# Experimental review of neutrinos masses and oscillation

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( ULB - VUB )

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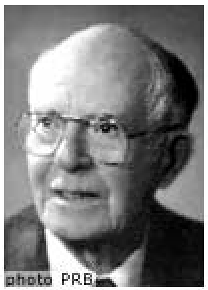
## The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"




**Raymond Davis Jr.**

1/4 of the prize

USA

University of Pennsylvania
Philadelphia, PA, USA

b. 1914


**Masatoshi Koshiba**

1/4 of the prize

Japan

University of Tokyo
Tokyo, Japan

b. 1926


**Riccardo Giacconi**

1/2 of the prize

USA

Associated Universities Inc.

Washington, DC, USA

b. 19

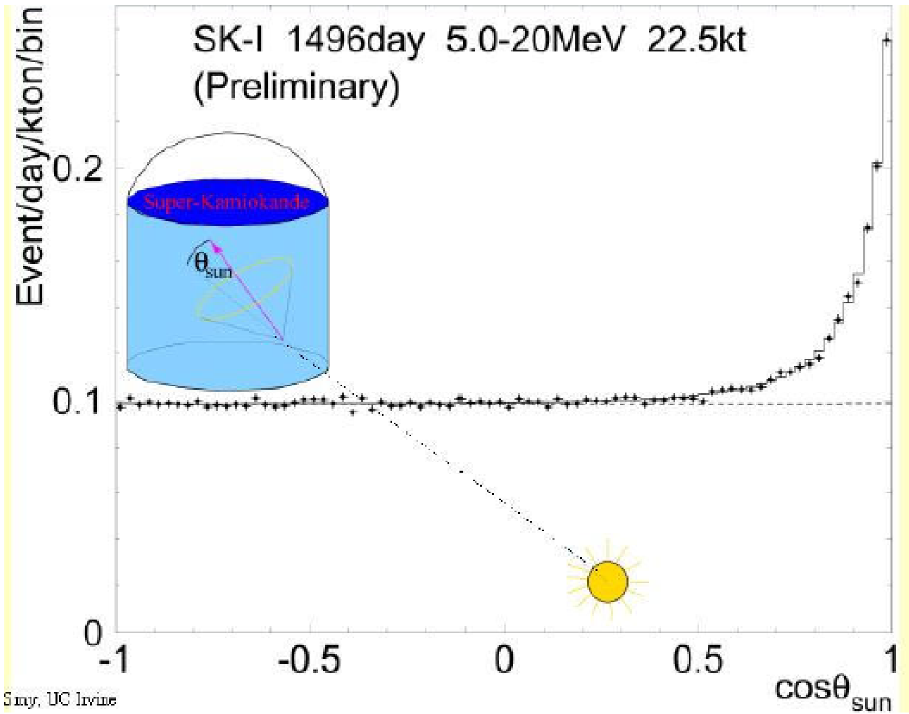
(in Geno... aly)

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

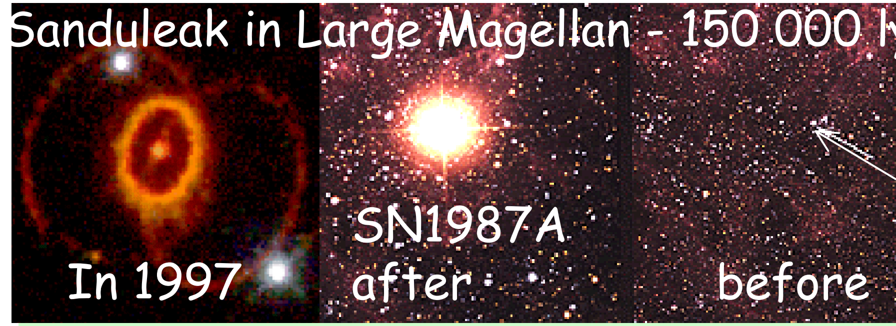
1968: First detection of solar neutrinos in Homestake mine.
Proof of the solar nuclear fusion model of Bethe and Fowler.
30 years of solar neutrinos data taking.

Confirmation that solar neutrinos
… really come from the Sun with Kamiokande-II
Observation of SN1987a (somehow by chance…and not alone:
Fred Reines group with IMB, Ohio
Baksan detector in Oural)
Proof of the Super Nova-type II collapse model and beginning of neutrino astronomy

Latest Super-Kamiokande plot:
correlation between
the directions of the Sun and
the electrons emitted
in solar neutrinos interactions




Yet, I shall not speak of
neutrino astronomy




Much less spectacular with neutrinos
Usual rate: 6 events/day
Kamiokande-II Observation:
12 events in 12.4 s gate
SN-II models:
$10^{43}$ neutrinos cross Earth in 10s
$10^{16}$ neutrinos cross detector
10 neutrinos interact

Kamiokande-II + IMB + Baksan :
25 events - expected E spectrum

From time dispersion at Earth:

$$m_{\bar{\nu}_e} \leq 25\,\mathrm{eV}$$

much larger $\bar{\nu}_e + n \rightarrow e^- + p$ cross-section

## Contents of my talk

1-Neutrino mixing and effective masses

2-Direct and double-beta decay effective mass limits

3-Neutrino oscillation in vacuum and matter effects

4-Principle of oscillation experiment design

5-The main recent negative oscillation searches

6-The solar neutrinos oscillation signal ***

7-The atmospheric neutrinos oscillation signal **

8-The beam dump neutrinos oscillation signal *

9-Summary on one slide

10-The home work for the next twenty years

# Neutrino mixing

- Measurements of neutrino intrinsic properties are obtained with $\nu_\ell$ or $\bar{\nu}_\ell$ of definite flavour $\ell = e, \mu, \tau$ produced by CC with lepton $\ell^{\pm}$

- If neutrinos are massive, a priori mixing

  $\nu_\ell \quad \ell = e, \mu, \tau$ family eigenstates

  $\nu_k \quad k = 1,3$ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \left.\begin{aligned} \nu_\ell &= \sum_{k=1,}^{3} U_{\ell k}\, \nu_k \\ \sum_{k=1,}^{3} |U_{\ell k}|^2 &= 1 \end{aligned}\right\} \ \ell = e, \mu, \tau$$

4 (6) parameters $\begin{cases} 3 \text{ mixing angles} \\ 1\ (3) \text{ phases} \end{cases}$

Dirac (Majorana)

- Extension to $\geq 4$ mass eigenstates straightforward but additionnal flavour eigenstates are sterile :

  $N(\text{active neutrino with } m < M_Z/2) = 2.994 \pm 0.012$ from $Z^0$ invisible width at LEP

- In contrast to quarks (small off-diagonal CKM matrix terms):

  two oscillation results point to large or maximal mixing

$\Rightarrow$ no dominant $\nu_k \leftrightarrow \nu_\ell$ association

- Effective measurement of $\nu_\ell$ mass (and intrinsic properties)

$$m^{2\,eff}_{\nu_\ell} = \sum_{k=1,}^{3} \left|U_{\ell k}\right|^2 m^2_{\nu_k}$$

$$m_{\nu_k} \leq m^{eff}_{\nu_\ell} \qquad k = 1,3$$

# Direct effective neutrino mass measurements

**Measure shape of spectra of decay products in which n is emitted**

## $\nu_e$ mass

End point of tritium β-decay : $^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

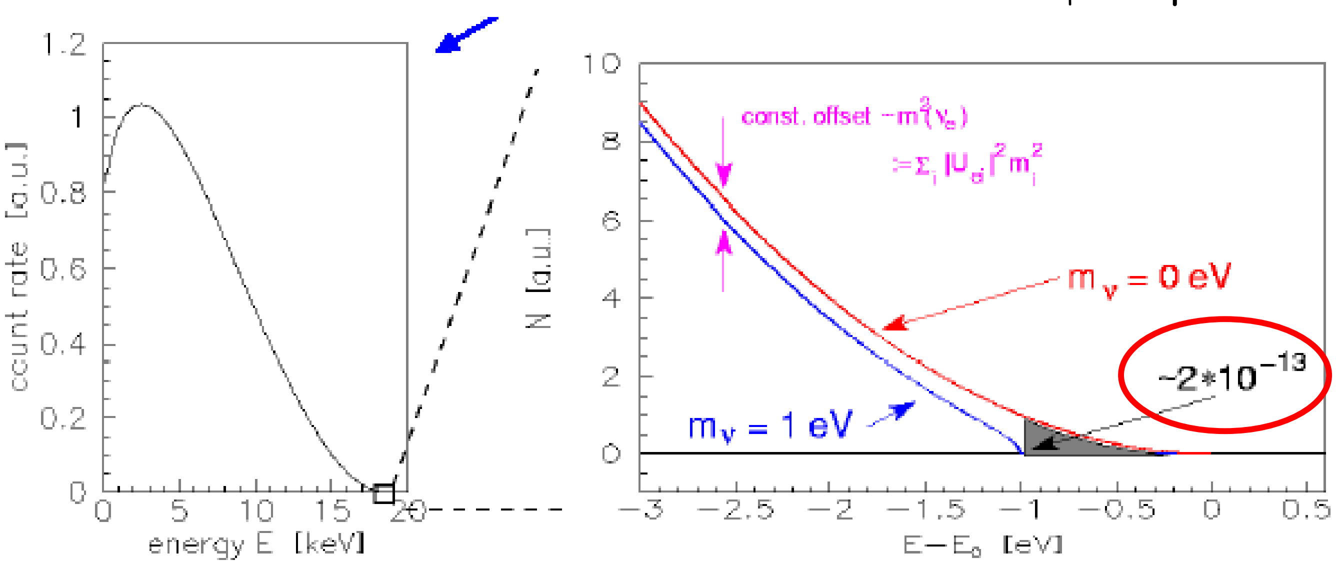
$$\frac{dN(E_e)}{dE_e} \div A\, F(Z,E_e)\; E_e\; p_e \sum_i w_i\, (E_{0i} - E_e)\sqrt{(E_{0i} - E_e)^2 - m_\nu^2}$$

$\Uparrow$

Nuclear matrix element

$E_{0i} = E_e^{max}$ partial decay to final state i

$w_i$ probability of final state i



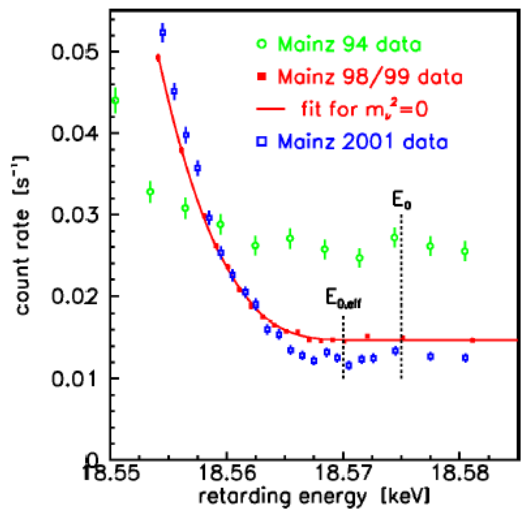

Very high E resolution
& counts rate
Very low background

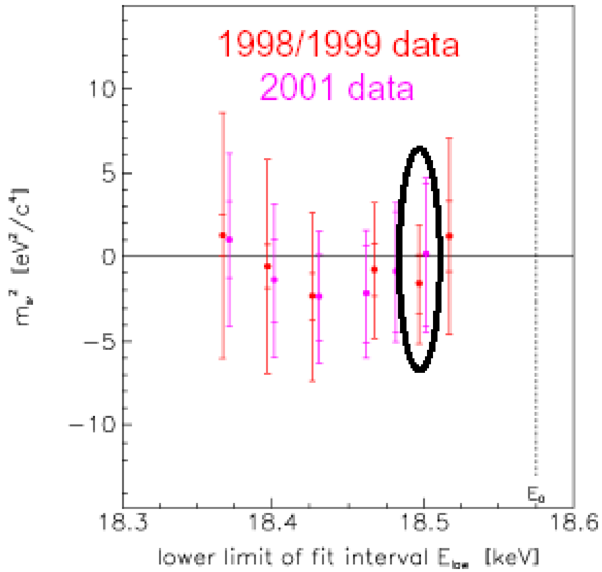
Why tritium? 1- low $E^{max} \approx 18.6$ keV : relative $m_\nu$ effect larger
2- lowest Z : smallest Coulomb effect
3- low density gaseous source
4- high activity : $T_{1/2} = 12.3$ a

Mainz experiment

$m^2_{\nu_e} = -1.2 \pm 2.2 \pm 2.1 \text{ eV}^2$

$m_{\nu_e} < 2.2$ eV at 95% C.L.




Troitsk experiment

$m_{\nu_e} < 2.5$ eV at 95% C.L.

## $\nu_\mu$ and $\nu_\tau$ masses

measure $p_\mu$ in $\pi^+ \to \mu^+ \nu_\mu$ $\quad m_\mu < 170$ keV (Assamagan et al. 1996)

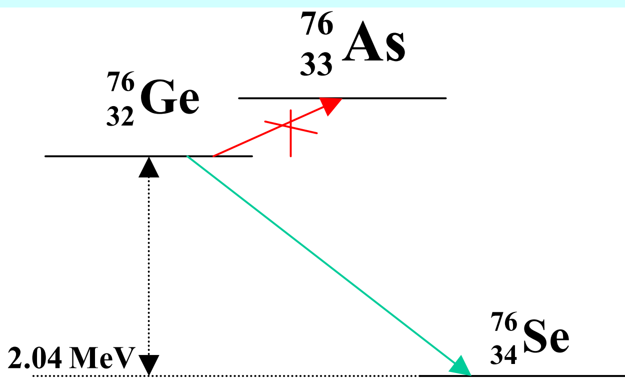
shape of spectra of $\tau$ decay products $\quad m_\tau < 18.2$ MeV (ALEPH @ LEP)

bring little information if the $\Delta m^2$ from oscillation have sense

much larger than the cosmology limit : $\sum_{light} m_\nu + m_{\bar{\nu}} \leq 25$ eV

# Effective neutrino mass from neutrino-less ββ-decay

$(A,Z) \rightarrow (A,Z+2) + 2\ e^- + 2\ \bar{\nu}_e$  $\Delta L = 0$ 2nd order weak interaction




$$T_{1/2}^{Ge,2\nu\beta\beta} = (1.77 \pm 0.01 \pm 0.12)\ 10^{21}\ y$$

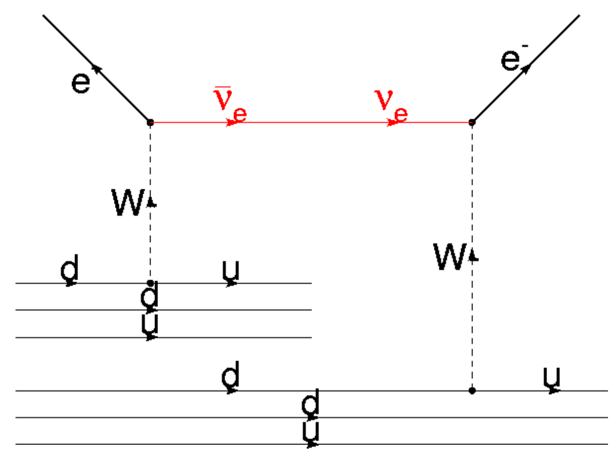
$(A,Z) \rightarrow (A,Z+2) + 2\ e^-$  $\Delta L = 2$ forbidden in SM

- $\bar{\nu}_e$ emitted at vertex 1

  absorbed as $\nu_e$ at vertex 2

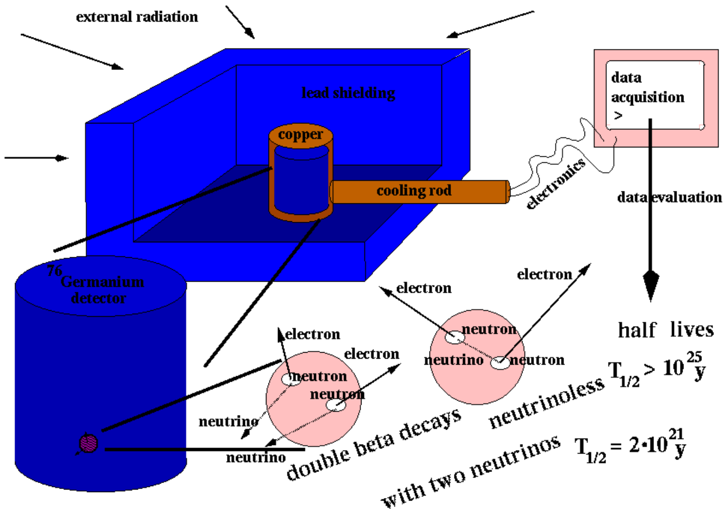
  $\Rightarrow \bar{\nu}_e \equiv \nu_e$  $\Rightarrow$ *Majorana* neutrino
- V-A interaction at each vertex

  $\Rightarrow$ spin flip  $\Rightarrow$ massive neutrino
- Limits on small admixture of right handed current



# Example of an active source experiment: Moscow-Heidelberg experiment

**5 Ge crystals diodes - 11 kg - 86% $^{36}$Ge enriched in Gran Sasso Laboratory**




$2\nu\beta\beta$ - *decay*

model : $T_{1/2}^{2\nu\beta\beta} = (1.38 \pm 0.14) \times 10^{21}$ y

measured : $T_{1/2}^{2\nu\beta\beta} = (1.55 \pm 0.01^{-19}_{-15}) \times 10^{21}$ y

Klapdor-Kleingrothaus HV et al. Eur. Phys. J. 12 (2001) 14

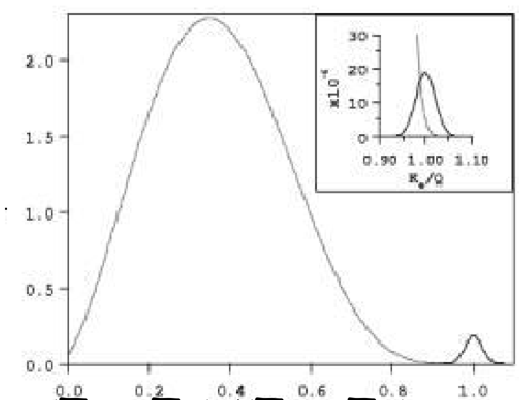
What is measured?

$$\langle m_\nu \rangle \sim \frac{1}{T_{1/2}^{0\nu\beta\beta}}$$

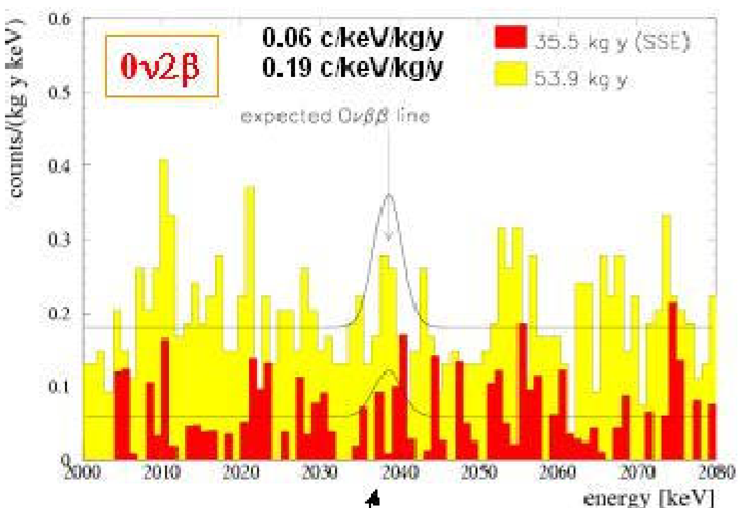
$$\langle m_\nu \rangle = \left| \sum_{i=1}^{n} U_{ei}^2 m_{\nu_i} \right|$$

n Majorana neutrinos

**Signature of 0υββ-decay**



$(T_{e_1} + T_{e_2})/(T_{e_1} + T_{e_2})_{max}$




$T_{1/2}^{0\nu\beta\beta} > 1.9 \times 10^{25}$ y @ 90% C.L.

