Neutrinos physics

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- Introduction
- Neutrino oscillations
- The nature of the neutrino

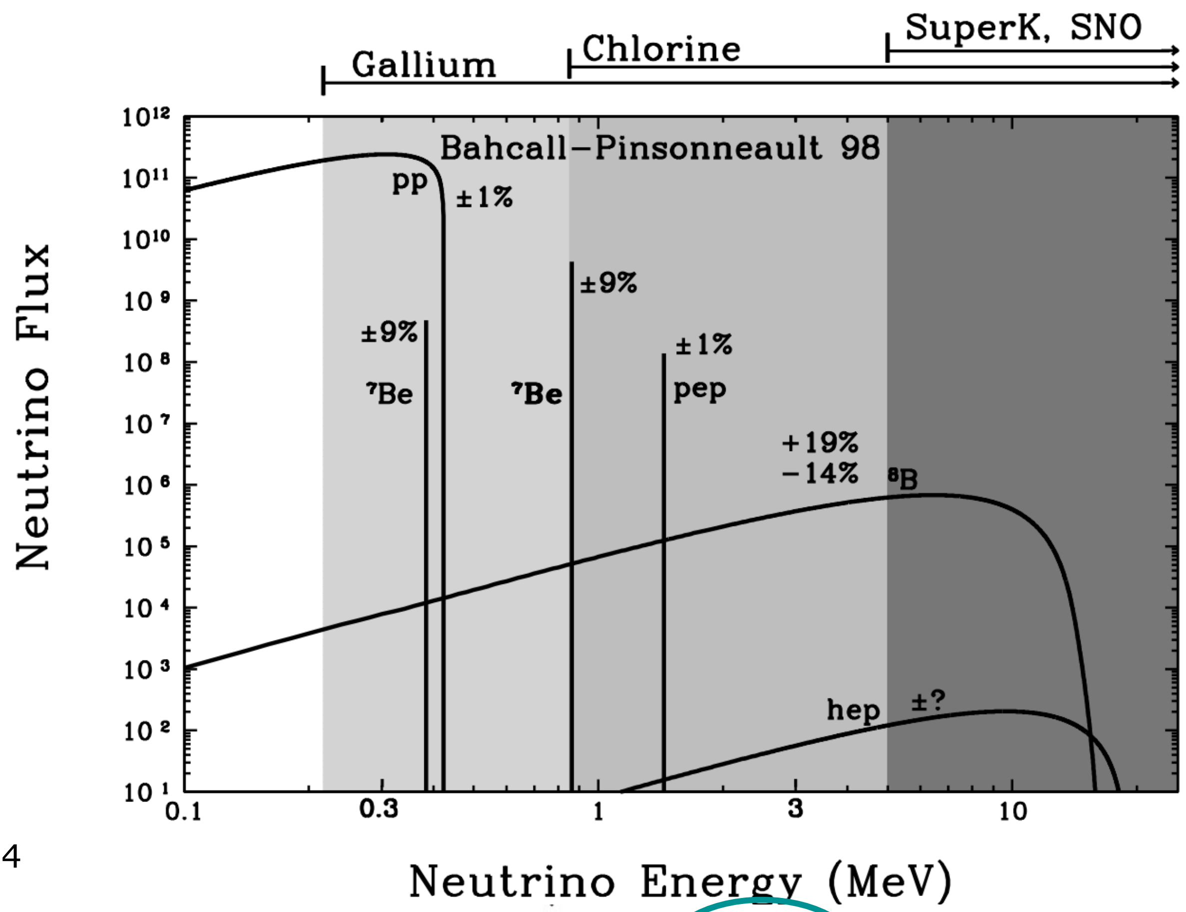
Highly selective in terms of exp. results (and theoretical details …)

European Research Council
Established by the European Commission

neutrino oscillations

Homestake: Davis' pioneer experiment (1967)

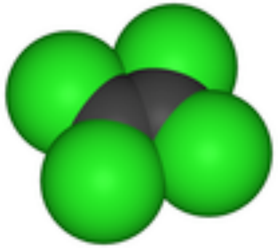
Sun is emiting ν_e → inverse β decay



hep-ph/0009044

Ray David

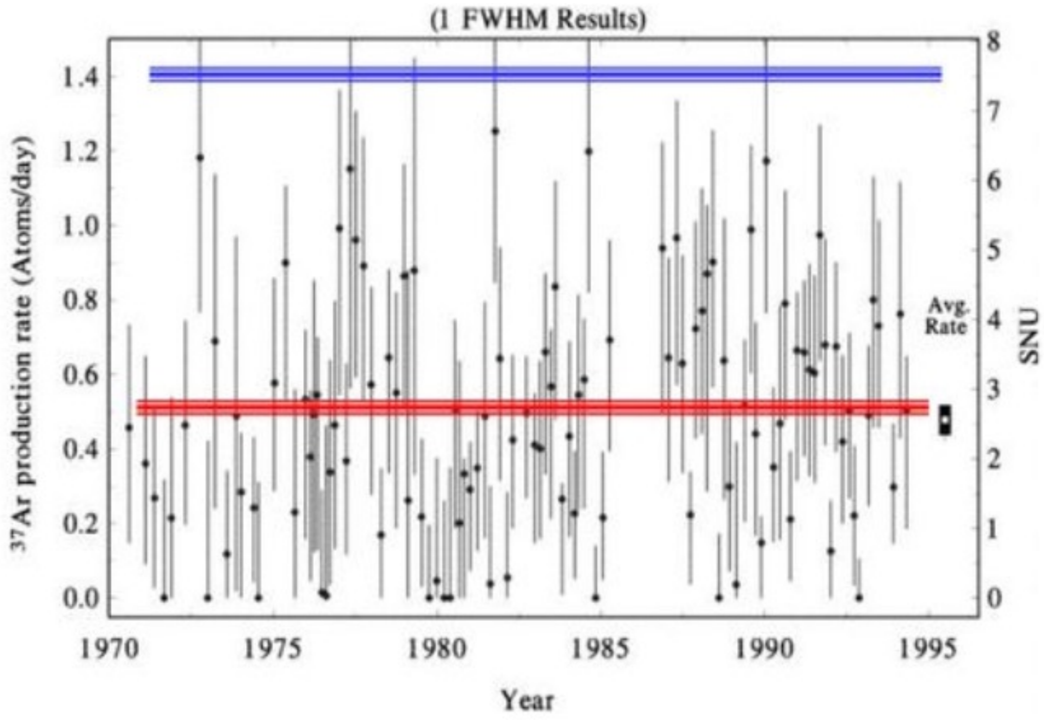
Count a few atoms in a tank of 615 tons of Tetrachloroethylene (C_2Cl_4) !



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

Ar is chemically very different from Chlorine → can be separated

It is radioactive and reverts to Cl^{37} emitting an Auger electron (lifetime 35 days)



SSM predicted SNU

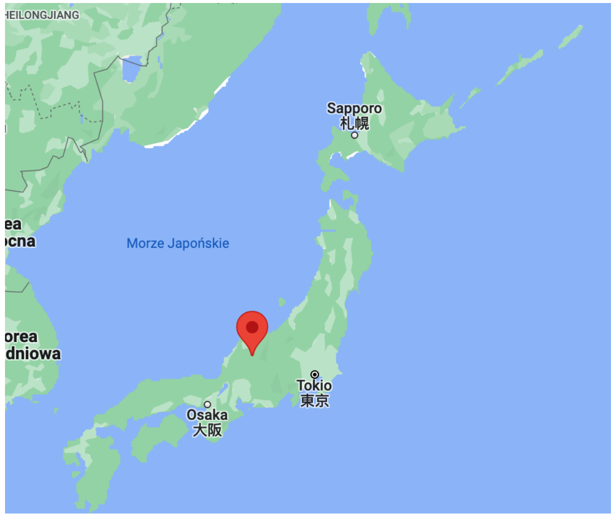
Average rate
2.56 ± 0.20 SNU

The observed rate was about 3 times smaller than the predicted one (7.6 ±1.2 SNU)…

30 years running
~ 2000 neutrinos from the Sun

Is it seen by others ?

