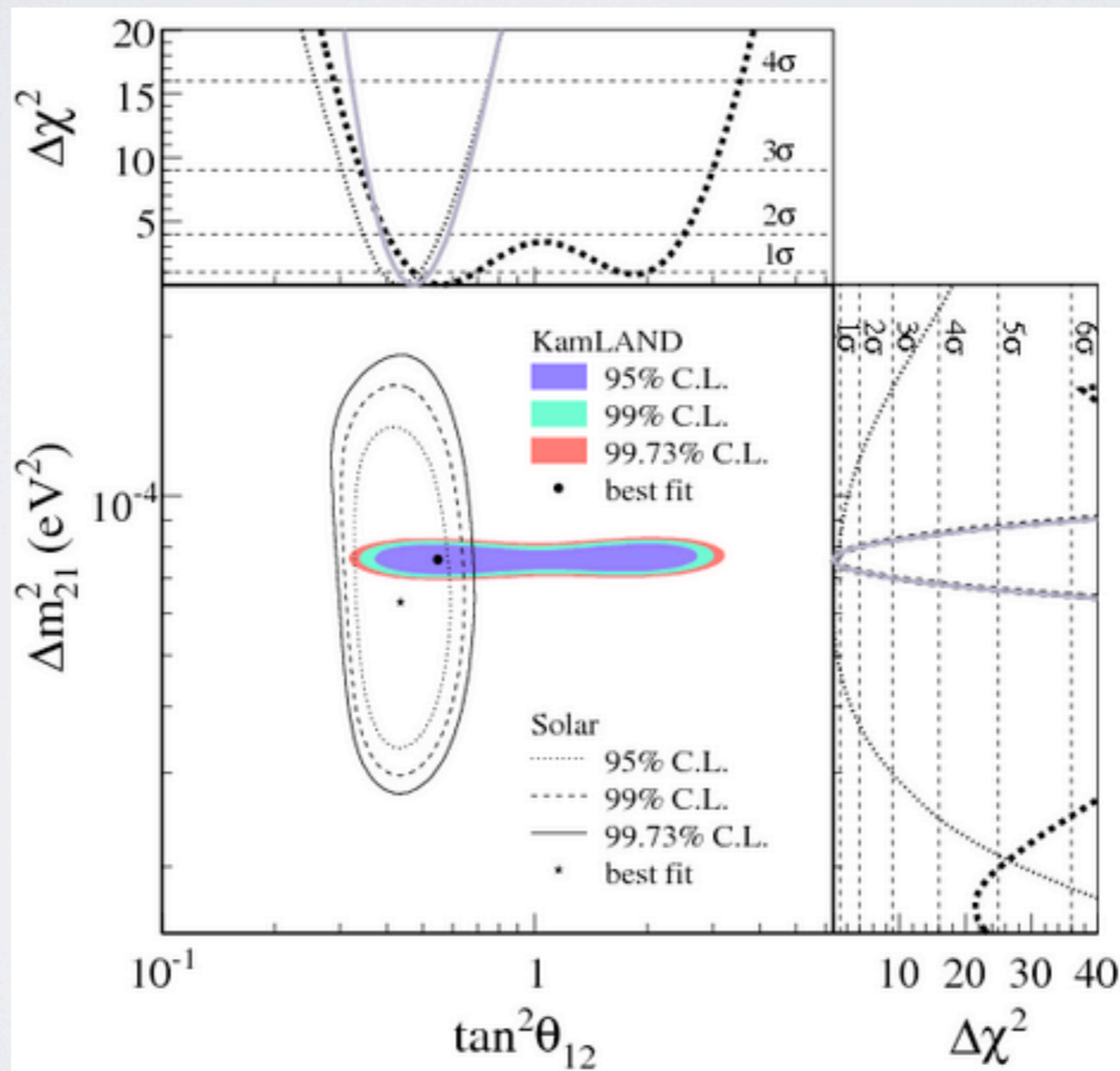
No oscillation expectation

Energy (MeV) corresponding to a baseline of 180 km



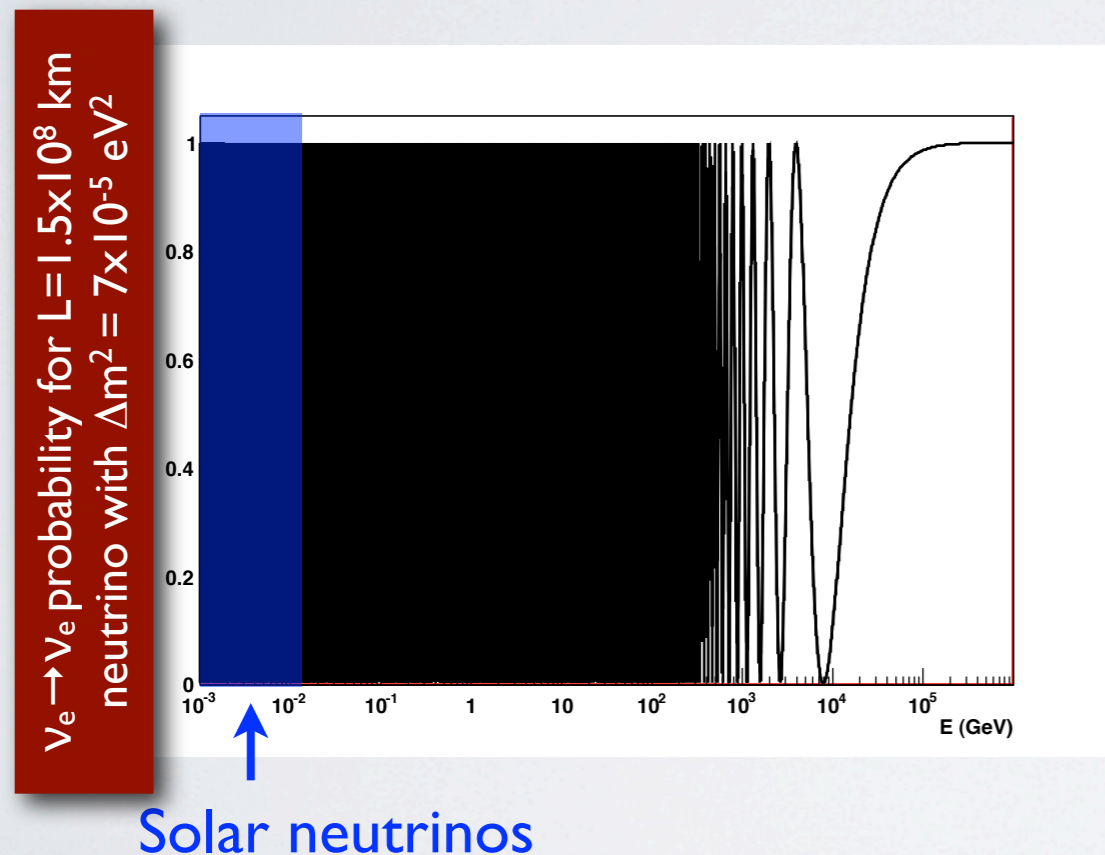
RESULTS

- **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).