$\langle m_\nu \rangle < 0.35$ eV

## Current limits

Active targets

| Experiment | Isotope | $T_{1/2}^{0\nu}$ (y) | $\langle m_\nu \rangle$ (eV) |
|---|---|---|---|
| You Ke et al. 1998 | $^{48}Ca$ | $> 9.5 \times 10^{21}$ (76%) | < 8.3 |
| Klapdor-Kleingrothaus 2001 | $^{76}Ge$ | $> 1.9 \times 10^{25}$ | < 0.35 |
| Aalseth et al 2002 | | $> 1.57 \times 10^{25}$ | < 0.33 - 1.35 |
| Elliott et al. 1992 | $^{82}Se$ | $> 2.7 \times 10^{22}$ (68%) | < 5 |
| Ejiri et al. 2001 | $^{100}Mo$ | $> 5.5 \times 10^{22}$ | < 2.1 |
| Danevich et al. 2000 | $^{116}Cd$ | $> 7 \times 10^{22}$ | < 2.6 |
| Bernatowicz et al. 1993 | $^{130/128}Te^*$ | $(3.52 \pm 0.11) \times 10^{-4}$ | < 1.1 – 1.5 |
| Bernatowicz et al. 1993 | $^{128}Te^*$ | $> 7.7 \times 10^{24}$ | < 1.1 – 1.5 |
| Mi DBD – ν 2002 | $^{130}Te$ | $> 2.1 \times 10^{23}$ | < 0.85 – 2.1 |
| Luescher et al. 1998 | $^{136}Xe$ | $> 4.4 \times 10^{23}$ | < 1.8 – 5.2 |
| Belli et al. 2001 | $^{136}Xe$ | $> 7 \times 10^{23}$ | < 1.4 – 4.1 |
| De Silva et al. 1997 | $^{150}Nd$ | $> 1.2 \times 10^{21}$ | < 3 |
| Danevich et al. 2001 | $^{160}Gd$ | $> 1.3 \times 10^{21}$ | < 26 |

$$\langle m_\nu \rangle < \sim 1 \text{ eV}$$

Claim (2001 reanalysis of Moscow-Heidelberg data) for a 2.2-3.1 sigma signal in $^{76}Ge$

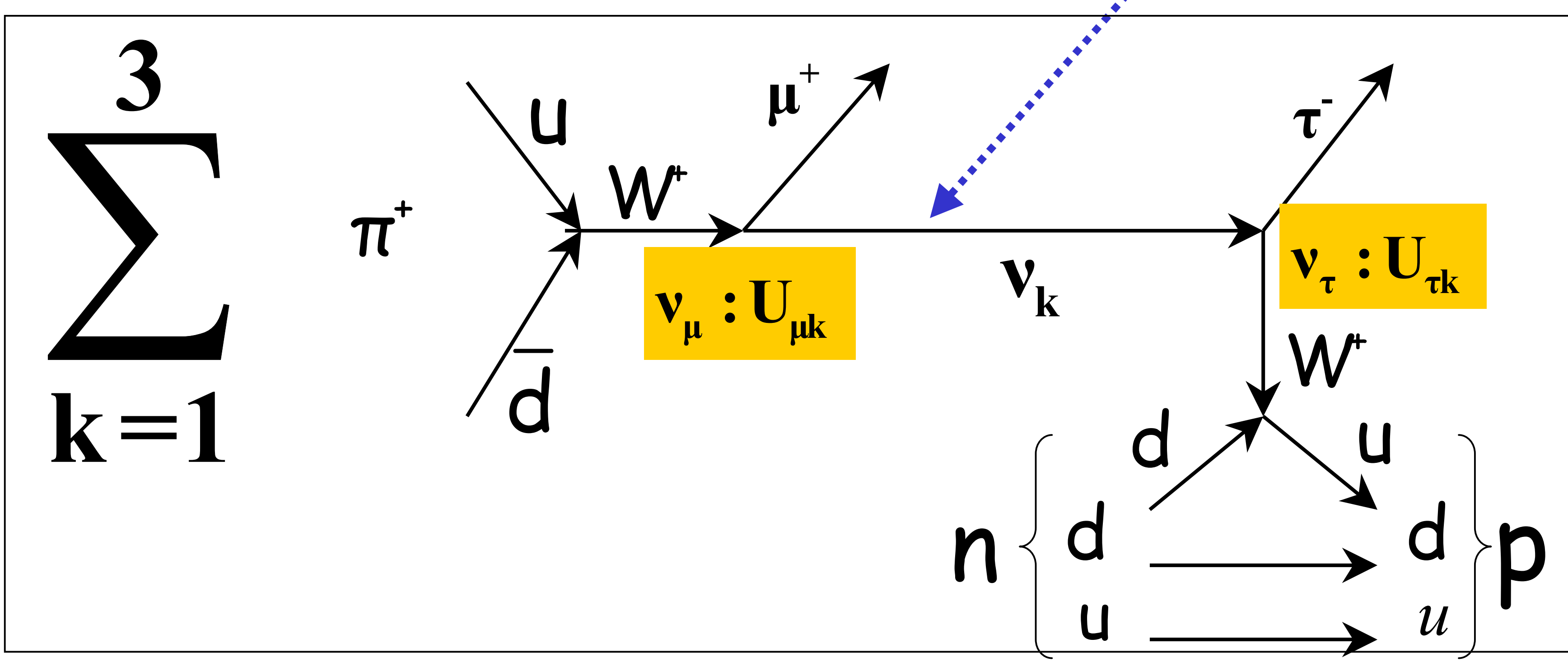
$$< m_\nu >= 0.39^{+17}_{-28} \text{ eV}$$

Wait for confirmation and see ...

# Neutrino oscillation in vacuum

Propagation phase

$$E \approx p \gg m \Rightarrow \; e^{-i(E_k t - p_k L)} \approx e^{-i(m_k^2/(2E))L}$$




IF: Mass - flavour eigenstates mixing
Non-degenerated mass matrix - some masses > 0
Small mass differences for coherent propagation over long $L$

# Oscillation probability (in practical units)

$$P(\nu_\ell(L=0) \to \nu_{\ell'}(L)) = \delta_{\ell\ell'} -$$

$$-4\sum_{k'>k}^{1,3} \underbrace{\Re\left(U^*_{\ell'k'}U_{\ell'k}U_{\ell k'}U^*_{\ell k}\right)}_{\text{Mixings define Maximum probability}} \quad \underbrace{\sin^2 1.27\frac{\Delta m^2_{kk'}[eV^2]\,L[km]}{E[GeV]}}_{\text{L/E Oscillation term}}$$

$$+2\sum_{k'>k}^{1,3} \Im\left(U^*_{\ell'k'}U_{\ell'k}U_{\ell k'}U^*_{\ell k}\right) \quad \sin 2.54\frac{\Delta m^2_{kk'}[eV^2]\,L[km]}{E[GeV]}$$

$\Delta m^2_{kk'} = m^2_k - m^2_{k'}$ $\qquad\qquad$ $\Delta m^2_{12} + \Delta m^2_{23} + \Delta m^2_{31} = 0$

6 parameters : 3 mixing angles , 1 CP violation phase, 2 $\Delta m^2_{kk'}$

- not sensitive to two additional Majorana CP violation phases
- cannot distinguish Dirac - Majorana
- if CPT : $P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}\ ;U) = P(\nu_{\ell'} \to \nu_\ell\ ;U) = P(\nu_\ell \to \nu_{\ell'}\ ;U^*)$

## One mixing negligible : effective 2-family approximation

e.g. $\nu_\tau \approx \nu_3$

$$U \approx \begin{pmatrix} \cos\theta_{e\mu} & \sin\theta_{e\mu} \\ -\sin\theta_{e\mu} & \cos\theta_{e\mu} \end{pmatrix}$$

1 mixing angle, no phase

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{e\mu} \quad \sin^2(1.27 \frac{\Delta m^2_{12} L}{E})$$

## All mixings small : effective 2-family approximation

all $\nu_l \approx \nu_k$

$$U \approx \begin{pmatrix} 1 & \theta_{e\mu} & \theta_{e\tau} \\ -\theta_{e\mu} & 1 & \theta_{\mu\tau} \\ -\theta_{e\tau} & -\theta_{\mu\tau} & 1 \end{pmatrix}$$

$$P(\nu_l \to \nu_{l'\neq l}) = (2\theta_{ll'}) \quad \sin^2(1.27 \frac{\Delta m^2_{kk'} L}{E})$$

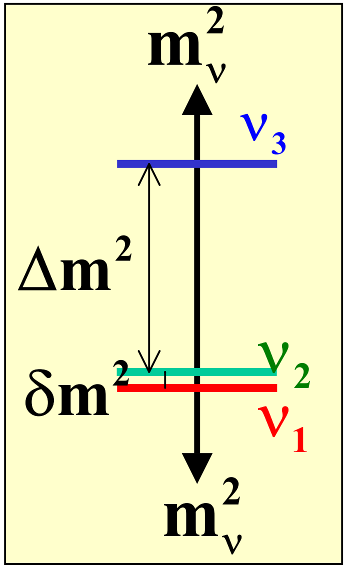
# If strong mass hierarchy : effective 2-family approximation

if $m_3 \gg m_1, m_2$ like quarks and charged leptons

$$\Delta m^2 = m_3^2 - m_1^2 \approx m_3^2 - m_2^2$$

$$\delta m^2 = m_2^2 - m_1^2$$

$$\Delta m^2 \gg \delta m^2$$




L/E region where $\Delta m^2 L/E$ causes oscillation

and $\delta m^2 L/E \approx 0$

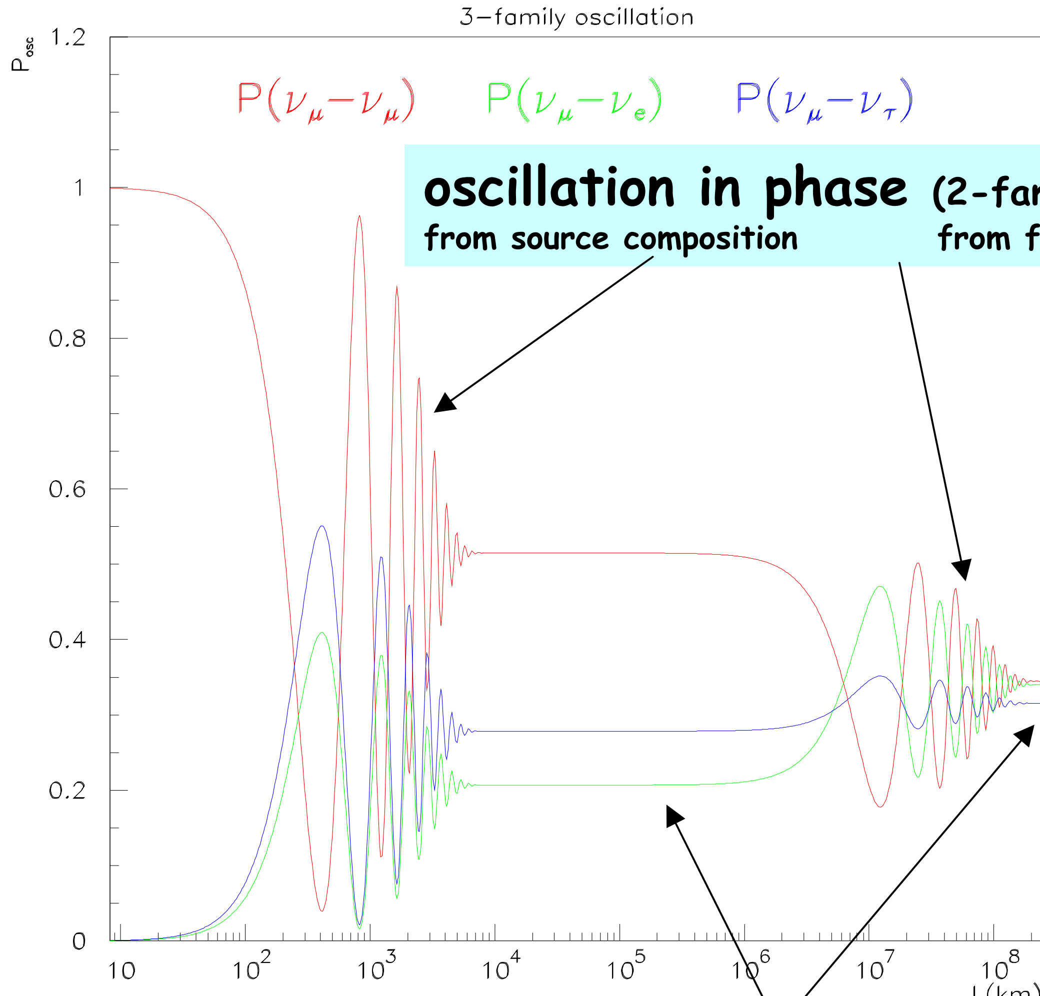
$$P(\nu_l \to \nu_{l' \neq l}) \approx \sin^2 2\theta_{ll'}^{eff} \sin^2(1.27 \Delta m^2 L/E)$$

$$\sin^2 2\theta_{ll'}^{eff} = 4 \left| U_{l3}^* U_{l'3} \right|^2$$

$$P(\nu_l \to \nu_l) = 1 - 4 \left| U_{l3} \right|^2 \left( 1 - \left| U_{l3} \right|^2 \right) \sin^2(1.27 \Delta m^2 L/E)$$

Physics governed by:
- $\Delta m^2$
- family composition of $\nu_3$ only

# Example of 2-family approximation: large mixing and strong mass hierarchy




**oscillation in phase** (2-family like)

from source composition | from first process

$E = 1GeV$

**strong mass hierarchy**

$\Delta m^2 = 3\times10^{-3} eV^2 \rightarrow \lambda = 825 km$

$\delta m^2 = 1\times10^{-7} eV^2 \rightarrow \Lambda = 2.5 \times 10^7 km$

**large mixing**

$$U = \begin{pmatrix} -0.567 & 0.820 & -0.0782 \\ 0.515 & 0.279 & -0.811 \\ 0.643 & 0.500 & 0.580 \end{pmatrix}$$

**oscillation damping for large $\Delta m^2$**
**dispersion and resolution in L/E**

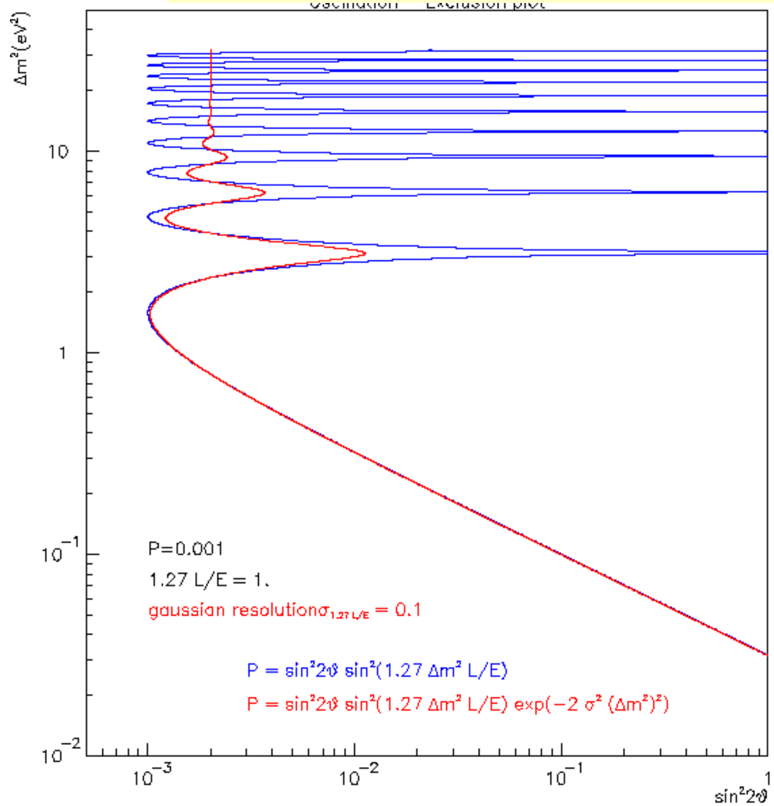
$$\left\langle \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)\right\rangle \Rightarrow \frac{1}{2}$$

Two – flavour oscillation in vacuum, e.g.

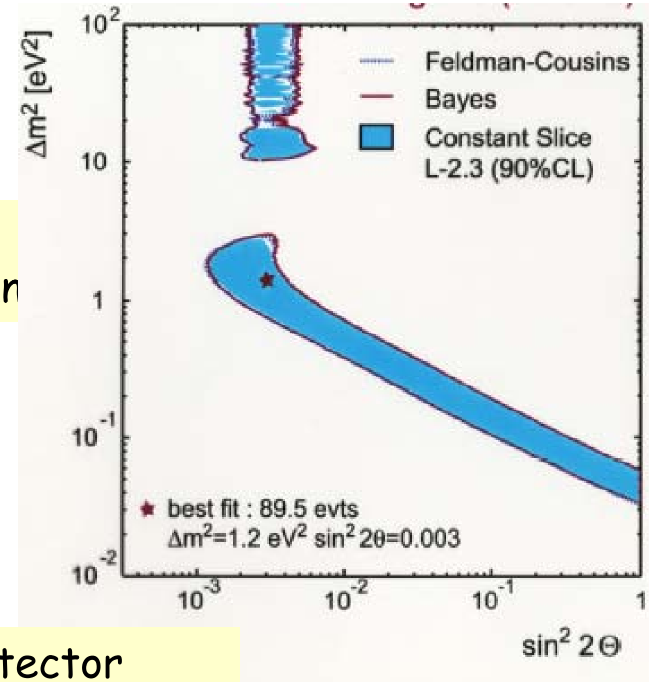
$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_{e\mu} \quad \sin^2(1.27 \quad \frac{\Delta m_{12}^2 L}{E})$$

- take $m_2^2 > m_1^2$ by convention
- cannot distinguish $\theta_{e\mu}$ from $\pi/2 - \theta_{e\mu}$ : 2 mixing solutions

# No signal : exclusion region

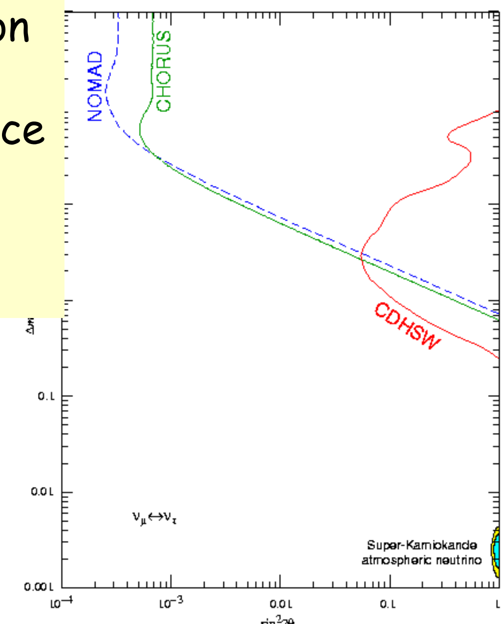



If signal :
allowed ban




If "long" detector
- assume no oscillation at small L
- search disappearance at large L

$\Rightarrow$ no information at large $\Delta m^2$




- $P_{osc}^{max} = (\sin^2 2\theta)_{min}$ at given C.L. : experiment nunber

$$\Delta m^2 = \frac{\pi/2}{1.27\langle L/E\rangle}$$

- if $\sin^2 2\theta = 1$ (full mixing) : $(\Delta m^2)_{min} = \dfrac{\sqrt{P_{osc}^{max}}}{1.27\langle L/E\rangle}$
- at small $\Delta m^2$ : $\log(\Delta m^2) = -\dfrac{1}{2}\log(\sin^2 2\theta) + \log\left((\Delta m^2)_{min}\right)$
- at large $\Delta m^2 >> E/L$ : damping : $\sin^2 2\theta = 2P_{osc}^{max}$

# Matter effect on neutrino oscillations

- Propagation phase in matter for weakly interacting particles

$$e^{ipx}e^{-iEt} \Rightarrow e^{inpx}e^{-iEt} \qquad n = 1 + 2\pi\rho f(0)/E \quad \text{with} \begin{cases} \rho = \text{matter density} \\ f(0) = \text{forward diffusion amplitude} \end{cases}$$

$$E_\nu = 1\,\text{MeV}: \qquad 0 < |n-1| = 6.10^{-19}\frac{Z}{A}\rho\,[\text{g cm}^{-3}] \ll 1$$

