Natural neutrinos

1. Sun, ν_e, 60 10^9 /cm^2/s on earth
2. Atmosphere, $2\nu_\mu/1\nu_e$, 100 /m^2/s
3. Supernova (type II), ν_μ, ν_e, ν_τ, 10^{58} in 10 s

Cerenkov effect

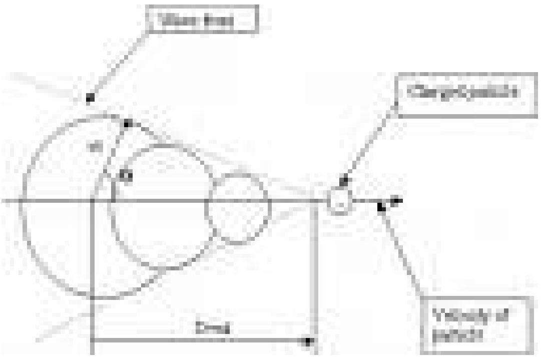
When a charged particle propagates at a velocity > c/n

Water n=1.33 V=220000km/s

EM shock wave

Light emission over a cone

$\cos\theta = 1 / \beta n$

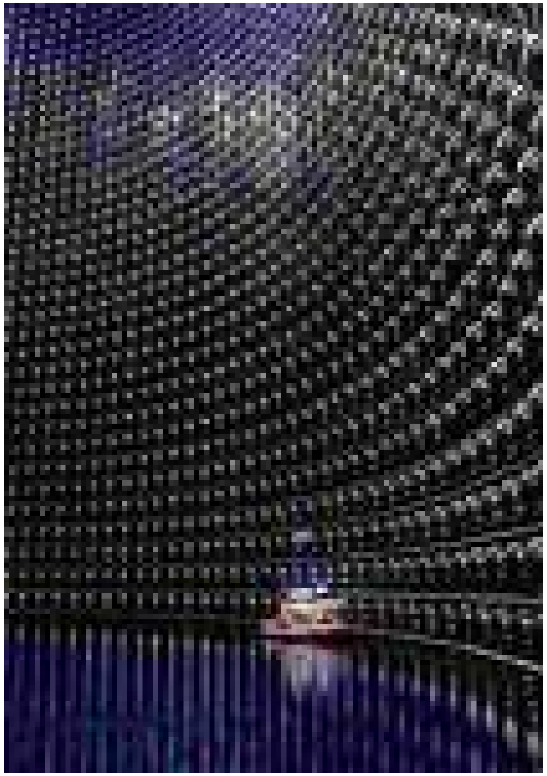


The SuperKamiokande detector

•Built under a mountain in Japan, SuperK is an immense reservoir of 50 kilotons of purified water, seen by 11000 giant phototubes.

□ν_e from the Sun interact on electrons.

•Cerenkov effect for energies above 5 MeV.

