# Neutrinos

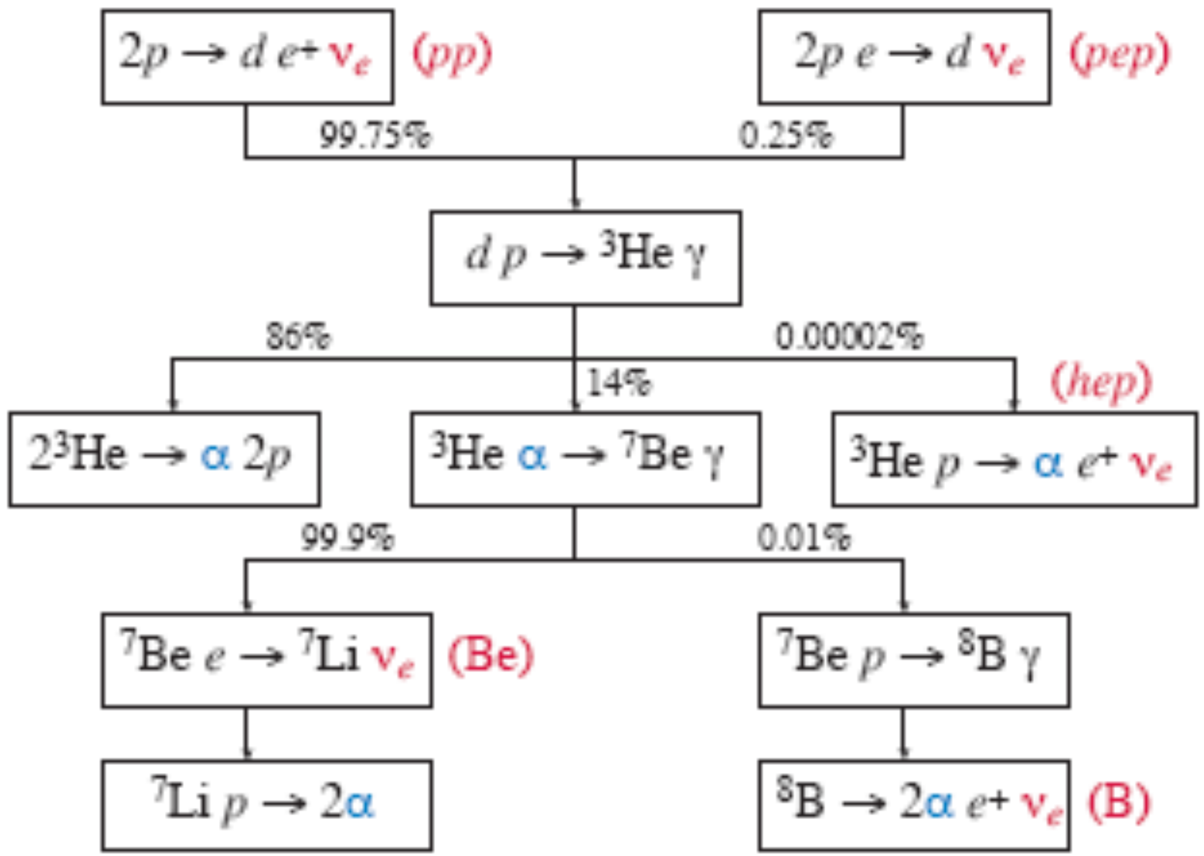
- Solar neutrinos problem
- Atmospheric neutrinos
- neutrinos oscillation
-

# What is the “fuel” of the Sun?

- Ancient Egyptian: the Sun is a fire ball
- Anassagora: the Sun is made of incandescent iron
- 1850: J.Waterstone shows that “chemical energy” (combustion) could substain the Sun for 10 thousand years only (stone age).
  Another fuel was needed: gravity force, but not enough meteora around.
- 1860: Lord Kelvin. Sun contraction under the gravity force. Sun could at the best be 100 milion years old.
- He discredits the Darwin theory that needs more time.
- 1897: radioactivity discovery. It could provide enough energy, but in the Sun there are not heavy elements, since it is made mainly by hydrogen and helium.
- 1920: Eddington. It is burnt hydrogen to produce helium.
- 1938: Bethe. Quantitative theory of the fusion processes inside the Sun.
- 1960: John Bahcall. Standard Solar Model.