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

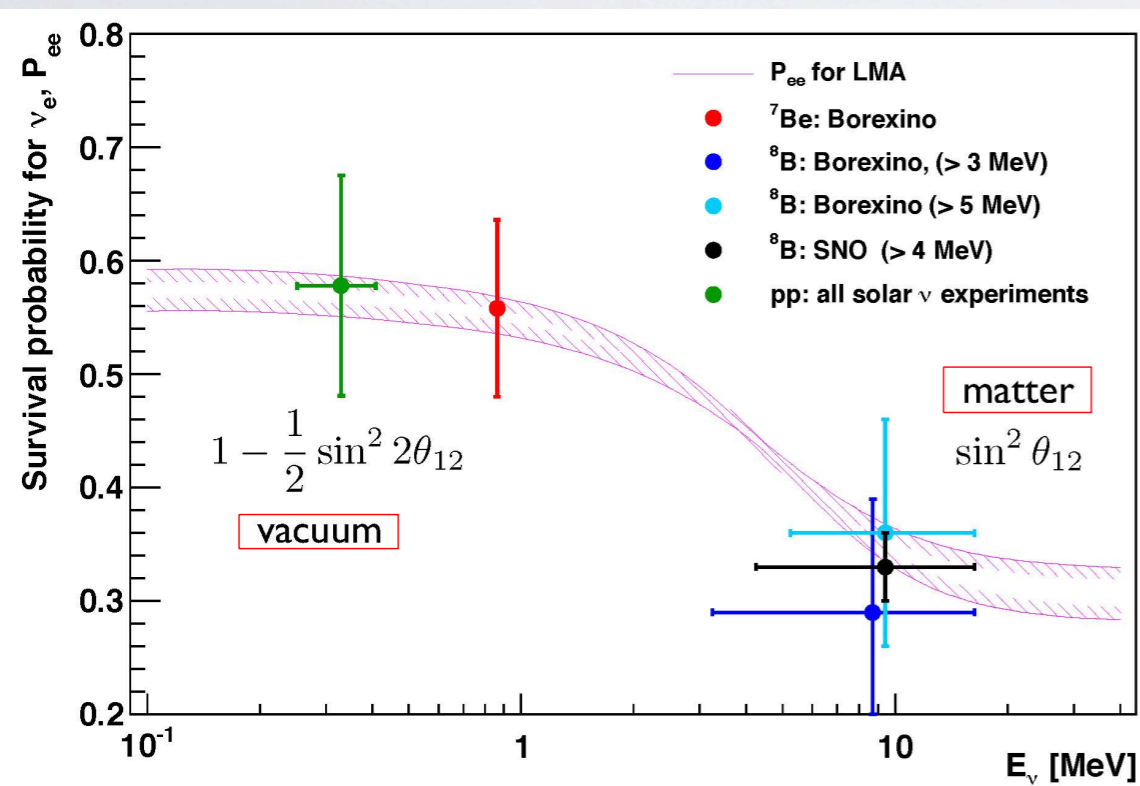
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{12} \sin^2\left(1.27 \frac{\Delta m_{12}^2 L}{E}\right)$$

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

- 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}	$\sin^2(2\theta_{23}) \geq 0.96$	$P(\nu_\mu \rightarrow \nu_\mu)$	SK, (K2K, MINOS)	T2K
θ_{12}				
θ_{13}				
$ \Delta m^2_{21} $				
Sign (Δm^2_{21})				
$ \Delta m^2_{31} $	$2.24 \leq \Delta m^2_{31} / 10^{-3} \text{ eV}^2 \leq 2.44$	$P(\nu_\mu \rightarrow \nu_\mu)$	(SK, K2K), MINOS	MINOS, T2K
Sign (Δm^2_{31})				
δ_{CP}				

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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)

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

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

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

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

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

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

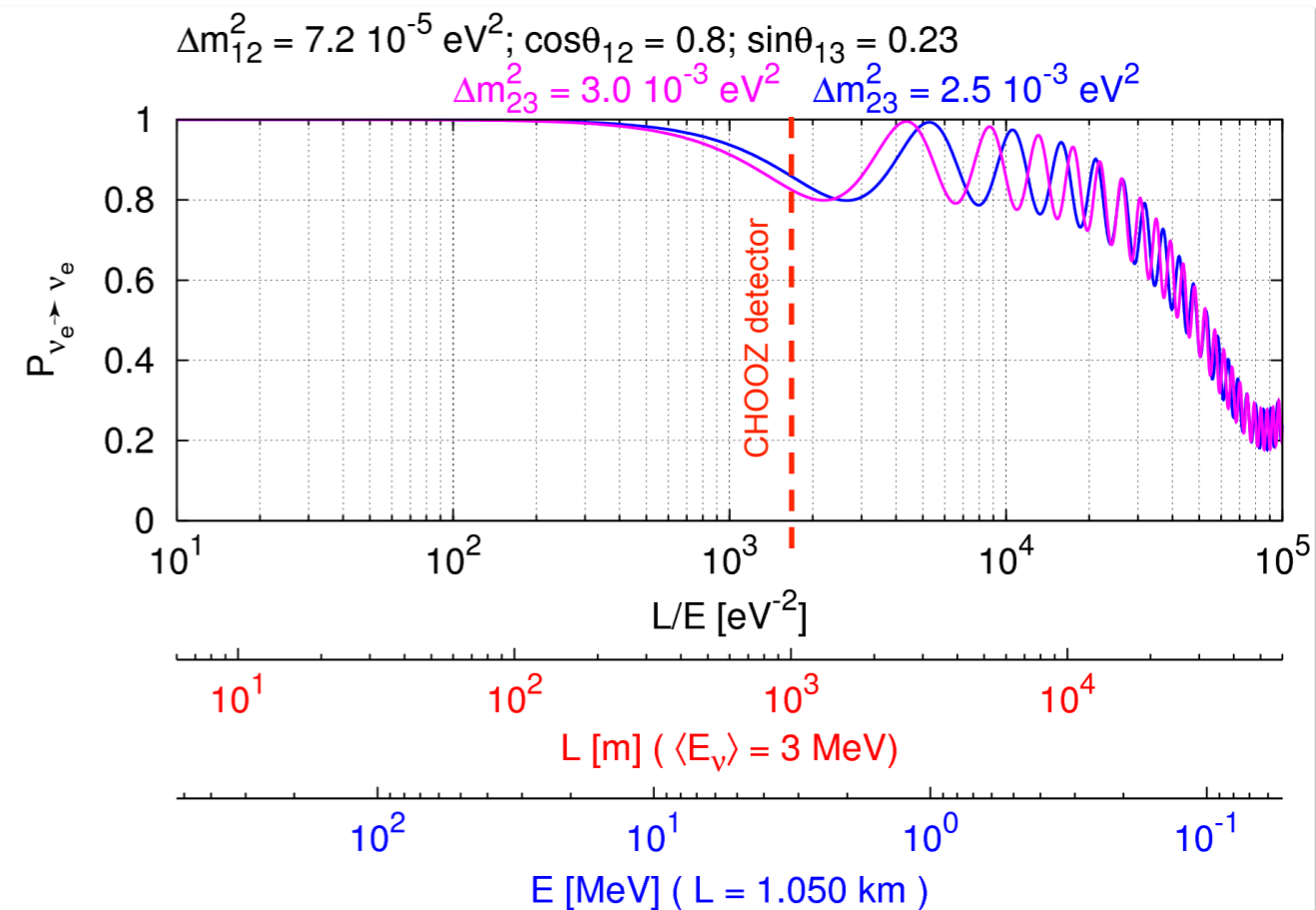
$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{2E_\nu}$$

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

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

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

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



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

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.

