

# 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 sustain 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 million 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” hydrogen

pp cycle

In the center of the sun

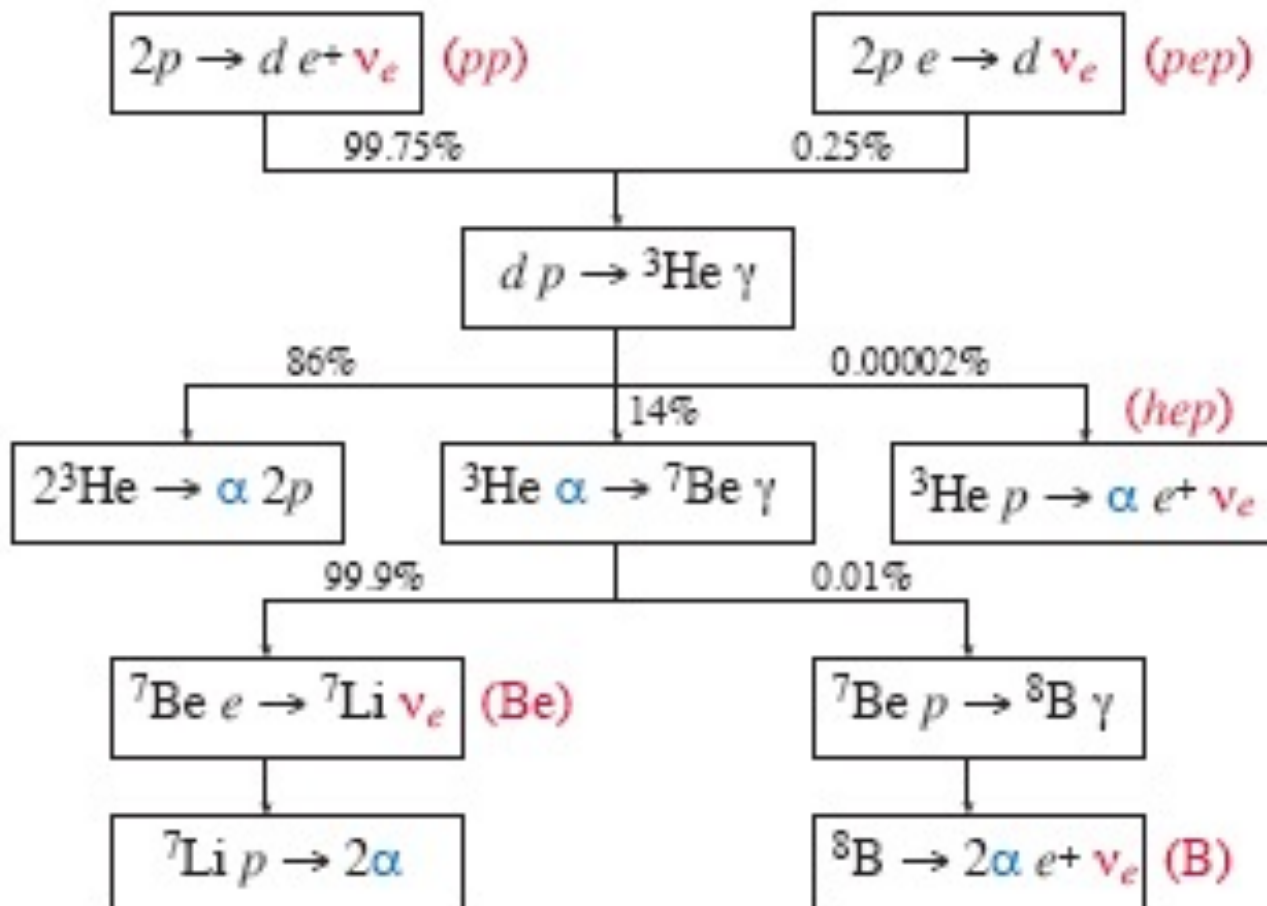


$$Q = 26.73 \text{ MeV}$$

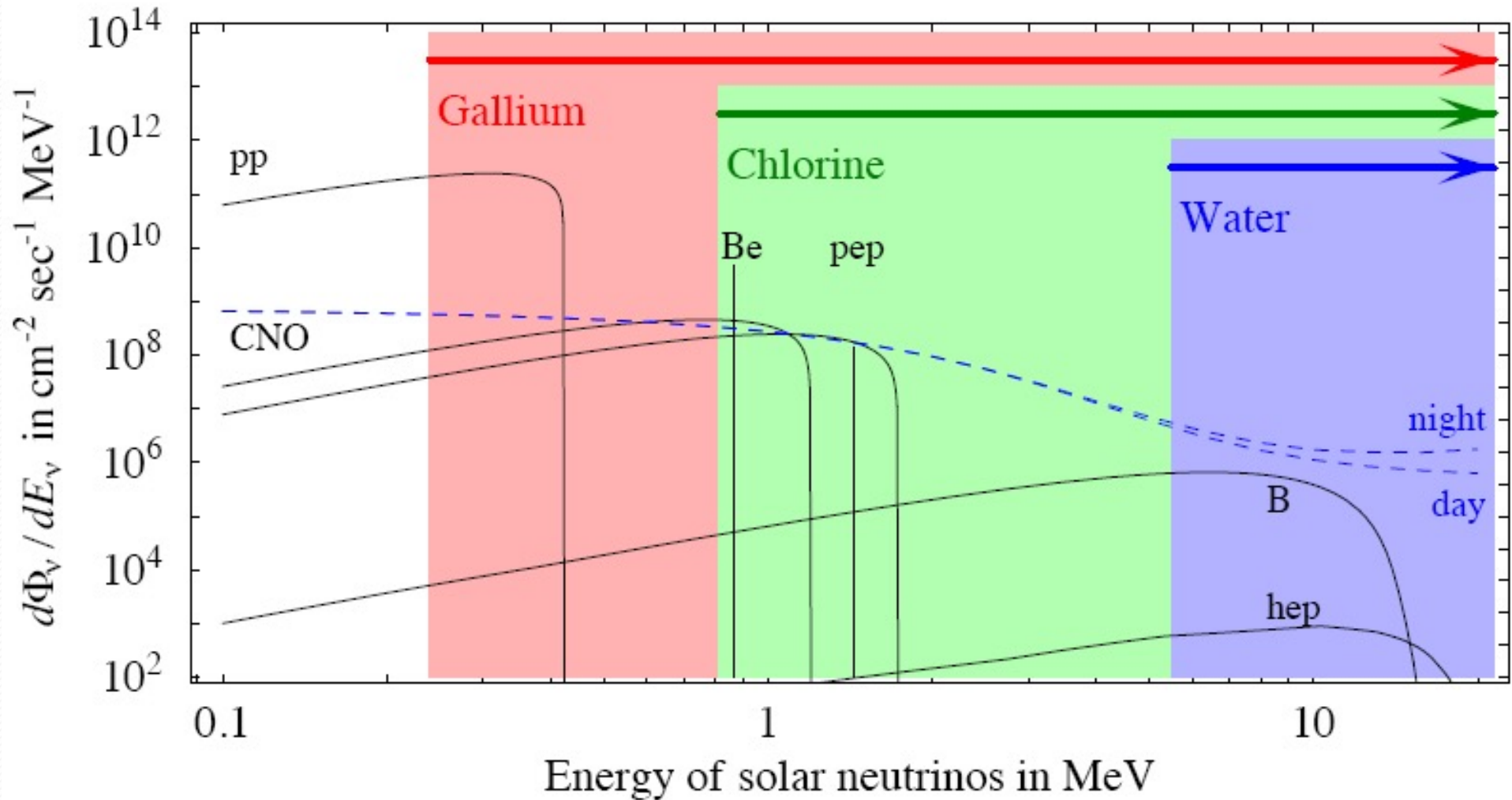
$$\langle E_\nu \rangle \approx 0.3 \text{ MeV}$$