- $\nu_e, \nu_\mu, \nu_\tau, \nu_s$ have different interactions thus $n_{e,\mu,\tau,s}$ :

$$\nu_{e,\mu,\tau} + e^-, q \to \nu_{e,\mu,\tau} + e^-, q \quad \text{(NC)}$$

$$\nu_e + e^- \to e^- \nu_e \quad \text{(CC)}$$

$$\nu_s \quad \text{no interaction}$$

- Mass eigenstates have different family eigenstates composition ⇒

Coherence of propagation affected by electron density $\rho_e(r)$ in matter

- $$\begin{pmatrix} H^{ee}_{mat} & H^{\mu e}_{mat} \\ H^{e\mu}_{mat} & H^{\mu\mu}_{mat} \end{pmatrix}(r) = \begin{pmatrix} E_1\cos^2\theta + E_2\sin^2\theta + V(r) & (E_1 - E_2)\sin\theta\cos\theta \\ (E_1 - E_2)\sin\theta\cos\theta & E_1\sin^2\theta + E_2\cos^2\theta \end{pmatrix}$$

$\nu_e$ CC interactions: $V(r) = \sqrt{2}\,G_F\,\rho_e(r) > 0$ ⇒ matter effects resolve $\theta$ from $\pi/2-\theta$

$\sin^2 2\theta \Rightarrow \tan^2\theta$

# Slow variation of $\rho_e$ : example of the Sun

- at $r \approx 0$ : $\rho_e \approx 10^{26}\,\text{cm}^{-3}$ $\Rightarrow V \ll$ typical E of observable $\nu \approx$ some MeV

  $\nu$ created as a $\nu_e$ and approximately as heavier (V>0) propagation eigenstates $\nu_2^m(r \approx 0)$
- propagation eigenstate to be evaluated at each r

- adiabatic regime: slow $\rho_e(r)$ variation

  propagation state remains r-dependant eigenstate

  flavour composition vary with $\rho_e(r)$

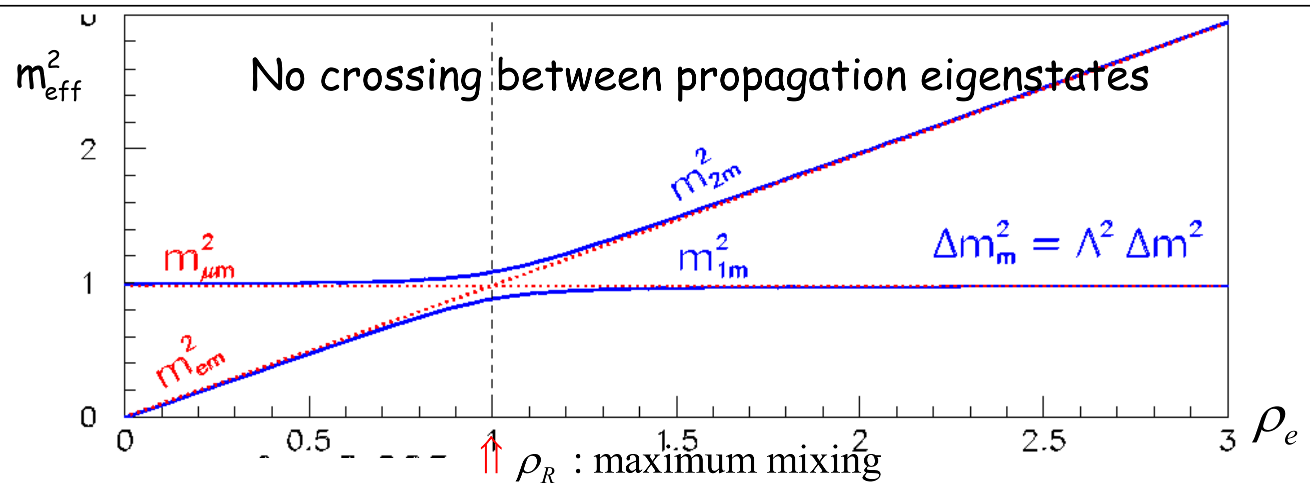
**MSW effect**

- at $\rho_e = 0$ : eigenstate propagation to Earth

  $\nu_2 = \nu_e \sin(\theta) + \nu_\mu \cos(\theta)$

at Earth : $P(\nu_e \rightarrow \nu_e) = \sin^2(\theta)$

the smaller the mixing in vacuum, the smaller the survival probability



# Experiment design : max $P_{osc}$ if $\langle E\rangle/L=2.54\times\Delta m^2/\pi$

Disappearance evidence:

measured flux of a given flavour smaller than expected from calculation or measurement at small distance

Pros: small contamination by other flavours unimportant
flux measurable by NC interactions : no threshold

Cons:effect must be large $N_{obs} < N_{exp} - 4\sqrt{N_{exp}}$

Appearance evidence:

measured flux of given flavour is larger than expected

Pros: one event is enough if the flavour is absent at the source

Cons: very small background known with high precision
flavour identified by CC interaction :
$E_{thresold}$ for $\mu$ >> nuclear physics energy domain
for $\tau$ : ~ 4 GeV with slowly growing cross-section

Natural sources are what they are.
Reactor : L optimised, becomes difficult for Long Base Line (flux, location).
Accelerator : mainly $\nu_\mu$ beams with contamination in $\nu_e$ ~ 1%,
$\langle E\rangle/L$ optimised, becomes difficult for Long Base Line.
Very small event rates (except near human made sources) $\Rightarrow$ buried detectors

# The experimental evidences in one slide

***** Solar neutrinos**

- $\nu_e$ flux measured at Earth < 1/2 prediction of Standard Solar Model
- total $\nu$ flux measured agrees with prediction of SSM $\Leftarrow$ new SNO result

  $\Rightarrow \nu_e \to \nu_x$ combination of $\nu_\mu - \nu_\tau$
- preferred region : $10^{-5} eV^2 < \Delta m^2 < 10^{-4} eV^2$

  large mixing $0.3 < \tan^2\theta < 0.6$

  MSW effect in Sun

**** Atmos-pheric neutrinos**

- $\nu_e$ flux measured at Earth agrees with models of cosmic rays interactions
- $\nu_\mu$ flux measured at Earth $\approx$ 1/2 of models predictions

  with strong zenithal dependence $\Rightarrow \nu_\mu \to \nu_\tau$ (prefered) or $\nu_s$
- preferred region : $1.5 \times 10^{-3} eV^2 < \Delta m^2 < 4 \times 10^{-3} eV^2$

  maximun mixing $\sin^2 2\theta \simeq 1$

  "vacuum" oscillation with small Earth matter effects

*** Accelerator neutrinos**

- $\bar{\nu}_e$ $(\nu_e)$ in excess to small contamination in $\bar{\nu}_\mu$ $(\nu_\mu)$ beam

  see by one of two experiments, statistically not contradictory
- preferred region : large $\Delta m^2 > 0.5\ eV^2$

  small mixing $\sin^2 2\theta < 5 \times 10^{-3}$

# The main recent exclusions in four slides

## Chooz (& Palo Verde) long base line reactor experiments

$\bar{\nu}_e$ disappearance at $\Delta m^2 > 10^{-3}$ $eV^2$

motivation : $\Delta m^2$ of atmospheric neutrinos signal

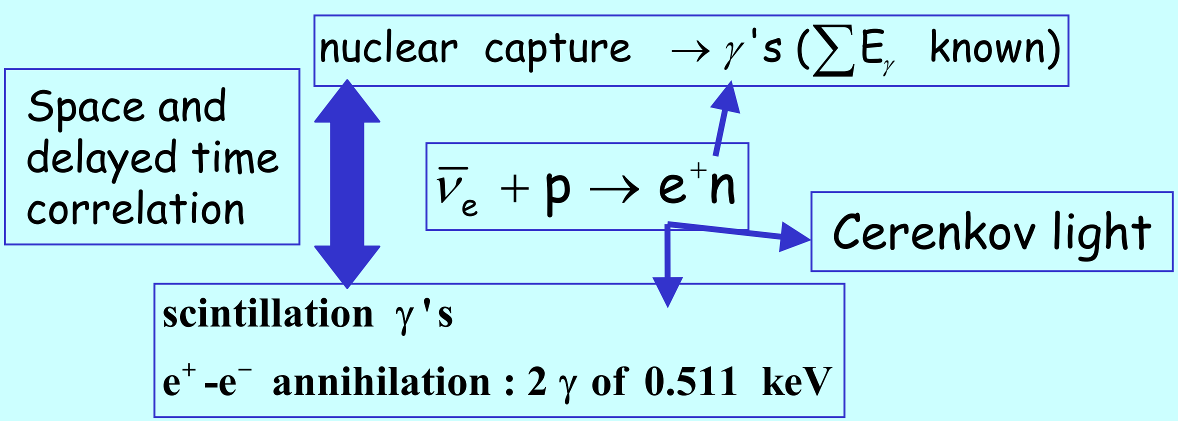
limit on $\nu_\mu \to \nu_e$ contribution to $\nu_\mu$ disappearance

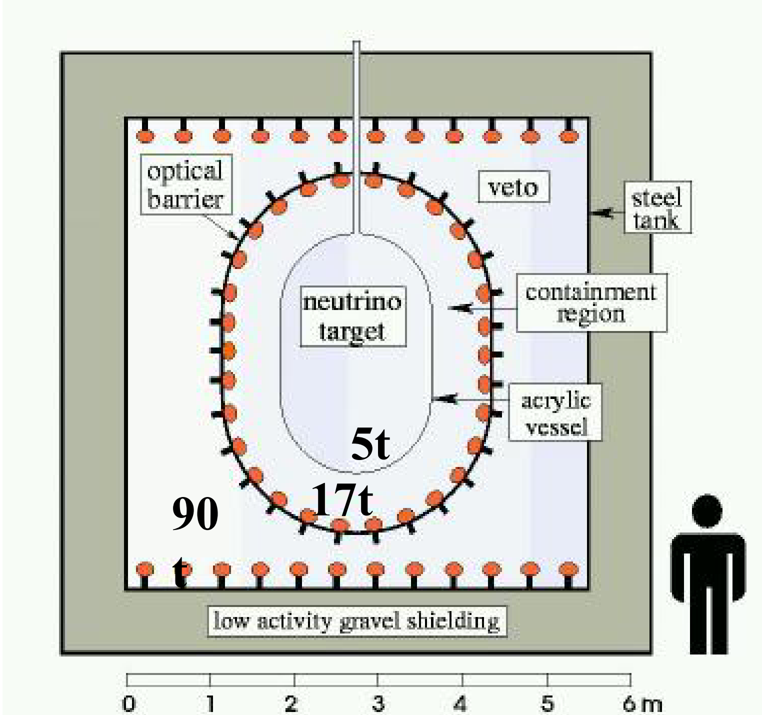
$\langle E \rangle \approx 3$ MeV $\Rightarrow$ L $\approx 1$ km : 2 reactors (8.5GW) @ L= 998, 1114m

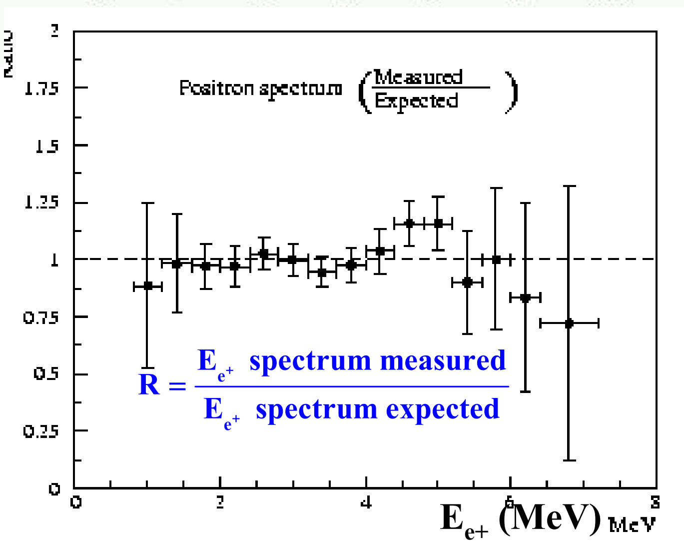
overburden under 300 m water equivalent : 0.4 cosmic muon $m^{-2}$ $s^{-1}$

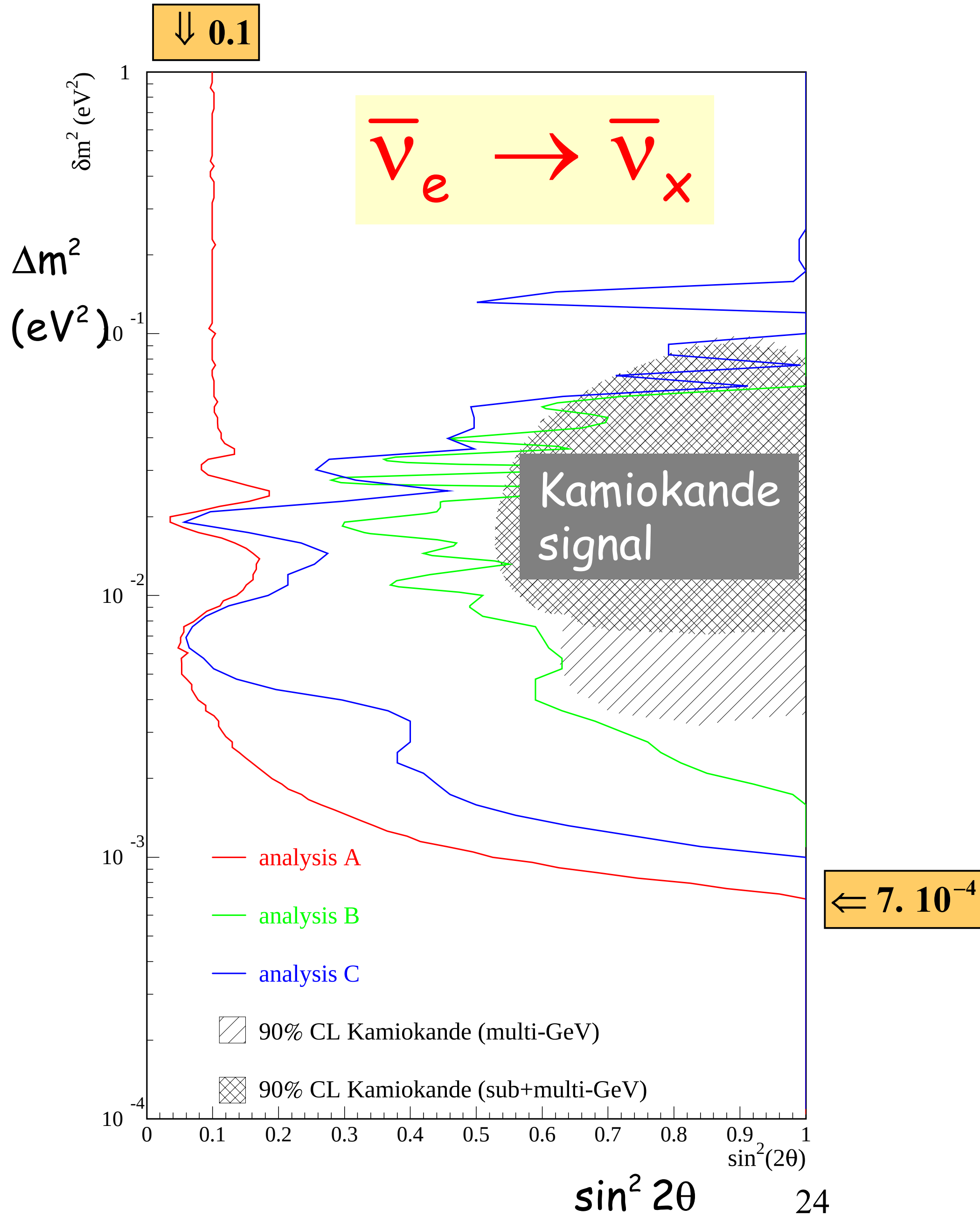
Gd-doped liquid scintillator vessel + PM tubes

Standard scheme of $\bar{\nu}_e$ detection via inverse $\beta$ decay in liquid scintillator (mineral oil)






$$R = 1.010 \pm 0.028(\text{stat}) \pm 0.027(\text{syst})$$

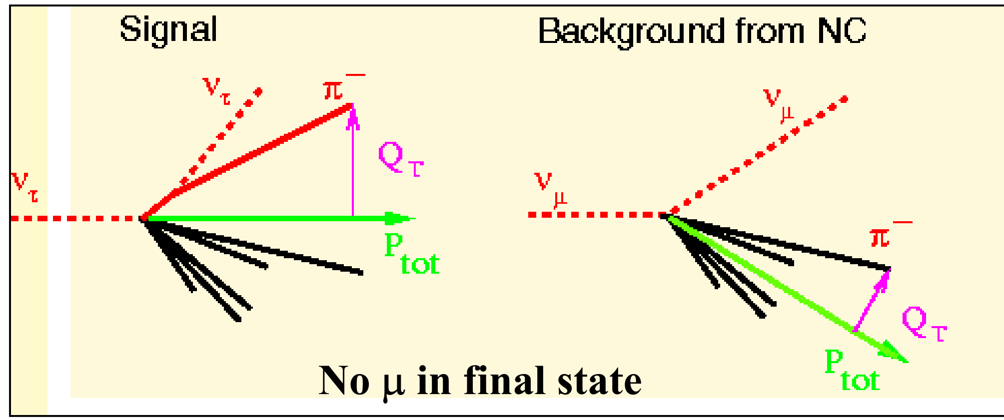
# CHORUS & NOMAD at CERN

$\nu_\mu \to \nu_\tau$ (and $\nu_e \to \nu_\tau$) in high E $\nu_\mu(\nu_e)$ accelerator beams at $\Delta m^2 > 1\ eV^2$

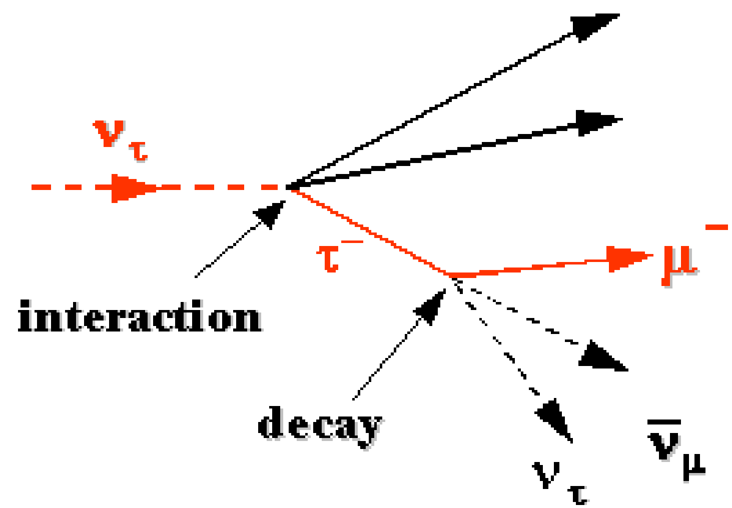
motivation : masses of cosmological relevance for hot dark matter

no intrinsic $\nu_\tau$ background

NOMAD: kinematics of $\nu_{\mu,e}$ NC event and $\nu_\tau$ CC event

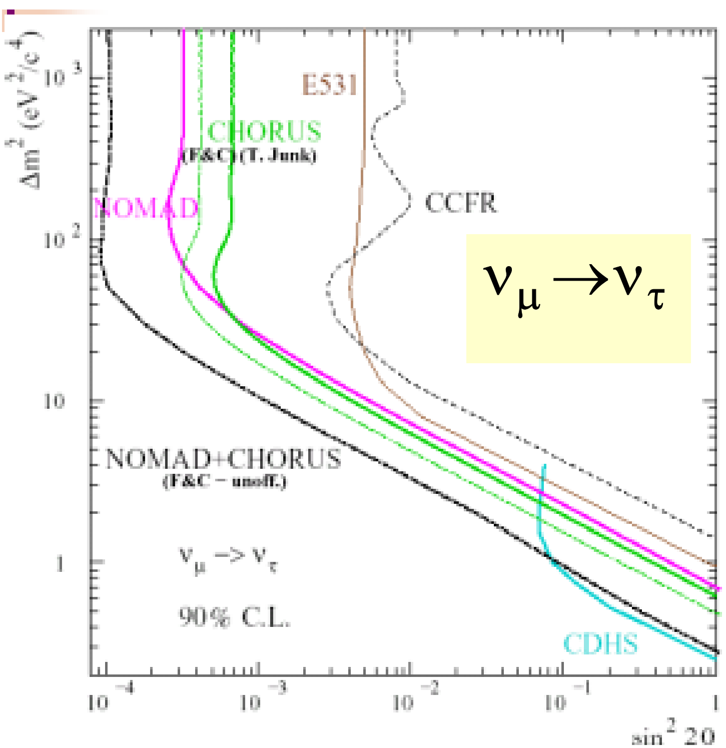



CHORUS: Observe $\tau$ track ($\beta\gamma c\tau \approx 1$ mm) in high resolution 770 kg nuclear emulsion target