(Super)-Kamiokande



Kamioka in Japan

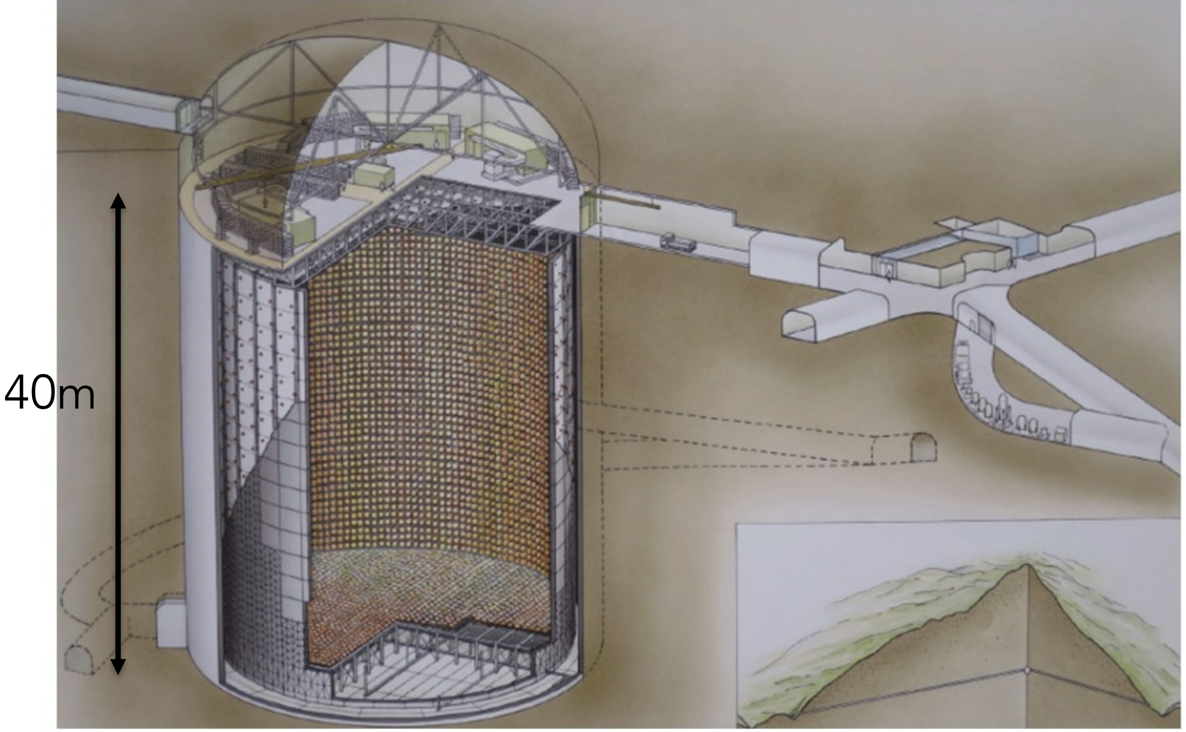
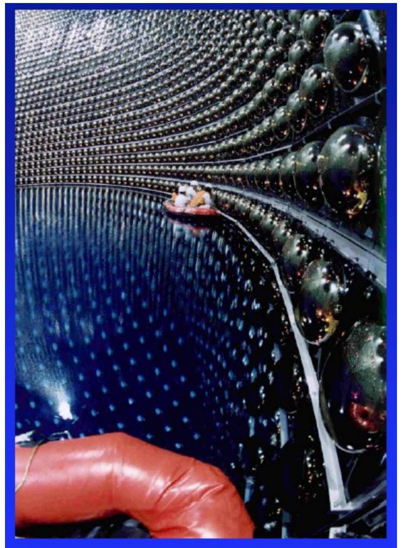
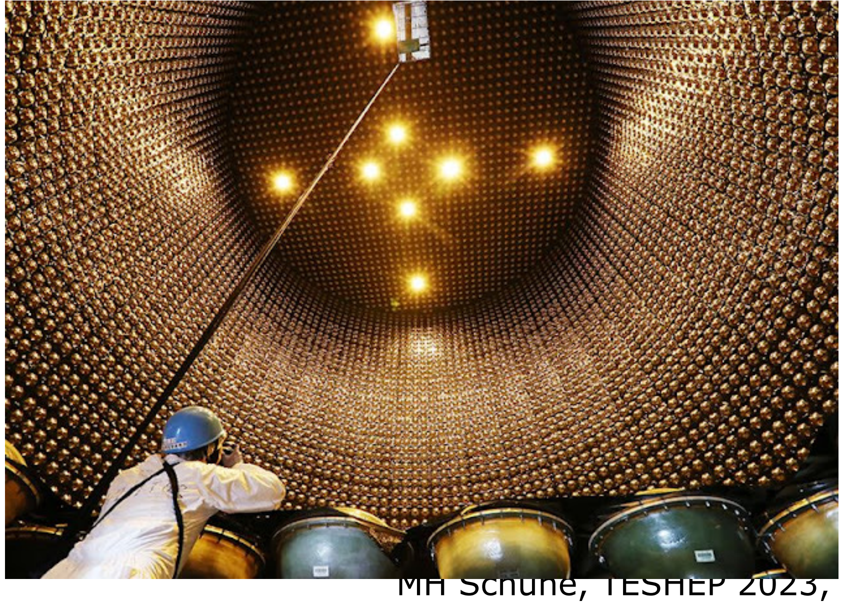
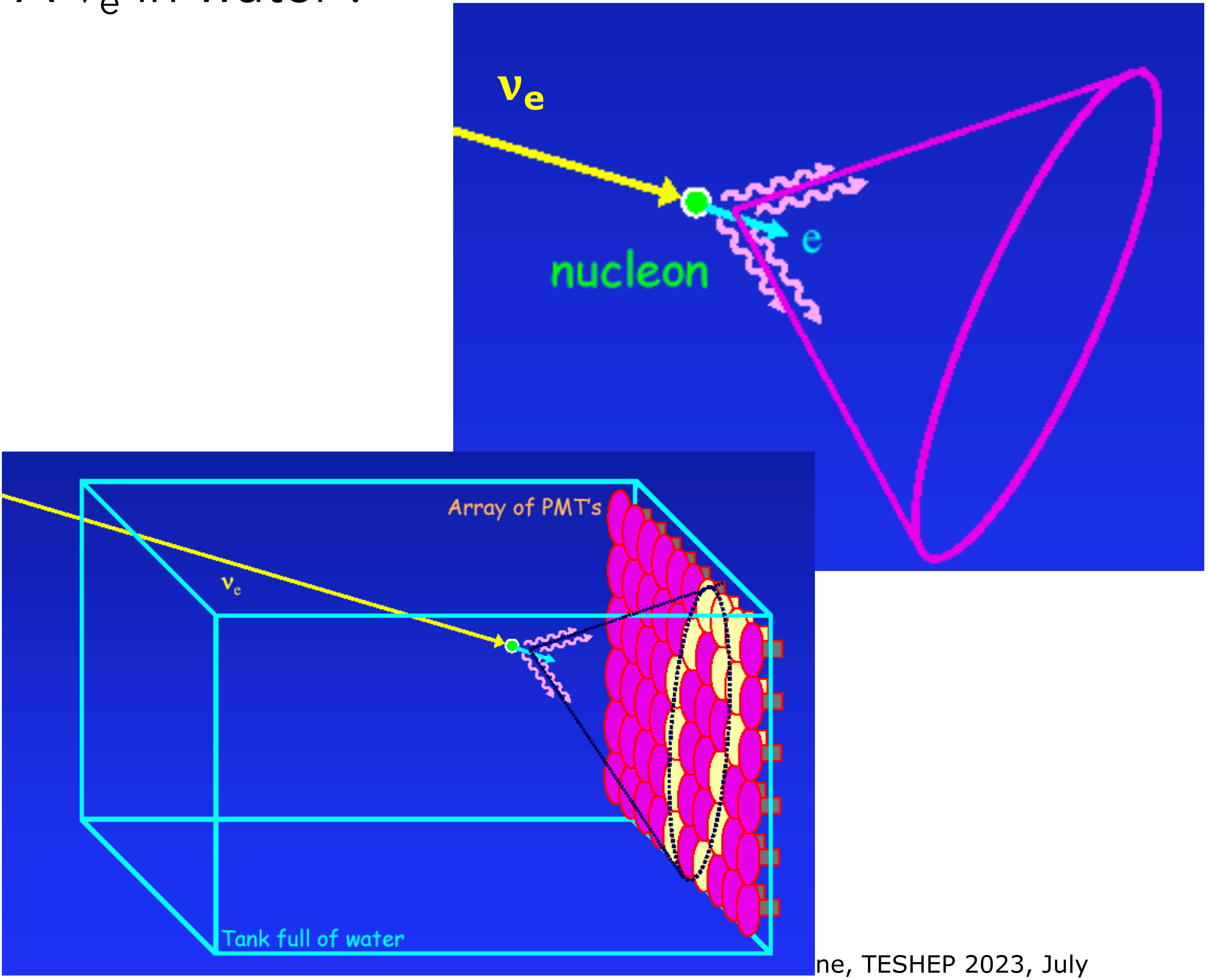


Fig. 1 Super-Kamiokande Detector. The 50 kton water is viewed by ∼ 11, 000 photomultiplier tubes (PMT) and placed 1000 m underground



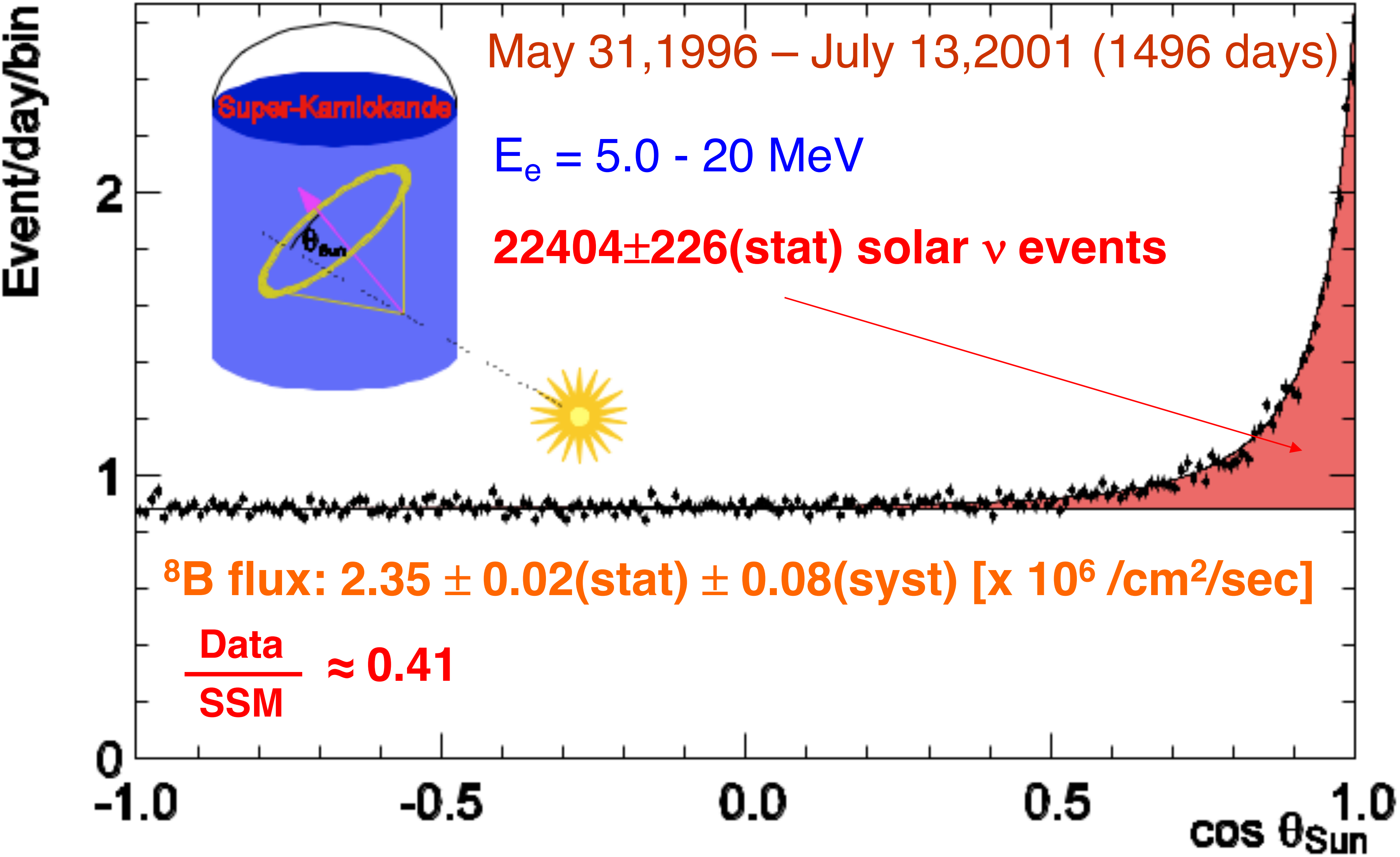


A ν_e in water :



The shape of the oval and the time at which the light reaches the PMT : neutrino direction

The amount of light : energy of the neutrino



May 31,1996 – July 13,2001 (1496 days)

E_e = 5.0 - 20 MeV

22404±226(stat) solar ν events

^{8}B flux: 2.35 ± 0.02(stat) ± 0.08(syst) [x 10^6 /cm^2/sec]

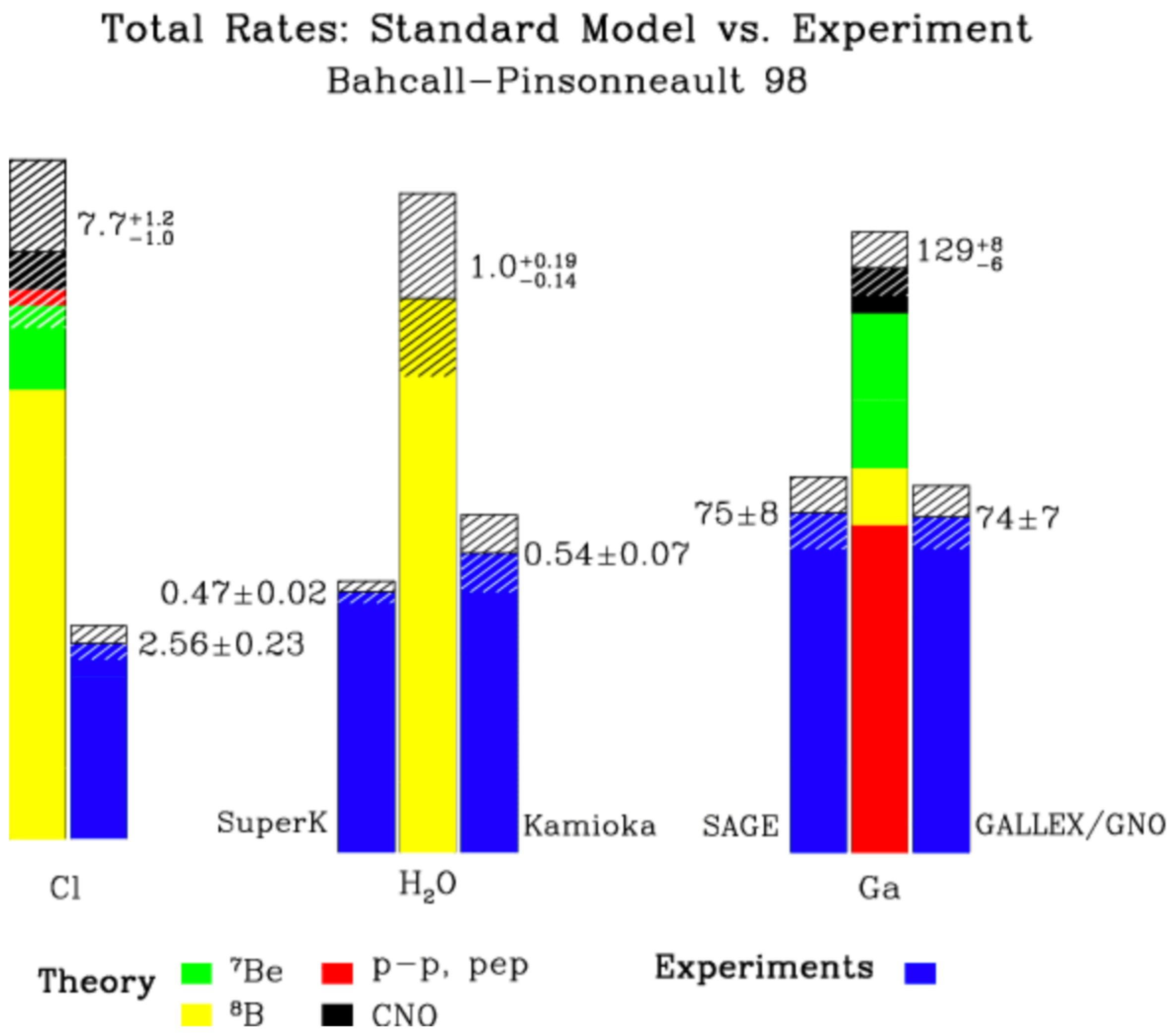
$$\frac{\textbf{Data}}{\textbf{SSM}} \approx \mathbf{0.41}$$