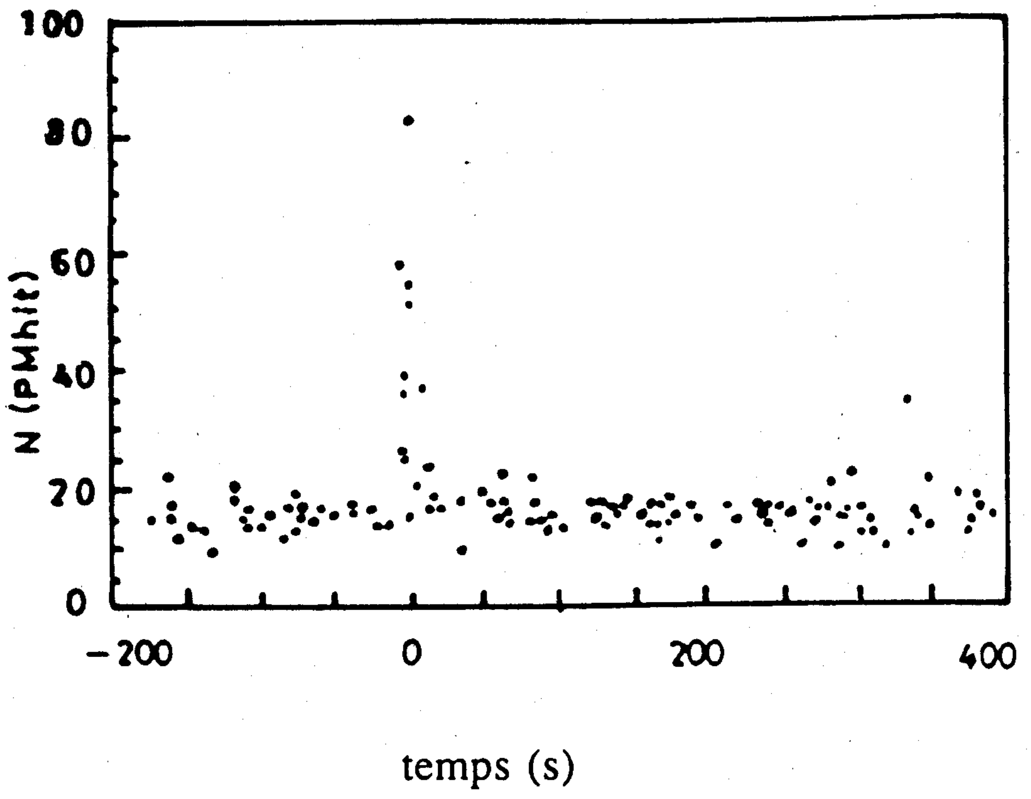


Neutrinos from SN1987

Kamiokande
1000 tons of water

Looking for…
proton decay

23 february 1987



Standard solar model

REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.423
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.445
${}^2H + p \rightarrow {}^3He + \gamma$	(100)	
${}^3He + {}^3He \rightarrow \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(15)	{0.863 90%; 0.385 10%
${}^7Li + p \rightarrow 2\alpha$		
or		
${}^7Be + p \rightarrow {}^8B + \gamma$	(0.02)	
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$		< 15
${}^8Be^* \rightarrow 2\alpha$		
or		
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	(0.00003)	< 18.8

Neutrino terminations from BP2000 solar model. Neutrino energies include solar corrections: J. Bahcall, Phys. Rev. C, 56, 3391 (1997).

Solar neutrinos

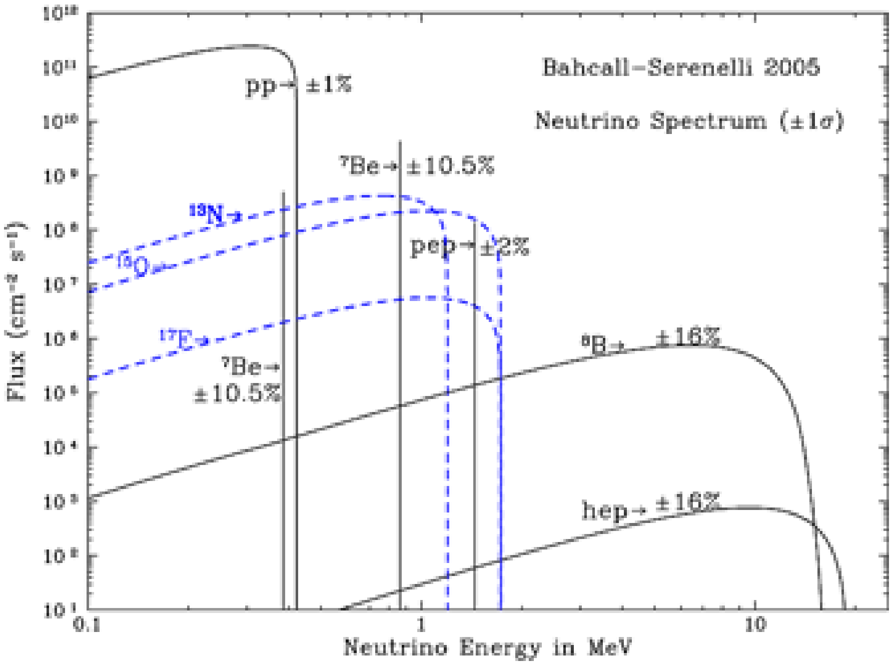
- Main fusion reaction

  $4p \Rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 27$ MeV.

- Knowing the solar luminosity, this gives a flux of 60 $10^6/cm^2/s$ arriving on earth surface.

- Neutrinos from the main chain have an energy limited to 430 keV, but other secondary production processes give neutrinos up to 15 MeV.