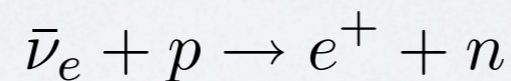
CHOOZ

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

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



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



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

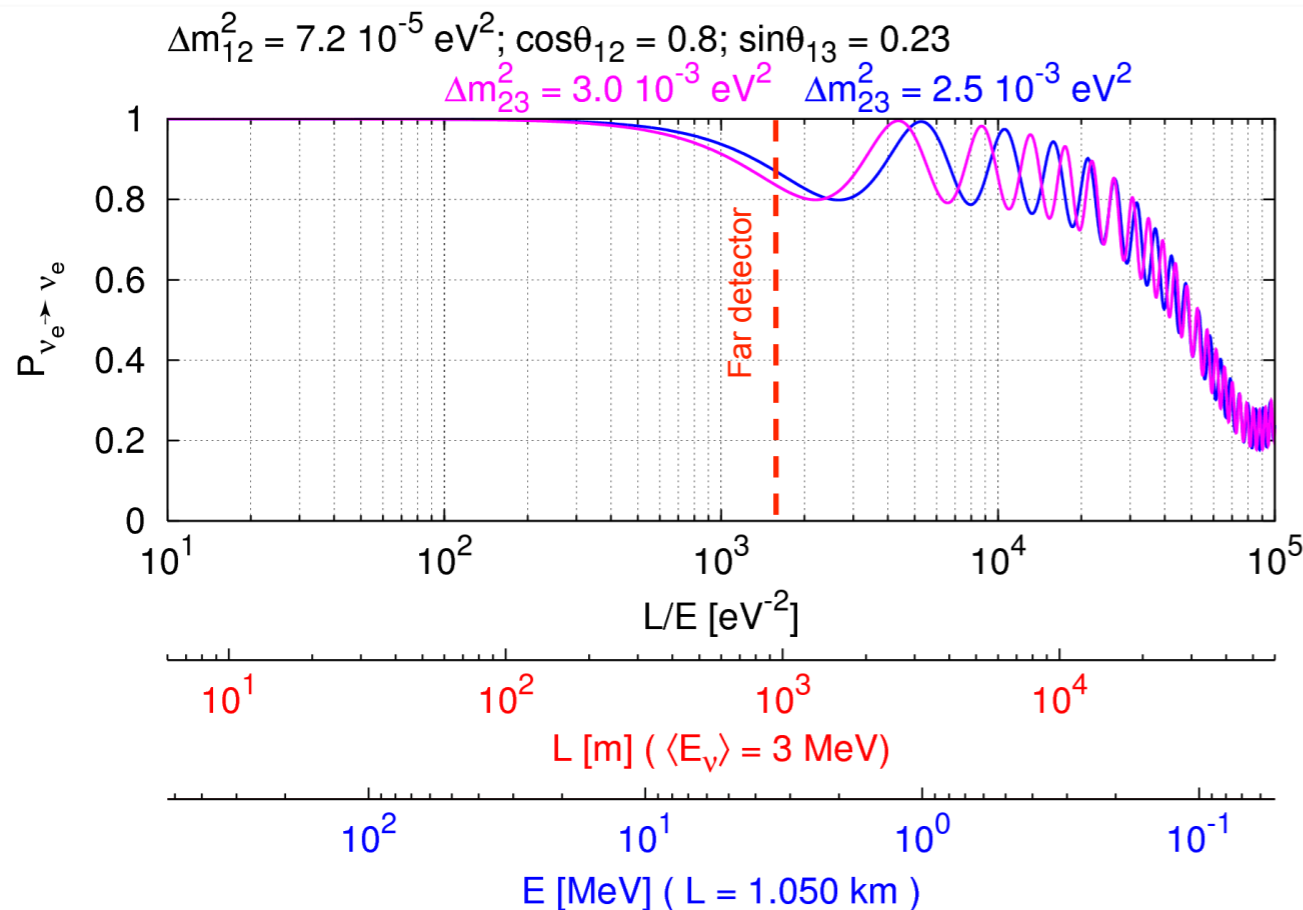
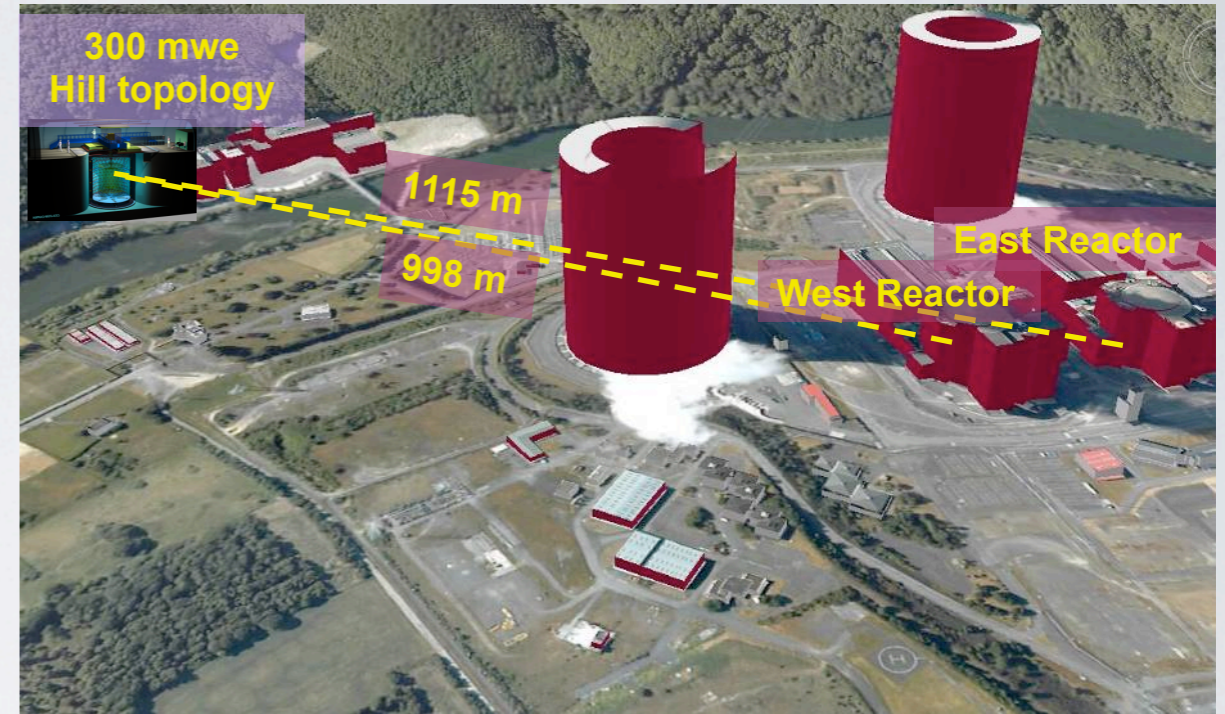


producing gammas at
8 MeV

Delayed signal ($\sim 30 \mu\text{s}$)

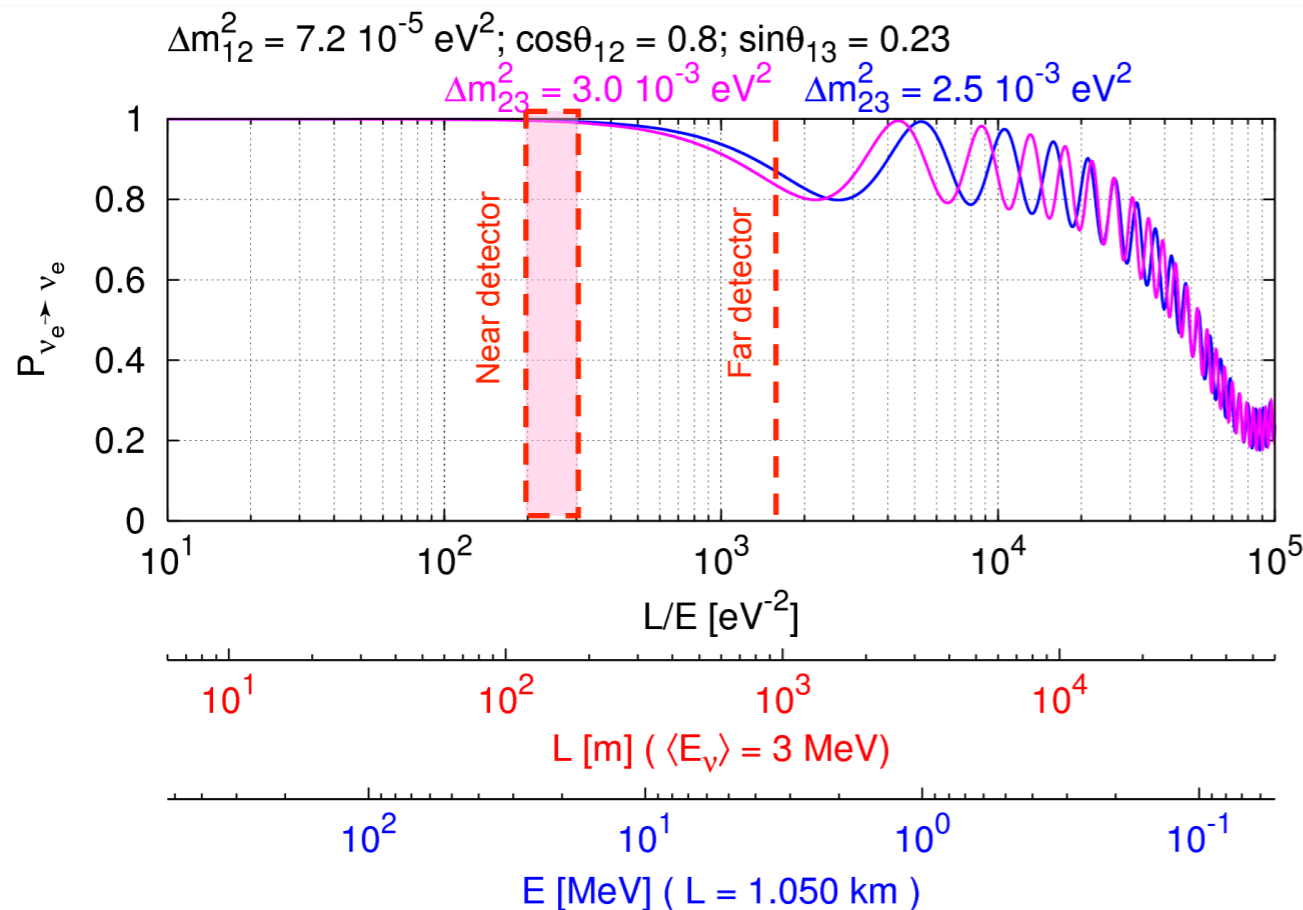
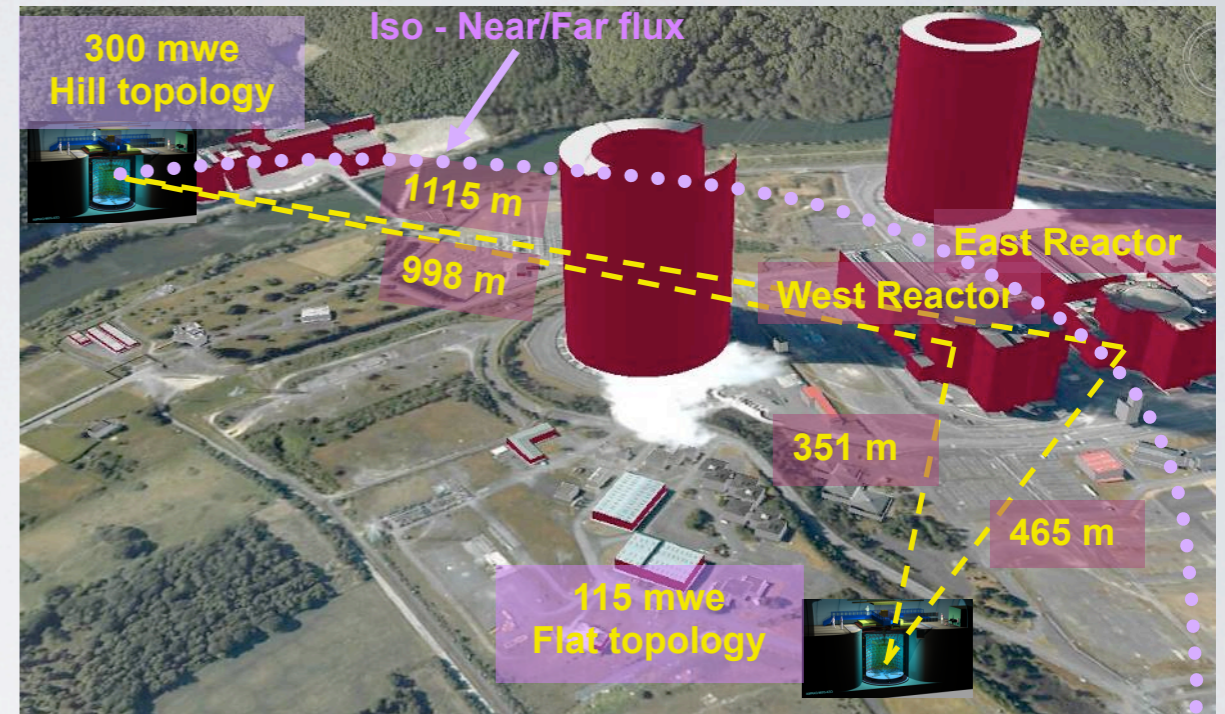
DOUBLE CHOOZ