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

CNO cycle is important  
in the older star



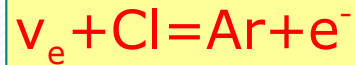
# Solar neutrino spectrum





# How detect neutrinos?

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



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  ${}^7\text{Be}$  and John Bahcall started his calculation on the expected neutrino flux.
- 1965: began the work at the Homestake mine to install 400 m<sup>3</sup> of chlorine (cleaning liquid).
- 1966: data taking started.
- 1968: they found less neutrinos than expected. Wrong computation?



# How many neutrinos?

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

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

- Bahcall calculation:  $7.5 \pm 3$  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.



Davis & Bahcall

# 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 weeks

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 the decays

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

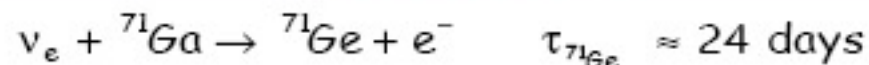
The glorious Homestake exp<sup>t</sup> (1968-99) 31 years of data taking, 2000 int.<sup>ions</sup>



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

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

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



$$E_{\text{thresh}} = 0.233 \text{ MeV} < E_{\nu_{\text{pp}}}^{\text{max}} = 0.423 \text{ MeV}$$

Prime importance to measure the bulk of the flux



# 1986: Kamiokande Detector

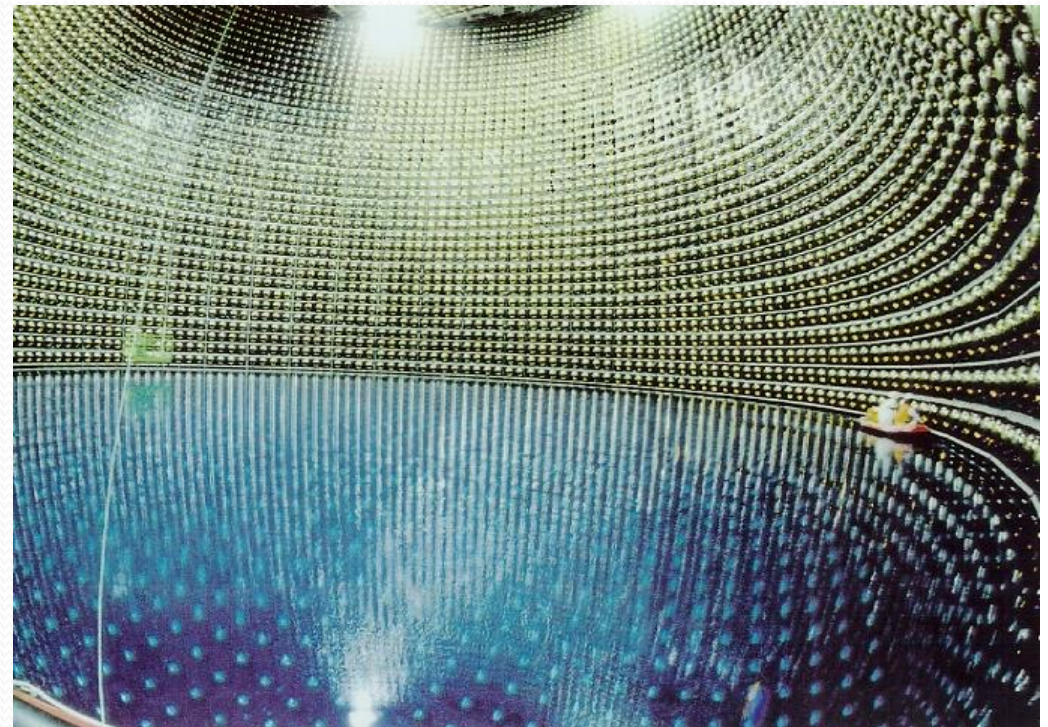
At the of 1986 started to take data the Kamiokande experiment (Kamioca Nucleon Decay Experiment), located in the Kamioka mine, in Japan.

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.