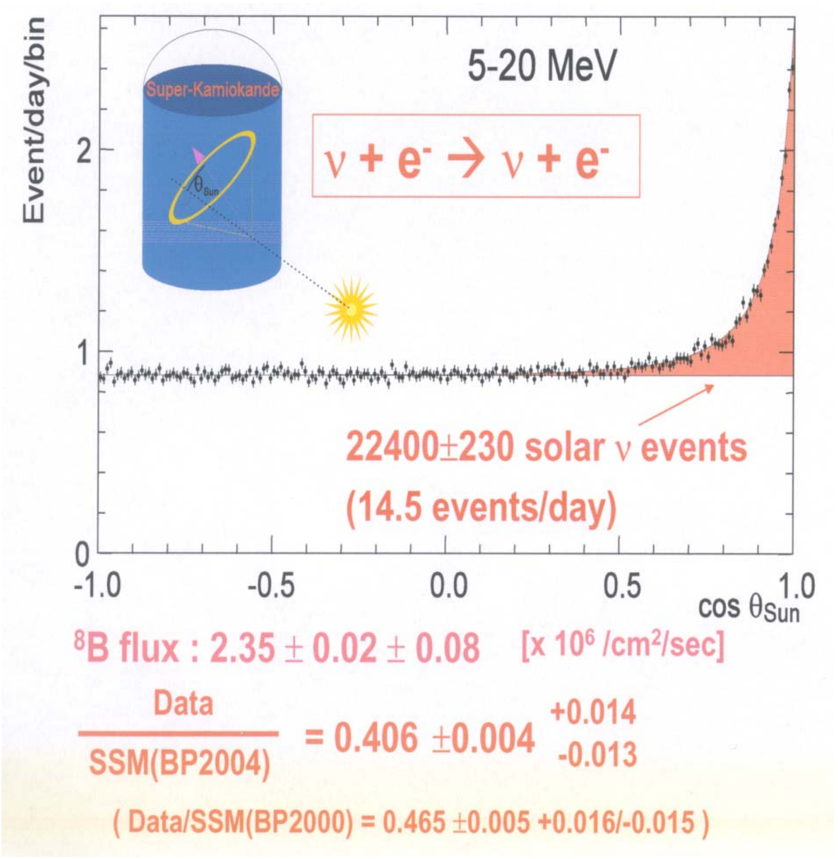
Solar neutrino spectrum



Detection with SuperK

- In 1500 days, SuperK detected 22000 events while 48000 were predicted.
- This is the so-called *deficit* of solar neutrinos

Already seen with Homestake and Gallex/Sage experiments.



Prehistory of solar neutrino searches

Radiochemical searches

1. Homestake chlorine experiment

615 tons of tetrachloroethylene

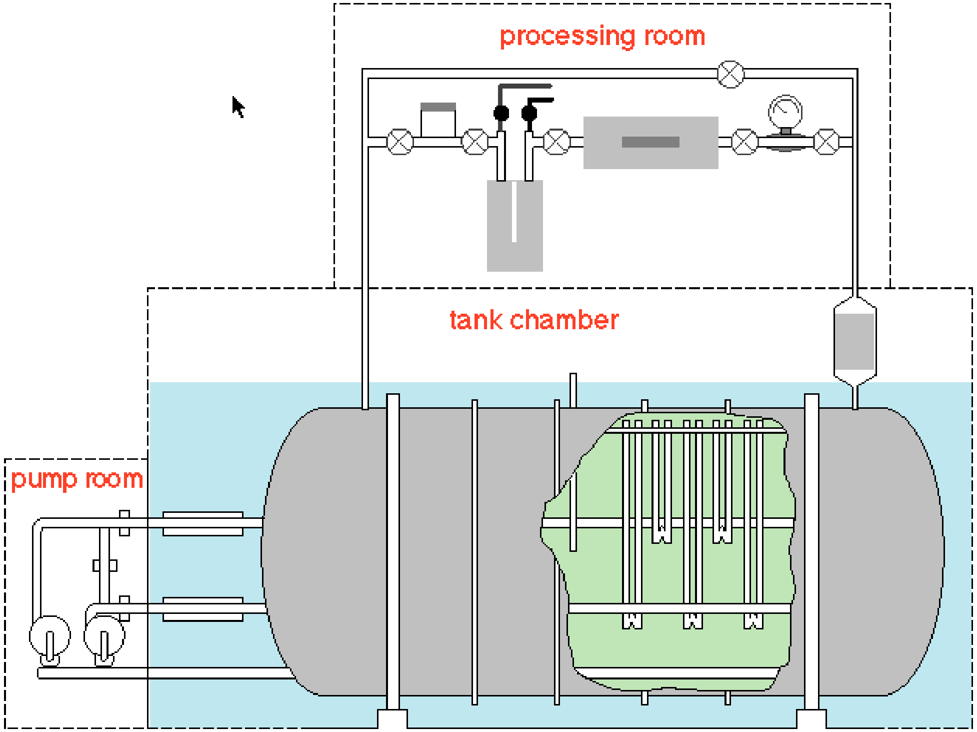
$$\nu + {}^{37}Cl \Rightarrow {}^{37}Ar + e^-$$