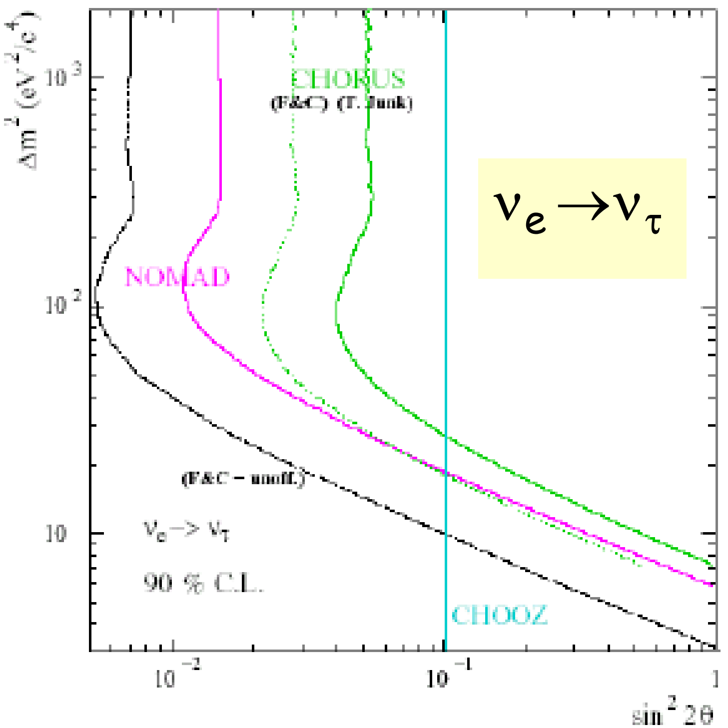


# Combined CHORUS&NOMAD exclusion contours

| | events | $\nu_\tau$ candidates | expected background |
|---|---|---|---|
| CHORUS | 7018 | 0 | 1.2 |
| NOMAD | 8844 | 1 | 1.69 |




$P \leq 5 \times 10^{-5}$




$P \leq 4 \times 10^{-3}$

Combination unpublished
courtesy R.Peti (NOMAD)

# Solar neutrinos experiments

1962: Ray Davis builds first large underground detector to observe neutrinos from the Sun

1968: First indication of solar neutrinos deficit problem
compare measured flux with predictions of newly born Solar Standard Model from John Bachall

Until 2002:

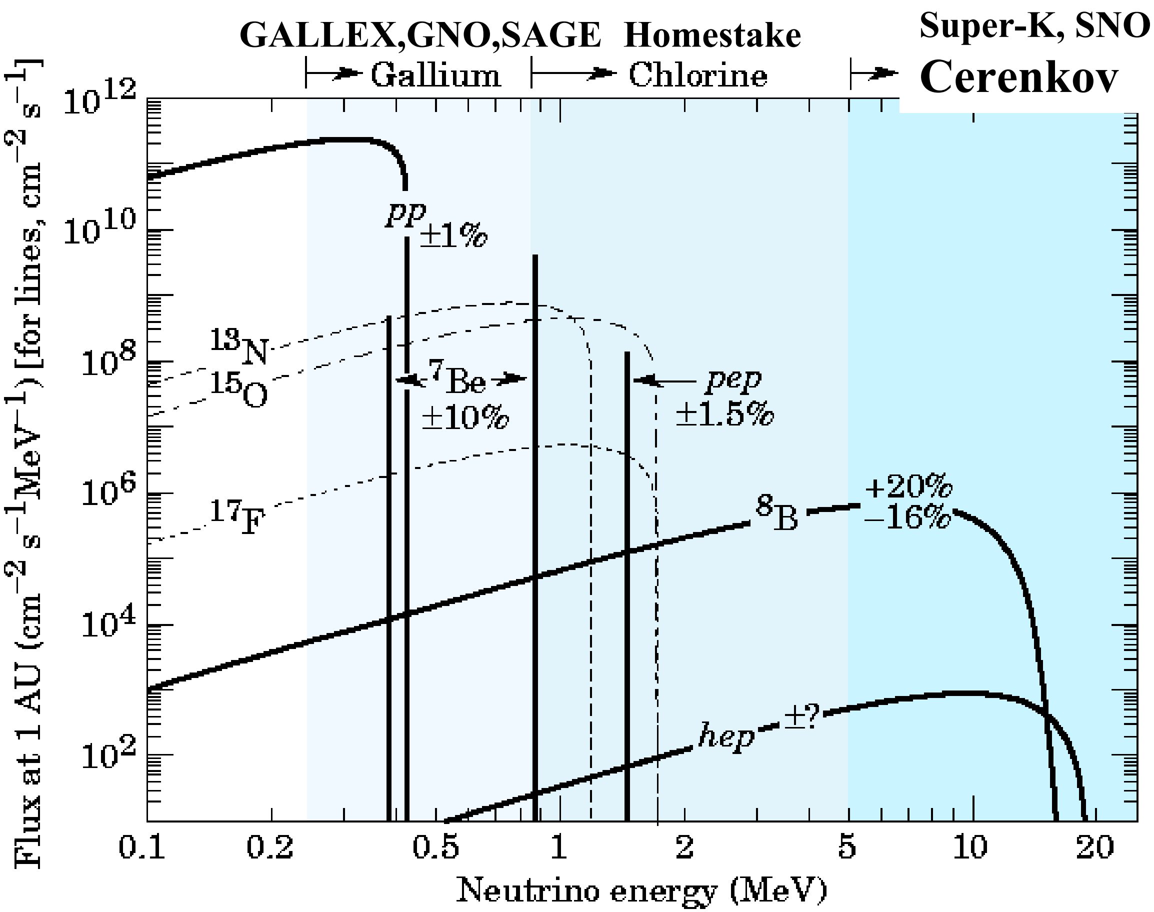
- strong deficit confirmed by all experiments.
- different deficits in energy domains populated by neutrinos emitted in very correlated reactions in solar nuclear fusion chain, unless SSM is totally wrong
- 40 years of SSM upgrade and tuning : many successes
  helio-seismography to better than 1%

Natural explanation:

- solar $\nu_e$ oscillate to $\nu_x$ in the Sun (MSW) or in vacuum between Sun and Earth

# Solar neutrinos spectrum
# Detectors / experiments thresholds

$$4\ {}^{1}H \rightarrow {}^{4}He + 2\ e^{+} + 2\ \nu_e + 25\ \text{MeV}$$




$\Phi(\text{Sun}) = 1.8 \times 10^{38}\ \nu_e\ s^{-1}$

$\Phi(\text{Earth}) = 6.5\ 10^{10}\ \nu_e\ cm^{-2}\ s^{-1}$

$\nu_{pp}$ 99.75% of flux:

bound by Sun luminosity

$\nu_{Be}$ and $\nu_B$ fluxes not well known

but

strong correlation $\nu_{Be} - \nu_B$ fluxes

## Low threshold radio-chemical counting experiments

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

lowest possible threshold

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 ($^{51}Cr$, 1.8 MCi !!!)

## The glorious Homestake (1968-99) 31 years of datataking, 2000 interactions)

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

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

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

## Gallium experiments : GALLEX, GNO (under Gran Sasso) , SAGE (Baksan mine)

1992-97 1998- 1991-

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

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

Prime inportance to measure the bulk of the flux

# Real-time water Cerenkov experiments : Kamiokande II & Super-K
1987-95 1996-

Cerenkov light from elastic scattering $\nu + e^- \rightarrow \nu + e^-$

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

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

largest possible target mass : 50 (4) ktons of highly purified water

seen by 11 200 (950) PM tubes arrays

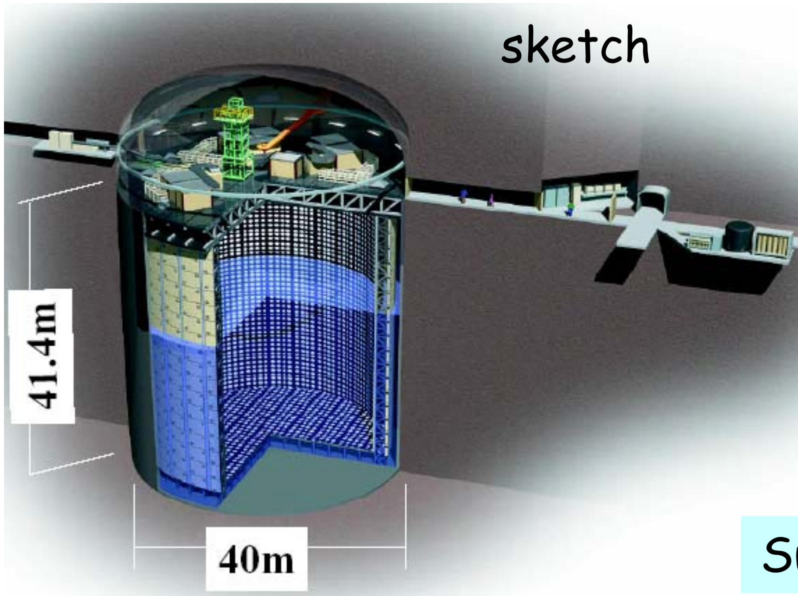
event rate $\approx$ 0.5 event/(kton day)

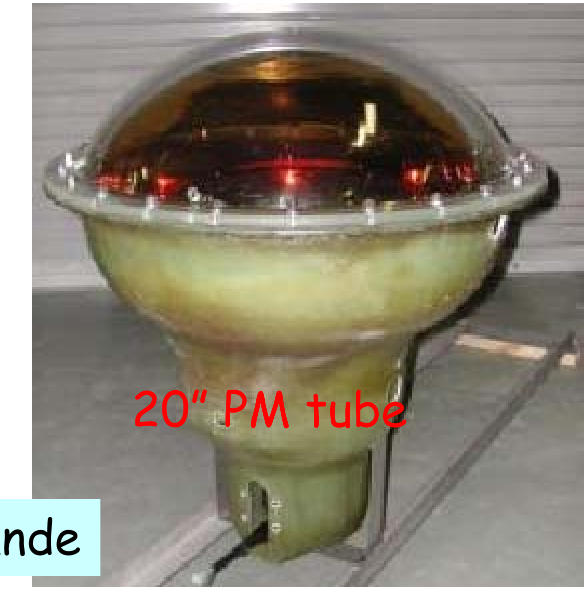
deeply buried in Mozumi mine under Mt Ikenoyama near Kamioka (2700 m.w.e)

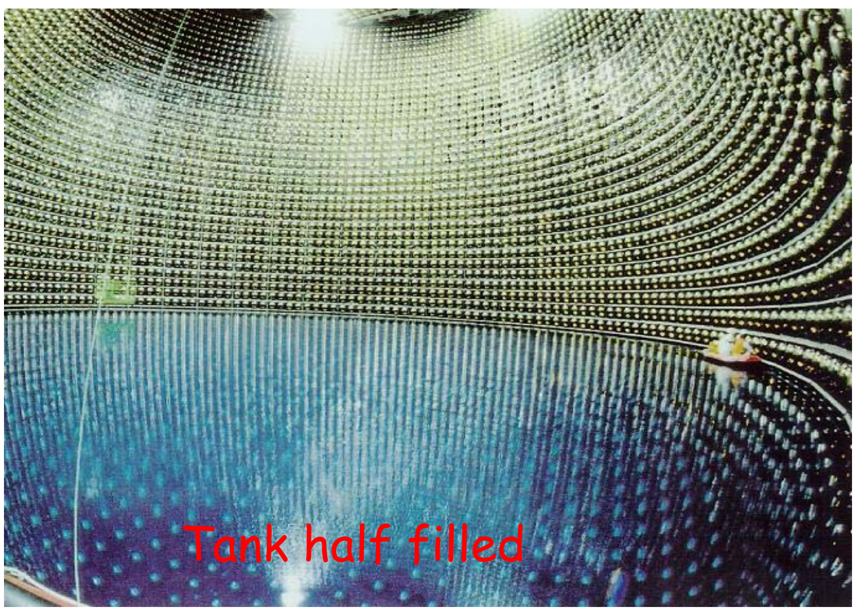
Pros:
- correlation between $e^-$ track and Sun directions : background control
  precise timing of PMT light signal arrival
- electron spectrum measurement : check for distortion
  total light yield collected by the PMT
- real-time : seasonal Sun-Earth distance and day-night Earth matter effects

Cons:
- high energy effective threshold 5 (7) MeV : see only $\nu_B$
- November 12, 2001: 60% PMT imploded in a chain reaction…

Super-Kamiokande




## 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

??? 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%

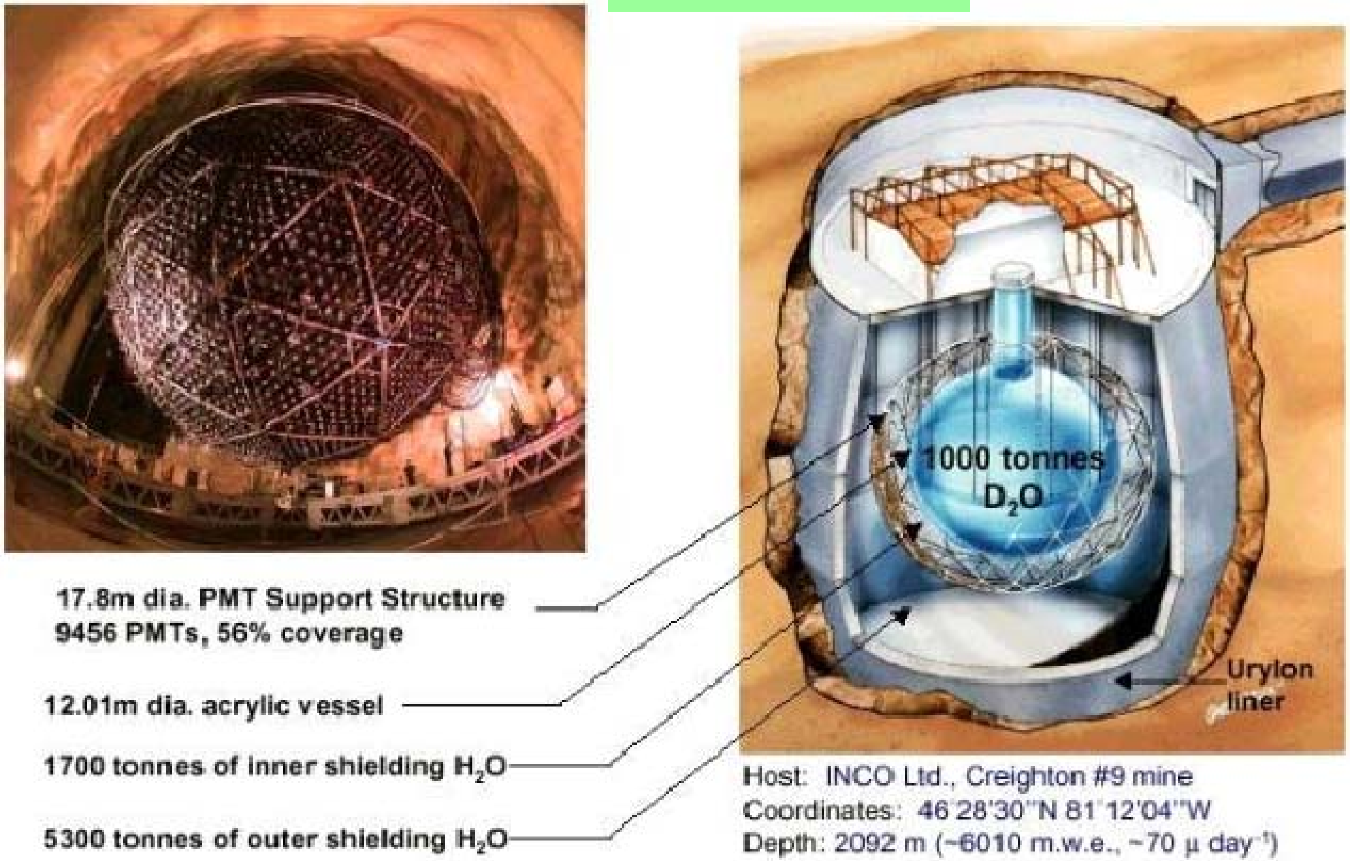
NC : $\nu_{\mu\tau} + e^- \rightarrow \nu_{\mu\tau} + e^-$ 14% some sensitivity

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

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

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

# SNO detector

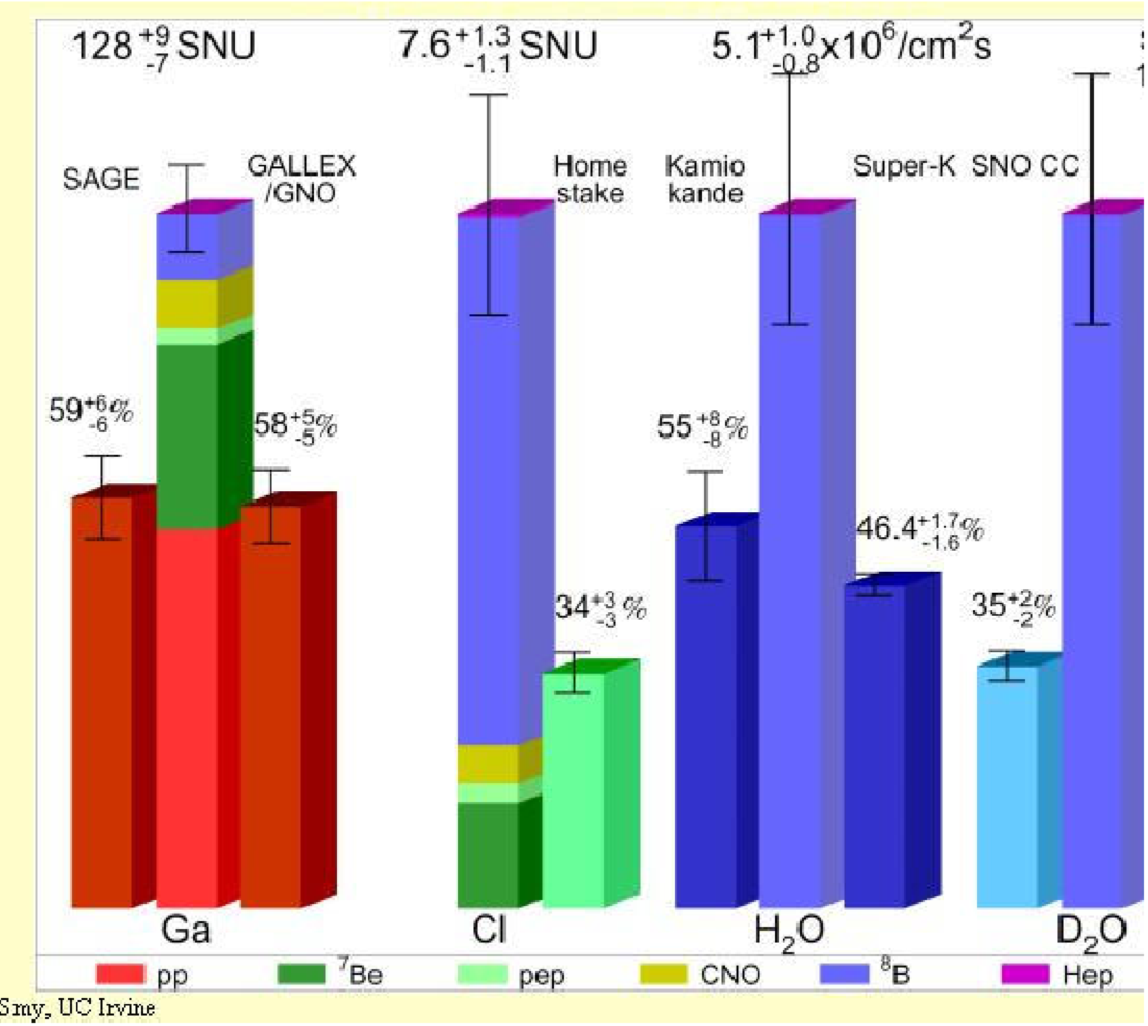



Nucl. Inst. and Meth. A449, p172 (2000)