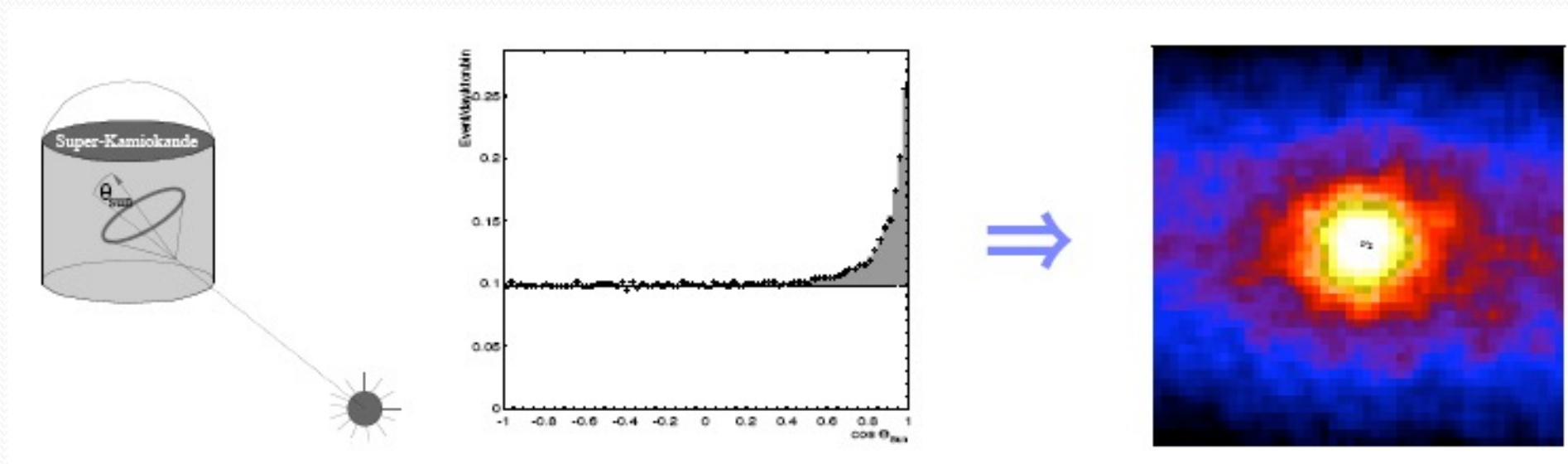


It was found an **ANOMALY** in the atmosferic neutrinos.

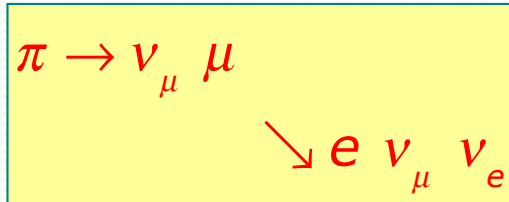


# “the Sun neutrino graphy”

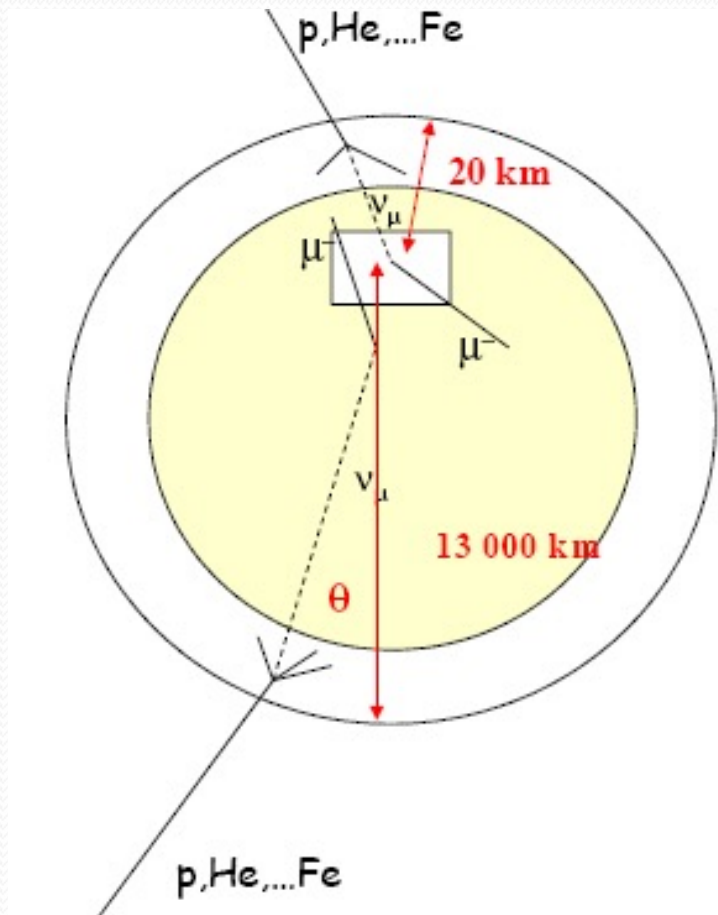
- The photons produced in the core of the Sun take about one million years to arrive to the surface. As far as we know the Sun could be off!
- With the neutrons we can observe the Sun “istantaneously”.



# Production of atmospheric neutrinos

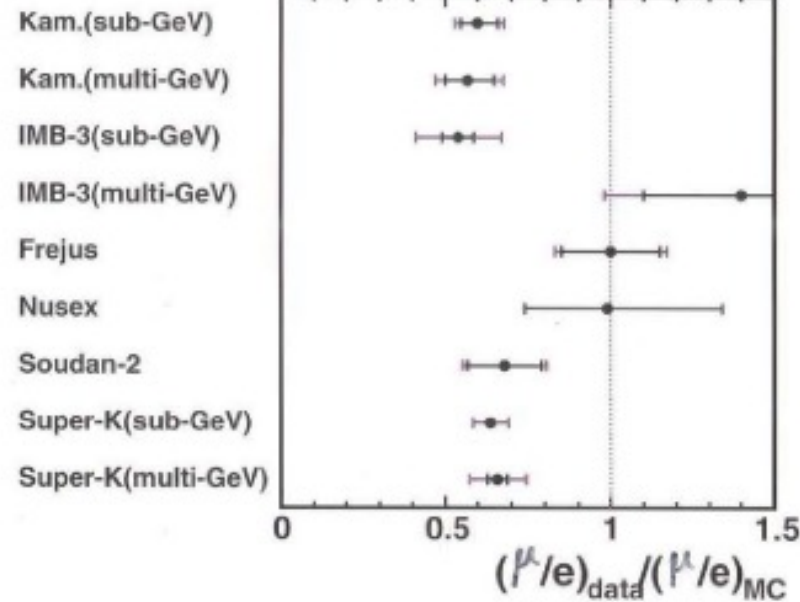


$$R = \frac{\Phi(\nu_{\mu})}{\Phi(\nu_e)} \approx 2$$



## $\mu/e$ ratio

Y. Fukuda et al., Phys. Lett. B 335 (1994) 237.  
M. Shiozawa, for the SK collab., talk at Neutrino 2002, Munich, May 2002