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



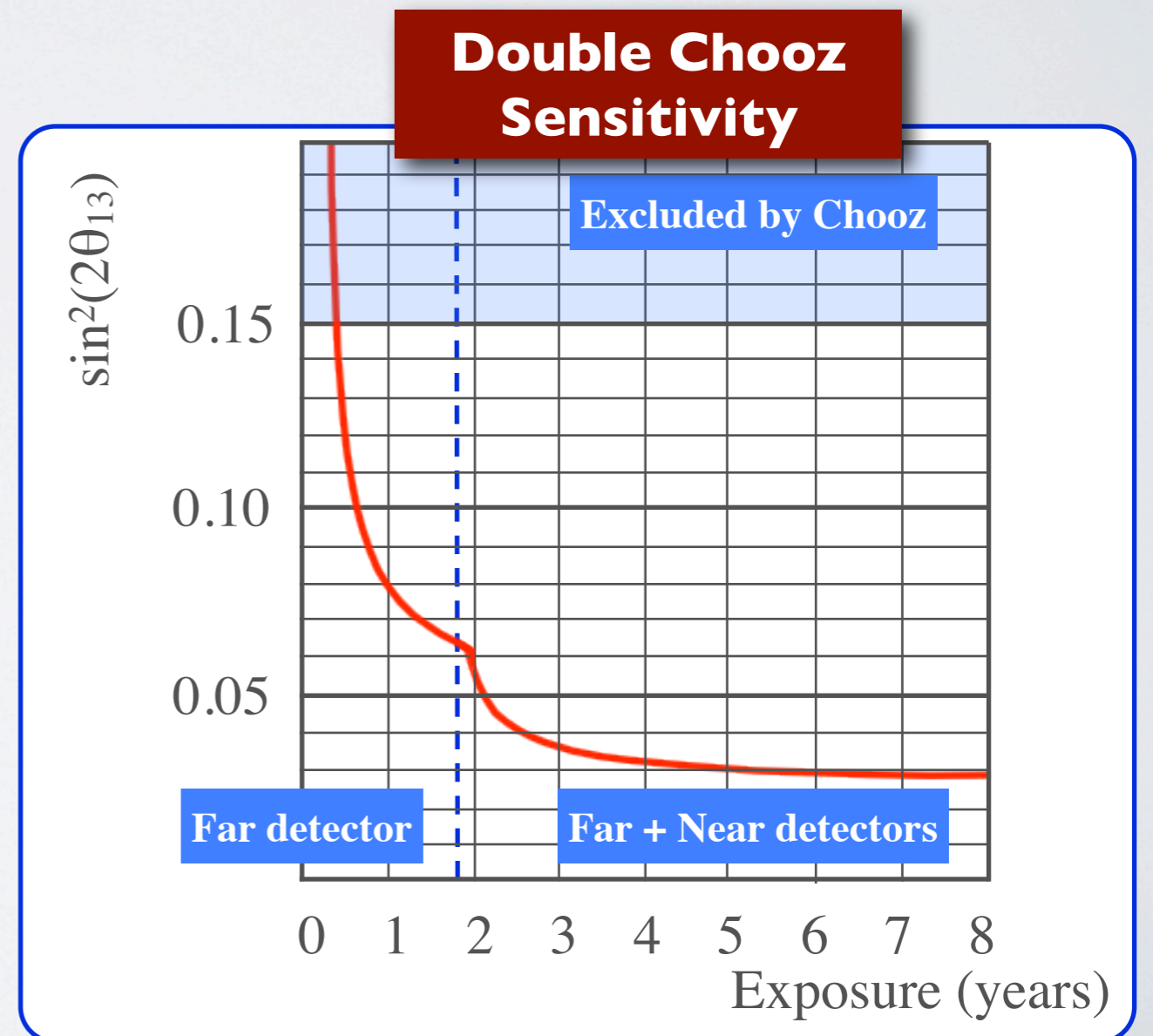
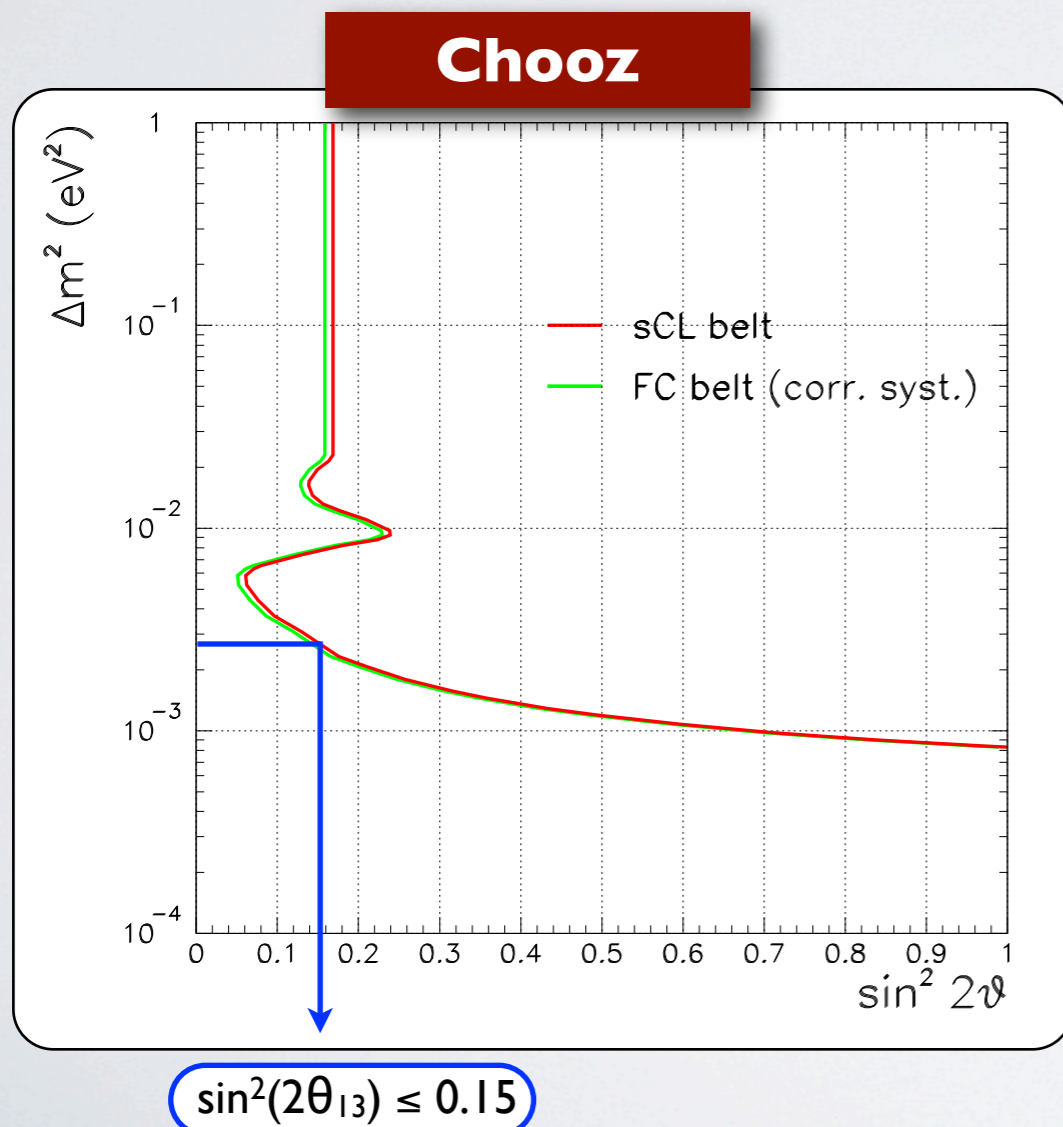
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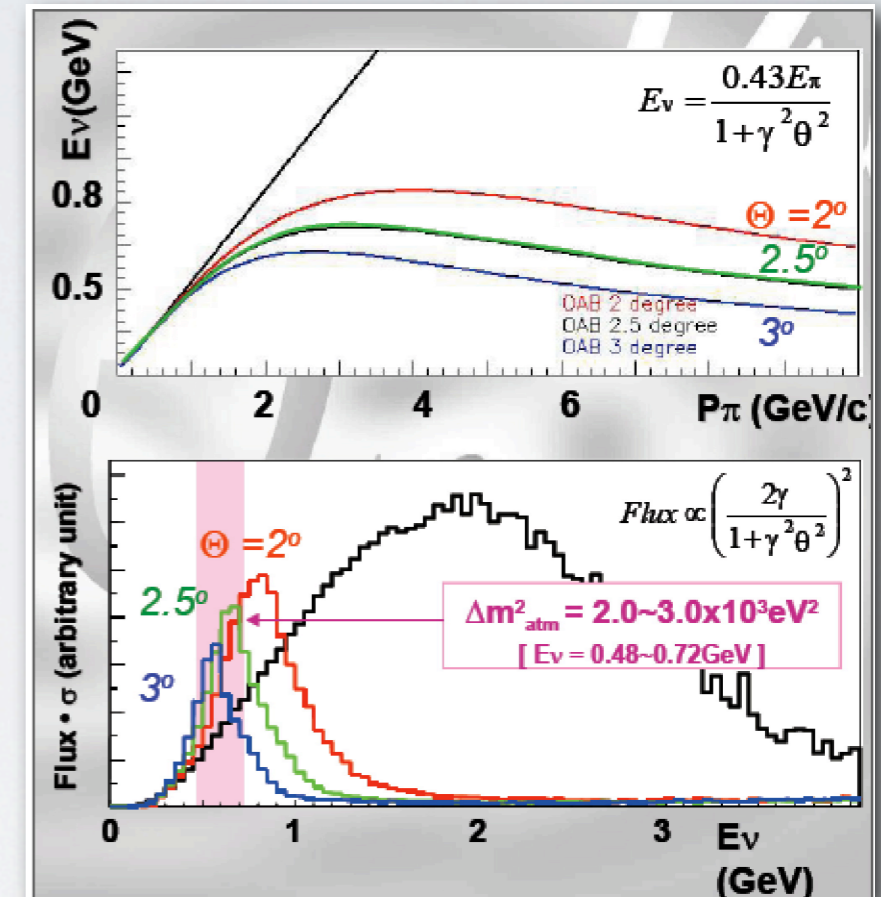
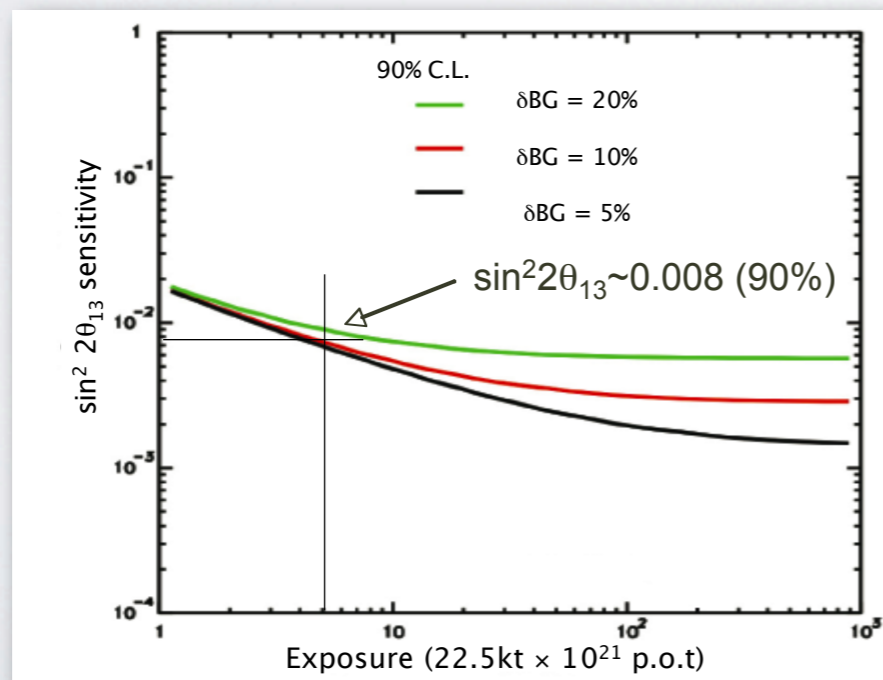
(DOUBLE) CHOOZ

- **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.