Neutron detection : ε ~14%

- capture n + d → t + 6.5 MeV γ-ray
- γ-ray conversion to $e^+$- $e^-$ pairs: Cerenkov signal

Measured event rates v.z.SSM predictions as for 2001
… i.e. assuming SNO is a light water Cerenkov experiment




Overall flux deficit :

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

Crude solution

$\Phi^{meas}_{\nu pp} \approx \Phi^{pred}_{\nu pp}$ bound by luminosity

$\Phi^{meas}_{\nu B} \approx 0.5 \times \Phi^{pred}_{\nu B}$ not well known

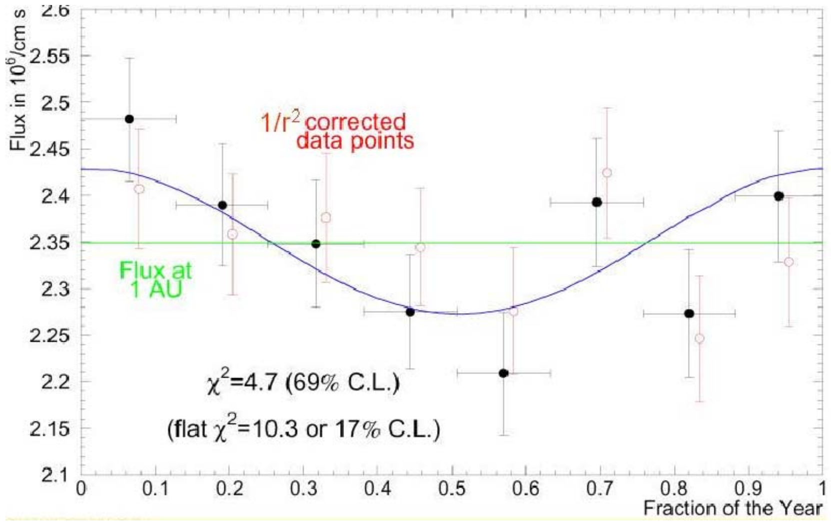
$\Phi^{meas}_{\nu Be} \approx 0$ not well known

But strong $\Phi^{pred}_{\nu Be} - \Phi^{pred}_{\nu B}$ correlation

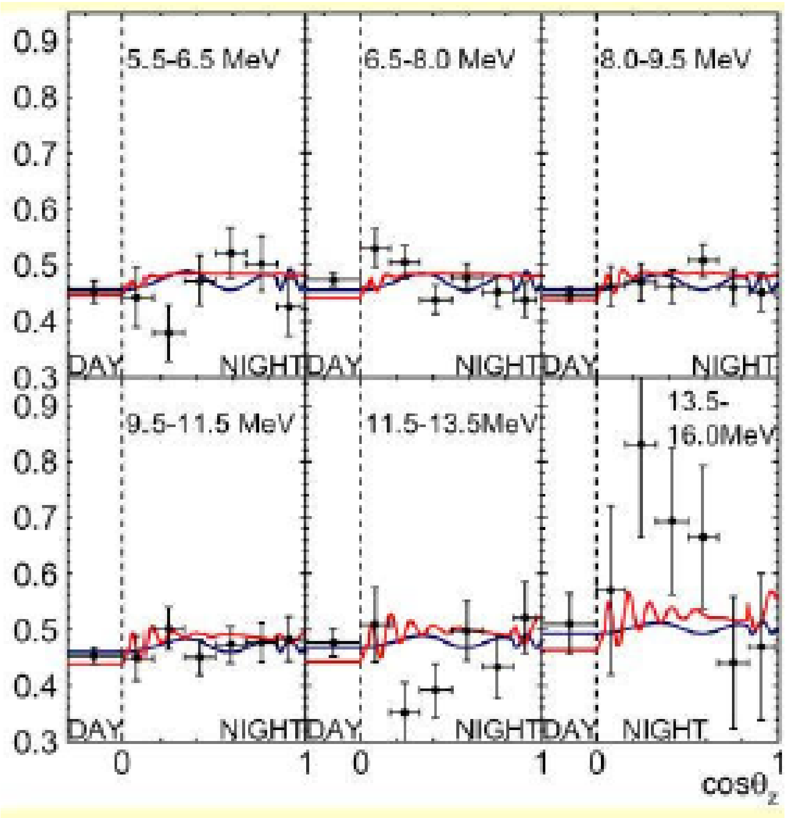
> 30 years of Solar models by many authors.
No, even fancy, astrophysical explanation
> 30 years of experiments using four techniques.
No instrumental explanation.

# Other main Super-K pre-SNO 2002 observations

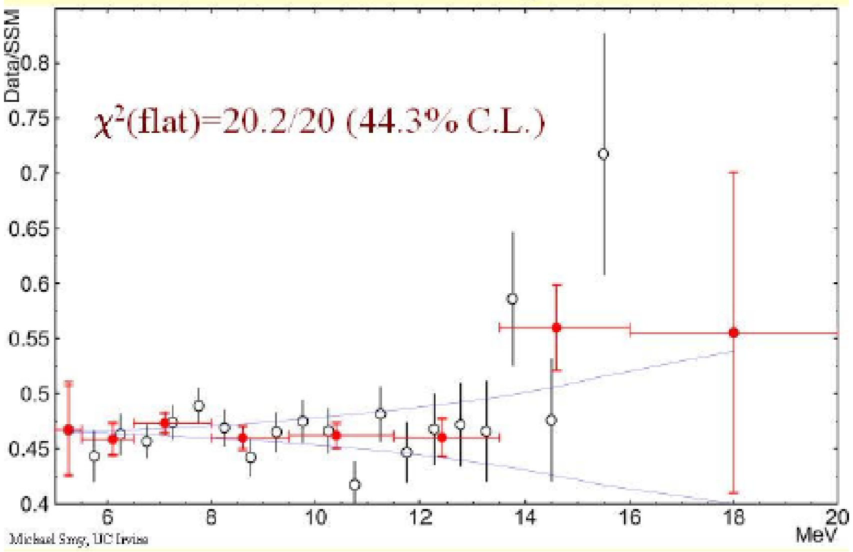
No seasonal variation: length in vacuum




No zenith angle variation
Earth matter effect

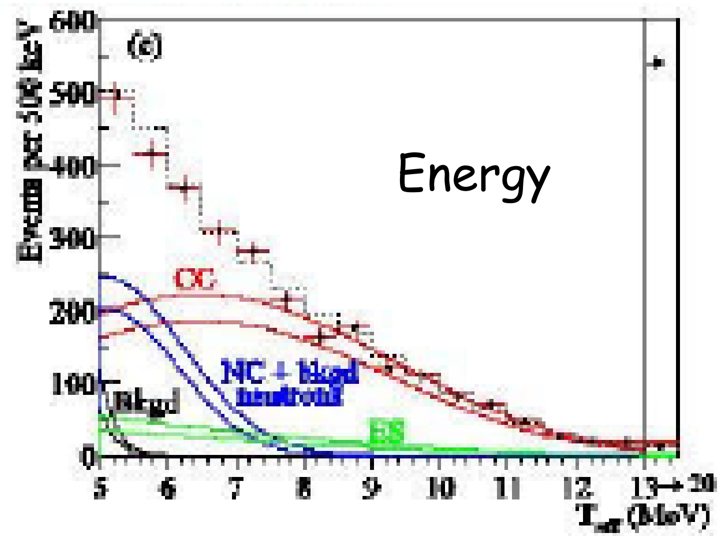


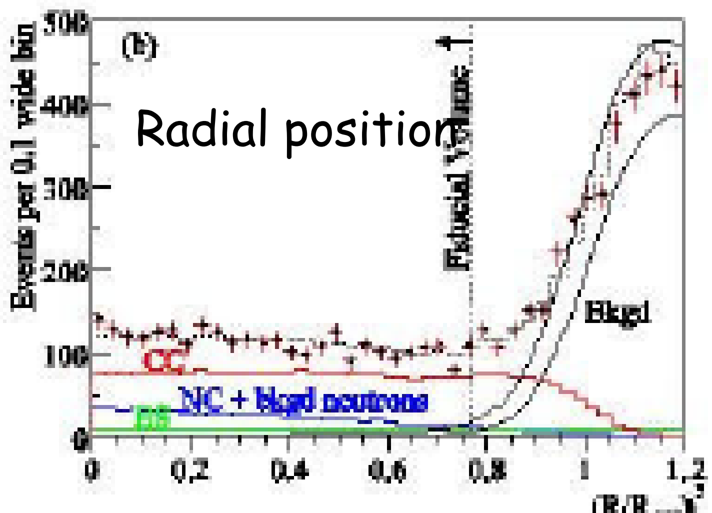

No $\nu_B$ spectral distortion :
E dependence of oscillation prob

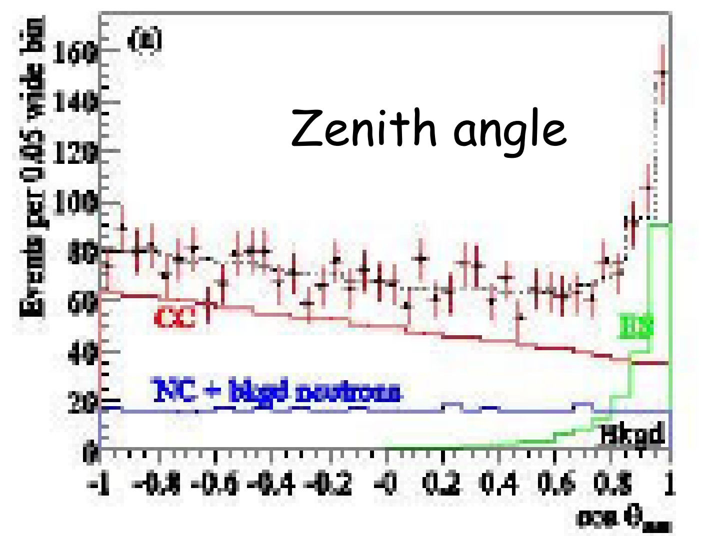


## And then, came SNO 2002 ...

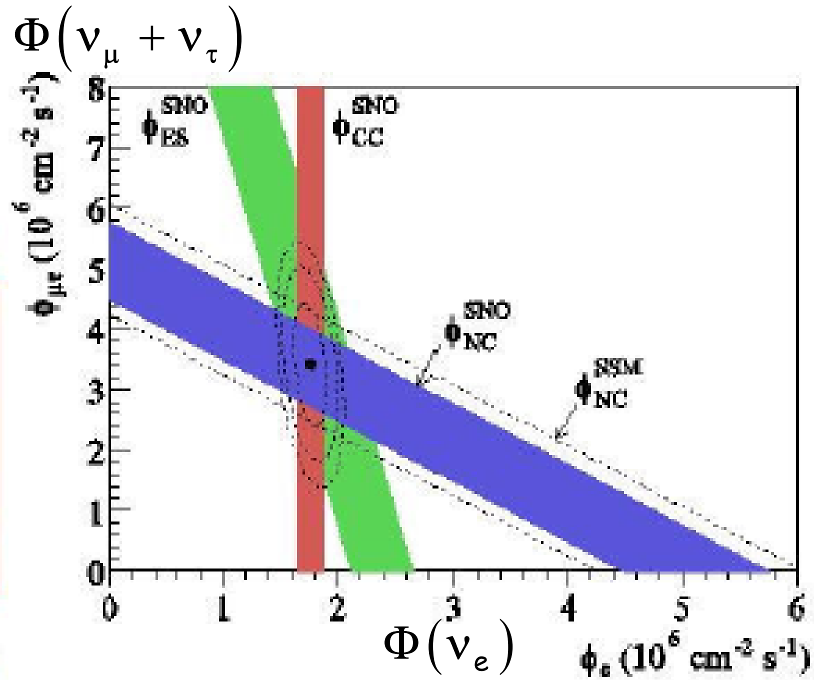
Compute 3 sample sizes by fitting MC spectra to 3 experimental spectra

## SNO 2002 : solar $B^8$ $\nu$ flux




Signal Extraction in $\Phi_{CC}$, $\Phi_{NC}$, $\Phi_{ES}$. $E_{Theshold}$ > 5 MeV

$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}$ (stat.) $^{+0.09}_{-0.09}$ (syst.) x$10^6$ cm$^{-2}$s$^{-1}$

$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}$ (stat.) $^{+0.12}_{-0.12}$ (syst.) x$10^6$ cm$^{-2}$s$^{-1}$

$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}$ (stat.) $^{+0.46}_{-0.43}$ (syst.) x$10^6$ cm$^{-2}$s$^{-1}$

Signal Extraction in $\Phi_e$, $\Phi_{\mu\tau}$.

$\Phi_e = 1.76^{+0.05}_{-0.05}$ (stat.) $^{+0.09}_{-0.09}$ (syst.) x$10^6$ cm$^{-2}$s$^{-1}$

$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}$ (stat.) $^{+0.48}_{-0.45}$ (syst.) x$10^6$ cm$^{-2}$s$^{-1}$

5.2 $\sigma$ above 0

&

Super – K

$\Phi_{es}(\nu_x) 2.32 \pm 0.03^{+0.08}_{-0.07}$

$\Downarrow$

$\Phi_{\mu\tau} = 3.45^{+65}_{-62}$

5.5 $\sigma$ above 0

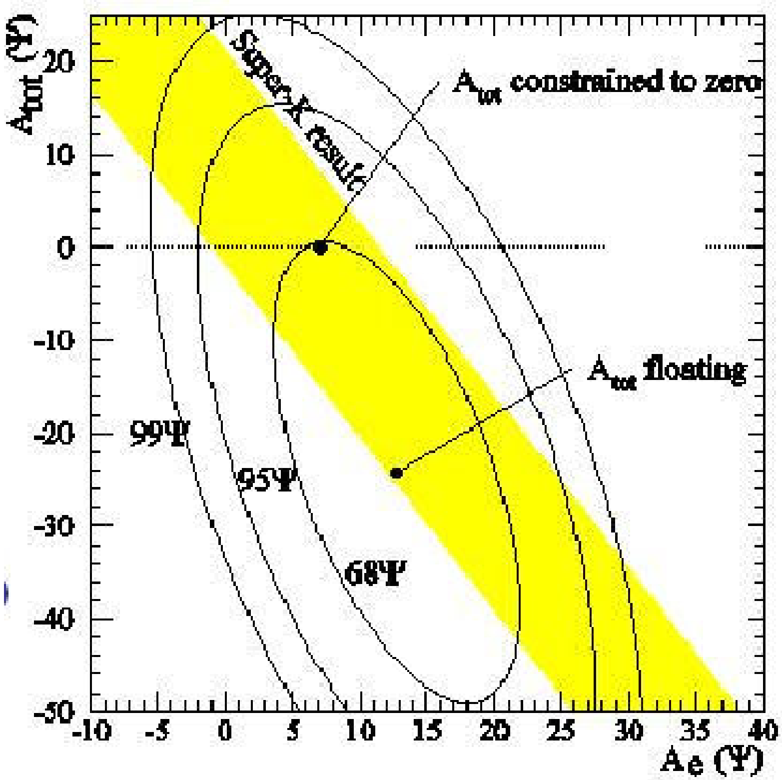
Sun Standard Model predictions:

$5.05^{+1.01}_{-0.81}$ Bahcall & Pinsonneault 2001

$4.95 \pm 0.72$ Turck-Chieze 2001

# SNO 2002 : additional data

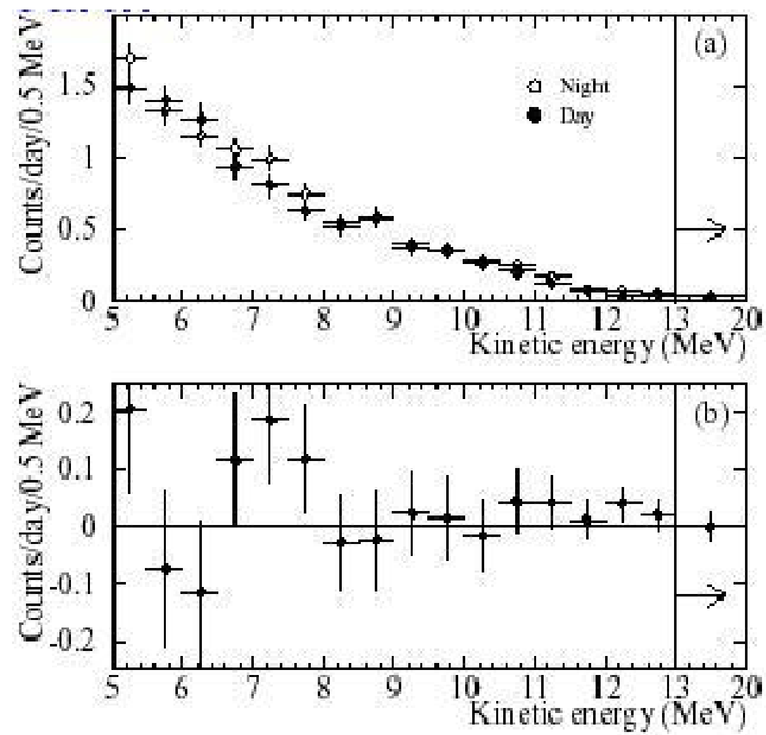
Day/night asymmetry (%)
for $\nu_e + \nu_\mu + \nu_\tau$ : $A_{tot}$
versus $\nu_e$ : $A_e$




For matter effects in Earth

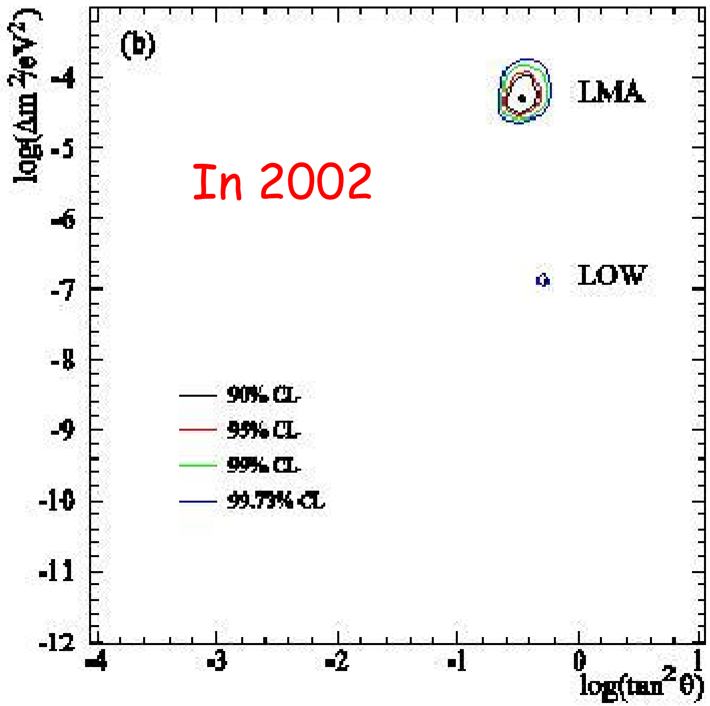
Day/night Energy spectra

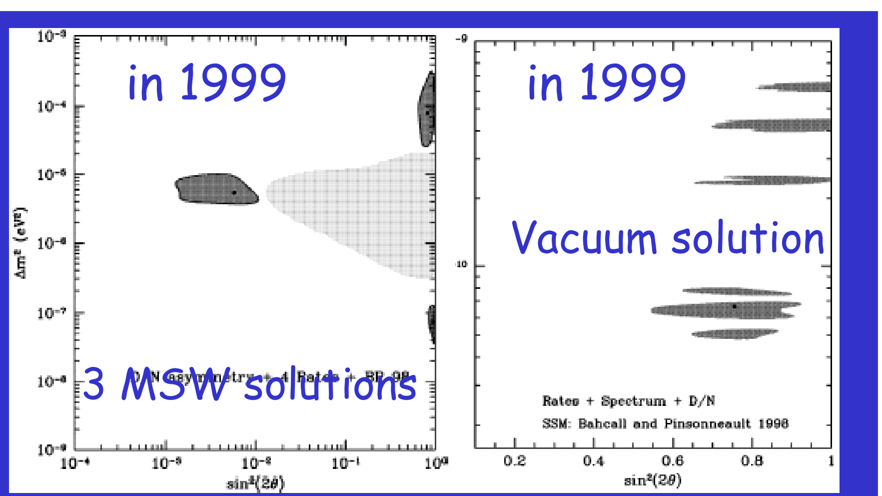
Day: $9.23 \pm 0.27$ events/day
Night: $9.79 \pm 0.24$ events/day




For energy dependence of oscillation prob

$\nu_e$ - $\nu_x$ oscillation signal plot using all solar neutrino data




Total $\nu$ flux measured by SNO agrees with total $\nu_e$ flux predicted by SSM.