Phys. Rev. D 73, 112001 (2006)

The observed neutrinos are indeed coming from the sun

The rate is ~1/2 the expected one (SSM) …

the deficit is confirmed



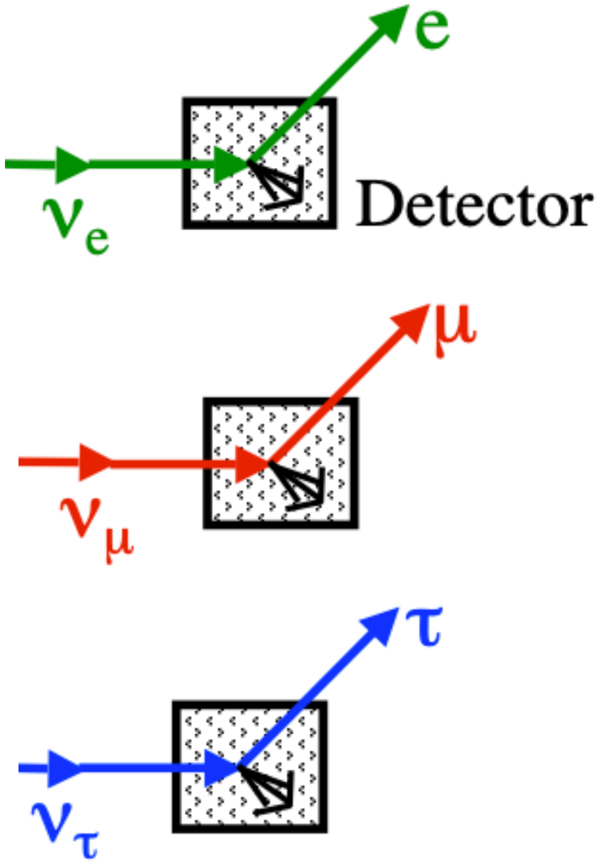
→ theory (SM, SSM) was wrong
→ experiments were wrong (all of them?)
→ something was happening to neutrinos

1968 flavour change (oscillation) of electron neutrinos to muon neutrinos ? (Gribov & Pontecorvo)

Three flavours of neutrinos:

$$\begin{tikzcd}
\nu_e \arrow[d, leftrightarrow] & , & \nu_\mu \arrow[d, leftrightarrow] & , & \nu_\tau \arrow[d, leftrightarrow] \\
e & , & \mu & , & \tau
\end{tikzcd}$$

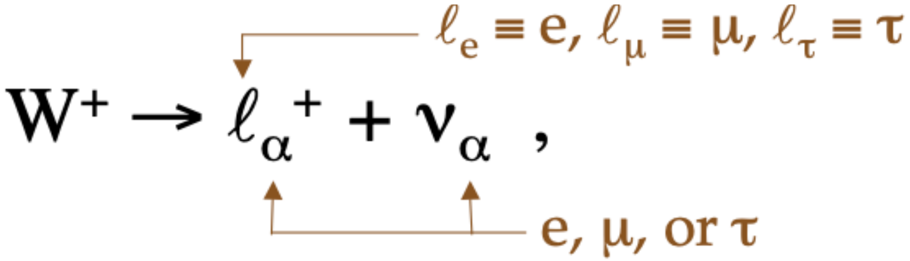
→ experimental meaning:



Let's assume neutrinos have masses

Mass eigenstates:
$\boldsymbol{\nu}_i$ with masses m_i

Flavour (weak) eigenstates: $\boldsymbol{\nu}_\alpha$



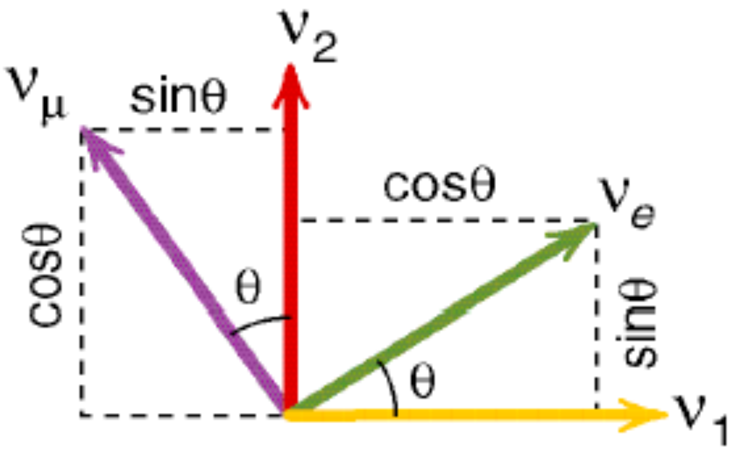
$$W^+ \to \ell_\alpha^+ + \nu_\alpha \ ,$$

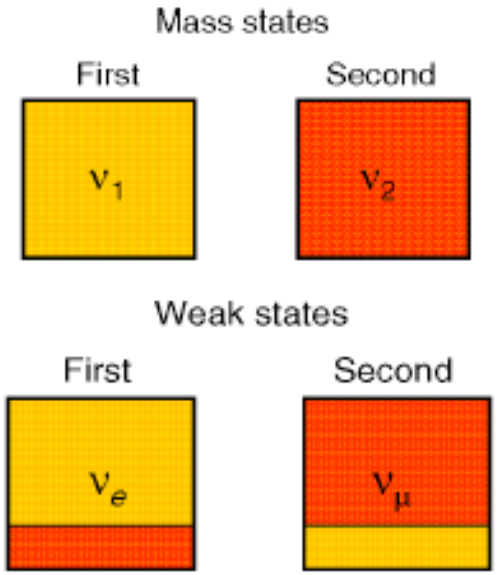
$\ell_e \equiv e, \ell_\mu \equiv \mu, \ell_\tau \equiv \tau$

e, μ, or τ

Assuming for simplicity a two-family case:

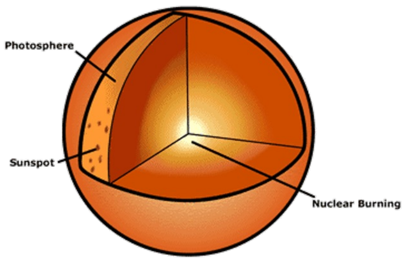
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$





Neutrinos oscillations : the case for 2 families

source

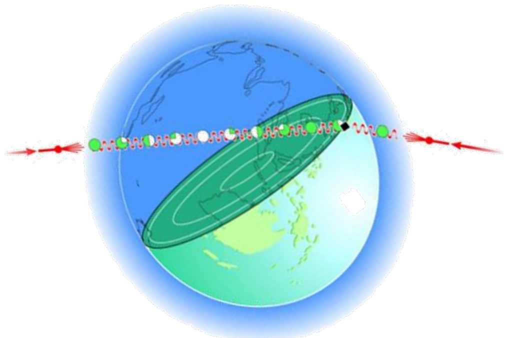


ν_e

propagation

L

detection



The weak interaction produces neutrinos of a given flavor

$$|\nu(x=0)\rangle = |\nu_e\rangle$$
$$= \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Evolution with time in the mass eigenstates basis follows Schrödinger equation (lab frame):

$$|\nu(L)\rangle =$$
$$e^{-i(E_1t-p_1L)}\cos\theta|\nu_1\rangle + e^{-i(E_2t-p_2L)}\sin\theta|\nu_2\rangle$$

Ultra relativistic neutrinos (E average energy of the mass eigenstates)

$$p_i = \sqrt{E^2 - m_i^2} \sim E - \frac{m_i^2}{2E}$$

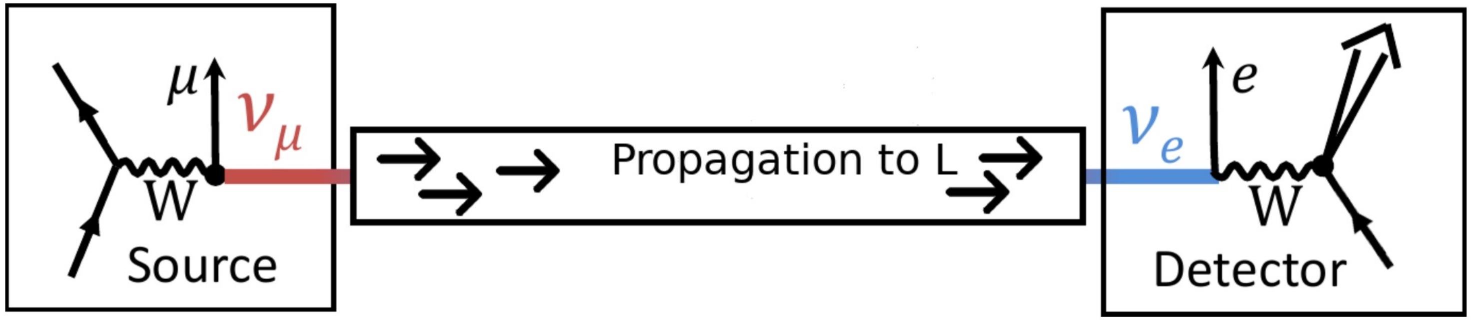
$$|\nu(L)\rangle = e^{-i\frac{m_1^2}{2E}L}\cos\theta\,|\nu_1\rangle + e^{-i\frac{m_2^2}{2E}L}\sin\theta\,|\nu_2\rangle$$

Detection again via weak interaction :

$$\nu_\mu N \to \mu^- X$$
$$\nu_e N \to e^- X$$

$$P(\nu_e \to \nu_\mu) = |<\nu_\mu|\nu(L)>|^2$$
$$\approx \sin^2 2\theta \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$
$$\Delta m_{12}^2 = M_1^2 - M_2^2$$

ν Oscillation



Probability for a ν_μ to transform into a ν_e at a distance L:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\frac{(m_2^2 - m_1^2)L}{4E}$$

Mixing angle between flavor and mass states **Neutrino masses**

2 parameters
1 measurement

$$\boxed{P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

appearance

$$\boxed{P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1}$$

disappearance

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix.

3x3 unitarity matrix

Flavour eigenstates
(interaction)

3 angles and 1 CP violating phase

Mass eigenstates
(propagation)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\mathrm{CP}}} & c_{13}\,c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

$$P_{\alpha\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = |\sum_{i=1}^{n}\sum_{j=1}^{n} U^*_{\alpha i}U_{\beta j}\langle\nu_j|\nu_i(t)\rangle|^2$$

CP conserving CP violating

$$\mathrm{Prob}(\alpha \to \beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(J_{ij}^{\alpha\beta}\right)\sin^2\left[1.27\Delta m_{ij}^2 \frac{L}{E}\right] + 2\sum_{i>j} \mathrm{Im}\left(J_{ij}^{\alpha\beta}\right)\sin\left[2.54\Delta m_{ij}^2 \frac{L}{E}\right]$$

with $J_{ij}^{\alpha\beta} = U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*$

Δm_{ij}^2 in eV^2

L in *m* and E in MeV

For anti-neutrino: exchange U → U*

is CP conserved ???