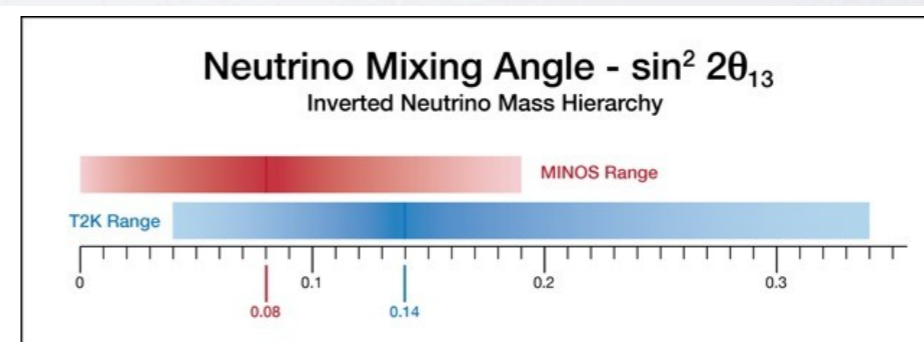
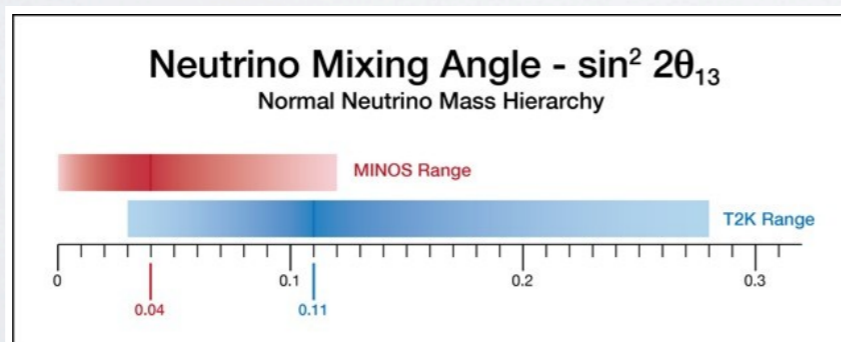
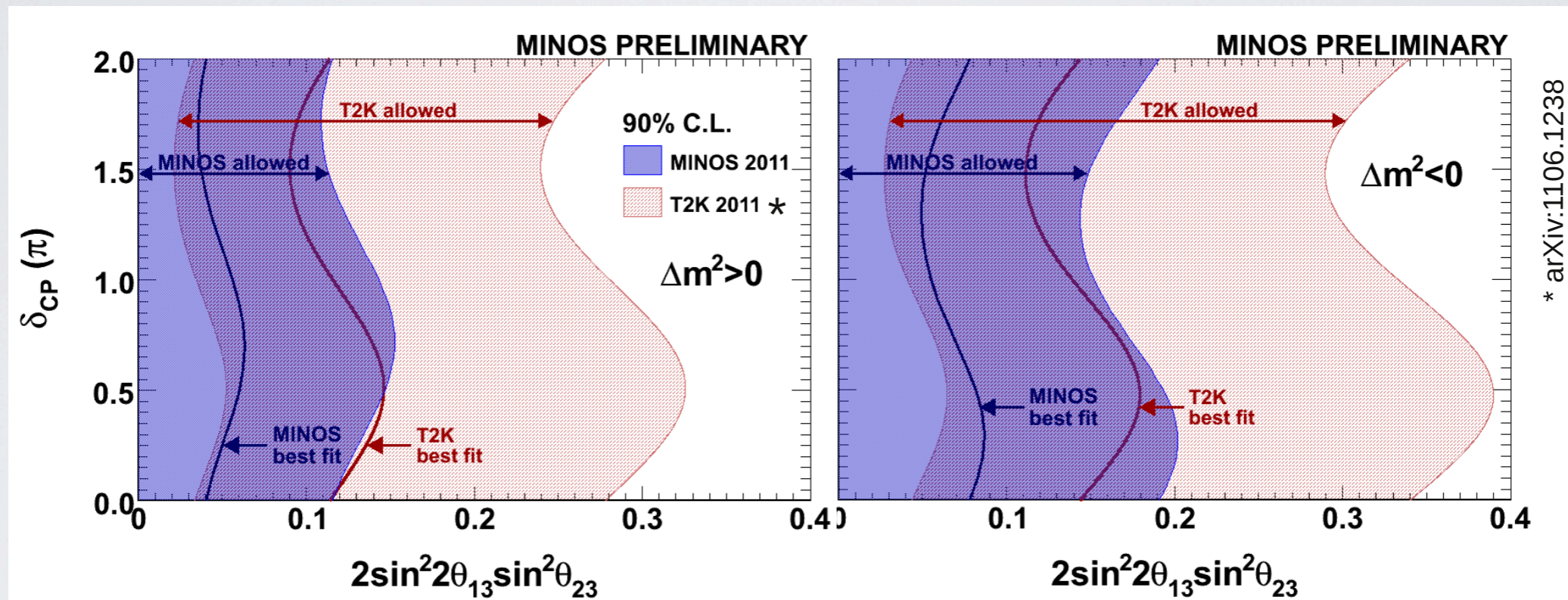
T2K

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

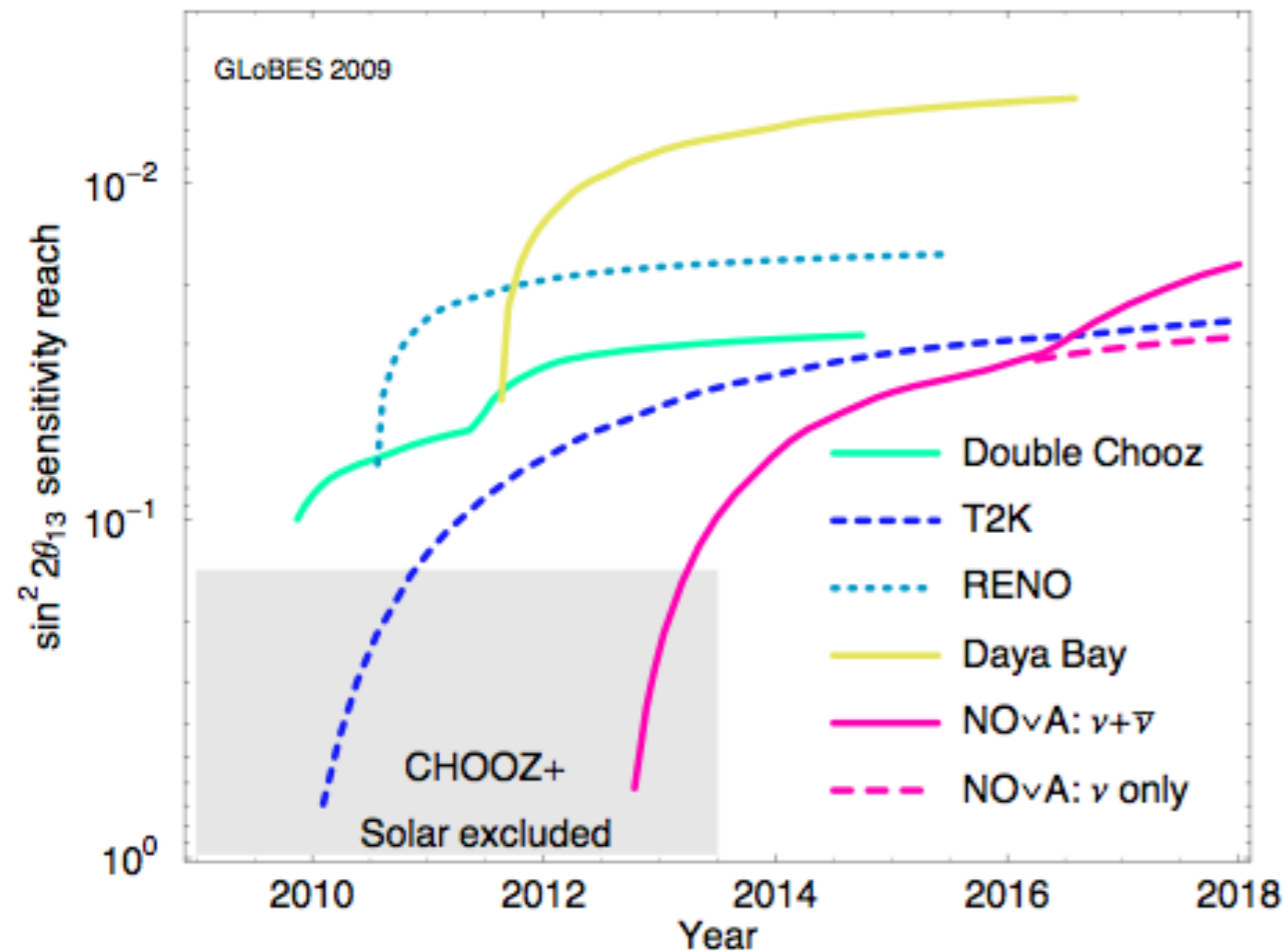
- **T2K** and **MINOS** have recently published some results that strongly disfavour the possibility of a vanishing θ_{13} mixing angle.
- The two experiments found an excess of events over the background of 2.5 and 1.7 sigma respectively.