Astrophysical explanation ruled out.

Something happens to $\nu_e$ between Sun core and Earth.

Neutrino oscillation is less extravagant explanation

Using all solar data and model predictions constraints the parameter space to a small region.

Best fit

$$\Delta m^2 = 5.0 \times 10^{-5}\ eV^2$$

$$\tan^2(\theta) = 0.34$$

Yet a second solution not excluded at 99.5%

# The atmospheric neutrino problem

- 1965 : experiments CWI and KJF both record first interactions of neutrinos produced in high atmosphere by cosmic rays.

- 1986 : the beginning of the problem: Irvine-Michigan-Brookhaven experiment

Crude approximation: $\dfrac{(\Phi_{\bar{\nu}_u} + \Phi_{\nu_u})}{(\Phi_{\bar{\nu}_e} + \Phi_{\nu_e})} \approx 2$ because

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

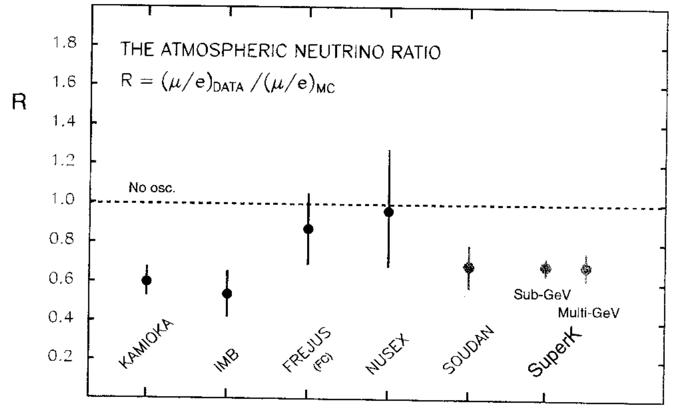
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

To reduce systematics from models : use

$$R = \frac{\left.\dfrac{(\Phi_{\bar{\nu}_u} + \Phi_{\nu_u})}{(\Phi_{\bar{\nu}_e} + \Phi_{\nu_e})}\right|_{measured}}{\left.\dfrac{(\Phi_{\bar{\nu}_u} + \Phi_{\nu_u})}{(\Phi_{\bar{\nu}_e} + \Phi_{\nu_e})}\right|_{expected}}$$

IMB reports enough $\nu_e$ and 25% too few $\nu_\mu$

• Lack of events with muons confirmed by all statistically significant (~10) experiments using large palette of technologies




•During recent years, detailed measurements by

SOUDAN-II large calorimeter in Tower-Soudan mine, Minnesota

MACRO 5.3 kt of layers of passive crushed planes of streamer tubes and liquid scintillator under Gran Sasso

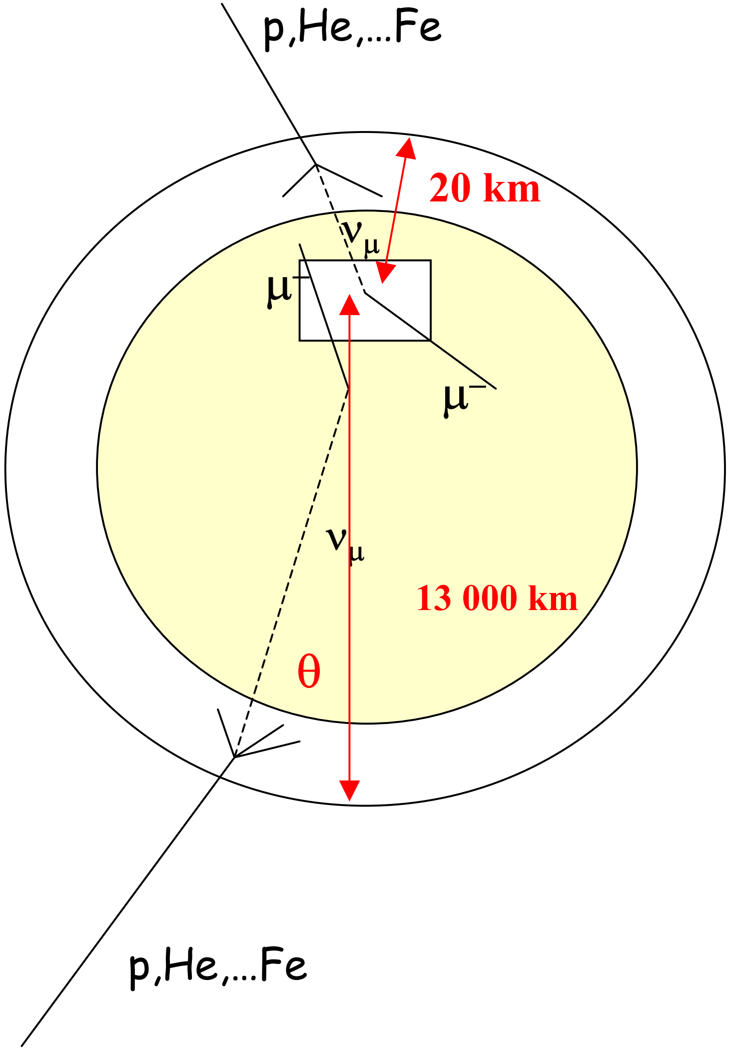
• By far most complete and precise results provided by Super-Kamiokande

• Verification by K2K: $\nu_\mu$ beam from KEK to Super-K <E>/L=1.3GeV/250 km

⇓

Super-K and K2K results only

# The magic free of charge atmospheric neutrinos beam line



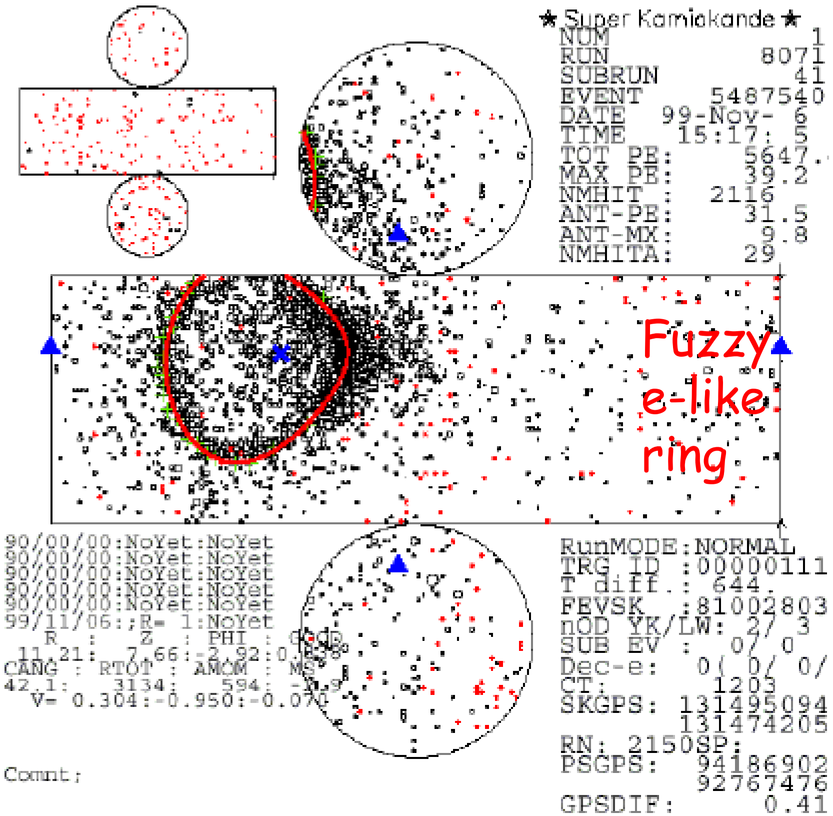

- 20 < L < 13 000 km
- Earth to produce matter effects and help solving ambiguities
- Within small computable corrections due to geomagnetic effects: Up/Down flux symmetry at neutrino emission

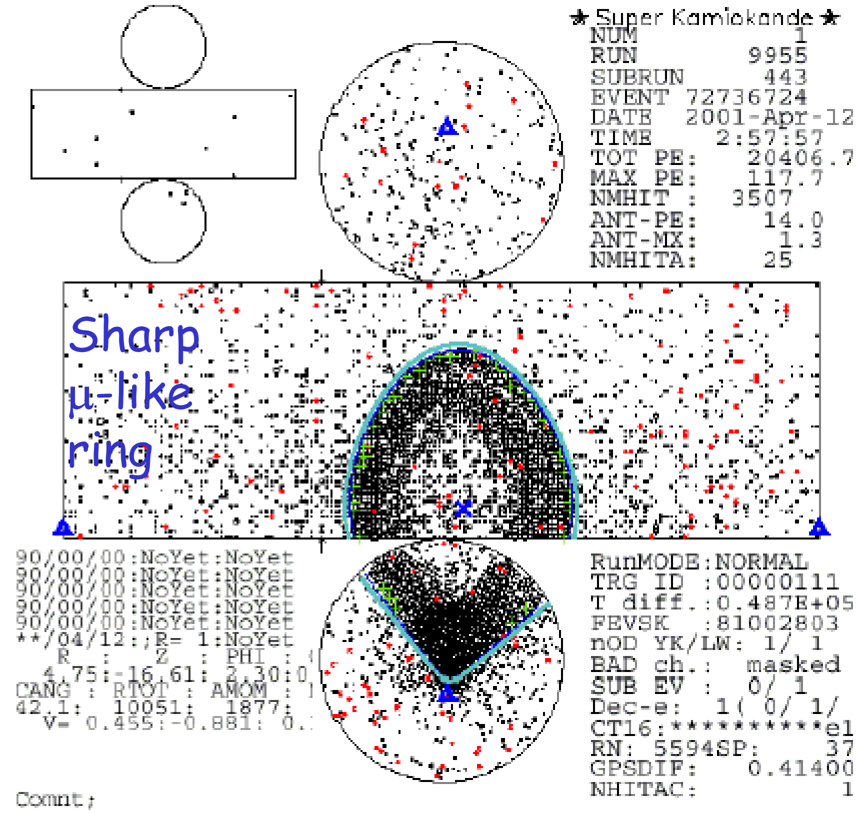
□ $\Phi(\theta) = \Phi(\pi - \theta)$ $\theta$ zenith angle

- But beam composition and spectra relies on models

# The Super-K events topology based Cerenkov ring :

No obvious difference but Particle Id ~ 100%




Not all e-like events are $\nu_e$ interactions

prompt $\pi/\mu$ decays to electron

$\pi^0 \rightarrow \gamma \rightarrow$ electrons

Not all μ-like events are $\nu_\mu$ interactions

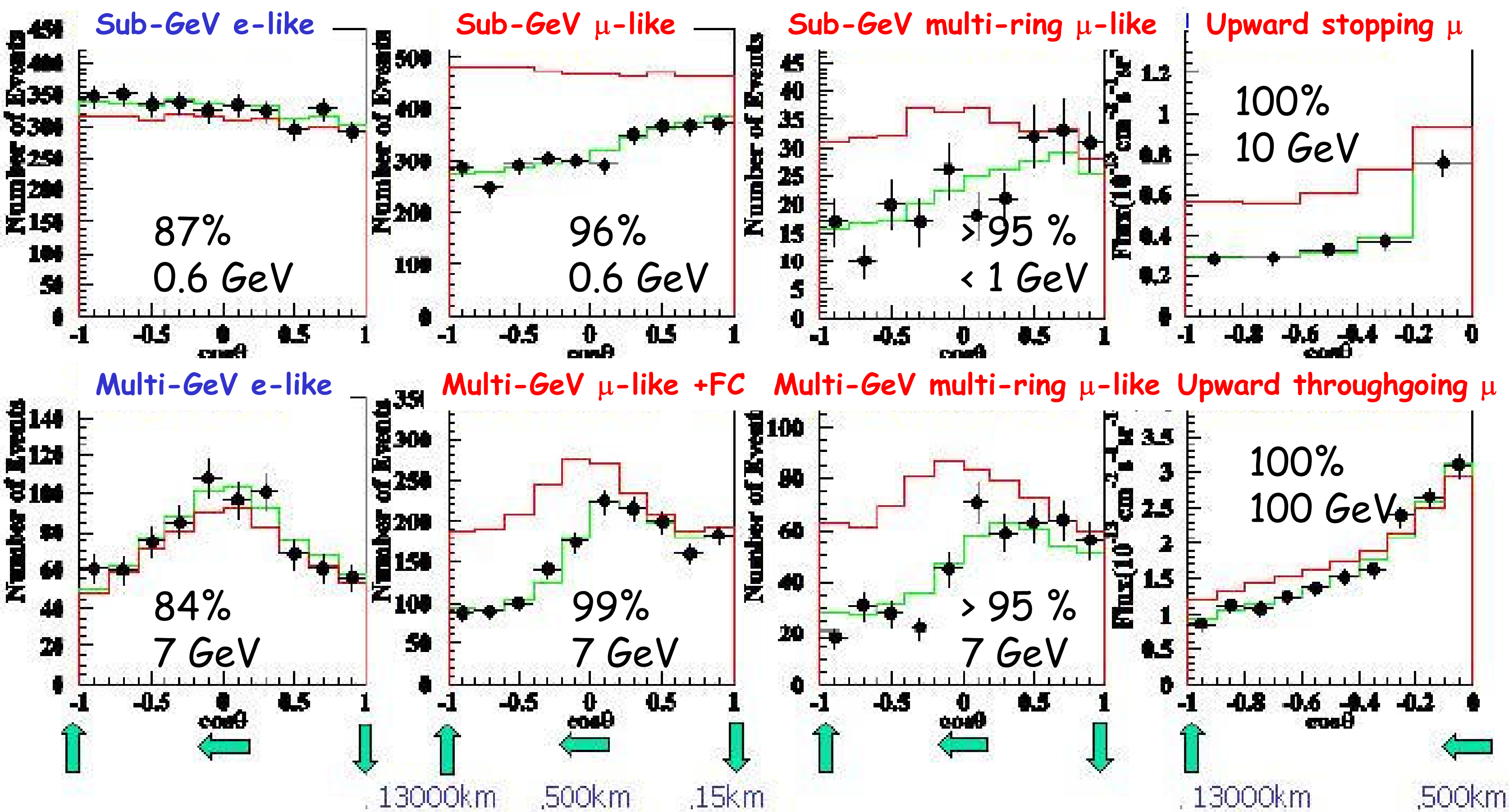
prompt $\pi$ decays to $\mu$

## Zenith angle distributions

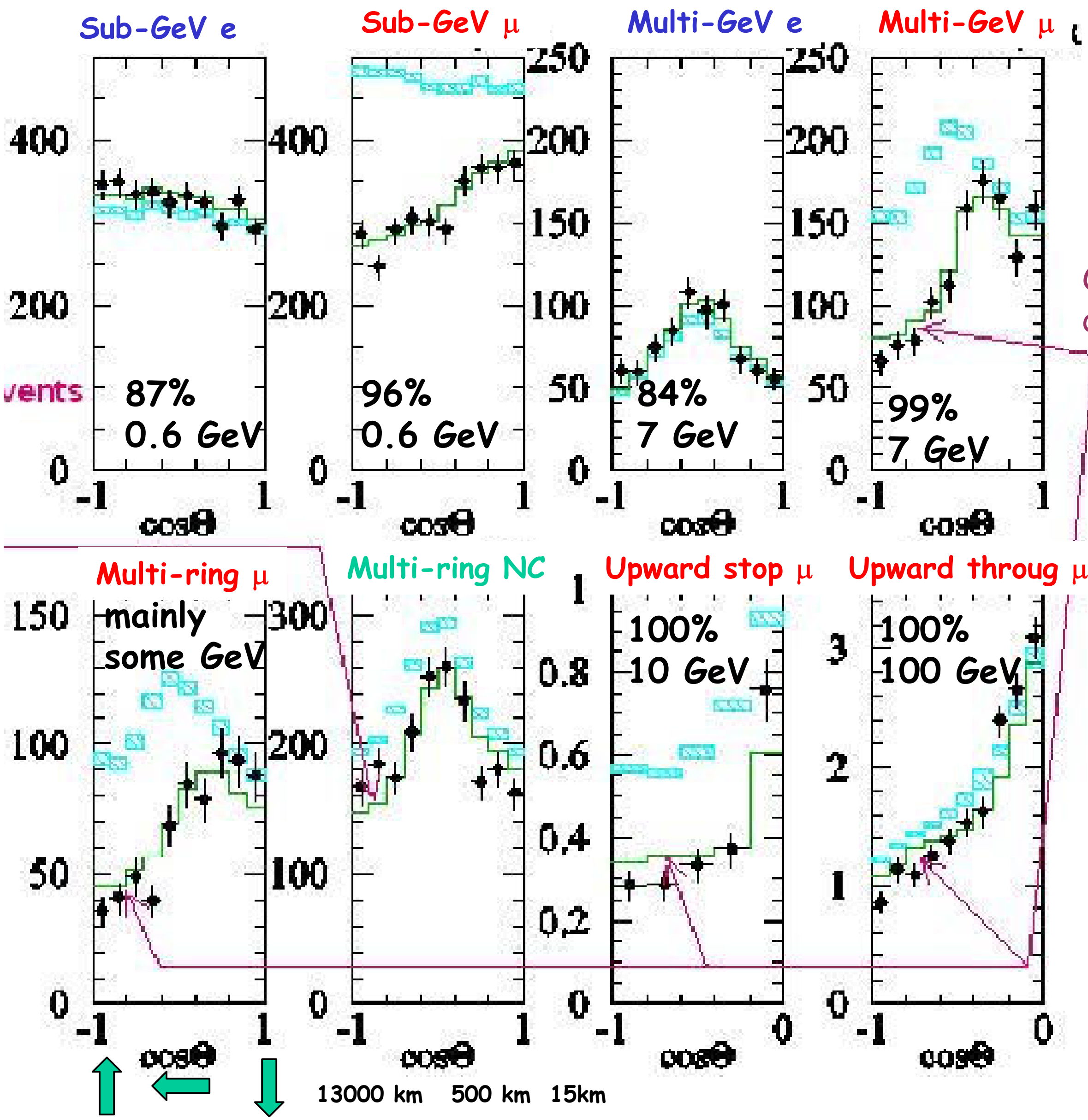
Two numbers per graph computed by Monte-Carlo:
% of main flavour
<E> in GeV

e-like
$\mu$-like

Best $\nu_\mu \rightarrow \nu_\tau$ fit
No oscillation



# Zenith angle distributions




Best $\nu_\mu \to \nu_s$ fit

No oscillation

Oscillation suppression
due to matter effects in Earth

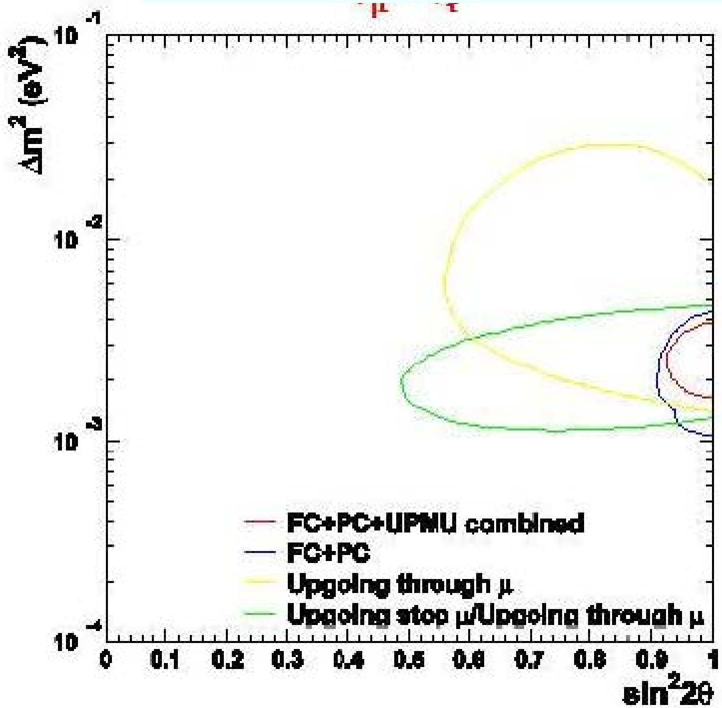
Two numbers per graph computed by Monte-Carlo:
% of main flavour
<E> in GeV

e-like

μ-like

Multi-ring NC events: enriched sample (29%) in NC events: several tracks and no muon