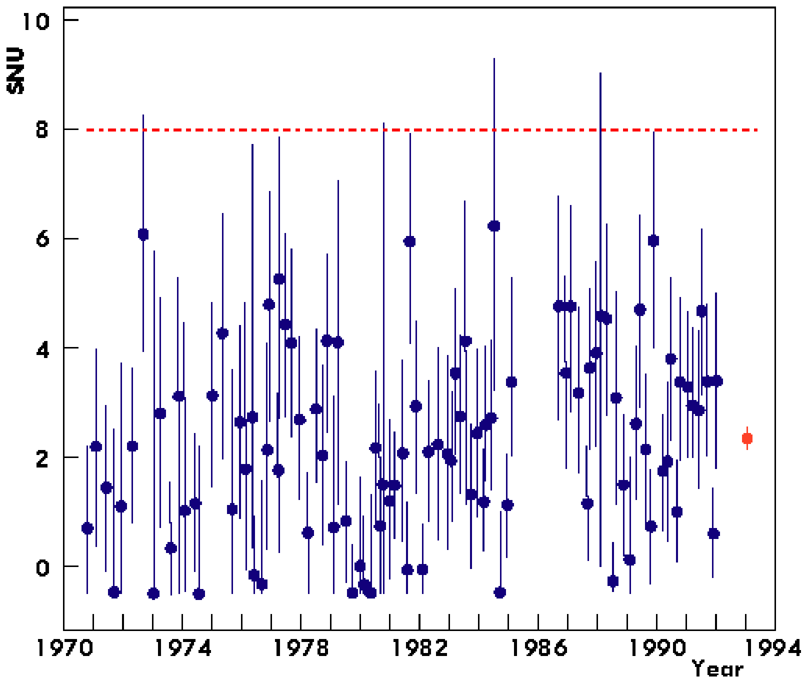
2. Gallex/Sage

15 tons of watered gallium 71

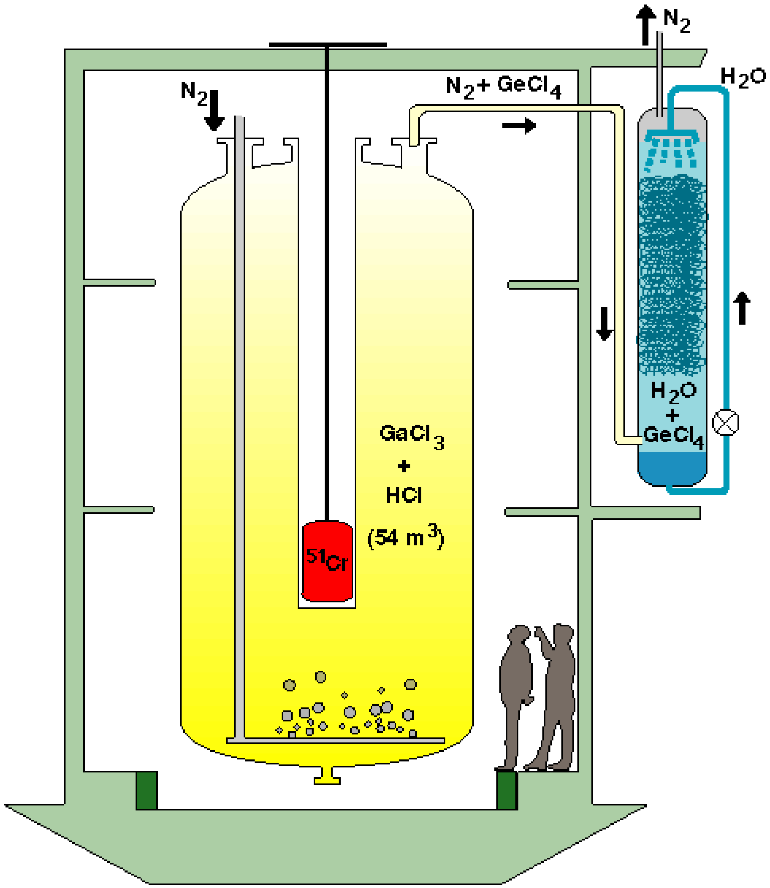
$$\nu + {}^{71}Ga \Rightarrow {}^{71}Ge + e^-$$