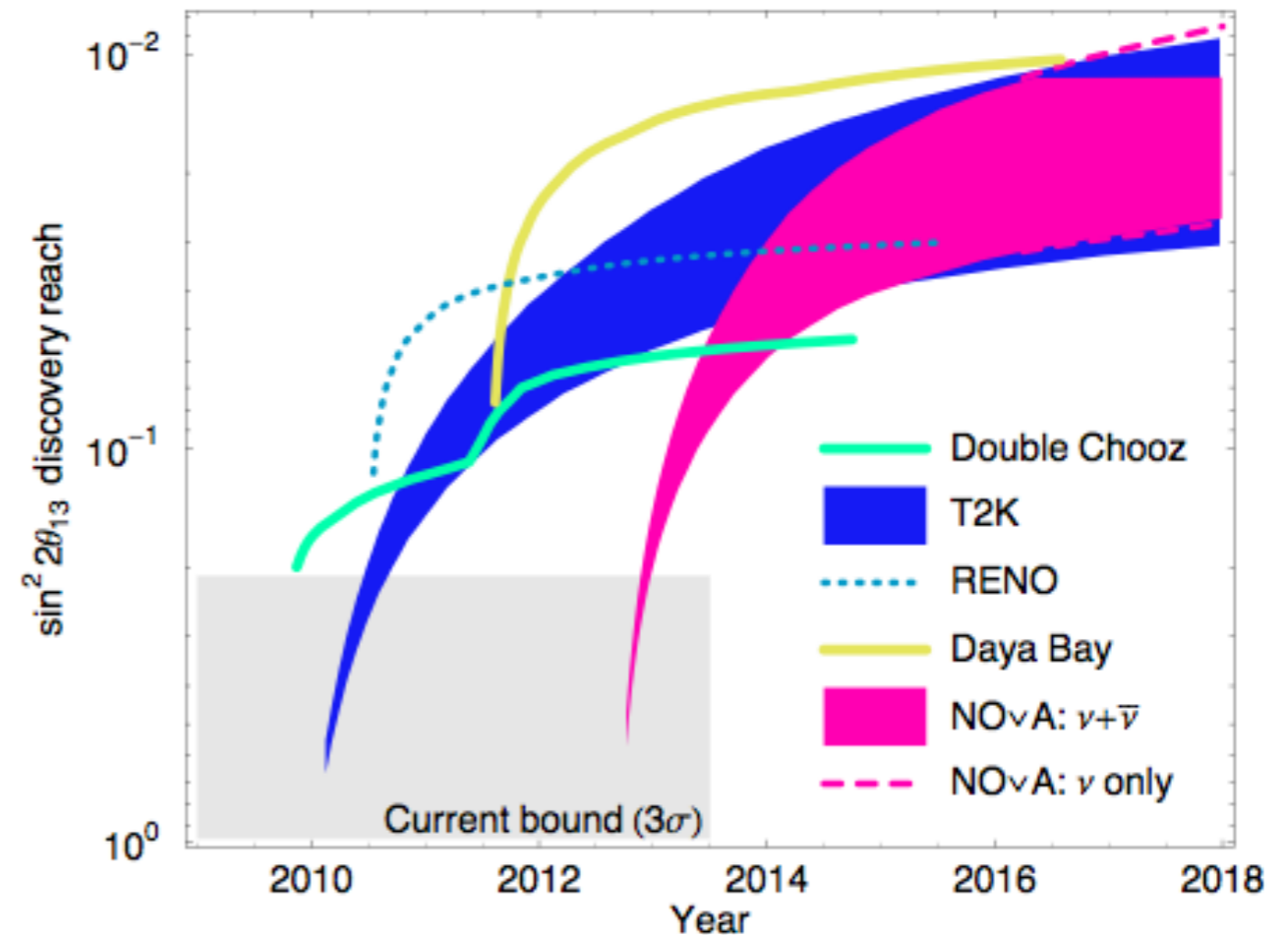
RESULTS

- **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.

$\sin^2 2\theta_{13}$ sensitivity limit (NH, 90% CL)



$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)



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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
$ \Delta m_{21}^2 $	$7.2 \leq \Delta m_{21}^2 / 10^{-5} \text{ eV}^2 \leq 7.9$	Solar ν + $P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$	SK, SNO, KamLAND	
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Sign (Δm_{31}^2)				
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 $(0, \pi)$ 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**.