# Bethe: the Sun “burns” hidrogen

pp cycle




In the center of the sun

$4p + 2e^- \rightarrow {}^4He + 2\nu_e$

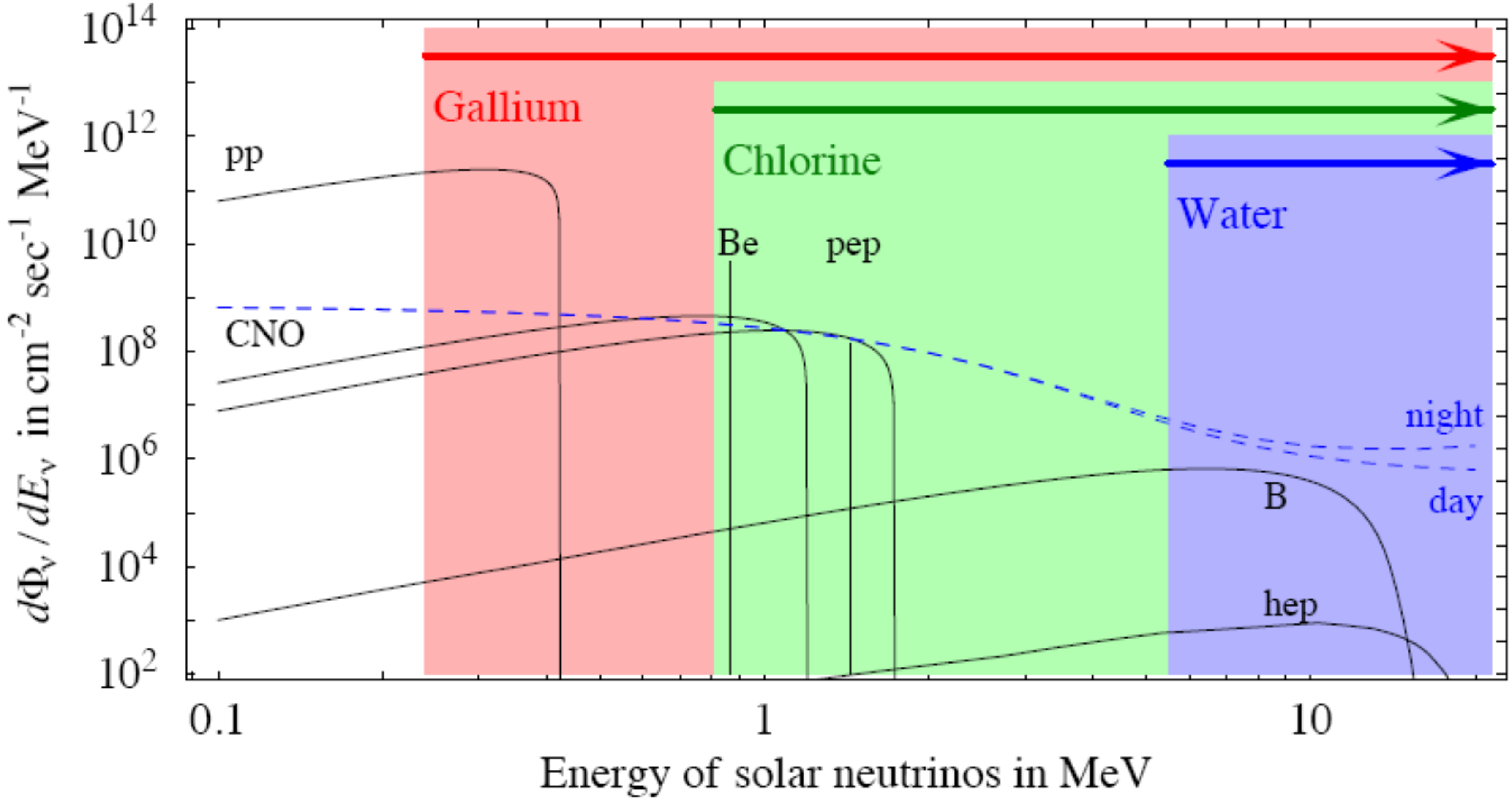
Q=26.73 MeV

$\langle E_\nu \rangle \approx 0.3$ MeV

Solar $\Phi(\nu) \approx 6 \cdot 10^{10}\ \nu/cm^2 s$

CNO cycle is important in the older star

# Solar neutrino spectrum



# How detect neutrinos?

- From an idea of Bruno Pontecorvo in 1946. Use the reaction:

$\nu_e + Cl = Ar + e^-$

Threshold energy: 860 KeV

Radioactive with half-time of 35 days

- Ray Davis in 1955 looked for this reaction in the nuclear reactor of Savannah River in South Carolina, but he found NOTHING (why?).
- In 1956 Reines and Cowan discovered the antineutrino in the same reactor.
- In 1959 Davis started to look for the solar neutrinos produced by the $^7Be$ and John Bahcall started his calculation on the expected neutrino flux.
- 1965: began the work at the Homestake mine to install 400 $m^3$ of chlorine (cleaning liquid).
- 1966: data taking started.
- 1968: they found less neutrinos than expected. Wrong computation?

# How many neutrinos?

- J. Bahcall : $\Phi(\nu_e) = 6.6 \cdot 10^{10}\ cm^{-2}s^{-1}$
- Neutrinos from $Be^7$: flux reduced by a factor $10^4$.
- Solar Neutrino Unit: 1 $\nu_e$ capture pe second per $10^{36}$ target atoms

$$SNU = 10^{-36}\ \text{capture/atom/second}$$

Davis & Bahcall

- Bahcall calculation: 7.5 ±3 SNU
- Davis measurement (1968): 3 SNU

- Good News: Davis had seen for the first time the solar neutrinos.

- Bad News: the measured rate was half of the expected one.

- 1968. Pontecorvo: speculation about neutrino oscillation.

# Other radiochemical experiments

Low threshold radio-chemical counting experiments

$\nu_e + (A,Z) \rightarrow (A,Z+1) + e^-$ with $(A,Z+1)$ unstable, lifetime of some weks

largest possible target mass : tens of tons to 100 tons (GNO)

event rate $\approx$ 1 event/day

buried under mountains or in deep mines : reduce cosmic muons to some tens / day

extract 10-20 atoms of $(A,Z+1)$ every some weeks and count thedecays

extraction efficiency > 99% calibrated with $\nu$ source ($^{51}Cr$, 1.8 MCi !!!)

The glorious Homestake exp$^t$ (1968-99) 31 years of datataking, 2000 int.$^{ions}$

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \qquad \tau_{^{37}Ar} \approx 50 \text{ days}$$

$$E_{\nu Be} = 0.861 \text{ MeV} > E_{thresh} = 0.813 \text{ MeV} > E^{max}_{\nu pp} = 0.423 \text{ MeV}$$

Prime importance given the $\nu_{Be} - \nu_B$ strong correlation

Gallium experiments : GALLEX, GNO (under Gran Sasso) , SAGE (Baksan mine)
1992-97 1998- 1991-

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^- \qquad \tau_{^{71}Ge} \approx 24 \text{ days}$$

$$E_{thresh} = 0.233 \text{ MeV} < E^{max}_{\nu pp} = 0.423 \text{ MeV}$$

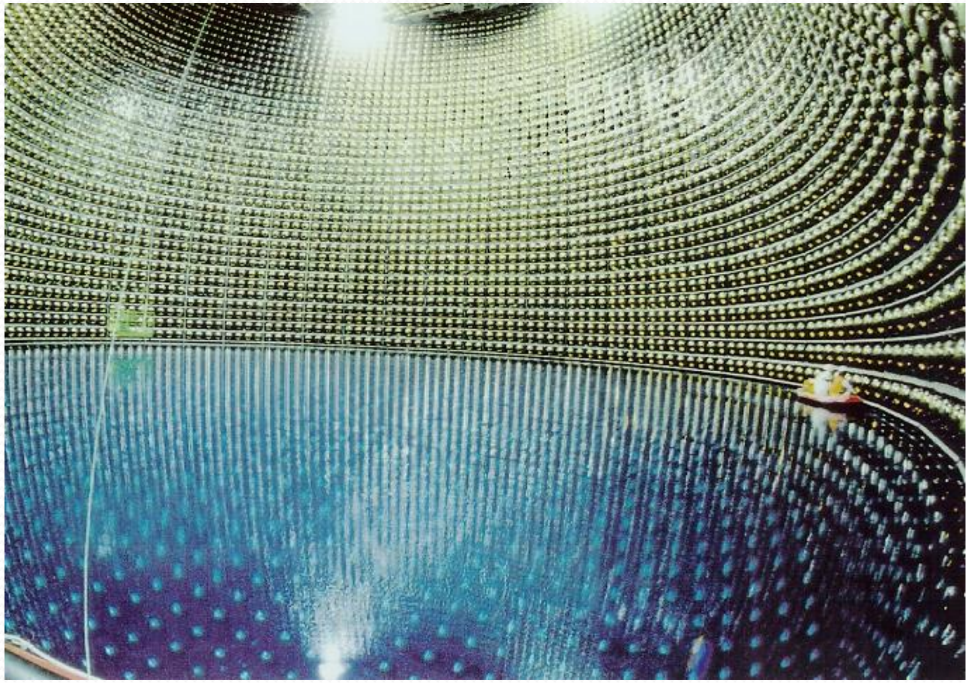
Prime inportance to measure the bulk of the flux

# 1986: Kamiokande Detector

At the of 1986 started to take data the Kamiokande experiment (Kamioca Nucleon Decay Experiment), located in the Kamioka mine, in Japan.

In USA started to function the IMB experiment.

The signal is given by the Cherenkov light produced by the electrons or muons, read by photomultipliers.



Kamiokande was able to see the neutrinos produced in the supernova explosion in the Large Magellanic Cloud on 23/2/2987.