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

Weak interaction eigenstates (ν_α)

PMNS matrix (Pontecorvo, Maki, Nakagawa, Sakata)

Mass eigenstates (ν_i)

We can now check if $\mathrm{Prob}(\nu_\alpha \rightarrow \nu_\beta) = \mathrm{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

Assuming CPT holds : $\mathrm{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \mathrm{Prob}(\nu_\beta \rightarrow \nu_\alpha)$

Lectures from Alexander Korchin, Stephane Monteil and Achille Stocchi

But : $\mathrm{Prob}(\nu_\alpha \underset{\overset{\big\uparrow}{U}}{\rightarrow} \nu_\beta)$ $\qquad$ $\mathrm{Prob}(\nu_\beta \underset{\overset{\big\uparrow}{U^*}}{\rightarrow} \nu_\alpha)$

If the *U* matrix is complex then CP violation should be seen in the neutrino sector

With at least three families the *U* matrix is complex

Similar to the quarks sector (CKM matrix) , we should see CP violation effects in the neutrino sector

It turns out that:

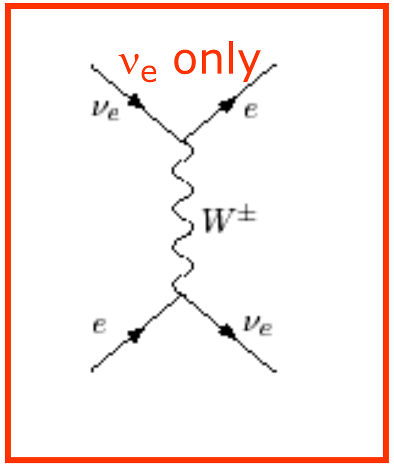
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric, beam}} \underbrace{\begin{pmatrix} c_{13} & 0 & \boxed{s_{13} e^{-i\delta_{\mathrm{CP}}}} \\ 0 & 1 & 0 \\ \boxed{-s_{13} e^{i\delta_{\mathrm{CP}}}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor, beam}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, reactor}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour eigenstates
(interaction)

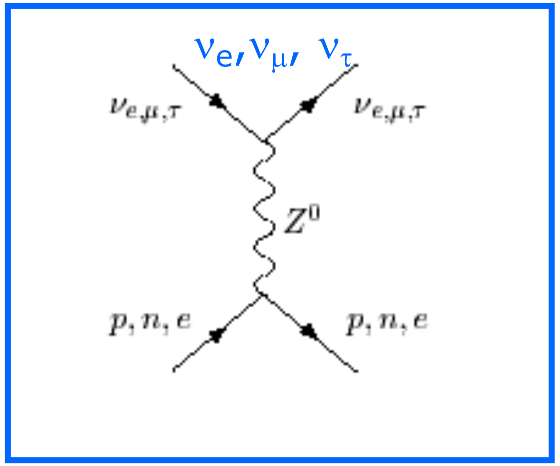
Mass eigenstates
(propagation)

but this ad-hoc decomposition is an experimental fact, no (a-priori) theory behind it

Additional complication for neutrinos propagating in matter (but manageable)



ν_e only



ν_e, ν_μ, ν_τ

For 2 types of neutrinos the interaction potential in the flavour basis is :

$$H = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta_V & \sin 2\theta_V \\ \sin 2\theta_V & \cos 2\theta_V \end{pmatrix} + \sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \qquad H = \begin{pmatrix} a & x \\ x & b \end{pmatrix}$$

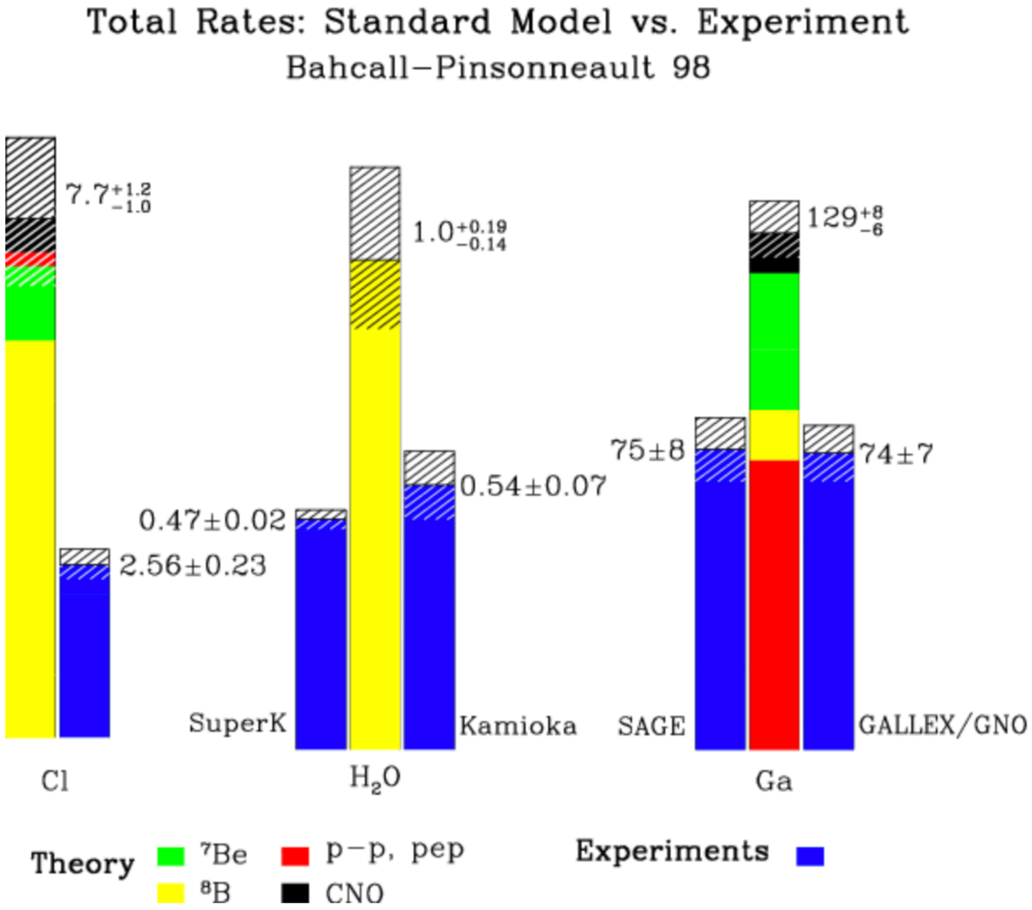
θ_V is the mixing angle in vacuum and N_e is the electron density in the medium

→ Effective mixing angle: $\tan 2\theta_M = \frac{2x}{a-b} = \frac{\Delta m^2 \sin 2\theta_V}{\Delta m^2 \cos 2\theta_V - 2\sqrt{2}G_F N_e E}$

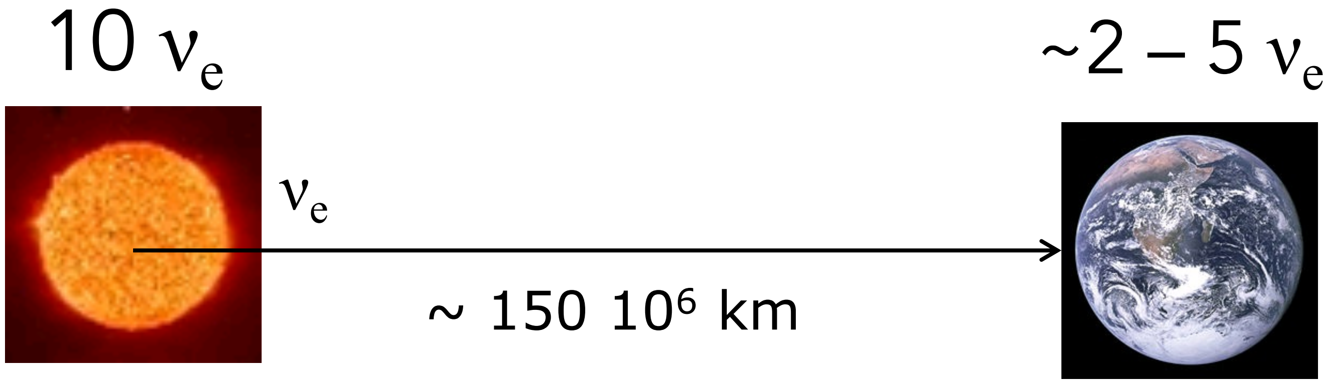
When $a=b$: maximal mixing ; MSW (Mikheyev, Smirnov, Wolfenstein) resonance effet

a=b is possible even for small θ_V

Solar Neutrino Problem



Measured ~ Predicted/2



10 ν_e

ν_e

~ $150\ 10^6$ km

~2 – 5 ν_e

What about the total flux ?

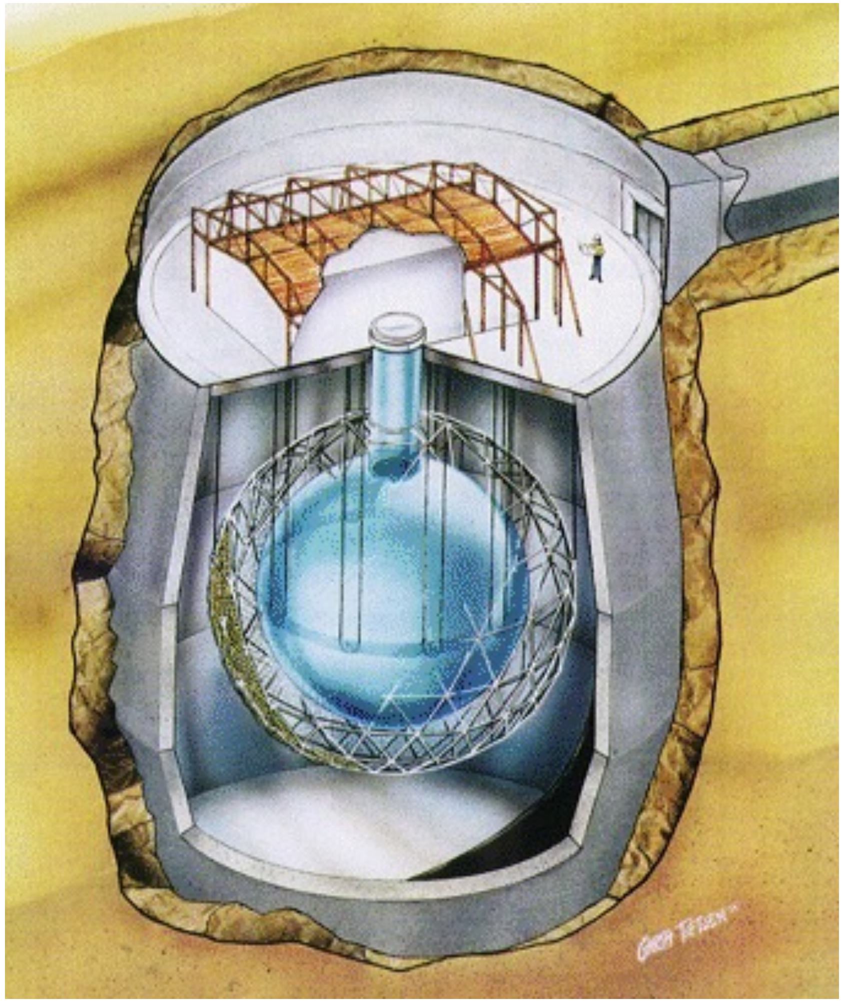
SNO experiment

Principle similar to Superkamiokande except that it uses salty heavy water :

Can measure separately $\boldsymbol{\nu}_e$ and $\boldsymbol{\nu}_\mu$ $\boldsymbol{\nu}_\tau$,

--> also an appearance experiment

CC	$\nu_e + d \Rightarrow p + p + e^-$	e-neutrinos only
ES	$\nu_x + e^- \Rightarrow \nu_x + e^-$	All neutrinos species
NC	$\nu_x + d \Rightarrow p + n + \nu_x$	All neutrinos species