## Super-K parameters for $\nu_\mu \to \nu_\tau$ oscillation




Best fit($\Delta m^2$=2.5x10$^{-3}$, $\sin^2 2\theta$=1.0

$\chi^2_{min}$=163.2/170 d.o.f)

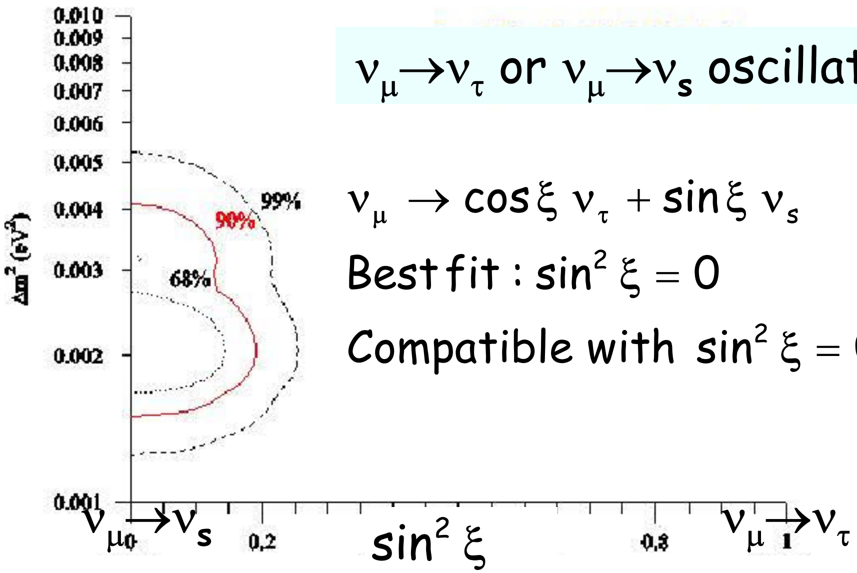
No oscillation

($\chi^2$ =456.5/172 d.o.f)

$\Delta m^2$ = (1.6~3.9)x10$^{-3}$eV$^2$

$\sin^2 2\theta$ > 0.92 @ 90%CL

## $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$ oscillation ?




$\nu_\mu \to \cos\xi\, \nu_\tau + \sin\xi\, \nu_s$

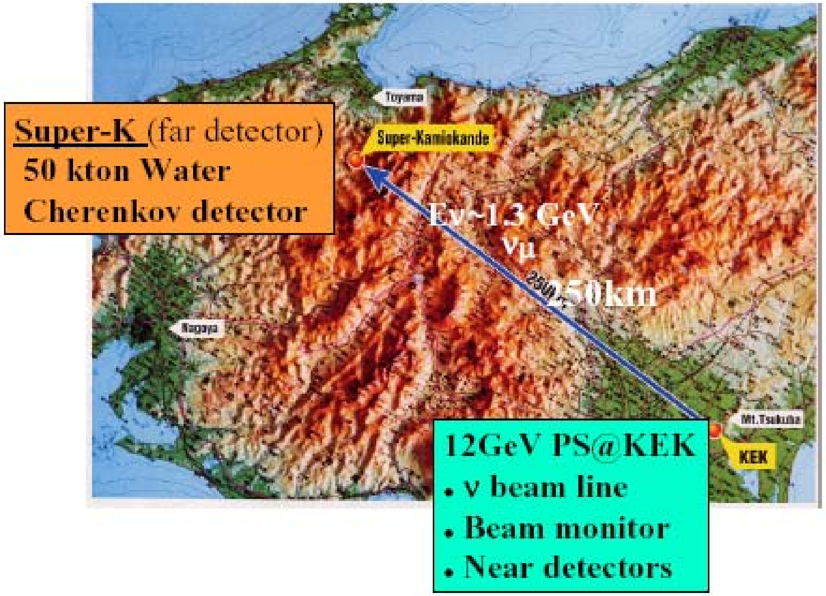
Best fit : $\sin^2 \xi = 0$

Compatible with $\sin^2 \xi = 0.25$ @ 99% C.L.

# K2K : the KEK to Kamioka Long Base Line experiment

<E>/L = 1.3 GeV / 250 km

Maximum sensitivity for $\Delta m^2 = 0.006\ eV^2$



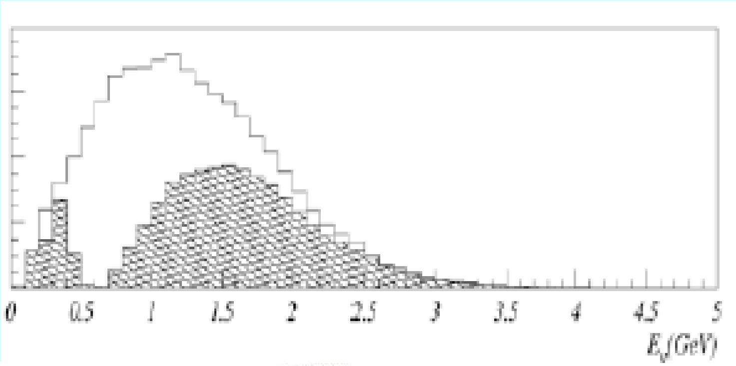

$\nu_\mu$ disappearance experiment

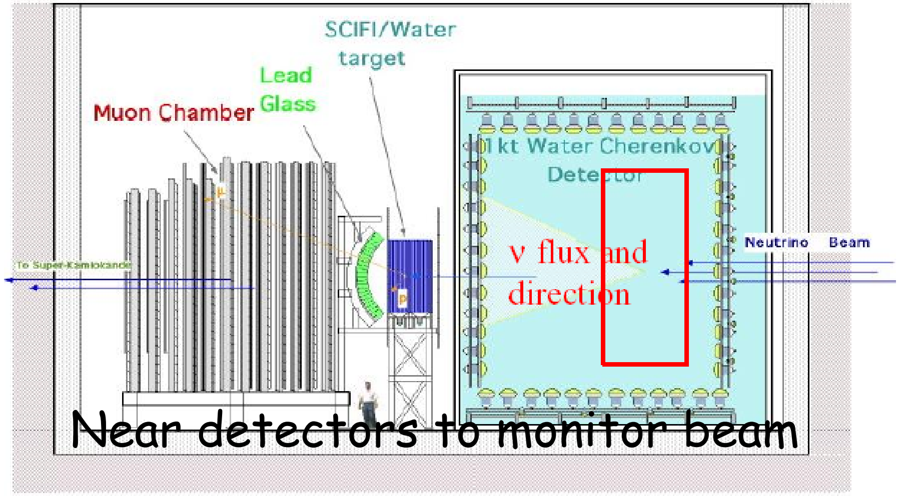
below the $\nu_\tau$ CC energy threshold

Observed energy spectra and relative rates if

No oscillation

$\nu_\mu \rightarrow \nu_\tau$ oscillation with $\Delta m^2 = 0.003\ eV^2$



E spectrum shape

- in agreement with no oscillation : 15% probability
- statistic small

Event rate

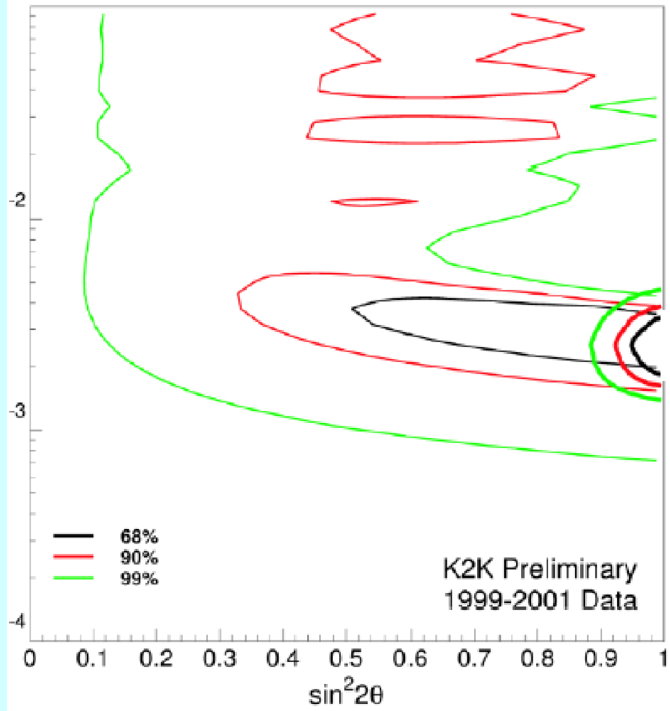
- 56 events observed
- 80 events expected if no oscillation
- 52 events expected if oscillation a la SuperK
- marginally in agreement with no oscillation : 1% probability

Best fit : $\Delta m^2 = 2.8 \times 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.0$

Compatible with Super-K signal

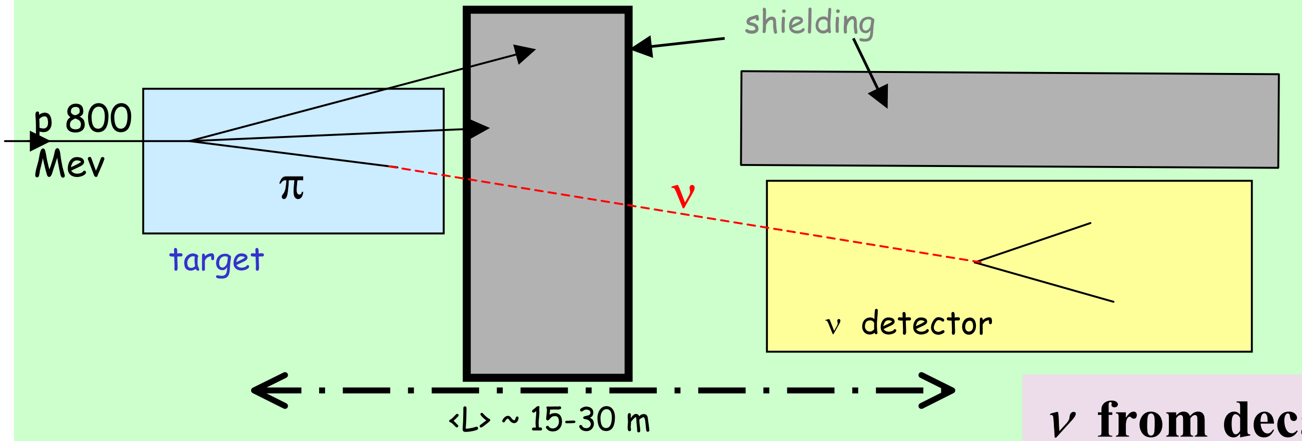
## K2K preliminary results




Super-K

# Neutrino oscillation at accelerator beam dumps

Search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at rather large $\Delta m^2$ >~ 0.1eV$^2$

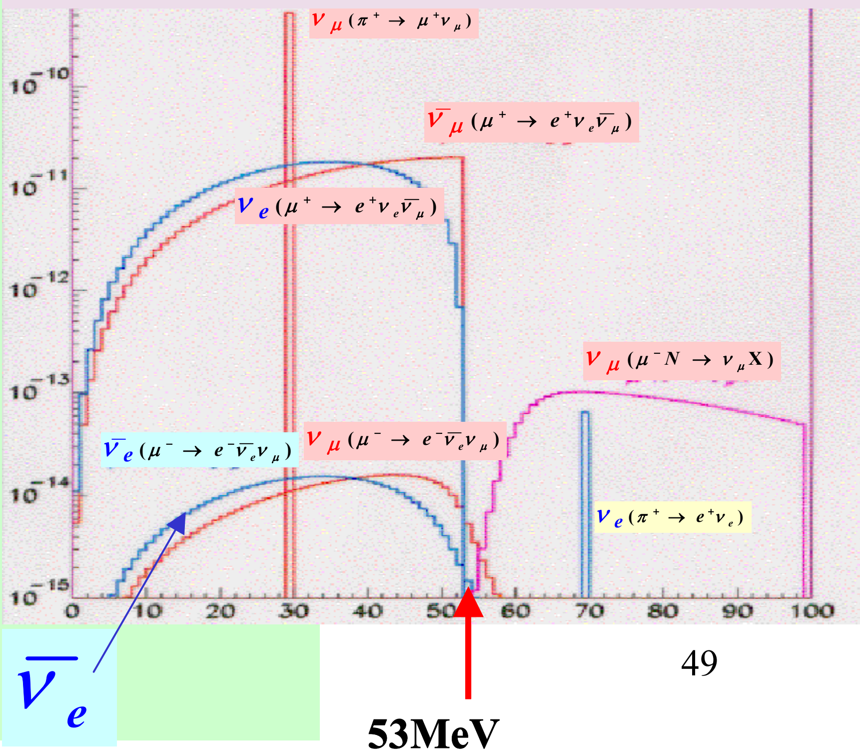



- $\pi^+, \mu^+$ stopped and decays at rest
- only $\nu_\mu, \bar{\nu}_\mu, \nu_e$ produced (below 53 MeV)
- Almost no $\bar{\nu}_e$ (<$10^{-3}$)

Detector: vessel filled liquid scintillator
doped with neutrophage
arrays of PMTs

Signal : inverse β decay $\bar{\nu}_e + p \to e^+ n$
remember CHOOZ

## ν from decays/captures at rest



## LSND experiment @ LANSCE, Los Alamos

167 tons low concentration liquid scintillator : sees Cerenkov light from $e^+$
checks direction correlation to beam

<L> = 29 m

Data taken till 1999

$32.7 \pm 9.2\ \bar{\nu}_e$ events ($3.5\ \sigma$) above 50.3 expected background

within statistics : all spectra compatible with expectation from oscillation signal

taken as signature of $\bar{\nu}_\mu - \bar{\nu}_e$ oscillation

## Karmen-II experiment @ ISIS, Rutherford Lab

56 tons liquid scintillator

Very sharp pulsed beam structure : events in 10 $\mu$s gate
very low & measurable background

<L> = 15 m

Data taken till 2001

11 $\bar{\nu}_e$ events observed

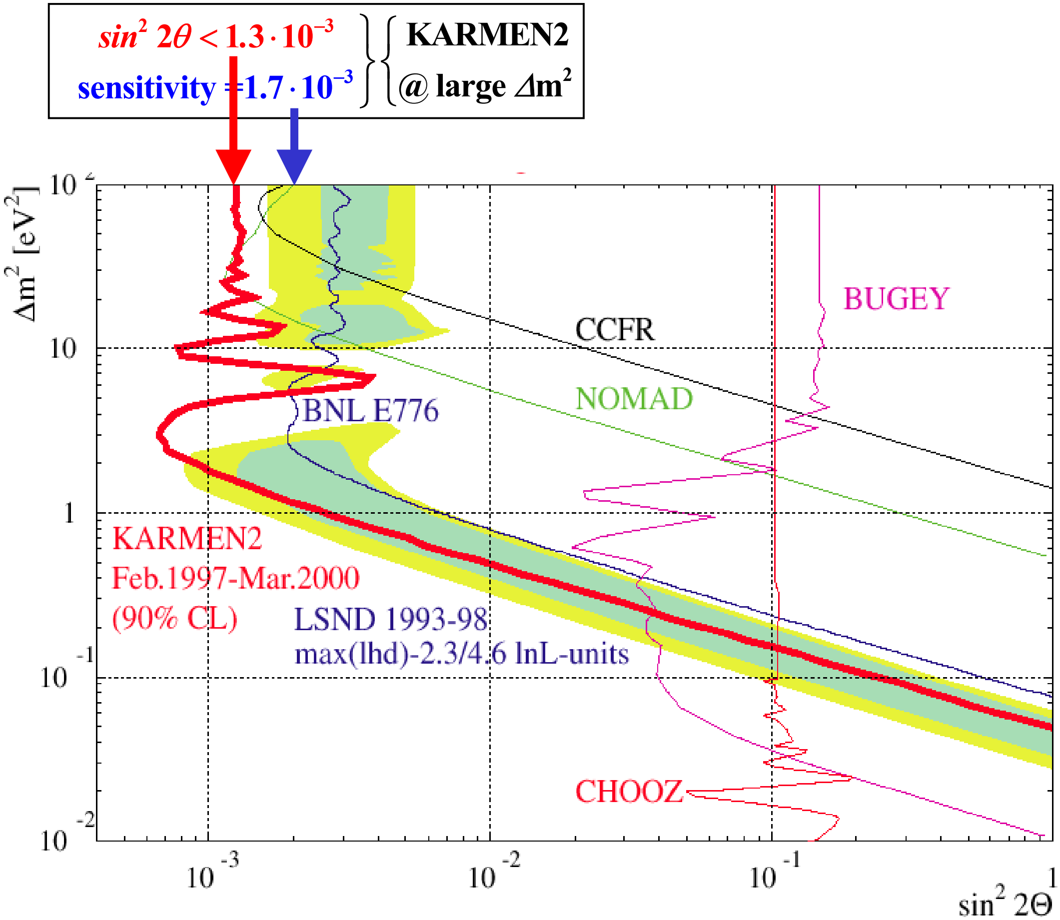
$12.29 \pm 0.63$ expected background

within statistics : all spectra agree with background expectation

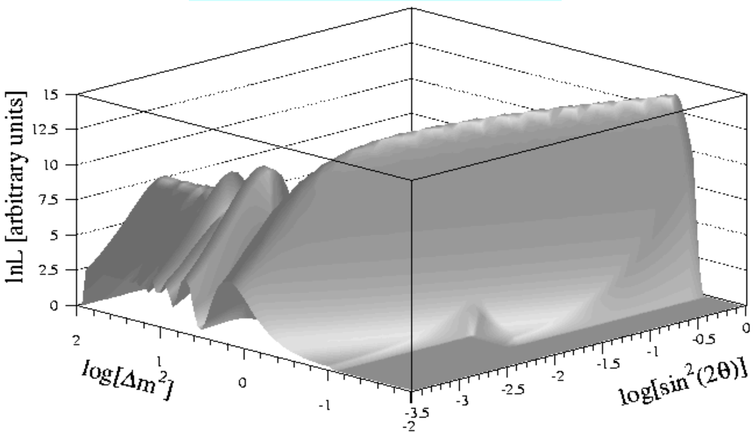
no signature of $\bar{\nu}_\mu - \bar{\nu}_e$ oscillation

KARMEN-II exclusion and LSND signal regions

Who is right, who is wrong ?
???????
Don't know ! So far compatible !