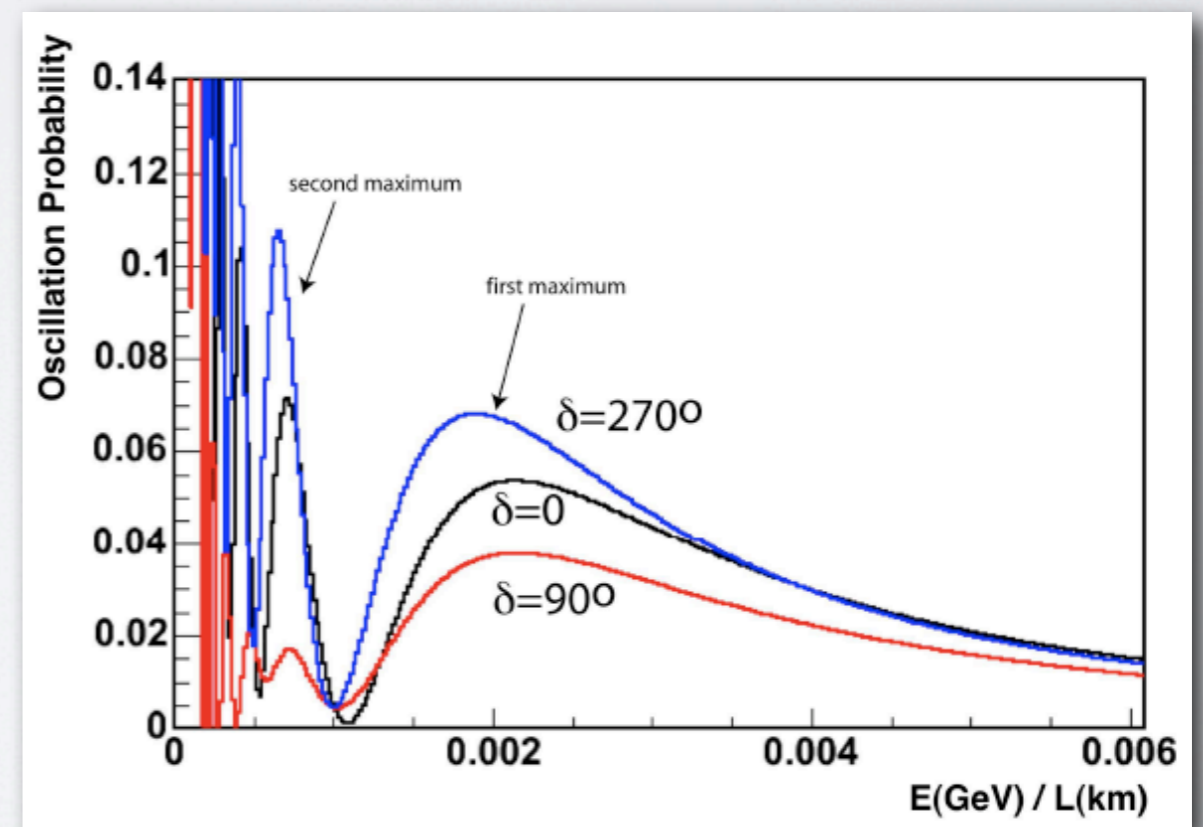
CP VIOLATION

- 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. $\geq \sim 1000$ km) and **matter effects** become measurable (**effect dependent on the baseline**).
- The intrinsic **CP violation** is **independent on the baseline**.
- 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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- The **mass hierarchy** can be observed when the baseline is long enough (i.e. $\geq \sim 1000$ km) and **matter effects** become measurable (**effect dependent on the baseline**).
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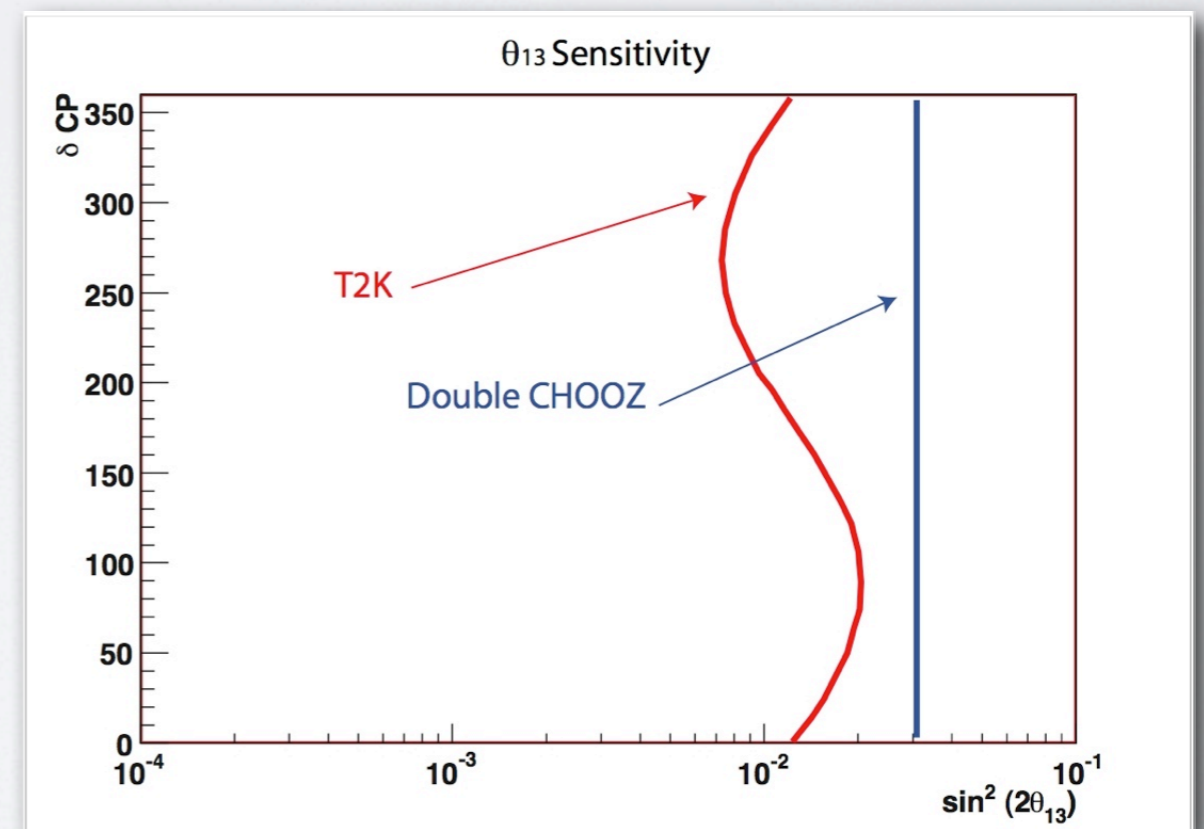
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- The **mass hierarchy** can be observed when the baseline is long enough (i.e. $\geq \sim 1000$ km) and **matter effects** become measurable (**effect dependent on the baseline**).
- The intrinsic **CP violation** is **independent on the baseline**.
- 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**:

$$P(\nu_\alpha \rightarrow \nu_x) = 1 - P(\nu_\alpha \rightarrow \nu_\alpha)$$

CPT conserved + T conserved

CP conserved



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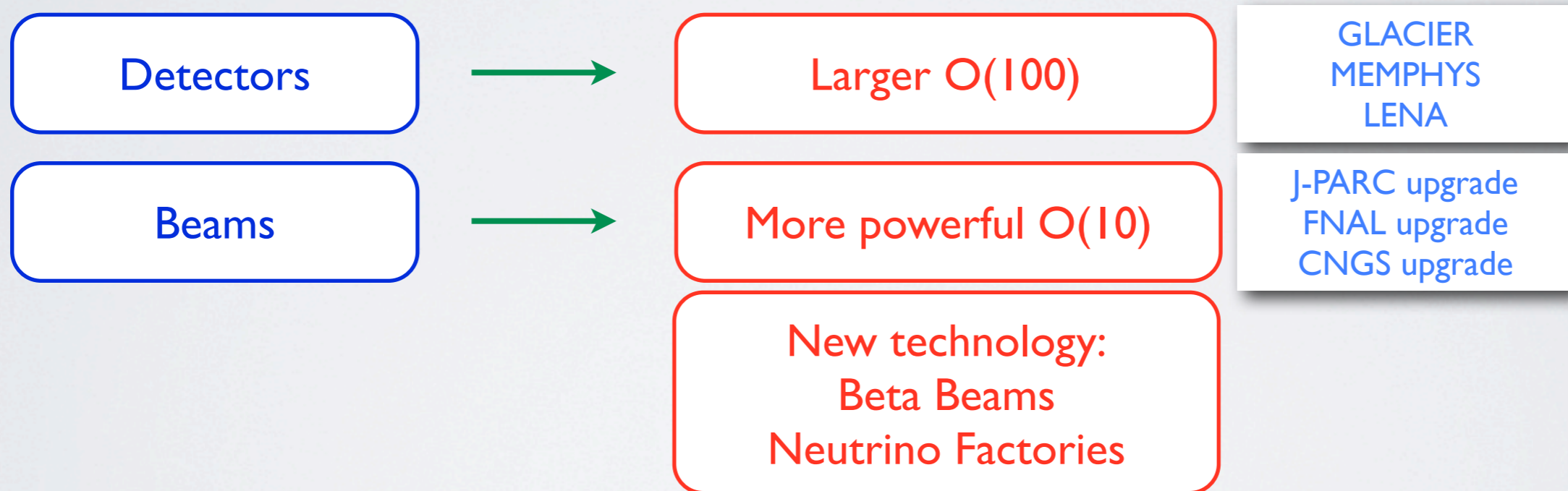
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Sign (Δm^2_{31})	Unknown	$P(\nu_\mu \rightarrow \nu_e)$ Vs $P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$		Future LBL
δ_{CP}	Unknown	$P(\nu_\mu \rightarrow \nu_e)$ Vs $P(\text{anti } \nu_e \rightarrow \text{anti } \nu_e)$		T2K+Reactor Future 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:

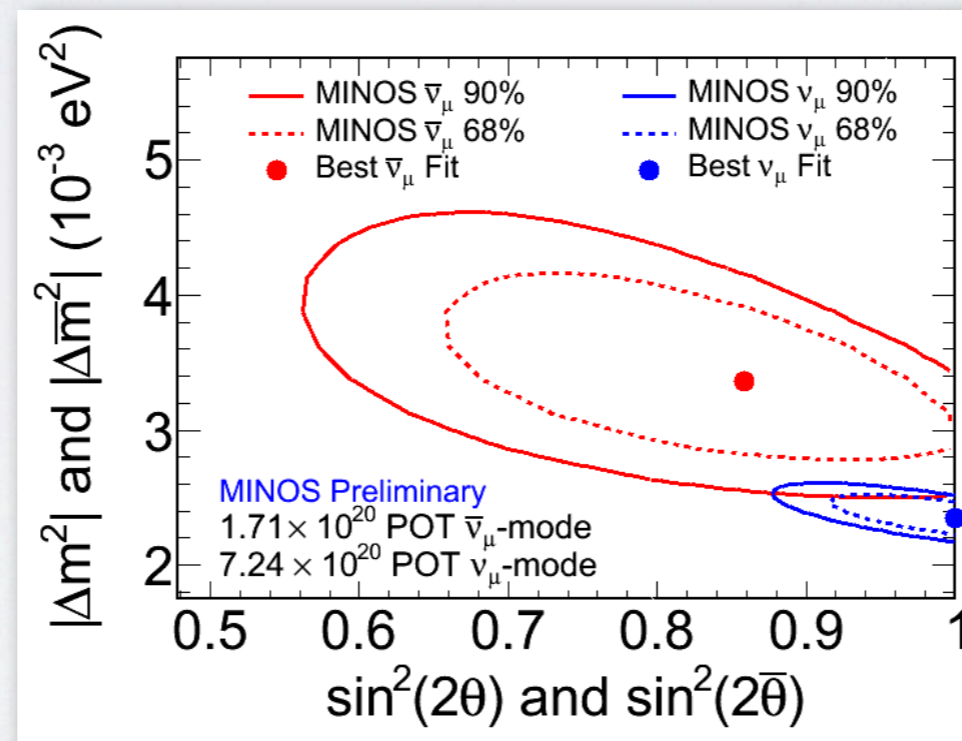


All these projects require a huge amount of money and R&D.

The neutrino community is evaluating all the different options (projects such as **LAGUNA** or **EURO ν**) 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 transitions: 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...