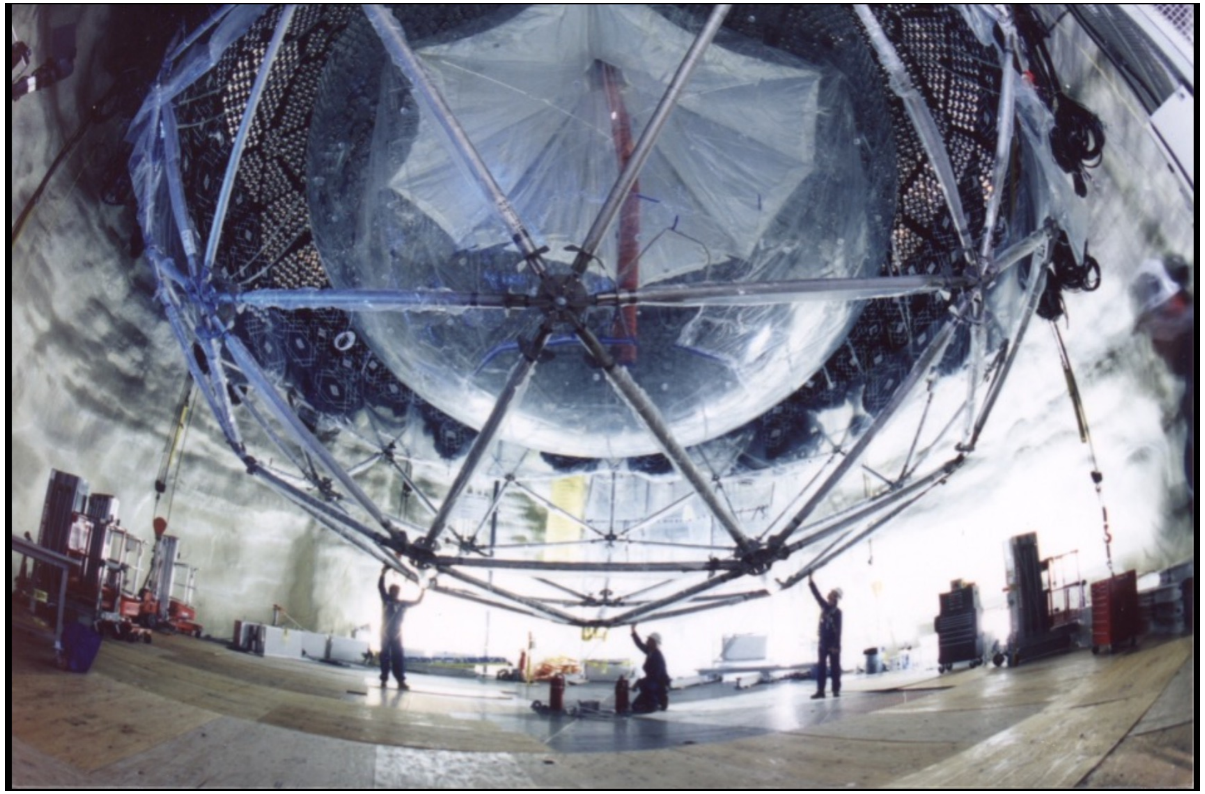


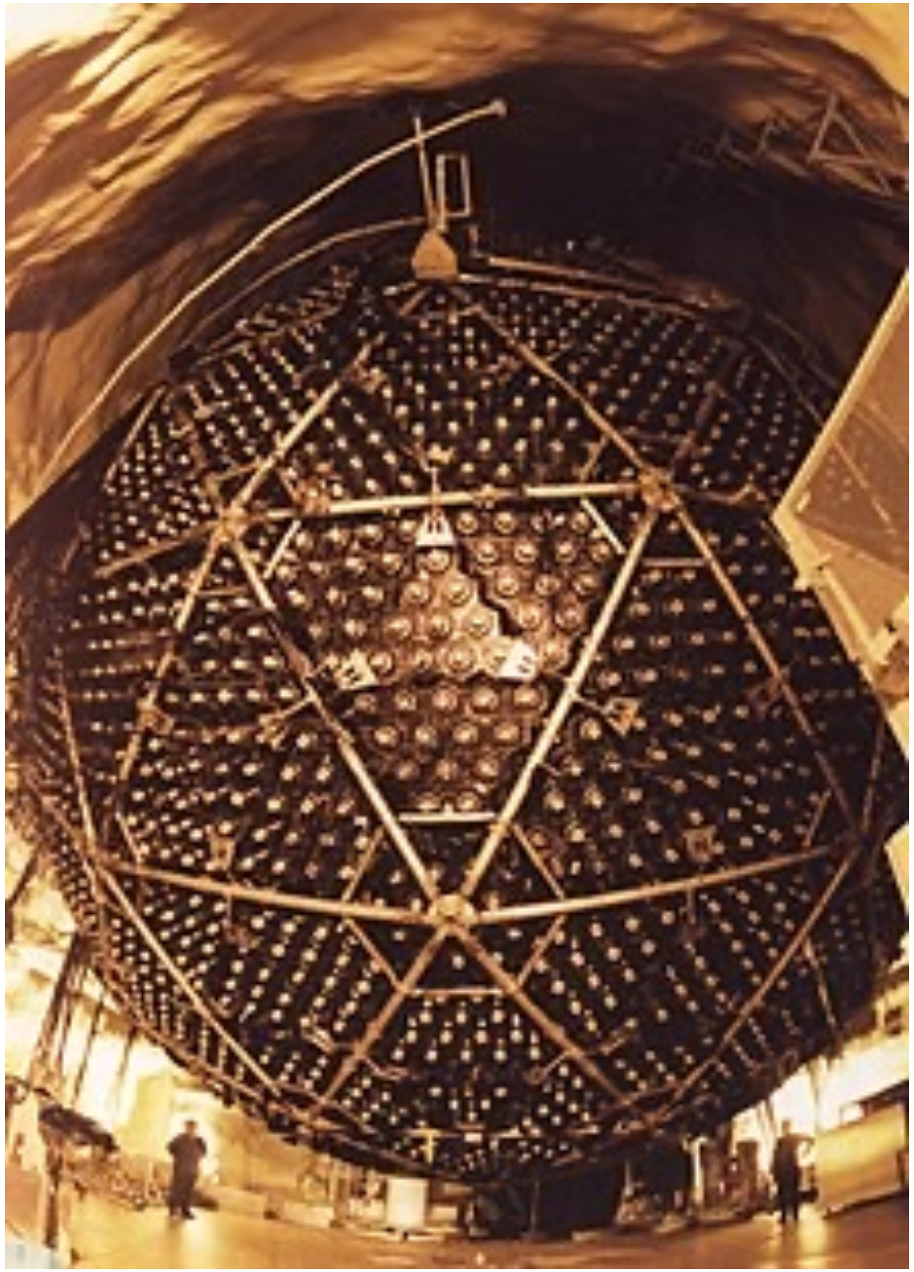
The charged current (CC) reaction measures the $\boldsymbol{\nu}_e$ flux

the neutral current one (NC) the ($\boldsymbol{\nu}_e + \boldsymbol{\nu}_\mu + \boldsymbol{\nu}_\tau$,) flux

34 m height
2000 m deep

SNO detector





$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$$

30% of solar neutrinos (ν_e) are detected as ν_e

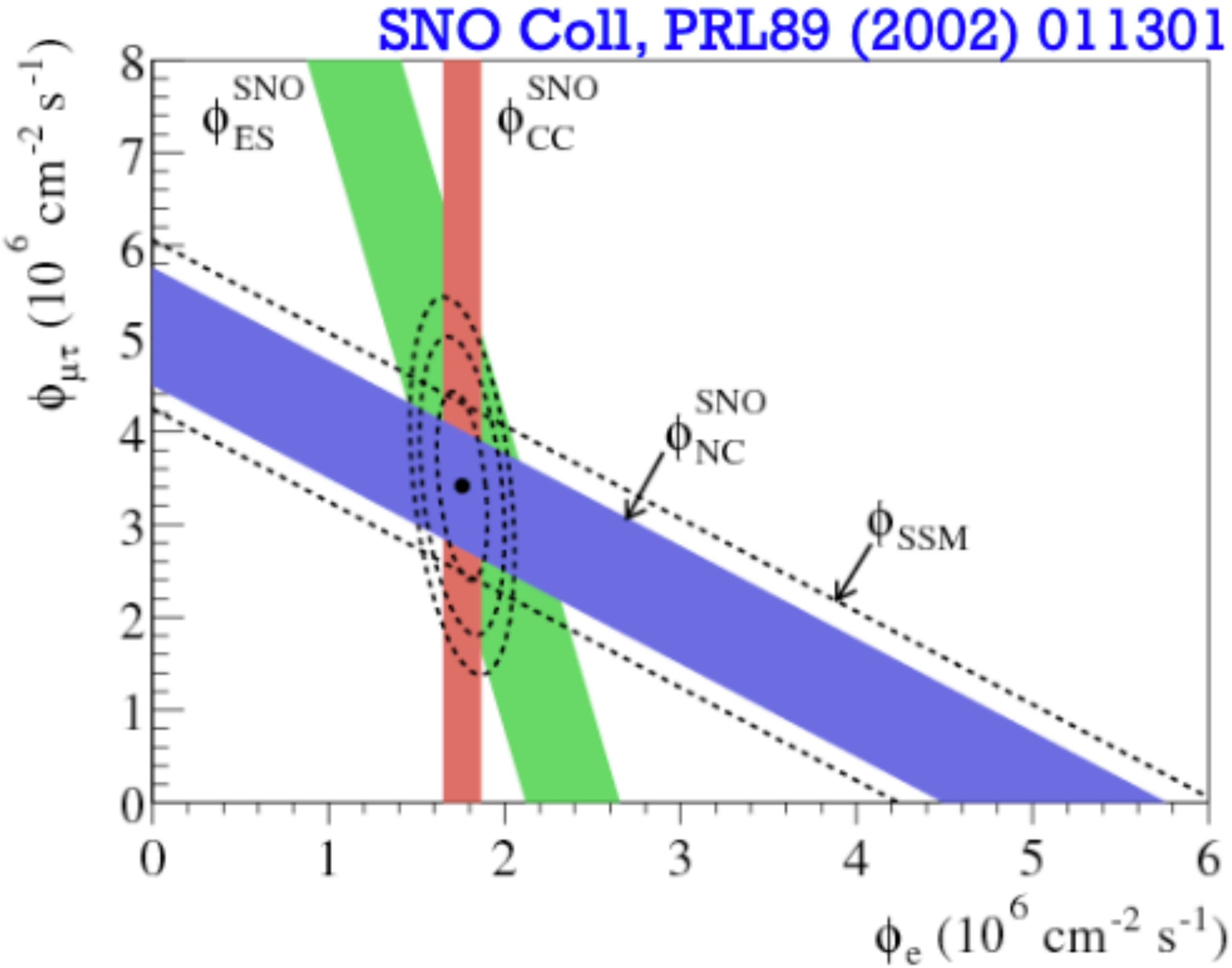
$$\phi_{NC}^{SNO} \simeq \phi_{^8B}^{SSM}$$