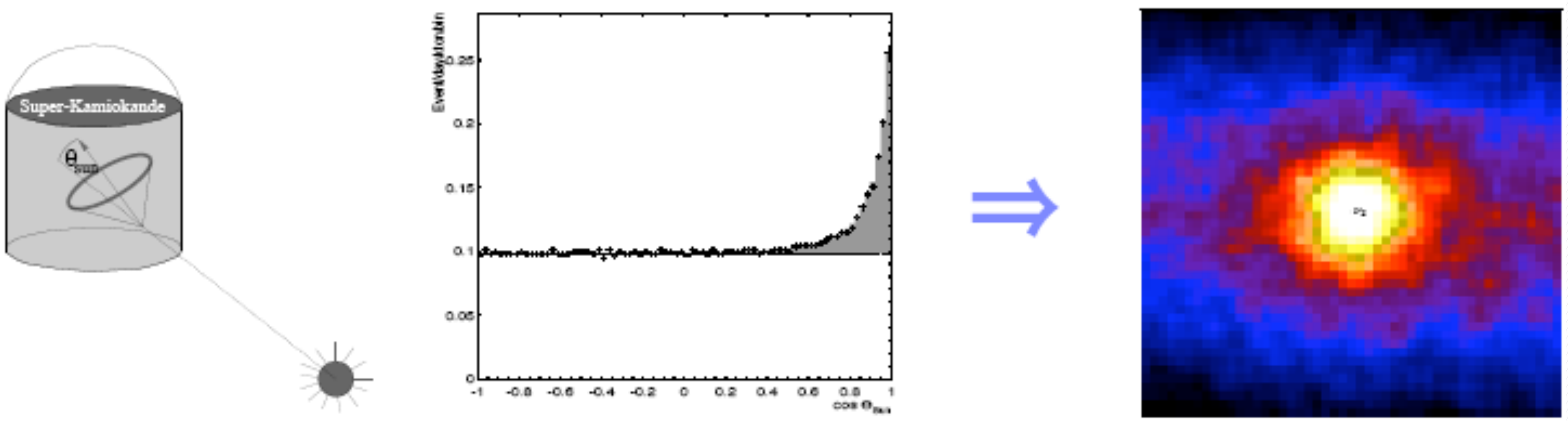
Kamiokande is able to record the neutrino interaction in real time and to measure the neutrino direction and its energy.

It was found an ANOMALY in the atmosferic neutrinos.

# “the Sun neutrinography”

- The photons produced in the core of the Sun take about one milion years to arrive to the surface. As far as we know the Sun could be off!

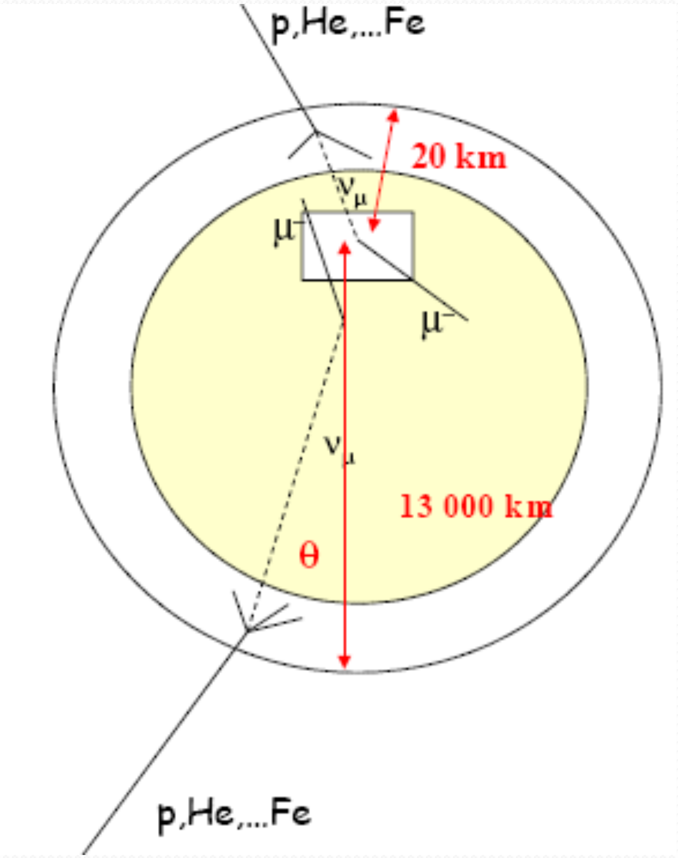
- With the neutrons we can observe the Sun “istantaneously”.

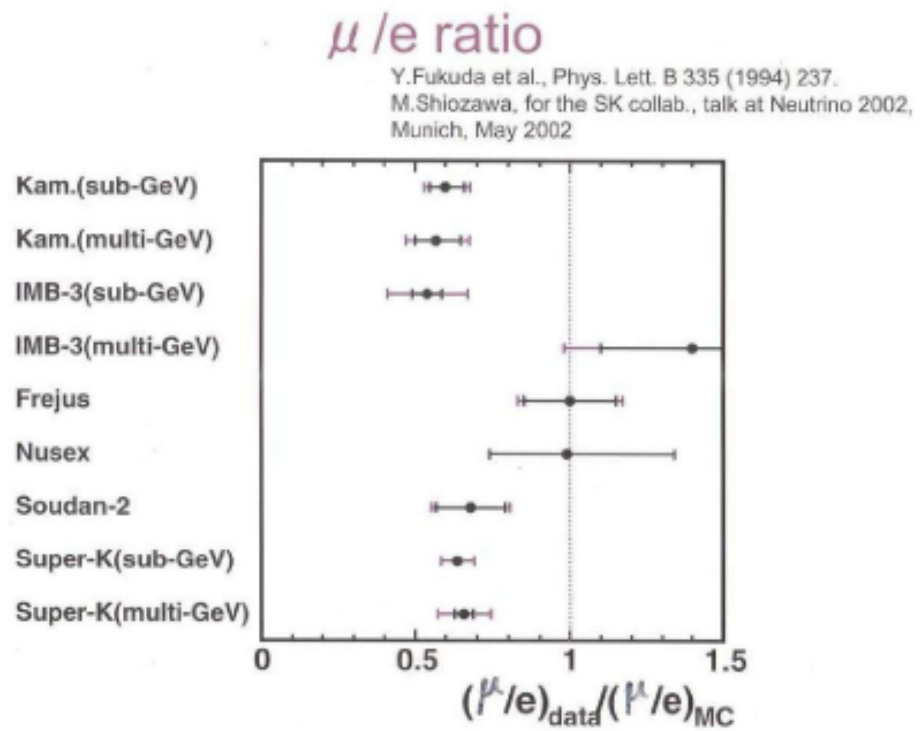


# Production of atmosheric neutrinos

$$\pi \rightarrow \nu_\mu \; \mu$$
$$\searrow e \; \nu_\mu \; \nu_e$$

$$R = \frac{\Phi(\nu_\mu)}{\Phi(\nu_e)} \approx 2$$




We have a deficit on muon neutrinos

The deficit is higher for the neutrinos passing through the Earth

# Where are going the neutrinos?

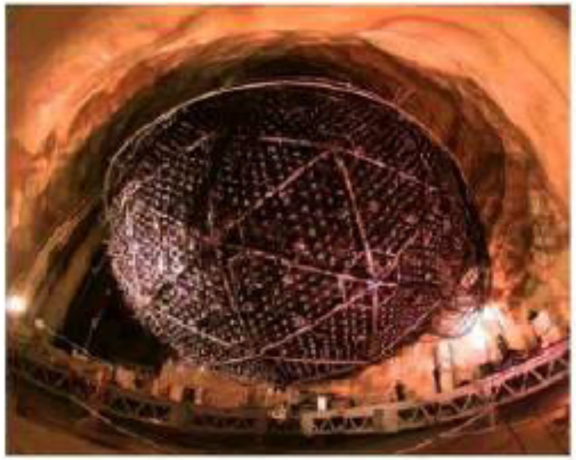
Hypothesis: they oscillate in another type that does not produce a signal in the detector. We need a “smoking gun” to confirm the hypothesis: the SNO detector