Homestake

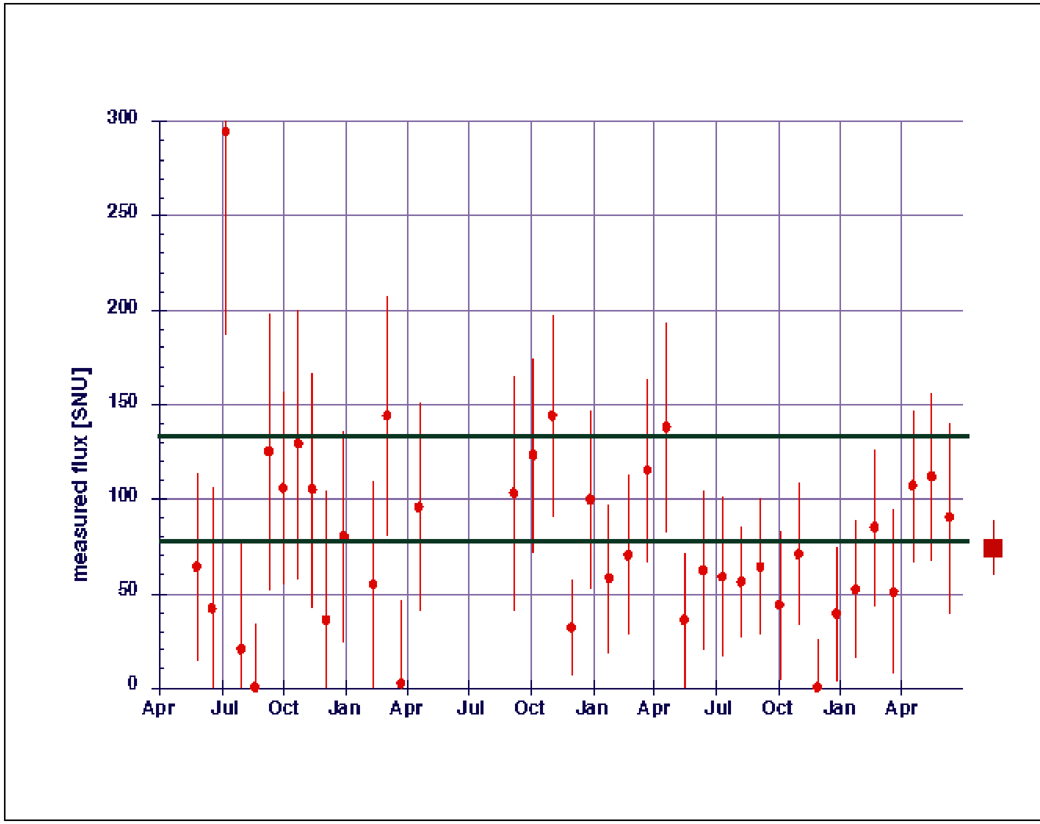

processing room
tank chamber
pump room


10
8
6
4
2
0
SNU
1970
1974
1978
1982
1986
1990
1994
Year

Gallex



N_2
H_2O
N_2
N_2+ $GeCl_4$
$GaCl_3$
+
HCl
(54 m^3)
^{51}Cr
H_2O
+
$GeCl_4$



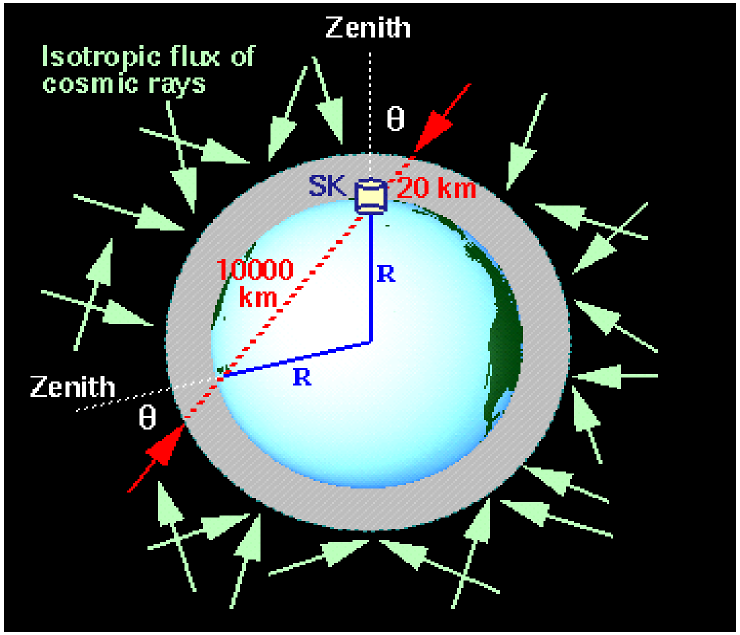
measured flux [SNU]
300
250
200
150
100
50
0
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr