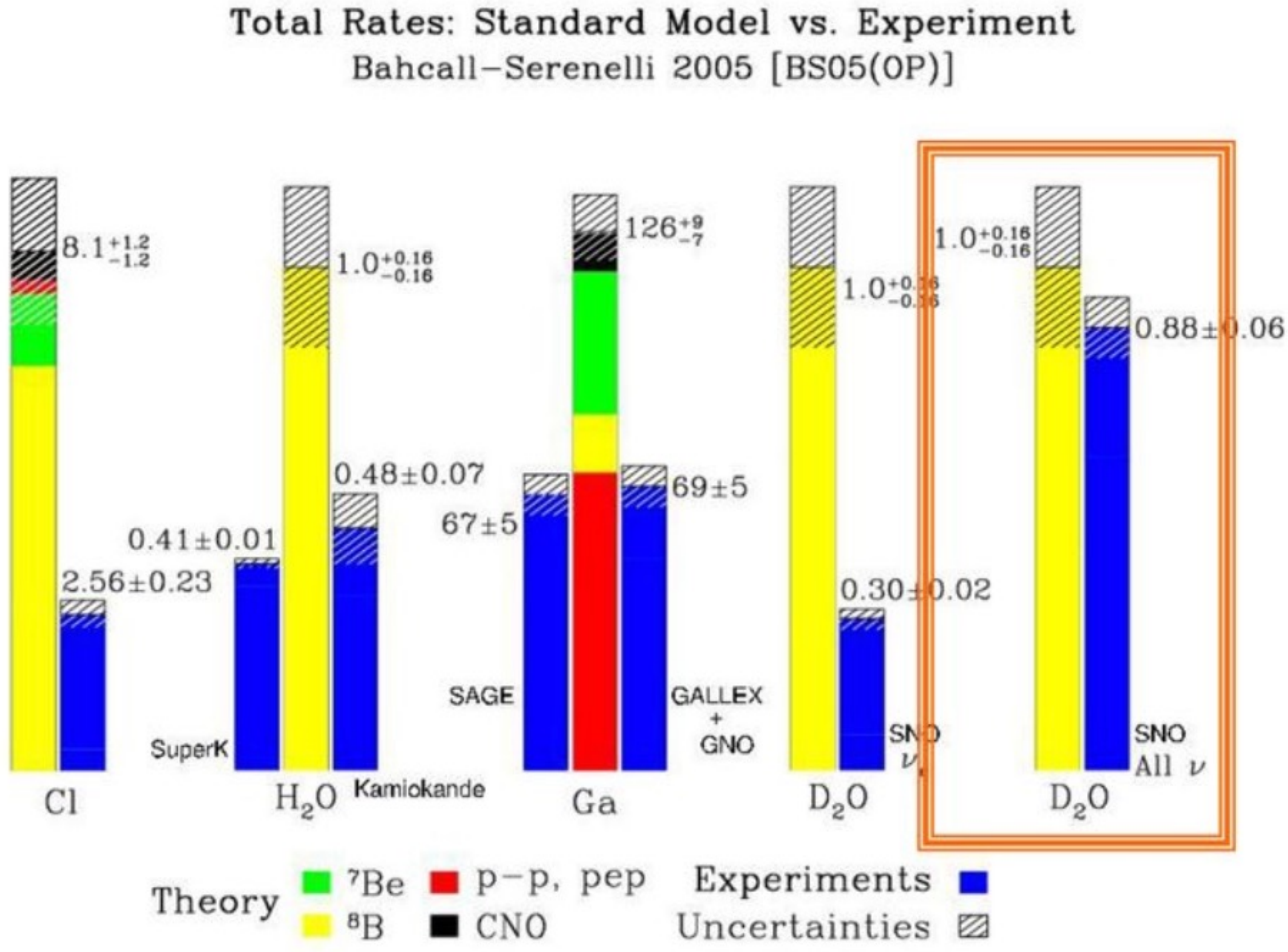
The total flux of solar neutrinos is well predicted

CC : e-neutrinos only

NC : all neutrinos species

SNO Coll, PRL89 (2002) 011301



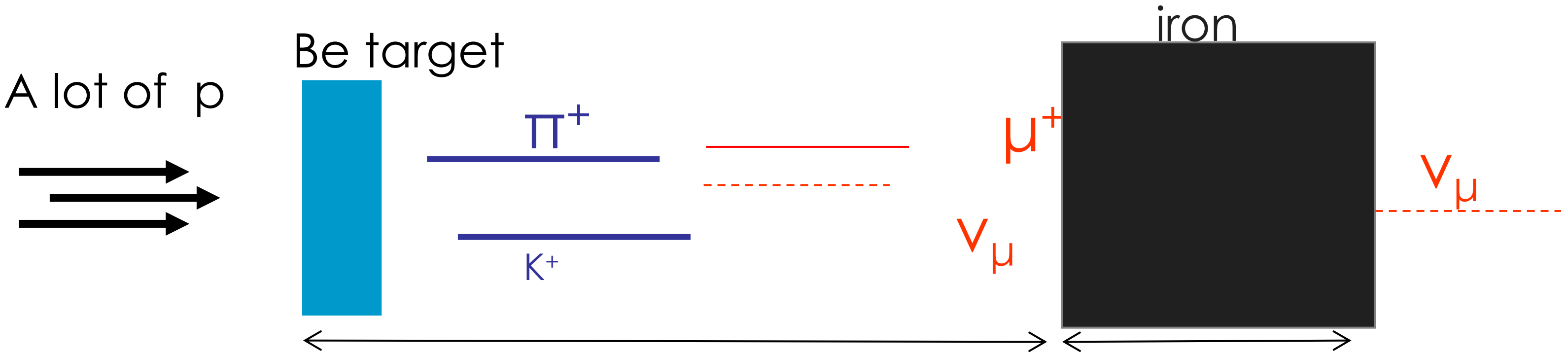


Total Rates: Standard Model vs. Experiment
Bahcall–Serenelli 2005 [BS05(OP)]

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{atmospheric, beam}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13}\end{pmatrix}}_{\text{reactor, beam}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{solar, reactor}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Many MANY experiments … with very different sources of neutrinos:

- reactors : remember the neutrino discovery ?
- accelerators



A lot of p

Be target

π^+

K^+

μ^+

ν_μ

iron

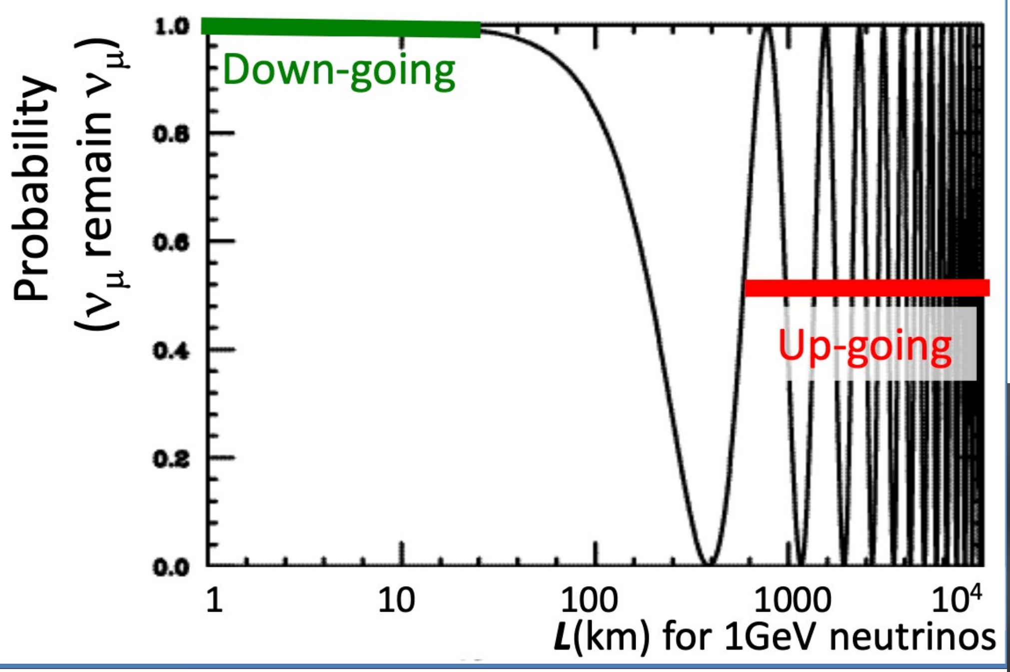
ν_μ

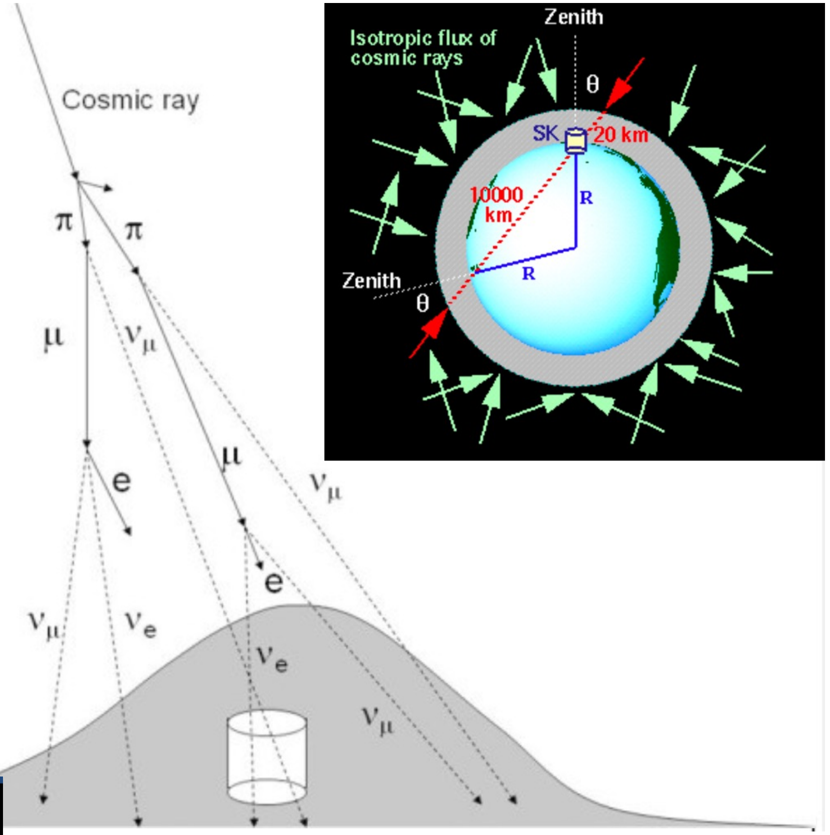
Can also select π^- → anti-neutrino beam

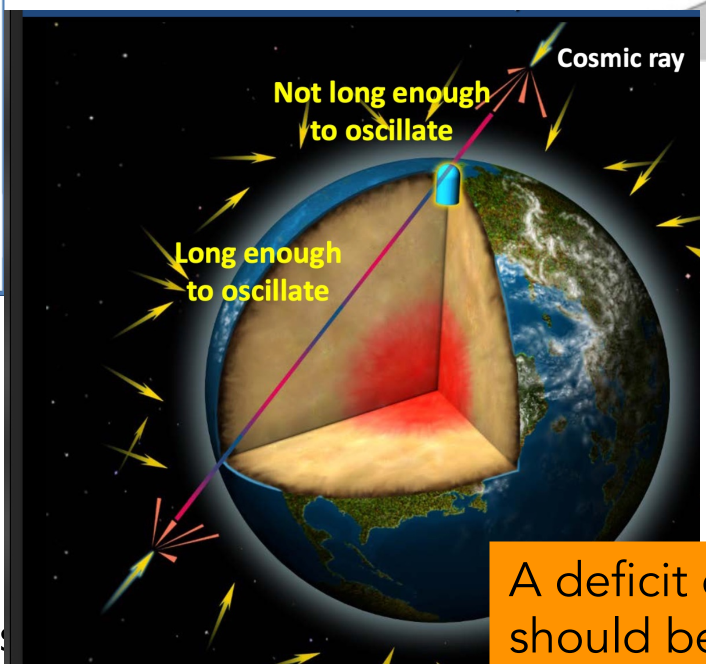
Atmospheric neutrinos

- → $\nu_\mu/\nu_e \simeq 2$, below 1 GeV
- → $\nu_\mu/\nu_e > 2$, above 1 GeV

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

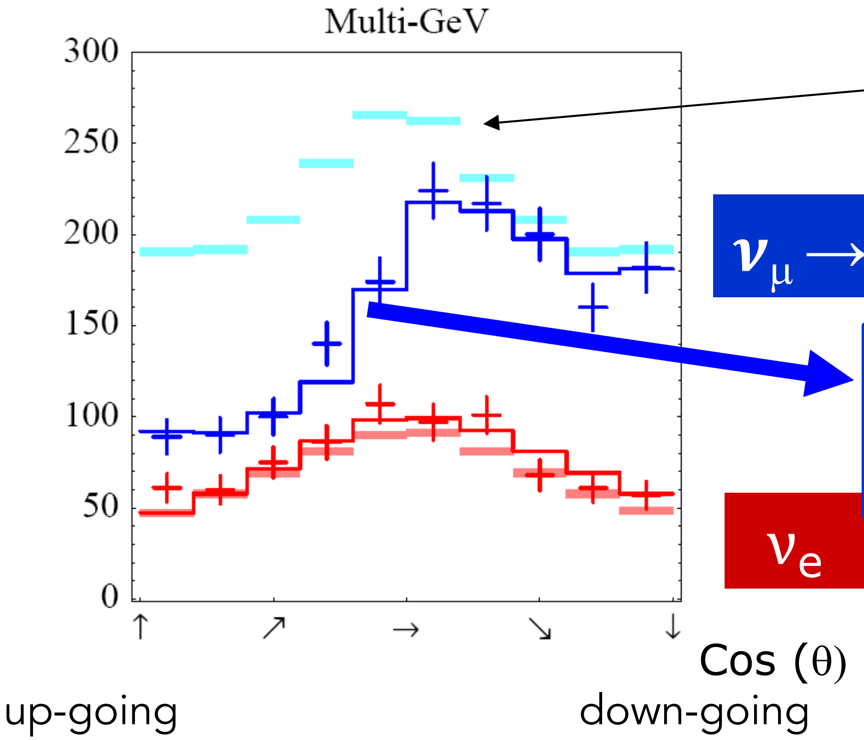






Different L
Different E
3 flavours of neutrinos
Matter effects
.....