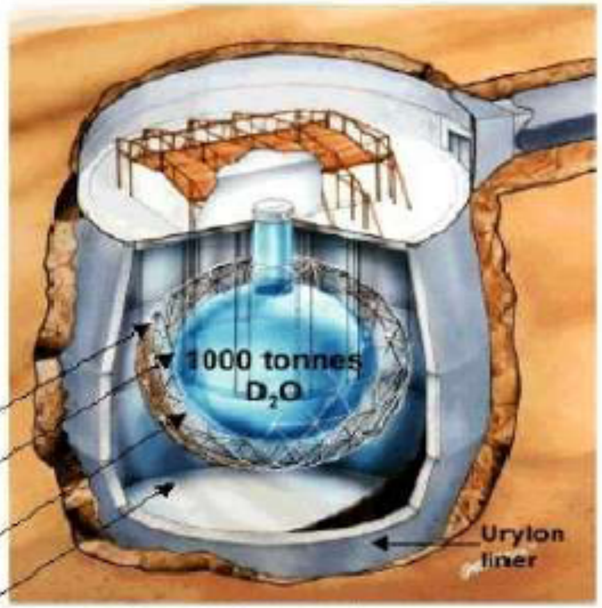
Real-time heavy-water Cerenkov experiment : Sudbury Neutrino Observatory (SNO) (2001-2003)

1 kton of highly purified heavy water seen by ~ 9 500 PM tubes

7 kton light water shielding and veto

deeply buried at - 1300 m in Creighton mine, Sudbury : 70 cosmic μ / day






Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day$^{-1}$)

Nucl. Inst. and Meth. A449, p172 (2000)

# SNO

??? Why heavy water ???

Elastic scattering (ES) $\nu + e^- \rightarrow \nu + e^-$ directionnal sensitivity

like light water

CC & NC : $\nu_e + e^- \rightarrow \nu_e + e^-$ 86%

NC : $\nu_{\mu\tau} + e^- \rightarrow \nu_{\mu\tau} + e^-$ 14% some sensitivity

Charged current (CC) $\nu_e + d \rightarrow p + p + e^-$ $E_{thesh} = 1.4$ MeV

$E_\nu$ ; $E_e$ $\sigma_E \approx 10 - 15\%$

Neutral current (NC) $\nu + d \rightarrow p + n + \nu$ measures $\nu_B$ total flux

Neutron detection : $\varepsilon$ ~14%

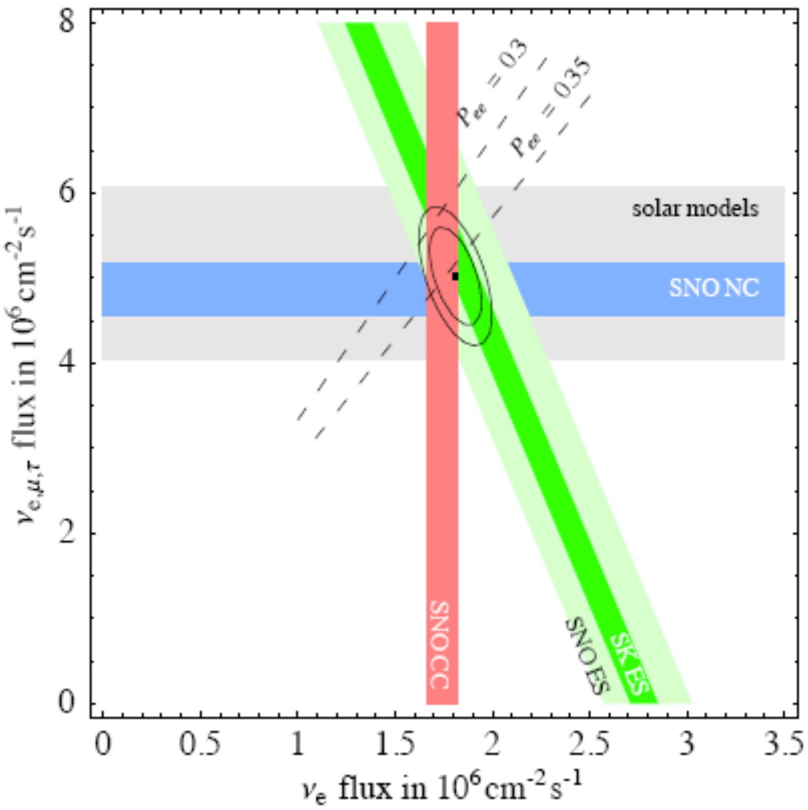
- capture n + d $\rightarrow$ t + 6.5 MeV $\gamma$-ray
- $\gamma$-ray conversion to $e^+$ - $e^-$ pairs: Cerenkovsignal

# SNO: results

- SNO($D_2$0 Cerenkov detector) measure **both charged and total ν flux:**
  - ES: $\nu_{e,\mu,\tau}e \rightarrow \nu_{e,\mu,\tau}e \Rightarrow \Phi(\nu_e) + 0.155\,\Phi(\nu_{\mu,\tau})$
  - CC: $\nu_e D \rightarrow e^- pp \quad \Rightarrow \Phi(\nu_e)$
  - NC: $\nu D \rightarrow \nu pn \quad \Rightarrow \Phi(\nu_{e,\mu,\tau})$

- NC rate as expected from Solar Model

- CC/NC ratio: $$\frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})} = 0.357 \pm 0.030$$