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  $\mu$  / day

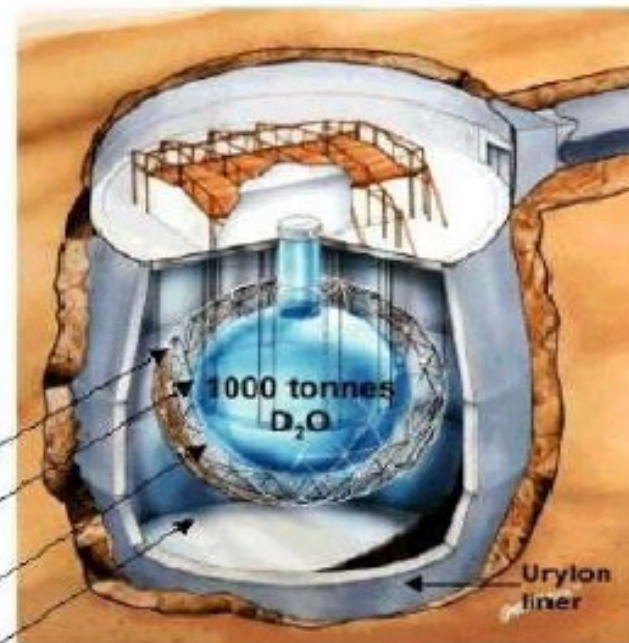


17.8m dia. PMT Support Structure  
9456 PMTs, 56% coverage

12.01m dia. acrylic vessel

1700 tonnes of inner shielding  $H_2O$

5300 tonnes of outer shielding  $H_2O$



Host: INCO Ltd., Creighton #9 mine  
Coordinates: 46°28'30"N 81°12'04"W  
Depth: 2092 m (-6010 m.w.e., ~70  $\mu$  day<sup>-1</sup>)

Urylon  
liner

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

# SNO

??? Why heavy water ???

Elastic scattering (ES)  $\nu + e^- \rightarrow \nu + e^-$   
like light water

directional sensitivity

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

$E_{\text{thesh}} = 1.4 \text{ MeV}$

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

Neutral current (NC)  $\nu + d \rightarrow p + n + \nu$

measures  $\nu_B$  total flux

Neutron detection :  $\varepsilon \sim 14\%$

- capture  $n + d \rightarrow t + 6.5 \text{ MeV } \gamma\text{-ray}$

-  $\gamma\text{-ray conversion to } e^+ - e^- \text{ pairs: Cerenkovsignal}$



# SNO: results

- SNO(D<sub>2</sub>O Cerenkov detector) measure **both charged and total  $\nu$  flux**:

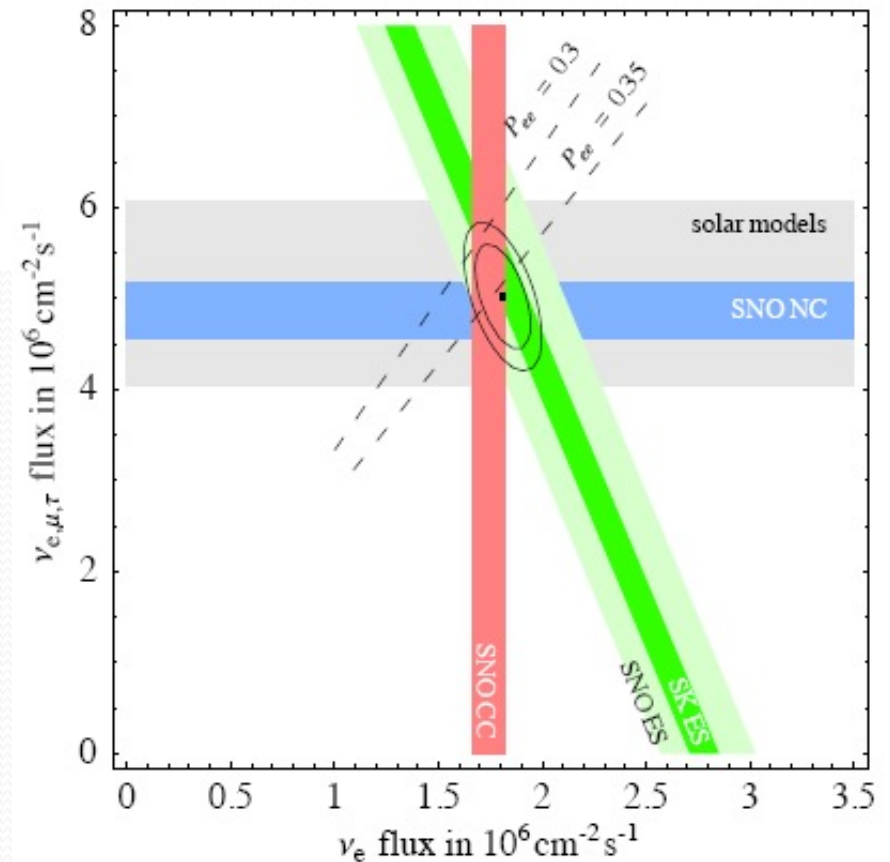
- ES:  $\nu_{e,\mu,\tau}e \rightarrow \nu_{e,\mu,\tau}e \Rightarrow \Phi(\nu_e) + 0.155 \Phi(\nu_{\mu,\tau})$