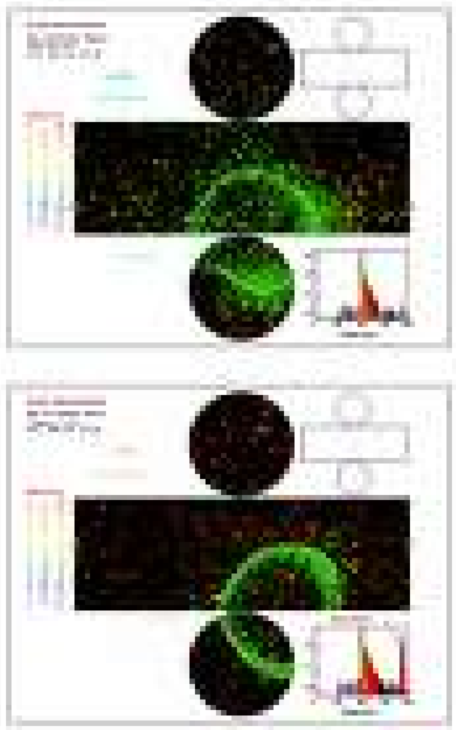
Solar neutrino results

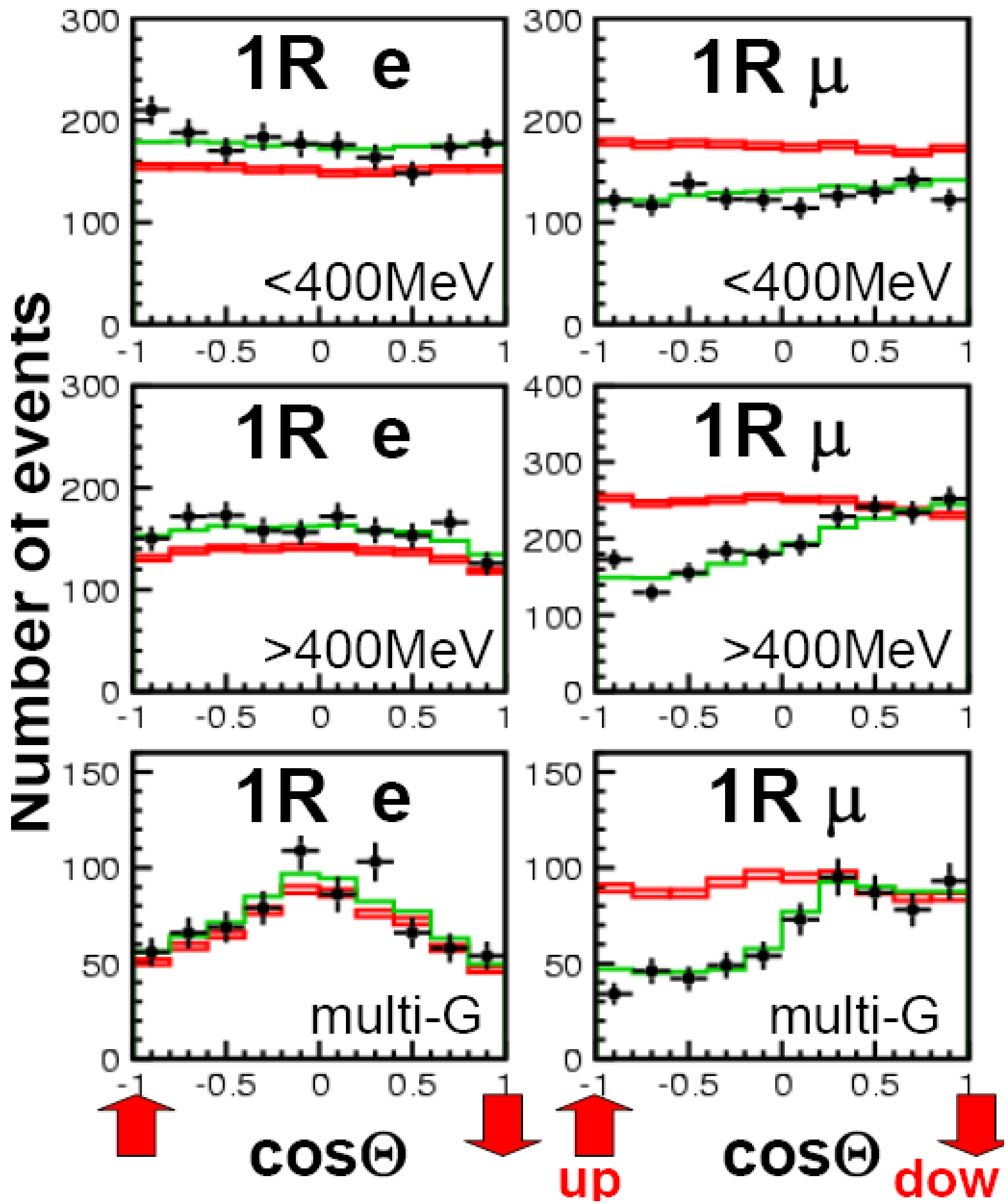
- Homestake deficit
  - *Seen/expected = 0.3*
- Gallium deficit
  - *Seen/expected = 0.6*
- SuperK deficit
  - *Seen/expected = 0.45*
  - The deficit changes with energy!

Atmospheric neutrinos

- **New deficit observed.**
- Production 2 ν_μ pour 1 ν_e from all horizons. A few 100 MeV energy.
- SuperK distinguishes e and μ
- Azimuthal distribution of ν_e OK
- But for ν_μ deficit for neutrinos crossing the earth, having propagated over few 1000 km.