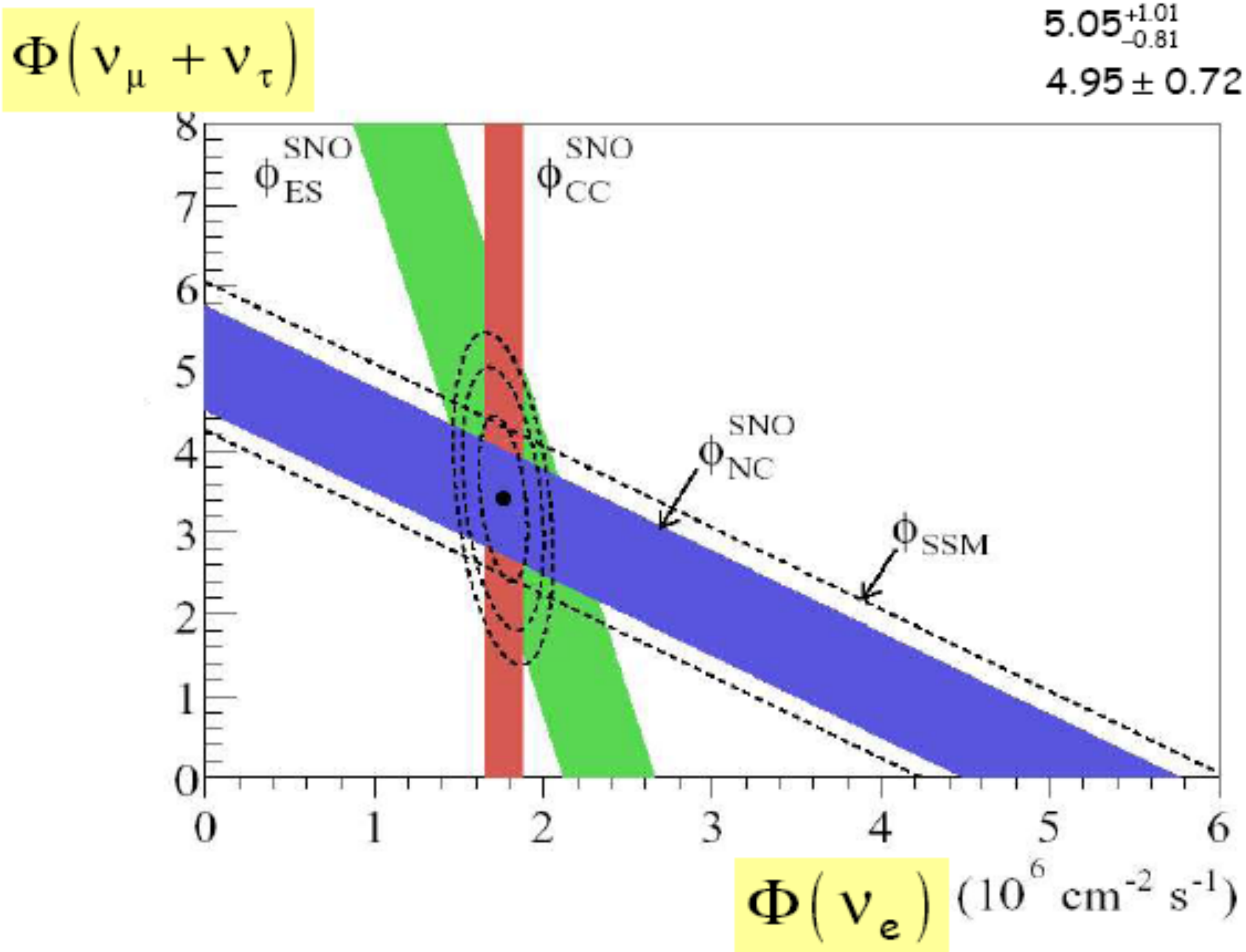


SNO 2002 : evidence for FLAVOR CHANGE

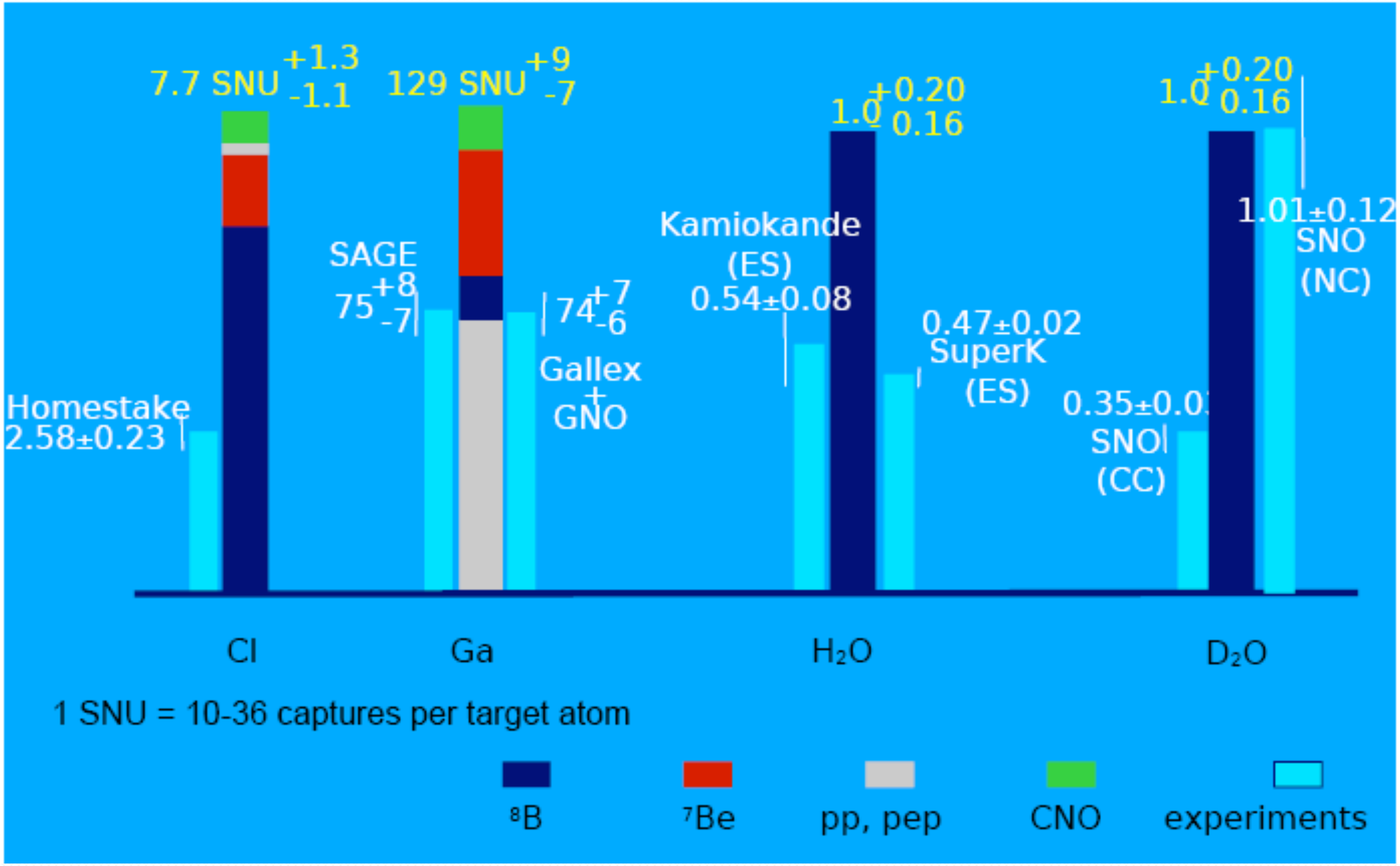
Standard Solar Model :

$5.05^{+1.01}_{-0.81}$ Bahcall et al.