- CC:  $\nu_e D \rightarrow e^- pp \Rightarrow \Phi(\nu_e)$

- NC:  $\nu D \rightarrow \nu pn \Rightarrow \Phi(\nu_{e,\mu,\tau})$

- 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

$$\Phi(\nu_{\mu} + \nu_{\tau})$$

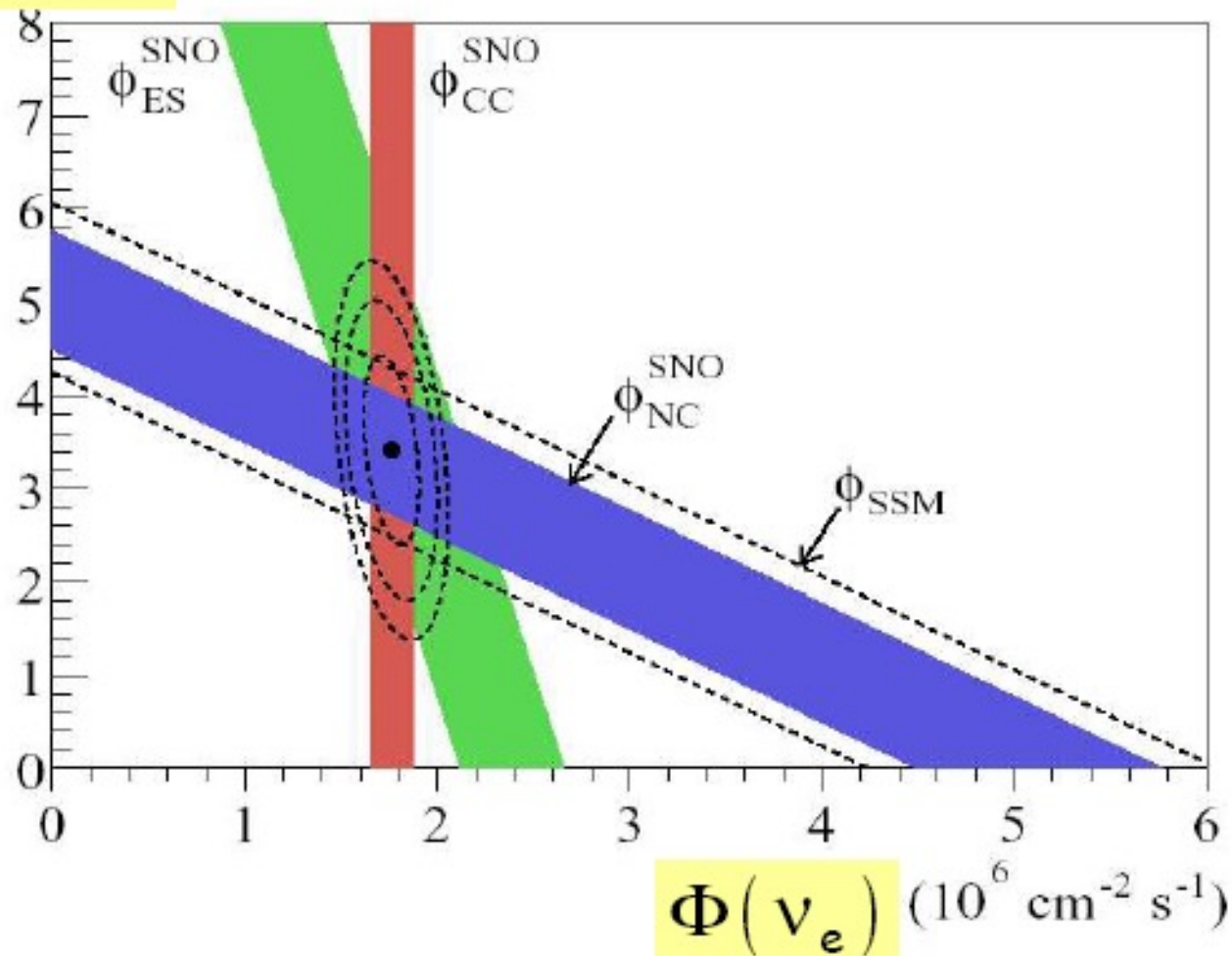
Standard Solar Model :

$$5.05^{+1.01}_{-0.81}$$

Bahcall et al.