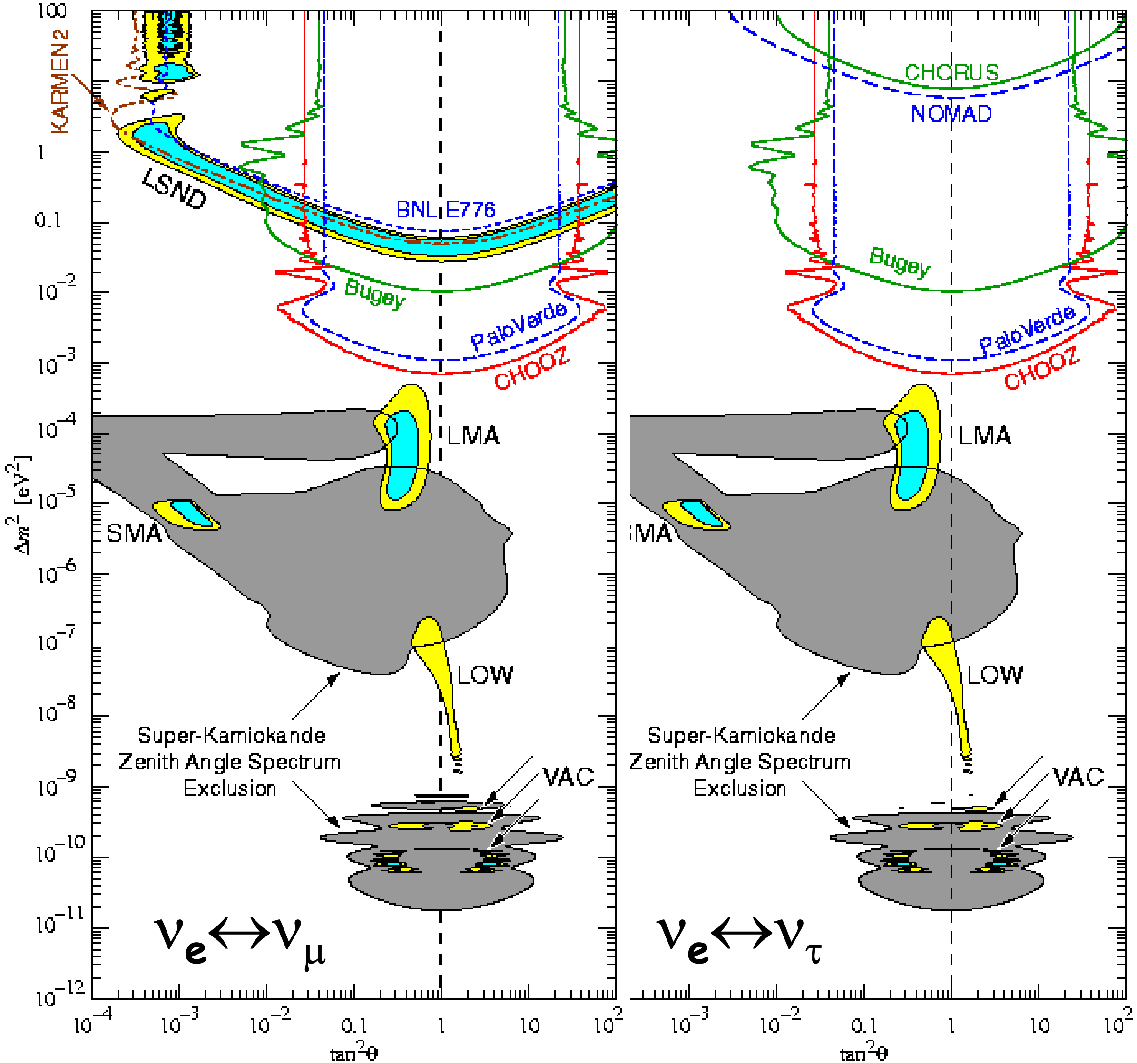


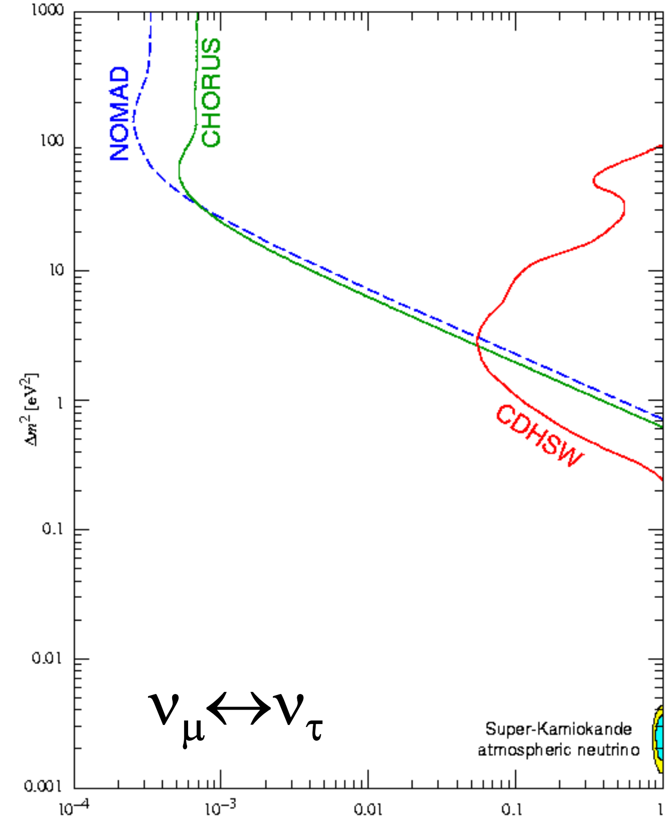

Joined likelihood




The combined result is NOT the intersection of the two plots.

# To summarise within the 2-family oscillation models




If all three signals are genuine:
At least 4 mass eigenstates
At least one sterile neutrino
Neutrino sector departs from minimal extensions of SM.

## The home work for the next 20 years
## to understand the neutrinos sectors ?

1 - Three or more neutrinos ?
Fixing the mixing matrix and the mass differences
forthcoming LBL oscillation experiments

2 - Fixing the zero of the mass scale
and Dirac v.z. Majorana neutrinos
forthcoming 3H and double-beta decay

3 - Is CP conservation violated as in the quark sector?
the most difficult, the very long term

# 1 - Fixing the mixing matrix and the mass differences

The simplest scheme

Ignore two additionnal phases if Majorana neutrinos : cannot be resolved by oscillation

Assume LSND signal is fake : 3 neutrinos flavours, no $\nu_s$

$$
U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array}
\begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{bmatrix}
c_{12}\ c_{13} & s_{12} c_{13} & s_{13}\ e^{-i\delta} \\
-s_{12} c_{23} - c_{12} s_{23}\ s_{13} e^{i\delta} & c_{12} c_{23} - s_{12}\ s_{23} s_{13}\ e^{i\delta} & c_{23} c_{13} \\
s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13}\ e^{i\delta} & s_{23}\ c_{13}
\end{bmatrix} \end{array}
$$

as CKM for quarks

$c_{ij} \equiv \cos\left(\theta_{ij}\right),\ \ s_{ij} \equiv \sin\left(\theta_{ij}\right)$

$\theta_{ij}$ relates to the mixing between generations i and j

In case of mass hierarchy: $m_3 \gg m1 \approx m2$ or $m_3 \ll m1 \approx m2$,

$$\Delta m^2 = \left|m_3^2 - m_2^2\right| \approx \left|m_3^2 - m_1^2\right| \qquad \delta m^2 = \left|m_2^2 - m_1^2\right|$$

it was shown that the oscillation probability simplifies:

$$P(\nu_l \to \nu_{l'\neq l}) \approx \sin^2 2\theta_{ll'}^{eff} \sin^2(1.27\Delta m^2 L/E)$$

with $\sin^2 2\theta_{ll'}^{eff} = 4\left|U_{l3}^* U_{l'3}\right|^2$

$$P(\nu_l \to \nu_l) = 1 - 4\left|U_{l3}\right|^2 \left(1 - \left|U_{l3}\right|^2\right) \sin^2\left(1.27\Delta m^2 L/E\right)$$

Assuming also CP conservation, $\delta$=0, it follows for the atmospheric neutrinos :

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(1.27\Delta m^2_{atm} L/E\right)$$
$$P(\nu_\mu \to \nu_\tau) = (\sin^2 2\theta_{atm} - \sin^2 2\theta_{13} \sin^2 2\theta_{23}) \sin^2\left(1.27\Delta m^2_{atm} L/E\right)$$
$$P(\nu_\tau \to \nu_e) = \sin^2 2\theta_{13} \cos^2 2\theta_{23} \sin^2\left(1.27\Delta m^2_{atm} L/E\right)$$
$$\text{with } \sin\theta_{atm} = \cos\theta_{13} \sin\theta_{23}$$

and thus

$$P(\nu_e \to \nu_x) = \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m^2_{atm} L/E\right)$$
$$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{atm} \sin^2\left(1.27\Delta m^2_{atm} L/E\right)$$
$$P(\nu_\tau \to \nu_x) = (\sin^2 2\theta_{atm} + \sin^2 2\theta_{13}(\cos^2 2\theta_{23} - \sin^2 2\theta_{23})) \sin^2\left(1.27\Delta m^2_{atm} L/E\right)$$

and for the solar neutrinos

$$P(\nu_e \to \nu_e) = \cos^4 2\theta_{13} \left(1 - \sin^2 2\theta_{sol} \sin^2(1.27\Delta m^2_{sol} L/E)\right)$$
$$\text{with } \sin\theta_{sol} = \sin\theta_{12}$$

What we know on the masses and the mixing angles:

$\Delta m^2_{atm} \approx 2.5\times10^{-3}\,eV^2 \gg \delta m^2_{sol} \approx 5\times10^{-5}\,eV^2$

Reactor (CHOOZ) : $\sin^2\theta_{ex} < 0.03$ at $\Delta m^2_{atm} \Rightarrow \theta_{13}$ is small $\Rightarrow c_{13}\sim 1$

Atmospheric : maximum mixing $\theta_{atm} \approx \pi/4$ ; $\sin\theta_{atm} \approx \cos\theta_{atm} \approx 1/\sqrt{2}$

Solar : large maxing : $\sin^2\theta_{sol} \approx \sin^2\theta_{12} \approx 0.25$

Including again a possible non-zero CP phase $\delta$

$$
\begin{array}{c} \\ U = \begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \end{array}
\begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\
\begin{bmatrix} c_{sol} & s_{sol} & s_{13}\,e^{-i\delta} \\ -s_{sol}/\sqrt{2} & c_{sol}/\sqrt{2} & 1/\sqrt{2} \\ s_{sol}/\sqrt{2} & -c_{sol}/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \end{array}
$$

$\theta_{sol}$ is large and its measurement will be improved.

Given that $s_{13}$ is small, if $\delta$ is also small, $s_{13}\ e^{-i\delta}$ will be difficult to measure.

## Oscillation : the immediate and the approved medium term future (1)

**Solar signal** $\nu_e - \nu_x$

| | |
|---|---|
| SNO phase 2 - Add NaCl in $D_2O$ : increase neutron capture<br>Increase NC sensitivity | Data taking June 2001 |
| SNO phase 3 - insert $He^3$ counters : increase neutron capture | 2003 |
| KamLAND conversion of Kamioka-II: 1 kton liquid scintillator inside water-Cerenkov tank<br>Watch neutrinos from Japanese nuclear power plants<br>Low energy (some MeV) Long Base Line ($\langle L \rangle = 150$ km) | Data taking Fall 2001 |
| BOREXINO in Gran Sasso Laboratory: 300 tons liquid scintillator inside water tank<br>Low energy threshold below 0.862 MeV $\nu_{Be7}$ line<br>See both $\nu_{Be7}$ an $\nu_{B8}$ | Should have started Fall 2002<br>Incident… |

# Oscillation: the immediate and the approved medium term future (2)

## Atmospheric signal - $\nu_\mu - \nu_\tau$    Accelerator Long Base Line Experiments (730km)

| | | |
|---|---|---|
| K2K | resume data taking after repair of Super-K detector<br>disappearance experiment | 2003 |
| OPERA - CERN/CNGS beam $\nu_\mu$ to Gran Sasso Laboratory | detect the prompt $\tau$ track in 2 kton Pb target<br>instrumented with nuclear emulsion films | 2006 |
| MINOS - NUMI/FermiLab $\nu_\mu$ beam to Soudan Mine | 5.4 kton iron/scintillator magnetised calorimeter<br>Measure NC/CC rates and CC energy spectrum | 2005 |

## LSND signal - $\nu_\mu - \nu_e$    Accelerator Short Base Line Experiment

MiniBOONE at FermiLab — Data taling October 2002

- 770 tons mineral oil : scintillation + Cerenkov light
- $L/\langle E\rangle = 0.5$ km / 1 GeV
- sensitivity in parameter space largely covers LSND signal

Oscillation experiment program will tell us by ~2008 :

- if 3 or $\geq 4$ neutrino flavours
  - if not, the physics will become maybe even more interesting
  - but the picture much more complicated
- precise measurements of $\Delta m^2_{atm}$ , $\Delta m^2_{sol}$ : the mass scale,
- precise measurements of a fair part of the mixing matrix $\theta_{atm}$ , $\theta_{sol}$
- confirm if $\nu_\mu \rightarrow \nu_\tau$
- the oscillation pattern in L/E is observed

## 2 - The direct mass and the double-beta decay

Where is the zero on the mass scale ?

KATRIN project in Bonn on $^3H$ $\beta$ decay to start in 2006 :

$m_{\nu_e}$ down to sub-eV

Dirac or Majorana neutrinos ?

$0\nu\beta\beta$ decay

About 15 experiments aim at $m_{\nu_e}$ down to tens keV in 10 years

Both very difficult : sensitivity, background, resolution, long term stability, etc...

# 3 - Is CP conservation violated as in the quark sector?

- if CPT conserved: $P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}\ ;U) = P(\nu_\ell \to \nu_{\ell'}\ ;U^*)$
- if CP violated: $P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \neq P(\nu_\ell \to \nu_{\ell'})$

CP violation comes as $s_{13}\ e^{-i\delta}$ in the mixing matrix

with $s_{13} < 0.1$

Very long base line. Is CP violated in the lepton sector as in the quark sector?

Very intense neutrino beams (super-beams, neutrino factories, β-decay beams),

Very massive detectors

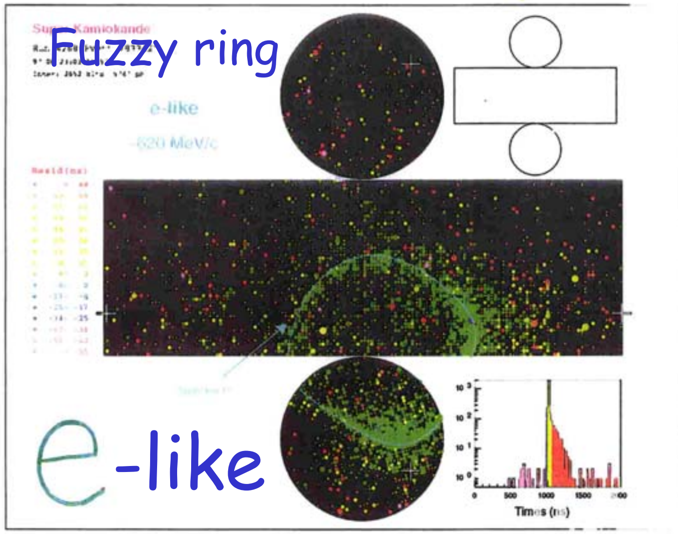
Neutrino factories : $\pi^+ \to \mu^+ \to e^+$ only $\nu_e$ - no $\bar{\nu}_e$

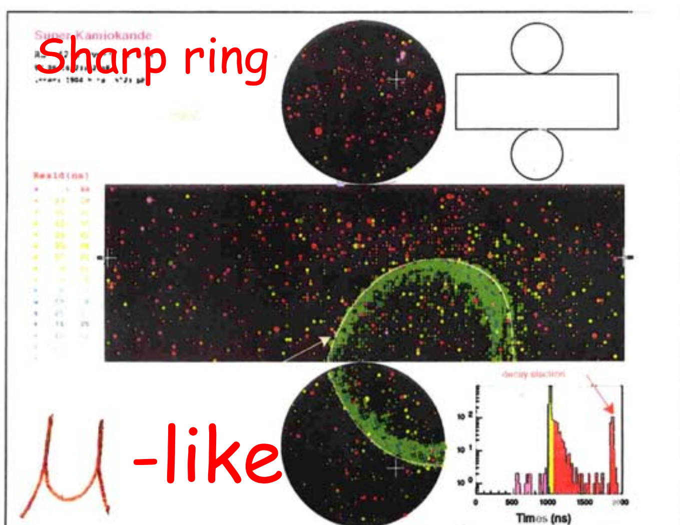
$\pi^- \to \mu^- \to e^e$ only $\bar{\nu}_e$ - no $\nu_e$

The very long term program, well in the next decade

# Extras

## The Super-K jargon : topology and energy classes (1)
## Events with a single Cerenkov ring :




Inside detector fiducial volume : 82%

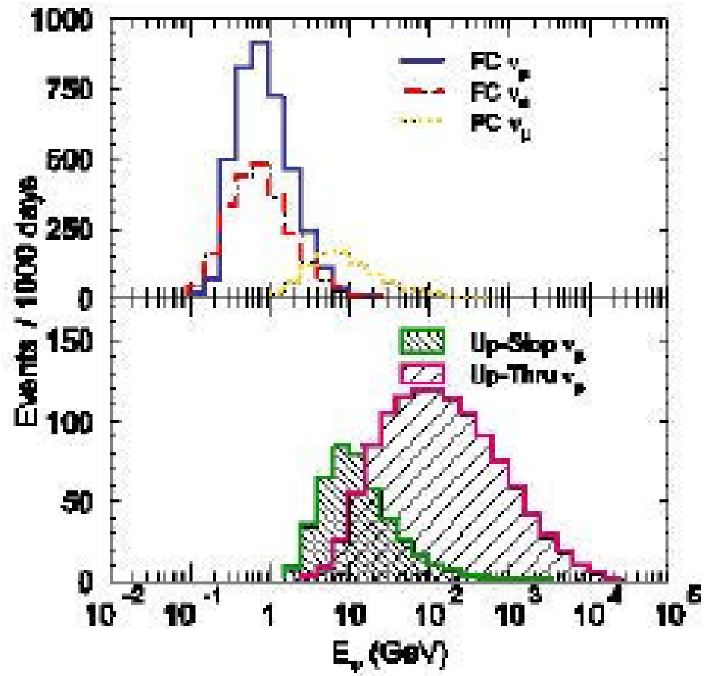
| Fully Contained events 75% | | Partially contained |
|---|---|---|
| Sub GeV | Mutli GeV | 7% |
| <E>=0 .6 GeV | <E>=7 GeV | <E>=10 GeV |
| 62% | 13% | |
| 31% 87% $\nu_e$ 1.7% $\nu_\mu$ 9.8% NC | 7% 84% $\nu_e$ 7.1% $\nu_\mu$ 8.6% NC | |
| 30% 0.3% $\nu_e$ 96% $\nu_\mu$ 4.2% NC | 6% 0.6% $\nu_e$ 99% $\nu_\mu$ 0.4% NC | 1.9% $\nu_e$ 98% $\nu_\mu$ 0.9% NC |

Monte-Carlo estimations of CC $\nu_e$ and CC $\nu_\mu$ and NC as fractions of concerned sample

# The Super-K jargon : topology and energy classes (2)
## Events with single Cerenkov ring :

+ 18 % Upward muons :
Interactions of neutrinos arriving from
South hemisphere in the rock below the detector

(Downward going muons from the North hemisphere
overwhelmed by cosmic muons)




| Through going muons (+11%) | Stopping muons (+2%) |
|---|---|
| ~100% $\nu_\mu$ | ~100% $\nu_\mu$ |
| <E>=100 GeV | <E>=10 GeV |

# The Super-K jargon : topology and energy classes
## Multi-Cerenkov rings

Additional sample (35% of single-ring)
85% e-like enriched in NC events (29% compared to 6%)
15% $\mu$-like CC $\nu_\mu$