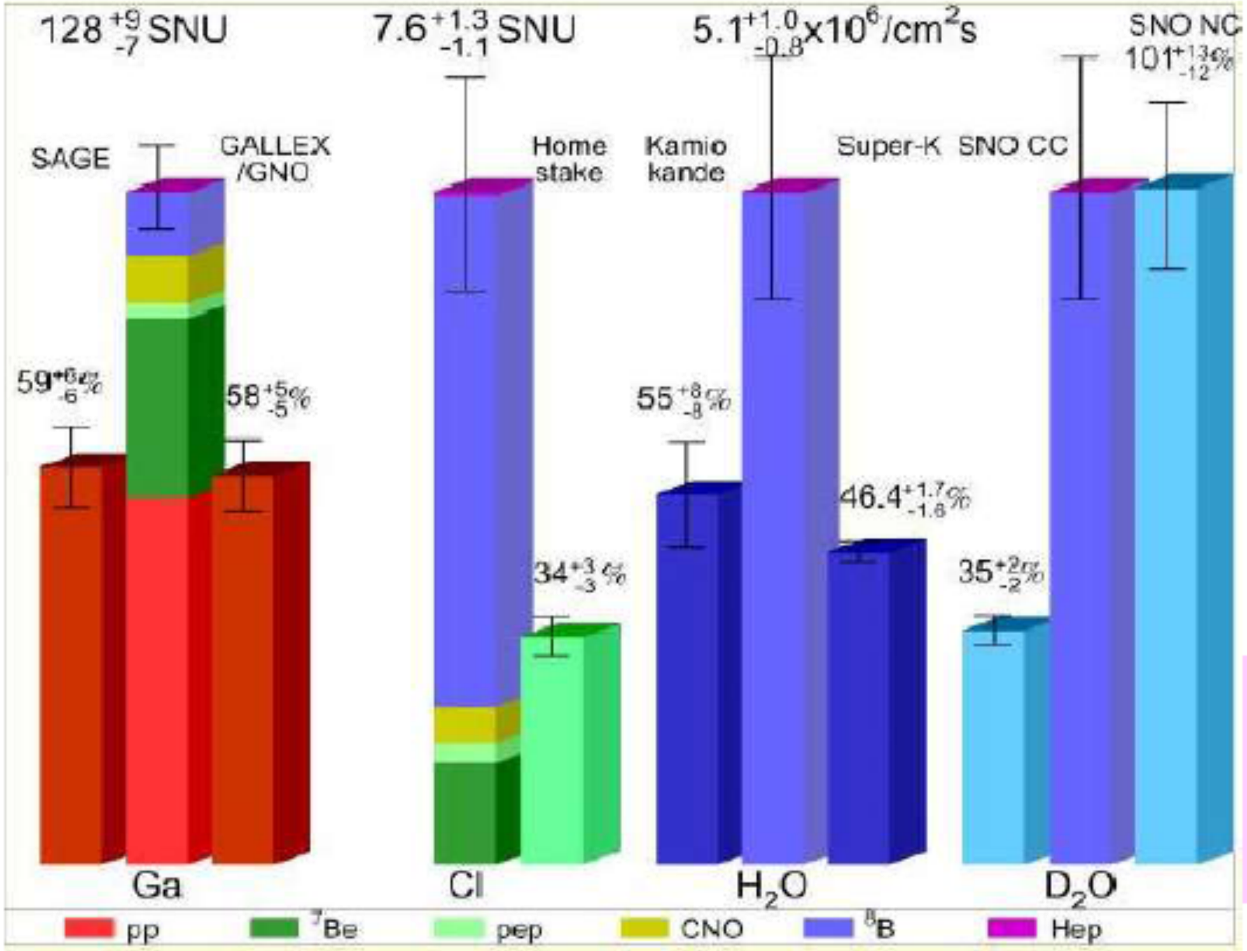
$4.95 \pm 0.72$ Turck-Chieze



# Solar neutrinos: summary



Measured event rates v.z.SSM predictions (Bahcall et al.)



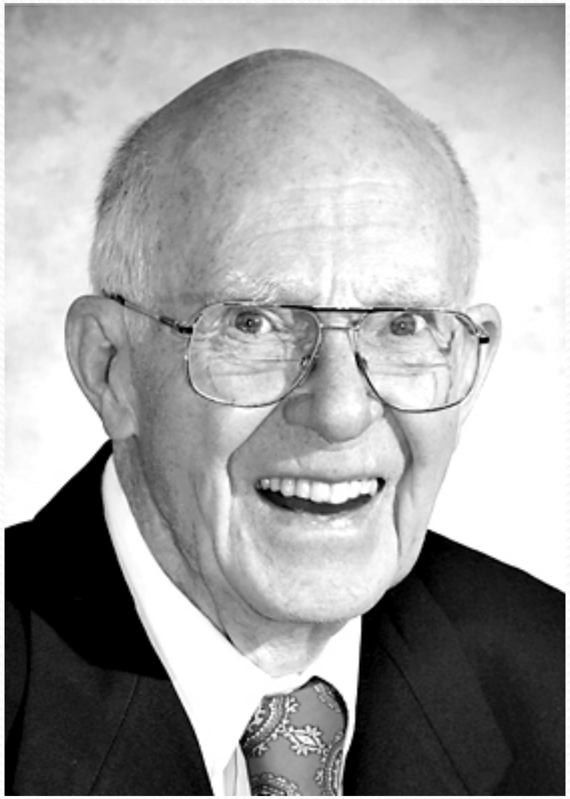

Overall flux deficit :

$0.3 \leq \Phi^{meas} / \Phi^{pred} \leq 0.6$

No astrophysical or instrumental explanation

$\rightarrow \nu_e$ disappearance

# 2002 Nobel Prize



**Raymond Davis Jr.**

**Masatoshi Koshiba**

to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"*

# 2015 Nobel Prize

**Takaaki Kajita**

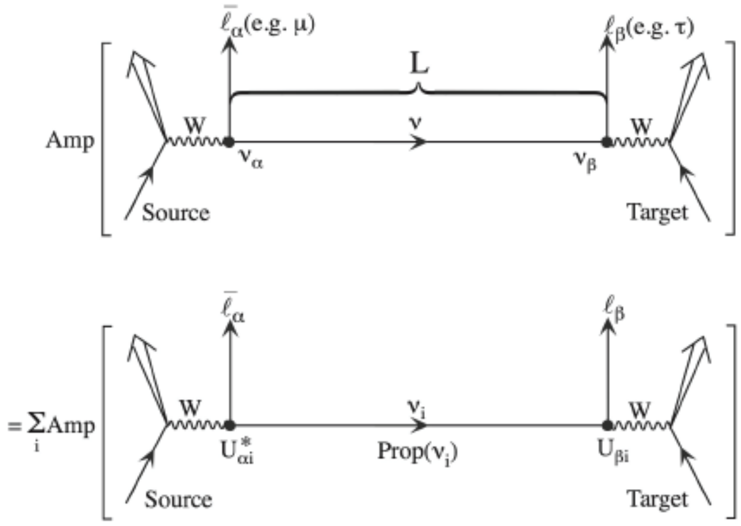
**Arthur B. McDonald**

To Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

# SPECIAL CASE: 2 NEUTRINOS

- Similar to $K^0$-$\bar{K}^0$ mixing: weak eigenstates ≠ strong eigenstates
  - but neutrinos don't decay (no exponential term)
  - always relativistic and tiny mass difference
    - Flavour change in vacuum oscillates with L/E:

      (macroscopic quantum coherence interference)




- Why quarks and charged leptons don't oscillate?