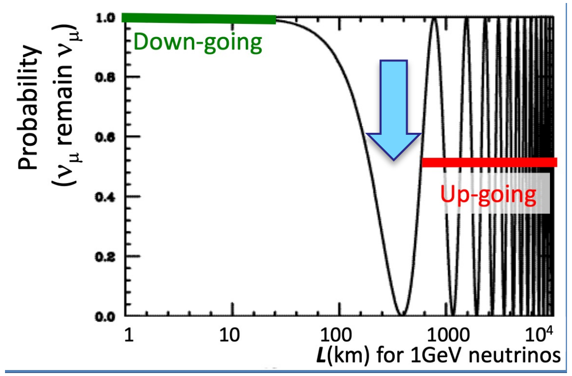
A deficit of up-going ν_μ should be observed

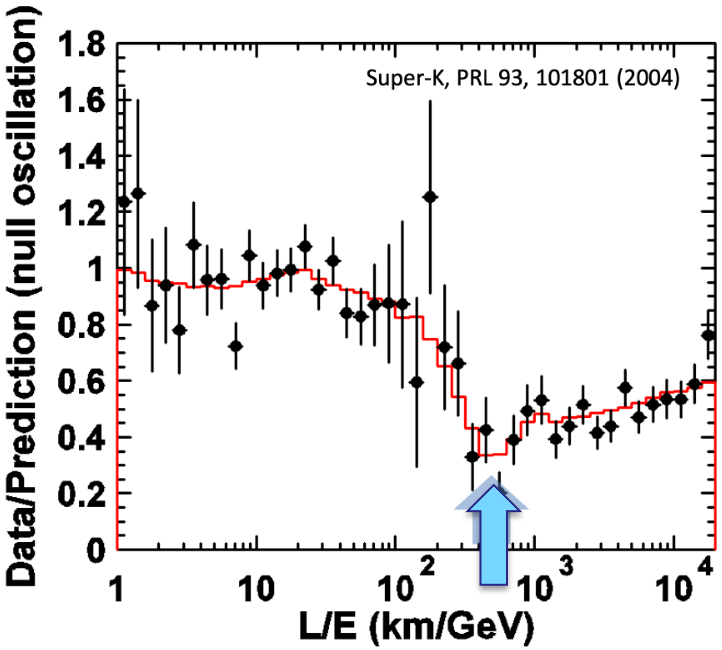


No oscillation

$$\left(\frac{N_{UP}-N_{DOWN}}{N_{UP}+N_{DOWN}}\right)_{\mu\text{-like}} = -0.303 \pm \underset{\text{stat.}}{0.030} \pm \underset{\text{sys.}}{0.004}$$

> 10σ deviation!





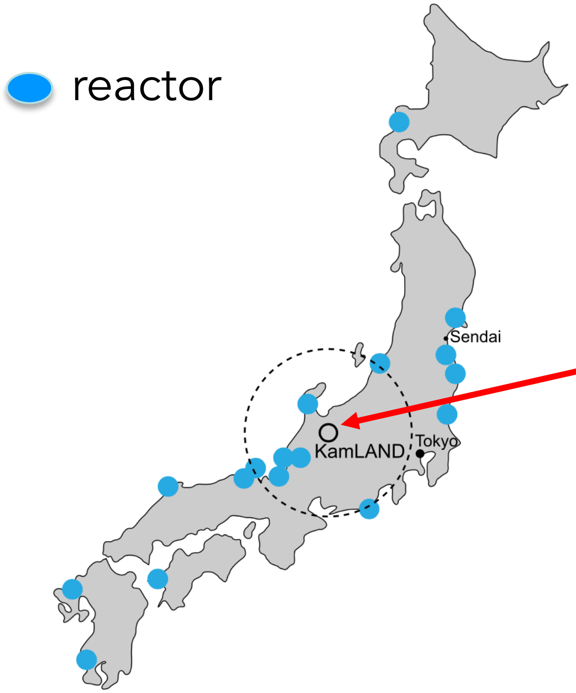
Zenith dependence

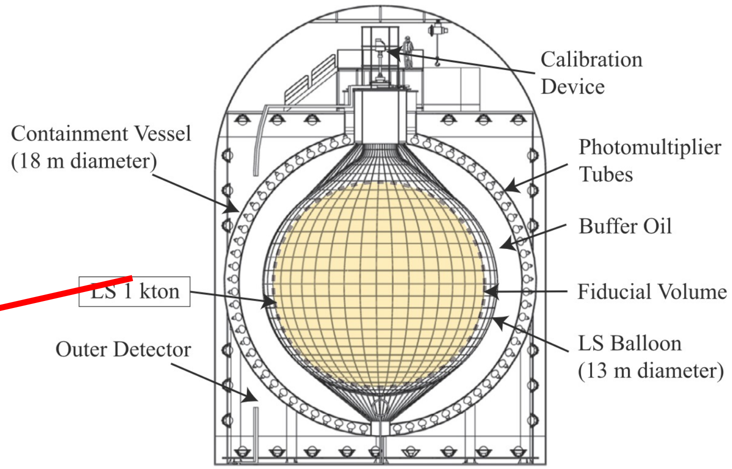
→ ν_μ (but not ν_ε) produced in the atmosphere are also disappearing

→ The effect depends on the zenith angle, that is on the neutrino path length, between production and detection and on the energy

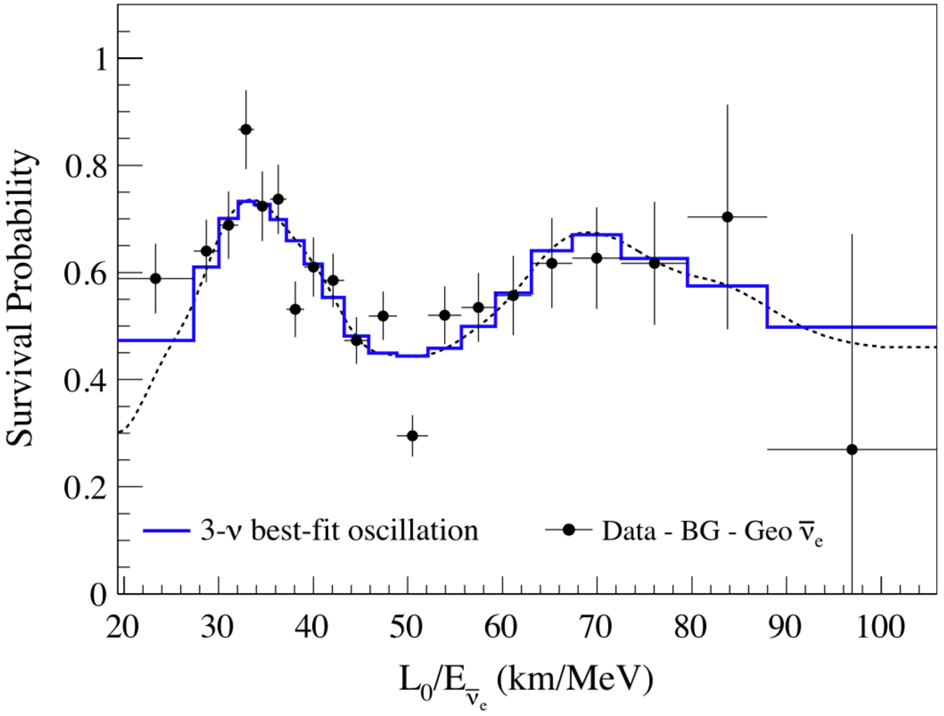
The reactor neutrino : KamLAND results

(as suggested by Stephane)

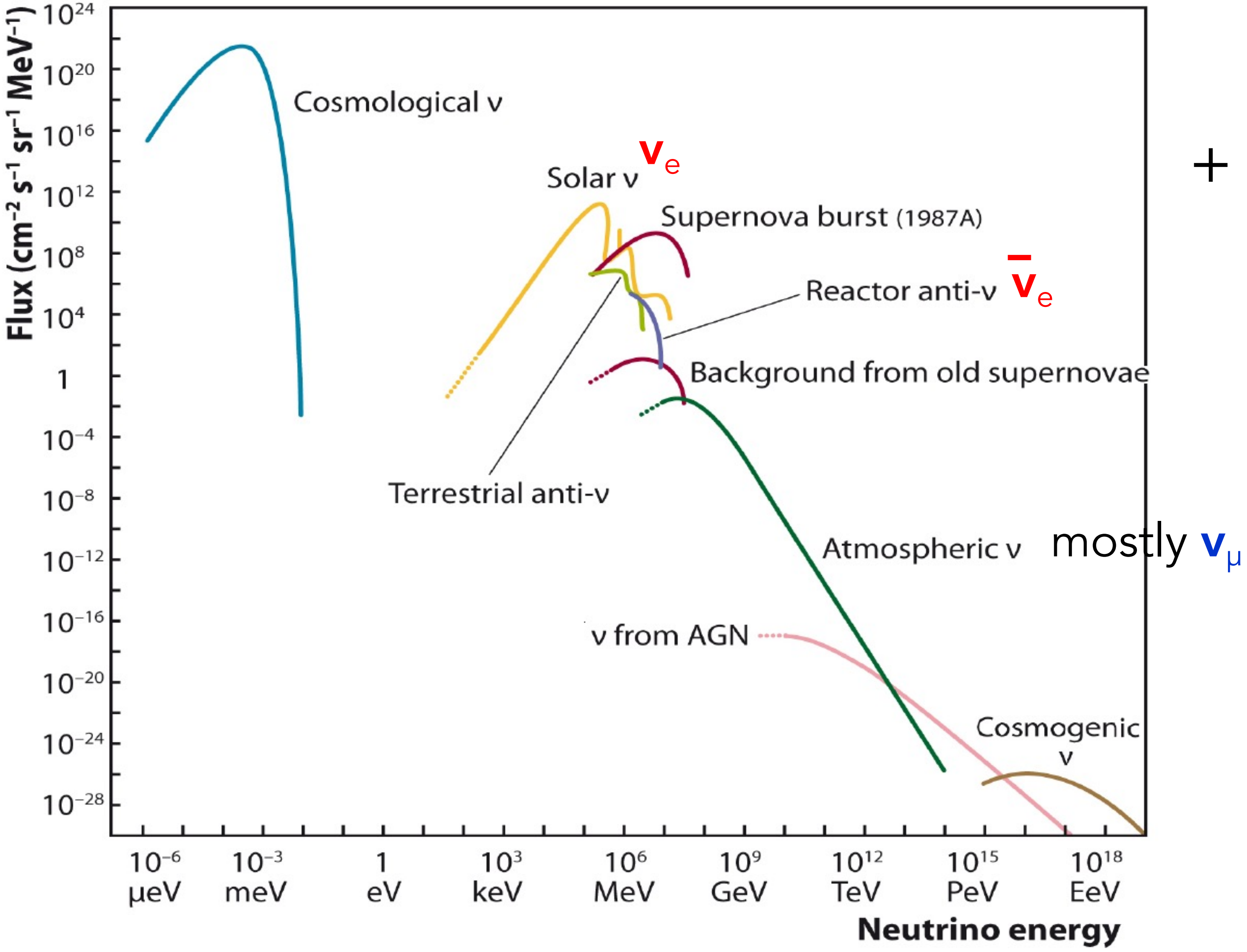




The oscillating aspect of the process is measured !