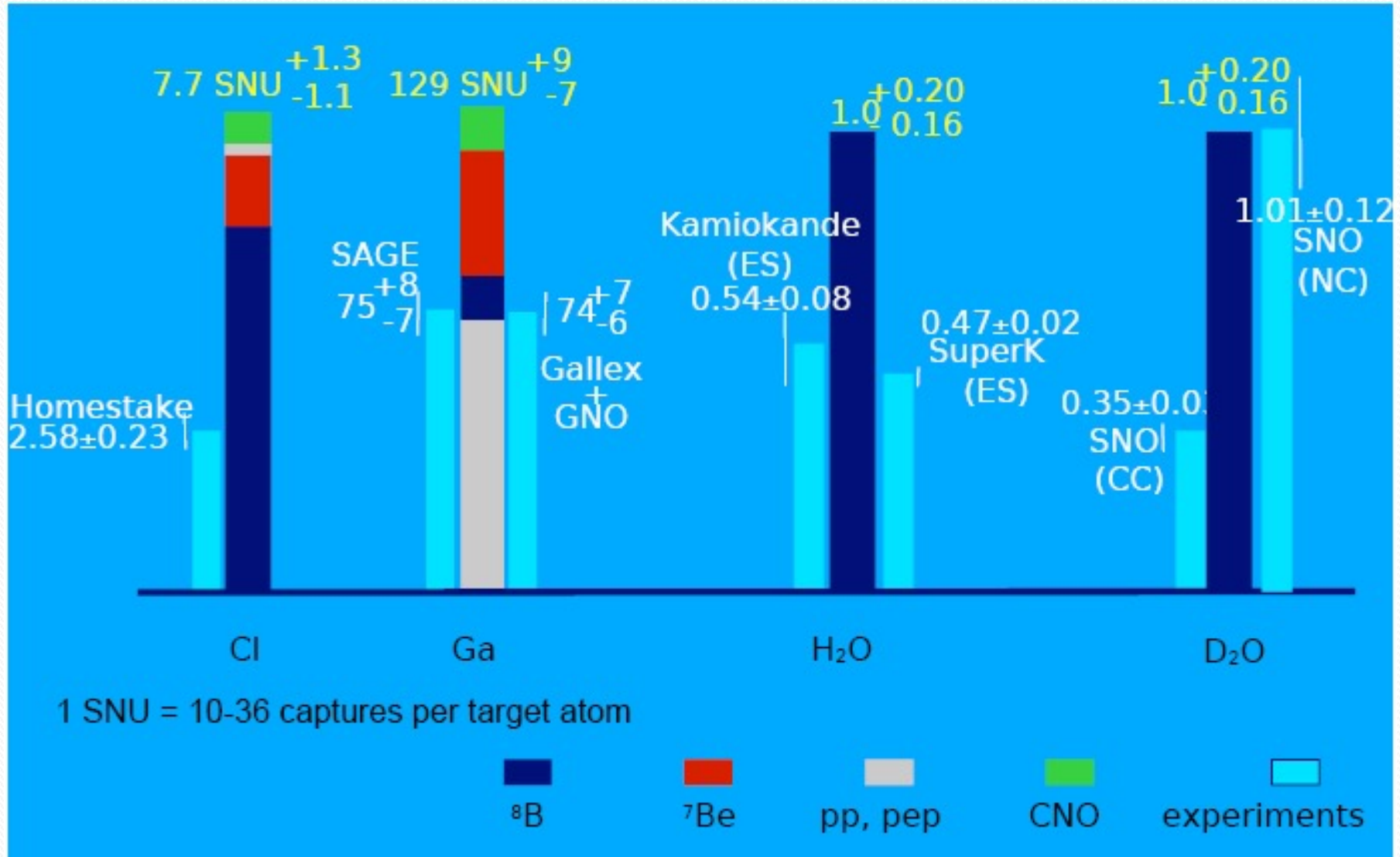
$$4.95 \pm 0.72$$

Turck-Chieze

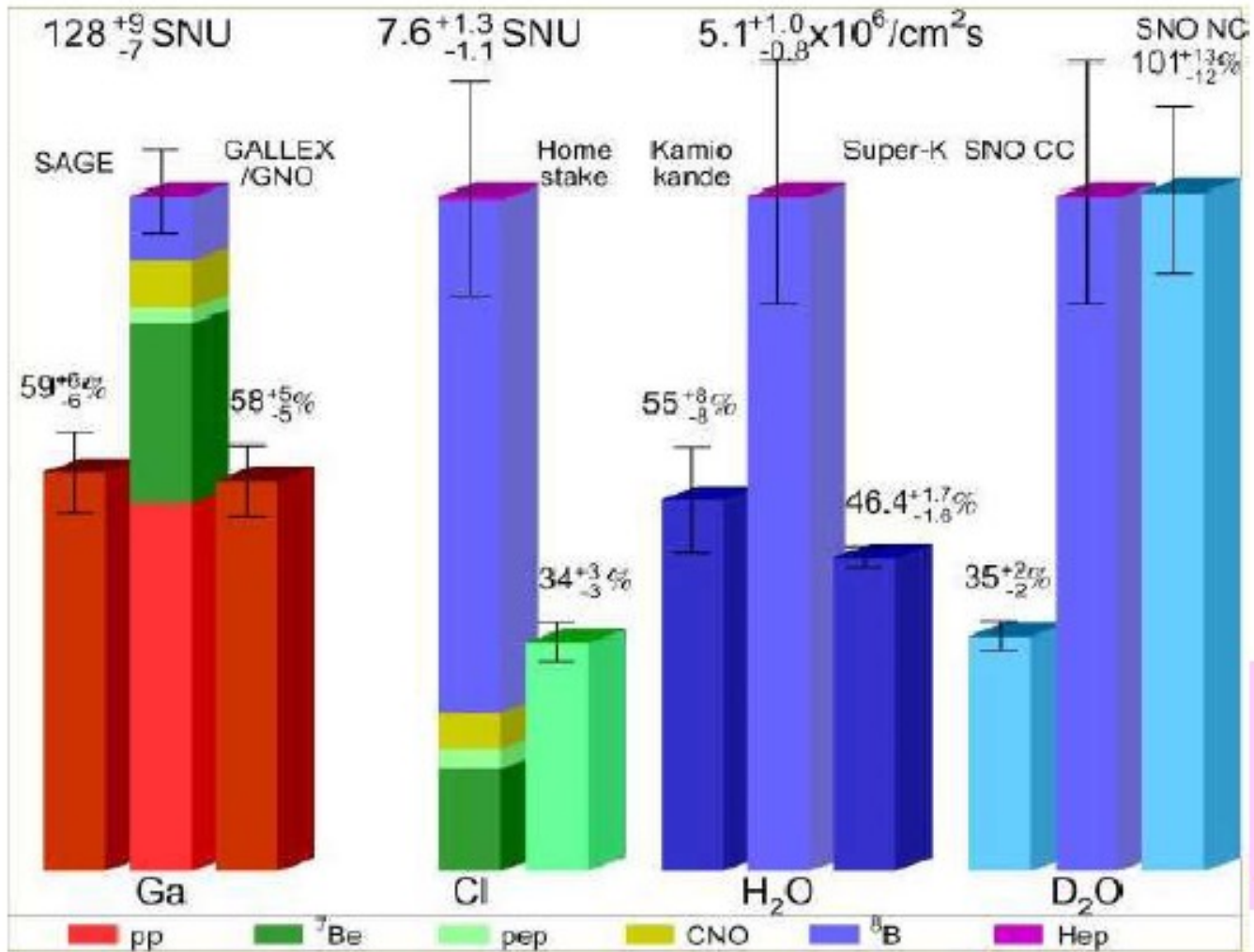




# Solar neutrinos: summary



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



Overall flux deficit :

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

No astrophysical or instrumental explanation

→  $\bar{\nu}_e$  disappearance



# 2002 Nobel Prize



**Raymond Davis Jr.**



**Masatoshi Koshihara**

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

# 2015 Nobel Prize



**Takaaki Kajita**



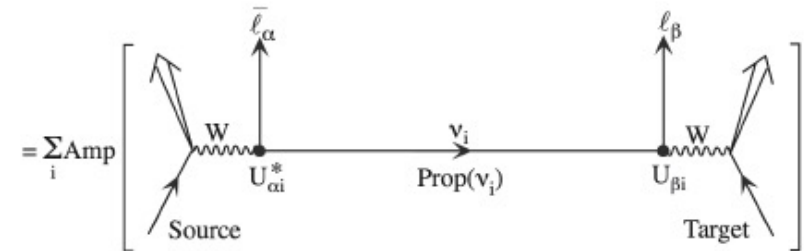
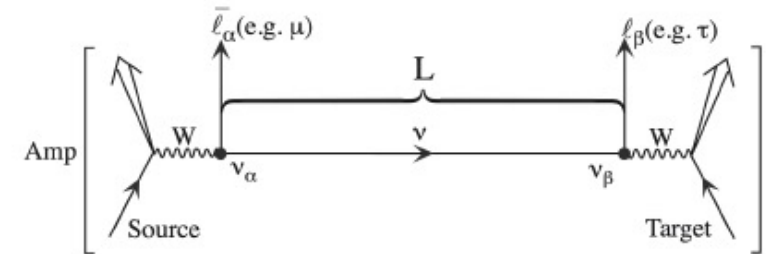
**Arthur B. McDonald**

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  $\neq$  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?