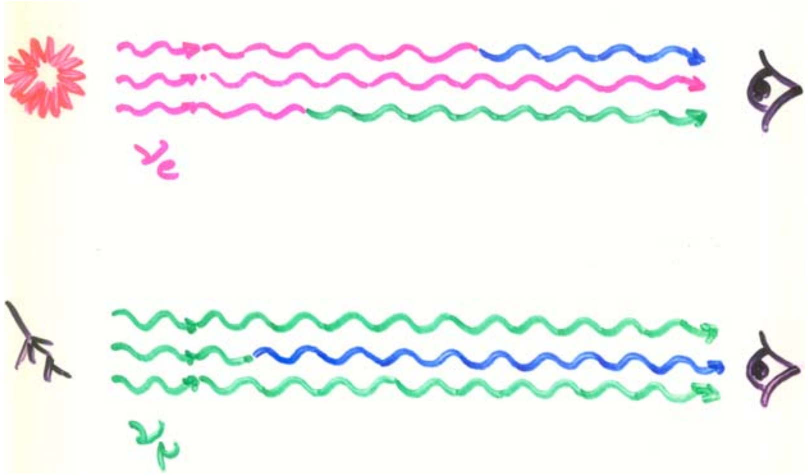




Number of events
1R e
<400MeV
1R μ
<400MeV
1R e
>400MeV
1R μ
>400MeV
1R e
multi-G
1R μ
multi-G
cosΘ
cosΘ
up
dow

Do neutrinos oscillate?

- The *deficits* can be explained by a change of flavor during propagation



Case of two neutrino flavors

Old idea from B. Pontecorvo: same as in K^0 system

Weak interaction eigenstates ν_e, ν_μ different from mass eigenstates (propagation) ν_1, ν_2

Mixing matrix unitary 2x2

- $\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$
- $\nu_\mu = -\nu_1 \sin\theta + \nu_2 \cos\theta$

- *Probability of oscillation*
  - $P = \sin^2 2\theta \sin^2(\pi R/L)$
- with $L = 2,5\ E(\mathrm{GeV})/\Delta m^2(\mathrm{eV}^2)$