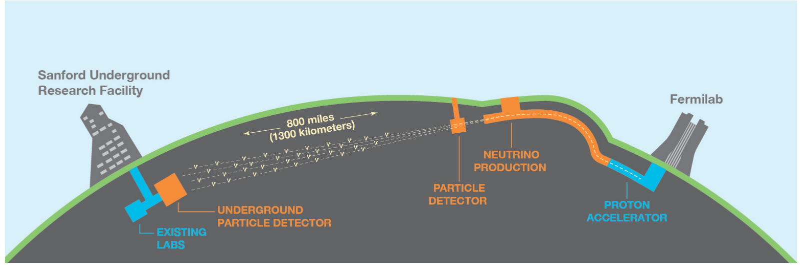
Measurements of Mixing (θ_{ij}) and mass differences (Δm^2_{ij})

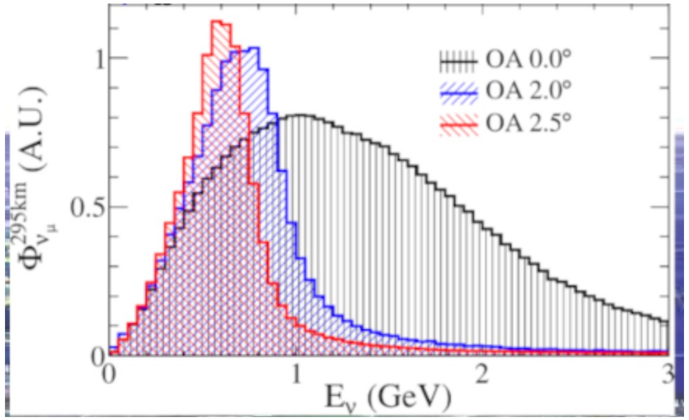


\+ accelerators: mostly ν_μ and $\bar{\nu}_\mu$

control of L/E choice of ν or $\bar{\nu}$

Eg DUNE : E ~ few GeV L ~ 1300 km





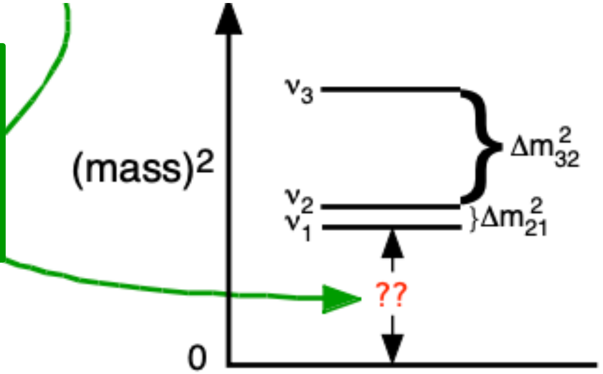
Comments

If all $m_i=0$ then Prob($\nu_\alpha \rightarrow \nu_\beta$) = $\delta_{\alpha\beta}$ Flavour change→ neutrinos have masses

If there is no mixing ($U_{\alpha i}U_{\beta\neq\alpha,l} = 0$) then Prob($\nu_\alpha \rightarrow \nu_\beta$) = $\delta_{\alpha\beta}$

Flavour change→ mixing

Oscillation experiments cannot tell us (may be not fully true due to matter effects …)



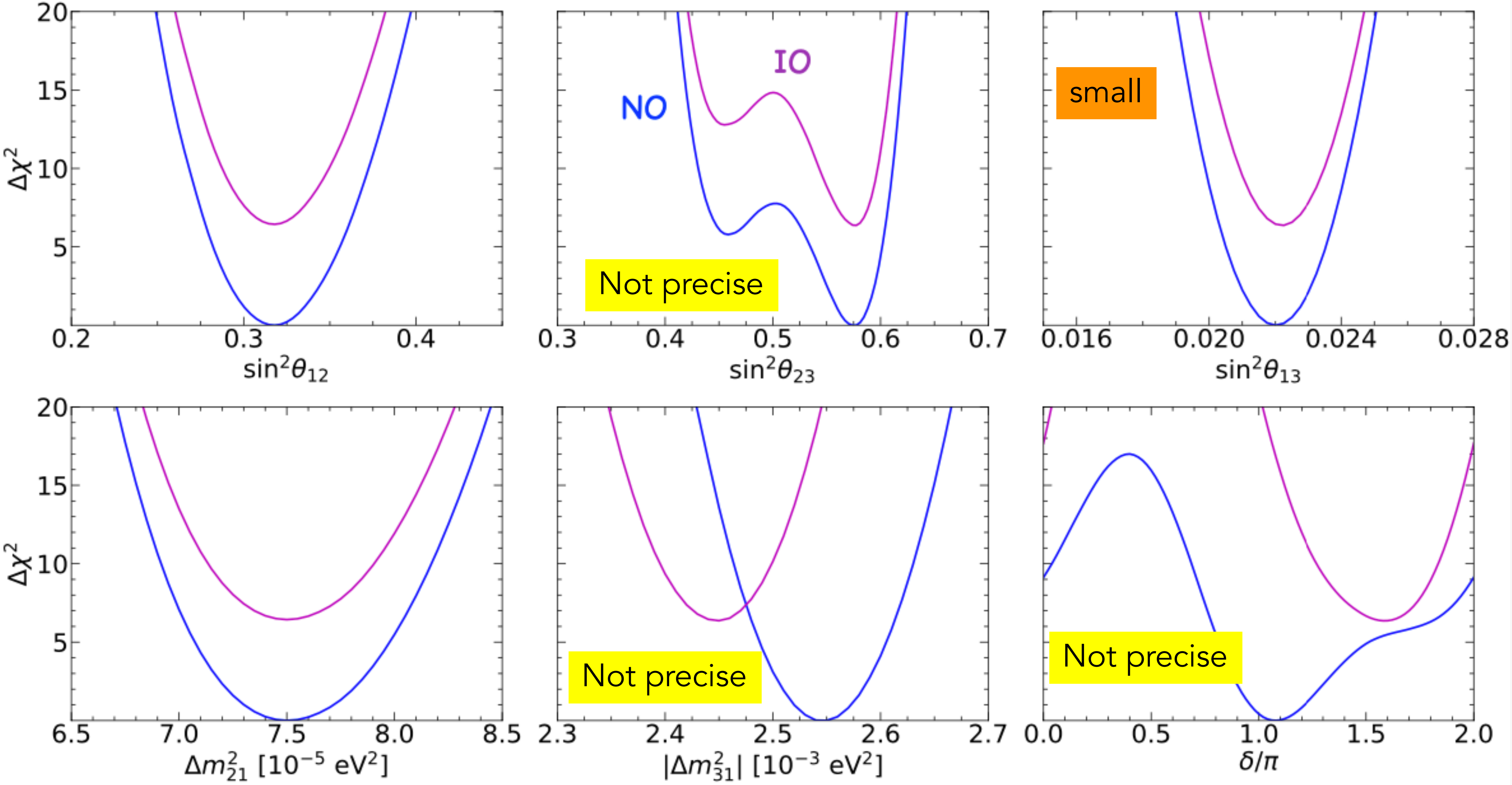
Total neutrino flux does not change, it gets redistributed among the flavours

$$\sum_{\text{All }\alpha} P(\nu_\alpha \rightarrow \nu_\beta) = 1 \qquad \sum_{\text{All }\alpha} P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = 1$$

One example of a global fit

Matter effects are taken into account

de Salas et al, JHEP 02 (2021) 071[arXiv:2006.11237]



$$|V_{\mathrm{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

$$J_{CP}^{PMNS} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

$$J_{CP}^{CKM} \sim 3\ 10^{-5}\ |\sin\delta_{CP}^{CKM}\ \ |$$

$$J_{CP}^{PMNS} \sim 0.03\sin\delta_{CP}$$

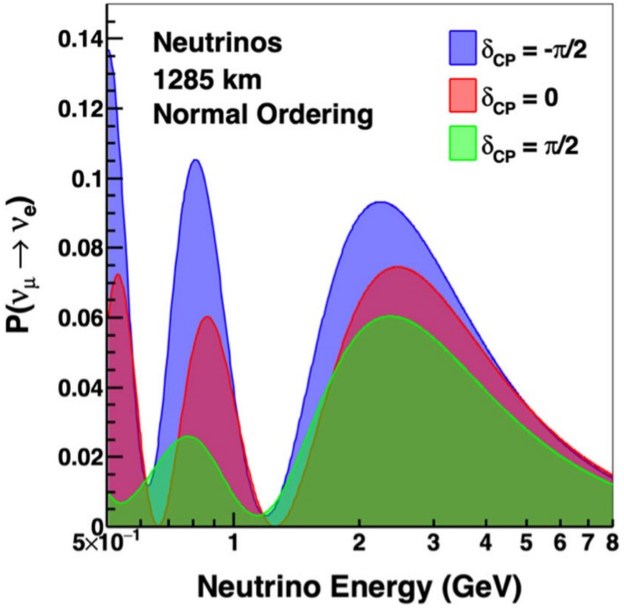
$$\delta_{CP}^{CKM} \sim 65°$$

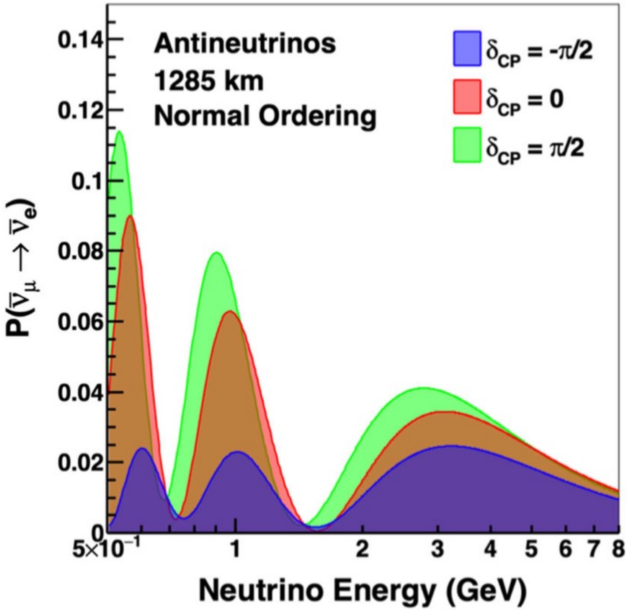
CP violation potentially large

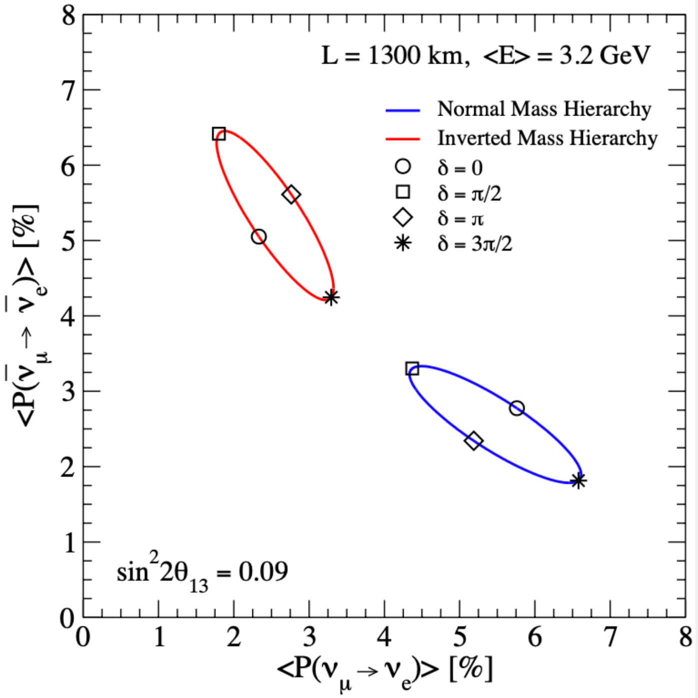
As you have seen in Alexander Korchin's lecture it may be a way to matter antimatter asymmetry in the Universe (leptogenesis)

CP violation

L = 1300 km = DUNE







Differences between **v** and **v** oscillations: CP violation … and matter effect !
But different dependences on L and E

→ **access to the mass hierarchy**
→ and can to be **disentangled from the δ_{CP} contribution** thanks to the distance