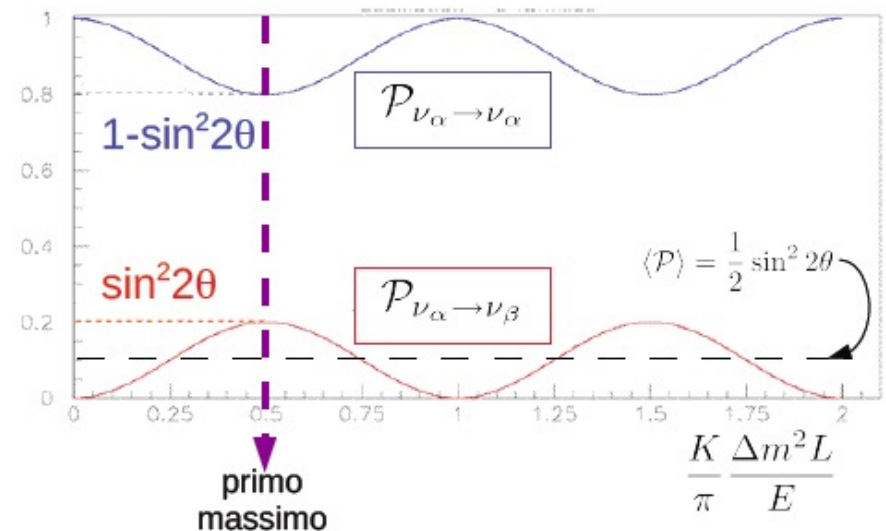


$$U = \begin{matrix} \nu_1 & \nu_2 \\ \nu_e & \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \\ \nu_\mu & \end{matrix}$$

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

**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  $|\nu_\alpha\rangle$  beam:

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

$$\begin{aligned} E_i &= \sqrt{p^2 + m_i^2} = p + \frac{m_i^2}{2p} \\ E_2 - E_1 &= \frac{m_1^2 - m_2^2}{2p} \approx \frac{\Delta m^2}{2E} \\ &\text{(assuming } p_i \text{ is the same)} \\ t &= L/\beta \quad \text{w/ } \beta \approx 1 : \\ (E_2 - E_1) t &= \frac{\Delta m^2}{2E} L \end{aligned}$$

Mixing probability:

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

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



# WHAT WE KNOW FROM EXPERIMENTS

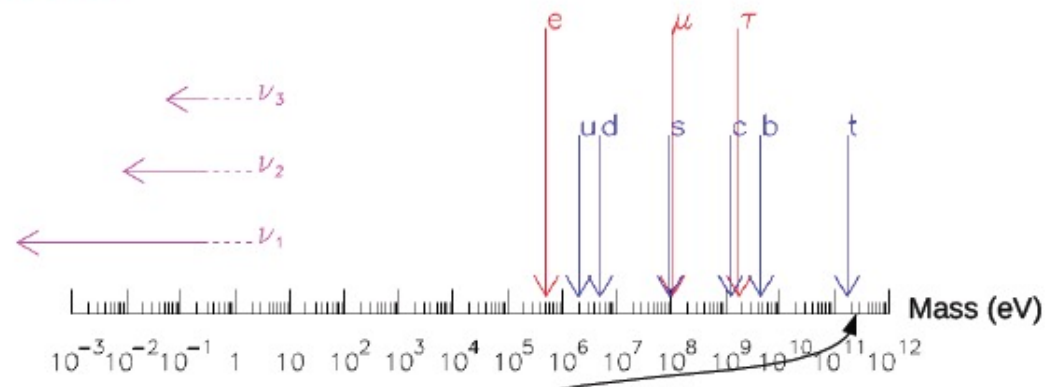
- **Neutrino mixing matrix:**

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

**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:

$$s_{23}^2 \sim 0.5$$

$$s_{13}^2 < \text{few } \%$$

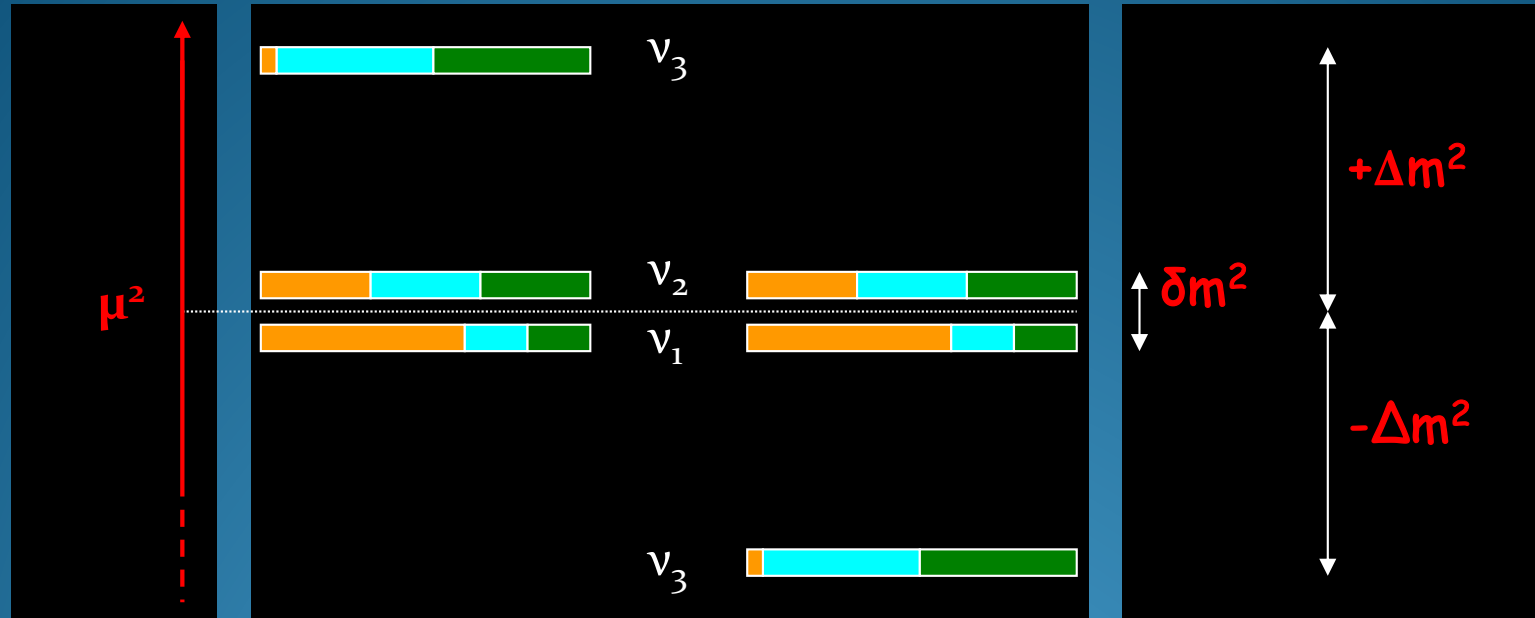
$$s_{12}^2 \sim 0.3$$

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



# 3ν: mass<sup>2</sup> spectrum and flavour mixing (e μ τ)

abs. scale    Standard hierarchy    invers hierarchy    mass<sup>2</sup> difference