$\Rightarrow$ *Two unknows Δm^2 and $\sin^2 2\theta$*

Experimental hints

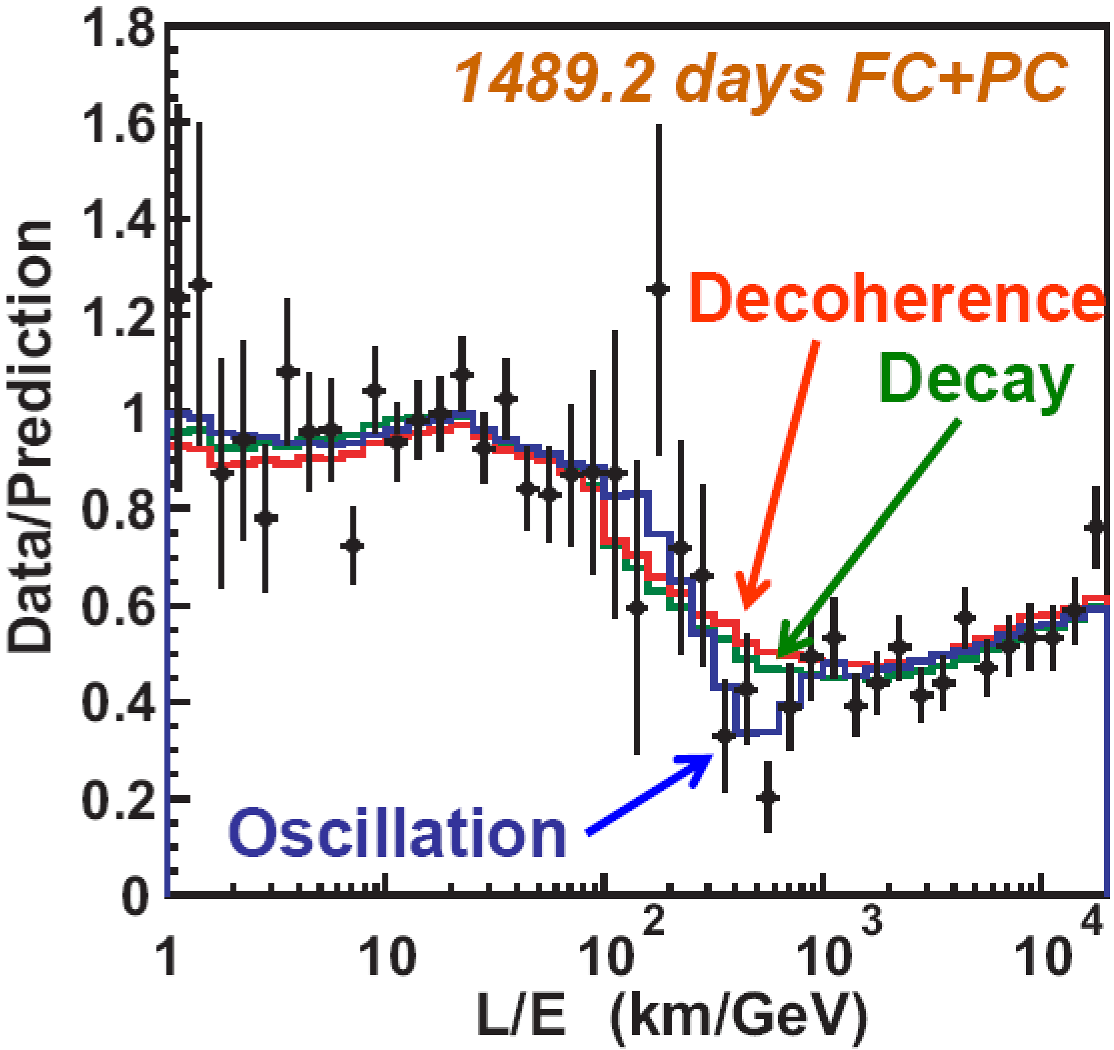
1. Deficit of solar neutrinos

Disappearance of ν_e

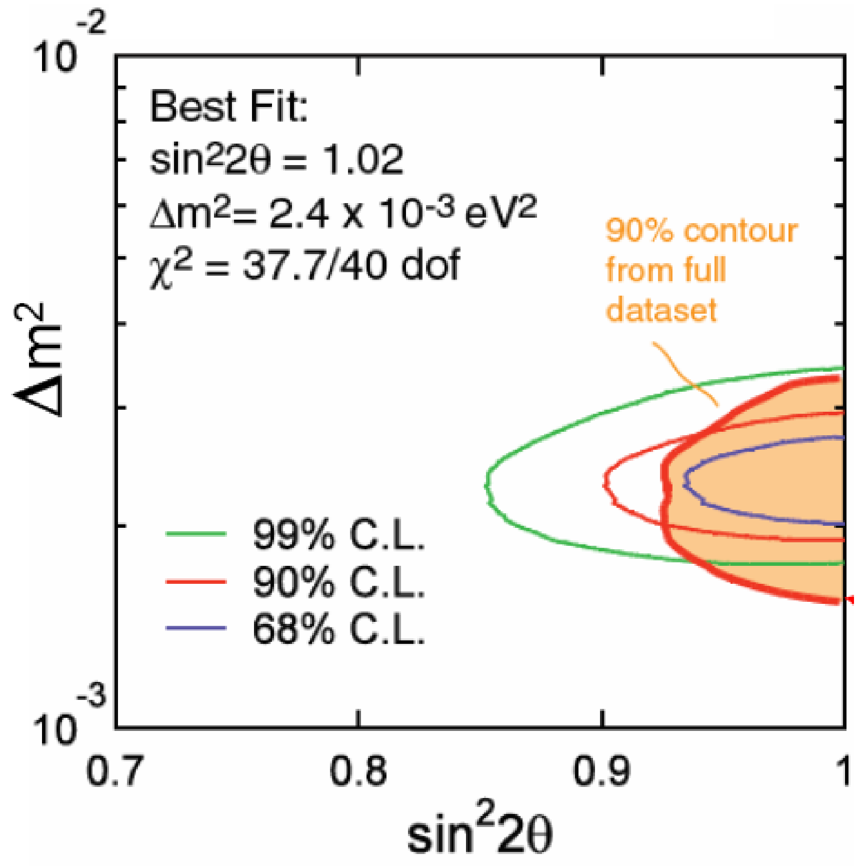
2. Deficit of atmospheric neutrinos

Diappearance of ν_μ

Note: experimentally 2 complementary search methods, disappearance of initial neutrinos or appearance of new flavor not present at the source


1489.2 days FC+PC
Decoherence
Decay
Oscillation
Data/Prediction
L/E (km/GeV)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
10
10^2
10^3
10^4

SK result (atmospheric ν_μ)



Pontecorvo-Maki-Nakagawa-Sakata matrix

Three neutrinos. Mixing matrix, unitary 3x3

3 mixing angles + 1 phase

Solar neutrinos θ_{12}, Δm_{12}^2

Atmospheric neutrinos θ_{23}, Δm_{23}^2

$$\qquad \Delta m^2_{31} \qquad\qquad\qquad\qquad\qquad\qquad \Delta m^2_{21}$$

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

atmospheric+LBL   Chooz   solar+KamLAND

Remains to measure: θ_{12}, δ and absolute mass scale

Resonant oscillation in matter
MSW effect

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}=H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} \qquad H=\begin{bmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta+\sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{bmatrix}$$

$$\sin^2 2\theta_m=\frac{\sin^2 2\theta}{(\omega-\cos 2\theta)^2+\sin^2 2\theta}$$

$$\omega=-\sqrt{2}G_F N_e E/\Delta m^2$$

MSW effect can produce an energy spectrum distortion and flavor regeneration in Earth giving a Day-night effect.

In fact, for solar ν, oscillations occur inside the Sun.

When observed, matter interactions define the mass hierarchy