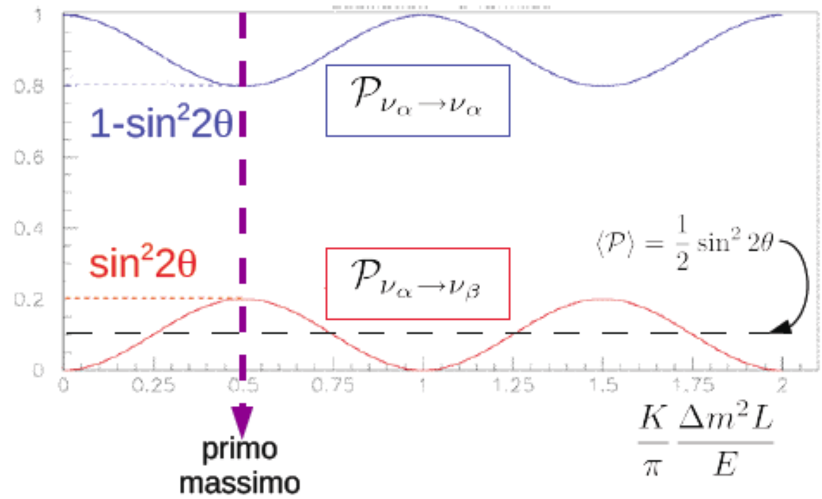
$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \end{array} \begin{array}{c} \begin{array}{cc} \nu_1 & \nu_2 \end{array} \\ \left[ \begin{array}{cc} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{array} \right] \end{array}$$

$$P[\nu_\alpha \to \nu_\beta] = sin^2(2\theta) sin^2(\Delta m^2 L/4E)$$

**no distinction**

**$\theta \Leftrightarrow \pi/2-\theta$ , $\Delta m^2 \Leftrightarrow -\Delta m^2$**

**if $\Delta m$ or $\theta = 0$ $P(\nu_\alpha \Rightarrow \nu_\beta) = \delta_{\alpha\beta}$**



# Two-Flavor mixing (for simplicity)

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Definite momentum p; same for all mass eigenstate components

Time development for an initially pure $|\nu_\alpha>$ beam:

$$|\nu_\alpha(t)\rangle = \cos\theta\, e^{-iE_1 t}|\nu_1\rangle + \sin\theta\, e^{-iE_2 t}|\nu_2\rangle$$
$$= \left[\cos^2\theta\, e^{-iE_1 t} + \sin^2\theta\, e^{-iE_2 t}\right] \cdot |\nu_\alpha\rangle$$
$$+ \left[\cos\theta \sin\theta \left(e^{-iE_1 t} - e^{-iE_2 t}\right)\right] \cdot |\nu_\beta\rangle$$

$$E_i = \sqrt{p^2 + m_i^2} = p + \frac{m_i^2}{2p}$$

$$E_2 - E_1 = \frac{m_1^2 - m_2^2}{2p} \approx \frac{\Delta m^2}{2E}$$

(assuming $p_i$ is the same)

$t = L/\beta$ w/ $\beta \approx 1$ :

$$(E_2 - E_1)\, t = \frac{\Delta m^2}{2E} L$$

Mixing probability:

$$P(\nu_\alpha \rightarrow \nu_\beta, t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = 2(\cos\theta \sin\theta)^2 \left[1 - \cos^2 \frac{E_2 - E_1}{2} t\right]$$

$$\boxed{P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)} = \sin^2 2\theta \sin^2\left(\frac{1.27 \cdot \Delta m^2[eV]}{4E[GeV]} L[km]\right)$$

# WHAT WE KNOW FROM EXPERIMENTS

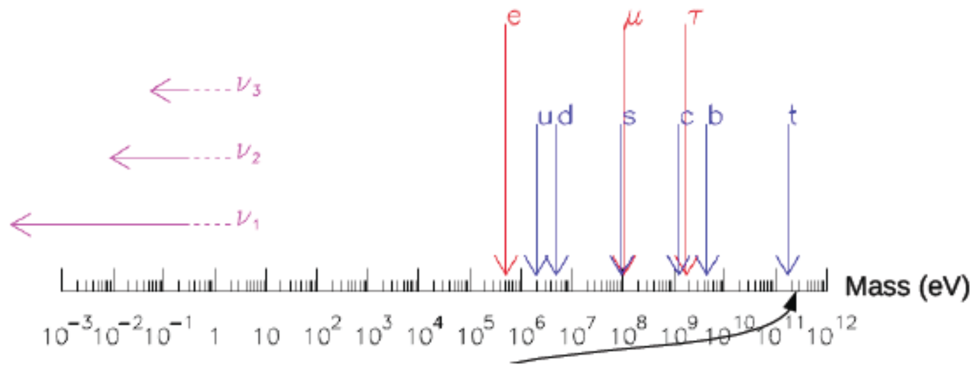
- **Neutrino mixing matrix:**

$$U_{PMNS} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 0.84 & 0.54 & 0.14 \\ 0.38 & 0.60 & 0.70 \\ 0.38 & 0.60 & 0.70 \end{bmatrix}$$

**CKM**

$$\begin{bmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 0.97 & 0.04 \\ 0.009 & 0.04 & 0.99 \end{bmatrix}$$

- **Neutrino mass spectrum**




- Quarks and charged leptons produced as mass eigenstates
- Neutrinos as flavour eigenstates
- Unitary triangles, useful when measure sides and angles, have no practical use in lepton flavour mixing
  - neutrino oscillation theory

# The general case: 3ν

- Flavour mixing:

$$(\nu_e,\, \nu_\mu,\, \nu_\tau)^T = U\,(\nu_1,\, \nu_2,\, \nu_3)^T$$

- Convention on the Euler rotation (one phase is complex):

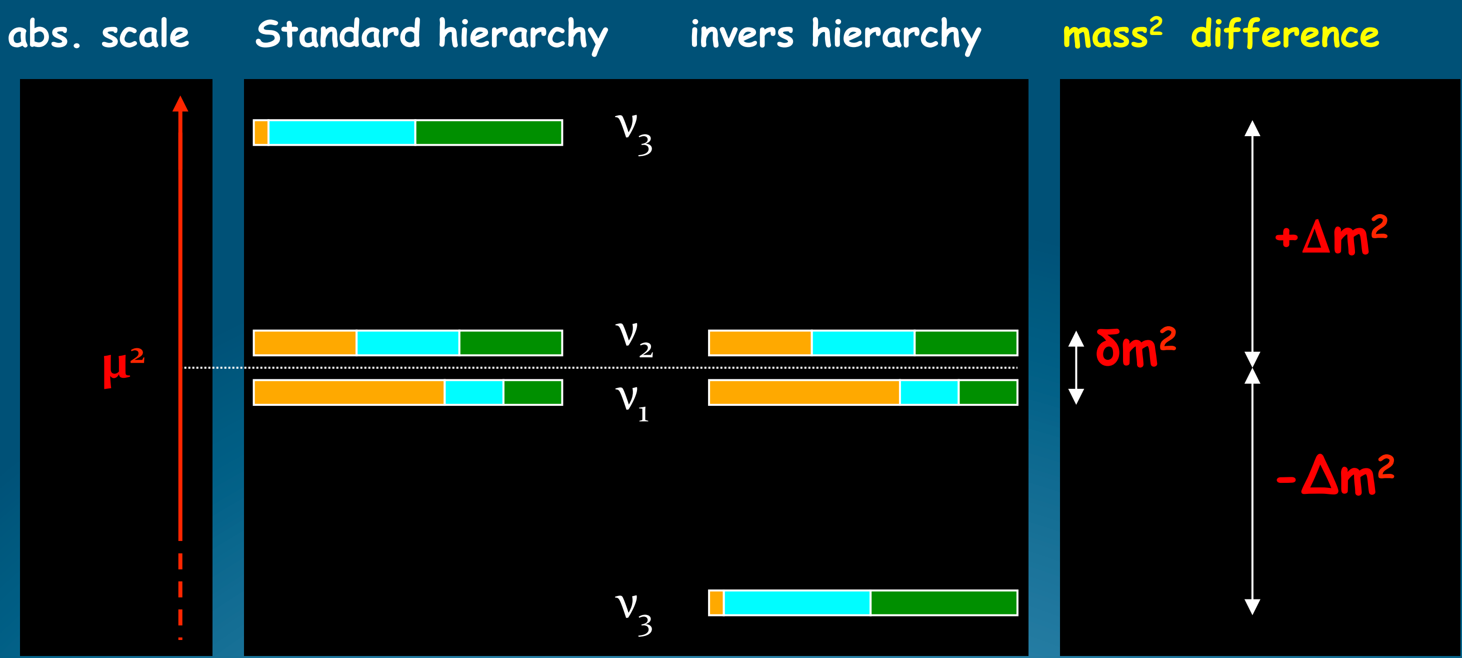
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