Absolute mass scale  $\mu$  unknown [but  $< O(\text{eV})$ ]

Hierarchy [ $\text{sign}(\Delta m^2)$ ] unknown

"amount" of  $\nu_e$  in  $\nu_3$  unknown [but  $< \text{a few } \%$ ]

$$\delta m^2 \simeq 8.0 \times 10^{-5} \text{ eV}^2$$

("solar" mass gap)

$$\Delta m^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2$$

("atmospheric" mass gap)

## State of the art in 2004, with error of $\pm 2\sigma$ (95% CL per 1dof)

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

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

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

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

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

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

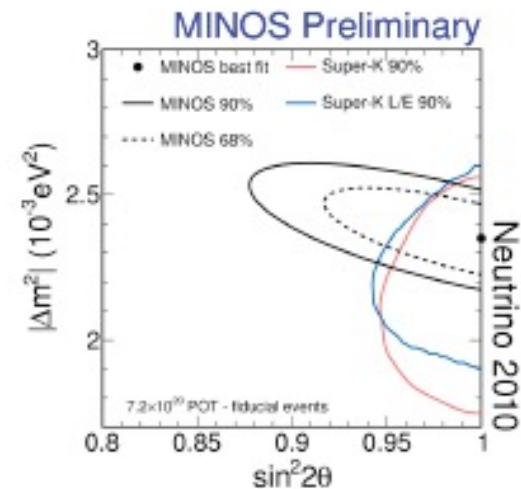
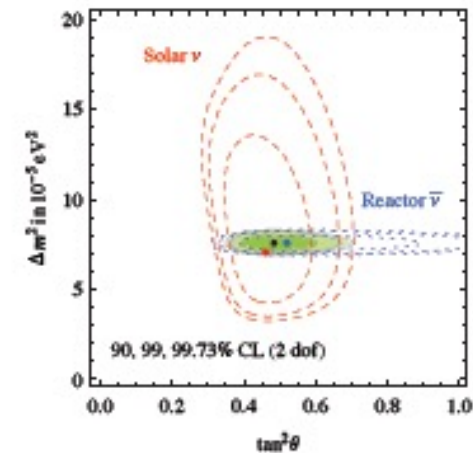
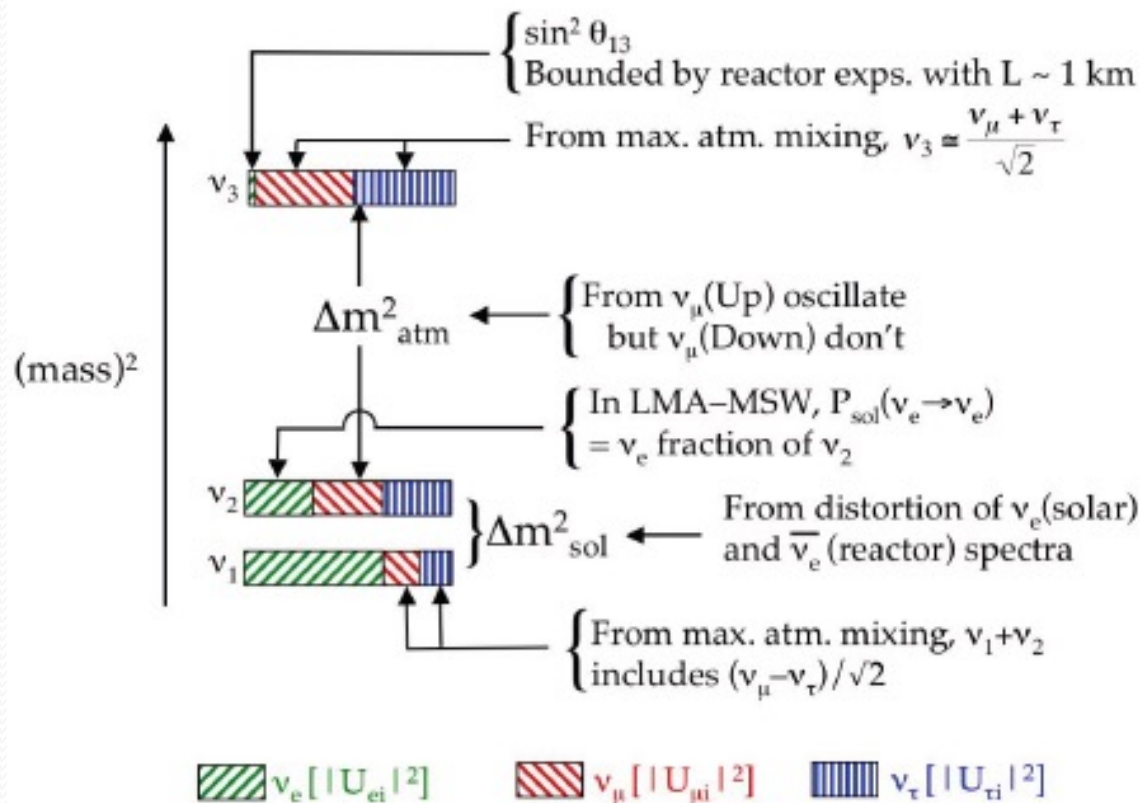
CP phase  $\delta$  : unknown



# THE WHOLE PICTURE

$$\theta_{\text{atm}} \approx \theta_{13} \approx 45^\circ, \theta_{\text{sun}} \approx \theta_{12} \approx 30^\circ, \theta_{13} \leq 10^\circ$$

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



# MASS SPECTRUM

- From oscillation experiments we know that neutrinos are massive:

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

- Oscillation experiments are not sensitive to the absolute neutrino mass

- Which is the absolute mass scale?

- Cosmology
- Beta Decay
- Neutrinoless Double Beta Decay