… similar to the quark matrix, but with very different angles:

$s_{23}^2 \sim 0.5$ $s_{13}^2 <$ few % $s_{12}^2 \sim 0.3$

- **Only if $s^2_{13} \neq 0$ we can hope to discover a phase δ of CP violation.**
  (This is the "holy graal" of future experiment of neutrino oscillations)

# 3ν: mass² spectrum and flavour mixing (e μ τ)




Absolute mass scale μ unkown [but < O(eV)]
Hierarchy [sign($\Delta m^2$)] unknown
"amount" of $\nu_e$ in $\nu_3$ unknown [but < a few %]

$\delta m^2 \simeq 8.0 \times 10^{-5}\ \mathrm{eV}^2$ ("solar" mass gap)

$\Delta m^2 \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$ ("atmosheric" mass gap)

# State of the art in 2004, with error of ±2σ (95% CL per 1dof)

$$\delta m^2 \simeq 8.0^{+0.8}_{-0.7} \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2 \simeq 2.4^{+0.5}_{-0.6} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} \simeq 0.29^{+0.05}_{-0.04} \quad (\mathrm{SNO}\ '05:\ \ 0.29 \rightarrow 0.31)$$

$$\sin^2\theta_{23} \simeq 0.45^{+0.18}_{-0.11}$$

$$\sin^2\theta_{13} <\sim 0.035$$

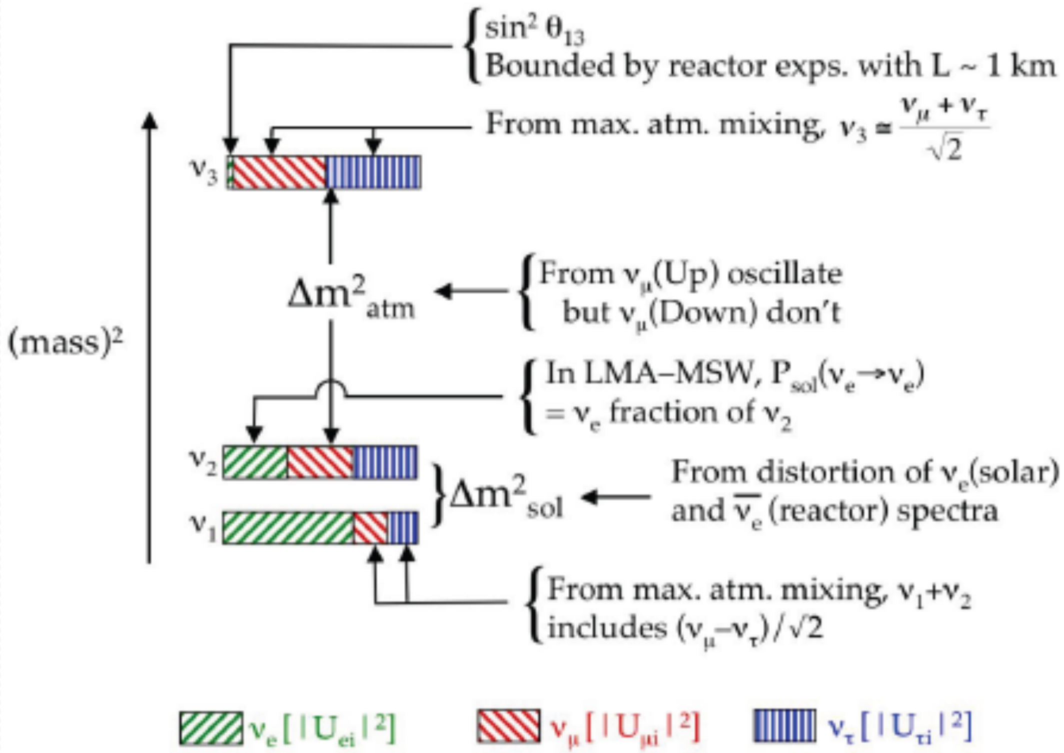
$$\mathrm{sign}(\pm\Delta m^2):\ \ \mathrm{unknown}$$

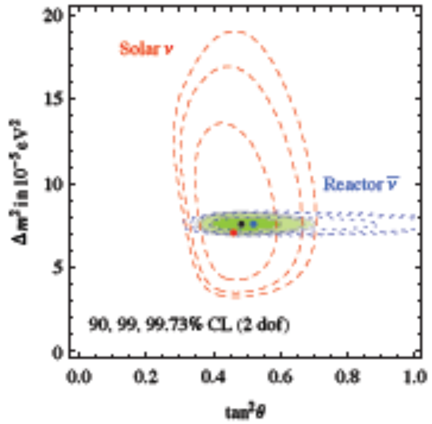
$$\mathrm{CP\ phase}\ \delta:\ \ \mathrm{unknown}$$

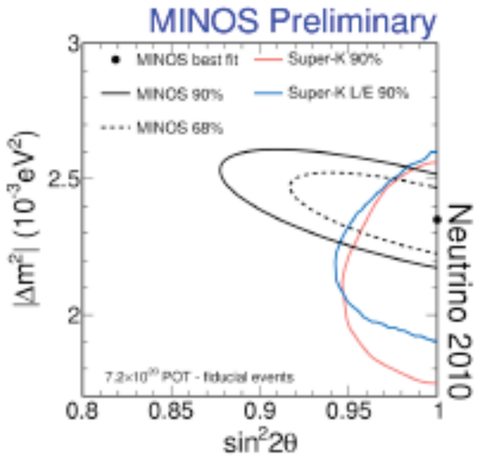
# THE WHOLE PICTURE

$\theta_{atm} \approx \theta_{13} \approx 45°$, $\theta_{sun} \approx \theta_{12} \approx 30°$, $\theta_{13} \lesssim 10°$

$|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \approx |\Delta m^2_{atm}| \approx (2.40 \pm 0.15) \cdot 10^{-3}\ eV^2$ $\Delta m^2_{12} \approx \Delta m^2_{sol} \approx (7.58 \pm 0.21) \cdot 10^{-5}\ eV^2$



# Mass spectrum

- From oscillation experiments we know that neutrinos are massive:

  $|\Delta m^2_{13}| \approx |\Delta m^2_{23}| \approx |\Delta m^2_{atm}| \approx (2.40 \pm 0.15) \cdot 10^{-3}\ eV^2 \quad \Delta m^2_{12} \approx \Delta m^2_{sol} \approx (7.58 \pm 0.21) \cdot 10^{-5}\ eV^2$

- Oscillation experiments <u>are not sensitive</u> to the absolute neutrino mass

- **Which is the absolute mass scale?**
  - Cosmology
  - Beta Decay
  - Neutrinoless Double Beta Decay